UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# CHANGES IN THE DISCHARGE CHARACTERISTICS OF THERMAL SPRINGS AND FUMAROLES IN THE LONG VALLEY CALDERA, CALIFORNIA, RESULTING FROM EARTHQUAKES ON MAY 25-27, 1980

By Michael L. Sorey, U.S. Geological Survey

Mark D. Clark, U.S. Forest Service

---

OPEN-FILE REPORT 81-203

CONTENTS

Page

Abstract---------------------------------------------------------------- 1

Introduction------------------------------------------------------------ 2

Previous studies of hydrothermal discharge------------------------------ 3

Results of recent field investigations---------------------------------- 7

Hot Creek gorge------------------------------------------------------ 7

Little Hot Creek----------------------------------------------------- 14

Hot Creek Fish Hatchery---------------------------------------------- 17

Fumarolic activity--------------------------------------------------- 18

Conclusions and recommendations----------------------------------------- 19

References-------------------------------------------------------------- 21

ILLUSTRATIONS

Page

FIGURE 1. Map of the southwest portion of the Long Valley caldera showing various hydrothermal features-------------------- 4

2. Detailed map of Hot Creek near the bathing area in the gorge showing locations of springs and sites of stream gaging and sampling in this investigation---------------- 9

3. Records of water stage at the weir on Little Hot Creek and earthquake events of magnitude 4 and larger registered between May 8, 1980 and May 28, 1980 on the seismograph maintained by the U.S. Forest Service at the Ranger Station in Mammoth Lakes---------------------- 15

TABLES

Page

TABLE 1. Selected streamflow measurements for Hot Creek at sections within and immediately outside the gorge------------------ 10

2. Chemical data for hot springs along the banks of Hot Creek in the gorge. Locations of springs shown in figure 2----- 12

3. Calculated total hot-spring discharge in Hot Creek gorge based on measurements of salinity gain between sections D and E (figures 1 and 2)-------------------------------- 13

# CHANGES IN THE DISCHARGE CHARACTERISTICS OF THERMAL SPRINGS AND FUMAROLES IN THE LONG VALLEY CALDERA, CALIFORNIA, RESULTING FROM EARTHQUAKES ON MAY 25-27, 1980

By

Michael L. Sorey, USGS, and Mark D. Clark, USFS.

## ABSTRACT

Temporary increases in discharge and turbidity occurred in hot springs located within the Hot Creek gorge and near the head of Little Hot Creek following earthquakes with magnitudes up to 6.3 on May 25-27, 1980. Continuous recording of water stage at a weir in Little Hot Creek indicated that the combined discharge of the Little Hot Creek springs increased from 7.7 liters per second (L/s) to 52.6 L/s within one-half hour after the initial earthquakes on May 25, but had returned to normal by May 28, 1980. For the hot springs within Hot Creek gorge, a series of salinity and discharge measurements along Hot Creek dating back to October 1972 indicate that the total hot-spring discharge in the gorge has not changed significantly despite evidence of new spring activity along the banks following earthquakes in 1973, 1978 and 1980. Additional changes observed in the hydrothermal system in the Long Valley caldera following the May 1980 earthquakes include emptying and refilling of water in the Hot Bubbling Pool, temporary increases in turbidity due to siltation in springs at Hot Creek Fish Hatchery, Hot Creek gorge, Little Hot Creek, and along Sherwin Creek, and temporary increases in fumarolic activity on the flanks of the resurgent dome northwest of the Fish Hatchery. Continued monitoring of hot spring discharge and water levels in selected observation wells is recommended to provide a useful record of the effects of earthquakes and volcanic eruptions, as well as future exploration and development for geothermal energy, on the caldera's hydrothermal system.

# INTRODUCTION

The Long Valley caldera, located along the east base of the Sierra Nevada 50 km ~~sou~~northwest of Bishop, Californa, contains an active hydrothermal convection system. Numerous hot springs and fumaroles discharge along extensions of the Hilton Creek fault, an active Sierra Nevada frontal fault. On May 25, 26 and 27, 1980, earthquakes with Richter magnitudes up to 6.3 occurred along the Hilton Creek fault south of the Long Valley caldera. These shocks caused changes in the discharge characteristics of thermal springs and fumaroles in the caldera. This report is a discussion of observations and measurements of temperature, chemistry, and flow of hot springs in Long Valley made by employees of the U.S. Forest Service and the U.S. Geological Survey before and after the earthquakes.

