Report of the Secretary of the Interior under

Section 7 of Public Law 100-443

on the

PRESENCE OR ABSENCE OF SIGNIFICANT THERMAL FEATURES WITHIN CRATER LAKE NATIONAL PARK

NATIONAL PARK SERVICE

in consultation with

U.S. GEOLOGICAL SURVEY

BUREAU OF LAND MANAGEMENT

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I. EXECUTIVE SUMMARY

Public Law 99-591, October 30, 1986, directed the Secretary of the Interior to prepare a final list of significant thermal features in twenty-two specified units of the National Park System, including Crater Lake National Park. On June 30, 1987, the Secretary transmitted to Congress a final report listing significant thermal features in thirteen units of the National Park System. A decision on whether to include Crater Lake National Park was deferred until completion of ongoing research. Sections 2 and 6 of the Geothermal Steam Act Amendments of 1988, P.L. 100-443, included Crater Lake National Park on a list of units within the National Park System which contained significant thermal features. Section 7 of the Act mandated a report to Congress "on the presence or absence of significant thermal features within Crater Lake National Park." This report is in response to that requirement. The scientific research and this report do not address the possibility of a connection between the hydrothermal features of Crater Lake and the geothermal lease sites outside the boundary of the National Park.

Under an agreement between the National Park Service and Oregon State University at Corvallis, Drs. Robert W. Collier and Jack Dymond began intensive studies of the lake in 1987. By using a remotely operated vehicle in 1987 and a submersible, Deep-Rover, in 1988 and 1989, geological, geochemical and biological features in the deep lake were studied. Based on these studies, the researchers concluded:

> "...there <u>are</u> inputs of hydrothermal fluids into the bottom of Crater Lake. The dissolved materials associated with these thermally and chemically enriched fluids, coupled with the overall hydrologic balance, control the observed chemical composition of the lake. Because the hydrothermal input dominates the flux of most dissolved chemicals into Crater Lake, the hydrothermal process is highly significant. Furthermore, the geothermal inputs have a direct effect on the density structure of the deep lake, and therefore can profoundly affect the rate of heat transport and the redistribution of dissolved salts and nutrients within the body of the lake." (See Executive Summary, Appendix A.)

A peer review panel was formed in 1989 to review the summary of research for 1988 and proposed research for 1989. The original panel and two new members convened to review the draft final research report in January 1991. The panel was chaired by Dr. Charles R. Goldman, University of California at Davis, and included other distinguished scientists from appropriate fields. The peer review report includes some requests for additional research, but concludes that, "...the Panel has been convinced of the input of SHEF [Salinity- and Heat-Enriched Fluids] to the lake bottom and its significance for lake chemistry." (See Section III, C, page 9 and Executive Summary, Appendix B.)

An independent review of the literature by the U.S. Geological Survey also concludes that, "... the research program at Crater Lake has demonstrated an

inflow of thermal water that is important to lake dynamics." (See Section III, B, page 8.)

Based on the scientific research, reviews of the research by peers and the Department's application of the criteria in Public Law 100-443, Crater Lake National Park qualifies for listing as a National Park Service Unit with significant thermal features. (See Section IV.) The moratorium placed on geothermal leasing adjacent to Crater Lake National Park is lifted with the submission of this report to the Congress, and the Department will treat all lease applications according to the provisions of the Interagency Agreement (IA) for implementing the provisions of the Geothermal Steam Act Amendments of 1988. (See Section IV and Appendix C.) The Bureau of Land Management has suspended all existing leases in the Winema National Forest as of February 20, 1991, for a period of two years in order to develop appropriate operating requirements before proceeding with exploration activities. (See Appendix D.)

II. INTRODUCTION

A. Legislative Requirement for this Report

This report is required under Section 7 of the Geothermal Steam Act Amendments of 1988 (Public Law 100-443). However, the legislative history of this requirement dates back to 1986. The Department of the Interior and Related Agencies Appropriations Act (P.L. 99-591) was passed by Congress and signed into law on October 30, 1986. Paragraph 2(a) of Section 115 of the General Provisions for the Act directed the Secretary of the Interior to publish for public comment a proposed list, consider public comments, and prepare a final list of significant thermal features in twenty-two specified units of the National Park System. Crater Lake National Park was one of the units under consideration.

NPS proposed to list significant thermal features located in seventeen of the twenty-two units and published a Proposed Notice in the Federal Register on February 13, 1987 (52 FR 4700). The final report listed significant thermal features in only thirteen units of the National Park System and was transmitted to Congress on June 30, 1987. A final notice of this list was published in the Federal Register for public review on August 3, 1987 (52 FR 28790). The Secretary of the Interior deferred a decision on whether to list the hydrothermal features in Crater Lake National Park as significant thermal features until after the completion of ongoing research. This decision was based on a finding that insufficient information on the features existed at that time.

On December 8, 1987, the Secretary of the Interior transmitted to the Congress a copy of the preliminary field report from the studies at Crater Lake. The Department estimated that the research necessary to demonstrate the location, magnitude, and ecological role of hydrothermal features in Crater Lake would take four years to conduct. Once the studies were completed, the Secretary promised to report on the significance of the thermal features and indicate whether the Report to the Congress dated June 30, 1987, needed to be revised. Further, the Secretary advised the Congress that until the needed data were collected and analyzed, the Department would not issue any leases on lands surrounding Crater Lake National Park under the discretionary authority vested in the Secretary under Section 3 of the Geothermal Steam Act of 1970.

On August 23, 1988, Secretary Hodel forwarded a copy of the 1987 field report covering the studies conducted during the summer of 1987 on the hydrothermal processes in Crater Lake. In the transmittal letter, the Secretary promised additional reports on these studies as they became available.

On September 22, 1988, the Geothermal Steam Act Amendments of 1988 (P.L. 100-443) were signed into law (hereinafter referred to as the Act). Sections 2 and 6 of the Act directed the Secretary of the Interior to maintain a list of significant thermal features within units of the National Park System, and listed 16 units of the National Park System as containing significant thermal features. The Act legislatively adopted the Department's list of thirteen and

expanded it to include Crater Lake National Park and two other units of the National Park System as comprising the list of significant thermal features. Further, Section 7 of the Act mandated a report to Congress "on the presence or absence of significant thermal features within Crater Lake National Park" by March 1989.

B. Departmental Activities to Respond to the Act

On December 5, 1988, the Director of the National Park Service (NPS) asked the Congress for a delay in the submission date for the report until the summer of 1990 and promised to provide an interim report on the progress of the investigations at Crater Lake. In the Fall of 1989, the NPS submitted the interim report to the Senate Committee on Energy and Natural Resources and the House Committee on Interior and Insular Affairs.

The House Interior Subcommittee on Mining and Natural Resources held oversight hearings on September 28, 1989. The hearings addressed the implementation of the Federal Onshore Oil and Gas Leasing Reform Act of 1987 and the Geothermal Steam Act Amendments of 1988. The Subcommittee Chair asked the Department of the Interior to provide updates on the studies conducted at the Corwin Springs area north of Yellowstone National Park and those at Crater Lake National Park. Interior testified at the hearings that the final report would be completed for submission to the Congress by late summer of 1991. This report represents the findings of the completed research on the hydrothermal features at Crater Lake National Park and fulfills the requirements of Section 7 of the Act. This report does not address the question of a connection between the hydrothermal features in Crater Lake and areas of geothermal exploration on U.S. Forest Service lands near the Park. (The history of geothermal leasing near the park is included as Appendix D.)

III. CONCLUSIONS REGARDING SIGNIFICANCE OF THE HYDROTHERMAL FEATURES OF CRATER LAKE

A. Congressional Criteria for Determining Significance

As explained in the Introduction, Sections 2 and 6 of the Act includes Crater Lake National Park on the list of units of the National Park System containing significant thermal features. To some degree, the listing of Crater Lake National Park by the Congress supercedes this discussion of whether the hydrothermal features in Crater Lake "qualify" for significance under the criteria established by Congress under Section 6 of the Act. However, this chapter of the report addresses the significance of the hydrothermal features located in Crater Lake and will evaluate whether the hydrothermal features in Crater Lake would qualify for listing as if they were under consideration for the first time.

The Act requires the Secretary of the Interior to consider the following criteria in determining the significance of thermal features:

(1) Size, extent and uniqueness;
(2) Scientific and geologic significance;
(3) The extent to which such features remain in a natural, undisturbed condition;
(4) Significance of thermal features to the authorized purposes for which the National Park System unit was established.

The Department of the Interior provided an explanation of how these criteria would be applied to thermal features undergoing a determination of significance when it published the final list of significant thermal features in the Federal Register on August 3, 1987 (52 FR 28790). This discussion was revised to accommodate public comments received on the proposed notice published in the Federal Register in February 1987 (52 FR 4700). The Department's final explanation of how it would apply the Congressional criteria is excerpted below:

> "(1) Size, extent and uniqueness - Neither lower nor upper limits on the size or extent of a feature were established. Each feature is still identified according to its existing surface dimensions. In the proposed notice, a feature could be considered significant under this criterion as long as it was identified as unique to the park unit, as well as to Region, the Nation, or in some cases, the World. Public comments received on the application of this criterion stated that it was applied too broadly. As a result of reevaluating the application of this criterion, the Department decided that unless a feature was identified as unique to at least the Region, it should not automatically qualify as a significant thermal feature.
>
> "(2) Scientific and geologic significance - Under the proposed notice, a feature qualified as 'significant' if the feature contributed important information to scientific or geologic knowledge, to the

understanding of thermal regimes, or to the history or origin of the feature within the park unit, the Region, or the Nation. Also, the proposal considered biological factors as important to the scientific significance of a feature. The Department decided to define 'scientific significance' so as to exclude consideration of biological factors because they are considered and protected under the provisions of other laws, such as the National Environmental Policy Act and the Endangered Species Act. Also, the Department decided to narrow the qualifiers of this criterion so that only those features that satisfy the following conditions would meet this criterion: a feature must contribute to geologic knowledge compared with similar features in other areas or must make a unique contribution to the understanding of similar systems.

"(3) The extent to which such features remain in a natural, undisturbed condition - Under the proposed notice, the existing condition of identified features, described a full range of conditions, from completely undisturbed to commercially developed. As with size and extent, there were no limits established for amount or degree of development, but rather a judgment was made as to whether the amount of development was compatible with the purposes for which the park unit was established. The Department decided to limit qualification for significance under this criterion to those features which remain in a natural, relatively undisturbed condition, unless modifications were necessary to preserve a developed feature, consistent with the intent of the enabling legislation.

"(4) Significance of thermal features to the authorized purposes for which the National Park System units was created - The proposed notice considered this criterion being met if either: (a) A feature was specifically identified within the enabling legislation for the unit, or (b) a feature is being used in a manner consistent with the stated purposes for which the unit was created. The Department decided that features that are the basis for establishing the unit in the first instance (e.g., Yellowstone National Park or Hot Springs National Park) automatically meet this criterion, and that features that now significantly contribute to the statutory purposes for which the area was set aside by Congress could meet this criterion, but not automatically."

In the Geothermal Steam Act Amendments of 1988, Congress listed Crater Lake National Park as a unit containing significant thermal features. Congressional listing was effective September 22, 1988. The Department deferred its determination of significance until after the completion of research on the hydrothermal processes in the lake. Now that the studies are completed and the Department has more information upon which to base its determination, the Department determines that hydrothermal features are present at the bottom of Crater Lake and qualify as significant thermal features according to the following evaluation:

Crater Lake National Park

Feature: *Hydrothermal Features Located on the Floor of Crater Lake and Associated Thermal Water Entering Crater Lake*

Significance Criteria:

1. ***Size, Extent and Uniqueness:*** *The size and extent of significant thermal features in Crater Lake are defined by the areal distribution of fluid inflow at sites on the lake floor, the magnitude of the thermal water inflow, and the effect of the inflow on the entire lake (area of 53 square kilometers). The areal extent of the sites of fluid inflow is indicated by large areas of bacterial mats and visually spectacular blue pools located in the south basin and off Palisade Point. The magnitude of the thermal water inflow is approximately 10% of the total inflow to the lake and the dissolved constituents in the thermal waters dominate lake chemistry. The thermal fluids result in a convective heat flow which is the second largest of the 31 thermal spring systems in the U.S. portion of the Cascades. Crater Lake is the deepest and one of the clearest caldera lakes in the world and the hydrothermal inputs and their effect on the entire lake represent a thermal feature that is unique at least to the Region.*

2. ***Scientific and Geologic Significance*** *- The mixing processes at Crater Lake, driven by a combination of surface heat transfer and thermal input from the inflow of thermal water from the lake bottom, are scientifically and geologically important among deep, temperate lakes of the world. The inflow of thermal water has a direct effect on the density structure of the deep lake and affects the rate of heat transport and distribution of lake constituents. Also, the studies conducted and the techniques used to describe these thermal features contribute to the scientific understanding of deep lake processes.*

3. ***The extent to which the features remain in a natural, undisturbed condition*** *- The thermal features at the bottom of Crater Lake and the inflow of thermal water to the lake remain in a natural, undisturbed condition and were temporarily disturbed only to the extent necessary to conduct scientific research.*

4. ***Significance of the feature to the authorized purposes for which the unit was created*** *- Crater Lake National Park was established in 1902 to preserve the caldera lake and to assure the retention of its water quality (16 U.S.C. 121 et seq.). The hydrothermal inputs contribute to the properties of Crater Lake by affecting the lake's geochemical regimes and influencing the lake's mixing rates. Therefore, the hydrothermal inflow is an important contributor to lake processes and water quality.*

B. Hydrothermal Research in Crater Lake

by U. S. Geological Survey

Review of studies concerning the presence of
thermal water inflows into Crater Lake
by
Manuel Nathenson
U.S. Geological Survey

INTRODUCTION

The purpose of this section is to review available research that is relevant to the question of existence and significance of inflow of thermal water into Crater Lake. The pertinent research topics are:

- the formation of Crater Lake
- hydrologic and chemical balances for the lake as a well-mixed body of water
- thermal and chemical characteristics of springs on the flanks of Mount Mazama
- distributions of dissolved constituents as a function of depth in Crater Lake
- submersible observations in the deep part of the lake

The chemical balance of the lake shows that the inflow of warm, slightly saline fluid is important to explaining the chemical balance of Crater Lake. The data for springs on the flanks of Mount Mazama show what the temperatures and chemistry of non-thermal springs are in order to provide a basis for understanding the anomalies found in the lake. The distributions of dissolved constituents with depth show how the inflow of warm, slightly saline water affects the characteristics of water in the bottom part of the lake. The section on submersible observations describes features such as pools and bacterial mats on the bottom that result from the inflow of warm, slightly saline water and the samples that were obtained from these features.

This review is a summary of a large body of research performed by investigators primarily from Oregon State University, the National Park Service, the U.S. Geological Survey, and other institutions. Details of the various investigations can be found in the original references. Figures have been reproduced from the original studies with minor modifications to labels.

FORMATION OF CRATER LAKE

Mount Mazama is the name for the volcanic mountain in which Crater Lake caldera formed (Bacon and Lanphere, 1990). The oldest lavas of Mount Mazama are approximately 400,000 years old, and continuing volcanic eruptions built the mountain to a summit elevation of approximately 3600 m. At 6850 years before present, a violent eruption destroyed the top of Mount Mazama and created the Crater Lake caldera. The total volume of magma erupted was approximately 50 km^3. After the formation of the caldera, eruptions took place on its floor to form the central platform, Merriam Cone, and Wizard Island (Figure 1). The lake reached nearly its current level before the end of these eruptions. At about 4,000 years before present, a small dome was extruded on the east flank of Wizard Island (Figure 1). Whether these post-caldera eruptions are from the

magma chamber related to the climactic eruption or represent a new influx of magma is uncertain. In addition to the lava flows mentioned above, the floor of Crater Lake is comprised of debris from the caldera walls and relatively flat-lying sediments in the deep basins (Barber and Nelson, 1990).

HYDROLOGIC AND CHEMICAL BALANCES OF CRATER LAKE

Crater Lake is 53 km^2 in area, 589 m deep at its maximum depth, and has an average depth of 325 m. The average elevation of the lake is 1882 m, and steep caldera walls surrounding it range in elevation from 2050 to 2480 m. Most of the water supply is as direct precipitation because the lake area is 78 % of the total watershed area of 68 km^2. The lake has no surface outlet, and water is lost by evaporation and leakage. Phillips (1968) and Redmond (1990) have analyzed precipitation and lake-level data to calculate water balances for Crater Lake (Table 1). Although Redmond (1990) obtained a greater total water supply and a correspondingly larger value for evaporation than Phillips (1968), the two analyses are in reasonable agreement. None of the large springs in the area adjacent to Crater Lake show clear evidence of containing any of the leakage from Crater Lake (Thompson *et al.*, 1990).

Table 1. Water balance for Crater Lake in units of cm/year (volume per year divided by the lake area). Precipitation is volume per year for area of rain gauge.

	Runoff	Direct Precipitation	Total Water Supply	Leakage	Evaporation	Precipitation at Park Headquarters
Phillips	32	175	207	149	58	165
Redmond			247	127	120	169

The chemistry of dissolved constituents in Crater Lake water shows that there is an input of constituents in addition to those in precipitation and runoff from the caldera walls. For purposes of analyzing the amounts of major ions dissolved in Crater Lake water, the lake may be considered to be well mixed because vertical and horizontal gradients are small. Based on the water balance, known inputs from precipitation and runoff, and the assumption that the concentrations of dissolved constituents are constant over time, the theoretical major-ion chemical composition of the lake can be calculated. Because the amount of evaporation is an important parameter in this calculation, the calculated concentrations are given in Table 2 for the two values of the fraction of the total water supply lost to evaporation (28 % from Phillips, 1968, and 49 % from Redmond, 1990). For each major dissolved constituent in Table 2, the calculated concentration is substantially less than the measured concentration. This difference is strong evidence of input of thermal water into Crater Lake (Simpson, 1970; Nathenson, 1990b). Although the measured amounts of dissolved constituents in Crater Lake are anomalously high, overall the water is very low in total dissolved solids because of the direct input of large amounts of dilute precipitation.

Table 2. Concentrations of dissolved constituents (mg/L) in Crater Lake and calculated values based on available water supply (Nathenson, 1990b).

	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl
Measured	17.7	7.2	2.6	10.9	1.8	36.4	10.5	10.2
28 % evaporation	6.8	1.2	0.4	0.7	0.3	5.5	2.1	0.3
49 % evaporation	9.6	1.7	0.5	1.0	0.4	7.7	3.0	0.4

Analysis of historical data shows that concentrations of dissolved constituents in Crater Lake do not appear to be changing with time, and it is appropriate to do a steady-state chemical balance of the lake (Nathenson, 1990b). Using concentrations in the lake, precipitation, and flow from springs on the caldera walls, along with the assumption that inflows and leakage are steady-state, the steady-state rate of inflow of each constituent to the lake has been calculated and summed to obtain a rate of inflow of total dissolved solids. Nathenson (1990b) calculated an inflow of 200,000 mg/s using Phillips' (1968) value for the leakage from Crater Lake, and Collier *et al.* (1991) calculated an inflow of 110,000-140,000 mg/s using Redmond's (1990) value for the leakage. An independent calculation of the current rate of inflow of total dissolved solids was obtained from measurements of the vertical distribution of total dissolved solids in the bottom part of the water column for two periods in 1989 and 1990 (McManus *et al.*, 1991). Because these measurements are at the limit of available precision and because a precise measure of the area of increased dissolved solids is not possible without making many more measurements than is practical, the rate of current inflow calculated by McManus *et al.* (1991) is quite uncertain. However, the later value, which is 110,000±60,000 mg/s, demonstrates that inflow is still happening today, and that it is approximately equal to the steady-state inflow. Because the water residence time (lake volume divided by rate of leakage) of Crater Lake is about 220 years, a small change in the rate of inflow in the recent past would not be easily detected from the historical data for concentrations of dissolved constituents in Crater Lake.

SPRINGS IN THE VICINITY OF CRATER LAKE

A useful comparison for understanding thermal measurements in Crater Lake is provided by data for springs in the vicinity (Nathenson and Thompson, 1990; Nathenson, 1990a). To determine if a spring is thermal, the temperatures of other springs in the area provide a basis for determining that a spring has an elevated temperature. Figure 2 shows data for spring temperatures in the vicinity of Crater Lake versus elevation. The line shown on the diagram is a least-squares fit to air temperatures from twelve weather stations in southwestern Oregon showing the decreasing air temperatures with elevation. Except for the spring vents that are the source for the Wood River and other springs near the Wood River south of Crater Lake National Park, spring temperatures are generally less than air temperatures, and their variation with elevation is similar to that for air temperatures. Also shown are temperatures for Crater Lake taken at a time when the effects of summer heating in the upper 300 m were minimal. Temperatures in the bottom part of Crater Lake (that are less affected by seasonal variations) are neither particularly hot nor cold compared to spring temperatures at the surface elevation of Crater Lake. Temperatures for the various springs

that are the source of the Wood River range from less than air temperature to more than 2°C greater than air temperature. Springs of the Wood River group also have temperatures warmer than expected for their altitude. Temperatures for the Cedar Spring group on the other side of the Wood River Valley are not warmer than expected.

Concentrations of dissolved constituents in springs indicate the different processes involved in water/rock reaction. The first analysis in Table 3 is an average of data for springs above the lake and is typical of the process of low-temperature weathering of volcanic glass driven by dissolved carbon dioxide. The resulting water is notably low in dissolved chloride and sulfate, because these constituents are from precipitation, not low-temperature weathering of volcanic rock. The second analysis is for a spring on the caldera wall at Chaski Bay slide (not included in average of springs above the lake). In addition to constituents from low-temperature weathering, this water has excess calcium and sulfate that are dissolved from hydrothermal minerals formed during an earlier period of high-temperature alteration in the Chaski Bay slide. The chloride concentration in Crater Lake (the third analysis of Table 3) is noticeably elevated compared to either of these low-temperature waters. The composition of Crater Lake is also elevated in sulfate compared to most spring water, except for water from the Chaski Bay slide springs.

Table 3. Concentrations (mg/L) of dissolved constituents in representative springs (Nathenson and Thompson, 1990) and Crater Lake (Nathenson, 1990b).

	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl
Average of springs above lake	34	1.7	0.7	2.4	0.9	21	0.8	0.3
Chaski Slide-West	22	10.1	3.2	3.3	0.4	20	26	0.2
Crater Lake	17.7	7.2	2.6	10.9	1.8	36.4	10.5	10.2
Source of Crooked Creek	36.3	8.0	2.4	15.6	1.9	53	6.2	8.4

The last analysis of Table 3 is for one of the more concentrated springs near the Wood River south of the park. This water is very similar in chemistry to Crater Lake, with elevated chloride and sulfate concentrations. The lower silica in Crater Lake is caused by diatoms consuming silica and then settling to the floor of the lake when they die. Based on chemistry, one could interpret the water in springs in the vicinity of the Wood River as leakage from Crater Lake; however, the stable isotopes of water (deuterium and oxygen-18) show that these waters are not from Crater Lake. The slightly elevated temperatures of the springs near the Wood River and the similarity of their chemistry to that of Crater Lake water indicate that one component of the mixed waters found in the Wood River Valley has probably undergone the same reactions with rock as the water flowing into Crater Lake and that these reactions took place at some elevated temperature.

Soda springs on Minnehaha Creek northwest of the park boundary represent another type of anomalous water chemistry (Thompson *et al.*, 1990; Nathenson and Thompson, 1990; Mariner *et al.*, 1990). Both springs have elevated chloride concentrations (18 and 4 mg/L), but only one has elevated sulfate. Bicarbonate concentrations are quite high compared to all other springs (2300 and 420 mg/L), and the chemistry of these springs is probably caused by carbon dioxide dissolving in local groundwater and reacting with rock in the near surface. Other soda springs with high amounts of dissolved constituents and little or no anomalous temperature occur in the Cascades, and the source of the carbon dioxide is not well understood. The high amounts of bicarbonate relative to chloride for the soda springs on Minnehaha Creek probably indicates that these springs are unrelated to the process that produces the chemistry of the inflow to Crater Lake and the Wood River springs.

