PROCEEDINGS, Eleventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 21-23, 1986
SGP-TR-93

HOT SPRING MONITORING AT LASSEN VOLCANIC NATIONAL PARK, CALIFORNIA 1983-1985

Michael L. Sorey

U.S. Geological Survey
Menlo Park, California

ABSTRACT

Data collected on several occasions between 1983 and 1985 as part of a hydrologic monitoring program by the U.S. Geological Survey permit preliminary estimation of the natural varability in the discharge characteristics of hydrothermal features in Lassen Volcanic National Park and the Lassen KGRA in northern California. The total rate of discharge of high-chloride hot springs along Mill Creek and Canyon Creek in the Lassen KGRA has averaged 20.9 $\pm$ 1.7 L/s, based on seven measurements of the flux of chloride in these streams. Measured chloride flux does not appear to increase with streamflow during the spring-summer snowmelt period, as observed at Yellowstone and Long Valley Caldera. The corresponding fluxes of arsenic in Mill Creek and Canyon Creek decrease within distances of about 2 km downstream from the hot springs by approximately 30%, most likely due to chemical absorption on streambed sediments. Within Lassen Volcanic National Park, measurements of sulfate flux in streams draining steam-heated thermal features at Sulphur Works and Bumpass Hell have averaged 7.5 $\pm$ 1.0 and 4.0 $\pm$ 1.5 g/s, respectively. Calculated rates of steam upflow containing dissolved H_2S to supply these sulfate fluxes are 1.8 kg/s at Sulphur Works and 1.0 kg/s at Bumpass Hell.

INTRODUCTION

This paper summarizes data collected in a hydrologic monitoring program conducted by the U.S. Geological Survey between 1983 and 1985 in the vicinity of Lassen Volcanic National Park (LVNP). The area of study is located in north-central California at the southern end of the Cascade Range and includes LVNP and the adjacent Lassen Known Geothermal Resource Area (KGRA, fig. 1). The monitoring program has been funded by the National Park Service in an effort to determine the natural level of variability in the discharge characteristics of surficial hydrothermal features in this area. Such information may be needed to assess the impacts of future geothermal development on the Lassen hydrothermal system. An Environmental Impact Statement is currently being prepared for geothermal leasing of federal lands adjacent to LVNP.

Late Pliocene to Holocene volcanic rocks in the Lassen region were extruded from several long-lived volcanic centers, each producing composite cones of andesite to rhyolite lavas and pyroclastics (Clynne, 1984, 1985). A silica magma chamber associated with the Lassen volcanic center (0.6 m.y. to present) provides heat for the present-day hydrothermal system which occurs primarily within the southern half of LVNP and the adjacent KGRA (fig. 2).

Surface thermal discharge includes fumaroles and steam-heated hot springs at relatively high elevations within the Park and high-chloride hot springs at relatively low elevation in the KGRA. Geochemical evidence and temperature measurements in a 1.2 km deep well near Terminal Geyser indicate that the Lassen hydrothermal system is liquid-dominated but includes a parasitic vapor-dominated region associated with the central upflow zone beneath Bumpass Hell (Muffler et al., 1982, Sorey and Ingebritsen, 1984, Ingebritsen and Sorey, 1985). Zones of lateral outflow of hot water derived from this upflow zone trend southward and southeastward, extending to discharge points within the KGRA. Thermal fluid discharge occurs in high chloride hot springs at Growler and Morgan Hot Springs and in diluted low chloride springs at Domingo Springs (fig. 2). Additional thermal fluid may flow in shallow aquifers south of Morgan Hot Springs and may discharge as seeps into Willow Creek and Warner Creek (Sorey and Ingebritsen, 1984).

THE MONITORING PROGRAM

The monitoring program described in this paper includes periodic streamflow measurements and chemical sampling at several sites in Mill Creek, Canyon Creek, and at Domingo Springs, and similar measurements in streams draining steam-heated thermal features at Sulphur Works and Bumpass Hell (fig. 2). Such data permit calculation of hot spring discharge within the KGRA from measurements of the flux of chemical elements contributed to the streams by hot spring waters. With few exceptions, the flow of hot springs in the Lassen area cannot be gaged directly and much of the thermal water occurs as streambed seepage. Hence thermal fluid discharge must be calculated from chemical flux measurements.

