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SECOND WORKSHOP ON HYDROLOGIC AND GEOCHEMICAL MONITORING IN THE LONG VALLEY CALDERA

July 15–17, 1986
Mammoth Lakes, California

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COVER PHOTO: View westward across Hot Creek Gorge. (Photo by M. Sorey)

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INTRODUCTION

A second workshop was hosted by the U.S. Geological Survey and the Earth Sciences Division of Lawrence Berkeley Laboratory on July 15-17, 1986 to review the results of hydrologic and geochemical monitoring and scientific drilling in the Long Valley caldera. Such monitoring is being done to detect changes in the hydrothermal system induced by ongoing magmatic and tectonic processes. The first workshop of this kind was held on October 8-10, 1984 (Sorey et al., 1984). These workshops have provided an opportunity for investigators from various government agencies and academic institutions to compare results and to look for consistent trends between different sets of observations. Data from a 2400-ft deep core hole completed in June 1986 were also presented at the 1986 workshop and participants discussed the need and rationale for siting locations for future scientific drilling in the caldera.

In 1979 the Long Valley caldera was one of five sites selected by the Thermal Regimes panel of the Continental Scientific Drilling Committee for review in preparation for proposed drilling into an active hydrothermal system for scientific purposes (Kasameyer, 1980; Goff and Waters, 1980; Luth and Hardee, 1980; and White, et al., 1980). Similar in some respects to other young silicic calderas in the western United States, the Long Valley caldera-as a history of episodic volcanic activity that began about 1 m.y. ago and has continued to as recently as 550-650 years ago when a series of eruptive centers became active along the Inyo volcanic chain (Miller, 1985). Suspicions that there was renewed magma movement from a deeper chamber arose following a series of large-magnitude (M_L6) earthquakes and aftershocks in 1980 and analysis of U.S. Geological Survey (USGS) leveling data (Savage and Clark, 1982). These indications, along with increased fumarolic discharge, raised concern over the possibility of a volcanic eruption in the near future and caused the USGS to intensify its activities within the caldera (Miller et al., 1982). The USGS workers were joined by other scientists from State agencies, universities, and Department of Energy (DOE) laboratories who initiated supplemental surveys and implemented monitoring projects.

Reports containing preliminary results of some of these monitoring projects were published by Hill et al. (1984), following a workshop held in Napa, California in January 1984; by Goldstein (1984), following a workshop on geophysical modeling held in Berkeley in February 1984; and by Sorey et al. (1984) as noted above. A collection of papers describing recent findings on active tectonic and magmatic processes beneath the Long Valley caldera is contained in the November 1985 issue of the Journal of Geophysical Research.

Although the level of crustal unrest in the Long Valley area has steadily decreased since 1983, the caldera remains the focus of monitoring activity and a prime candidate for a phased, deep exploration drilling program to penetrate into the "near magmatic" environment. Such drilling is being contemplated by DOE, Geothermal Technologies Division (GTD) , under the Magma Energy Extraction program. Lawrence Berkeley Laboratory has been authorized to coordinate and expedite a pre-drilling data review (PDDR), co-funded by DOE/GTD and DOE, Basic Energy Sciences (BES) leading to a major workshop in 1987. The goal of the workshop is to present improved interpretations regarding subsurface structure, thermal and hydrologic conditions and more defensible arguments for drilling a hole to serve the purposes of both the DOE/GTD Magma Program and the DOE/BES Scientific Drilling Program. As noted in the abstract by Goldstein (this volume), several working groups have been formed to carry out this PDDR including a geohydrology-geochemistry group who organized and conducted the workshop described in this report.

The 1986 workshop agenda is given in Appendix A and a list of participants and their affiliations is included in Appendix B. Extended abstracts provided by most of the participants are reproduced here following the order of presentation at the workshop. Short sections summarizing the workshop discussions in terms of scientific findings and recommendations for future drilling are also included. The editors are indebted to the workshop participants who freely shared their results and ideas.

PRE-DRILLING DATA REVIEW FOR THE LONG VALLEY CALDERA, CALIFORNIA

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ABSTRACT

The Long Valley caldera is one of the best studied Pleistocene silicic volcanic features in the world, and a prime candidate site for a phased, deep exploratory hole to penetrate into the "near-magmatic" environment. Such a hole is being contemplated by DOE, Geothermal Technologies Division (GTD) under the Magma Energy Extraction program. A preliminary site for this hole is near the center of the resurgent dome, close to the union of some tantalizing geophysical anomalies which some have concluded indicate the presence of a melt zone at a depth of about 6 km (Rundle et al., 1986). The site is also favored because there is a drilling pad to which DOE has been granted access by Santa Fe Minerals, Inc. In spite of those factors there exist a number of large uninterpreted geophysical data sets for the Long Valley caldera, and several scientists have raised doubts regarding past interpretations. As a result, LBL has been authorized to coordinate and expedite the processing and interpretation of the outstanding data sets. This pre-drilling data review (PDDR), co-funded by DOE/GTD and DOE Basic Energy Sciences (BES), will lead to a major workshop in early 1987. At the workshop we hope to present improved interpretations regarding subsurface structure and thermal conditions and more defensible arguments for drilling a hole to serve the purposes of both the DOE/GTD Magma Program and the DOE/BES Scientific Drilling Program.

To carry out the data review we have attempted to identify all research work being conducted in Long Valley and all researchers with data sets under or needing evaluation. Using pass-through funds from DOE, LBL is supporting several critical studies proposed by researchers who have no other means for completing the processing, modeling and interpretation in time for the workshop. The USGS is supporting its own scientists involved in Long Valley research as part of their ongoing program.

Three working groups have been organized to keep the various researchers informed of what the others are doing and to plan presentations at the workshop. The groups are Seismology, Electrical-Gravity-Magnetics, and Geohydrology-Geochemistry. For the most part these groups are a continuation of existing research consortia to which new investigators have been added. Each working group will conduct its own mini-workshop prior to the winter workshop. The electrical geophysicists have already had a meeting in June at U.C. Berkeley, and this gathering is essentially a meeting of the Geohydrologists and Geochemists.

Among the new studies now underway because of this project are the following:

1. 2-D and 3-D resistivity models will be developed on the basis of nearly 60 new magnetotelluric soundings, an airborne electromagnetic survey (INPUT), and various controlled-source soundings.

2. Processing and interpretation of two lines of high resolution CDP and wide-angle reflection seismic data will be completed.

3. 3-D inversions of P-wave delay and seismic wave attenuation will be carried out using data from teleseisms and local earthquakes.

4. 3-D density inversions will be conducted using over 400 gravity stations with topographic, isostatic and regional corrections, and using constraints from drill hole and seismic refraction analyses.

5. Combined interpretations of gravity, P-wave delay and magnetic data will be attempted.

In addition, to the new data from the ~2400-ft-deep Shady Rest core hole, we are currently negotiating with Unocal, Geothermal Division to find a basis by which Unocal will provide us with data from their 44-16 well in the west moat and their sets of surface geophysical data.

Lastly, we have identified several studies recently completed by graduate students. These studies include a Curie isotherm analysis based on the high-level aeromagnetic data, and 3-D extremal inversions of vertical uplift and P-wave travel time data. Results of these studies will be folded into the subsurface models.

ACCESSIBLE CORE HOLE IN THE LONG VALLEY CALDERA

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ABSTRACT

On June 17, 1986 a continuously-cored hole was completed in the southwestern moat area of the Long Valley caldera, approximately 2 km northeast of the town of Mammoth Lakes near the Shady Rest campground (Fig. 1). The primary purpose of the hole is to provide access for periodic measurement of the thermal gradient, pressure, and chemistry of water in the thermal aquifer of the caldera's southwestern moat. The hole also investigates the geothermal energy potential in the vicinity of Mammoth Lakes. Core will be available for experiments by interested scientists.

The project was sponsored as part of the thermal regimes sector of the Continental Scientific Drilling Program by the Department of Energy's Office of Basic Energy Sciences, with contributions by the California Energy Commission, Mono County, and the U.S. Geological Survey.

The hole was rotary drilled to 92 m, and a 14.3 cm diameter surface casing installed. The hole was then cored by HQ wireline to a total depth of 715 m. Core recovery exceeded 90%, and lithologic units are well represented.

Lithologic units encountered, in descending order, include glacial till to ~90 m, rhyolitic ash-fall, ash-flow and volcaniclastic deposits, probably the moat rhyolite and early rhyolite of Bailey and Koeppen (1977) to ~430 m, and ~285 m of predominantly welded ash-flow tuff (most likely the Bishop Tuff) to total depth (Fig. 2). Temperatures measured by a maximum-reading thermometer during coring and by Kuster tool surveys run during and soon after drilling indicate a roughly linear increase to 156°C at a depth of ~330 m. Temperatures then rise abruptly to a nearly isothermal pattern, mostly between 190 and 200°C, that extends into the Bishop Tuff and to the bottom of the hole. Steeply-dipping open fractures, lined by quartz and calcite covering sulfide minerals, are preserved in core from the high temperature zone.

The depth to the Bishop is the shallowest encountered in holes in the caldera, and the temperatures measured are among the hottest observed in wells drilled within the caldera. This structural and hydrothermal setting has important implications for understanding the nature of heat sources underlying the caldera's western moat.

Difficulties were encountered in completing the hole; sloughing, squeezing, and lost circulation prevented installation of casing over the full 715 m depth. Attempts to redrill and recover the portion of the hole below 245 m resulted in a "new" hole, diverging from the original at 241 m (Fig. 3). The "new" hold was cored to a depth of 426 m, where N-sized casing (6 cm I.D.) was cemented in and filled with water; temporarily configured as a thermal gradient hole.

Following repeated temperature surveys to determine an equilibrium profile, a portion of the cased zone in the high temperature zone was perforated in October, and fluids were sampled for chemical analysis in November 1986.

The core resides at DOE's curatorial facility in Grand Junction, Colorado where it is available for inspection. Persons interested in experiments with portions of the core, aliquots of fluid samples, and in experiments in the permanently accessible cased hole should contact one of the above investigators.

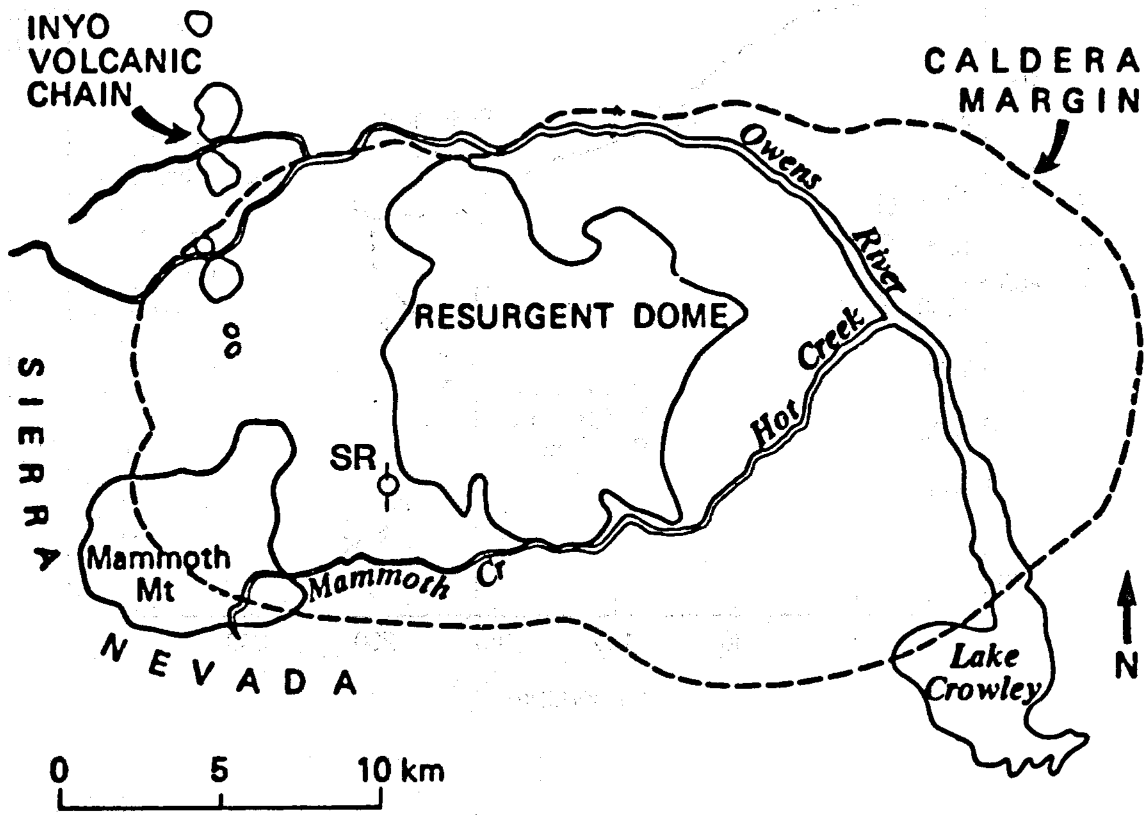

Figure 1. Map of Long Valley caldera, showing outline of caldera floor (dashed line), and major features. SR designates the Shady Rest corehole.

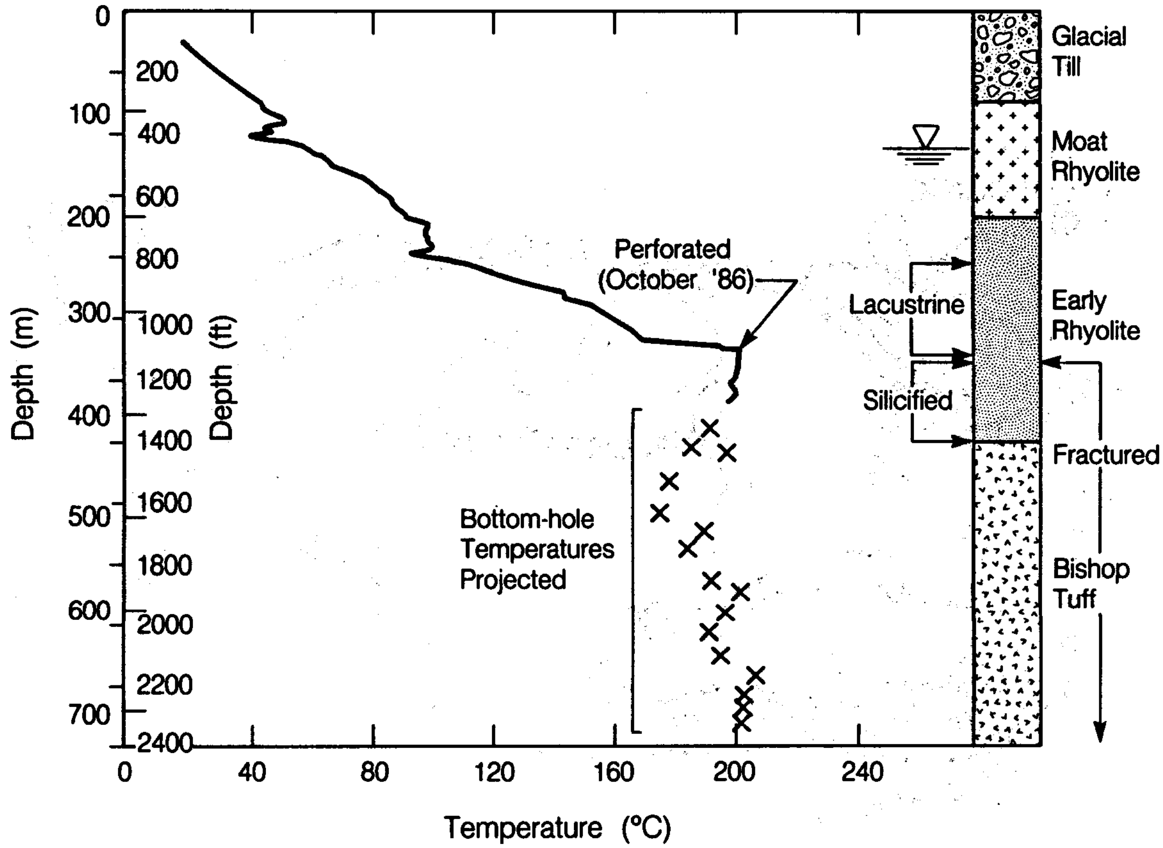

Figure 2. Equilibrium temperature profile (7/7/86) with projected temperatures from bottom-hole measurements made during coring, together with a lithologic diagram of the Shady Rest hole.

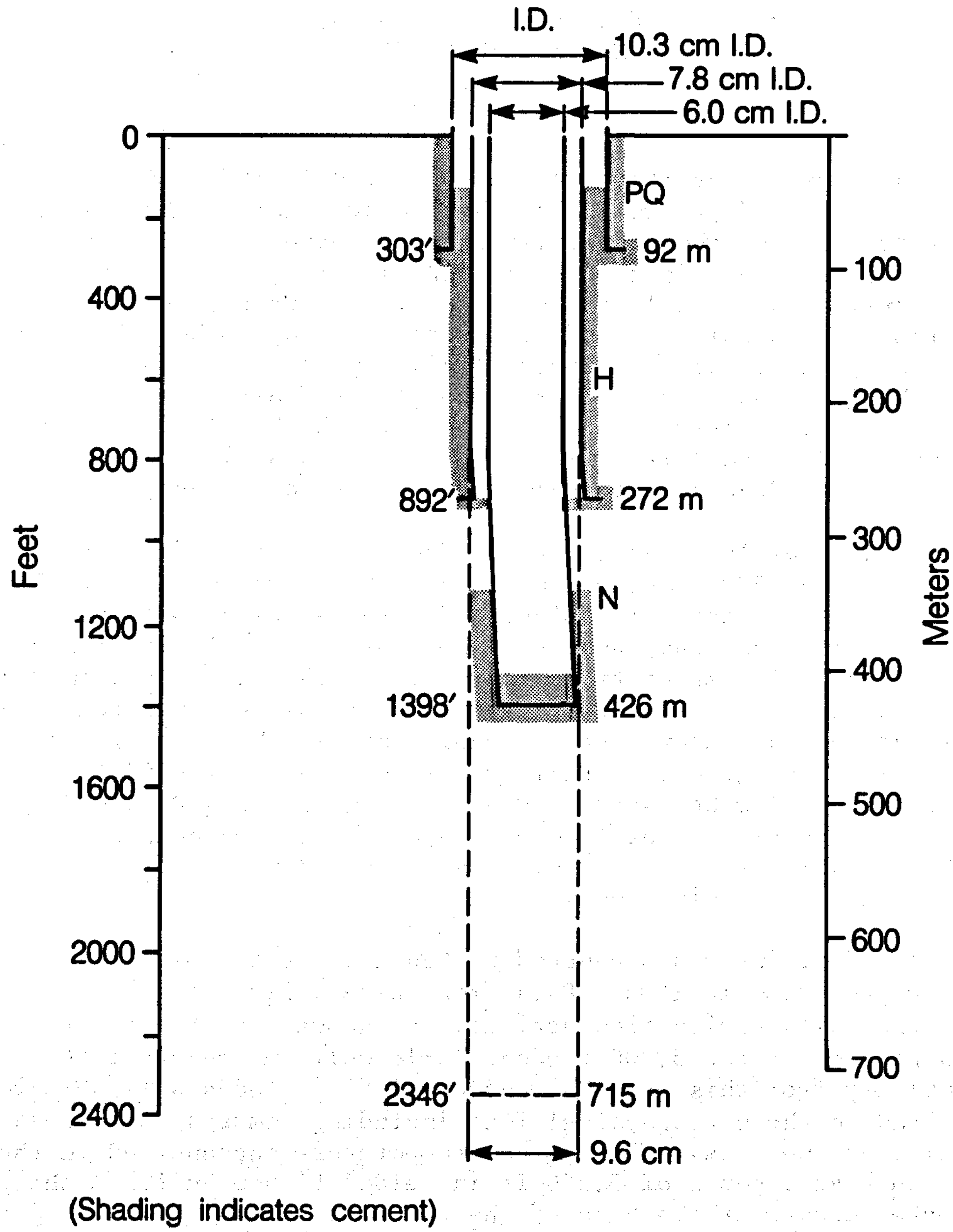

Figure 3. Completion diagram of the Shady Rest hole.

UPDATES ON DRILLING AND GEOTHERMAL EXPLORATION

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ABSTRACT

Since the time of the first workshop in October 1984, new data from shallow and intermediate depth wells have become available. These include data from wells drilled for the Bonneville Pacific Corporation near Hot Bubbling Pool (Fig. 1), the Shady Rest core hole (Wollenberg, et al., this volume), and well 44-16 drilled by Unocal Geothermal near Inyo Craters. Although the new data confirm the general model of flow within the hydrothermal system discussed by Sorey et al. (1984), Sorey (1985), and certain aspects of the analysis by Blackwell (1985), they add some complexity to the pattern of west to east flow of thermal water within and above the Bishop Tuff. Such complexity is also indicated by data from wells drilled at Casa Diablo for the Mammoth Pacific Geothermal Development Project (Farrar et al., 1985).

New data from wells located west of Casa Diablo show that water at temperatures in excess of 200°C occurs in reservoirs in fractured Early Rhyolite and welded Bishop Tuff. Chemical analyses of water samples collected downhole in November 1986 from the Shady Rest core hole are currently in progress. Some degree of structural complexity is indicated by this well data in terms of depths and thicknesses of various lithologic units. One particularly interesting feature of the Shady Rest core-hole data is that the altitude of the upper thermal reservoir within Early Rhyolite (2040 m or 6690 ft) is similar to that of the shallow hot-water production zone at Casa Diablo (~2070 m). This suggests a continuity of flow of thermal water southeastward from Shady Rest to Casa Diablo, in spite of stratigraphic discontinuities associated with normal faulting along this trend.

Test-well drilling was conducted by Santa Fe Geothermal at several sites on the resurgent dome in 1984. Data from these wells remains proprietary. Unocal Geothermal's exploration activity in the west moat was curtailed following completion of the 5,900 ft-deep 44-16 well in January 1986. Data released publicly from this well in November 1986 includes a lithologic log from cuttings, and borehole geophysical logs including temperature, pressure, electric, sonic, and neutron. The maximum temperature encountered in the hole (218°C) occurs at a depth of 3,500 ft in welded Bishop Tuff. A sharp temperature reversal occurs at the base of the welded tuff at a depth of 4,000 ft, in a zone where significant loss of drilling fluids occurred. This indicates that cooler water flows laterally beneath the thermal reservoir encountered in the welded tuff at this location.

The 10 MW Mammoth Pacific geothermal power plant has operated more-or-less continuously at Casa Diablo since January 1985. Total hot-water production from four wells that supply the binary power plant averages about 3,000 gpm (190 L/s). Although up to three additional 10 MW-size units are planned for this area by Pacific Lighting Energy Systems (PLES), to date only one new well (487 ft deep) has been drilled. Permits are currently being sought for these new developments by PLES from federal, state, and county agencies. On the Mammoth/Chance geothermal lease near Hot Bubbling Pool, modular binary units

with a total installed capacity of 10-20 MW are planned by the Bonneville-Pacific Corporation. To date two exploration/production wells have been drilled to depths of 900 ft and 1,800 ft, and a two-week flow test was conducted in December 1985. Bonneville-Pacific is currently seeking approval of an Environmental Impact Report and a use permit for power development from Mono County.

