Geothermal Resources Council, TRANSACTIONS, Vol. 11, October 1987

HYDROTHERMAL REGIME OF THE SOUTHWEST MOAT OF THE LONG VALLEY CALDERA, MONO COUNTY, CALIFORNIA, AND ITS RELATION TO SEISMICITY--NEW EVIDENCE FROM THE SHADY REST BOREHOLE (RD08)

T.C. Urban[1] W.H. Diment[1] and M.L. Sorey[2]

(1) U.S. Geological Survey, Denver, CO 80225
(2) U.S. Geological Survey, Menlo Park, CA 94025

ABSTRACT

The Shady Rest borehole (RD08) located near the Shady Rest Campground 2 km northeast of the town of Mammoth Lakes, California (lat. 37°39.4'N., long. 118°57.2'W., elev. 7,792 ft), was cored to a depth of 2,346 ft. Unexpectedly high temperatures (202°C) were encountered at shallow depths (1,110 ft). Assuming hydrostatic conditions, these temperatures are within 10°C of boiling. Although the results of the drilling, sampling, and logging programs have not yet been fully integrated, and critical experiments and analyses remain underway, we present precision temperature and natural gamma-ray logs that may be relevant to future interpretations, as well as some preliminary speculations as to the meaning of the results.

Although the initial hole was cored to a depth of 2,346 ft between 5/7/86 and 5/30/86 with little difficulty, attempts to ream it for insertion of casing caused sloughing in some of the softer rocks. Somewhere between four and eight off-track holes were drilled. Attempts to completely cement the annulus between hole and pipe failed. A water-injection experiment revealed the permeable zones. The hole was completed to 1,394 ft when NQ drill rods were left in the hole with no cement in the annulus above 1,106 ft. Six precision temperature logs obtained between 7/7/86 and 9/23/86, as well as bottom-hole temperatures obtained during drilling and Kuster-gage temperature measurements obtained 3 days after drilling was completed (6/17/86), attest to these thermal perturbations.

The fact that temperatures in RD08 are close to boiling at 1,110 ft and that RD08 is located near the western terminus of a WNW zone of strike-slip faulting some 10 km long, 2 km wide, and extending to a depth about about 8 km leads us to speculate as to the cause and consequence of this seismicity, particularly with regard to spasmodic tremor evident in earthquake swarms in this zone.

The fragile hydrothermal regime of Long Valley caldera was severely disrupted by strong local earthquakes beginning between 1978 and 1980. Subsurface boiling may have occurred along dilational jogs (a la Sibson, 1986) in the south moat. Consequent brecciation of rocks may have produced a significant positive change in volume, the process being fortified by the large heat release upon hydrothermal alteration of previously unaltered rocks. Whether this hypothetical volume change is large enough to have significantly influenced tectonic events remains obscure.

INTRODUCTION

Although much is known about the hydrothermal regime of the Long Valley caldera (most recently summarized by Blackwell, 1985; Sorey, 1985) many questions remain as to the location of heat sources and the nature of the deep flow-regime in this tectonically active caldera (e.g., Savage et al., 1987). Shady Rest RD08 was drilled in the southwest moat where little subsurface information was previously available. Preliminary results from the hole indicate anomalously high temperatures and an unexpectedly shallow depth to the Bishop Tuff (e.g., Wollenberg et al., 1986, 1987), suggesting that some modification of previous hydrothermal models is required.

The town of Mammoth Lakes is located in the Long Valley caldera on the eastern margin of the Sierra Nevada block in Mono County, Calif. Numerous surface manifestations of hydrothermal activity are readily apparent at a number of locations in Long Valley. Hot springs and pools, fumeroles, mudpots, warm ground, clay, and other hydrothermal alteration products are present. Most of the surface thermal activity is in the area near Casa Diablo Hot Springs, along Hot Creek, and along Little Hot Creek (fig. 1). Bailey et al. (1976) recently discussed the geology of the Long Valley caldera. Cleveland (1962) discussed the geology of the area with special emphasis on the clay deposits. Hydrologic and geochemical data have been summarized by Sorey et al. (1978) and Farrar et al. (1985).

To evaluate the geothermal potential of the Mammoth Lakes area, a test well, RD08 (fig. 1) was cored to a total depth of 2,346 ft. The location is about 2 km northeast of the town of Mammoth Lakes, adjacent to the Shady Rest campground of Inyo National Forest. The

