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LONG VALLEY, CALIFORNIA: A CALDERA UNDER STRESS

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ABSTRACT

Long Valley caldera in east-central California has been the site of intermittent volcanism up until as recently as 550-650 years ago, and since **1980** has experienced active seismicity and magmatic inflation. Such processes have caused changes in the caldera's hydrothermal system **as** has fluid production for geothermal energy development. A program of hydrologic and chemical monitoring by the U.S. Geological Survey has been in effect since **1982** to detect and quantify changes in hot spring discharge, chemistry and isotopic content of springs and fumaroles, and temperature and pressure in wells. The results of this monitoring have lead to increased understanding of the hydrothermal system and the level of natural variability within the system, and documented decreases in hot spring flow at one site where fluid is produced for geothermal development.

INTRODUCTION

The Long Valley caldera, located in east-central California (fig. 1), formed 0.7 m.y. ago with the eruption of approximately **600** km^3 of rhyolite ash referred to as the Bishop Tuff. Bailey and others **(1976)** describe the Pliestocene volcanic history of the Long Valley area, which involves intermittent eruptions of lavas and pyroclastic rocks of rhyolitic to basaltic composition. Holocence volcanic activity has occurred along a **26** km-long north-south alignment of rhyolite domes and phreatic craters stretching from the south shore of Mono Lake to the west moat of Long Valley caldera (Miller, **1985).** The most recent activity occurred **550-650** years ago along the southern segment, referred to as the Inyo volcanic chain, accompanied by injection of one or more silicic dikes beneath the west moat between Obsidian dome and Mammoth Mountain (fig. 2). At least two additional eruptive episodes occurred along this chain during the past 3,000 years.

Earthquakes of magnitude near **6** occurred in the south moat of the caldera in May **1980** and January **1983.** During the period **1980-84,** numerous earthquakes **of** similar magnitude were centered in the Sierra Nevada to the south of Long Valley and frequent seismic swarms of lesser magnitude have been observed beneath the south moat and Mammoth Mountain. Associated with this increase in seismicity has been uplift and extension of the caldera floor in patterns suggestive of magmatic inflation of the Long Valley magma chamber. Earthquakes

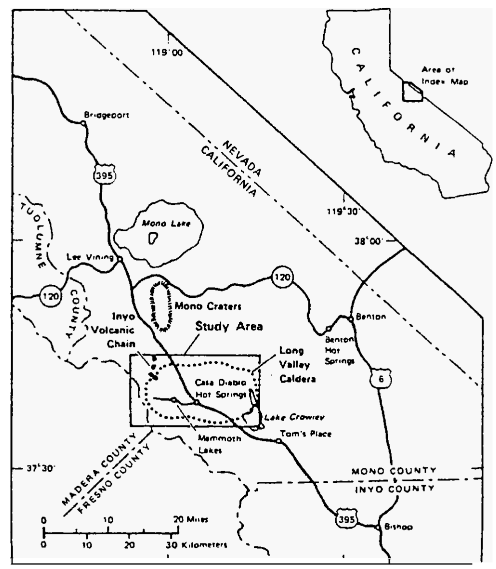

Figure 1. Location map for the Long Valley study area in east-central California.

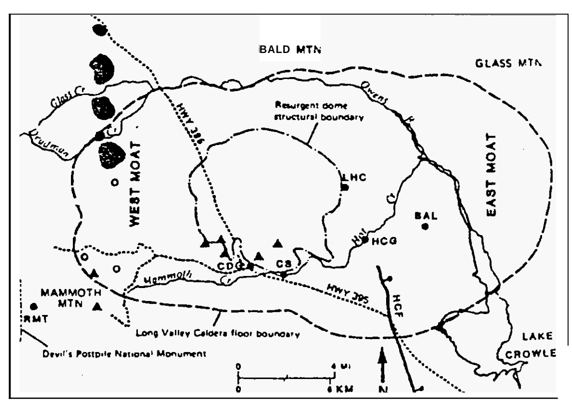

Figure 2. Map of the Long Valley caldera and surroundings showing locations of principal hot springs (filled circles), fumaroles (triangles), rhyolite domes (dark blobs) and phreatic craters (open circles) of the **Inyo** volcanic chain, and the surface expression of the Hilton Creek Fault (HCF).

in January **1983** may have been accompanied by emplacement of a northward-dipping dike whose upper surface lies south of Casa Diablo Hot Springs at depths of **3-8** km (Savage and Cockerham, **1984).** Zones of shear wave attenuation delineated beneath parts of the resurgent dome indicate that magma currently exist within the Long Valley magma chamber at depths as shallow as **4-5** km (Sanders, **1984).** Although levels **of** uplift and seismicity have decreased significantly since 1983, the Long Valley area continues to experience higher levels of crustal unrest than elsewhere in California and more intense activity could occur in the near future.