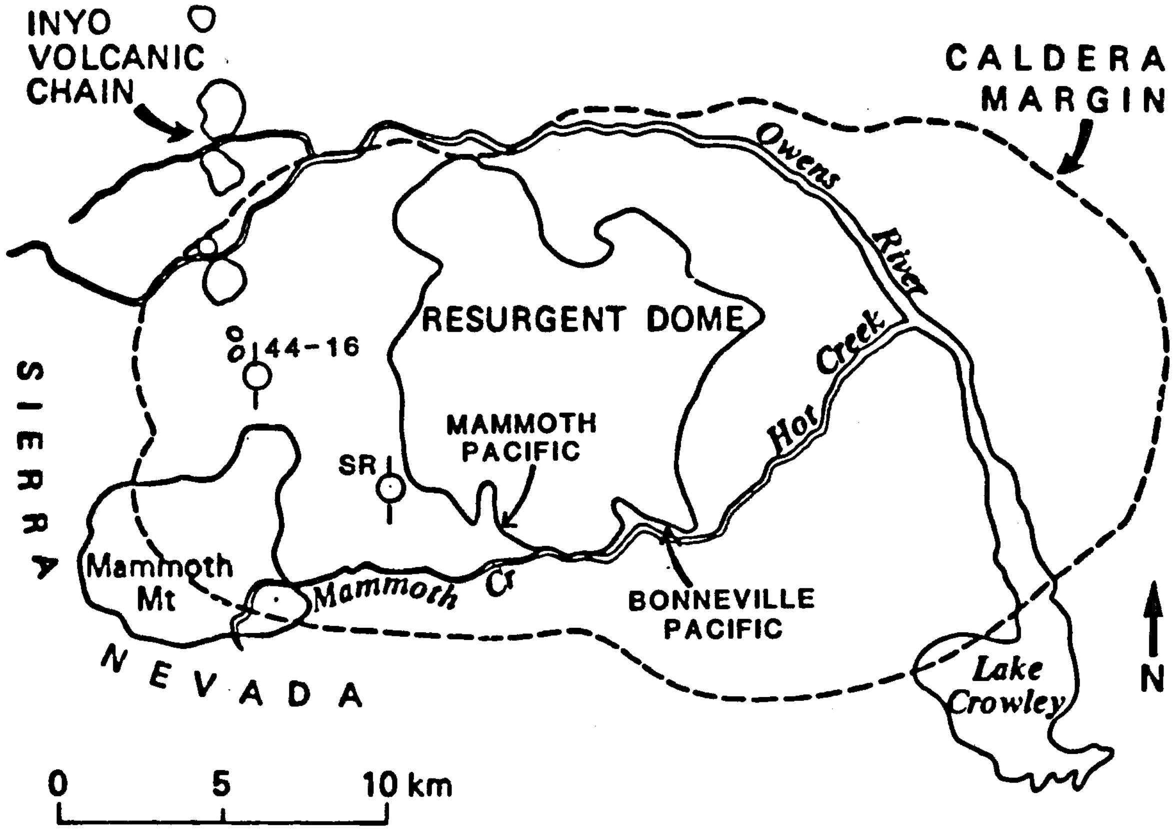

Figure 1. Location map for recently drilled test holes in the west moat of Long Valley caldera (44-16 and SR) and current and planned geothermal power plant developments by Mammoth Pacific and Bonneville Pacific.

HYDROTHERMAL COOLING OF SHALLOW INTRUSIONS*

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ABSTRACT

Boiling of groundwater evidently occurs as a more or less steady-state process producing fumaroles in volcanic regions. Estimates by Gerlach and Casadevall (1986) for the Mt. St. Helens hydrothermal system indicate that up to 70% of fumarole emissions are of groundwater origin. Exit gas temperatures for these emissions may exceed 650°C. For modeling the near-surface interaction between intruded magma and hydrothermal systems, these results suggest that boiling and superheating must be included in determining heat transfer from magma into the surrounding groundwater regime.

A model based on the thermomechanical properties of magma is illustrated in Figure 1 (Carrigan, 1986). In the highest temperature regime (Zone I), magma can freely convect. In Zone II, temperatures are low enough that the magma behaves as a plastic causing convection to cease. While being stiff, the zone is not sufficiently brittle to permit thermal stress cracking. Hence Zone II acts as a more or less impermeable envelope between the magma and the groundwater regime. Zones III and IV comprise the vapor and liquid groundwater regime. If the rate of heat loss from the convecting magma is less than the rate of removal by the vapor/liquid hydrothermal zone, then infiltration of the intrusion by groundwater occurs until the groundwater front finally reaches the center of the intrusion. Figure 2 provides a comparison of times required for the centerline of a dike to fall from 1050°C to 725°C when cooling is by conduction and by groundwater convection (.1 and .01 darcy). The model predicts that the dike and conduits associated with the Inyo domes would have been infiltrated within a few tens of years by groundwater. The known extent of the 600-year-old Inyo system is inadequate for it to be a significant heat source in the Long Valley hydrothermal reservoir.

*This work performed at Sandia National Laboratories is supported by the U.S. Department of Energy under contract number DE-AC04-76DP00789 for the Office of Basic Energy Sciences.

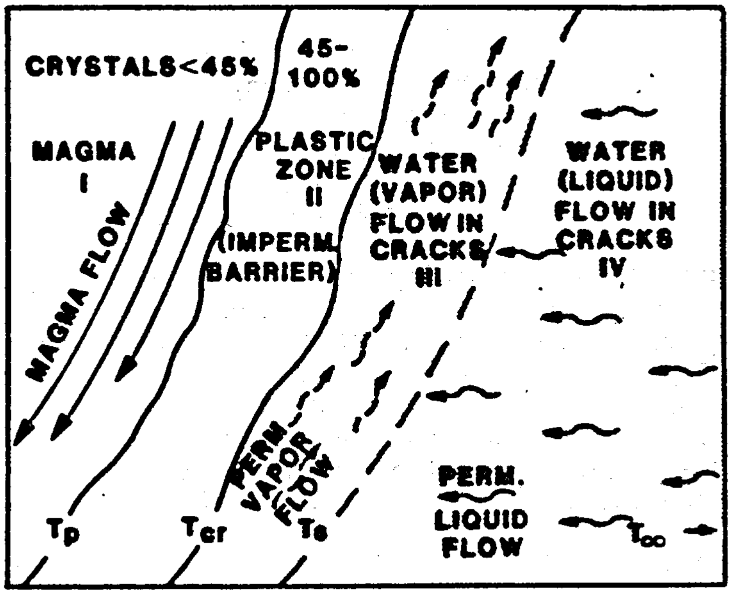

Figure 1. Model of four zones within the magma-hydrothermal regime.

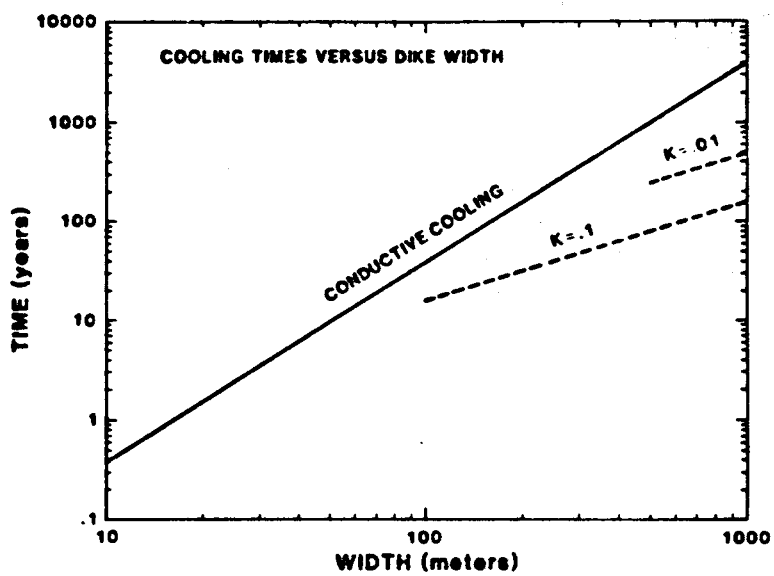

Figure 2. Estimates of times for cooling magma to 725°C by conduction (solid line) and by hydrothermal means (dashed lines based on maximum infiltration velocity for various permeabilities in darcys) plotted against dike width.

U/Th GEOCHRONOLOGY OF HYDROTHERMAL ACTIVITY IN THE LONG VALLEY CALDERA: LITTLE HOT CREEK AND THE BLUE CHERT

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ABSTRACT

Available evidence from within the Long Valley caldera suggests that its hydrothermal system reached maximum development at about 0.3 Ma (Bailey et al., 1976). Less direct evidence for hydrothermal activity in Long Valley is found in the Searles Lake evaporites; the source of the sodium carbonate component in the evaporites younger than 0.31 Ma may have been hot spring discharge from Long Valley (Smith et al., 1983). Evaporites younger than 32 Ka are distinctly richer in borate, sulfate, and potassium salts than older deposits, consistent with discharge of modern-type hot spring water from Long Valley at a near-present rate since 32 Ka. This change in evaporite composition at 32 Ka may have been related to redistribution of hydrothermal flow paths within the Long Valley caldera (Sorey et al., 1978 and Sorey, 1985). However, the evaporite record is not easily interpreted with regard to Long Valley hot spring activity between about 0.31 and 0.04 Ma because of low lake paleosalinities during pluvial periods.

To better define the evolution of the Long Valley hydrothermal system, we have embarked on a program of U/Th age determinations of hydrothermal products from outcrops and drill cores within the caldera. The U/Th system is appropriate for determining ages less than about 350 Ka in suitable materials (Ivanovich and Harmon, 1982). Results presented below are from dense chalcedonic silica veins, collected from base to top of the outcrop beginning 40 m N of hot spring LHC-1 in Little Hot Creek canyon, and from samples of the Blue Chert (BC).

Samples were prepared for analysis by cutting and/or grinding away exterior surfaces, or gentle crushing and handpicking of interior fragments, to obtain pure vein material. These coarse sample portions were rinsed briefly and sonicated in deionized distilled water, then dried under a heat lamp prior to pulverization with a steel piston mortar. Amounts of sample dissolved for U and Th separations ranged from about 0.13 to 4.9 g. Spikes of 236-U and 229-Th, their ratio calibrated to NBS-610, were added at the beginning of the dissolution. U and Th were separated by anion exchange chromatography and electrodeposited onto stainless steel planchets for alpha spectrometry. Alpha activity data were corrected slightly for background and reagent blanks.

Analytical results are shown in Table 1. The majority of the samples have (230-Th/234-U) near 1.0, consistent with an age of near 0.3 Ma (or older). However, three samples from Little Hot Creek appear to be significantly younger. These samples, LHC-2B, -4, and -5, have (230-Th/234-U) values consistent with maximum ages of about 83, 189, and 126 Ka, respectively. The

actual ages of these veins are probably younger, but cannot be calculated without better knowledge of the initial (230-Th/232-Th). Nonetheless, these results are interesting as they may indicate the occurrence of episodic hydrothermal activity during the interim from about 300 to 32 Ka. Further work (in progress) may allow more precise temporal constraints to be placed on the hydrothermal (and geomorphic) evolution of the Little Hot Creek canyon and other sites within the Long Valley caldera.

Table 1. U/Th data for samples from Little Hot Creek (LHC) and the Blue Chert (BC)*

Sample	ppm U		(234-U/238-U)		(230-Th/232-Th)		(230-Th/234-U)	
LHC-2A	2.01	(.07)	1.006	(.023)	1.141	(.052)	1.030	(.076)
LHC-2B	1.13	(.06)	0.960	(.045)	1.364	(.067)	0.533	(.040)
LHC-3A	1.20	(.06)	1.019	(.057)	1.446	(.119)	0.956	(.089)
LHC-3C	0.075	(.004)	0.916	(.063)	0.364	(.023)	1.122	(.099)
LHC-4	2.03	(.09)	1.034	(.039)	1.197	(.057)	0.831	(.065)
LHC-5	2.76	(.13)	1.008	(.030)	1.457	(.067)	0.688	(.056)
BC-3B-2	21.7	(1.0)	1.147	(.038)	78.14	(15.7)	1.064	(.069)
BC-3B-3	18.5	(0.9)	1.375	(.057)	202.2	(79.4)	1.053	(.068)
BC-3W-2	6.81	(.35)	1.171	(.028)	10.08	(0.69)	0.937	(.075)

*1-sigma analytical uncertainties in parentheses.

Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract W-31-109-Eng-38. We thank Chris Farrar for assistance in sampling.

HYDROTHERMAL ALTERATION MINERAL STUDIES IN LONG VALLEY

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ABSTRACT

During the late spring of 1983 areas of rock alteration delineated by Roy Bailey were visited and temperatures of springs and fumaroles throughout the Long Valley area were measured. Warm areas of quiet fumaroles were found in several areas of extensively altered rock which had been considered to have been inactive. Samples of altered rock and alteration deposits have been studied to determine mineralogy and a few have been analyzed for trace elements.

Several types of rock alteration have been identified in the Long Valley caldera and preliminary studies have been initiated.

1. Surficial acid-sulfate alteration is perhaps the most widespread and conspicuous alteration which has occurred. The areas of Huntley clay pit and the head of Long Canyon are large concentrations of kaolintie-alunite-silica deposits. The east Casa Diablo area appears to be a presently active analogue of this type of alteration. Small additional areas of acid-sulfate alteration are scattered in the western part of the resurgent dome; some have warm, but quiet associated fumaroles. These altered areas appear to be concentrated along faults.

2. Active hot springs at Hot Creek and Little Hot Creek have mostly siliceous deposits but travertine has been sporadically locally deposited. Aprons of older hot spring deposits, now inactive, occur along the Hot Creek banks. Colton Hot Spring was depositing amorphous silica with concentrations of K, Na, Ca and Al with occasional travertine at 94°C in 1983. Although the present spring had been active only a year, the adjacent area has extensive cemented cobbles indicative of previous hot spring activity.

3. Opal-cemented lake sediments and the alkali spring area on the east side of the caldera are of interest in sorting out the detailed history of the lake which once occupied the area relative to the amount of heat and hot spring activity associated with the young dome. Burial diagenesis may be a part of this section's alteration history, but a hydrothermal alteration component may also have contributed to the alteration. Hot Bubbling Pool area has similar silica-cemented lake sediments.

4. The Blue Chert area close to the east margin of the dome may have been formed by flooding of high silica thermal water in a brecciated area. Conceivably, the brecciation was due to hydrofracturing with immediate flooding. Trace element metals include Ag, Sb, Zr (which may cause the blue color) and Hg.

5. Siliceous sinter deposits occur at former hot springs and present fumaroles at the Pioneer Cabin site. Significant amounts of cinnabar, metacinnabar, and sulfur are actively (or recently) deposited from a vent within a

sinter deposit. Along with Hg, these sinter deposits are high in Sb, Se, As, and Tl.

6. A small solfatara was active at the southwest edge of the resurgent dome and at the edge of a basaltic lava flow in late spring 1983. Its origin is not clear.

In addition to outcrop sampling, samples have become available from several drill holes including Phillips coreholes PLV-1 and PLV-2 on the west side of the caldera, and from Union's LV 13-21 on the north-central part of the dome.

WATER CHEMISTRY, GEOCHEMICAL RESERVOIR-TEMPERATURE ESTIMATES, AND THERMAL SPRING DISCHARGE IN HOT CREEK GORGE

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ABSTRACT

A monitoring program to detect hydrologic and geochemical responses to stress produced by tectonic or magmatic activity in Long Valley was begun by the U.S. Geological Survey in 1982 (Farrar and others, 1985). At the present time the monitoring program consists of a network of instrumented sites (Fig. 1) that includes recording water levels and atmospheric pressure in six wells, discharge of springs at four sites, stage and temperature at Hot Bubbling Pool, discharge and chemical flux below Hot Creek Gorge, and temperature at Basalt Fumarole. In addition to the continuous recording sites, water samples were periodically collected from springs and wells and analyzed to determine isotopic and chemical composition. Data from this monitoring program and other related investigations reported in this volume provide a comprehensive inventory of water chemistry in springs and wells in Long Valley. This more frequent and areally extensive sampling since 1982 has added significant information to earlier published data (Lewis, 1974; Mariner and Willey, 1976, and California Dept. of Water Resources, 1967). The chemical data are useful for making estimates of reservoir temperatures by geochemical thermometry and estimating thermal spring discharge volumes.

Chemical analyses reported by different laboratories for water samples collected in 1985 from selected thermal and nothermal features (Fig. 1) are listed in Table 1. Comparable data from earlier analyses are reported by Farrar et al. (1985), Sorey et al. (1984), and Mariner and Willey (1976). Analyses for well samples from Casa Diablo are for total flow of single-phase liquid cooled and condensed through a stainless steel coil immersed in a water and ice bath. Ionic concentrations listed for these samples are lower than those reported previously for samples from these wells collected in 1983, because the 1983 samples were collected from two-phase flow with no correction for steam fraction. Of all the spring and well chemistry data reported through 1985, the 1985 Casa Diablo well sample analyses are the least affected by near-surface boiling, mixing, and reequilibration. As such, they provide the best indications of fluid chemistry in the deeper, hotter parts of the Long Valley hydrothermal system. Although agreement in results reported for these well samples by the three laboratories listed is in general very good, differences in Cl and SO_4 are greater than expected on the basis of analytical precision. Followup work is in progress using splits of standard solutions analyzed at each laboratory to determine the causes of these differences.

Geochemical Thermometers

Estimates of subsurface reservoir temperatures can be obtained from chemical geothermometers that are based on concentrations of silica and ratios of sodium, potassium, calcium, magnesium, and lithium concentrations in water samples (Fournier and Truesdell, 1973; Fournier and Rowe, 1966; Kharaka and Mariner, 1986). Results of geothermometer calculations for springs and wells are listed in Table 2. Four different geochemical thermometers were used:

silica-quartz (conductive), Na/K, Na-K-Ca, and Mg/Li. Temperatures were calculated using the computer program "SOLMNEQ," version 6/85 (Kharaka and Barnes, 1973).

Good agreement is obtained for most sample sites between the various geothermometers. For well sites in the Casa Diablo area, reservoir temperature estimates based on the four geothermometers applied to the 1985 data range from 195° to 228°C. For wells MBP-1 and MBP-3, temperature calculations were made for four analyses obtained from three laboratories. These calculations give some idea of the variability in reservoir temperature estimates depending on which set of analytical data is used. Previously published results for well END-5 (Mariner and Wiley, 1976), based on a sample collected in 1972 are included for comparison with the 1985 samples collected from the MBP wells. The 1985 samples (single-phase liquid) yield reservoir temperature estimates that are, in general, 10-20 degrees lower than the estimates based on the 1972 END-5 sample (two-phase fluid condensed in water bath). The average value of reservoir temperature based on geothermometer results for 1985 samples from all Casa Diablo wells analyzed at the U.S. Geological Survey Laboratory in Colorado is 208°C. The actual well water temperatures at Casa Diablo are cooler (170°-175°C), presumably due to conductive heat losses as the hotter fluid flows toward this area.

Sites located east of the Casa Diablo area give considerably lower reservoir temperature estimates, mostly between about 140 and 190°C. Cooler temperature estimates in these areas cannot be explained by simple dilution of thermal waters by meteoric waters along the ground-water flow path because the geothermometers based on ionic ratios are relatively insensitive to this factor. Either these waters are heated in a cooler part of the reservoir or they have undergone chemical reequilibration along the flow path before discharging at the surface. Figure 2 compares silica temperatures with corresponding Na-K-Ca temperatures. Points plotting above the line of equal temperature may be due to evaporative losses that cause a concentration of silica, or the lower cation temperature may be caused by minor mixing of water relatively high in Ca ions. Points falling below the line may be caused by precipitation of calcium carbonate as CO_2 is lost in hot springs near boiling temperatures; this is likely for springs CDG, HC-2, and HC-3 and for well CW-2. The depressed silica temperatures for all but one of the MBP well calculations may be due to minor silica loss by precipitation in the condensing coil during sampling.

Hot Spring Discharge in Hot Creek Gorge

Approximately 80 percent of the thermal water discharge in Long Valley caldera occurs in the hot springs within Hot Creek gorge (Sorey et al. 1978). Modest changes in total spring flow in the gorge and spectacular changes in the flow from individual vents have been observed to accompany earthquake activity in the 1973-1985 period (Farrar et al., 1985). Changes in spring flow associated directly with postulated magmatic intrusions in 1980 and 1983 cannot be discerned from the available data. Continuous measurements of spring discharge based on chloride flux determinations at the Hot Creek flume did not begin until August 1983.

Direct measurement of spring flow in the gorge is not possible because of the subaqueous discharge of some springs in the creek and boiling and fountaining discharge of others. Further, taking the difference between flows of Hot Creek upstream and downstream of the springs is not sufficiently accurate to detect changes in spring flow because of less than ideal conditions at available measuring sections and variable rates of exchange between stream water and ground water. Instead, a salinity-gain technique involving measurements of chloride and boron fluxes in the stream is employed, as discussed by Farrar et al. (1985).

Total hot-spring discharge in the gorge averaged 244 $\pm$ 85 L/s during 1985, based on 7 measurements of the difference in chloride flux at sites above and below the springs (Farrar et al., 1987). The corresponding value based on differences in boron flux is 243 $\pm$ 12 L/s. The average value for total spring flow from 8 measurements of chloride flux made in the 1973-1984 period reported in the previous workshop proceedings (271 L/s) is greater than the 1985 value because the streamflow rating curve for the Hot Creek flume was revised in 1985 to yield stream flows lower by about 10 percent. Preliminary analysis of chemical flux data for 1986 suggests that spring flow increased during the spring snow melt period by about 20 percent, then subsequently decreased. Such changes are more likely related to shallow hydrologic processes than to crustal unrest.

The continuous record of chloride flux at Hot Creek flume referred to above is obtained from measurements of specific conductance and gage height in the stream. The record for 1984 was given in the 1984 workshop report and was discussed in detail by Farrar et al. (1985). The record for 1985 from Farrar et al. (1987) is shown in Fig. 2, along with chloride flux determinations from periodic sampling at the flume (instantaneous measurements). Good agreement exists between the two sets of data until June when the conductivity probe began to malfunction. Chloride flux at this site is derived from the total thermal water contributed to Hot Creek by hot springs located in and above the gorge. The available record indicates that total hot spring flow remained relatively constant during 1985.

