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PRESENT STATE OF THE HYDROTHERMAL SYSTEM IN LONG VALLEY CALDERA, CALIFORNIA

Michael L. Sorey

U.S. Geological Survey, Menlo Park, California

ABSTRACT

Results of test drilling to depths of 2 km and data on the chemical and isotopic content of waters from hot springs and fumaroles permit a conceptual model of the present-day hydrothermal system in Long Valley caldera to be delineated. The model consists of two principal zones in which hot water flows laterally from west to east at depths less than 1 km within and around the resurgent dome. Maximum measured temperatures within these zones are near 170°C, but estimates from chemical geothermometers and extrapolation of a high temperature gradient measured in a recent drill hole indicate that a source reservoir at temperatures near 240°C may exist at greater depths in the Bishop Tuff beneath the west moat. The heat source for this relatively short-lived circulation system appears to be shallow magmatic intrusions beneath the west moat. This preliminary model should be updated when results of additional deep drilling planned by private industry become available.

INTRODUCTION

Hydrothermal systems in many Pleistocene calderas of silicic composition appear to have persisted for periods of hundreds of thousands of years and to include regions where temperatures exceed 300°C at depths of less than 2 km. Such is the case at the 0.6 m.y.-old Yellowstone caldera in Wyoming (Fournier, White, and Truesdell, 1976; Christiansen, 1984) and the 1.1 m.y.-old Valles caldera in New Mexico (Smith and Bailey, 1968; Grant et al., 1984). Necessary conditions for such activity include resupply of magma to sustain continued volcanism and high convective heat flow, and active faulting to provide open channels for fluid convection. Although these conditions appear to be met in the case of the 0.7 m.y.-old Long Valley caldera (Sorey, et al., 1978), temperature measurements in wells drilled to depths of 2 km in Long Valley show maximum values of only about 170°C at depths near 0.15 km and in most cases cooler temperatures at greater depths. This suggests that the present state of the hydrothermal system in LVC differs significantly from conditions at the Yellowstone and Valles calderas, although regions of higher temperature at drillable depths may as yet remain undiscovered.

Data available as of 1977 on the hydrology, geochemistry, and thermal regime of Long Valley caldera were discussed by Sorey et al. (1978). These authors also described a numerical model of the deep hydrothermal system that involved west to east circulation of meteoric water beneath the resurgent dome with heat supplied by the main Long Valley magma chamber. Depths of fluid circulation in the model required to reach reservoir temperatures in excess of 200°C varied from 1-2 km to 4-5 km, depending on the time period over which such circulation had persisted. At the time of that study, only one deep well (the 2.1 km deep test hole drilled by Republic Geothermal in the east moat of the caldera) had been completed.

Since 1978, new wells have been drilled by private industry and additional chemical and isotopic data on spring and fumarolic discharges have been collected as part of a monitoring program to detect changes related to ongoing magmatic and tectonic processes. Recent studies of Holocene eruptions at the Inyo-Mono volcanic chain that extends into the west moat of the Long Valley caldera have also delineated three major episodes during the past several thousand years that were probably accompanied by silicic dike injection at relatively shallow depths (Miller, 1985). This information along with the analyses by Blackwell (1984) of the shapes of temperature reversals in various wells, which suggests that hot-water flow in shallow aquifers tapped by these wells has persisted for periods less than about 3,000 years, has resulted in the revised conceptual model of the Long Valley hydrothermal system presented in this paper.

SURFICIAL DISCHARGE OF FLUID AND HEAT

Areas of hot-spring and fumarolic discharge in and around Long Valley caldera are distributed primarily around the southern and southeastern sides of the resurgent dome and to the east of the intra-caldera extension of the Hilton Creek Fault (figure 1). Areas of thermal-fluid discharge located west of the extension of this fault occur along north to northwest-trending normal faults which provide conduits for upflow from underlying reservoirs. Hot springs located in the east moat are fed by upflow from relatively shallow lenses of thermal water moving in a southeastwardly direction toward Lake Crowley (Sorey et al., 1978). Areas of steam discharge in fumaroles and diffuse seepage through soil occur in the general vicinity of Casa Diablo and on the flanks of Mammoth Mountain.