Exploration for geothermal energy in Long Valley by private industry began in the late 1950's. At the present time one 7.5 MW binary electric power plant is on line at Casa Diablo Hot Springs and drilling is in progress or planned at several other sites. Reservoir temperatures thus far encountered in the vicinity of thg resurgent dome, ranging from 130°-175 C, are adequate for power producton using binary fluids. Reservoir temperatures ranging from 200°-300°C are assumed to exist within the welded Bishop Tuff beneath the west moat on the basis of extrapolated temperature gradients, but existing wells have not been drilled deeply enough to encounter such reservoirs.

Measurements of the discharge characteristics of springs and temperatures and pressures in wells in the Long Valley area were initiated by the U.S. Geological Survey in 1972 (Lewis, 1974), and additional data of this type are presented by Sorey and Lewis (1976) and Sorey and others (1978). Monitoring of the hydrothermal system on a continuous basis was initiated in 1982, following issuence of a Notice of Volcanic Hazard for this area (Miller and others, 1982). This monitoring program and the changes observed in response to recent crustal unrest and fluid production for geothermal power production are described below, following a summary of the characteristics of the hydrothermal system.

THE HYDROTHERMAL SYSTEM

Hot springs and fumaroles are distributed primarily around the south and east sides of the resurgent dome (fig. 2). These features occur along northwest-trending normal faults which provide conduits for upflow from underlying reservoirs. Warm springs located east of Hot Creek are fed from relatively shallow lenses of thermal water moving in a southeasterly direction toward Lake Crowley (Sorey and others, 1978). Warm springs and fumaroles also occur on the flanks of Mammoth Mountain within a zone of north-south trending extensional faulting that characterizes the Inyo volcanic chain.

Chemical analyses of waters from the springs located in figure 2 (table 1) show that the surficial hydrothermal system is liquid-dominated and contains NaCl-type water with total dissolved solids less than 1,500 mg/L and Cl concentrations of 300 mg/L or less. The most concentrated spring waters discharge at Casa Diablo; springs east of Casa Diablo show evidence of dilution with less mineralized water. Measured temperatures of springs CDG, CS, and HCG are near the boiling point for the local altitude (93°C). Spring waters at RMT on the west side of Mammoth Mountain discharge at temperatures similar to that of spring BAL east of Hot Creek, but contain significantly less Cl and B. This comparison, along with measured tritium concentrations of 8.4 and 0.5 T.U. in RMT and BAL, respectively, implies a relatively short travel path and shallow circulation depths for waters discharging at RMT. Thus, the elevated temperature of spring RMT could result from heat input form a shallow magma body beneath Mammoth Mountain.

Steam discharges in fumarolgs at temperatures at or below 93 C; the most active fumaroles occur at Casa Diablo and discharge approximately 99.4 percent H_2O and 0.5 percent CO_2 by volume (Taylor and Gerlach, 1983). Although ratios of $^{13}C/^{12}C$ and $He/^4He$ suggest that there is a component of magmatic origin in the fumarolic gases (Taylor and Gerlach, 1983; Rison and others, 1983), steam discharge is most likely derived from underlying hot-water reservoirs.

Concentrations of deuterium and oxygen-18 in thermal and nonthermal waters show that the recharge area for the hydrothermal system is around the western rim of the caldera, consistent with a general model involving fluid downflow and heating in the west and lateral flow of thermal water from west to east (Sorey and others, 1978). These data, along with water table altitudes, differences in spring chemistry between Casa Diablo and Lake Crowley, and occurrences of areas of steam discharge west of Casa Diablo, suggest that maximum temperatures indicated by cation geothermometry (240°C) may be attained in reservoirs located beneath the west moat. Data from temperature measurements in wells are consistent with this model, as discussed below.