Table 1. Chemical analyses of waters from selected springs and wells in the Long Valley area, Mono County, California
Results in milligrams per liter.
Laboratory: LBL: Lawrence Berkeley Laboratory (A. White); USGS-C: U.S. Geological Survey Central Lab, Arvada CO; LANL: Los Alamos National Laboratory (analyzed by P. Trujillo and D. Counce)

Feature	Collection date (mo-day-yr)	Laboratory	Temperature (°C)	pH	Ca	Mg	Na	K	ALK	SO_4	Cl	F	SiO_2	Dissolved solids	As	B	Li
Casa Diablo area springs																	
Colton spr. (CS)	02-04-85	USGS-C	93.1	8.3	1.4	<0.01	360	26	335	130	270	11.0	300	1320	1.7	11.0	2.5
North spr. (CDN)	02-06-85	USGS-C	86.1	6.3	11.	1.4	230	21	43	180	260	8.9	260	1020	1.9	11.0	1.0
Milky Pool 3 MP-3	02-06-85	USGS-C	77.7	7.0	1.7	0.01	260	28	101	150	260	12.0	220	1030	1.9	11.0	1.0
Casa Diablo wells																	
MBP-1	07-11-85[1]	USGS-C	168	6.2	3.9	0.10	360	33	355L	110	260	11.0	250	1270	1.0	11.0	2.7
		LANL	168	6.2	2.2	0.15	352	38	348L	107	245	11.0	257	1240c	1.1	11.0	3.1
		LBL	168	ND	1.8	0.12	348	35	360L	60	262	10.4	362	1252c	ND	10.8	2.5
MBP-3	07-12-85[1]	USGS-C	171	6.1	1.2	0.10	350	36	345L	120	270	11.0	250	1250	1.1	11.0	2.6
		LANL	171	6.1	1.3	0.19	344	38	345L	106	237	10.2	259	1212c	0.8	10.7	3.1
		LBL	171	ND	3.2	0.12	349	35	363L	64	253	10.3	315	1205c	ND	10.4	2.5
MBP-4	10-13-85[1]	USGS-C	173	6.0	1.8	0.10	340	34	360	110	270	10.5	240	1270	1.2	11.0	2.6
MBP-5	10-13-85[1]	USGS-C	168	6.3	6.0	0.10	340	31	360	110	270	10.5	240	1270	0.7	11.0	2.7
Fish Hatchery area springs and wells																	
AB Supply (AB)	04-28-85	USGS-C	15.9	7.0	ND	11	27	5.9	110	13	11	0.2	61	197	0.036	0.42	0.094
CD Supply (CD)	04-28-85	USGS-C	14.4	7.1	12	8.8	21	4.6	89	11	3.9	0.3	57	167	0.039	0.20	0.063
Chance-2 Well (CW-2)	05-28-85[2]	LANL	104	9.0	2.6	0.16	362	20	348L	111	233	9.8	173	1109	1.2	10.6	3.0
	06-03-85[3]	USGS-C	92.5	6.0	1.4	0.10	290	20	290	88	210	8.7	140	936	1.20	9.1	2.1
Hot Creek Gorge																	
Geysers (HC-3)	07-16-85	USGS-C	92.8	7.8	4.4	0.20	410	22	457L	98	220	9.7	140	1190	1.10	10.0	2.5

Table 1. (cont.) Chemical analyses of waters from selected springs and wells in the Long Valley area, Mono County, California

Feature	Collection date (mo-day-yr)	Laboratory	Temperature (°C)	pH	Ca	Mg	Na	K	ALK	SO_4	Cl	F	SiO_2	Dissolved solids	As	B	Li
Little Hot Creek																	
Flume spr. (LHC-1)	03-21-85	USGS-C	82.5	6.7	24	0.70	370	26	578	95	210	7.9	100	1210	0.60	8.7	2.70
Nonthermal Springs																	
Laurel spr. (LS)	02-02-85	USGS-C	12.0	8.9	17	0.60	6.2	1.3	38	19.0	0.6	0.2	22	85	0.001	0.020	0.004
Big spr. (BS)	07-18-85	USGS-C	11.5	7.1	5.3	6.6	24.	4.0	81	6.4	4.5	0.5	60	147	0.022	0.26	0.038

[1]Total-flow sample - collected by condensing single-phase flow in discharge pipe through stainless steel tubing in ice bath.
[2]Total flow of two-phase fluid at 4.5 psig - 104° collected through separator at same conditions, 4.4% steam fraction; analysis is for separated water.
[3]Total flow of two-phase fluid at 4.5 psig - 104°C collected through stainless steel tubing in ice bath; analysis is for total flow sample.
L Laboratory determination
c Calculated

Table 2. Chemical geothermometer temperatures for selected well and spring samples.

Laboratory: USGS-M: U.S. Geological Survey, Menlo Park, CA (analyzed by T. Presser); USGS-C: U.S. Geological Survey Central Lab, Arvada, CO; LANL: Los Alamos National Lab (analyzed by P. Trujillo and D. Counce); LBL: Lawrence Berkeley Lab (A. White).

			Temperature (°C) based on specified geothermometer (see Farrar et al., 1987, for equations used in calculations)			
Site ID	Sample Date	Lab	Quartz-Conductive	Na/K	Cation 1/3 (Na-K-Ca)	Mg/Li
Casa Diablo area - wells						
END-5	05-19-72	USGS-M	219	230	238	201
MBP-1	05-29-85	LANL	203	213	219	213
	07-12-85	USGS-C	196	210	205	212
		LANL	198	224	221	209
		LBL	220	218	218	204
MBP-3	05-28-85	LANL	200	211	211	204
	07-12-85	USGS-C	196	219	224	210
		LANL	198	226	228	203
		LBL	209	217	212	204
MBP-4	10-13-85	USGS-C	193	220	220	210
MBP-5	10-13-85	USGS-C	193	209	200	212
Casa Diablo area - springs						
CDG	05-28-85	LANL	209	214	219	241
CDN	02-06-85	USGS-C	198	209	186	124
CS	02-04-85	USGS-C	209	191	201	167
Fish Hatchery, Hot Creek Gorge, Little Hot Creek - springs and wells						
CW-2	05-28-85	LANL	170	171	180	206
	06-03-85	USGS-C	157	187	194	200
CMS	01-16-85	USGS-C	165	138	148	140
HC-2	02-04-85	USGS-C	173	177	177	189
HC-3	02-04-85	USGS-C	173	177	187	191
LHC-1	03-21-85	USGS-C	137	188	174	168

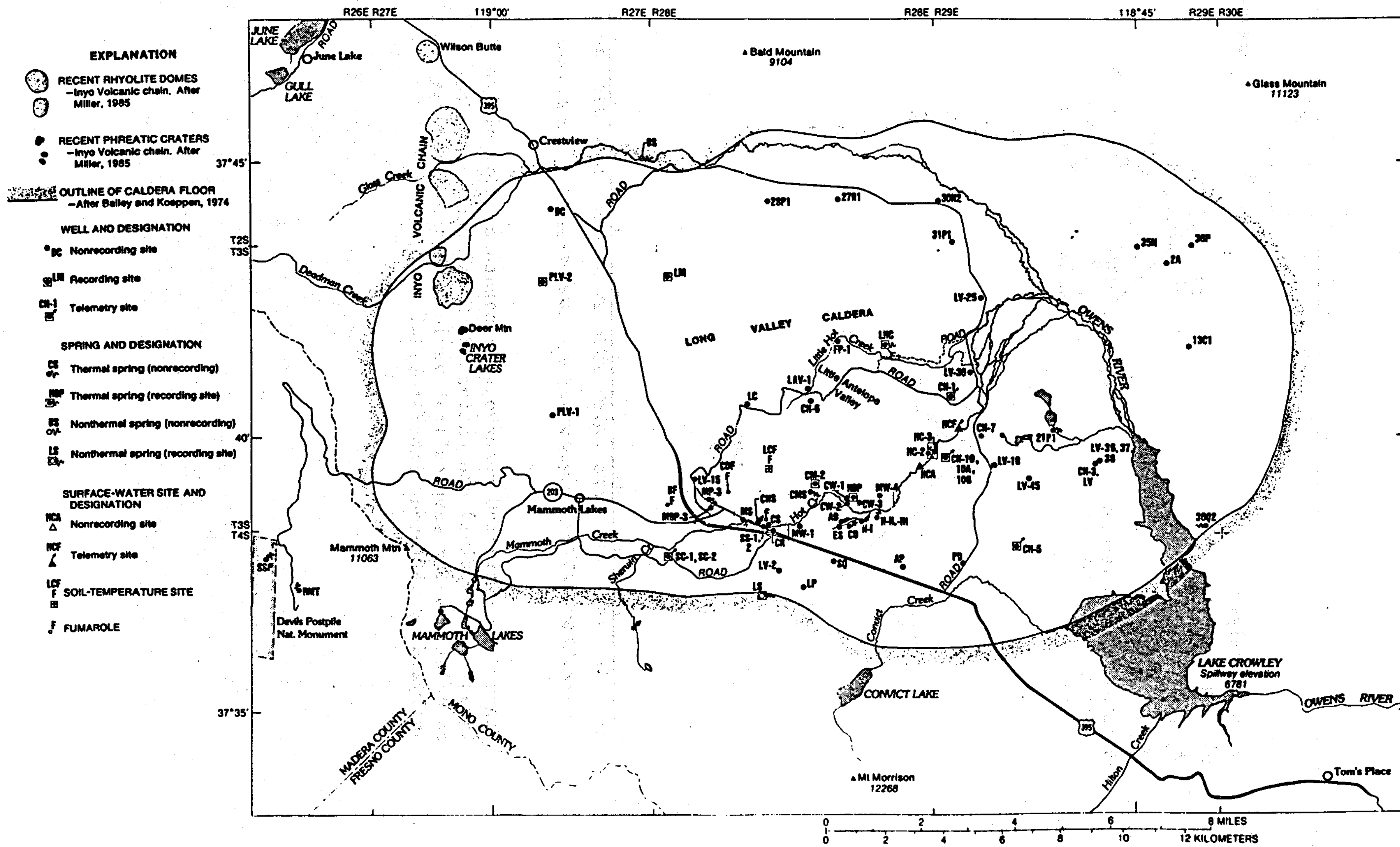

Figure 1. Map showing locations of instrumented sites in U.S. Geological Survey's hydrologic monitoring program in Long Valley caldera.

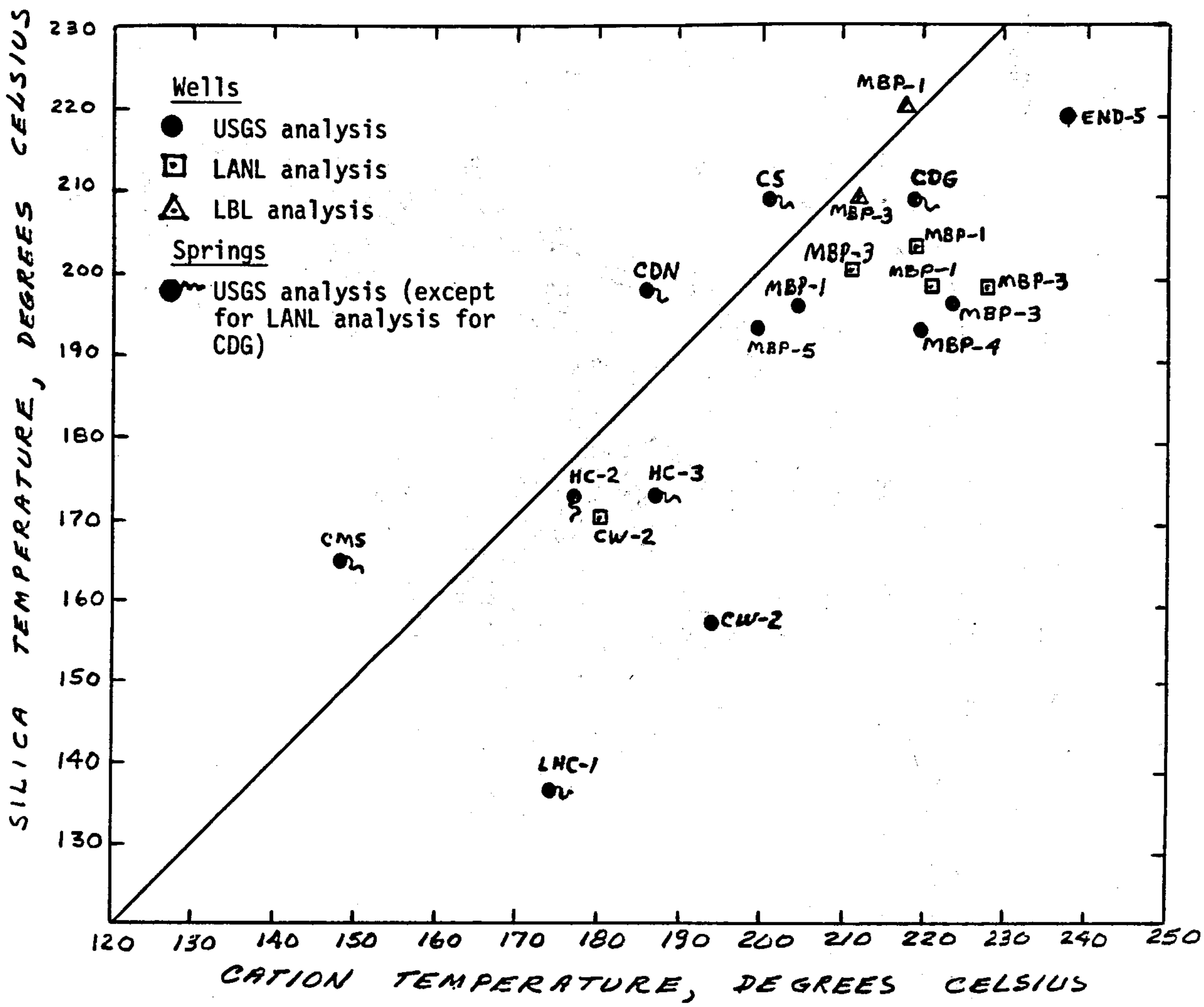

Figure 2. Estimated reservoir temperatures from silica (quartz conductive) and cation (Na-K-Ca) geothermometer calculations for samples from various thermal features analyzed by different laboratories.

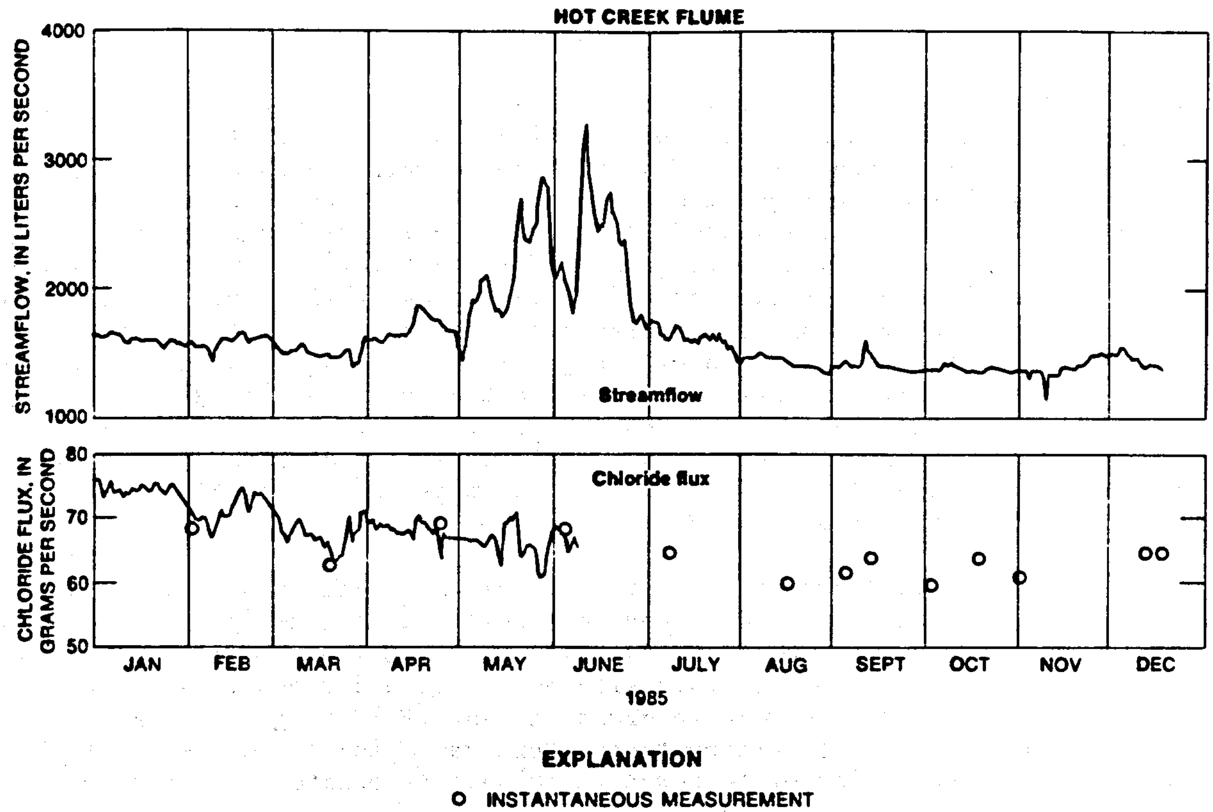

Figure 3. Streamflow and chloride flux during 1985 at the Hot Creek flume based on values of river stage and specific conductance recorded at 15-minute intervals and averaged over 24-hour periods.

THERMAL SPRING DISCHARGE AT LITTLE HOT CREEK AND CASA DIABLO

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ABSTRACT

Continuous records of spring discharge at Little Hot Creek have been obtained since 1979 and at Casa Diablo since 1985. At Little Hot Creek the measuring station, consisting of a 90° V-notch weir and chart recorder located on the creek below the area of hot-spring inflow, was discontinued in November 1985. This site was established in November 1979. Although changes in spring flow immediately following earthquakes of large magnitude and close proximity have frequently been observed at this site (Sorey et al., 1984), the measured flow is affected by snowmelt and precipitation from the upstream watershed. This complicates the detection of changes in hot-spring flow during several months of the year. Another station was established on a single hot-spring vent (LHC-1 in Fig. 1) in July 1984. This station consists of a 3-inch fiberglass modified Parshall flume with a stilling well and graphic recorder. Flow at this vent ranges from 3.4 to 3.7 L/s, compared with a total thermal water discharge from the area of 10.2 L/s.

Since the establishment of station LHC-1, no significant seismic activity has occurred within the caldera and no significant change in spring discharge has been recorded. During the July 20-21, 1986, Chalfant Valley earthquake sequence, record was lost at this site due to recorder problems. Continuous temperature measurements were recorded at vent LHC-2 (Fig. 1) from November 1979 to May 1984. No long-term temperature variation at the vent was observed and no clear indication of temperature changes associated with coseismic discharge changes can be discerned.

At Casa Diablo, the total thermal water discharge has been measured by gaging an unnamed stream at sites above and below the geothermal power plant (Fig. 2). Continuous measurements at each site were initiated in June 1985 using graphic recorders with stilling wells to measure stage at a 6-inch modified Parshall flume (below power plant) and a 90° V-notch weir (above power plant). The record for 1985 (Fig. 3), which also includes periodic measurements of streamflow at both sites prior to June, shows a variable degree of inverse correlation between spring flow and total well pumpage until mid-October. After mid-October, the average daily spring flow remained relatively constant at levels approximately five times greater than the minimum flow recorded during previous periods of sustained geothermal well pumpage. Although the record for 1986 has not yet been analyzed in detail, a general decline in spring flow with more-or-less constant well pumpage can be discerned, as can specific instances of changes in spring flow closely following changes in well pumpage.

To eliminate problems associated with maintaining discharge stations above and below the plant, a single recording station was installed in July 1986 to measure the combined flow from several of the most active vents (labeled CDG in Fig. 2). Measured mean daily flows at CDG during October-November 1986 ranged from 1.4 to 5.1 L/s and show some degree of inverse correlation with well pumpage.

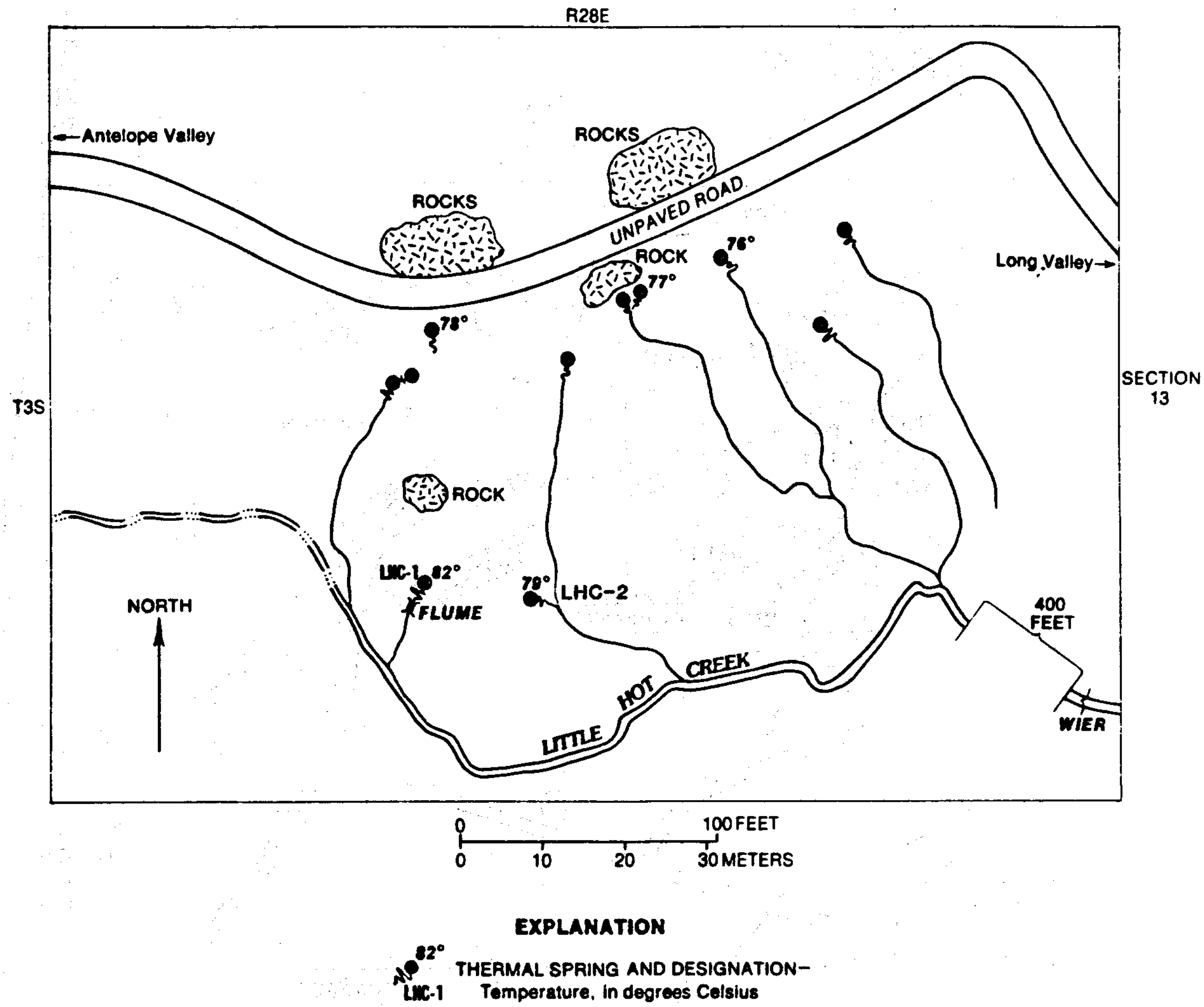

Figure 1. Little Hot Creek thermal area and locations of thermal springs and gaging sites.