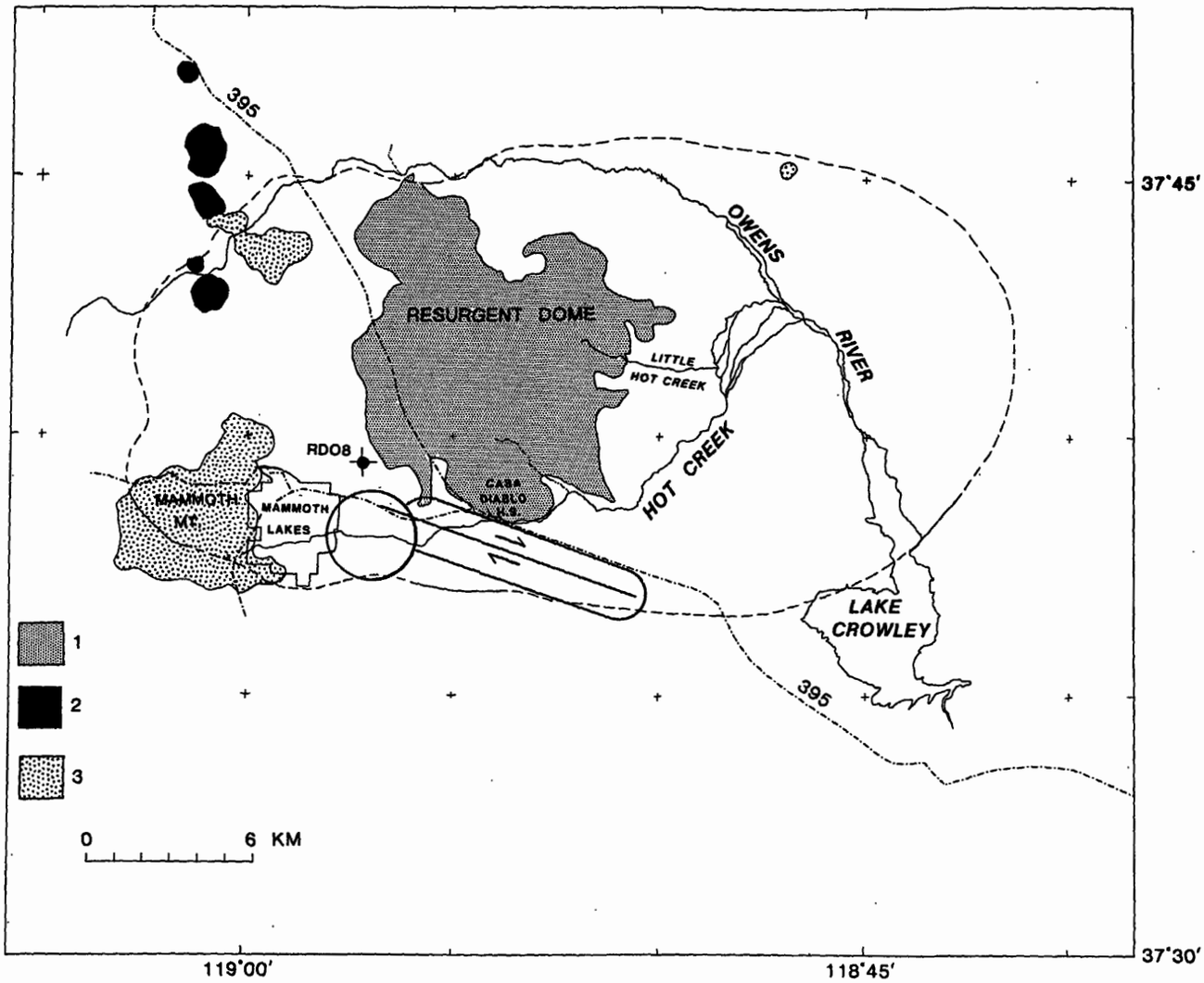

FIGURE 1. Location of drill hole RDO8 2 km northeast of Mammoth Lakes in the Long Valley caldera (dashed line). Circle east of Mammoth Lakes is approximate location of intense earthquake swarms and spasmodic tremor outlined by Ryall and Ryall (1983). Strike-slip fault extending from the circle toward the southeast is the south moat fault (inferred from seismicity). The elliptical feature surrounding the south moat fault is the approximate extent of seismicity during the interval from August 1982 to August 1985 (Savage et al., 1987). The early rhyolite (1) is exposed in the uplifted and tilted blocks of the resurgent dome in the central part of the caldera. Rhyolite to rhyodacite lava domes of the Inyo Domes (2) are in the northwestern part of the caldera. Rhyodacite of the caldera rim (3) is primarily at Mammoth Mountain with smaller flows near the northwestern and northeastern rim of the caldera. Geology adapted from Bailey and Koeppen (1977). Casa Diablo H.S. (hot spring), Hot Creek, and Little Hot Creek are the locations of most of the surface thermal discharge.

existence of the hole presented an opportunity to periodically monitor temperature, pressure, and chemistry of water in a thermal aquifer of the southwestern moat of the caldera (Wollenberg et al., 1986; 1987). Drilling operations were completed on June 17, 1986. The rock types encountered were glacial till (0-210 ft), moat rhyolite (210-672 ft), early rhyolite (672-1,407 ft), and Bishop Tuff (1,407-2,346 ft) (Flexser and Dayvault, 1987). A preliminary Kuster-gage temperature-survey, at 25-, 50-, and 100-ft intervals, indicated an overall pattern of high temperatures at shallow depth that we report here.

Temperature and natural gamma-ray logs from RDO8 contained in this report are presented in graphical form at reduced scale. Tabular listings of data at 1-ft intervals and plots of individual logs are contained in a U.S. Geological Survey Open-File Report (Urban et al., 1987b) along with details of instrumentation and calibration.

ACKNOWLEDGMENTS

The project was sponsored as part of the Continental Scientific Drilling Program by the Department of Energy, Office of Basic Energy Sciences, with contributions by the California

Energy Commission, Mono County, and the U.S. Geological Survey.

H. A. Wollenberg of Lawrence Berkeley Laboratory provided the geologic log of the core from RDO8. L. C. Bartel and R. Jacobson of Sandia National Laboratory provided details of the drilling operation, the driller's log, and a completion diagram of the hole. M. D. Clark of the U.S. Forest Service shared his knowledge of the geothermal system and arranged for logistical support. C. G. Bufe, A. J. Crone, and K. M. Shedlock reviewed the manuscript and suggested significant improvements.

DRILLING HISTORY

RDO8 (Research Drilling Office No. 8) was drilled by the Tonto Drilling Company under the auspices of DOE's Geosciences Research Drilling Office at Sandia National Laboratories. The hole is sometimes referred to as the Shady Rest (SR) hole because of its proximity to the Shady Rest campground.

Drilling commenced on May 7, 1986. The hole was drilled with a rotary tricone bit (7-3/8 in.) to 303 ft, measured from the ground surface. Subsequently, a PQ casing was set from the surface to 303 ft and the annulus cemented. The hole was then cored to 2,346 ft (using HQ diamond-core bits) with greater than 90 percent recovery (Wollenberg et al., 1986; 1987). Due to the high temperatures and alteration of the early rhyolite (Bailey et al., 1976), attempts to ream the hole in order to set casing were unsuccessful. After several attempts (fig. 2) to clear the hole of material that sloughed (causing multiple bit deviations from the initial track), an HQ casing was set at 898 ft and the annulus cemented. An NQ hole was subsequently drilled to 1,397 ft (almost to the Bishop Tuff at 1,407 ft) and past the point of maximum temperature, as determined by maximum- and Kuster-gage thermometers. The drill rods were cemented in place, and excess cement was pumped down the NQ rods to fill the annulus. No cement circulated to the surface, despite pumping a wiper plug down the NQ drill rods to displace the cement in the rods with water. The wiper plug did not hold, and the cement level stabilized at about 1,276 ft (fig. 3). On the basis of the temperature logs and the cold water "slug" test conducted on July 8, 1986, it appeared that the cement filled the annulus around the NQ rods to about 1,106 ft (fig. 3).