CHARACTERISTICS OF THE WATER COLUMN

The distribution of temperature with depth in Crater Lake shows that upper 200 m is well mixed and that the deep part of the lake is minimally affected by surface heating and cooling. Figure 3 shows profiles of temperature versus depth from the north basin for January and May (McManus and Collier, 1990). Note that the figure has a range of temperatures from 3.2° to 4.2°C. Lake surface temperatures reach a maximum in August (about 15° to 20°C). From around mid-August to the beginning of spring, the surface temperature of the lake decreases, and the cooled water produced at the surface sinks and mixes with warmer water in the near surface. As the surface cooling proceeds, the mixed layer becomes progressively deeper. The January 1990 profile shows that surface temperatures have cooled to less than 4.2°C and that the vertical mixed zone of uniform temperatures has proceeded to 200 m. Continued cooling for the rest of the winter forces temperatures in the near surface below 3°C. Temperatures in the upper 150 m are less than temperatures shown for the May profile and less than temperatures for the line shown for the maximum density of water as a function of depth (pressure). At a given depth, water at temperatures greater or less than value shown for the line is less dense than water with a temperature on the line shown for temperature of maximum density. In late March, surface temperatures start to increase. This warm surface-water is actually denser than cooler water below it in the upper 150 m, because the lake temperature is less than the temperature of maximum density, and the surface water sinks and mixes with cooler water. The profile for May 1989 shows uniform temperatures to a depth of 200 m, indicating that mixing has been maintained to this depth. Salinity measurements for the upper 200 m of the lake (not shown) confirm that the mixing process is also effective in making the salinity uniform, except for near surface concentration due to evaporation. The two temperature profiles are closest at about 400 m, and this is probably the deepest effect of the seasonal heating and cooling at the surface. Continued warming in the spring and early summer produces warmer, less dense water at the surface of the lake that is stable.

Below 350 m, lake temperatures increase with depth, and this increase requires an active input of thermal energy at depth. Figure 4 shows temperature for the south and north basins of the lake and salinity for the south basin. Note that the temperature scale in this diagram is expanded compared to Figure 3, and the range is only 0.1°C. The salinity

measurements are at the limit of sensitivity of the instrument used, and that is part of the reason for the step nature of those values. The increase in temperature with depth below 350 m is found throughout the lake. The difference in temperature between the south and north basins reflects a greater input of thermal energy in the south basin. Additional temperature data in McManus *et al.* (1991) show that warm water flows from the south basin to the north basin. The increase in salinity with depth by itself causes increased density with depth, but the increasing temperature with depth by itself causes decreased density with depth. The stability of the deep part of the water column is shown in the last diagram which is Sigma (theta) = (potential density-1)x1000. The potential density is used to show water column stability by removing the effects of pressure and adiabatic cooling on density. Potential density is the calculated density at each depth as if the water parcel was moved adiabatically to a common reference pressure at the surface. There is a very slight increase in potential density with depth in Figure 4, implying that the deep water column is stable at this time of year.

Although the increase in temperature with depth in Crater Lake is very small, it is real and implies that there is high heat flow into the bottom part of the lake (McManus *et al.*, 1991). Temperature-depth profiles taken at three times over a four-month period in 1989 (Figure 5a) show a small but significant increase in temperature in the deep part of the lake as the year proceeds. Given the stable depth stratification of the lake water, this increase must be due to heat addition in the bottom part of the lake. The two profiles in Figure 5b show that warm water in the bottom part of the January 1990 profile has mixed with water above it by July 1990, and the bottom part of the lake has cooled by a small but significant amount. This mixing event probably took place in February 1990 at a time of minimum stability for the water column in the upper part of the lake. Calculation of the rate of heating shows that even though the change in deep lake temperatures is very small, the large size of the lake yields a heating rate of 20 megawatts of thermal energy. Dividing this total heat flow by the 31 km^2 area of the deep part of the lake as represented by the 300-m depth contour yields an average heat flow of 650 mW/m^2 (milliwatts per square meter). Regional heat flow in the high Cascades of Oregon is 100 mW/m^2 (Blackwell *et al.*, 1990). Thus, this estimate of the average heat flow into the bottom of Crater Lake is approximately 6 times the regional value. Heat flow measurements in the sediments of Crater Lake using oceanographic techniques found that 12 out of 62 measurements were higher than 300 mW/m^2, and 7 of those 12 were greater than 550 mW/m^2 (Williams and von Herzen, 1983). Although these are conductive heat flows because they are calculated as the product of thermal conductivity times the measured temperature gradient, the high values reflect convection of water either through the sediments or localized in a nearby vent. Thus the source of the heating found from increased bottom-water temperature must be from an inflow of warm water.

The small change in salinity with depth shown in Figure 4 indicates that major elements measured at usual analytical sensitivities will not easily yield diagnostic information on lake processes. Fortunately, measurements of some other constituents are more readily diagnostic (Collier *et al.*, 1991). For example, helium isotopes provide a tool with much higher analytical sensitivity. Figure 6 shows ^3He versus ^4He for various samples, and Figure 7 shows ^3He versus depth. In the atmosphere, ^3He and ^4He are

found in a fixed ratio shown by the constant slope of the broken line in Figure 6. The two samples for caldera wall springs are close to this line, indicating that the springs are in equilibrium with helium in air, as expected. The other samples in Figure 6 have a constant ratio as shown by their following the solid line, and the slope of this line is diagnostic of the input of helium derived from the mantle. Helium from the mantle that is found near the surface is frequently associated with the degassing of magma. The variation of ^{3}He and ^{4}He along the solid line in Figure 6 reflects mixing of water that was in equilibrium with air with varying amounts of helium with a mantle ratio. Based on this model for sources of helium, the variation with depth of ^{3}He shown in Figure 7 is diagnostic of several lake processes. The upper 200 m of the lake are essentially at a uniform concentration of ^{3}He that reflects equilibrium with the helium in air. This confirms the interpretation of the temperature data in Figure 3 that this upper part of the lake is very well mixed. The lower part of the profiles shows higher concentration in the south basin where higher temperatures are found and lower concentrations in the north basin where lower temperatures are found. The variation with depth shows that the deep-lake mixing process is not as efficient as the near-surface mixing process.

Inefficient deep mixing is confirmed by model calculations for the input of anthropogenic chlorofluorocarbons that show that the time scale for complete mixing of water in the bottom part of the lake with water in the upper part of the lake is about 2 to 3 years (Weiss, 1991). The bottom part of Crater Lake is well oxygenated but slightly deficient compared to the upper lake which is in equilibrium with the atmosphere (McManus *et al.*, 1991). The well oxygenated character also confirms that the lake does mix to total depth, whereas the slight deficiency confirms that this mixing is not as efficient as in the upper lake. Additional confirmation of mixing to total depth comes from the stable isotopes of deuterium and oxygen in water. Evaporation at the lake surface fractionates these isotopes in a characteristic manner, and samples obtained at various depths show that this evaporated water is found throughout water column (Thompson *et al.*, 1990).

That a fluid must be entering the south basin is demonstrated by the two profiles of ^{222}Rn versus depth in Figure 8 (Collier *et al.*, 1991). The radioactive element ^{222}Rn has a half-life of 3.8 days and is added to water as it circulates through rock. The high values at total depth in Figure 8 show that this deepest water was recently circulating through rock.

The basic process that governs the properties of the water column in the deep part of the lake is mixing between an inflow of a warm, slightly saline, helium-enriched fluid with lake water that is lower in salinity and helium concentration. The mixing of warm, slightly saline water with lake water is shown by the plots in Figure 9 of temperature and several major dissolved constituents versus ^{3}He for samples of the deep water column in the south basin. The range of variation for temperature and dissolved constituents is quite narrow in Figure 9. Recognizing that some of the scatter is from analytical uncertainty, the data show a linear correlation between each quantity and ^{3}He, which implies that there is a single source fluid that is warmer and contains higher levels of ^{3}He and dissolved constituents. Because of rapid dilution of the inflow at sites of fluid venting, there could be a fluid with values of temperature and dissolved constituents well beyond the range shown in Figure 9.

DEEP-LAKE OBSERVATIONS

A major objective of submersible operations in Crater Lake was to find sites of inflow and to obtain samples of the warm, slightly saline source fluid. Deep lake observations are given in Collier *et al.* (1991), which contain photographs of pools and bacterial mats found on the lake floor. No obvious large-scale plume was visually observed; however, some hydrothermal systems found by submersible operations in the ocean also lack visual evidence of plumes. Features observed in the submersible operations in Crater Lake were pools and bacterial mats in the south basin and a mat and pool complex off Palisade Point northeast of Merriam Cone. Maximum temperatures measured in the two major pools studied were 4.5°C in Llao's Bath and 5.5°C in the Palisade Point pool. Temperatures in bacterial mats and in sediments were significantly higher than lake temperature (Figure 10) and ranged to 18.9°C in a single-point measurement in a mat during dive CD229. The nonlinear character of temperature versus depth in the measurements for some of the mats and sediments (Figure 10) shows that there is movement of warm fluid through the sediments. Fluid samples obtained from gravity cores in the sediments also have nonlinear variations of concentrations of major dissolved constituents with depth, showing that there is movement of more saline water through the sediments (Wheat, 1991). Mat material was found to have iron as the most abundant material and to be enriched in arsenic and manganese.

The pools are an ideal environment for collecting samples, but they are lower in temperature than the bacterial mats. The mats appear to be the site of higher temperature venting, but it is difficult to collect samples that are not well mixed with lake water. Thus the observations of higher temperatures in the mats cannot be connected directly with the most concentrated water samples from the pools. Nevertheless, the correlations of temperature and solutes with ^{3}He (Figure 9) demonstrate that there is a source of fluid with a high value of the ratio of temperature to solutes. That there is more than one fluid with differing ratios of temperature to solutes is shown by data for simultaneous measurements of temperature and salinity obtained during several dives of the submersible (Figure 11). The data for higher salinities and temperatures define a field that can be enclosed by projections towards two compositions of differing ratios of temperature to salinity. Based on finding low-temperature, more saline fluid in the pools, it seems likely that the point labeled "b" with a low ratio of temperature to solutes is produced by fluids losing thermal energy in the subsurface before they flow into the pools. The point labeled "a" with a high ratio of temperature to solutes is probably that from the higher-temperature bacterial mats. The submersible measurements define the ratios of temperature to salinity for these two fluids but are too diluted with lake water to define the limiting temperature or concentration. Figure 12 shows the extrapolation of these ratios to the highest salinity fluid sampled. The maximum temperature obtained is about 25°C.

Fluid-chemistry samples from Llao's Bath and the Palisade Point pool (Table 4) show enrichment in those elements necessary to explain the composition of Crater Lake compared to the available water supply from precipitation and runoff from the caldera walls. The bottom part of the table presents the major-ion chemistry as amounts of ionic

charge expressed as per cent of total cations (Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}) and anions (HCO_3^{-}, SO_4^{-2}, and Cl^{-}). The utility of looking at a water analysis in this manner is that it allows the relative proportions of the various dissolved constituents to be compared on a common basis. The equivalent percentages shown in the table for magnesium and chloride, for example, indicate that the waters from the pools are different in relative concentrations from each other and from that in Crater Lake. This difference in relative concentrations can be more easily assessed from the mass ratios in the last two columns of the table. The ratio Na/Cl is 1.0 in the lake, but it is 1.8 and 2.9 in the pools. Assuming that the major determinant of lake chemistry is the concentrated inflows, there are a couple of possibilities to explain this difference. One interpretation is that the major fluid source feeding the lake has not yet been found. A second is that the hydrothermal system at Crater Lake is evolving, and that the chemistry of the water has recently changed. An indication that this might be the case is the discovery of apparently inactive silica spires near Skell Head in the north basin southeast of the Palisade Point pools. The precipitation of silica indicates a higher temperature at these locations than any yet measured on the lake floor.

The stable isotopes of water for samples from Llao's Bath and the Palisade Point pool show that the source of the water is circulating lake water and that the water has probably not undergone high-temperature (>200°C) reaction with rock (Collier *et al.*, 1991). The samples from Llao's Bath and the Palisade Point pool have essentially the same concentrations as lake water of the stable isotopes of deuterium and oxygen in water.

Table 4. Concentrations, equivalents per cents, and mass ratios of dissolved constituents in the deep part of Crater Lake and for pool samples obtained by the submersible (Collier *et al.*, 1991).

			Concentrations (mg/L)								
	T (°C)	pH	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Li
Crater Lake (deep samples)	3.67	6.95	19.7	7.2	2.9	10.8	1.8	39	9.6	10.3	0.05
Llao's Bath	4.4	7.6	71.4	37.7	27.2	64.4	8.8	303	66	36.5	0.24
Palisade Point pool	5	8.91	45.8	25.7	53.7	118.2	4.85	531	81	40.8	0.21

	Equivalents (%)								
	Cations				Anions			Mass ratios	
	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{-2}	Cl^{-}	Na/Cl	SO_4/Cl
Crater Lake (deep samples)	32	21	42	4.2	57	18	26	1.0	0.93
Llao's Bath	26	31	39	3.1	67	19	14	1.8	1.8
Palisade Point pool	12	40	47	1.1	75	15	10	2.9	2.0

Deuterium values in spring samples in the vicinity of Crater Lake are quite different from lake water, because the deuterium and oxygen isotopes in precipitation are modified by evaporation in the lake. If the water feeding the pools had a deuterium content similar to that of the springs before mixing with lake water, the pool samples would have to mix with 10 to 20 parts of lake water in order for the pool samples to end up with a deuterium content that is indistinguishable from lake water. The carbon-14 isotope content for the sample from Llao's Bath shows that it can be no more than 50 % lake water. The dissolved oxygen content of the sample for the Palisade Point pool is very low, indicating very little mixture with well oxygenated lake water. Thus, the deuterium contents of the pools are only slightly modified from that for the fluid that feeds the pools, and the source of the fluid in the pools is lake water that has circulated to depth to be heated and react with rock. The oxygen isotopes of lake water are also modified by evaporation of precipitation, but they can undergo additional change if they react with rock at high-temperature. Collier *et al.* (1991) have calculated the change in oxygen isotopes of water for various ratios of water to rock as a function of temperature. Unless the water to rock ratio is very high, the similarity of the oxygen isotopes of the pool samples and lake water indicates that equilibration temperatures are less than 200°C.

Chemical geothermometer temperatures calculated from major-element concentrations for the pool samples suggest that inflow temperatures may be higher than measured temperatures. These chemical geothermometers are experimental or empirical relations for temperatures determined by the equilibrium between major elements dissolved in water and rock. The calculation of geothermometer temperatures for the composition of lake water is not strictly appropriate, because the lake water is clearly a mixture of a more saline water with water from precipitation and springs on the caldera walls. The pools provide more appropriate samples for geothermometer calculations, but their high magnesium concentration compared to calcium and potassium concentrations indicates caution in using geothermometer temperatures. In most thermal waters, magnesium concentrations are very low, because magnesium preferentially stays in the solid phase when water reacts with volcanic rock at elevated temperatures. Accordingly, in some waters, high magnesium concentrations indicate that the water is equilibrated at low temperature. However, in other cases, high magnesium concentrations are caused by mixing a higher-temperature water with a cold water and subsequent reaction at the mixed temperature. Geothermometer temperatures (chalcedony, Mg-Li, K-Mg) for Llao's Bath range from 50° to 90°C and for Palisade Point pool from 35° to 70°C. Based on the high magnesium concentration, the Mg-corrected Na-K-Ca geothermometer relations of Fournier and Potter (1979) would indicate that the water has equilibrated at the spring temperature (for example the 19°C temperature measured in one mat). Na-Li geothermometer temperatures are 165°C for Llao's Bath and 110°C for Palisade Point pool (Collier *et al.*, 1991), but these high temperatures are not corroborated by other geothermometers.

An interesting comparison can be made to Swim Warm Springs on the flanks of Mt. Hood, Oregon. The measured spring temperatures range to 26°C, and the geothermometer temperatures range from 30° to 110°C, also with high magnesium contents (Wollenberg *et al.*, 1979; Mariner *et al.*, 1990). The chemistry of Swim Warm Springs is

interpreted to result from a higher temperature water (≈110°C) from near the central vent of the Mount Hood volcano flowing in the subsurface, mixing with cold water, and re-equilibrating some of its constituents to the mixing temperature. A similar model could explain the chemistry of waters sampled in the two pools in Crater Lake. Furthermore, a maximum temperature of 130°C was measured at a depth of 1067 m in a well drilled east of the park in the Winema National Forest to a depth of 1423 m (LaFleur, 1990). Based on the comparison to Swim Warm Springs and the high measured temperature in the well, it is reasonable to speculate that there are higher temperatures in the inflow to Crater Lake than those that have been measured.

CONCLUSIONS

Several important conclusions about characteristics of Crater Lake and fluid inflow into the lake have been reached as a result of recent research studies. Submersible operations have measured temperatures of 8, 10, 13, and 19°C in the bacterial mats at the bottom of the lake. Ambient temperatures in the lake are 3.6°C, and springs at the surface elevation of the lake range in temperature from about 2° to 5°C. Thus the measured mat temperatures are clearly anomalous and meet definitions of thermal springs on land (several definitions are reviewed in Nathenson, 1990a and Mariner *et al.*, 1990). Pools found on the floor of the lake have elevated amounts of the dissolved constituents needed to explain the chemistry of the lake but not quite in the right proportions to account for the present composition of lake water. Temperatures of these pools are elevated compared to the lake temperature, but are not as high as temperatures measured in the bacterial mats. Geothermometer temperatures calculated from analyses of pool samples tend to indicate that the fluid is low-temperature (30°-90°C). The presence of $^{3}He/^{4}He$ with a mantle signature and significant amounts of chloride, boron, and lithium permit speculation that there is an intermediate-temperature (>90°C) water that has been modified by subsequent reaction. The source of the fluid in the pools is lake water that has circulated to depth to be heated and react with rock. Although no obvious venting was visually observed, the nonlinear gradients of temperature and dissolved constituents found in the sediments and bacterial mats clearly indicate flow into the lake, as does the presence of pools with anomalous fluid compositions. The warm, slightly saline water that flows into the lake is found to collect in the bottom part of the lake for much of the year. At the time during the year of minimum water-column stability, the warmer bottom water mixes imperfectly with surface water. Although the greater salinity of the added water tends to make the bottom water stable, the added temperature tends to make it unstable. Without the input of warm water at depth, the mixing properties of the deep lake likely would change, and Crater Lake might no longer mix to total depth. Lake Tahoe depends on winter storms to mix and mixes to total depth only in some years (Goldman and Jassby, 1990). Because of the much smaller average radius of Crater Lake (4.1 km) compared to Lake Tahoe (12.6 km) but similar total depths (589 m compared to 501 m), winter storms might not be effective in mixing Crater Lake to total depth.

In summary, the research program at Crater Lake has demonstrated an inflow of thermal water that is important to lake dynamics. The characteristics of this thermal water and its impact on lake dynamics remain imperfectly understood.

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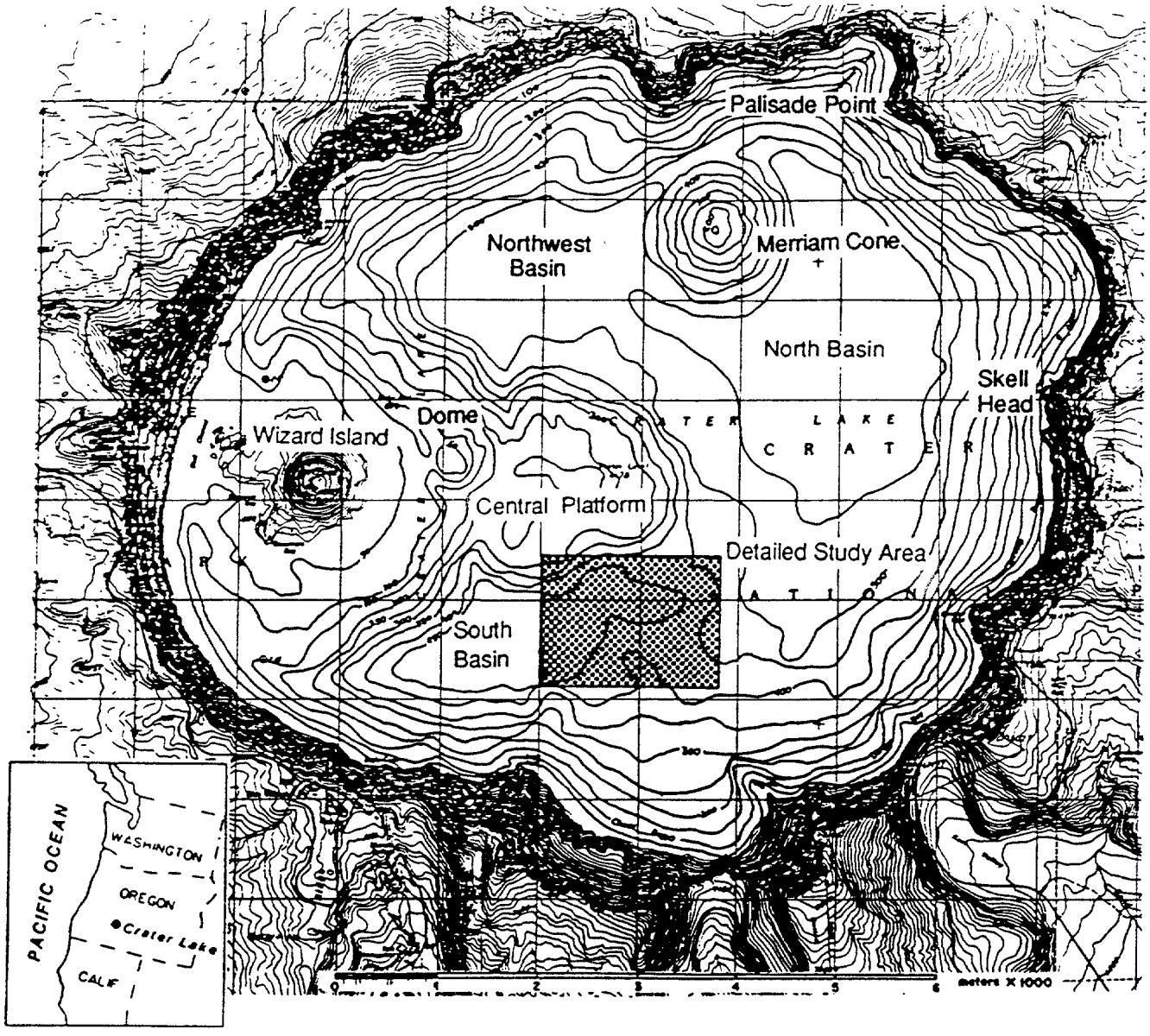

Figure 1. Bathymetric map of Crater Lake along with topography of immediate vicinity (Collier *et al.*, 1991). Bathymetry in meters and topography in feet. Detailed study area is where most of the sampling and submersible operations took place.