## PREVIOUS STUDIES OF HYDROTHERMAL DISCHARGE

Measurements of the chemical composition and discharge of waters from springs and streams in the Long Valley caldera have been reported by the California State Department of Water Resources (1967); Eccles (1976); Lewis (1974); Mariner and Willey (1976); Sorey and Lewis (1976) Sorey, Lewis, and Olmsted (1978); and Clark (1979). Locations of various hydrologic and hydrothermal features are shown in figure 1. Approximately 80 percent of the surficial discharge of thermal water in the caldera occurs along Hot Creek within the "gorge". Numerous springs, some with boiling temperatures, discharge along the banks of the stream but most of the thermal discharge in the gorge is contributed by springs issuing from the bed of Hot Creek and cannot be easily measured. A salinity-gain technique has been used to estimate the total spring flow within the gorge, as discussed below.

The second largest source of surficial thermal water discharge in the caldera occurs in the springs at Hot Creek Fish Hatchery. The composite temperature of the Hatchery springs is 14.4$^{o}$C and their total flow is approximately 900 L/s. Assuming that this spring water is a mixture of hot water similar in composition to that discharged in the Magma Power wells at Casa Diablo and cold water similar to that in Mammoth Creek, Sorey and Lewis (1976) estimated the hot water discharge at the Hatchery as 16 L/s.

