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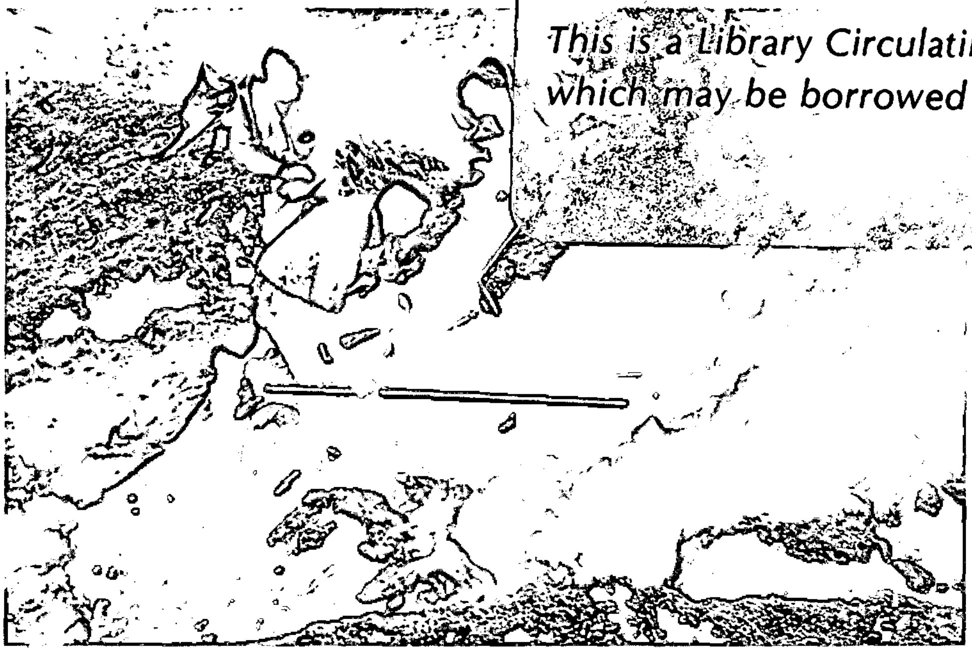
Proceedings of the Workshop on Hydrologic and Geochemical Monitoring in The Long Valley Caldera

Mammoth Lakes, California
October 8–10, 1984

October 1984



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LBL-20020

Proceedings
of the

WORKSHOP ON HYDROLOGIC AND GEOCHEMICAL MONITORING IN THE LONG VALLEY CALDERA

October 8–10, 1984
Mammoth Lakes, California

Editors

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COVER PHOTO - Sampling for $^3He/^4He$ at Casa Diablo Hot Springs during Workshop field trip, 9 October 1984. Photo taken by Michael Sorey.

INTRODUCTION

A workshop was hosted by the U.S. Geological Survey and the Earth Sciences Division of the Lawrence Berkeley Laboratory on October 8–10, 1984 to review the results of hydrologic and geochemical monitoring 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 workshop, which included two days of oral presentations and discussions and a one-day field trip, 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. Workshop participants also discussed the need to instrument sites for continuous measurements of several parameters and to obtain additional hydrologic and chemical information from intermediate and deep drill holes.

Detailed studies of the hydrothermal system in Long Valley were initiated in 1972 by the U.S. Geological Survey in order to assess the potential for geothermal energy development (Muffler and Williams, 1976). Parts of the caldera were opened to competitive leasing in 1976 and to date approximately 20 exploratory wells have been drilled by private developers. A 7.5 MW geothermal plant is currently in operation at Casa Diablo Hot Springs.

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 U.S., the Long Valley caldera has 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. 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. A workshop on geophysical modeling of Long Valley caldera was held in Berkeley in February 1984, the proceedings of which are described by Goldstein (1984).

In addition to seismic and deformation monitoring, programs are currently in progress to monitor changes in the discharge characteristics of hot springs, fumaroles, and soil gases, as well as pressures and temperatures in wells. Some hydrochemical parameters are measured continuously, others are measured monthly or at longer intervals. The various parameters being monitored are listed below along with the principal investigator involved in the measurements. A list of workshop participants is included in Appendix B.

This report summarizes the information presented at the hydrologic monitoring workshop, following the workshop agenda which was divided into four sessions:

1) Overview of the Hydrothermal System
2) Monitoring Springs, Fumaroles, and Wells
3) Monitoring Gas Emissions
4) Conclusions and Recommendations

The authors are indebted to the workshop participants who freely shared their results and provided written summaries of their studies.

Parameter	Investigator (Affiliation)
Hot-spring discharge and chemistry	Farrar, Sorey, Mariner (USGS) White (LBL), Clark (USFS), Valette-Silver (Carnegie)
Gas chemistry and ^{13}C	Janik, Mariner (USGS) Gerlach (Sandia), Taylor (UBC) Rison (N.M. Tech)
Helium isotopes ($^3He/^4He$)	Rison (N.M. Tech), Kennedy (UCB)
Water isotopes (^{18}O, D)	Farrar, Sorey, Janik, Mariner (USGS) White (LBL)
Hydrogen gas	McGee, Sutton (USGS)
Radon gas in springs	Wollenberg, Flexser (LBL)
Soil gas (helium)	Reimer (USGS)
Soil gases (radon, mercury)	Williams (Louisiana St. U.) Verekamp (Wesleyan U.) Buseck (Arizona St. U.)
Temperature profiles in wells	Sorey, Urban, Diment (USGS)
Pressures in wells	Rojstaczer, Farrar, Sorey (USGS) Clark (USFS)

OVERVIEW OF THE HYDROTHERMAL SYSTEM

Formation of the Long Valley caldera, a 450 km^2 elliptical depression in east-central California (Fig. 1), occurred 0.7 m.y. ago with eruption of 600 km^3 of rhyolite ash that formed the Bishop Tuff (Bailey et al., 1976). Subsequent volcanic activity produced lavas and pyroclastic rocks of rhyolite to basaltic compositions and built a resurgent dome in the west-central part of the caldera. Streamflow runoff from the Sierra Nevada and glacial melt water filled the moat around the resurgent dome with Pleistocene Long Valley Lake that persisted at decreasing levels until complete drainage occurred sometime within the past 0.1 m.y. (Bailey et al., 1976). Intermittent volcanic activity has continued until as recently as 550–650 years ago (Miller, 1985) when intrusion of one or more silicic dikes produced three rhyolite domes and numerous phreatic explosion craters along the Inyo volcanic chain that intersects the northwest rim of the caldera.

Present-Day Hydrothermal System

Areas of present-day hydrothermal activity are distributed around the southern and southeastern sides of the resurgent dome and to the east of the intra-caldera extension of the Hilton Creek fault (Fig. 2). Hot springs and fumaroles discharge water at temperatures near or below the boiling point for the local land-surface altitude (93 ° C); no significant degree of superheat has been detected in any of the fumaroles. With the exception of weak fumaroles and warm springs on the flanks of Mammoth Mountain, no surficial hydrothermal activity occurs outside the topographic floor of the caldera.

Estimates of the rate of hot water flow through the hydrothermal system vary from 190 kg/s to 250 kg/s, depending on the assumed value for the chemical composition of the thermal component in the hot-spring waters (Sorey et al., 1978). The rate of natural heat discharge by convection and conduction amounts to 2.9×10^8W. This is equivalent to an average heat flux over the caldera floor of 630 mWm^{-2}. Comparison of these measures of the intensity of hydrothermal circulation and magmatic heating with values for other calderas (Table 1) indicates that the

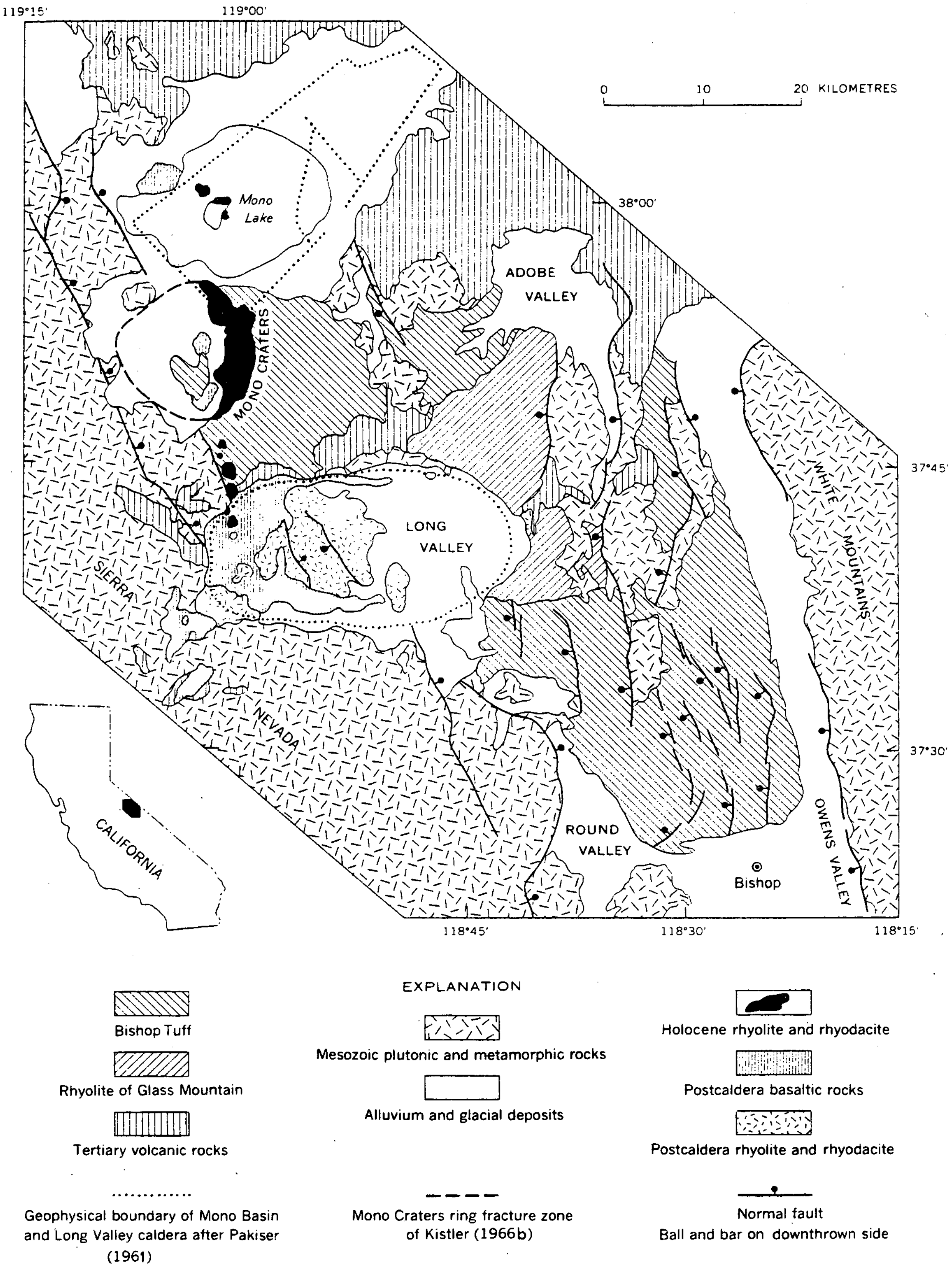


Figure 1. Index map and generalized geologic map of the Long Valley caldera-Mono basin area (from Bailey et al., 1976).

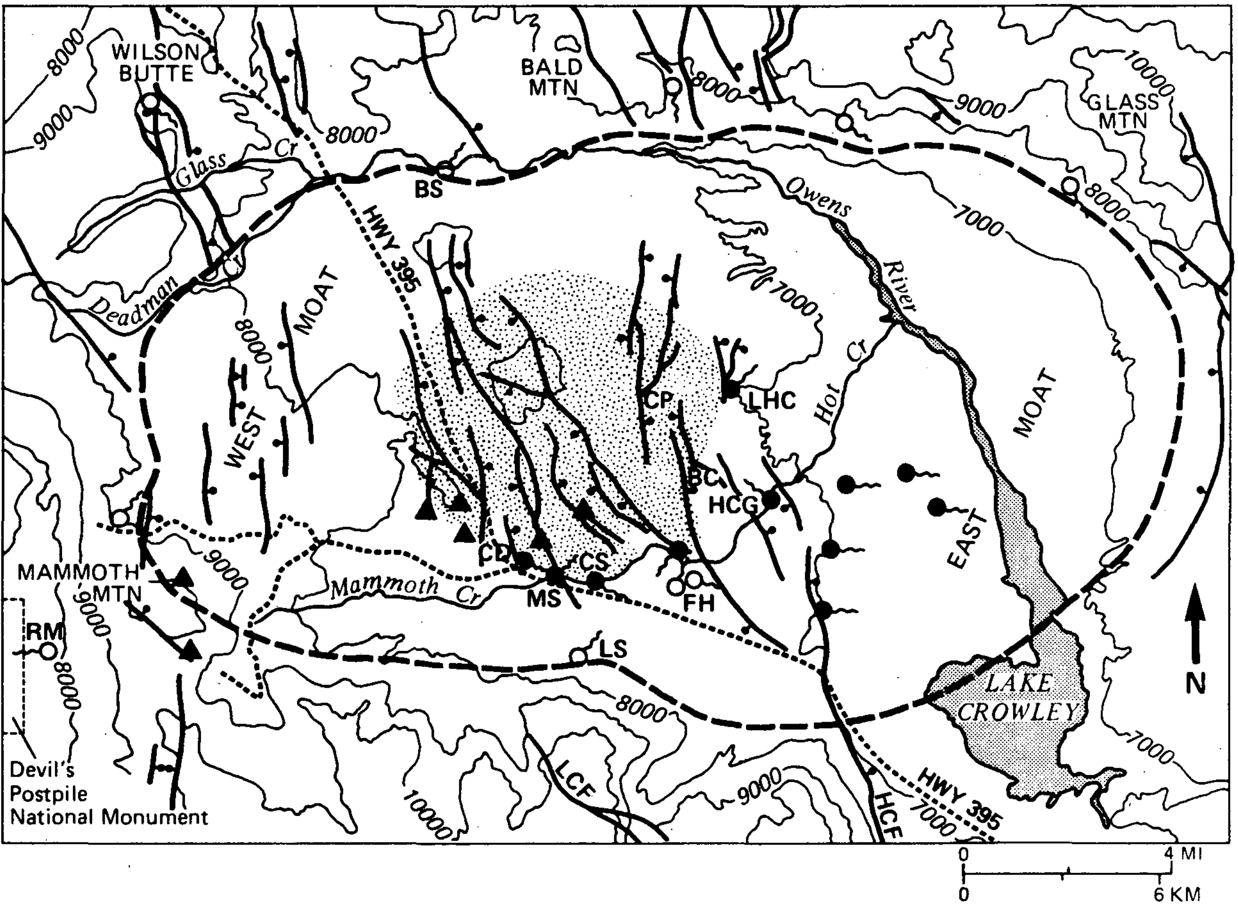


Figure 2. Map of Long Valley caldera (heavy dashed line) showing locations of active thermal springs (filled circles with tails), nonthermal springs (open circles with tails), fumaroles (triangles), and areas of fossil hydrothermal alteration noted in text (CP = Clay Pit, BC = Blue Chert). Also shown are principal faults as mapped by Bailey and Koeppen (1977) (HCF = Hilton Creek Fault, LCF = Laurel-Convict Fault), contours of land-surface altitude (in feet), paved roads (dotted lines), and the structural outline of the resurgent dome (patterned area). Springs referred to in text and tables are labeled RM (Reds Meadow Hot Springs), CD (Casa Diablo Hot Springs), MS (Meadow Spring), CS (Colton Spring), HCG (Hot Creek Gorge Springs), LHC (Little Hot Creek Springs), LS (Laurel Spring), BS (Big Spring), and FH (Fish Hatchery Springs).

Table 1. Comparisons of different measures of the intensity of hydrothermal activity at several young silicic calderas.

Caldera (age)	Fluid discharge[1] kg/s	Heat discharge[2] 10^8 W	Heat flux[3] mWm^{-2}
Yellowstone[4] (0.6 m.y.)	3,000	42	2100
Long Valley[5] (0.7 m.y.)	250	2.9	630
Valles[6] (1.1 m.y.)	35	0.75	500

[1] Discharge of high-chloride thermal water in hot springs and river seepage.

[2] For Yellowstone caldera, heat discharge represents convective heat flow in deep reservoirs from which thermal water discharges at the land surface within part of the caldera draining east of the Continental Divide. For Long Valley caldera, heat discharge represents the surficial discharge of heat by conduction and convection within the caldera area. For Valles caldera, heat discharge represents the sum of conductive and convective heat flow within the caldera and convective heat flow in subsurface outflow of thermal water that discharges in springs and river seepage outside the caldera.

[3] Calculated as heat discharge divided by caldera area (2,023 km for Yellowstone, 450 km for Long Valley, and 150 km for Valles).

[4] Data from Fournier, White, and Truesdell (1976).

[5] Data from Sorey, Lewis, and Olmsted (1978).

[6] Data from Faust et al. (1984) and Goff and Sayer (1980).

present-day Long Valley system is intermediate between the Yellowstone caldera (most intense) and the Valles caldera (least intense).

Calculations based on chemical geothermometers applied to hot-spring waters indicate that fluid reservoirs exists at depth at temperatures exceeding 200 ° C (Sorey et al., 1978). Although no such reservoirs have yet been encountered in drill holes as deep as 2,100 m, temperature measurements in wells do show indirect evidence of high-temperature zones within the Bishop Tuff beneath the west moat and direct evidence of temperatures of 150 °-175 ° C within reservoirs in and above the Bishop Tuff beneath the Casa Diablo area (Fig. 2). The available temperature data and data based on spring chemistry and isotopic content (deuterium and oxygen-18) are consistent with a conceptual model of the present-day hydrothermal system involving recharge around the west rim of the caldera and lateral flow of thermal water from west to east.

Temperature profiles in wells show evidence of such a circulation system at depths less than 1 km beneath the southern half of the caldera (Fig. 3–5). Notable features in the temperature profiles are the reversals in temperature gradient that are indicative of transient thermal regimes caused by lateral flows of hot water. Along or near section AA', one or more zones appear to transmit hot water laterally from Casa Diablo eastward at altitudes near that of Lake Crowley (2,070 m), as evidenced by temperature reversals at similar altitudes in wells along this section and similarities in the chemistry of waters from hot springs discharging along or near this section. Temperatures in these zones decrease from about 170 ° C under Casa Diablo (well Ml) to less than 70 ° C near Lake Crowley. The degree of hydrologic continuity within this shallow flow system cannot be evaluated without additional drilling and well testing. Hot springs and fumaroles located along or near this section appear to be fed from this shallow flow system by upflow along fault conduits.

Temperature profiles in wells west of Casa Diablo show no evidence of the thermal flow zone near 2,070 m altitude, although data are not yet available from several industry wells drilled in the west moat north of section AA'. A zone of high temperature gradient was measured in well Pl below a depth of 550 m; an extrapolated profile beneath this well would reach a temperature of

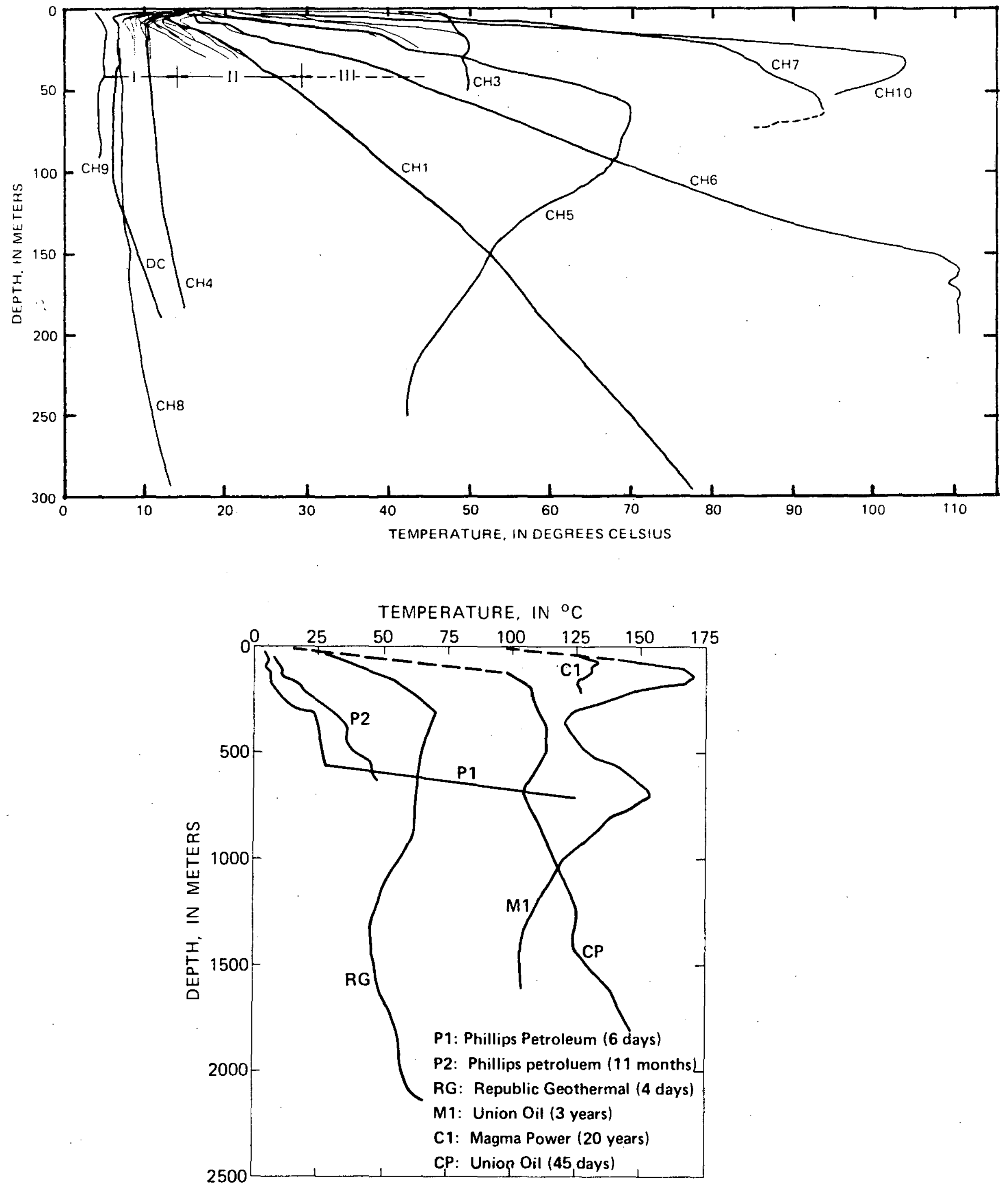


Figure 3. Temperature profiles in wells in the Long Valley caldera (from Sorey, 1984). Top graph includes profiles in coreholes (labeled CH and DC) and shallow water-level holes (unlabeled), and roman numerals indentifying groups of profiles associated with areas of ground-water recharge (I), Discharge (III), and conductive heat flow (II). Bottom graph includes profiles in deep wells drilled by private industry, with the time interval between well completion and temperature measurements shown in parentheses. Well locations shown in Figure 4.