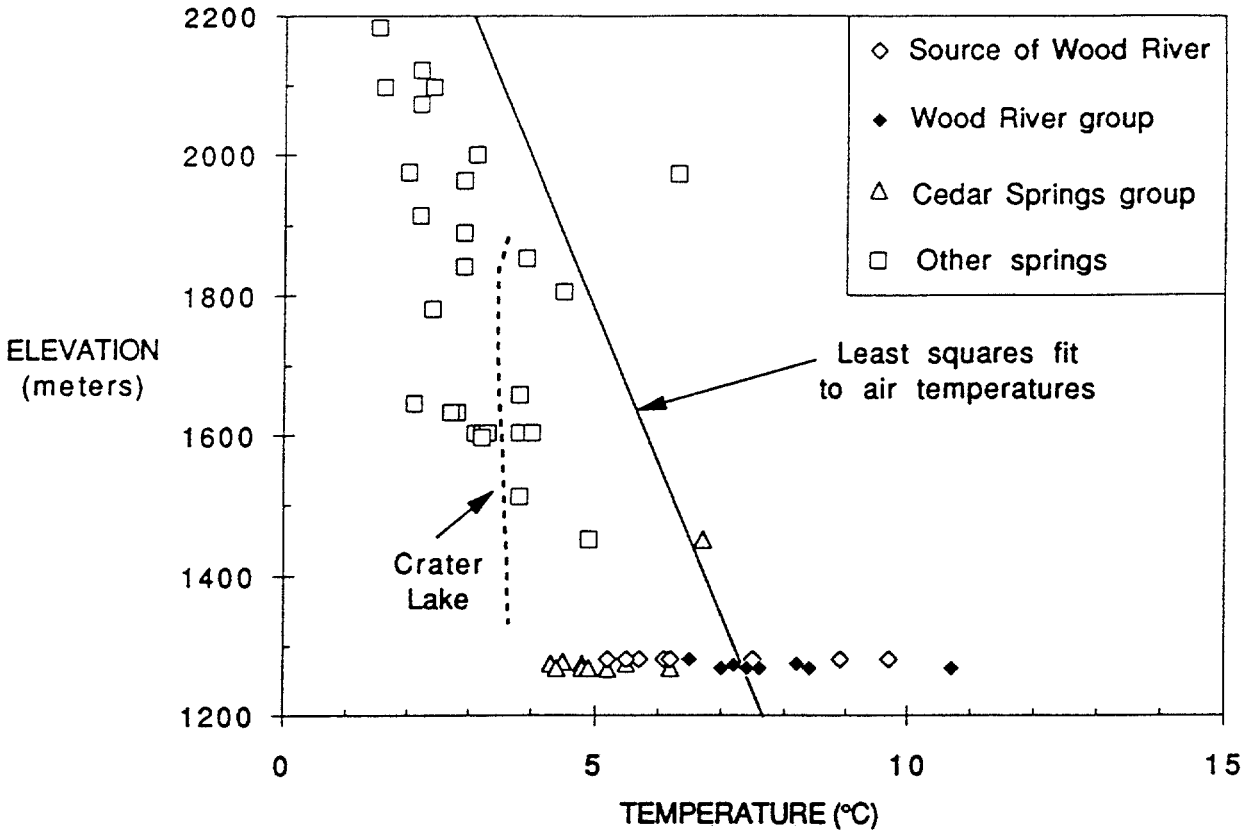

Figure 2. Elevation versus temperature for springs in the vicinity of Crater Lake (Nathenson, 1990a). Cedar Springs group, source of Wood River, and Wood River group are located south of the park boundary. Solid line is least squares fit to air temperatures from weather stations in southwestern Oregon. Broken line shows water temperature versus elevation for Crater Lake for 19 June 1971 when effects of near-surface heating or cooling are minimal.

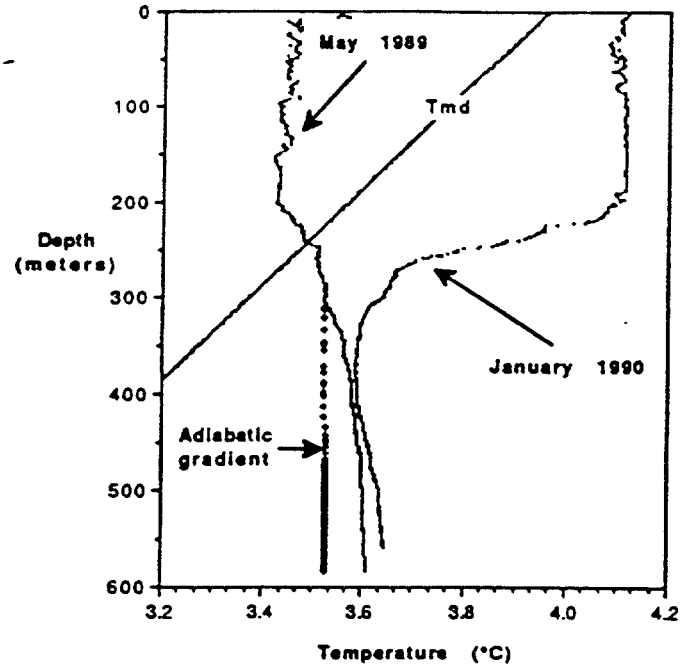

Figure 3. Depth versus temperature for Crater Lake for May 1989 and January 1990 (McManus and Collier, 1990). The line marked Tmd shows the temperature at which water is at its maximum density versus depth (pressure). The adiabatic temperature increase shows what temperatures would occur in the deep part of the lake if the lake were well mixed from 310 m to total depth.

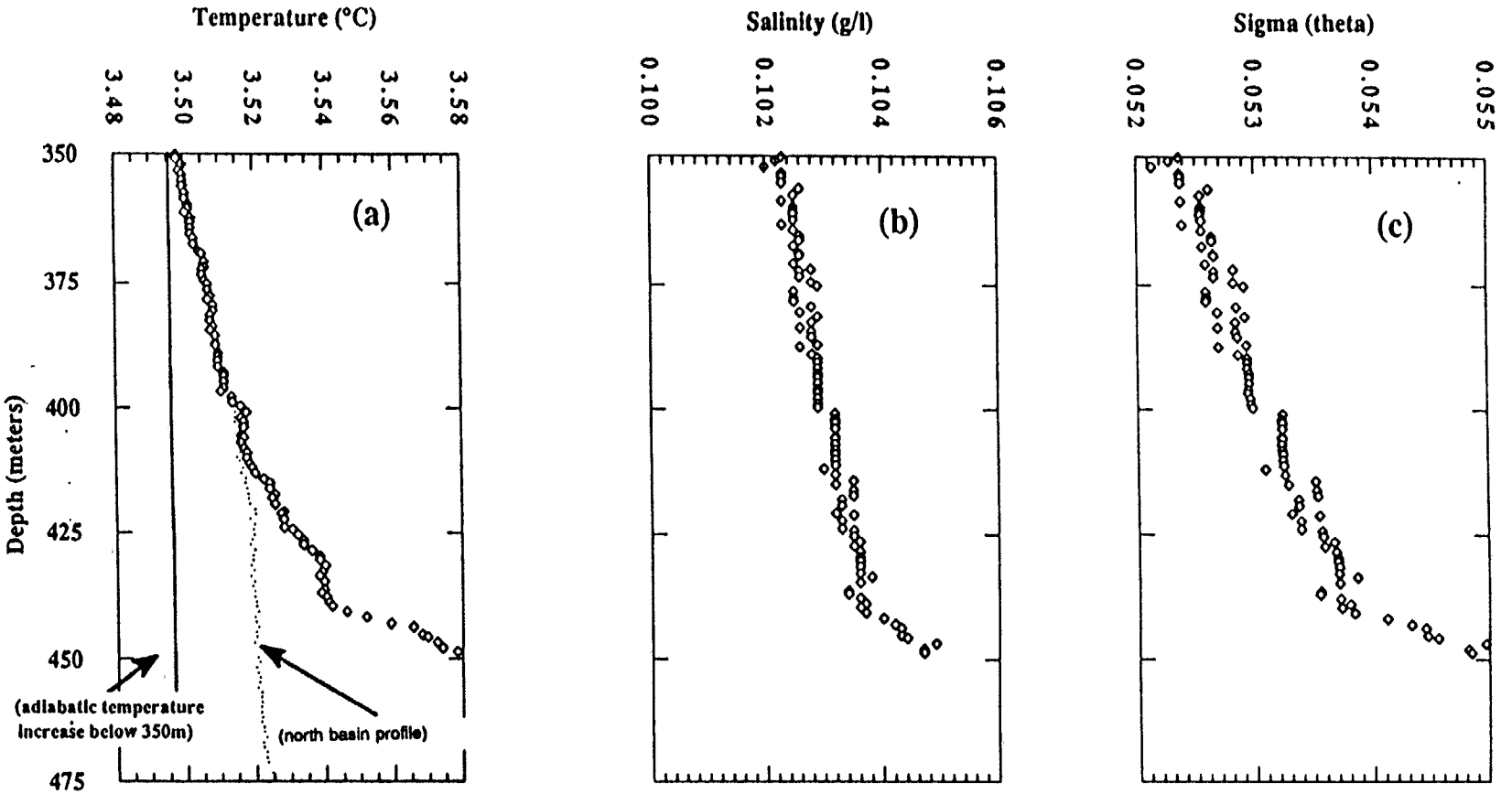

Figure 4. Plots at expanded scales for data in the bottom 100 meters of the south basin and for temperature only of the north basin of Crater Lake (Collier *et al.*, 1991). (a) Plot of temperature versus depth for south basin (diamonds) and north basin (points). The adiabatic temperature increase shows what temperatures would occur in the deep part of the lake if the lake were well mixed from 350 m to total depth. (b) Plot of salinity versus depth for south basin. (c) Plot of Sigma (theta) = (potential density-1)x1000 versus depth.

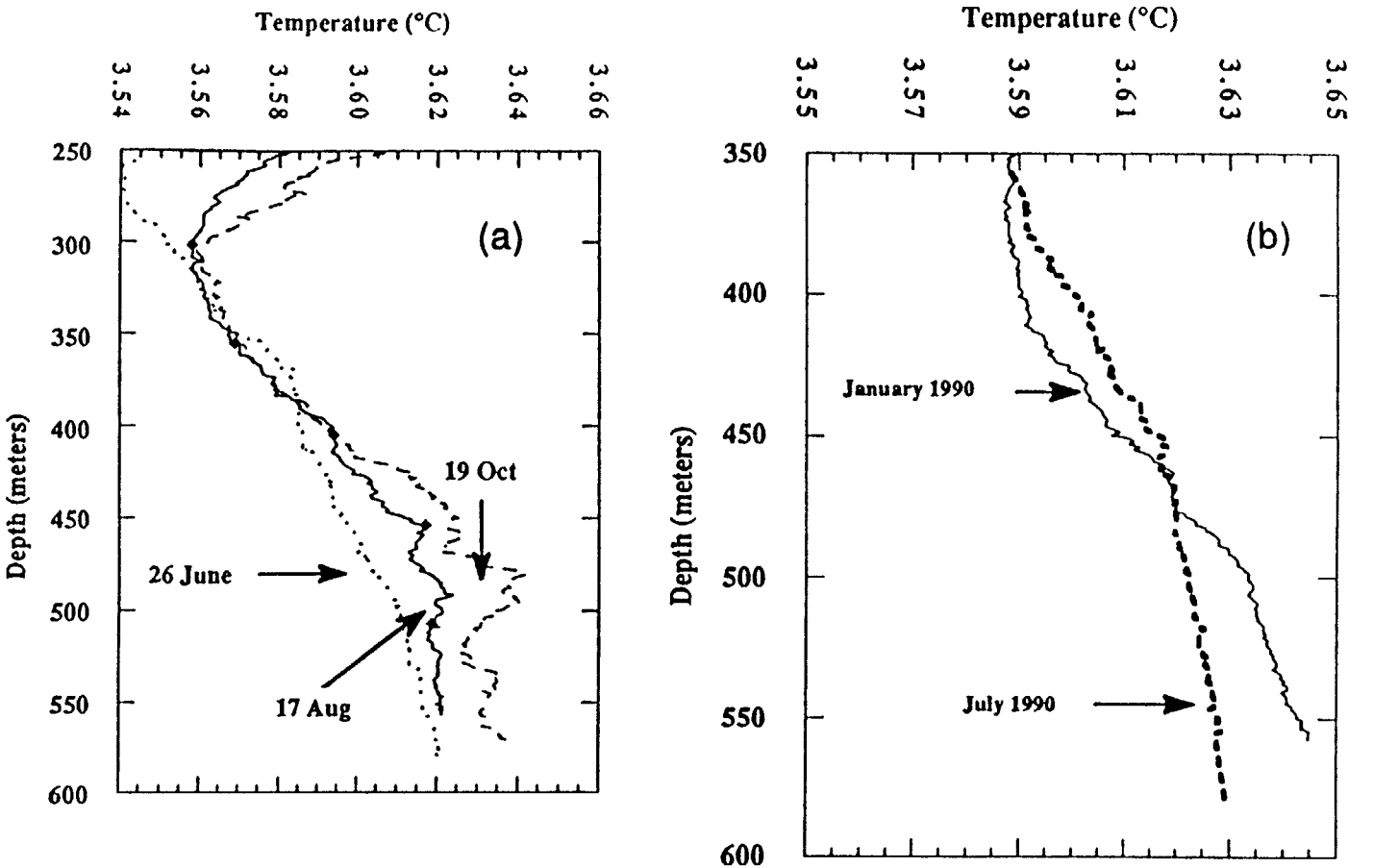

Figure 5. Temperature versus depth in the north basin of Crater Lake (McManus *et al.*, 1991). Note that depth range is different in the two diagrams. (a) Temperatures in 1989 showing addition of thermal energy over a four-month period. (b) Temperatures in 1990 showing decrease in bottom-water temperature from January to July 1990.

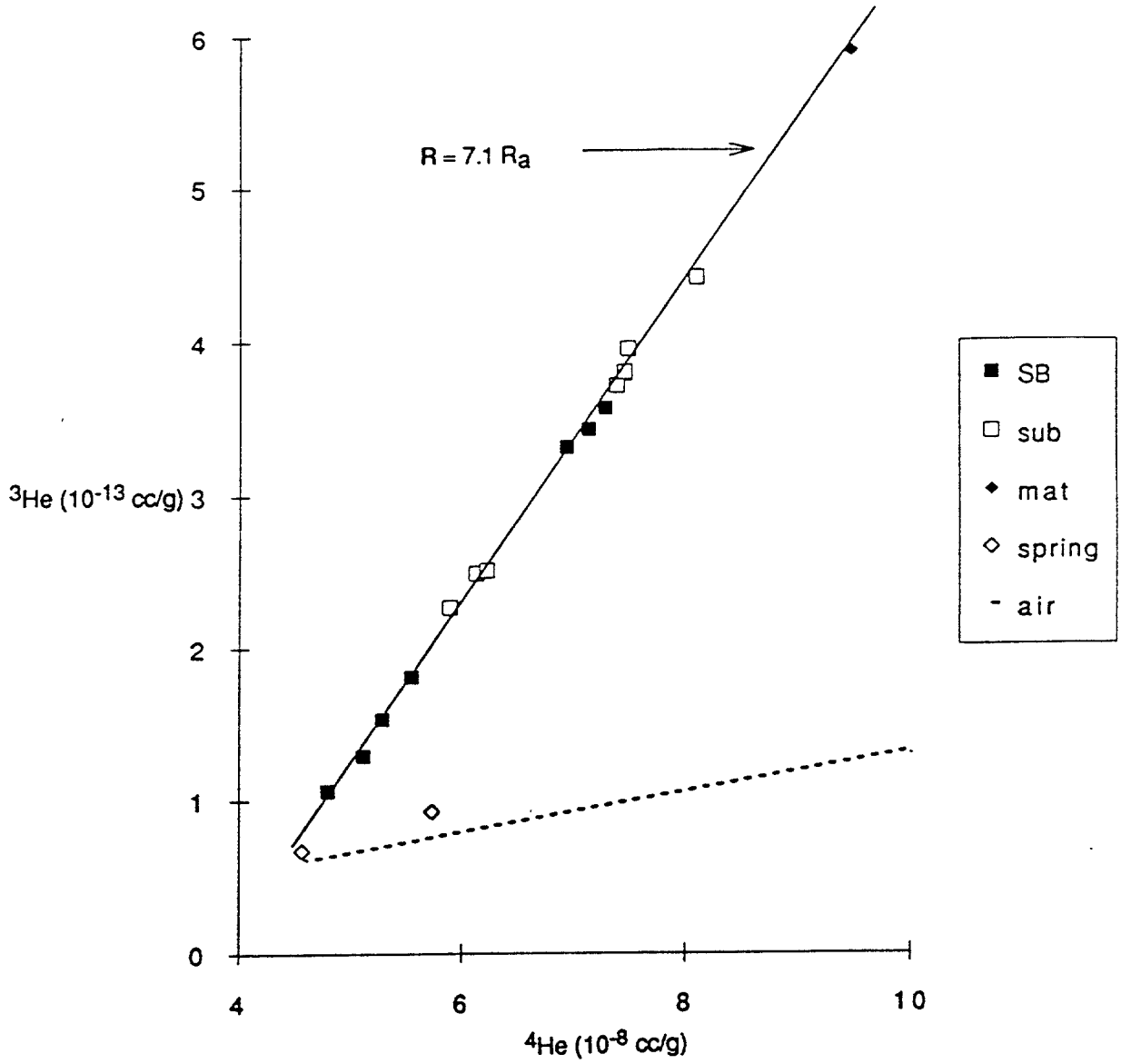

Figure 6. Concentration of ^3He versus ^4He for Crater Lake and spring samples collected in 1989 (Collier *et al.*, 1991). Broken line shows variation for samples in equilibrium with air of ratio $R_a = (^3He/^4He)_a \approx 1.4 \times 10^{-6}$. Solid line shows relation for Crater Lake samples with a slope $R = 7.1\ R_a$. SB is south basin.

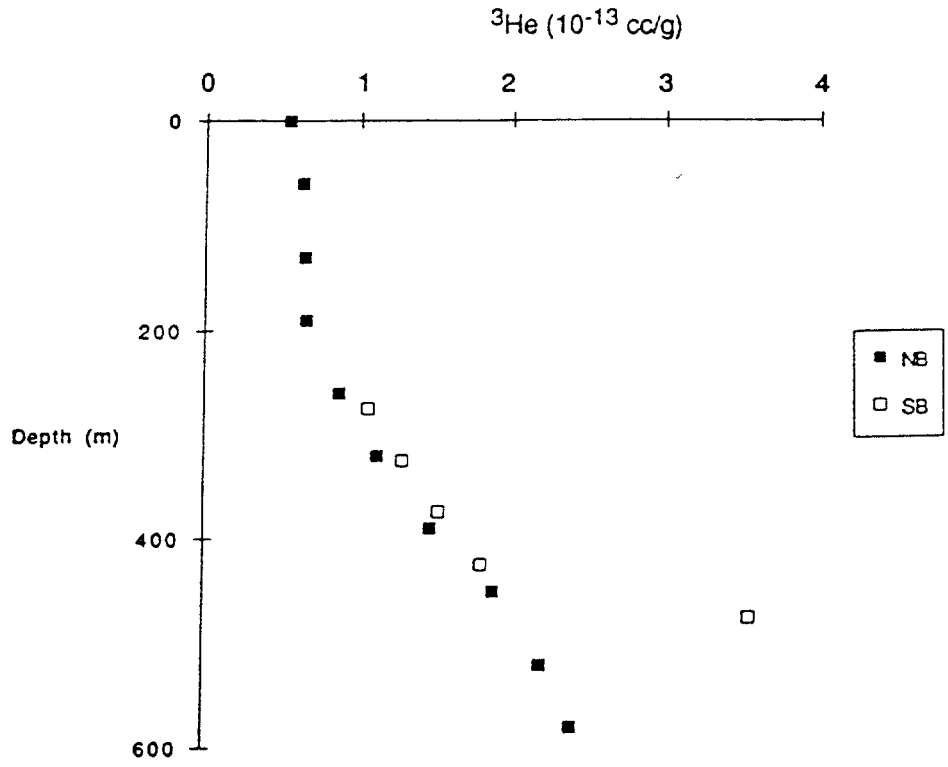

Figure 7. ^{3}He concentration (cubic centimeters at standard temperature and pressure per gram of water) versus depth for north basin (NB) and south basin (SB) of Crater Lake (Collier *et al.*, 1991).

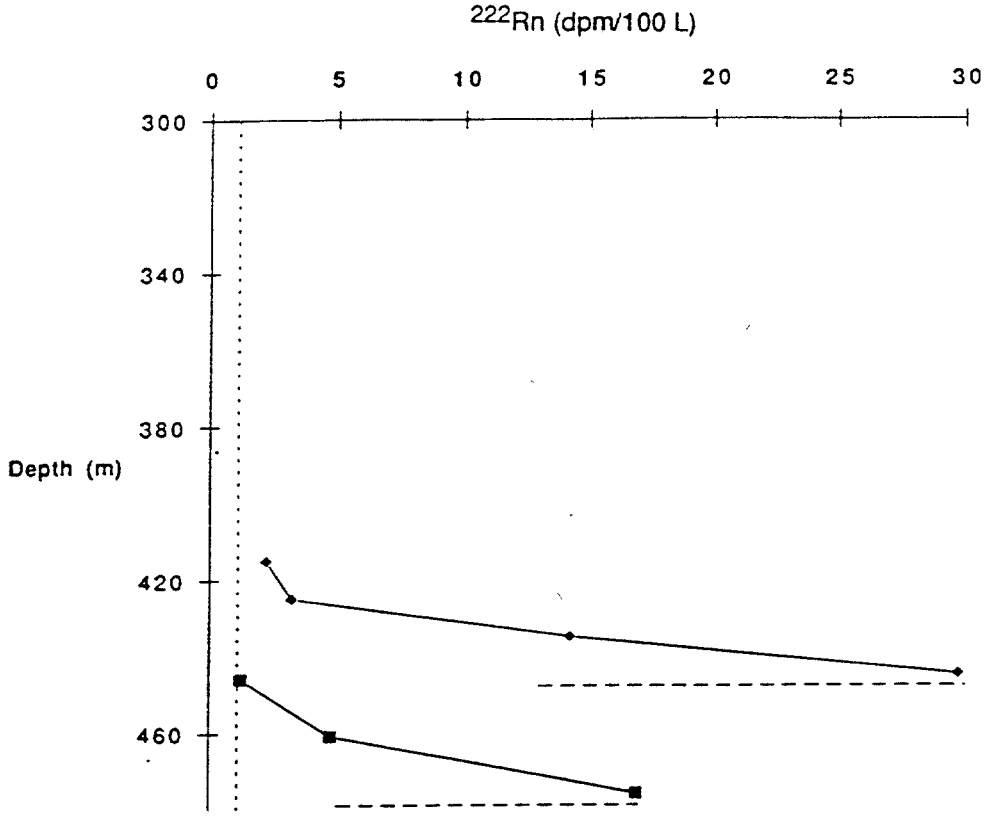

Figure 8. ^{222}Rn contents in disintegrations per minute per 100 liters (dpm/100 L) versus depth for two profiles in the south basin (Collier *et al.*, 1991). Vertical broken line shows the amount of ^{222}Rn from the decay of ^{226}Ra dissolved in the lake water.