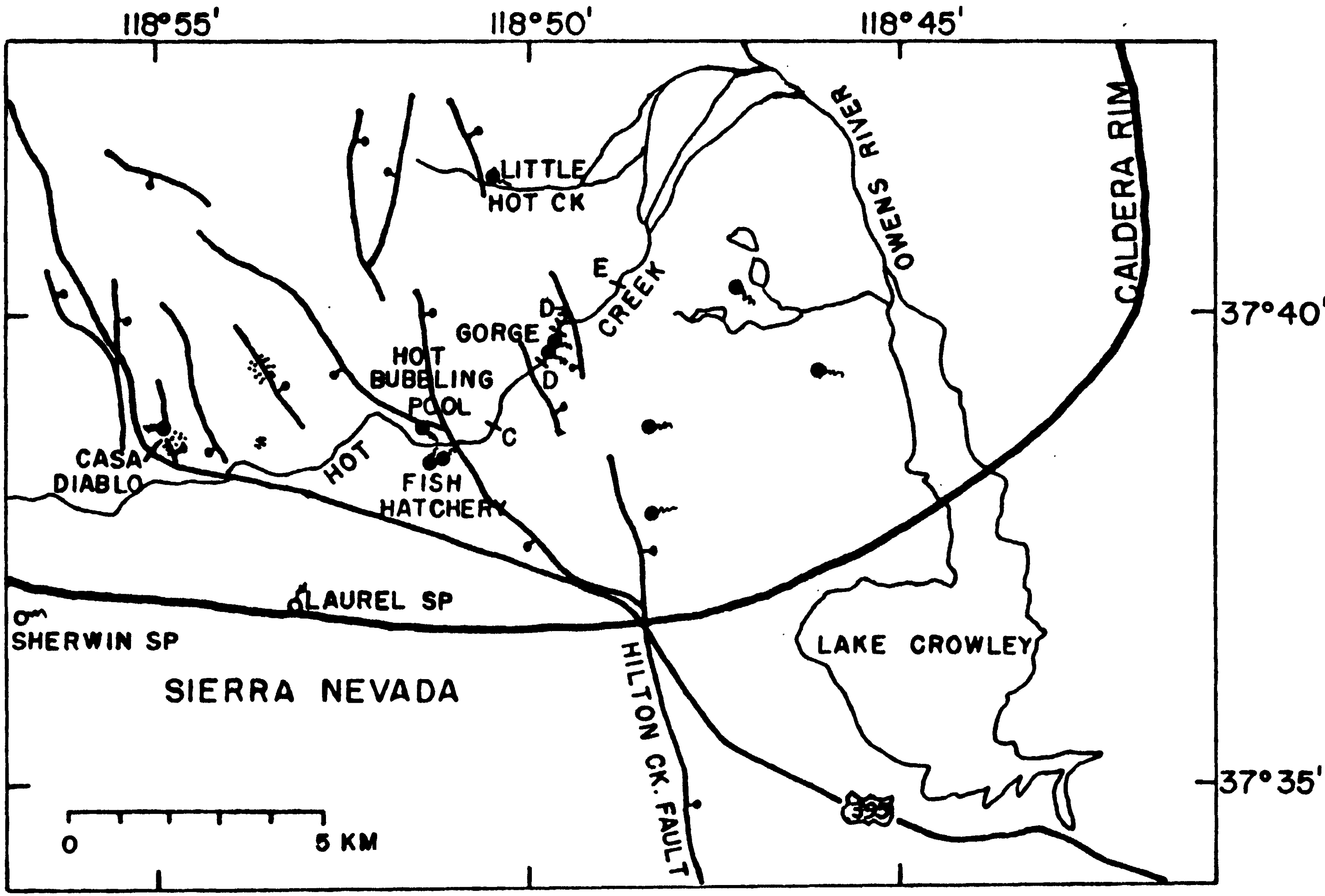


FIGURE 1.--Map of southwest portion of Long Valley caldera showing various hydrothermal features. Faults shown with bar and ball on downthrown side, thermal springs as solid circles with tail, non-thermal springs as open circles with tail, and fumarolic areas as dotted pattern. Letters C, D, $D_3$, and E refer to stream-gaging and sampling stations along Hot Creek.

Near the head of Little Hot Creek, water at temperatures between 68$^{\circ}$C and 80$^{\circ}$C discharges from four main springs. A total flow of 12 L/s was estimated by Lewis (1974). A set of discharge and temperature measurements for Little Hot Creek, along with pH, dissolved oxygen, alkalinity, hardness, and specific conductance values are reported by Clark (1979) for the period May 9, 1979 to October 16, 1979. In November, 1979, the Forest Service installed a thermograph on the hottest spring, and a V-notch weir in the creek with a stage recorder for measurement of the total spring flow. The record of total flow available from the Little Hot Creek site spans the May 1980 earthquakes and offers valuable documentation of seismically-induced changes in hot spring discharge.

Hot Bubbling Pool (also known as Casa Diablo Hot Pool) lies along the eastern fault of the central graben mapped by Bailey (1974) on the resurgent dome. There is no surface discharge from the pool now, although a well-defined channel leading in the direction of Hot Creek indicates flow in the past. Measured temperatures at vents around the margins of the 650 m$^2$ pool range from 49$^{\circ}$ to 82$^{\circ}$C and calculated upflow required to maintain a surface temperature near 55$^{\circ}$C is 6.5 L/s (Sorey and Lewis, 1976). This upflow presumably discharges laterally before reaching the surface of the pool. The pool dried up following the May 25-27 earthquakes and then refilled after about a week, although the exact timing of these events is not known.

Other hot springs discharge east of Hot Creek as shown in figure 1. Most of this water appears to have flowed laterally in shallow aquifers, cooled conductively, and reequilibrated chemically with the aquifer rocks. In addition to the thermal water which enters Hot Creek and Little Hot Creek and subsequently discharges as streamflow into Lake Crowley, temperature profiles in heat-flow wells east of Hot Creek and rates of boron discharge from Lake Crowley suggest that hot water also discharges from the subsurface directly into the lake, as discussed by Sorey, Lewis, and Olmsted (1978).

Fumarolic activity within the caldera is restricted at present to one site on Mammoth Mountain and two areas along the southern margin of the resurgent dome, one at Casa Diablo and one 4 km northwest of the Hot Creek Fish Hatchery (Bailey, 1974). Hot spring and fumarolic activity at Casa Diablo has been nearly eliminated by discharge from the Magma Power wells during the 1960's. Intermittent fumarolic activity northwest of the Hatchery occurs along a fault set mapped by Bailey (1974) which exhibits the largest vertical and horizontal displacements related to the May 1980 earthquakes of any of the intracaldera extensions of the Hilton Creek fault (Bryant and others, 1980).

## RESULTS OF RECENT FIELD INVESTIGATIONS

Field studies conducted July 15-19, 1980, consisted of detailed conversations with Forest Service observers in Mammoth Lakes, stream gaging and chemical sampling at several sections along Hot Creek, and chemical sampling of springs in Hot Creek gorge and Little Hot Creek. Additional data on discharge and salinity in Hot Creek were obtained on December 10, 1980. Records are also available from visual observations of changes in hot-spring flow and daily temperature measurements at several locations in Hot Creek made by Forest Service employees stationed at the bathing area in the gorge during the summer of 1980. Continuous records of spring temperatures at the Fish Hatchery have also been kept by Hatchery employees for several years.

### Hot Creek Gorge

After the May, 1980, earthquakes several new areas of discharge, including some short-lived geysers, developed along the banks of Hot Creek in the gorge, and visual observations showed additional flow from pre-existing springs. Increased discharge from streambed springs was also observed. As with previous large earthquakes in 1973 and 1978, the output of many of the bank springs gradually decreased in the months following the May 1980 earthquakes, although on July 17, 1980, the total flow of hot water from the bank springs appeared to be substantially greater than before May 25. Since July, 1980, temperatures of the new bank hot springs have gradually decreased from near boiling to around 80°C in December, 1980.

