

U.S. Department of the Interior

INTERIM REPORT TO CONGRESS
PRESENCE OR ABSENCE OF SIGNIFICANT
THERMAL FEATURES
in
CRATER LAKE NATIONAL PARK

September 1989

CRLA

National Park Service

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1989.

INTERIM REPORT TO CONGRESS

on

PRESENCE OR ABSENCE OF SIGNIFICANT THERMAL FEATURES

in

CRATER LAKE NATIONAL PARK

September 1989

In response to Section 115 of the General Provisions of the Department of the Interior and Related Agencies Appropriations Act for 1987 (Public Law 99-591), the National Park Service initiated a scientific study in the summer of 1987 to determine the presence or absence of significant thermal features within Crater Lake National Park. That research has uncovered some important new scientific data including water temperature and chemical anomalies and the presence of bacterial mats on the floor of the lake. All members of the peer review panel appear to agree that "...some form of ground water is entering the lake beneath the South Basin, and this water is responsible for temperatures slightly elevated above the normal lake values, for some of the anomalous chemistry in the lake water, and possibly for the growth of bacterial mats on the lake bottom."

While the research results bear directly on the question of the presence or absence of significant thermal features, the peer review panel and the researchers have identified information gaps which are critical to arriving at a final conclusion. The additional research necessary to fill these data gaps and the associated laboratory analyses, interpretation, report preparation and peer review will require additional time beyond the current schedule. Accordingly, we propose late summer 1991 as a target time for submitting the final report to Congress.

I. Legislative Requirements

Section 115 of Public Law 99-591 instructed the Secretary of the Interior to publish a proposed list of significant thermal features within selected units of the National Park System, including Crater Lake National Park. On February 13, 1987, the National Park Service published a proposed list of significant thermal features. This list included hydrothermal vents on the south central floor of the basin of Crater Lake.

A final list of significant thermal features, published on August 3, 1987, did not include Crater Lake because the Department decided that there was "...insufficient information upon which

to list Crater Lake as a significant thermal feature under the criteria of the Act," and deferred making a determination of significance until further research and review were conducted.

The Geothermal Steam Act Amendments of 1988 (Public Law 100-443), dated September 22, 1988, included a list of significant thermal features within units of the National Park System and included Crater Lake National Park. Section 7 of the Act also directed the Secretary to submit to Congress "a report on the presence or absence of significant thermal features within Crater Lake National Park" within 6 months after becoming law.

The National Park Service has subsequently informed Congress that a report on the presence or absence of significant thermal features--as called for in Section 7--will be possible only when the results of the completed research effort and subsequent peer review are available. A new reporting schedule is proposed in the last section of this report.

II. Research To Date

Research targeted specifically at determining if hydrothermal activity exists in Crater Lake began in the summer of 1987. Drs. Robert Collier and Jack Dymond of Oregon State University under a cooperative agreement with the National Park Service, carried out an initial exploration phase of the multi-year study. A remotely operated submersible vehicle was used to obtain videos of underwater features, water column physical properties were measured, and samples were obtained for chemical and isotopic analyses. The first year's efforts provided valuable information for developing a detailed research proposal for the next year. The report on the first year's work and the draft proposal for the second year's work were distributed to the U.S. Geological Survey, Bureau of Land Management, California Energy Company, Inc., and professional peers for review. Review comments were provided to the principal investigators for consideration in revising work plans for the second year.

The goals of the second year (1988) program were: (1) to determine if hydrothermal venting is occurring within the lake; (2) if evidence of venting was found, to clarify the nature of the venting; (3) to define the composition and temperature of venting fluids; (4) to understand the biological consequences of thermal or cold-spring inputs to the lake; and (5) to carry out ancillary geological and biological sampling and observations in those regions of the lake that lie beyond the depths of free divers. Important progress was made toward all of these goals. A one-person submersible considerably extended the scientists abilities to make observations and collect data.

The report of field studies conducted in 1988, which summarizes the findings to date (Appendix I), and the proposal for a third year of research (Appendix II) were subjected to formal peer review. The peer review panel, chaired by Dr. Charles R. Goldman, met on May 2, 1989, to consider the adequacy of research being done to answer the question of whether geothermal venting and/or diffuse heat flow was occurring in Crater Lake. The panel report (Appendix III) was submitted to the National Park Service on August 4, 1989. Drs. Collier and Dymond produced an appendix to their draft research proposal based on recommendations from the panel (Appendix IV).

III. Research Findings

The following summary is taken in its entirety from the report of field studies conducted in 1988 by Drs. Collier and Dymond (Appendix I):

"Submersible observations within the South Basin have defined fine-scale variations in temperature and salt content of the near-bottom waters. Temperature variations of up to 0.5°C and conductivity variations of more than a factor of two occur over distances of a few meters. The magnitude and spatial scale of these variations require a continuing input of warmer and more saline water to maintain such high gradients. Variations in the conductivity-to-heat ratios within the South Basin indicate that the necessary fluid inputs cannot result from a single source of anomalous water. Despite these temperature and conductivity evidences of anomalous fluid sources, no actual vents were observed within our detailed study area of the South Basin. The lack of visual evidence of venting could either be a consequence of incomplete survey coverage of the study area or diffuse venting that cannot be detected visually. Either explanation can be defended. Less than 10% of the study area was observed visually; lack of precise navigation prevented highly detailed search patterns that might have found the source of some of the most impressive anomalies. On the other hand, diffuse hydrothermal advection is well documented in sedimented areas of the ocean. Advection velocities of centimeters to a few meters per year have been measured by studies of sediment pore water that are influenced by marine hydrothermal systems. Although such flows could not be detected visually they could introduce significant heat and ions into the bottom waters.

"The communities of bacteria, which produce impressive mat features on rock outcrops and sediment surfaces, provide evidence of diffuse venting on the lake floor. These features cover areas up to several meters across and have internal temperatures elevated by as much as 6.0°C . They appear to be chemolithotrophic communities which use abundant reduced iron in advecting fluids to fuel their metabolism. There were no visual

indications of flow from the mats, and the internal chemical and density gradients, which could constrain the advection rate, were not measured. Advection is implied because it seems unlikely that such a prolific bacterial communities could be maintained by a slower process like diffusion. Moreover, only fluid advection can maintain the 6°C temperature gradient that is observed across the interface between the mat and the bottom waters. Despite the striking nature of the mats, temperature and conductivity anomalies in the immediate vicinity of the mats were often not exceptional. In fact, at the site of the largest mats, the temperature anomalies were quite small. We could only note a general association (on a spatial scale of 100 to 200m) of mat presence with near-bottom temperature anomalies. The lack of anomalies in close proximity to mats is compatible with diffuse venting. Consequently, the bacteria mats are aptly described as visual markers of this type of venting. A possible inconsistency in this argument is the fact that we did record near-bottom temperature anomalies which were at least 2-5 times greater than those measured in the near vicinity of mats. One might presume that such anomalies must be accompanied by either larger or more vigorous venting than the diffuse venting which apparently results in the bacterial mats. This analogy seems to suggest our submersible transects may indeed have missed the most impressive visual indications of venting.

"Sampling of the near-bottom waters and mat fluids has extended the range of anomalous water composition which are found within Crater Lake. For example, the anomalies with respect to background lake levels for major elements are nearly a factor of two. Manganese and ^{222}Rn , both important tracers of hydrothermal sources in the ocean, are as much as 1900 and 200 times enriched over typical lake values, respectively. Helium-3, perhaps the most distinctive indicator of a magmatic source, is more than a factor of five enriched over values which would be in equilibrium with atmospheric sources. Even more important than the magnitude of these enrichments is the fact that the ionic relationships of the anomalous waters can now be defined sufficiently to account for the bulk lake compositions, which were hitherto unexplainable by known water sources (e.g. precipitation and caldera springs). These data have permitted us to attempt the geochemical mass balances for the lake which include realistic estimates of composition of a hydrothermal input. The models delimit the range of possible hydrothermal flows into the lake.

"We have made some important steps as a result of the 1988 field program. These results help to constrain the important hypotheses that may influence the physical, chemical, and biological processes of Crater Lake and provide a foundation for identifying new experiments for the coming field season."

IV. Peer Review

A peer review panel was formed with a broad mandate to look at the entire research work, the results and the proposed plans and to make appropriate comments and recommendations. The panel members, selected by the Chairman, Dr. Charles R. Goldman, met in formal session in Corvallis, Oregon, on May 2, 1989. Panel members were:

Limnology: Dr. Charles R. Goldman, Chairman and Professor of Limnology, Division of Environmental Studies, University of California, Davis

Geophysics: Dr. David Blackwell, Hamilton Professor of Geophysics, Department of Geological Sciences, Southern Methodist University, Dallas, Texas

Geochemistry: Dr. Joris Gieskes, Professor, Scripps Institution of Oceanography, University of California, La Jolla, California

Geology: Dr. James McClain, Professor, Department of Geology, University of California, Davis, California
Dr. Ivan Barnes, U.S. Geological Survey, Portland, Oregon.
Corresponding Member (Now deceased)

Microbiology: Dr. Ken Nealson, Centre for Great Lakes Research, University of Wisconsin, Milwaukee, Wisconsin

Thermal Modeling: Dr. Jorg Imberger, Centre for Water Research, Department of Civil Engineering, University of Western Australia, Nedlands, Western Australia. (Corresponding Member)

The Panel report summarizes the research question as follows:

"We presume from the beginning that the observations are designed to test the hypothesis that deep circulating hydrothermal waters are entering the bottom of Crater Lake. It appears that all parties agree that some form of ground water is entering the lake beneath the South Basin, and this water is responsible for temperatures slightly elevated above the normal lake values, for some of the anomalous chemistry in the lake water, and possibly for the growth of bacterial mats on the lake bottom. It is the origin and significance of this water that remains in question."

In addition to the materials produced by Drs. Collier and Dymond, the panel members were provided comments prepared by the Bureau of Land Management and the California Energy Company and a collection of published and in-press papers on the subject provided by Wilson Goddard Associates, consultants for California Energy Company, Inc.

The panel report (Appendix III) is a concise document and is best read in its entirety rather than abstracted or highlighted. The work is a scholarly effort and the authors provide a number of

recommendations which they believe will help address the basic research question. Draft recommendations were made available to the principal investigators in time for them to modify and amplify the research proposal for the 1989 field season (Appendix IV).

V. Proposed Research - Year Three

Specific goals for the final field season (summer, 1989) and subsequent analysis period are: (1) to evaluate known sites of spring inputs and investigate the origin of known chemical and thermal anomalies, (2) to expand surveys to areas outside of the current Detailed Study Area, (3) to determine the mode and rates of venting in the deep lake, (4) to determine rates of vertical and horizontal mixing in the deep lake, (5) to evaluate the sedimentological and paleolimnological consequences of hydrothermal activity in the lake, and (6) to support ancillary biological and geological research programs. A manned submersible is being used again in support of the research program.

The principal investigators, in their proposal for a third year of research, anticipated many of the information gaps identified by the peer review panel. In addition they speak to nearly all the points raised by the panel in their "Responses to the List of Recommendations from the Peer Review Panel on the Proposed Research." In their words, "We have carefully considered the recommendations of the peer review committee and feel we have included as many of their suggestions as possible."

VI. Proposed Research - Year Four

The diversity and magnitude of the data sets which will have been collected over the three years of the project will be substantial. Recently it was determined that the currently agreed to date of June 30, 1990, for submission of the final report to Congress, is unrealistic. The time necessary to complete laboratory work, data analysis and interpretation, report preparation, peer review, and review by other agencies is greater than the time allowed following the field season.

Work which would be accomplished with additional time includes initial evaluation of hydrothermal activity over the 6900 year history of the lake; evaluation of the influence of anomalous fluids (possibly hydrothermal) on the mixing of the lake and nutrient cycling following additional winter data obtained from 1989 and 1990; and preparation of one or more major synthesis papers which will use the full range of chemical, physical, biological, and geological data which will have been collected during the project. Completion of this work will be important to

understanding the significance of anomalous fluids to the lake ecosystem and to addressing the question of presence or absence of significant thermal features in Crater Lake .

We estimate that an additional year will be needed for completion of the research, peer review, and preparation of the draft final report to Congress, including consultation and collaboration with the U.S. Geological Survey and the Bureau of Land Management at the regional level. We expect agency review at the national level and departmental review to take an additional two months. Accordingly, we propose late summer 1991 as a target time for submitting the final report to Congress.

Studies of Hydrothermal Processes in Crater Lake

A Report of Field Studies Conducted in 1988 for
The National Park Service

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Studies of Hydrothermal Processes in Crater Lake

A report of field studies conducted in 1988 for the National Park Service

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Introduction

Crater Lake sits atop Mt. Mazama, a center of volcanism in the Oregon Cascades for more than 400,000 years (Bacon and Lanphere, in press). The caldera morphology of the lake is largely a consequence of a climactic eruption that occurred 7845 ± 50 years b.p.; however, intercaldera volcanism took place as recently as 4000 years ago (Bacon and Lanphere, in press). This morphology has provided a basin for what is now the deepest lake in the United States (594 m). The volcanic terrain strongly limits the nutrient fluxes into the lake, mostly because the lake covers 78% of the total drainage area. As a consequence, the lake is highly oligotrophic and one of the clearest lakes in the world.

Our studies of Crater Lake began as an attempt to understand the causes of important physical, chemical, and geological features. As we have reported in the past (Collier and Dymond, 1988a), a number of these features are consistent with hydrothermal inputs to the lake. Given the location of the lake directly above a relatively recent and major magmatic source (Bacon and Druitt, 1988), thermal spring input to the lake would not be surprising. Such a source was first suggested by Van Denburgh (1968), who, noting the relatively high sulfate and chloride content of Crater Lake compared to nearby Davis Lake, suggested that these two constituents ".... may have been contributed to the lake by thermal springs or fumaroles, probably located below the present lake level. Such springs and fumaroles are a common expression of hydrothermal activity at a site of volcanic eruptions". Van Denburgh did not state whether he thought hydrothermal input was active today. Simpson (1970a) demonstrated that the deep lake had strong gradients in both ^{14}C and stable carbon isotopes. These gradients were consistent with a source of carbon with isotopic compositions similar to magmatic sources. Simpson also constructed a mass balance model that indicated only a fraction of the ionic content of Crater Lake could be accounted for by known inputs. He suggested the missing source was the result of "fumarole or hot spring activity near the bottom", and he estimated fluxes from this proposed source.

More recently Williams and Von Herzen (1983) measured high conductive heat flow in certain areas of the lake's sedimented bottom. In one of these areas of high heat flow they also documented anomalous near-bottom temperatures. This study reinforced earlier work describing the deep temperature structure of the lake as hyperadiabatic (Neal et al., 1972). On the basis of the heatflow pattern and the water column measurements, Williams and Von Herzen (1983) suggested that there is thermal spring input to the deep lake.

Studies of Crater Lake water composition have provided further support for hydrothermal hypotheses. Thompson et al. (in press) pointed out that Crater Lake has high boron and lithium contents compared to local meteoric water; these elements are typically enriched in thermal waters of volcanic origin. In addition, they showed that Cl/Li ratios of Crater Lake waters are very similar to those observed in hot springs from volcanic sources but lie outside the range of values observed in Mt. Mazama cold springs. Nathenson (in press) demonstrated that a hydrologic model which incorporates precipitation, cold springs, evaporation, and seepage cannot account for the major element content of Crater Lake. He suggested thermal springs provide the missing input and, based on geochemical mass balance models, constrains the input of thermal waters to range between 80 and 1900 liters/second. Nathenson points out that this inflow can easily provide the convective heat flux estimated by Williams and Von Herzen (1983). Nathenson's low estimate of hydrothermal flux is similar to that of Sorey (1985) who suggested a thermal-spring discharge into the lake of 30 - 150 liters/second.

Evidence of hydrothermal sources to the lake have not gone unchallenged. La Fleur (1987) argues against any hydrothermal inputs to the lake and suggests that underestimated evaporation rates, fumarolic inputs, and weathering of Mazama ash could account for the anomalous composition of

the lake. He suggests conductive heating rather than convective inputs accounts for the temperature anomalies.

The question of whether there are hydrothermal sources to Crater Lake has important implications for understanding the lake ecology. For example, the relatively rapid mixing that has been suggested for Crater Lake (Simpson, 1970b; Volchok, et al. 1970) may be a consequence of hydrothermal inputs to the bottom of the lake. If this is true, temporal variability in this source could impact the nutrient cycling and the plant productivity of the lake. In 1987, in response to the requirement of Public Law 99-591 for identification of significant thermal features in national parks, the Park Service initiated a three-year program to evaluate possible hydrothermal sources to Crater Lake. The research, which is part of a 10-year Limnological Study of Crater Lake, is designed to: (1) define the thermal and chemical variability in the deep lake, (2) examine the data for evidence of a hydrothermal source, (3) design and carry out a program that would find possible venting sites and sample any associated fluids, and (4) evaluate alternative mechanisms to explain the observed thermal and chemical variability.

The results for the 1987 field program have been reported in Collier and Dymond (1988a), Collier and Dymond (1988b), Dymond and Collier (in press), and Collier et al. (in press). During the summer of 1988 our research group spent approximately 35 days at the lake in an expanded program that included deployment of a research submersible to search the lake floor for evidence of hydrothermal activity. This report summarizes the field program and laboratory analyses that have been carried out to the present. Additional analyses are currently underway and will not be available for several months. In addition to the water and sediment analyses that have been carried out at Oregon State University, we have distributed samples for analysis to the following people: Dr. Charles Bacon, US Geological Survey (rock samples); Dr. John Lupton, University of Santa Barbara (helium isotopic analyses); Drs Clifford Dahm and Maribeth Watwood of the University of New Mexico (bacterial investigations); Dr. Marvin Lilley, University of Washington (methane analysis).

We will refer to some of the results from outside investigators in this report. For completeness in our discussions, we have also incorporated some of the information and figures that were contained in our previous report (Collier and Dymond, 1988a).

Methods

General

In Figure 1 we show the major bathymetric features of the lake and the location of what we will refer to as the "Detailed Study Area" throughout the text. The detailed study area was a focus of the operations from last year and is also the general region that Williams and Von Herzen (1983) observed high heat flow and water column anomalies. Much of our surface ship sampling has been conducted within this area, and all of the submersible dives that had a hydrothermal focus were carried out at this site.

The hydrothermal field program for 1988 was based on three separate expeditions to the lake. In early July, eight days were used to recover and redeploy a sediment trap mooring, establish our navigational stations, carryout several hydrocasts, make numerous CTD casts, and generally prepare for the submersible program in August. We spent 25 days in August with a field program that focused on using a submersible to locate, observe, and sample geological, geochemical, and biological features in the deep lake that have been hitherto inaccessible. Although much of our efforts were directed toward the submersible operations, we also carried out bathymetric surveying, conducted hydrocasts, made CTD (conductivity, temperature, and depth) measurements, and collected cores during this period. In September we returned to the lake to

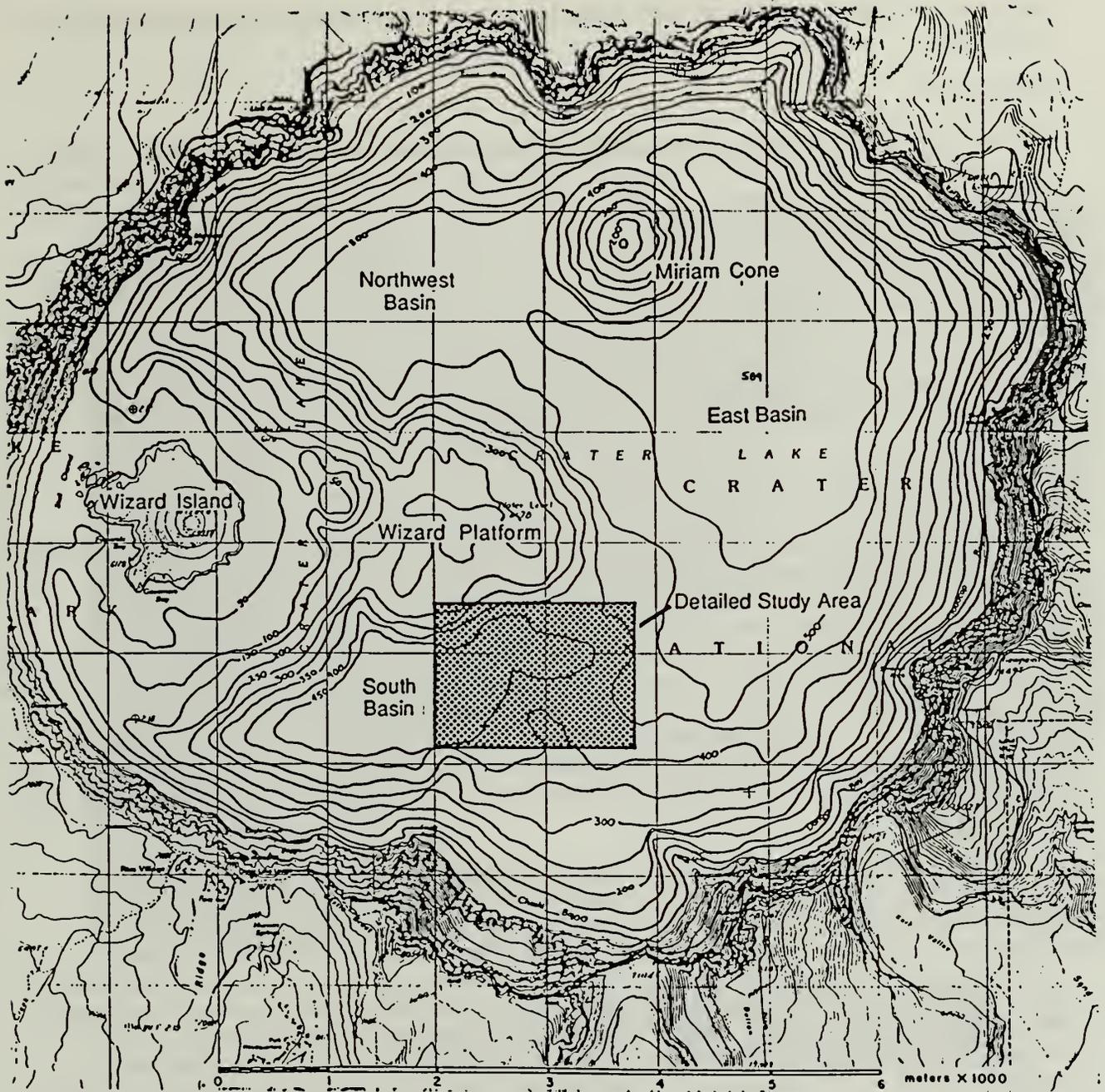


Figure 1. Bathymetry for Crater Lake (Byrne, 1965). Major geologic features are shown. The detailed study area is the focus of the 1988 hydrothermal investigations and is the site of extensive observation and sampling.

recover and redeploy the sediment trap mooring and carry out additional CTD measurements and hydrocasts.

Bathymetry

A more detailed bathymetric map than the one available for the entire lake bottom (Byrne, 1962) was constructed for the detailed survey area. Twenty navigated transects of the area were used to construct the new map (Figure 2). A 50 kHz echo sounder, which incorporated a 22° transducer, was used to determine the depths. Since the CTD (see below) produced a visible trace on our fathometer record when attached to the research wire during water sampling, the depth measurements could be calibrated against the pressure recorded by the CTD. Depths of the map were also verified with the CTD pressure record collected on board the submersible. The wide cone of the transducer signal tends to obscure sharp changes in slope, however. Areas on the map with steep slopes are therefore less accurate. Navigation for the transects was obtained with a microwave ranging system (Motorola Mini-Ranger III) that used shore stations on Eagle Point and Phantom Ship. The precision of the navigation, based on repeated ranges to the same location, is ± 5 meters.

Submersible Operations

A one person submersible, Deep Rover, was chosen for this research because of its relatively light weight, easy operation and maneuverability, operating depth of 3000 feet, and external manipulators capable of handling diverse scientific sampling gear. Deep Rover's weight of approximately 3000 kilograms made helicopter transport to the lake feasible. The submarine, which is owned and operated by Can-Dive Inc. in Vancouver, BC., has a spherical acrylic hull that maximizes operator visibility. The propulsion and control system is designed for easy use by non-professional operators. Deep Rover's electric motors were powered by batteries and typically provided five hours of operations before requiring a 12 hour recharge. An air-ballast system controlled buoyancy and allowed descents and ascents of approximately 20 minutes each direction. Thus, each day of diving would result in approximately four hours of bottom time for observations and sampling.

A total of 21 dives were made during the August expedition. These are listed along with the general location and purpose in Table 1. Four of the dives were devoted to pilot training or systems checks. Four of the dives were funded by the USGS with the survey sites and goals defined by Dr. Charles Bacon. Preliminary results of these dives are described in Appendix I. Dives 180 and 181 were funded by Deep Ocean Engineering, the designers of the submersible. On dive 180 Graham Hawkes, chief designer of Deep Rover, evaluated the systems and performance of the submarine and collected video observations and a sample from the caldera wall. Dive 181 was primarily a biological dive, to observe and sample the attached algae on the south facing caldera wall. Dr. Gary Larson describes the results of the biological dives in Appendix II. The remaining 11 dives were located within the detailed study area and were dedicated to searching for evidence of hydrothermal inputs to the lake, sampling the near-bottom waters, and collecting sediments and other materials from the bottom.

Navigation

In addition to the microwave ranging system that provided accurate navigation for the research boat, long-baseline acoustic navigation was used to position both the boat and the submersible. Unfortunately, problems with the acoustic navigation system, contracted from Oceano Instruments (detailed in Appendix III), greatly reduced the accuracy and reliability of the submersible

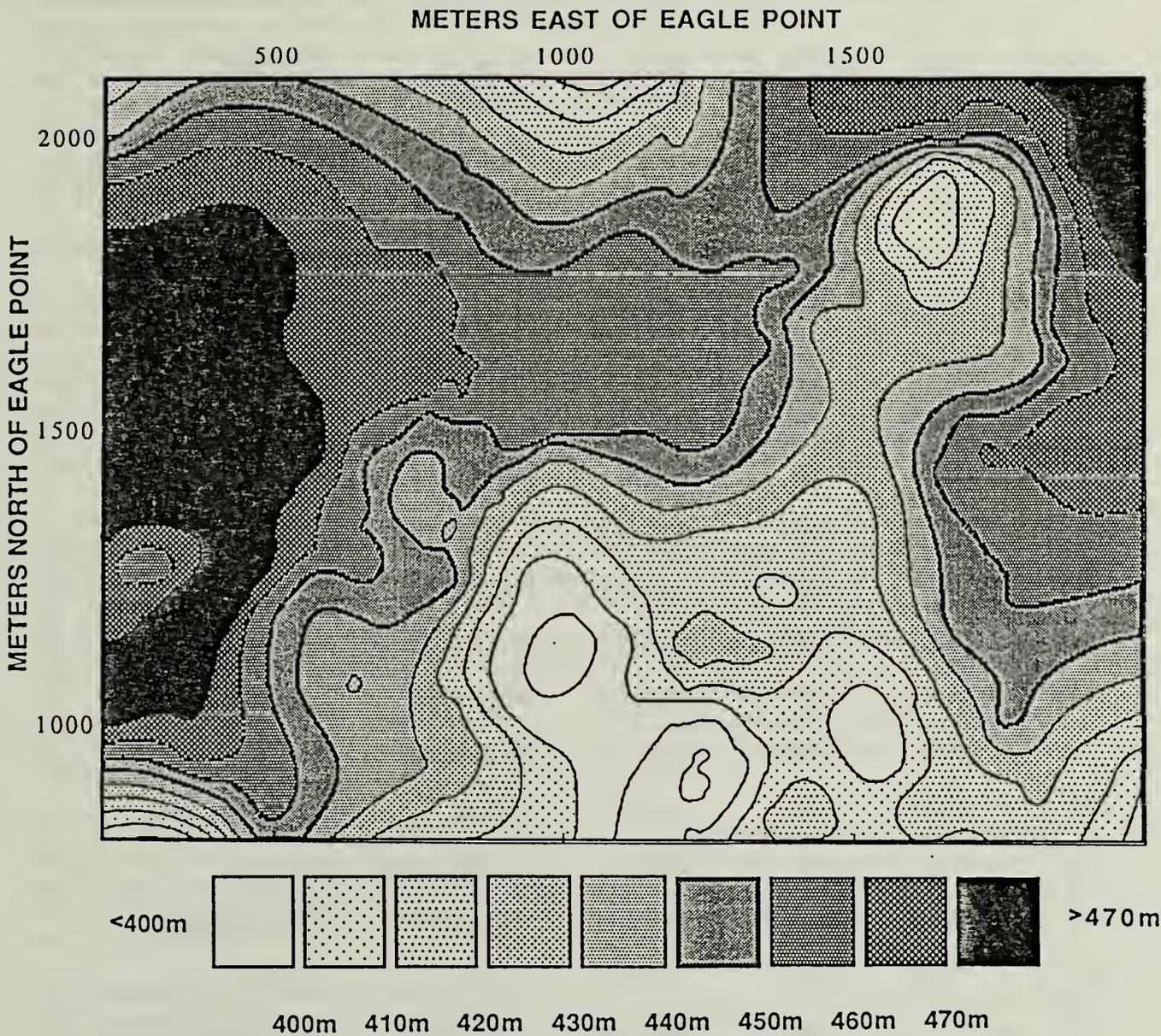


Figure 2. A bathymetric chart constructed for the detailed study area. The contour interval is 10 m. Darker tones indicate greater depths.

Table 1: 1988 Crater Lake Submersible Dive Summary

<u>Dive #</u>	<u>Date</u>	<u>Can-Dive #</u>	<u>Pilot</u>	<u>Location</u>	<u>Purpose</u>
1	8/3	167	Fuzessery	S.of Wizard Is.	Systems Check
2	8/4	168	Dymond	Dacite Dome	Training
3	8/4	169	Collier	Wizard Platform	Training
4	8/5	170	Dymond	Study Area	Hydrothermal
5	8/6	171	Collier	Study Area	Hydrothermal
6	8/7	172	Buktenica	Eagle Point	Training/Biology
7	8/8	173	Dymond	Study Area	Hydrothermal
8	8/9	174	Collier	SW Miriam Cone	USGS
9	8/10	175	Dymond	N.Wizard Plat.	USGS
10	8/11	176	Buktenica	Eagle Pt.	USGS
11	8/12	177	Collier	Study Area	Hydrothermal
12	8/13	178	Dymond	Study Area	Hydrothermal
13	8/14	179	Collier	Study Area	Hydrothermal
14	8/17	180	Hawkes	Pumice Pt.	Systems Check
15	8/17	181	Earle	Palisades Pt.	Biology
16	8/18	182	Dymond	Study Area	Hydrothermal
17	8/19	183	Collier	Study Area	Hydrothermal
18	8/20	184	Dymond	Study Area	Hydrothermal
19	8/21	185	Buktenica	E.Wizard Plat.	USGS
20	8/22	186	Collier	Study Area	Hydrothermal
21	8/23	187	Dymond	Study Area	Hydrothermal

navigation. During several dives, the acoustic system failed to locate the submersible for periods of an hour or more. Large but inconsistent errors in positioning frustrated efforts to survey the study area and made relocating important features tedious and time-consuming. A greater reliance on the microwave ranging system and on dead reckoning partially compensated for these difficulties in the field. We have refined this dead-reckoning navigation with the support of dive logs and bathymetry to produce track lines for most of the dives within the detailed study area. Approximate track lines for nine dives in the detailed study area are shown in Figures 3a, 3b, 3c, and 3d. The errors in these lines cannot be estimated directly and will vary depending on the quality of surface to submersible communications and the complexity of the track line. In general, the early and late portions of the dives may have navigation errors on the order of ± 10 meters but mid-dive periods, far removed from any geodetic reference points, may have errors ranging from 50-100 meters.

Submersible Sampling and Photography

For the Crater Lake operations the submersible was equipped with a forward sample basket which served both to carry sampling and measurement tools and as a receptacle for retrieving rock and sediment samples. Lighting for the deep lake operations were provided by several 250 and 500 watt incandescent lights and a 1500 Watt-sec strobe. These lights, although adequate for close in sampling and observations, did not allow us to take full advantage of the exceptional clarity of the lake. Typically, only a swath 5 to 10 m across our path was adequately lighted to allow detailed observations.

By making some assumptions about submersible speed and this 5-10 m visual swath, we have estimated the percentage of the bottom covered by our observations with Deep Rover. The 16 science dives had an average bottom time of 4 hours, and typical speeds were 0.5 knots. This results in 60 kilometers of track. For a 10 m swath we observed 6×10^5 m² of lake bottom. Because of track crossing and sampling stops, we estimate that the observations are only 60% efficient. Consequently, we have covered approximately 3.6×10^5 m² of the bottom. Of this, 63% was spent in the detailed study area and 37% was divided between biology and USGS dives. The total lake area is 48 km². Consequently, we covered approximately 0.7% of the lake floor with Deep Rover. Within the South Basin, the site of the thermal anomalies within the water column, our dive tracks covered less than 15% of the bottom.

Still photography was accomplished with a Photo-Sea camera system. The camera and strobe were mounted on the starboard arm of Deep Rover. With this system the aperture is fixed at the surface and so exposure is sensitive to the brightness of and the distance to the subject. Some of the dives were photographed in stereo. Fujichrome 400 film, with a camera aperture of f. 5.8 was used on most dives.

Both internal and external video cameras were used. The external video camera, which provided the highest quality images, was also located on the starboard arm of the submarine. It was connected to an internal 8 mm video recorder. The internal camera was located above the pilot's left shoulder and provided a broader but somewhat degraded visual perspective through the acrylic hull.

Sampling of rocks and crusts could be accomplished by picking up specimens with the mechanical arm and dropping them into the basket. A small push core was used to take two cores within the Detailed Study Area. Because of a poorly designed valve at the top of the core tube, the corer tended to exclude core material and produced a non-representative sample. We are in the process of designing a small box core that will recover undisturbed sediment samples for a 1989 diving program.

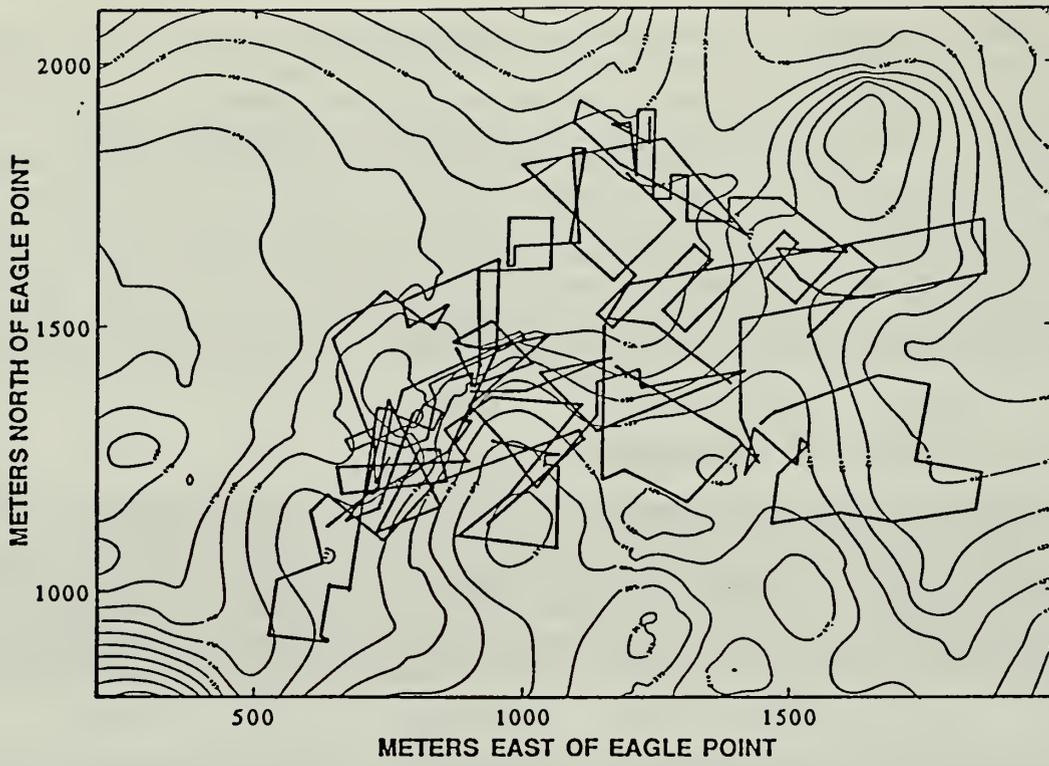


Figure 3a. Submersible navigation for all dives in the detailed study area, except 171 and 173. The thickness of the line denotes the approximate effective visual swath of the submersible.

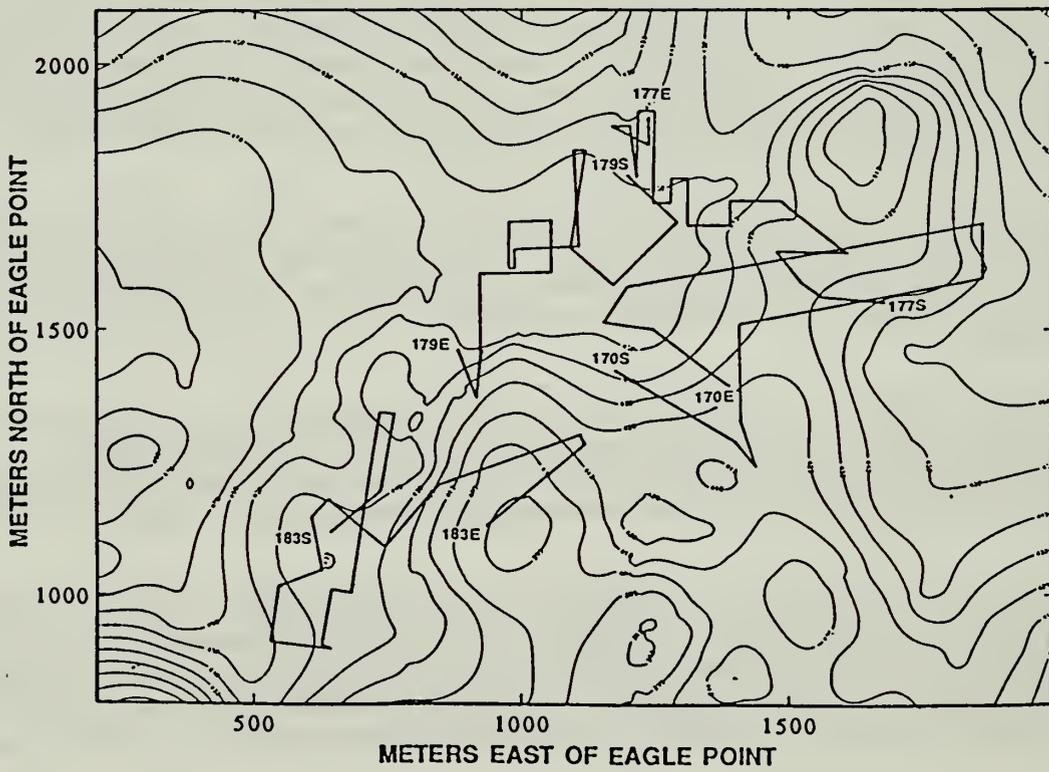


Figure 3b. Submersible navigation for dives 170, 177, 179, and 183. "S" and "E" refer to start and end of dives.

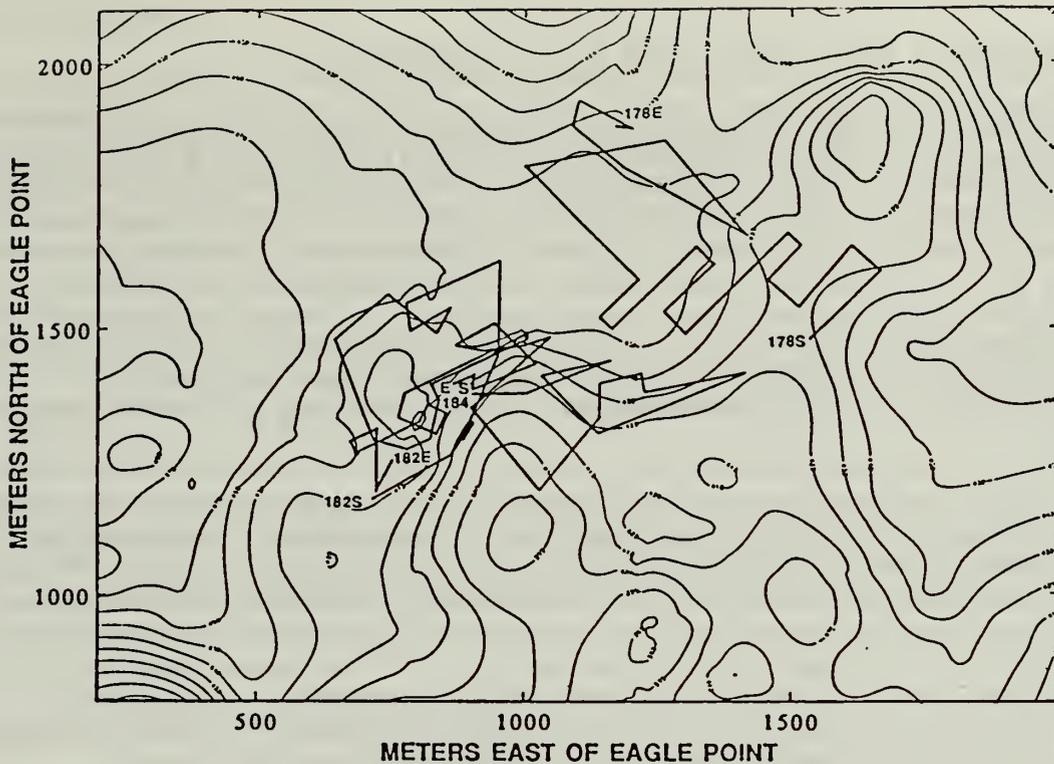


Figure 3c. Submersible navigation for dives 178, 182, and 184. "S" and "E" refer to start and end of dives.

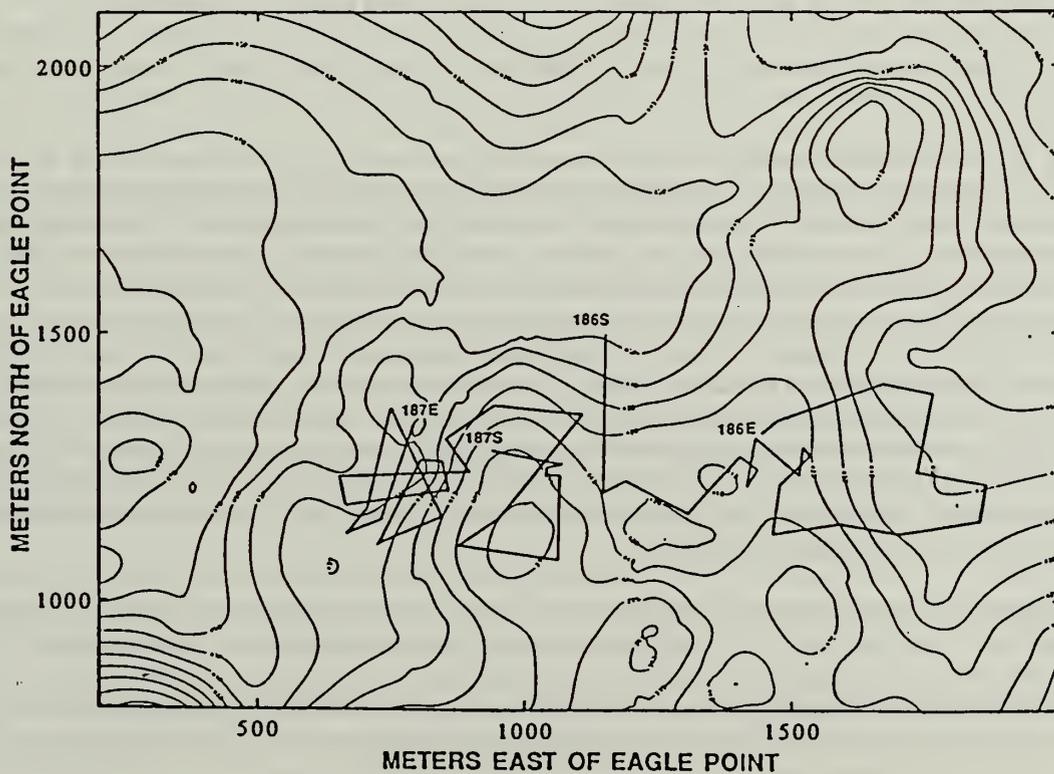


Figure 3d. Submersible navigation for dives 186 and 187. "S" and "E" refer to start and end of dives.

Water Temperature, Conductivity, and Light Transmission

A profiling instrument package was deployed on a hydrographic wire and was carried on the submersible to measure the conductivity, temperature, and light transmissivity as a function of depth in the water column. This instrument package, which we will refer to as a "CTD", was a SEACAT® model SBE19 (Sea-Bird Electronics, Inc.) coupled to a 25-cm path-length beam transmissometer (Sea Tech, Inc.). The CTD records all data internally (2 scans per second of all sensors for up to 4 hours) and was also monitored in real-time through a special conducting hydrographic cable attached to the computer on the research boat or onboard the submersible. This instrument was specifically modified by the manufacturer to optimize conductivity measurements in this fresh water system. The CTD has a temperature resolution of better than 0.001 °C; conductivity resolution of 4×10^{-5} Siemens/meter (0.4 µmhos/cm); and a pressure resolution of 0.5 decibars.

Conductivity data will be presented in the accepted SI unit for conductivity: Siemens/meter. For conversion to the common limnologic units of µmho/cm: 1 siemen/meter = 1000 µmhos/cm. However, also note that the CTD records conductivity at *in situ* temperatures - not at 25 °C as is conventional for reporting the conductivity of discrete samples. Therefore, our data cannot be directly compared to general tabulations of lake conductivities (e.g. data in Thompson et. al., 1987). There is a major temperature effect on conductivity: 15 °C surface water and 3.6 °C deep water have conductivities of 0.010 and 0.007 siemens/meter, respectively. Using rigorous physical chemical models, this temperature effect can only be corrected to 25 °C for a few simple electrolytes such as KCl (Harned and Owen, 1958). Tabulations of single-ion specific conductances and functions describing their change in conductance with increasing concentration exist, but the temperature effects on these functions have not been determined for each ion and cannot be predicted from "first principles" (Conway, 1952; Robinson and Stokes, 1959). The most accurate alternative, which we have chosen for our work, is a complete temperature calibration of the instrument using the actual ionic composition of Crater Lake water. We believe that the precision and accuracy necessary for computations of density in the deep lake justify this effort.