Chemical flux measurements in the Lassen KGRA have been made for three conservative thermal fluid elements - Cl, B, and As. The precision of this technique is enhanced by the relatively high concentration of these elements in the hot springs (table 1). Such concentrations may be indicative of a fluid component of marine origin within the Lassen hydrothermal system (Sorey and Ingebritsen, 1984; Thompson, 1985). Although the fraction of hot-spring water in Mill Creek and Canyon Creek at the measuring sites ranges from about 0.5% to 5% during the year, concentrations of Cl, B, and As remain well above detection limits. As noted below, however, a significant portion of the arsenic contributed to these streams by the hot springs appears to be taken out of solution by adsorption on streambed sediments, making chloride flux measurements the most reliable for calculating hot spring discharge.

At Domingo Springs, water that flows from several vents at temperatures near 9^{o}C is channeled through a culvert. Streamflow measurements and chemical samples have been taken below the discharge end of the culvert. Although the measured chloride concentrations in this water (11-19 mg/L) are signifcantly lower than chloride concentrations in Growler and Morgan Hot Springs, they are approximately 10 times higher than chloride concentrations in other cold springs in the KGRA. This indicates that some component of thermal water from the Lassen hydrothermal system discharges in Domingo Springs. In results shown in the next section, thermal fluid discharge at Domingo Springs is calculated from the measured flow of the springs by assuming that the chloride concentration of the thermal component is equal to that measured in water produced from the well at Terminal Geyser (2180 mg/L). This, in turn, is based on the assumption that some or all of the thermal water flowing southeast in the lateral outflow zone beneath Terminal Geyser eventually discharges in Domingo Springs.

The rate of discharge of fluids from thermal areas within LVNP cannot be determined by the same type of chemical flux measurements because of the loss of steam in fumaroles and the lack of conservative elements such as Cl in the steam-heated hot springs. The discharge characteristics of individual vents in such areas may undergo considerable fluctuation due to seasonal and annual hydrologic variations. Published and unpublished data on the temperature and gas concentration of selected steam vents at thermal areas in LVNP document some of these changes that have occurred since 1975 (Muffler et al., 1982; Truesdell et. al., 1983; Janik, written communication, 1986). For the purposes of delineating changes in the rate of upflow of steam and gas from underlying vapor-dominated zones, measurements of the total heat output from each thermal area would be most useful. Such measurements, although difficult to obtain, have been successfully made at Wairakei, New Zealand, to quantify changes in steam upflow induced by geothermal development (Allis, 1981). Total heat output determinations require measurements of heat loss by advection in hot springs and fumaroles, by conduction, and by evaporation.

Data collected during the present monitoring program on the flux of sulfate in streams draining thermal areas at Sulphur Works and Bumpass Hell provide a preliminary basis on which to assess the natural variability in heat discharge at these areas. Some or all of this sulfate flux must come from near-surface oxidation of H_2S which originates along with steam upflow from underlying vapor-dominated zones. If the ratio of H_2S to steam in such upflow is known, the sulfate flux measurements provide an estimate of the fraction of the total steam upflow that is condensed in the hot spring waters in these areas. Such measurements were originally suggested by A.H. Truesdell (written communication, 1984), based on the work of Giggenbach and Stewart (1982). Complicating factors include the possibility that sulfate is also contributed to the streams draining these areas from products of rock weathering and that some H_2S reacts with near-surface rocks to form pyrite and sulfur. Measurements of sulfate flux and the associated steam upflow reported here are compared with estimates of steam upflow made by other means and by other investigators to evaluate the effects of such complicating factors.