From the driller's log (L.C. Bartel, written commun., 1987), it was evident that there were problems during drilling, including lost circulation, hard and soft layers, badly fractured zones, and deviations from the initial hole. The number of holes that were subsequently drilled will probably never be known, but it is conceivable that as many as nine separate holes were drilled during the drilling and subsequent reaming processes (fig. 2), although only five "new" holes are mentioned in the drilling log. This multiplicity of holes complicated any

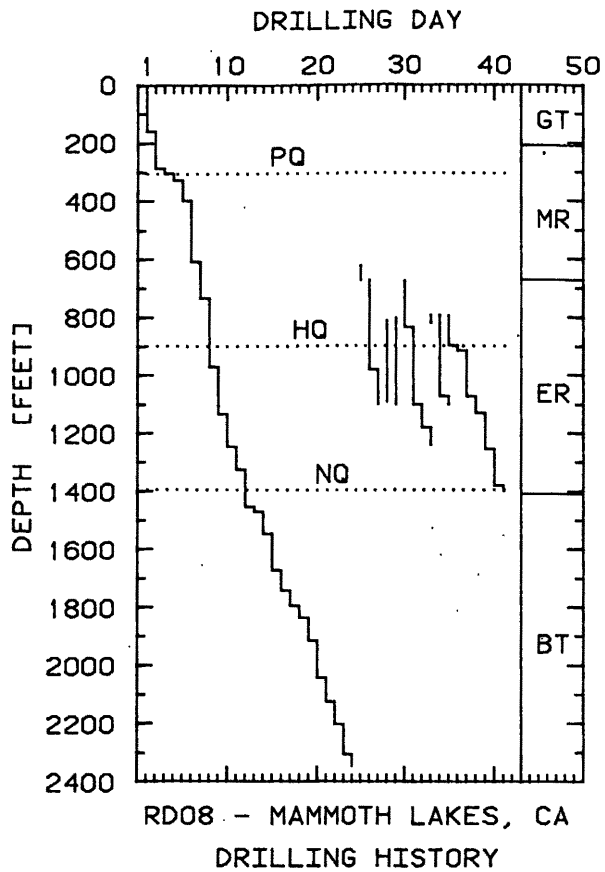

FIGURE 2. Drilling history of RDO8 showing depths drilled on a given date. Depths drilled are shown only to the nearest day for emphasis, although drilling was actually conducted on a 24-hr basis. The bottom of the PQ, HQ, and NQ casings are shown as dotted lines. The generalized geologic section from Flexser and Dayvault (1987) is shown on right-hand margin of the plot. Units represented are GT (glacial till), MR (moat rhyolite), ER (early rhyolite), and BT (Bishop Tuff).

interpretation of the thermal regime since, depending upon whether the previous holes had filled-in or collapsed, they could have provided fluid conduits in addition to existing fractures in the formations.

BHT AND KUSTER-GAGE TEMPERATURES

Temperatures were measured during drilling using maximum thermometers lowered to the bottom of the hole and retrieved after several minutes. The temperature recorded by the thermometer was the maximum temperature that the thermometer encountered in the hole, not necessarily the temperature at the bottom of the hole (BHT). A maximum thermometer records the temperature at the bottom of the hole only if the temperature increases monotonically with depth; i.e., there are no major reversals. In an attempt to minimize any effects on the readings due to hot zones above the bottom of the hole,

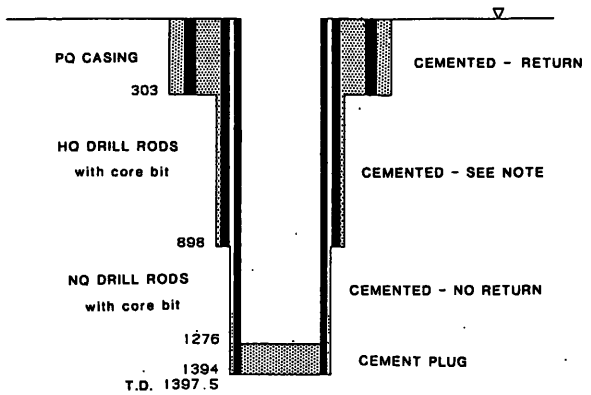

FIGURE 3. Casing diagram for RD08. Casing (solid thick line), hole wall (solid thin lines), and cement (dotted pattern). Measurements in feet are from ground surface. HQ drill rod was cemented with 200 ft^3 of cement with no return to the surface on June 11, 1986. Cement (140 ft^3) was pumped down from the top on June 17, 1986. PQ casing is 5 in. I.D. and 5-5/8 in. O.D. HQ drill rod is 3-1/16 in. I.D. and 3-1/2 in. O.D. NQ drill rod is 2-3/8 in. I.D. and 2-3/4 in. O.D. HQ bit was 3.782 in. O.D. and the NQ bit was 2.980 in. O.D.

the thermometer was encased in a water-filled tube. This increased the thermal inertia of the thermometer and required that it be left at the bottom of the hole for a longer period of time in order to reach temperature equilibrium with its surroundings. This method was used to collect data from the first hole (BHT of fig. 4) which was drilled to 2,346 ft. Successive "holes" were also measured using this technique and temperatures are shown as plus signs (+) in figure 4.

A Kuster-gage temperature survey was obtained in the cased hole on June 20, 1986 (labeled 6/20, fig. 4). The temperatures below 1,100 ft are close to those we obtained on July 7, 1986, and subsequently using a thermistor probe. The hole below 1,100 ft is close to thermal equilibrium whereas that above is not.

THERMISTOR TEMPERATURES--METHOD

Temperatures were measured in RD08 on six occasions during July and September 1986 using thermistor probe no. 100-13. The probe was manufactured by Conax and is a single, glass-encapsulated thermistor bead housed in a 1/8-in.-diameter stainless steel tube, with the void space in the tubing filled with manganese oxide to increase the thermal contact between the thermistor and the tubing. The probe has a nominal time constant of less than 2 s in stirred water. The probe was attached to a probe housing (1 in. diameter by 3 in. long) by a compression fitting with a Viton seal. The probe housing was attached to a 4-conductor, teflon-insulated cable through a Gearhart-Owen cablehead. The 7/32-in.-diameter armored cable was manufactured by Rochester Cable. To add weight to the probe, two sinker bars were positioned above the cablehead. The first was 1 in. diameter and the next in line up the cable was 1-3/4 in. diameter. The