It is not possible to quantify accurately these changes in spring activity within the gorge. Because the flow of individual springs is difficult to measure, attempts have been made to calculate the total hot-spring discharge into Hot Creek within the gorge from measurements of streamflow at different sites within and immediately outside the gorge. The results of these measurements, dating back to October 1972, are difficult to interpret because of contributions to Hot Creek from both thermal and nonthermal ground-water sources, however, and this causes considerable variability in calculated values of seepage gain or loss between different sections, depending largely on whether measurements were made during periods of high or low streamflow.

Selected values for streamflow at different sections (located in figures 1 and 2) are listed in table 1. The reach between sections C and D, both of which are upstream from the principal hot-spring area within the gorge, shows the most variability with seepage losses of 140 L/s and 230 L/s at low flow in October 1972, and September 1973, but seepage gain of 960 L/s at high flow in July 1980. Between sections D and $D_3$ or E, where most of the hot-spring discharge occurs, the magnitude of seepage gain is affected by ground-water/surface-water interactions further upstream and appears to be largest during low flow periods.

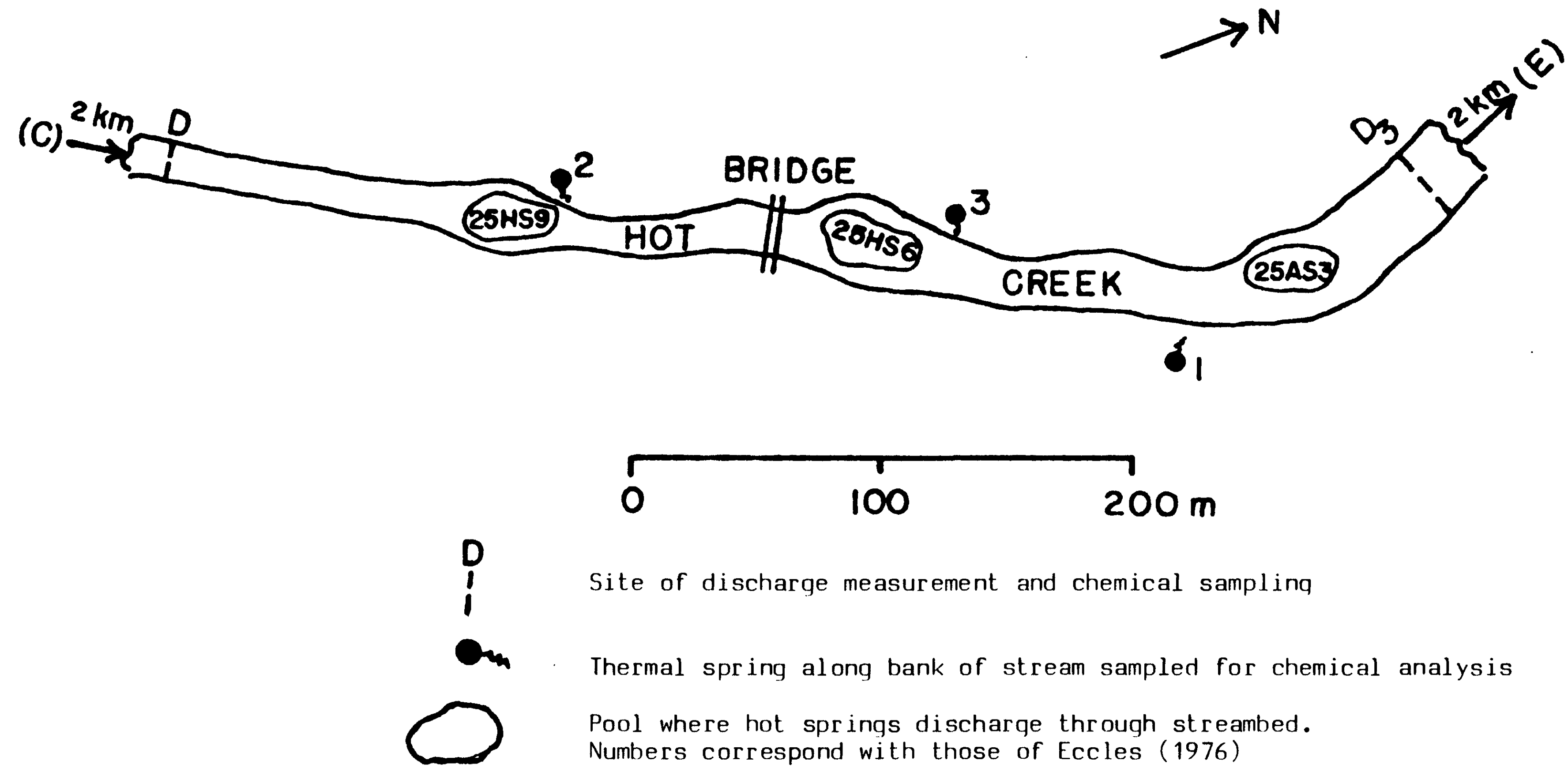


FIGURE 2.-- Detailed map of Hot Creek near the bathing area in the gorge showing locations of springs sampled and stream gaging and sampled stations in Hot Creek.

TABLE 1.-- Selected streamflow measurements for Hot Creek at sections within and immediately outside the gorge.

| Date | Measuring section[1/] | Total flow L/s |
|---|---|---|
| 10-17-72[2/] | C | 1,076 |
| | D | 935 |
| | E | 1,388 |
| 9-25-73[2/] | C | 1,388 |
| | D | 1,161 |
| | E | 1,614 |
| 8-10-79[3/] | D | 1,274 |
| | $D_3$ | 1,869 |
| 6-17-80[4/] | D | 3,568 |
| | $D_3$ | 3,965 |
| 7-17-80[4/] | C | 4,021 |
| | D | 4,981 |
| | E | 5,122 |
| 12-10-80[4/] | C | 1,255 |
| | D | 1,233 |
| | $D_3$ | 1,742 |
| | E | 1,912 |

[1/] location of sections shown in figures 1 and 2.

[2/] Data from Eccles (1976).

[3/] Data from Clark (1979).

[4/] Measurements by M. D. Clark, U.S. Forest Service.