The CTD was recalibrated for temperature and conductivity at the OSU calibration facility in January, 1988. Some correlations of chemical parameters with temperature suggest the possibility of a shift in temperature of ~0.02 °C between the 1988 and 1987 data sets. We will evaluate this with a new calibration this winter. Conversion of pressure (decibars) to depth (meters) is carried out by the integration of water densities down through the water column. The depths are effectively equal to 1.02 times the pressure. All physical properties based on the measurement of temperature, conductivity and pressure were calculated using an equation of state for water adapted for application to lakes (Chen and Millero, 1986). The temperatures of specific water samples collected from the hydrographic wire were estimated from the CTD record collected on the same hydrocast. Similar estimates for submersible-collected samples were attempted from the on-board CTD record. The separation of the CTD sensor from the water sampler on the sub, coupled with a lack of control between the time base of the dive-logs and CTD-logs, made accurate determination of these water sample temperatures difficult.

The submersible also carried a separate temperature probe assembly with three thermistors spaced at ~15 cm intervals along the probe. This probe could be picked up from the submersible's sample basket by the manipulators and inserted into sediments, thin crusts and other relatively soft substrates. The data from these probes was displayed onboard the submersible for readout by the pilot. This data was logged on voice tapes or through communication with the surface vessel.

Water Samples

Water samples from throughout the water column were collected from the NPS research boat using the standard 1/8" stainless steel hydrographic wire. Various oceanographic water samplers were mounted on the wire depending on the demands of individual chemical analyses. Typically, 5- or 30-liter Niskin[®]-type samplers (General Oceanics) were used. Some of the sampling for trace-metal analyses used teflon-coated 5- and 20- liter GoFlo[®]-type (General Oceanics) samplers. In order to avoid contamination and preserve the integrity of each sample, great care was taken in each step of collection, preservation and analysis (Bruland et al., 1979).

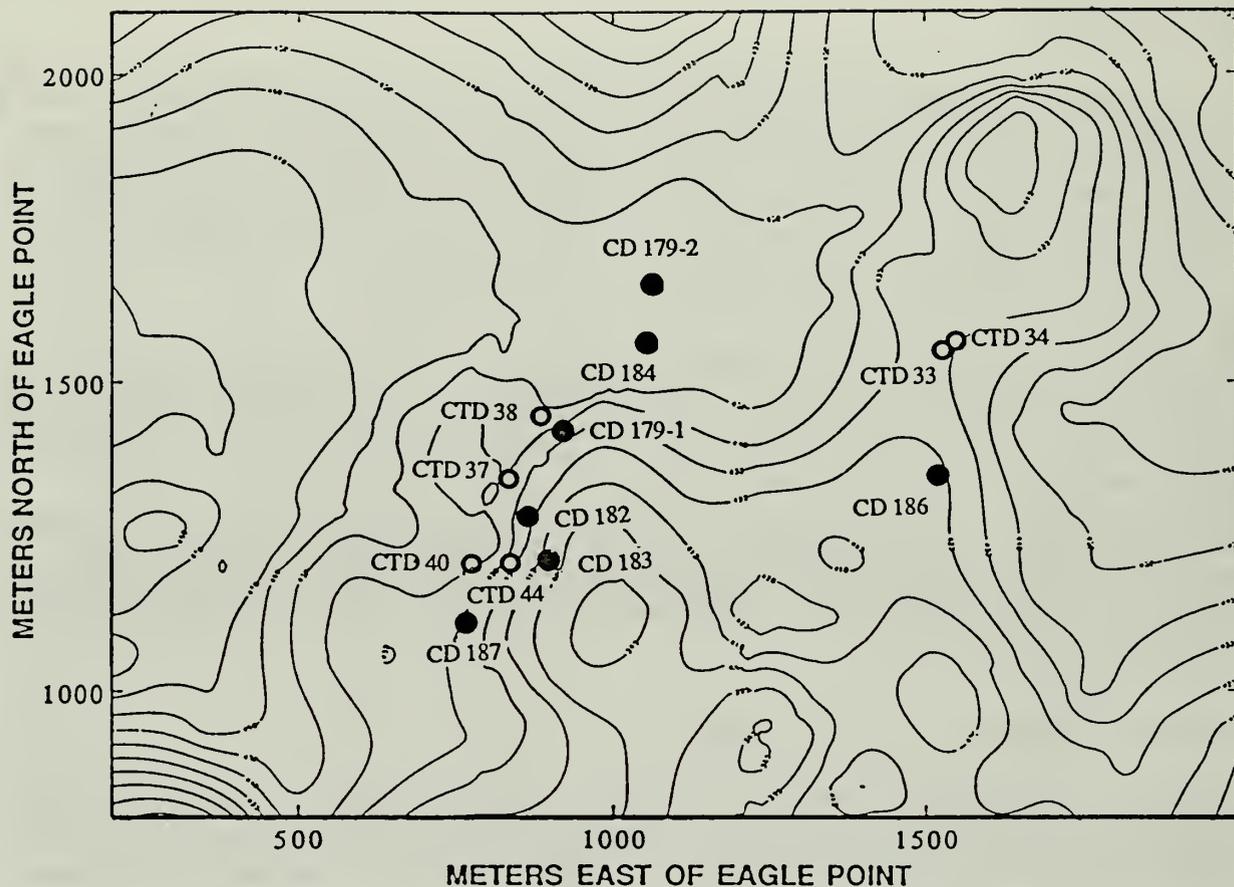
Water sampling on the submersible was accomplished with Niskin-type samplers designed and owned by Dr. Bruce Robison, Monterey Bay Research Institution. These all-plastic samplers held five liters of water. They were tripped with solenoids operated by the submersible pilot. Early in the dive program, paired water samplers were carried in the sample basket and were lifted out and into place with the mechanical arm prior to tripping. This allowed the sampler to be placed relatively accurately in relation to specific features (like the bacterial mats that are discussed below). The basket placement, however, subjected the samples to jostling and possible leakage during submersible recovery. Consequently, for most of the later dives, the water bottles were mounted on the port side of the submersible, just forward of the acrylic hull. Water sample locations from 1988 are presented in Figure 4.

Chemical Analyses of Water Samples

All water samples for ionic analyses were filtered through an acid-cleaned, 0.4 μ m polycarbonate filter (Nuclepore[®]) under a clean atmosphere. Samples for major and trace cation analyses were acidified to pH 2 with sub-boiling redistilled HCl. All samples were subsequently stored in the dark at 4°C until analysis.

The cations Na, K, Ca, Mg and Li were analyzed directly by flame atomic absorption spectrophotometry using a Perkin Elmer model-5000 spectrophotometer. All samples and standards were matrix adjusted with CsCl to suppress ionization interferences. Calcium analyses included LaCl₃ as a releasing agent to suppress interferences from dissolved silicon. The instrumental setup involved for each element generally followed Perkin Elmer (1982) or EPA (1979) methods. Each individual sample was analyzed two to four times where each "analysis" is the average of 3 separate 3-second instrument readings. The instrument is recalibrated ("resloped") between each sample. Standard additions methods were applied to some samples to verify the absence of matrix interferences between samples and standards. Sample replicates on approximately 10% of the total number of samples are carried through each analysis sequence to check the overall precision. These repetitive analyses are critical to achieving the maximum precision which is necessary for interpreting the small changes in concentrations present in Crater Lake. The precision of the major cation analyses based on replicate samples is better than $\pm 0.5\%$ (0.2% for Mg, 0.3% for Ca, 0.4% for Na and K). For quality control, preserved samples from earlier data sets (e.g. 1987) are rerun along with new samples (e.g. 1988). The accuracy of the analyses can be traced to certified single-element standards and our results are consistent with other published and unpublished analyses (Thompson et al, 1987; Larson, 1987). Manganese was determined with a precision of approximately 5% by Zeeman-corrected atomic absorption spectrophotometry with graphite furnace atomization.

Silicate concentrations were determined as silicic acid by a colorimetric molybdenum blue method using an Alpkem rapid flow analyzer with a precision of 0.3%. pH values were measured on gas-tight samples in a thermostated system at 25.0 °C using low-ionic strength electrodes and buffers.



CTD/Dive	Location*	Date	Sample numbers
CTD 33	1535, 1555	7/11/88	2.2-5, 2.2-6, 2.2-7
CTD 34	1540, 1560	7/11/88	2.3-1 -- 2.3-4
CTD 37	837, 1347	8/18/88	81801-04, 07, 09, 11
CTD 38	880, 1450	8/20/88	82001-04
CTD 40	773, 1203	8/22/88	82201, 02, 03
CTD 44	825, 1210	8/24/88	82501-07
CD 179-1	915, 1420	8/14/88	179.1
CD 179-2	1065, 1660	8/14/88	179.2
CD 182	860, 1295	8/18/88	182.1, 182.2
CD 184	1050, 1575	8/20/88	184
CD 183	895, 1210	8/19/88	183
CD 186	1510, 1340	8/22/88	186
CD 187	750, 1100	8/23/88	187

*Locations are meters east and north of Eagle Point

Figure 4. Water sampling locations collected during 1988 within the detailed study area. The open circles are hydrocasts made with the surface vessel. The closed circles are samples collected by the submersible, Deep Rover. Below the map, the dates, locations and samples collected from each hydrocast or submersible dive are tabulated.

Alkalinities were determined in the same system by full Gran titrations using a microburet. Due to the low ionic strength of lake water (e.g. compared to seawater), the precision of the alkalinity determination is only about 3-4%. Sulfate and chloride analyses are determined by ion chromatography. These analyses are still incomplete but they appear to have a precision of better than 1%. Overall charge balance calculations for a typical sample agree to within 4% (e.g. $\Sigma_{\text{cations}} = 1.08$ meq and $\Sigma_{\text{anions}} = 1.11$ meq) and are probably constrained by the accuracy of the bicarbonate determination (pH, Alk.).

Radon-222 and radium-226 were measured using the procedures developed in Mathieu (1977). Water from the sampler is transferred to evacuated 20 liter glass bottles. Radon was stripped by bubbling helium through the sample with collection on an activated charcoal column at dry ice temperature. The column was heated and the radon transferred to an evacuated ZnS-coated scintillation cell. This cell was placed in a photomultiplier tube counting system calibrated with ^{226}Ra standards. Radium-226 is measured in a similar fashion except that the water sample is kept sealed in the 20 liter bottles for two weeks to allow ^{222}Rn to achieve radioactive equilibrium. Counting errors for both analyses are always less than 10%.

Sediment and Crust Analyses

Samples were prepared for analysis by freeze drying the wet solids and grinding with agate mortar and pestle. Atomic absorption spectrophotometry (AAS) was used to determine concentrations of Li, Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, and Ba in the sediment using the dissolution and analytical procedures outlined in Dymond, et al., 1984. Comparison with USGS standard rocks demonstrates there are no systematic errors. In most cases, splits of the samples are analyzed for Na, Al, Sc, V, Mn, and Ba by instrumental neutron activation analysis. For elements measured by both techniques, the agreement is within 10%.

Acknowledgements

We thank the many people who have helped to make this research effort possible. John Lupton, U.C. Santa Barbara, has been a co-investigator on the project for the past three years. His helium isotopic measurements provide some of the most critical data for understanding the sources of fluids which enter Crater Lake. Gary Larson, our co-PI for the project, provides an important link to the U.S. Park Service. Particular thanks goes to James Milestone and Mark Buktenica, Park personnel who worked for many months prior to the submersible operations to provide the necessary logistic support for the research. Their outstanding efforts during the field programs are also greatly appreciated. A host of other Park personnel were critical to the smooth operations that we experienced for this very complex program. Can-Dive, Inc. not only provided the submersible but also kept it functioning so that we were able to carry out the complete dive program with no lost time. Jim English and Steve Fuzessery were superb with their sub-operations. Deep Ocean Engineering, Inc. provided us with equipment and expertise. They made available a state-of-the-art ROV, which was used as a backup for the submersible. In addition, Silvia Earle enabled us to obtain some key equipment from other sources, and Rodney Moore was a very able submersible technician. The field and analytical efforts of the OSU research team was outstanding. We especially thank Roberta Conard, Chris Moser, Pat Collier, Jim McManus, Brad Beeson, William Rugh, and Milo Clauson. Continuing discussions with Charles Bacon of the US Geological Survey have been especially helpful. Funding for this project has been provided for by the U.S. National Park Service.

Technical Findings

The Distribution of Temperature and Salt

The vertical distribution of temperature in the lake was discussed by Neal et al. (1972) who presented the first detailed high-precision measurements of the complete water column. The general features they discussed were the strong seasonal thermocline in the upper 100 meters, a decrease in temperature to a minimum value of 3.53°C at mid-depth (295 meters), and an increase in temperature below this point to values as high as 3.69°C. The average temperature of the sediments below these profiles was 3.80°C. These authors postulated that the stability of this hyperadiabatic deep water column was maintained by an increase in dissolved ions or suspended sediments with depth. However, their field methods did not include any way of directly demonstrating this hypothesis. The history of temperature measurements in the lake was reviewed by Williams and Von Herzen (1983) in a paper presenting detailed water column temperatures and sediment heatflow analyses. Their research mapped several areas of the lake bottom with very high heatflow and provided a detailed demonstration of deep lake warming. The vertical structure and horizontal heterogeneity of several deep profiles were directly attributed to convection from active thermal springs which seemed to provide a warm water layer that was "ponding" in the South Basin.

General temperature and density structure. Details of data collected in 1987 were discussed in Collier and Dymond (1988a) and Collier et al. (in press). The important features of these general distributions will be reviewed here. The high-precision CTD data collected in 1987 and again in 1988 refines the general descriptions of Neal et al. (1972) and Williams and Von Herzen (1983) and adds the first detailed measurements of *in situ* conductivity allowing the calculation of densities. The data set focuses on the magnitude and areal extent of the thermal anomalies in the deep lake and introduces the first significant evidence of high dissolved salts associated with these increases in temperature. Figure 5 shows the full water column distribution of temperature and density at the east end of the south basin (Figure 1). These data are based on direct measurements from the CTD package as well as on calculated quantities derived from the equation of state applicable to this lake water (Chen and Millero, 1986).

These data were collected late in the summer (1987) and demonstrate the fully developed seasonal thermocline in the upper 100 meters (Figure 5a) and the associated decrease in density within this stable warm surface water layer (Figure 5b). Below 100 meters depth, the density of the water is very nearly homogeneous with a total change of less than 4 ppm (Figure 5b, 5c). When the seasonal thermocline erodes and is cooled during winter, storms will drive significant mixing from above. Preliminary data collected over several months in 1988, demonstrate a number of mixing events which are evident below 150 meters depth. As first noted by Williams and Von Herzen (1983), any significant heating from below by conductive and/or convective inputs may drive convection and mixing of these deep waters. It is difficult, however, to put time scales on mixing rates based on physical models alone. Rapid mixing is indeed suggested by the vertically-homogeneous tritium data of Simpson (1970), and by dissolved oxygen concentrations which are near-saturation throughout the water column. However, further analysis of these data, new winter data collected in 1988-89, and lake-based meteorological data will help provide constraints on the overall mixing rates. It is very likely that both the intensity of summer heating and the nature and severity of winter storms will cause variations in the mixing rate from year to year. This mixing rate is a critical factor for estimating the overall rates of input for heat, hydrothermal chemicals, and other materials to the deep lake.

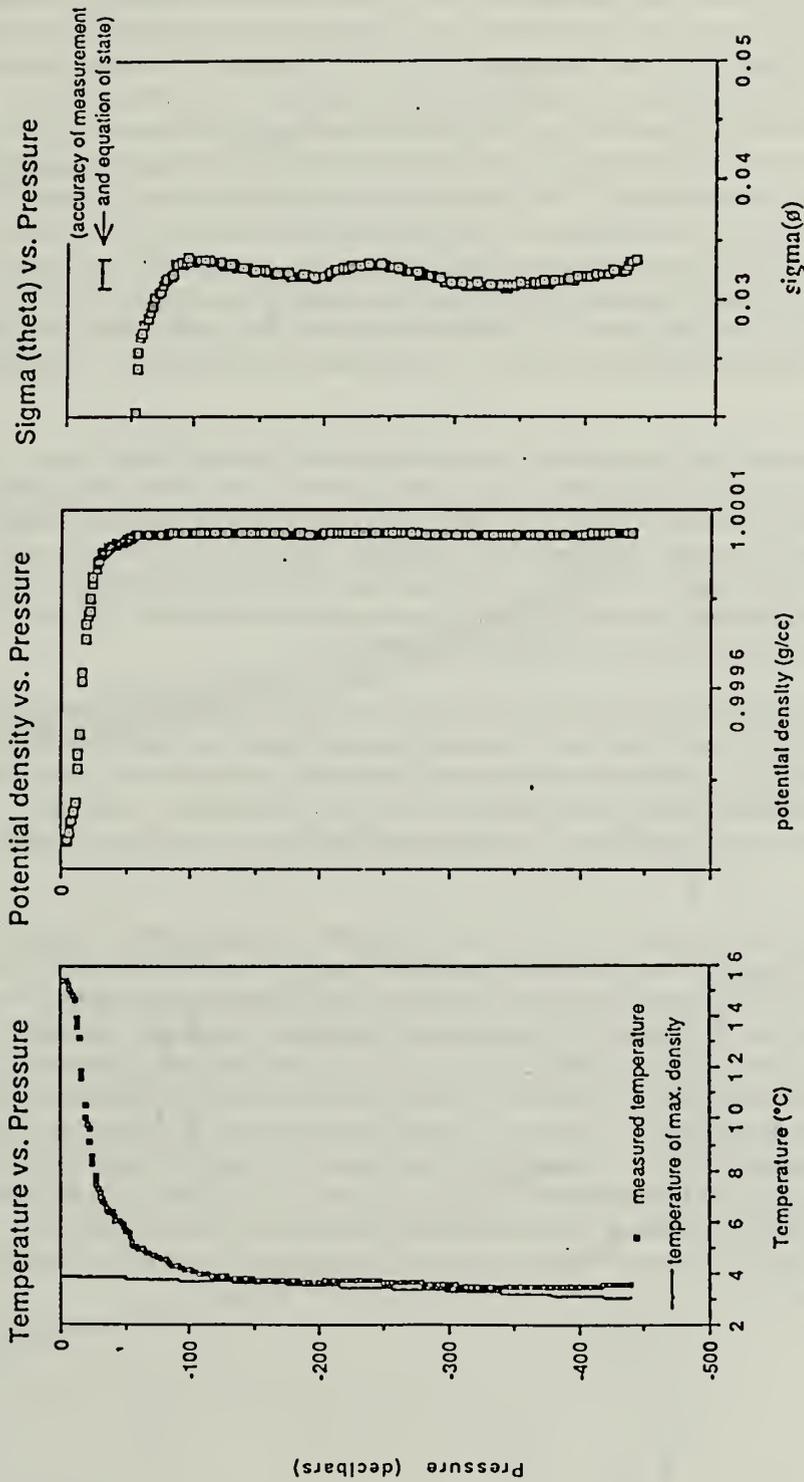


Figure 5. CTD data from a water column profile in the east end of the South Basin (Collier and Dymond, 1988a). All calculated physical properties are based on the equation of state for limnologic waters developed by Chen and Millero (1986): (a) Vertical distribution of temperature ($^{\circ}\text{C}$) as a function of pressure (decibars, which is numerically equivalent to $[0.98 \times \text{depth}]$ in meters). The solid line indicates the temperature of maximum density for Crater Lake water at *in situ* pressure; (b) potential density vs. pressure. The potential density is the density of a water parcel moved adiabatically to a common reference pressure - in this case to the lake surface. This parameter is critical in considering the stability of the water column and the rate of turbulent mixing. It can be seen that the water column below 100 meters has a nearly uniform density; (c) Sigma (θ) vs. pressure. This parameter, derived from b, is defined as Sigma (θ) = (potential density - 1) \times 1000.

Deep lake distributions. An expanded view of the lower 100 meters at the east end of the South Basin is shown in Figure 6. All data scales for temperature (a), conductivity (b), and potential density (c) have been significantly expanded over those in Figure 5. The major feature apparent in Figure 6a is the increase of temperature with depth. The slow increase, which begins below 300 meters depth, is seen throughout the lake and appears to reflect the net effect of any conductive and convective heat inputs. The light dotted line shown in Figure 6a shows this temperature structure in the central basin. The adiabatic increase in temperature with depth can be calculated from the equation of state (Chen and Millero, 1986) and averages 3.2×10^{-6} C°/meter. This is shown to be an insignificant portion of the observed temperature increase (Figure 6a). The general warming observed throughout the lake below 350 meters (e.g: the central basin profile shown in Figure 6b) has a gradient of 3.3×10^{-4} C°/meter which is two orders of magnitude larger than the adiabatic gradient - thus derives the term *hyperadiabatic*. The gradient seen near the bottom of the south basin study area is approximately 1×10^{-2} C°/meter - a gradient which is 3400 times larger than the adiabatic gradient. These "sharp" gradients in temperature, such as that seen at 430 meters in Figure 6a, are horizontally heterogeneous and are sometimes followed by a complete reversal in the temperature suggesting a locally unstable system. Consistent with the interpretations of Williams and Von Herzen (1983) and Collier and Dymond (1988), we attribute these features to active input of thermal water.

A vertical integration of the "excess heat" contained in a portion of the Special Study Area, originally presented in Collier and Dymond (1988a), is replotted here on our new bathymetric map of the study area (Figure 7). For this calculation, we have defined excess heat as the heat content of water with temperatures greater than water at equivalent depths in the central basin (e.g. subtracting the central basin profile, dotted in Figure 6a, from the south basin profiles). New CTD data collected in 1988, at locations shown in Figure 4, are consistent with the 1987 data but do not add enough coverage to expand the contouring in Figure 7.

The conductivity (Figure 6b) also increases with depth due to an increase in the concentration of dissolved salts. This is very clearly correlated with the temperature signal. As noted in the methods section, the conductivity of a solution increases with increasing temperature; yet this effect accounts for only about 5% of the conductivity increase seen in the south basin. Thus, the observed conductivity increase in the South Basin is unequivocally due to an increase in salt content.

The net effect of the temperature and conductivity increase is that the potential density (Figure 6c) increases very slightly with depth such that this water is stable (barely). Both Neal et al. (1972) and Williams and Von Herzen (1983) hypothesized that the lake should have an increase in dissolved solids in order to stabilize the measured temperature increase. However, the total increase in density (less than 2 ppm in 100 meters) produces only a very weak stratification. The static stability E , an expression of the density gradient normalized to the absolute density, is only $2 \times 10^{-8} \text{ m}^{-1}$. The Brunt-Väisälä frequency, N , is 1×10^{-4} cycles/sec where N is also related to the density gradient and can be thought of as the frequency of oscillation of a water parcel displaced vertically from its equilibrium position in the water column (Ruttner, 1974; Pond and Pickard, 1978). If the observed temperature increase is due to hydrothermal inputs, the increase in conductivity suggests that the input of warm water may carry enough salts to stabilize the fluid relatively near the lake bottom.

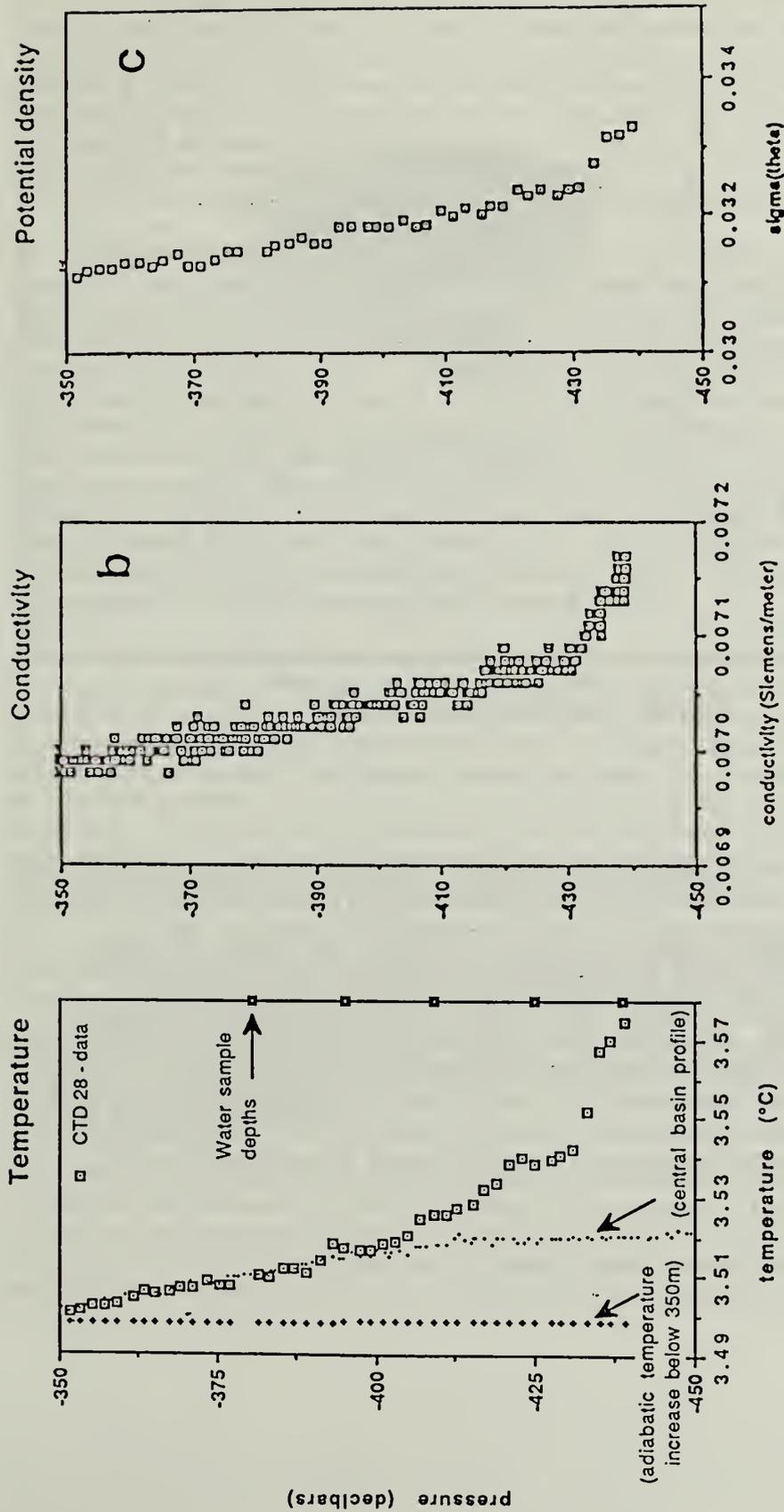


Figure 6. Expanded plots of the CTD data from Figure 5 which focus on the bottom 100 meters of the water column: (a) Plot of temperature vs. pressure. Three major features are demonstrated: (1) the adiabatic increase in temperature, starting from the minimum temperature in the water column (at 345 decibars), accounts for less than 1 millidegree warming (the adiabatic gradient over this interval averages 3.2×10^{-6} degrees/decibar); (2) the general warming below 350 decibars, which is seen throughout the lake, has a gradient which is two orders of magnitude larger (3.3×10^{-4} degrees/decibar) and is thus *hyperadiabatic*; (3) the gradient seen near the bottom of the thermal study area is approximately 1×10^{-2} degrees/decibar - a gradient which is 3400 times larger than the adiabatic increase. The depths of discrete water samples taken along with the CTD cast are noted along side of (a) for reference; (b) *In situ* Conductivity (Siemens/meter = $10,000 \mu\text{mho/cm}$) vs pressure. This increase is primarily due to the increase in dissolved ions with depth (approximately 5% of the increase is due to the temperature increase); (c) $\sigma_t(\theta)$ vs pressure noting the marginal stability of the deep water column (less than 2ppm in density over 100 meters) driven by the combination of heat and dissolved ion increases.

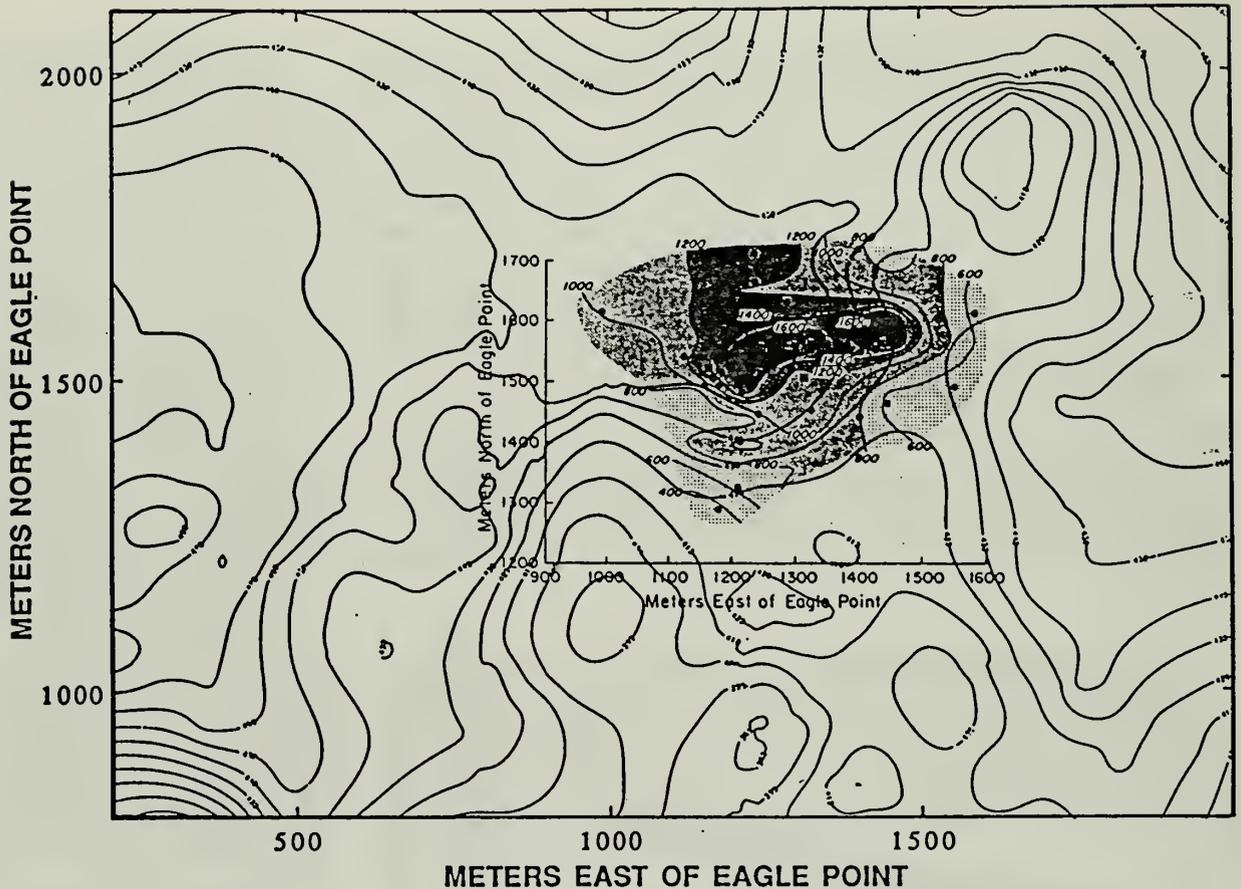


Figure 7. Contour plot of total water column heat "anomaly" (integrated vertically, kcal/m²) from 1987 CTD casts presented by Collier and Dymond (1988a) overlaid on the new bathymetric map. Points within the shaded area represent the CTD locations used for this analysis. For this calculation, we have defined the heat anomaly as the heat content of water with temperatures greater than water at equivalent depths in the central basin. In practice, this is achieved by subtracting the central basin profile (the dotted line in Figure 6) from the south basin profiles. New CTD data collected in 1988, at locations shown in Figure 4, are consistent with the 1987 data but do not add enough coverage to expand the contouring into other portions of the Study Area. The region containing most of the warm water (some values over 2000 kcal/m²) coincides with zones of hydrothermal precipitates observed from the ROV videos in 1987 (Collier and Dymond, 1988a) and with the general line of alteration seen along the base of the scarp in Figure 29.

Near-bottom observations with the submersible. Measurements made with the CTD carried by the submersible provide data on the temperature and salt content of the bottom two to four meters of the lake. We show the temporal variability of the data for three dives (179, 187, and 182) from the detailed study area in Figures 8, 9, and 10. Because these data can be affected by the submersible operations, we have annotated the record with summaries of the dive log. The primary concern is that heat generated by lights from the submersible can affect the CTD temperature if the submersible is not moving across the bottom. Since the CTD was mounted on the port arm that was extended to the left of the submersible path, there would be no effect of the lights when the submersible was moving. The conductivity measured by the CTD could not be affected by submersible operations. Consequently, variability in this measurement is always real.

Dive 179 traversed an area in the north central part of the detailed study area (Figure 3b). Over the entire dive track the total temperature variation that was observed is 0.2 °C (Figure 8). Very significant variations in conductivity are also observed during this dive, and the two variables are clearly correlated. Thus, the major variability that is observed in temperature can not be an artifact of heating by submersible lights. Possible exceptions are some of the small temperature spikes that occur after the submarine first reached bottom and before getting underway. Near the end of this dive, bacterial mats, which are discussed in detail in a later section were observed and sampled. One of the mats was found to have an internal temperature of 5.7°C. It is of interest that the highest temperatures and conductivities were observed shortly before finding the bacterial mats (Figure 3b). In the immediate vicinity of the mats the CTD temperatures were equivalent to those measured at similar depths elsewhere in the basin. As discussed below in the "Bacterial Mat" section, the lack of major temperature anomalies adjacent to the warm mats is probably a consequence of highly diffuse venting of thermal fluids.

Dive 187 covered a relatively small area in the west-central part of the detailed study area (Figure 3d). Total temperature variations during the dive were 0.19°C and correlated well with significant conductivity variations (Figure 9). A region of consistent thermal and conductivity anomalies was observed during the last 40 minutes of the dive. A small bacterial mat was observed to be growing on the sediment surface in this area of anomalous water. The temperature and conductivity record of this dive provides clear evidence of strong spatial variability in the bottom waters of the detailed study area. Some of the largest anomalies observed were limited to areas a few tens of meters across. Even the consistently large anomalies observed late in the dive were only 100 m from areas of relatively low temperatures measured earlier in the dive.

The highest temperatures and conductivity anomalies detected during the entire dive program were observed during dive 182. The maximum temperatures, which were measured 1.4 hours into the dive, are off scale on Figure 10 and reached a value of 4.1°C. This is an anomaly with respect to the coolest waters in the detailed study area of more than 0.5°C. These relatively large anomalies are located in a region of anomalous sediment appearance. Frequent mottled dark brown sediments were observed, and in some places very fine, dark brown to black precipitates covered the bottom (see log notes on Figure 10).

We have contoured the near-bottom temperature measurements (Figure 11) and these show several regions of warmer waters separated by areas of cooler waters. The highest temperatures and general area of anomalous waters are found in the west-central part of the detailed study area. This area of warmer water is near many of the bacterial mats, although (as discussed above) there is not a one-to-one correlation between mat sightings and near-bottom temperatures.

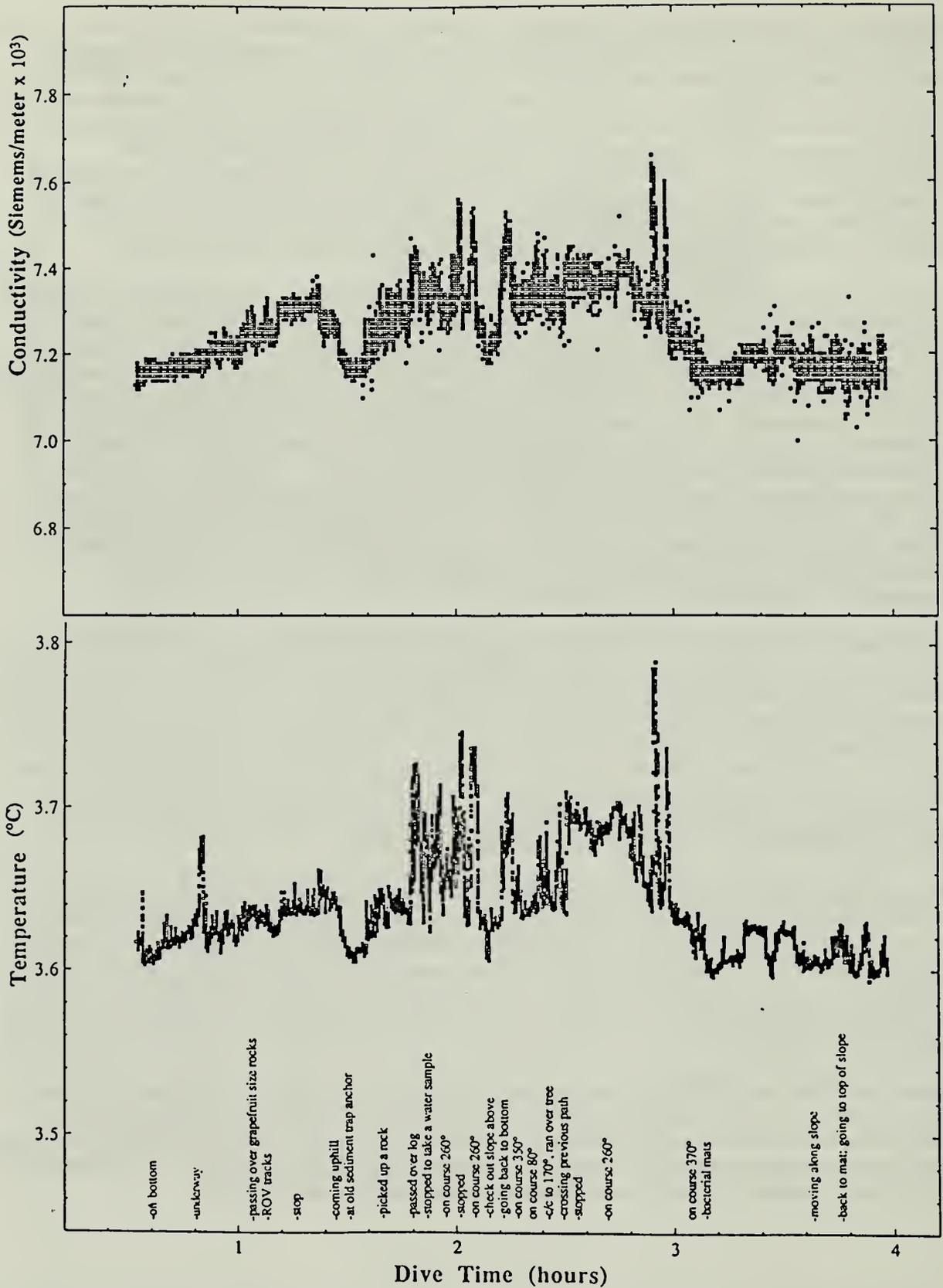


Figure 8. Conductivity (upper panel) and temperature (lower panel) measured with the CTD during dive 179. Dive time in hours along the x-axis is measured from the time the submersible leaves the surface. The annotation of submersible operations are shown along the x-axis.

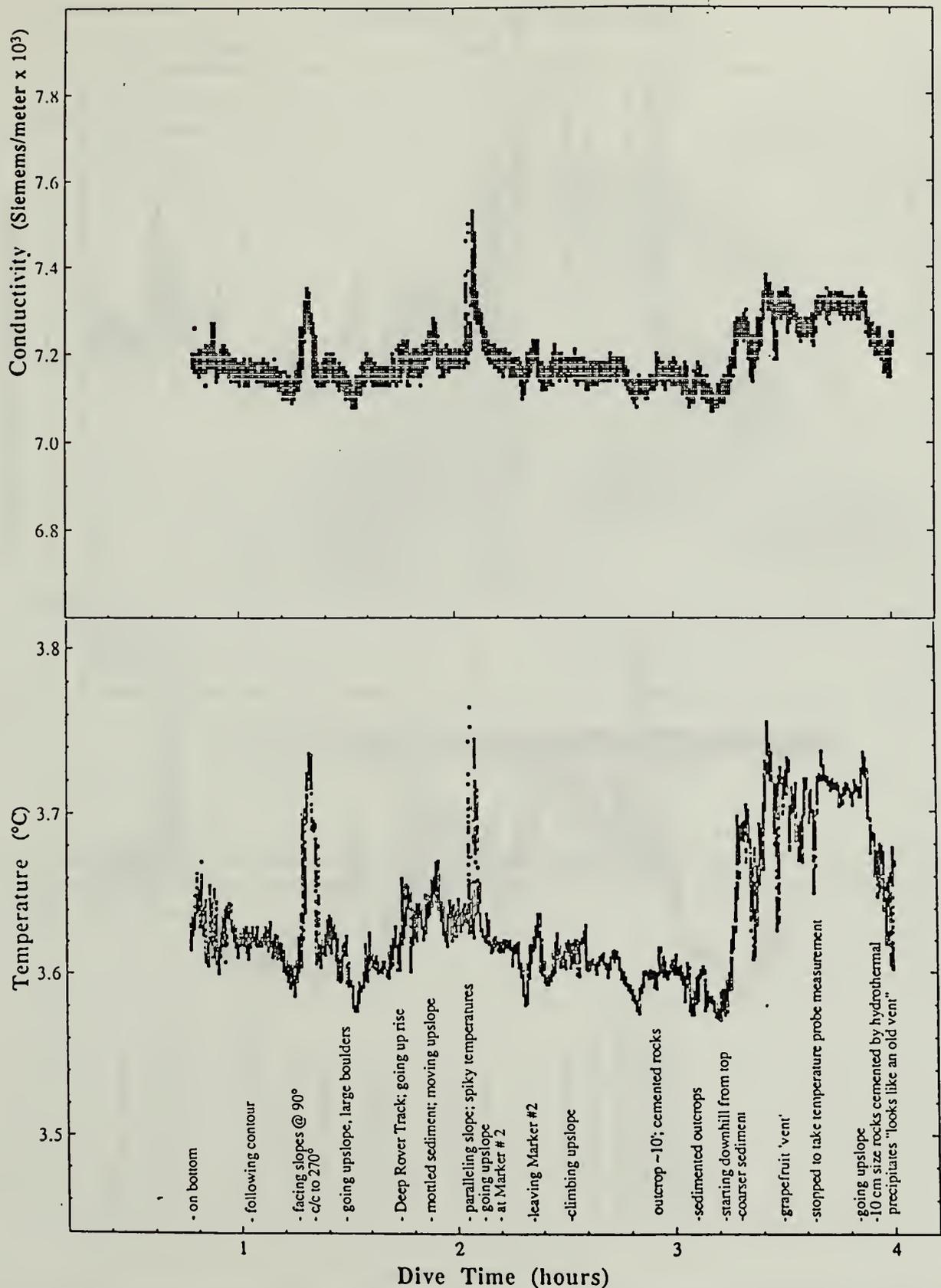


Figure 9. Conductivity (upper panel) and temperature (lower panel) measured with the CTD during dive 187. Dive time in hours along the x-axis is measured from the time the submersible leaves the surface. The annotation of submersible operations are shown along the x-axis.

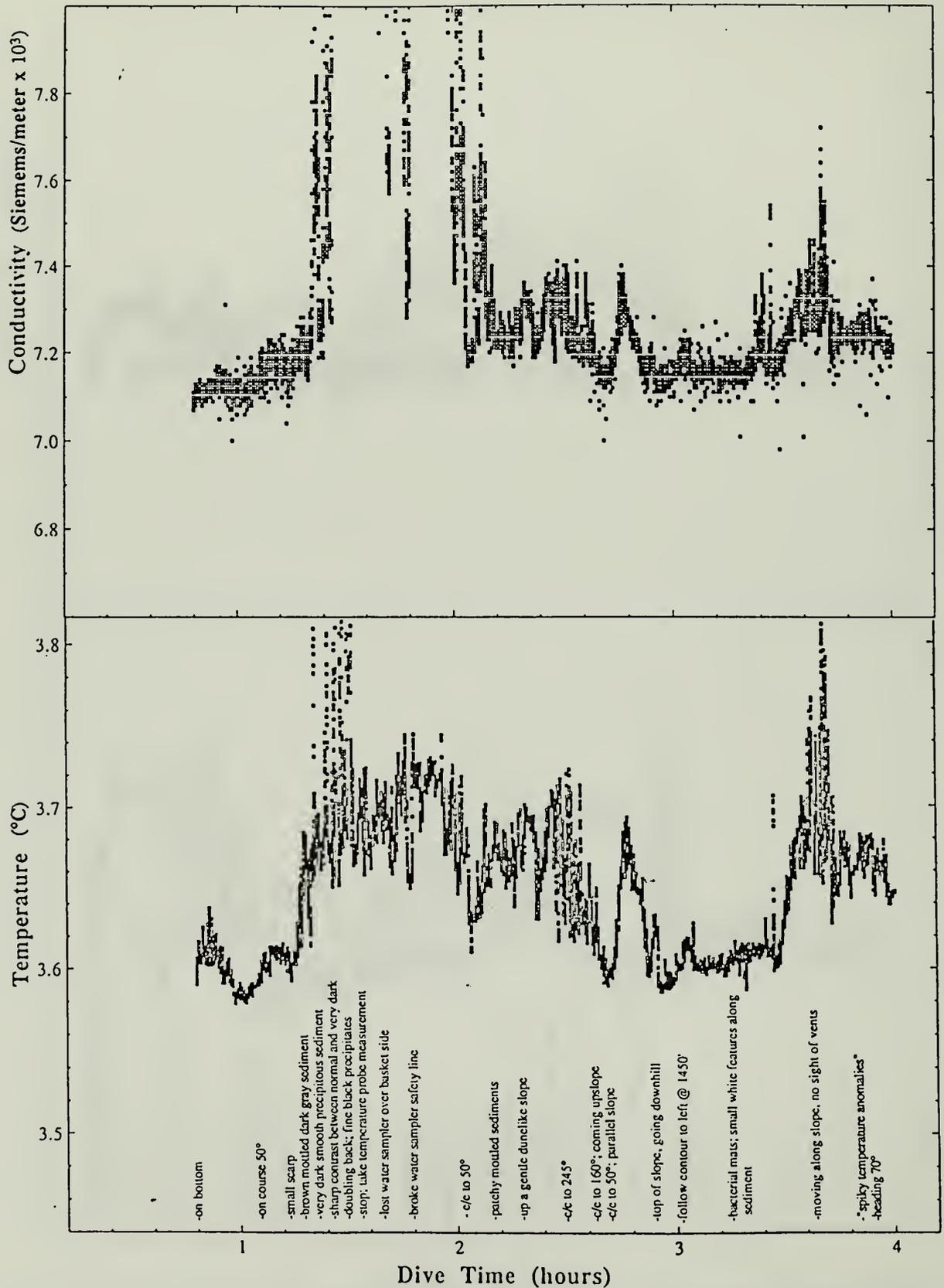


Figure 10. Conductivity (upper panel) and temperature (lower panel) measured with the CTD during dive 182. Dive time in hours along the x-axis is measured from the time the submersible leaves the surface. The annotation of submersible operations are shown along the x-axis.