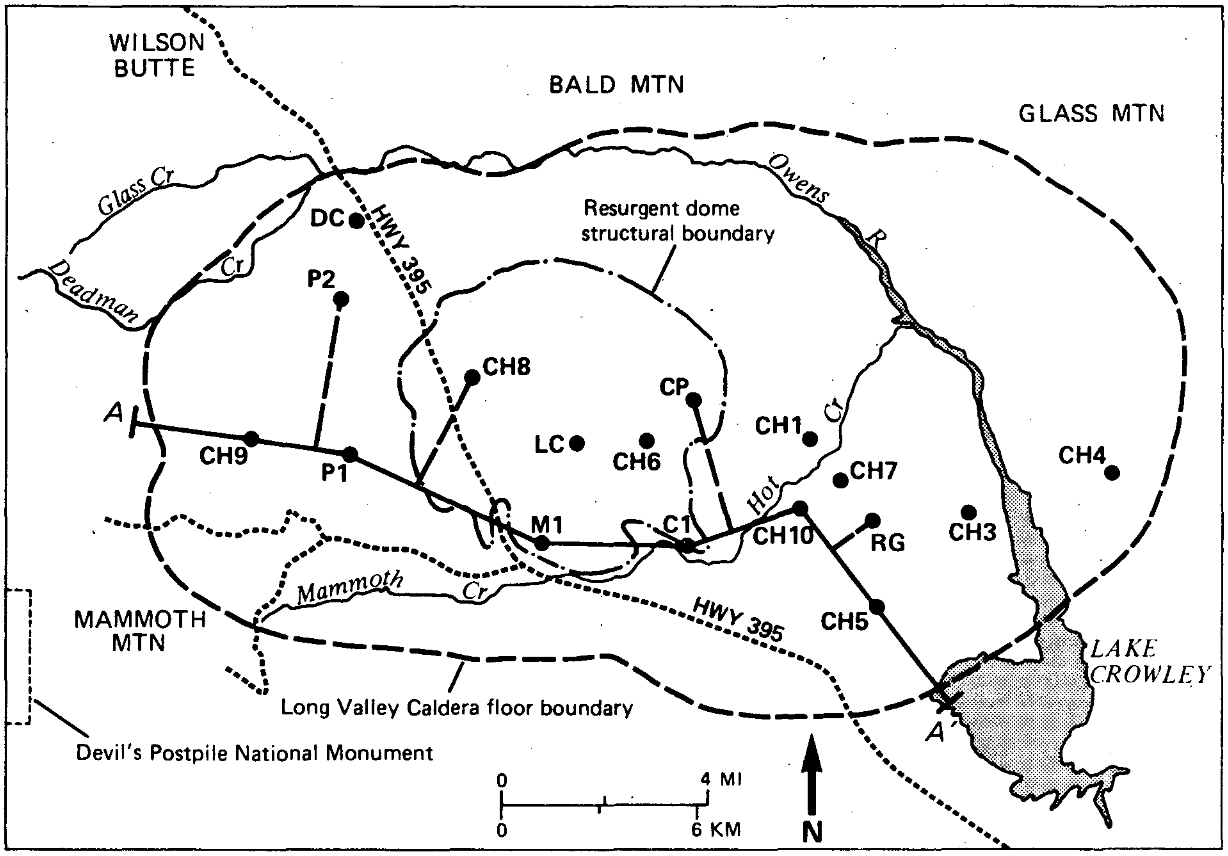


Figure 4. Map of Long Valley caldera showing locations of wells for which temperature profiles are plotted in Figure 3 and the position of Section AA' for which a conceptual model of fluid flow is depicted in Figure 5.

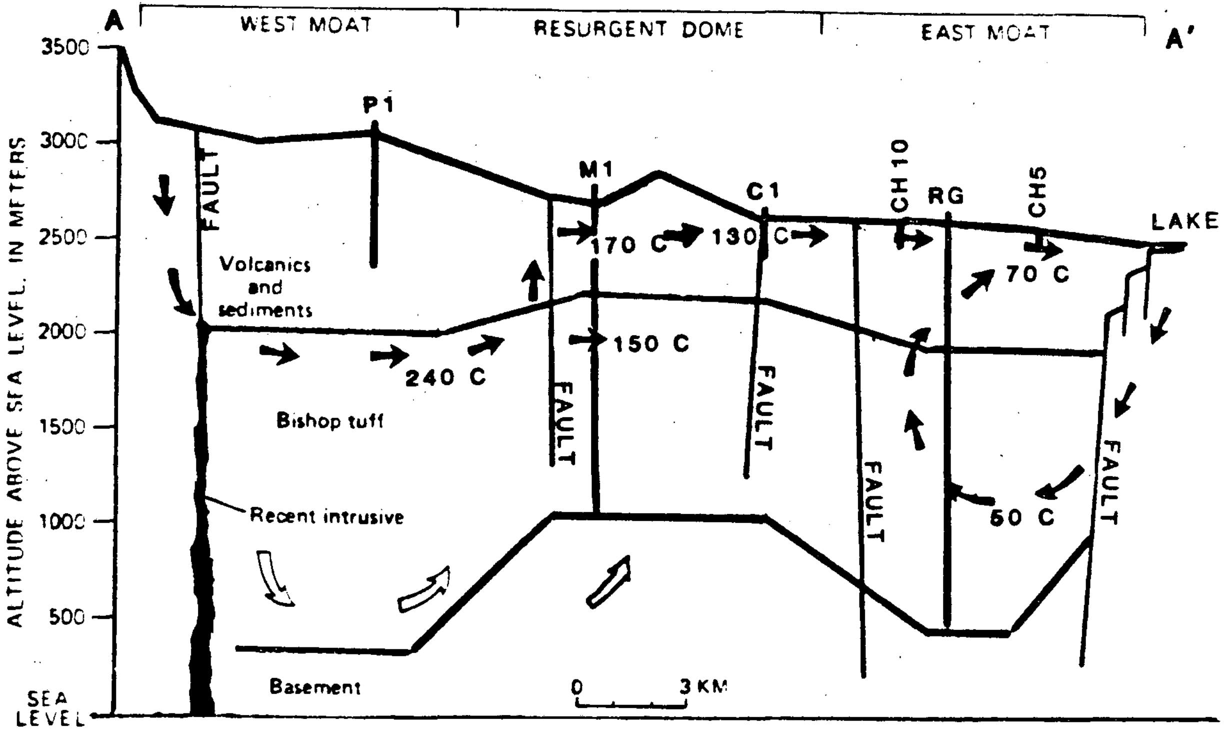


Figure 5. Conceptual model of flow in the present-day hydrothermal system along section AA' (location in Figure 4) in the southern half of the Long Valley caldera. Directions, depths, and temperatures of fluid flow inferred from temperature profiles in wells indicated by black arrows. Heat source for present-day system assumed to be recent dike intrusions beneath the west moat. Deeper circulation during previous periods of hydrothermal activity indicated by white arrows. Position of contacts at top and bottom of the Bishop Tuff are simplified approximations based on well data and seismic and gravity measurements.

240 ° C near the top of the Bishop Tuff, estimated from seismic and gravity data to lie at an altitude of 1520 m in this vicinity. This suggests that the source of hot water flowing at shallow depths beneath the Casa Diablo area and to east may be within the Bishop Tuff under the west moat. The occurrence of fumaroles and hot springs on the flanks of Mammoth Mountain (Fig. 2) may be related to the postulated hot-water reservoir beneath the west moat or may instead be associated with a more localized, shallow-rooted circulation system.

The inferred source reservoir may be in hydrologic communication with the deeper thermal flow zone delineated by the temperature reversal at a depth of 690 m (altitude 1590 m) in well Ml at Casa Diablo. A plausible model that fits the available temperature data involves eastward flow of hot water in the Bishop Tuff beneath the west moat to the general vicinity of the faults bounding the western edge of the resurgent dome (Sorey, 1984, 1985). As shown in Figure 5, a portion of this deeper flow moves up these faults and then flows eastward in the shallow flow zone toward Casa Diablo and around the southern side of the resurgent dome. Fumarolic discharge at several locations west of Casa Diablo (Fig. 2) may be related to such a zone of upflow. Continuity of flow in the deeper aquifer east of Casa Diablo cannot be delineated because of a lack of data from deep drill holes. If it extends within the Bishop Tuff under the resurgent dome, upflow from this zone may feed the springs near the head of Little Hot Creek (Fig. 2).

Temperatures measured in well RG in the east moat suggest lateral flow of thermal water at about 70 ° C above the Bishop Tuff and lateral flow of cooler water within the Bishop at altitudes near 800 m (1350 m depth). Because measured temperatures at this altitude are higher to the west, Blackwell (1984, 1985) proposes a model involving large-scale convection of groundwater westward within the Bishop Tuff and eastward in sediments and volcanics above the tuff. However, hydraulic-head differences based on water-table altitudes and stable isotope relationships are not consistent with such a deep flow system (Sorey et al., 1978). Instead, a separate convection system is postulated for the east moat with recharge along the ring fracture, most likely around the northeast rim, and upflow in the vicinity of the intra-caldera extension of the Hilton Creek Fault.

Analyses of the shapes of temperature profiles in wells that show gradient reversals suggests that fluid has circulated through the thermal reservoirs discussed above for less than about 3,100 years (Blackwell, 1984). If the heat source for this most recent period of activity is silicic intrusives beneath the west moat that solidify and cool from 800 ° C to 300 ° C, the rate of emplacement would need to be about 3 km^3/ 1000 yrs. Such intrusive activity has apparently taken place along the Inyo volcanic chain during the past 3,000 years (Miller, 1985).

Regions possibly containing silicic melt detected by shear-wave attentuation at depths of 4-5 km beneath the resurgent dome (Sanders, 1984) have probably not been in place long enough (60,000 yrs) to sensibly influence the overlying thermal regime within the upper 2 km of caldera fill. However, such shallow magma bodies could have contributed gases such as ^{13}C and ^{3}He to the hydrothermal system. The question of whether recent intrusions of magma that may have been associated with the uplift and seismicity detected since 1980 could contribute these gases rapidly enough to cause the isotopic changes in surficial gas discharges, as discussed later in this summary, received considerable debate among workshop participants.

Previous Hydrothermal Activity

Evidence of extensive periods of hydrothermal activity in Long Valley during the past 0.3 million years exists from areas of fossil alteration within the caldera and saline deposits that were contributed from hot springs in Long Valley to Searles Lake, located southeast of Long Valley along the Owens River system (Sorey, 1984). Extensive development of hydrothermal alteration in lacustrine deposits that are interbedded with the 0.28 m.y.-old Hot Creek rhyolite flow suggests that the hydrothermal system reached maximum development at about 0.3 m.y.B.P. (Bailey et al., 1976). At the adjacent Clay Pit and Blue Chert areas (labeled CP and BC in Fig. 2), evidence of intensive argillic alteration by acidic hot spring and fumarolic activity (CP) and siliceous sinter deposition (BC) are preserved at the land surface. At Searles Lake, saline deposits younger than 32,000 years contain borate, potassium, and sulfate-bearing minerals in quantities that could have been contributed by hot springs in Long Valley over the past 30,000–40,000 years, if present-day rates of spring discharge have persisted over that interval.

The heat input required from magmatic sources to sustain convective heat flow at present-day rates for periods of 30,000–40,000 years or longer could not reasonably be supplied by the cooling of shallow intrusives. Thus, the heat source for previous periods of hydrothermal activity must have been the Long Valley magma chamber or an adjacent magma chamber that may underlie the Inyo volcanic chain. Depths of fluid circulation during these periods must have been greater than at present, as pictured in Fig. 5. Limited temperature data from wells on the resurgent dome shows little evidence of the thermal regime associated with this deeper flow system and related zones of upflow, as discussed by Sorey (1984, 1985).

MONITORING SPRINGS, FUMAROLES, AND WELLS

Monitoring activities related to springs, fumaroles, and wells include: chemical and isotopic sampling of waters and gases, measurements of liquid flow rates and temperatures in wells. The latter activity was not discussed at the workshop but is described by Farrar et al (1985). Discussions of the other monitoring activities noted above are given here.

Locations of springs and fumaroles for which chemical and isotopic data are listed here are shown in Figure 6. Abbreviations used correspond with those used in Tables 2, 5, and 7. As noted previously, areas of surficial hydrothermal activity occur primarily around the southern and southeastern sides of the resurgent dome. Monitoring of changes in spring chemistry and flow rate has focused on the areas of greatest spring flow at Casa Diablo (CD), Hot Creek gorge (HCG), and Little Hot Creek (LHC). Detailed maps of each of these areas are shown in Figures 7-9.

Chemistry of Fluids

Several investigations of the chemical composition of fluids are being carried out in Long Valley. The scope and purpose of each investigation varies somewhat. Mariner has sampled water from springs and wells in Long Valley on several occasions since 1972. His studies have addressed the role of mixing and conductive cooling as controls on chemical composition and the use of chemical concentrations for geothermometry (Mariner and Willey, 1976). Farrar, Sorey, and Clark are involved in monitoring selected sites for changes in chemistry that may relate to magmatic processes (Farrar et al., 1985). White and Wollenberg are gathering chemical data to aid in defining the flow system for the purpose of siting deep scientific exploration holes. Valette-Silver has collected data from selected springs in Long Valley for comparison with spring chemistry at the Phlegrean Fields caldera in Italy. Gas chemistry from springs and fumaroles is the subject of individual studies by Janik, Gerlach, Mariner, and Rison.

In the Long Valley caldera ground water circulates within one or more shallow nonthermal aquifers underlain by a hydrothermal system that also contains multiple aquifers. Although geo-

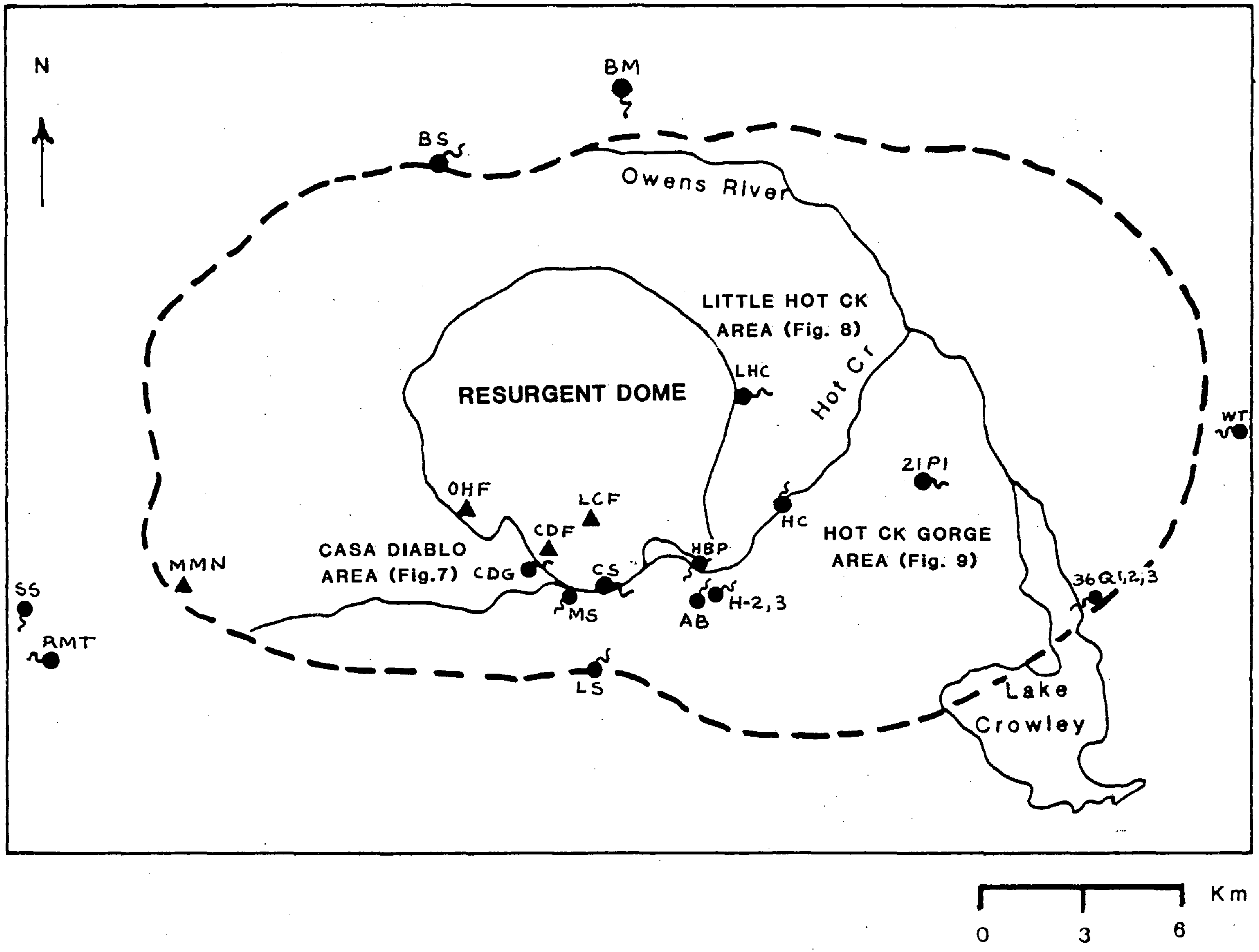


Figure 6. Map of Long Valley caldera showing locations of springs and fumaroles with chemical and/or isotopic analyses presented in this report.

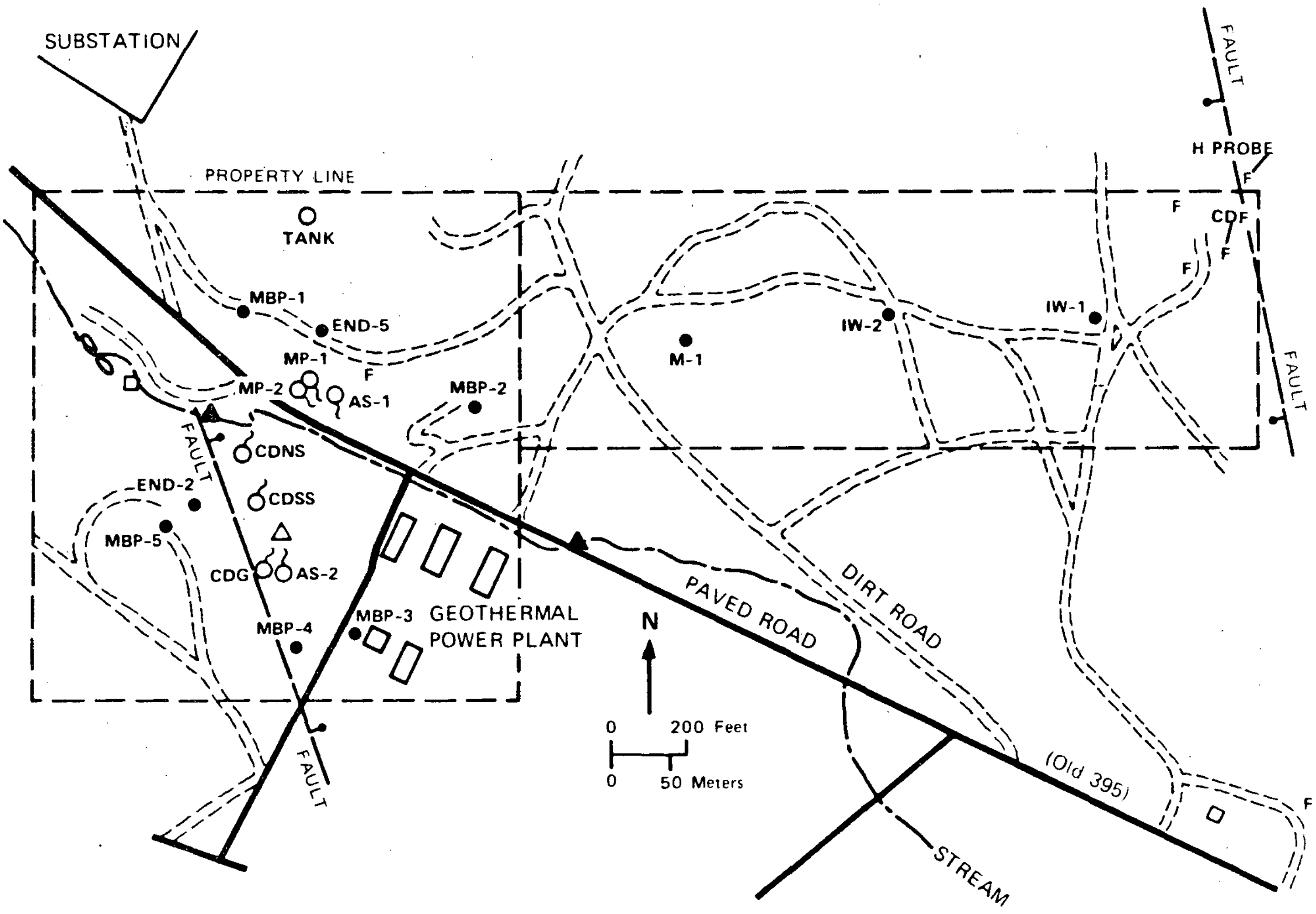


Figure 7. Map of the Casa Diablo area (T.3S., R.28E., sec.32) showing locations of hot springs (open circles with tails), fumaroles (F), and wells (filled circles) labeled with abbreviations as used in text and tables. The site where a flume and recorder were in place during part of 1984 to measure the flow of water from the geysers (CDG) is shown by an open triangle, sites where flumes were installed in 1985 to measure the total flow of hot springs shown by filled triangles. Locations based on maps provided by the Ben Holt Company, Pasadena, California.

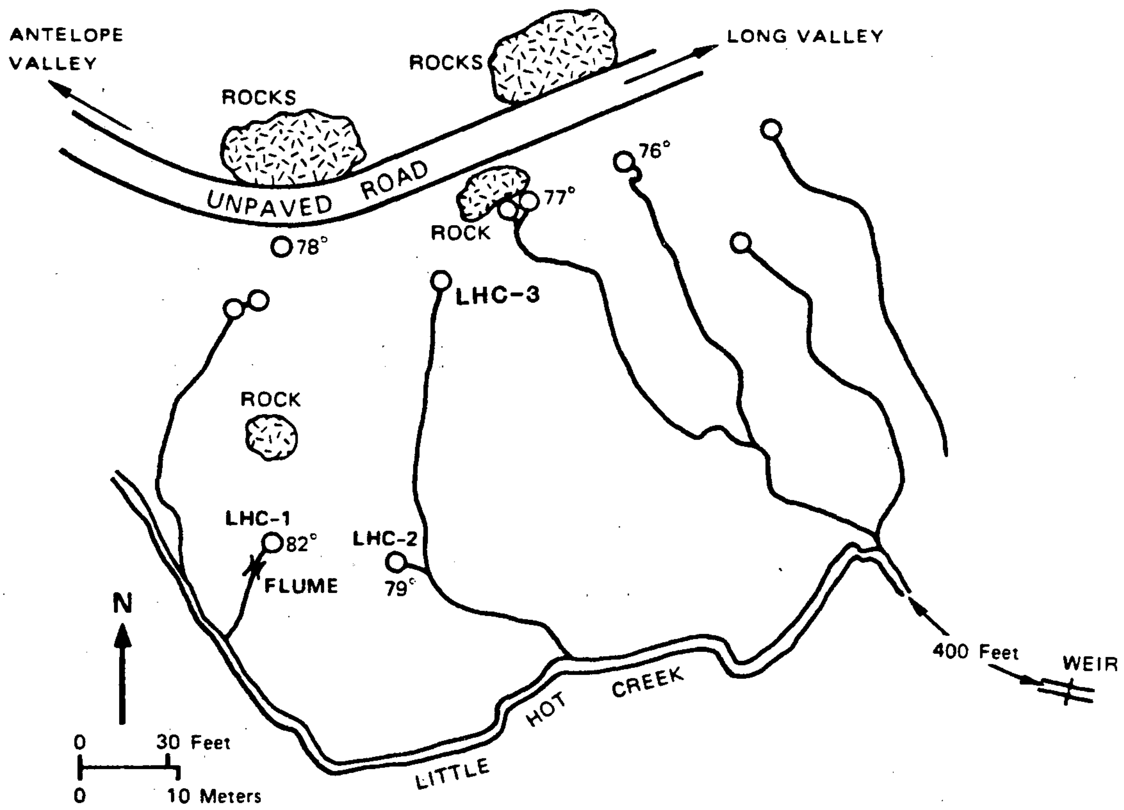


Figure 8. Map of the hot-spring area along Little Hot Creek (T.3S., R.28E., sec. 13) showing principal hot springs as open circles and spring temperatures in degrees celsius, as measured in May 1984. Springs for which chemical and isotopic data are available are labeled with the abbreviation used in the data tables. Locations based on an unpublished may prepared by Frederick Wilson, U.S. Geological Survey, 1974.