Considering these difficulties, a better method for estimating hot-spring flow in the gorge consists of measuring the addition of characteristic hot-spring elements such as boron, chloride, and arsenic into the flow of Hot Creek. With this salinity-gain technique the total flow of the hot springs can be calculated as the difference in chemical discharge between upstream and downstream sections divided by the average concentration of these elements in the hot-spring waters. Measured concentrations of B, Cl, and As in various spring orifices on the banks of Hot Creek near the bathing area, listed in table 2, indicate that variations in chemistry between different springs and changes with time are relatively small. It must be assumed, however, that concentrations of B, Cl and As in hot spring waters discharging from the streambed are the same as in the bank springs.

Measurements of streamflow and concentrations of B, Cl, and As at sections D and E yield the values given in table 3 for the total flow of hot springs in the gorge. Variations in calculated discharge for each date using different chemical elements reflect the errors associated with the salinity-gain technique. Average values for total discharge on each date are probably more reliable and show remarkably little change over the period of record, which includes earthquakes in August 1973, October 1978, and May 1980, large enough to initiate new hot-spring activity along the banks of Hot Creek. This data, along with visual observations in the gorge and the continuous record of flow for the Little Hot Creek springs discussed below, indicate that although there may be short-term increases in spring discharge following the larger earthquakes the total hot spring discharge gradually returns to the pre-earthquake value. This could reflect some limiting conditions imposed on the total flow by pressures and permeabilities in reservoir rocks at greater depths which are not significantly altered by these tectonic events.

TABLE 2.-- Chemical data for hot springs along the banks of Hot Creek in the gorge. Locations of springs shown in figure 2.

| Spring number | Date sampled | T °C | B mg/L | Cl mg/L | As mg/L |
|---|---|---|---|---|---|
| 1 | 8-29-73 | 90 | 10 | 225 | .90 |
| | 1-18-76 | -- | -- | --- | .92 |
| | 5-29-80 | 92 | -- | 220 | --- |
| | 12-10-80 | 82 | 9.7 | 210 | .93 |
| 2 | 5-29-80 | 92 | -- | 210 | --- |
| | 7-18-80 | 91 | 10 | 210 | --- |
| 3 | 7-18-80 | 91 | -- | 210 | --- |

TABLE 3.-- Calculated total hot-spring discharge in Hot Creek gorge based on measurements of salinity gain between sections D and E (figures 1 and 2).

| Date | Calculated hot spring discharge in L/s, based on gain of: | | | |
|---|---|---|---|---|
| | B 2/ | Cl 3/ | As 4/ | Average |
| 10-17-72 1/ | 281 | 277 | 263 | 274 |
| 1-17-73 1/ | 266 | 237 | 234 | 246 |
| 3-21-73 1/ | 213 | 232 | 287 | 244 |
| 9-05-73 1/ | 263 | 252 | 278 | 263 |
| 9-25-73 1/ | 323 | 249 | 313 | 274 |
| 7-17-80 | 259 5/ | 273 5/ | --- | 267 |
| 12-10-80 | 311 6/ | --- | 337 6/ | 324 |

1/ Data from Eccles (1976).