THERMAL WATER DISCHARGE IN LASSEN KGRA

The rate of discharge of thermal water from hot springs along Mill Creek and Canyon Creek can be estimated from the difference in the flux of chloride at sites above and below the hot springs divided by the chloride concentration in the spring waters. Data for the site on Mill Creek at Highway 36 (table 2) exemplify the way this is done. Calculated values of hot spring flow (thermal water component) are based on an average chloride concentration of 2300 mg/L in hot springs above this site. The average spring flow is calculated as 17.2 L/s with a standard deviation of 1.2 L/s. Thermal water discharge at Morgan Hot Springs and Growler Hot Springs contributes to this total.

Differences between calculated values of hot spring discharge at this site and other sites within the KGRA between the seven sampling visits during the 1983-1985 period could be caused by several factors. These include errors in streamflow measurements and chloride determinations, loss (or gain) of stream water to the shallow ground-water system below the hot spring areas, and actual differences in hot spring discharge. Data from chemical analysis on duplicate water samples and subjective ratings of stream gaging accuracy suggest that the accuracy of the flux measurements at this site is $\pm$ 10%. Thus, most if not all of the variation in calculated spring flow at this site could be due to errors in streamflow and chloride concentration determinations. There does not appear to be a consistent increase in chloride flux at this site (or any of the other sites in the KGRA) with increasing streamflow. Such a correlation has been shown for hot spring areas at Yellowstone National Park (Norton and Friedman, 1985) and Long Valley Caldera (Farrar, et al., 1985). In those areas the correlation has been attributed to a release of chloride from storage within drainage basins accompanying the spring-summer runoff period.

Results of hot spring discharge calculations based on chloride flux determinations for each thermal area in the KGRA are listed in table 3. The total hot spring flow along Mill Creek (from Morgan Hot Springs) and Canyon Creek (from Growler Hot Springs) has average 20.9 L/s with a standard deviation of 1.7 L/s. Note that the total for Morgan Hot Springs is calculated from the thermal component in Mill Creek at Highway 36 (17.2 L/s from table 2) less the thermal component in Canyon Creek below Growler Hot Springs (2.19 L/s from table 3) plus the thermal component (3.7 L/s) in a tributary to Mill Creek at Highway 36 that is also derived from hot springs at Morgan Hot Springs. At Domingo Springs, chloride flux measurements indicate an average thermal component of 0.93 $\pm$ 0.18 L/s with chloride concentration equal to that measured in the well at Terminal Geyser.

Measured fluxes of arsenic in Mill Creek and Canyon Creek are significantly lower than values calculated from estimates of the thermal-fluid component in these streams (based on measured chloride fluxes). This is not true for the measured boron fluxes, which agree with the calculated fluxes. Data for Mill Creek at Highway 36 (table 4) indicate that 10-39% of the hot-spring derived arsenic is lost between the springs and this measurement site over a distance of 2.5 km. The most likely explanation for this loss is chemical adsorption on streambed sediments. Similar calculations for Canyon Creek show arsenic losses of 19-50% over a distance of 1.6 km.

SULFATE DISCHARGE IN LVNP

Measurements of sulfate flux in streams draining steam-heated thermal features at Sulphur Works (SW) and Bumpass Hell (BH) in LVNP are reported in table 5. Measurements at SW have been made at four culverts through which branches of West Sulphur Creek flow. Data in table 5 apply to two of these branches which drain active thermal features; sulfate discharge in the other two branches is contributed entirely by erosion of sulfate-rich surficial deposits. The total hot-spring derived sulfate flux at SW averages 7.5 $\pm$ 1.0 g/s, and the corresponding total for BH averages 4.0 +

1.5 L/s. At both areas, the reported sulfate flux does not vary significantly with streamflow, indicating that the sulfate contribution from nonthermal sources is minimal.