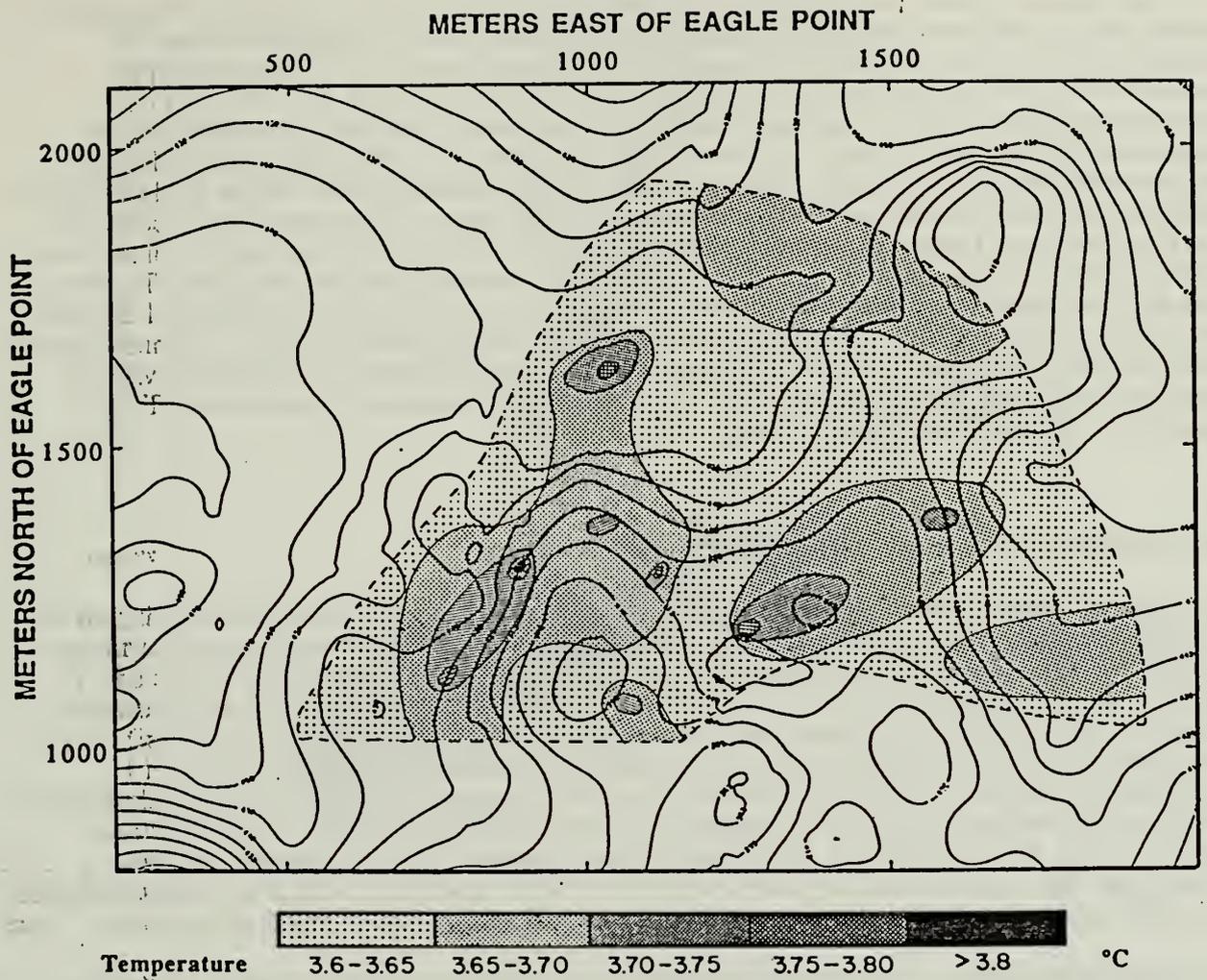


Figure 11. Contour map of near-bottom temperatures as recorded by the CTD on Deep Rover. The small area with temperatures $>3.8^{\circ}\text{C}$ is the location on dive 182 where temperatures as high as 4.1°C were measured.

The relationship of conductivity (salinity) and temperature is often used in analyzing water masses because both quantities are essentially conservative during mixing and because they can be measured *in situ* with a very high degree of precision (Hutchinson, 1957). The relationship between conductivity and temperature during CD182 is shown in Figure 12. This data demonstrates mixing between three end-members present during the dive. The majority of the samples during the dive fall along the lower data trend, marked "b" and actually fall within the darkest center portion of this trend. The two largest thermal anomalies seen during dive CD182 are represented by two different fluid end-members seen in this figure. The upper "arm" of the data set ("a") represents a fluid with a higher conductivity/heat ratio apparently mixing with water along the main trend at a temperature of 3.65 °C. This fluid was sampled over the very dark sediment patch (@ dive time 1.4 in Figure 10) and had manganese concentrations more than 1000x greater than other deep water values. The temperature of this anomaly extended to 4.1 °C. The other large thermal anomaly seen during the dive (@ dive time 3.7 hours in Figure 10) is represented at the end of the main "arm" of the data set ("b"). This fluid appears to be more representative of the source of the general South Basin anomaly.

The Chemistry of Crater Lake Waters

Introduction. Despite its remote location, the lake has been studied by numerous limnologists and oceanographers since the turn of the century. A summary of the earlier chemical studies of Crater Lake by the U.S. Geological Survey can be found in a USGS water supply paper by Phillips (1968) and by Van Denburgh (1968). More recent research efforts by the USGS are presented by Thompson et al. (1987), Thompson et al. (in press), Nathenson (in press) and Nathenson and Thompson (in press). In 1969, a group of investigators studied the fission-produced radioisotopic inventory in the lake (Volchok et al, 1970; Simpson, 1970a,b). Water chemistry and biological data collected as part of the on-going 10-year limnological program at the park are reported within the annual reports for this project (e.g. Larson, 1988). In general, all these investigators have reported that the lake is well-mixed with respect to the major ion concentrations. The radioisotope distributions also suggest a rapid vertical mixing rate of less than ten years.

Distributions with Depth. The vertical distribution of sodium, magnesium, potassium, calcium, silicate and manganese from samples collected within the Special Study Area are shown in Figure 13. These distributions are similar to those reported for the 1987 sampling program (Collier and Dymond, 1988a). It can clearly be seen that the concentration of these dissolved ions increases with depth in the south basin and that this increase correlates with the increase in temperature and total salt measured by the CTD (Figure 6). Note that without the use of high precision analyses, these increases could not be characterized. This correlation seen in the south basin is consistent with a common carrier of the signals - warm, salty fluids. These data alone do not constrain the specific source location, character or temperature. The horizontal and vertical complexity of this temperature and salt signal must be actively maintained against mixing and diffusion processes.

The increase of magnesium (Figure 13b) in this fluid end-member might be contrasted to marine hydrothermal fluids which are always depleted in magnesium due to greenschist metamorphism of basalt by seawater (Edmond et al. 1979). However, this depletion is relative to the seawater concentration of magnesium which is a factor of 500 times higher than that in Crater Lake. Indeed, magnesium does increase in many continental hydrothermal systems of low-to-intermediate temperatures which are supplied by relatively pure waters (Mariner et al. 1980, 1982; Fournier and Potter, 1979). Hurst and Dibble (1981) demonstrated an increase in magnesium concentration in Ruapehu Crater Lake (New Zealand) which was associated with lake water interaction with hot andesitic materials. Also, the concentrations of magnesium in Paulina and East Lake (within Newberry Crater) are elevated due to hot spring inputs (Phillips, 1968; Johnson et al., 1985).

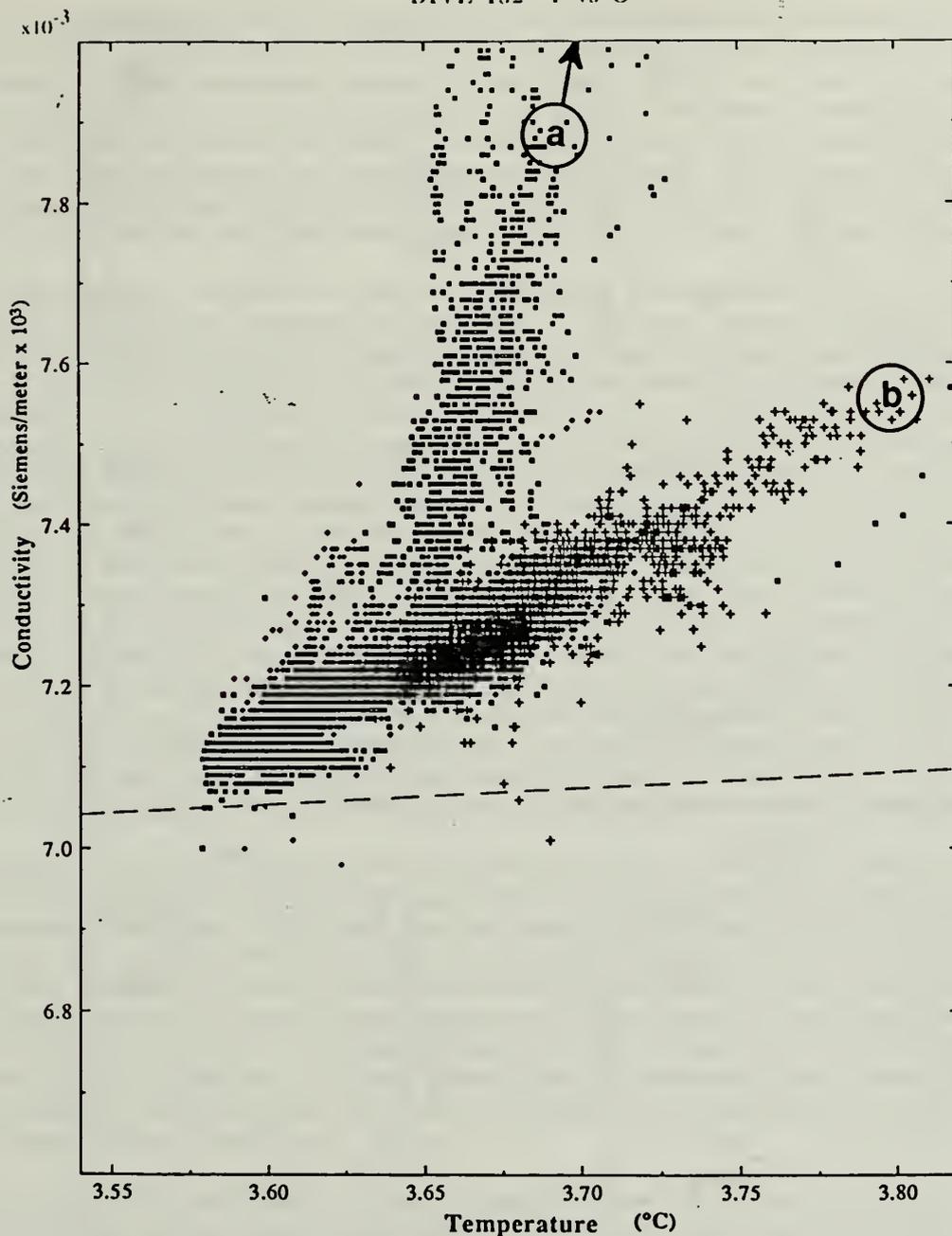


Figure 12. The relationship between conductivity and temperature during CD182. The dotted line represents the ideal increase in conductivity of a constant salinity sample due to a change in temperature. Data would fall along this line if conductive heating (or heating by the submersible) were responsible for the changes observed. This type of plot can be used to evaluate the temperature/salinity relationship of end members present during the dive. The majority of the samples fall along the lower trend (actually within the darker center portion). The two largest thermal anomalies seen during dive CD182 (@ dive time 1.4 hours and 3.7 hours in Figure 10) are represented by the two different fluid end members seen in this figure. The upper "arm" of the data set ("a") represents a fluid with a higher conductivity/heat ratio. This fluid was sampled over the very dark sediment patch and had manganese concentrations more than 1000x greater than other deep water values. The other thermal anomaly is represented at the end of the main "arm" of the data set ("b"). This fluid appears to be more representative of the source of the general South Basin anomaly.

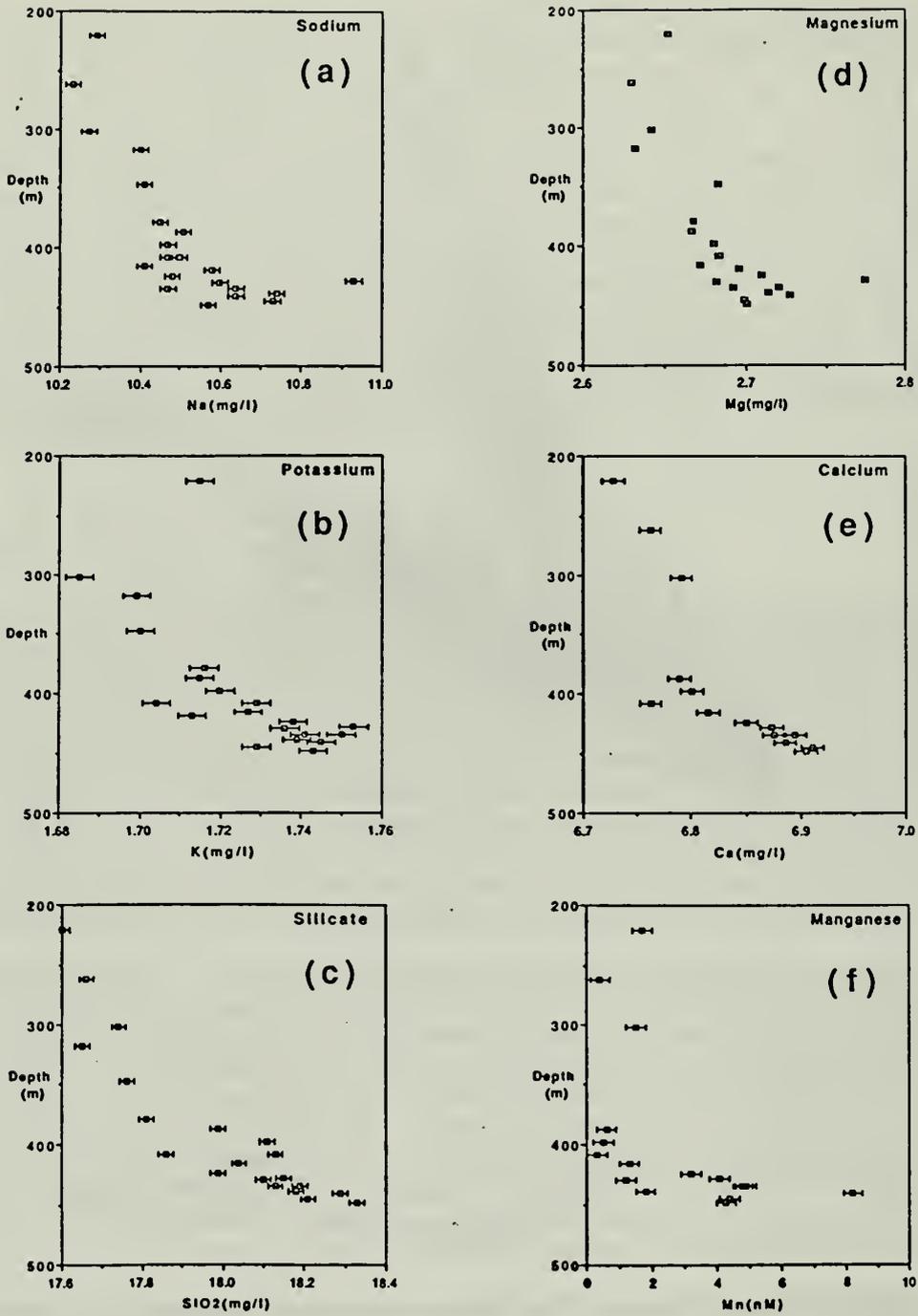


Figure 13. The concentration of various ions as a function of depth in the South Basin: (a) sodium; (b) magnesium; (c) potassium; (d) calcium; (e) silicate; (f) manganese.

However, detailed comparisons of concentrations of elements in these systems must be used with caution since the concentrations are primarily controlled by the ratio of hydrothermal to total water in the system - not the existence or absence of hot springs. For instance, East Lake and Paulina Lake which occupy a single volcanic crater, are only separated by water-permeable lava and ash flows. Both lakes have known hot springs with measured temperatures up to 48°C at their outflow, yet their bulk lake water compositions are very different. While the concentrations of some cations are quite high in Paulina Lake compared to Crater Lake (e.g. Ca, Mg), the concentrations of sulfate and chloride are a factor of 2 higher in Crater Lake than in Paulina.

Ion-Ion Systematics. A more useful method of displaying the major ion data for interpretation of sources is to consider the covariation of these ions. For instance, Figure 14 displays the systematics of sodium vs. calcium in various portions of the Crater Lake hydrologic system. Figure 14a shows the covariation of these ions within the Special Study Area as determined on samples from the 1987 and 1988 hydrocast program. The data from the two years do not show any systematic shifts. While sodium is our least precise analysis, its covariation with calcium is still clear. Figure 14b expands this plot to include all of the data available for waters within the Crater Lake hydrologic system: the south basin hydrocast data; data from samples collected during dives by the submersible within near-bottom thermal anomalies; the concentrations of various surface springs within the caldera; the concentration of ions in precipitation at the Park (Reilly et al., 1989; G. Larson, unpublished data). Several features of this system are immediately apparent. First, the composition of the lake cannot be accounted for by any reasonable combination of the major hydrologic inputs. The concentrations of these inputs are depleted in sodium and the Na/Ca ratios in the springs (the only significant carrier of these ions) can be quite different than the lake. The only end-members sampled that can account for the lake's high concentration of Na and Ca are the fluids sampled by the submersible within the south basin study area. The lake water composition lies directly on a mixing line between these fluids and precipitation. More details of these systematics will be discussed below in terms of the geochemical mass balances in the lake.

For comparison, Figure 14c presents the systematics of sodium vs calcium in other high Cascade lakes and Newberry Crater. Crater Lake stands out from all the Cascade lakes in terms of the concentration of both ions. These High Cascade lakes lie in geochemically similar volcanic terrain and should receive similar precipitation and low-temperature weathering inputs to those entering Crater Lake. In fact, since most of these lakes have a higher relative drainage basin (compared with lake surface area), the weathering inputs to these lakes should be more significant than at Crater Lake. As noted above, East Lake has known hydrothermal inputs and also stands apart from other lakes in this region. As seen in the Figure 14c, mixtures of precipitation and of sources similar to those responsible for East Lake's unique composition and can account for the Na/Ca composition of Crater Lake.

Figure 15 presents the relationship of potassium and sodium in the Crater Lake system. The relationship of these ions can be controlled by a series of low temperature weathering reactions such as the alteration of volcanic glass to kaolinite (Nathenson and Thompson, in press) and higher temperature reactions such as exchange equilibria between albite and K-feldspar (Fournier, 1981). As is the case for the other chemical data, the concentrations and trends seen in the 1987 data set are repeated in the 1988 hydrocast data (Figure 15a). Figure 15b again demonstrates that it is impossible to account for Crater Lake water by mixtures of precipitation and runoff: the concentration of sodium in the lake is too high and the Na/K ratios in the springs are too low. The only waters sampled, to date, that can explain the lake composition are mixtures of the South Basin waters, sampled by the submersible, and the major input of precipitation which dilutes this single end-member. More details on these budgets will be discussed below.

Figure 15c displays the conductivity (related to the concentration of total dissolved ions) vs. the Na/K ratio in Crater Lake, other High Cascade Lakes, and East Lake. Again, Crater Lake stands out from the bulk of the other Cascade Lakes in both its Na/K ratio and the total dissolved ion

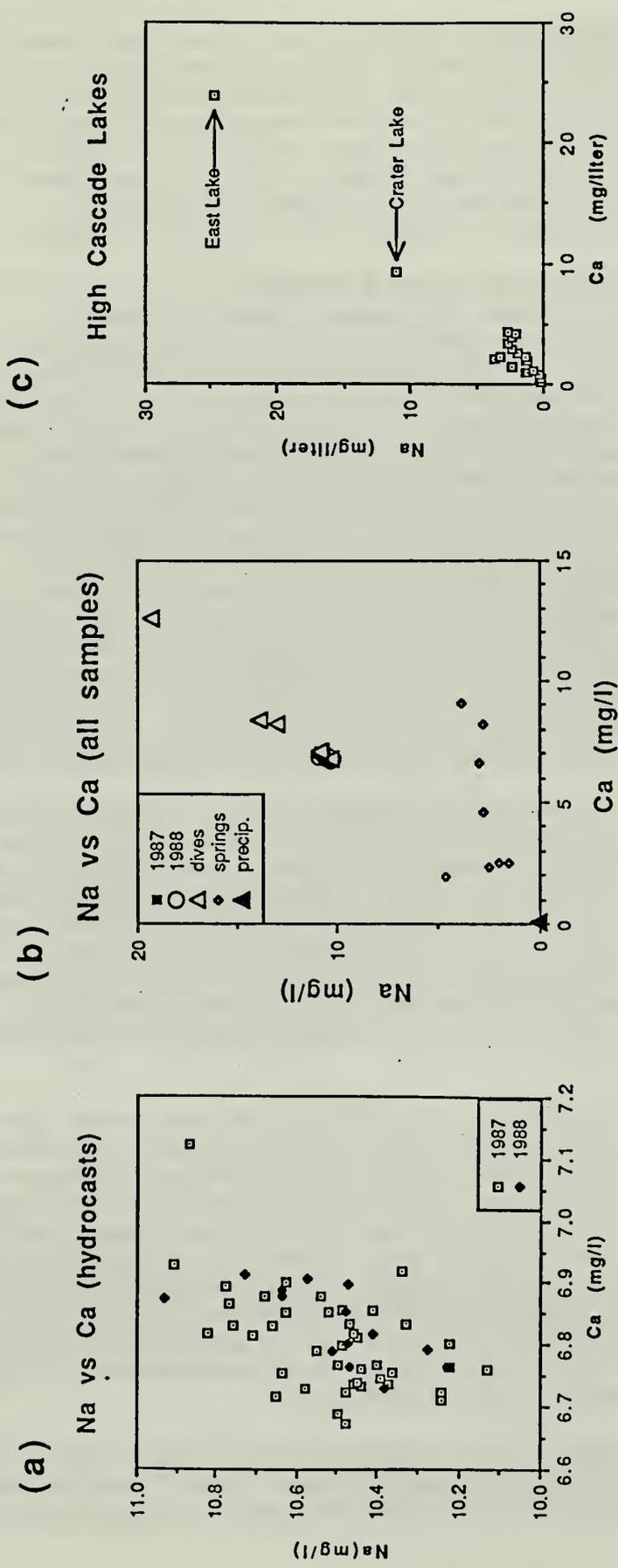


Figure 14. The concentration of sodium (Na) vs. calcium (Ca) in Crater Lake and associated waters: (a) Expanded scale plot of concentrations in hydrocast samples from the South Basin collected in 1987 and 1988; (b) Na vs. Ca in all hydrologic components of the Crater Lake system - lake water (data from figure 14a), near-bottom dive samples of waters displaying thermal anomalies, caldera springs, and precipitation. Precipitation data are from Reilly et al. (1989); (c) Concentrations of Na and Ca in Crater Lake compared with other high Cascade Lakes and East Lake (in Newberry Crater). High Cascade Lake data are from Johnson et al. (1985) and include Big, Blue, Clear, Crescent, Cultus, Davis, Devils, Diamond, East, Elk, Middle Green, Lava, Lost, Marion, Odell, Olallie, Sparks, Summit, Suttle, and Waldo lakes. Paulina Lake, also located within Newberry Crater with East Lake, plots off the diagram with Na = 41 mg/l and Ca = 23 mg/l.

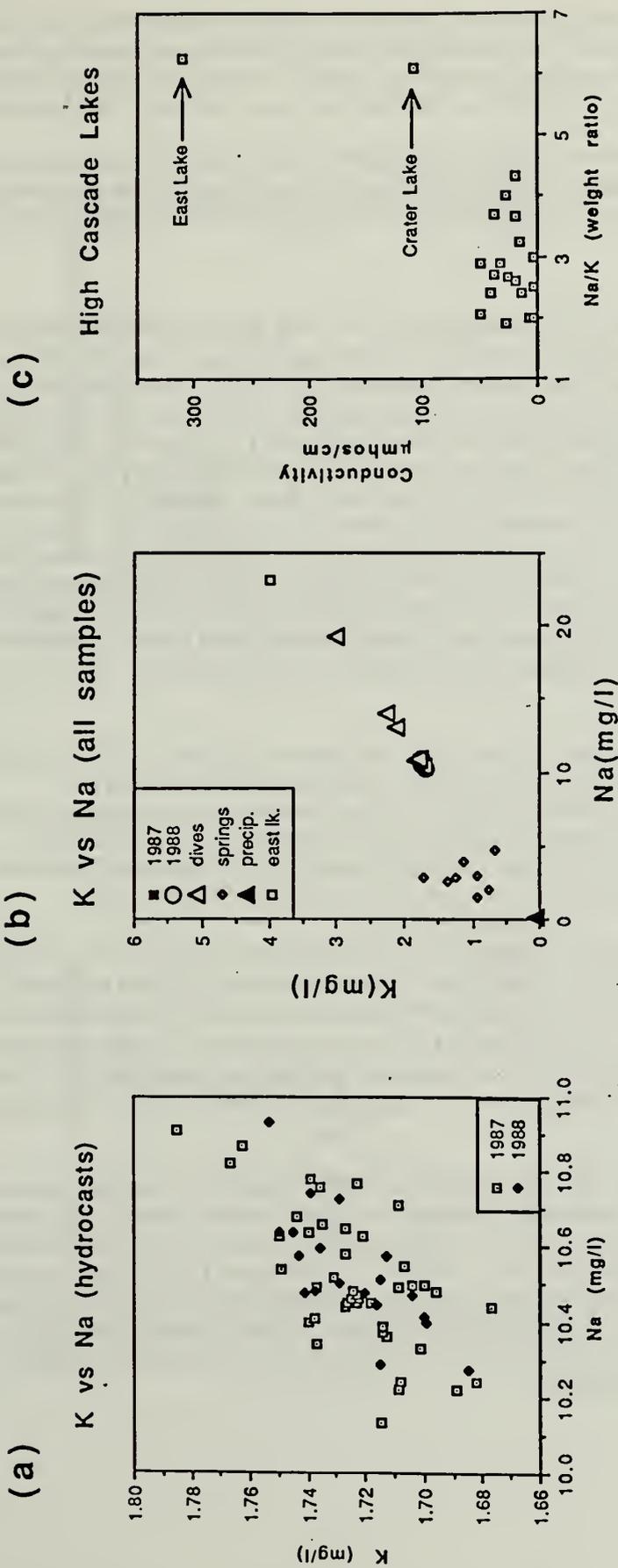


Figure 15. The concentration of potassium (K) vs. sodium (Na) in Crater Lake and associated waters: (a) Expanded scale plot of concentrations in hydrocast samples from the South Basin collected in 1987 and 1988; (b) K vs. Na in all hydrologic components of the Crater Lake system - lake water (figure 15a), near-bottom dive samples of waters displaying thermal anomalies, caldera springs, and precipitation. Precipitation data are from Reilly et al. (1989); (c) Conductivity ($\mu\text{mhos/cm}$) vs. Na/K (weight ratio) in Crater Lake compared with other high Cascade Lakes and East Lake (in Newberry Crater). High Cascade Lake data are from Johnson et al. (1985); specific lakes included are listed in the caption to Figure 14. Paulina Lake, also located within Newberry Crater with East Lake, plots off the diagram with a conductivity of 558 $\mu\text{mhos/cm}$ and Na/K = 7.7.

content. For comparison, although East Lake has a significantly higher conductivity (3x), its Na/K ratio is quite similar to Crater Lake. This relationship could be simply explained by variable dilution of a single input end-member - such as hot springs. Again, these types of relationships do not in themselves prove the existence of hot springs, but they are consistent with this hypothesis.

Figure 16 presents the relationship between sodium and silicate. Examination of the Na/Si ratio in the possible source waters (surface springs, precipitation, and thermal fluids of the type sampled by the submersible) again demonstrates the significance of the inputs seen in the South Basin to the bulk composition of Crater Lake.

Helium data. One of the most exciting early discoveries in our work was the identification of extreme enrichments of helium in Crater Lake which had a very high isotopic ratio ($^3\text{He}/^4\text{He} = 7.1$), clearly reflecting a mantle origin for the helium (Lupton et al., 1987). The significance of these results with respect to hydrothermal activity were discussed by Collier and Dymond (1988a). The depth distribution of He-3 in the South Basin is shown in Figure 17. The 1987 and 1988 data sets follow identical trends and are also consistent with our 1985 data sets (Collier and Dymond, 1988a). The water samples near the bottom of the Detailed Study Area contain >500% more He-3 than air-saturated fresh water (surface lake water at 1882 meters elevation and 4 °C). Since helium exchanges rapidly with the atmosphere in well-mixed surface waters, the process injecting this mantle-derived helium into the deep lake must occur faster than the deep lake exchanges with the atmosphere. Simpson (1970b) estimated that this mixing took place rapidly with a characteristic time of one year. Assuming that all of this excess helium would be stripped from the lake over this same timescale, Lupton et al. (1987) calculated a total ^3He flux into the lake - 1.8×10^{22} atoms of $^3\text{He}/\text{year}$.

The concentrations of the helium isotopes, ^3He and ^4He , are shown in Figure 18. The remarkable correlation of all deep lake values demonstrates a two end-member mixture between the atmospheric helium near the surface of the lake ($R/R_{\text{atm}} = 1$) and mantle-enriched helium with $R/R_{\text{atm}} = 7.1$. This ratio is similar to values in Lassen Peak hot springs (7.2), Mt. Hood fumaroles (7.2), Mt. Baker fumaroles (7.6), hydrothermal plumes at the Galapagos Spreading Center (7.8) and the East Pacific Rise (8.0) (Lupton et al., 1987; 1980; Poreda, 1983).

As shown for the 1987 data set (Lupton et al., 1987), the concentration of ^3He is well correlated with the increase in temperature seen in the South Basin. These data are displayed in Figure 19a. The slope of this relationship is 1.5×10^{-12} cc $^3\text{He}/\text{gram}^\circ\text{C}$ which is similar to the helium-heat ratio seen in marine hydrothermal systems. This ratio can be combined with the ^3He flux estimate (Lupton et al., 1987) to arrive at an estimate of the convective heat input to the Lake - 5.8×10^7 joules/sec or 58 megawatts. This value is similar to that calculated by Williams and Von Herzen (1983).

Also shown in Figure 19 (b-f) are the excellent correlations of He-3 with the dissolved ions in the South Basin. When we examine the geochemical budgets in a later section, we will use these correlations to refine our estimates of total heat flux associated with the input of these salty thermal waters. While the submersible samples CD179.1, CD184, CD186.1 and CD187 have among the highest He concentrations in our data set, we were unable to collect good helium samples from dives CD182 or from the bacterial mats (CD179BT) which showed the highest anomalies in dissolved ions (c.f. Figures 14, 15, 16, Appendix IV). Therefore, we do not yet know the He concentrations in these extreme end-members.

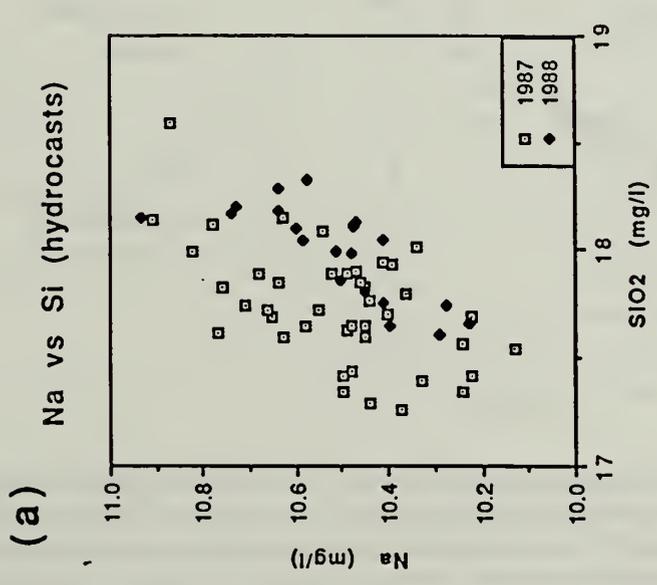
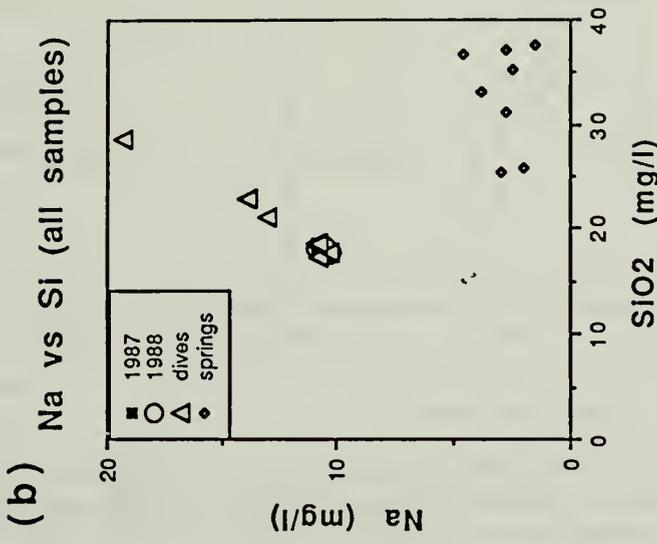


Figure 16. The concentration of sodium (Na) vs. silicate (as SiO₂) in Crater Lake and associated waters: (a) Expanded scale plot of concentrations in hydrocast samples from the South Basin collected in 1987 and 1988; (b) Na vs. SiO₂ in all hydrologic components of the Crater Lake system - lake water, near-bottom dive samples of waters displaying thermal anomalies, caldera springs, and precipitation. Precipitation data are from Reilly et al. (1989).

Helium-3 vs depth

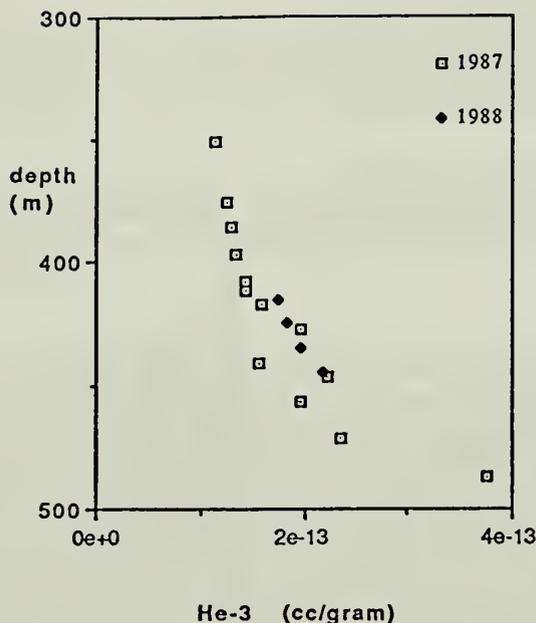


Figure 17. The concentration of He-3 vs. depth in the South Basin Study Area (Figure 1). Included are hydrocast samples from 1987 (Collier and Dymond, 1988a) and new samples from the 1988 program. The highest concentrations are enriched by more than a factor of 500 above the air-saturated concentration of He-3. These data are preliminary results provided by Dr. J. Lupton, UC Santa Barbara. Final results will be presented in Lupton et al., in preparation.

Helium Isotope Ratios - Crater Lake

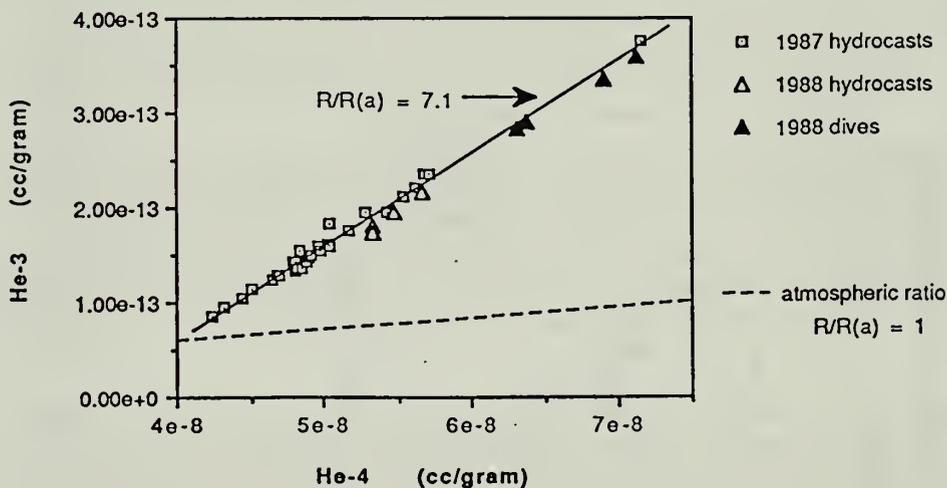


Figure 18. The concentration of He-3 vs. the concentration of He-4 in Crater Lake for all data from 1987 and 1988. Helium derived from the atmosphere has an isotope ratio displayed by the dotted line ($R/R_{atm} = 1$). The air-saturation concentration for Crater Lake lies at the intersection of the two lines on the figure. Helium is greatly enriched in the lake and the source of this added helium has an isotopic ratio greatly different from the atmospheric ratio. The linear regression of He-3 vs. He-4 in the lake gives a slope of 9.9×10^{-6} which results in $R/R_{atm} = 7.1$. These data are preliminary results provided by Dr. J. Lupton, UC Santa Barbara. Final results will be presented in Lupton et al., in preparation.

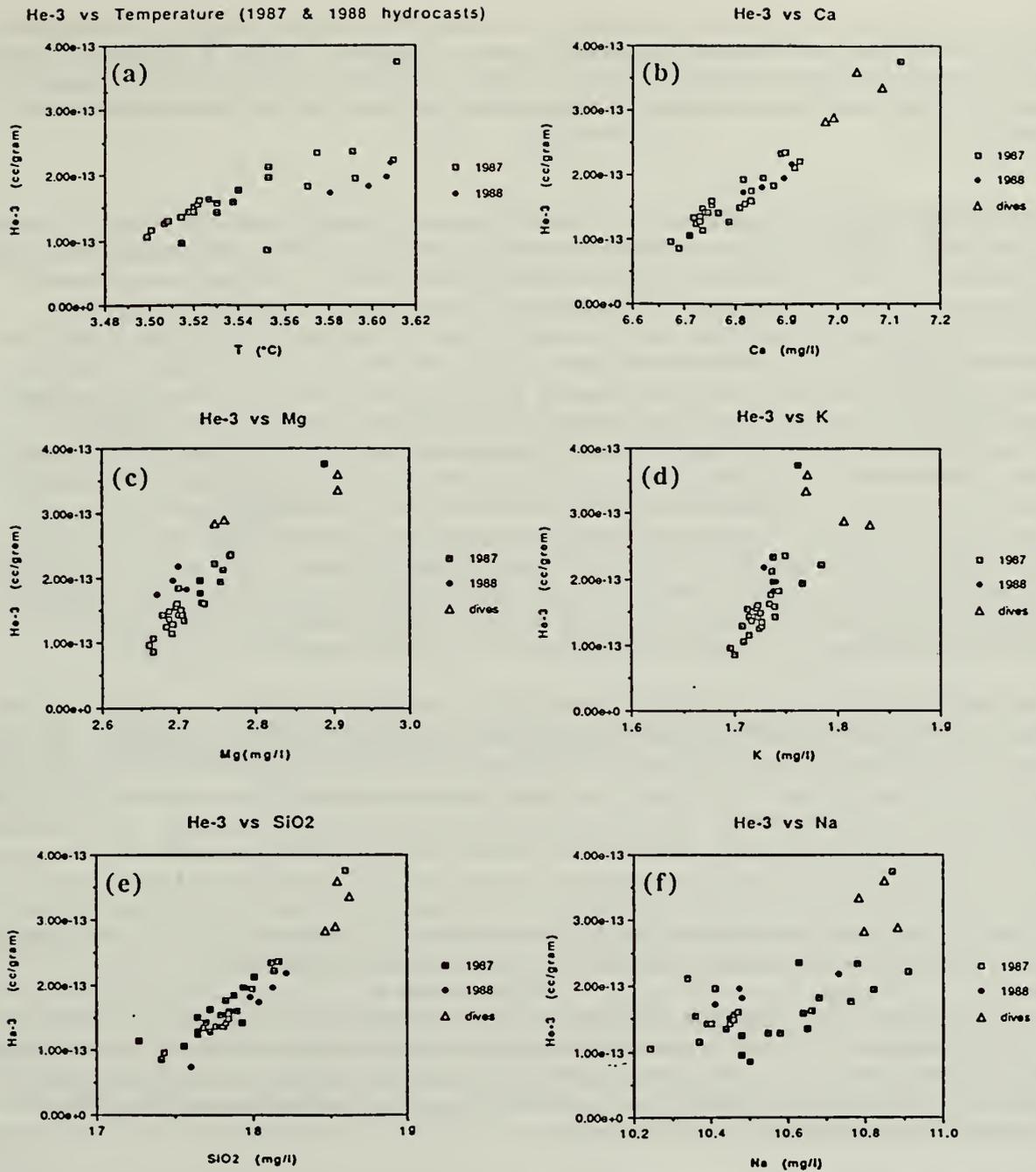


Figure 19. The concentration of He-3 vs. (a) temperature and (b-f) dissolved ions in the lake. These plots include all data currently available from 1987 and 1988 and demonstrate excellent agreement between the two years data sets. The slope of the He-temperature relationship (a) is approximately 1.5×10^{-12} cc He-3/gram \cdot °C. The Helium data are preliminary results provided by Dr. J. Lupton, UC Santa Barbara. Final results will be presented in Lupton et al., in preparation.

These correlations support the hypothesis of a common carrier for these signals - thermal waters with high total dissolved ions carrying dissolved gases of magmatic origin. If the helium is carried into the deep lake in another form such as a non-condensable gas phase, then other independent processes must be combined to create the observed correlations of helium with temperature and dissolved ions.

Radon-222 and Radium-226. One of the most effective tracers of hydrothermal input to the oceans has been radon-222: hydrothermal fluids are strongly enriched in ^{222}Rn over normal ocean waters (Dymond et al., 1983); radon is a noble gas (therefore conservative); and measurements can be made at sea to give real-time data. Unfortunately, ^{222}Rn is not an unequivocal indicator of hydrothermal inputs because other there are other sources of the isotope. Diffusive inputs from sediments can be a significant source of radon-222 (Broecker et al., 1968; Kadko, 1981). In addition, ^{222}Rn is enriched in all ground waters, thermal or non-thermal, as a result of α -recoil injection from the surfaces of uranium-bearing solids (Asikainen, 1981). Consequently, for application to Crater Lake this tracer can not distinguish between hydrothermal and cold spring inputs. Despite these complicating factors, measurement of this isotope is important because the 3.8 day half life adds a temporal component that does not exist with nonradioactive tracers of spring inputs. Of special significance is the possibility of studying variability in the $^{222}\text{Rn}/^3\text{He}$ values, which because both isotopes are noble gases, should decrease according to the radon half life upon injection into bottom water. If there is input of hydrothermal fluid into the deep lake, the rates of dispersion and the removal kinetics of nonconservative hydrothermal tracers could be evaluated by studies of this isotope pair (Kadko et al., 1986; Rosenberg et al., 1987).

In our previous report of hydrothermal studies (Collier and Dymond, 1988), we pointed out that ^{222}Rn enrichments occur in the detailed study area but not in the East Basin of the lake. We were also able to demonstrate that diffusion of ^{222}Rn from Crater Lake sediments was not a significant source to the water column. In Figure 20 we have plotted measured ^{222}Rn contents of Crater Lake as a function of sampling depth. This figure includes all previous measurements. The significant features of this plot are the high values that occur between 400 and 470 meters depth. Above and below this depth, the radon contents decrease to values near those which would be supported by dissolved radium-226 in the lake (~1 dpm/100 L). Because the radon-222 analysis consumes a large amount of sample, only two of the analyses made in 1988 were collected by the submersible (dives 183 and 187). The other 1988 results are from navigated hydrocasts.

The data from the 1988 studies has extended the degree of enrichment observed in the detailed study by more than a factor of six over the previous data. Both submersible samples were higher than any other previous measurements. The highest value with a ^{222}Rn content of over 200 dpm/100 l was collected on dive 187 near a bacterial mat. The other submersible sample was collected 200 m to the east of the 187 sample.