2/ Assumes boron concentration in springs of 10 mg/L.

3/ Assumes chloride concentration in springs of 215 mg/L.

4/ Assumes arsenic concentration in springs of 0.92 mg/L.

5/ Based on streamflow data listed in table 1, and corresponding boron concentrations of 0.21 mg/L (section D) and 0.71 mg/L (section E), and chloride concentrations of 2.6 mg/L (section D) and 14.0 (section E).

6/ Based on streamflow data listed in table 1, and corresponding boron concentrations of 0.27 mg/L (section D) and 1.8 mg/L (section E), and arsenic concentrations of 0.043 mg/L (section D) and 0.19 mg/L (section E).

## Little Hot Creek

Continuous records of variations in hot-spring flow and temperature since November, 1979, are available for the springs along Little Hot Creek. The water stage record for the weir on Little Hot Creek for the period May 24 to May 28, 1980, is shown in figure 3 along with the seismograph record at Mammoth Lakes showing earthquakes of magnitude 4.0 and larger. Thermographs at Little Hot Creek and Hot Creek gorge were tipped over by the initial shock on May 25, so that measured temperatures during the earthquakes are not reliable. Temperatures of hot-spring water at both locations were the same before and after the May 1980 earthquakes.

The water stage at Little Hot Creek rose from 0.12 m (7.70 L/s) to 0.27 m (52.6 L/s) in a time span of 20-25 minutes after the initial 5.0-6.0 shock series between 9:30-10:00 a.m. on May 25. Subsequent rapid increases in stage and flow occured after the later shocks at 12:45 p.m., 1:36 p.m., and 2:00 p.m. on May 25 and 7:50 a.m. on May 27. Following the latter event, the stage returned to pre-earthquake levels where it has since remained. The nearly vertical lines preceeding each rise in stage are apparently caused by local ground shaking rather than actual variations in spring flow. Tremors below about magnitude 5 appeared to have little effect on the discharge of the springs.