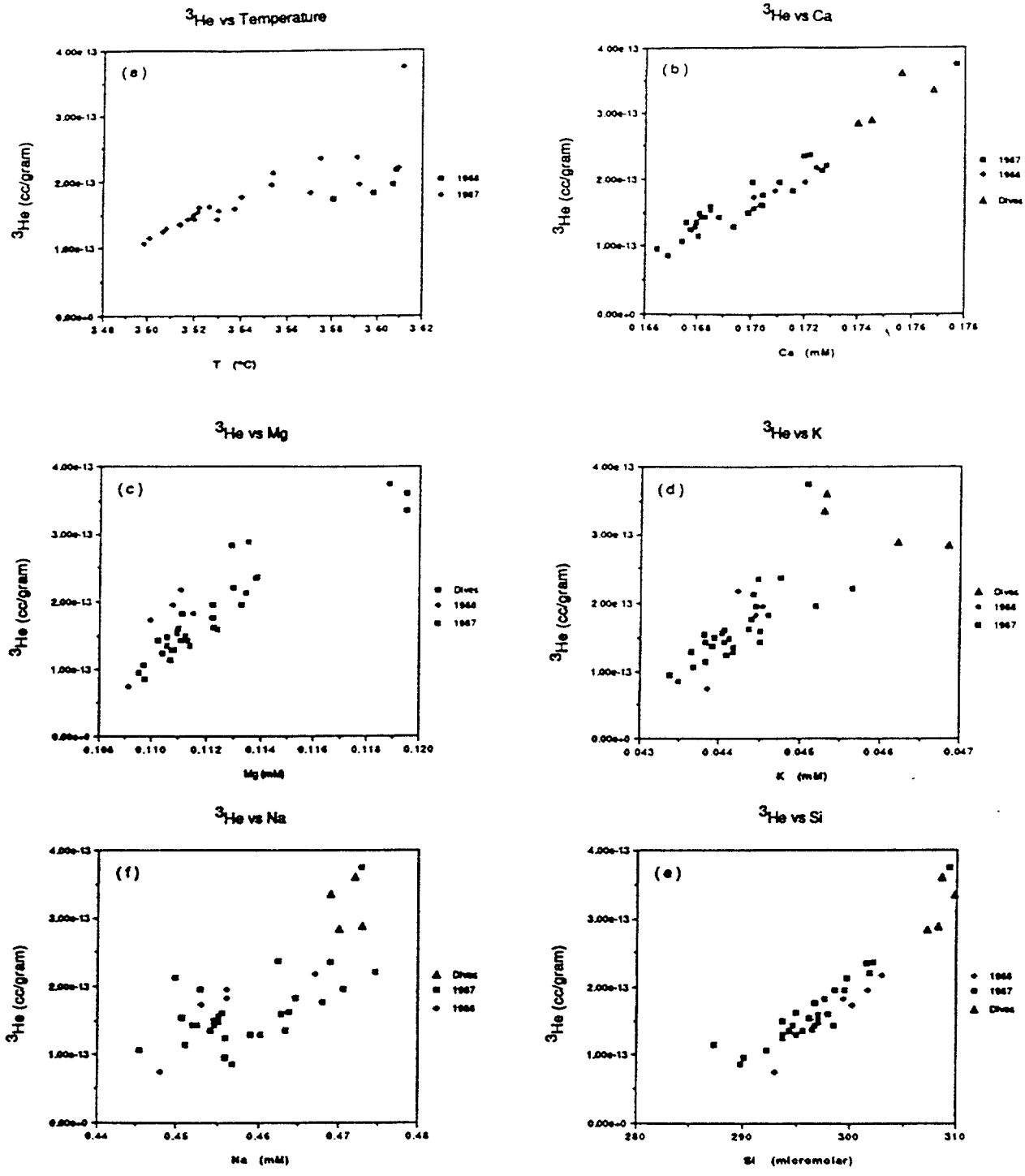

Figure 9. Concentration of ^3He versus temperature and dissolved constituents for samples from 1987 and 1988 (Collier *et al.*, 1991). Dissolved constituents are reported as millimoles (mM) and micromoles per liter. Molar concentrations are obtained from weight concentrations by dividing by molecular weight of constituent.

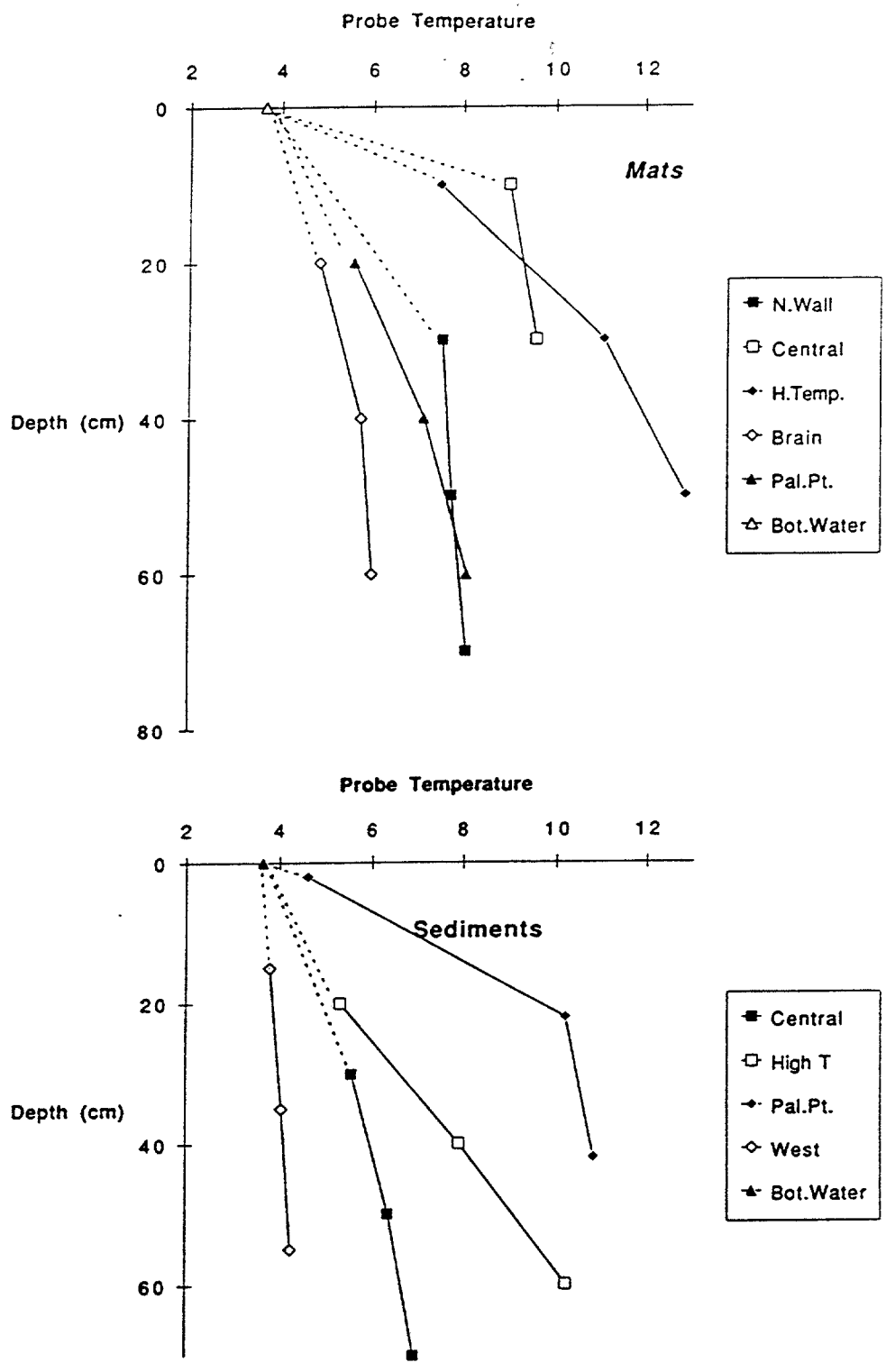

Figure 10. Temperature versus depth for mats (top) and sediments (bottom) obtained by using probe from submersible (Collier *et al.*, 1991). Key is for locations named in Collier *et al.* (1991). Generalized bottom water temperature shown.

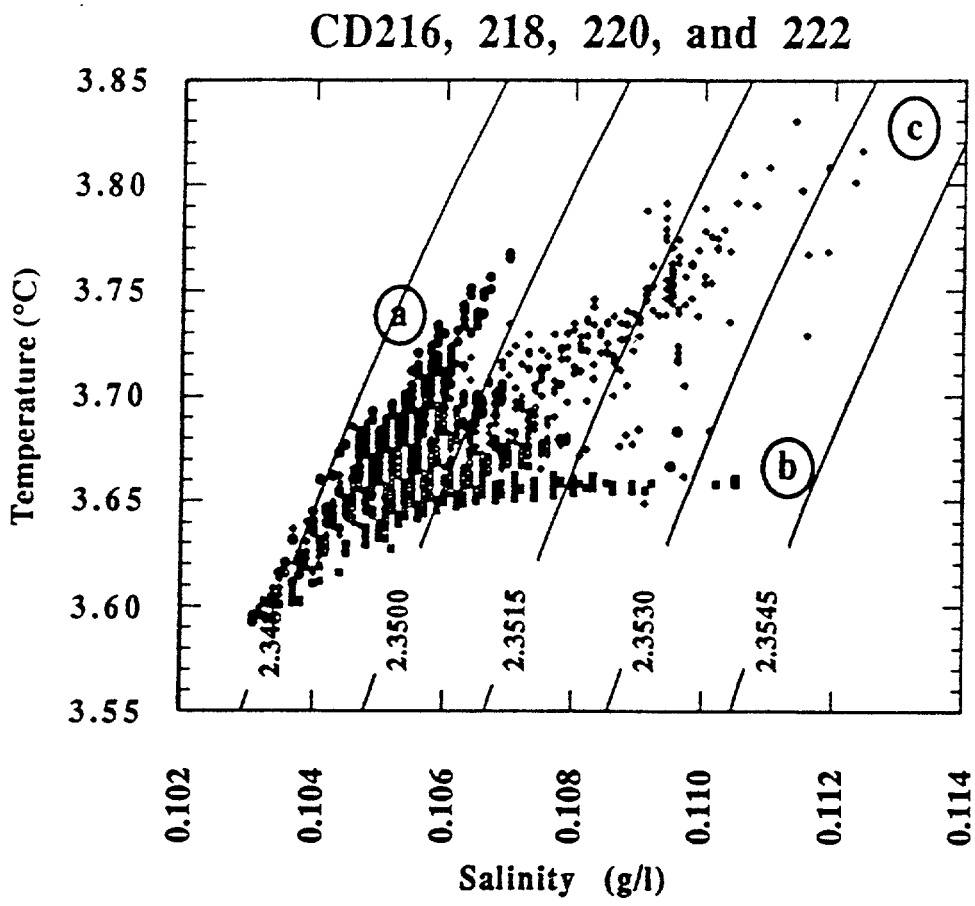

Figure 11. Temperature versus salinity data taken during listed submersible dives in the south basin and adjacent area (Collier *et al.*, 1991). Lines on figure are isopycnals or lines of constant density calculated at a pressure of 43.5 bars. Circled letters show correlations of fluid properties towards a high temperature/salinity ratio fluid (a), a low temperature/salinity ratio fluid (b), and an intermediate fluid (c).

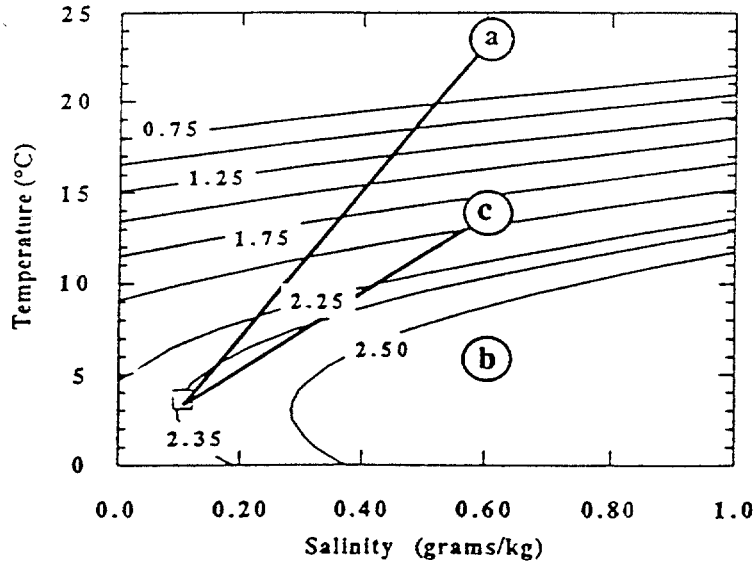

Figure 12. Temperature versus salinity showing extrapolation to highest salinity found in pool samples (McManus *et al.*, 1991). Lines on figure are isopycnals or lines of constant density calculated at a pressure of 46.5 bars. Circled letters show extrapolated values from correlations of fluid properties from Figure 11 towards a high temperature/salinity ratio fluid (a), a low temperature/salinity ratio fluid (b), and an intermediate fluid (c). Area of Figure 11 is shown by small box in lower left corner of figure.

C. Review of the Peer Review Report

A peer review panel was formed in 1989 to review the summary of research for 1988 and proposed research for 1989 conducted by Oregon State University for the National Park Service. This panel was continued and the membership expanded to review the research conducted in 1989 by Oregon State University. The peer panel's purpose was to evaluate the research design, methods, results, analyses, interpretations, and conclusions from materials presented to them. The panel was to assess if the data and analyses support the conclusions of the studies.

The panel met on January 14-15, 1991 in Corvallis, Oregon, with Dr. Charles R. Goldman as chairman. The panel was provided with the draft report, and other papers and materials. The panel received oral presentations from Robert Collier, Jack Dymond, and associated investigators covering the written material and describing new data and interpretations available after the report was written. Panel members were:

Limnology

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

Dr. Alan D. Jassby, Division of Environmental Studies, University of California, Davis, California (Corresponding Member)

Geophysics

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

Geochemistry

Dr. Joris M. Gieskes, Scripps Institution of Oceanography, University of California, La Jolla, California

Dr. Wilfred A. Elders, Department of Earth Sciences, University of California, Riverside, California

Dr. H. James Simpson, Department of Geological Sciences, Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York

Geology

Dr. James McClain, Department of Geology, University of California, Davis, California

Microbiology

Dr. Ken H. Nealson, Centre for Greater 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, Australia (Corresponding Member)

The panel report (Appendix B) contains an extensive discussion of the research findings and this section summarizes some of the major findings. The panel agrees that there is an input of warm, slightly saline water into Crater Lake and that these inputs "strongly influence the major element geochemistry and environmental isotope compositions of the lake waters." This fluid is 5 to 7 times higher in the concentration of total dissolved solids than lake water and has enhanced levels of ^{3}He, ^{222}Rn, and reduced iron. The He isotope composition of this fluid is dominated by a mantle or magmatic source leaking into the lake. The panel comments that temperatures calculated from geothermometers for these waters must be treated with caution, although some evidence suggests that the original temperatures may have been above 19°C.

The input of this warm, slightly saline water strongly influences the major element geochemistry and environmental isotope composition of the lake waters. The ^{222}Rn activities clearly establish the depth and general location at which the warm, slightly saline fluids are delivered to the deep waters of the lake. Water column measurements indicate that the greatest influx of fluids occurs in the south basin. The panel also highlights the importance of freon data as a sensitive indicator of the time scale of deep water ventilation, and these data establish the deep water renewal time to be about two years.

The venting of this warm, slightly saline water is associated with interesting features. The bacterial mats are particularly unusual and fascinating. The discovery of the Palisade Point features is important because it demonstrates that inflow of warm, slightly saline water is not restricted to the Chaski Bay slide portion of the detailed study area. The discovery of siliceous spires at Skell Head indicates that influx of higher temperature buoyant fluids has occurred on the lake bottom sometime in the past.

The panel comments that this warm, slightly saline water is orders of magnitude lower in total dissolved solids than is typical for geothermal fluids from a wide variety of environments; however, the panel appears to have been focusing on fluids found in intermediate-temperature (90°-150°C) and high-temperature (>150°) hydrothermal systems for this characterization. There are many examples of low-temperature (<90°C) hydrothermal systems in the Cascades with similar levels of dissolved constituents to that found in the pools in Crater Lake.

The peer review panel notes that, "While the above results and conclusions are both interesting and important there remain some uncertainties about the origin and characteristics of the SHEF [Salinity- and Heat-Enriched Fluids] inputs to the deep waters of Crater Lake. These uncertainties include: 1. The role of the SHEF fluids in the mixing of Crater Lake cannot be defined at the present time... 2. The nature of the system that supplies SHEF fluids to the lake bottom is very poorly defined... 3. Arguments that the siliceous spires at Skell Head (which strongly indicate high temperature fluid input) are 'recent' features are not conclusively supported by existing evidence... 4. The nature of the bacterial mats is still unknown despite recommendations from the previous Panel... 5. A geological model of the hydrothermal system cannot be made."

The panel also offered a number of suggestions relative to research in the 10-year limnological study of processes affecting the clarity of Crater Lake that are helpful lines of investigation for that program.

IV. RECOMMENDATIONS REGARDING INTERIOR'S FINDINGS

A. Departmental Moratorium on Geothermal Leasing Outside Crater Lake National Park

Under the discretionary authority vested in the Department of the Interior by the Geothermal Steam Act of 1970, the Secretary imposed a moratorium on geothermal leasing on Federal lands surrounding Crater Lake National Park. This moratorium, in place since 1987, is hereby lifted with the submission of this report to the Congress and the Department will evaluate all proposals on a case-by-case basis. All lease applications received after this moratorium is lifted, will be treated according to the provisions of the Interagency Agreement (IA) for implementing the provisions of the Geothermal Steam Act Amendments of 1988. (See the discussion of the IA which follows.) We assure the Congress that the Department will protect the significant thermal features of Crater Lake National Park and accord them all the protective measures of the Geothermal Steam Act Amendments of 1988.

B. Procedures for Evaluating Future Lease Applications Outside of Crater Lake National Park

Interior Bureaus (National Park Service, Bureau of Land Management, U.S. Geological Survey) entered into an Interagency Agreement with the U.S. Forest Service of the Department of Agriculture in November 1987. Although the purpose of this IA is to establish the procedures to be used for ensuring compliance with the Department of the Interior and Related Agencies Appropriations Act for 1987, this IA continues to be followed by the participating agencies in implementing the provisions of the Geothermal Steam Act Amendments of 1988. Since Crater Lake National Park is listed by the Congress as a unit of the National Park System containing significant thermal features, the provisions of this IA will apply to all lease applications received after the Secretarial moratorium on geothermal leasing is lifted. This IA will expire or come under consideration for renewal in the Fall of 1992, at which time the citations for incorporating the Geothermal Steam Act Amendments of 1988 will be updated and revised. This IA is included as Appendix C.

The IA defines the functions and roles of each participating agency. The National Park Service (NPS) identified areas directly adjacent to listed units of the National Park System in those counties within which NPS needs to review geothermal leasing proposals on a case-by-case basis. In the instance of Crater Lake NP, NPS took the opportunity to define the counties to which the geothermal leasing moratorium applied. Counties identified included the three surrounding counties of Jackson, Klamath and Douglas counties in the State of Oregon. NPS, after having received word that the

Secretarial moratorium is lifted, will forward to the BLM a complete list of those lands surrounding Crater Lake National Park on which NPS needs to review geothermal leasing proposals on a case-by-case basis.

Section III, B, of the IA provides that when the Bureau of Land Management (BLM) receives an application to lease lands, they will complete a checklist analysis of whether there is a potential for a geologic or hydrologic connection between the lease area and the significant thermal feature located in the park unit. If lands under consideration for leasing are on lands in the National Forest System, as could be the case outside of Crater Lake National Park, BLM will consult with the U.S. Forest Service (USFS) for advice. If the BLM suspects a connection exists between the proposed lease area and the listed significant thermal feature in the park, BLM forwards their analysis to the NPS. USGS is asked to evaluate the adequacy of the data and to verify the potential for connection. USGS, in consultation with the BLM, will prepare a detailed analysis of the proposal. The detailed analysis will estimate the type, extent, and magnitude of likely effects, and consider the effectiveness of mitigating measures.

In accordance with Section III, C, 4, of the IA, the BLM, NPS, and USGS will consult to determine whether the proposed leasing actions are reasonably likely to result in no effect, an adverse effect, or a significant adverse effect. BLM will prepare a notice presenting the determination and announcing the action to be taken as a result of this determination. If it is determined that the geothermal proposal could cause significant adverse impacts, the lands will be withdrawn from leasing. If it is determined that the geothermal proposal could cause adverse impacts, the BLM will meet with the applicants to discuss proposed mitigating measures, lease stipulations, and a monitoring program to be required of the lessees. One of the lease stipulations to be adopted will be one that will allow cessation of operations, if they are found to offer significant adverse impacts to the listed thermal features. If it is determined that the geothermal proposal would result in neither significant adverse nor adverse effects, the BLM and FS, as appropriate, will proceed with NEPA compliance and the procedures of the Geothermal Steam Act as amended toward the goal of issuing a lease in the proposed area.

C. Listing Recommendation

The Department of the Interior has evaluated the Crater Lake study findings and confirms with this report that there is an inflow of thermal water into Crater Lake that meets the tests of criteria for determining significance under Section 6 of the Act.

V. APPENDICES

A. Final Research Report by Drs. Collier and Dymond

B. Peer Review Report

C. Interagency Agreement Among the Bureau of Land Management, National Park Service, U.S. Geological Survey, and the U.S. Forest Service for implementing Section 115 of the FY'87 Appropriations Act dated December 9, 1987.

D. History of Geothermal Leasing Near Crater Lake National Park by the Bureau of Land Management

A. Final Research Report by Drs. Collier and Dymond (Studies of Hydrothermal Processes in Crater Lake, OR accompanies this report under separate cover.)

B. Peer Review Report

CRATER LAKE

March 1991

PEER REVIEW OF RESEARCH PROGRAM AND DRAFT REPORT ON STUDIES OF HYDROTHERMAL PROCESSES IN CRATER LAKE, OREGON

A Report of Field Studies Conducted in 1989
for the National Park Service

PANEL MEMBERS

Dr. Charles R. Goldman, Chairman
Dr. David D. Blackwell
Dr. Wilfred A. Elders
Dr. Joris M. Gieskes
Dr. James McClain
Dr. Kenneth H. Nealson
Dr. H. James Simpson

CORRESPONDING MEMBERS

Dr. Jorg Imberger
Dr. Alan D. Jassby

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EXECUTIVE SUMMARY

The Panel has discussed in great detail exactly what warm, slightly-saline inflows to Crater Lake should be called, and settled on "Salinity- and Heat-Enriched Fluids", or SHEF. We considered using "hydrothermal water", the American Geological Institute's definition of which is "subsurface water whose temperature is high enough to make it geologically or hydrologically significant, whether or not it is hotter than the rock containing it", and decided to avoid the strict implication of this definition. The Panel also considered using either SELTHF ("salinity-enriched low temperature hydrothermal fluids") or SAM ("slightly-warmer and more-saline water"), and finally settled on SHEF as a good and understandable compromise.

Some concern has been expressed in the limnology section of the Panel's report on the validity of the original assumption that the lake has actually been losing transparency. A close examination of the available Secchi data suggests that there may not have been a significant loss. Evidence from sedimentary profiles suggests that phytoplankton productivity is correlated with hydrothermal fluid inputs on a 100-1000 year time scale. But in shorter time scales, anthropogenic influences may be much greater than hydrothermal ones. Refinement of the nitrogen budget, as noted by the previous Panel, remains one of the most important research needs for understanding Crater Lake's water quality.

Geochemical information presented by Dymond and Collier has shown that an input of SHEF occurs into the deep waters of the lake, particularly in the South Basin. These fluids are primarily sodium/magnesium/calcium bicarbonate waters with a moderate amount of sulfate and chloride, with total dissolved solids (TDS) of about 5 to 7 times higher concentration than the 90 mg/liter TDS of the lake water, which is a very dilute, near-neutral $NaCl\text{-}SO_4$, water. These SHEF waters are also characterized by enhanced levels of ^{3}He, ^{222}Rn, and reduced iron, but their TDS contents are orders of magnitude lower than those typical for geothermal fluids from a wide variety of environments. Because of their dilute nature and unusual chemistry, caution is necessary in using geochemical geothermometers on these waters, although some evidence suggests that the original temperatures may have been above 19 ^{o}C, the highest measured SHEF water temperature. We have no knowledge of the subterranean fluid pathway and, therefore, can only speculate on the depth of origin of the

fluids and the temperature of the interaction. Of importance, however, is the observation that SHEF fluids are a major contributor to the salt balance of this lake, with the heat balance being affected only locally. The geochemical evidence agrees with the postulate that the chemistry of the SHEF fluids is affected by water-rock interaction at some elevated, although unspecified, temperatures.

The freon data reported provide the most sensitive indicators currently available of the time scale of deep water ventilation and establish the deep water renewal time to be about two years, assuming a steady-state vertical mixing process. This finding is a critical new result which helps constrain the magnitude of chemical fluxes from SHEF fluids into the deep waters of the lake, averaged over the mean vertical mixing time.

The ^{222}Rn activities observed in samples of deep water clearly establish the depth and general location at which the SHEF fluids are delivered to the deep waters of the lake. The distribution of this tracer in the lake water provides unequivocal evidence of influx of high ^{222}Rn fluids to the deep waters of the lake at the time of sampling during August 1989.

With regard to the microbiological component, the Panel feels that the discovery of the microbial mat communities in Crater Lake was a major finding and may, if followed up, lead to an appreciation of several aspects of biogeochemical cycling in Crater Lake, as well as making possible its comparison with other lacustrine and oceanic environments. Considerable laboratory and fieldwork will be required before the most positive aspects of the microbiology can be realized. Future work should be done in close collaboration with microbiologists and biogeochemists familiar with the biology and biochemistry of iron cycling.