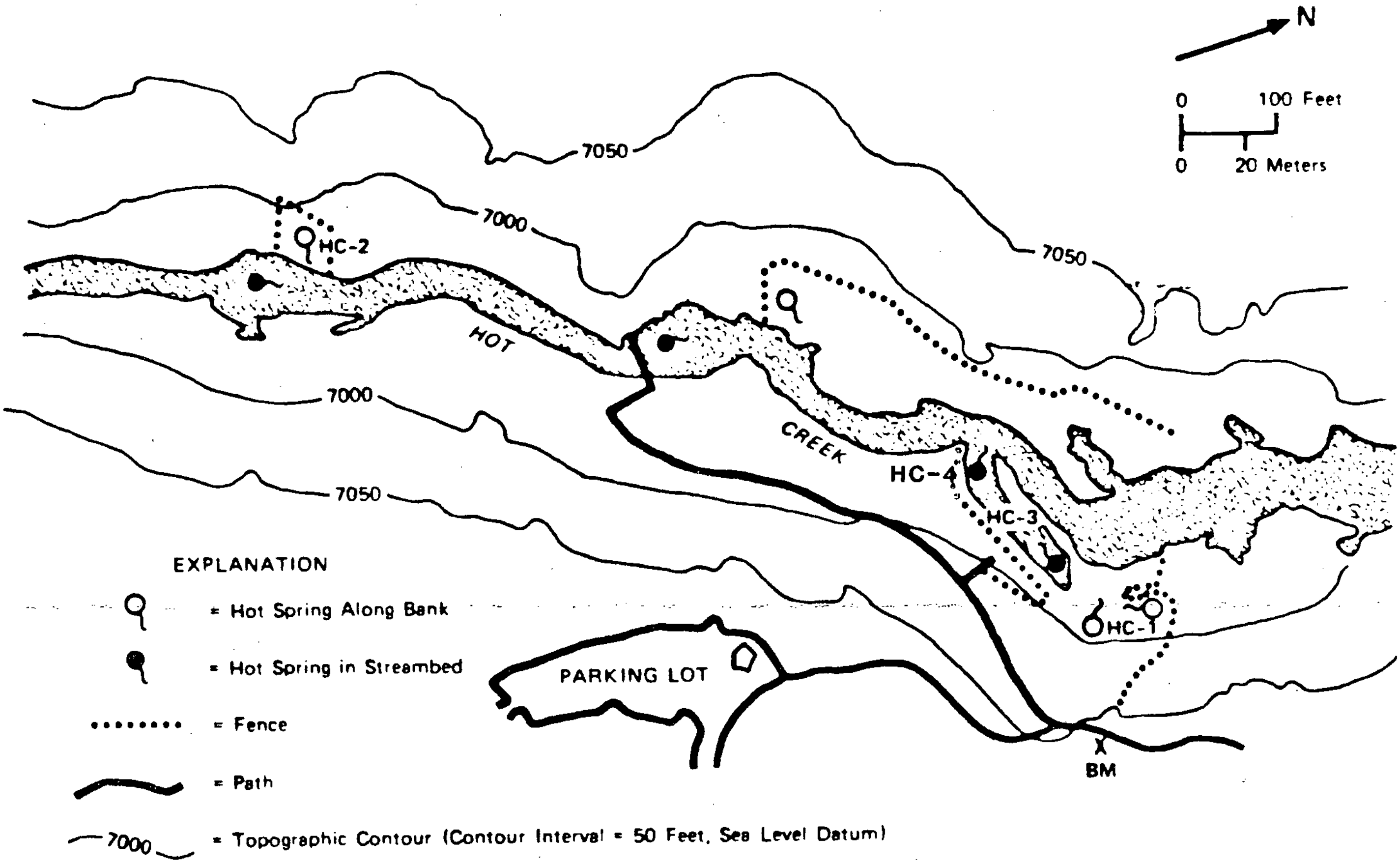


Figure 9. Map of a part of Hot Creek gorge (T.3S., R.28E., sec.25) showing locations of hot springs referred to in text, tables and unnamed features that are conspicuous on the land surface. Locations and altitudes based on an unpublished map prepared by Frederick Wilson, U.S. Geological Survey, 1974, and modified to include changes induced by subsequent seismic activity.

Table 2. Chemical analyses for selected springs in Long Valley caldera. All analyses run in USGS Central Laboratory, Arvada, CO, except analyses for springs 21P1 and BM, which were run at Lawrence Berkeley Laboratory, Berkeley, CA.

Map ID	Spring	Date	T oC	pH	Ca	Mg	Na	K	Alk	SO_4	Cl	F	SiO_2	D.S.	As	B	Li	Fe	Hg	Mn	Zn
										(milligrams per liter)								(milligrams per liter)			
									THERMAL WATERS Casa Diablo Area												
CS	Colton Sp.	05-09-84	91.4	8.3	1.3	<0.01	370	28	353	150	270	12.0	230	1340	1.3	11.0	3.3	5	0.3	6	5
MS	Meadow Sp.	05-10-84	63.3	6.3	3.4	0.60	210	39	115	120	200	7.7	190	865	1.8	8.6	1.5	6	0.3	14	18
MP1	Milky Pool 1	08-19-83	87.3	7.6	2.4	0.04	330	37	206	160	270	14.0	170	1120	1.6	13.0	-	-	-	-	-
MP2	Milky Pool 2	05-09-84	91.2	6.8	2.4	0.04	230	33	73	160	240	10.0	210	967	1.5	9.8	1.0	96	0.7	45	27
CDN	North Sp.	05-09-84	89.5	6.9	10.0	1.4	250	25	61	190	270	9.1	200	1020	1.5	11.0	1.3	16	0.5	31	8
CDS	South Sp.	06-03-83	84.0	6.7	23.0	3.3	320	31	281	225	205	8.2	200	-	-	9.6	1.8	-	-	-	-
CDG	Geyser Sp.	05-09-84	90.1	8.2	0.8	0.1	410	38	382	160	300	12.0	-	1480	1.8	12.0	3.2	110	1.2	<10	<10
AS2	Sulfate Sp. 2	10-09-84	93.0	4.5	11.2	3.2	230	21	2.5	1.4	0.5	0.0	160	-	.75	7.1	1.2	725	-	-	-
									Hot Creek Gorge Area												
HC-1	Morning Glory Pool	12-13-83	73.3	6.8	1.4	0.29	380	22	495	110	230	9.5	140	1210	.90	11.0	2.5	5	0.3	25	23
HC-2	Spring above bridge	05-08-84	79.2	7.3	6.5	0.20	360	24	435	110	220	9.8	130	1150	.90	9.5	2.7	6	0.1	12	20
HC-3	Geysers	05-08-84	91.4	8.1	2.3	0.20	380	24	490	96	230	10.0	130	1190	.90	9.8	2.9	7	0.2	1	79
CH-10A	Well CH-10A	11-09-84	93.3	7.2	-	0.40	340	21	463	93	200	8.4	230	1120	.60	9.9	2.3	37	0.2	120	11
									Little Hot Creek Area												
LHC-1	Flume	05-09-84	81.2	6.8	22	0.60	400	29	579	100	210	8.3	82	1230	.59	8.6	3.3	47	0.3	200	17
									MIXED WATERS												
21P1	Big Alkalai Lake Sp.	11-11-83	50.0	6.9	27	0.71	338	34	334	160	160	4.7	171	1164	0.76	6.1	2.0	-	-	-	-
AB	AB supply	06-21-84	16.0	7.1	13	9.7	24	5.1	111	10	10	0.40	57	187	0.02	0.37	0.08	7	0.1	1	4
H-II,III	H-II,III supply	06-21-84	11.1	7.3	13.0	4.7	12	2.9	70	11	1.5	0.20	39	104	-	0.09	0.04	-	-	-	-
									COLD SPRINGS												
LS	Laurel Sp.	05-10-84	12.0	8.9	15.0	0.60	5.8	1.4	39	20	0.5	0.10	19	81	.004	0.02	.006	3	0.1	1	3
BM	Bald Mtn Sp.	08-03-84	11.0	6.8	9.3	1.9	6.5	3.4	37	0.65	0.4	-	47	-	0.0	0.08	0.0	14	-	-	-

chemists are in general agreement that much of the areal variability in water chemistry results from the mixing of thermal with nonthermal waters where flow paths intersect, there is no generally accepted detailed flow model of the system. White and Wollenberg suggest the shallow hydrothermal system may not be homogeneous but rather consists of several cells each having different recharge sources and hydrothermal evolution, whereas Sorey suggests that a high degree of lateral continuity exists within the shallow hydrothermal system.

Selected chemical analyses for several springs and one shallow well (Table 2) provides representative analyses. However, the discussion that follows is based on a larger data set of published and unpublished chemical data (California Department of Water Resources, 1967; Lewis, 1974; Farrar et al., 1985; written communications: Valette-Silver, 1984 and White, 1974). The following descriptions of thermal and nonthermal waters are based on these data.

Nonthermal spring waters—The range in composition of nonthermal recharge waters is not known, however the assumption is made that waters discharged from cold springs around the caldera margin are representative of nonthermal recharge waters. The probable shallow travel-path and short travel-time from point of recharge to discharge accounts for the lack of elevated temperature and low dissolved-solids concentrations in the nonthermal waters. Chemical analyses of water from Laurel Spring and Bald Mountain Spring are representative of nonthermal waters. These two analyses along with analyses from seven other cold springs obtained by White show that nonthermal waters are generally neutral to slightly alkaline and contain less than 100 mg/L dissolved-solids. The proportions of major ions (Ca, Mg, Na, K, SO_4, Cl, HCO_3) in nonthermal waters are variable, probably mostly related to local rock type.

Sodium is the most abundant cation in waters from five of nine cold springs sampled, calcium is most abundant in the other four. Potassium shows considerable variability in concentration but is always subordinant to sodium and exceeds the calcium concentration in only one sample. Magnesium is the least abundant cation in samples from seven of nine springs.

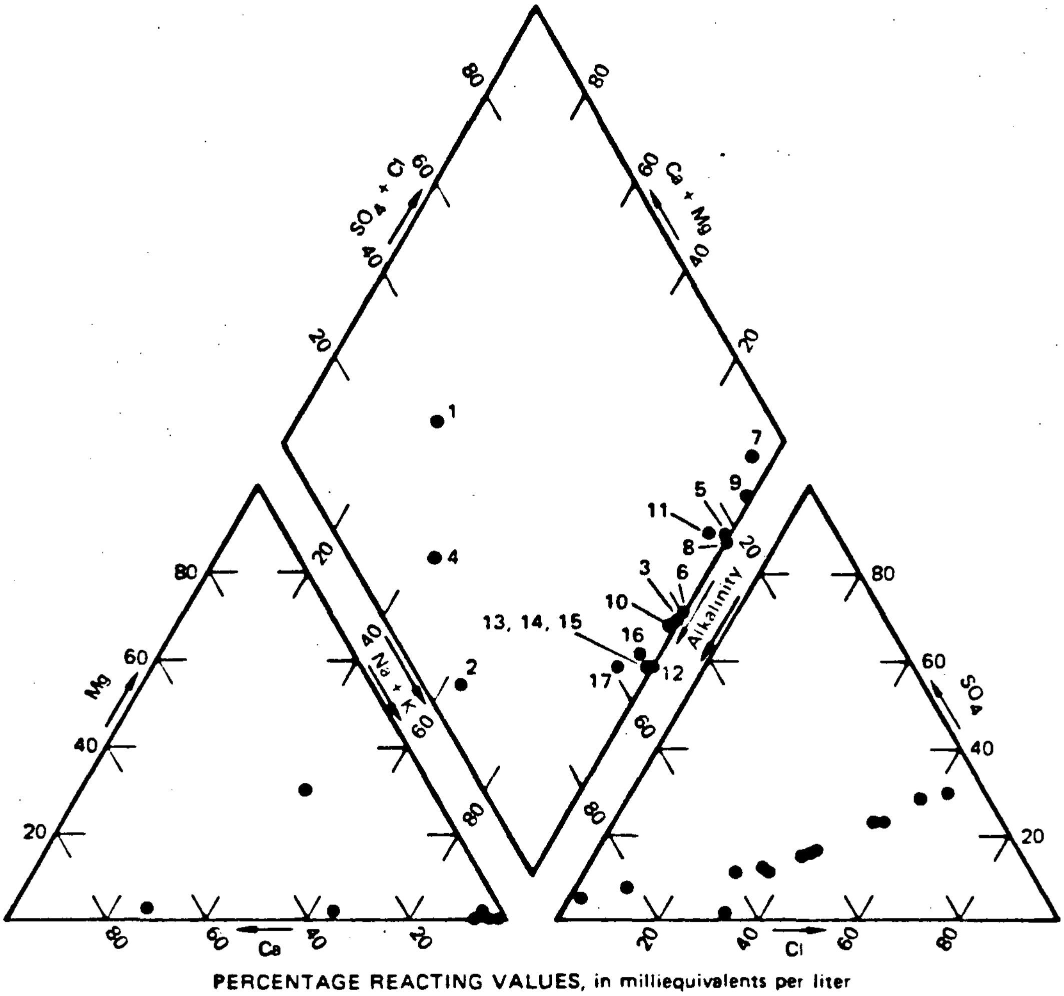
Assuming alkalinity is mostly due to carbonate-family ions, bicarbonate is the most abundant anion in waters from all nine cold springs sampled. Sulfate is generally next in anionic abundance followed by chloride. Where chloride does exceed the sulfate concentration both are present in quantities less than 2 mg/L. Minor elements typical of thermal waters (As, B, F, Li) are present in cold spring waters in concentrations generally considerably less than 1 mg/L.

Thermal spring waters—The main areas with surface manifestations of thermal fluid discharge are Casa Diablo, Hot Creek Fish Hatchery, Little Hot Creek, Hot Creek gorge, and Alkali Lakes. These areas lie mostly within the southern half of the caldera (Fig. 6), along northwest-trending faults. The total discharge rate of springs with temperatures exceeding 60 ° C is approximately 300 L/s, over 80 percent of which issues from hot springs in Hot Creek gorge.

Fumaroles are confined to the southwest quadrant of the caldera and generally occupy topographically higher points than the hot springs. This topographic separation of fumaroles from hot springs probably reflects phase separation at shallow depth. Fumarolic activity is greatest in the Casa Diablo area (Fig. 7). Fumaroles west of Casa Diablo tend to be obscure with meager flow rates often making uncontaminated gas sampling a difficult proposition.

The chemical composition of thermal fluids is variable from area to area and from vent to vent at any one area. In general, thermal waters are near neutral to slightly alkaline in pH and contain 1000–1500 mg/L dissolved-solids. The cationic composition is dominated by sodium (Fig.10), potassium is generally next in abundance followed by calcium and magnesium. The order of prevalence in cations and the high concentration of silica are consistent with dissolution of feldspars and volcanic glass from reservoir host rocks.

The proportions of major anions (HCO_3, SO_4, Cl) in thermal waters is more variable than the proportions of major cations. Chloride concentrations, generally ranging between 200 and 300 mg/L, are the least variable between sample sites and show a decrease along the general groundwater flow path from west to east, suggestive of dilution. The chloride concentration is greatly reduced in the two samples from acid springs at Casa Diablo. The acidic water from these springs probably results from steam condensation and sulfide oxidation. Sulfate concentrations, excluding the acid water samples for Casa Diablo range from about 100–225 mg/L. As with the chloride, sulfate shows a decrease in concentration from west to east suggestive of dilution. Alkalinity



1. Laurel spring (LS)
2. Reds Meadow Tub spring (RMT)
3. Colton spring (CS)
4. Fish Hatchery - AB Supply
5. Meadow spring (MS)
6. Casa Diablo Geyser (CDG)
7. Casa Diablo North spring (CDNS)
8. Casa Diablo Milky Pool 1 (MP-1)
9. Casa Diablo Milky Pool 2 (MP-2)
10. Hot Bubbling Pool (HBP)
11. Casa Diablo South spring (CDSS)
12. Well CH-10A
13. Well CH-10B
14. Hot Creek gorge spring (HC-2)
15. Hot Creek gorge spring (HC-3)
16. Hot Creek gorge spring (HC-1)
17. Little Hot Creek Flume spring (LHC-1)

Figure 10. Major ion composition of water from selected springs and wells in the Long Valley area.

(largely accounted for by carbonate species) tends to increase in concentration from west to east. The increasing alkalinity may indicate a decrease in carbon dioxide caused by reaction with reservoir rocks that fixes the CO_2 as bicarbonate. Alkalinity concentrations at Casa Diablo range from 2.5 to 382 mg/L but fall roughly into two classes: 1) pH $<$ 7, alkalinity 200 mg/L and 2) pH $>$ 7, alkalinity $>$200 mg/L.

Among the minor elements characteristic of hot springs are arsenic, boron, fluoride, and lithium. In Long Valley thermal waters with neutral to alkaline pH the range in concentrations are: arsenic 0.6 to 1.8 mg/L, boron 7.1 to 13.0 mg/L, fluoride 7.7 to 14.0, and lithium 1.0 to 3.3 mg/L. The highest concentrations of these minor elements are found in neutral to alkaline pH springs at Casa Diablo. Concentrations of these elements are much lower at this site in the acid springs samples from Sulfate Spring 2 and 3. Concentrations of arsenic, boron, and fluoride are lower in thermal-spring areas east of Casa Diablo.

Thermal well sources—In the quest for representative samples of unmixed thermal waters, samples from deep wells are most desirable. Unfortunately deep wells in the caldera have not been available for sampling. However, four production wells drilled to depths of 650 ft in the Casa Diablo area tap a shallow thermal aquifer and now supply hot water to a 7.5 MW binary-electric generating plant (Fig. 7). Injection wells Ml and IW-2 are 1900 and 1800 ft deep, respectively, well Ml having been drilled to a depth of 5200 ft and latter plugged back to 1900 ft. Six of these wells were sampled by White in January 1983 (Table 3). An older 810 ft deep exploration hole in this same area (END-5) was sampled in 1972 by Mariner. The samples collected by White had flashed in the well casings and discharge lines before collection. The concentrations given in Table 3 are not corrected for an estimated 20 percent water loss due to flashing. The two-phase sample collected under Mariner's direction was passed through stainless steel tubing coiled in an ice bath allowing collection and analysis of a fully condensed sample.

Although the flashed samples are not ideal they provide some knowledge relating to multiple aquifers in the Casa Diablo area. From temperature profiles run in these wells (e.g. Ml in Fig. 3) two hot water flow zones have been identified at depths of about 500 ft (170°C) and 2500 ft

Table 3. Chemical analyses of waters from geothermal wells in the Casa Diablo area. All analyses were run at Lawrence Berkeley Laboratory, Berkeley, CA, except for END-5 which was analyzed under the direction of R. Mariner at U.S. Geological Survey Laboratory, Menlo Park, CA.

	Collection date	Temperature (oC)	pH	Ca	Mg	Na	K	ALK	SO<4>	Cl	F	SiO<2>	As	B	Li
								(milligrams per liter)							
Endogenous-5 (END-5)	05-19-72	94.0	9.2	0.9	0.1	390	45	368	130	280	12.0	340	2.2	14.0	2.8
MBP-1	01-04-83	-	8.8	5.1	0.04	431	47	405	132	300	12.1	63	0.205	10.6	3.48
MBP-2	01-04-83	-	9.1	1.8	0.03	430	45	410	133	288	12.8	65	0.232	10.8	3.52
MBP-4	01-04-83	-	8.8	1.4	0.02	453	52	425	135	300	13.6	188	0.242	11.7	3.98
MBP-5	01-04-83	-	9.2	2.6	0.02	435	34	389	172	267	14.7	75	0.202	10.3	3.98
Union (M1)	01-04-83	-	9.4	0.9	0.02	422	18	415	172	180	14.5	61	0.139	7.57	0.82
IW-2	01-04-83	-	9.7	3.5	.008	401	10	464	118	132	23.7	91	0.181	10.8	0.22

(150 ° C). A cooler zone (120 ° C) lies between the two thermal aquifers. The chemical analyses show water from the two injection wells (IW-2 and Ml), that both tap the cooler zone, contains lower concentrations of chloride (132 and 180 mg/L) than the production wells (267–300 mg/L) completed in the upper hot-water zone. The boron concentration in injection well Ml is also lower than in the production wells.

Mariner's sample from END-5 is probably more representative of the chemical composition of the upper hot-water zone. Mariner cautions that reservoir temperature estimates based on the Na-K-Ca geothermometer(238 ° C) maybe to high if loss of carbon dioxide from the well caused precipitation of calcium carbonate and reduced the calcium concentration in the water sample. Instead, Mariner suggests that the silica geothermometer, using the conductive quartz curve to give an estimate of 219 ° C provides a better estimate of reservoir temperature.

Mixed waters—The mixing of thermal and non-thermal waters results in springs discharging waters of intermediate temperatures and chemical compositions. Such springs are found in the Fish Hatchery area and the Alkali Lakes—Whitmore Hot Springs area. An estimate of the relative proportions of hot to cold water in such springs can be made by comparing temperatures and arsenic, boron, chloride, and fluoride concentrations with those in the hotter springs in the Casa Diablo area.

Observed variations in chemistry—Farrar, Sorey, and Clark are monitoring hot springs to detect changes in temperature, chemistry, and flow rate related to tectonism and volcanism. Many thermal features have been sampled on several occasions; often the samples are collected by different personnel for analysis in different laboratories. Farrar expressed concern that the analyses obtained by various workers may not be comparable. Table 4 presents selected analyses for five sample sites. Some variability in reported concentrations is evident from the table.

Differences in the point of sample collection, collection and field preservation techniques, laboratories and analytical procedures may account for some of the differences seen in the analytical data. These factors may be responsible for differences in concentrations detected at Colton Spring, Little Hot Creek-Flume Spring, and Laurel Spring. The general character of these springs

Table 4. Comparison of chemical analysis of waters from selected springs run by different laboratories: (UM - USGS laboratory, Menlo Park, CA; L - LBL laboratory, Berkeley, CA; UC - USGS laboratory, Arvada, CO; C - Carnegie Institution, Washington, D.C.)