As discussed previously, the sulfate flux estimates can be converted to estimates of steam condensed in the hot springs, assuming the sulfate is derived from oxidation of H_2S and that the ratio of oxidized H_2S to condensed steam is the same as the H_2S to steam ratio in the vapor-dominated reservoir. Data from Muffler et. al. (1982) based on analyses of fumarolic gases at BH indicate that the steam to H_2S molar ratio in the vapor-dominated reservoir is 1290. The corresponding weight ratio of steam to SO_4 would be 242. Thus the average sulfate fluxes at BH and SW noted above convert to 1.1 kg/s and 1.8 kg/s of condensed steam, respectively. For comparison, the rate of steam condensation required to provide the advective heat loss in the streams draining these areas is approximately twice the values calculated from the sulfate measurements. This suggests that the actual ratio of condensed steam to oxidized H_2S is at least twice the steam to H_2S ratio in the vapor-dominated reservoir. The higher steam to H_2S ratios implied by the advective heat loss rates may be accounted for by near surface loss of H_2S to form pyrite and sulfur deposits and by surficial discharge of H_2S in gas vents and seeps.

Estimates of the total rate of steam upflow at Bumpass Hell can also be obtained from the calculations of total heat flow at this area discussed by Friedman and Frank (1978). Their data, based on ground temperature measurements and meterological calculations, together with the advective heat loss estimates from the current monitoring program, indicate a total heat loss of 36 MW over an area of 0.045 km^2 at Bumpass Hell (fig. 3). This total does not include heat loss in fumarolic steam discharge. The rate of steam upflow required to maintain this heat flow is approximately 13 kg/s, or ten times flow rate suggested by the sulfate flux measurements. Additional study and field observations will be required to verify this heat flow estimate and to delineate more clearly the processes responsible for these differences in steam upflow estimates.

REFERENCES

Clynne, M.A., 1984, Stratigraphy and major-element geochemistry of the Lassen Volcanic Center, California: U.S. Geological Survey Open-File Report 84-224, 168 p.

Clynne, M.A., 1985, Quaternary volcanism in the Southern Cascade Range, California: in Proceedings of the Workshop on Geothermal Resources of the Cascade Range, ed. Guffant, M., and Muffler, L.J.P.: U.S. Geological Survey Open-File Report 85-521, p. 24-30.

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

Friedman, J.D. and Frank, D., 1978, Thermal surveillance of active volcanoes using Landsat-1 Data Collection System: Part 4, Lassen volcanic region: National Technical Information Services, NTIS N78 23499/LL, 46 p.

Giggenbach, W.F. and Stewart, M.K., 1982, Processes controlling the isotopic composition of steam and water discharge from steam vents and steam-heated pools in geothermal areas: Geothermics, v. 11, p. 71-80.

Ingebritsen, S.E. and Sorey, M.L., 1985, A quantitative analysis of the Lassen hydrothermal system, north-central California, Water Resources Research, v. 21, no. 6, p. 853-868.

Muffler, L.J.P., Nehring, N.L., Truesdell, A.H., Janik, C.J., Clynne, M.A., and Thompson, J.M., 1982, The Lassen geothermal system: Proceedings of the Pacific Geothermal Conference, Auckland, New Zealand, p. 349-356.

Norton, D.R., and Friedman, I., 1985, Chloride flux out of Yellowstone National Park: Journal of Volcanology and Geothermal Research, v. 26, p. 231-250.

Sorey, M.L., and Ingebritsen, S.E., 1984, Quantitative analysis of the hydrothermal system in Lassen Volcanic National Park and Lassen Known Geothermal Resource Area: U.S. Geological Survey Water

Resources Investigations Report 84-4278, 80 p.

Thompson, J.M., 1985, Chemistry of thermal and nonthermal springs in the vicinity of Lassen Volcanic National Park: Journal of Volcanology and Geothermal Energy, v. 25, p. 81-104.

Truesdell, A.H., Mazor, E., and Nehring, N.L., 1983, The origin of thermal fluids at Lassen Volcanic National Park: Evidence from noble and reactive gas abundances: Geothermal Resources Council Transactions, v. 7, p. 343-348.

Table 1. Average concentrations of selected ions in thermal waters from the Lassen area, based on analytical results from the U.S. Geological Survey Central Laboratory, Arvada, Colorado on samples collected 1983 - 1985 (except for data for the Terminal Geyser well which are from Thompson, 1985).