In retrospect, one problem with the report was that its experimental design was limited to consideration of only part of the important relevant issues. Answering the overriding question, "Are there hydrothermal inputs to the lake which are significant in influencing its transparency or its ecology?", breaks down into answering the following more specific questions: (a) "What is the nature and size of detectable or probable inputs of hotter water into the lake?"; (b) "Is the chemical budget from such hotter sources significant in affecting the lake's clarity or ecology?"; and (c) "Is the thermal budget from such sources significant in affecting the clarity and ecology?". At the outset, it seems that the investigators made the implicit

assumption that finding hotter water inputs of any level of intensity would be enough to show that they were significant, i.e., they are defined as hydrothermal. Thus, attention was focused almost entirely on question (a), above, so that questions (b) and (c) to some extent still remain unanswered. The research to date has laid much of the groundwork for a better understanding of Crater Lake, and the Panel has been convinced of the input of SHEF to the lake bottom and its significance for lake chemistry. It remains for future studies to determine just how important these inputs are to the dynamics of biological and other processes related to water clarity in Crater Lake. A great effort was made by the principal investigators despite the limited funding available for a research effort which included expensive submersible time.

I. INTRODUCTION: THE REVIEW PROCESS

In 1989, a scientific controversy regarding possible hydrothermal heating and the roles of hydrothermal fluids in the ecology and particularly the clarity of Crater Lake, Oregon, resulted in the formation of a special Peer Review Panel to evaluate the research findings and recommend any necessary further study. The main question -- whether or not Crater Lake contained significant geothermal features -- could not be resolved at the time. The National Park Service sponsored additional research still centered on this issue, and subsequently re-assembled an interdisciplinary Peer Review Panel to evaluate the 1990 draft report summarizing the research on possible geothermal features at Crater Lake.

The 1991 Peer Review Panel consisted of seven regular members and two corresponding members (see Table 1). To the original Panel of Drs. Blackwell, Gieskes, Goldman, McClain and Nealson were added Drs. Elders and Simpson. Drs. Imberger and Jassby were the two corresponding members. The Panel examined relevant documents and met for a technical workshop to consider to what extent geothermal venting and/or a diffuse heat flow were occurring in Crater Lake. Included in the Charge to the Panel was a request to evaluate the adequacy of the research and make recommendations as to the strength of the evidence for both scientists and decision-makers on the geothermal heating question.

After its appointment, the Peer Review Panel received the 1990 draft report and other documents, together with reviews from both the U.S. Bureau of Land Management and the CE Exploration Company. Each Panel member benefited from the additional research information provided at the presentations made by Drs. Dymond and Collier. The Panel also received supplementary information on the modeling effort and reports from its two corresponding members. 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 14 January 1991 in Corvallis, Oregon at the request of Dr. Gary Larson of the National Park Service. After introduction of the Panel, an attorney for CE Exploration, Mr. Ivan Lewis Gold, made an opening presentation to the Panel regarding their concerns about the report. A summary of the research program and its findings was made by Drs. Collier and Dymond and their associates. Following the presentations, the Panel asked a number of questions, then went into Executive Session on

Table 1

Crater Lake Hydrothermal Peer Review Panel - 1991

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15 January to discuss the material presented and start work on the Panel's report. Each Panel member provided an individual report to the Chairman that included suggestions for modification of existing research as well as recommendations for any additional research they felt would contribute to an understanding of Crater Lake. A draft report was first prepared by the Chairman from the individual reports, circulated to the Panel members, then revised for a second review by the Panel before final submittal to the National Park Service.

The Panel wishes to emphasize that this report responds only to the 1990 draft report of Collier and Dymond, which was supplemented by their oral presentation. Subsequent changes to their report have not been reviewed by the Panel.

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 issues include regional setting, bottom bathymetry and other bottom observations, bottom samples, heat transfer, lake thermal mixing dynamics, geochemistry, and microbiology. Each of these will be discussed here. We have presumed from the beginning of our first review (Goldman et al. 1989a) that the research program was designed to test the hypothesis that deep circulating hydrothermal waters are entering the bottom of Crater Lake. It now appears that all members of our Panel are in substantial agreement that some form of fluid input is in fact entering the lake beneath the South and East basins, and this water is responsible for temperatures slightly elevated above the normal ambient lake values along the lake bottom, for most of the chemistry in the lake water, and for the growth of bacterial mats on the lake bottom. Although this report focuses on the work of Dymond and Collier as the authors of the Draft Report (October 26, 1990) which served as the focus for our review, it also utilizes a variety of other sources of information and the extensive collective experience of the Panel.

III. LIMNOLOGY

Crater Lake is a classic example of a collapsed volcano 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 et al. in 1942 and color by Smith et al. in 1973. A variety of limnological studies have been in progress for the last decade. These have recently been included in a volume edited by Drake et al. (1990), and summarized in a paper by Goldman (1990) appearing in the same volume.

One of the serious gaps which still remains in the existing limnological data for Crater Lake is knowledge of the lake's annual mixing regime. Crater Lake has a volume of about 16 cubic kilometers and, as a result, a great capacity to dilute any hydrothermal or cold-groundwater inflows to the deep

unable to resolve variability at scales of 1 to 10 years, and different mechanisms could be operating at these shorter time scales.

Of mechanisms 2 and 3, Dymond and Collier (1990) favor the latter, arguing that the former could not have sustained the long-term enhanced losses of nutrients to the sediments. In actual fact, long-term enhanced loss of Si may have been sustainable if Si was not limiting phytoplankton biomass. The critical issue is whether long-term loss of the nutrient limiting maximum biomass was significantly enhanced, i.e., whether the increased loss represented a significant fraction of the water column pool for this nutrient. This question still appears to be unanswered. Although the "Salinity- and Heat-Enriched Fluids", or SHEF as the Panel has chosen to refer to them, are probably too dense to contribute to instability, spire morphology does suggest the existence in the past of buoyant fluids (Sec. V.B.4).

The influence of these fluids is extremely important both from a scientific point of view and for a practical understanding of how alterations in this input might affect lake productivity. Future Crater Lake research teams should be encouraged to examine further the paleolimnological evidence, particularly with an eye to more accurate dating and higher temporal resolution. Because the sediment deposition rate is so low, resolution is limited, however.

B. The extent of water quality degradation

The current 10-year program at Crater Lake was initiated in part because of concern over a suspected decrease in lake clarity since 1937. Although this concern is legitimate in any case since Crater Lake's extreme clarity merits protection, the actual evidence for decreased clarity is rather weak.

From 1931 through 1942, the water level of Crater Lake was unusually low, 3 to 4 m below current levels, suggesting a time of unusually low precipitation (Redmond 1990). This period also may have been one of reduced vertical mixing, particularly if the probability of storms was reduced at times of minimum lake stability in early spring and late fall. A natural consequence would have been reduced upwelling of regenerated nutrients, a lower annual primary productivity, and probably a lower maximum phytoplankton biomass (Goldman et al. 1989b). This could account for the record high Secchi depths measured in 1937, the first year of Secchi data (Larson et al. 1990).

Secchi depths were not measured again until 1954 and then again in 1968 (Larson 1990); in both of these later years, they fell well within the range of the past decade (e.g. 1980, 1987). The 1969 values had a higher maximum than all subsequent years, but it should be noted that a major El Niño/Southern Oscillation occurred in 1969 and could have resulted in extreme lake conditions. At Castle Lake, California, for example, 1969 was a year of unusually low productivity (Goldman et al. 1989b).

Thus, the high Secchi measurements prior to 1970 could have been due to a bias that entered because of the small number of years sampled and the high interannual variability (Fig. 1A). The small number of measurements made within a year combined with high seasonal variability could also introduce bias. As pointed out by G. Larson (1990), the dependence of Secchi depth is extremely sensitive to particle density in clear lakes. The consequences of interannual and seasonal variability for water clarity are therefore most pronounced for low-fertility, ultraoligotrophic waters such as Crater Lake.

Although a statistical test (Dahm et al. 1990, Table 2) seems to imply that water clarity decreased after 1969, the chance bias described above suggests that such a test be considered only as weak evidence. Furthermore, the t-test used by Dahm et al. (1990) is inappropriate if there is actually serial correlation (such as trend) in any of the populations being measured. Alternative distribution-free tests are available for trend detection in the presence of serial dependence and other problems. In addition, from 1982 (when the number of measurements within a single year increased substantially) through 1987, the trend -- if one can be substantiated at all -- may be one of increasing water clarity (Fig. 1B). The evidence for increased chlorophyll _a_ concentrations (D. Larson et al. 1990, Table 4) or primary productivity (Dahm et al. 1990, Table 3) is as uncompelling as that for decreased Secchi depths.

Unfortunately, the combination of interannual variability and a sparsely sampled -- but large -- seasonal variability may preclude any dependable conclusions regarding trend for some time. Because of the difficulty of getting higher-resolution data and a time series of measurements of sufficient length, we recommend that more emphasis should be given to the sediment evidence (see above).

CRATER LAKE

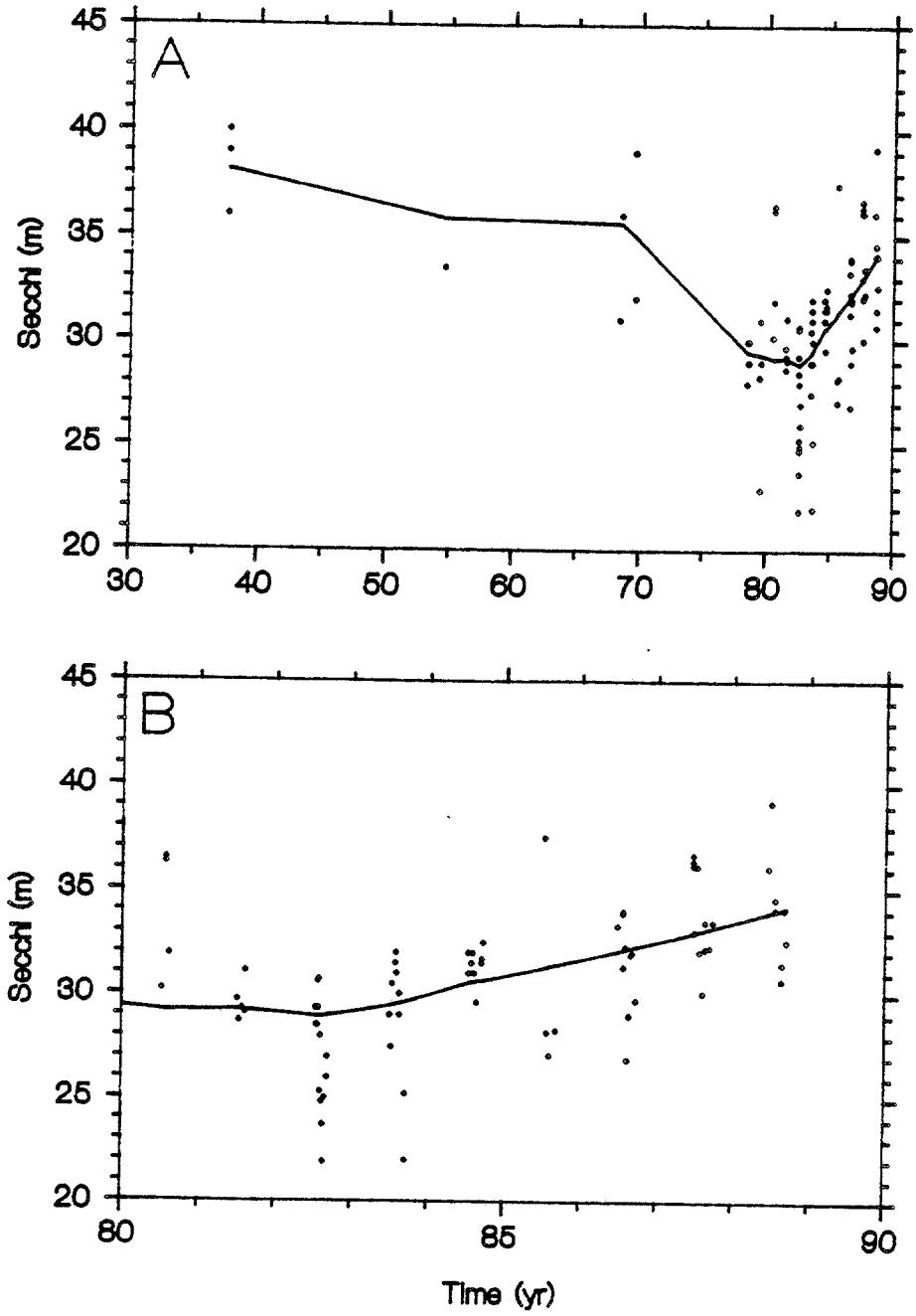

Figure 1. (A) Secchi depth measurements for Crater Lake, from the first samples in 1937 through 1989. The solid line was determined by the LOWESS algorithm (tension = 0.5). (B) An expanded view of A for the period 1980-1989.

C. Nutrients and decrease in water clarity

Several threats to the lake's clarity can be hypothesized. Ironically, one of these is the input of hydrothermal waters, at least according to the evidence put forward by Dymond and Collier (1990; Section A above). D. Larson et al. (1990) postulate a role for sewage contamination.

Because the conclusions of Collier, Dymond and McManus (1990) are so heavily dependent on geochemical arguments, it is instructive to compare important geochemical fluxes from hydrothermal processes with those from other sources. According to D. Larson et al. (1990, p. 207), nitrate is the limiting nutrient for phytoplankton in Crater Lake. They estimate about 62 x 10^6 liters of sewage each summer flows into septic tanks on the south rim, with subsequent infiltration into the lake. For a summer season of 90 days this is an average sewage-related flux of about 8 liters/second. For comparison, the calculations based on chemical mass balances in the Dymond and Collier report (1990, p. 111), "yield a total flow of hydrothermal fluid of approximately 290 liters/second". Thus, the hypothetical SHEF flux is one to two orders of magnitude greater than the estimated sewage-related flux.

However, the nitrate contents of the waters of Lloa's pool, Palisades pool, and the deep lake are reported as being essentially identical (Collier, Dymond and McManus, 1990, Table 7, p. 108), so the SHEF pools could not be an important source of nitrogen for the very dilute lake water. On the other hand, a spring which discharges at 2 liters/second to the lake, and which Larson et al. (1990) believe to be contaminated by sewage effluent, has a nitrate content enriched by two orders of magnitude relative to that of the lake water. Thus it seems possible that the flux of the most-likely limiting nutrient (N) into the lake may be dominated by anthropogenic sources rather than by hydrothermal inputs. This is particularly evident when we remember that in addition to wastewater from sewage, these anthropogenic sources of nitrogen also include the probability of atmospheric contaminants.

Enhanced algal growth typically occurs as one approaches nitrogen-to-phosphorus ratios of from 10-15 to one. Since Crater Lake owes its great transparency to low nutrient content, any increase in nitrogen, the major limiting factor, is certain to enhance algal growth and reduce transparency. As hypothesized for Tahoe and supported by lake-moored dry and wet fallout collectors in Tahoe, increased atmospheric deposition of nitrate could also increase eutrophication of the Crater Lake system. In the case of Crater

Lake, though, the atmospheric deposition probably would not be derived from local sources of air pollution, but rather from long-range transport from populated areas where NO_x vehicle emissions are common, or from agricultural areas where fertilizer NH_3 is heavily used. In order to distinguish among these and other possible alternatives, several pieces of evidence would be valuable:

1. An annual nitrogen budget still needs to be established. From the documents made available to the Panel, it does not appear to be available. Mass balance studies have investigated the major ions, but the absence of nitrate -- and not phosphate -- from euphotic waters implicates nitrogen as the element most limiting for maximum algal biomass and, therefore, minimum Secchi depth. Nitrogen tends to be limiting in oligotrophic western lakes and, in fact, there appears to be about as much nitrogen as phosphorus limitation in lakes in general (Elser et al. 1990). Particularly important is the atmospheric deposition of NO_3. Deposition is typically heterogeneous and an appropriate spatial array of samplers is usually necessary. At Tahoe, for example, the difference between shore and midlake stations is marked. Dry fallout as well as precipitation should also be measured. Although dry fallout at Tahoe is only about 10-15% of wet deposition for both NO_3 and NH_4, the percentage can be much higher for other substances, up to 100% in the case of soluble reactive P and 70% in the case of Na (Byron et al. 1989).

2. Synoptic samples are required to document the spatial heterogeneity of Secchi depth, primary productivity and nitrogen ion levels. In the vicinity of the Rim Village, such studies could assess directly the possible impact of the septic system. The annual amount of fixed nitrogen in Rim Village wastewater (2500 kg) is approaching the same order of magnitude as that in precipitation (5000-9000 kg; D. Larson et al. 1990).

3. Compartment model activities should be extended to an analysis of long-term nitrogen dynamics, with a resolution of 1 year. Such modeling activities may be able to differentiate among nitrogen sources that have different time courses. Annual primary production estimates are necessary for such modeling activity.

4. Higher resolution of mixing activity as recommended in the previous peer review is still needed. Following the evolution of the nitrate vertical profile in spring still seems to be a viable possibility for accurately tracing mixing depth, although it would require higher-frequency measurements

at the start of each sampling year. Nevertheless, some more accurate measure of annual mixing activity is essential if interannual variability in water clarity is to be understood.

IV. MICROBIOLOGY OF BENTHIC MAT COMMUNITIES

A. Introduction and general comments

During the 1989 Panel review meeting we were presented with the findings of widely-dispersed microbial communities that exist in localized areas on the bottom of Crater Lake. These observations were judged to be quite exciting by the Panel, both for the reason that they may be indicators of the SHEF input, and because they may have intrinsic interest as unusual microbial communities. Because of these general and specific interests, several areas of research were suggested to the PI's:

1) Carbon isotope ($\delta^{13}C$) analysis of sediments in the mat areas vs those elsewhere
2) Taxonomic analyses of the mat materials
3) Culture and physiological analyses of the suspected organisms
4) Flux measurements in mat areas of likely critical nutrients
5) Pore water chemistry in mat vs non-mat areas

The PI's were unable to respond directly to the requests for microbiological data that the Panel recommended after the first review. We wish to stress that Dymond and Collier are not microbiologists, and were dependent on the work of volunteer collaborators. Unfortunately, the collaborator presented a report which included virtually no data, only statements as to what did and did not work. This is not the fault of the PI's, but, unfortunately, the issues of what the critical biological communities in the mats are, or how fast they may be growing, remain unresolved. Both of these issues are central to assessing the possible importance of the mats to the ecology of the lake and their possible significance in terms of estimating SHEF inputs more enriched in metals than the lake water.

On a more positive note, it is obvious that some substantial progress was made in the identification of new areas of mat formation. This demonstrates that the mats are much more diverse and widely distributed than was previously known. The Panel is in agreement that the funding agencies

would have been well-advised to have committed more effort, resources, time and funding to investigating more fully the microbial mats in Crater Lake.

B. Report

1. Experimental design

The major approaches used for mat analyses to this date have been descriptive. Descriptions include gross morphology and distribution of mats, microscopy and electron microscopy of bacterial communities, and bulk chemical analyses of mat samples. While these descriptive results have definite limitations, as a first approach, they have yielded valuable data.

As mentioned above, the previous review panel had some specific recommendations that required a different experimental design in addition to description. The experimental design followed to answer these questions was, by and large, not adequate. For example, 1) the methods for culturing and identifying organisms were not documented, 2) a strategy for studying rates in the lab or field was not outlined, and 3) no strategy for isotope fractionation analysis was outlined or attempted.

2. Methods

The methods used for the descriptive part of the program done by the Dymond/Collier group included photography, microscopy, electron microscopy, and bulk chemistry. These methods seem adequate and well described, between the draft report and the published data.

The methods for the more detailed microbiological work were not well documented in this report. It was not possible to tell what was done, nor is it, in general, possible to tell what did or did not work.

3. Results

Descriptive work: The report begins with a recapitulation of the data from 1988. This shows the photography of mat zones from the north wall, some SEM analyses of these mat areas, and a discussion of what they might be, based on morphology of the cultures. This essentially repeats the material contained in the report from 1.5 years ago. This remains a very interesting discovery; whether or not the input to the lake is hydrothermal, or from some other source, the existence of these major communities is an important finding.

Defining the environmental settings of mat communities: One new development involved the identification of further areas of mat growth, and confirmation of what had been seen earlier.

a) One mat area that had been dispersed during sampling in 1988 had grown back by 1989. Unfortunately, no detailed information was provided about these observations. What is meant by dispersed? How large was the mat community? How much organic carbon was involved in the process? If this latter amount were known, it might be possible to get new insights on the fluxes of iron into the lake, or through the sediments.

b) Temperatures as high as 10 ^{o}C were observed in 1989, and were primarily along the Chaski Slide area. In probing experiments, temperatures as high as 18.9 ^{o}C were recorded, with several values >15 ^{o}C. In general these mats (found at approximately 400 m depth) were not as large or well developed as those seen at the north wall site. It is suggested that the venting of fluids is heterogeneous because of the localized distribution of the mat communities. These mats have high concentrations of arsenic and rare earth elements.

c) The saline pool mats or communities represented the third group of mat types found in the study area. These communities formed a vast array of morphologies, ranging from well-developed mats associated with small pools to thin coatings or crusts on adjacent rocks and sediments. Some were many meters across, while others were narrow rims around the fringe of the pools. They also tended to be the lowest temperature features (about 6 ^{o}C).

d) In addition to the mat types discussed above, all in the study area from 1988, a major community was found across the lake in the Palisades Point area. This particularly interesting community was a zone 20-30 meters long by 5 m wide, with many small rivulet-like structures. The micro "rivers" that seemed to feed the mats often originated under rocks in the area, and "flowed" into pools that supported mat growth. Temperatures here were on the order of 8.1 ^{o}C.

Microbiological results: In a previous paper, Dymond et al. (1989) proposed on the basis of electron microscopic work that these organisms were iron chemolithoautotrophs. The ensuing results were aimed at answering some specific questions about the purported iron oxidizers. All of the data relevant to these questions, and to the specific recommendations of the previous Panel are contained in Appendix E, supplied by Dr. D. Karl of the University of Hawaii. A review of these results is presented below.

C. Pure culture studies

Enrichment cultures were set up on a variety of different media for Sphaerotilus, Leptothrix, Gallionella ferruginea, Thiobacillus thiooxidans (obligate sulfur autotroph), and T. intermedius (facultative S oxidizer). This section was troubling to the Panel, as there are no descriptions of the media used, or the conditions used for growth (T, atmosphere, medium components, etc.).

It is stated that positive enrichments "were common" on all media except those for T. ferroxidans and T. oxidans, both of which are usually thought of as obligate S (and/or Fe) oxidizing autotrophs.

No cultures were isolated as pure colonies, nor studied with regard to any of their properties.

D. Enzyme assays

Bacterial mat assemblages were examined for two different CO_2-fixing enzyme activities, RuBisCo (Ribulose 1,5-bisphosphate carboxylase) and PEP Case (Phosphoenol pyruvate carboxylase). No success was obtained with the assay of either enzyme. Also, no data are shown for any assays, positive controls, other organisms, etc.

E. Dissolved substrate analyses

This project, to look at pore water samples for dissolved organic matter, was discussed, but no data were presented.

F. Other relevant data

Since no pure cultures were obtained, it was impossible to address many of the issues we had suggested in our 1989 review. There is no further information regarding the identification of the mat community, its physiology, growth rates, response to temperature, nutrients, etc.

No attempts were made (or mentioned) regarding the ^{13}C fractionation of mat material, which would have been another way of implicating an autotrophic community.

No attempt was made to look at rates of growth or metal oxidation activity in the lab or the field.

G. Analyses, interpretations, and conclusions

The analyses of the microbiological data are few, since the results are primarily descriptive. There is no substantiation of the identity of these organisms, their physiology, or the flux of material through them.

The refined studies of the bacterial communities still need to be done to support the statements that are made in the report. There is no indication, other than structural, that the community is composed of the organisms suggested, or that they are actually metal oxidizing bacteria growing autotrophically. There is no information, other than anecdotal, regarding their growth rates, their metabolism, or their relation to metal oxidation in the lake. This latter point may be critical. If the fluid fluxes are on the order of 200 liters/sec, and if iron is in the range of 0.5-1.0 mM in the pore waters, and if the lake has been in steady state for the past 100 years, then in the upper layers of the bottom sediments, there should be on the order of 5-50 kg of iron as iron oxide per square meter of sediment. If this amount is not there, then there may be some fundamental role that the mats are playing that could be used to the advantage of understanding the environment. However to do this, the dynamics of the mat community must first be understood.