The analyses of radium-226 are currently in progress, however, results from two of the 1988 samples are completed. Analyses of dive 187 provide the first evidence of radium-226 enrichments in the detailed study area. The radium activity in this sample is 15.3 dpm/100 liters in marked contrast to the concentration in a hydrocast sample from outside the detailed study area, 0.69 dpm/100 liters. The highly enriched sample, which is 10 to 15 times higher than that measured in any samples from previous years, has significance regarding the question of warm vs cold spring sources of radon and radium. Krishnaswami and Turekian (1982) argue that rock alteration and not α -decay is the dominant source of ^{226}Ra in hydrothermal solutions. Barium is a chemical analogue to radium in many geochemical reactions. It is well known that Ba is readily leached from rocks by hydrothermal solutions (Mottl and Holland, 1978). Consequently, the observed radium enrichment may also indicate an input of hydrothermal fluids to the detailed study area.

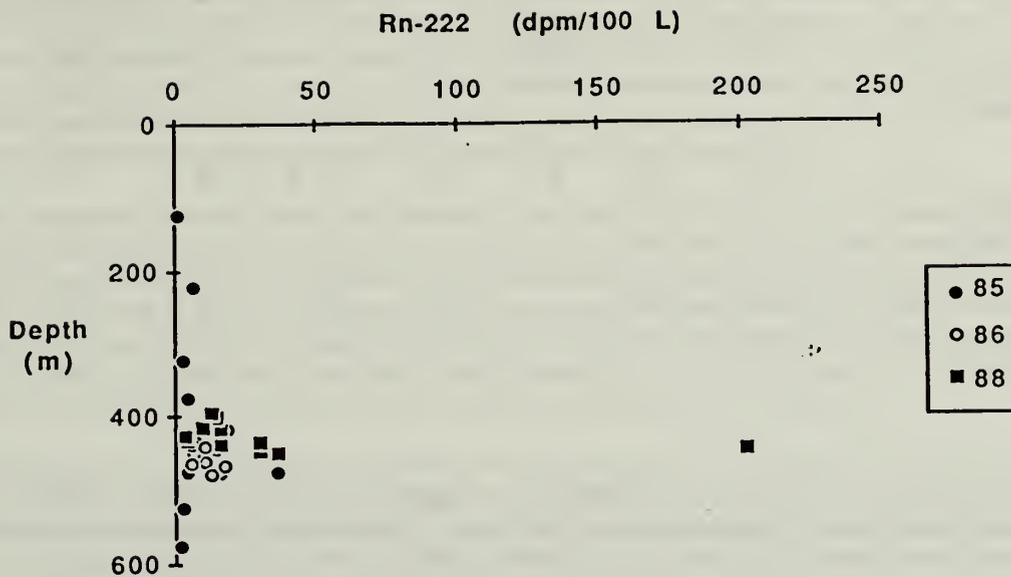


Figure 20. Radon-222 vs depth of sample. Data from 1985, 1986, and 1988 are shown. The two highest samples from 1988 were collected with Deep Rover. All other samples are from hydrocasts.

Compositions of bacterial mat fluids. During dive CD179, the first of several bacterial mats discovered during our dive program was sampled. The specific sample was collected from a mat shown later in Figures 23 and 25. The thermistor probe registered a temperature of 5.7 °C in the mat surrounded by a background water temperature of 3.60 °C. The sample was collected by placing the open end of a Niskin-type water sampler directly within the mat. The cylinder of the sampler penetrated the mat approximately 5-10 cm with the rest of the sampler body extending out into the water column. After closing, the sampler retained several centimeters of mat material and a water sample that represents a mixture of the "mat water" and of the local bottom water around the mat.

The composition of this sample represents the most evolved end-member collected within the lake, to date. The chemistry of this sample (Table 2) can be contrasted with "normal" deep lake water (sample 7.3 from 351 meters) and with a South Basin sample which has anomalous temperature and ionic composition (sample 2.2-7 from 429 meters). Many of the concentrations of the major ions are nearly a factor of two higher in the mat fluids and Mn concentrations are 2-3 orders of magnitude higher than surrounding lake waters. These compositions define major thermal, chemical and density gradients across this interface.

Table 2. Chemical composition of bacterial mat water

sample	Na (mg/liter) --->	K	Ca	Mg	SO ₄	Cl	SiO ₂	Li (µg/liter)	Mn (nM)
7.3 (hydrocast, 1987, 351m)	10.4	1.71	6.73	2.69	-	-	17.3	44.1	0.6
2.2-7 (hydrocast, 1988, 429m)	10.9	1.75	6.87	2.77	10.2	10.6	18.2	-	4.1
CD179BT (bacterial mat water)	19.3	3.01	12.6	-	20.4	15.7	28.7	77.2	590

Because of the method of collecting this sample, we cannot be sure of the extent of dilution of the actual bacterial mat fluids by the background lake water. We believe a conservative estimate, based on relative volumes alone, would be a 1:10 dilution of mat water by lake water. This would suggest that *in situ* concentrations for mat water are probably nearly an order of magnitude larger than those shown in Table 2. Similarly, the temperature probe measurements in this gelatinous "fluff" can only represent a minimum value for the seep fluid present.

Given that this sample may represent our best end-member for a hypothesized hydrothermal flow, it may be instructive to consider its composition in more detail. Various ion-ion relationships in this dive sample have been discussed earlier in association with Figures 14-16. This sample represents an extreme end-member of the group of dive samples which can explain several deficits in accounting for the lake composition (see Geochemical Budgets below).

Assuming, for demonstration purposes, that the sample was diluted 10x with surrounding lake water, the original concentration would be: Na = 99 mg/liter; Ca = 65; Mg = 37; K = 15; SiO₂ = 128. If this represents the true end-member fluid, then we can consider applying any of several chemical geothermometers to the estimated composition (Fournier, 1981). Because the predicted temperatures appear to be relatively low, we have chosen chalcedony (a microcrystalline form of quartz) as a controlling silica phase and have also applied the Na-K-Ca geothermometer (Fournier and Truesdell, 1973; Fournier and Potter, 1979). These equilibria were also considered by Nathenson and Thompson (in press) for samples in the Wood River area, southeast of Crater Lake. The chalcedony geothermometer applied to the "undiluted" mat fluid (x10) gives 81 °C and the Na-K-Ca system gives 86 °C (no Mg correction is applied). Although these both give similar values, errors that may exist in the application of these geothermometers to these samples may make this agreement fortuitous. First, the predicted temperatures are fairly low and the solubility and exchange reactions modelled by the geothermometers are slow to reach equilibrium at low temperatures. Second, these functions are very sensitive to mixing with background waters. Although we have tried a first-order correction for this dilution, this is clearly a major unknown for this sample. Finally, at these relatively low temperatures, secondary alteration reactions may become important in controlling the ions modelled by the geothermometer equations. All we can say at this point is that ~80 °C may be the temperature controlling the final composition of this fluid, and we will use this estimate as a first-order constraint on total convective flow rates into the deep lake.

Geochemical mass balances. The closed basin and relatively simple hydrologic budget for Crater Lake have inspired many investigators to evaluate the geochemical budgets for materials in this system (e.g. Simpson, 1970a; Volchok et al., 1970; Nathenson, in press; Reilly et al, 1989). During discussion of our 1987 results (Collier and Dymond, 1988a), we also applied a similar geochemical model to compare the input rate of an hypothesized hydrothermal fluid with the major imbalance in the budget for several (most) of the major dissolved ions in the lake. All investigators cited have demonstrated that at steady state, only a small fraction of the dissolved ions leaving the lake with seepage can be accounted for by known, non-hydrothermal inputs (precipitation and low-temperature weathering products carried by runoff from the caldera wall).

It has been suggested that the lake is not at steady state and that the elevated concentrations of ions such as chloride and lithium remaining in the lake can be traced back to the lake's early volcanic history (LaFleur, 1987). An associated implication of this hypothesis would be that the concentration of these ions is still decreasing. Nathenson (in press) evaluated the possibility of these non-steady state conditions using all available USGS measurements of lake composition; he found no evidence of significant chemical change since 1912. We will present a similar model here in order to discuss some other features of this "early injection" hypothesis.

Figure 21 diagrams a mass balance "box model" for Crater Lake. The left hand diagram represents the mass balance of ions; the right hand diagram represents the hydrologic budget (the mass balance of water). The two parallel models are directly coupled through the calculation of concentration (mass/volume) in the lake. Boxes represent the reservoirs with flows in and out represented by the large arrows. Rates of flow ("valves" on flow arrows) are determined by initial conditions (constants) or by auxiliary first order equations. The system of equations represented is presented in Table 3 with an example of the initial values for chloride.

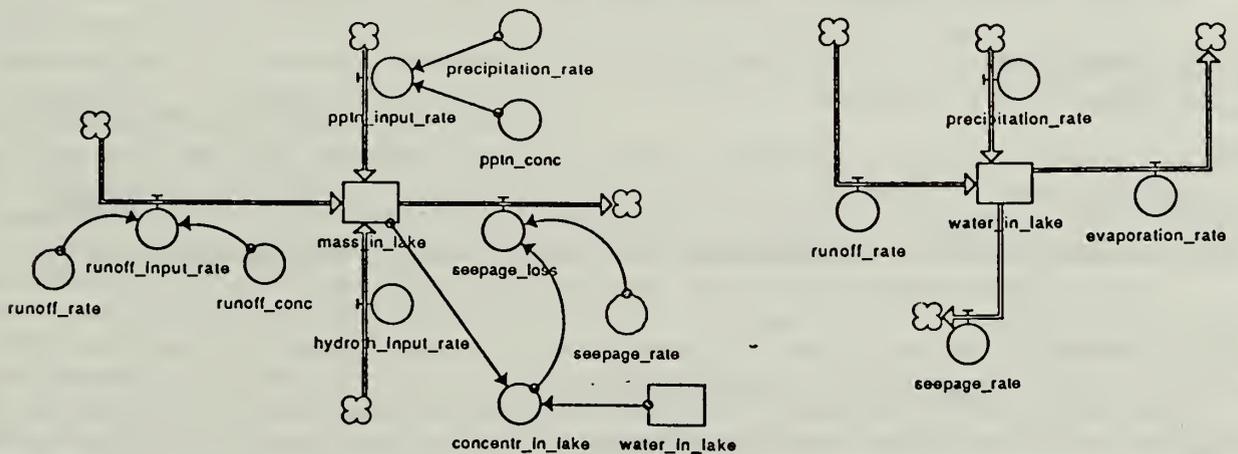


Figure 21. A schematic diagram representing a simple box model for dissolved ions in Crater Lake. The left hand diagram represents the mass balance of ions; the right hand diagram represents the hydrologic budget (the mass balance of water). The two parallel models are coupled through the calculation of concentration (mass/volume) in the lake. Boxes represent the reservoirs with flows in and out represented by the large arrows. Rates of flow ("valves" on flow arrows) are determined by initial conditions (constants) or by auxiliary first order equations. The system of equations is presented in Table 6. A form of this model was used by Collier and Dymond (1988a) in their discussion of geochemical balances in the lake. This model is essentially identical to those used by Simpson (1970a), Nathenson (in press), and Reilly et al. (1989) with updates to the hydrologic budget by Redmond (in press).

TABLE 3. -- SIMPLE CRATER LAKE BOX MODEL -- (chloride example)

SYSTEM OF EQUATIONS

(see Figure 21 for schematic relationships and Figure 22 for results)

Initialization equations:

- INITIAL (mass_in_lake) = 1.24×10^{10} kg (results in an initial chloride concentration of 718 mg/liter)
- INITIAL (water_in_lake) = 17.3×10^{12} liters (ref. 1)
- concentr_in_lake = (mass_in_lake) / (water_in_lake)
- evaporation_rate = 6.38×10^{10} liters/yr (ref. 2)
- hydroth_input_rate = 0 (assumed for demonstration purposes)
- pptn_conc = 3.75×10^{-7} kg/liter (ref. 3)
- precipitation_rate = 9.51×10^{10} liters/yr (ref. 2)
- pptn_input_rate = (precipitation_rate) x (pptn_conc)
- runoff_conc = 5.79×10^{-7} kg/year (ref. 3)
- runoff_rate = 3.62×10^{10} liters/yr (ref. 2)
- runoff_input_rate = (runoff_rate) * (runoff_conc)
- seepage_rate = 6.75×10^{10} liters/yr (ref. 2)
- seepage_loss = (seepage_rate) x (concentr_in_lake)

Structure equations:

- mass_in_lake = *(element mass budget)*
(mass_in_lake) + (Δt) x [pptn_input_rate + runoff_input_rate + hydroth_input_rate - seepage_loss]
- water_in_lake = *(hydrologic budget)*
(water_in_lake) + (Δt) x [precipitation_rate + runoff_rate - seepage_rate - evaporation_rate]

Auxiliary equations:

- concentr_in_lake = (mass_in_lake) / (water_in_lake)
- pptn_input_rate = (precipitation_rate) x (pptn_conc)
- runoff_input_rate = (runoff_rate) x (runoff_conc)
- seepage_loss = (seepage_rate) x (concentr_in_lake)

References: (1) Phillips, 1968; (2) Redmond, 1989; (3) Reilly et al., 1989.

We have adopted the steady state hydrologic budget refined by Redmond (in press). The changes in this budget, when compared to Phillips (1968), are based on very detailed climatic and lake level data. Redmond increased the estimate of precipitation arriving at the lake (by 19%) and increased the required evaporation rate, leaving the seepage rate estimate nearly the same. The balance of water loss we will use from his data is 49% by evaporation and 51% from seepage. The residence time for dissolved ions, with respect to seepage, is approximately 250 years. Initial values of the hydrologic budget are fixed in the model (see Table 3).

The model has been run to demonstrate the effects of massive, early hydrothermal and fumerolic inputs associated with the formation of the caldera. The two examples are run with very high initial conditions and assume no active hydrothermal inputs. These test the hypothesis that the high concentrations of certain solutes in Crater Lake are residual from very early in lake history. Two modern-day analogs of the formation stages of Crater Lake (Oregon) were considered for initial chemical conditions: Lake Oskjuvatn, Iceland and the crater lake in Soufriere volcano, St. Vincent Island. Lake Oskjuvatn is a 217m deep caldera lake formed after an eruption in 1875 with further eruptions in 1921 and 1926 (Olafsson, 1980). The crater lake in Soufriere volcano, St. Vincent Island is a 200m deep caldera lake which was reduced to 1/3 of its original volume in 1971-72 by the eruption of $80 \times 10^6 \text{ m}^3$ of lava up through the lake floor (Sigurdsson, 1977). We have chosen the higher concentration for any element between these two caldera lakes as the initial conditions for Crater Lake, Oregon.

The models are run for 6000 years - the approximate age of the lake, but the time axis can be considered as any Δt from the cessation of the volcanism. There is no evidence of volcanic eruptions inside the caldera within the last 4000 years (Bacon and Lanphere, in press). The initial chloride concentration (Figure 22A) is chosen to be 718 mg/liter (Soufriere). The concentration in the Crater Lake model reaches 101% of a steady state value (0.84 mg/liter) within 3000 years. This is less than 10% of the actual chloride concentration in Crater Lake (shown with a dotted line). The initial lithium concentration (B) was chosen to be 0.29 mg/liter (Soufriere) and the concentration falls below the Crater Lake value even more rapidly (B - curve a). The actual concentration of Li is shown by the dotted line. As an extreme example, an initial concentration of 1 gram Li/liter, five times higher than the Salton Sea Brines (Thompson and Fournier, 1988) still falls to the same steady state within 3600 years.

In summary, the model demonstrates that (1) Crater Lake water has very little "memory" of any reasonable volcanic inputs which occurred more than a few thousand years ago; and (2) the steady state concentrations of these ions would be very much lower than those measured today without a major active input from another source for these ions. While a steady-state model can not be proven, such models have great utility for defining the functioning of environmental systems. For Crater Lake there is no question that the important terms in the model have been identified (precipitation, runoff, evaporation, and seepage). The function of the model is to evaluate the relative importance of these terms, estimate their uncertainty, and to indicate the response of the lake to variations in these parameters. The model demonstrates the need for an active input which would represent the major flux of dissolved materials to the lake.

We can make use of the deficits predicted by the box models, coupled with the ion-He-temperature systematics (Figure 19) to arrive at an estimate of the total convective heat flux into the lake (Collier and Dymond, 1988a). This calculation attributes the ion flux deficits to the inflow of fluids similar to those sampled in the South Basin during 1987 and 1988 (e.g. Figures 14,15,16, and 19). Since these fluids are also warmer than deep lake water, this cation flux is associated with a heat flux. Thus, the total convective heat flux into the deep lake is estimated as the product of the cation deficit and the heat/cation ratio. The results of these calculations are presented in Table 4.

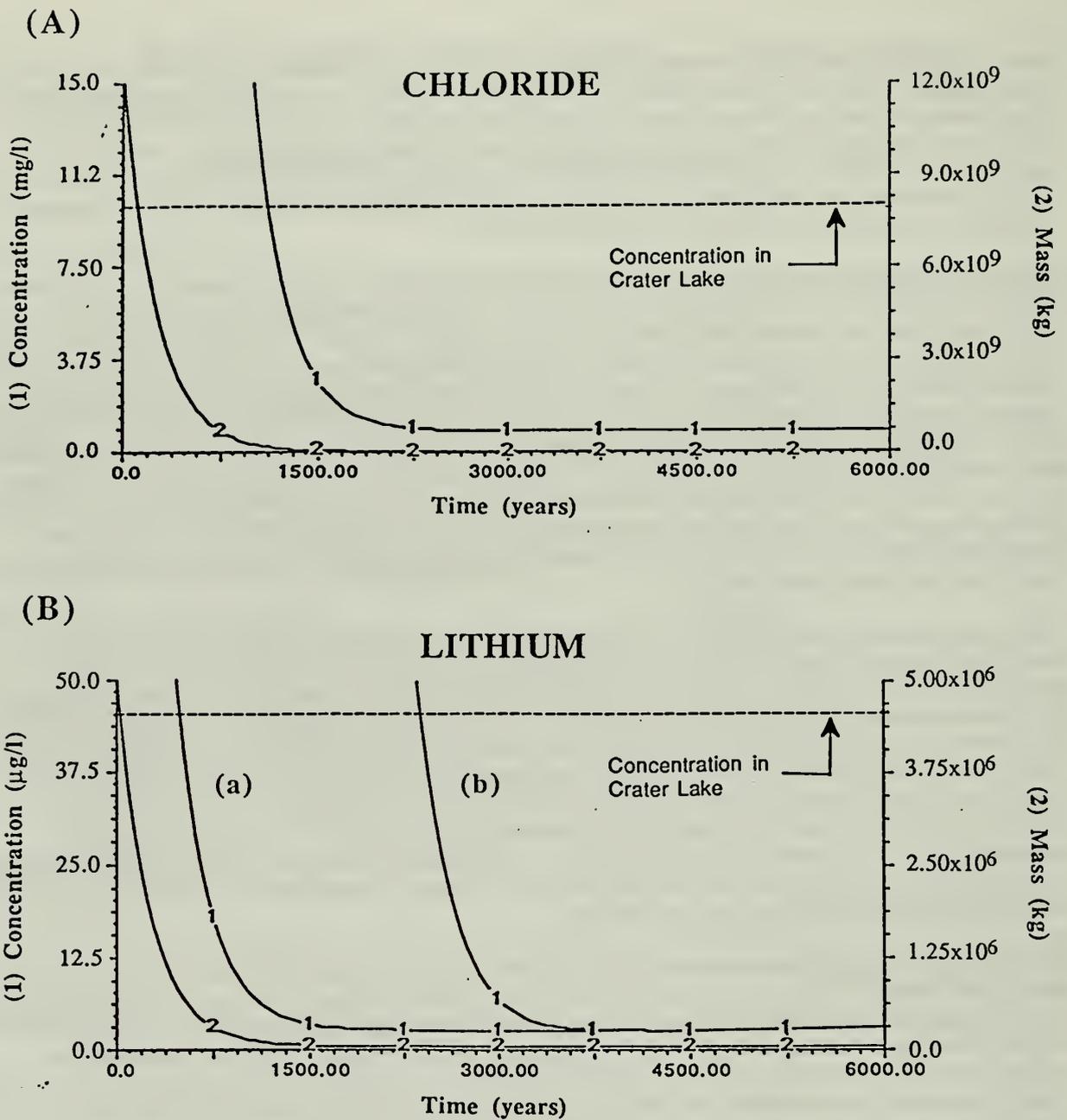


Figure 22. Results from the box model (Figure 21 and Table 3) applied to chloride (A), and lithium (B). Curves with a 1 represent concentration in units labeled to the left and those with a 2 represent mass in units labeled to the right. The overall residence time of ions in this model, with respect to seepage, is approximately 250 years. The initial chloride concentration (A) is chosen to be 718 mg/liter (Soufriere volcano). The concentration in the lake reaches 101% of the steady state value determined by precipitation and runoff (0.84 mg/liter) within 3000 years. The actual chloride concentration in Crater Lake is shown with a dotted line. The initial lithium concentration (B) was chosen to be 0.29 mg/liter (Soufriere volcano) and the concentration falls off even more rapidly (B - curve a). The actual concentration of Li in Crater Lake is shown by the dotted line. As an extreme example, an initial Li concentration of 1 gram/liter still falls to the same steady state within 3600 years (B - curve b).

Table 4. Cation-based heat flux estimates.

$$\frac{\text{cation}}{^3\text{He}} \cdot \frac{^3\text{He}}{\text{temp.}} = \frac{\text{cation}}{\text{temp.}} \Rightarrow \frac{\text{heat}}{\text{cation}} \cdot \text{cation flux} = \text{heat flux}$$

units	$\frac{\text{mg/liter}}{\text{cc/gram}}$	$\frac{\text{cc/gram}}{^\circ\text{C}}$	$\frac{\text{mg/liter}}{^\circ\text{C}}$	$\frac{\text{calorie}}{\text{kg}}$	$\frac{\text{kg}}{\text{year}}$	$\frac{\text{calorie}}{\text{year}}$
sodium	27×10^{11}	1.5×10^{-12}	4.1	2.4×10^8	$6.4\text{-}6.6 \times 10^5$	$1.5\text{-}1.6 \times 10^{14}$
calcium	17	"	2.6	3.8	$3.1\text{-}4.0 \times 10^5$	$1.2\text{-}1.5 \times 10^{14}$
magnesium	8.4	"	1.3	7.7	$1.4\text{-}1.7 \times 10^5$	$1.1\text{-}1.3 \times 10^{14}$
potassium	4.5	"	0.68	15	$8.3\text{-}9.6 \times 10^4$	$1.2\text{-}1.4 \times 10^{14}$
lithium	0.20	"	0.030	330	3.1×10^3	1.0×10^{14}

\Rightarrow average heat flux estimate = $1.3 \times 10^{14} \frac{\text{calories}}{\text{year}}$ (17 MWatts)

(footnote) (1) (2) (3) (4) (5) (6)

- (1) Cation / ^3He ratio derived from the correlations of these parameters shown in Figure 19.
- (2) ^3He / temperature ratio derived from data in Figure 19a (Lupton et al., 1987).
- (3) The product of (1) and (2) yields the slope of the cation / temperature relationship. This quantity was also calculated by Collier and Dymond (1988a).
- (4) Conversion of (3) yields the heat flux associated with each kg of cation input.
- (5) The cation flux into the lake to balance the steady state box model. The value for lithium is derived from our box model (Figures 21,22) with values based on our lake and spring analyses and assumes that the Li concentration in precipitation is very low. All the other cation fluxes are taken from Reilly et al. (1989) based on their direct estimates of atmospheric input and their ranges for runoff inputs.
- (6) If we assume as an hypothesis that the measured heat/cation relationship (4) is driven by the input of cation-rich thermal fluids, then the product of (4) and (5) yields an estimate of the convective heat flux carried by these fluids.

Although the models are based on a number of assumptions, their predictions are relatively insensitive to reasonable errors in those assumptions. Furthermore, the excellent agreement of each of the independent heat flux estimates in Table 4 suggests that the model calculation may be a good representation of a single process carrying the dissolved ions, the mantle-derived helium and the heat into the deep lake. The cation-based heat flux estimate, 17 megawatts, is three times smaller than the estimate based on stripping all the excess ^3He out of the lake each year (see the previous

section on helium). This disagreement suggests we need to consider the sensitivity of each model to their internal assumptions - such as the estimate of vertical mixing rate of water in the lake. The cation-based estimate is a factor of two smaller than Williams and Von Herzen's (1983) lower estimate of convective heat flux. Even still, all of these models, which are dramatically different in structure and underlying assumptions, calculate a convective heat flux to Crater Lake of approximately 10^{14} calories/year.

We can now take our cation-based heat flux estimate and look at different total fluid flow rates as a function of differing exit temperatures. This type of calculation has been done by Sorey (1985) and by Nathenson (in press) using his box model constraints. We choose two fluid exit temperatures as examples: 9.5 °C and 80 °C. The smaller number is the highest measured temperature of fluids in the South Basin bacterial mats from the 1988 dive program. The higher fluid temperature was our geothermometric prediction for an undiluted bacterial mat water sample. Again, these choices are reasonable based on our samples, but they do not necessarily represent the average temperature of all fluids entering the deep lake. The higher temperature fluid must enter at a rate of 54 liters/second and the lower temperature fluid at 700 liters/second to balance to net heat flux. These can be compared to ranges of 80-1900 liters/second estimated by Nathenson (in press) and 120 liters/second estimated by Reilly et al. (1989). Since we have hypothesized that some or all of this flux might be in the form of diffuse flow through sediments, it is useful to evaluate the vertical velocity of porewaters that could carry this flux. For demonstration purposes, assume that all of this fluid flow occurs in an area represented by the Detailed Study Area (2.3×10^6 m², Figure 1). The lower flow rate of warmer fluids results in an upwards velocity of 2.3 cm/year and the higher flow rate would occur at 30 cm/year. Rates of flow of this magnitude have been observed through sedimented marine hydrothermal regions (Wheat and McDuff). In 1989, we will examine benthic chambers and porewater profiles in an attempt to determine if the flows exist and study their compositions.

Bacterial Mats

Description and location. The existence of communities of bacteria that formed mats of various sizes and morphologies was one of the most exciting observations made with Deep Rover. Several of the mat types and forms are shown in Figures 23 through 27. The mats are gelatinous, low-density features (Figure 25) that are 15 cm to 300 cm in diameter and 2 to 15 cm thick. Some of the largest mats were draped over steep rock outcrops (Figure 23 and 24); however, smaller mats lay directly on sediments (Figures 26 and 27). Rusty-brown colors within the mats suggest iron oxidation may be important in the mat formation. The sediments near the mats contrast strongly with the normal buff sediments that cover most of the bottom (Figure 28). The mats were not observed on any of the dives outside the thermal basin region, suggesting that they may be related to the anomalous temperatures and water compositions that are observed in this part of the lake.

Although CTD measurements of bottom water in the immediate vicinity of the mat did not reveal temperature anomalies that exceeded the 0.1°C variability that is common in the thermal basin, temperature measurements made by inserting the temperature probe into the mat exhibited much higher temperatures. Table 5 lists the dives where mats were observed and the temperature measurements made on four separate dives to different mats. The temperatures range from 4.70 to 9.52 °C, or anomalies of approximately to 6.0 degrees. During dive 182 the temperature probe was inserted into sediments at the base of the rock outcrop covered by the mat with the 9.52 °C internal temperature. This sediment had a temperature of only 3.88°C, an observation which demonstrates the localized nature of the warmer fluids and suggests that the mats are specific visual indications of the warmer fluid sources. By the nature of these measurements, the temperatures must be considered minimum values. Only one insertion of the temperature probe was made at each mat, and it is probable that this did not define the highest temperature within a given mat. The

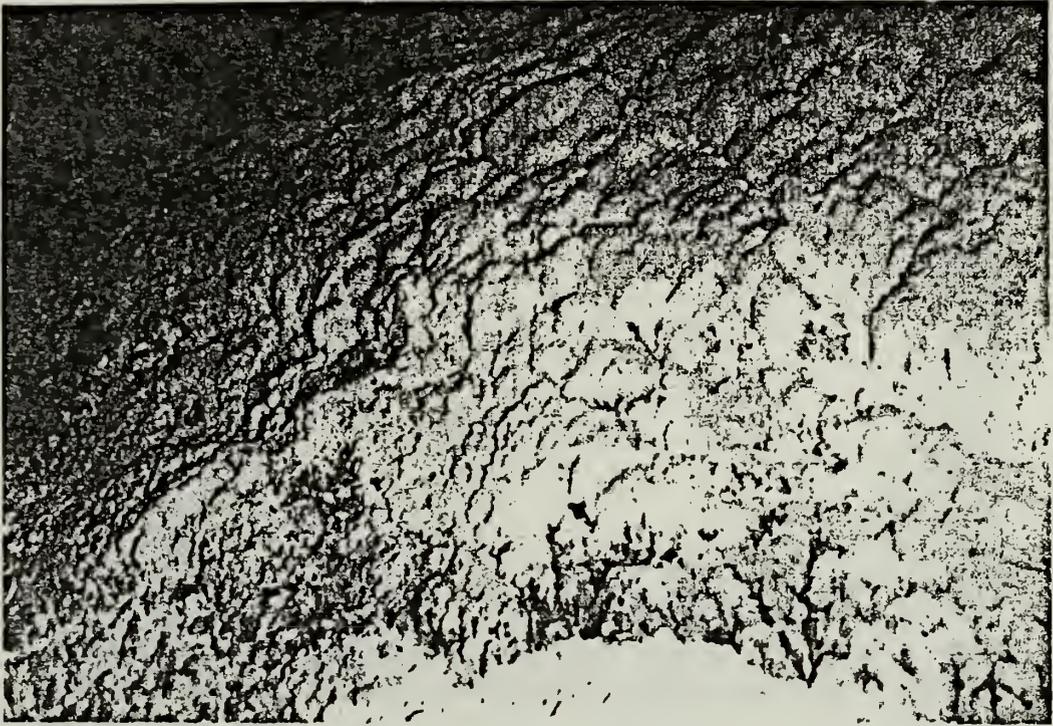


Figure 23. Bacterial mat growing from the top of a cliff face observed on dive 179. The field of view is approximately two meters. This mat is the same as mat "a" in Figure 30.



Figure 24. Bacterial mat from the top of a cliff face observed in dive 179. The field of view is approximately two meters. This mat is the same as mat "c" in Figure 30. The mat extends down the cliff face 10 m below this location.

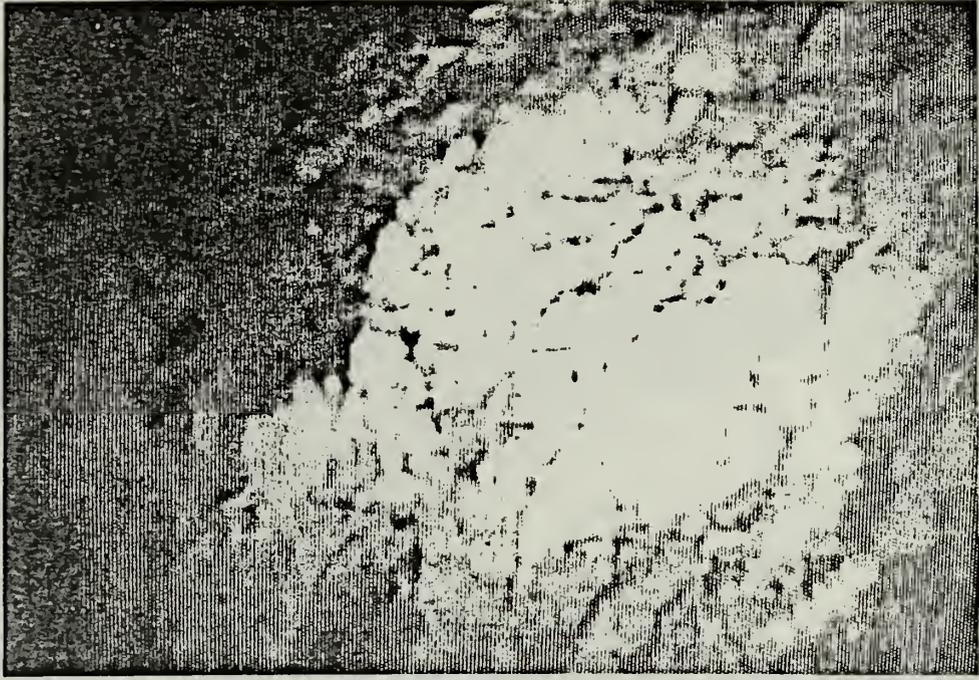


Figure 25. Close up of the same mat seen in Figure 23. Field of view is approximately 20 centimeters.

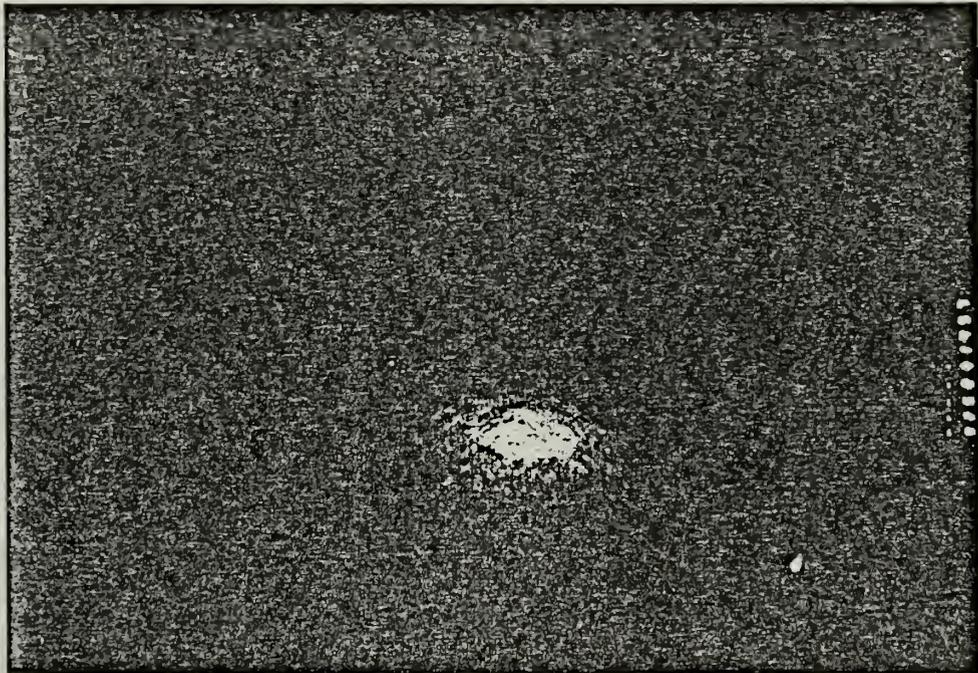


Figure 26. A small bacterial mat growing on a flat sedimented surface (dive 187). This mat is approximately 30 cm across.

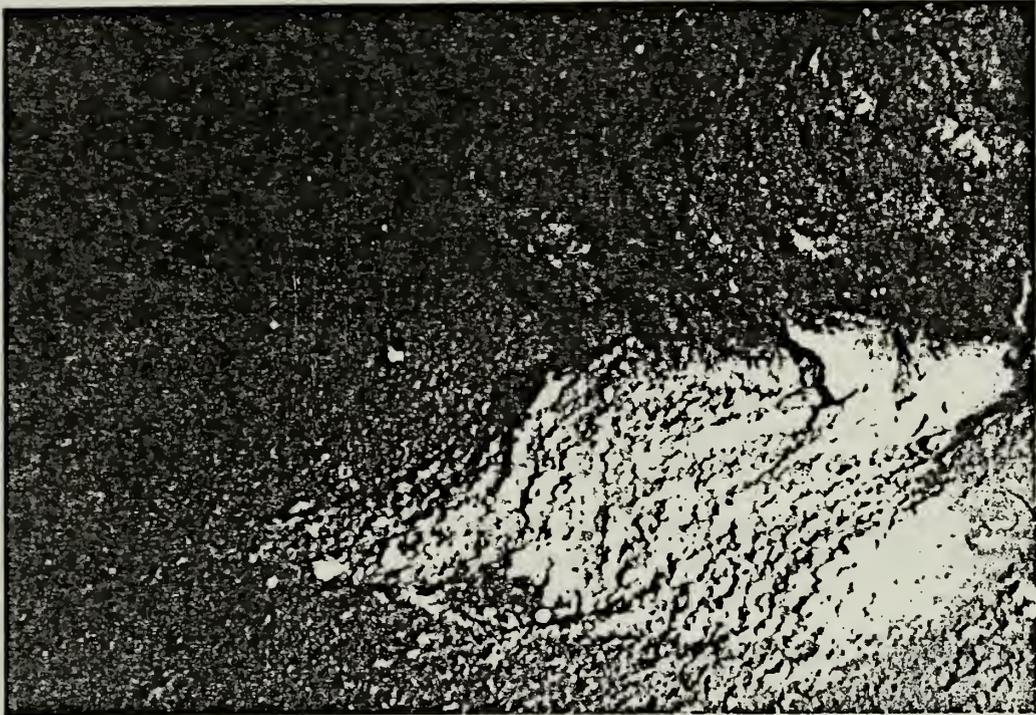


Figure 27. A small bacterial mat growing on sediments that underly a small rock outcrop. This mat was observed on dive 183. Note the discoloration of the sediments both immediately adjacent to the mat in the foreground and in the background. These colors suggest iron or manganese deposition.



Figure 28. Photograph of the typical sedimented floor of Crater Lake. This shot was taken in the detailed study area; it is the most common type of terrain and is typical of the relatively level parts of the lake.

mats may be umbrella-like structures that trap advecting fluids from a relatively small outlet. Alternatively, the mats may mark the location of very diffuse fluid venting. Only multiple probing of the features could discern a more complete character of the spring. Because these unusual features are very easily disturbed by the submersible prop wash, we did not attempt multiple probe insertions and only attempted to measure temperatures at one of the several mats that were observed at each site.

Table 5. Bacterial Mat Temperatures and Descriptions

<u>Dive</u>	<u>Measured Temperature °C</u>	<u>Description</u>
179	5.70	Three large mats draped on a cliff face; two mats are 2-3 m across; one mat is 2 m wide and 10-15 m long; small mats are attached to sediment at base of slope (see Figure 30).
182	9.52	One mat 3 m in diameter on a sloping, sedimented surface; mat thickness is only 2-4 cm thick; sediment is discolored.
183a	5.70	Three mats, 20-40 cm in diameter, on discolored sediment associated with outcrops
183b	4.30	Four mats, 10-30 cm in diameter, on thin sediments with outcrops.
183c	n.d.	One mat 15 cm by 30 cm, on discolored sediments.
187	n.d.	One mat, 30 cm in diameter, on discolored sediments.

Mats were observed at four locations shown in Figure 29. At two of the sites, three to six individual mats were observed. The mat locations are all within 300 m of each other and are either on or near the scarp that extends across the detailed study area with a NE-SW orientation. Several of the mats were found in the relatively flat sedimented sites at the base of the scarp (Figure 26). The largest mats, however, were found draped over the cliff face, 15 meters above the base of the slope. A schematic drawing of the mats observed during dive 179 is shown in Figure 30. The mat on the right was the largest mat observed and extends from a dome-like mass, down the cliff as a continuous feature for more than 10 meters.

Electron microscopy and composition. A bacterial composition of the mats is confirmed by scanning electron microscopy (Figures 31, 32, and 33). The forms shown are sheath-forming bacteria of the genera *Gallionella* and *Leptothrix* as tentatively identified by Drs. Maribeth Watwood and Clifford Dahm of the University of New Mexico. *Gallionella* is generally considered to be a chemolithoautotroph (Erlich, 1981) as it requires a source of reduced iron (Hanert, 1981) and will grow in the absence of significant organic carbon (Wolfe, 1964). It is not a thermophilic organism and has been found in low temperature springs, wells, and drainages (Hanert, 1981). This genus, however, has also been observed in thermal springs with temperatures up to 47°C (Hanert, 1973).

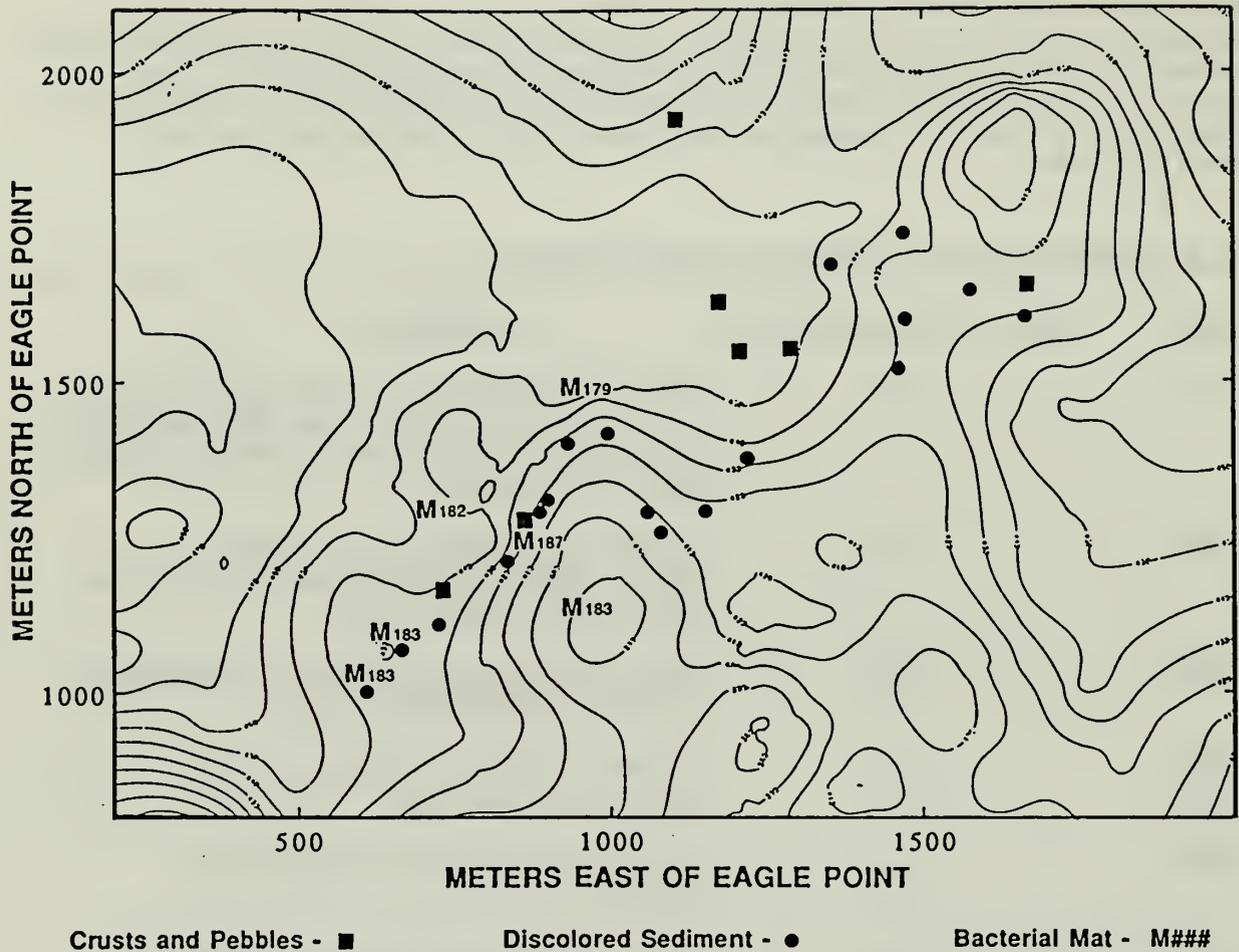


Figure 29. Locations of bacterial mats, crusts, and discolored sediments in the detailed study area. M179, M182, M183, and M187 refer to bacterial mats and the associated dive number. Filled squares are crusts and broken crusts (metal-rich pebbles). Filled circles are areas of discolored sediments, which in some cases are mottled shades of brown and in other cases more even dark tones.

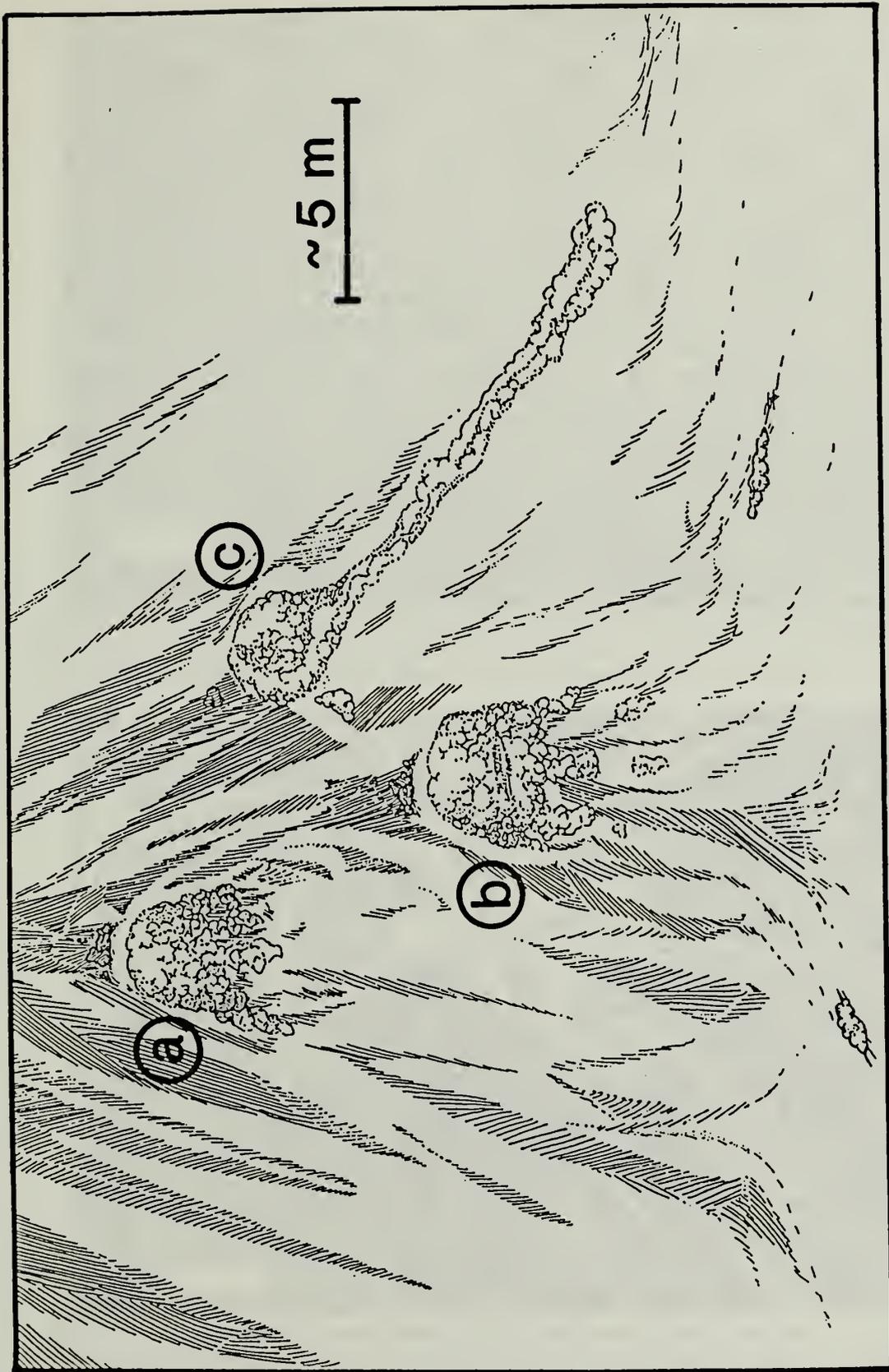


Figure 30. A schematic drawing of bacterial mats observed during dive 179. The letters "a", "b", and "c" identify the three principal mats observed at this site. These three large mats appear to be attached to rocky cliff faces. Mat "c" extends down the cliff face an additional 10 m below the primary structure. This extension appears to be actively growing and not simply a consequence of pieces that roll down the slope. Small mats are growing at the base of the slope on sediments. The sediments all along the base of the slope are discolored.