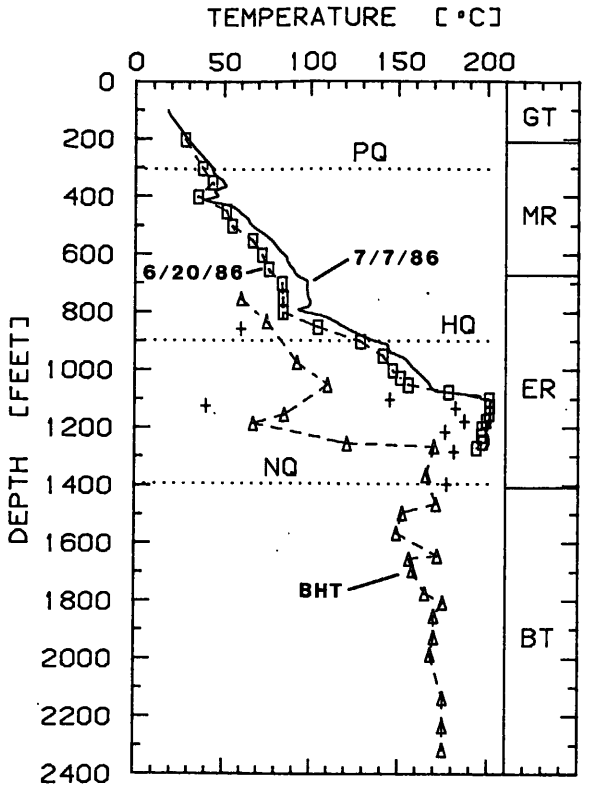

FIGURE 4. BHT and Kuster-gage temperatures for RD08. BHT (Bottom Hole Temperature, Δ) obtained near bottom of hole during drilling. Dashed line connecting triangles is for clarity and should not be interpreted as a continuous log. The Kuster-gage temperatures (□) were obtained June 20, 1986. Remaining temperature points (+) are BHT measurements obtained in off-track holes after first hole was drilled. Thermistor temperatures (7/7/86) are solid lines. Generalized geologic section is from figure 2.

sinker bars were made of steel and were 4 ft long.

The probe was calibrated on June 27, 1986, and on January 31, 1987, according to procedures described by Urban et al. (1987b). The maximum correction to the field data was 0.2°C at 200°C.

The logs were obtained by lowering the probe down the hole at a continuous rate of 10 ft/min. The depths obtained from the measuring sheave were continuously sampled at integer 1-ft intervals. The depths for the thermistor temperatures were referenced to the top of the casing, 1.8 ft above ground level.

THERMISTOR TEMPERATURES--MEASUREMENTS

A composite plot of all six thermistor probe temperature logs is presented in figure 5. Individual plots and tables of temperatures are given by Urban et al. (1987b).

Several observations can be made concerning figure 5. The first is that hot water, greater than 200°C, existed at depths below 1,100 ft. The second observation is that the irregular shape of the profiles was most likely due to the complex drilling history, multiple casing strings, lost circulation, and changes in lithology. The temperature profile of July 8, 1986, differed from the others because it was obtained immediately after about 1,100 gal of water was dumped down the annulus between the HQ and the NQ drill rod (fig. 3). Finally, some of the temperature anomalies coincided with void spaces or fractures, as noted in the driller's log (L.C. Bartel, written commun., 1987) or in the core log (Flexser and Dayvault, 1987), and may have been zones of fluid flow or zones that accepted drilling fluid.

The starting depths of the temperature logs vary on different dates because the logging starts at the top of the water column. We routinely measured the depth to the surface of the water in the casing. The primary reason for this was that although the time constant for the probe in stirred water, or a probe moving though still water, is less than 2 s, the time constant for the same probe is on the order of tens of minutes or hours in still or slowly moving air. Therefore, the probe moving down the hole at 10 ft/min was severely out of equilibrium with the surroundings in an air-filled hole. Since this data would be discarded later, it was more convenient to start the log at about the water level in the hole. The reason for the decline in the water level in the hole was probably leakage through the joints in the casing. We filled the NQ rods to the surface on July 8, 1986, and by July 9th the water level had dropped to 6.95 ft. After logging on July 9th, the level had decreased slightly due to adhesion of the water to the cable, sinker bars, and probe assembly. However, by July 14th, the level had dropped to 45 ft below the top of the casing. In the driller's log entry dated May 19, 1986, the fluid level was at 150 ft, when the total depth of the hole was 1,462 ft. Measurements made in November 1986, after the NQ rod was perforated at a depth of 1,110-1,120 ft on October 20, 1986, indicated a static water level of 443 ft below the top of the casing.

THERMISTOR TEMPERATURE DIFFERENCES

Due to the large temperature range in RD08, the change in temperature with time at various depths is not discernible in figure 5. We, therefore, have taken our first log (July 7, 1986) as a reference set of temperatures and have substracted them from the temperatures of the same depth from each of the succeeding logs. The differences plotted as a function of depth (fig. 6) illustrate, in an amplified manner, the complexity of the temperatures in this hole. We used the July 7, 1986, temperatures as a base and not the Kuster-gage temperatures of June 20, 1986, because the Kuster-gage temperature log obtained at 25-, 50-, or 100-ft intervals did not provide the detail needed for comparison. It

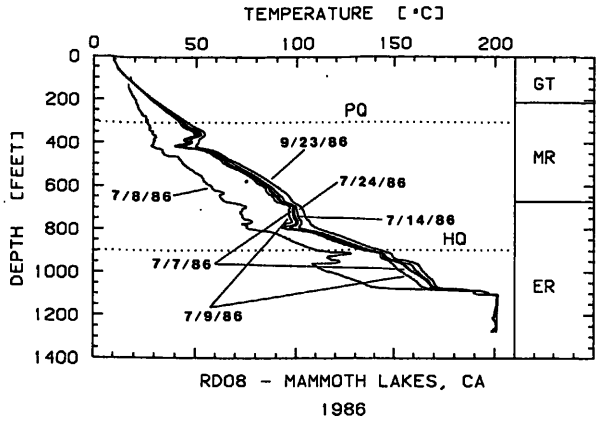

FIGURE 5. Composite thermistor temperature plot for measurements obtained in July and September 1986. Measurements started at water level in NQ drill rod and are referenced to top of casing, 1.8 ft above ground level. Log obtained July 14, 1986, is nearly the same as that of July 7, 1986. Slight warming can be observed in plot of figure 6. Chalfant earthquake (M_L=6.4) occurred July 21, 1986. Generalized geologic section is from figure 2.