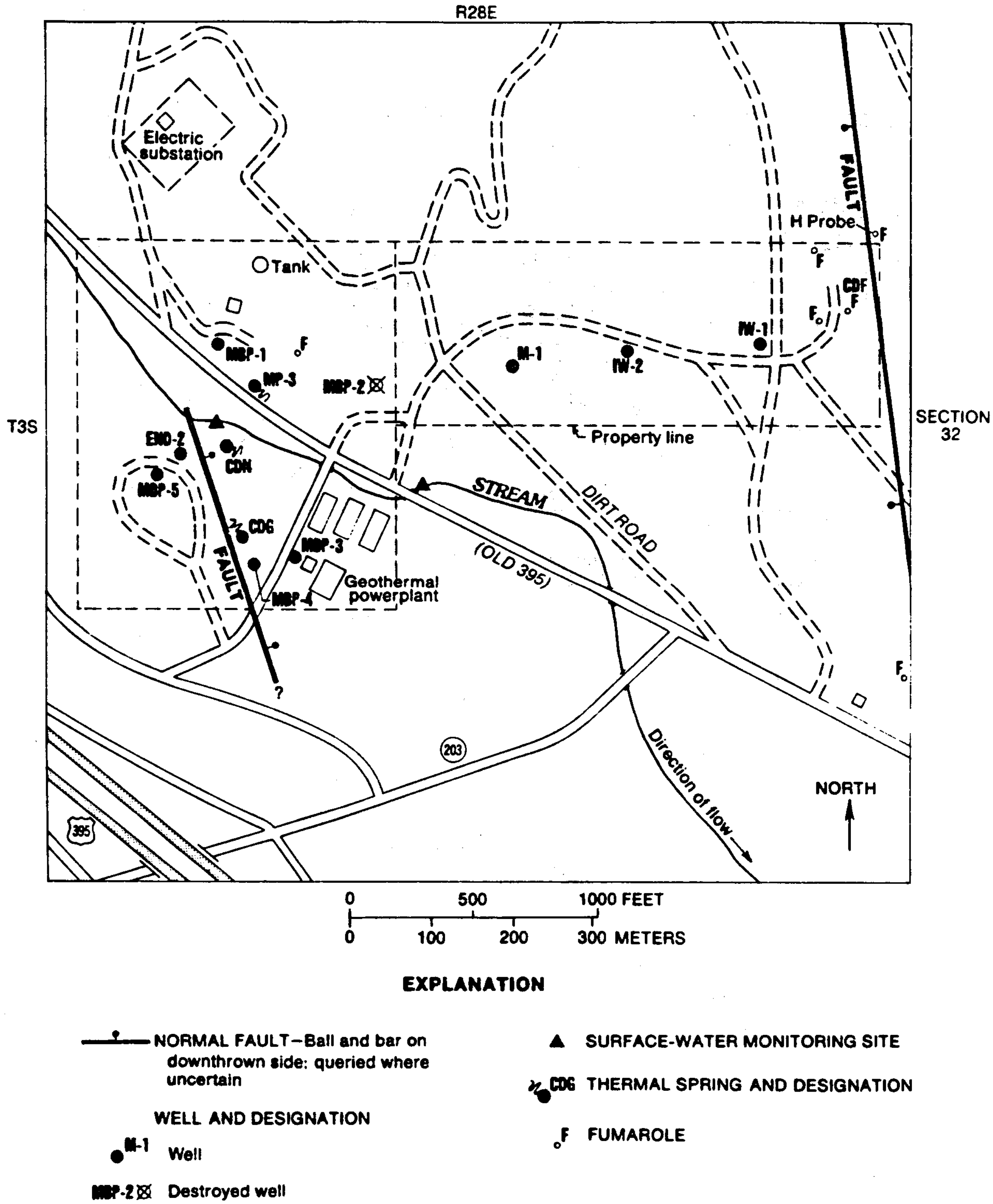

Figure 2. Casa Diablo area showing locations of thermal springs, fumaroles, wells, and surface-water monitoring sites.

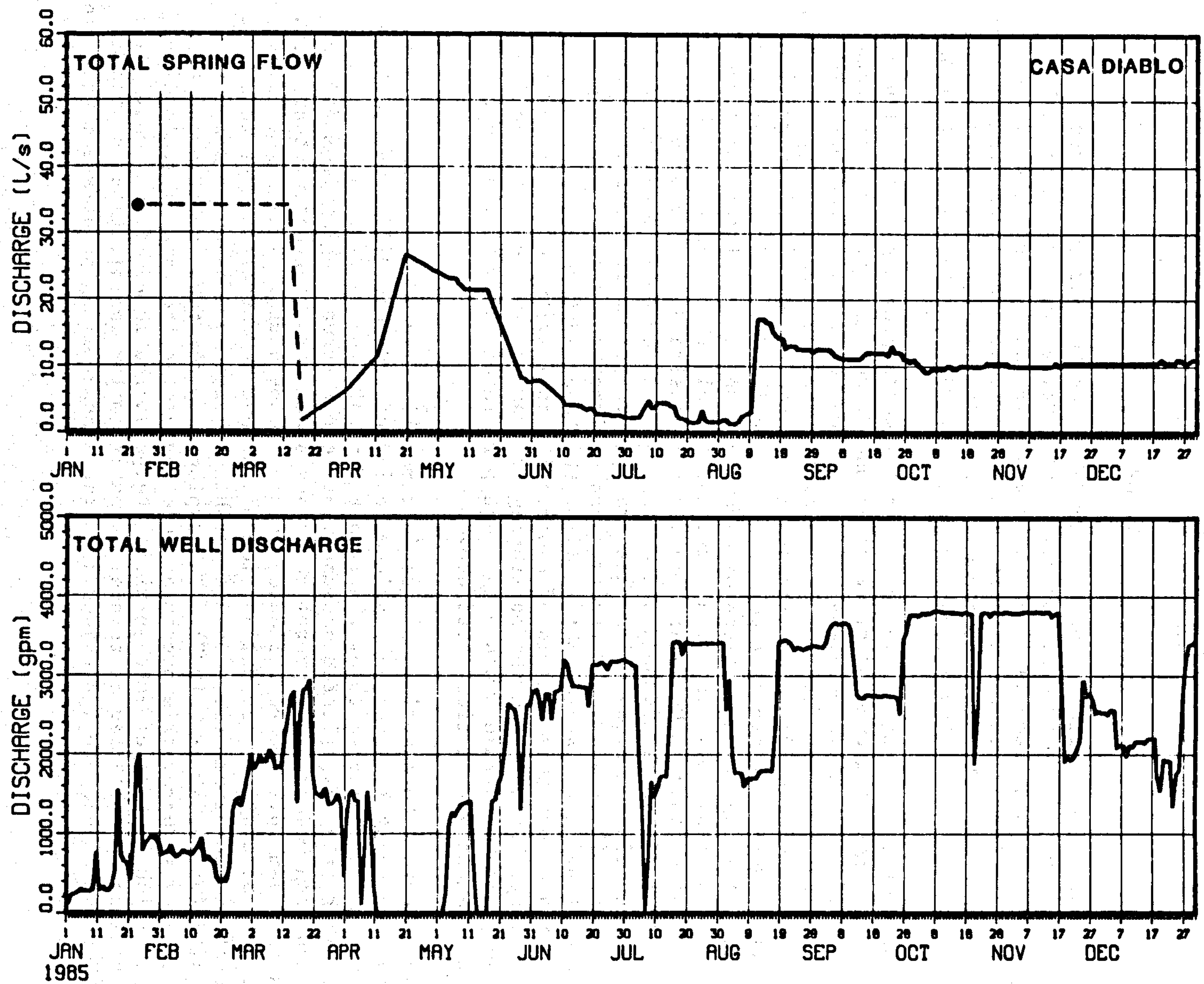

Figure 3. Plots of hot-spring flow and well discharge at Casa Diablo. Spring flow based on periodic stage measurements at flume above and below power plant prior to June 11 and mean-daily values computed from continuous records on and after June 11. Dashed portion of graph represents extrapolated spring flow based on measurements on January 22 and March 18 and visual observations between these dates.

FLUID PRESSURES IN WELLS AND FUMAROLIC TEMPERATURES

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ABSTRACT

The hydrologic monitoring program conducted by the Water Resources Division of the U.S. Geological Survey in Long Valley includes among other things periodic measurements of depth to water in shallow wells, continuous recording of fluid pressure in deeper wells, and continuous recording of temperature in a sub-boiling point steam vent. These data are presented and discussed in Sorey et al. (1984), Farrar et al. (1985), and Farrar et al. (1987).

Measurements of depth to water in shallow wells provides information on seasonal changes in ground-water recharge and discharge which may influence near-surface hydrothermal processes. Continuous records of fluid pressure in wells perforated in aquifers located below the shallow unconfined ground-water system can provide evidence of rock strain related to seismic and magmatic activity. Over two years of record has been analyzed for six such well sites (Fig. 1), allowing determinations of barometric and tidal efficiencies and aquifer transmissivity. The tidal response in well LKT, located at the southeastern base of Lookout Mountain, indicates that strains on the order of 10^{-9} can be resolved from fluid pressure measurements under optimum conditions. Optimum conditions include wells that are open to permeable zones in rocks of low compressibility and low porosity, such as fractured welded tuff or granite. Analyses of pressure records obtained for the Shady Rest core hole in November 1986 indicate that this well is of comparable sensitivity to the LKT well, whereas the other wells in the monitoring program are an order of magnitude less sensitive to strain because they are perforated in formations that do not exhibit the characteristics noted above.

In an effort to quantify changes in fumarolic discharge that may be associated with crustal unrest, a platinum resistance detector (RTD) was installed in a steam vent referred to as the Basalt Fumarole (BF in Fig. 1) in October 1985. This site was selected because vent temperatures ranging from 71° to 85°C had been measured on several occasions since 1983, suggesting that variations in steam upflow were reflected in vent temperature. This relationship appears to be confirmed by delineation of an inverse correlation between vent temperature and barometric pressure established from continuous records at this site (Farrar et al., 1987). The explanation for these relationships is that changes in barometric pressure cause changes in the rate of steam discharge, which in turn affects surficial temperatures in the steam vent. Data are still being collected at this site and a similar installation is planned for the Casa Diablo area, provided a suitable sub-boiling point steam vent can be located.

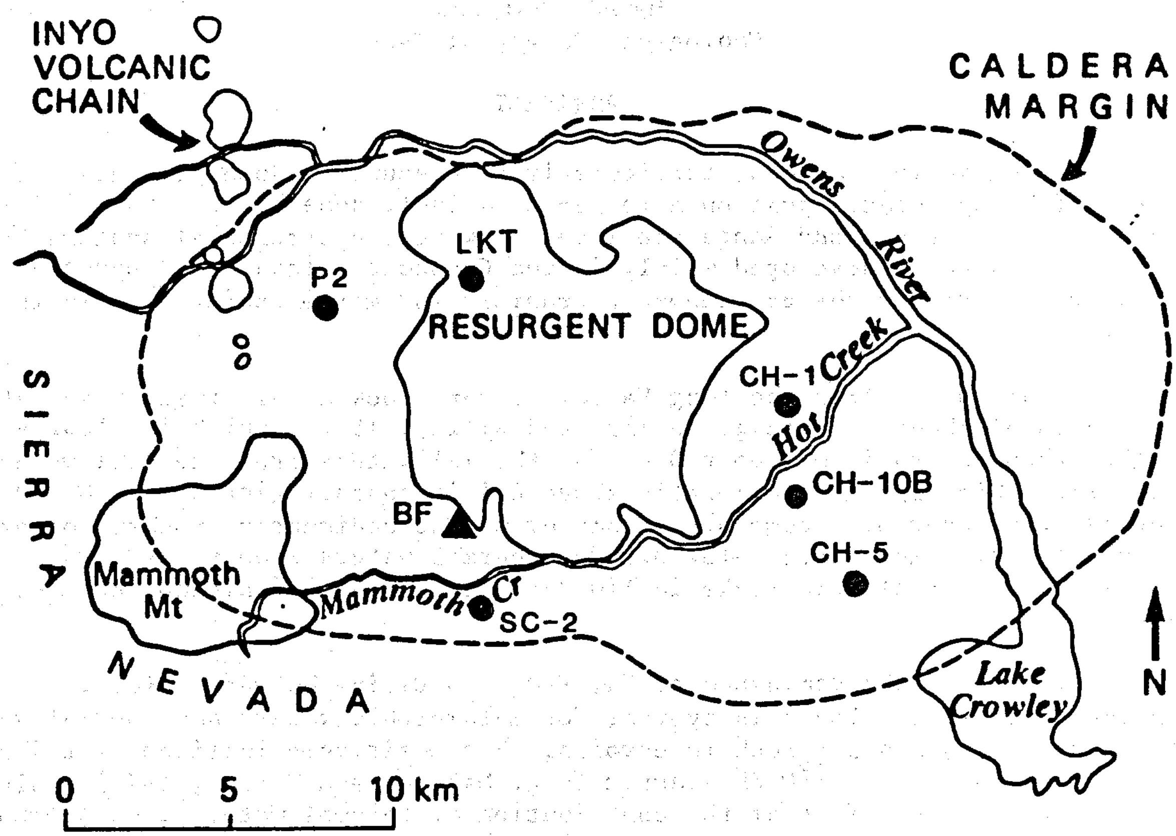

Figure 1. Locations of monitoring sites for continuous measurement of water level in wells (circles) and gas temperature in a steam vent (triangle).

CHEMICAL INDICATIONS OF A DEEP HYDROTHERMAL SYSTEM IN METASEDIMENTARY ROCKS IN LONG VALLEY CALDERA, CALIFORNIA

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ABSTRACT

The Long Valley caldera, particularly its resurgent dome, is unique in terms of being located just on a large-scale fault zone between the Sierra Nevada and the Basin and Range province. However, hydrothermal systems have been assumed to be developed mainly in the Cenozoic volcanic and pyroclastic rocks which overlay the pre-Cenozoic granitic and metamorphic rocks in this area.

Thermal waters from the Long Valley caldera show a relatively high B/Cl mol ratio of about 0.17 (e.g. Mariner and Willey, 1976), which is clearly higher than the ratio of about 0.04 for thermal waters from the Yellowstone caldera. This high B/Cl mol ratio above 0.1 is characteristic for thermal waters from reservoirs composed mainly of marine sedimentary rocks, compared to the low B/Cl mol ratio below 0.1 for thermal waters from reservoirs of volcanic and pyroclastic rocks in New Zealand and Japan (Shigeno and Abe, 1983).

In addition, the dominance of Na, HCO_3 and Cl in the waters (e.g. Mariner and Willey, 1976) is typical for metamorphic waters and thermal waters from marine sedimentary rock reservoirs. The positively inclined distribution of the waters in the $\delta^{18}O$-δD diagram (e.g. Mariner and Willey, 1976) could be interpreted as an effect of the contribution of thermal water of metamorphic water origin.

These chemical characteristics of the thermal waters suggest that a hydrothermal system is developed deeply in the Paleozoic to Mesozoic metasedimentary rocks, and supplies thermal waters to shallower reservoirs in the Cenozoic volcanic and pyroclastic rocks and to the surface along the large-scale normal faults in the Long Valley caldera.

HOT SPRING MONITORING IN ROTORUA, NEW ZEALAND

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ABSTRACT

The Rotorua geothermal field supports a variety of spectacular hydrothermal features most of which are located in an area of 1 km^2 at Whakarewarewa. Over 450 shallow wells (<200 m deep) extract geothermal fluid from a lateral subsurface discharge which extends beneath the city of Rotorua. As exploitation rates have increased with time, the geothermal aquifer has become progressively more stressed and pressures have declined across the field. Recognizing the threat that declining pressures poses to the hot springs and geysers at Whakarewarewa, the New Zealand government initiated a 3 year programme of hydrologic monitoring. A task force was also set up to investigate engineering aspects of geothermal usage in Rotorua. Both these programmes were completed in 1985 and their final reports (Ministry of Energy, 1985a,b) are available from Oil and Gas Division, Ministry of Energy, Private Bag, Wellington, New Zealand.

Monitoring activity necessarily involved close investigations of hot springs with a view to better understanding their discharge characteristics. Four alkaline chloride springs were instrumented for continuous records of stage height and temperature, and another 20 springs were visited twice weekly for manual measurements of stage height, temperature, electrical conductivity, chloride and pH. The continuous records are valuable for resolving spring responses to high frequency variables (e.g. barometer) while the manual measurements adequately define low frequency changes.

Hot spring behaviour cannot be understood independently of regional hydrology and so two networks of monitoring wells were installed throughout Rotorua city to observe (i) the phreatic surface and (ii) pressure in the underlying geothermal aquifer. Data from these show that the geothermal aquifer has very high lateral permeability but it is not significantly connected to shallow groundwater storage. Furthermore, its pressures vary seasonally in response to public demand for steam; the same seasonal variation has also been observed in hot springs.

The main objective of the monitoring programme was to gain enough understanding of the hydrological system that a numerical model could be developed for use in future management. In addition to the hydrological monitoring already described, structural geology, extensive chemical sampling and analysis of temperature and enthalpy data all contributed to the evolution of a new conceptual model for Rotorua. The programme also involved establishment of a precise leveling network throughout Rotorua, but levels are changing too slowly for valid conclusions to be drawn at this stage.

MIXING AND BOILING OF THERMAL FLUIDS IN LONG VALLEY CALDERA, CALIFORNIA

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ABSTRACT

Recharge to the Long Valley system occurs in the western part of the caldera along the Sierra Nevada Front with the water being heated at depth and flowing laterally eastward into the caldera (Farrar, et al., 1985). As the Na-HCO_3-Cl fluids flow eastward they are increasingly mixed with near surface meteoric water to form the more diluted fluids found within the caldera. Evidence for mixing is illustrated in plots of B and Li versus Cl (Fig. 1) and ^{18}O versus deuterium (Fig. 2). Clear mixing trends exist between fluids similar in composition to thermal waters in the Casa Diablo area and near surface waters similar in composition to Fish Hatchery Spring, with the more concentrated fluids emerging in the western part of the caldera. Because the dilute end-member on these plots could also represent the composition of steam, it is possible that some thermal fluids east of Casa Diablo are mixtures of thermal fluid and steam.

Boiling is an important mechanism controlling thermal fluids in the Casa Diablo area. While boiling trends are coincident with mixing trends on the stable isotope and Li and B versus Cl plots, a plot of NH_4 versus Cl (Fig. 2) more clearly identifies the end-member, boiled, and mixed components of the thermal fluids. Assuming that the Casa Diablo well fluid is conductively cooled end-member geothermal water, we calculate steam fractions with Cl mass balance for Colton Hot Spring and Casa Diablo Hot Spring. Using these steam fractions and the gas distribution coefficient for NH_3 for single-stage boiling at 100°C (Henley, et al., 1984), we can show that near surface boiling of Casa Diablo well fluids can form waters with the compositions of Colton Hot Spring and Casa Diablo hot spring with loss of 9% and 19% steam, respectively. Waters to the east of the Casa Diablo area are mixtures of near surface meteoric water and boiled thermal fluids with a composition close to that of Colton Hot Spring, which may be slightly mixed.

From ^{3}H and ^{36}Cl data, one would expect an increase of these constituents from west to east as fluids are progressively mixed. However, no correlation exists from between ^{3}H and ^{36}Cl (Fig. 3) in thermal fluids or between these components and conservative species. Except for the hot spring north of Whitmore and Meadow hot spring, it appears that cold end-member fluids involved in mixing must be relatively old fluids low in both meteoric ^{3}H and ^{36}Cl.

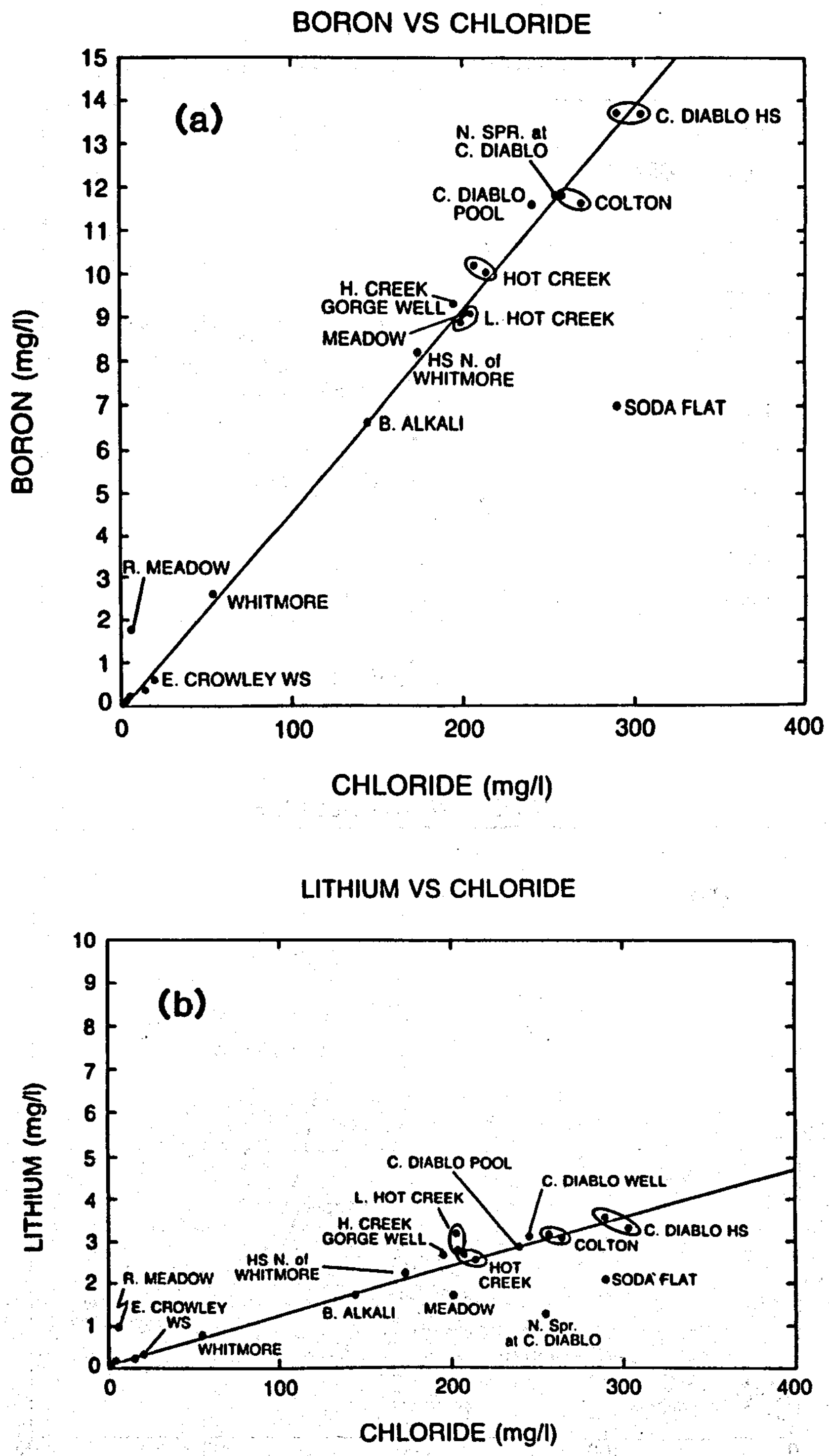

Figure 1. Plots of boron versus chloride (a) and lithium versus chloride (b) in waters from various thermal features.