More than 70 wells have been drilled in the Long Valley caldera since 1959 by government agencies and private industry. Well depths range from 3 to 2,100 m; over that interval aquifers at temperatures ranging from 5° to 175°C have been encountered. In general, temperature profiles in wells located within the outer margins of the caldera are isothermal and cold and thus indicative of

Table 1. Chemical analyses of waters from selected springs in the Long Valley area. Results in mg/L. All analyses run by U.S. Geological Survey Central Laboratory, Arvada, Colorado, except for water from BAL which was analyzed by Lawrence Berkeley Laboratory.

Spring (abbreviation)	Date mo/yr	T °C	pH	Ca	Mg	Na	K	Alk	SO_4	Cl	F	SiO_2	As	B	Dissolved Solids
Reds Meadow (RMT)	6/84	48	6.6	60	2.3	130	6	409	31	7	6.0	140	0.2	1.6	640
Casa Diablo (CDG)	5/84	90	8.2	0.8	0.1	410	38	382	160	300	12	---	1.8	12	1480
Colton spring (CS)	5/84	91	8.3	1.3	0.01	370	28	353	150	270	12	230	1.3	11	1340
Hot Creek Gorge (HCG)	5/84	91	8.1	2.3	0.2	380	24	490	96	230	10	130	0.9	9.8	1190
Little Hot Creek (LHC)	5/84	81	6.8	22	0.6	400	29	579	100	210	8.3	82	0.6	8.6	1230
Big Akalai Lake (BAL)	11/83	50	6.9	27	0.7	338	34	334	160	160	4.7	171	0.8	6.1	1164

the effects of ground-water recharge. Temperature profiles in most other wells show considerable variability in gradient, and include zones of temperature reversals indicative of lateral convective heat transfer. Recent profiles measured in six of the deepest wells drilled to date are shown in figure 3 (locations in fig. 4). Temperature reversals in some of these wells could reflect transient thermal regimes caused by lateral flows of hot water.

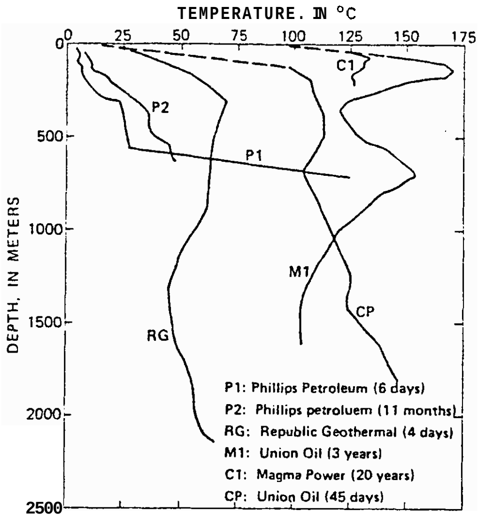

Figure 3. Temperature profiles in deep wells drilled by private industry in Long Valley. Elapsed time between well completion and temperature measurements shown in ( ).

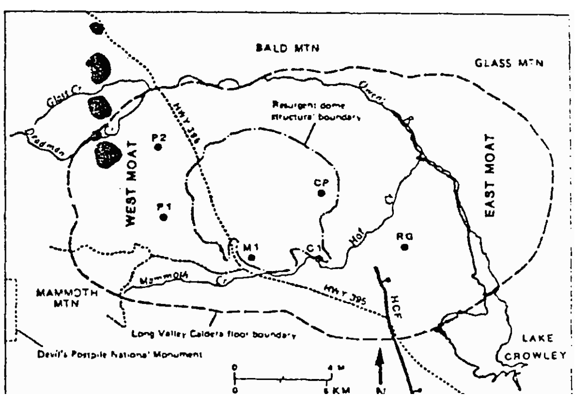

Figure 4. Map of Long Valley caldera showing locations of deep wells drilled by private industry.