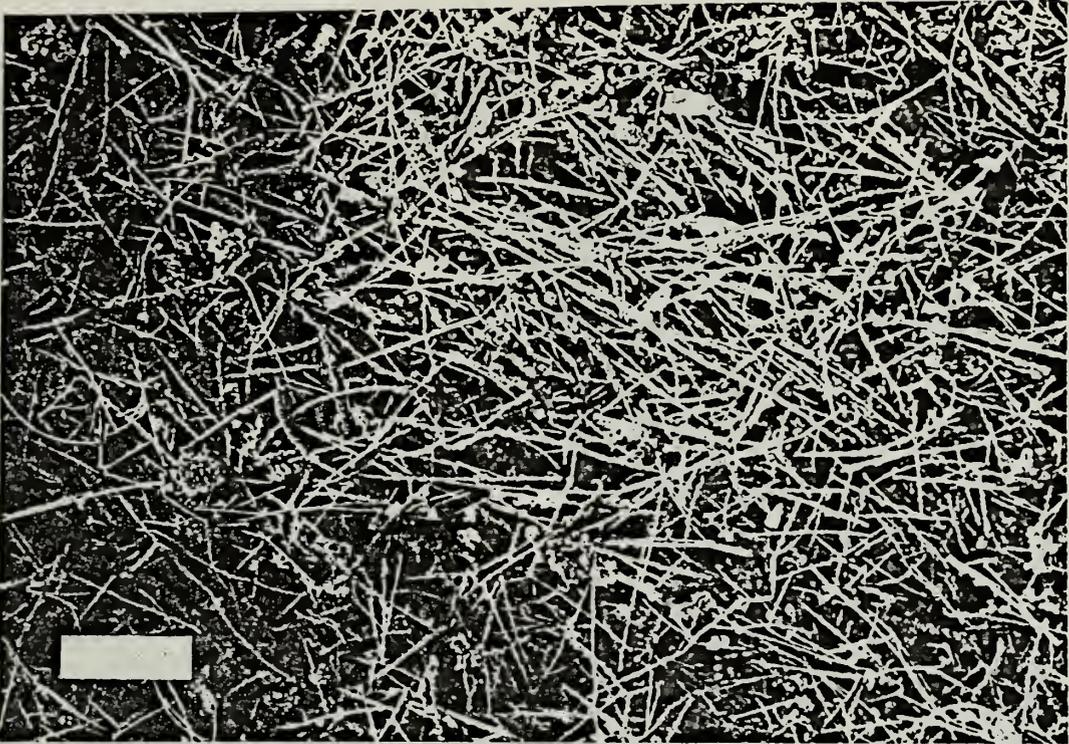


Figure 31. A low-power scanning electron micrograph of the bacterial mat from dive 179. Tentative identification indicates these forms are iron-oxidizing sheath-forming bacteria of the genera, *Gallionella* and *Leptothrix*. The scale-bar is 100 μm in length.



Figure 32. A scanning electron micrograph of the bacterial mat from dive 179. The scale-bar is 10 μm in length. The genus, *Gallionella* are the forms with twisted sheaths; *Leptothrix* are the straight sheaths. The ribbed dome-like form in the center is thought to be a protozoa. This form is seen on many of the SEM photos and could be feeding on the bacteria. The tube-like form in the center-right with a blunt end is part of a diatom.

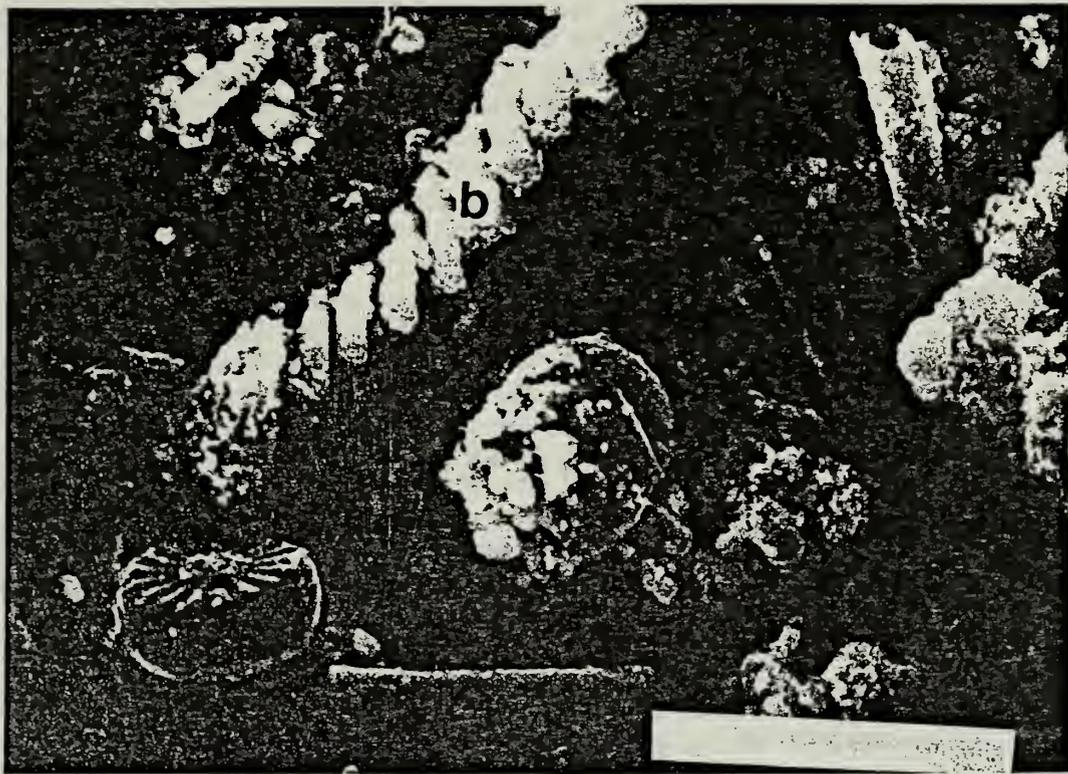


Figure 33. A scanning electron micrograph of the bacterial mat from dive 179. The scale-bar is 10 μm in length. The symbol "b" on the *Gallionella* specimen marks the location for the EDAX spectrum shown in Figure 34. A diatom is in the lower left.

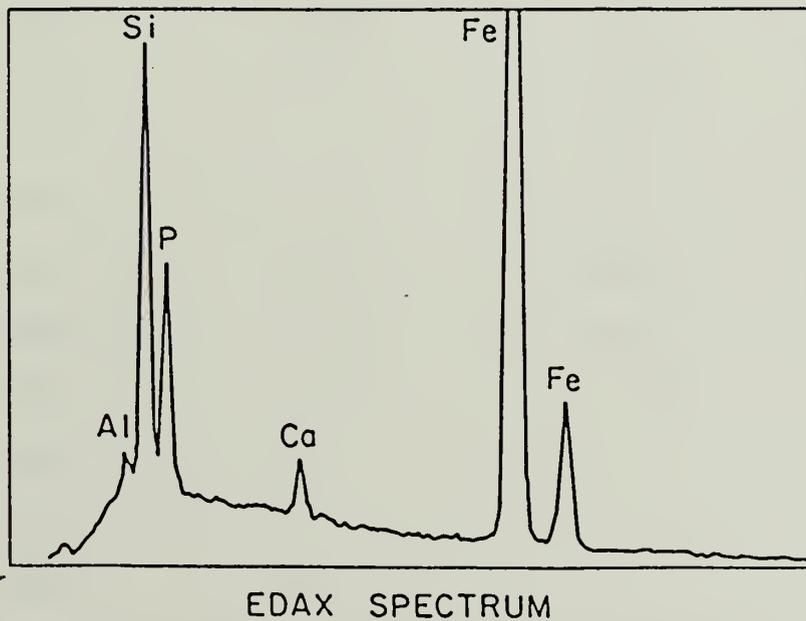


Figure 34. An EDAX spectrum for the *Gallionella* form shown in Figure 8. Note the strong peaks of Fe, Si, and P.

Because of the large amounts of ferric hydroxide and manganese dioxide accumulations on the sheaths of *Leptothrix*, these bacteria are thought to oxidize ferrous and manganous ions (Mulder and Deinema, 1981). An autotrophic metabolism for *Leptothrix* has not been demonstrated. However, like *Gallionella*, it seems to thrive in environments which provide a gradient between reduced and oxidized forms of iron and manganese. *Leptothrix* is also not a thermophilic form, but it has been observed in the recently discovered thermal springs on Loihi Seamount, the most eastward extension of Hawaiian-chain volcanism (Karl et al., in press). There, thick mats similar to the Crater Lake communities (D. Karl, pers. comm.) surround vents with temperatures that range between 15 and 30°C (Karl, et al., 1988).

Along with the SEM observations, we made semi-quantitative measurements of the composition of individual particles using EDAX (energy dispersive X-ray analysis). In Figure 34 we show a typical EDAX spectrum of one of the encrusted sheaths. These analyses demonstrate that the sheaths are composed dominantly of iron phases, an observation consistent with other studies which have found that iron compounds can comprise up to 90% of bacteria mats composed of iron oxidizers. The EDAX spectra also show that Si and P are important components of the structures.

In Table 6, bulk compositional data for a bacterial mat sample is compared with data for hydrothermal iron oxide precipitates from several marine hydrothermal deposits. The mat contains more than 35% iron, which would account for more than 70% of the mass of the mat (as FeOOH). Significant amounts of silica and phosphorus are also present. The relatively low sulfur content indicates that sulfur oxidizing bacteria, which would transform H₂S into elemental sulfur or sulfate, are not important members of the bacterial community. The concentrations of Fe, Al, Si, and P in the mats and the hydrothermal oxide deposits are similar. Manganese varies widely, apparently reflecting the ease at which iron and manganese can be separated under differing redox conditions (Krauskopf, 1957).

Table 6. Bacterial mat and hydrothermal deposit compositions

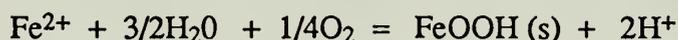
	Bacterial Mat	Galapagos Mounds [^]	Nazca Plate ⁺	Santorini [*]
Al	0.21	0.32	0.2	0.87
Si	7.2	13.3	5.0	6.8
P	3.7	---	2.4	0.11
Ca	0.8	1.4	---	1.3
Fe	37.9	27.5	36.0	27.8
Mn	0.014	7.9	10.4	0.045
Ba	0.02	0.07	0.18	0.005
S	0.3	---	---	0.41
C	2.44	---	---	4.0
N	0.97	---	---	---

[^] Corliss et al., 1978; ⁺ Dymond, 1981; ^{*} Bostrom and Widenfalk, 1984
All values are in weight per cent.

Although the scanning electron micrographs demonstrate that the bacterial mats are predominantly composed of sheath forming bacteria, the organic carbon comprises only 2.4% of the material. More detailed analyses of the organic fraction demonstrates that the extractable fraction lipid fraction is composed of simple fatty acids. There were no sterols or other biomarkers that are indicative of phytoplankton, zooplankton, or local terrigenous sources. These analyses are consistent with fresh organic matter of microbial origin. The results also suggest that the organic matter has not been thermally altered above a temperature of 80°C (B.R.T. Simoneit, pers. comm.). The ratio of carbon to nitrogen in the mat sample is 2.9 on an atomic basis. This ratio is quite low compared to organic matter from plankton, which commonly have C/N values ranging between 6 to 7. The observed low values, however, are consistent with bacterial sources of organic matter (Goldman et al., 1987).

Summary. We conclude that the mats are produced by bacteria communities which oxidize ferrous iron carried in the chemically altered fluids that apparently advect through the mat. We make the assertion of fluid advection based only on the observed thermal gradients across the mats and the probability that such abundant growth of organisms must require a constant supply of reduced iron. We did not, however, measure a flow or see evidence of flow through the mat. Diffuse and subtle flow of fluids would not be observable in the presence of "prop-wash" that was always present with Deep Rover. Prop-wash prevented us from approaching with the submersible without causing some physical disturbance to the mat structure.

The fact that the temperature of fluids within the mat are elevated above normal bottom waters of the lake suggests geothermal heating. Before concluding that this is the case, we can evaluate the effects of metabolic heat from the bacterial community that could be added to the fluids. A rigorous answer to this question cannot be made without knowledge of the advective flow, the exchange rate of fluids around the mat, and the metabolism and growth rate of the bacteria. We can calculate an upper limit to the metabolic heat by assuming that all the iron in a quantity of water within the mat is oxidized from its ferrous form to a solid oxide form. If all of the heat of this reaction is retained within the mat, it represents the maximum increase in temperature that is possible by metabolic activity. Any flow of water through the system would bring cooler, ferrous-rich waters into the mat. In addition, mixing of bottom waters at the margins of the mat would reduce the mat temperature. Using this closed system assumption, the increase in temperature is strictly a function of the concentration of iron in the fluids. An appropriate reaction is:



The enthalpy of this reaction is -9.2 kcal/mole (Garrels and Christ, 1965). By choosing an appropriate iron concentration in the hypothetical cold spring, the heat production can be calculated. Iron concentrations in mineral and thermal springs in the Cascades are all less than 0.3 millimolar (Mariner, 1982). Assuming an upper limit of 1.0 millimolar Fe, conversion of all the dissolved iron to solid form would add approximately 9 calories of heat to each liter of water. Thus, the reaction would raise the temperature of that water by less than 0.01 degrees. Clearly, the temperature anomalies of approximately 6.0 °C cannot be a consequence of bacterial metabolism.

Sediment and Precipitate Observations

Description and locations. During the dives within the detailed study area numerous examples of discolored sediments and crusts were observed. These deposits are in strong contrast with the fine grained, light buff colored sediments that blanket most of the Crater Lake floor (Figure 28). Some anomalous sediments had a mottled dark brown to gray color. At other sites lithified crusts of iron

and manganese enriched material were observed (Figure 35), and at some locations slumping revealed lithified iron-rich bands (Figure 36). Multicolored, pebble-sized material covered the bottom at a number of locations (Figure 37). The reddish-brown to black color of these materials also suggests iron and manganese enrichment. These pebbles appear to be broken-up portions of the lithified crusts shown in Figure 35.

The location of the anomalous sediments and crusts is shown in Figure 29. These deposits are located in a band 100 to 300 m wide and 1100 m long. The orientation of the band is approximately NE-SW. The observation of crusts within this area is probably biased to some extent because our submersible tracks concentrated in this region (Figure 3a). Some dives, however, extended well outside this band and did not observe any crusts. Moreover, the four USGS dives covered a number of sedimented areas outside the detailed study area, and no crusts were observed in any of these dives.

At locations where there were some of the best developed lithified crusts (e.g. Figure 35), only small water-column temperature anomalies were observed. During dive 182, however, an area with a dark, flocculant surface sediment layer had thermal anomalies of up to 0.5 °C and relatively large chemical anomalies (for example, the Mn contents of these waters were 1000 the normal bottom water values). Within close proximity to the bacterial mats no lithified crusts or pebbly areas were observed, however, the sediments near the mats that covered sediments were generally dark and variable in color (Figure 27).

Compositions of precipitates and crusts. In Table 7 we report the composition of some of the crusts. The data demonstrate a range in compositions. Some crusts are highly enriched in iron, and these also contain important quantities of silica and relatively large quantities of phosphorus. The aluminium concentration is in all cases low compared to the aluminosilicate debris which is transported into the lake from the caldera walls. For those samples with intermediate Al values (e.g. 177, 179, and 182-4) the crusts are probably normal lake sediments that have been cemented with iron oxyhydroxides. For others (182-1 and 187), however, the Al concentration is so low that significant aluminosilicate debris is precluded. This suggests rapid precipitation at the sediment-water interface or possibly at the upper surface of a crust.

An iron-rich precipitate-sediment mixing line is demonstrated by Figure 39, a plot of Fe vs Si/Al. To a first approximation three end-members can explain the composition of all sediments recovered to date from the bottom of Crater Lake. A biogenic end-member is enriched in opal (and thus, Si), and organic matter, and is depleted in Al and other common elements in igneous rocks. This component is most clearly observed in our sediment trap samples. An aluminosilicate end-member has a Si/Al value of approximately 3.0, and iron contents of 3-5 %. The third end-member is referred to as a precipitate end-member and has only been observed in surficial sediments of a core from the South Basin and deep sediments from one core from the Wizard Platform (Dymond and Collier, in press). This end-member is highly enriched in Fe, P, Zn, Ba, and variably enriched in Mn. It is strongly depleted in Al compared to the aluminosilicate debris from the caldera walls.

In Figure 40 we have added data for the crust composition to our analyses of lake sediments. These data extend the precipitate composition to values that must approximate the pure end-member composed primarily of hydrated iron oxides. Silicon is either carried as a clay mineral such as nontronite (an aluminium-poor phase) or simply coprecipitated with the iron hydroxyoxide. In the samples that are most enriched in Fe, the Si/Al values become very high.

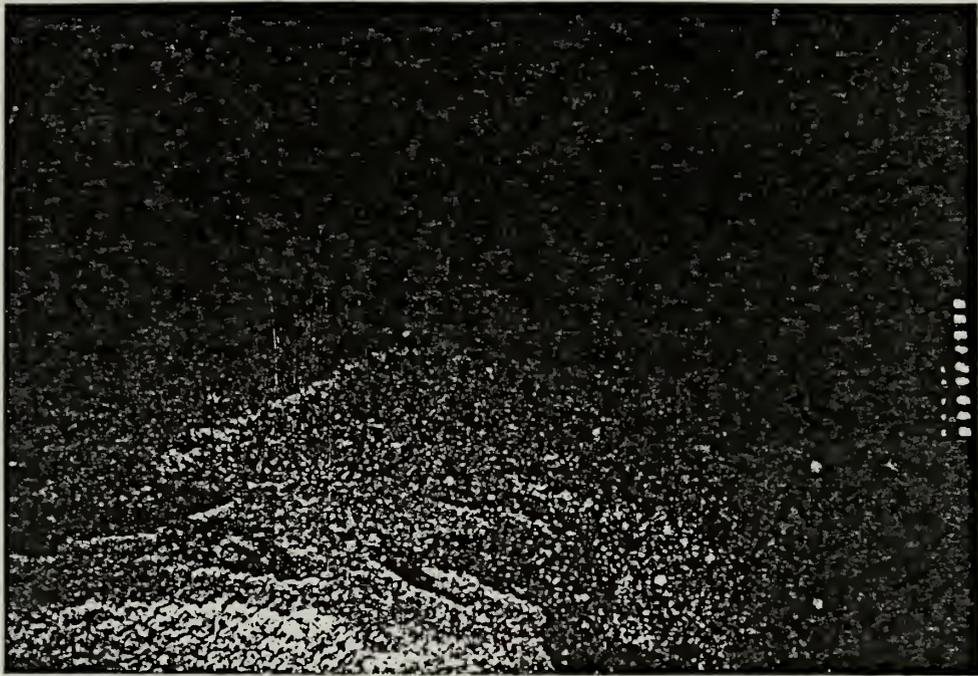


Figure 35. Photograph of a metal-rich crusts from dive 178. The reddish brown layers are iron rich and the dark gray to black layers are manganese rich. The field of view is approximately five meters; however, the full extent of this particular encrusted area covers at least a 30 m by 30 m area.

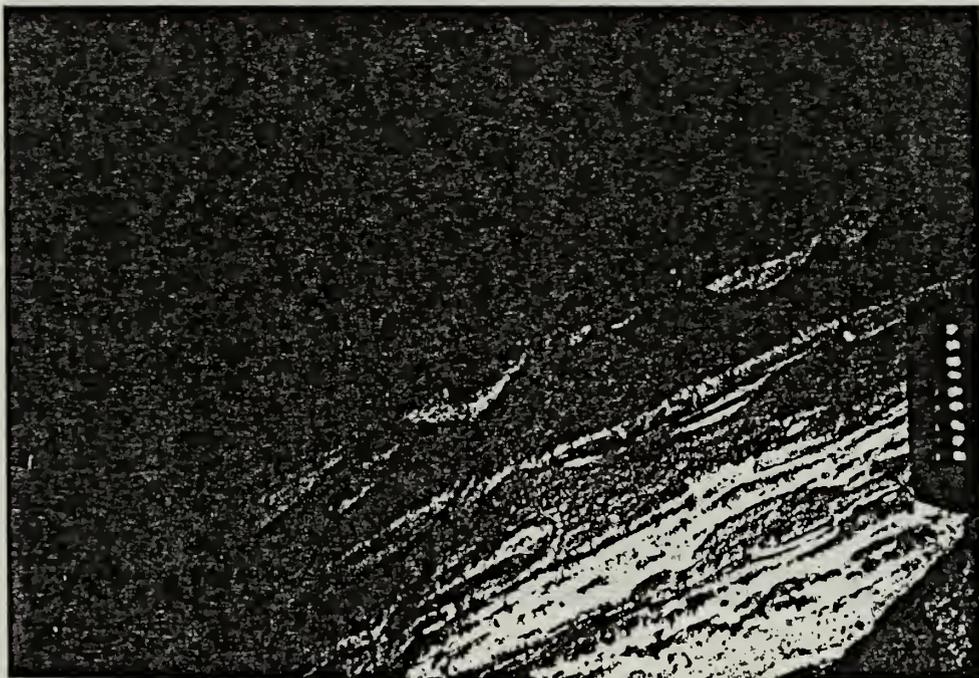


Figure 36. Slumping on a sedimented slope reveals multiple iron-rich crusts.

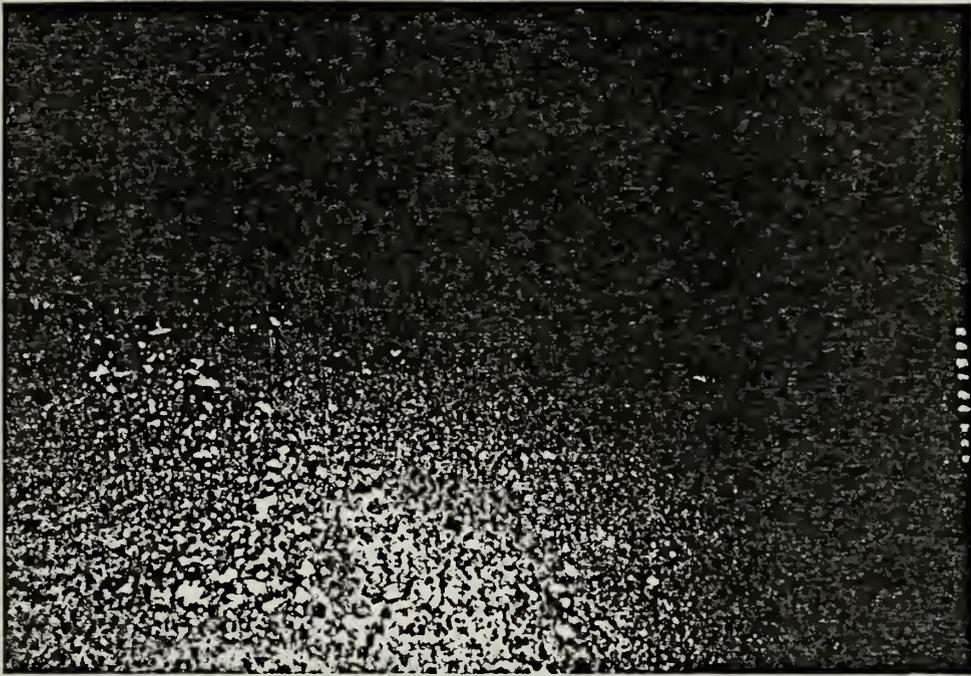


Figure 37. Typical view of the multi-colored crust pieces. These pebbles range from 1-5 cm in size.

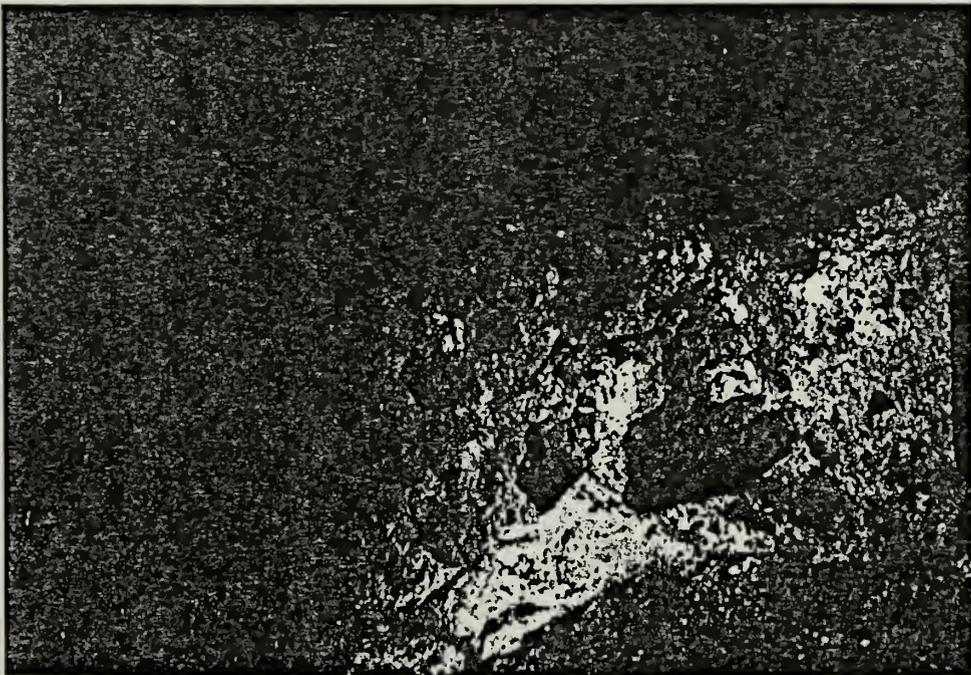


Figure 38. Bottom photograph of an outcrop in the detailed study area showing extensive alteration that appears to be hydrothermal in origin.

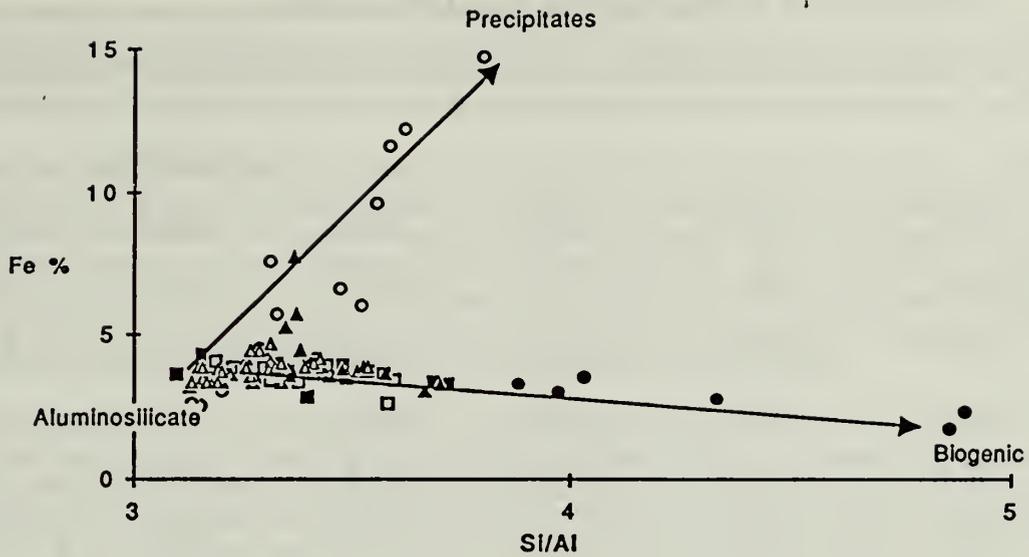


Figure 39. Fe vs Si/Al of Crater Lake sediments and sediment trap samples (data from Dymond and Collier, 1989). "Biogenic", "aluminosilicate", and "precipitate" refer to the three end-members discussed in the text. Open circles exhibiting Fe-enrichment are from a core in the detailed study area. The other cores are from the East Basin, South Basin, and Wizard Platform. Samples exhibiting higher Si/Al values are sediment trap samples.

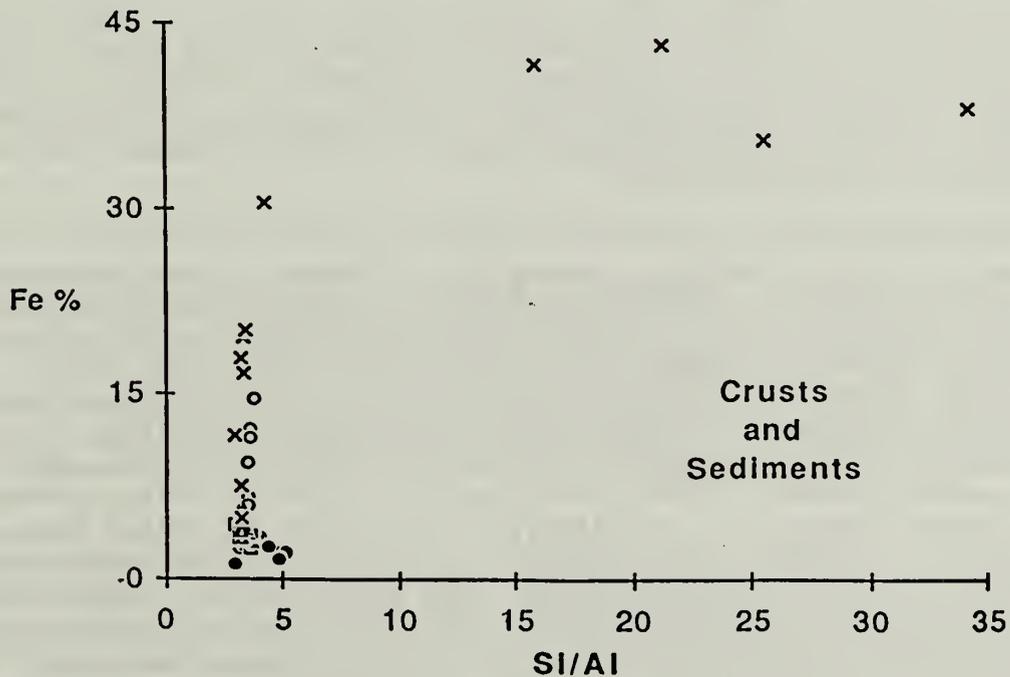


Figure 40. Fe vs Si/Al of crust samples recovered from the detailed study area. The same samples shown in Figure 39 are also plotted, however, there is a large change in scale. (The symbol x represents crust samples from the detailed study area; all other symbols are the same as for figure 39.)

Table 7: Composition of crusts collected with Deep Rover.

All values are in weight per cent except Cu and Zn which are in parts per million by weight.

Element	Dive Number					
	<u>171</u>	<u>177</u>	<u>179</u>	<u>182-1</u>	<u>182-4</u>	<u>187</u>
Al	2.58	4.97	5.37	0.65	5.48	0.46
Si	10.88	25.71	18.42	10.28	17.93	11.66
Ca	1.40	2.69	1.88	0.85	2.17	0.87
Fe	30.6	5.0	20.2	41.6	18.0	35.5
Mn	0.48	1.94	0.38	0.11	0.09	0.45
Cu	41	94	64	19	104	29
Zn	27	65	47	20	55	23
Ba	0.18	0.043	0.053	0.020	0.24	0.052
P	3.01	0.15	1.25	0.99	2.51	1.96

Origin of Mats and Crusts

We suggest the bacterial mats, lithified crusts, and pebbled surfaces, represent different stages in the evolution of precipitates that form from heated fluids which advect through sediments and rocky outcrops at certain locations on the lake floor. The enrichment of these waters in some established indicators of hydrothermal fluids (Collier, et al. 1987; Lupton, et al. 1987) suggests the fluids are the result of hydrothermal circulation, meaning they result from interaction between local formation waters and a cooling igneous body.

We propose the following scenario, which involves hydrothermal circulation, to account for the presence of mats and crusts: iron-oxidizing, chemolithotrophic bacteria precipitate large amounts of iron in mats at interfaces between the anoxic advecting fluids and the oxic lake waters. Since these organisms require a source of ferrous (soluble, reduced) iron, they thrive only as long as the advection of fluids continues. Precipitation within the conduits of hydrothermal systems, however, eventually blocks the flow and venting stops at any given site. When this occurs, the bacterial mat will be transformed from a gelatinous, living structure to a lithified crust. If the thermal fluid advection is through sediments, as opposed to rock, excess pore pressure and doming of the sediments will result, similar to that observed in sediment-hosted hydrothermal systems in the oceans (Williams et al., 1979; Maris et al., 1984; Wheat and McDuff, 1988). Cessation of venting would result in dome collapse and breaking of the lithified crusts would account for the pebble fields of mixed crust varieties. These pebbles eventually become buried by aluminosilicate and biogenic debris which comprise the typical sedimentation in the lake. Lithified pieces have been found at a depth of 9 cm in a core recovered by the USGS (Dymond and Collier, in press). This material may be such an example of a buried iron-rich crust .

It may be possible to test the link between mats and crusts by SEM analysis. If the crusts were bacterial in origin, the characteristic sheaths which are encrusted in iron may still be preserved in the lithified crusts. We propose to test this by microprobe/SEM analyses of some of the crusts shown in Table 7. Fossilized iron bacteria (*Gallionella*) have been reported (Ehrenberg, 1836).

An alternative origin for the crusts is cool mineral springs. Iron is soluble in anoxic, acidic waters and mixing of such waters with lake waters could result in precipitation of a hydrated iron oxide phase similar to the crusts. The enrichments of silica and some of the minor elements in the crusts, however, might seem to support a hydrothermal source of metals. Silica solubility is highly dependent on temperature and to a lesser extent on pH, and the most iron-rich crusts contain 8 to 12 % Si. It is possible that this quantity of silica is the result of coprecipitation from normal lake waters or cool springs and does not require a hydrothermal source of silica.

A few measurements of arsenic and antimony demonstrate enrichments of these elements in the iron enriched sediments from the South Basin (Dymond and Collier, in press). For example, a sediment sample from a core in the detailed study area has 7.6% iron, 860 ppm arsenic, and 2.6 ppm of antimony. In contrast, another core from the South Basin, but outside the detailed study area, has 4.2 % iron (a typical value for Crater Lake sediments), 78 ppm arsenic, and 0.7 ppm antimony. Since arsenic and antimony are anions in aqueous solution, they are easily coprecipitated with iron. Both elements are similar to phosphorus in this respect. Thus, high concentrations in the iron-rich sediments do not necessarily indicate enrichment in the spring solution. The observed phosphorus enrichments in iron-rich crusts probably can be explained by coprecipitation of phosphorus derived from the lake. For arsenic and antimony, however, the case is not so clear. Neither element has been analyzed in Crater Lake waters, but in general, arsenic and antimony concentrations in surface waters from volcanic terrains are very low compared to the concentrations in thermal springs (Onishi, 1969).

Geological Observations in the Detailed Study Area

The detailed study area is located in a geologically complex portion of the Crater Lake basin. The base of the relatively shallow Wizard Island platform bounds the northern edge of the area. Crossing diagonally through the study area with a NE-SW orientation is a zone of rather steep topography which descends from local high spots of 380 to 405 m in the southern part of the study area to basin depths of 450 to 475 m in the center of the area (Figure 2). The entire detailed study area and much of the south basin lies within a proposed ring fracture zone that marks the line of caldera collapse which followed the climactic eruption (Nelson, et al., 1988). A saddle between the south basin and the deeper east basin of Crater Lake is formed by the elevated topography on the north and south margins of the area, and this saddle lies within the ring fracture zone.

The Wizard Island Platform is a large, relatively shallow portion of the lake believed to be formed as part of the extensive outpourings of andesite lavas that produced Wizard Island and Miriam Cone. Submersible observations and sampling from this program indicate rocks of similar composition to Wizard Island, but with some subaqueous flows, are found on the Platform. (See Appendix I.) The andesites are thought to comprise a ring-phase of eruptions which occurred shortly after caldera collapse (Bacon, 1983). The subaqueous lava structures observed with Deep Rover indicate the lake had at least partially filled before this eruptive phase ended.

The elevated topography on the south side of the detailed study area may be an extension of a submarine portion of Chaski Bay Slide, a prominent catastrophic feature on the south caldera wall. An acoustic profile across the southern edge of our detailed study area shows the presence of chaotic beds beneath flat-lying turbidites and slowly accumulating lake sediments (Nelson et al., 1988). The lake bathymetry (Byrne, 1962) exhibit a deflection of the contours into the south basin away from the subareal portion of the Chaski Bay Slide. Nelson et al., 1988, use the bathymetry and the chaotic acoustic stratigraphy as evidence of debris flow and avalanche deposits

at this location. They suggest that deposits of this type formed in response to seismic activity associated with postcaldera volcanism that began soon after the caldera collapsed. The hummocky topography, which is revealed by our finer-scale bathymetry (Figure 2), is also compatible with a debris flow.

The area identified as possible debris flow terminates near the middle of our detailed study area. Its northern limit may coincide with escarpments and steep rock outcrops observed in the region by the submersible. Some of the bacterial mats were found on the face of one of the escarpments, and other mats were found near the base of cliffs on flat lying sediments. The association of the escarpments with the bacterial mats suggest these cliffs may be related to the origin of the anomalous fluids that provide a chemosynthetic energy source for the bacteria. If the escarpments mark a fault, perhaps part of a ring-fracture zone that has continued to subside since the original caldera collapse, then the association may be simply the fact that faults provide a conduit for convecting waters. Movement on this hypothetical fault would maintain the conduit and prevent blockage of flow through precipitation of hydrothermal minerals.

Alternatively, the escarpment might mark the northern limit of the debris flow. If this is the case, any causal or spatial relationship of possible hydrothermal activity to the debris flow is less clear. One could speculate that the debris flow forms a cap over the ring-fracture zone and directs hydrothermal flow to the face of the cliff that marks the termination of the chaotic beds. It is perhaps more reasonable, however, to think that the debris flow, if it is composed of large blocks, is more permeable than horizontally bedded lake sediments that have accumulated over the past 5-6000 years of lake history. If this is the case, deposition of the debris flow on top of a ring-fracture zone may provide pathways for fluid flow that extend from deep within the volcano to the lake floor. In any case, the chaotic beds in deeper parts of our detailed study area are overlain by 20 to 25 m of flat-lying lake sediments (Nelson et al., 1988). This indicates the landslide event must have taken place early in lake history. From a seismic reflection record through our detailed study area (Nelson et al., 1988), it is possible to infer normal faulting in the region where we observe scarps. Because of the difficulty in interpreting chaotic beds in the record, however, such an interpretation is equivocal. Nonetheless, faulting does provide a mechanism for maintaining exposure of the chaotic beds despite deposition of a relatively thick sequence of turbidites and more slowly deposited sediments.

Only two rocks were collected from the escarpments by the submersible, and these have not been analyzed by C. Bacon at the present time. The visual and photographic evidence, however, suggests hydrothermally altered rock dominates these cliff faces and outcrops (Figure 38). The fact that much of the rock making up the south caldera wall and the Chaski Slide is also hydrothermally altered and similar in appearance to the submerged outcrops (C. Bacon, pers. comm.), supports the concept that many of the submerged outcrops are exposures of debris flow. This subareal alteration probably predates the climactic eruption considerably, since these particular caldera rocks are at least 200,000 years old (C. Bacon, pers. comm.). However, in some cases, the sediments adjacent to the subaqueous cliff faces appeared to be highly altered, an observation which may indicate at least some *in situ* alteration has occurred.

Discussion and Conclusions

Important hypotheses

In our report of field studies conducted in 1987 (Collier and Dymond, 1988a) we considered five hypotheses to account for the chemical composition of the bulk lake, the thermal and chemical variability in near-bottom waters, and chemical variability in deep lake sediments:

- (1) hydrothermal inputs to the lake are driven by convection of waters through cooling magmatic bodies that underlie Crater Lake.
- (2) the observed temperature pattern of the deep lake is a consequence of conductive heat flux through the lake bottom and does not involve any fluid injection.
- (3) the near-bottom increases in major-ion content are the consequence of cold, saline spring input and are unrelated to thermal input.
- (4) the anomalous volatile contents (helium and radon) are a consequence of gaseous injection (i.e., non-condensable volatiles) and do not require a hot water source.
- (5) the metal-rich deposits are the result of precipitation from cold springs and not hot springs.

A paper by La Fleur (1987) suggests three other hypotheses that should be considered as well:

- (6) the chemical alteration of Mazama ash could introduce chloride and other elements into the lake, thereby accounting for the high content of these elements compared to other Cascade lakes which are fed dominantly by precipitation.
- (7) evaporation rates of the lake are greater than previous estimates and can account for its salt content.
- (8) the high salt content of the lake is a consequence of fumarolic and thermal spring inputs that occurred soon after the collapse of Mt. Mazama.

The hydrothermal hypothesis. The major appeal of the first hypothesis is that it can account for many and perhaps all of the unusual thermal and chemical features of Crater Lake. The high ionic content of the lake compared to other precipitation-dominated lakes can be accounted for by input of thermal springs which are known to carry elevated concentrations of many elements compared to precipitation sources or cold-spring sources (Mariner et al. 1982). Comparisons of the concentrations of several elements in Crater Lake compared to those in other Cascade lakes (Figures 14c and 15c) demonstrate the relatively high ionic contents of Crater Lake. These data show that East Lake, which is known to have hot spring inputs has concentrations that are even higher. These comparisons suggest that thermal springs can dominate the ion content of lakes. Similar conclusions have come from various studies of lakes found in the volcanically active region of the North Island of New Zealand (Timperly, 1986; Hoare, 1985; McColl, 1975 ; Forsyth, 1977).

Hydrothermal sources can explain not only the elevated concentrations of elements in Crater Lake, they also account for the inter-element relationships. As shown in Figures 14b, 15b, and 16b, a mixture of precipitation sources with the warmer fluids sampled at the bacterial mat can account for the major element relationships in the lake.

Enrichments of certain minor elements are also compatible with hydrothermal sources. Thompson et al. (in press) have reported that boron is enriched by a factor of two and lithium enriched by a factor of 10 in Crater Lake compared to the average waters from Mazama cold springs. Both elements are typically enriched in geothermal waters (White et al., 1976; Ellis and Mahon, 1977). Moreover, Cl/Li values in Crater Lake lie within those observed for typical thermal waters but outside the values measured in Mazama cold spring (Thompson et al., in press). Thompson et al. (in press) suggest both the chloride and lithium concentrations in the lake are controlled by hydrothermal input. Our results demonstrate that lithium is correlated with temperature in near-bottom samples from the South Basin (Collier and Dymond, 1988a), and the data from submersible sampling demonstrate that these enrichments in the bacterial mat water are nearly a factor of two greater than the bulk lake composition (Table 2). Lithium enrichments are particularly relevant because low temperature weathering of rocks does not extract Li efficiently (Thompson, 1973), whereas, high temperature, hydrothermal alteration can remove much of the Li in rocks, thereby strongly enriching the hydrothermal fluid (Von Damm et al., 1985). The temperature influence is demonstrated by the relatively low concentrations of Li in all inter-caldera springs (J. McManus, unpublished data) and in Mazama springs in general (Thompson et al., in press).

Two other highly successful tracers of hydrothermal activity in the oceans, manganese and radon-222, can not be unequivocally linked to this source because other processes can also result in enrichments. Enrichments of these species are, however, necessary, but not sufficient evidence for hydrothermal inputs. Thus, the hydrothermal hypothesis can account for the localized, strong enrichments of these tracers observed in the detailed study area.

The very high ^3He content, an isotope which is a distinctive tracer of mantle origin, is rigorous evidence for injection of magmatic volatiles into the deep lake. The observation that this isotopic tracer positively correlates with temperature in the deep lake waters is consistent with helium injection by a hydrothermal fluid. Further support for a hydrothermal input to the lake is provided by a ^3He to heat ratio which is very similar to that observed in known deep ocean hydrothermal vents (Lupton et al, 1989).