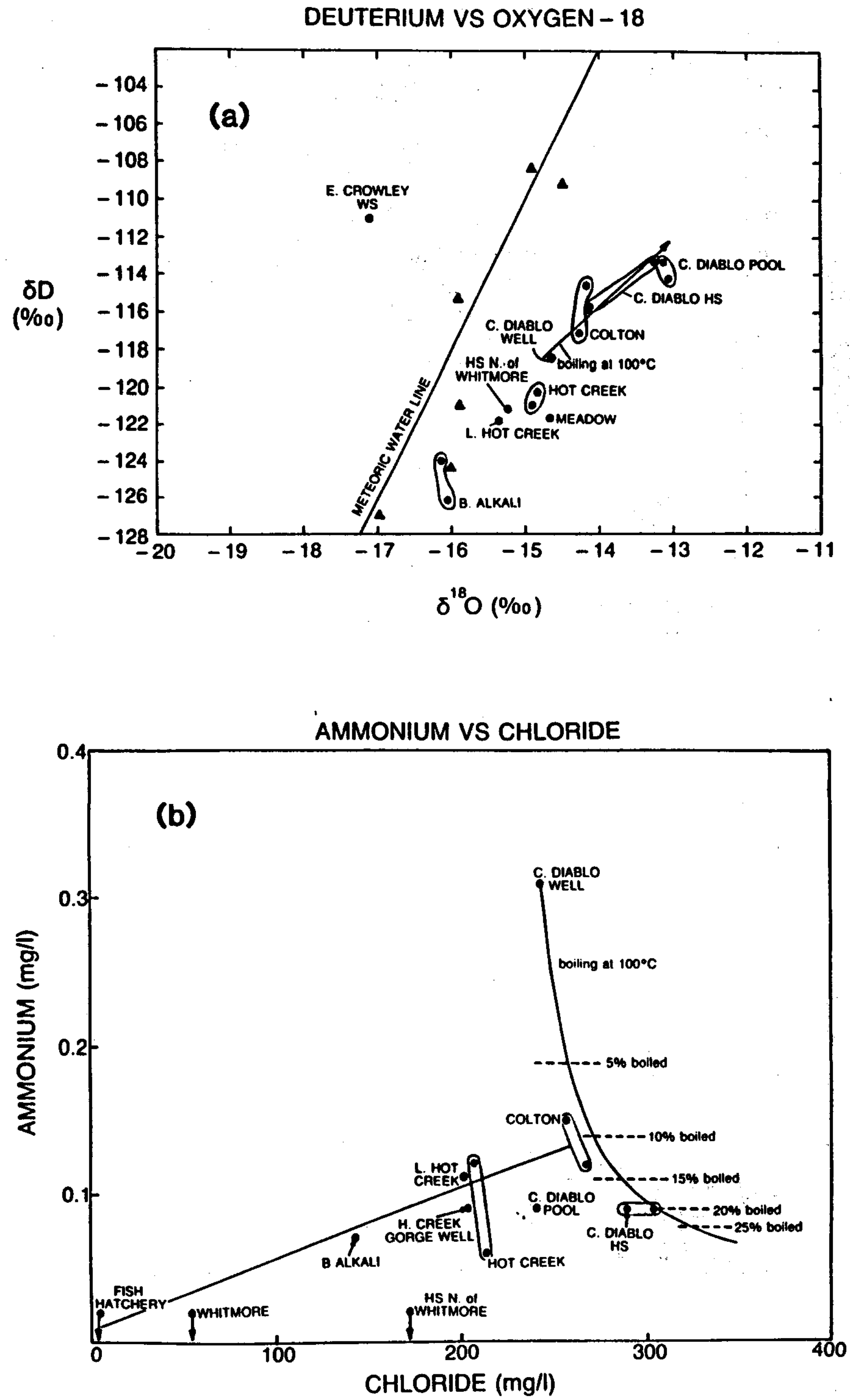

Figure 2. Plots of deuterium versus oxygen-18 (a) and ammonium versus chloride concentrations (b) in waters from various features.

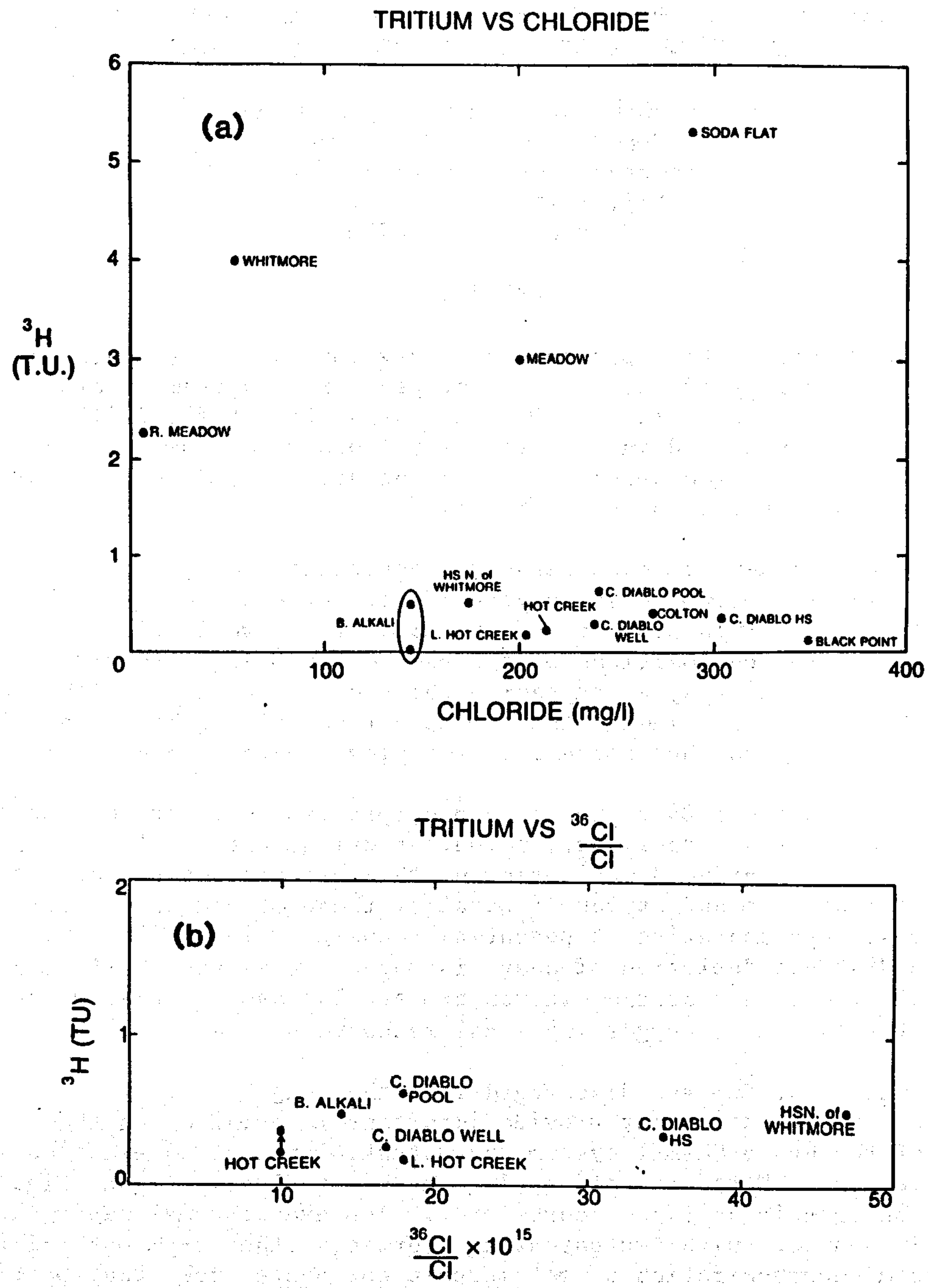

Figure 3. Plots of tritium versus chloride concentration (a) and tritium versus the ratio of chlorine-36 to chlorine in waters from various thermal features.

ISOTOPIC AND CHEMICAL COMPOSITIONS OF HOT SPRINGS AND GEOTHERMAL WELLS IN THE LONG VALLEY CALDERA, CALIFORNIA

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ABSTRACT

The primary goal of this program is to develop an understanding of the geochemistry and hydrology of the Long Valley geothermal system to aid in siting potential deep drill holes for the DOE Contential Scientific Drilling Program. This involves obtaining and interpreting available data from hot and cold springs and accessible geothermal wells in the area. Locations of springs and wells sampled to date are shown in Fig. 1.

Oxygen and hydrogen isotopes serve as convenient hydrological and chemical tracers. A plot deuterium versus oxygen-18 for meteoric and hydrothermal waters (collected by this project and the USGS) is shown in Fig. 2. As expected, cold water compositions plot close to the Craig meteoric line while hydrothermal waters display an oxygen-18 shift due to exchange with mineral phases in the reservoir. The isotopic compositions of the hydrothermal water also exhibit significant heterogeneity, implying separate recharge sources.

As reported in the 1984 workshop, a precipitation collection network across Long Valley was established, to better define potential recharge sources (Fig. 1). Continued monitoring of this network shows that trends of hydrothermal deuterium and oxygen-18 parallel those of winter precipitation which are most representative of potential recharge values. The precipitation data show a distinct depletion of heavy isotopes across Long Valley, due to the fall-out effect east of the Sierran crest. The hydrothermal water data also exhibit this trend, suggesting local recharge sources.

Large amounts of CO_2 are discharged from the Long Valley hydrothermal system, and $^{13}C/^{12}C$ ratios may provide important information on the evolution of the hydrothermal system and potential recent interaction with a deeper magma body. Meteoric cold springs are isotopically light (Fig. 3) indicating an organic soil gas source of C. The hydrothermal waters are considerably heavier, with two potential sources, either from outgasing of magma or from decarbonization of metamorphic carbonate rocks that partially comprise in the caldera basement. The spread of $\delta^{13}C$ values of the meta-carbonate rock (Sorey, et al., 1984) favors the latter interpretation. A comparison of $\delta^{13}C$ between the water and recently formed tufa deposits shows general isotopic equilibrium fractionation.

Tufa deposits associated with inactive hydrothermal vents are isotopically heavy, indicating either a shift in the isotopic composition of the CO_2 source or deposition in a lacustrine environment.

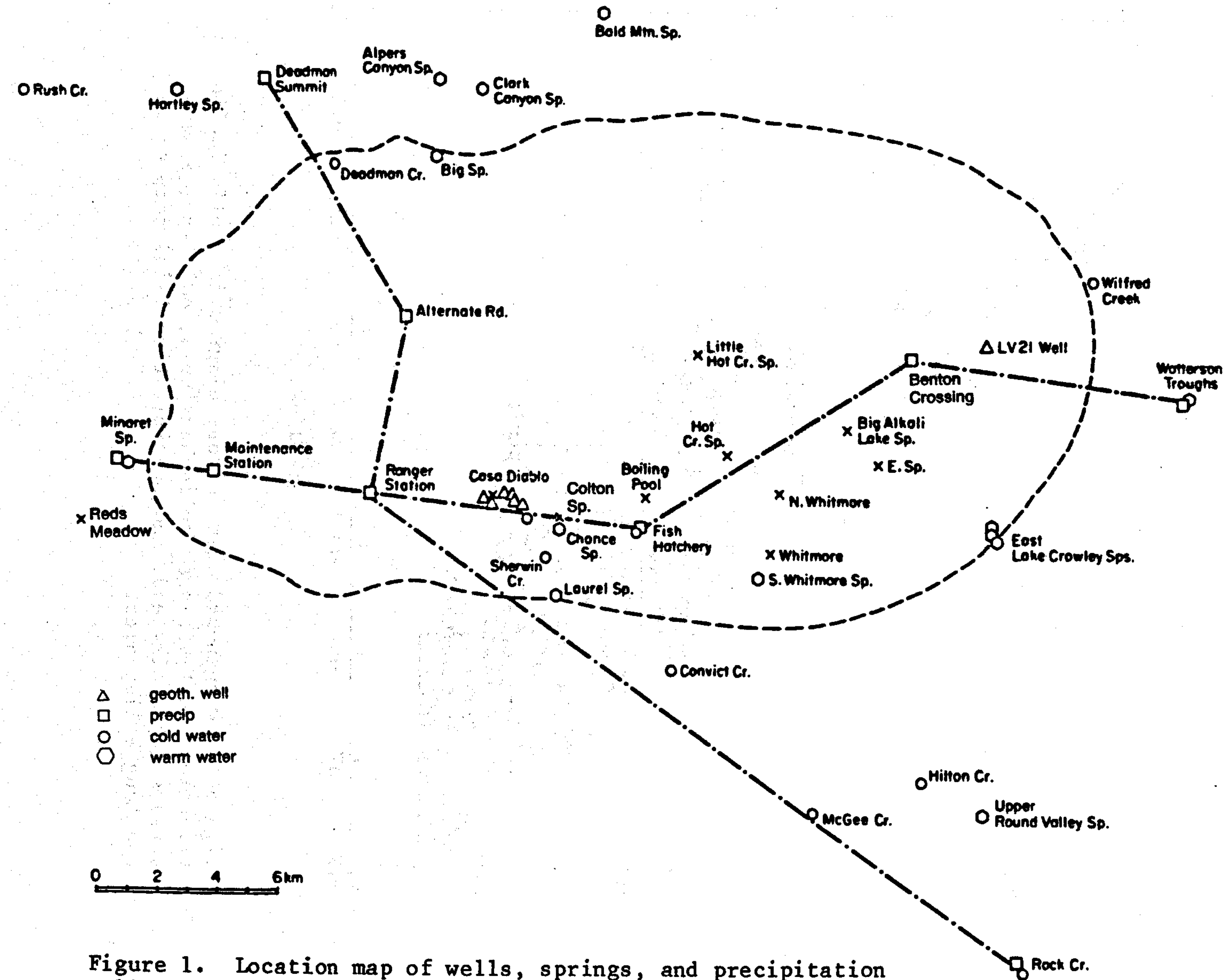

Figure 1. Location map of wells, springs, and precipitation collectors sampled in the Long Valley caldera.

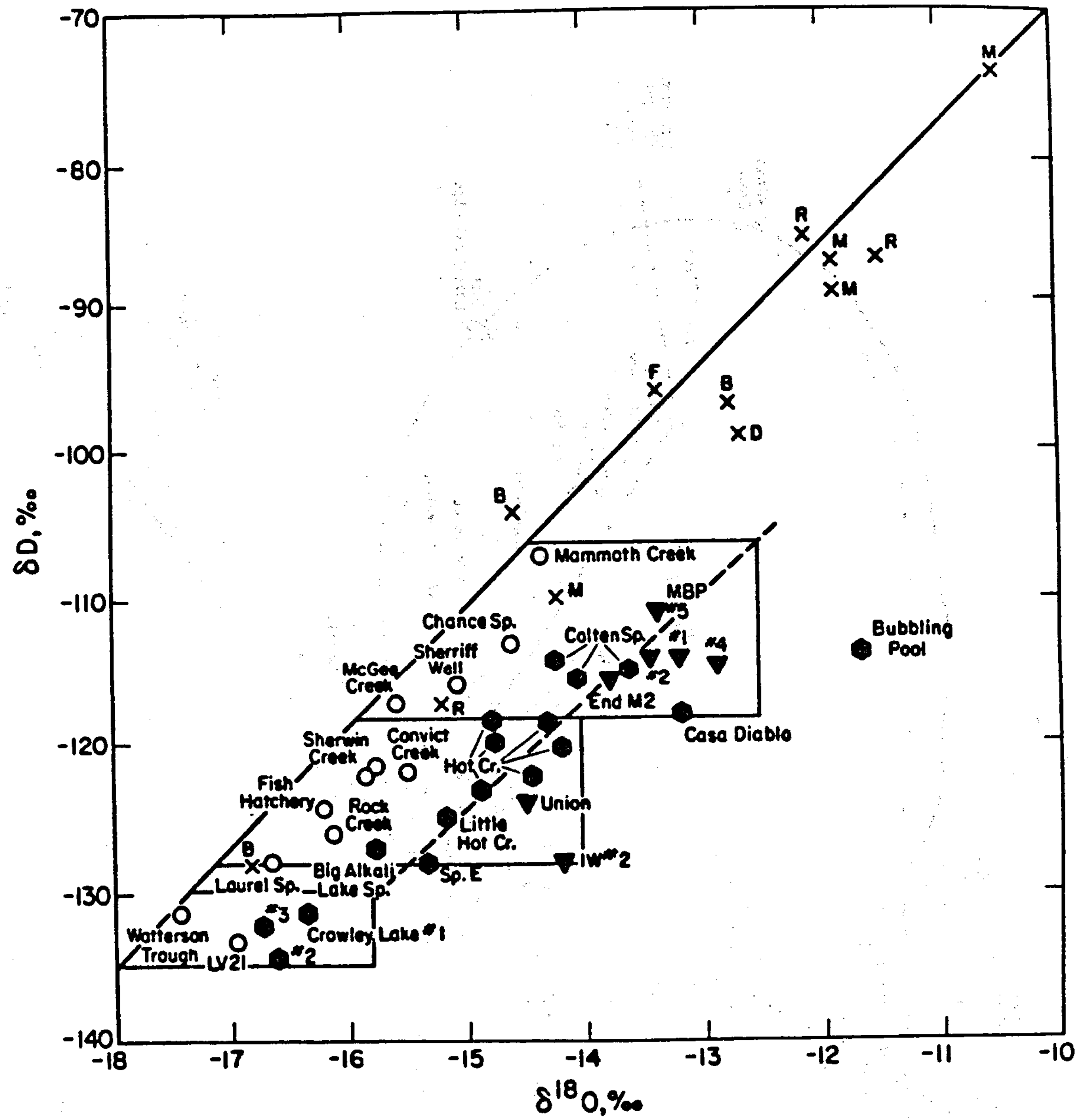

Figure 2. Oxygen-hydrogen isotope diagram for wells (solid triangles), hot springs (solid hexagons), cold springs and streams (open circles), and precipitation (X's) sampled in the Long Valley area.

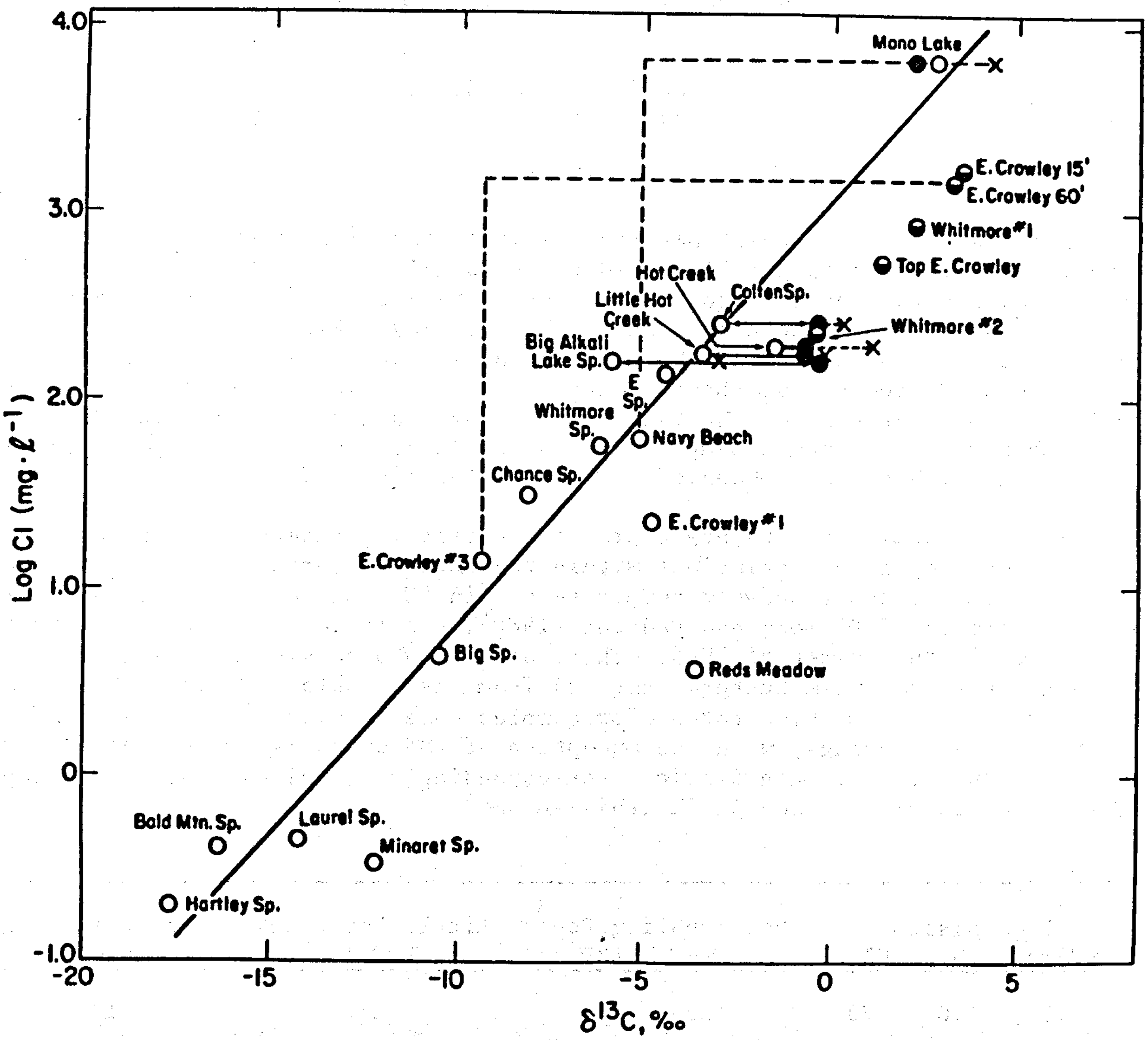

Figure 3. Carbon-isotope ratios and chloride concentrations of springs in the Long Valley area.