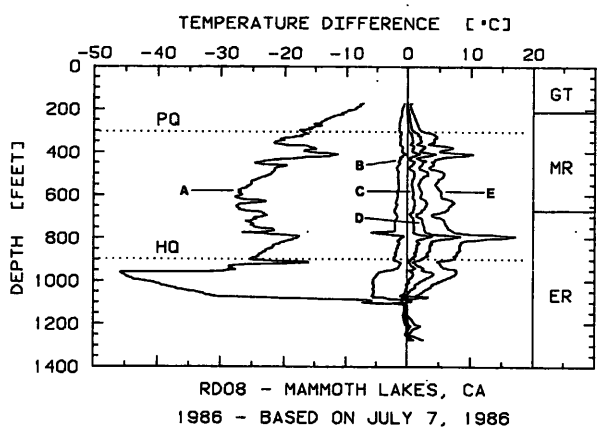

FIGURE 6. Plot of temperature differences in RD08 as a function of depth, based on July 7, 1986, temperature log. A is the difference between temperatures obtained 7/8/86 and 7/7/86. B is between 7/9/86 and 7/7/86. C is between 7/14/86 and 7/7/86. D is between 7/24/86 and 7/7/86. E is between 9/23/86 and 7/7/86. About 1,100 gal of water was poured down the annulus between NQ and HQ drill rods before temperature log of 7/8/86. Flow started at 08:36 PDT and was completed at 09:20 PDT. Temperature log started at water surface (123 ft below surface) at 10:00 PDT and was completed at 11:45 PDT. Curve A represents the cooling that occurred due to this injection of water. Apparently most of the water entered the formation below the HQ casing at 898 ft and above 1,106 ft. Below 1,106 ft, the annulus between NQ drill rod and hole wall appears to have been effectively sealed with cement (see fig. 3). Generalized geologic section is from figure 2.

should also be noted that the temperatures of July 7, 1986, were out of thermal equilibrium with the formation due to the drilling disturbance, lost circulation, and curing of cement. Although the "first" hole was completed quickly (drilled to about 1,300 ft in 11 days), subsequent reaming and redrilling extended the circulation time above 800 ft to roughly 35-42 days. If the decay in the drilling disturbance was by conduction alone, then the temperature gradient, or the rate of change in temperature with depth, will reach its equilibrium value in about 10 times the drilling disturbance (Diment and Weaver, 1964) or about 1 year. The gradient will be at about 95 percent of its equilibrium value in about 1.5 times the drilling disturbance (Diment and Weaver, 1964; Lachenbruch and Brewer, 1959) or about 2 months. The absolute temperatures, however, could continue to increase slightly for much greater lengths of time. If lost circulation was significant, and from the driller's log, this appeared to be the case at some depths, then the return of the temperatures at certain depths to their predrilling values may be on the order of several years. The same is true for the dissipation of heat due to the curing of the cement if a fracture, void, or washout accepted a large quantity of cement.

NATURAL GAMMA-RAY MEASUREMENTS

On September 23 and 24, 1986, we obtained a series of natural gamma-ray logs in RD08 (fig. 7). We used a Geiger-Mueller tool manufactured by Geosource/SIE with a diameter of 1-11/16 in. As with the thermistor temperatures, these measurements were referenced to the top of the casing. We logged down the hole at about 150 ft/min. The high logging rate was necessary due to the high temperatures encountered in the hole. The tool has nominal rating of 125°C for continuous exposure. By logging at the high rate we were able to reach the bottom of the hole without damaging the instrument.

The last gamma-ray log (labeled 9/24-3 in fig. 7) was run with a time constant of 0.5 s, whereas the previous logs had a 1-s time constant. The logging speed was about 150 ft/min.

DISCUSSION AND CONCLUSIONS

The shallow thermal regime of the Long Valley caldera has been discussed by Lachenbruch et al. (1976), Sorey and Lewis (1976), Sorey et al. (1978), Diment et al. (1980), Sorey (1985), Blackwell (1985), and Diment et al. (1985). Although geochemical studies (Mariner and Willey, 1976; Fournier et al., 1979) indicated reservoir temperatures in excess of 200°C and possibly as high as 282°C, the maximum temperature previously observed in the south moat was 172°C at Casa Diablo in Mammoth No. 1 (Urban and Diment, 1984). Although the shallow thermal regime was fairly well known over a significant part of the caldera, the southwestern moat in and around Mammoth Lakes had not been explored as extensively as other parts of Long Valley. The high temperatures (~202°C at 1,110 ft) at the

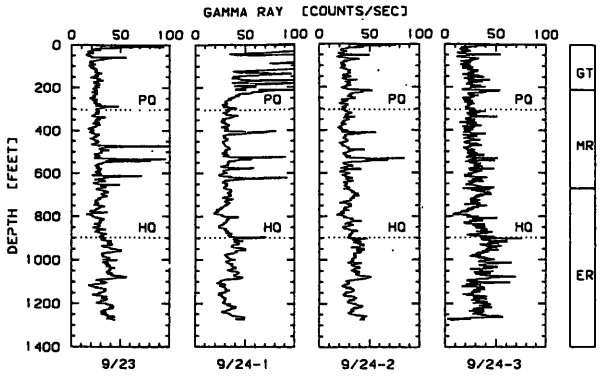

FIGURE 7. Natural gamma-ray logs obtained in RD08 9/23 and 9/24/86. Data was obtained with a Geiger-Mueller tool, logging down at about 150 ft/min. Time constant for first three logs was 1 s and for fourth log (9/24-3), 0.5 s. Plot data (not filtered) obtained from analog stripchart recordings by digitizing at 1-ft intervals. Generalized geologic section is from figure 2.

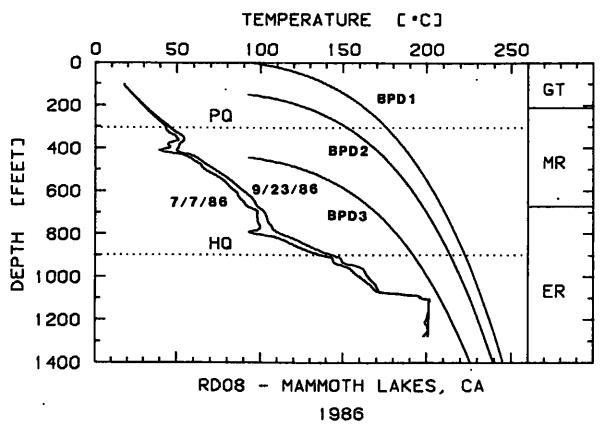

FIGURE 8. Temperatures and calculated boiling-point-depth (BPD) curves for RD08 with fluid at the surface (BPD 1), 150 ft (BPD 2), and 443 ft (BPD 3) below the surface. Generalized geologic section is from figure 2.