Thermal spring inputs can account for the strong gradient in ^{14}C in near-bottom waters of the lake (Simpson, 1970a). Despite the rapid mixing of the lake, Simpson observed that the deep waters were surprisingly "old" and did not reveal evidence of bomb-produced ^{14}C . An active input of "dead" carbon is required to explain this observation. Magmatic carbon, released as CO_2 to circulating hydrothermal fluids could provide a source of dead carbon. Reaction of the hydrothermal fluids with wall rock will result in leaching of cations, neutralization of the acidity of the fluids, and increase in carbonate alkalinity. Consequently, hydrothermal fluids generally have high bicarbonate ion content (Mariner, 1982). Bicarbonate is the major anion in Crater Lake waters and is in greater concentration than can be accounted for by low temperature weathering reactions (Nathenson, 1989). Some of the samples collected during the submersible program have enrichments in alkalinity, however, the precision of the data is insufficient to demonstrate a clear trend.

The observation of bacterial mats and the elevated temperatures and chemical anomalies that are associated with these chemolithotrophic communities is perhaps the most direct evidence of hydrothermal fluid venting into the lake. The elevated temperatures within the mat, although not high, are compatible with a diffuse and highly mixed source of hydrothermal fluids. The bacterial mats, have a composition similar to the metal-rich crusts and pebbles that have been observed at a number of locations in the detailed study area, but no where else in the lake. These deposits may be fossilized equivalents of the mats and represent previous sites of hydrothermal fluid venting.

The conductive heat hypothesis. This hypothesis may be able to explain the gradual increase in temperature in the deep lake; however, to explain the variability in the horizontal and vertical thermal gradients requires amplification of the hypothesis. Conductive heat transport into the lake should produce monotonic decreases in temperature with increasing height above bottom. This is observed in some cases; however, a number of profiles in the detailed study area exhibited complex patterns with warmer water overlying colder water (Collier and Dymond, 1988a). Moreover, conductive input of heat alone cannot explain the horizontal gradients in temperature (Figures 7 and 11) except with even stronger gradients in the conductive heat flux. Variability in conductive heat flow is present in Crater Lake, but this variability has been interpreted to be a consequence of variable proximity to a convective heat source (Williams and Von Herzen, 1983). Finally, conductive thermal input alone cannot explain the chemical anomalies that are observed in the deep lake and the correlation between temperature and salt content (Figures 12 and 19a).

The cold spring hypothesis. This hypothesis could possibly account for the increase in ionic content seen near the bottom. Cold, saline springs entering the deep lake would be denser than than ambient lake water and could form a near-bottom layer. If the hypothetical cold springs were located such that dense pools happened to form in the areas of anomalous conductive heat flow, the thermal and chemical anomalies could be correlated.

The cold spring hypothesis could account for the high ^{222}Rn observed in the detailed study area. Since the source of ^{222}Rn in springs is dominated by α -recoil and not high temperature alteration of rocks (Dymond, et al., 1983), both hot and cold springs have high ^{222}Rn values. In the case of radium-226, however, it is uncertain whether cold springs could account for the factor of 10-20 enrichment of this isotope that was observed in a submersible-collected sample from an area of thermal anomalies. It has been argued that, in contrast to ^{222}Rn , the source of ^{226}Ra in thermal springs is high temperature rock alteration (Krishnaswami and Turekian, 1982). However, without knowing more about the crustal residence time of the fluids that carry high radium contents and adsorption rates of radium carried by spring fluids (Dymond et al., 1983), a unequivocal distinction between cold or thermal spring sources of ^{226}Ra cannot be made.

For cold springs to account for Crater Lake's ionic concentrations the springs must either be very saline or of high volume. Springs from the Chaski Slide area, which are relatively close to the detailed study area, have Mg, Ca, and SO_4 concentrations that are sufficiently enriched (Nathenson and Thompson, in press) to account for the observed anomalies in the most chemically-altered water sample collected at the bacterial mat. Even for these elements, however, springs of a Chaski Slide composition would have to be a major source of water to the lake in order to account for the abundance of Mg, Ca, and SO_4 observed in the lake. Moreover, Chaski Slide spring samples are no more enriched in Na, K, Li, and Cl than other Mazama springs and, thus, cannot simultaneously account for the enrichments observed in these elements in the Detailed Study Area and their abundance in the lake in general. Highly saline cold springs have not been observed in the vicinity of Crater Lake (Thompson et al., in press). Voluminous cold input would require major modification of the water budget of the lake which have been defined by several researchers (Van Denburgh, 1968; Simpson, 1970b; Redmond, in press).

Volatile transport hypothesis. Since volcanic gases are enriched in ^3He , it is possible that volatile transport of helium into the deep lake, independent of advecting thermal waters, could account for the observed ^3He anomalies. For example, magmatic degassing has been suggested for the CO_2 buildup of Lake Monoun and Lake Nyos in Cameroon which led to a lethal gas burst (Sigurdsson, 1987). At these lakes, the SO_4 and Cl levels are very low, suggesting little fumarolic or hydrothermal input. The $^3\text{He}/^4\text{He}$ values, however, are similar to mantle values (Sigurdsson, 1987). If volcanic emanations carry HCl, this process could also account for the relatively high

concentration of chloride (La Fleur, 1987) that is observed in Crater Lake compared to other precipitation-dominated lakes in the Cascades. An input of volatile CO₂ to the lake could account for the "dead" carbon inputs that are necessary to account for the gradients in ¹⁴C observed by Simpson (1970a) in the deep lake.

This hypothesis by itself does not account for thermal anomalies or the anomalies of nonvolatile species such as K, Ca, Mg, and Si that are observed in the deep lake. In order to account for the observed correlation between these elements, the hypothesis must be interwoven with the conductive heat and cold spring hypothesis in such a way that the volcanic degassing would most directly impact those sites of the lake that receive cold spring input and experience high conductive heating. Moreover, the fact that the ³He to heat ratio measured in the bottom of Crater Lake is very similar to values measured in oceanic hot springs (Lupton et al., 1989) suggests that only by a series of remarkable circumstances could volatile degassing account for the data.

Moreover, Thompson et al. (in press) argue that because Crater Lake is a near neutral lake (pH ~7.5), acidic gases such as HCl and H₂S are not the source of chloride and sulfate in the lake. They suggest Na and Cl enter the lake together in aqueous solution. Since nearly all of the chloride in the lake cannot be accounted for by precipitation and runoff, sufficient injection of HCl to balance the chloride deficit (Simpson, 1970a; Nathenson, in press; Reilly et al., 1989; Figure 22) would have a major impact on the observed pH and the alkalinity of the lake. If volatile CO₂ were injected to the lake, it would also result in a lower pH and would not directly account for Crater Lake's bicarbonate content which is high relative to precipitation-dominated lakes in the Cascades.

Formation of metal deposits and bacterial mats by cold springs. The metal-rich deposits and sediments observed in the detailed study area and recovered by cores (Dymond and Collier, in press) do not in themselves demonstrate a thermal spring input to the lake. A variety of low-temperature processes can mobilize metals, and precipitation of metals from cold springs is possible, especially if a change in pH or oxygen content accompanies mixing of spring and lake water. Cold springs could also account for the observed bacterial mats. Although these particular genera have been observed in geothermal waters, they are not thermophilic bacteria. All that is required for their growth (particularly the genus *Gallionella*) is a continuing source of reduced iron and a redox boundary. Anoxic cold springs could provide such a source, and the observation of iron-oxidizing bacteria in cold springs, wells, and ditches is a demonstration of their ubiquity.

As discussed by Dymond and Collier (in press), a simple redox mobilization and precipitation of manganese and iron in the sediments is incompatible with the spatial variability in the metal enrichment. Cold spring input of metals, however, cannot be ruled out. Such springs, however, must be in the area of present-day thermal anomalies, since there seems to be a very clear relationship among anomalous water chemistry, temperature, and metal-rich deposition. This hypothesis also requires that cold springs must have occurred episodically in different parts of the lake in the past to account for the metal enrichments observed in older sediments (Dymond and Collier, in press).

Although the bacterial mats could form by iron-bearing cold springs, the mats are in fact at least 6°C warmer than ambient lake temperatures. As we discussed, these warmer waters cannot be a consequence of metabolic iron oxidation. Could it be that the mat waters, although warmer than deep lake waters, are simply supplied by caldera wall springs that are warm relative to deep lake waters, but not geothermally heated? There is no unequivocal answer to this question. Reported temperatures of springs above the surface elevation of Crater Lake range from 3 to 18 °C (Nathenson and Thompson, 1989). These researchers report temperatures of 9.5 and 12 °C for two Chaski Slide springs. These and many of the springs which were sampled, however, are

subject to solar heating since they traverse considerable distances of the caldera wall before they reach sampling locations. Large springs such as Annie Springs, which probably tap deep aquifers, more commonly have reported temperatures of 3 to 4 °C even in August (Nathenson and Thompson, 1989).

The ash alteration hypothesis. Volcanic ash is notably reactive and can be readily altered to various hydrous phases. The classic weathering reactions of Garrels and MacKenzie (1967) release cations and silicon to solution and produce alkalinity. Because of the abundance of fine, glassy pumice debris on the rim and caldera wall of Crater Lake, this type of weathering could provide a source of cations to Crater Lake waters. This hypothesis has been proposed by La Fleur (1987) as a source of chloride to the lake.

Weathering of volcanic phases as a source of elements in Crater Lake waters and Mazama springs has been discussed in detail by Nathenson and Thompson (in press). They found that simple weathering reactions involving transformation of glass and clinopyroxene to kaolinite could account for the composition of most Mazama springs. The computed and observed contents of most cations in springs, however, were 25 to 35% of those observed in Crater Lake. In addition, Nathenson and Thompson (in press) computed the Cl contribution of weathering to spring waters using measured ratios of chloride to sodium and assuming that all the chloride would dissolve with the sodium. The resulting value is more than 100 times less than observed chloride contents in Crater Lake. These data suggest weathering of volcanic materials cannot account for the chloride or other ionic contents of Crater Lake.

Evaporation hypothesis. If a major fraction of the waters entering the lake evaporated, this would concentrate the ions dissolved in the lake and increase its salt content above that predicted by losses due to seepage outflow alone. A high evaporation rate has been hypothesized to explain the anomalously high chloride in the lake (La Fleur, 1987).

It has long been recognized that a significant fraction of the water in Crater Lake evaporates (Diller, 1902; Phillips, 1968; Simpson, 1970a; Redmond, in press), and all the hydrologic budgets used in examining the mass balance of ions in the lake include evaporation (Simpson, 1970a; Nathenson, in press). The hydrogen and oxygen isotope ratios in Crater Lake water fall off the meteoric trend and follow a reasonable evaporation trend (Thompson et al., 1987; in press). As discussed by Redmond (in press), direct measurements of evaporation are inaccurate and can't represent an annual average until observations are made in the winter. Therefore, most estimates have been based on water budget considerations. The values most frequently used for evaporation are quoted or derived from Phillips (1968). His water budget allows that approximately 28% of the water entering the lake evaporates. The value chosen by Simpson (1970a,b) results in 33% loss by evaporation. In a detailed analysis of extensive records of climate and lake level variations, Redmond (in press) demonstrates an evaporation rate of approximately 50% of the total water input and shows that this is most consistent with available data.

In our application of the mass balance model for chloride and lithium (Figure 22), we have used the hydrologic data set of Redmond (in press), including the high evaporation rate. Our mass balance calculation demonstrates that the steady state concentration of chloride in the lake, assuming zero hydrothermal input, would be less than 10% of the observed level. Even if the evaporation accounted for 60% of the net water loss, the steady state chloride value is barely 10% of the concentration present in Crater Lake.

During evaporation, the ionic ratios between conservative salts remain constant - the final brine has the same ratio as the parent fluids. If the source of these ions in the lake is primarily the weathering products carried by runoff, then the lake must have the same ion ratios as those seen in

that runoff. Figures 14-16 show that this is not the case for ratios measured in the lake compared to those in the caldera springs. Although evaporation removes approximately half of the annual inflow of water, it is not responsible for the observed character or magnitude of the concentration of ions in Crater Lake.

Early Fumerolic Input Hypothesis. The early formation phases of caldera lakes are often associated with continued volcanism, hot springs and fumerolic inputs. Caldera lakes can become extremely concentrated in dissolved ions and gases as a result of these inputs. For instance, in our discussion of the mass balance and residence time of ions, we used two such lakes as possible analogues for the young Crater Lake (Olafsson, 1980; Sigurdsson, 1977). We then applied simple mass balance calculations using the current hydrologic model and demonstrated that Crater Lake (or any reservoir) has relatively little residual "memory" of events occurring more than ten residence times in the past. Therefore, dissolved chloride or soluble materials added to Crater Lake following the collapse of Mount Mazama (La Fluer, 1987) would be effectively purged from the lake within 2500 years. It is clearly more difficult to evaluate steady states over time scales that are short compared to the response time of the system. Nonetheless, since the current concentration of ions in Crater Lake is high compared to the concentration supported by precipitation and weathering, the exponential drop towards that steady state should still be easily visible (Figure 22). Nathenson (in press) has shown that there have been no such significant changes discernable in the chemical composition data for Crater Lake since 1912.

Summary

Submersible observations within the South Basin have defined fine-scale variations in temperature and salt content of the near-bottom waters. Temperature variations of up to 0.5°C and conductivity variations of more than a factor of two occur over distances of a few meters. The magnitude and spatial scale of these variations require a continuing input of warmer and more saline water to maintain such high gradients. Variations in the conductivity-to-heat ratios within the South Basin indicate that the necessary fluid inputs cannot result from a single source of anomalous water. Despite these temperature and conductivity evidences of anomalous fluid sources, no actual vents were observed within our detailed study area of the South Basin. The lack of visual evidence of venting could either be a consequence of incomplete survey coverage of the study area or diffuse venting that cannot be detected visually. Either explanation can be defended. Less than 10 % of the study area was observed visually; lack of precise navigation prevented highly detailed search patterns that might have found the source of some of the most impressive anomalies. On the other hand, diffuse hydrothermal advection is well documented in sedimented areas of the ocean. Advection velocities of centimeters to a few meters per year have been measured by studies of sediment pore water that are influenced by marine hydrothermal systems. Although such flows could not be detected visually they could introduce significant heat and ions into the bottom waters.

The communities of bacteria, which produce impressive mat features on rock outcrops and sediment surfaces, provide evidence of diffuse venting on the lake floor. These features cover areas up to several meters across and have internal temperatures elevated by as much as 6.0°C. They appear to be chemolithotrophic communities which use abundant reduced iron in advecting fluids to fuel their metabolism. There were no visual indications of flow from the mats, and the internal chemical and density gradients, which could constrain the advection rate, were not measured. Advection is implied because it seems unlikely that such a prolific bacterial communities could be maintained by a slower process like diffusion. Moreover, only fluid advection can maintain the 6°C temperature gradient that is observed across the interface between the mat and the bottom waters. Despite the striking nature of the mats, temperature and conductivity anomalies in the immediate vicinity of the mats were often not exceptional. In fact, at the site of the largest mats, the temperature anomalies were quite small. We could only note a

general association (on a spatial scale of 100 to 200 m) of mat presence with near-bottom temperature anomalies. The lack of anomalies in close proximity to mats is compatible with diffuse venting. Consequently, the bacterial mats are aptly described as visual markers of this type of venting. A possible inconsistency in this argument is the fact that we did record near-bottom temperature anomalies which were at least 2-5 times greater than those measured in the near vicinity of mats. One might presume that such anomalies must be accompanied by either larger or more vigorous venting than the diffuse venting which apparently results in the bacterial mats. This analogy seems to suggest our submersible transects may indeed have missed the most impressive visual indications of venting.

Sampling of the near-bottom waters and mat fluids has extended the range of anomalous water composition which are found within Crater Lake. For example, the anomalies with respect to background lake levels for major elements are nearly a factor of two. Manganese and ^{222}Rn , both important tracers of hydrothermal sources in the ocean, are as much as 1900 and 200 times enriched over typical lake values, respectively. Helium-3, perhaps the most distinctive indicator of a magmatic source, is more than a factor of five enriched over values which would be in equilibrium with atmospheric sources. Even more important than the magnitude of these enrichments is the fact that the ionic relationships of the anomalous waters can now be defined sufficiently to account for the bulk lake compositions, which were hitherto unexplainable by known water sources (e.g. precipitation and caldera springs). These data have permitted us to attempt the geochemical mass balances for the lake which include realistic estimates of composition of a hydrothermal input. The models delimit the range of possible hydrothermal flows into the lake.

We have made some important steps as a result of the 1988 field program. These results help to constrain the important hypotheses that may influence the physical, chemical, and biological processes of Crater Lake and provide a foundation for identifying new experiments for the coming field season.

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APPENDIX I

Geological observations and sampling

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Four dives of the 1988 season were dedicated to geologic studies (USGS). The major objective of this program was to characterize the postcaldera volcanic rocks which previously were only known from a few dredge samples and, of course, the exposed part of Wizard Island. The postcaldera volcanics are those lavas and pyroclastic rocks that were erupted after collapse of Crater Lake caldera 6,845 +/- 50 yr B.P. All postcaldera volcanic activity in the Crater Lake area occurred within the caldera. Observations made from Deep Rover coupled with morphologic features of rock samples have allowed us to determine, with varying degrees of confidence, which postcaldera lava flows were emplaced beneath lake water and which cooled subareally. This is important because it helps to constrain the relative ages of volcanic features, using filling of the lake as a timing device to supplement relative age information based on morphology and superposition of features (i.e., younger lava overlies older lava).

All postcaldera volcanic rocks, with the exception of the little rhyodacite dome east of Wizard Island, are andesites. These form the central platform (east of Wizard Island) and lava flows beneath it on the north and probably east sides (covered by sediment), Merriam Cone, and the Wizard Island edifice, only the tip of which projects above the lake surface. The oldest postcaldera andesite from which a sample was recovered is a flow north of the central platform. Domes or thick flows that form the central platform rest on this lava and were erupted before the lake filled to their level. Merriam Cone and the lava flows that form most of the surface of the submerged part of the Wizard Island volcano were erupted into water, the Wizard Island lavas when lake level was approximately 250 feet lower than at present. The rhyodacite dome east of Wizard Island is the youngest postcaldera volcanic feature on the basis of other previous work. The dome may have been emplaced when the lake surface was close to its present level.

Thin sections were cut from about thirty rock samples collected with Deep Rover. Samples from the central platform have relatively large (1-3 mm) plagioclase phenocrysts set in a glassy groundmass containing comparatively few small crystals, while lavas of Wizard Island and Merriam Cone have plagioclase phenocrysts generally less than 2 mm and abundant microphenocrysts in glassy groundmasses. Fifteen postcaldera andesite samples were analyzed for major and trace elements by x-ray fluorescence, instrumental neutron activation, and inductively-coupled plasma techniques. Results of this work and earlier analysis of dredge and Wizard Island samples show that: (1) SiO₂ content ranges from 58.3 to 62.7 wt % among unaltered andesites; (2) Wizard Platform lavas (n=5) have relatively high K/Na, Mg/Fe, and, SiO₂; (3) Merriam Cone and the earliest Wizard Island lavas are more differentiated than later Wizard Island flows, and there is continuous variation between compositional extremes; (4) The morphology of the central platform, which suggests a group of coalescing domes, is consistent with the more SiO₂-rich compositions of its lavas that imply somewhat higher viscosities than for other postcaldera andesites. Some types of chemical analyses (e.g., F and Cl contents) are still in progress.

The next phase of study of the postcaldera lava samples will be electron microprobe analysis of phenocrysts in representative samples so that crystal compositions may be used in quantitative models of fractionation, assimilation, and mixing processes that may have caused the compositional diversity among the postcaldera andesites. We will attempt to determine if the postcaldera lavas contain residual magma from the chamber responsible for the caldera-forming eruption and how the postcaldera rhyodacite may have formed.

The second objective of the geologic dives was to explore the deep caldera walls. Time was sufficient to allow one locality north of Eagle Point to be visited. From here we recovered three samples of highly-altered andesite lava from a single outcrop at 1427 ft depth. These

apparently are Mazama lavas that are older than those of the exposed caldera wall, although we cannot say with certainty that the approximately 400 ft high steeply-sloping pile of lava flows above the sampled outcrop is not a large landslide block. Based on K-Ar dates from the caldera wall, these rocks are older than 300,000 yrs. Hydrothermal alteration of these samples occurred before collapse of the caldera but the age of the alteration is not yet known. Alteration minerals include chlorite and epidote, which probably formed at a temperature well in excess of 200 °C. Further study of the most altered sample is in progress.

If dives dedicated to geology are undertaken in 1989 the main objective will be to observe and sample as many outcrops on the submerged caldera walls as possible in order to determine what kind of rocks are present and to characterize their hydrothermal alteration history.

APPENDIX II

Deep Water Plants and Animals in Crater Lake

Gary Larson, OSU

(with contributions by H. Phinney, D. McIntire, S. Loeb, M. Buktenica, N. Anderson and S. Earle)

Exploration of the bottom of Crater Lake in August, 1988, using a one-person submersible provided a unique opportunity to observe and collect benthic fauna and flora directly off the lake bottom. Several oligochaetes were collected from the soft mud surface. One dive was dedicated to exploring the caldera walls for moss (Drepanocladis) and periphyton. Moss was observed at 253 m, and a sample was collected at a depth of 221 m. The sample extended the known depth of the moss by about 100 m in the lake, and this is probably a world record depth. Periphyton was observed on the caldera walls to a depth of 147 m, but no samples were collected.

The moss sample ranged in color from bright green through greenish golden to a dark brownish red. The cells of the axes and "leaves" of green axes exhibited numerous and prominent chloroplasts. The plastids in plants that had aged and darkened were impossible to discern. The cells of the darker leaves appeared to have reduced cell contents, including reduced numbers of plastids. The leaves of the darkest axes had usually lost their tips, and commonly, all of the lamina had eroded except for the very base of the leaf. Three means of vegetative reproduction were observed. No sexual or asexual reproduction was observed.

The moss sample supported a rather uniform epiphytic flora as well as some loosely entwined and entangled filaments. The latter consisted of an unbranched green alga Rhizoclonium and a branched siphonaceous alga Vaucheria (Xanthophyceae). The epiphytes were a filamentous diatom Melosira and three species of green algae, two Oedogonium species and a Bulbochaete. In addition, there were a number of pennate diatoms attached to the primary leaves of the moss and to a less extent to Rhizoclonium, Melosira, and Vaucheria.

A sparse fauna was found in the moss sample. This included a single tartigrade, two unidentified nematodes, two species of rotifer, probably Collotheca and Philodina, several species of ciliates, including Strichotricha and Vorticella, and midge larvae.

A rock collected at 379 m was examined in the laboratory, and a single living specimen of epilithic algae was found. Although it was impossible to remove the specimen from the rock, it was photographed and tentatively identified as Tribonema. This appears to be a world record depth of growth for epilithic algae in fresh water.

The great depths at which plants were found living in the lake is an important discovery to our ten-year limnological assessment of Crater Lake. Such growth is probably an integrated measure of water clarity. Since small changes in turbidity could have substantial impacts on the amount of available light at these great depths, documentation of the floral assemblages and their depth distributions provide very important baseline data for future monitoring of the clarity of Crater Lake.

Appendix III - Acoustic Navigation

Long baseline acoustic navigation was used to position both the research boat and the submersible. With this type of navigation an array of moored transponders are interrogated alternately by the research boat and the submersible. In the first navigation "cycle", an acoustic signal at a frequency F_1 from the boat is answered by each of the transponders. Since each transponder has a separate reply frequency, the travel-time, and thus the distance, to each transponder can be measured as shown in Figure AIII.1.a. Triangulation using these distances determines the location of the boat relative to the transponders. The second navigation cycle sends a signal to the submersible's *relay transponder* at a different frequency F_2 , triggering a signal at frequency F_1 from the sub's transponder. This determines the boat to sub distance and also interrogates the moored transponders array again. Upon receiving the reply from these transponders, a computer onboard the research boat reconstructs the triangular path of the acoustic signals illustrated in Figure AIII.1.b. Now knowing the total travel time around the triangle, the computer subtracts the boat-to-sub distance and the boat-to-transponder distance determined in the first cycle to arrive at the third side of the triangle - the sub-to-transponder distance. Another triangulation gives the position of the submersible with respect to the transponders. Notice that the accuracy of this position is dependant upon the accuracy of the ship to transponder distances determined in the first cycle, and, of course, on the quality of the relative calibration of the transponder array. Absolute calibration of the array was accomplished with a microwave ranging system (Motorola Mini-Ranger III) that used transmitters on Phantom Ship Island and Eagle Point. From measurements of the travel-times from the surface boat to transponders made at different locations on the lake, an absolute calibration (latitude, longitude, and depth) of each transponder could be determined. This type of navigation system typically has a precision of \pm a few meters.

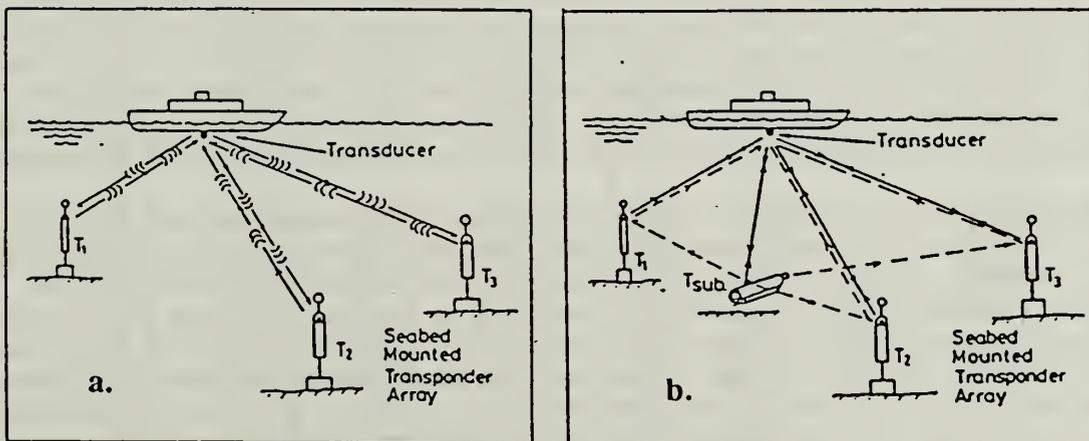


Figure AIII.1.- Acoustic navigation with an array of 3 moored transponders, a research boat transducer and a submersible mounted relay transponder. a). First navigation cycle: the research boat ranges to the transponder array. b). Second navigation cycle: the signal travels from the boat to the sub to the transponder array and back to the boat.

Oceano Instruments, Inc. in Seattle, Washington was contracted to provide the navigation system and calibrate the acoustic net. A four-transponder acoustic net was deployed, calibrated, and given a preliminary test in July. During this test the relay transponder was attached to the hydrographic wire of the research boat and lowered to the bottom in order to mimic its use on the sub. The system appeared to work satisfactorily. However, it was noted that in several lowerings the relay reply was lost when the transponder got within 50 m of the bottom. These problems were underrated by the Oceano technician, but he proposed to further evaluate the travel-time data to determine what might have caused the loss of relay navigation.

Our acoustic navigation during the diving program proved to be a disaster. Throughout the entire period, from the first dive to the last, we did not have useful acoustic transponder navigation. Although an Oceano Instruments technician returned at the beginning of August to provide final systems checks and instructions to our technicians who would use the system, he had to leave the Park just before the submarine reached the bottom on the first deep dive. On that dive and many later dives we could not track the submarine near the bottom. Many times the reply from the relay would not be received for much of the dive. At other times the system would be tracking the submersible with degraded but acceptable precision (± 10 -20 m) for short periods, but at some point the track line would instantaneously switch to a new and parallel track. These jumps were the result of multiple acoustic paths (bounces off caldera walls, lake floor or surface when a direct line-of-sight path is blocked) that resulted in stable but totally inaccurate tracking of the submersible. This, however, was not the entire problem: the initial net calibration proved to be unsatisfactory; one of the moored transponders stopped replying; there was acoustic interference between transponders that had similar frequencies. These difficulties combined to make real-time acoustic navigation of the submersible impossible.

Oceano Instruments were not able to help us with these problems in the field because of a lack of qualified field personnel. However, since we still recorded all the basic acoustic data they promised to post-process the data and provide track lines for each dives. The post-processing would include recalibration of the net and removal of multiple acoustic path data. They apparently have been working on the problem, but it does not have the same priority as new contracts. In spite of the pressure (and even threats) we have applied, they have not provided any navigational tracks to this date. Recent communications with the company indicated that they were no longer going to honor their commitment without further charges to us. Consequently, we are now faced with carrying out the post-processing ourselves. There exists within the College of Oceanography and within the University some expertise in this area. We are currently exploring these options.

In the mean time, we have refined the dead-reckoning navigation to produce track lines for most of the dives within the detailed study area. In the most favorable cases we have documented the positions where the submarine submerged and later surfaced with our Mini-Ranger surface navigation. The dead-reckoning speed and direction can be constrained to some extent by the known bathymetry (Figure 2). Repeated encounters with the distinctive tracks of Deep Rover, markers previously deployed from the submersible, and identifiable bottom features helped make the dead-reckoning navigation internally consistent. In some cases, however, the Mini-Ranger positions were not available and difficulties in communicating with the submersible prevented us from being able to accurately reconstruct the dive tracks. This was the case for dives 171 and 173. Approximate track lines for the other nine dives in the detailed study area are shown in Figure 3a-3d. The errors in these lines cannot be estimated directly and vary depending on the quality of surface to submersible communications and the complexity of the track line. In general, the early and late portions of the dives may have navigation errors on the order of ± 10 meters but mid-dive periods, far-removed from any geodetic reference points, may have errors ranging from 50-100 meters.

Appendix IV - Water Chemistry Data

1987 Hydrocast Data

Sample	Depth	T (°C)	[Na] (mg/l)	[Ca] (mg/l)	[Mg] (mg/l)	[K] (mg/l)	[Li] (µg/l)	[SiO ₂] (mg/l)	[Mn] (nM)
6.1	446.1	3.6095	10.91	6.926	2.746	1.785	46.6	18.14	17.82
6.3	427.0	3.5922	10.82	6.816	2.753	1.767	46.2	17.99	11.27
6.4	416.7	3.5372	10.64	6.753	2.732	1.740	45.1	17.85	2.78
6.5	407.5	3.5299	10.40	6.766	2.705	1.740	44.7	17.71	3.13
6.6	397.2	3.5138	10.65	6.716	2.707	1.727	44.5	17.69	1.03
7.1	385.3	3.5081	10.58	6.730	2.693	1.727	44.6	17.65	0.37
7.2	375.8	3.5064	10.48	6.723	2.683	1.724	44.3	17.65	0.49
7.3	350.9	3.5006	10.37	6.734	2.690	1.714	44.1	17.27	0.59
7.4	325.7	3.4985	10.24	6.710	2.666	1.708	44.1	17.56	0.33
7.5	300.9	3.5142	10.48	6.672	2.662	1.696	44.5	17.44	0.75
7.6	276.4	3.5524	10.50	6.688	2.667	1.700	44.7	17.42	0.51
18.1	418.5					1.717	44.9	17.81	1.31
18.6	404.1	3.5143	10.44	6.731	2.687	1.727	44.1	17.76	1.05
18.2	433.5	3.5174	10.45	6.739	2.679	1.723	45.5	17.83	0.63
18.3	449.2	3.5198	10.46	6.736	2.687	1.725	45.5	17.85	1.16
18.5	464.1	3.5214	10.36	6.753	2.696	1.713	44.5	17.80	2.84
19.4	476.7	3.5221	10.47	6.831	2.697	1.723	45.7	17.90	0.55
20.1	486.7	3.6115	10.87	7.121	2.888	1.763	45.9	18.59	5.10
20.2	471.0	3.5745	10.78	6.892	2.766	1.739	45.3	18.12	2.50
20.3	456.8	3.5528	10.41	6.855	2.728	1.738	45.3	17.94	1.98
20.4	441.2	3.5303	10.46	6.817	2.696	1.722	44.9	17.85	0.78
20.5	427.0	3.5263							
20.6	411.3	3.5200	10.39	6.745	2.699	1.714	44.9	17.93	0.75
21.6	456.5	3.5912	10.63	6.900	2.767	1.750	45.5	18.16	5.64
21.5	440.8	3.5705	10.68	6.876	2.700	1.744	44.9	17.89	8.26
26.1	443.3	3.5583	10.52	6.852	2.708	1.731	45.3	17.89	2.76
26.2	435.2	3.5436	10.77	6.865	2.72	1.723	44.3	17.62	1.85
26.3	424.9	3.5299	10.63	6.852	2.696	1.721	44.3	17.60	1.86
26.4	414.2	3.5227	10.45	6.809	2.700	1.726	44.3	17.60	1.18
26.5	405.4	3.5235	10.13	6.761	2.688	1.715	44.1	17.54	1.19
27.1	582.2	3.5532	10.34	6.918	2.757	1.737	44.7	18.01	5.03
27.2	533.3	3.5399	10.76	6.830	2.728	1.736	44.7	17.83	1.62
27.3	483.6	3.5262	10.66	6.828	2.729	1.735	44.7	17.72	1.74
27.4	434.3	3.5198	10.45	6.809	2.703	1.718	44.1	17.65	1.78
27.5	383.1	3.5079	10.55	6.787	2.691	1.707	44.3	17.72	1.45
28.1	447.7	3.5772	10.54	6.878	2.731	1.749	45.3	18.08	3.98
28.2	433.5	3.5384	10.49	6.853	2.706	1.737	44.9	17.89	1.48
28.3	417.5	3.5259	10.71	6.814	2.679	1.709	45.1	17.74	0.86
28.4	403.3	3.5173	10.22	6.801	2.684	1.709	43.7	17.69	0.77
28.5	388.0	3.5091	10.49	6.799	2.678	1.709	44.5	17.63	0.39
29.1	324.2	3.5139	10.33	6.832	2.657	1.701	44.1	17.40	0.47
29.2	250.4	3.7269	10.22	6.762	2.647	1.689	44.1	17.42	0.72
29.3	175.1	3.7254	10.24	6.724	2.650	1.682	43.7	17.34	0.61
29.4	100.5	4.1023	10.44	6.760	2.651	1.677	43.5	17.29	0.19
29.5	24.9	8.4294	10.50	6.766	2.663	1.704	43.9	17.34	4.13

Appendix IV (cont)

1988 Hydrocast Data

Sample	Depth	T (°C)	[Mg] (mg/l)	[K] (mg/l)	[Na] (mg/l)	[SiO ₂] (mg/l)	[Ca] (mg/l)	pH	Alk (meq/l)	[Mn] (nM)
2.2-5	441.3	3.6193	2.727	1.745	10.64	18.29	6.886			8.2
2.2-6	434.4	3.5968	2.720	1.750	10.64	18.19	6.876			4.9
2.2-7	428.8	3.5800	2.774	1.753	10.93	18.15	6.874			4.1
2.3-1	448.2	3.6100	2.701	1.743	10.57	18.33	6.905			4.3
2.3-2	408.1	3.5640	2.683	1.704	10.47	18.13	6.762			0.3
2.3-3	398.1	3.5612	2.681	1.720	10.47	18.11	6.801			0.5
2.3-4	387.4	3.5587	2.667	1.715	10.51	17.99	6.789			0.6
81801	439.0	3.5988	2.714	1.739	10.74	18.18		7.103	0.583	1.8
81802	429.5	3.5862	2.682	1.736	10.60	18.10		7.197	0.626	1.2
81803	419.1	3.5782	2.696	1.713	10.58			7.106	0.627	
81804	408.8	3.5682	2.684	1.729	10.50	17.86		7.098	0.629	
81807	378.6	3.5631	2.668	1.716	10.45	17.81		7.135	0.622	
81809	347.6	3.5695	2.683	1.700	10.41	17.76		7.226	0.605	
81811	318.0	3.5720	2.632	1.699	10.40	17.65		7.307	0.624	
82501	445.1	3.6086	2.699	1.729	10.73	18.21	6.911	7.168	0.634	4.4
82502	434.8	3.6069	2.692	1.741	10.47	18.13	6.895	7.184	0.636	4.8
82503	424.1	3.5982	2.710	1.738	10.48	17.99	6.851	7.257	0.634	3.2
82504	415.3	3.5805	2.672	1.727	10.41	18.04	6.816	7.153	0.613	1.3
82505	302.2	3.5948	2.642	1.685	10.27	17.74	6.791			1.5
82506	262.4	3.6585	2.630		10.23	17.66	6.762			0.4
82507	221.5	3.7309	2.652	1.715	10.29	17.60	6.728			1.7

Appendix IV (cont.)

1988 Dive Data

Dive	[Mg] (mg/l)	[K] (mg/l)	[Na] (mg/l)	[SiO ₂] (mg/l)	[Ca] (mg/l)	pH	Alk (meq/l)	[Mn] (nM)
CD179.1	2.906	1.771	10.78	18.62	7.086			3.55
CD179.2	2.922	1.774	10.88	18.56	7.086			10.21
CD179 BT		3.011	19.28	28.69	12.573			589.70
CD182.1	3.931	2.119	13.06	21.28	8.253			36.01
CD182.2	4.197	2.254	13.92	22.94	8.409			9572.00
CD183.2	2.770	1.808	10.82	17.30	6.982			114.90
CD184.0	2.905	1.772	10.85	18.54	7.036	6.501	0.696	10.66
CD185.1	2.749	1.755	10.80	18.33	6.882			6.41
CD185.2	2.682	1.710	10.37	17.77	6.778			5.40
CD186.1	2.746	1.832	10.80	18.46	6.976	7.403	0.641	41.47
CD186.2	2.785	1.796		18.38	6.972			45.43
CD187.0	2.759	1.807	10.88	18.52	6.993	7.151	0.653	34.17

1988 Spring Data

Spring	[Mg] (mg/l)	[K] (mg/l)	[Na] (mg/l)	[Ca] (mg/l)	[SiO ₂] (mg/l)	[Mn] (nM)
20	1.600	0.935	2.98	6.581	25.40	
16		1.651			26.66	5.7
48	0.509	1.360	2.53	2.319	35.28	
02	0.872	0.928	1.53	2.517	37.57	2.0
38	2.854	1.126	3.89	9.077	33.14	
42	1.292	1.714	2.80	4.582	37.17	
19	3.417	0.611		11.743	8.02	2.0
11	1.011	0.659	4.64	1.961	36.73	
39	0.499	0.752	2.00	2.492	25.89	5.7
24		0.328		20.913	36.37	
35	0.245	1.244	2.79	8.224	31.14	76.0

Studies of Hydrothermal Processes in Crater Lake

A proposal for a third year of research conducted for the National Park Service through the CPSU, Oregon State University.

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Introduction.

In 1983, we began a study of geochemical cycling at Crater Lake as part of the on-going 10-year limnological program (Larson, 1986). As part of this research, we conducted studies of water chemistry, settling particulate matter, and sediments accumulating on the lake floor. By the end of 1986, we had collected a data set including helium isotopes, dissolved trace metals, radon-222 activities and sediment core analyses which lead us to hypothesize that active hydrothermal inputs existed deep within the South Basin of Crater Lake (Figure 1). This hypothesis, based on our studies, was consistent with the work of a number of previous researchers.

In early 1987, we proposed a three-year research program to "demonstrate the location, magnitude and ecological role of hydrothermal springs in Crater Lake". The initial field work was carried out during the summer of 1987 (Collier and Dymond, 1988) and expanded in 1988 with the deployment of the submersible Deep Rover (Collier and Dymond, 1989). This proposal covers our research plan for the final field season in 1989. The report for the 1988 program (Collier and Dymond, 1989) should be reviewed along with this proposal for background details on our progress to date. We will also refer directly to several figures from that report.

Perhaps the major goal of this program is to evaluate the environmental significance of hydrothermal activity in the lake as part of an overall ecological model of the lake. This understanding of "how the lake works" is one of the overall goals of the 10-year limnological program. The remarkable clarity and the resulting blue color of the lake are among the most significant resources of this National Park. This clarity is a direct consequence of the oligotrophic nature of this caldera lake which supports only a sparse population of phytoplankton in the upper waters. However, the specific processes regulating this nutrient limitation are not well known. Although nitrate is depleted throughout the upper water column and is certainly a limiting nutrient, there is abundant nitrate stored in the the deep lake. Thus, analogous to marine ecosystems, the rates of nutrient cycling from the deep lake to the euphotic zone may provide the most significant control on the rate of primary production. Any process which controls this mixing rate can have a direct effect on phytoplankton concentrations and clarity. Previous researchers have hypothesized that hydrothermal inputs exist in the lake and that they affect the rate of vertical mixing (Simpson, 1970a; Williams and Von Herzen, 1983). A goal of our research program is to directly evaluate the existence and nature of hydrothermal inputs and to examine their effect on vertical mixing rates. Such inputs could help determine the chemical and biological character of the lake and of the materials buried within the sediment record.



Figure 1. Bathymetry for Crater Lake (Byrne, 1965). Major geologic features are shown. The detailed study area was the focus of the 1988 hydrothermal investigations and the site of extensive observation and sampling.

Background

Previous Studies

The possibility that Crater Lake is receiving hydrothermal inputs of water and heat was first proposed by Van Denburgh (1968), who, noting the relatively high sulfate and chloride content of Crater Lake compared to nearby Davis Lake, suggested that these two constituents " may have been contributed to the lake by thermal springs or fumaroles, probably located below the present lake level. Such springs and fumaroles are a common expression of hydrothermal activity at a site of volcanic eruptions". Van Denburgh did not state whether he thought hydrothermal input was active today. Simpson (1970a) measured strong gradients in both ^{14}C and stable carbon isotopes in the deep lake. These gradients were consistent with a source of carbon with isotopic compositions similar to magmatic sources. Simpson also constructed a mass balance model that indicated only a fraction of the ionic content of Crater Lake could be accounted for by known inputs. He suggested the missing source was the result of "fumarole or hot spring activity near the bottom", and he estimated fluxes from this proposed source.

More recently Williams and Von Herzen (1983) measured high conductive heat flow in certain areas of the lake's sedimented bottom. In one of these areas of high heat flow they also documented anomalous near-bottom temperatures. This study reinforced earlier work describing the deep temperature structure of the lake as hyperadiabatic (Neal et al., 1972). On the basis of the heatflow pattern and the water column measurements, Williams and Von Herzen (1983) suggested that there is thermal spring input to the deep lake.

Studies of Crater Lake water composition have provided further support for hydrothermal hypotheses. Thompson et al. (in press) pointed out that Crater Lake has high boron and lithium contents compared to local meteoric water; these elements are typically enriched in thermal waters of volcanic origin. In addition, they showed that Cl/Li ratios of Crater Lake waters are very similar to those observed in hot springs from volcanic sources but lie outside the range of values observed in Mt. Mazama cold springs. Nathenson (in press) demonstrated that a hydrologic model which incorporates precipitation, cold springs, evaporation, and seepage cannot account for the major element content of Crater Lake. He suggested thermal springs provide the missing input and, based on geochemical mass balance models, constrains the input of thermal waters to range between 80 and 1900 liters/second. Nathenson points out that this inflow can easily provide the convective heat flux estimated by Williams and Von Herzen (1983). Nathenson's low estimate of hydrothermal flux is similar to that of Sorey (1985) who suggested a thermal-spring discharge into the lake of 30 - 150 liters/second.

Evidence of hydrothermal sources to the lake have not gone unchallenged. LaFleur (1987) argues against any hydrothermal inputs to the lake and suggests that underestimated evaporation rates, fumarolic inputs, and weathering of Mazama ash could account for the anomalous composition of the lake. He suggests conductive heating rather than convective inputs accounts for the temperature anomalies.

Progress of the current OSU research program.

Between 1984-86, we studied the water column chemistry at Crater Lake in conjunction with our geochemical research project supported by the 10-year limnological program (Holbrook et al., 1985; Collier et al., in press). During this initial work, we discovered major enrichments of ^3He , Mn and ^{222}Rn in the deep lake and collected several sediment cores with metalliferous deposits. We began an intensive study of possible hydrothermal inputs to Crater Lake in 1987 (Collier et al.,

1987; Dymond et al., 1987; Lupton et al., 1987). Under this program, we have conducted detailed water column sampling and measurements within the South Basin, an area identified by Williams and Von Herzen (1983) as having temperature anomalies and strong variability in sediment heat flow. Our detailed CTD surveys demonstrated significant gradients in salt content and temperature in the bottom 100 meters of the South Basin. The thermal gradient measured near the bottom of the South Basin was approximately $1 \times 10^{-2} \text{ C}^\circ/\text{meter}$ - a gradient which is 3400 times larger than the adiabatic gradient. These "sharp" gradients in temperature were horizontally heterogeneous and sometimes exhibited temperature reversals, thus suggesting a locally unstable system. Consistent with the interpretations of Williams and Von Herzen (1983), we attributed these features to active input of thermal water (Collier and Dymond, 1988a).

Analyses of water samples collected in this region demonstrated the presence of chemical anomalies that are correlated with temperature. The major elements (Mg, Na, K, Ca, and SiO_2), minor elements (Li, Mn) and noble gases (^{222}Rn and ^3He) are all significantly enriched in near-bottom water from the South Basin.

During the 1987 field program we deployed a remotely operated vehicle (ROV) to make video observations of the bottom within the same area that thermal and chemical anomalies were measured. The ROV studies revealed deposits of what appeared to be iron and manganese precipitates at several locations.

The 1988 field program provided a blend of innovative submersible studies, water sampling and CTD measurements. The goals of the program were: (1) to determine if hydrothermal venting is occurring within the lake; (2) if evidence of venting was found, to clarify the nature of the venting (diffuse venting through sediments or localized venting at fault scarps); (3) to define the composition and temperature of venting fluids; (4) to understand the biological consequences of thermal or cold-spring inputs to the lake; (5) to carryout ancillary geological and biological sampling and observations in those regions of the lake that lie beyond the depths of free divers. We have achieved important progress toward all of these goals.

CTD measurements made with the submersible demonstrated fine-scale variations in temperature and salt content of the near-bottom waters that are consistent with hydrothermal inputs to the South Basin. Temperature variations of up to 0.5°C and conductivity variations of more than a factor of two occur over distances of a few meters. The magnitude and spatial scale of these variations produce strong gradients which require a continuing input of warmer and more saline water. Variations in the conductivity-to-heat ratios within the South Basin indicate that the necessary fluid inputs cannot result from a single source of anomalous water (Figure 12 in Collier and Dymond, 1989).