Blackwell (1984) assumed that temperature reversals such as those seen at depths of 150 m and 670 m in well M1 (at Casa Diablo) are caused by west to east flow of hot water in two aquifers. His analysis of the shapes of these reversals suggests that flow in the deeper aquifer, within the welded Bishop Tuff, was initiated 3,000 years ago and that flow in shallower aquifer, located above the welded tuff, was initiated 500-700 years ago. While these ages are consistent with the ages of magmatic intrusions along the Inyo volcanic chain which could provide the heat source for the present-day hydrothermal system, their validity may be questioned in the case of well M1 because temperature minima observed at depths of 400 m and 1,500 m could be controlled by the flow of cooler water in aquifers detected at those depths. The age calculations of Blackwell are based, instead, on the assumption of conductive heat flow at all depths except where thermal aquifers occur.

A plausible model of flow within the present-day hydrothermal system (fig. 5) is described by Sorey (1984, 85). This model is dominated by lateral flow of hot water in regionally continuous aquifers within and above the welded tuff. Evidence for a 240°C reservoir beneath the west moat comes primarily from extrapolation of the high temperature gradient measured in well P1 below a depth of 550 m. Confirmation of its existence and delineation of its extent must await the results of deep drilling planned by private industry. As shown in figure 5, a portion of this deeper flow may move upward along faults bounding the western edge of the resurgent dome and then flow eastward in the shallow thermal aquifer toward Casa Diablo and around the south side of the resurgent dome to Lake Crowley. Fumarolic discharge at several locations west of Casa Diablo may related to such a zone of upflow. In the east moat, temperatures measured in well RG suggest lateral flow of thermal water at temperatures near 70°C above the Bishop Tuff and flow of cooler water within the welded tuff. These data along with hydraulic head differences and stable isotope relationships suggest that a separate convection system exists beneath the east moat with recharge along the ring fracture around the northeast rim, lateral flow through the welded tuff, and upflow in the vicinity of the Hilton Creek Fault (Sorey and others, 1978; Sorey, 1984).

Evidence for extensive periods of hydrothermal activity in Long Valley during the past 0.3 m.y. includes areas of fossil argillic alteration and silicious sinter deposition on the east side of the resurgent dome as well as saline deposits that were contributed from Long Valley to Searles Lake, located 225 km southeast along the ancestral Owens River (Sorey, 1984). The ages and amounts of saline minerals in Searles Lake evaporites suggest that hot spring discharge in Long Valley has been

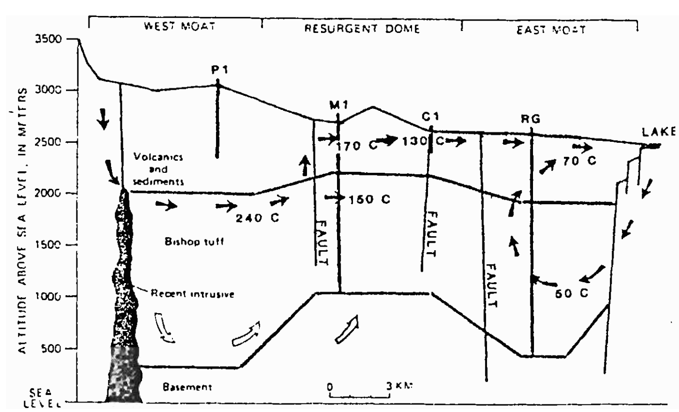

Figure 5. East-west crossection through the southern part of the resurgent dome showing inferred directions of fluid flow in present-day hydrothermal system (dark arrows) and deeper circulation during previous periods of hydrothermal activity (open arrows). Measured or estimated reservoir temperatures shown at various dept

relatively continuous for the past 40,000 years. The present-day rate of heat output from the caldera is 2.5 X 10^8 W, which is equivalent to an average heat flux of 630 mWm^{-2} over the area of the caldera floor (Sorey and others, 1978). Although heat input at this rate could come from shallow intrusions beneath the west moat for periods of a few thousand years, longer periods of hydrothermal activity would have required deeper levels of fluid circulation and heat input from the main Long Valley magma chamber. This situation is depicted in figure 5 by the open flow arrows.