Site	Collection Date	Lab	T	pH	Ca	Mg	Na	K	Alk	SO<4>	Cl	F	SiO<2>	D.S.	As	B	Li	Fe	Hg	Mn	Zn
			oC							(milligrams per liter)								(micrograms per liter)			
Colton Sp.	06-03-83	UM	93.0	8.3	1.2	0.01	385	25	370	135	250	10.0	240	-	-	11.0	2.8	-	-	-	-
	04-25-84	L	70.0	8.4	1.4	0.02	384	32	390	129	258	9.6	315	-	1.4	11.4	2.9	4,500	-	-	-
	05-09-84	UC	91.4	8.3	1.3	<0.01	370	28	353	150	270	12.0	230	1340	1.3	11.0	3.3	5	0.3	6	5
	05-09-84	C	91.4	8.3	1.3	<0.01	378	-	-	-	-	-	234	-	2.0	11.4	-	2	-	5	<3
Little Hot Creek Sp. (LHC-1)	11-18-83	L	80.0	7.4	13	0.67	377	27	625	101	173	5.5	84	-	1.14	9.0	3.3	8	-	-	-
	01-17-84	UC	80.0	6.7	23	0.61	370	27	610	100	210	9.2	78	1210	0.58	9.1	2.6	35	1.3	200	19
	05-09-84	UC	81.2	6.8	22	0.60	400	29	579	100	210	8.3	82	1230	0.59	8.6	3.3	47	0.3	200	17
	05-09-84	C	81.2	6.8	22	0.55	398	-	-	-	-	-	81	-	0.78	8.6	-	44	-	195	<3
Laurel Sp.	06-19-66	D	12.0	7.6	16	0	5	1.0	37	13	1.0	0.2	-	65	0.01	-	-	-	-	-	-
	11-17-83	L	10.0	8.8	14	0.6	5.3	1.2	37	17	0.4	-	20	-	0.13	0.05	-	5	-	-	-
	05-10-84	UC	12.0	8.9	15	0.6	5.8	1.4	39	20	0.5	0.1	19	81	.004	0.02	.006	3	0.1	1	3
	05-10-84	C	12.0	8.9	15	0.59	5.7	-	-	-	-	-	20	-	<0.2	<0.02	-	2.7	-	<3	<3
Sulphate Sp.	10-09-84	L	93.0	4.5	11.2	3.2	230	21	2.5	1.4	0.5	0	160	-	0.75	7.12	1.2	725	-	-	-
	10-13-84	UC	88.0	6.8	5.1	2.3	230	16	62	190	210	8.5	120	857	0.73	7.6	1.1	130	-	120	11
Hot Creek Gorge Sp. (HC-2)	08-19-83	UC	82.0	7.2	6.6	0.29	370	24	449	99	220	9.2	140	1150	1.3	10.0	2.4	-	1.1	-	21
	12-13-83	UC	76.3	7.3	13	0.43	360	17	439	98	220	9.1	140	1130	0.9	9.6	2.4	8	0.2	17	33
	05-08-84	UC	79.2	7.3	6.5	0.20	360	24	435	100	220	9.8	130	1150	0.9	9.5	2.7	6	0.1	12	20
	05-08-84	C	79.2	7.3	6.4	0.20	364	-	-	-	-	-	135	-	1.3	10.1	-	<3	-	10	<3

have not changed over the sample. period. Some of the variability of data may reflect actual variations in water chemistry but the large range of values, exceeding 100 percent in some cases, suggests other factors may be predominant. The largest percent differences are found for elements with low concentrations (Mg, As, Fe, Mn, Hg, Zn). Better agreement between analyses is found for the nonthermal water (Laurel spring) than from the thermal springs. The best comparison of results obtained from different laboratories can be made for samples collected May 8-10, 1984. Splits of one sample with identical field preservation were sent to the U.S. Geological Survey Central Laboratory and to the Carnegie Institute, Washington D.C. Unfortunately not all the results are available for comparison but good agreement was obtained for those elements with reported values.

Significant differences in water chemistry at some sites probably relate to physical changes around the discharge point. Rapid change in chemical composition is reported for Sulfate Spring 2 (Table 4). Two samples collected four days apart show the temperature declined 5 °C and pH rose from 4.5 to 6.8, and the concentrations of several constituents changed significantly. The changes in pH and temperature may be due to changes in the flow of gases at this site or due to mixing with other waters. The pH and temperature changes then produce changes in constituent concentrations because of the interrelationship of these factors with mineral solubilities.

The analyses shown for hot spring HC-2 in Hot Creek gorge also show large differences in some ionic concentrations reported. However, the flow rate and temperature of this spring have varied over time. The diminished flow may allow for greater conductive cooling causing lower temperature and changing stability of dissolved mineral phases.

Gas sampling—Gas sampling through 1984 by Gerlach, Mariner, and Janik, each working independently, has provided chemical data for eight sites but with repeat sampling at only two sites (Table 5). Vapor at the eight sample sites is emitted at temperatures between 64° and 96 °C. The ratios of water to noncondensible gases determined for four sites range from 0.27 to 830 on a volumetric basis. For the two sites with ratios less than one, temperatures (64° and 79 °C) are significantly below the ambient boiling temperature and therefore the steam fraction is

Table 5. Chemical analyses of gas from springs and fumaroles in the Long Valley area, Mono County, California.

Results in percent, on a water-free basis, except for values of H<2>O/gas, which are expressed as a volumetric ratio. nd indicates no laboratory determination was made.

Feature: Name of sample site with abbreviation used in figures, and other tables given in parentheses. Sample from Colton spring was collected from a steam vent 100 ft above the hot springs.

Analytical lab: USGS-ml: U.S. Geological Survey, Menlo Park, CA (C. Janik); USGS-m2: U.S. Geological Survey, Menlo Park, CA (R. Mariner); Sandia: Sandia National Laboratory (T. Gerlach), results shown are average values for samples collected on same date.

H<2>S: Total sulfur calculated as H<2>S.

O<2>: For samples with nd shown for Ar, O<2>, = O<2> + Ar.

Feature (abbrev.)	Collection date	Analytical lab	T oC	CO<2>	H<2>S	H<2>	CH<4>	NH<3>	He	N<2>	O<2>	Ar	H<2>O/gas (volumetric)
						(volume percent-water free)							
Casa Diablo area springs and fumaroles in sections 32 and 33, T.3S, R.28E.													
Colton spring (CS)	06-27-84	USGS-ml	96	95.36	0.76	0.0623	0.0656	0.00	0.006064	3.53	0.0	0.084	-
Geyser (CDG)	06-26-83	USGS-ml	94	95.44	1.69	0.0142	0.0116	1.13	0.000119	1.75	0.00262	0.0321	830
Fumarole (CDF)	11-11-82	Sandia	96	93.2	5.5	0.028	0.016	nd	nd	0.56	0.013	nd	195
	01-14-83	Sandia	94	95.8	0.37	0.021	0.021	nd	nd	3.1	0.39	nd	190
	04-25-83	Sandia	95	96.9	0.69	0.47	0.047	nd	nd	1.7	0.13	0.012	255
	04-28-83	Sandia	94	96.7	0.65	0.22	0.044	nd	nd	1.6	0.17	0.02	242
	06-26-83	USGS-ml	94	89.78	0.66	0.031	0.026	0.387	0.000377	7.62	0.80	0.0974	260
	09-23-83	Sandia	94	96.7	0.93	0.30	0.06	nd	nd	1.6	0.07	0.032	237
	05-31-84	Sandia	93	97.7	0.78	0.055	0.031	nd	nd	0.80	0.03	nd	285
Fish Hatchery area - springs in sections 35, T.3S, R.28E.													

Table 5 (cont.)

Hot Bubbling Pool (HBP)	06-26-83	USGS-ml	64	97.25	0.0132	0.0403	0.0694	0.0114	0.000498	2.42	0.177	0.00168	0.27
Hot Creek Gorge area - springs in sections 25, T.3S, R.28E.													
Morning Glory Pool (HC-1)	05-31-84	Sandia	93	96.1	0.13	nd	nd	nd	nd	3.03	0.74	nd	nd
Geysers (HC-3)	06-27-83	USGS-ml	79	96.69	0.0338	0.0123	0.0741	0.0053	0.0024	2.98	0.0747	0.0758	0.67
Little Hot Creek area - springs in sections 13, T.3S, R.28E.													
LHC-1	05-31-84	Sandia	80	96.5	0.05	nd	nd	nd	nd	2.77	0.66	nd	nd
	06-28-84	USGS-ml	80	40.8	0.47	0.0299	0.186	0.057	0	47.44	10.61	0.690	-
Mammoth Mountain area - fumaroles in sections 31, T.3S, R.28E.													
MMN	06-00-82	USGS-m2	80	91.22	<0.02	<0.01	0.008	nd	<0.005	8.27	0.01	0.11	nd

reduced; for the other two sites with temperatures of 94–96 ° C, large quantities of steam dilute the noncondensible gas fraction.

Air contamination of gas samples is always of concern, especially where the flow of gas is small. The diminutive flow of gas from most fumaroles and springs in Long Valley limits potential sample sites to those listed in Table 5. Air contamination may have occurred in samples showing above average nitrogen concentration and a nitrogen to oxygen ratio near four. Various collection procedures have been devised to improve the quality of samples. Gerlach and Janik employ the use of evacuated bottles containing sodium hydroxide solution as gas collection vessels. Mariner uses evacuated bottles without the hydroxide solution. The use by Janik and Gerlach of an inert conductor tube inserted about a meter into fumarole vents or vinyl tubing with a plastic funnel fitted over spring vents channels the gas sample to the collection vessel, excluding the atmosphere.

The data in Table 5 show that carbon dioxide generally accounts for greater than 90 percent by volume of the noncondensible gases. The remaining fraction is made up of N_2, H_2, O_2, H_2S, He, CH_2, NH_3, Ar. Gas compositions show consistent differences between sites from west to east. The proportions of He and CH_4 increase, and the less volatile components, NH_3 and H_2, decrease.

The CDF fumarole is the only site with enough repetition of sampling to make a judgment regarding chemical changes over time, however no consistent trend is seen. Nonquantitative observations of this fumarole indicate the volume of gas and steam discharged has diminished since its reactivation in 1982. The drop in temperature from 96 ° to 93 ° C may be a reflection of the decrease in flow rate.

Stable-Isotope Composition of Fluids

Stable-isotope data collected for Long Valley include the elements hydrogen, oxygen, carbon, and helium. The hydrogen and oxygen isotope data (D/H and $^{18}O/^{16}O$) have proved useful for determining recharge sources. Carbon ($^{13}C/^{12}C$) and helium ($^{4}He/^{3}He$) isotope data are being collected to determine the origin of these elements in the system and to detect recent inputs from magmatic sources.

The earliest stable isotope data, including hydrogen and oxygen values for waters from eight hot springs and two meteoric water samples, were collected and analyzed in 1972 under Mariner's direction. Additional hydrogen and oxygen data were obtained during 1975–76 for several cold springs marginal to the caldera by Sorey. Intensified sampling, beginning in 1982, includes carbon data for both aqueous carbon and carbon dioxide gas. Farrar and Sorey have collected replicate hydrogen, oxygen, and carbon isotope data from several hot springs and one cold spring, looking for variations over time. White and Wollenberg have established a precipitation collection network across the caldera (Fig.11) for obtaining oxygen and hydrogen data on potential recharge waters. In addition they have collected isotopic data (D, ^{18}O, ^{13}C) from many of the hot springs and geothermal wells. Janik has collected hydrogen, oxygen, and carbon data, concentrating on the hot springs sites with sufficient gas discharge for collecting ^{13}C data on both liquid and gas phases. Rison has determined helium isotope ratios in gas and the volumetric ratio of helium to carbon dioxide. Gerlach's study of isotopic composition has concentrated on ^{13}C in gases and he has experimented with leaching samples of Bishop Tuff to determine potential ^{13}C sources. Wheeler has begun a study of aqueous sulfur isotopes to add to the knowledge of fluid origins and flow dynamics.

Hydrogen and oxygen isotopes—The variations of the isotopic ratios D/H and ^{18}O/^{16}O in water samples are expressed in terms of permil difference (0/00) with respect to the isotopic ratios of mean sea water, which constitutes the reference standard SMOW (Craig, 1961). A plot of isotopic ratios of oxygen versus hydrogen for selected samples collected after 1982 is shown in Figure 12. As expected, cold waters plot close to the meteoric-water line while hydrothermal waters display an ^{18}O shift due to exchange with mineral phases in the reservoir. Stable-isotope compositions of meteoric and hot-spring waters show some variability between analyses, but relations between deuterium and oxygen-18 for water and steam samples do not show qualitative changes from the patterns described in Fournier and others (1979). The isotopic data for the thermal waters are consistent with the conceptual model that deep circulation of precipitation recharges the

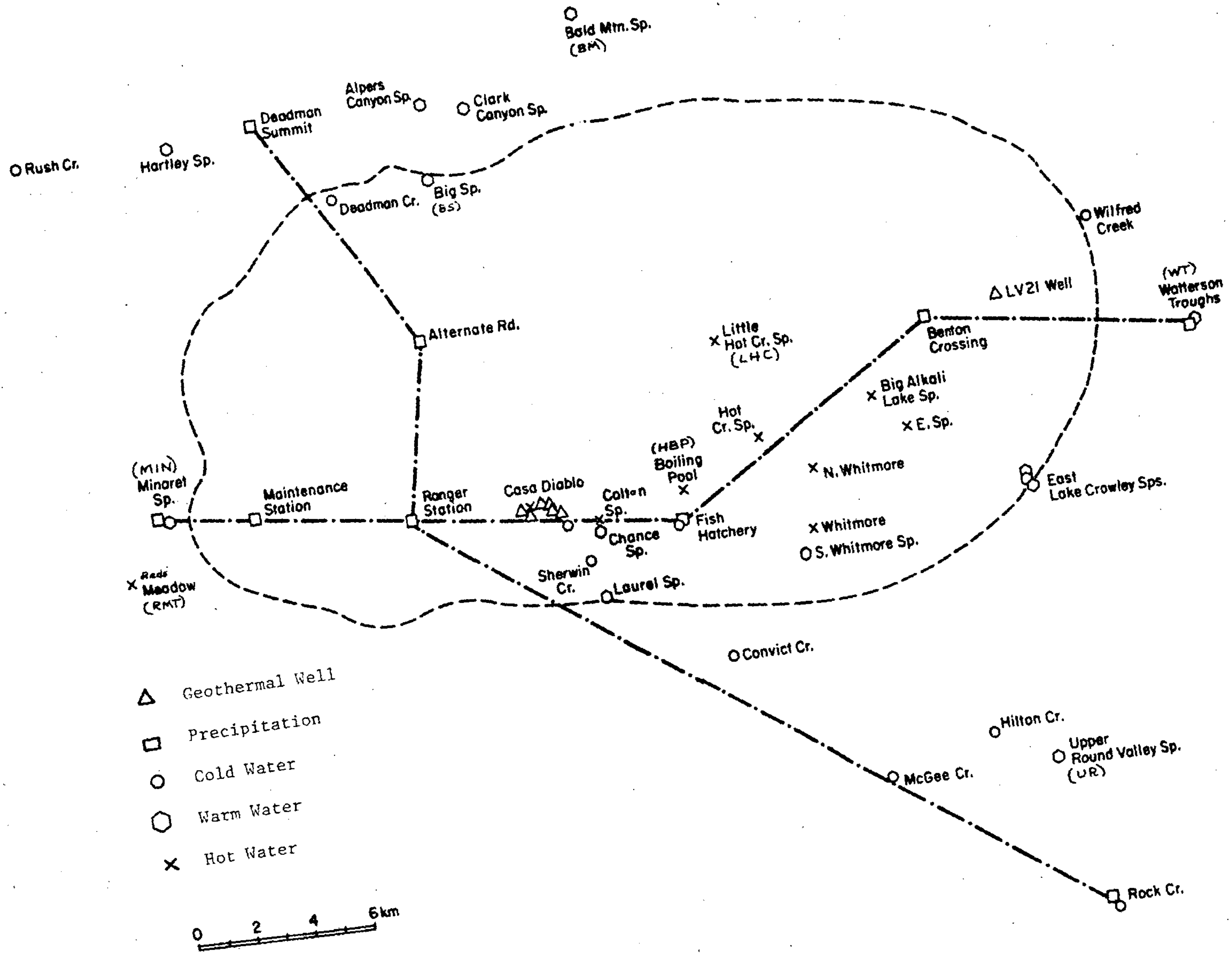


Figure 11. Location of sites in the precipitation sampling network.

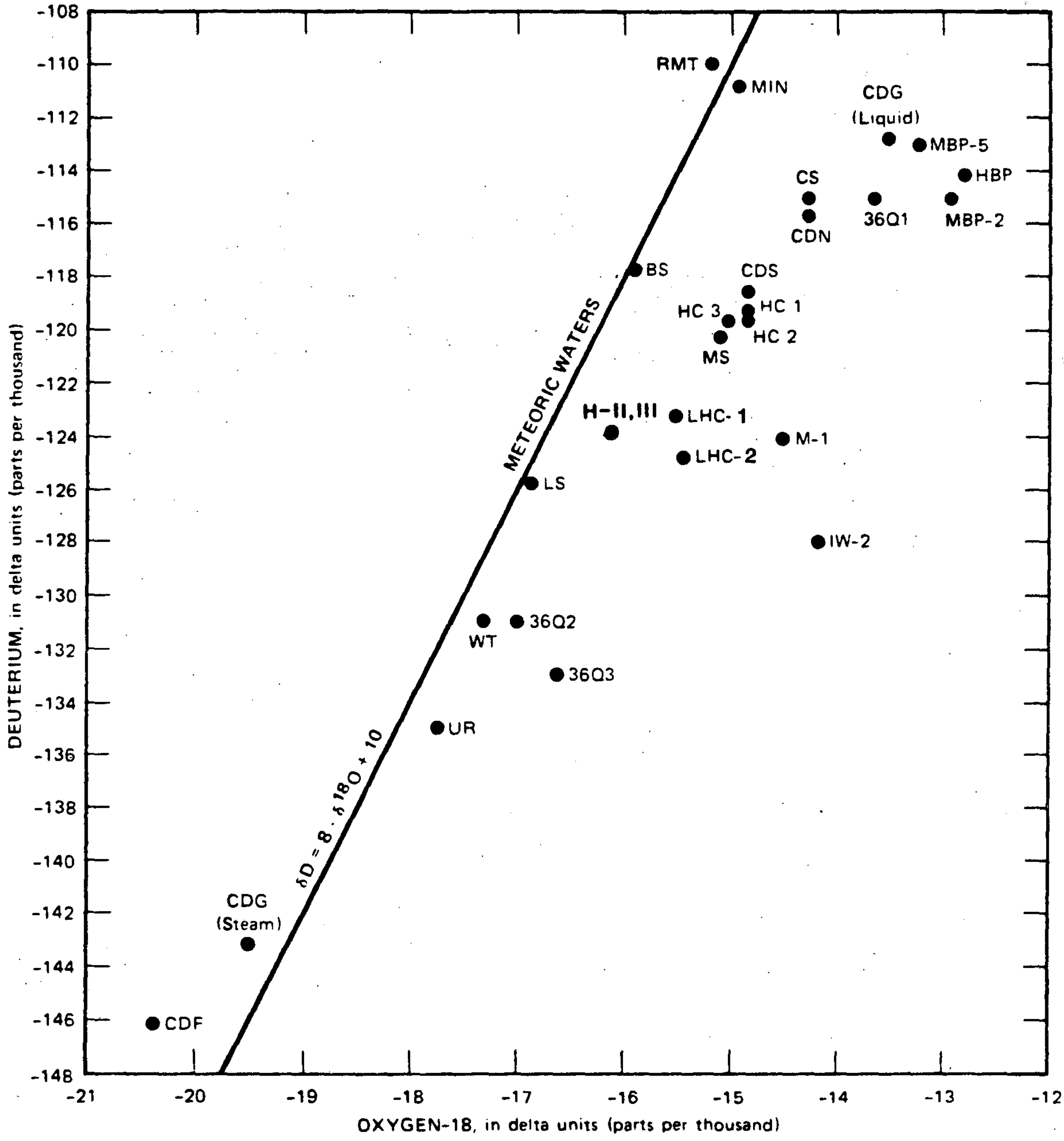


Figure 12. Dueterium versus oxygen-18 for selected springs, fumaroles, and wells. Site abbreviations follow those used in tables and text; locations are shown on Figures 6–9 and 11.

hydrothermal system and juvenile water does not contribute significantly to the flow of hot water.

The precipitation collection network established by White and Wollenberg provides information on the variability of potential recharge waters. Plots of deuterium and oxygen-18 versus sampling location along a east-west line across the caldera are shown in Figures 13 and 14. The figures show that isotopic composition of precipitation changes seasonally, the lightest precipitation occurs in late autumn and generally becomes heavier in late winter. The areal pattern of isotopic data shows that the precipitation falling on the Sierra (south and west caldera margins) is isotopically heaviest, while that falling to the north and northeast, on the Bald Mountain and Glass Mountain is lightest. White notes that this trend of lighter isotopes to the east is also seen in the data from hydrothermal samples (Fig. 13 and 14), indicating the possibility of local recharge sources.

The isotopically lightest fluid sampled comes from steam sources at Casa Diablo where two samples give values of $D = -143.2$, $^{18}O = -19.6$ and $D = -146.3$, $^{18}O = -20.4$. Because both detuerium and oxygen-18 in these samples are depleted relative to local precipitation, water/rock reactions do not account for the observed data. A more likely explanation is that fractionation during steam separation accounts for the isotopic shift. At temperatures below 220 ° C isotopic fractionation between vapor and liquid tends to concentrate deuterium in the liquid phase and deplete it in the vapor phase. At temperatures at least up to 300 ° C, ^{18}O is concentrated in the liquid (Friedman and O'Neil, 1977). The isotopic ratios of steam samples from Casa Diablo vents appear to indicate that fractionation due to steam separation is taking place at temperatures below 220 ° C. Correspondingly, water from the liquid fraction in the boiling spring CDG is isotopically heavier than waters from two nearby nonboiling or weakly boiling springs (CDN and CDS).