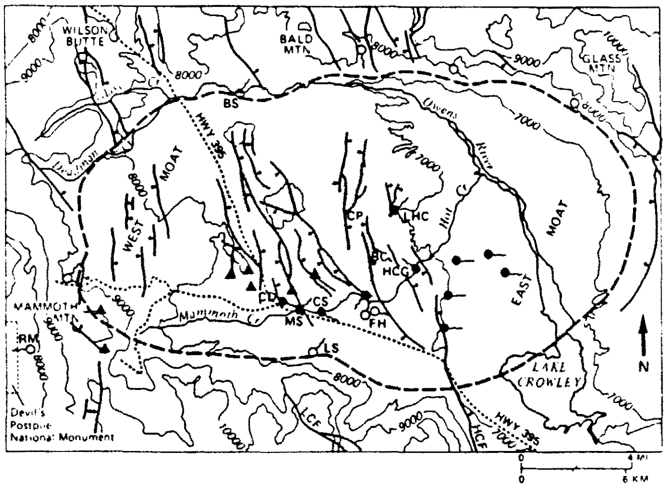

Figure 1. Map of Long Valley caldera (heavy dashed line) showing locations of active thermal springs (filled circles with tails), nonthermal springs (open circles with tails), fumaroles (triangles), and principal faults (HCF = Hilton Creek fault, LCF = Laurel-Convict fault). Dotted lines are paved roads and patterned area is the resurgent dome. Sites noted in text are abbreviated CD (Casa Diablo) and FH (Fish Hatchery). Additional sites with significant spring discharge are discussed in Sorey (1984).

Chemical analyses of hot-spring waters indicate that the underlying hydrothermal system is liquid-dominated and contains water with total dissolved solids less than 1500 mg/l and chloride concentrations of about 300 mg/l. Estimates of the temperature of reservoirs feeding the hot springs at Casa Diablo, based on cation geothermometry applied to water produced from a 120 m-deep well at Casa Diablo, are near 240°C (Mariner et al., 1976). Springs discharging east of Casa Diablo have lower chloride concentrations and yield lower estimated reservoir temperatures based on cation geothermometry.

Steam discharges in Long Valley at temperatures at or below the boiling point for local land-surface altitudes (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 ^{13}C values and $^{3}He/^{4}He$ ratios suggest that there may be a component of magmatic origin in the fumarolic gases (Taylor and Gerlach, 1983; Rison et al., 1983), steam discharge is most likely derived from underlying hot-water reservoirs.

Concentrations of deuterium and ^{18}O 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 et al., 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 may be attained within reservoirs located beneath the west moat. Data from temperature measurements in wells are consistent with this model, as discussed below.

The rate of natural heat discharge from the Long Valley caldera was estimated by Sorey et al. (1978) to be 2.5×10^8 W. If heat were supplied at this rate from a magma heat flux would average 630 mWm^{-2} (15 HFU). Comparison of these measures of the intensity of the geothermal system with corresponding estimates for other calderas places Long Valley intermediate between the Yellowstone caldera (most intense) and the Valles caldera (least intense) (Sorey, 1984). Sorey (1984) discusses evidence of extensive periods of hydrothermal activity in Long Valley within the past 0.3 m.y. Such evidence include areas of fossil hydrothermal activity in Long Valley and saline deposits that were contributed from Long Valley to Searles Lake, located 225 km southeast along the Owens River system. The heat source for such activity must have been related to the main Long Valley magma chamber and fluid circulation required to sustain a conductive heat flux at rates equal to or greater than that measured today would have to extend to within about 2 km of the top of the magma chamber (Sorey et al., 1978; Lachenbruch and Sass, 1977).