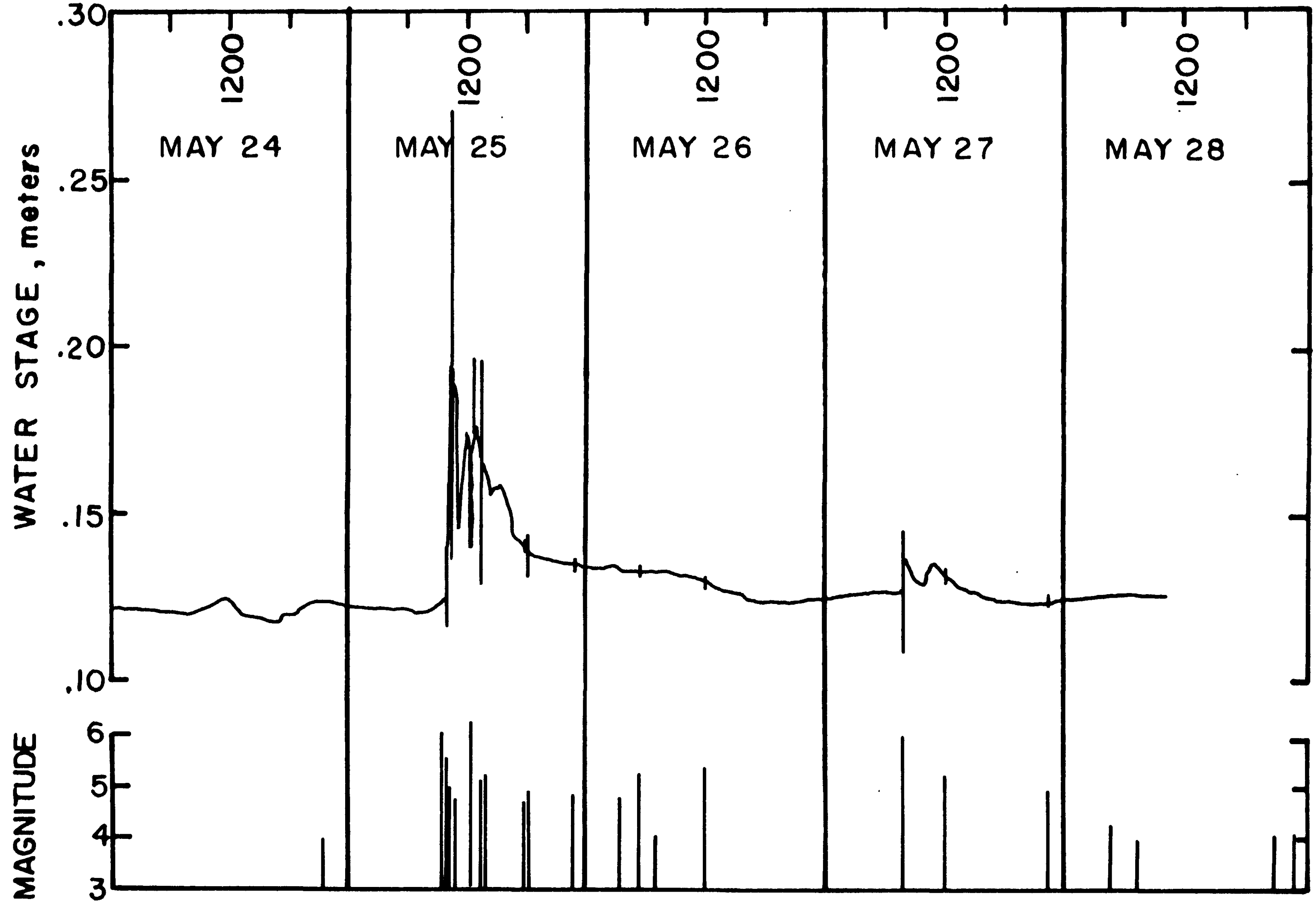


FIGURE 3.--Records of water stage at the weir on Little Hot Creek and earthquakes of magnitude 4 and greater registered between May 24, 1980, and May 28, 1980, on the seismograph maintained by the Forest Service at the Ranger Station in Mammoth Lakes, California.

This pattern of a rapid rise in discharge followed by a somewhat slower decline to pre-earthquake levels probably occurs in the Hot Creek gorge springs as well as in those at Little Hot Creek. The existence of a threshhold earthquake magnitude below which spring flow remains constant also appears characteristic. The mechanisms responsible for this response can be speculated on but not confirmed at the present time. For example, the increase in discharge could be caused by earthquake-induced increases in the permeability of the conduits transmitting hot water upwards to the springs. Subsequent decreases in flow would then reflect pressure reductions at depth resulting from the temporary increase in upflow. The return of surface discharge to pre-earthquake levels may signify that the product of vertical pressure gradient and conduit permeability has returned to its former value. Of course, fluid pressures at depth and hence spring discharge could also change during earthquake activity as a result of the elastic compression/dilation process which accounts for earthquake-induced changes in water levels in wells tapping confined aquifers.

At the Hot Bubbling pool, where the May 1980 earthquake caused a drop in water level followed by a rise to near pre-earthquake levels, it seems likely that a temporary increase in the permeability of the conduit(s) carrying hot water in the subsurface away from the pool area caused the rapid emptying of the pool. Subsequent reductions in the permeability and porosity of these conduits due to siltation and soil creep could have allowed the fluid pressures to recover and the water level in the pool to rise. Longer term but smaller magnitude fluctuations in the water level in this pool have also been observed in the past, although no attempt has been made to document these changes or to correlate them with earthquakes.

## Hot Creek Fish Hatchery

The only noticeable effect of the May 1980 earthquakes on thermal springs at the Fish Hatchery was a significant increase in turbidity due to siltation. Corresponding turbidity increases noted in Hot Creek, in the gorge, were due partly to silt contributed by the Hatchery springs and partly to siltation in some of the gorge hot springs. Turbidity levels in both areas returned to normal following the earthquakes. Records from thermographs in place at several of the Hatchery springs show no changes in water temperature after the earthquakes. Spring discharges also appear to have remained nearly constant although no accurate measurements have been made since 1973.

As discussed by Sorey (1976), the Hatchery springs issue from a surficial basalt layer in an area consisting of alternating basalt and glacial till. It seems likely that earthquake-induced increases in silt in the springs were derived in large part from the till. This is supported by observations of turbidity increases in springs discharging from a moraine in the Sherwin Creek drainage basin in contrast with a lack of siltation in the Laurel spring located 3.5 km southwest of the Hatchery along the granitic south wall of the caldera. Turbidity levels in Little Hot Creek also increased significantly after the initial shock on May 25, returning to normal within about 48 hours. The source of silt in this area was probably the shallow alluvial and lacustrine sediments which deformed and liquified during and after the earthquakes.