GAS CHEMISTRY, GAS GEOTHERMOMETRY, AND SULFATE ISOTOPE GEOTHERMOMETRY

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ABSTRACT

Analyses of gas compositions from periodic sampling of springs, steam vents, and wells in Long Valley caldera are available for the period 1982-1985. Data from several investigators are reported by Sorey et al. (1984), Farrar et al. (1985), and Winnett and Janik (this volume). Rates of steam and non-condensible gas discharge at the various thermal vents are relatively low. No significant degree of superheat occurs in the steam vents; all but the fumaroles on the east side of the Casa Diablo area discharge steam at temperatures less than 90°C. Although sampling frequency is low, no consistent trends in gas chemistry have been observed at these sites since 1982.

The gas chemistry data are useful for estimating reservoir temperatures and for delineating areal variations within the shallow hydrothermal system. For example, calculated reservoir temperatures (in °C), based on the methane/CO_2 geothermometer of D'Amore and Panichi (1980), are listed below for gas samples collected in the summer of 1985. These data show a consistent trend of decreasing reservoir temperature eastward from Casa Diablo. Features MBP-3 and CW-2 are wells from which total flow samples were obtained. The other features listed are hot springs, with the exception of CDF which is the so-called Lower Clay Pit fumarole at Casa Diablo. Corresponding gas analyses for these samples are listed in Winnett and Janik (this volume).

Casa Diablo			Hot Bubbling Pool		Little Hot Creek	Hot Creek Gorge
MPB-3	CDF	CS	CW-2	HBP	LHC-1	HC-3
175	170	170	153	140	125	113

Applications of the sulfate-water isotope geothermometer to Casa Diablo well waters sampled in 1985 yield reservoir temperature estimates of 222°-232°C. Previous estimates using the sulfate geothermometer applied to hot-spring waters in Long Valley (McKenzie and Truesdell, 1977; Fournier et al., 1979; and Sorey et al., 1984) ranged from 269°-287°C. The temperature estimates reported here are lower because the well samples were not affected by boiling and because the measured $\delta^{18}O(H_2O)$ rather than a calculated deep water $\delta^{18}O(H_2O)$ from isotope mixing models was assumed to be in equilibrium with the measured $\delta^{18}O(SO_4)$.

ISOTOPIC COMPOSITION OF CARBON IN FLUIDS FROM THE LONG VALLEY GEOTHERMAL SYSTEM, CALIFORNIA, U.S.A.*

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ABSTRACT

The Long Valley caldera in Mono County, California (Fig. 1) is one of several volcanic systems in the western United States that may contain residual magma at depth. The current hydrologic model (Sorey, 1985) of the geothermal system associated with this caldera includes a zone of upwelling fluid several kilometers west of Casa Diablo that feeds at least one eastward-flowing, 170°C shallow aquifer. The fluid cools as it flows around the southern end of the resurgent dome through moat volcanics and lake sediments, and comes to the surface along N- and NW-trending normal faults.

Carbon is a very reactive element, and the isotopic behavior of the various carbon species is affected by reactions within hydrothermal systems. This study is a preliminary attempt to couple the isotopic composition, chemical speciation, and flux of carbon species with supporting chemical and isotopic data to aid the understanding of physical and chemical processes within the Long Valley geothermal system.

It is difficult to identify the source(s) of carbon in this geothermal system because of poor knowledge of lithologies beneath the caldera fill and because of overlapping or unconstrained isotopic compositions of potential sources. For example, Sierran metamorphic carbonate roof pendant rocks that crop out at the north and south margins of the caldera have $\delta^{13}C$ values in the range 0 to -12 (Farrar, et al., 1985). Magmatic CO_2 formed as the result of partial melting of crustal rocks is generally accepted to fall in the range -5 to -7, but does not have a truly constrained carbon isotopic signature (e.g., Hoefs, 1978).

Measurements of $\delta^{13}C$ of CO_2 gas (approximately -5.7) at Casa Diablo led Taylor and Gerlach (1984) to conclude that CO_2 is supplied to the Long Valley hydrothermal system from a magmatic source. This conclusion implies that the isotopic composition of CO_2 gas at Casa Diablo is stable and is representative of the carbon input to the system. After examining well and spring data, this assumption appears unlikely.

Sampling and Analytical Results

During June 1983, June 1984, October 1984, and May 1985 samples of hot, warm, and cold spring water, condensed steam, and gas were collected for chemical and isotopic analyses. During May and July 1985 two single-phase wells near Casa Diablo (MBP-1, MBP-3) were sampled. A two-phase well near Hot

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*This abstract has been modified from a paper to be given at the 5th Water-Rock Interaction Symposium in Iceland, August 1986.

Bubbling Pool (Chance-2) was sampled in May 1985. Both total flow and separated steam and water fraction samples were collected where possible.

Carbon isotope measurements include $\delta^{13}C$ of CO_2 gas and total dissolved CO_2 ($CO_2(aq) + H_2CO_3 + HCL_3^- + CO_3^{2-}$). Total dissolved CO_2 was quantitatively precipitated as $SrCO_3$ with a saturated $SrCl_2$-NH_4OH solution immediately after collection. Gas samples were collected in 300 or 500 ml evacuated flasks containing 100 ml of 4N NaOH, and were analyzed by gas chromatography and wet chemistry. An aliquot of NaOH solution from each gas flask was treated with $SrCl_2$-NH_4OH to precipitate dissolved Na_2CO_3 (fixed CO_2 gas) as $SrCO_3$. Carbon isotope analyses were made on CO_2 liberated from the $SrCO_3$ by the addition of 100 percent H_3PO_4.

The temperature dependence of the equilibrium carbon isotope fractionation between CO_2 gas and dissolved HCO_3^- was investigated experimentally by Mook et al. (1974) and Malinin et al. (1967). Application of these experimental data sets to the Long Valley carbon isotope data is complicated by at least three factors. The first is the disagreement between the two experimental data sets. Neither set of experimental data suggests equilibrium carbon fractionation in the Long Valley geothermal system throughout the entire range of spring and well separation temperatures. Both sets of experimental data are considered in tabulations, but the preliminary interpretations in this study are based on the data of Mook et al.

The second factor involves carbon speciation, since the experimental data is restricted to fractionation between CO_2 gas and HCO_3^-. The natural samples contain other dissolved carbon species (especially $CO_2(aq)$) whose isotopic fractionation factors relative to HCO_3^- or CO_2 gas are not well known. The concentration of total dissolved carbon species, calculated from the yield of CO_2 gas extracted from the $SrCO_3$ precipitate, is often greater than the concentration of $HCO_3^- + CO_3^{2-}$ from chemical analysis of the same spring or well water. The third factor involves the poorly-defined effect of ion-pairing on carbon fractionation. All of these considerations indicate that one should be cautious about applying experimental fractionation data to natural fluids.

Well Data

Carbon isotope analyses of several well samples are presented in Table 1. Gas analyses from wells are shown with those from springs and fumaroles in Table 2. Indicated equilibrium temperatures from oxygen isotope fractionation between steam and water are in agreement with separation temperatures. If total dissolved CO_2 species can be represented as HCO_3 and if equilibrium were attained between HCO_3^- and CO_2 gas, the corresponding carbon isotope fractionation temperatures should also be in agreement. However, CO_2 gas is isotopically lighter than expected for equilibrium fractionation at the separation temperatures (i.e., the temperature suggested by comparison with experimental data is lower than the separation temperature, which is impossible). This suggests that equilibration between dissolved and exsolved carbon species is a slower and more complicated process than equilibration between oxygen or hydrogen during the phase separation of water.

Samples were collected with steam fractions of 2.5-4.5 percent. In this temperature range (100-175°C) a few percent $CO_2(aq)$ remained dissolved in the water fraction, possible complicating interpretation of the isotopic data, since it is probable that CO_2(aq) will not have the same carbon isotopic composition as HCO_3^-.

Neither the total concentration nor the total $\delta^{13}C$ of carbon species in the total flow (steam + water fractions) among the MBP wells are constant, resulting from either temporal or spatial fluctuations in the system. The MBP-3 well (100 m SE of the Casa Diablo geyser) sampled in May 1985 contained both a higher percentage of CO_2(aq), lower total flow $\delta^{13}C$, and a higher concentration of total carbon species than MBP-1 (200 m N of Casa Diablo geyser) sampled in July 1985. The average of these two recombined total flow samples gives a total carbon concentration of 1130 ppm (as HCO_3) with $\delta^{13}C$ of -5.1. The pH of the deep fluid at 170°C is approximately 6.7 (neutral = 5.7), calculated with the "PH" program of Henley, et al. (1984).

The recombined well sample from the Chance-2 well near Hot Bubbling Pool has a total carbon concentration of 800 ppm (as HCO_3^-) with $\delta^{13}C$ of -4.9. Mass balance between these two sets of well data suggests that 330 ppm carbon (as HCO_3^-) with an effective $\delta^{13}C$ of -5.6 was lost from the 170°C aquifer fluid between Casa Diablo and Hot Bubbling Pool.

It is not clear how the MBP and CH-2 wells are connected hydrologically. However, analyses of $\delta^{18}O$ in dissolved sulfate (M. Stallard, USGS) show that fluid from CH-2 has a similar sulfate-oxygen isotope composition to MBP-3 fluid, and Casa Diablo geyser water resembles MBP-1 fluid. If this data indicates subsurface connection between MBP-3 and CH-2, then even more CO_2 gas of an isotopically lighter composition (-6) could have been lost from the aquifer fluid between Casa Diablo and Hot Bubbling Pool.

Hot Springs

Boiling springs and fumaroles (Casa Diablo, Lower Clay Pit, Colton) are located west of Long Canyon. Springs that are not boiling at the surface (Hot Bubbling Pool, Little Hot Creek) occur east of it. Several boiling springs occur in Hot Creek Gorge, but their isotopic behavior is more like that of the non-boiling springs. Isotopic data are presented in Table 3.

The springs west of Long Canyon generally do not show isotopic equilibration between CO_2 gas and HCO_3^-; when compared with the experimental data of Mook et al. (1974), the results from these springs indicate unreasonably low separation temperatures. Like results from separated well samples, data from these springs show that exsolved CO_2 gas was lighter than expected for equilibrium separation. Therefore the total dissolved carbon is not (or does not behave like) HCO_3^- and/or a nonequilibrium process controls carbon fractionation in the hotter part of the system. Surface discharge at Colton is low and began only a few years ago. The lightest CO_2 gas in the system is seen there and may have a contribution from the oxidation of residual organic matter in the soil. Concentrations of conservative chemical species (e.g., Cl^-) and oxygen isotope data suggest that Casa Diablo and Colton spring waters are derived from original aquifer fluid after 15-20% and 5-10% boiling, respectively.

The carbon isotope data from eastern springs are consistent with equilibrium fractionation between HCO_3^- and CO_2 gas at temperatures slightly higher than spring discharge temperatures. Based on data from a nearby corehole

(Farrar, et al., 1985), the temperature of the shallow aquifer tapped by normal faults at Hot Creek Gorge is 105-110°C, similar to that indicated by carbon isotope fractionation in boiling springs in the gorge.

DISCUSSION

The ^{13}C of dissolved carbon generally decreases from west to east as the HCO_3^- concentration increases. As temperature decreases from 170°C, more CO_2 dissolves and can be fixed as HCO_3^- by reacting with rocks, releasing cations. Additional alkalis and carbon may also be contributed by cool groundwater from the eastern caldera, leaching old lake sediments and perhaps carrying isotopically light organically-derived carbon.

Hot spring data indicate that apparent equilibrium carbon fractionation between CO_2 gas and total dissolved CO_2 (represented by HCO_3^-) is achieved in those springs whose discharge temperatures are not much lower than the local "reservoirs" that are tapped (forming relatively small or no steam fractions). The contrast between disequilibrium and equilibrium fractionation processes and progressive exsolution of isotopically light CO_2 are responsible for increasing ^{13}C values of CO_2 gas from west to east.

Gas chemistry and the isotopic composition of carbon at Casa Diablo varied considerably during 1984-1985. It is not clear whether the system responded to a seasonal change or a preseismic disturbance. Three weeks after the October 1984 samples were collected, Casa Diablo geyser discharge increased (Farrar, et al., 1985) and after an additional three weeks an earthquake occurred. The CO_2/H_2S ratio in the gas increased dramatically and the $\delta^{18}O$ of steam increased at Lower Clay Pit from spring to autumn. Both dissolved carbon and CO_2 gas were isotopically heavier in the autumn and the difference between their $\delta^{13}C$ values indicates a reasonable separation temperature. However the isotopic compositions of these samples do not bracket the carbon isotopic composition of the aquifer, calculated the following summer, suggesting that either the carbon isotopic composition of the entire aquifer changed, the Casa Diablo feeder zone fluid changed, or the fractionation process changed during the year. Since seasonal chemical changes in spring waters are ambiguous and shallow mixing with dilute water is not supported by autumn $\delta^{18}O$ data, these changes suggest that a higher boiling temperature at depth may be responsible, perhaps with extra input from a concentrated water source in the autumn.

In contrast to the implications of Taylor and Gerlach (1984), the isotopic composition of CO_2 gas at Casa Diablo is variable (-4.1 to -7.9) and is not the same as the total carbon isotopic composition of the 170°C aquifer (apparently -4.9 to -5.2). The isotopic composition of exsolved CO_2 gas from the aquifer depends on both the original isotopic composition and the fractionation process, and should not, therefore, be expected to be representative of carbon in the entire system.

CONCLUSION

Too few data are available to adequately constrain the origin of carbon in the Long Valley system, but once carbon is in the system, its composition and behavior may eventually be useful tools for the understanding of processes such as boiling, mixing, and mineral precipitation. Carbon isotopes may be sensitive to seasonal or seismic disturbances.

Table 1. Carbon isotope data and total carbon concentration in separated liquid water and steam samples and total flow from wells at Long Valley, California. Also reported are total-flow compositions reconstructed from separate samples.

Well	WHT	sepT	$T\text{-}^{13}C$ fract. (1)	$T\text{-}^{13}C$ fract. (2)	Y_{sep}		Sep. water	Sep. stream	Calc. total flow	Meas. total flow
MBP-1 (7-85)	168	156	108	145	.0250	mg/kg°C as HCO_3	490	510	1000	1190
						$\delta^{13}C$	-4.4 o/oo	-5.3 o/oo	-4/9 o/oo	-5.3 o/oo
MBP-3 (5-85)	171	154	125	165	.0350		430	830	1260	--
							-5.4 o/oo	-5.2 o/oo	-5.3 o/oo	--
CH-2 (5-85)	127	104	78	107	.0435		425	375	800	--
							-3.5 o/oo	-6.5 o/oo	-4.9 o/oo	--

(1) Mook et al., 1974; (2) Malinen et al., 1967.
Wellhead (WHT), separator (sep) and carbon isotope equilibrium fractionation temperatures in °C.

Table 2. Analyses of dry gas (in mole percent) from wells and springs in the Casa Diablo area, Long Valley, California.

Location	Date	T/sepT	CO_2	H_2S	H_2	CH_4	NH_3	N_2	Ar	O_2	He	G/S
Obsidian Hill Fum (OHF)	84OCT10	85.3	6.77	0.000	0.000	0.000	0.0161	72.29	0.8419	19.11	0.000	-
Casa Diablo Spg. (CDG)	83JUN26	94	95.41	2.689	0.0142	0.0116	1.131	1.746	0.0321	0.0026	1.2E-4	-
Casa Diablo Spg.	83OCT05	95.4	98.06	0.0948	0.0218	0.0323	0.0041	1.47	0.0337	0.2895	6.3E-4	-
Casa Diablo frying pan	85MAY29	92	96.32	1.586	0.0298	0.0424	0.2569	1.734	0.0403	0.000	0.00302	-
Lower Clay Pit Fum (CDF)	83JUN26	94	89.78	0.6568	0.0305	0.026	0.387	7.617	0.0974	0.7998	3.8E-4	-
Lower Clay Pit Fum (CDF)	84OCT10	94.2	98.17	0.6547	0.0449	0.0452	0.0949	0.963	0.023	0.000	0.00104	-
Lower Clay Pit Fum (CDF)	85MAY30	95	97.7	0.8505	0.0494	0.0392	0.3088	1.04	0.0228	0.0018	9.1E-4	-
Colton Spg. (CS)	85MAY26	93.8	59.4	2.125	0.0357	0.0107	0.1316	31.25	0.3946	6.856	0.000	-
Colton Fum	85JUN27	96.5	95.36	0.7626	0.0623	0.0657	0.000	3.527	0.084	0.000	0.00606	-
Colton Fum	85MAY26	93.3	97.02	1.016	0.0339	0.0258	0.000	1.902	0.047	0.000	5.7E-4	-
Hot Bubbling Pool (HBP)	83JUN26	64	97.25	0.0132	0.0403	0.0694	0.0114	2.422	0.0017	0.1768	5.0E-4	-
Hot Bubbling Pool	84OCT05	68.5	94.35	0.1138	0.0308	0.0305	0.000	4.729	0.1231	0.5754	0.000	-
Hot Bubbling Pool	85MAY28	69.3	96.58	0.275	0.0078	0.005	0.000	2.904	0.0506	0.2175	0.000	-
Little Hot Creek (LHC)	84JUN28	80	91.01	0.1823	4.0E-4	0.0308	0.019	7.041	0.1038	1.474	0.000	-
Little Hot Creek	85MAY25	83	98.37	0.0534	0.0011	0.032	0.0026	1.506	0.0396	0.0182	9.6E-4	-
Hot Creek Gorge (HCG)	83JUN27	79	96.69	0.0338	0.0123	0.0741	0.0053	2.977	0.0758	0.0747	0.00214	-
Hot Creek Gorge	84OCT06	85.9	96.43	0.0582	0.0018	0.0087	0.000	2.929	0.0811	0.4256	0.000	-
Hot Creek Gorge	85MAY30	89	96.06	0.0193	0.0045	0.0035	0.0035	3.537	0.0881	0.3389	0.000	-
Soda Flat Spg. (SPS)	84OCT06	14	79.29	0.253	0.000	0.000	0.000	19.99	0.2275	0.000	0.02787	-
Casa Diablo Well #1 (MBP-1)	85MAY29	138	98.29	0.936	0.0249	0.0332	0.0752	0.632	0.0139	0.000	7.8E-4	0.003901
Casa Diablo Well #1	84JUL11	156	98.46	0.617	0.0636	0.0365	0.053	0.763	0.0174	0.000	7.7E-4	0.00614
Casa Diablo Well #3 (MBP-3)	85MAY29	154	98.54	0.5381	0.0334	0.0423	0.0889	0.748	0.0165	7.0E-4	0.00103	0.007023
Casa Diablo Well #3	85JUL12	164	98.7	0.4322	0.0376	0.043	0.0268	0.749	0.0167	0.000	0.00106	0.0175
Hot Bubbling Pool Well (CH-2)	85MAY28	103.9	97.43	0.5438	0.0237	0.0225	0.117	1.849	0.0446	0.000	2.9E-4	0.002604

Table 3. Isotopic and selected chemical analyses of thermal and meteoric spring waters (w) and steam (s) from Long Valley, California.

	Date	Temp	Cl	HCO_3^-	$\delta^{13}C_w$	$\delta^{13}C_s$	T_{eq}-13C (1)	T_{eq}-13C (2)	$^{18}O_w$	D_w	$^{18}O_s$	D_s	T_{eq}-18O
Casa Diablo Spg. (geyser) (CDG)	06-26-83	94	--	--	- 3.5	- 7.9	60	82	-13.5	-112	-19.6	-143	75
	10-05-84	95	304	444	- 3.0	- 4.1	104	141	-13.3	-113	--	--	--
	05-29-85	92	298	482	- 4.0	- 7.6	72	97	-13.6	-114	-19.5	-146	85
Lower Clay Pit fumarole (CDF)	06-26-83	94	--	--	--	- 7.5	--	--	--	--	-20.4	-146	(90)
	10-10-84	94	--	--	--	- 5.5	--	--	--	--	-18.9	-135	(130)
	05-30-85	95	--	--	--	- 6.5	--	--	--	--	-21.9	-152	(75)
Colton Spg. (CS)	06-26-83	94	--	440	- 3.6	--	--	--	-14.4	-118	--	--	--
	06-27-84	95	--	--	- 3.4	-10.5	35	37	-14.3	-116	--	--	--
	10-05-84	94	269	440	- 3.8	--	--	--	-14.3	-117	--	--	--
	05-26-85	94	260	445	- 3.0	- 8.8	46	58	-14.2	-115	--	--	--
Hot Bubbling Pool (HBP)	06-26-83	82	--	--	- 2.7	- 5.8	78	107	-13.0	-115	--	--	--
	10-05-84	69	241	407	- 3.3	- 5.7	86	117	-13.1	-114	--	--	--
	05-28-85	69	244	459	- 3.2	- 5.3	90	120	-13.2	-113	--	--	--
Little Hot Creek (LHC)	06-28-84	80	--	--	- 4.2	- 6.7	85	116	-15.6	-125	--	--	--
	10-05-84	83	204	712	- 4.7	--	--	--	-15.6	--	--	--	--
	05-25-85	82	199	711	- 4.3	- 6.4	90	122	-15.5	--	--	--	--
Hot Creek Gorge (HCG)	06-27-83	79	--	--	- 4.0	- 5.2	105	141	-14.4	-121	--	--	--
	10-06-84	86	214	564	- 4.1	- 6.3	90	122	-14.9	--	--	--	--
	05-30-85	91	209	554	- 3.9	- 5.0	104	140	-14.9	-121	--	--	--
Spg. S. of Big Alkali Lake (BAL)	10-06-84	58	144	769	- 4.7	--	--	--	-16.1	--	--	--	--
	05-25-85	58	150	775	- 5.0	--	--	--	-16.0	-126	--	--	--
Laurel Spg. Composite (LS)	05-26-85	12	2	46	-11.7	--	--	--	-17.0	-128	--	--	--

(1) Mook et al., 1974; (2) Malinin et al., 1967.

Isotope analyses in permil (o/ooo); measured and indicated isotope equilibrium fractionation temperatures in °C; chemical data (in mg/kg) from F. Goff, P. Trujillo and D. Counce, Los Alamos National Laboratory.