Heat requirements from magmatic sources for shorter periods of hydrothermal activity are less severe. If the present-day hydrothermal system is relatively short-lived, the heat needed to sustain it could be supplied by shallow intrusions beneath the west moat. The rate of emplacement of silicic intrusives that solidify and cool from 800°C to 300°C required to supply heat to fluid convecting at present-day rates is on the order of 3 km^3 / 1000 years (Sorey, 1984). Such activity has apparently taken place along the Inyo-Mono volcanic chain during the past 3,000 years (Miller, 1985).

SUBSURFACE THERMAL REGIME

More than 70 wells have been drilled in Long Valley since 1960 by government agencies and private industry. Well depths range from 3 to 2,100 m; over that interval, aquifers at temperatures ranging from 5^{o} to $175^{o}C$ 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 the effects of groundwater recharge. Temperature profiles in most other wells show considerable variability in gradient, including zones of temperature reversals indicative of the effects of lateral convective heat transfer. Recent profiles measured in six of the deepest wells drilled to date are shown in figure 2; well locations are shown in figure 3. Also shown in figure 3 are locations of core holes CH-5 and CH-10 for which temperature profiles show large gradients and temperature reversals at shallow depths.

Temperature reversals shown in figure 2 could reflect the transient thermal regime caused by lateral flows of hot or cold water, or steady-state conditions associated with lateral flow in (vertically) adjacent aquifers at different temperature. Blackwell (1984) assumed that temperature reversals such as those seen at depths of 150 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 was initiated 3,000 years ago and that flow in the shallower aquifer was initiated 500-700 years ago.

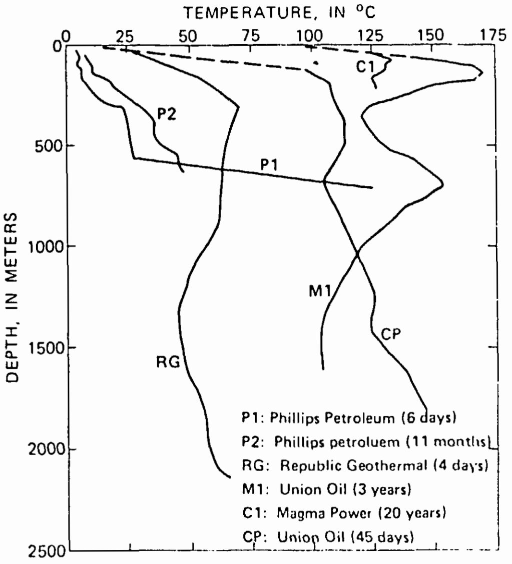

Figure 2. Temperature profiles in deep wells drilled by private industry in Long Valley caldera. Elapsed time between well completion and temperature measurements shown in parentheses.

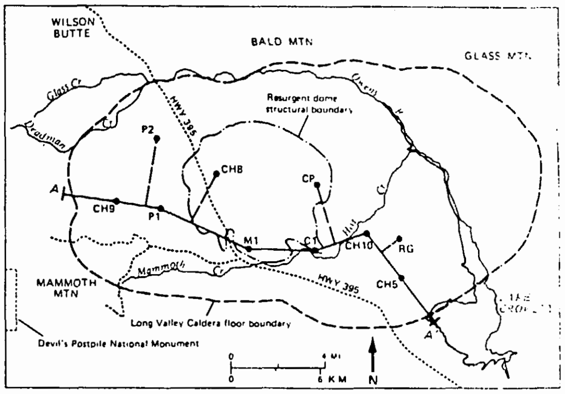

Figure 3. Map of Long Valley caldera showing locations of wells along or projected onto section AA', for which temperature profiles are plotted in figure 4. Dotted lines are paved roads.