Despite these temperature and conductivity evidences of anomalous fluid sources, no actual vents were observed within our detailed study area of the South Basin. The lack of visual evidence of venting could either be a consequence of incomplete coverage of the study area or diffuse inputs that cannot be detected visually. Either explanation can be defended. Less than 10 % of the Detailed Study Area was observed visually; lack of precise navigation prevented highly detailed search patterns that might have found the source of some of the most impressive anomalies. On the other hand, diffuse hydrothermal advection is well documented in sedimented areas of the ocean. Studies of sediment pore water have measured advection velocities of centimeters to a few meters per year (Sayles and Jenkins, 1982; Becker and Von Herzen, 1983; Maris et al., 1984; Wheat and McDuff, 1988). Although venting of this speed could not be detected visually, when occurring over a large area of the bottom it could introduce significant heat and ions into the bottom waters.

Submersible sampling of the near-bottom waters has extended the range of anomalous water compositions found within Crater Lake. For example, we have measured anomalies with respect to background lake levels for major elements that are nearly a factor of two higher. Manganese and ^{222}Rn , both important tracers of hydrothermal sources in the ocean, are as much as 1900 and 200 times enriched over typical lake values, respectively. Helium-3, perhaps the most distinctive indicator of a magmatic source, is more than a factor of five enriched over values which would be in equilibrium with atmospheric sources. Radium-226 is enriched by a factor of 10 to 20 over background levels. Even more important than the magnitude of these enrichments is the fact that the ionic relationships of the anomalous waters can now be defined sufficiently to account for the bulk lake compositions, which were hitherto unexplainable by known water sources (e.g. precipitation and caldera springs). These data have permitted us to attempt geochemical mass balances for the lake which include realistic estimates of composition of a hydrothermal input. Our model suggests a convective heat flux to the lake of approximately 17 MWatts.

Communities of bacteria, which produce impressive mat features on rock outcrops and sediment surfaces, provide evidence of diffuse venting on the lake floor. These features cover areas up to several meters across and have internal temperatures elevated by as much as 6.0°C . They appear to be chemolithotrophic communities which use abundant reduced iron from advecting fluids to fuel their metabolism. The bacterial mats were observed at six sites within the Detailed Study Area but were not found in other areas of the lake. Although the genera of bacteria which comprise the mat are not thermophilic, these forms have been observed in warm hydrothermal fluids at Santorini (Hanert, 1973) and Loihi Seamount (Karl et al., 1988).

US Geological Survey funding of submersible dives provided the opportunity to collect rock samples from the deep caldera walls and the postcaldera lavas which erupted in the vicinity of Wizard Island. Observations made from Deep Rover coupled with morphologic features of rock samples have allowed us to determine, with varying degrees of confidence, which postcaldera lava flows were emplaced beneath lake water and which cooled subareally. This is important because it helps to constrain the relative ages of volcanic features, using filling of the lake as a timing device to supplement relative age information based on morphology and superposition of features (i.e., younger lava overlies older lava). A dive to the base of the caldera wall at Eagle Point recovered three samples of highly-altered andesite lava from a single outcrop at 1427 foot depth. These apparently are Mazama lavas that are older than those of the exposed caldera wall. Consequently, the rocks are probably older than 300,000 years (Bacon and Lanphere, in press). Hydrothermal alteration of these samples occurred before collapse of the caldera, but the age of the alteration is not yet known. Alteration minerals include chlorite and epidote, which probably formed at a temperature well in excess of 200°C .

A single dive to explore the depth distribution of attached algae and moss was funded by Deep Ocean Engineering. Moss was observed at 253 m, and a sample was collected at a depth of 221 m. The sample extended the known depth of the moss by about 100 m in the lake, and this is probably a world record depth. Periphyton was observed on the caldera walls to a depth of 147 m, but no samples were collected. The great depths at which plants were found living in the lake is an important discovery to the ten-year limnological assessment of Crater Lake. Such growth is probably an integrated measure of water clarity. Since small changes in turbidity could have substantial impacts on the amount of available light at these great depths, documentation of the floral assemblages and their depth distributions provide very important baseline data for future monitoring of the clarity of Crater Lake.

We are now entering the third year of our research program. Work completed to date has allowed us to make significant progress towards our original goals (Collier and Dymond, 1988, 1989). We can now build on these results to focus and refine the activities of the upcoming field season, as discussed below.

Proposed Research

Goals

The overall goal of our research program is to demonstrate the mode, location, magnitude and biogeochemical role of hydrothermal inputs to Crater Lake. The specific goals of this final field season are outlined here and discussed in more detail in the following sections:

(1) *Evaluate known sites of spring inputs and investigate the origin of known chemical and thermal anomalies.* A number of important lake bottom and water column features were identified in 1988 which will require more study from the submersible and from the surface research boat in 1989.

(2) *Expand surveys to areas outside of the current Detailed Study Area.* Several other regions of high and low heat flow, identified by Williams and Von Herzen (1983), should be investigated further. This work would start with remote observations (e.g. CTD and water chemistry) and could lead to possible submersible targets.

(3) *Determine the mode and rates of venting in the deep lake.* Does venting occur primarily in sedimented areas? What are the rates and compositions of diffuse flow through sediments? Are there sites of localized venting? If so, what are the rates? These studies would also focus on temporal variability of inputs and would provide more complete compositional data for the end-member fluids.

(4) *Determine rates of vertical and horizontal mixing in the deep lake.* Are these rates consistent with estimated fluxes of surface-derived particles and venting fluids? Are these mixing rates enhanced by hydrothermal heating of the deep lake? The interpretation of many of the chemical and physical tracers of hydrothermal activity are dependent on a knowledge of the mixing rates of water in the lake.

(5) *Evaluate the sedimentological and paleolimnological consequences of hydrothermal activity in the lake.* Has there been variability in the hydrothermal inputs to Crater Lake throughout its history? What is the relationship between hydrothermal flux and changes in biological productivity or floral assemblages of the lake? The processes currently active in the lake can be compared with the sediment record of hydrothermal inputs since the lake's formation. We will continue work on this goal through the collection of several more cores for radiochemical dating, chemical analysis, and microfossil studies.

(6) *Support ancillary biological and geological research programs.* Several separate research projects are proposed elsewhere which will explore the nature of biological activities and geological processes in those portions of the lake that lie beyond the depths of free divers. This will make maximum use of the unique opportunity provided by the submersible, and will allow us to operate the primary research program - the hydrothermal studies - in an efficient and cost effective manner.

Field Program Overview

The proposed field program, which will take place in July and August of 1989, involves a broad spectrum of sampling, measurement, and observational approaches. Proven technologies such as water sampling, sediment coring, CTD measurements, and submersible sampling and measurements will be supplemented with some new approaches. The new components of the research program involve the submersible placement of a diffuse flow sampler (the benthic barrel), a box-corer that can be deployed with Deep Rover, studies of pore waters to determine the rate of advection through sediments, and some time-series measurements of near-bottom temperatures.

The proposed field program has two stages. In early July, we will deploy and test the navigational equipment needed for the submersible operations and at the same time make precisely navigated CTD casts. Five to six days of research vessel time will be required. The major field program, which includes the submersible operations, would occur during the month of August. During this time the research boat will also be used for water sampling, CTD casts, submersible operations, and navigation. Deep Rover will be used for 15 dive days over a period of 27 days for sampling and instrument deployment operations (Appendix I).

The scientific plan for the field program will be coordinated by Jack Dymond and Robert Collier at OSU, however, the effort will involve critical contributions from a number of individuals and organizations. Crater Lake National Park will provide the logistic foundation that makes the program possible. This includes small boat maintenance and operations, helicopter operations, power generation, laboratory facilities, housing, and communications. The submersible will be leased and operated through Can-Dive Services Ltd, Vancouver, B.C. They have operated the one-person submersible, Deep Rover, for many years and have extensive experience in oceanic research operations that are similar to our program. Deep Ocean Engineering (DOE), who participated in both the 1987 and 1988 field programs, will continue their involvement in this year's proposed research. The submersible, Deep Rover, was designed and built by DOE, and their assistance will be important to the operation of the submarine in Crater Lake. DOE also will provide an ROV which will provide necessary safety backup for attachment of a cable to Deep Rover in case it is fouled on the bottom or disabled.

Scientists from a number of organizations will be involved in the research and the analytical program. Dr. John Lupton of University of California, Santa Barbara, will carry out the helium isotopic analyses, assist in the design and execution of the field sampling program, and participate in the interpretation of experimental results. Dr. Charles Bacon, US Geological Survey, Menlo Park, will examine video and photographic data from the rocky portions of the bottom visited by the submarine. He also will analyze any rock samples picked up by the submersible. Dr. Bacon is seeking additional funds from the US Geological Survey which would purchase approximately five dive days that would be used to conduct geological transects for the purpose of sampling and observing the subsurface rock formations throughout the caldera. Drs. Harry Phinney and David McIntire, OSU, have submitted a proposal to the National Geographic Society to study the deep-water benthic flora and fauna in the lake. This work would add five dives to the program to study the depth distributions of the moss population, associated flora and fauna, epilithic periphyton and benthic macro-invertebrates. As well as taking advantage of the unique opportunity of the submersible, these ancillary programs would share the fixed costs of deploying the submersible and would thereby make the hydrothermal studies more cost effective.

Submersible Research Program

Conducting submersible operations in a relatively inaccessible area like Crater Lake presents some major challenges. When the project was first conceived there were problems regarding helicopter transport to and from the lake, questions about transporting the submersible from a Wizard Island base station to the dive site, doubts about carrying out the daily servicing required by the submersible, difficult logistics needs, concerns about fuel requirements, and a variety of information flow issues. As a result of a strong team effort involving many capable Park Service personnel, a highly trained technical crew from Can-Dive, and a dedicated OSU team of researchers, the 1988 submersible program was able to overcome the major obstacles. Considering the accomplishments of the first year and the lessons which resulted from this program, we expect the 1989 field effort to be an even greater success.

We propose to use Deep-Rover, the same submersible we used in the 1988 program, which is owned and operated by Can-Dive of Vancouver, B.C. This submarine has the following features: an acrylic hull which provides exceptional visibility, a depth limit of 3000 feet, speed of 1.0 knots, and a weight of 3000 kg (allowing helicopter transport even at Crater Lake's elevation). The submarine is highly maneuverable, having vertical and horizontal thrusters that are relatively easy to control. An air-ballast system permits the operator to achieve neutral buoyancy. Two manipulators were used for water sampling, coring, rock sampling and temperature probing of sediments and bacterial mats. The battery capacity of the submersible limits dive-time to 4 - 6 hours, followed by a 12 hour recharging. Therefore, only a single dive is possible within any given day.

Several modifications of the submersible which will enhance our program will be made by Can-Dive, Inc. New lighting, which should extend visibility, is being installed. A hydraulically moveable sample basket has been designed, which can be withdrawn for unobstructed view and sampling and then extended for sample placement with the manipulator. A data logging system has been developed which will allow storage of date, time, depth, and compass heading on the video tape. A submarine-systems data logger has been designed which can monitor cabin pressure, O₂ content, O₂ pressure, air ballast pressure, and battery voltage and telemeter the data to the surface. Eliminating this monitoring from the pilot's tasks will make submersible operations far more efficient.

Liability for the submersible operations will be covered by a \$5,000,000 general liability policy that is carried by Can-Dive Incorporated. This insurance covers any loss to equipment and Can-Dive personnel. Liability insurance for OSU personnel is covered through Workman's Compensation Program of the State of Oregon. The Deep Rover was designed and fabricated to meet the Lloyds of London Rules and Regulations for the Classification for Submersibles and Diving System, 1980 (Can-Dive, 1985). It is fully certified for operation to depths of 3000 feet. Basic to this certification is the establishment of a chain of command that defines the relationship between the Can-Dive submersible team and the scientific team (Can-Dive, 1985). Our operations will follow this chain of command. Submersible safety, which is a fundamental aspect of the research, is detailed in the Can-Dive operations manual (Can-Dive, 1985). Our program will follow the constraints and procedures listed in this manual.

Navigation. The efficiency of our search for thermal venting during the 1988 field program was strongly limited by navigation difficulties. These problems were a consequence of poor service from our contractor and difficult acoustic properties of Crater Lake (see Appendix III, Collier and Dymond, 1989). For the 1988 field program we chose a combination of micro-wave ranging and long-baseline acoustic navigation. We were able to navigate the surface boat with high precision with the micro-wave system; however, the acoustic navigation provided very unreliable submersible navigation. For the 1989 field program we have chosen an integrated navigation package which relies on short-baseline acoustic navigation and micro-wave ranging. These systems differ from long-baseline approaches in that no bottom-moored transponders are used. Consequently, line-of-sight problems that are inherent in long-baseline navigation are much less of a problem.

We are negotiating with several companies who offer complete hardware, software, and personnel packages that provide constant positioning of the submarine and surface ship with a 5-10 m accuracy. We propose to chose a vendor who will come to the lake in early July to optimize the acoustic frequencies and allow us to completely evaluate the system before our August expedition.

Studies of known sites of venting, seepage and anomalous water.

A number of important lake bottom and water column features were identified in 1988 which will require more study from the submersible and from the surface research boat in 1989. In particular, bacterial mat features, metalliferous sediment deposits and crusts, and water column temperature and conductivity anomalies will be investigated.

Numerous bacterial mats and metalliferous sediments were located during the 1988 program (Figure 2). We will focus a portion of our 1989 program on more detailed chemical, physical and biological sampling of these sites. The mats, in particular, will be studied in considerably more detail. To date, we only have samples from the major mat discovered during CD179 (Figure 30, in Collier and Dymond, 1989). We will revisit the mat at this site as well as collect samples from other mats for chemical, taxonomic and other microbiological studies. We are currently discussing microbiological studies with Watwood and Dahm (UNM), Mandernack and Tebo (SIO) and Karl (UH). Specific metabolic studies identifying primary substrates and rates are of particular interest.

The bacterial mats observed in 1988 lacked visual evidence of venting flows. This is compatible with diffuse venting of thermal fluids rather than more vigorous, localized venting. It is possible, however, that more vigorous venting exists within the Detailed Study Area. Some of the largest bacterial mats were not accompanied by large bottom water temperature anomalies. Consequently, the near-by presence of thermal anomalies of more than 0.5 °C and conductivity anomalies of more than a factor of two suggests more vigorous input than that which accompanies the mats. Either this presumed venting does not have an obvious visual expression (such as a bacterial mat) or our survey, which covered less than 10% of the detailed study area, missed the specific vent sites. In Figure 3 we show near-bottom temperatures defined by submersible traverses (also see Figures 8,9,10 and 12 in Collier and Dymond,1989). These stronger thermal and chemical anomalies will be investigated in 1989. We will use systematic submersible CTD surveys and water sampling to characterize the source and end member compositions of these thermal fluids.

Investigations of hydrothermal venting outside the Detailed Study Area

We plan to extend our CTD sections and ²²²Rn analyses in the west of the Detailed Study Area (Figure 1) to include the deepest portion of the South Basin. The highest single value of ³He concentration we have ever measured is from this point. If older, dense fluids are accumulating there, the radon analyses will be useful in distinguishing this "ponding" from local, active inputs. We will also carry out CTD surveys of the other major basins in the lake and will include examination of the other high heat flow regions identified by Williams and Von Herzen (1983). We will look for near-bottom thermal anomalies and structures similar to the anomalies demonstrated within our Detailed Study Area (Figure 1). If CTD data suggests positive anomalies, we will use ²²²Rn analyses to investigate the recent activity of the inputs. If these tests prove positive, we will consider adding these other regions to our dive plan later in the month.

Studies to define the modes and rates of venting within the lake

Much of our efforts with the submersible in 1989 will focus on defining: a) the modes of fluid input (e.g. specific vent orifices, seepage through features marked by bacterial mats, upward percolation of fluids through sediments); b) the composition and rates of input; c) the temporal variability of inputs.

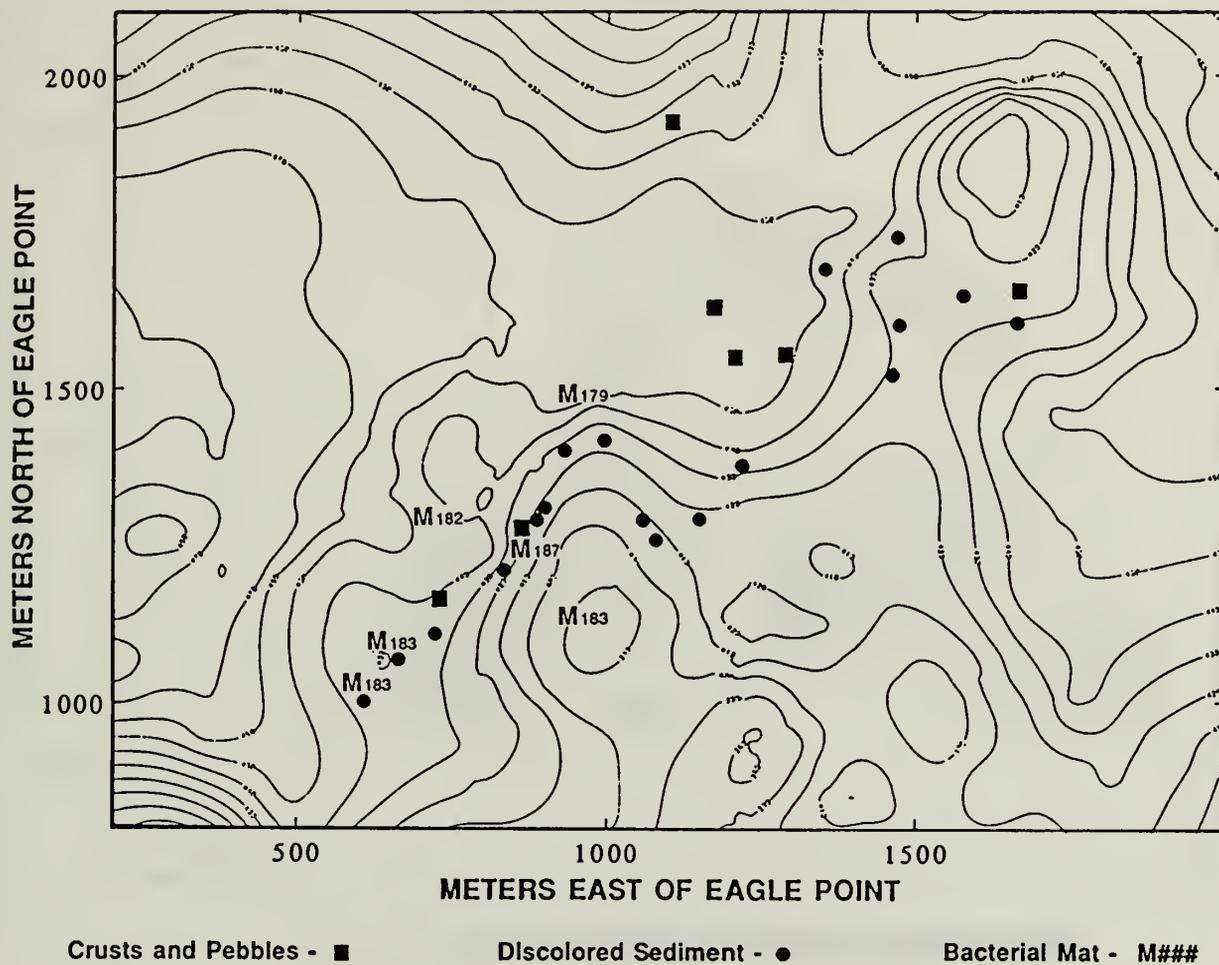


Figure 2. Locations of bacterial mats, crusts, and discolored sediments in the detailed study area. M179, M182, M183, and M187 refer to bacterial mats and the associated dive number. Filled squares are crusts and broken crusts (metal-rich pebbles). Filled circles are areas of discolored sediments, which in some cases are mottled shades of brown and in other cases are uniform dark tones.

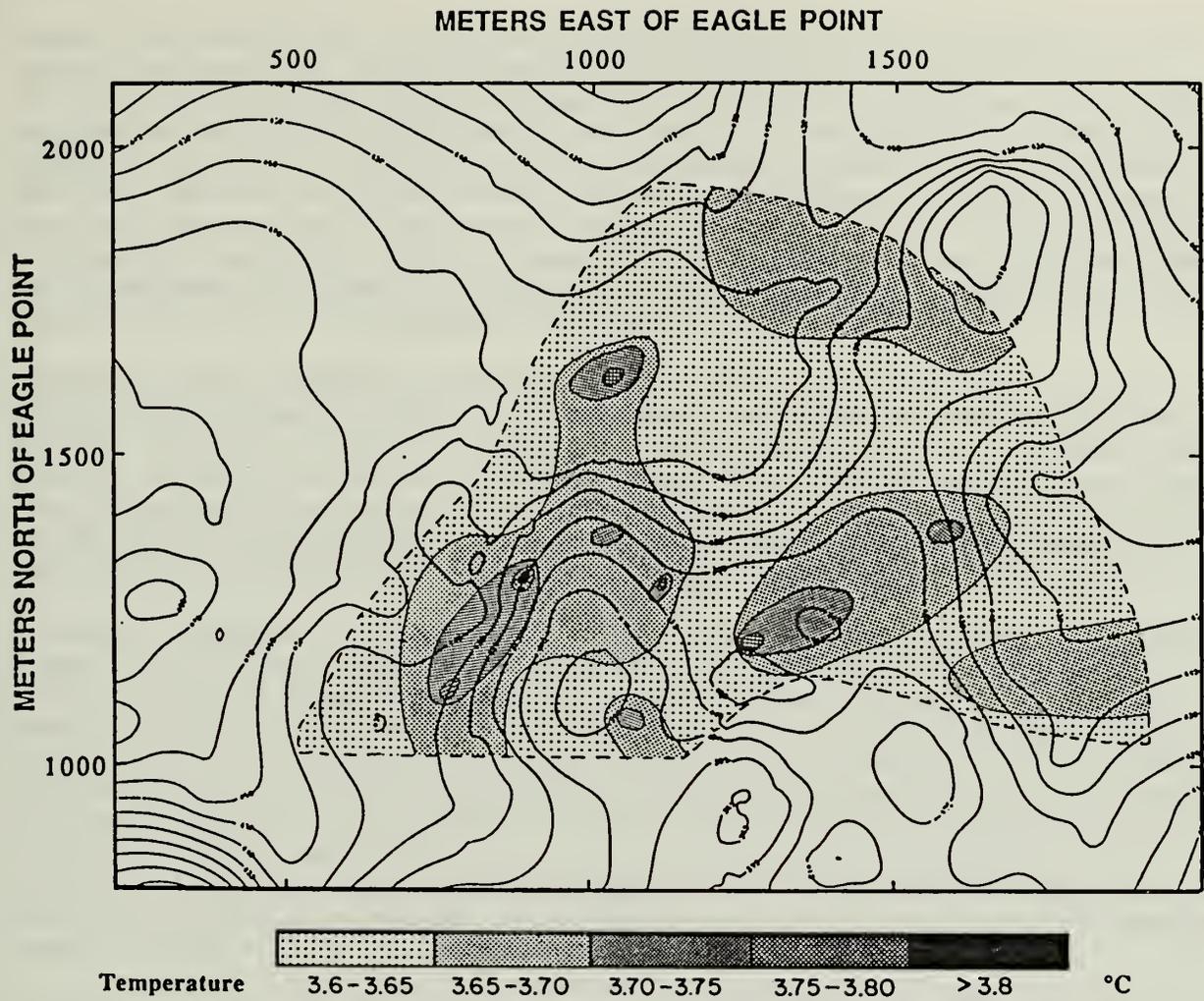


Figure 3. Contour map of near-bottom temperatures as recorded by the CTD on Deep Rover. The small area with temperatures $>3.8^{\circ}\text{C}$ is the location on dive 182 where temperatures as high as 4.1°C were measured.

Results from previous work suggests the possibility of diffuse flow through sediments or sites marked by bacterial mats. Because at least one of the bacteria genera is thought to be a chemoautotroph, a constant supply of reduced iron is required for its metabolism. This suggests that advection of fluids is occurring through these bacterially-covered surfaces. Detailed CTD "sniffing" and water sampling will be carried out around the wall mats to look for any evidence of fluid flow. However, some of the bacterial mats and the metalliferous sediment patches were located on relatively level sediment surfaces, and these were correlated with near-bottom thermal and conductivity anomalies. We plan to investigate the rates and composition of fluids advecting through sediments in two ways: (1) deployment of the "benthic barrel", a bottom chamber which samples diffuse flow through sediments and (2) chemical analyses of pore waters.

Direct pore fluid flow sampling. The Benthic Barrel was developed by Dr. Erwin Suess for studies of fluids released by compression of sediments at the Oregon continental margin (Suess et al, 1987). It consists of a vented, 188 liter plastic chamber that is placed over a sedimented surface to confine the flow to a small outlet. Flow rates through the outlet can be measured directly, and six water samples within the chamber can be closed according to a predetermined timetable. In this way the change in fluid composition can be monitored with time and an undiluted sample of the venting fluid can be sampled or its composition estimated from the time series of 6 samples.

Several promising sites for deployment of the Benthic Barrel were observed during the 1988 dive program. For example, on dives 179, 182, 183, and 187 bacterial mats were observed on sediments (Figure 2). Some of the mats were small enough to be completely enclosed by the barrel. Also, a site of discolored sediments and strong near-bottom temperature anomalies was observed during dive 182 (Figure 3). No bacterial mats were in the vicinity ; it may be that the entire area was a site of diffuse venting. Because of the size of the barrel and the need to place it in a proper location we expect that each site where we use the barrel will require one dive to deploy and recover. We propose to deploy the device in three or four locations to examine spatial variability in the venting process. Analyses of silicon and ^{222}Rn in the sample bottles will be made at the lake to provide some feedback as to the appropriateness of our chosen deployment times and sampling schedule.

Pore water chemistry. Measurements of porewater chemical gradients are an alternative means to define advection in sediments. By fitting equations of advection-diffusion-reaction models to pore water compositional variations, advective rates in the range of mm/y to tens of m/y can be defined (Maris and Bender, 1984; Maris, 1983, Wheat and McDuff, 1989). Pore water composition can be a more sensitive indicator of fluid advection than sediment temperature gradients (Williams et al., 1979; Bredehoeft and Papadopoulos, 1965).

Pore water chemical measurements rely upon recovery of undisturbed cores. Our coring locations will be designed to characterize regional and hydrothermal features. Conventional coring from the research boat will be adequate for retrieving samples to characterize diagenetic processes in non-hydrothermal areas. A four-inch gravity corer will be used to recover samples for this sampling. Coring of individual "hydrothermal" features (Figure 2) will be accomplished by using the Deep Rover to position a box corer in precise relation to geological features. We will use one of the small box cores designed by Andrew Soutar (Scripps Institution of Oceanography). Sampling of individual features in zones of focused upflow is necessary as they may be affected by different chemical exchange processes and represent the greatest flux of fluid and chemical constituents into Crater Lake.

The gravity cores recovered by the surface boat will be up to two meters in length and will be subsampled for pore water as described by Jahnke (1988). Thirty centimeter box cores positioned by the submersible will be subsampled for pore waters by a new technique that incorporates whole core squeezing (Bender et al., 1987) and the method described by Jahnke (1988). Sub-sampling

will be at *in situ* temperatures, and analyses for silica will be carried out at the lake to provide ongoing feed-back for coring selection. Samples will be saved for analysis of the major cations and anions. Geoff Wheat, an advanced PhD candidate at the University of Washington, will assist in the pore-water sampling program and the modeling of the chemical gradients. His thesis is a study of a hydrothermal region in the Marianas Basin; he brings considerable expertise to this part of our project.

Rates of diagenetic reactions and possible advective rates can be modeled by fitting results from an advection-diffusion-reaction equation to pore water chemical profiles. A generalized form of the model is:

$$\frac{\partial(\phi c)}{\partial t} = \frac{\partial(\phi D_s \frac{\partial c}{\partial z})}{\partial z} - \frac{\partial(\phi v c)}{\partial z} + \phi \Sigma R_d \quad (1)$$

where c is the chemical concentration of interest, t is time, D_s is the diffusion coefficient in the sediment which accounts for the tortuosity, ϕ is the porosity, z is depth, v is the advective rate, and R_d is a reaction equation. This equation can be easily solved and manipulated if one assumes steady state, constant porosity and tortuosity, and simple equations describing reaction processes.

The approach for interpreting the data will be to divide the cores into two categories depending on their systematic variations in pore water chemistries and physical environment. One group of cores will consist of the gravity cores that were collected from in the Central Basin where advective rates are probably less than a few mm/y and early diagenetic processes dominate chemical profiles. The longer length of these cores will enable us to constrain slow reaction rates that may be misinterpreted in a shorter core. Diagenetic reactions can be modeled using equation 1 assuming no advection is occurring and an appropriate reaction equation is chosen depending on the individual ion chemistries. The rates of diffusional flux due to these diagenetic processes will allow a quantification of the importance of low temperature alteration of caldera wall material as a source of ions to the lake. LaFleur (1987) suggests that this source could account for the elevated ionic content of Crater Lake.

The other category will consist of cores retrieved from high heat flow areas where upwelling is fast enough to alter chemical profiles produced by diagenetic processes. Most of these cores will be box cores that sampled individual hydrothermal features but may include some gravity cores. Diagenetic reaction rates constrained from the low heat flow cores will be used to fit various advective rates to chemical profiles. Diagenetic reactions must be considered in model calculations as they influence chemical profiles and can increase or decrease calculated advective rates if one assumes a purely advection-diffusion environment. Whole core squeezing of these samples is necessary, since most of the curvature in model profiles occurs in the top 2 cm for flows of greater than 1 m/y.

Pore water chemical profiles can be used to determine hydrothermal flow rates, chemical anomalies due to water-rock and water-sediment interactions, and diagenetic processes. Sampling and submersible observations will allow estimates of the areal extent of upflow regions and, coupled with chemical anomalies, chemical fluxes from hydrothermal inputs can be calculated. These chemical fluxes can be compared to fluxes dominated by diffusive processes in low heat flow areas. The extent of hydrothermal flow and chemical fluxes into the lake are important in elucidating the dynamics controlling biological communities, sediment deposition, and the physical processes occurring in the lake.

Investigations of temporal variability of venting. In our previous studies we have not investigated the possibility that there may be temporal variability in venting within the Detailed Study Area. If the venting is due to hydrothermal processes, long-term variability is expected due to cooling of the magmatic source and mineral deposition within hydrothermal conduits. The temporal scale of such variability may be years, and we could not expect to define it with our experiment. Other investigators, however, have observed variability in frequency of geyser eruption in Yellowstone National Park that is related to variations in barometric pressure, earth tidal forces, and earthquake activity (Rinehart, 1972; Trimble and Smith, 1975). On the Oregon Continental Margin a periodicity in the venting rate through sediments was observed which had a diurnal tidal frequency (E. Suess, pers. comm.). Variations in venting which are a consequence of earth tides, changes in tectonic strain, or adjustments of cooling fracture size and abundance (Norton, 1984) could have a temporal scale that is resolvable with time series measurements of weeks to months.

If the venting in the Detailed Study Area is a consequence of a flow of ground water down the caldera wall and through the Chaski Slide (LaFleur, 1989), there may be variations which follow a seasonal cycle. It is conceivable that the flow in the winter may have a lower temperature because of the low air temperatures and a lower rate because of reduced runoff at this time of year. Runoff and ground water inputs may peak in early summer and diminish during late summer and fall when the water temperatures might also reach a maximum.

Consequently, it is possible that definition of temporal variability of venting could distinguish between a hydrothermal hypothesis and the groundwater input hypothesis. In addition, temporal variability within the water column may also contribute to an understanding of the mixing of the deep lake. We propose three approaches to provide data on the issue: (1) a time-series of CTD casts at a single site within the Detailed Study Area, (2) a moored thermistor chain within an area of known thermal anomalies, and (3) deployment of a sediment temperature probe at sites of possible porewater advection.

The CTD time-series would be carried out at the base of the major south wall defining the South Basin near one of our stronger thermal anomalies. We already have data at this site from two years of CTD work and will emphasize an added series of casts starting this summer. We should also be able to collect a winter or spring cast nearby, if the limnological program is able to get to the lake with a helicopter this year. However, due to logistical constraints, this sample will not have radar navigation or bathymetric support (Brunton compass and sextant will be used).

To investigate changes in structure which could be related to input variations, we are currently considering the deployment of a moored Aanderra® thermistor "chain" which contains a vertical series of sensors to record temperature. These units are currently deployed in the arctic and will be recalibrated after their return to OSU in June. Depending on logistics, we will consider a short term deployment (July - September), followed by an over-winter deployment. This instrumentation could also demonstrate the existence of any turbulent flows associated with active inputs of thermal fluids.

A sediment thermistor probe with three sensors built on a Seacat® instrument (similar to our CTD) will be inserted in sediments within possible flow regions to record sediment thermal gradients and any changes in pore water temperature structure. This instrument has previously been deployed along with the benthic barrel from the DSV Alvin on the Oregon Margin where it demonstrated porewater temperature changes occurring at tidal frequencies (E. Suess, pers. comm.).

Enhanced compositional data for venting fluids. To date, we have only limited water samples and analyses from the thermal fluids associated with the bacterial mats and other near-bottom anomalies. The water sampling program from the submersible will receive more priority in 1989 and we will make several changes in the samplers to provide better gas-tight samples during

submarine recovery. In particular, we will expand our analyses of all the major anions, cations and dissolved gases as well as numerous minor element tracers of hydrothermal venting. Analytical methods were outlined in Collier and Dymond (1989). We will carry out a number of isotopic analyses from the various end-member water samples. These analyses will be carried out at OSU or through collaborating investigators: the water isotopes (H,D, O-16,18 through Thompson, Nathenson and White, USGS Menlo Park); carbon isotopes (C-12,13 at OSU and we are discussing C-14 analyses with P. Schlosser, Heidelberg, FRG); and the helium isotopes (He-3,4 by J.Lupton, UCSB). These samples should significantly improve our understanding of the origin of these waters and the geochemical significance of the associated inputs.

The concentration of ^{222}Rn ($t_{1/2} = 3.8$ days) can be a sensitive tracer of active input of spring water and we have demonstrated anomalous concentrations of this radiotracer in the hydrothermal basin (Figure 20 in Collier and Dymond, 1989). Because of the very short half life of this natural radioisotope, these concentrations of ^{222}Rn indicate a recent (and nearby) input of spring water. This chemical tracer will continue to be useful to demonstrate active springs. Furthermore, the estimation of total ^{222}Rn inventories coupled with element/ ^{222}Rn ratios in the vent waters may allow us to make another independent estimate of the total hydrothermal flux of elements into the lake (Kadko et al., 1986; Rosenberg et al., 1988). Since the ^{222}Rn injected into the deep lake is continuously decaying away, its total inventory is equal to its total input flux. If we know the ratio of another component to ^{222}Rn (e.g. $^3\text{He}/^{222}\text{Rn}$ or heat/ ^{222}Rn) at the hydrothermal input source, we can calculate its flux by multiplying this ratio by the radon inventory. As in 1988, we will set up a radon extraction and counting system at the Park Service water laboratory to analyze water samples for the concentration of ^{222}Rn (Matthieu, 1977; Dymond et al., 1983). Large volume samples (~15 liters) will be collected at the lake by hydrocasts and by the submersible and transported to the laboratory for analysis.

Determinations of the mixing rates of Crater Lake

In general, the chemical distributions in Crater Lake have been described as "well mixed" (e.g. Thompson et al., in press). However, with our expanded high-precision data set, we have demonstrated that a group of dissolved materials and heat are accumulating in the deep lake. Clear gradients have been demonstrated for temperature, salinity (conductivity), nitrate (Larson, 1986), oxygen, helium, and individual cations, anions and trace metals. Independent of the source of these changes (e.g. - meteorological forcing, biogenic cycling, hydrothermal inputs, etc.), a critical parameter in understanding the rates of inputs is a knowledge of the rates of mixing within the deep lake (e.g. between basins) and between the deep water and surface waters. A better knowledge of the mixing rates of water in the lake is critical to our interpretation of hydrothermal input rates (e.g. He-3 and heat accumulation; Collier and Dymond, 1989), as well as our understanding of nutrient cycling in the lake.

There are two general categories of measurements and models that we use to approach these estimates: 1) physical models of stability, turbulent diffusivity and advection derived from measurements of the vertical and horizontal distribution and temporal variability of heat and salt (density); 2) models for the dispersion of chemical tracers through the system given known boundary conditions and reaction rates. Our graduate student, James McManus, is working on this problem as part of his thesis.

The physical measurements will consist of a continuation of our CTD-transmissometer surveys taken regularly between June and September as well as once or twice in the winter/spring. These full water column CTD casts will be carried out in all three basins. We will examine the evolution of the seasonal thermocline, seasonal changes in deep water structure, and inter-basin heterogeneities. Also, two cross sections will be run: one into the Central Basin from the northeast

and one into the South Basin from Chaski slide. We will examine these data for evidence of wind-driven upwelling or seiching in the upper waters as well as for evidence of inputs of dissolved materials from submerged springs.

The chemical measurements will focus on time series measurements of oxygen and the determination of a new tritium profile in the lake. Dissolved oxygen is very high throughout the water column of this oligotrophic lake. Even still, some depletion can be measured in the deep waters and supersaturation is evident in the upper thermocline during the summer. We will use these seasonal variations coupled with our sediment trap organic matter fluxes to constrain vertical mixing rates within different portions of the water column. Tritium (^3H , $t_{1/2} = 12.3$ years) will be determined by J. Lupton, UCSB, after determination of He isotopes in our samples. He will analyze one complete vertical profile and several deep samples from the separate basins to evaluate the homogeneity of this surface-derived isotope throughout the water column. Analyses of this isotope, carried out by Simpson (1970b), gave the first quantitative estimates of the rapid vertical mixing rate in the lake (~1 year).

Studies of iron-rich crusts and sediments

Our previous studies have demonstrated significant variability in the chemical composition of Crater Lake sediments (Dymond and Collier, in press). These variations are consistent with temporal and spatial changes in biological and hydrothermal inputs to the lake. Consequently, the sediments provide an indicator of present-day processes and a record of these processes throughout the history of the lake. We propose to continue our investigations of iron-rich crusts as possible indicators of on-going or very recent hydrothermal activity

Metal-rich crusts. Iron and manganese-rich crusts were recovered with Deep Rover in the 1988 field program (Figure 2). Some of these crusts have compositions which are similar to the bacterial mat and may represent different stages of a common formation process (Dymond and Collier, in press). We propose to conduct more complete comparisons of both mats and crusts during the next phase of the program. We would like to recover some crusts and associated sediments with our box coring to determine if the crusts are found in typical lake sediments or whether the underlying sediments have evidence of hydrothermal leaching or precipitation. Measurement of the solid phase chemistry will complement the pore water measurements on the same cores and help constrain the interpretations of possible diagenetic reactions. We will carry out activation analyses of some crusts to determine the concentrations of arsenic and antimony, two elements which are strongly enriched in thermal fluids.

Paleolimnological Studies. Although we have not analyzed a large number of sediment cores from Crater Lake, the existing data indicate that hydrothermal activity may have occurred at widely spaced sites during the history of the lake (Dymond and Collier, in press). It appears that the intensity of activity at any one site has varied over time. This suggestion is consistent with the concept that conduits for hydrothermal flow become clogged as a result of precipitation of the dissolved load carried by the fluids. This would lead to the eventual blockage of any venting site; however, new conduits may form as a consequence of faulting and fracture formation. It is also possible that crustal injection of magma and associated hydrothermal activity has occurred episodically during the history of Mt. Mazama. Consequently, hydrothermal inputs may have waxed and waned throughout the history of the lake.

The implications of variable inputs of hydrothermal activity during the history of Crater Lake are largely unknown. However, study of the lake's sedimentary record may help to unravel the consequences of variable hydrothermal input. Dymond and Collier (in press) have examined the opal concentrations in a core from the Wizard Island Platform. These data suggest that there have

been variations in biological productivity during the lake history; correlations of opal abundance and elements with possible hydrothermal sources is consistent with greater productivities accompanying enhanced hydrothermal outputs.

We propose to investigate this subject further by collecting a few cores from each basin which are longer and of larger diameter than our present cores. The greater length will give a longer historic record, and the 4-inch diameter corer we propose to use will provide more opportunity to recover pieces of wood, moss and debris from trees that can be ^{14}C dated. Bulk ^{14}C measurements of sedimentary carbon from Crater Lake have a major (~2000 yr) age offset (S. Robinson, pers. comm.), and the dates may not be reliable. In contrast, a pine cone from one Crater Lake core gave what appears to be a valid age (Dymond and Collier, in press). In addition to measuring the opal contents in dated cores, we propose to determine the As, Fe, Mn, Zn, Ba, Li and other elemental concentrations as possible indicators of venting to the lake. We propose to provide samples of the dated cores to Dr. David McIntire (OSU Botany Department) for study of the variations of diatom assemblages. A study of diatoms in a Crater Lake core was recently completed by Dr. Platt Bradbury (US Geological Survey). His study observed that sediments older than 4400 years contain more abundant *Stephanodiscus* diatoms. He suggests these forms are an indicator of higher productivity in the lake. In the upper portions of the core (<1500 years B.P.), the concentration of all diatoms is reduced. Bradbury and McIntire will collaborate in this part of the project. Our graduate student, Brad Beeson, will evaluate the sediment record for geochemical evidence of hydrothermal venting as part of his thesis.

Summary

This proposal has presented our goals and research plans for the final field season of our studies of hydrothermal processes in Crater Lake. The immediate goals include: 1) Evaluate known sites of spring inputs and investigate the origin of known chemical and thermal anomalies; 2) Expand surveys to new study areas; 3) Determine the modes and rates of venting in the deep lake; 4) Determine rates of vertical and horizontal mixing in the deep lake; 5) Evaluate the sedimentological and paleolimnological consequences of hydrothermal activity in the lake; 6) Support ancillary biological and geological research programs. These plans have been developed through our ongoing interpretation of results and have been tempered by the practical experience gained during the first two years of our program. Technically, this is an extremely difficult and physically demanding project which could only come about through the cooperation of many persons and agencies. We look forward to this final field season with expectations for continued success.

Publication and Release of Information

We anticipate the results of this innovative program will have implications for broad aspects of limnology and hydrothermal research. Consequently, timely presentation at national scientific meetings and publication in reviewed science journals is one of our basic goals. We will provide copies of abstracts and articles to the National Park Service at the time of submission to a journal.

Presentations, reports and publications derived from this research:

- Collier, R., J. Dymond, J. Lupton, A.Chen, M. Lilley, and M. Thompson (1987). Effects of hydrothermal inputs on the chemistry and physics of Crater Lake, OR. EOS, 68(50):1721 (abstract).
- Collier, R., and J. Dymond (1988a). Studies of hydrothermal processes in Crater Lake. A preliminary report of field studies conducted in 1987 for the Crater Lake National Park. Oregon State University, College of Oceanography Reference #88-5, 49 pp.
- Collier, R. and J. Dymond (1988b). Observations of Bacterial Mats Associated with Thermal Springs at 450 Meters Depth in Crater Lake, OR., EOS, 1138 (abstract).
- Collier, R. and J. Dymond (1989) Studies of hydrothermal processes in Crater Lake. A report of field studies conducted in 1988 for the National Park Service. Oregon State University, College of Oceanography Reference #89-2, 79 pp.
- Collier, R., J. Dymond, J. McManus, and J. Lupton (in press). Chemical and Physical Properties of the Water Column at Crater Lake, OR. In: Crater Lake: An Ecosystem Study, E.T. Drake, G.L. Larson, J. Dymond, and R.Collier (eds), American Association for the Advancement of Science Special Volume, Pacific Division, San Francisco, CA.
- Dymond, J., C. Perhats, R. Conard and R. Collier (1987). Hydrothermal activity in Crater Lake: Evidence from sediments. EOS, 68:1721 (abstract).
- Dymond and Collier (in press). The chemistry of Crater Lake sediments: Definition of sources and implications for hydrothermal activity. In: Crater Lake: An Ecosystem Study, E.T. Drake, G.L. Larson, J. Dymond, and R.Collier (eds), American Association for the Advancement of Science Special Volume, Pacific Division, San Francisco, CA.
- Holbrook, S., R. Collier and J. Dymond (1985) Dissolved and particulate trace metal distributions in Crater Lake, Oregon. EOS, 66:1326 (abstract).
- Lupton, J.E., R. Collier, J. Dymond (1987). Excess ^3He in Crater Lake, Oregon: Evidence for geothermal input. EOS, 68:1722.

Manuscripts in preparation:

- Dymond, J. and R. Collier (in preparation). Observations of Bacterial Mats Associated with Thermal Springs at 450 Meters Depth in Crater Lake, OR. In preparation for Nature.
- Collier, R. and J. Dymond (in preparation). Evidence for hydrothermal inputs to Crater Lake, OR. I - The physics and chemistry of the water column. In preparation for Limnol. and Oceanogr.
- Lupton, J.E., R. Collier and J. Dymond (in preparation). Evidence for hydrothermal inputs to Crater Lake, OR. II. -The Helium isotopes. In preparation for Limnol. and Oceanogr.

Information will be released to the news media only after mutual agreement between representatives of the National Park Service and the two principle investigators. Film and photographs, like other samples and analyses, are part of the scientific data set and in many cases will require interpretation to prevent misuse by those having access to the data. We will negotiate a plan for final archiving of all data, including the photographic and video materials, which will assure continued access to both the principal investigators and the National Park Service.

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Budget Justification

Attached is our proposed budget for the final year of the current research program. It is broken into two parts: part I (FY89) covers the costs of the field program during the summer of 1989; part II (FY90) covers the costs of sample and data analysis, synthesis, and preparation of final project reports (similar to Collier and Dymond, 1988 & 1989). We believe that a further year of salary support for the PI's and graduate students will be needed to continue the analysis and publication of the complete data set. This would include completing two MS theses, and publishing several manuscripts in scientific journals. Specific justifications for the current budget are provided below:

Salaries

The principal investigators, Dymond and Collier, are responsible for execution of the scientific plan. This includes organization of the field program, coordination of scientific logistics, overseeing analyses and data reduction, and synthesis and reporting of the results.