location of RD08 (figs. 1 and 5) was unexpected at such shallow depths (see Blackwell, 1985). RD08 also encountered the Bishop Tuff at about 1,407 ft, which is the shallowest that it has been found in the caldera (Wollenberg et al., 1986; 1987). Soft tuffs in the 700- to 800-ft interval, made it impossible to ream the hole for casing and, at the same time, to remain in the original hole. Thus, multiple reaming and drilling of new holes may have affected the temperature logs (fig. 5) by creating new conduits for fluid flow. On the other hand, detailed logging of the core by Stephen Flexser

of Lawrence Berkeley Laboratory and Richard Dayvault of the Department of Energy, Curatorial Office (Flexser and Dayvault, 1987) indicates that many of the fractures in the formations have deposits of chalcedony, clay, zeolite, pyrite, euhedral quartz, calcite, and sulfide minerals, indicating that fluid flow has occurred in the fractures under predrilling conditions. In addition, the temperature reversal at 350 to 400 ft was similar in appearance to the reversals and isothermal sections below 700-800 ft. Thus, the multiplicity of holes may not have had a significant effect on the total flow regime, except possibly immediately in the vicinity of the hole as it now exists. Since it was not clear where all the cement ended up in the hole, on July 8, 1986, about 1,100 gal of water was pumped down the annulus between the NQ and HQ casings (fig. 3). The formation accepted all of the water without any pressure buildup, and no water was observed in the annulus near the surface. The temperature of the water pumped down the hole was about 17.7°C. From figures 5, and 6, it can be seen that the temperatures in the hole cooled by 40°C or more in the sections above 1,100 ft. However, at about 1,110 ft (depth of maximum temperature) there was only about 0.4°C decrease in temperature compared to that observed on the previous day (July 7, 1986). Several anomalies on the difference plot of figure 6 can be associated with the drilling or casing history. The bottoms of the PQ casing and HQ drill hole are marked by sharp breaks in the temperature plots (fig. 5) and in the temperature difference plots (fig. 6). Not only does this depth mark the bottom of the casings, it is also the depth where a significant, or at least known, change in hole diameter occurred (fig. 3). Normally, an anomaly associated with change in hole diameter only occurs in holes in which the annulus is not cemented. From figure 6, it appears that the annulus around the PQ casing had been filled successfully with cement as there has been little subsequent change with time in the temperatures. What changes have occurred can probably be related to the uncemented annulus between NQ and HQ drill rods. At the base of the HQ drill rod, the cementing operation appears not to have been as good as for the PQ casing and therefore hole diameter may have had an effect.

The most striking anomaly is that of curve A (fig. 6) between 900 and 1,100 ft. It appears that most of the water pumped down the hole between the HQ and NQ drill rod entered the early rhyolite between about 750 and 1,000 ft. The temperatures in the hole recovered rapidly, however, since by July 9, 1986 (curve B of fig. 6), the differences were substantially reduced from those of the previous day. Certain anomalies persist, such as those associated with the PQ and HQ casings at 303 and 898 ft and the anomalies at 410 and 800 ft. Both of the anomalies at 410 and 800 ft appear to be lost circulation zones (fig. 5). The persistence of these two anomalies and subsequent warming at these depths probably represents a continued warming of the formations in these sections in response to the decay of the drilling disturbance and lost circulation. The section starting at about 800 ft may also represent a washout zone, as this was the depth where serious problems developed in drilling the hole (fig. 2).

Another temperature anomaly between 600 and 700 ft appears to be related to the change from the moat rhyolite to the early rhyolite. Finally, the section of the hole below 1,106 ft shows little change due to the slug test (fig. 6). It appears that the annulus below about 1,106 ft was successfully filled with cement. By July 9, 1986, the temperatures in the hole had recovered almost the same values as those of July 7th. Thus, it appears that the cement returned up the annulus only to about the 1,106-ft level. The wiper plug, which was pumped to the bottom, migrated up the hole to about 1,276 ft and, therefore, the lower 120 ft of the hole was not accessible.

It is apparent that the temperatures increased in subsequent logs after July 9, 1986 (figs. 5 and 6), and is probably related to the recovery from the drilling disturbance, lost circulation, water injection, and multiple holes in this section of the hole. However, based on the September 23, 1986, temperature log, it appears that the temperature increase extends up beyond the problem section in the hole (fig. 2). We note that the Chalfant earthquake (M_L=6.4) occurred on July 21, 1986 (Cockerham and Corbett, 1987) and that the seismicity increased in the Sierran block just south of the caldera, beginning about mid-June (Cockerham et al., 1987). After the Chalfant mainshock, the occurrence rate of earthquakes decreased in the Sierran block. However, in the Long Valley caldera, the occurrence rate increased slightly starting in early July and continued through the Chalfant sequence. Whether the ground shaking altered the flow regime in the vicinity of RD08 enough to perturb the observed temperature profiles is not clear. Gradual changes in temperature have been observed in other parts of Long Valley since the 1980 earthquake sequence (Diment et al., 1985), so it is also possible that some of the thermal anomalies observed in RD08 may be in response to the 1980 and 1983 earthquake sequences in and near Long Valley.

The presence of secondary minerals in fractures indicates fluid flows have occurred through the rock in the past and are possibly continuing at present. An examination of the natural gamma-ray log (fig. 7) illustrates some character that might be attributed to casing, mineralization, solution cavities, or washouts. The break above 1,100 ft possibly correlates with the change in the core log at 1,076 ft, where the rock abruptly became a silicified, pumice-rich tuff. The zone from 672 to 1,407 ft is part of the early rhyolite, with the section from 800 to 1,050 ft containing zones of lacustrine tuff, some pumiceous, with pyritic bands. Flexser and Dayvault (1987) noted that by 1,115-ft, solution cavities were common. The decrease in radioactivity at about 800 ft corresponds to a change

in the rhyolite containing tuff with pyrite to zones of lacustrine tuff. This is also the depth at which the hole started to deviate from the original track when attempts were made to ream it. Therefore, this zone might be a large washout or cavity due to the multiple reamings and drillings.

The large spikes in the logs of figure 7 are not understood. The pulses from the gamma-ray tool were monitored by an oscilloscope, and on several occasions the spikes were observed to correlate with bursts of pulses. The spikes generally occurred above 600 ft, well within the operating temperature of the tool. The slip-ring assemblies were rated to operate at the voltages and rotational speeds under which they were operating and were periodically tested for noise. The noise tests indicated that the slip ring produces only about 1μV of DC voltage, so it is unlikely that this was the source of the spikes. Killion (1978) noted that fluid motion behind casings can produce radioactive anomalies by a chemical reaction between the dissolved radioactive minerals and the casing, depositing a "radioactive crust" on the casing. However, such anomalies should be stationary, whereas most that we observed occurred at different depths on different logs. On July 24, 1986, 3 days after the Chalfant earthquake, the 4-in. plug in the surface casing was bubbling at the threads, and we also observed water in the annulus between the HQ and NQ casing for the first time. On September 23, 1986, the water level in the NQ casing had dropped to 166 ft and the wellhead was under a vacuum, although the water level in the annulus was at the same level as on July 24, 1986. We noted that repeated logs on September 24, 1986, resulted in a decrease in the number and amplitude of the spikes with time. The first log on September 24, 1986, was run shortly after the hole was uncapped. The hole remained open for subsequent logs. However, no gas pressure or vacuum was noted on this date, although the water level in the NQ casing had dropped about 2 ft. Conceivably, the spikes were somehow related to bubble transport by gases up the hole.