Isotopic data from seven geothermal wells at Casa Diablo can be grouped into two classes. Samples from injection wells IW-2 and MI, are more depleted in deuterium and oxygen-18 than samples from the shallower production wells, End-5, MBP-1, MBP-4, and MBP-5. The differences in isotopic ratios between these sets of wells may reflect recharge from the west for the shallow

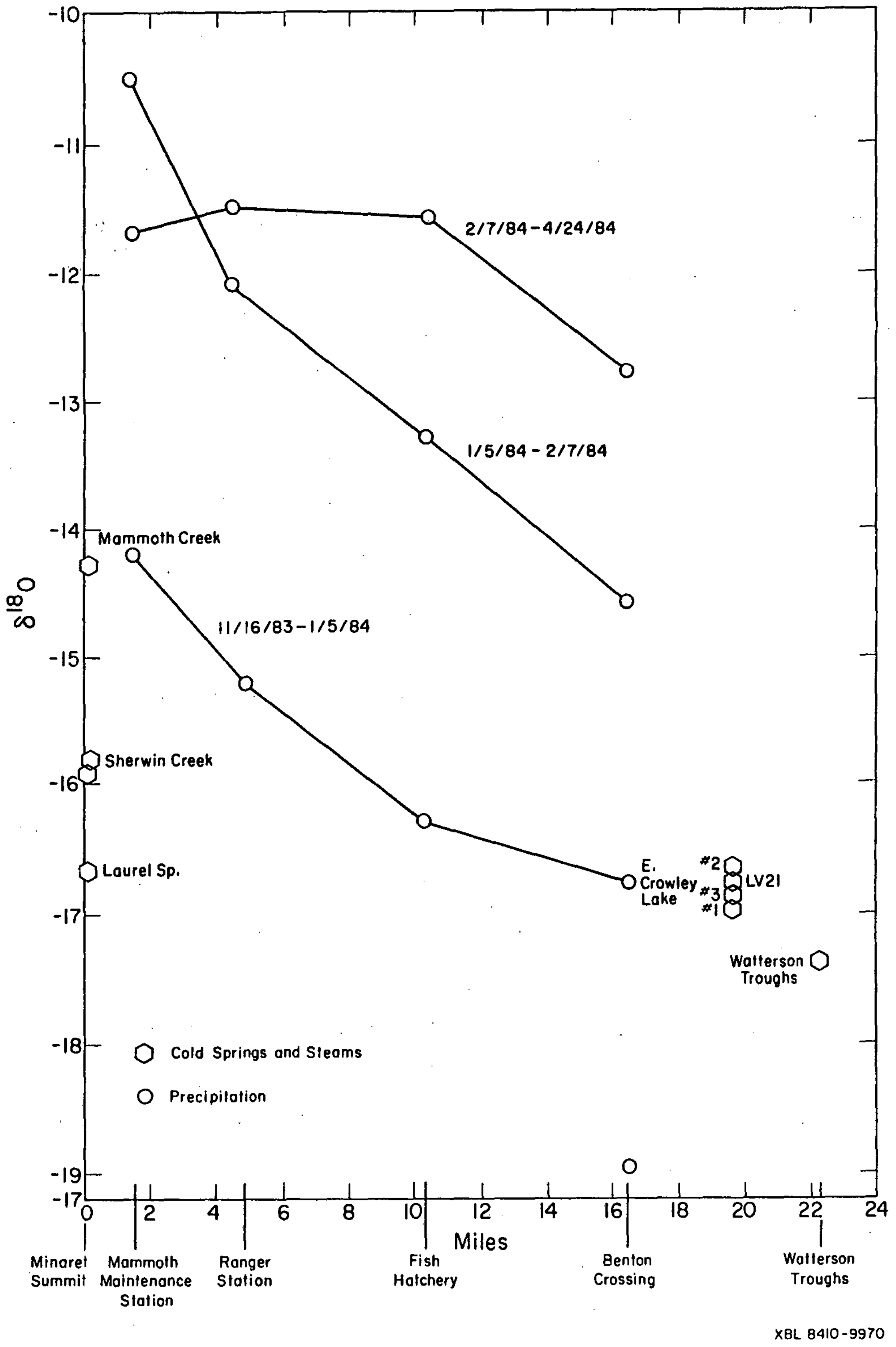


Figure 13. Oxygen-18 versus location along west to east transect.

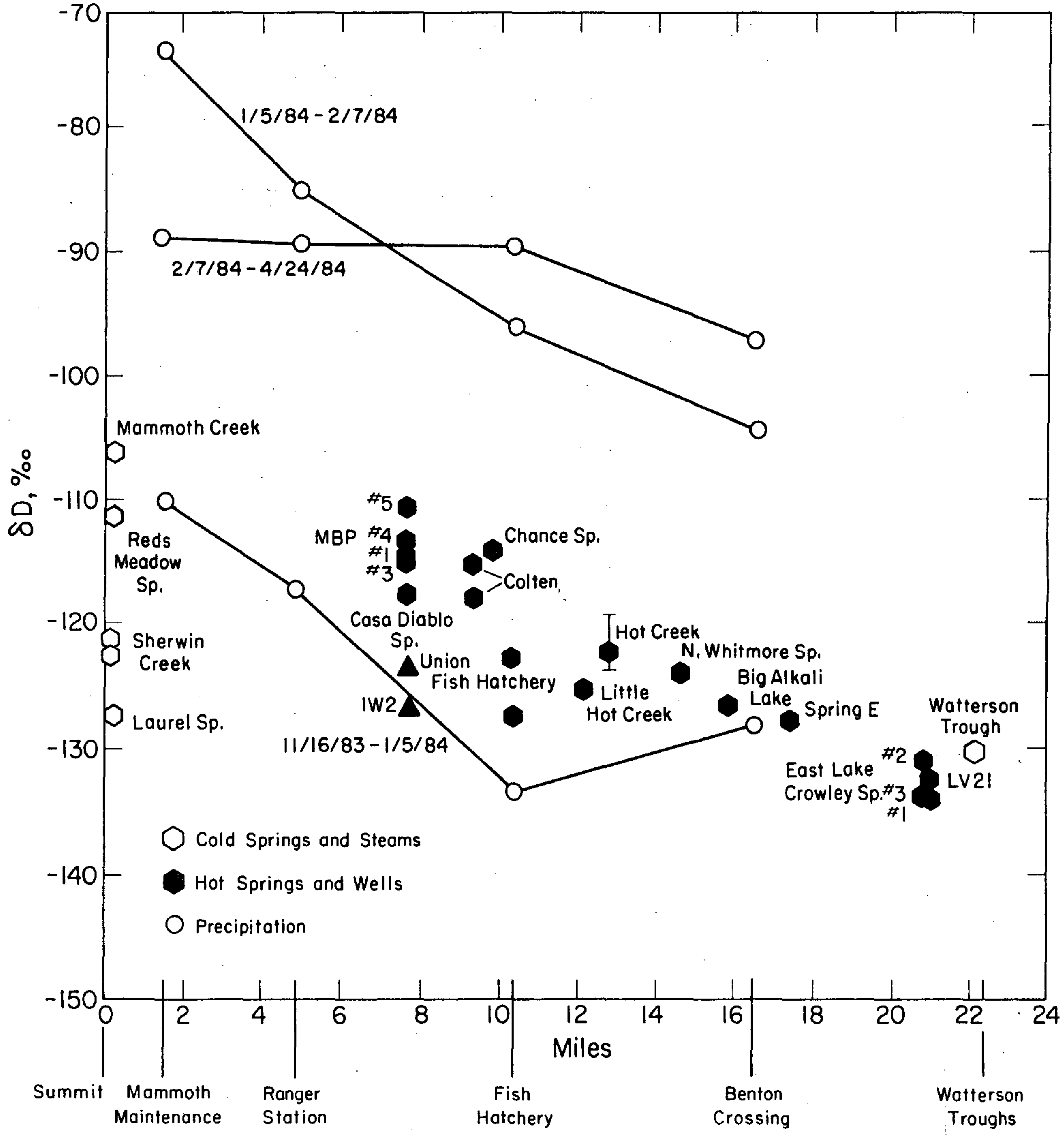


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Figure 14. Deuterium versus location along west to transect.

thermal aquifer (water isotopically similar to MIN) and recharge from the south (water isotopically similar to LS) for the injection zone beneath the shallow thermal aquifer.

The stable isotope data set as a whole shows considerable variability between samples from different vents within each thermal area and between analyses from different laboratories for waters from the same vent. These differences may result from a combination of several factors: actual isotopic variations, laboratory procedures, different sampling points, changes in the physical characteristics of the springs, or random errors. Although the observed variations are greater than the precision of the analytical methods used (2 δ-units for hydrogen, and 0.2 δ-units for oxygen), no systematic study of variations within this data set has yet been made from which actual changes in isotopic content with time could be discerned.

Janik and Wheeler are investigating the isotopic composition of aqueous sulfate to provide estimates of reservoir temperatures. Values of $\delta^{18}O$ of sulfate in thermal waters at Casa Diablo, Hot Bubbling Pool, and Hot Creek gorge range from -8.1 to -8.3 permil SMOW. Sulfate in water from Colton Spring has slightly heavier $\delta^{18}O$ values, measuring -7.6 for June 1983 and—8.0 for June 1984. Except for the 1983 Colton Spring analysis, these values are lighter than those reported by Fournier and others (1979); their $\delta^{18}O$ (SO_4) values ranged from -7.2 to -7.8 permil SMOW. Using their average $\delta^{18}O$ (SO_4) value and the calculated deep water $\delta^{18}O(H_2O)$ value from isotope mixing models, the sulfate-water oxygen-isotope geothermometer (McKenzie and Truesdell, 1977) indicates a deep thermal water temperature of 269 ° C. Using the average of the six post-1982 $\delta^{18}O$ (SO_4) measurements, the calculated temperature is 284 ° C; a temperature of 287 ° C is obtained if the 1983 Colton spring analysis is omitted. These higher geothermometer temperatures may indicate an increase with time in source reservoir temperature, or may reflect changes in sulfate-oxygen isotope compositions caused by mixing of deep thermal water with water containing sulfate that is relatively depleted of ^{18}O.

Nineteen aqueous sulfate samples, collected by Wheeler during 1983 and 1984 in the vicinity of the caldera, have been analyzed for sulfur- and oxygen-isotope compositions. Thermal waters from Casa Diablo, Colton Spring, Meadow Spring, Hot Bubbling Pool, and Hot Creek gorge have the highest δ^{34}S (SO_4) values (+12 to 14.5 permil) and highest ratios of Cl/SO_4 concentrations (average = 2.2) of all the intracaldera thermal and non-thermal waters analyzed. Based on the relative constancy of the values of Cl/SO_4, δ^{34}S (SO_4), and δ^{18}O (SO_4), these waters appear to derived from the same deep parent water; minor differences in the sulfate-isotope compositions and constituent concentrations are due mainly to variable dilution with non-thermal water of low sulfate concentration (<20 mg/L), low Cl/SO_4 ratio (<1.0), and low δ^{34}S (SO_4) value (most probable range: 4 to 7 permil).

Because thermal waters at Little Hot Creek and south of Big Alkali Lake have δ^{34}S(SO_4) values 2 to 3.5 permil lower than the main group of thermal waters but are similar in Cl/SO_4 ratio, they could not be derived from the main parent water by dilution alone. Addition of chloride and sulfate from other sources, such as Pleistocene Long Valley Lake sediments, would also be required. Thermal water at Red's Meadow Campground has a δ^{34}S (SO_4) value of about +3 permil, which is consistent with other chemical evidence for a fluid origin different than that of the intracaldera thermal waters. Analyses of the sulfur-isotope compositions of hydrothermal hydrogen sulfide gas and of different possible reservoir host rocks are planned by Wheeler and should provide additional constraints on the possible source(s) of sulfur in the thermal fluids.

Carbon isotopes—Carbon 13/12 ratios in CO_2 discharging at the land surface may reflect the origin of volatiles in hydrothermal systems, because of differences in values of the ratio in CO_2 derived from various crustal sources. The importance of CO_2 in volcanic processes and earthquakes has been noted by Barnes and others (1978), and Irwin and Barnes (1980).

Carbon isotope ratios have been determined on samples from most of the thermal and nonthermal springs. All stable carbon isotope data presented herein are expressed as δ^{13}C, in parts permil, relative to the Peedee belemnite standard (Craig, 1957). The ^{13}C values for thermal springs discharging waters above 70 °C fall in the range –1.7 to –6.1, and for nonthermal springs from –10.5 to –17.9 (Fig.15). Nonequilibrium fractionation apparently causes ^{13}C values in CO_2

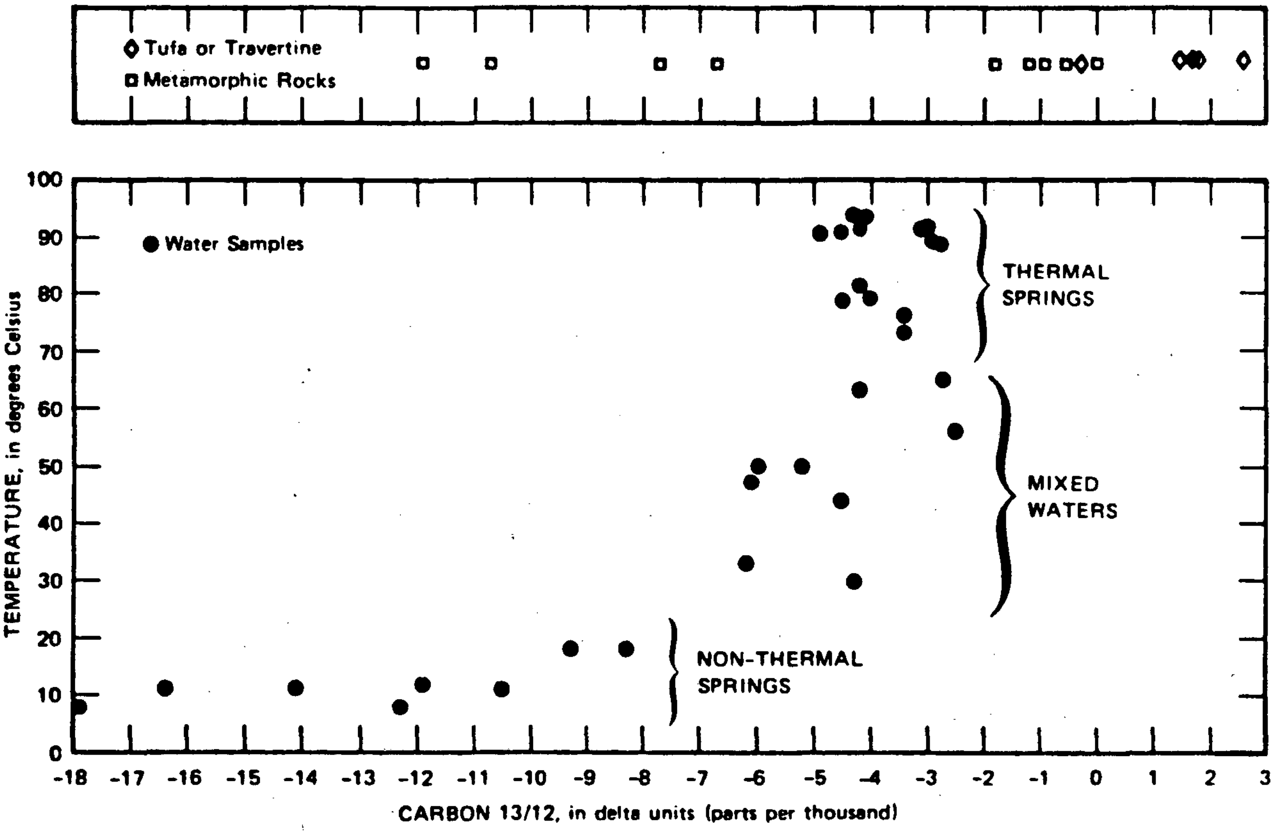


Figure 15. Carbon 13/12 ratios in selected rock samples and carbon 13/12 ratios for spring waters plotted against water temperature.

gas to be 1-2 permil lighter than in dissolved carbon at each hot spring.

The $\delta^{13}C$ content of CO_2 gas reported by Janik for 1983 samples varies in an eastwardly direction from –7.9 at Casa Diablo to –5.2 at Hot Creek gorge. These data prompted some discussion on whether the areal variations in carbon-isotope composition reflected (1) the differences in CO_2 gas chemistry from west to east, (2) the addition of CO_2 from underlying magmatic sources, or (3) the addition of CO_2 derived from other carbon sources such as the thermal decomposition of carbonate rocks. Further work is needed to determine the source of reservoir CO_2 and possible reactions that may cause changes in the carbon-isotope composition of the CO_2 gas.

The range of values for the thermal waters and gases is consistent with values obtained for mantle derived carbon (Fig. 15 and Table 6), but carbon 13/12 ratios from Paleozoic carbonate rocks collected immediately south and north of the caldera margin by Wollenberg also cover this range. The $\delta^{13}C$ values for carbonate rock samples from these Sierran roof pendant rocks range from 0.0 to –11.9, and values for tufa and travertine samples collected from outcrops within the caldera range from +2.6 to –0.3. None of the water or gas samples showed ^{13}C values in the range covered by the recent tufa and travertine, indicating these deposits probably do not contribute carbonate ions to the hydrothermal system or to the meteoric springs. In a system with aqueous carbonate species and carbon dioxide gas, fractionation processes tend to concentrate ^{13}C in the aqueous carbonates. This relation may explain why the gas samples are more depleted in ^{13}C than waters from thermal springs.

The most negative $\delta^{13}C$ values were measured in waters from cold springs and probably result from the pick up of carbonate ions enriched in ^{12}C derived from organic matter in recent sediments.

Experiments to determine the ^{13}C content in fluids and mineral phases from the Bishop Tuff by Gerlach yield values ranging from –15 to –40. This range is considerably lighter than the range of $\delta^{13}C$ values for both thermal and nonthermal waters and gases in the caldera. Gerlach also noted that the concentration of CO_2 in the Bishop Tuff is much too low for it to be a viable

Table 6. Range of carbon isotope ratios in nature. Values are given in delta notation relative to the PDB standard.

Material	$\delta^{13}C$
Fresh Water Carbonates[1]	–14.1 to +9.8
Marine Carbonates[1]	–3.3 to +2.4
Carbonatites and colorless diamonds[2]	–10 to –2
Colored diamonds[2]	–10 to –2
CO_2-fluid inclusions, oceanic basalts[3]	–32.3 to –5
Atmospheric carbon dioxide[1]	–10 to –7
Aquatic plants—terrestrial[2]	–19 to –6
Basalts-whole rock[1]	–26 to –19
Organic matter in recent sediments[2]	–30 to –10
Rocks from Long Valley Area:	
Tufa and travertine*[4]	–0.3 to +2.6
Sierran metamorphic carbonates*[4]	–11.9 to 0
Bishop Tuff-fluid inclusions**[5]	–40 to –15

[1] Data from Craig, 1953.

[2] Data from Faure, 1977.

[3] Data from Pineau and others, 1976, and Moore and others, 1977.

[4] Data from H.A. Wollenberg, written communication, 1985.

[5] Data from T. Gerlach, written communications, 1984.

source of CO_2 in the fumaroles (Taylor and Gerlach, 1984).

Helium isotopes—Rison et al. (1983) reported results of helium isotope sampling at Hot Creek gorge between 1978 and 1983. Based on four samples from the vicinity of hot spring HC-4 (Fig. 9), these data show concomitant increases in $^3He/^4He$ and He/CO_2 ratios which were attributed to an increase in the mantle helium component in this spring. Additional sampling in 1983 and 1984 by Rison yields a larger data set that includes values for these ratios at other sites of thermal fluid discharge (Table 7). Sampling sites listed in Table 7 are arranged by increasing distance eastward from Reds Meadow.

The helium isotope data for Long Valley show a general trend of increasing $^3He/^4He$ from west to east. Such a trend could reflect input of ^3He from a magma chamber beneath the western half of the caldera to an eastward-circulating hydrothermal system. Alternatively, the input of ^4He from Sierran basement rocks may decrease from west to east as the thickness of roof pendant rocks increases. The range in $^3He/^4He$ for intracaldera sites is small (4–6), however, and approximately equal to the range (4–5) measured for samples from wells that tap the Baca geothermal reservoir in the Valles Caldera, New Mexico (Smith and Kennedy, 1985). At the Yellowstone Caldera, Wyoming, larger variations in this ratio are observed from one region to another and within each thermal area (Kennedy et al., 1985). Values of the maximum $^3He/^4He$ for different thermal area at Yellowstone cluster in two groups at approximately 7 times the air value and 15 times the air value. Kennedy attributes variations in $^3He/^4He_{max}$ between thermal areas to variations in the efficiency with which mantle volatiles are extracted from the cooling batholith and transported to the surface. Kennedy described the mechanism of transport to the surface as the entrainment of mantle volatiles by hydrothermal fluids circulating in one or more laterally extensive reservoirs.

Values of $^3He/^4He$ and He/CO_2 decreased between 1983 and 1984 at each of the three sites in Long Valley caldera for which repetitive measurements have been made. The data for site HC-4 in Hot Creek gorge listed in Table 7 also show the increase in these ratios reported by Rison et al. (1983) for the 1978-1983 period. These changes are consistent with likely variations in the

Table 7. Ratios of $^3He/^4He$ in helium gas from hot springs and fumaroles to the helium isotope ratio in air and ratios of He concentration ($\times 10^6$) to CO_2 concentration. Data from Rison et al. (1983) and Rison (verbal communication, 1985). Locations of features sampled are shown in Figs. 6–9.

Feature (type) Date:	$^3He/^4He$ (He/CO_2) 10/78	 8/81	 6/83	 10/84
RMT (hot spring)				2.5 (5.3)
SS (soda spring)				0.5 (4.2)
MMN (fumarole)				4.5 (29)
OH (fumarole)				3.0 (133)
CDG (hot spring)				4.5 (13)
CDF (fumarole)			4.9 (11)	4.5 (19)
CS (hot spring)*				4.5 (436)
LCF (fumarole)				4.0 (100)
HBP				3.7 (0.2)
HC-4	4.8 (0.75)	5.2 (2.3)	5.7 (6.5)	5.2 (5.8)
HC-3				4.7 (4.9)
LHC-3			6.5 (21)	6.0 (16)
21P1				6.0 (10)

*Sampled from steam vent 100 ft above hot spring level of ^{3}He input from mantle sources accompanying magmatic intrusions inferred to have taken place during May 198O and January 1983 (Hill et al., 1984). Detection of such variations at the land surface requires that helium move into and through the hydrothermal system in periods of months to years. Additional monitoring of helium and other noble gases along with $^{13}C/^{12}C$ ratios is required to adequately assess the significance of the helium isotope data for Long Valley.

Radioisotopic Data

Radioisotope data for Long Valley waters include tritium analyses for waters from approximately 20 sites collected in 1983 and 1984. The analytical results show detectable concentrations of tritium in all samples from springs and wells. Concentrations are reported in tritium units (T.U.), values range from less than 1 T.U. in several hot spring samples to 25 T.U. for a sample from Big Spring. there is a general inverse correlation between tritium concentration and spring temperature.

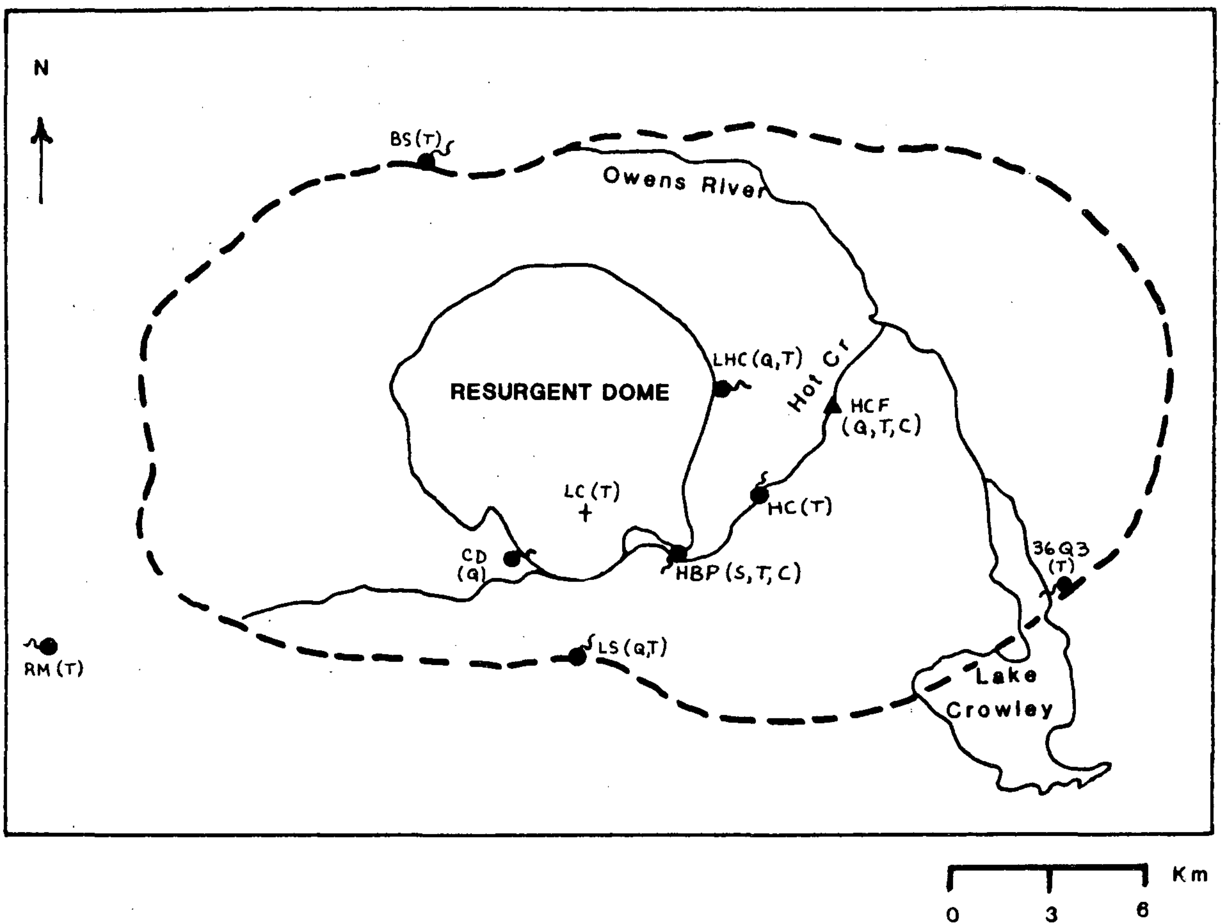
For age-dating waters using tritium it is generally assumed that if concentrations are less than 5 T.U. the water entered the ground-water system sometime prior to 1953. If concentrations are much higher it is an indication that all or part of the water entered the ground-water system after 1953. Mixing of pre- and post-1953 waters can greatly complicate the interpretation of tritium data.