Third and finally, the mat communities described here may be unusual and unique, or they may be simply larger analogues of well known systems in other lakes that are driven by anaerobic groundwater input. Because of the lack of bacteriological results it is not possible to distinguish between these two alternatives.

H. Additional studies and suggestions for the future

Stable isotopes: If future work is to be done, the establishment of the nutritional base of the mat communities via carbon isotope studies should definitely be included as a high priority.

Identification and characterization of the mat communities: Determining whether or not the Crater Lake system is unique will be greatly aided by identifying the members of the community. It will be straightforward to compare it to other iron-driven systems, and to look for differences and similarities. While it seems likely that the system is a unique one, there is not yet a sufficiently good data base to defend this conclusion.

Field and laboratory studies of bacterial physiology: There are a wide variety of questions regarding fluxes of nutrients, iron, fluids, etc., which could be well addressed using pure cultures in the laboratory, and later, careful analogous studies in the field. With regard to the question of establishing an iron budget, it will be critical to know the role of the iron bacterial communities in maintaining this budget or quantifying fluxes in the lake.

V. GEOPHYSICS AND GEOLOGY

A. Introduction and general comments

The investigators have focused their attention on geochemical techniques, and particularly on geochemical techniques with which they are familiar. Their interest in, and apparent understanding of, the local and regional geological, geophysical, and even continental, geothermal setting of the lake, is limited. Thus, some important factors are lacking for the evaluation of the significance of their results. This still remains a shortcoming which could be considered serious from the point of view of the National Park Service objectives.

B. Report

1. Experimental design

The experimental design had only limited emphasis on geology and geophysics and the geochemical investigations were focused on a small area of the lake bottom based on the findings of Williams and Von Herzen (1983). The Von Herzen study had some limitations in terms of very limited penetration into the sediments that cause uncertainties with the results. Thus, some further evaluation of the historical data was suggested by the Panel report of July 1989. Because of the limited use of geological/geophysical techniques to investigate the hydrologic system, the report could be described as incomplete.

The Panel felt that an oversight in the report was the lack of an attempt to put the data and models presented for Crater Lake into a regional context which compares them with the broad range of volcanic and hydrothermal phenomena displayed in the Cascade Ranges. Because of the very extensive and quite recent volcanism of Mt. Mazama, it would not be surprising to find

abundant and pervasive hydrothermal phenomena in the area. The eruptions of Merriam Cone and Wizard Island, which occurred as recently as 4,000 yr. B.P., suggest that the magma chamber beneath the volcano was not completely depleted by the catastrophic eruption which formed the crater about 6850 yr. B.P. (Bacon and Lanphere, 1990). In fact, some Panel members were surprised by the small-scale and limited-range of the SHEF phenomena which have so far been described by the Crater Lake studies.

However, because of high rainfall, permeable rocks, and steep topography, surface hydrothermal manifestations in the Cascades are usually highly modified or often suppressed. On the other hand, useful comparisons to Crater Lake could be made, for example, with the situation at Newberry Crater, where geothermal exploration has revealed the existence of a large high-temperature system. Such a comparison might help focus the discussion of why significant hydrothermal features at Crater Lake were so difficult to find.

2. Methods

The methods of hydrothermal geology/geophysics used were primarily visual investigation from the submersible of the lake bottom, focusing on the detailed study area (pp. 19-31, draft report). Even allowing for a limited role of these studies in the overall research plan, there are some major problems. As an example, the submersible passes right by a fault scarp on the bottom (tape sequence, Plate 4) but the location, the orientation or the displacement was not recorded. Such faults and fracture zones are the most likely localizers of fluid leakage to the lake floor and hence their locations are extremely important to establish or document. The existence of the area of study at the end of a major regional normal fault zone (and significance of such a location) appears to be unknown to the investigators.

No physical property measurements of any sort (such as porosity or permeability measurements) have been made on core samples.

The investigators have also ignored the information and studies of Cascade volcano geothermal systems, so the report has no context for the reviewers or the NPS to evaluate the results and implications.

3. Results

The results can best be understood in the context of the hydrologic systems associated with stratovolcanoes. The researchers have oversimplified the hydrologic systems expected to two end members rather than the full

spectrum of groundwater thermal and chemical possibilities. Such systems consist of a shallow high flow rate groundwater system (flow rates of meters to 100's of meters per year, extremely low TDS, short resident times) that dominates the surface manifestations in an area of high rainfall such as the Cascades. Examples of this type of groundwater system include nearly all of the springs in the Crater Lake region. This system gives way at depths of 200 to 500 m to a regime of much lower flow rate and more complete and complicated interaction with the rocks and other deep waters. The diversity of flow rates (m/year or less) and chemistry is great. Most Cascade volcanoes have summit fumaroles with temperatures of over 90 ^{o}C. For example, Mount Hood has a fumarole at its top with a temperature of 92 ^{o}C and an estimated thermal energy discharge rate of 25 MW. Acid alteration zones are often found over the top of such fumarole zones if there is a perched water table. In the core of such a system, high temperature geothermal systems can be found. Such systems are usually NaCl solutions of neutral pH.

4. Interpretations and conclusions

One of the primary conclusions of the study is that there are inputs of hydrothermal fluids into the bottom of Crater Lake. The estimated composition of the fluid is shown in Table 7 of the Draft Report. The Panel suggests that this fluid at its zone of discharge into Crater Lake be referred to as a "salinity- and heat-enriched fluid" (SHEF). On the basis of the present data, null hypothesis 4a rather than 5 (Dymond, Panel presentation, 1/14/91) is the best way to describe the findings, i.e., there is injection of a SHEF into Crater Lake at a rate of 300 $\pm$100 liters/sec with the majority of this injection occurring in the southeast basin. This fluid contains the gases carbon dioxide and helium, which can be readily detected in the overlying lake water. There is a large ^{3}He excess component in this water and the CO_2 is old (see Sec. VI). We note that there may be inputs and outputs to and from Crater Lake from the groundwater system of compositions not inventoried that could impact the calculations of input flow rates and chemistry and the interpretations drawn therefrom. The data allow the comparison of the inferred fluid to waters of various sorts in the Cascades (Table 7, Collier et al. 1990). It is interesting to note that these SHEF waters are so dilute that they could still be classified as potable with respect to the major chemical elements they contain. The water chemistry as it is presently known is not characteristic of medium or high temperature geothermal systems in the

Cascade Range (see Mariner et al. [1990] for analyses of hot spring waters in the Cascade Range). The water is, therefore, less characteristic of high-temperature geothermal systems as we presently know them. Some of the surface springs in the vicinity of Mt. Mazama are more concentrated than these SHEF inputs. For example, an unnamed calcium bicarbonate spring on Minnehaha Creek has a TDS of about 640 mg/liter, and Soda Spring on Minnehaha Creek has a TDS of 3035 mg/liter. The analyses of Llao's and Palisades pools (SHEF) differ markedly for the Mt. Mazama springs listed in Thompson et al. (1990, Table 1A), in having Mg > Ca >> K, a situation which is most unusual for typical geothermal waters (Ellis and Mahon 1977), which are normally depleted in magnesium and enriched in K.

Although the outflow temperature is about 19 ^{o}C, the fluids, when circulating at a slow rate, may have lost temperature to surrounding rock. In the Galapagos, Dr. Gieskes recalls "hydrothermal fluids" of 25 ^{o}C, but silica thermometry which indicated an original temperature of about 350 ^{o}C. The temperature is typical of a depth of circulation of 300 to 500 m below the bottom of the zone of rapid cold groundwater flow described above. For example, Swanberg and Morgan (1979) found that the average silica temperatures of water from wells in the western United States are 55 to 95 ^{o}C, equal to or higher than the fluid inferred to charge Crater Lake.

C. The discovery of spires near Skell Head

The discovery of high (10 m) spires near the base of the caldera walls is important for several reasons. First, the spires are predominantly amorphous silica (Fig. 50a) according to the draft report. This suggests precipitation from fluids at higher temperatures than any yet measured in the present study. The height of the spires supports vigorous outflow and/or very buoyant, high-temperature, fluids.

Although it is not clear that the system that formed the spires is still active, their discovery is perhaps the best direct evidence yet that "hydrothermal" processes have operated through the floor of the lake. Furthermore the morphology of these spires suggests that the fluids from which they precipitated were rising buoyantly. This is not the case with the SHEF waters, as can be seen by comparing Plate 15 and Plate 16. Similarly in Figures 42 and 45 of the draft report, it is apparent that the SHEF water is dense enough to flow down slope. Thus it seems unlikely that it could be

contributing in a major way to density instability which increases mixing in the lake.

These SHEF bottom flows appear to be vigorous enough to form localized erosional channels, but the fragile and complex structure of the bacterial mats suggests that the exit velocity of the venting SHEF water is not great enough to destroy or modify them.

In the oral presentation, Dr. Dymond commented that the spire sample contained bands of material. From microprobe studies, these bands are apparently accompanied by variations in the composition of the spire. In particular, iron and silica appear to vary inversely (Fig. 49). These results also support hydrothermal precipitation in a varying chemical environment. Dr. Dymond also commented that the banding in the sample appeared to form an incomplete cross section through rings of precipitated material. Here, some photographs in the report would have been helpful to the reviewers.

The spires are also important because they appear at the base of the caldera wall and, like the Palisades Point features, they exist far from the Chaski slide region. In the original Panel recommendations, we urged the researchers to look for features outside the Detailed Study Area. While they did not plan a major search for thermal features, it was fortunate that the dives located some. These later discoveries indicate that some of the features could not possibly be associated with groundwater flowing down the Chaski Slide. In addition, the discovery of the spires is consistent with the hypothesis that thermal waters are flowing up along the caldera walls or ring fractures.

In the report, the authors suggest that the spire features are rather young (<50 years) because they found no spire debris or broken spires. In addition, the spires have only a light dusting of sediment, even in their crevices. These observations are consistent with the age estimate. However, in the video shown for the Panel, the spires appeared more broken up, which suggested to one Panel member a greater age. In addition, the survey of the spires was necessarily brief and perhaps evidence of debris could be found on further research. While the details of the spire sample recovery are not clear, it appears that only half a chimney was recovered from a top of the spire. If so, this suggests that the missing part of the spire was broken off sometime in the past. It is regrettable that more time was not spent on investigating the spires by the submersible since the petrological data on

these interesting features could be valuable. It may eventually be possible to date them by a study of their actinide chemistry, and to determine their temperature of formation using oxygen isotopes.

In any event, the Panel suggests that although estimates of spire age are premature at this time, the spires are extremely interesting and potentially important. Future work on the known spires and a search for additional ones could certainly be interesting and potentially rewarding.

D. Comments on mixing calculations

1. Experimental design

The researchers have made a serious effort to understand the mixing dynamics of the lake. This is a scientifically important problem, and is definitely important in understanding the role of the SHEF inputs at the bottom of the lake. The bulk of this material was presented orally to the Panel and, unfortunately, was not included in the draft report. The Panel feels strongly that the material presented to the Panel that was not included in the draft report should definitely be included in the final report.

In the opinion of the Panel, these mixing models should be included in the final report as the required sublake influxes of He, Rn, SO_4 and Cl, etc. constitute perhaps the best indirect evidence of hydrothermal processes. Enhanced concentrations of such dissolved components are characteristic of warm springs in volcanic terrains. For example, mixed bicarbonate/sulfate waters are often the product of reaction by steam-heated groundwater with volcanic rocks, and the source of sulfate is often oxidation of H_2S, concentrated into and transported by the steam phase.

On the other hand, it does not necessarily require that the hydrothermal system is active today. As Nathenson and Thompson (1990) point out, we could have a low flux of high salinity water or a high flux of low salinity water, to give the same mass flow of the necessary components. Sufficient inflow of relatively dilute groundwater, such as that sampled from Llao's Pool, which had traversed and leached rocks which were altered in previous hydrothermal episodes, would achieve the same results. On the other hand, Collier and Dymond's modeling reaches conclusions somewhat similar to those of Nathenson and Thompson (1990); however, discussion of the similarities and differences between the modeling by the OSU and the USGS teams would be a valuable addition and should be included in the final report.

2. Results

Seasonal mixing is well documented in the data. A series of nitrate profiles strongly suggests the accumulation of nitrate in the bottom waters of the lake. This vertical mixing is not as complete at the bottom of the lake, as revealed by the seasonal temperature profiles and the presence of higher nitrate levels near the bottom (Larson et al. 1990). Sampling in February and March would improve our understanding of the mixing dynamics of the lake.

The SHEF are relatively dense, and pools on the bottom appear to form. Further, there is evidence from the ^{3}He and the ion profiles for mixing. There is also evidence of spill-over (horizontal flow) of south basin bottom waters into the northeast basin and some vertical mixing near the bottom is apparently occurring there. Further, elevated ionic concentrations at mid-water levels (<300 m) support the hypothesis that bottom waters (with an SHEF component) are incorporated into the lake as a whole.

3. Comments on the conclusions

The Panel, with the available data, was unable to reach a consensus as to whether or not the input of SHEF fluids at the bottom of the lake is sufficient to strongly influence the mixing of Crater Lake. Since lake mixing is so dominated by seasonal variations and climatic changes, the role of SHEF fluids in the mixing patterns is not yet known. One note of caution should be mentioned. The accuracy of chemical analyses has improved markedly during the last 80 years, and this is particularly true for elements like Na and Li.

E. Comments on "box" modeling effort

1. Experimental design

The design of models includes the assumptions used, in this case the steady-state assumption, and the nature of model inputs. One of the goals of the modeling was to test the hypothesis that ionic concentrations in the lake today are a result of the original volcanic inputs four-to-seven thousand years ago.

Model inputs are derived from several hydrological studies. While values for various parameters may be disputed, the authors attempted to be conservative in their use of values throughout their study. For the modeling process, the authors used a finite difference approach to examine the time-

history of chloride and lithium levels in the lake. The finite difference approach is standard and noncontroversial. A reference for the code used would, however, be helpful for the reviewers.

2. Results and conclusions of the "box" model

The major result of this section is that the lake water has a relatively short memory with respect to its entire history. Thus, ionic concentrations soon after initial formation are not reflected in the present-day chemistry of the lake. This conclusion is not in question and the issue of steady-state assumptions is not critical. That is, they argue that the original volcanic eruptions cannot be the source of present chloride concentrations. Whether or not more recent, but possibly extinct, fumarolic inputs have played a role is not known.

In their presentation to the Panel, the authors extended this box model. They "reversed" the model by forcing it to be non-steady state and found that the concentration of sodium would have had to change over the last 80 years if it resulted from an impulse input sometime in the recent past. This change would have been seen within the range of previous observations. Since it hasn't, they conclude that sodium inputs have been steady state during the last few decades. This result also appears sound.

3. General comments about the "box" model

The box model approach is useful because it indicates that present-day ionic concentrations must be maintained by a steady-state input. Alternatively, current ionic concentrations could be maintained by frequent, small, transient inputs. If this is actually the case, then these inputs have occurred recently and perhaps are occurring now.

Obviously, a box model cannot locate sources, but the mass balance argument does indicate that SHEF do substantially contribute to the lake's salt balance (see Geochemistry Sec. F and the Summary). One question that remains is whether or not SHEF also have a major impact on the thermal structure of the lake and on its mixing characteristics. This question is addressed to the best of the Panel's ability in the Limnology section.

VI. GEOCHEMISTRY

A. Introduction

Since the last review (Goldman et al. 1989a) of the Dymond/Collier preliminary report, several suggestions have been followed up, which included more detailed sampling of fluids in bacterial mats as well as of pore fluids in the sediments, both in areas of background sediments as well as in areas of bacterial mats. In addition samples have been obtained from the newly (1989) discovered "saline" pools. No work has been done as yet on oxygen isotope systematics and we strongly urge that this be carried out in the future. It is essential that all samples are preserved in glass containers for the oxygen isotope analysis.

The Panel noted that, on page 18, the report lists at least thirteen other investigators who received water and sediment samples from Dr. Collier and Dr. Dymond as part of their sampling of Crater Lake. The report presents very few results from these other related geochemical studies. Apparently, those studies were regarded as being of lower priority and presumably they were not funded by this project. Many on the Panel would have preferred giving a higher priority to this work than some of the work actually reported; for example, a major deficiency remains the lack of data on light stable isotopes.

B. Inorganic constituents

The previous work on the chemical composition of the lake waters (Na, Cl, K, Mg, Ca, Mn, H_4SiO_4) has continued, but, more importantly, it has been extended to include analyses of bacterial mat fluids, pool waters, and interstitial waters.

The concentration-depth profiles of Figure 21 are useful, but it would be more effective to show on an enlarged plot all of the data, including those of previous years and of the North Basin. This would allow comparison of small differences and features that get lost in composite plots with error bars (which can be indicated separately in these graphs). The main features, like those in the salinity-depth profiles, will remain and will demonstrate the relative importance of South Basin with respect to salt inputs into the lake.

The ion-ion correlations (especially if consistent labeling is used) can now be extended to include the data of mats and pools. The importance of such

plots is well demonstrated in Figure 22 (Na vs Cl), but Figures 23 and 24 could be improved by including all water data now available. In addition other ion-ion plots should be made in a similar manner. The inclusion of Ca from GC1 and GC8, but the omission of the other pore water data, which appear to fall along the main regression line, is awkward. It appears, if anything, that Ca in GC1 and GC8 were different from the majority of the cores. This, of course, begs the question of how Ca behaved in cores GC2 and GC3 in the North Basins. Did they also show little increase in Na but relatively large increases in Ca (and Mg)? Indeed, why was Mg of the pore waters omitted from the correlation plots in Figure 23?

As such the ion-ion correlations suggest strongly that the higher salinity fluids in the South Basin have a common compositional origin. This is also evident from ^{3}He ion correlations which follow later in the report.

C. Pore water chemistry

In accordance with the Panel's previous suggestion, detailed pore water studies have been carried out. The data presented orally by Dr. C.G. Wheat were more extensive than included in the report and we urge the reporting of the entire data set in Appendix F, including data on Cores GC2 and GC3. This is of importance as is the inclusion of the data in the ion-ion correlations, as shown by Dr. Wheat during his presentation to the Panel.

It would be helpful for future readers if the potential error of the calculated fluxes is indicated. There is no doubt that the box cores were taken closer to the mats than were the gravity cores. It would be particularly helpful to reviewers if a short description of the location of the box cores vis-a-vis the bacterial mats were provided in the report.

D. Oxygen mass balance

The question arose in our discussions as to the importance of dissolved reduced iron with respect to oxygen depletion in the deep waters (Figure 19; Appendix A). There is a clear correlation between dissolved oxygen and Na as well as with temperature (Figure 19). Considerations of dissolved nitrate distributions should be made in order to determine how much decomposition of organic material would contribute to the oxygen utilization. In addition the question arises if this calculated oxygen utilization can to some extent be the result of mixing processes between lake waters and anoxic input waters, or

whether oxidation of reduced iron in the bacterial mats leads to a significant chemical oxygen demand. In other words, with the information available on dissolved iron in pore fluids and mat fluids, can a reduced iron flux be estimated that would yield an estimate of the "chemical" oxygen demand. Indeed, such an estimate might well be of considerable importance with respect to the problem of the genesis of the iron rich bacterial mats.

E. Rare Earth elements

The data on REE compositions of lake waters, pool waters, as well as pore waters presented by Dr. Gary Klinkhammer are most relevant and they should be included in the final report. The additional data provided to the Panel on Mazama solids and aluminosilicate debris from the caldera wall indicated no Europium (Eu) anomalies in the solid phases, but the dissolved REE data of Dr. Klinkhammer indicated a pronounced positive Eu anomaly. Such anomalies have also been observed in fluids emanating from hydrothermal vents on oceanic ridges (Campbell et al. 1988).

This information is of great significance and deserves further elaboration in the report with regards the potential origin of this Eu anomaly. Does it require interaction with the rocks at higher temperatures?

F. Geochemical modeling

The presentation of the geochemical models in the preliminary report (pages 107-115) was felt to be much less clear than that presented orally by Dr. Collier to the Panel. We urge a revision to make this section more conformant with the oral presentation. This is particularly important because the calculations help emphasize that the ion flux deficits are very large when the bottom input is ignored in the geochemical mass balance. A sensitivity analysis of this mass balance is appropriate. In any case, the "hydrothermal" flux constitutes well over 50% of the total input flux.

The results of the mass balance calculations constitute one of the important conclusions of the work:

> Inputs of thermally enhanced (~19 ^{o}C) and more saline fluids (475-750 mg dm^{-3}) into the bottom waters of the South Basin are the principal contributors to the salt balance of the entire lake.

G. Geothermometry

The analyses of Llao's and Palisades pools (SHEF) differ markedly from the Mt. Mazama springs listed in Thompson et al. (1990, Table 1A), in having Mg > Ca >> K, a situation which is most unusual for geothermal waters (Ellis and Mahon 1977), which are normally depleted in magnesium, and enriched in K. The Panel recommends caution in using semi-empirical geothermometers which have been derived from data on much more concentrated chloride-dominated solutions at higher temperatures (Fournier 1981) on the cold dilute fluids, with the unusual chemistry, shown in Table 7, page 108. For example, experience shows that the most reliable geothermometer for geothermal waters which have mixed with cold dilute water is the Na K Ca geothermometer with a Mg correction (Fournier 1981). The authors claim to have used this Na K Ca thermometer, with a Mg correction factor of R = 100 Mg/(Mg+Ca+K), for the SHEF waters of Table 7. For the Palisades Pool water this gives a correction factor R of more than 100, showing just how meaningless this widely used geothermometer is for compositions such as these. Collier and Dymond, on page 123 of their report, cite the temperature of 165 ^{o}C for Llao's pool based on the Na Li thermometer. In normal hydrothermal fluids ratios of Na/Li are controlled by reactions between water and minerals such as albite and mica, and so this thermometer is most appropriate for moderate to high temperature systems. Geothermal waters have Na/Li ratios in the range of 20 to 5,000 (Ellis and Mahon 1977, Table 2.3). However the concentration of Li in the SHEF waters is very low, with ratios of Na/Li of 10^{6}, showing an inappropriate use of geothermometry.

H. Geochemistry of sediments

Much of the sediment chemistry discussed in the present report results from earlier studies by Collier and Dymond (1988, 1989, 1990). This information is summarized in Figure 46 and indicates the results of the three component analysis of the sediment composition. One of the shortcomings of the section is the lack of mineralogical and petrographic data on the sediments and precipitates. See also our previous comments on the silica spires.

The chemical information has been extended to an analysis of selected samples of Fe-crusts, Si-crusts, spires, and pool sediments (Table 5; Figures 47, 48, and 49). On page 98 it is argued that pool sediments are enriched in

sulfur and carbon and reference is made to Table 5, which is erroneous. If Table 5 is examined, one notes no data for C and S. This reference in the draft report needs corrective action.

The observations on the spires is interesting - see also comments in Section V - perhaps some work on oxygen isotopes of the amorphous silica might be useful. However, it would be of great importance if the age of the spires could be established in an unambiguous manner. If these spires are only 60 years old, it would imply that episodic inputs of higher temperature fluids must occur in Crater Lake.

The section of REE in the sediments can now be strengthened with the availability of the data on dissolved REE as presented by Dr. Klinkhammer. As this section stands at present it does not contribute as much as it could.

New sediment core analyses on box cores BC6 and BC8 needs to be expanded and put together with relevant profiles of dissolved Fe and Mn (if available). As such again this section (page 101) is incomplete and should be strengthened. It is our understanding that more work is planned on these cores and, if anything, this section could be left in abeyance. Mass balance calculations would be relevant to understand the large enrichments in solid iron.