Our first (July 7, 1986) and last (September 23, 1986) temperature logs are plotted on figure 8 along with boiling point depth (BPD) curves. In calculating the BPD curves it was assumed that hydrostatic conditions prevailed and that the hypothetical fluid column was at the boiling point of "pure" water throughout (Urban et al., 1987a). BPD 3 was probably closest to reality as an indicator of how close the observed temperatures were to boiling. Evidently fluids near 1,110 ft were closest to boiling, but how close is difficult to specify with precision. The difference between the maximum observed temperature (201.8°C, 1,110 ft, September 23, 1986) and BPD 3 (208.7°C at 1,110 ft) was 6.9°C. But, this difference was too small because the actual pressure at 1,110 ft was greater than that used to calculate BPD 3 (that is, the whole fluid column above 1,110 ft was assumed to be at the boiling point of "pure" water). In order to correct for this effect, we calculated the actual pressure at 1,110 ft (assuming "pure" water) using the temperatures observed on September 23rd and assuming the top of the fluid column was at 443 ft. This shifted the BPD 3 curve at 1,110 ft from 208.7 to 211.4°C. Thus, the observed temperature (201.8°C) was 9.6°C below the corrected BPD 3 (211.4°C). Although further corrections could be made if the distribution of salinity with depth were known, it is pointless at this time. In no event would this have elevated BPD 3 by more than a few tenths of a degree (Hass, 1971), providing pressures were hydrostatic. The important point is that temperatures near 1,110 ft were close to boiling.

Although fluids in and about RDO8 are not presently boiling, some evidence suggests that they may have boiled in 1980 when the fragile hydrothermal system of the caldera was severely shaken by large (M_L>6) earthquakes near the caldera. Intense swarms of earthquakes, some with appearance of spasmodic tremor (fig. 1), occurred immediately east of Mammoth Lakes in 1980 (Ryall and Ryall, 1983, fig. 2). This is also the location (fig. 1) of the western terminus of the right-lateral strike-slip south moat fault zone (e.g., Savage et al., 1987, fig. 8). By invoking a pull-apart mechanism (dilational jog) such as that described by Sibson (Sibson, 1986; Kerr, 1987), pressures could be reduced so that water in the pores and fractures of the rocks would boil. Sibson (1987, p. 1188) notes that "There is historical evidence for boiling events triggered by the arrest of strike-slip ruptures in the fault jog" at Cerro Prieto. The boiling would cease when pressure rose, when fluid was exhausted, or when the supply of heat was insufficient to maintain boiling. Clearly, scenarios could be constructed where interplay among these factors could result in periodic boiling.

The problem with invoking Sibson's mechanism for subsurface boiling and brecciation is that there is no evidence for a right-stepping jog to the northwest of the south moat fault. However, RDO8 does fall in the dilational strain field of a right-lateral strike-slip fault (e.g., Chinnery, 1963, fig. 3). But, if this model is adopted, the zone of intense swarm activity (fig. 1) would be in the compressional field. An increase in pressure would tend to decrease the potential for boiling if the pressure increase did not cause the upward movement of hot waters along faults and joints. If, however, hot waters did rise, the consequent pressure reduction upon the ascending hot waters might be sufficient to cause boiling. The notion that we can have it either way is a strong testament as to the complexity of the processes involved and our ignorance of their details.

In the preceding discussion, it has been assumed that pressures are hydrostatic. They need not be. Pressures in excess of hydrostatic will shift the BPD curves to the right (fig. 8). Pressures less than hydrostatic will shift them to the left. It is important to recognize that the distribution of pressure with depth is

one of the most poorly known parameters in geothermal systems. Witness The Geysers steam field where pressures are far below hydrostatic pressure at steam-production depths of 6,000 ft or more (for example, White, 1973). The point is that without knowing the distribution of both temperature and pressure with depth it is difficult to predict explosive spalling with depth in response to earthquake generated faulting and shaking. The process could occur at considerable depths.

Another factor may be important. According to Ellis (1967, p. 500): "Hydration reactions of silicates are in general exothermic. For a glassy ignimbrite or pumice typical of the New Zealand Taupo Volcanic zone, a reasonable heat of devitrification and alteration would be about 75 cal/gram. With a specific heat for the rock of 0.2 cal/gram [°C] and, for example, an associated water content of 0.1 gram/cc, the adiabatic temperature rise during alteration would be about 300°C. Each cubic kilometer of volcanic rock would give by this means sufficient heat to maintain the natural heat output of a major area such as Wairakei (about $3X10^{15}$ cal/year) for 100 years. As rock volumes of the order of hundreds of cubic kilometers are involved, the heat of alteration could make a significant contribution during the life of an area. The mechanism would be particularly effective as a means of propagating heat during the initial heating up of a large aquifer volume."

Although the surficial discharge of water out of the caldera has not changed significantly since the onset of the most recent episode of seismicity (about 1980; Farrar et al., 1985), hot waters have moved in the subsurface. The questions are: how much and where? Ascending hot waters probably avoid previously altered rocks (unless they are newly faulted) because hydrothermal alteration is an effective self-sealing mechanism (e.g., White, 1973). Now, if we suppose that the rock beneath the south moat in the zone of high seismicity (fig. 1) contains a large fraction of rock susceptible to alteration, and we suppose that some of it has been brecciated by the previously mentioned seismic process, we have a mechanism for raising the temperatures, perhaps significantly. The volume of the hydrothermally altered rocks may also increase but the size and sign of the effect are uncertain because they depend on the amount of material carried away in solution, which could vary locally. The timing of the alteration is an even more difficult question because it involves the temperature and chemistry of the altering solutions, as well as the degree of brecciation.

REFERENCES

Bailey, R.A., Dalrymple, G.B., and Lanphere, M.A., 1976, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, no. 5, p. 725-744.

Bailey, R.A., and Koeppen, R.P., 1977, Preliminary geologic map of Long Valley caldera, Mono County, California: U.S. Geological Survey, Open-File Map, 2 p.

Blackwell, D.D., 1985, A transient model of the geothermal system of the Long Valley caldera, California: Journal of Geophysical Research, v. 90, no. B13, p.11229-11241.