## Fumarolic activity

Minor changes in fumarolic activity also followed the May 25-27 earthquakes. Increased steam discharge was observed in the area 4 km northwest of the Hatchery, and a new fumarole discharged on the south-facing side of the rhyolite hill immediately north of the Sheriff's Substation along Highway 395 (figure 1). By August 1 steam discharge had ceased at both sites. Jim Coleman, Fire Prevention Officer for the Mammoth Lakes Ranger District, noted steam discharge at the site northwest of the Hatchery a few days before May 25 and had not seen any steam in previous visits to the area more than a year ago. However, fumarolic activity at this site was observed by one of the authors in the fall of 1979, casting doubt on the possibility that fumaroles in this area serve as earthquake precursers. On the other hand, increased steam discharge following the May 25-27 earthquakes correlates with the appearance of an 0.8 km-long surface crack with 0.25 m (or more) of vertical displacement and abnormally high temperatures in the surrounding soil. Additional geologic and hydrologic investigation in the area seems warranted given the degree of active faulting and its probable extension into the vicinity of the Fish Hatchery.

## CONCLUSIONS AND RECOMMENDATIONS

The results of investigations and observations described in this report indicate that increases in hot spring and fumarolic discharge in the Long Valley caldera may follow earthquakes of magnitude greater than about 5. These changes appear to be only temporary, with a return to pre-earthquake conditions occuring sometime after such earthquake activity ceases. The time required for this return to pre-earthquake conditions may take months for the large-volume hot springs in Hot Creek gorge compared with hours or days for small-volume hot springs near the head of Little Hot Creek. The mechanisms responsible for these changes are not well understood, but could involve changes in the permeabilities and vertical pressure gradients existing in the upflow conduits connecting the hot springs to deeper reservoir(s).

Records are currently being kept on the temperature and total flow of both the Little Hot Creek springs and the Fish Hatchery springs. These data, along with a continuing series of calculations of total hot-spring flow in the Hot Creek gorge based on periodic measurements of discharge and salinity for Hot Creek within the gorge, should provide valuable background information with which to assess the effects on thermal springs of both earthquake activity and future exploration and development for geothermal power.

The response of water level in the Hot Bubbling Pool to the May 1980 earthquakes suggests that the monitoring of water-level changes in this pool and in nearby wells containing hot water may also provide documentation of the effects of earthquakes and geothermal development on the caldera's hydrothermal system. Two possible locations for water-level-recorder installations are Magma Power's Chance 1 well, located 100 m west of the Hot Bubbling Pool, and well CH-10, drilled by the U.S. Geological Survey as a heat-flow test well in the Hot Creek gorge area (see Sorey, Lewis, and Olmsted, 1978) and recently perforated at a depth of 35 m. As suggested by Kilbourne, Chesterman, and Wood (1980), records of water level and salinity at these sites may also prove useful in the event that changes in these quantities become precursers to either earthquakes or volcanic eruptions.

REFERENCES

Bailey, R.A., 1974, Preliminary geologic map and cross-sections of the Casa Diablo geothermal area, Long Valley caldera, Mono County, California: U.S. Geological Survey Open-File map, 2 p.

Bryant, W. A., Taylor, G. C., Hart, E. W., Kahle, J. E., Bedrossian, T. L., and McJunkin, R. D., 1980, Preliminary map of surface rupture associated with Mammoth Lakes Earthquakes of 25 and 27 May 1980: California Division of Mines and Geology Open-File Report 80-12 SAC.

California State Department of Water Resources, 1967, Investigation of geothermal waters in the Long Valley area, Mono County: Report, 141 p.

Clark, M. D., 1979, Water resources data for Mammoth Ranger District, Inyo National Forest, California: U.S. Forest Service Water Resource Data Report, 45 p.

Eccles, L. A., 1976, Sources of arsenic in streams tributary to Lake Crowley, California: U.S. Geological Survey Water Resources Investigations, 76-36, 39 p.

Kilbourne, R. T., Chesterman, C. W., Wood, S. H., 1980, Recent volcanism in in the Mono Basin - Long Valley region of Mono County, California: <u>in</u> Mammoth Lakes, California Earthquakes of May, 1980, Special Report 150: California Division of Mines and Geology, Sherburne, R. W., p. 7-22.

Lewis, R. E., 1974, Data on wells, springs, and thermal springs in Long Valley, Mono County, California: U.S. Geological Survey Open-File Report, 52 p.

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

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.