A degree of lateral continuity of flow in such zones is indicated in the crossection shown in figure 4, which includes plots of temperature profiles in wells located on or near section AA' that runs from the

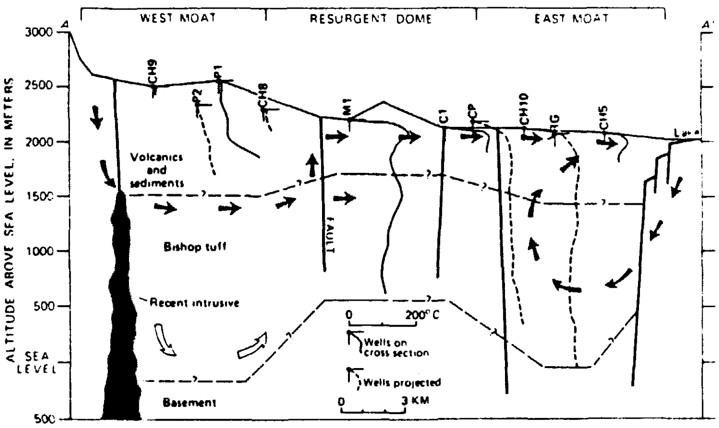

Figure 4. Temperature profiles in wells located along or projected onto section AA' (see figure 3). Inferred directions of fluid flow in present-day hydrothermal system indicated by dark arrows. Deeper circulation beneath the west moat during periods of activity within the past 40,000 years indicated by light arrows.

west moat, around the south side of the resurgent dome, to Lake Crowley. Along this section there appears to be a continuous zone of hot water flowing eastward from Casa Diablo at altitudes near that of Lake Crowley (2070 m). This zone is evidenced by temperature reversals at similar altitudes in wells along this section as well as similarities in the chemistry of waters from hot springs discharging along or near this section. Temperatures in this zone decrease from about 170°C under Casa Diablo to less than 70°C near the lake. Hydrologic continuity for such flow could be provided within lacustrine sediments that underlie this region, although some complexity must be introduced by the normal faults crossing the section. It should also be pointed out that this zone of thermal water flow lies below the shallow water-table aquifer that transmits relatively cold groundwater to discharge points such as the springs at the (Hot Creek) Fish Hatchery (figure 1).

Temperature profiles in wells located north of section AA' suggest that the thermal flow zone near 2070 m altitude is not continuous under the resurgent dome because the associated temperature reversal do not occur there. Similarly, temperature profiles in wells located west of Casa Diablo show no evidence of the shallow thermal aquifer, 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 P1 below a depth of 550 m, as reported by Benoit (1984). Extrapolation of this high measured gradient to deeper depths indicates that temperatures near 240°C could be reached within the Bishop Tuff, estimated from seismic and gravity data to lie at an altitude of 1520 m (depth of 1100 m) in this vicinity. This suggests that the source of hot water flowing at shallow depths beneath the Casa Diablo area and to the east may be within the welded tuff under the west moat. Fumaroles and hot springs on the flanks of Mammoth Mountain (figure 1) could be related to this postulated hot-water reservoir or could instead be associated with a more localized and shallow-rooted circulation system. The postulated deep reservoir could also be in hydrologic communication with the deeper thermal flow zone delineated by the temperature reversal at a depth of 670 m in well M1 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 (figure 1). As shown in figure 4, 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 south side of the resurgent dome. Fumarolic discharge at several locations west of Casa Diablo 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.

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 tuff at altitudes near 800 m (1350 m depth). These data along with hydraulic head differences based on water-table altitudes and stable isotope relationships (Sorey et al., 1978) 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 extensions of the Hilton Creek fault (Sorey, 1984).

EVIDENCE FOR DEEPER FLUID CIRCULATION

The model of the present-day hydrothermal system discussed above implies that zones of active hot-water circulation are limited to the upper 1.5 km of caldera fill. Indirect evidence for deeper levels of hydrothermal circulation in the past was noted previously. However, the available temperature data is as yet too limited to adequately delineate the nature of the thermal regime at such depths. Nevertheless, a plot of bottom-hole temperatures vs depth for three wells that penetrate the Bishop Tuff (figure 5) indicates some of the possibilities. Although the bottom-hole temperatures for wells M1 and CP on the resurgent dome may be affected by convective heat flow in aquifers at shallower depths, they plot reasonably close to a line drawn through the origin with a slope of 75°C/km. If this slope represents a first-order approximation to the background thermal regime upon which the effects of short-term convective heat of shallow depths are superimposed, the corresponding conductive heat flux would be 160 mWm^{-2}. Because this is smaller by a factor of about 4 than the present-day rate of heat loss from the caldera, either the gradient and heat flux below the depth of fluid circulation are 4 times greater or the shallow zone is losing heat provided from somewhere else.