Chinnery, M.A., 1963, The stress changes that accompany strike-slip faulting: Bulletin of the Seismological Society of America, v. 53, p. 921-932.

Cleveland, G.B., 1962, Geology of the Little Antelope Valley clay deposits Mono County, California: California Division Mines and Geology Special Report 72, 28 p.; 2 plates.

Cockerham, R.S., and Corbett, E.J., 1987, The July 1986 Chalfant Valley, California earthquake sequence: Bulletin of the Seismological Society of America, v. 77, p. 280-289.

Cockerham, R.S., Eaton, J.P., and Pitt, A.M., 1987, Seismic analysis of large earthquakes and special sequences in northern California, in National Earthquake Hazards Reduction Program, Summaries of Technical Reports Volume XXIII, U.S. Geological Survey Open-File Report 87-63, p. 191-196.

Diment, W.H., Urban, T.C., and Nathenson, Manuel, 1980, Notes on the shallow thermal regime of the Long Valley Caldera, Mono County, California: Geothermal Resources Council, Transactions, v. 4, p. 37-40.

Diment, W.H., Urban, T.C., and Nathenson, Manuel, 1985, Temperature variations with time in a perennially boiling well in the Long Valley Caldera, Mono County, California: Observations in Chance No. 1 (1976-1983): Geothermal Resources Council, Transactions, v. 9, pt. 1, p. 417-422.

Diment, W.H., and Weaver, J.D., 1964, Subsurface temperatures and heat flow in the AMSOC core hole near Mayagues, Puerto Rico, in Burk, C.A., ed., A study of Serpentinite-the AMSOC core hole near Mayaquez, Puerto Rico: NAS-NRC Publication 1188, p. 75-91.

Ellis, A.J., 1967, The chemistry of some explored geothermal systems, in Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, p. 465-514.

Farrar, C.D., Sorey, M.L., Rojstaczer, S.A., Janik, C.J., Mariner, R.H., Winnett, T.L., and Clark, M.D., 1985, Hydrologic and geochemical monitoring in Long Valley caldera, Mono County, California, 1982-1984: U.S. Geological Survey, Water Resources Investigation Report 85-4183, 137 p.

Flexser, Stevan, and Dayvault, Richard, 1987, Megascopic description of Shady Rest hole core: Lawrence Berkeley Laboratory Internal Report, 210 p.

Fournier, R.O., Sorey, M.L., Marinier, R.H., and Truesdell, A.H., 1979, Chemical and isotopic prediction of aquifer temperatures in the geothermal system at Long Valley, California: Journal of Volcanology and Geothermal Research, v. 5, p. 17-34.

Haas, J.L., Jr., 1971, The effect of salinity on the maximum thermal gradient of a hydrothermal system at hydrostatic pressure: Economic Geology, v. 66, p. 940-946.

Kerr, R.A., 1987, Delving into faults and earthquake behavior: Science, v. 235, p. 65-66.

Killion, H.W., 1978, Fluid migration behind casing revealed by gamma ray logs (originally in The Log Analyst, January-March 1966, p. 46-49): in SPWLA Reprint Volume Gamma Ray, Neutron and Density Logging, Society of Professional Well Log Analysts, Inc., Houston, Texas.

Lachenbruch, A.H., and Brewer, M.C., 1959, Dissipation of the temperature effect of drilling a well in Arctic Alaska: U.S. Geological Survey Bulletin 1083-C, p. 73-109.

Lachenbruch, A.H., Lewis, R.E., and Sass, J.H., 1976, The near-surface hydrothermal regime of Long Valley Caldera: Journal of Geophysical Research, v. 81, no. 5, p. 763-768.

Mariner, R.H. and Willey, L.M., 1976, Geochemistry of thermal waters in Long Valley, Mono County, California: Journal of Geophysical Research, v. 81, no. 5, p. 792-800.

Ryall, Alan, and Ryall, Florina, 1983, Spasmodic tremor and possible magma injection in Long Valley caldera, eastern California: Science, v. 219, p. 1432-1433.

Savage, J.C., Cockerham, R.S., Estrem, J.E., and Moore, L.R., 1987, Deformation near the Long Valley caldera, eastern California, 1982-1986: Journal of Geophysical Research, v. 92, no. B3, p. 2721-2746.

Sibson, R.H., 1986, Internal structure of Parkfield-scale dilational fault jog: the Martha Hill lode system, Waihi, New Zealand: EOS [Transaction of the American Geophysical Union], v. 67, no. 44, p. 1188.

Sorey, M.L., 1985, Evolution and present state of the hydrothermal system in Long Valley Caldera: Journal of Geophysical Research, v. 90, no. B13, p. 11219-11228.

Sorey, M.L. and Lewis, R.E., 1976, Convective heat flow from hot springs in the Long Valley Caldera, Mono County, California: Journal of Geophysical Research, v. 81, no. 5, p. 785-791.

Sorey, M.L., Lewis, R.E., and Olmsted, F.H., 1978, The hydrothermal system of Long Valley caldera, California: U.S. Geological Survey Professional Paper 1044-A, 60 p.

Urban, T.C. and Diment, W.H., 1984, Precision temperature measurements in a deep geothermal well in the Long Valley caldera, Mono County, California: EOS [Transactions of the American Geophysical Union], v. 65, no. 45, p. 1084-1085.

Urban, T.C., Nathenson, Manuel, and Diment, W.H., 1987a, BPE and BPD-BASIC programs for microcomputers to calculate the local boiling point and the boiling-point depth curve for "pure" water: U.S. Geological Survey Open-File Report 87-17, 58 p.

Urban, T.C., Diment, W.H., and Sorey, M.L., 1987b, Temperatures and natural gamma-ray logs obtained in 1986 from Shady Rest drill hole RD08, Mammoth Lakes, Mono County, California: U.S. Geological Survey Open-File Report 87-291, 100 p.

White, D.E., 1973, Characteristics of geothermal resources, in Kruger, Paul, and Otte, Carel, eds., Geothermal Energy: Stanford, Stanford University Press, p. 67-94.

Wollenberg, H.A., White, A.F., Sorey, M.L., Farrar, C.D., and Bartel, L.C., 1986, Research core hole completed at Long Valley: EOS [Transactions of the American Geophysical Union], v. 67, no. 29, p. 582.

Wollenberg, H.A., Sorey, M.L., Farrar, C.D., White, A.F., Flexser, Stevan, and Bartel, L.C., 1987, A core hole in the southwestern moat of the Long Valley caldera--early results: EOS [Transactions of the American Geophysical Union], v. 68, no. 20, p. 529-534.