Location	T °C	Cl mg/L	B mg/L	As mg/L
Growler Hot Springs	94	2500	87	11
Morgan Hot Springs	94	2300	80	10
Terminal Geyser Well	175	2180	62	10
Domingo Springs	9	15	0.5	0.03

Table 2. Data on streamflow and chloride concentration in Mill Creek at Highway 36 and corresponding calculated values of chloride flux and thermal-water component.

Date	Streamflow (L/s)	Cl (mg/L)	Cl flux (g/s)	Thermal component (L/s)
8/83	4840	7.5	36	15.8
10/83	1146	34	39	17.0
6/84	4871	8.5	41	18.0
8/84	1170	31	36	15.8
11/84	1034	40	41	18.0
7/85	793	46	36	15.9
10/85	1025	45	46	20.1

Average springflow = 17.2 ± 1.2 l/s

Table 3. Average values of thermal-water discharge at thermal areas in the Lassen KGRA, based on chloride flux measurements between 1983 and 1985. Standard deviations for each set of values shown with ±.

Spring area	Thermal water discharge (L/s)
Growler Hot Springs	2.19 ± 0.35
Morgan Hot Springs	18.7 ± 1.67
Domingo Springs	0.93 ± 0.18
Total	21.8 ± 1.72

Table 4. Calculated losses of hot-spring derived boron and arsenic in Mill Creek above Highway 36, based on hot spring discharge computed from measured chloride fluxes (see table 2).

Date	Streamflow (l/s)	Arsenic Calculated (g/s)	Arsenic Measured (g/s)	Arsenic Lost (o/o)	Boron flux Calculated (g/s)	Boron flux Measured (g/s)	Boron flux Lost (o/o)
6/84	4871	0.18	0.12	32	1.44	1.46	-1
8/84	1170	0.16	0.10	39	1.27	1.17	8
11/84	1034	0.18	0.12	31	1.44	1.34	7
7/85	793	0.16	0.14	10	1.27	1.31	-3
10/85	1025	0.20	0.16	18	1.61	1.54	4

Table 5. Sulfate flux measurements at Sulphur Works and Bumpass Hell.

Date	Sulphur Works Streamflow (L/s)	Sulphur Works SO_4 (mg/L)	Sulphur Works SO_4 flux (g/s)	Bumpass Hell Streamflow (L/s)	Bumpass Hell SO_4 (mg/L)	Bumpass Hell SO_4 flux (g/s)
8/83*	280	13	3.6	57	68	3.9
8/84	54	118	6.4	5.4	440	2.4
11/84	52	148	7.7	6.2	850	5.3
5/85*	72	60	4.3	36	180	6.5
7/85	52	117	6.1	4.0	740	3.0
10/85	39	203	7.9	2.8	990	2.8

*Measurements made only at "central" culvert - SO_4 flux applies only to "central" culvert; measurements on all other dates made at "central" culvert and "east" culvert - SO_4 flux applies to the total for both culverts.

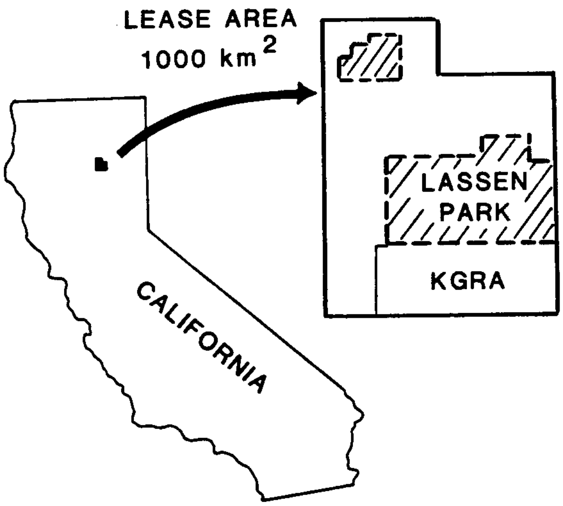

Figure 1. Map showing location of the Lassen study area in north-central California, which includes Lassen (Volcanic National) Park, Lassen KGRA, and Thousand Lakes Wilderness Area (cross-hatched pattern in upper left). All or part of the study area excluding the cross-hatched areas may be leased for geothermal development by the Bureau of Land Management during 1986.