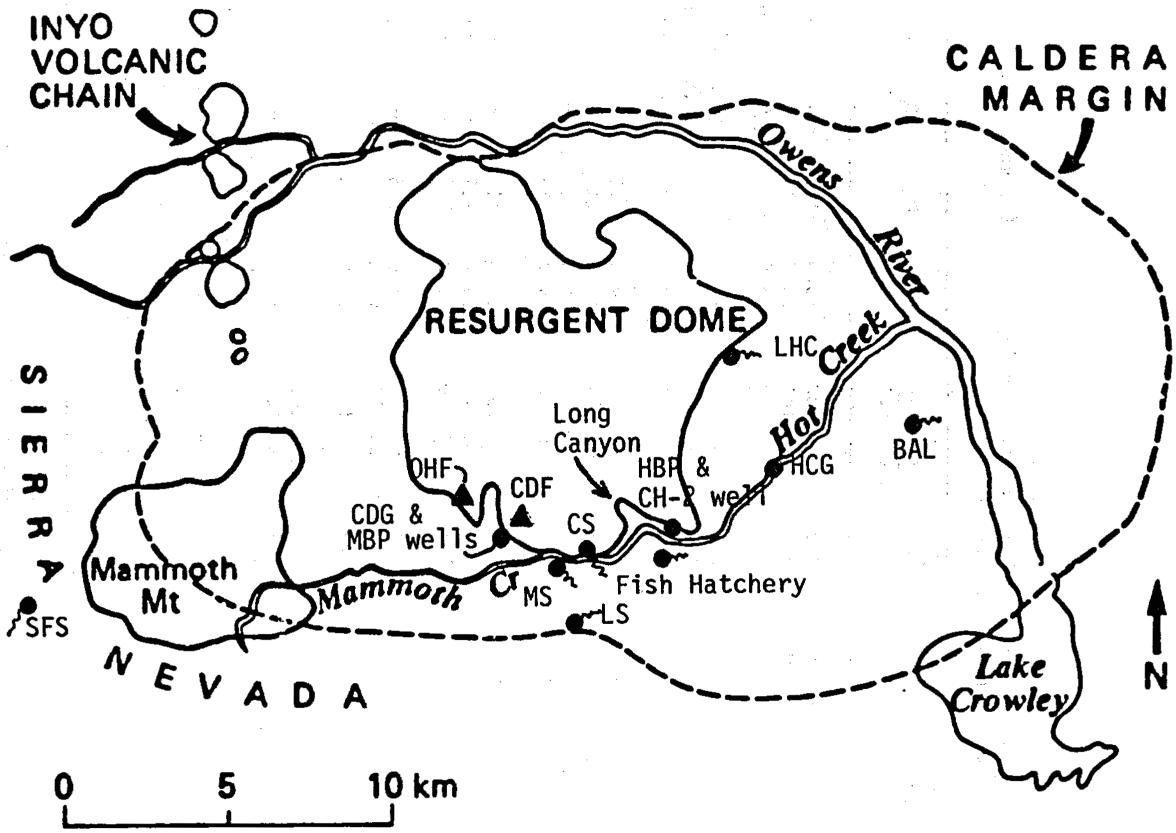

Figure 1. Locations of springs, wells, and fumaroles sampled for gas composition and isotopic analyses.

SOURCES OF NATURAL GAS IN MONO LAKE AND LONG VALLEY

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ABSTRACT

Four sources of natural gas (predominantly methane) have been identified in Mono Lake. Dissolved methane in the lake's anoxic water column (conc'n CH_4 = 45 µM) is derived from current bacterial activity occurring in the bottom sediments (conc'n CH_4 = 1.8 mM). However, because the lake contains high sulfate (128 mM), current methanogenic activity is low and is derived from a restricted suite of "non-competitive" substrates (e.g., methylated amines, dimethylsulfide) rather than hydrogen or acetate. This low activity precludes active bubble ebullition. Nonetheless, numerous methane-rich, continuous flow gas seeps were observed at various locations in the lake. We counted about 500 such seeps and measured individual ebullition rates as high as 4 liters min^{-1}. Most of these seeps had $CH_4/(C_2H_6 + C_3H_8)$ ratios greater than 1000, and had $\delta^{13}CH_4$ values more negative than - 64 o/oo. Therefore, these seeps were derived from a biological source. However this source represents ancient entrapped methane associated with the lake's earlier depositional periods. Current release of this methane is probably due to the formation of conduits formed during seismic/magmatic events. Some of the gas seeps on the south part of Paoha Island in the region of active hot springs had a more thermogenic character ($\delta^{13}CH_4$ = - 53 o/oo; $CH_4/(C_2H_6 + C_3H_8)$ = 15). These seeps represent a mixture of biogenic and thermogenic sources. Finally, biologically formed methane is also associated with the decomposition of tufa-entrapped grasses located in proximity to the CO_2-rich volcanic seeps occurring on the lake's south shore.

We have also examined the methane content of several gas seeps present in Long Valley hot springs. Although methane can be as high as 49% v/v in some of these gases, the source of this methane is from a very active bacterial methanogenesis occurring at the surface. Vents not associated with such process had only traces of methane.

RADON MONITORING AT LONG VALLEY FISH HATCHERY

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ABSTRACT

A continuous monitoring system for the detection of radon-222 in spring water was first installed at the Fish Hatchery in August, 1983 and has been in operation for most of the time since (Wollenberg, et al.; 1985). A gamma detector is submerged in a natural pool, and surrounded on all sides by at least 1 m of water. The pool is fed by springs issuing from fractured basalt, and residence time of water in the pool is of the order of a few hours. Measured radioactivity is due almost entirely to the radon-222 concentration of the water, and radon counts are integrated over a period of 1 hour.

The radon record shows a pronounced diurnal variation of approximately 25% of the mean count rate, as well as a less well-defined semi-diurnal variation. There is also a seasonal effect, with the winter pattern showing higher amplitude, more regularity, and smaller diurnal peaks than the summer pattern. While initial data suggested that the daily radon variations could be ascribed directly to tidal effects, it is now apparent that the radon record does not correlate with the secondary features of the earth tide pattern, and other factors must play a major role in determining radon concentration.

The non-tidal factors influencing the radon record are not yet understood, but clues may be provided by observed responses of radon concentration to major changes in atmospheric pressure and/or precipitation, and by correlations with small changes (<1°C) in water temperature in the pool. Changes in the radon record have also occurred in connection with at least one earthquake, but until we have achieved a better understanding of the "normal" variation in the record, it will probably be difficult to discern correlations with most seismic events.

HELIUM ISOTOPE VARIATIONS AND SEISMICITY AT LONG VALLEY CALDERA

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ABSTRACT

Dramatic changes in the level of seismicity, hydrothermal activity and ground deformation have typified the Long Valley/Mono Lake region of the Sierra Nevada Range in recent years. Since the first major earthquake (M>5) in October 1978 we have monitored a number of hot springs and fumaroles in the area to investigate the relationship between variations in the thermal and seismic activity and changes in the gas chemistry of nearby hydrothermal fluids. The focus of our study has been on helium, as its isotopic composition ($^3He/^4He$) can be uniquely exploited to discriminate between magmatic and crustal provenance. The helium results are discussed here; however, we have also analysed samples for Ne, H_2, CO_2, O_2 CH_4 and $^{13}C/^{12}C$.

In Figure 1 we present helium isotope results for six of the localities which have been monitored on a long-term basis. During the period of most intense seismic activity (October 1978 to June 1983) the $^3He/^4He$ ratio (R), normalised to its value in air (R_a), increased monotonically at the Hot Creek locality from 4.7 to 5.6 indicating an increasing contribution to an already significant proportion of primordial (magmatic) helium. The results from 1983 to 1985 show a decrease in R/R_a values, both at Hot Creek and other springs in the vicinity, concomitant with an approximately 10-fold decline in the level of seismicity. Although the rate of seismicity continues to decline the increased sampling frequency adopted this year (1986) has revealed a gradual increase in R/R_a ratios for all our regular sampling localities with Hot Creek and Big Alkali Lake returning to their maximum measured values. In addition, we have observed a possible seasonal perturbation to the $^3He/^4He$ ratio in our first and, as yet, only winter sampling trip. Interestingly, samples obtained a week either side of the time of the Chalfant Valley earthquake in July (30 Km SE of Long Valley, M=6.2) show a significant increase in R/R_a at the Hot Bubbling Pool and Big Alkaline Lake localities. It is noteworthy that both these localities are situated closest to the south-east rim of the caldera and would be predicted to respond preferentially to seismicity in the Chalfant Valley region.

There are several possible reasons why the helium isotope ratio should respond to changes in seismic activity and migration of magma. If the highest $^3He/^4He$ ratio observed (6.5 R_a) is indicative of the magmatic source, then lower $^3He/^4He$ ratios must be due to either admixture of a low $^3He/^4He$ water or leaching of ^4He from crustal rocks. In either case, new fractures related to earthquakes would facilitate the migration of hydrothermal fluid. This would result in a greater percentage of the magmatic component relative to the crustal one in the observed fluid or in a shorter residence time in the reservoir for the hydrothermal fluid, thereby reducing the amount of leaching of ^4He. Similarly, movement of magma to shallower depths would increase the convective heat flux in the region, thereby bringing more of the magmatic hydrothermal component to the surface. Unexpectedly, the South Mono Lake hot spring, 25 km to the north of Long Valley, also seems to respond to the changes

in seismic activity; thus, this hydrothermal system is responding to similar changes in the stress regime and fracture pattern as Long Valley or, perhaps more speculatively, the Long Valley and Mono magma chambers are connected.

The $^3He/^4He$ ratios also have a bearing on present hydrological models of the area, which generally assume recharge to the west of Long Valley and continuous lateral flow of fluid through the Bishop Tuff aquifer in an easterly direction. The consistently higher $^3He/^4He$ ratios on the eastern side of the caldera (see Figure 2), at Hot Creek, Little Hot Creek and Big Alkali Lake for example, if indicative of a more direct magmatic input to this area, imply that the fluid regime in the east is controlled principally by circulation of fluids in close contact with the thermal resource. Alternatively, the western-most fluid in the reservoir, representing recharge of cold groundwater and upwelling recirculated thermal water, could be most affected by addition of radiogenic ^4He. In this case the recent (1986) discrepancies between Hot Creek and other adjacent monitoring sites, as best exemplified by the decrease in R/R_a at Hot Creek in January whilst ratios increase at all the other sites, would seem to indicate that a prominent hydraulic discontinuity exists between the shallow hydrothermal system at Hot Creek and others in the caldera.

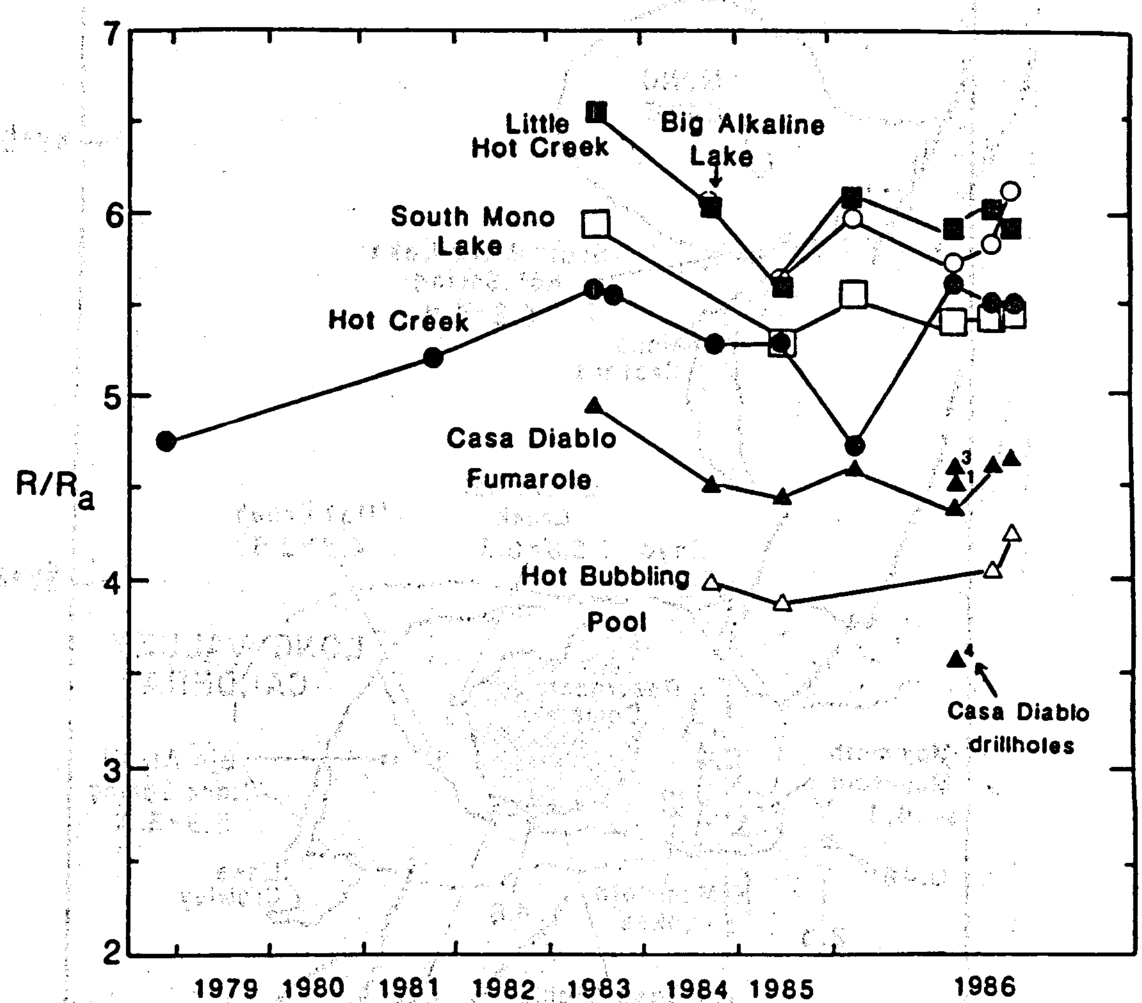

Figure 1. Temporal variations in R/R_a for long-term monitoring sites at Long Valley caldera.

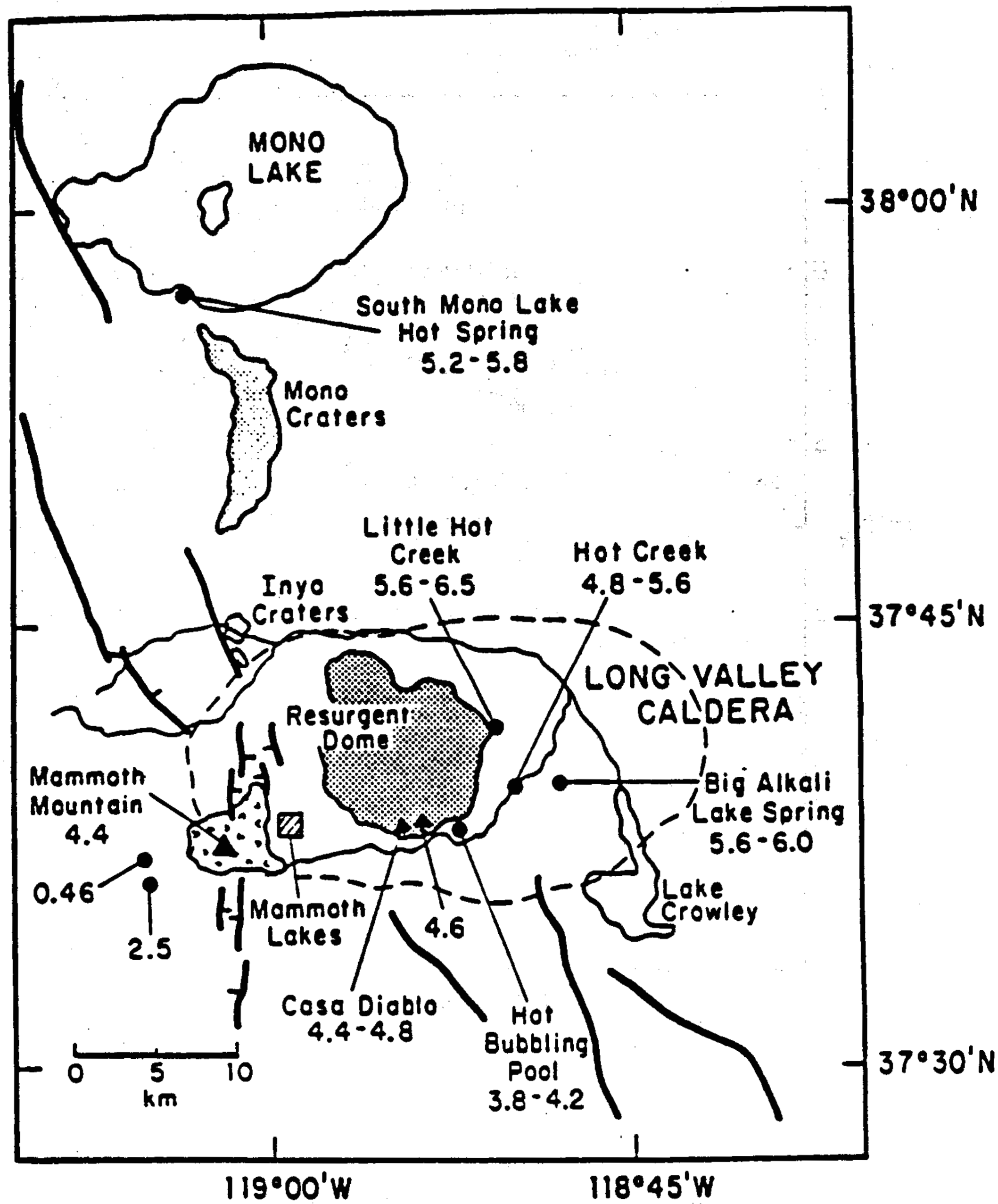

Figure 2. Sample locations and helium isotope ratios (as R/R_A) of hot springs (●) and fumaroles (▲) in the Long Valley caldera.

GAS MONITORING AT LONG VALLEY - STATUS REPORT

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ABSTRACT

During August and September, 1985, a field study was conducted in the Casa Diablo area of Long Valley caldera consisting of several experiments designed to test the USGS hydrogen sensor and its method of deployment, to verify sensor readings by independent analytical means, and to determine the effect of structure, fumaroles, weather, and changes in geothermal activity on hydrogen degassing.

At the start of the field study, the Long Valley hydrogen monitoring network at Casa Diablo consisted of three gas sensors deployed in a small boiling temperature fumarole in the upper clay pit area. Ten additional sensors were deployed on or near the keystone graben fault along which the clay pits (altered areas) are aligned. Some of the sensors were located directly in the fault zone while others were located some distance away to test whether degassing patterns are influenced by fault structure. Data collected at 10 minute intervals over the term of the field study indicate that sensors deployed adjacent to the fault show essentially no variation, while sensors deployed in the middle of the fault zone have a well developed diurnal cycle and show interesting variations probably related to activity in the caldera or other parameters.

A weather station consisting of sensors for wind direction, wind speed, air temperature, relative humidity, barometric pressure, and rainfall and an L-4 seismometer with portacorder were also deployed in the Casa Diablo area for the term of the study. A definitive analysis of the gas emission variations recorded from the gas sensors and comparison with the other recorded parameters is not yet complete.

Another portion of the field study was designed to field check the performance of the USGS hydrogen sensors located in fumaroles by an independent method such as gas chromatography. Accordingly, an experiment was set up to sample one of the monitored fumaroles every 3-4 hours for at least a 24-hour period. A 1.25 cm O.D. CPVC tube, perforated at the bottom end, was inserted into a fumarole in the upper clay pit area to facilitate sampling. Samples were drawn out through the tube into glass flow-through sampling bottles by a small pump. The samples were analyzed using a gas chromatograph constructed at the Cascades Volcano Observatory. This instrument is an ambient oven gas chromatograph that uses a multifunctional ten port valve. Gases of interest, such as hydrogen, can be separated from unwanted gases (O_2, N_2, H_2O, et.) on a pre-column. With a switch of the valve, the unwanted gases can be backflushed to a vent while the gases of interest can be separated on the analytical column under an argon carrier. The sensitivity of the instrument is at the low ppm level for the gases of interest.

The results of the 24-hour experiment for the monitored fumarole plus two other fumaroles are shown in Figure 1. Hydrogen concentrations in all three fumaroles decreased to minimum values inn the late evening hours (local time) and later increased back to higher, more normal, levels. This agrees closely with the diurnal pattern seen by the USGS gas sensors and suggests that this pattern is real and not due to outside meteorological or other influences on the sensor. While the data must be considered tentative, they suggest that fumarole degassing is not constant and may follow a diurnal pattern. This has important ramifications for those who sample and analyze fumarole gases.

In order to answer the question of how the flux of hydrogen might vary in areas such as fault zones or thermal areas, several surveys of soil gas hydrogen were made across the Casa Diablo area. For each soil gas survey sample, a 1.25 cm O.D. CPVC tube, perforated at the bottom was driven into the ground to a depth of 0.6 m and capped with a rubber septum. Approximately one day later, a sample was withdrawn from the tube by syringe and analyzed with the gas chromatograph described above. Since neon was readily detectable in nearly all of the samples, the hydrogen values were normalized to neon by calculating the H_2/Ne ratio to eliminate any variation in the results due to drift or changes in instrument sensitivity. A plot of the H_2/Ne ratio versus the distance along the traverse shows a dramatic spike in the area of the keystone graben fault. Equally interesting are minima on both sides of the spike. These results seem to show that degassing, as reflected in the soil gas, can vary considerably across structural features.

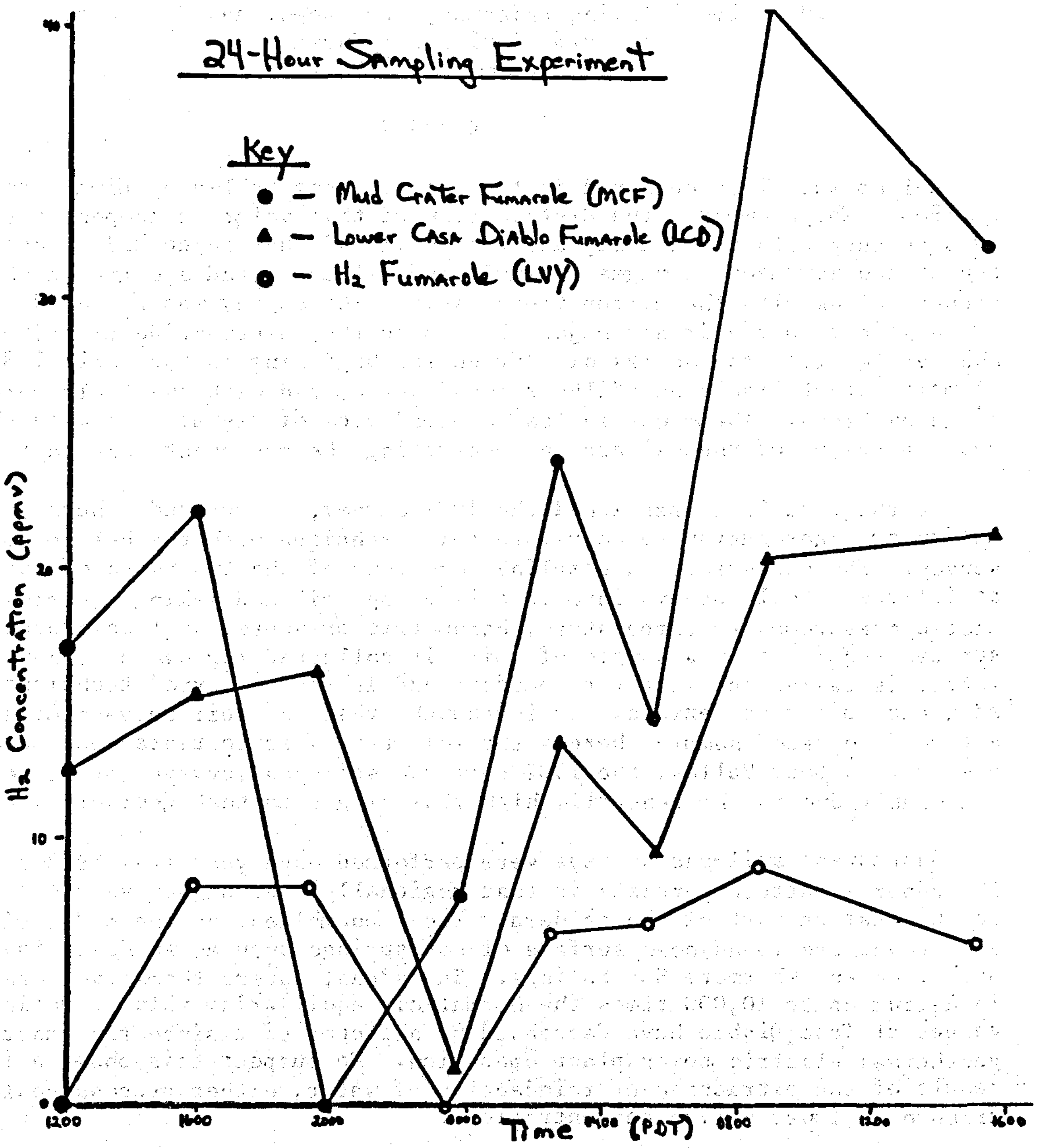

Figure 1. Variations in hydrogen concentration in fumarolic gas from three vents at Casa Diablo during a 24-hour period in the summer of 1985.