MONITORING PROGRAM

The types of data collected by the U.S. Geological Survey during the period of monitoring which began in 1982 include: (1) periodic and continuous recording of water levels, temperatures, and barometric pressure in wells, (2) measurements of spring flow by direct and indirect means, (3) chemical analyses of water samples from springs and wells, (4) stable isotopes, tritium, and isotopes of dissolved carbon in spring water, *(5)* chemistry and isotopic content of gas and steam from fumaroles and hot springs, (6) continuous monitoring of hydrogen concentrations in fumaroles and hot springs, (7) periodic measurements of helium concentrations in soil gas, and (8) lithologic and stratigraphic information from exploratory wells. Additional monitoring conducted during this period by other agencies and institutions included helium isotopes in fumaroles and hot springs, radon concentrations in springs, and mercury and radon in soil gas. Detailed discussions of these activities are given by Farrar and others (1985) and Sorey and others (1985). Only selected results are presented here.

The flow rate of individual springs and groups of springs has been measured directly using small flumes and weir plates and indirectly from measurements of the chemical load in streams. The latter technique has been used in Hot Creek to estimate the total flow of hot springs in the gorge (labeled HCG in fig. 2). At a site 1 km downstream from HCG continuous records have been obtained since September 1983 of the flow of Hot Creek through a concrete flume, along with measuremetns of stream temperature and specific conductance. From chemical analyses of samples of creek water correlations have been established between specific conductance and concentrations of Cl and B. Multiplication of stream flow times concentration yields the flux of each element past the gaging site, most of which is contributed by hot springs in the gorge. Changes in the calculated flux of Cl and B are then proportional to changes in hot. spring flow.

The spring flow data show changes that can be attributed to earthquakes for Casa Diablo, Hot Creek gorge, and Little Hot Creek. In most cases these changes represent increased discharge immediately following earthquakes of relatively large magnitude and close proximity, followed by decreases in discharge to pre-earthquake levels within hours to days. No clear evidence of precursery changes in spring flow have been documented. The flow of hot springs and fumaroles at Casa Diablo increased during the period 1980-84 along with the general increase in seismic activity; the response of these features to earthquakes appears to be more qradual than at the other sites noted above. During 1985, several periods of sustained fluid production from wells at Casa Diablo that supply the nearby geothermal power plant occurred. In each case, total hot spring flow decreased from about 20 L/s to 3 L/s within a period of a few days after pumping commenced and then recovered to pre-production level following well shut-in. No effects of the fluid production at Casa Diablo have yet been observed at springs located to the east of Casa Diablo.

Observed variations in water chemistry of hot springs are attributed mainly to differences in analytical or collection procedures rather than to tectonic or magmatic processes. The same is true of variations in stable isotopes of water (D and ^{18}O). At Casa Diablo Hot Springs, significant differences in water chemistry between individual hot springs are observed. Such differences probably relate to near-surface boiling and steam separation and mixing with shallow ground water. Casa Diablo is also the only thermal area where acid-sulfate springs are sometimes observed.

As noted previously, ratios of $^{13}C/^{12}C$ and $^3He/^4He$ for hot springs and fumaroles have been taken to indicate a magmatic source for some or all of the surficial He and CO_2. Farrar and others (1985) point out, however, that values of $^{13}C/^{12}C$ from metamorphic carbonate rocks collected within the study area bracket the values observed in the springs. Because these rocks form part of the roof pendant over grantitic rocks that lie below the caldera fill, they could also be a source of CO_2 discharged at the surface. Values of $^3He/^4He$ at a spring in Hot Creek gorge showed an increase between 1978 and 1983 and a subsequent decrease in 1984, consistent with possible variations in ^3He input from magmatic intrusions in May 1980 and January 1983 (Farrar and others, 1985; Sorey and others, 1985).

Temperature-depth measurements made in wells before and after 1980 show little evidence of changes with time. In particular, profiles run in well M1 at Casa Diablo in December 1982 and September 1983 are essentially identical from the surface to total depth of 1600 m. Although this area may have been the site of the dike emplacement in January 1983 noted previously, the lack of temperature change in well M1 contrasts with observations of Valette-Silver and others (1985) of significant temperature increases in the reservoir at Cerro Prieto, Mexico, assoicated with a spreading event and possible magmatic intrusion during the period 1979-80.

Continuous measurements of water level in selected wells, which began in 1983, show coseismic changes but no changes attributable to magmatic intrusions. This is due in part to the likelihood that no such intrusions have occurred since January 1983. Optimum well sites for detecting crustal strain involve deep holes open to reservoir rocks of low compressibility, such as the welded