•Funds for three categories of analytical support are requested:

- (1) Six months of funding are requested for Chris Moser, our technical/logistic person. Moser will assure that the hardware needs for the field program are available. This includes working closely with Can-Dive and DOE engineers to define the technical specifications of submersible hardware. Moser will obtain, prepare, and construct all of the OSU equipment for the project. Consequently, he will build and deploy the mooring which holds the thermistor chain. He is also in charge of preparing the water samplers and sediment coring gear, and he will do much of this sampling in the field. He will take care of a wide variety of hands-on logistics for the field program. In short: he is indispensable.
- (2) Four months of funding are requested for Roberta Conard. Conard is our top laboratory analyst. She will carry out many of the laboratory analyses that are the heart of the program, and she oversees the data processing. She is also responsible for preparing the sampling and analytical components of the field program.
- (3) Four and a half months of lab analyst/field support are requested. Several people fill this need. We need field sampling assistants to collect, preserve and transport samples for analysis. We require field analysts for radon, ΣCO_2 , alkalinity, and oxygen measurements (three people). Following the field program, approximately one month of technical support is required for editing the extensive video and still camera data that will result from the submersible program.

•Funds for two graduate students are requested:

- (1) James McManus is currently funded by the project and is a second-year masters candidate. His thesis will investigate the physical chemistry and mixing properties of the deep lake as constrained by our CTD data and major ion analyses.
- (2) Brad Beeson, currently a first-year graduate student plans to do a thesis based on the geochemical aspects of the lake's paleolimnology.

•Funds for secretarial salaries are set by a College of Oceanography formula.

Permanent Equipment

Permanent equipment funds (\$3000) are requested to purchase a small Soutar box corer that will be used for coring with the submersible. This instrument is the only feasible approach for obtaining undisturbed sediment cores using Deep Rover and can also be deployed from the surface.

Travel

Domestic travel funds are requested for travel for all field operations. These expenses primarily result from state vehicle charges, travel expenses of the scientific team to and from the lake, and charges for using Park accommodations (House #19). In addition, expenses for one PI to attend a national meeting are requested.

Miscellaneous Expenses

Laboratory materials and supplies expenses cover the following: analytical instrument use charges within the college of oceanography, chemicals, laboratory gases, instrument facility charges, laboratory supplies, field supplies, line, floats, and other mooring hardware, video tapes (\$750), film, film processing, and video laboratory editing time (~\$1500), batteries and other hardware for navigation, and commercial ¹⁴C analyses.

Subcontracts

Three subcontracts are covered in the budget: Helium analyses (J. Lupton, UCSB); Submersible leasing costs (Can-Dive, Inc., Vancouver, Canada); Navigation.

The subcontract to J. Lupton, UCSB, will cover the costs of helium isotope analyses (@ \$200/sample) as a continuation of our collaboration on this project. Lupton will also carry out tritium analyses on a selected set of samples.

The subcontract to Can-Dive, Inc., is a continuation of our submersible contract from 1988. This contract covers all costs directly billed to the hydrothermal program for the use of the submersible. Since the current plans are to operate two ancillary programs (USGS and Biology dives), our requested subcontract costs (\$59,000) represent only a portion of the total costs. If these other programs are funded, they will carry the additional costs of their operation as well as share in the fixed costs of deploying the submersible in proportion to the total number of dives they receive. A table outlining the current estimates of the total submersible costs (assuming and including all three programs) is presented below:

Fixed Expenses

Can-Dive

Travel and Shipping	10,560
Mob and Demob	12,450
Two-day break	2,300
Consumables	2,000
Submarine Modifications	5,500
Camera (Photosea)	<u>4,500</u>
TOTAL FIXED EXPENSES:	37,310

Active Dive Costs (to Can-Dive)

15 hydrothermal dives	36,750
5 USGS dives	12,250
5 Biology dives	<u>12,250</u>
	61,250

TOTAL FIXED + DIVE COSTS **\$98,560** (Per Science Dive **\$3,942)**

The hydrothermal subcontract represents our 60% share of the fixed costs plus our direct dive costs (or 15 dives x \$3,942/dive).

The navigation subcontract will be awarded to a vendor that will provide long and/or short baseline navigation for the full submersible program. This will include surface navigation, submersible navigation, and personnel support for the testing, deployment, operation and post-cruise data work-up. We have at least one bid in hand (\$32,000 for a 26 day operation) which we believe represents the minimum possible costs of this critical program.

1988-9	FY1989 (6/1-9/30/89)		FY 1990 (10/1-5/30)		FY89-90 TOTAL	
	months	data	months	data		
Senior Personnel						
- Dymond	1	\$5,915	2	\$11,830	\$17,745	
- Collier	1	\$4,000	2	\$8,000	\$12,000	
Total senior personnel		\$9,915		\$19,830	\$29,745	
Other Personnel						
post dococtoral personnel						
other professionals:						
- logistic/technical support (Moser)	6	\$14,112			\$14,112	
- senior lab analyst (Conard)	4	\$9,756			\$9,756	
- lab analyst/field support	4.5	\$9,000			\$9,000	
total other professionals		\$32,868			\$32,868	
graduate students (2)		\$5,466		\$16,398	\$21,864	
undergraduate students						
secretary		\$2,412	\$2,412	\$1,811	\$1,811	\$4,223
other civil service						
total salary and wages (A+B)		\$50,661		\$38,039	\$88,700	
Fringe benefit rates						
- academic (A6,B1,B2)						
- student (B3,B4)						
- civil service (B5,B6)						
Total fringe benefits		\$14,239		\$7,556	\$21,795	
salary + fringe benefits		\$64,900		\$45,595	\$110,495	
permanent equipment		\$3,000			\$3,000	
domestic travel		\$6,000			\$6,000	
foreign travel						
Other Direct Costs						
lab materials & supplies		\$9,000		\$500	\$9,500	
office supplies		\$1,013		\$761	\$1,774	
total material and supplies		\$10,013		\$1,261	\$11,274	
publication costs				\$500	\$500	
consultants						
computer (ADPE) services		\$1,100		\$1,854	\$2,954	
subcontracts subject to overhead		\$25,000		\$5,000	\$30,000	
subcontracts not subject to overhead		\$66,000			\$66,000	
total subcontracts		\$91,000		\$5,000	\$96,000	
other misc.						
- tuition		\$1,456		\$4,336	\$5,792	
total other misc.		\$1,456		\$4,336	\$5,792	
Total other direct costs		\$103,569		\$12,951	\$116,520	
Total direct costs		\$177,469		\$58,546	\$236,015	
Indirect costs: rate*(H - *'d values)		\$10,701		\$5,421	\$16,122	
TOTAL		\$188,170		\$63,967	\$252,137	
subcontracts: Can Dive (submarine)		\$59,000				
Navigation		\$32,000				
Helium isotopes				\$5,000		

APPENDIX 1. Draft schedule for submersible operations (assuming 25 dive days: 15 "hydrothermal" (this program); 5 "USGS" (Bacon); 5 "biology" (Phinney and McIntire).

Date	Operation
July 31	Unpack gear
August 1	Helicopter gear and set up camp
2	Helicopter sub
3	Systems check and training dives
4	Hydrothermal 1
5	USGS 1
6	Hydrothermal 2
7	Biology 1
8	Hydrothermal 3
9	USGS 2
10	Hydrothermal 4
11	Biology 2
12	Hydrothermal 5
13	Biology 3
14	Hydrothermal 6
15	USGS 3
16	Break
17	Break
18	Hydrothermal 7
19	Biology 4
20	Hydrothermal 8
21	USGS 4
22	Hydrothermal 9
23	USGS 5
24	Hydrothermal 10
25	Biology 5
26	Hydrothermal 11
27	Hydrothermal 12
28	Hydrothermal 13
29	Hydrothermal 14
30	Hydrothermal 15
31	Demobilization
Sept 1	Helicopter gear
2	Helicopter sub

CRATER LAKE

July 1989

PEER REVIEW OF RESEARCH PROGRAM AND RECOMMENDATIONS FOR ADDITIONAL INVESTIGATIONS OF POSSIBLE HYDROTHERMAL ACTIVITY

PANEL MEMBERS

Dr. Charles R. Goldman, Chairman

Dr. David Blackwell

Dr. Joris Gieskes

Dr. James McClain

Dr. Ken Nealson

CORRESPONDING MEMBERS

Dr. Ivan Barnes

Dr. Jorg Imberger

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APPENDIX: J. Dymond and R.W. Collier. Treatment of Hypothesis,
Question and Problem, and Proposed Studies.

I. INTRODUCTION

The Review Process

A scientific controversy has surrounded the question of possible geothermal heating of Crater Lake, Oregon. The importance of the question was brought into focus by the plans of a geothermal exploration and development company, California Energy, to do exploratory drilling along the periphery of Crater Lake National Park. To work toward resolution of the question, whether or not Crater Lake contains significant geothermal features, the National Park Service has sponsored a detailed research program at Crater Lake and has subsequently assembled an interdisciplinary Peer Review Panel to evaluate existing data and examine the proposed research program for 1989.

After examining a large number of recommendations for appointments to the Peer Review Panel, seven experts were selected (see Table 1) to examine relevant documents and meet for a technical workshop to consider the question of whether geothermal venting and/or a diffuse heat flow was occurring in Crater Lake. Two of the panel, Drs. Ivan Barnes and Jorg Imberger, were corresponding members and we regret to report that Dr. Barnes died before the review process was completed. Included in the Charge to the Committee was a request to evaluate the adequacy of the research plan for 1989-90 and make recommendations as to how it might be better focused to provide more unequivocal evidence for both scientists and decision makers on the geothermal heating question.

Soon after its appointment, the Peer Review Committee received reports and other documents on this issue, together with reviews from both the U.S. Bureau of Land Management and the California Energy Company. In addition, a useful collection of published papers on the subject had been assembled for the panel by Wilson Goddard Associates at the request of the California Energy Company. It is quite natural that, in coming to a final decision, each expert would have greatly benefitted from additional research information in his specialty area. The panel considers the recommendation for additional research which has been included at the end of the report to be a vital component.

The Panel met in an open meeting on May 2, 1989 in Corvallis, Oregon at the request of Dr. Gary Larson of the National Park Service. Dr. Larson presented a review of the ten-year Crater Lake limnological program, followed by a summary of the research program by Drs. Collier and Dymond. After asking a number of questions, the Panel went into Executive Session to discuss the material presented. Following these discussions, the Panel again opened the meeting to explain the general impression gained by each member and how this review report would be assembled and coordinated among the panel members. Each panel member then submitted an individual report to the Chairman with suggestions and recommendations for modification of existing research as well as any additional research they felt would help to further clarify the Crater Lake situation. A draft report was first prepared by the Chairman from the individual reports, circulated to the panel members, and revised to final form for submittal to the Park Service. Because of the necessity of getting the 1989 summer program underway, an advance, draft, copy of the research recommendations was provided to the Park Service. Some minor modifications of the draft recommendations are included in this final report.

Table 1. Crater Lake Peer Review Panel and Corresponding Members with Specialty Areas Indicated.

Panel Members:

Limnology: Dr. Charles R. Goldman, Chairman and Professor of Limnology, Division of Environmental studies, University of California, Davis, California 95616. (Panel Chairperson)

Geophysics: Dr. David Blackwell, Hamilton Professor of Geophysics, Department of Geological Sciences, Southern Methodist University, Dallas, Texas 75275.

Geochemistry: Dr. Joris Gieskes, Professor, Scripps Institution of Oceanography, University of California, La Jolla, California 92093.

Geology: Dr. James McClain, Professor, Dept. of Geology, University of California, Davis, California 95616.

Dr. Ivan Barnes, U.S. Geological Survey, 5000 NW Cornell, Portland, Oregon 97210. Corresponding Member (Deceased).

Microbiology: Dr. Ken Nealson, Centre for Great Lakes research, University of Wisconsin, PO Box 413, Milwaukee, Wisconsin 53201.

Thermal Modeling: Dr. Jorg Imberger, Centre for Water Research, Dept. of Civil Engineering, University of Western Australia, Nedlands, Western Australia 9009. Corresponding Member.

II. CRATER LAKE OVERVIEW

The major evidence regarding the presence or absence of hydrothermal systems in Crater Lake is thermal and geochemical. Geological arguments have not as yet played a major role in the controversy. The pertinent questions include regional setting, bottom bathymetry and other bottom observations, bottom samples, heat transfer, lake thermal mixing dynamics, geochemistry, microbiology, and seismicity. Each of these will be discussed here. We presume from the beginning that the observations are designed to test the hypothesis that deep circulating hydrothermal waters are entering the bottom of Crater Lake. It appears that all parties agree that some form of ground water is entering the lake beneath the South Basin, and this water is responsible for temperatures slightly elevated above the normal lake values, for some of the anomalous chemistry in the lake water, and possibly for the growth of bacterial mats on the lake bottom. It is the origin and significance of this water that remains in question.

Limnology

Crater Lake is a classic example of a collapsed volcanic peak forming a caldera lake. It is the second deepest lake in the Western Hemisphere and is renowned for its clarity and beauty. Extinction coefficients were measured by Utterback, Phifer, and Robinson in 1942 and color by Smith, Tyler, and Goldman in 1973. A variety of limnological studies have been in progress for the last decade. These have recently been summarized at an AAAS-Pacific Division Symposium and are soon to appear in an edited volume. This report focuses on the work of Dymond and Collier since they are the main proponents of geothermal heating of Crater Lake.

Perhaps the most serious gap in the existing limnological data for Crater Lake is knowledge of the lake's mixing regime. Since Crater Lake's 16-cubic kilometer volume has an enormous capacity to dilute any diffuse hydrothermal or cold-groundwater venting on the lake floor, the importance of knowing how deep Crater Lake mixes in any given year is essential for evaluating vertical profiles of temperature and lake chemistry.

A surprising number of deep lakes undergo only partial mixing during years which are warmer or lack sufficiently-violent storms to achieve complete mixing during the coldest period when lake strata density difference is lowest. Relative depth (Z_r), the maximum depth as a percentage of the mean surface diameter, is a convenient scaler quantity which summarizes the effect of basin morphometry on the likelihood of complete mixing. Herdendorf (1982) tabulated the data necessary to calculate Z_r for 164 of the 253 largest natural lakes in the world. Lake Tahoe, for example, has the highest Z_r value (1.84) of those lakes and, in comparison to other large lakes, is most prone to incomplete mixing by virtue of its shape (Goldman and Jassby, In Press). Crater Lake's smaller surface area and greater depth give it an even higher Z_r value (6.58) than Tahoe, indicating that years of partial mixing are also probably quite common.

Determining the depth of mixing requires rather intensive limnological sampling during the coldest period of the year or immediately following ice-out. Lakes that freeze are usually considered to undergo complete mixing soon after ice-out. In reality, in protected basins like Crater Lake, thermal

stratification may set up without complete mixing even if an ice cover has been present. From a technical standpoint, determining the depth of mixing during the period of minimum thermal stability is not easy. Neither temperature nor conductivity gradients may be adequate to determine the depth of mixing with precision. In Lake Tahoe, the use of a nitrate profile which develops during the spring and summer from the depletion of near-surface nitrate by phytoplankton proved to be the most sensitive means of determining the depth of mixing (Paerl et al., 1975; Goldman and Jassby, In Press). Since nitrate depletion is evident in the surface waters of Crater Lake, this same procedure of doing very careful nitrate profiles using the sensitive hydrazine reduction method should be sufficient to determine the depth of mixing within a few meters.

Geophysics

The results of studies regarding the possible existence of deep hydrothermal inputs to Crater Lake will continue to be closely scrutinized from both a scientific and political point of view. By laying out the framework of the investigations as evidenced by the hypotheses, questions and problems (see Appendix), the investigators can gain valuable input from interested parties. Future research should be process-oriented and directed toward understanding the physical and chemical processes which characterize the limnology of Crater Lake. It is essential that researchers be encouraged to use those scientific tools/techniques which are the most appropriate to answer the important questions and not merely the tools which they have available or only those they are particularly familiar with.

At present there is a significant lack of sufficient "hard" data on physical-chemical cycling in Crater Lake, making analysis of the questions at hand more difficult. In particular, there is little conclusive data from which we can evaluate lake mixing and model lake chemistry. At this time, evaluation of lake mixing (using a modelling approach) is largely based on assumptions which may or may not be valid. One of the first major efforts, as already noted in the Limnology section, should be to determine the mixing time scale of the lake. In addition, the water budget of the lake also needs further refinement. Similarly, a re-evaluation of the original heat flow survey by Williams and Von Herzen (1985) should be done. Finally, a determination of the physical properties of sediments in the areas of apparent normal-versus-high heat flow are needed before the hypothesis of sub-bottom interaction can be fully evaluated.

Thermal Modeling

To interpret the observed thermal anomalies, it is essential that seasonal measurements be included in the current program to establish the frequency and depth of annual mixing events. Nitrate profiles, based on summer depletion, are likely to be the best measure of the depth and frequency of mixing. This information is essential for developing any meaningful heat budget for Crater Lake.

Considerable microstructure in the upper 265 meters of Crater Lake was observed by Neal et al. (1972). We still need to determine what causes the hyperadiabatic warming at depth which has been the subject of recent investigations, and factors stabilizing it pose an interesting question. It is important to determine also, what causes the large-scale (1-2 kilometer)

horizontal temperature variability in the lake basins. And last, but of equal importance, is what causes a small-scale, 10-100 meter temperature variability along the floor of the lake (Collier and Dymond, 1989 report of field studies).

These questions may be answered with a careful application of a simulation model such as DYRESM (dynamic reservoir simulation model) if the necessary data are available. The model requires accurate surface heat and momentum flux information, inflow and outflow data, as well as good topographic information. With these factors, the model simulates the temperature structure in the lake. Considerable accuracy can be achieved in testing various scenarios if the quality of the input data is high. The questions that could be addressed include:

- 1) Given the necessary data inputs, is the heating with depth reproduced? If not, how much heat must be added at depth to reproduce the observed temperature distribution.
- 2) The addition of a plume is easily simulated with existing models, and the source strength (buoyancy flux) could be varied to investigate the height of rise.
- 3) The addition of cold boundary inflows can be incorporated to assess the correlations between temperature differential and depth of plunge.
- 4) The addition of salts could be modelled to see whether the lake is meromictic or whether it is convectively unstable.

Models of this type are especially applicable to lakes where the lake number L_n (stability divided by the overturn moment) is large. Preliminary calculations suggest that the Crater Lake L_n value is very large (of the order of 10^3) implying that the water in the hypolimnion in the summer is not disturbed by the surface winds, so that it is most likely laminar. Under such conditions temperature distributions should be reproducible with great accuracy and any departure from this condition should be attributable to thermal activity.

Given that the surface layer almost certainly insulates the hypolimnion from the mechanical effects of the surface wind stress (L_n large) it would be informative to determine the level of turbulence in the hypolimnion. Naturally, if it is found that a direct simulation with molecular diffusion coefficients is able to simulate the observed temperature distribution, then the only remaining puzzle is the patchy nature of the temperature field. This would then point to temperature anomalies introduced by prior events. It is more likely that the observed small temperature rise with depth is the result of a thermal input which in turn introduces patches and small-scale turbulence. Both would be visible from temperature microstructure data. It is recommended that a rising microstructure probe be constructed and deployed at approximately 500 m intervals along the axis of the lake. This should then be followed by time series at the point (station) where the greatest activity or temperature anomalies are observed. Such a data set would:

- 1) Verify temperature patchiness.

2) Yield estimates of the dissipation of turbulent kinetic energy and thus vertical diffusion coefficients. These estimates should then be compared to those required in the simulation runs.

3) By comparing the displacement scales observed from the microstructure measurements with the Ozmidor length, the age and source of the turbulence can be determined. This would reveal plumes if any are present.

4) The patches could perhaps be induced by turbulence generated in the benthic boundary layer. A program of turbulence measurements with a rising microstructure profiler would again answer this question. Such a profiler can be sent to the bottom, released, and then used to measure microstructure to within the length of the profile (~30 cm). Although temperature microstructure profilers of this type are not commercially available, they are easily manufactured or would be available on loan for use in Crater Lake.

Geology

The various papers by Collier and Dymond are quite correct in pointing out that "an input of thermal springs would not be surprising" (Collier and Dymond, 1988 Final Report). Numerous hot springs exist in the Cascades, including a number of lakes (e.g., Geothermal Energy Resources of the Western United States, 1977). However, it should be noted that the Crater Lake area has no surface warm springs, in contrast to other areas of the Oregon Cascades (Geothermal Resources of Oregon, 1982). The Belknap-Foley Hot Springs, for example, has at least seven springs or thermal wells.

In particular, the geological observations of Collier and Dymond include:

1) The Cascades are the location of numerous hot springs. However, Crater Lake is rather low in presently known geothermal features (Geothermal Resources of Oregon, 1982).

2) The bathymetry of the main study is that of a flat sedimented bottom bounded by volcanic edifices to the north and by the caldera rim to the south. There is considerable evidence that escarpments to the south are the lobate distal portions of the Chaski Slide.

3) The study area lies astride the proposed ring fracture system associated with the collapse of the Mazama Caldera. However, the bathymetry and bottom observations do not confirm the existence of such fractures.

4) Collier and Dymond discovered bacterial mats, semi-lithified crusts, pebble zones and discolored sediments during the dives in 1988. Some of these features occurred on the face of the escarpment to the south (possible part of the Chaski Slide). The mechanism and temperature of formation for these phenomena are not known, but additional information could be obtained from petrographic and mineralogical studies of samples.

5) Alteration on the escarpment face was observed. This alteration may have occurred in situ or before the slide occurred, when the material was under many meters of cover before it slid to its present position. More detailed observations and sampling would resolve this question. Petrographic and mineralogical studies may provide evidence for the temperature of alteration.

6) The features noted in (4) and (5) above were observed in a region of high heat flow and near the edge of the sedimented south basin. The location is consistent with water flow controlled by the ring fissure zone [see (2) above] as Collier and Dymond state, but it is also consistent with ground water flow down the Chaski Slide as La Fleur suggests. *It should be noted it is not known whether such features are present outside the study area.* Some observations should be made outside the study area to see if bacterial mats, alteration, and crusts are truly restricted in distribution.

7) Seismicity in the Crater Lake Region is low, as it is under a number of known hot springs in the Oregon Cascades. A focused microseismicity study would be helpful, but is not considered a high priority for new studies of Crater Lake.

Geochemistry

The studies carried out so far by Collier and Dymond (1988, 1989) on the water column geochemistry of Crater Lake indicate that:

- 1) Inputs of both heat and dissolved chemicals may occur at localized areas of lake bottom in the South Basin of Crater Lake;
- 2) Mass balance calculations suggest that these dissolved salt inputs may be significant contributors to the relatively high dissolved ion contents (which nonetheless are quite low) of the lake;
- 3) Though there exists strong evidence, especially based on high ^3He inputs, for hydrothermal contributions to the dissolved salt inputs, the relatively low inflow rates and the lack of any observed vents suggest that any hydrothermal fluids present may well have mixed with local ground waters, prior to entering the lake bottom;
- 4) The suggestion of the existence of pure ground water input, as well as the hydrothermal hypothesis, still requires further study. The proposed studies for 1989 will address some of these problems and should be encouraged, together with some additional study;
- 5) Comparison with other Cascade lakes should be complemented with ^3He studies. In any case, East Lake and Paulina Lake, with their much higher salt contents, should also show a higher "hydrothermal" contribution;
- 6) As indicated in the next section on microbiology, the planned emphasis on bacterial mat fluids and pore fluids in areas of bacterial mats, colored sediments, as well as "background" sediments must be encouraged. At the same time, more water column geochemistry may confirm apparent small changes in water column chemistry which may be the result of variability in inputs and outputs from the lake.

Finally, further comment on the sediment geochemistry in the framework of "hydrothermal" activity is premature at this time. The proposed 1989 fieldwork should serve as a more solid basis of information than is available from the preliminary set of sediment cores.

Microbiology

The work of Collier and Dymond on bacterial mats in Crater Lake is best viewed as a good, preliminary study. There is a strong possibility that this microbial community will provide an improved understanding of subsurface inputs to the Crater Lake system. It is therefore critical that in the coming year these investigators collaborate with experienced microbiologists to systematically answer some of the questions raised by their initial observations.

As opposed to oceanic bacterial mats, which are often dominated by S-oxidizing bacteria and highly evolved symbiotic systems, the Crater Lake bacterial mats appeared to be composed primarily of Fe-oxidizing organisms (i.e. Sphaerotilus and Gallionella). While these observations are suggestive, they are not compelling for the input of hydrothermal water. The mats reported here are reminiscent of those found elsewhere (e.g. Mediterranean Sea and northern Wisconsin lakes) where the Fe and Mn for these mats come primarily from anaerobic groundwater. While this does not necessarily argue that the Crater Lake situation is a groundwater one, it does raise this possibility. It is interesting that the photographs of the lake bottom look very similar to what we have observed in Yellowstone Lake in systems that are definitely hydrothermal. A number of useful, future research activities should include; taxonomic studies, carbon fractionation work, culturing these organisms to better understand their metabolic requirements, measuring temperature gradients and pore-water chemistry in the mats, and finally, conducting physiological rate measurements of the mat-forming organisms.

III. LIST OF RECOMMENDATIONS FOR ADDITIONAL RESEARCH WORK AT CRATER LAKE TO RESOLVE THE HYDROTHERMAL VENT ISSUE

General Considerations

For completeness, the proposed research of Collier and Dymond is presented as an Appendix to this report. Their investigations cover the following areas: ash alteration, conductive heat input, cold spring (groundwater) input, volatile transport, and hydrothermal input. We hope that the research recommendations suggested by the Panel and given below will be incorporated into the research efforts.

- 1) All investigators need to set out clear objectives for the study of physical and chemical process in Crater Lake, and carefully define the criteria on which conclusions will be based.
- 2) All investigators should make sure that the methodologies used to collect data are the most appropriate for answering the question at hand, even if this requires hiring subcontractors.

Lake Mixing Investigations

It is absolutely imperative that a detailed understanding of the lake's mixing regime be established. Since the periodicity and vertical extent of mixing are almost certainly not consistent from year to year and since mixing influences the distribution of heat and chemical constituents in the lake, interpretation of temperature and chemistry data must be carried out in light of the lake's mixing history. Determination of the depth of mixing during the period of minimum thermal stability is not easy from a technical standpoint. Neither temperature nor conductivity measurements may be adequate to determine the depth of mixing with precision. The use of seasonal vertical profiles of nitrate throughout the water column (i.e., formation and breakdown of nitracline) has proved to be a very sensitive means determining the depth of mixing.

Water Column Physico-Chemical Investigations

- 1) Continued careful hydrographic studies related to vertical profiles of water column chemistry, similar to those conducted in the past in both the East and South Basins, should be performed. Further, the use of temperature and conductivity microstructure measurements to document turbulent activity in the deep part of the lake could help resolve the question of whether the origin of the observed temperature and conductivity anomalies is hydrothermal or conductive.
- 2) The use of a "low speed" current meter to measure bottom currents would allow for estimates of the advective transports in the benthic boundary layer. Measurements of the temperature microstructure in the benthic boundary layer would allow for estimates of the diffusive transport in this region.
- 3) The appropriateness of using the steady state box model to model lake chemistry should be evaluated.

4) A very careful quantitative heat budget such as that possible using the "Sea Bird" technology would yield net heat input and define the magnitude of thermal disruption.

^3He and ^{222}Rn Isotope Investigations

1) $^3\text{He}/^4\text{He}$ and ^{222}Rn samples should be taken whenever possible in the bacterial mat zones and other bottom areas. Evaluation of ^{222}Rn from a variety of benthic regions deserves further attention.

2) The extended data base on ^3He and ^{222}Rn anomalies should then be used to evaluate the possible inputs of ^3He and ^{222}Rn from fumarole activity at depth or the possible correlation of these parameters with inputs of heat and salts related to hydrothermal activity.

3) Measurement of $^3\text{He}/^4\text{He}$ in other Cascade lakes should yield information useful for evaluating the potential for hydrothermal inputs.

4) $^{18}\text{O}/^{16}\text{O}$ ratios of waters, especially from bacterial mats and sediment pore fluids, will prove valuable.

Sediment Physico-Chemical and Hydrology Investigations

1) Careful documentation of temperature values and gradients within the bacterial mat communities and other sediments (e.g. colored sediment and "background sediments") will be very important. This should help answer the question of hydrothermal input versus slightly warmer ground water. Concomittant measurements of pore water chemistry in these areas are also critical.

2) The collection of additional data on the chemical composition of sediment cores (from various lake bottom types) should be encouraged. Mercury in water and sediment has not been measured and might yield valuable information.

3) The hypothesis that hydrothermal inputs undergo extensive subsurface mixing with less saline ground waters requires consideration.

4) A detailed understanding of processes occurring within a few 10's of meters above and below the bottom (i.e. lake-bottom interactions) should be a major objective of future research.

Bacteriological Investigations

1) Efforts should be made to taxonomically define the bacteria present in the mats.

2) To test the hypothesis of chemolithotrophy and an iron-based system it would be helpful to (1) culture these bacteria and observe growth patterns when grown on Fe and/or Mn and (2) obtain carbon fractionation data (i.e., strength of del ^{13}C signal). In addition, detailed knowledge of oxygen profiles and pore water chemistry would greatly help in the interpretation of the bacterial data.

3) If possible, measurements of rate of specific physiological processes (e.g. rates of Fe, CH₄, H₂ oxidation) could shed light on the issue of hydrothermal versus non-hydrothermal environment. This assumes that CH₄ and H₂ are detectable.

Geological Investigations

1) The altered rock on the cliff face should be sampled to determine if it occurred in situ or has slumped to its present position.

2) The lithified crust and pebbles should be examined for their mineralogy, and for evidence that they evolved from the bacterial mats.

3) One or more dives should be devoted to exploring the lake bottom outside the areas of high heat flow. In particular, searches should be conducted for bacterial mats, lithified crust, pebbles and other anomalous features presently attributed to the high heat flow region in the study area.

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APPENDIX

J. Dymond and R.W. Collier's Treatment of Hypothesis, Question and Problem,
and Proposed Studies

Ash Alteration

Observations consistent with the hypothesis

1. Fresh volcanic ash (glass) is relatively reactive to low-temperature weathering

Questions and problems

1. No evidence of high Cl or Na in cold springs within the caldera or in other Cascade lakes.

Proposed Studies

1. Examine the pore water gradients in low heat flow areas to define leaching rates and elemental fluxes.
2. Compare compositions of fresh caldera volcanics, sediment trap materials, and sediment core samples.

Conductive Heat Input

Observations consistent with the hypothesis

1. General increases in temperature with depth

Questions and problems

1. Inconsistent with observed horizontal and vertical gradients of temperature in the near bottom region of the lake.
2. Conductive heating alone cannot account for the increase in dissolved ions and gases in the deep lake or the overall chemical balance of the lake.

Proposed Studies

1. Studying the stability and mixing of the deep lake will help constrain the degree to which conductive heat will be trapped near the bottom.

Cold Spring (Groundwater) Input

Observations consistent with the hypothesis

1. Observed enrichments in ^{222}Rn , Mn, and Fe in deep lake waters.
2. Observed mat-temperatures could be typical ground-water temperatures.
3. The absence of observable flow through the mats may relate to the seasonal cycle of shallow aquifers.
4. Bacterial communities and metal-oxide deposits.

Questions and problems

1. Enrichments of Cl, Li, and B in the bulk lake and the anomalous waters within and near the bacterial mats are much lower than those observed in caldera springs.
2. Mat fluids, corrected for dilution, yield geothermometric temperatures that are too high for ground water.
3. What are the aquifer characteristics which would constrict the flows to the bottom of the lake. Stable carbon isotopic, and ^{14}C data in the deep lake cannot be explained by seasonal cold spring inputs.
4. How do cold springs account for the scales of spatial variability observed in mats and crusts and the temporal variability of iron-rich precipitates observed in core samples?

Proposed Studies

1. Expand the analytical program to include Ba, Rb, Cs, and possibly As and Hg.
2. Collect relatively undiluted mat and pore water samples (barrel, pore waters, and "peepers").
3. Moored thermistor chains may define seasonal variability of deep spring inputs. Water sampling for carbon isotopic analysis.
4. Collect and study more cores and mat samples; establish the spatial distribution of mats and crusts.

Volatile Transport

Observations consistent with hypothesis

1. ^3He is a mobile element and could enter the lake or springs in gaseous form.
2. Could account for the apparent input of carbon (^{14}C and stable C isotopic data).

Questions and Problems

1. ^3He correlates with T and dissolved ions
2. CO_2 and other acid-forming volatiles would result in lower pH than is observed in the lake and does not account for the alkalinity deficit.

Proposed Studies

1. Measure the ^3He in cold springs which have different temperatures.
2. Measure the isotopic and chemical composition of the CO_2 system in cold springs ;

Hydrothermal Input

Observations consistent with the hypothesis

1. The observed anomalies in dissolved major ions (Na, K, Mg, Ca, Cl, SO₄, HCO₃, and SiO₂); dissolved gases (helium and radon); minor elements (Mn, Fe, Ra, Li, and B)..
2. A source of elements in addition to precipitation which can account for the concentration of ions present in the lake.
3. The complex thermal structure of the deep lake and the correlation between temperature and dissolved contents.
4. Localized bacterial communities and metal oxyhydroxide deposits.

Questions and problems

1. No flow of fluids is observed from vent sites.
2. End-member fluid compositions are unknown because existing samples from possible vent sites (mats) are highly diluted by normal lake waters.
3. The mixing and dispersal pattern of vent fluids is unknown; the impact of venting fluids on convection of the deep lake is uncertain.
4. Do the mats represent the only sites of fluid input? The specific metabolisms of these communities are unknown.

Proposed Studies

1. Better navigation will permit more exhaustive search patterns which will confirm whether or not localized, vigorous venting occurs; pore-water studies will define the rates of diffuse venting through sediments.
2. Collect relatively undiluted mat and pore water samples (barrel, pore waters, and "peepers").
3. Moored thermistor chains may define the scales and seasonal variability of the mixing processes; ²²²Rn and ²²²Rn/^βHe ratios will define dispersion rates of venting fluids; continued CTD, O₂, and ³H measurements will define the rates of lake ventilation.
4. Pore-water studies of areas without mats and more detailed studies of the mats.

Appendix 2. Responses to the List of Recommendations from the Peer Review Panel on the Proposed Research July, 1989

Introduction

Recently, we have received a draft copy of recommendations for additional work at Crater Lake for 1989. We appreciated the review of our on-going study of hydrothermal processes at Crater Lake that was provided by the Peer Review Panel. In general these comments were highly supportive of the research that was submitted in our preliminary proposal (April 1989). We believe that a major rewrite of our draft proposal is therefore unnecessary. We have chosen, instead, to prepare this appendix which clarifies and expands upon our original proposal, outlines additional studies added, and otherwise responds to the suggestions made by the peer review panel.

General Considerations

The objectives of the overall project are defined in several pages of the proposal. For example on page 1 we state that the major goal of the program "is to evaluate the environmental significance of hydrothermal activity in the lake" and suggest that chemical and thermal inputs from this process could have implications for the clarity of the lake. Page 6 is a more detailed statement of research goals.

The expertise necessary to carry out a complete multidisciplinary study of hydrothermal activity and its biogeochemical effects can only be assembled through the collaboration of many scientists from a number of institutions. Some of these participants are listed on page 7 of the draft proposal; however, additional arrangements have been finalized in the past two month. Below we list all participants and the area of their research effort. Below we will discuss the specific contribution of some of these investigators in response to other recommendations of the peer review committee.

Table A.1 Collaborating Investigators

<u>Scientist</u>	<u>Institution</u>	<u>Research Expertise</u>
Gary Larson	OSU	Co-Principal Investig., biology, lake ecology
David Karl	U. Hawaii	microbiology
John Lupton	UCSB	He isotopes and tritium studies, lake mixing
Peter Schlosser	Heidelberg Univ.	accelerator ¹⁴ C analyses, stable carbon
Alan Mix	OSU	stable carbon isotopes
Marv Lilley	U. Washington	methane analyses
Ray Weiss	UCSD	chlorofluorocarbons, lake mixing
Andrew Soutar	UCSD	surficial sediment coring
Goef Wheat	U. Washington	porewater studies
Linda Anderson	UC Santa Cruz	arsenic concentrations and speciation
Charles Bacon	USGS	lake floor geology
Hans Nelson	USGS	lake floor geology
Harry Finney	OSU	biology, taxonomy
David McIntire	OSU	biology, diatoms
Stan Loeb	Purdue	biology, periphyton
Bruce Robison	MBARI	biology, pigment analyses

Water Column Physics and Chemistry

Mixing investigations have been and continue to be one of the main goals of our program (cf. p.6, goal 3&4; p15-16). As we have already demonstrated, the rates of vertical mixing play an important role in the nutrient cycle of the lake and in constraining the input of anomalous chemicals accumulating in the lake basin. Collection and interpretation of nitrate profiles is only one of many sensitive parameters already being acquired by the 10-year limnological program, under the direction of Dr. Gary Larson. We will continue to collaborate with Dr. Larson on the interpretation of these data sets.

As part of our on-going studies on mixing and lake dynamics, we have carried out more than 30 CTD casts covering all the major basins of the lake in 1989. These studies will continue through the winter of 1990. No specific "microstructure" studies have been scheduled since the methodological expertise does not exist in our group. However, OSU Oceanography has one of the foremost microstructure groups in the world, and we will consult with them on our data and on other possible collaborations.

It has been suggested that current meter investigations in the benthic boundary layer would help constrain advective transport. While current meter studies made in the deep lake could clearly be useful, such measurements may not be easy to make. Our submersible work from 1988 indicated that the bottom currents are very slow (essentially imperceptible). Measuring current speeds that are less than 1.7 cm/sec is technically very difficult (Dale Pillsbury, pers. comm.). The commonly used rotor current meters (Aanderaa, VACM, VCM) all have stall speeds at this level or higher. An electromagnetic current meter made by InterOcean (model S4) has promise as a low speed device; however, tests of this instrument (Bottero and Pillsbury, 1987) demonstrated that it is not sufficiently stable for accurate low-speed work. Instrument drift on the order of 1 cm/sec over a period of approximately two weeks has been documented. Despite the drift problem this instrument may be the only means of measuring the current speeds in the near-bottom region of Crater Lake. Consequently, we are exploring the deployment of an S4 meter for a two weeks during our 1989 field season. Hopefully, this deployment will provide sufficient data to determine whether a more detailed experiment is warranted.

The appropriateness of steady state box models has been evaluated within our on-going analysis. As discussed in our report (Collier and Dymond, 1989, p. 37) steady state models have been used by a number of investigators to clarify the the geochemical budgets in Crater Lake. The steady state model is only used as an approximation; a useful tool with which we discuss the major ion balance (or imbalance) in the lake. In our report, we have shown through various direct examples of sensitivity analysis, that this modelling is completely appropriate to pursue. Natheson (in press) has shown that the historic record of major ion concentrations in the lake is compatible with a steady state model. Applications of these models have demonstrated that the lake composition cannot be accounted for by known and estimated inputs and outputs of water and ions. An additional and continuing input of ions is necessary to account for the concentrations observed in the lake. The model does not say that the input must be hydrothermal, only that a major uncharacterized input must exist. In our report, we have done similar analyses using the most recent data for the hydrologic budget (Redmond, in press) which show that if the input required to balance the dissolved load were to cease, a measurable decrease in concentration would become apparent within a few decades.

Heat budgets using our Sea Bird CTD and the Sea Bird thermal probe will continue to be part of our data analysis. Again, mixing rates and physical models of the water column must play an important role in these efforts.

^3He and ^{222}Rn Isotope Investigations

It has been suggested that we continue to focus on the question of whether the heat, soluble ions and dissolved gasses must necessarily be coupled by a common carrier or input process. Direct testing of the hypothesis that radon and helium can enter the lake in volatile rather than dissolved in a hydrothermal fluid is difficult. There are certain lines of evidence, however, which argue against the hypothesis (see p. 63 of Collier and Dymond, 1989). In addition, we are evaluating the possibility of measuring ^3He in some spring samples from Mt. Mazama. If springs which have not received hydrothermal input, have mantle helium ratios, the volatile input hypothesis would be supported. Unfortunately there are still several complications in this approach. Demonstration of a lack of hydrothermal input to these spring may be equivocal. However, low temperatures or low ionic contents (particularly for elements like Li and K) might indicate insignificant hydrothermal input. Secondly, it is important to sample springs at the source to limit the exchange with the atmosphere. Springs from within the caldera make their entry high up on the caldera walls; it appears to be nearly impossible to reach them with the helium sampling gear. There are some springs outside the caldera that might be sampled appropriately, but would everyone agree that this was a good test? Helium isotopic measurements are expensive (\$150/analysis), and any samples chosen for these measurements must be made with care. Our approach at the present is to sample a few springs where we can be assured of sample integrity.

Our research plan calls for considerably more water sampling from bacterial mats than was accomplished last year. These samples will be analyzed for both $^3\text{He}/^4\text{He}$ and ^{222}Rn whenever possible. In addition, we propose to measure helium and radon in samples collected with the benthic barrel. This appears to be the only means of obtaining large samples (necessary for radon and helium measurements) of advecting pore waters which are relatively unmixed by normal bottom waters.

We hope to carryout a modest study of waters in East and Paulina Lakes to define the $^3\text{He}/^4\text{He}$ values in the hydrothermal systems which are apparently affecting these lakes. We won't be able to do much in this regard because of the expense of these measurements and time limitations; we simply aren't budgeted to do much outside Crater Lake. Moreover, this may not do much beyond documenting the $^3\text{He}/\text{heat}$ and $^3\text{He}/\text{ions}$ in these systems. If the ratios are similar to those we have in Crater Lake, it may imply that heat, ions, and helium are extracted by a common process. If they are different, it may imply that different hydrothermal systems operate differently. It is known from marine studies (Lupton, et al. 1988) that the $^3\text{He}/\text{heat}$ ratios differ from site to site.

Sediment Physics, Chemistry and Hydrology

We were dissatisfied with the number of temperature measurements we were able to make in bacterial mats last year and hope to significantly increase the number this year. We have improved the thermal probe to contain three sensors and digital recording of the data. We plan to use "peepers" (passive diffusion chamber water samplers) which will be inserted into mats to define the chemical gradients in mats and provide relatively undiluted samples of the mat fluids.

We plan an on-going coring program which will rely on both 4-inch diameter gravity coring and box cores (see p. 12 of the proposal). The 4-inch gravity cores, which were initiated in our program last year, provide relatively undisturbed cores of up to two meters length. We plan to use these cores to define the sediment composition and porewaters in areas that are not affected by advection. The box cores will be positioned by the submersible and will be used to obtain samples of discolored sediments and bacterial mats, which we believe to be areas of upward fluid advection.

If the bacterial mat fluids that were sampled last year are dominated by hydrothermal processes, it is highly probable that they have undergone extensive mixing with less saline and colder waters. Based on two different geothermometers we computed temperatures ranging between 81 and 86°C (p. 36 in Collier and Dymond, 1989) despite the fact that the measured mat temperatures were only a few degrees above background values. One explanation for this observation is that the fluids equilibrated with a cooling magmatic body at approximately 80°C and migrated upward to the mat while undergoing mixing with cooler waters.

The benthic boundary layer has and will continue to be a major focus of our research. In the 1989 field program CTD measurements and water sampling will be concentrated within the bottom 10 meters both by submersible and surface ship. In addition we have deployed a mooring within our Detailed Study Area which carries a thermistor chain that will record the vertical temperature structure in the bottom 100 m every 20 minutes; there is one thermistor every 10 meters. In addition, we will use coring, peepers, temperature probes, and porewater analyses to study the upper sediment column.

Microbiological Studies.

Dr. David Karl of the University of Hawaii will be involved in our microbiological studies of the bacterial communities discovered on the lake floor. Living and fixed samples will be collected from a number of bacterial mats and sediment sites during the 1989 dive program. The preserved samples will be analyzed with SEM and light microscope for taxonomic purposes.

Dr. Karl will attempt to culture the living samples from the Crater Lake bacterial communities. If this is successful, we will learn a great deal about their metabolisms. He has been heavily involved in the past year with very similar bacterial communities from Loihi Seamount and has had success in culturing these forms. In addition he will carry out C/N/S stable isotope analyses which will aid in evaluating the source of their carbon and the metabolism used to acquire it.

Although Dr. Karl will not directly measure the rates of specific physiological processes through uptake experiments carried out onsite, he does plan to measure CO₂ fixation enzymes, which is a critical test of whether the cells are autotrophic.

Geological Investigations

It has been suggested that we focus on determining the environment under which the hydrothermal alteration reported on the South Basin cliff faces occurred. We will attempt to directly sample the altered rock on the cliff face. Determining whether the alteration occurred *in situ* is important, but such a determination may not be unequivocal. Much of the alteration of the caldera wall is hydrothermal (C. Bacon, pers. comm.) and may resemble the *in situ* alteration that would take place on the lake floor. The recovery of altered and cemented lake sediments, however, would support *in situ* alteration.

Several of the lithified crusts have been analyzed by X-ray diffraction which demonstrates that these materials are amorphous. The only crystalline material are an occasional volcanic phase that represents volcanogenic minerals that are part of the normal sediments of the lake. We plan to continue our SEM measurements to evaluate the presence of fossil bacterial forms.

We will continue to examine as many different regions in the lake as possible. During the 1989 field program 10 dives are scheduled for areas outside the detailed hydrothermal study area. These dives are funded by the USGS, the National Geographic Society, and Deep Ocean Engineering. Although these dives do not have a direct hydrothermal mission, they will allow us to determine spatial distribution of features attributed to hydrothermal processes on the lake floor. As noted in our draft report, seven

dives made in 1988 in a variety of terrain indicates that the bacterial mats, lithified crust, and pebbles, which are relatively common in the detailed study, do not occur in other parts of the lake.

Summary

We have carefully considered the recommendations of the peer review committee and feel we have included as many of their suggestions as possible. We look forward to a successful field season in 1989. We continue to be fortunate to be associated with incredibly dedicated research staff, National Park Service personnel, scientific collaborators and reviewers whom have graciously donated much of their time and facilities to these studies. Without their help, this program would simply not be possible (and/or would cost much more than double our current budget).

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