The lack of knowledge regarding the age of ground waters could be remedied by investigating other isotopic dating methods. Carbon-14 is a likely candidate for providing age dates in the probable range of values expected in Long Valley waters. Other isotopes suggested for tracing movement and mixing of waters include chlorine and beryllium. Goff described the application of $^{36}Cl/Cl$ and the concentrations of ^{36}Cl and total chloride to determine water/rock interaction and mixing ratios of waters. This technique was recently applied in the Valles Caldera (Phillips and Goff, 1984). Valette-Silver discussed the use of ^{10}Be for determining recharge rates and ground-water flow paths. A discussion of ^{222}Rn in spring water is included in the section on gas emissions.

Discharge Rates and Temperatures of Springs

The discharge rate and temperature of selected springs and spring groups shown in Figure 16 are currently being monitored by Farrar, Sorey, and Clark. The purpose of this monitoring is to detect changes in response to earthquakes, magmatic intrusions, and fluid production for geothermal development. Prior to 1970, records of spring discharge are limited to the estimates noted by Waring (1915) for springs at Casa Diablo and subsequent qualitative descriptions of these springs and springs at several other thermal areas. A limited number of measurements and estimates of spring flow and temperature were made by different investigators during the 1970's in order to characterize fluid discharge from the hydrothermal system. Clark began continuous recording of spring flow on Little Hot Creek in 1979 and at Laurel Spring in 1980. Additional spring monitoring sites were added after 1980. Results of these monitoring activities are described below.

Casa Diablo area—The available historic record of spring flow at Casa Diablo through 1984 (Table 8) shows qualitatively that periods of low flow (1–2 L/s) and dormancy have been interrupted by periods of geyser-like activity and increased liquid outflow. Geyser-like activity refers to the spurting or fountaining behaviour of several boiling springs labeled CDG in Figure 7. Initiation of geyser-like activity at CDG may result from seismic activity, erosion and draining of the liquid pools around each vent, artificial stimulation, or other unknown causes. Beginning in June 1984, visual observations and measurements made using a 6-inch Parshall flume and stage recorder installed immediately below site CDG show that spring discharge in this area increased rapidly but stayed relatively constant during the period June 1–November 2, 1984. On November 2 the outflow from the CDG springs further increased from 10 to 25 L/s for unknown reasons, then subsequently declined to an average of 17 L/s with considerably more short-term variability during the remainder of 1984. The total outflow of hot water from springs located west of old highway 395 (including CDG) was measured by stream gaging as 43 L/s on December 19, 1984 and 34 L/s on January 22, 1985.



EXPLANATION

● HBP(S,T,C)	Location of spring; HBP is identifier; in parentheses, S is stage, T is temperature, and C is specific conductance
▲ HCF(Q,T,C)	Location of surface water site; HCF is identifier; in parenthese, Q is stream flow, other symbols as defined above
+ LC (T)	Location of soil temperature site

Figure 16. Map of Long Valley caldera showing locations of active and inactive sites for monitoring streamflow, stage, temperature and specific conductance,

Table 8. Record of measured and estimated spring flow at Casa Diablo Hot Springs.

Dates	Observation or measurement	Reference
Prior to 1931	Total spring flow about 2 L/s	Waring (1915), historic photos
1931	"Geyser" stimulated to erupt by drilling into vent. Flow diminished soon after.	Blake and Matthes (1938)
1931-37	"Geyser" dormant or slightly active	Blake and Matthes (1938)
12/21/37	"Geyser" reactivated by unknown cause	Blake and Matthes (1938)
1940's and 1950's	"Geyser" active	Photos in Smith (1976)
1960's	Spring flow diminished by drilling and testing of Magma Power Co. wells	Speculation
1972-73	Total spring flow estimated to vary between 0-1 L/s	Sorey and Lewis (1976)
1980-82	Spring flow estimated to gradually increase due to increased seismic activity	Photos by M.L. Sorey
6/1/84	Fountaining of "geyser" increased significantly (due to erosion and drainage of geyser pool?)	Photyos by M.L. Sorey
9/1/84 to 11/2/84	"Geyser" flow measured at 10 L/s, total spring flow estimated at 20 L/s	Measurements at flume below CDG
11/2/84	"Geyser" flow increased to 25 L/s	
11/3 to 12/19/84	"Geyser" flow averages 17 L/s, total spring flow measured on 12/19 as 43 L/s	Measurements at flume below CDG and stream-gaging measurements

Changing patterns of drainage of hot water from site CDG due to channel erosion made the discharge record for the CFG flume difficult to interpret after mid-December 1984. Consequently, additional flumes were installed at sites in the stream channel (Fig. 7) above and below the areas of hot spring discharge west of the old highway in 1985 to allow repeated measurements of total hot water flow. Such measurements indicate that fluid production from nearby geothermal wells (labeled MBP in Fig. 7) can cause drastic reductions in hot spring flow.

Little Hot Creek area—The springs along Little Hot Creek are located in a small canyon near the head of the creek (Fig. 8). Above the springs there is no perennial flow in the channel. Five main spring orifices discharge high-chloride water at temperatures of 76 ° -82 ° C.

A weir plate and stage recorder were installed by Clark in Little Hot Creek in November 1979 at a site about 400 ft downstream from the hot springs. The continuous record of flow at this site is tabulated in terms of average daily discharge for the period January 1980-December 1984 in data reports issued by the U.S. Forest Service, Mammoth Ranger District, Inyo National Forest. Based on these records the average total flow of the hot springs above the weir is approximately 11 L/s.

Changes in spring flow at Little Hot Creek following earthquakes of magnitude 6 in May 1980 were delineated by Sorey and Clark (1981), who recorded increases in the total spring discharge of as much as 45 L/s following the earthquakes on May 25, 1980 (Fig. 17). Spring flow returned to normal within a period of hours after the earthquakes and a similar response has occurred following several earthquakes of magnitude >5 in subsequent years. In contrast, continuous records of temperature in the spring orifice labeled LHC-2 show no significant coseismic temperature changes. In July 1984 a flume and recorder were installed immediately below the spring orifice labeled LHC-1 (Fig. 8) to monitor fluctuations in discharge unaffected by periods when Little Hot Creek is flowing above the hot springs.

Hot Creek gorge area—Numerous hot springs discharge into the creek along a 1 mile section of Hot Creek gorge (Fig. 9). The flow from individual spring vents in the gorge has been observed qualitatively to vary with time following the larger magnitude earthquakes that have occurred in

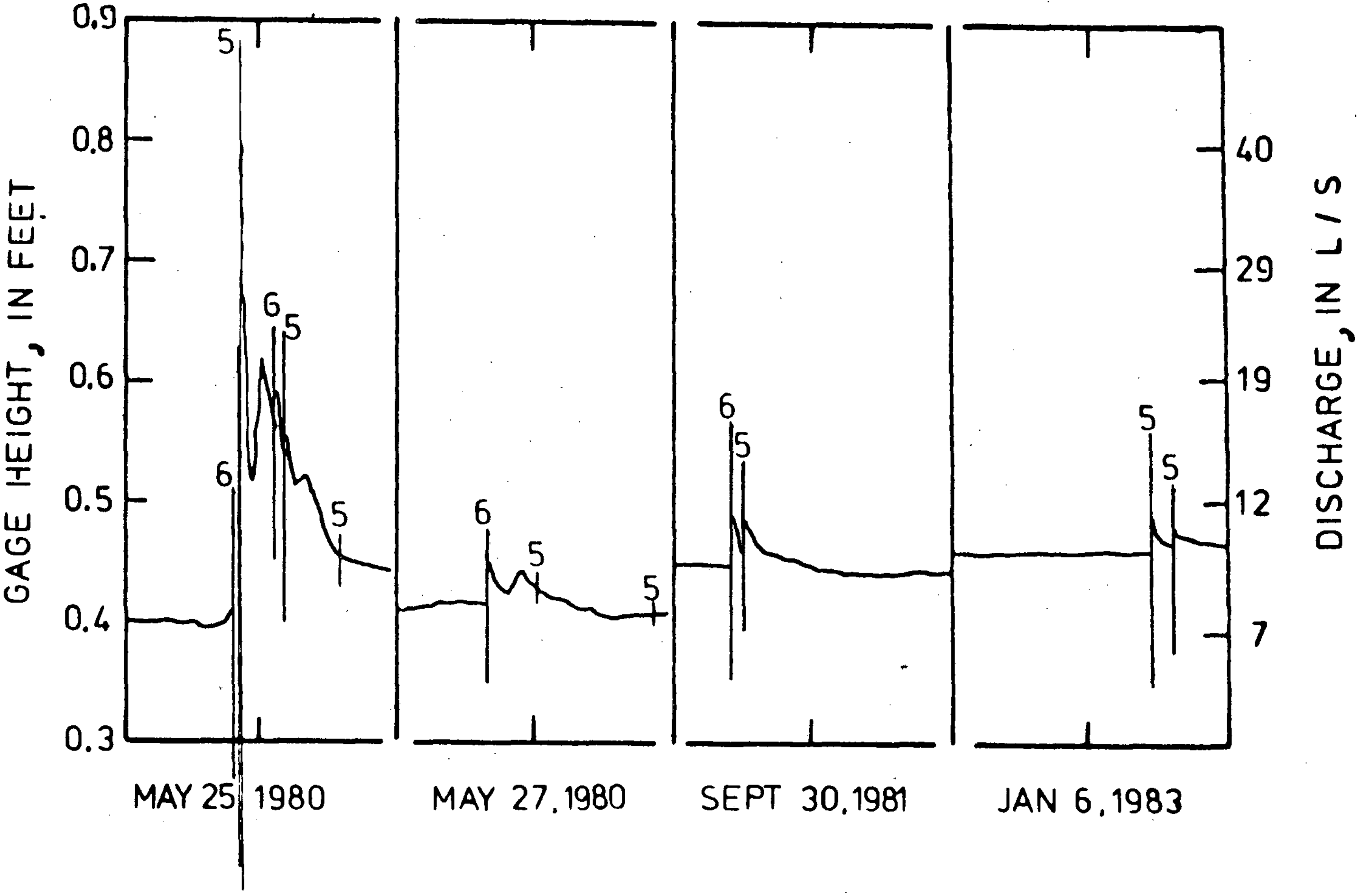


Figure 17. Records of water stage at the weir on Little Hot Creek and earthquakes of magnitude 5 and greater registered on four dates between May 1980 and June 1983, on the seismograph maintained by the Forest Service at the Ranger Station in Mammoth Lakes, California. Vertical lines at time of each earthquake caused by local ground motion and not changes in spring flow.

the Long Valley area since 1973. New vents have frequently been activated while flow from other vents has decreased or disappeared. Seismically induced increases in spring flow presumably reflect increases in the permeability of fault conduits which cut across the gorge; subsequent decreases in permeability could be due to mineral deposition and sediment clogging. As discussed below, however, the total discharge of hot water in the gorge is not significantly affected by these near-surface effects.

The total flow of hot springs in the gorge was estimated by Eccles (1976) and Sorey and Clark (1981) from measurements made between 1972 and 1980 of streamflow and chemical load in Hot Creek upstream and downstream from the gorge. Hot spring discharge is calculated as the increase in flux of chloride or boron divided by the concentration of these elements in the gorge hot springs. Attempts to estimate hot spring inflow from streamflow measurements alone would be of questionable value because such inflow is only about 10 percent of the average flow of the Hot Creek.

From these data the average discharge of hot springs in the gorge is calculated as 271 L/s (Farrar et al., 1985). There is an indication that this discharge was somewhat greater following the earthquakes in May, 1980 (average value for 1980 measurements is 312 L/s) and has subsequently returned to pre-1980 levels. However, such a conclusion is limited by the variability in individual chemical flux measurements, and the limited number of simultaneous measurements of chemical flux upstream and downstream from the gorge. Continuous records of chemical flux at the Hot Creek flume (HCF) which begin in August 1983 offer a better chance to discern changes in spring flow in Hot Creek gorge related to tectonic activity or other processes. The relationship of specific conductance, continuously recorded, to boron and chloride concentrations and continuous stream stage measurements allow calculation of chemical fluxes and corresponding estimates of hot spring discharge rates. Mean daily values of streamflow and chloride flux at HCF during 1984 are plotted in Figure 18.

Analysis of the chloride flux record at the Hot Creek flume is still in progress. Preliminary checks show evidence of changes in hot spring discharge preceding and following large magnitude

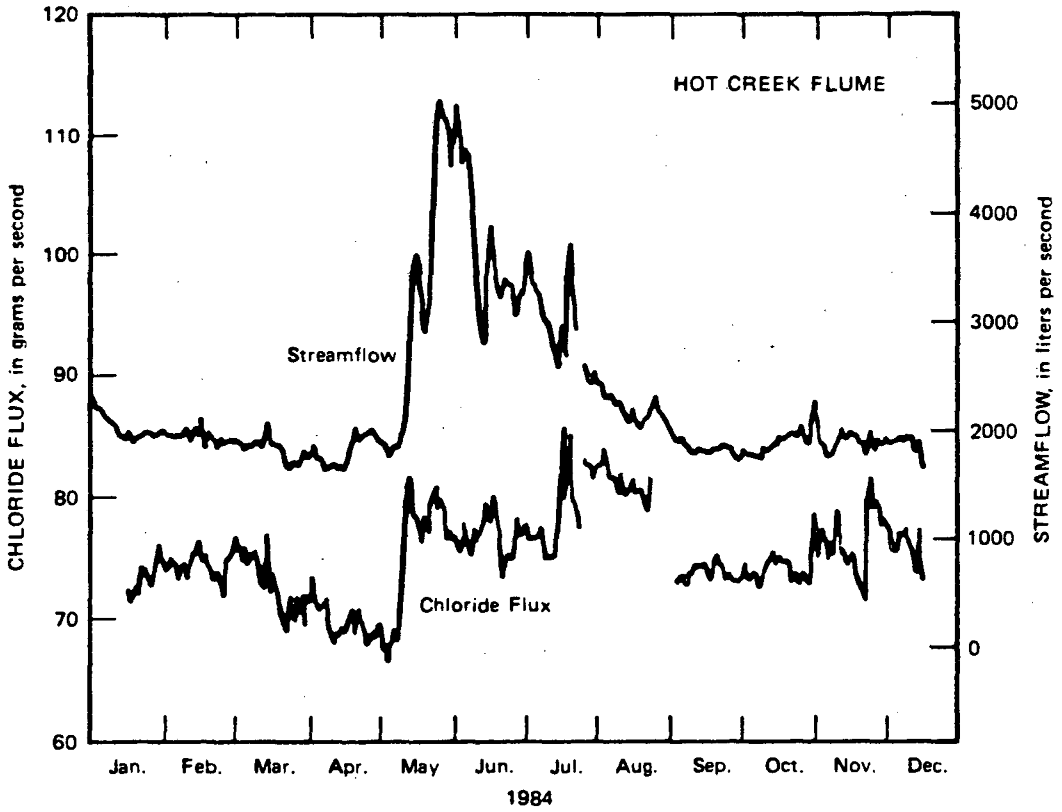


Figure 18. Plots of streamflow and chloride flux at Hot Creek flume for 1984, based on values of river state and specific conductance recorded at 15-minute intervals and averaged over 24-hour periods.

earthquakes such as the M_L5.7 event that occurred on November 23, 1984 within the Sierra south of the caldera. More detailed analyses of such effects requires comparisons of values of specific conductance, temperature, and streamflow averaged over time intervals shorter than 24 hours. Such efforts may be complicated during periods of rapidly increasing streamflow, as in May 1984, which appear to be accompanied by release of chloride from nonthermal sources within the drainage basin above Hot Creek flume. During periods of relatively constant streamflow, the chloride flux technique appears capable of detecting changes in hot spring discharge as small as 25 L/s, or about 10 percent of the total spring flow in the gorge.

Hot Bubbling Pool—Hot Bubbling Pool (HBP), also referred to as Casa Diablo Hot Pool, lies near the southeast margin of the resurgent dome along the eastern fault of the central graben (Figs. 1, 2 and 6). The surface area of the pool varies considerably with stage but averages about 650 m^2. The water temperature in the pool varies with time and location; a range of 50 °-80 ° C has been measured since 1983 at a depth of 4 ft at a site along the northern margin of the pool. There apparently has been no surface discharge from the pool since before 1908 (Waring, 1915), but a channel leading from the pool toward Hot Creek indicates surface flow may have occurred at sometime in the past. Sorey and Lewis (1976) calculated that 6.5 L/s of hot water upflow was needed to maintain a surface temperature near 55 ° C. The pool was reported to have dried up following the May 25–27, 1980 earthquakes, refilling about one week later (Sorey and Clark, 1981).

Beginning in 1983, instruments to record water temperature and pool stage were installed. A typical record (Fig. 19), for July 1984, shows a distinct cyclic nature for both temperature and stage with a nearly constant period of about 7 hours. The magnitude of the cycles varies seasonally and may relate to changes in water table altitude. No satisfactory explanation specifying the cause of the cyclical stage or the length of cycle period has been found to date. During rising stage the temperature increases indicating hot water inflow causes the stage to rise. At high stage, water must flow in the subsurface laterally away from the pool reducing hydrostatic pressure and allowing the cycle to begin again. Because this pool has been noted to respond to earth-

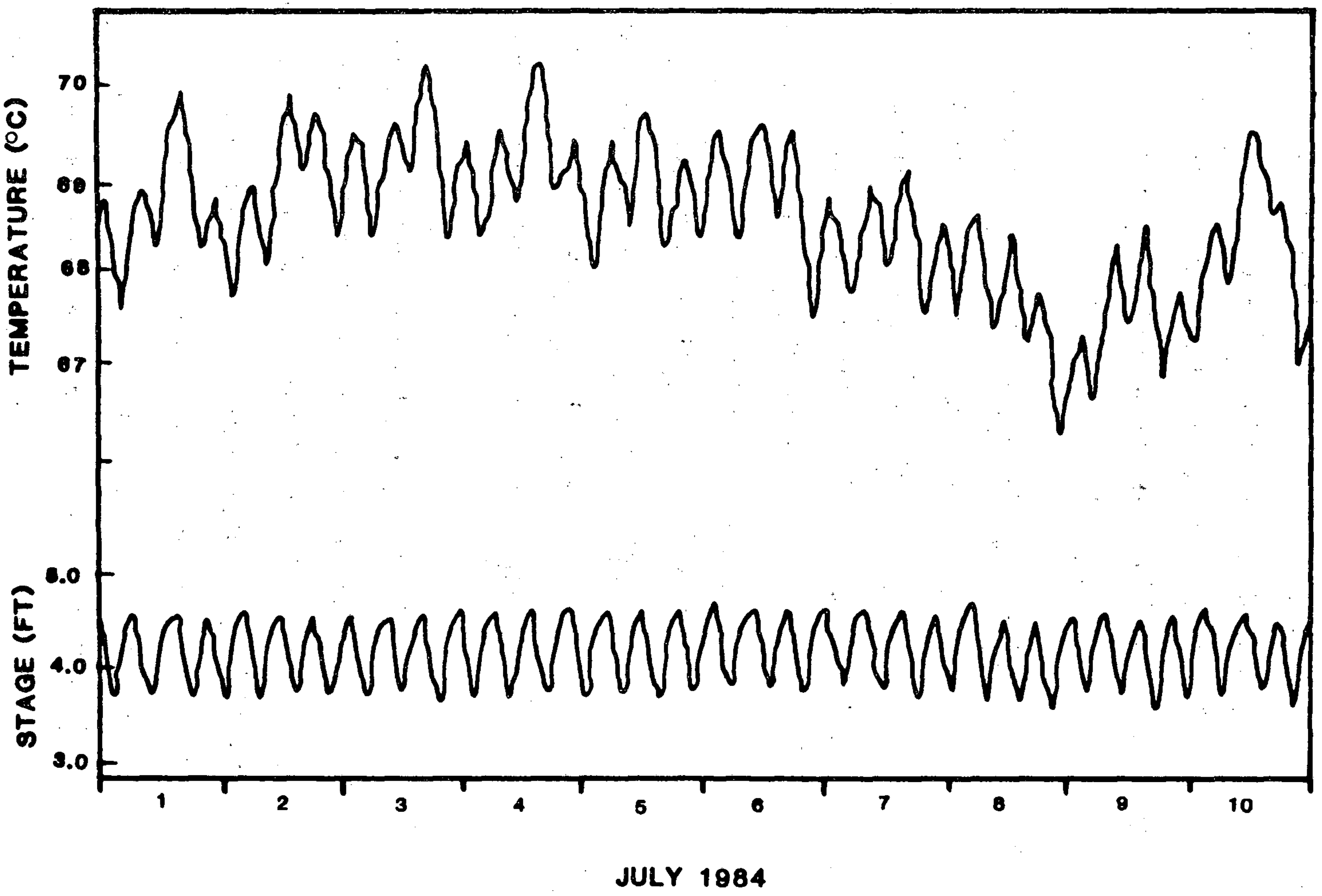


Figure 19. Temperature and stage record at Hot Bubbling Pool for 10 days in July 1984.

quakes, monitoring at this site may prove fruitful in detecting local crustal strain.

Laurel Spring—Laurel Spring (LS) lies at the foot of the Sierra along the south margin of the caldera. The site has been monitored by Clark for water temperature from March 1980 to March 1982, and for discharge rate from November 1980 to present. During the 1980–82 period, water temperature at this site remained within 0.5 ° C of 12.0 ° C. Discharge has varied from 34–41 L/s. Discharge increases of 10–15 percent have been recorded immediately following earthquakes greater than $M_L 5$. The flow returns to normal within several hours to 1 day.