I. Investigations with dissolved environmental isotopes and chlorofluoromethanes (freons)

1. General comments

Measurements of the distributions of a number of dissolved environmental isotopes and freons (CFC-11, CFC-12) have played a central role in advancing understanding of processes in Crater Lake in the present study and in those of a number of previous investigations. These data have been critical in quantifying the rates of vertical mixing of the water column, fluxes of hydrothermal ions and dissolved gases into the deep lake, locus of hydrothermal inflows, accumulation rate of bottom sediments and other processes involving interactions between the atmosphere and the lake surface.

These data represent key calibration measurements for model calculations of lake processes and qualitative indicators of several essential components of conceptual models of the dynamics of Crater Lake geochemical and hydrologic budgets.

Because of the central role of these data in a number of considerations, it would be very helpful to have all of the published data for a number of dissolved isotopes and freons collected in the final report in the form of tables and figures. In particular, the parameters for which summary tables should be included are ^{3}He, ^{4}He, ^{222}Rn, ^{226}Ra, ^{14}C, ^{13}C, CFC-11 and CFC-12.

The team of scientists involved in the study of hydrothermal processes in Crater Lake have, in general, made effective use of the above group of tracers, within the limitations of time, budgets and availability of collaborators.

2. Helium isotopes

These data lie at the heart of the development of improved understanding of chemical budgets in Crater Lake over the past five years. The approach employed for these tracers was based primarily on the experience gained from extensive research by many scientists in chemical oceanography over the past fifteen years. Since there are only a few laboratories capable of ^{3}He measurements in environmental samples, it was critical to obtain this collaboration. We are generally in agreement with the approach taken in application of He isotope measurements in Crater Lake, but also have suggestions for improving this aspect of the study. We believe the data reported unequivocally demonstrate the dominance of supply from mantle sources of helium isotopes dissolved in the deeper waters of the lake. Since these influxes near the bottom are rapidly lost to the atmosphere by gas exchange at the lake surface, the observed excess of ^{3}He and ^{4}He in the deeper waters can only be maintained by continued influx of mantle-derived He to the lake and what appears to be partial mixing during some winters.

We were especially impressed by the He isotope data obtained for the "end-member" samples collected from the bacterial mats and enhanced salinity pools on the lake floor. These samples could only have been acquired using a submersible, and their measured ^{3}He and ^{4}He concentrations provide key anchors upon which much of the subsequent chemical and hydrothermal budget calculations are based. However, a word of caution here. The influx of ^{3}He into the lake is in itself an interesting phenomenon; however, that its total flux is entirely associated with inflow of hydrothermal fluids remains an assumption which needs to tested by further study, as the permeability of fractured rocks to helium is very high.

We have two recommendations for treatment of He isotope data in the final report. First it would be very helpful to have all of the measured values for Crater Lake compiled together. At present the data can be found only by locating several references in addition to the draft report of October 26, 1990. The total number of separate samples analyzed for He isotopes over the past five years is less than three or four dozen. These could easily be presented in a single table and a limited number of essential figures, most of which are already present in the draft report.

Secondly, we suggest that the contribution of dissolved ^{3}He by decay of tritium should be explicitly included in the discussion. Although this addition would not alter the conclusions as presented in any significant way, it would help communicate the unusual nature of helium isotope budgets in this lake, compared to one of similar depth and tritium concentrations which did not have a source of mantle helium to the deep waters.

3. Radon and radium

Considering all of the tracers measured, the activities of ^{222}Rn in vertical profiles from the lake provide the most sensitive indicator of the primary locus of groundwater influx. The depth interval at which the dominant input occurs to the deep lake can be unequivocally established from the ^{222}Rn data because of the extremely high ratio of this tracer in groundwaters, including SHEF fluids, to ^{222}Rn concentrations in the open lake (about a factor of 10^{5}). Although these data alone are not sufficient to distinguish between inflows of ambient temperature groundwaters and hydrothermal fluids, when combined with the other observations discussed in the report, they help locate quite precisely the depth at which addition of SHEF fluids is occurring. Because of the short half-life of ^{222}Rn (3.825 days), the strong signal at a depth of about 450 meters can only be sustained by the continued influx of SHEF waters.

Measurements of ^{222}Rn in the lake obviously required a major investment of effort in collection and analysis. We suggest that it would be quite valuable to collect all of the ^{222}Rn and ^{226}Ra measurements from Crater Lake and springs within the Park in a single table (the 1989 data could be left in Appendix I as currently tabulated, and also included in a second Rn/Ra table with all of the previous data for these parameters.

4. Dissolved ^{14}C and ^{13}C

Measured values for these parameters were not included in the draft report of October 26, 1990. However, ^{14}C values for 4 samples from Crater Lake and 2 additional samples from a caldera spring and East Lake were obtained by the principal investigators a few days prior to the meeting of our Panel on January 14, 1991, and were discussed in the oral presentation. These data were extremely interesting, and one of the samples from an enhanced salinity pool at the lake bottom was essentially free of any ^{14}C, indicating that it is very old (greater than 25,000 years). This observation of old ^{14}C is consistent with a magmatic origin of the inorganic carbon in the hydrothermal influx near the lake bottom.

Dymond interpreted this observation as being consistent with a magmatic (He said "mantle" in his presentation) origin of inorganic carbon in a hydrothermal influx near the lake bottom, and suggested that it could not be explained by any plausible model of groundwater influx with no magmatic carbon. However, in the opinion of some of the Panel members, alternative models are perhaps as or more plausible than the one preferred by Dymond. The rather limited data available indicates that ^{14}C is below detection limits in the dissolved carbonate and bicarbonate in the SHEF water (which contains only 4.96 - 8.70 mM of total dissolved carbon). Dymond's inference is that it must be magmatic because, if the reservoir for this carbon was the atmosphere, it would have to be much older than the eruption which formed Crater Lake. However, this does not require that the carbon is derived directly from the degassing of an underlying magma chamber. One possible reservoir for the dead carbon beneath the lake is carbonate veins, which, as is typical for volcanic terrains, are ubiquitous in the vicinity of Mt. Mazama. For example, core samples from a 415 m deep borehole, drilled 5 km SE of Crater Lake, contain abundant calcite veins with associated zeolites and quartz, which formed in multiple stages of authigenic mineralization. U-Th geochronological techniques reveal that this authigenic mineralization was episodic, with varying degrees of oxidation, and it ranged in age from 140 Ka to >350 Ka BP (Hull and Waibel 1989). Because these ages are similar to the K-Ar ages of the silicic volcanic rocks, most of this mineralization was contemporaneous with construction of the Mt. Scott stratovolcano, on the SE flank of Mt. Mazama. Therefore, the carbon in these veins could be "dead" and appear to be "mantle" carbon. This interpretation, however, was not unanimous, since some

Panel members believe that the proposed source of dead carbon from carbonate veins could not sustain the necessary flux of ^{14}C-free carbon dioxide over thousands of years, noting that it has never been proven to be a major component of volcanic CO_2 in any andesitic volcano in the Pacific Northwest or elsewhere. There are a very small number of special volcanic situations with large volumes of associated carbonate rocks (e.g., East Africa) where it would be plausible to consider such a model, but Crater Lake is not one of these.

As for the rocks of Crater Lake, Bacon and Lanphere (1990, p 26) point out that, except between Pumice Point and Wineglass, the rocks at lake level are "everywhere subtly to severely hydrothermally altered". Most likely such alteration would form in the crater-fill, immediately after the climactic eruption and again during the Merriam Cone and Wizard Island eruptions. Subsequently cold, oxidizing meteoric water (lake water?) would encounter warmer, previously hydrothermally-altered, rocks beneath the lake floor, and dissolution of hydrothermal carbonates and sulfides would give rise to the mildly alkaline bicarbonate/sulfate SHEF waters.

These ^{14}C data were measured by accelerator mass spectrometry in Zurich, through collaboration with Peter Schlosser (formerly at the University of Heidelberg) and his colleagues. Unfortunately, ^{13}C data obtained by accelerator mass spectrometry are subject to poorly-defined fractionation processes which prevent them from being of use here. We strongly recommend that the ^{14}C data be included in the final report, accompanied by a detailed discussion of their important implications in this study.

5. Dissolved freons

Vertical profiles of these tracers in Crater Lake for August 1989 are given in a figure and brief discussion in Appendix G of the draft report. These data provide the most sensitive indicator of the time-scale of ventilation of deep waters in the lake and provide the basis for estimation of a mean renewal time of 2 years for these waters. The freon data are so critical to model calculations for a number of parameters, including helium isotopes, and dissolved oxygen, that we suggest discussion of this data be expanded and provided earlier in the report. At the minimum, details of renewal time calculations based on freons should be provided, perhaps in summary table form in Appendix G, and referred to earlier and with more emphasis in the final report.

6. Suggestions for future applications of environmental tracers in Crater Lake

Research at Crater Lake over the past three-four decades has revealed a great deal about the details of its chemical, physical and biological processes. These findings indicate that Crater Lake provides almost a unique location for obtaining accurate estimates of atmospheric input of tracers such as fission products and tritium, integrated over a number of years, as well as receiving an influx of the warmer, enhanced-salinity fluids (SHEF) near the bottom which play a critical role in the chemical budgets of the lake. With improved understanding of lake processes, the site has become even more valuable as a location for study of long-term processes involving atmosphere-surface water exchange, environmental controls of phytoplankton communities in highly oligotrophic lakes and their effects on water clarity, dynamics of microbial communities based on the influx of anoxic waters, as well as a number of other limnological subjects.

From the results obtained in this study and others, there appears to be considerable potential for further exploitation of tracer measurements in Crater Lake, especially involving He isotopes, carbon isotopes and freons. One issue of potential conflict with other areas of research involves ^{14}C. The distribution of this tracer in the lake is extremely sensitive to the input of magmatic carbon or carbon isotopes to the deep lake. To preserve the value of this natural tracer, it is essential that great care be taken in future measurements of primary production by incubation with radiotracer levels of ^{14}C to prevent contamination of the lake, or of any samples to be used for natural ^{14}C levels. This kind of potential conflict illustrates the value of some form of sustained planning and oversight of long-term research involving Crater Lake by scientists with a broad range of backgrounds.

J. Additional studies and suggestions for further work

1. Light stable isotopes

Among an otherwise comprehensive array of geochemical studies described and interpreted in the Draft Report on Crater Lake, there is one omission which the Panel regards as being particularly unfortunate; i.e., no investigations of light stable isotopes by the OSU team are reported. This is puzzling as among the co-investigators to whom water and sediment samples were sent, the Principal Investigators mention Dr. Alan Mix, of Oregon State

University, who received splits for oxygen and hydrogen isotopic analyses. However, the report presents no stable isotope data either from that study or from the studies of other investigators.

The Panel views light stable isotopes as being of particular importance in understanding both the limnological and the hydrothermal geochemistry of Crater Lake. The extensive literature developed during the last three decades on measurement and interpretation of isotopic ratios of hydrogen, carbon, oxygen, and to a lesser degree of sulfur, in the study of hydrologic systems in general and of hydrothermal systems in particular, testifies to the importance of this versatile and cost-effective approach (Craig 1961; Ellis and Mahon 1977; Fournier 1981; Gonfiantini 1986; IAEA 1979; Thompson et al. 1990).

The omission of stable isotope chemistry from the draft report of Collier, Dymond and McManus is therefore unfortunate. We suggest that a much higher priority should have been given to stable isotopes, and an appropriate level of funding should have been assigned to acquiring and interpreting the necessary data, particularly with respect to samples of the salinity- and heat-enriched fluid inputs to the floor of the lake. This deficiency should be remedied in the future, even if it is necessary to arrange for the work to be carried out by competent isotope geochemists outside of OSU. There are numerous investigators in the U.S.A. with the necessary analytical facilities and experience in using these techniques on hydrothermal rock/water systems of many kinds.

The lack of stable isotopic data in the draft report is also puzzling in that its authors are aware of the utility and importance of such an approach. For example, on page 116 of their report, they cite the work of colleagues in the USGS (Thompson et al. 1987, 1990) which shows that hydrogen and oxygen isotopic ratios of waters from Crater lake and surrounding springs indicate that its waters "fall off the meteoric water line and follow a reasonable evaporation trend". However, the USGS studies (Thompson et al. 1987, 1990) use stable isotope ratios to address much more than this single issue. Thompson and his co-workers compare the hydrogen and oxygen isotopic ratios of 26 samples of Crater Lake waters with 28 samples of cold springs discharging from the flanks of Mt. Mazama, and one from Diamond Lake, a lake about 20 km north of and 300 m lower than Crater Lake. Their results show that: (a) as might be expected, the isotopic ratios of the cold-water subaerial springs lie

on the meteoric water line; (b) samples of Crater Lake water obtained from throughout the water column show that the lake is isotopically well-mixed; (c) the Crater Lake waters are heavier isotopically than the spring waters due to evaporation from the lake; and (d) a few of the isotopically light spring waters are more chloride-rich than typical local springs by amounts which approach the chloride concentration of the lake.

However, Thompson and his coworkers did not have samples obtained during the submersible dives. It would have been highly desirable to compare their published data with the hydrogen and oxygen isotopic ratios of water samples from lake bottom water, from the pore waters in the lake-bottom sediment, and from the "anomalous", slightly-warmer and more-saline, pools on the lake bed.

On page 109 of their report Collier, Dymond and McManus infer, from the calculated Na/Li geothermometer temperature of 164 ^{o}C, that the waters in these small pools of SHEF have been cooled from a moderate-temperature hydrothermal source. If this were the case, their oxygen isotopes would exhibit characteristic ratios, due to exchange with the rocks in the hot zone, which are quite different from the evaporation trends observed by Thompson et al. (1987, 1990).

If, as might be expected, it were to be found that these different waters have characteristic hydrogen and oxygen isotopic signatures, we might then develop mixing models which, in turn, could be used to estimate end-member compositions of the different components of the hydrologic system, and specifically of the fluid which gives rise to the SHEF pools and bacterial mats on the lake floor.

If suitable water samples (stored in sealed glass containers) were available now, or were to be collected in the future, analysis of isotopic ratios of carbon and of sulfur might also be attempted, although this would require larger samples due to the lower concentration of these elements. Certainly, hydrothermal components in this system should have distinctive isotopic ratios, depending on their sources, equilibration temperatures, and water/rock ratios.

Studies of light stable isotopes should be extended to encompass geothermometry and rock/water ratios, by adding data on appropriate solids. Fresh and altered dacites and andesites, lake bottom sediments, bacterial mats, and the silica spires are obvious targets. Successful acquisition of

such data would allow more precise estimates concerning the nature and temperature of any hydrologic system which may underlie Crater Lake.

Such isotopic ratios could and should be used to address the following issues:

(a) The relationship of the local precipitation from different storm patterns and of cold-water subaerial springs to the world meteoric water line.

(b) Comparison of these data to the isotopic ratios of water samples from different levels in the lake, to lake bottom water, and to the anomalous, warmer SHEF forming the more saline pools, and pore waters which apparently enter the lake through its floor.

(c) If characteristic isotopic signatures are found for these different water sources, we could then develop mixing models which, in turn, could be used to estimate end-member compositions of the different components of the hydrologic system, and specifically of the fluid(s) which gives rise to the enhanced salinity pools and bacterial mats on the lake floor. The next step would then be to carry out mass balance calculations for the inputs and outputs of water and dissolved species of carbon and possibly of sulfur to the whole hydrologic budget of the lake. These calculations would enhance and extend the related mass balance modeling based on the element analyses which are included in the report on p. 107-117. If the data permit, it would also be possible to use these isotopic data to provide limits on estimates of geothermometry and possibly of water/rock ratios.

(d) A secondary but important aim of such isotopic studies would be to extend the geothermometry and rock/water ratios, by adding data on appropriate solids, fresh and altered dacites and andesites, lake bottom sediments, and bacterial mats. The silica spires are also obvious targets. If appropriate data on such materials is added to that on the fluids, we should be able to make more precise calculations concerning the nature and temperature of the hydrothermal system which has been postulated to underlie Crater Lake.

VII. SUMMARY

A. Important results from the 1989 and 1990 field seasons

The Panel is impressed by the effort made by Collier, Dymond and their coworkers to determine if hydrothermal inputs are present in Crater Lake. The data has been primarily descriptive and geochemical in nature, reflecting the expertise of the researchers and limitations of submersible and ROV research. Their work supports the following conclusions:

1. The Panel agrees that a slightly warmer and more saline water (SHEF) is entering the lake bottom.
2. The SHEF strongly influence the major element geochemistry and environmental isotope compositions of the lake waters.
3. The SHEF fluid "venting" is associated with interesting features. The bacterial mats are particularly unusual and fascinating. Descriptive evidence indicates that these mats are dynamic features. The presence of pools of relatively high density enhanced salinity water on the lake bottom is also an interesting observation. Descriptive evidence indicates that these pools form from the sinking and transport of fluids from vents or seep zones, some of which find their immediate source under rocks.
4. The work described in the 1990 report helps establish that SHEF includes a "magmatic" component, and that the He isotope composition is dominated by a mantle or magmatic source leaking into the lake.
5. The Panel notes the discovery of water with temperature in excess of 15 ^{o}C, which is appreciably higher than regional meteoric water, that is entering the lake near the bottom. It should also be noted that a reasonable geotherm within a Holocene volcanic edifice could reach these temperatures at a depth of 0.5 km.
6. The discovery of the Palisades Point features is important because it demonstrates the SHEF are not restricted to the Chaski Slide portion of the Detailed Study Area. However, water column measurements indicate that the greatest influx of fluids occurs in the South Basin, which tends to support the decision to utilize most of the submersible vehicle observation time within that basin.
7. The discovery of the siliceous spires at Skell Head indicates that influx of higher temperature buoyant fluids has occurred on the lake bottom sometime

in the past. The time when this influx occurred cannot be established from observations available up to the present.

8. There is evidence that the SHEF fluids are mixed in the bottom layer and that advection into the East Basin occurs at the depth of the sill between the South and East Basins.

9. The freon data reported provide the most sensitive indicators currently available of the time scale of deep water ventilation and establish the deep water renewal time to be about two years, assuming a steady-state vertical mixing process. This finding is a critical new result which helps constrain the magnitude of chemical fluxes from SHEF fluids into the deep waters of the lake, averaged over the mean vertical mixing time.

10. The ^{222}Rn activities observed in samples of deep water clearly establish the depth and general location at which the SHEF fluids are delivered to the deep waters of the lake. The distribution of this tracer in the lake water provides unequivocal evidence of influx of high ^{222}Rn fluids to the deep waters of the lake at the time of sampling during August 1989.

B. Other comments

While the above results and conclusions are both interesting and important there remain some uncertainties about the origin and characteristics of the SHEF inputs to the deep waters of Crater Lake. These uncertainties include:

1. The role of the SHEF fluids in the mixing of Crater Lake cannot be defined at the present time. Mixing dynamics are not well established from the available data, and improved sampling is recommended as part of any future monitoring program. Nitrate levels suggest that the lake is not completely mixed to its deepest level.

2. The nature of the system that supplies SHEF fluids to the lake bottom is very poorly defined. The size of the reservoir and the maximum temperatures in the reservoir are not constrained by the present data. The possibility that Crater Lake is underlain by a large high-temperature system still remains to be proved or refuted. Oxygen isotope work would be very helpful, as well as more reliable heat flow data, in resolving this issue. One Panel member believes that the work reported has established that the SHEF fluids form from reactions of lake or spring water with hydrothermally-altered volcanic rocks. This alteration may have occurred during earlier volcanic episodes. He argues

that the SHEF water chemistry is not consistent with being derived from a moderate or high-temperature hydrothermal system.

3. Arguments that the siliceous spires at Skell Head (which strongly indicate high temperature fluid input) are "recent" features are not conclusively supported by existing evidence. The submersible did not make a thorough study of the features, and the video tape shows the features to appear broken up. Without better knowledge of water movement, the lack of sediments is not conclusive evidence of recent activity.

4. The nature of the bacterial mats is still unknown despite recommendations from the previous Panel. The Panel recognized the investigators' efforts to secure volunteer help in this area; still, very little quantitative information about mat growth or metabolic rates has been obtained.

5. A geological model of the hydrothermal system cannot be made. The hypothesis that SHEF fluids enter the lake along the ring fractures that bound the caldera remains largely untested. We appreciate the limitations of submersible or ROV observations in collecting structural information. Even obtaining the strike of features is very difficult. However, until such data is obtained, the geological context of the SHEF fluids remains unknown.

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C. Interagency Agreement Among the Bureau of Land Management, National Park Service, U.S. Geological Survey, and the U.S. Forest Service for implementing Section 115 of the FY'87 Appropriations Act dated December 9, 1987.

Interagency Agreement Between
the Bureau of Land Management, the National Park Service,
the U.S. Geological Survey, and the Forest Service
for Implementing the Department of the Interior
and Related Agencies Appropriations Act for 1987
in Regard to Geothermal Leasing

I. Purpose

The purpose of this Interagency Agreement (IA) is to establish the procedures to be used for ensuring compliance with Section 115 of the General Provisions of the Department of the Interior and Related Agencies Appropriations Act for 1987.

II. Responsibilities

The principal officials responsible for implementation of this IA will be the Bureau of Land Management (BLM) State Directors, the National Park Service (NPS) Regional Directors, the U.S. Forest Service (FS) Regional Foresters, if National Forest System (NFS) lands are involved, and representatives of the U.S. Geological Survey (GS) for scientific information and advice as needed.

III. Procedures

A. Within 30 working days from the effective date of this Agreement, the NPS principal officials will identify for the BLM principal officials those areas within which NPS wishes to review geothermal leasing proposals on a case-by-case basis. For areas so identified, the procedures in this IA will be followed. For leasing proposals outside such areas, BLM will ensure compliance with section 115 and if connections between these areas and listed thermal features or potential impacts on listed features are identified, will notify the principal officials of the agencies party to this IA.

B. Within 10 working days of opening a geothermal lease application or at such time as BLM decides to hold a competitive lease sale, BLM will complete a checklist analysis (see Attachment 1). If the checklist indicates potential for a geologic/hydrologic connection between the proposed leasing area and a significant thermal feature that has been identified in accordance with section 115, the procedures established in section III.C. of this IA will be followed. If the checklist does not indicate a potential connection, the procedures will be as follows:

1. Within 10 working days, BLM will forward a copy of the checklist to NPS for review and concurrence.

2. Within 10 working days, NPS will either concur or request a meeting with 3LM to discuss concerns. If NPS concerns are not satisfactorily resolved at the meeting, BLM will prepare a more detailed analysis in accordance with III.C. of this IA.

3. If NPS concurs, BLM will post a notice of the determination in its public room and allow for a 30 calendar-day public comment period.

4. BLM will forward a copy of all comments received to NPS within 10 working days from the end of the comment period along with its proposed responses. The proposed responses will either reaffirm that no interconnection exists, or will conclude that an interconnection is possible, in which case a detailed analysis will be undertaken. NPS will, within 10 working days, either concur in the responses or inform BLM as to desired changes.

5. After resolution of comments, unless it has been determined that a detailed analysis should be prepared, BLM will proceed to process the leasing proposal.

C. When the BLM checklist indicates a more detailed analysis is required or when NPS requests that a more detailed analysis be done, the procedures will be as follows:

1. Within 10 working days, BLM will forward a copy of the checklist to the principal officials and request information pertaining to geology, hydrothermal systems, and relevant scientific evidence that the agencies believe would be useful to BLM in preparing the detailed analysis.

2. Within 20 working days, each principal official will provide available information to the BLM or notify BLM as to when the information will be forwarded.

3. Within 20 working days of receipt of the requested data, the BLM, in consultation with the USGS, will prepare and forward the detailed analysis (see Attachment 2) to NPS. The detailed analysis will be made on the basis of available scientific evidence, including any information received from the principal officials. It will evaluate the adequacy of available data for assessing potential effects, and assess the potential connection between the listed significant thermal features and the proposed lease area. It will also estimate the type, extent, and magnitude of reasonably likely effects, and consider the effectiveness of possible mitigating measures.