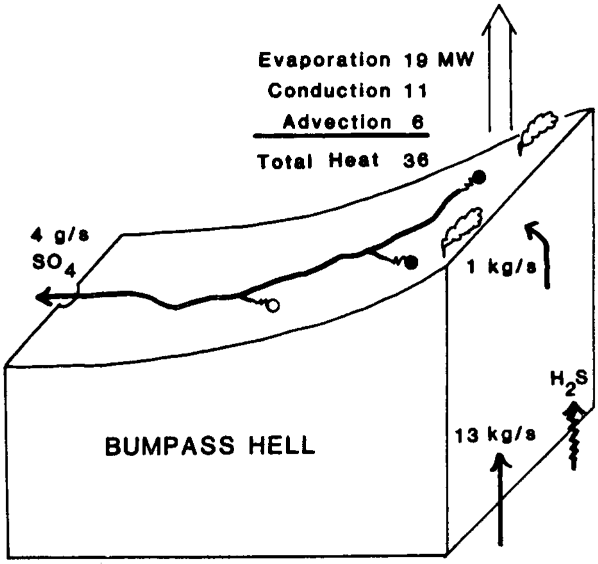

Figure 3. Diagram of Bumpass Hell thermal area depicting the average value of sulfate flux in Bumpass Creek (4 g/s) and the corresponding rate of steam condensation (1 kg/s) assuming a steam to H_2S molar ratio of 1290. Also shown are heat flow estimates based on the work of Friedman and Frank (1978) and the results of this study and the corresponding rate of steam upflow required to supply a total heat flow of 36 MW (13 kg/s).

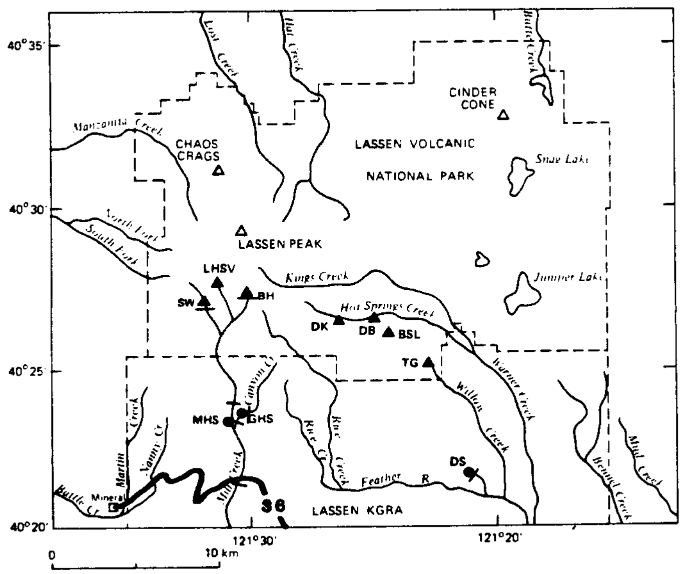

Figure 2. Map showing areas of thermal-fluid discharge and surface drainage in the Lassen region. Areas with fumaroles and steam-heated hot springs are shown as triangles (BH = Bumpass Hell, LHSV = Little Hot Springs Valley, SW = Sulphur Works, DK = Devils Kitchen, DB = Drakesbad, BSL = Boiling Springs Lake, TG = Terminal Geyser). Areas with high-chloride thermal water discharge are shown as dots (GHS = Growler Hot Springs, MHS = Morgan Hot Springs, DS = Domingo Springs). Short lines crossing streams at right angles signify sites where chemical flux measurements have been made for estimation of thermal-fluid discharge.