Other temperature recording sites—Temperature measuring instruments have been setup and maintained by Clark at four locations in and near the caldera. At Big Springs (BS), water temperature was essentially constant at 12.0 ° C during the period of record (April 1982 to October 1983). The temperature of individual vents at this site vary from 11.0 ° C-14.0 ° C. An unnamed thermal spring (36Q3), located east of Lake Crowley, has discharged water at a constant 22.5 ° C since the record began in April 1984. At Reds Meadow (RM), temperature is recorded in a spring located just uphill from the main spring which feeds the Forest Service campground bathhouse. Since the record began in June 1984 the temperature has averaged about 40 ° C with a range of ±2 ° C. Soil temperature at 1 meter depth along the western side of Long Canyon (LC) has been recorded from August 1982 to present. Temperatures have varied from 73.0 ° C to 83.0 ° C. No correlation of these variations to other factors has yet been made. Increased steam discharge in this area was first noted following the earthquakes in May 1980.

Geochemical Observations at Phlegrean Fields Caldera

One potentially useful approach to the interpretation of monitoring data collected at Long Valley is to compare these data with those collected at other areas with similar geologic and volcanologic settings. The Phlegrean Fields caldera in Italy is well suited for such comparison and has recently been the site of seismic activity and uplift at rates significantly greater than at Long Valley. Surficial hydrothermal activity at Phlegrean Fields caldera includes a central zone of steam and steam-heated discharge (La Solfatara), acid-sulfate hot springs outside the north rim of the caldera, and submarine fumaroles within the intracaldera Bay of pozzavoli (Valette-Silver, 1984). Temperatures of fumaroles within La Solfatara range from 142–157 ° C, whereas fumaroles in Long Valley show no significant degree of superheat. Steam discharge at La Solfatara is believed to be fed by upflow from a boiling reservoir at a depth of about 1450 m and at temperatures of 270–280 ° C (R. Cioni, written communication, 1985). Fumarolic gases may be derived in part from an underlying magma chamber at depths of 3–5 km.

A period of renewed uplift (2–3 mm/day) and seismicity began in 1982 and persisted through 1984. Although fumarolic temperatures and gas chemistry at La Solfatara changed little during this period, significant increases in steam/gas ratios and H_2/CH_4 and H_2S/CO_2 ratios have been observed (M. Martini, written communication, 1985). These observations, along with seismic and geodetic measurements, are consistent with intrusions of magma and associated convective heat inputs to overlying fluid reservoirs.

Geochemical changes similar to those detected at Phlegrean Fields caldera may not occur at Long Valley until levels of crustal unrest approach those in the Italian case. In the present-day hydrothermal system at Long Valley the only indications of magmatic contributions are the ratios of $^3He/^4He$ and $^{13}C/^{12}C$ in gas discharges. Nevertheless, further analysis of monitoring results at places like Phlegrean Fields caldera serve as a useful guide in future monitoring at Long Valley.

MONITORING GAS EMISSIONS

Gas constituents being measured and/or monitored in Long Valley include Rn, Hg, He and H. Reports covering surveys of these elements have been prepared by Williams (Rn and Hg), Wollenberg and co-workers (Rn), Reimer (He) and McGee and coworkers (H). In addition, published work on Hg by Varekamp and Busek (1984) also is summarized here. In the case of Rn, comparison can be made between soil-gas and spring-water temporal data.

Temporal changes in concentrations of these elements may reflect changes in stress in response to crustal deformation preceding or associated with seismicity and/or magma injection, and changes in the near-surface thermal regime, controlled to a large extend by movement of ground water. Soil-gas concentrations and their emanation may vary over short time spans in response to changes in atmospheric pressure, soil temperature, and soil moisture. To overcome the effects of these short-term changes, monitoring of Rn, He, and Hg involves long-term occupancy of detector systems where data are integrated over a period of several weeks. Surveys of soil-gas concentrations of these elements have emphasized regional patterns and their changes over one or more years, while H and He have been monitored to observe shorter-term (hourly - daily) variations. In this respect the H data may be compared with hourly monitoring of Rn in a cold spring at the Fish Hatchery. However, because Rn concentrations in spring waters are temperature dependent, regional soil-gas Rn patterns are probably not directly comparable with water Rn patterns.

Mercury

Surveys began in 1975, when Varekamp and Busek deployed soil-gas Hg monitors over a broad area of the Long Valley caldera. Results of re-occupation in 1982 showed increases in the western moat between Deer and Mammoth mountains. This increase was attributed to possible Hg emission from relatively shallow magmatic intrusions and/or the effects of increased upward flow of hot water in zones whose permeability was enhanced by seismicity. Varekamp and Busek pointed out that ground cracks formed in this area between the times of their surveys. A zone of lower emission was detected in 1982 in an area southeast of Casa Diablo, within the area of post-

1980 earthquake activity. Surveys by Williams and students, of 600 sites in 1983 and 140 sites in 1984 (Fig. 20) also showed the zone of low Hg concentrations over the epicentral area and extending southeastward out of the caldera (Williams, 1985). Hg highs occur in the western moat and Mammoth Mountain areas and over the resurgent dome. However, there is a general trend of decreasing Hg concentration since 1975 and 1982.

Radon

Soil-gas surveys

Track-etch cup surveys of soil gas ^{222}Rn (Fig. 21) were conducted by Williams and students in 1983 and repeated in 1984 (Williams, 1985). The highest values in the 1983 survey occurred in the epicentral zone, bisecting the surface projection of a dike proposed by Savage and Cockerham (1984) in the south moat. The background values of the 1984 survey are almost half those of 1983 (47, versus 82 tracks/mm^2 per 30 days). Though mean peak values were higher in 1984 than in 1983, they made up only 2% of the population, compared to 5% in 1983. The 1984 peak values were still concentrated in the south moat area, but covered a somewhat broader zone than in 1983. Therefore, the Rn data suggest that the overall soil-gas concentration of this element was lower in 1984 than in 1983, with the south moat epicentral zone anomalous in that peak values were higher in 1984. This is somewhat in keeping with the overall decrease in soil-gas Hg observed between 1975, 1982, and 1984. For comparison, water-borne Rn concentrations of Laurel Spring and at the Fish Hatchery (spring H-II, III) averaged slightly higher in 1984 than in 1983.

Water-borne Rn

Wollenberg and co-workers (1985) report that the ^{222}Rn concentration in the springs of the caldera varies inversely with their temperature and specific conductance. High concentrations (1500 to 2500 pico Curies/l) occur in dilute cold springs on the margins of the caldera, while low contents (12 to 25 pCi/l) occur in hot to boiling springs. Spring-water Rn concentrations also correlate slightly with the U content of the encompassing rocks.

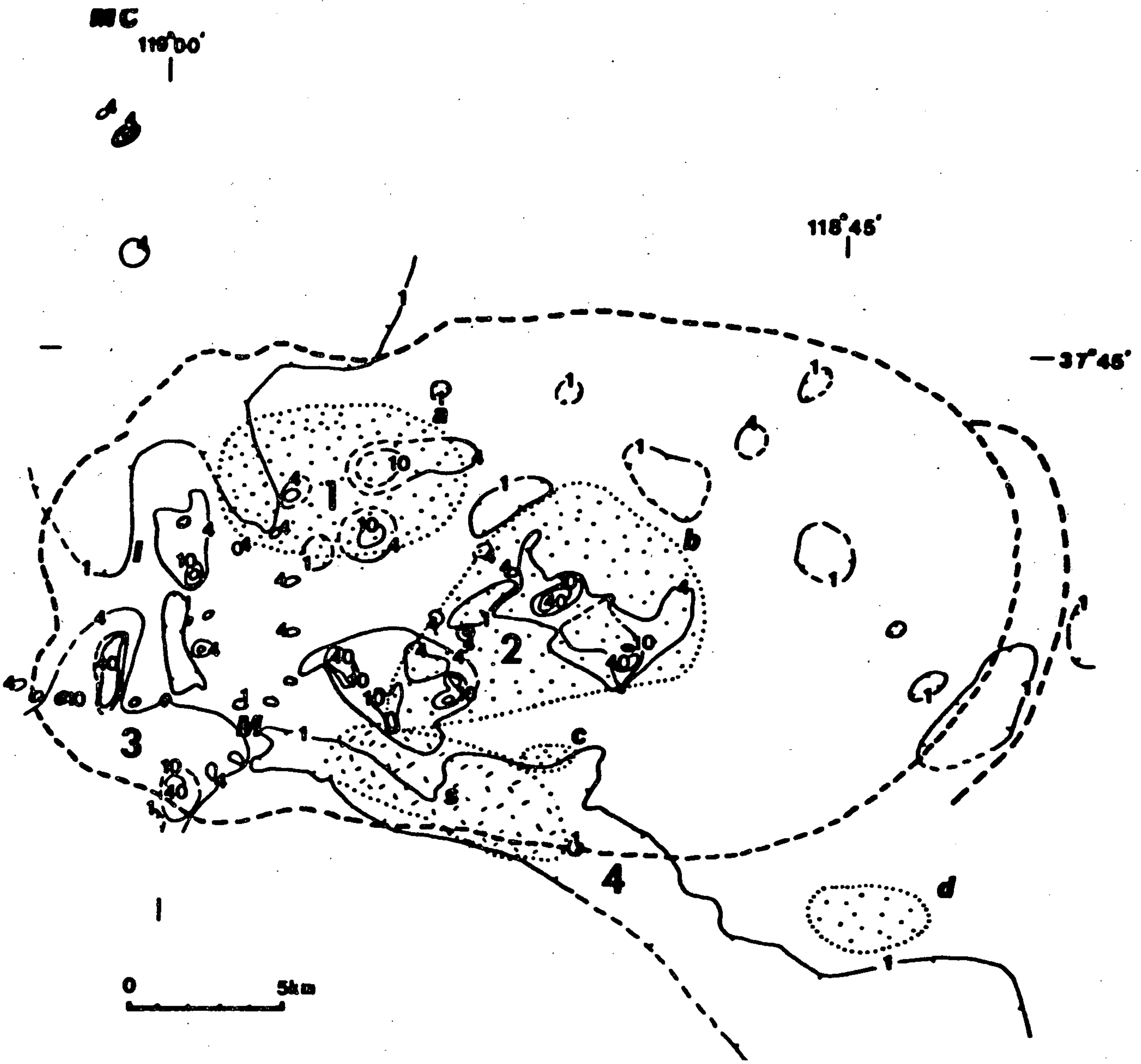


Figure 20. Outline map of Long Valley caldera showing geometrically contoured Hg° anomalies (solid lines) and magma bodies proposed by Sanders (1984) (stippled areas a-d). Hg° contours are 1 × background (6.6 ppb), 4 × background (26.4 ppb), 10 × background (66 ppb) and 40 × background (264 ppb). Values greater than 4 × background are threshold and greater than 10 × background are peak population. Bold numbers (1-3) indicate broad Hg° highs and (4) broad Hg° low. Areas 1 and 2 are closely associated with faults over magma bodies a and b. Area 4 is associated with the area of greatest seismicity. Area 3 Hg° high occurs outside region studied by Sanders (1984) in his study of possible magma bodies at Long Valley. M is site of Mammoth Lakes Village, MC is site of Mono Craters, and I is site of Inyo Craters. (Figure from Williams and Hudnut, 1984)

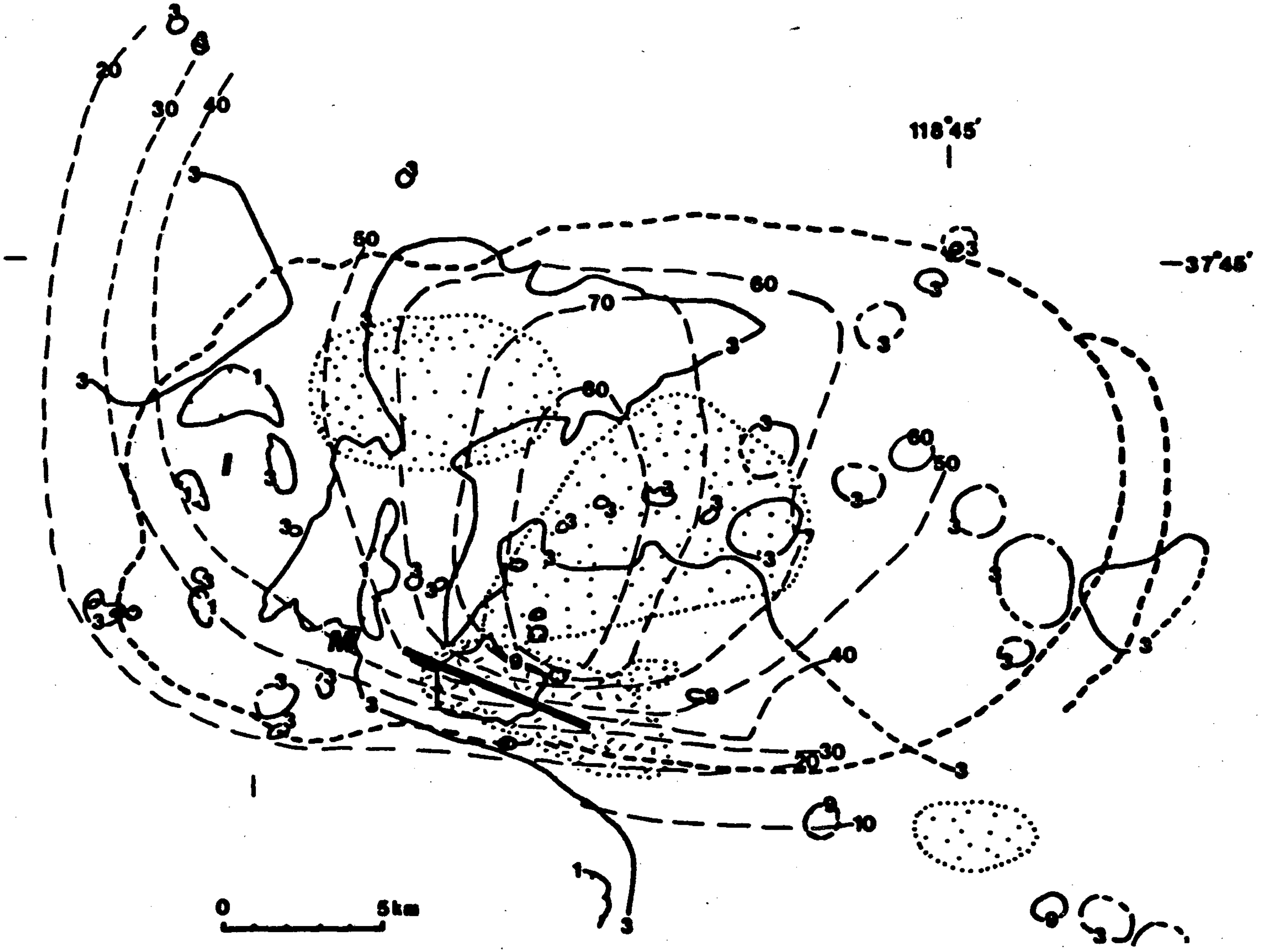


Figure 21. Outline map of Long Valley caldera showing geometrically contoured Rn anomalies (solid lines), magma bodies (stippled areas), area of seismic swarm (hatched), surface projection of dike proposed by Savage and Cockerham (1984) (solid heavy line), and 1982–1983 uplift (light dashed lines) in mm. Rn contours are 1 × background (82 T/mm^2/30 days), 3 × background (246 T/mm^2/30 days) and 9 × background (738 T/mm^2/30 days). Values greater than 3 × background are threshold and greater than 9 × background are peak population. (Figure from Williams and Hudnut, 1984).

A continuous monitoring system was installed in August, 1983 at a pool at the Hot Creek Fish Hatchery, fed by spring H-II, III issuing from basalt. The pool temperature remains nearly constant at ~12 ° C year-round, while the flow rate varies seasonally about a mean of 150 L/s. The system provides hourly records of ^{222}Rn concentration. A gamma detector is submerged in the pool, and the radioactivity measured in this manner is due almost entirely to the ^{222}Rn concentration of the water. Operation of the system shows 12 and 24-hour periodicities in variations in the ^{222}Rn concentration of the spring water. These periodicities are ascribed to earth tides, suggesting that ^{222}Rn variations are responding to small changes in stress in the rocks encompassing the hydrologic system that feeds the pool (Fig. 22).

The hourly-integrated record at the Fish Hatchery spring during September - November, 1983, together with the occurrence of caldera earthquakes of magnitude greater than 1.5., are shown in Figure 23. The character of the radon record changed between October and November, 1983. Larger amplitude, longer period fluctuations appear to precede the period of relatively active seismicity of November 14–16. A large "spike" of radioactivity is nearly coincident with the magnitude 3.4 earthquake of November 14 (epicenter approximately 5 km southwest of the Fish Hatchery). A more regular periodicity of radon fluctuations appears to follow the earthquakes of November 14–16, characterized by relatively large amplitude daily peaks. The later record indicates that this character continued through December and into 1984. A marked change in character of the Rn record (a sharp diminution of daily amplitudes) preceded the M 5.8 Round Valley quake of November 23, 1984 by approximately two days.

Hydrogen

Hydrogen monitoring is underway at Casa Diablo and near Laurel Spring. As reported by McGee and Sutton (1984), H emissions have a diurnal cycle, probably in response to variations in barometric pressure. Since the January 1983 seismic swarm in Long Valley, large departures from this diurnal background have been observed in the monitor at Casa Diablo within a few hours or a few days prior to every swarm in the south moat epicentral area. Examples are Figures 24 and 25 that show the March and May, 1983 records for Casa Diablo. The H record for the Laurel

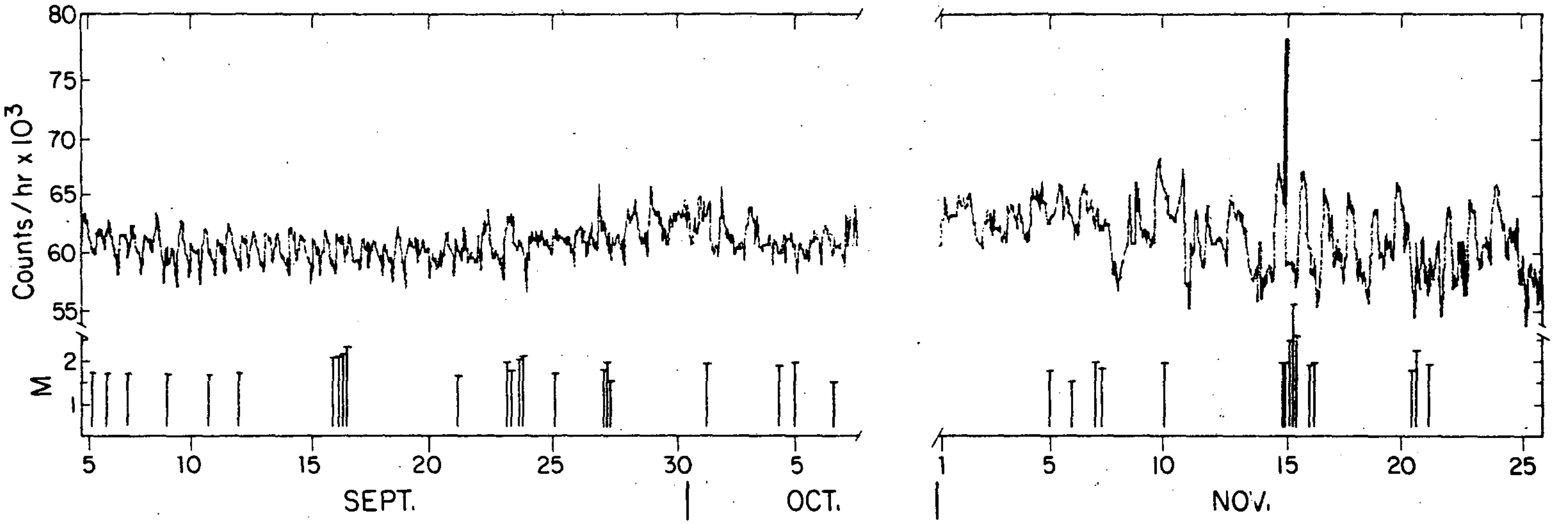


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Figure 22. Theoretical Earth tidal characteristic and hourly integrated gamma radioactivity from ^{222}Rn in water of the Fish Hatchery spring.

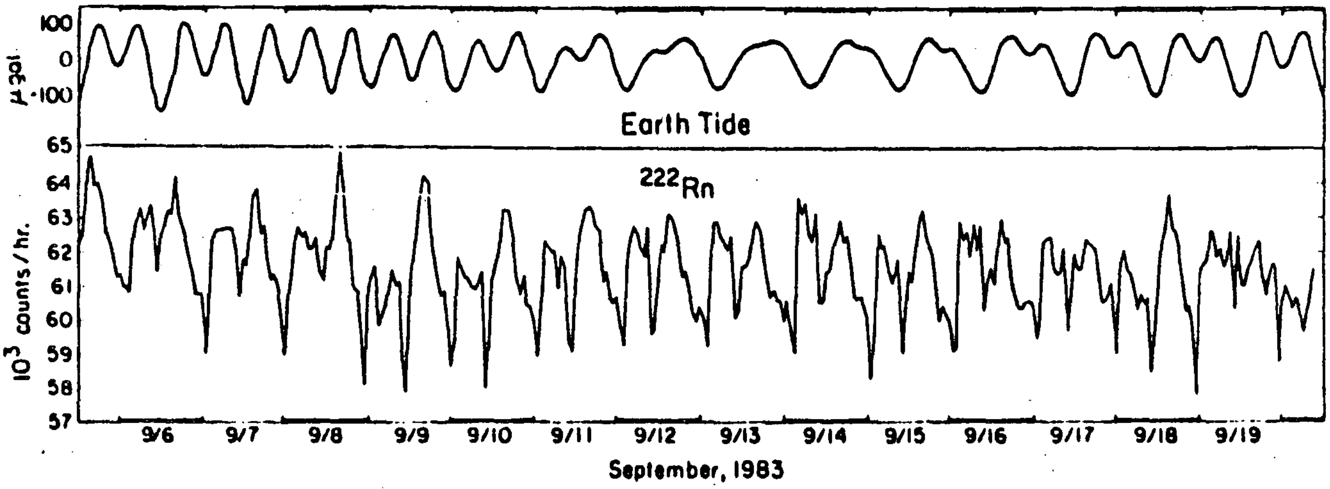

Figure 23. Hourly integrated radon record, September 5 to November 25, 1983, at the Fish Hatchery spring, Long Valley. Break in record between October 7 and 31 is due to instrumentation problems. Earthquakes of magnitude > 1.5 in the caldera shown by vertical lines below radon record. Earthquake data provided by R. Cockerham (written communication, 1984).