HELIUM-4 MEASUREMENTS IN LONG VALLEY

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ABSTRACT

Helium was first measured in the soil at Long Valley by Hinkle and Kilburn in 1980. They compared the distribution of this volatile component to the 1975 mercury data of Varekamp and Buseck (1984) that suggested changes in the subsurface movement of magma. Hinkle and Kilburn noted a correlation of higher helium with the Hilton Creek fault. The survey was repeated in 1982 by Green (1984) to see if any major changes in the caldera-wide distribution were observable after the series of earthquakes beginning in the early 1980's. The anomalies that Hinkle and Kilburn found associated with the fault were not found by Green. There was instead a broad area of higher helium in the western region of the caldera and encircling the resurgent dome on the north.

At the time Green performed the 1982 survey, Reimer and others performed a helium soil-gas survey to correlate this technique with the helium soil survey. The difference in sampling technique of the two types of surveys is as follows: Soil surveys involve collecting soil and making a series of associated measurements--temperature, barometric pressure, soil moisture; soil-gas surveys require only a sample of soil air collected through a probe. The latter is easier and faster to perform and is the preferred technique when adequate soil cover exists. It is thought that the soil surveys might provide a time integrated sample whereas the soil-gas is an instantaneous measurement. However, in Long Valley, the 1982 soil and soil-gas surveys correlated well, presumably due to the generally high flux of gas in that geologic setting.

Subsequent soil-gas surveys were performed each year from 1983 to 1986. The general pattern persists in that regionally, the higher values are found in the western part of the caldera. Local anomalies, on the order of 100 times background are found near surface of hot springs such as at Casa Diablo, Little Hot Creek and Whitmore Hot Springs. The actual waters themselves are elevated in helium up to 10,000 times the normal air equilibrium value. Helium soil-gas values at Casa Diablo have decreased by a factor of 2 since the startup of the geothermal-electric power plant operation. We suspect this observation is a result of the extraction or reinjection of water, either process could contribute to lower helium concentrations.

In 1985, an automatic helium analyzer was established at the Mammoth-June Lakes airport to measure the helium concentration in the well supplying the airport. It seemed that this aquifer was the same supplying the springs at the southern end of the Fish Hatchery, the one being monitored for radon by Harold Wollenberg of Lawrence Berkeley Laboratories. Originally, we had planned to use the same spring system for a helium/radon comparison but the helium content at the spring outlet was much less than that from the well (6 ppm compared to 10 ppm). We suspect that near the spring outlet, there is a highly fractured or permeable zone that permits degassing of the helium.

The sample for the automatic analyzer is obtained from the pipe that runs from the well to the holding tank. It flows continuously at about 0.5 l/min.

into a surplus 6 x 6 military van containing the analytical instrumentation. The water is passed through an atomizing shower head in a sealed vessel that permits degassing of the water. Analyses are performed once an hour by pumping some headspace gas from the vessel to a small mass spectrometer. Data is logged on a strip chart recorder and sent to Denver periodically by employees of the airport. There were problems with freezing the inlet and drain lines during the winter and spring of 1985/1986. No data were obtained for a 3 month period from April to July 15, 1986. Then the data showed an increase in helium from about 10 to 14 ppm. It has remained higher through the time of this report (November 1986) and was not affected by the Bishop earthquake of July 31 (M=5.8). We suspect the helium variation may be seasonal and an effect of ground water recharge.

It is hoped that the monitoring efforts of helium will reveal changes in subsurface conditions related to magma movements. A correlation of that nature was found by Lombardi and others (1984) in the Phlegraean Fields (Pozzuoli), Italy. Monitoring of helium will continue at Long Valley to examine correlation to earthquakes, uplift and magma movement.

SUMMARY OF ABSTRACTS

Abstracts and oral presentations at the workshop fall into two general categories - those dealing primarily with delineation of the hydrothermal system and those dealing primarily with changes in the system. Some studies have elements of both categories. Brief summaries are given below of the information contained in the abstracts and presented at the workshop.

System Delineation

Considerable progress has been made since the time of the first workshop in obtaining data on the hydrologic, thermal, and chemical characteristics of the hydrothermal system in Long Valley caldera. Useful information has come from well drilling and related borehole measurements (Sorey, this volume; Wollenberg et al, this volume), age determinations on fossil sinter deposits (Sturchio et al., this volume), additional measurements of helium and carbon isotopes in thermal fluids (Hilton et al., this volume; Winnett and Janik, this volume), and chemical analyses of well waters at Casa Diablo (Farrar, this volume). Reinterpretations of observed ion ratios and stable isotope concentrations have indicated a significant component of water derived from metamorphic basement rocks in shallow thermal fluids (Shigeno, this volume) and delineated plausible mechanisms boiling and mixing processes to account for variations in chemical characteristics of spring and well waters within the caldera (Shivenell et al., this volume). Revised estimates of maximum reservoir temperatures in the Long Valley system, based on fluid samples from wells at Casa Diablo, are near 220°C.

Questions remain as to the extent and distribution of possible magmatic volatile inputs to thermal fluids. For example, values of $^3He/^4He$ for thermal springs and fumaroles, which are relatively high and increase from west to east across the caldera, can be interpreted as resulting from input of magmatic helium from the Long Valley magma chamber beneath the resurgent dome. Alternatively, ^3He could be derived primarily from magma beneath the west moat and be added to water that is high in crustal helium (^4He) by virtue of its association with granitic basement rocks in that area. The observed increase in $^3He/^4He$ as fluid moves eastward in shallower reservoirs could then be accounted for by dilution with more locally derived waters low in ^4He. Similarly, inferences of a magmatic source for CO_2 in Long Valley fluids (Taylor and Gerlach, 1984), based on measurements of $\delta^{13}C$ in CO_2 gas must also be qualified by observations of areal and transient variability in this parameter (Winnett and Janik, this volume) and by the similarity of $\delta^{13}C$ values in Paleozoic carbonate rocks surrounding the caldera (Sorey et al., 1984).

In the opinion of the editors, the information available at this time favors a conceptual model for the present-day hydrothermal system involving recharge and heating of thermal fluids beneath the western or southwestern moat areas, within reservoirs located partly or wholly in metamorphic and granitic rocks forming the pre-caldera basement. Upflow of this heated source fluid into laterally extensive permeable zones within and above the Bishop Tuff must occur west of the resurgent dome to account for observed temperature reversals and fluid production characteristics of existing wells. The primary heat source for such a system could be magma or recently crystallized intrusives associated with the Inyo volcanic chain, including the Mammoth Mountain area within which phreatic eruptions occurred 550-650 yr ago (Miller, 1986) and fumaroles and hot springs are currently active.

Monitoring

As with the 1984 workshop, results of hydrologic and geochemical monitoring in the Long Valley area reported at the 1986 workshop show only limited evidence of changes in the hydrothermal system that may be related to seismic or magmatic activity. Listed below are the types of changes of this nature observed between 1978 and 1986:

1. temporary, coseismic increases in hot-spring flow
2. increases in fumarolic discharge and ground temperatures along active faults
3. anomalous patterns of hydrogen discharge associated with seismic swarms
4. changes in Rn and Hg in soil gas
5. changes in $^3He/^4He$ ratios in springs and fumaroles.

With the possible exception of observed increases in $^3He/^4He$ between 1978 and 1983, such changes appear to be related more directly to seismically induced permeability changes within the hydrothermal system than to magmatic inputs of volatiles or heat. Helium isotope data from more frequent sampling in 1986 (Hilton et al., this volume) show more complicated patterns of temporal variability at all sites (including the Mono Lake site) than were indicated by the pre-1986 data reported by Rison et al. (1983) and Sorey et al. (1984).

More commonly, changes observed in the various monitoring programs reflect the effects of other factors such as seasonal variations in shallow groundwater recharge and discharge, barometric pressure, differences in analytical results between different laboratories, and physical changes around points of discharge. At Casa Diablo, changes in spring flow during 1985 and 1986 are related in part to variations in fluid production from wells supplying hot water to the Mammoth Pacific geothermal power plant (Clark, this volume).

Changes in fumarolic discharge, although difficult to quantify, have been observed in Long Valley and could prove useful in assessments of renewed crustal unrest in the future. Sorey and Rojstaczer (this volume) discuss temperature data continuously recorded at steam vent BF (Basalt Fumarole) located 1.5 km west of Casa Diablo. The inverse correlation of vent temperature with barometric pressure indicates that variations in vent temperature are caused primarily by barometrically induced variations in steam discharge.

The usefulness of monitoring geochemical parameters for assessment of seismic or magmatic activity should be enhanced by the availability of wells for sampling thermal fluids. Interpretations of data from well samples are less influenced by complicating factors such as boiling and mixing in near-surface upflow conduits. Tradeoffs exist, however, in the choice of wells for sampling, in that wells not used for fluid production (e.g. the Shady Rest well) require bailing and downhole sampling equipment, while wells pumped for geothermal power production are relatively easy to sample but may be affected by production and associated fluid injection. No such effects have yet been observed in the wells sampled at Casa Diablo.

Of all the monitoring programs discussed at the workshop, the measurement of pressure (or water level) changes in wells offers perhaps the most direct indications of rock strain related to seismic or magmatic activity. Sorey and Rojstaczer (this volume) reported on continuously recorded measurements of fluid pressure in six wells in Long Valley. The response of fluid pressure to barometric pressure and to strains induced by earth tides allow some of these wells to be calibrated for use as strain meters, thus providing geophysical information similar to that obtained with the dilatometer at Reds Meadow. To date, only two wells (at Shady Rest and Lookout Mountain) have been found suitable for this purpose.

TARGETS FOR SCIENTIFIC DRILLING

The results from recent drilling in the west moat, the age of silicic volcanism along the Inyo volcanic chain, and soil gas surveys of helium and mercury concentrations support the concept that sources of hot water feeding thermal reservoirs encountered at Casa Diablo and to the east occur beneath the caldera's western moat. This implies further that the primary heat source for the present-day hydrothermal system lies beneath the west moat or along the southwestern caldera margin. Apparently, regions of deep fluid circulation that may have existed at depth under the resurgent dome during previous periods of hydrothermal activity are no longer sufficiently permeable or hot to allow significant fluid convection to occur (Sorey, 1985).

The details of fluid and heat flow within the west moat are not yet understood. For example, estimated source reservoir temperatures based on cation geothermometer calculations for waters pumped from the wells at Casa Diablo, which range from 190° to 224°C, and waters sampled from the Shady Rest well (Wollenberg, et al., 1987) suggest that maximum fluid temperatures within the hydrothermal system may not be significantly higher than those encountered in Unocal's 44-16 well (218°C). On the other hand, other chemical characteristics of hot water from the Long Valley system and temperature measurements in 44-16, which show a reversal below the zone of maximum temperatures in the Bishop Tuff, argue for a source reservoir in metamorphic basement rocks somewhere else than at the 44-16 location.

Adequate delineation of the hydrothermal system beneath the west moat could come from additional scientific drilling and from interpretations of extensive geophysical and geological studies conducted by Unocal in this area. Comments by a Unocal representative at the workshop indicated that the latter information could be made publically available. Consequently, workshop participants discussed targets and locations for future drill holes. The primary goals of this drilling would be to identify areas of maximum reservoir temperature, zones of hot-water upflow, and the location and nature of heat sources for the present-day system. A secondary goal would be to better define the depth, temperature, and areal extent of hot-water reservoirs that may underly the Mammoth Lakes region and provide an energy source for local residents. Four areas were considered favorable for these purposes (Figure 1).

Target area (1) is the existing Shady Rest drill site, where projected temperatures within the ∿1000-foot section of Bishop Tuff penetrated by the core hole are near 200°C and show little evidence of cooling with depth. This suggests that a zone of upflow of hotter water may exist in the immediate vicinity. Alternatively, a high conductive temperature gradient may occur at depths below 2,400 ft, indicative of a shallow magmatic heat source. Completion of a second well at this site to reach Sierran basement rock would allow these possibilities to be investigated.

Target area (2) is the Mammoth Lakes Community Center at the west end of town. Information gained by drilling in this area could be used to delineate the areal extent of high-temperature reservoirs within and adjacent to Mammoth Lakes and at the same time would indicate the possible role of shallow magma beneath Mammoth Mountain as a heat source for the hydrothermal system.

Financial support from the California State Energy Commission may be available for drilling in area (2) through their grant program for local development of geothermal resources.

Target area (3) is the eastern flank of Mammoth Mountain, near Warming Hut 2. This site represents a compromise of factors associated with drilling on Mammoth Mountain, including difficulties of access and elevation. Its location permits detection of a shallow magmatic heat source beneath the mountain and evaluation of the role of north-south trending faults and fractures along the Inyo volcanic chain as conduits for lateral flow of heated water. While the temperature reversal below the Bishop Tuff in Unocal's 44-16 argues against hot water flowing upward along this fault system from the west, it does not rule out the possibility of northward fluid flow along these conduits into the caldera from Mammoth Mountain.

Target area (4) is on the 100,000 year-old moat rhyolite referred to as the Knolls. The rationale for drilling on the Knolls is based in part on locations selected by Unocal for future geothermal wells within their lease holdings. Although Unocal's exploration strategy was not discussed at the workshop, it is clear that well sites in this area were selected on the bases of results from 44-16 and geophysical and geologic surveys conducted by Unocal. Favorable indications for drilling in area (4) include proximity to the intracaldera extension of the Hartley Spring fault and the age and volume of silicic volcanic rocks in the area. The high thermal gradient in the lower portion of well PLV-1 on the Knolls (Farrar et al., 1985; Benoit, 1984) suggests a high-temperature reservoir beneath this area.

It is anticipated that core drilling to depths of 4,000-5,000 ft would be required to meet the stated goals, although adequate delineation of the characteristics of the primary heat source may eventually require deeper, more extensive drilling. Ideally, drill-hole information from each of the target areas, combined with data available for other parts of the caldera, would yield a reasonably complete picture of the present-day hydrothermal system. Workshop participants agreed, however, that criteria should be established to enable drilling targets to be prioritized and that a more detailed drilling proposal should be developed in the near future.

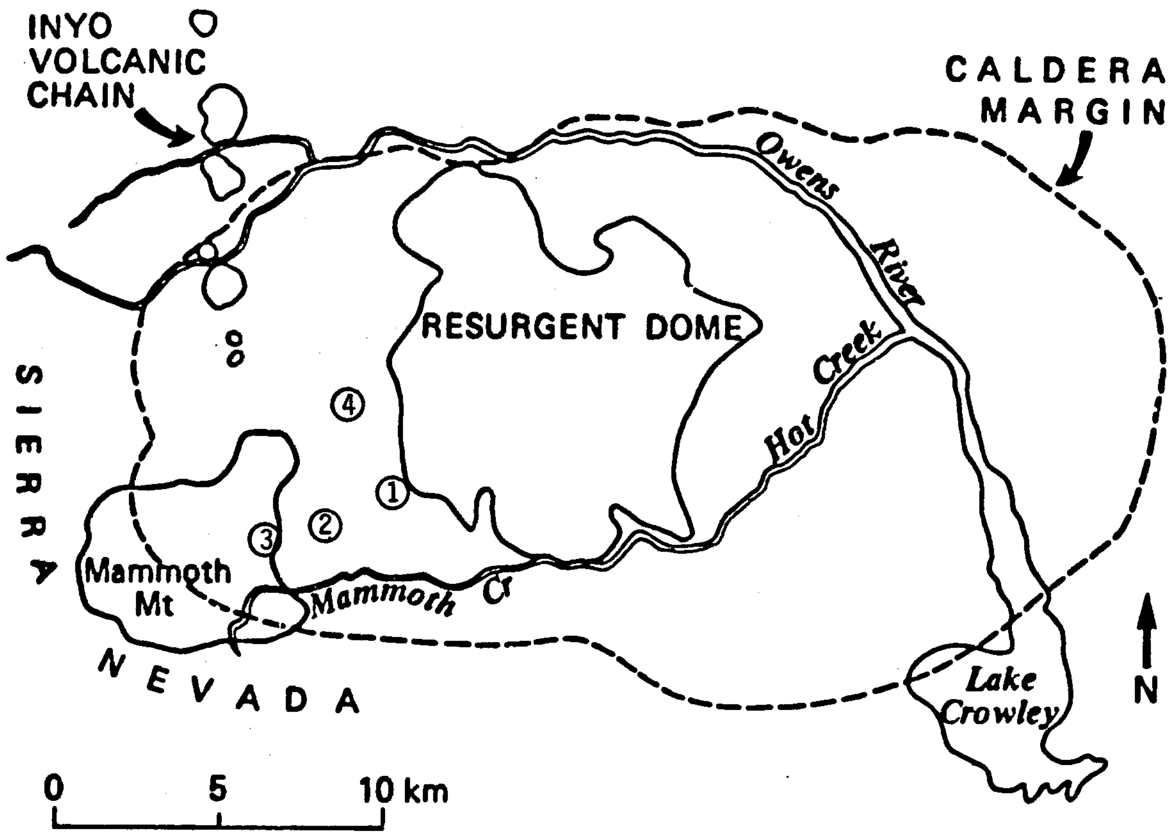

Figure 1. Target areas for future scientific drilling to identify areas of maximum reservoir temperature, zones of hot-water upflow, and the characteristics of the primary heat source for the present-day hydrothermal system in Long Valley caldera.

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APPENDIX A:

AGENDA

SECOND WORKSHOP ON MONITORING THE HYDROTHERMAL SYSTEM IN LONG VALLEY CALDERA

15-17 July, 1986
Mammoth Lakes, California

Tuesday, 15 July

8:30 - 8:45 — Assemble in meeting room at Fire Station

8:45 - 9:00 — Introductory Remarks
- M. Sorey

9:00 - 12:00 — Geologic, Geophysical, and Hydrologic Studies

Presentations:
- N. Goldstein - Pre-drilling data review
- R. Bailey - Volcanic geology
- M. Sorey - Hydrothermal system and geothermal developments
- H. Wollenberg - Shady Rest drill hole results
- C. Carrigan - Cooling rates for intrusive heat sources
- N. Sturchio - Age determinations on sinters

12:00 -1:00 — Lunch

1:00 - 5:00 — Hot-spring flow and chemistry and ground-water levels

Presentations:
- C. Farrar - Fluid chemistry and spring discharge
- M. Clark - Casa Diablo springs, Little Hot Creek springs
- M. Sorey - Ground-water levels, fumarolic temperatures
- H. Shigeno - B/Cl ratios in spring waters
- B. Simpson - Spring monitoring in Rotorua, New Zealand
- F. Goff - Mixing and boiling in thermal fluids
- A. White - Isotopic and chemical compositions of waters

Wednesday, 16 July

8:30 - 12:00 — Gas Emissions

Presentations:
- C. Janik - Gas chemistry
- T. Winnett - Carbon-13 monitoring
- D. Hilton - Helium-3 monitoring
- R. Oremland - Methane discharge in Mono Lake
- S. Flexser - Radon discharge at the Fish Hatchery springs
- J. Bean - Helium in soil gas and ground water
- C. Veltri - Radon monitoring at Phlegrean Fields caldera

Wednesday, 16 July, continued

12:00 - 1:00	Lunch
1:00 - 5:00	Targets for Scientific Drilling General discussion

Thursday, 17 July

7:00 - 12:00	Field trip above Convict Lake to view roof pendant rocks

APPENDIX B:

Participants

Name	Affiliation
Roy Bailey	U.S. Geological Survey, Menlo Park, CA
Josh Bean	U.S. Geological Survey, Denver, CO
Chuck Carrigan	Sandia National Laboratory, Albuquerque, NM
Mark Clark	U.S. Forest Service, Mammoth Lakes, CA
Chris Farrar	U.S. Geological Survey, Santa Rosa, CA
Steve Flexser	Lawrence Berkeley Laboratory, Berkeley, CA
Fraser Goff	Los Alamos National Laboratory, Los Alamos, NM
Norm Goldstein	Lawrence Berkeley Laboratory, Berkeley, CA
Dave Hilton	Scripps Institute of Oceanography, La Jolla, CA
Cathy Janik	U.S. Geological Survey, Menlo Park, CA
Terry Keith	U.S. Geological Survey, Menlo Park, CA
Ken McGee	U.S. Geological Survey, Vancouver, WA
Larry Miller	U.S. Geological Survey, Menlo Park, CA
Ron Oremland	U.S. Geological Survey, Menlo Park, CA
Bob Poreda	Scripps Institute of Oceanography, La Jolla, CA
Mike Reimer	U.S. Geological Survey, Denver, CO
Hiroshi Shigeno	Japanese Geological Survey
Lisa Shevenell	Los Alamos National Laboratory, Los Alamos, NM
Barbara Simpson	New Zealand Geological Survey
Mike Sorey	U.S. Geological Survey, Menlo Park, CA
Neil Sturchio	Argonne National Laboratory, Argonne, IL
Jeff Sutton	U.S. Geological Survey, Vancouver, WA
Alfred Truesdell	U.S. Geological Survey, Menlo Park, CA

Cornelia Veltri	Universita di Napoli, Italy
Art White	Lawrence Berkeley Laboratory, Berkeley, CA
Terry Winnett	U.S. Geological Survey, Menlo Park, CA
Harold Wollenberg	Lawrence Berkeley Laboratory, Berkeley, CA