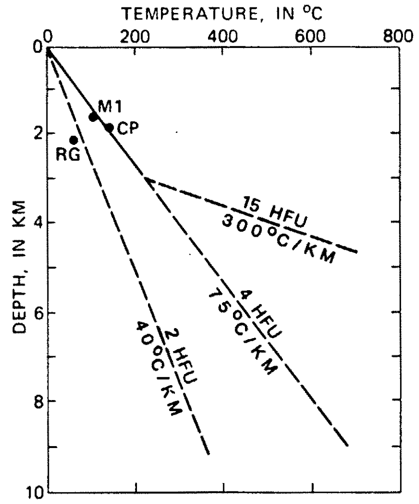

Figure 5. Plots of temperature vs depth based on bottom-hole temperatures in deep wells on the resurgent dome (M1 and CP) and in the east moat (RG). Temperature gradients and heat flux (thermal conductivity = 2.1 J/(s C m) corresponding to dashed lines are discussed in text.

The two extrapolations of the background thermal gradient (figure 5) illustrate these situations. For the 630 mWm^{-2} heat-flux extrapolation, the present-day heat loss from the caldera would be supplied to a long-lived convection system that extends to depths of about 3 km, and the temperature-depth trend defined by the bottom-hole temperature data would be the average gradient between cooler temperatures in regions of downflow and hotter temperatures in regions of upflow. Such a model would apply to the present-day thermal regime beneath the resurgent dome only if the hydrothermal system had been continuously active for a period on the order of 0.3 m.y. (i.e. reached steady-state). Further requirements are that zones of active upflow of hot water from depths of 3 km remain as yet undiscovered and that heat inputs are provided soley by the main Long Valley magma chamber.

The extrapolated trend for a conductive heat flux of 160 mWm^{-2} represents steady-state conditions for a magma chamber at depths of 10 km and no deep fluid circulation. This would be a possible interpretation of the assumed background thermal regime if the deep circulation system beneath the resurgent dome had been dormant for most of the past 0.3 m.y., during which time the magma chamber had remained at depths of 10 km. The hydrothermal alteration record along with geophysical studies that now detect magma at depths as shallow as 4-5 km (Sanders, 1984) indicate that neither of these conditions are met. Hence, the actual thermal regime at depths below 3 km beneath the resurgent dome probably lies somewhere between the extrapolations in figure 5. If there had been a deep circulation system in this region until a few thousand years ago, evidence of upflow beneath areas of surficial thermal-fluid discharge should still exist in the form of elevated temperatures, unless subsequent intrusion of cold water have removed such effects. Alternatively, deep circulation may have been confined to portions of the west moat during the past 40,000 year period when extensive saline layers containing borate, potassium, and sulfate-bearing minerals were deposited in Searles Lake (Sorey, 1984; Smith, 1976). Zones of hot-water flow beneath the resurgent dome during this period could have been restricted to permeable channels in and above the Bishop Tuff, as observed today. Heat for such a circulation system would have been provided by the Inyo-Mono magma chamber and overlapping parts of the Long Valley magma chamber.

The bottom-hole temperature data do suggest that temperatures close to the inferred maximum values attained in the present-day system (240°C) may occur within the basement rocks at depths of 3-4 km under the dome. Beneath the east moat, the bottom-hole temperature in well RG plots below the line corresponding to a gradient of 40°C/km and a heat flow of 80 mWm^{-2}, the regional heat flow reported by Lachenbruch et al. (1976) for wells east of the caldera rim. This comparison and the shape of the measured temperature profile in well RG suggest that temperatures at depths of at least 2.1 km beneath the east moat are being cooled by circulation of groundwater within the Bishop Tuff.

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