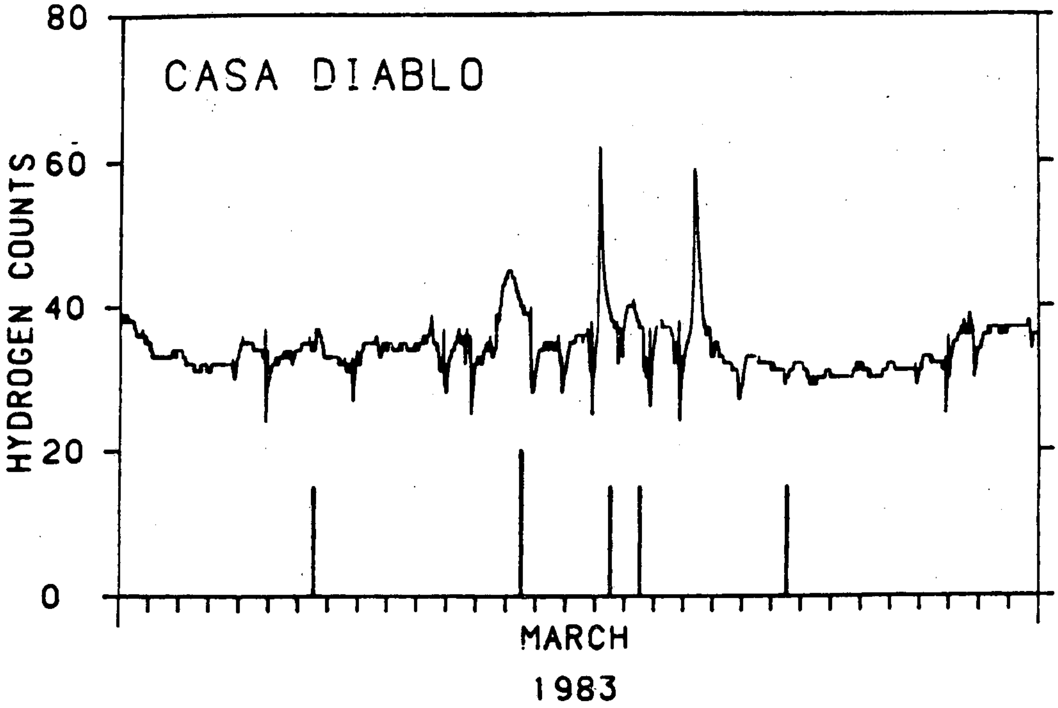

Figure 24. Plot of hydrogen data from Casa Diablo during March 1983. The lower bars represent seismic swarms on March 7, 14, 17, 18, and 23. The small seismic swarm on March 7 follows a hydrogen peak at the end of February (not shown). Hydrogen counts are proportional to hydrogen concentration.

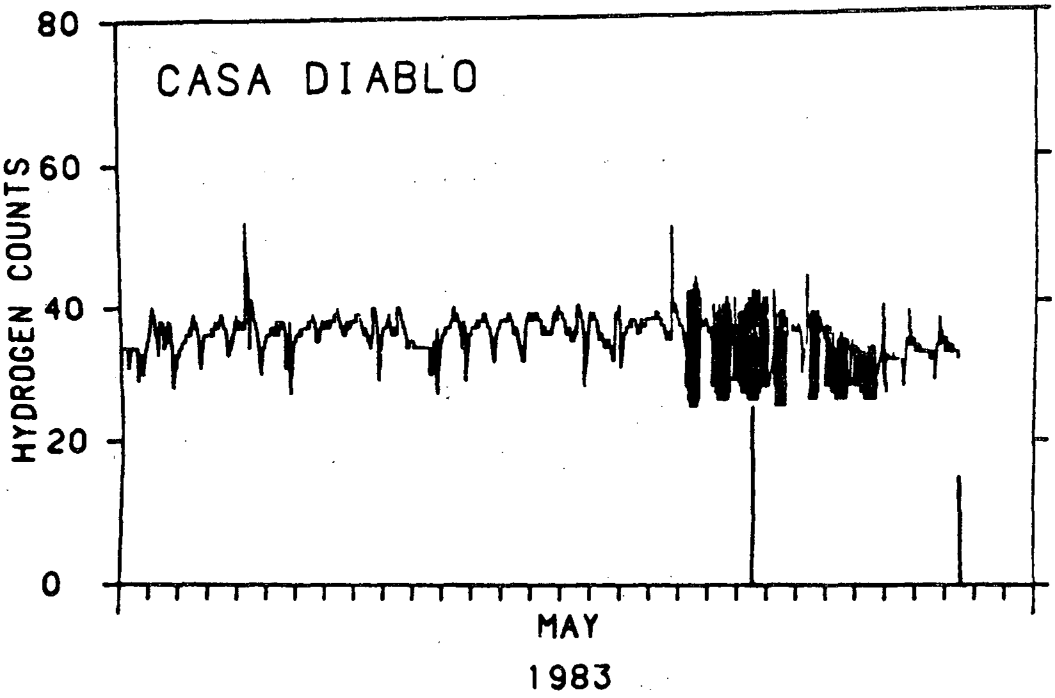

Figure 25. Plot of hydrogen data from Casa Diablo during May 1983. The tall bar represents the 150-event seismic swarm in the south moat on May 22. The short bar represents a small 17-event swarm on May 29. Hydrogen counts are proportional to hydrogen concentration.

Spring site is much more featureless than the Casa Diablo record, attributed by McGee and Sutton to the Casa Diablo system's position in a fumarole (94° C), while the Laurel Spring system is in cold ground at the south margin of the caldera. However, distinct H events have been observed at Laurel Spring, as shown in Figures 26 and 27 for September 1983 and May, 1984, respectively. These events preceded swarms centered near Mammoth Mountain. The Casa Diablo events then appear to be related only to earthquakes in the south moat epicentral area, while the Laurel Spring events appear to precede swarms in the southwestern margin of the caldera. Following the May, 1984 event the Laurel Spring H activity remained quiet through October, 1984.

With the exception of diurnal variations, there appears to be no close concordance between variations in the soil-gas H emissions and the water-borne Rn being monitored at the Fish Hatchery spring. A longer time base of monitoring is necessary to see if there may be long-period concordances between soil-gas H and water-borne Rn.

Helium

Helium surveys were started in 1978 when Hinkle and Kilburn (1980) detected anomalous (>2 standard deviations above the mean) zones associated with the Hilton Creek fault, and extending southeastward. A second survey by Green and Reimer in 1982 showed a much broader distribution of anomalous He, with zones in the western moat arcing around the northern portion of the resurgent dome area. This change of He toward the western region of the caldera over 4 years generally corresponds to changes in Hg observed by Varekamp and Busek between 1975 and 1982, and roughly coincides with the western moat—Mammoth Mountain areas of high Hg observed by Williams and students in 1983-1984.

A He survey was conducted in 1983 that included traverses over the 1980 epicentral area. No distinct differences in He concentration were observed compared to other areas in the Long Valley region, suggesting that neither magma movement nor the continued seismic activity were contributing appreciably to soil-gas concentrations of He in the south moat epicentral area.

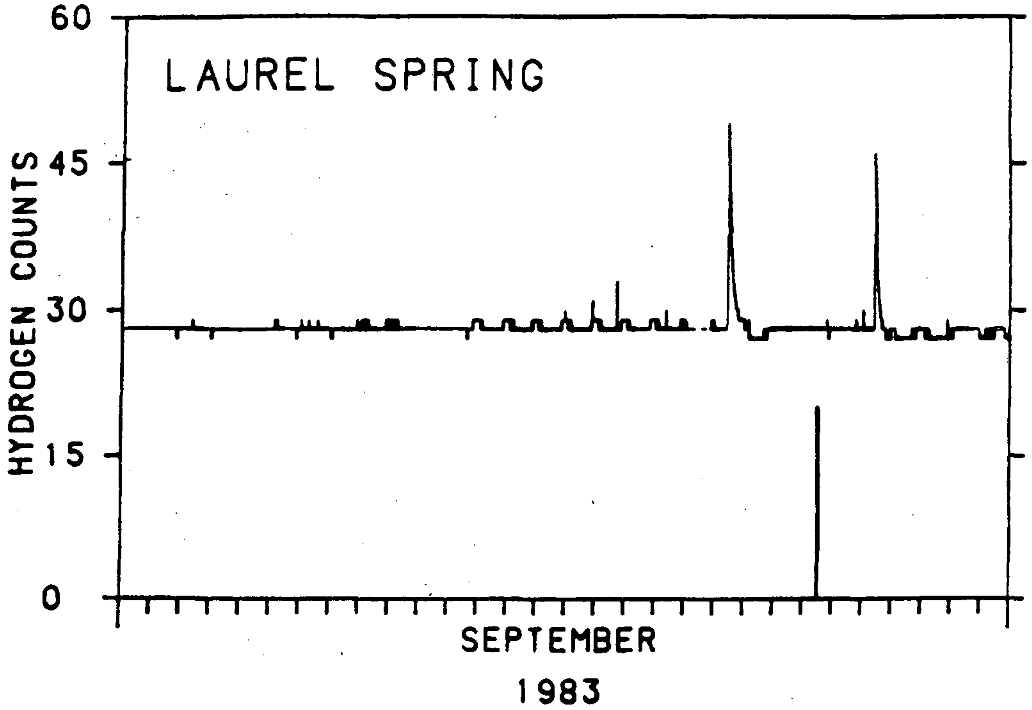

Figure 26. Plot of hydrogen data from Laurel Spring for September 1983. The bar on September 24 represents a 50-event seismic swarm in the southwest corner of the caldera near Mammoth Mountain. Hydrogen counts are proportional to hydrogen concentration.

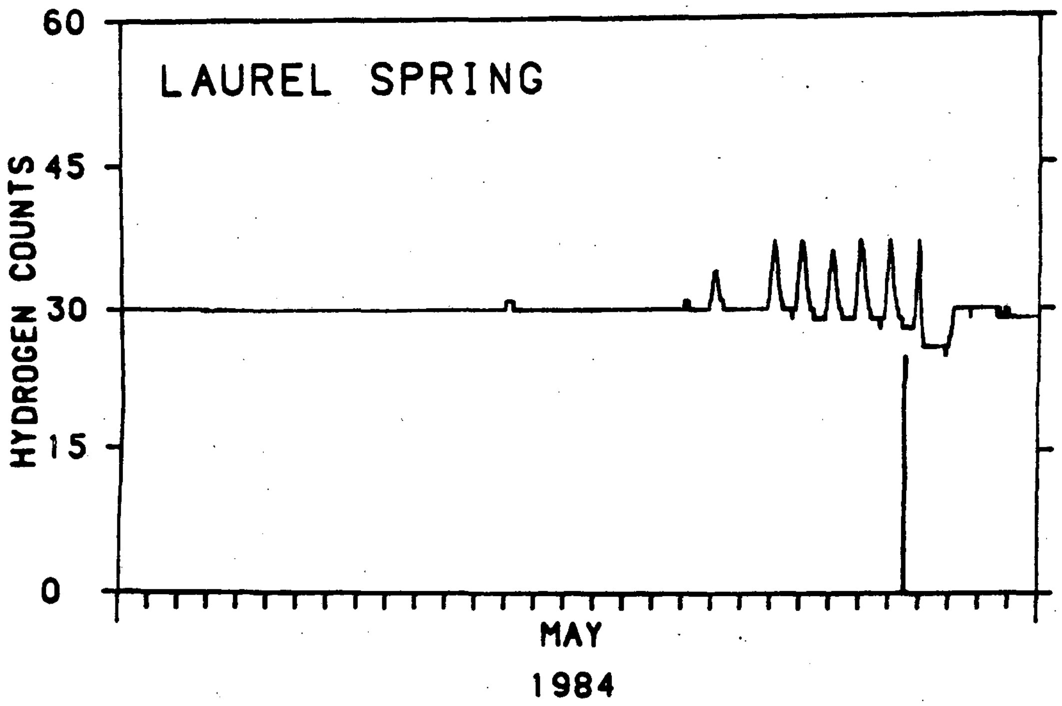

Figure 27. Plot of hydrogen data from Laurel Spring for May 1984. The bar on May 27 represents a 260-event swarm under Mammoth Mountain. Hydrogen counts are proportional to hydrogen concentration.

Bi-weekly samples of He are being obtained at four locations in the southern part of the caldera. Figure 28 shows that besides a large-scale seasonal variation, the most significant feature is a marked decrease in He in April, 1984, preceding a period of increased seismic activity in the caldera. This pattern is consistent with observations of He and seismicity on the San Andreas fault zone near San Juan Bautista (Reimer, 1985). Comparison of this He monitoring with the waterborne Rn shows that the seasonal decrease in soil-gas He between winter and summer is not matched by the record of Rn measured in the Fish Hatchery spring.

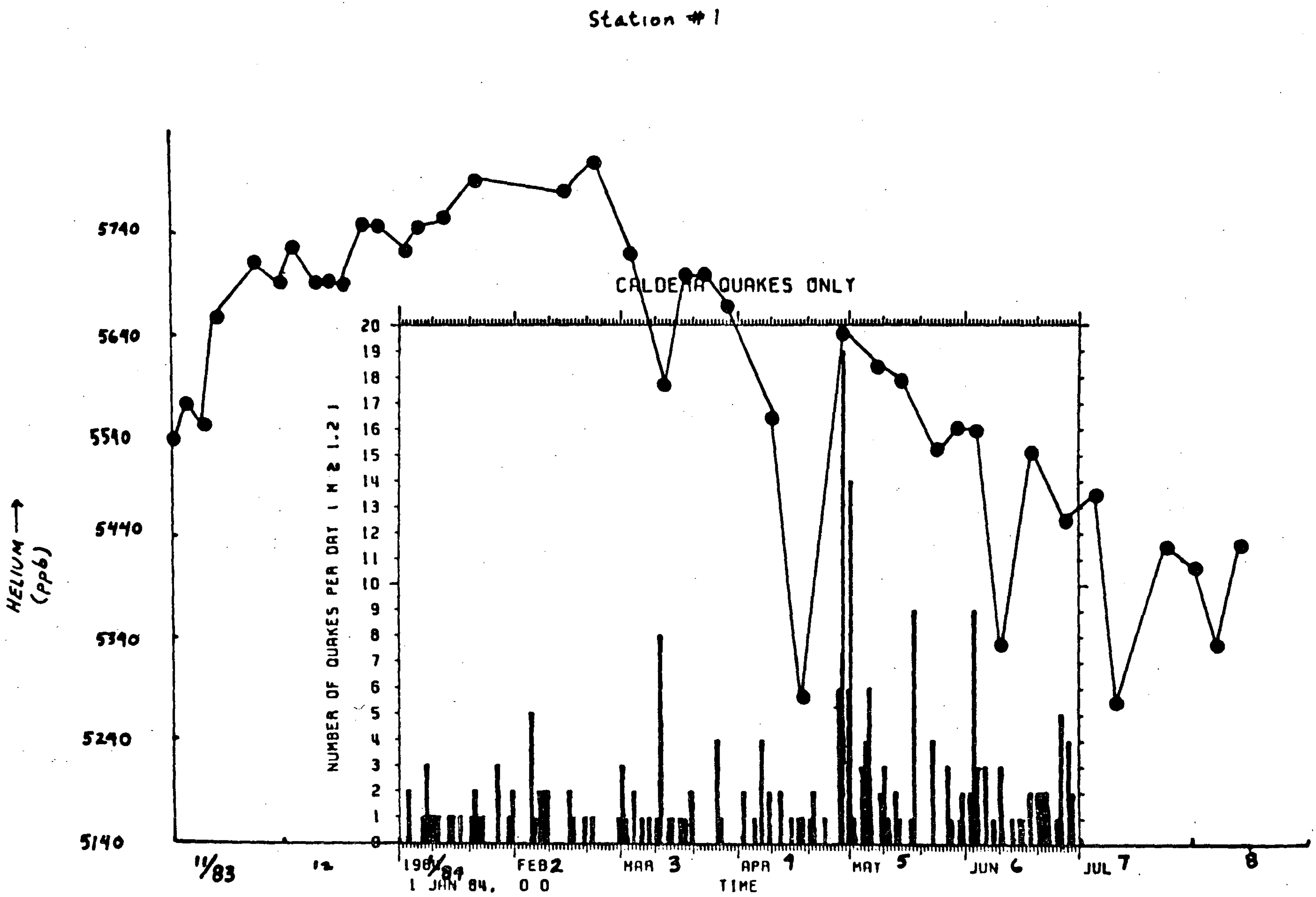

Figure 28. Helium in soil-gas at Long Valley permanent station number 1. Station 1 is located at the water treatment plant at Mammoth Lakes. The beginning of a seasonally influenced cycle is evident. The large decrease in helium occurs several weeks before the late-April seismicity.

SUMMARY AND RECOMMENDATIONS

Results of hydrologic and geochemical monitoring in the Long Valley area reported at the October 1984 workshop show only limited evidence of significant changes since initiation of increased seismicity and ground deformation in 1980. A general pattern of increased discharge of hot springs and fumaroles in the vicinity of Casa Diablo was established by the summer of 1982. However, since regular fluid sampling was initiated in 1982 no clear pattern of changes in spring or gas chemistry has been discerned. Chemical variations that have been observed probably relate more to errors in results reported by different laboratories, differences in sampling points used by various collectors, and physical changes around points of fluid discharge.

Temporary increases in spring flow have been recorded at Little Hot Creek, Hot Creek gorge, and Laurel Spring following earthquakes of relatively large magnitude and close proximity. Corresponding changes in spring temperature have not been observed. An apparent decrease in the temperature of a fumarole at Casa Diablo and fluctuations in soil temperature in an area of steaming ground along the western side of Long Canyon have been recorded since 1982, but these changes have not been correlated directly with tectonic or intrusive events. Unlike fumaroles in the Phlegrean Fields caldera in Italy which have measured temperatures up to 157 ° C and have shown changes in gas/steam ratio accompanying a period of renewed magmatic heating, fumaroles in the Long Valley caldera show no significant degree of superheat and appear to be less directly connected to magmatic sources.

Isotope ratios of $^{3}He/^{4}He$ and $^{13}C/^{12}C$ in hot spring and fumarolic gases at Long Valley are consistent with values obtained for mantle derived helium and carbon. Changes observed in $^{3}He/^{4}He$ at Hot Creek gorge are also consistent with increases in ^{3}He from possible magmatic intrusions in May 1980 and January 1983. However, alternative explanations of these isotopic data are also possible, and additional monitoring of these parameters along with isotopic ratios for other noble gases is required to establish their usefulness for volcanic hazards assessment. Further analysis of the influence of the caldera's hydrothermal system on the movement of mantle derived volatiles toward the surface is also needed.

Temporal changes have been observed in concentrations of various gas constituents emitted at the land surface that may reflect response to crustal deformation and changes in the near- surface hydrothermal regime. From the mid 1970's to the early 1980's there has been a westward shift in areas of high concentration of Hg and He in the Long Valley caldera. If these elements are responding to injection of magma, associated crustal deformation and hydrothermal circulation, then the western moat and the southwestern part of the caldera may be significant sites of these activities. Continued seismic swarm events in the south moat area are discernable by H monitoring in a fumarole at Casa Diablo, while a similar H monitoring system in ambient conditions near Laurel Spring appears to respond to seismic activity in the Mammoth Mountain area. To date, there are no apparent concordances between variations in measured soil-gas constituents and water-borne Rn monitored at the Fish Hatchery spring. Soil-gas monitors located near the spring would permit a better means of comparison of these phenomena with variations in water-borne gaseous constituents. Continuous monitoring of specific conductance, temperature and flow of the Fish Hatchery spring is presently underway and provides incentive for monitoring of other constituents at that site.

Recommendations for Monitoring

Workshop participants made numerous recommendations regarding the monitoring of hydrologic and geochemical parameters in Long Valley. A list of these recommendations is given below.

1. Instrument "community" sites for continuous and periodic monitoring of a range of parameters such as temperature, barometric pressure, and concentrations of H, CO_2, Rn, and He.
2. Collect additional baseline data during periods of low crustal activity.
3. Collect additional fluid and gas samples from wells.
4. Delineate source of gases, such as H, He and CO_2, in springs and fumaroles and mechanisms causing changes in concentrations and isotopic ratios at the land surface.
5. Delineate response mechanisms for soil gases.

6. Combine good quality data on gas, water, and isotope chemistry into a comprehensive hydrogeochemical model of the hydrothermal system.

Recommendations for Test Drilling

A limited number of existing wells drilled to relatively shallow depths are available for chemical sampling of hydrothermal fluids. This sampling will be carried out in 1985 by the U.S. Geological Survey and Lawrence Berkeley Laboratory. Hydrologic and geochemical data from deeper wells is obviously needed to better define the hydrothermal system and to understand ongoing crustal processes that affect the hydrothermal system. Recommendations by workshop participants regarding such drilling and data collection are listed below.

1. Data from intermediate depth drill holes (to ~4000 ft) could help delineate the extent of regional scale hydrothermal circulation within and above the Bishop Tuff.
2. Drilling targets west of the resurgent dome should focus on (a) hot water reservoirs in the Bishop Tuff, (b) heat sources along the trend of the Inyo volcanic chain, and (c) zones of upflow of hot water.
3. Drilling targets on or around the resurgent dome should focus on geophysical anomalies that may indicate the presence of shallow magma or deep hydrothermal circulation.
4. Test drilling near the town of Mammoth Lakes, in the vicinity of the Shady Rest Campground, would investigate the hydrothermal system west of Casa Diablo and would allow the participation of city and county agencies interested in developing a source of hot water for space heating.
5. Optimum drilling targets for intermediate-depth holes include (a) the west moat along the trend of the Inyo volcanic chain (b) the west moat along the caldera ring fracture (c) the flanks of Mammoth Mountain and (d) zones of fluid upflow west of Casa Diablo.

APPENDIX 1:
AGENDA
WORKSHOP ON HYDROLOGIC AND GEOCHEMICAL MONITORING IN THE LONG VALLEY CALDERA

7–9 October, 1984
Jagerhof Lodge
Mammoth Lakes, California

October 7
Sunday,

8:45 – 9:00	Assemble in meeting Room (basement of Jagerhof Lodge)	
9:00 – 9:15	Introduction and Discussion of Workshop Plan (M. Sorey and H. Wollenberg)	
9:15 – 10:30	Overview of the Long Valley Hydrothermal System and Current Research Efforts	
	Discussion Leader:	M. Sorey
	Presentations:	M. Sorey H. Wollenberg J. Dunn
10:30 – 10:45	Break	
10:45 – Noon	Discussion	
Noon – 1:30	Lunch	
1:30 – 3:30	Monitoring Hot Spring Chemistry and Flow	
	Discussion Leader:	C. Farrar
	Presentations:	R. Mariner C. Farrar A. White N. Valette-Silver M. Clark F. Goff
3:30 – 3:45	Break	
3:45 – 5:00	Discussion	
7:00 pm	Dinner at Cask and Cleaver	

Monday, 8

9:00 – 10:30	Monitoring Gas Discharge	
	Discussion Leader:	*H. Wollenberg*
	Presentations:	C. Janik T. Gerlach B. Kennedy B. Rison
10:30 – 10:45	Break	
10:45 – Noon	Discussion	
Noon – 1:30	Lunch	
1:30 – 3:30	*Presentations*:	H. Wollenberg S. Williams M. Reimer K. McGee
3:30 – 3:45	Break	
3:45 – 4:30	Discussion	
4:30 – 5:00	Summary session	

Tuesday, 9

9 am – 4 pm	Field Trip	
	Stops:	Casa Diablo Hot Creek Gorge Shady Rest Fumarole
	Lunch provided	

APPENDIX 2
WORKSHOP ON HYDROLOGIC AND GEOCHEMICAL MONITORING IN THE LONG VALLEY CALDERA

List of Participants

Name	*Address/Phone*
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Chris Farrar	USGS, POB 1298, Santa Rosa, CA 95402/ (707) 525-4265, FTS 450-4265
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Fraser Goff	Los Alamos National Lab, Los Alamos, NM 87545/ (505) 667-8060, FTS 843-8060, 843-7590 (secretary)
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Stan Williams	Louisiana State University, Dept. of Geology, Baton Rouge, LA 70803.
Harold Wollenberg	Lawrence Berkeley Lab, Bldg. 50A, Berkeley, CA 94720/ (415) 486-5344, FTS 451-5344

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