4. Within 20 working days of receiving the BLM analysis, the principal officials of BLM, NPS, and GS will consult to determine, based on the analysis, scientific evidence, NPS planning documents, and the criteria contained in IV.A. of this Agreement, whether lease activities are reasonably likely to have no effect, an adverse effect, or a significant adverse effect on a listed thermal feature. These consultations will result in either: a) a decision page appended to the BLM analysis, signed by the principal officials of BLM, NPS, and GS, indicating agreement with the determination regarding

the degree of the effect, and indicating that the determination being made is consistent with the BLM analysis, the NPS planning documents, and the criteria contained in IV.A. of this Agreement; or b) if there is disagreement, an issue paper explaining each area of disagreement, in which the participating principals shall articulate their position on each point of disagreement. The issue will then be referred to the next higher level for conflict resolution. If, in the opinion of any of the participating principal officials, there is an insufficient basis to project the likely effects of lease activities on listed thermal features, the question of sufficiency of information will be referred to USGS. If, in the opinion of the USGS, the information is not sufficient to project effects, the principals will decide how the information needed can best be obtained. If they disagree on how it can be obtained, the issue will be referred to the next higher level for conflict resolution. If, in the opinion of the USGS, the information is sufficient to project effects, and other principal officials agree, the principals will decide on the range of effects that are likely.

5. Within 10 working days of the determination of the significance of effect, the BLM will prepare a notice presenting the determination and announcing the action proposed to be taken as outlined below. The notice will be forwarded to NPS for final review and, upon notification from NPS, the BLM will post the notice in its public room and allow for a 30 calendar-day public comment period. BLM will also forward copies to all principal officials for distribution to interested parties by each agency. Within 20 working days of the closing of the comment period, the principal officials will jointly review the comments received and consult on which of the following actions will then be taken. If agreement cannot be reached, a document summarizing areas of agreement and disagreement will be prepared and the issue will be elevated for conflict resolution.

a. Where it has been determined that geothermal activities would be reasonably likely to cause significant adverse effects on a listed feature, BLM will take such actions as are necessary to withdraw the lands involved under the authority of section 115 of the Act.

b. Where it has been determined that geothermal activities would be reasonably likely to cause adverse, but not significant adverse effects on a listed feature, BLM will schedule a meeting between specialists designated by the principal officials. Each agency will provide suggested stipulations to the other agencies prior to the meeting. The purpose of the meeting will be to provide an opportunity for staff specialists to discuss proposed mitigation measures, lease stipulations, and a monitoring program, including monitoring required by lessees. After the specialists' meeting, the principal officials will consult and ensure agreement on the mitigation measures,

stipulations, and monitoring program. If the principal officials agree, the BLM will proceed with processing the lease. If the agreement cannot be reached, the issue will be elevated for conflict resolution.

The agreed upon measures, stipulations, and monitoring program will be incorporated into subsequent National Environmental Policy Act (NEPA) compliance documents. In cases where it is determined that there will be an adverse effect on thermal features, NPS will participate as a cooperating agency in the preparation of NEPA compliance documents. The NEPA compliance documents will address issues in addition to the direct impact of geothermal leasing and development on the listed thermal feature, such as air and water quality, Park land use, and effects on the park visitor's experience such as noise and visual intrusion. If NFS lands are involved, preparation of NEPA compliance documents will be in accordance with the IA between BLM and FS for Mineral Leasing.

c. Where it has been determined that lease activities would not likely cause either adverse or significant adverse effects, the BLM, and FS when appropriate, will proceed with NEPA compliance.

6. In the event an administrative appeal of any decision or action resulting from this agreement, NPS, USGS, and FS will assist BLM in addressing those aspects of the appeal that involve their roles under this agreement.

IV. General

A. For purposes of this IA, an effect will be considered adverse if it is reasonably likely, based on scientific evidence, that lease operations would cause a measurable or observable change (temporary or permanent) in the temperature, flow, pressure or other characteristics of a listed feature. An effect singularly or cumulatively will be considered significantly adverse if it is reasonably likely that:

- The thermal feature's size, extent, uniqueness, or other characteristics would be noticeably changed such that the visitor's experience would be altered, or
- The feature's geologic and scientific significance would be substantially diminished, or
- The flora and fauna dependent on the feature would be disrupted, or
- The purposes for which the park was established would be altered.

B. The public room notices may address a group of lease applications, applications within a number of areas, applications within an entire State, or all lands included in a competitive lease sale. Public comments will be considered those submitted by entities other than the agencies party to this IA which are participating in a particular review of comments and subsequent decision.

C. In developing its monitoring programs for listed features within Park boundaries to comply with section 115(2)(b) of the Act, NPS will consider the possible future use of data collected in making determinations required under section 115(2)(c) of the Act and will consult as necessary with USGS, BLM, and FS. In developing monitoring programs to be conducted by entities other than NPS in lease areas, the principals will consider the compatibility of data collection and analysis with NPS monitoring programs for listed features.

D. The principal officials will coordinate work plans relevant to implementation of this IA such that appropriate agencies will be able to include informed requests in their budget submissions.

E. The BLM, USGS, and NPS will be available to assist FS in meeting FS responsibilities under section 115 (2)(e).

V. Effect on Other Agreements and Conflict Resolution

Nothing in this agreement is intended to supersede existing agreements between agencies. The BLM, NPS, and FS acknowledge the potential for conflicts in their respective missions, plans, and programs. Throughout the conflict resolution process, the mission of each agency and the need for negotiations to proceed in good faith are to be recognized. To facilitate resolution and to avoid public misunderstanding, all public disclosures and contact relative to either pending decisions or issues in conflict will be coordinated through the principal officials. The agencies will strive to resolve conflicts at the lowest organizational level possible. Any conflict or issue that cannot be resolved shall be forwarded promptly to the next higher level of authority for resolution.

VI. Effect to this Agreement

This agreement shall be effective from the date of execution until modified by mutual agreement or terminated within 30 days of written notice from any of the parties to the others, but shall not exceed 5 years, at which time it may be renewed by mutual consent.

Director, Bureau of Land Management

Date: 11/4/87

Director, National Park Service

Date: 11/06/87

Director, U.S. Geological Survey

Date: 11/6/87

Chief, Forest Service

Date: 12/9/87

Attachments

Checklist for Analyzing
POTENTIAL EFFECT ON SIGNIFICANT
THERMAL FEATURES

LEASE APPLN. NO. _____ LOCATION: ____SEC____T.____. R.____

POTENTIALLY AFFECTED FEATURE NAME_____DISTANCE_____MI.

TYPE FEATURE:_____NPS UNIT_____

GEOLOGIC FACTORS REVIEWED — REMARKS

- EXTENT OF VOLCANIC/MAGMATIC SYSTEM
- STRUCTURAL CONTINUITY
- LITHOLOGIC CONTINUITY

HYDROLOGIC FACTORS REVIEWED

- EXTENT OF HYDROLOGIC SYSTEM — SURFACE
  SUBSURFACE
- GEOCHEMICAL SIMILARIY

GEOPHYSICAL FACTORS REVIEWED

- CONTINUITY OF GEOPHYSICAL ANOMALIES

SUMMARY ANALYSIS:

REFERENCES:

CONCLUSION: (Check one)

_____ There is no scientific information indicating geologic or hydrologic interconnection between the lands under lease application and parklands, and exploration, development, or utilization of the lands in the subject lease application is not reasonably likely to have any effect on any significant thermal feature.

_____ The scientific evidence indicates there may be a geologic or hydrologic interconnection between the lands under lease application and parklands. The type, extent, and magnitude of possible effects on significant thermal features will require additional analysis.

GEOLOGIST: _____ DATE: _____

MANAGEMENT: _____ DATE: _____

FY' 87 APPROPRIATIONS ACT
SEC 115 DETERMINATION
LEASE APPLICATION _____

I. SUMMARY OF FINDINGS AND RECOMMENDATION

II. INTRODUCTION
- A. PURPOSE
- B. LOCATION
- C. LANDS INVOLVED NEAREST SIGNIFICANT THERMAL FEATURE
- D. TOPOGRAPHY
- E. CLIMATE

III. GEOLOGY
- A. REGIONAL GEOLOGY
- B. GEOLOGY/HYDROTHERMAL SYSTEM OF SIGNIFICANT THERMAL FEATURE
- C. GEOLOGY/HYDROTHERMAL SYSTEM OF LEASE APPLICATION AREA

IV. ANALYSIS OF POTENTIAL FOR GEOLOGIC/HYDROLOGIC CONNECTION OF THE HYDROTHERMAL SYSTEMS
- A. EXTENT OF VOLCANIC/MAGMATIC SYSTEM
- B. STRUCTURAL CONTINUITY
- C. LITHOLOGIC CONTINUITY
- D. HYDROLOGIC CONTINUITY
- E. GEOCHEMICAL SIMILARITY
- F. GEOPHYSICAL ANOMALY CONTINUITY

V. FINDING AS TO TYPE, EXTENT, AND MAGNITUDE OF EFFECTS
* SEE FOOTNOTE

VI. MOST REASONABLE DEVELOPMENT SCENARIO
- A. RESOURCE POTENTIAL ASSESSMENT
- B. PRODUCTION VOLUME/# WELLS NEEDED
- C. UTILIZATION TECHNOLOGY
- D. REINJECTION STRATEGY

VII. ANALYSIS OF EFFECT
- A. TRANSMISSIVITY OF FLUID, LOSS
- B. TRANSMISSIVITY OF PRESSURE CHANGES
- C. TRANSMISSIVITY OF TEMPERATURE CHANGES
- D. PHYSICAL CHANGES TO SIGNIFICANT THERMAL FEATURE

VIII. FINDING AS TO TYPE, EXTENT, AND MAGNITUDE OF EFFECTS

* IF CONCLUSION IS REACHED THAT THE HYDROTHERMAL SYSTEMS ARE CONNECTED, THEN PROCEED TO SECTIONS VI, VII, and VIII.

D. History of Geothermal Leasing Near Crater Lake National Park by the Bureau of Land Management

GEOTHERMAL LEASING HISTORY AND CHRONOLOGY FOR GEOTHERMAL UNITS MAZAMA I AND II IN THE WINEMA NATIONAL FOREST ADJACENT TO CRATER LAKE NATIONAL PARK OREGON

Prepared by the Bureau of Land Management
Oregon State Office, Division of Mineral Resources

Mount Mazama, the collapsed volcano which contains Crater Lake, is often cited in the background and setting descriptions of Crater Lake National Park (CLNP). Mount Mazama is an irregular, east-west elongated, ellipsoidal volcano covering about 100 square miles entirely within CLNP. It is a shield and stratovolcano complex (with certain exceptions) that collapsed from a major eruption some 6800 years ago and created the spectacular Crater Lake caldera. CLNP occupies a roughly rectangular tract that includes additional smaller volcanos and covers about 286 square miles.

Its rocks indicate a history of active volcanism covering more than 400,000 years with the most recent volcanic episode estimated to be about 4,000 years before present. The tectonic/volcanic forces that operated throughout that period still operate today. There are, however, no known hot springs associated with Mount Mazama.

Geologic literature relating to the Mount Mazama area contains information that make it and adjacent lands, an attractive geothermal resource target. Since geothermal leasing is not possible within National Parks, adjoining lands have attracted interest in exploring for geothermal resources.

Lands adjoining Mount Mazama were largely ignored by the geothermal community in the initial surge of leasing from 1974-1980. In the spring and summer of 1982, California Energy Company Inc. (CECI) started to apply for leases on National Forest lands that border the Park. These National Forest lands have been harvested for timber and contain a well developed road network, log landings and clearings that could facilitate access to drill rigs and cleared drill sites.

Additional lease applications in National Forests nearby CLNP continued until the summer of 1985. Total applications reached 110 and covered about 213,199 acres. Presently (5/91) only 46 leases remain covering about 76,516 acres.

Leasing interest northwest of CLNP in Douglas and Jackson Counties started in the spring of 1982. The biggest push came in January 1984 when CECI applied for a lease block in the Rogue River National Forest. By the summer of 1985, there were 32 applications - 25 in the Rogue and 7 in the Umpqua National Forests covering 59,942 acres.

From this activity there are now (5/91) only 15 applications pending in the Rogue NF covering 25,712 acres. The Forest Service has never consented to leasing in this area and no leases have been issued.

The two main lease application blocks were in the Winema National Forest on the south and east side of CLNP covering about 85,475 acres. These blocks were formed into Geothermal Leasing Units - called Mazama I and Mazama II. Leases were issued beginning at the end of 1983 through the summer 1985, and contained a "contingent right" stipulation. The stipulation requires that each phase of exploration and development be analyzed and approved by the BLM Authorized Officer.

The Geothermal Leasing Unit rules are governed by the Code of Federal Regulations (43 CFR 3280) and are set up in the interest of cooperative exploration and conservation of the resource. Unit formation and agreements provide environmental benefits, bringing an element of harmony, order and cooperation among otherwise competing interests.

A Geothermal Leasing Unit is a block of land whose size and shape are based on geology and development potential. The Unit is formed by one or a group of lessees, and possibly non-lessees who have land or mineral rights in the unit area. The unit members enter into an agreement with the Bureau of Land Management on a plan of exploration with clear targets and guidelines. After discovery, production and development issues are addressed.

The Unit members agree to share costs for a plan of diligent exploration which is more rigorous than that normally required of geothermal lessees. In return for the rigorous unit commitments, the acreage within the unit is excluded from the member's statewide leasing acreage limitation of 51,200 acres. CECI is the only federal lessee in the two units (Mazama I & II), though the units contained both private and state lands.

At this writing, (5/91) the two units have about 76,516 acres under lease. Due to the uncertainties regarding the future possibility of lease development arising from the Congressional classification of Crater Lake as a Significant Thermal Feature, (P.L. 100-443) the Bureau of Land Management has suspended the leases and all unit obligations in Mazama I and II units.

Two major environmental reviews were completed addressing CECI's Plan of Exploration and proposed revisions to the plan. Both involved cooperative efforts between the Bureau of Land Management, the Forest Service, and the National Park Service, including extensive public participation and review. The reviews resulted in the creation of extensive reports, the involvement and consultation of agency and outside experts, and the development of significant protective stipulations for National Park and National Forest values, as well as public safety and conservation of potential geothermal resources. Both required the commitment of considerable workforce, budget and management attention.

Decisions arising from one of these reviews were challenged by several local and national public interest organizations. Appeal documents were presented to the Interior Board of Appeals (IBLA), and after an extensive eighteen month review, the Bureau of Land Management's decisions were affirmed. Subsequent petitions for reconsideration and a stay of action were dismissed. The integrity and quality of the Government's environmental review process stood the rigorous test

and was sustained. No environmental damage of any consequence can be cited as a result of the exploratory work performed since 1984.

In addition to the required environmental work performed in compliance with the National Environmental Policy Act (NEPA) of 1964, the Bureau of Land Management decided to learn more about the noise level generated by drilling. To do this, it was necessary to learn about normal sound level within CLNP. There were no previous sound studies within CLNP to use as a baseline.

Between 1985 and 1988, Bureau of Land Management staff took sound measurements at eight locations selected by CLNP officials within the Park. These were taken during times when both day and night drilling operations were ongoing, and when no drilling took place. While a final report has not been completed, preliminary data indicates that drilling sounds cannot be heard above the normal vehicular, airplane and visitor noise in the park.

In August 1988 CECI addressed the noise issue by simulating the sound of a 120 MW geothermal power plant from the MZ I-11A drill site about a half mile from the CLNP boundary. They used a powerful amplifier and large speakers to broadcast the sound and publicized the test with invitations to the media. The sound was not audible at the nearby Park boundary nor from other locations within the Park. In 1989, CECI began air monitoring work as well.

The Federal agencies involved in or interfacing with leasing activity have cooperatively exhibited a very high level of environmental responsibility and conservative decision making throughout the process. This kind of performance preceded and was independent of the Congressional classification of CLNP as a Significant Thermal Feature.

The Congressional classification of Crater Lake as a Significant Thermal Feature occurred in the midst of an approved exploration plan after about five years of expenditure and investment by the lessee. Continuance of the Significant Thermal Feature classification may impose regulatory and operational delays and costs that could effectively render geothermal leases marginally viable or inoperable and could deter or prevent future development of the geothermal resources nearby the Park.

The following chronology includes milestones and discrete steps in the leasing activity that occurred on Geothermal Leasing Units Mazama I & II (Klamath County):

MAZAMA I (MZ I): No. U-410R L 001G (East of CLNP)
MAZAMA II (MZ II): No. U-410R L 002G (South of CLNP)

Nov. 23, 1983: Unit Applications received by BLM with all supporting information, maps, plans, and geologic report.

Dec. 19, 1983: BLM approves unit agreement after review, coordination, discussion and revision.

Jan. 1, 1984: Agreement and leases take effect MZ I covers a logical unit of 80,690.97 acres, this is composed of: Federal Land 68,832.49 acres; state owned

land 2,500.22 acres; and privately owned land 9,358.26 acres. 38 leases cover about 68,284.65 acres. MZ II covers a logical unit of 18,682.66 acres. 12 leases cover 16,642.66 acres.

Mar. 1, 1984: BLM receives a Plan Of Exploration (POE) from CECI and begins work on an Environmental Analysis (EA). The plan calls for drilling 24 slim core temperature gradient drill holes about 4,000' deep, with 4-9 holes to be drilled the first field season.

Mar. 8, 1984: BLM requests comments from public on POE.

April 1, 1984: Suspension of leases in unit takes effect. Suspension due to delays required to perform environmental approval work.

April 2, 1984: Geothermal Drilling Permit (GDP) applications filed for 6 sites in MZ I and 3 sites in MZ II.

May 11, 1984: EA available for public review.

July 3, 1984: Geothermal Exploration Permit approved - Radon/Mercury sampling.

July 20, 1984: Public inspection of drill sites and Crater Lake N.P.

Nov. 9, 1984: BLM issued a decision suspending leases effective April 1, 1984.

Feb. 28, 1985: Forest Service provides concurrence for approval of a modified Plan of Exploration.

April 15, 1985: CECI submitted GDP for drill holes MZ I-11A and MZ II-1.

July 31, 1985: BLM decision issued, suspension of operations on leases in unit is rescinded, effective on date of decision.

July 1985: CECI informally notified BLM that planned drilling (of drill holes in MZ I and MZ II) would be postponed until Aug. 1985.

May 12, 1986: CECI informed BLM that it is relinquishing four leases at the northern end of the unit totalling 8,411.92 acres, so that the remaining Federal lease acreage in Mazama I is 59,872.73 acres. State and private land at the southern end of the unit were also dropped from the unit. BLM acknowledges the unit contraction.

May 27, 1986: CECI submitted an amended unit agreement commensurate with its now reduced acreage in MZ I.

June 3, 1986: BLM accepts the Mazama I amendment (referred to above) which contains specified escalating dollars per acre obligations.

Aug. 7, 1986: CECI submitted GDP application for Sundry Notice for drill hole MZ I-11A.

Aug. 15, 1986: CECI withdraws Sundry Notice.

Aug. 21, 1986: CECI Submitted an amended Sundry Notices (including one for drill hole MZ II-1) covering the size and length of surface casing.

Aug. 29, 1986: BLM approves the Sundry Notice for drill hole MZ I-11A, but postpones action on drill hole MZ II-1.

Oct. 3, 1986: CECI submits Emergency Contingency Plans for both Newberry and Mazama core hole drilling - safety/emergency procedures and H_2S contingency plans.

Nov. 3, 1986: CECI submitted Sundry Notice to temporarily abandon drill hole MZ I-11A.

Nov. 4, 1986: GDP for MZ II-1 approved.

Nov. 5, 1986: Drilling of MZ II-1 begins.

Nov. 10, 1986: BLM approved abandonment Sundry Notice for MZ I-11A.

Nov. 12 1986: CECI submitted Sundry Notice requesting: 1- deepening drill hole MZ I-11A from 4000′ to 5500′ and 2- drilling without returns. For MZ II-1, drilling reached TD @ 485′.

Dec. 1986: BLM began preparation of a supplemental EA for modifying the approved GDPs.

Jan. 2, 1987: Approved Sundry Notice for temporary abandonment of drill hole MZ II-1, TD-485′.

July 1, 1987: BLM signed a Decision Record approving 1- modifications of the GDPs and 2-permission to drill on previously disturbed sites.

July 28, 1987: Sierra Club and others filed appeal to IBLA of a July 1, 1987 Oregon State Office decision to permit continued temperature gradient drilling, deepening from 4,000′ to 5500′ and drilling w/o circulation) Case to be known as IBLA 87-735 Appeal of Sierra Club Inc. et. al. (107 IBLA 96).

Aug. 25, 28, and Oct. 29, 1987: CECI requested suspension of lease and unit obligations due to environmental events and litigation connected to drilling.

Nov. 12, 1987: BLM granted suspension of lease and unit obligations effective Nov. 1, 1986 (the first day of the month in which operations actually ceased.

Aug. 4, 1988: CECI invites the public to witness the simulated sounds of a 120 MW geothermal power plant broadcast from the MZ I-11A site, a halfmile from CLNP boundary.

Sept 22, 1988: Geothermal Steam Act Amendments of 1988 (P.L. 100-443) signed into law; Crater Lake NP classified as a Significant Thermal Feature.

Feb. 1, 1989: IBLA affirmed BLM's decision that no EIS is required and also affirmed BLM's approval of the amendments to CECI's drilling permits (IBLA No. 87-735/107 IBLA 96).

Mar. 24, 1989: BLM rescinded a previous decision (of Nov.12, 1987) suspending CECI's leasing and unit obligations for Mazama I and Mazama II Unit Agreements). Effective May 1, 1989, CECI may resume full enjoyment of its leasing rights and begin fulfillment of its leasing and unit obligations.

April 3, 1989: Sierra Club, Oregon Natural Resources Council, & National Parks and Conservation Association filed with IBLA a petition for reconsideration (of the IBLA 87-735/107 IBLA 96 decision) and a motion for a stay, pending the Board's decision on the petition for reconsideration.

April 27, 1989: Sundry Notice for revised drilling in the Winema NF is approved and sent to CECI.

July 7, 1989: CECI reentered drill hole MZ I-11A.

July 31, 1989: IBLA denied Sierra Club et. al. (April 3) petition for reconsideration and request for a stay on IBLA 87-735 (107 IBLA 96).

Aug. 5, 1989: Drill hole MZ I-11A reached Total Depth (TD); tubing placed to 4670' depth.

Aug. 14, 1989: Re-entry drilling began on MZ II-1.

Aug. 16, 1989: ONRC-Sierra Club appeals decision to withhold some of the Proprietary and Confidential Material.

Sept. 7, 1989: MZ II-1 reached TD @ 2844', well was set up and left for temperature observation.

Sept. 11, 1989: CECI spudded drill hole MZ I-11B.

Sept. 11, 1989: Two Geothermal Sundry Notices approved - Air monitoring stations (footings poured, but stations not yet erected).

Sept 26, 1989: Drill hole MZ I-11B plugged and abandoned @ 270' due to inability to maintain circulation.

Sept. 29, 1989: CECI sent expenditure period and exploration work status report.

Oct. 4, 1989: BLM acknowledged significant exploration expenditures incurred.

Jan. 1990: CECI informally notified BLM of preliminary plans to drill two more holes under existing EA. BLM solicited an opinion from the Sierra Club.

Feb. 16 1990: Sierra Club objected to approving two holes beyond drill hole MZ I-11B.

Mar. 26, 1990: CECI submitted Sundry Notice on MZ II-1 to allow for commencement of drilling operation, planned to begin on June 1, 1990 to a depth of 5500'.

April 24, 1990: MZ II-1 Sundry Notice approved. It allowed drilling to 4830' with drilling below that subject to additional approval.

May 1, 1990: BLM approved Designation of Operator from California Energy Co. to CE Exploration Co.

June 8, 1990: Geothermal Drilling Permit MZ I-1 approved.

Aug. 17, 1990: BLM received request from CE Exploration for suspension and/or extension of unit drilling obligations due to lack of market and extreme fire danger conditions.

Nov. 2, 1990: BLM responded to request for suspension/extension of unit drilling obligations and granted a conditional extension.

Nov. 16, 1990: CE Exploration submitted a unit obligations report.

Feb. 13, 1991: BLM Director Jamison directed that the leases in the Mazama units be suspended to allow time for consideration of
the pending report on presence or absence of significant thermal features at Crater Lake NP.

Feb. 20, 1991: BLM issued a formal Decision to the lessee on suspending the Mazama leases effective Feb. 13, 1991.