

HEAT AND MASS FLOW FROM THERMAL AREAS IN AND ADJACENT TO LASSEN VOLCANIC NATIONAL PARK, CALIFORNIA, USA

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ABSTRACT

Average rates of heat **loss** from eight steam-heated thermal areas in Lassen Volcanic National Park, California, range from 0.1 MW to 37 MW and total 115 ± 25 MW. The total rate of upflow of steam from underlying vapor-dominated reservoir(s) required to supply this heat loss is about 40 kg/s. Measurements of chloride flux in streams draining from the Park indicate that the total rate of liquid discharge from the Lassen geothermal system is also about 40 kg/s. Thus, the measured ratio of steam upflow to liquid outflow is approximately 1.0. This value is significantly greater than values predicted by a previously published numerical model of the Lassen system (steam:liquid ratios <0.1), which involved a deep upflow of 260°C water that boils as it rises. This discrepancy suggests either that additional thermal-water discharge remains undetected or that alternative models need to be considered for the Lassen geothermal system.

1. INTRODUCTION

Lassen Volcanic National Park (LVNP), located in northeastern California at the southern end of the Cascade Range, encompasses a 430 km² region of Cenozoic volcanic rocks and surficial hydrothermal activity (Figure 1). The most recent eruptions in the region occurred in 1914-1917 on Lassen Peak. Thermal waters discharge in the southern part of the Park and in the Lassen Known Geothermal Resources Area (KGRA) south of the Park. Thermal areas inside the Park are steam-heated, in contrast to the areas of high-chloride hot springs located south of the Park. High-chloride thermal water was also encountered in a well drilled inside the Park at Terminal Geyser (Figure 1). Conceptual models (Muffler *et al.*, 1982, and Ingebritsen and Sorey, 1985) describe the geothermal system at Lassen as being liquid-dominated with a parasitic vapor-dominated zone. In these models, areas of steam discharge situated at relatively high elevations (1,800 - 2,500 m) in LVNP and areas of high-chloride liquid discharge situated at relatively low elevations (1,500 m) in the KGRA are fed by an upflow of high-enthalpy liquid that boils beneath the Park (Figure 2). Liquid flows laterally away from the principal upflow area beneath the southern flank of Lassen Peak toward the springs along Mill Creek, Canyon Creek, and the Feather River, whereas steam rises through a vapor-dominated zone toward discharge areas in the southern part of the Park.

The purpose of this paper is to describe the results of measurements made over the period 1983-1994 that allow determination of the rates of discharge of steam and hot water from the Lassen system, and to discuss the implications of these results for quantitative models of the system. Details of the measurements are given by Sorey and Colvard (1994), Paulson and Ingebritsen (1991), and Sorey, Colvard, and Ingebritsen (1994).

2. MEASUREMENT TECHNIQUES

2.1 Steam-Heated Thermal Areas in LVNP

Rates of steam upflow beneath the steam-heated thermal areas were determined from measurements of the rate of heat **loss** divided by the

enthalpy of the upflowing steam ($-2,800$ kJ/kg). Heat is lost by a combination of advection in fumaroles and streams, evaporation from water surfaces, and conduction and radiation from bare ground. We evaluated the components of heat loss at each thermal area using methodology and techniques developed in New Zealand (Dawson, 1964; Dawson and Dickinson, 1970) and adapted to conditions at Lassen by Barbara Simpson, formerly with the New Zealand Geological Survey.

The key measurements for heat-loss determinations included (1) steam velocity in fumaroles, (2) stream flow rate and temperature, (3) temperatures and areas of thermal pools, and (4) the areal distribution of ground temperature at a depth of 15 cm. To evaluate and improve the accuracy of our heat-loss determinations, many of these measurements were repeated during site visits over the period 1984-1993. The dominant mode of heat loss differs between the thermal areas and, in the case of advective heat loss in streams, significant seasonal variations were observed. Most of our heat-loss determinations were made during the late summer-fall period, when streamflow had returned to baseflow conditions following the spring-early summer period of snowmelt runoff.

Velocity measurements in steam vents were made with a pitot tube and pressure transducer. Fumaroles at Lassen are commonly superheated (94 - 157°C) compared with the boiling point at local elevations (-93°C). Measured steam velocities in the strongest vents at each area ranged from -20 m/s to -130 m/s. The mass flow rate of steam from these vents was calculated as the product of velocity, vent area, and steam density under vent conditions. The advective heat loss was then computed as the product of mass flow and steam enthalpy ($-2,800$ kJ/kg).

2.2 Thermal-Water Discharge Outside LVNP

Only two closely spaced areas of hot-spring discharge occur outside LVNP - at Morgan Hot Springs and Growler Hot Springs, located adjacent to Mill Creek and Canyon Creek in the Lassen KGRA (Figure 1). Concentrations of Cl and B in these hot-spring waters are relatively high ($-2,400$ mg/L and -85 mg/L, respectively). Consequently, rates of discharge of thermal water can be determined from measurements of chloride and boron flux in the nearby creeks, as described by Sorey and Ingebritsen (1984). Thermal water with similar chemical composition has also been sampled from the geothermal well at Terminal Geyser (Figure 1), and a component of thermal water in Domingo Springs (temperature $\sim 10^\circ\text{C}$) is indicated by Cl concentrations of -20 mg/L, compared with concentrations of ≤ 2 mg/L in other cold springs in the area. Chloride-flux measurements have been made on many occasions since 1983 at gaging sites on Mill Creek and at Domingo Springs (Figure 1).

Paulson and Ingebritsen (1991) described efforts to detect Lassen-type thermal water in other streams draining the Lassen region. Although stream samples from many of the 116 sites sampled were chloride-enriched relative to a "background" sodium:chloride ratio established for nonthermal waters from the Cascade Range (5.4:1), most of these chloride-enriched samples were from streams at elevations <760 m that have flowed over Upper Cretaceous marine rocks. At higher elevations, only the major streams that bound the

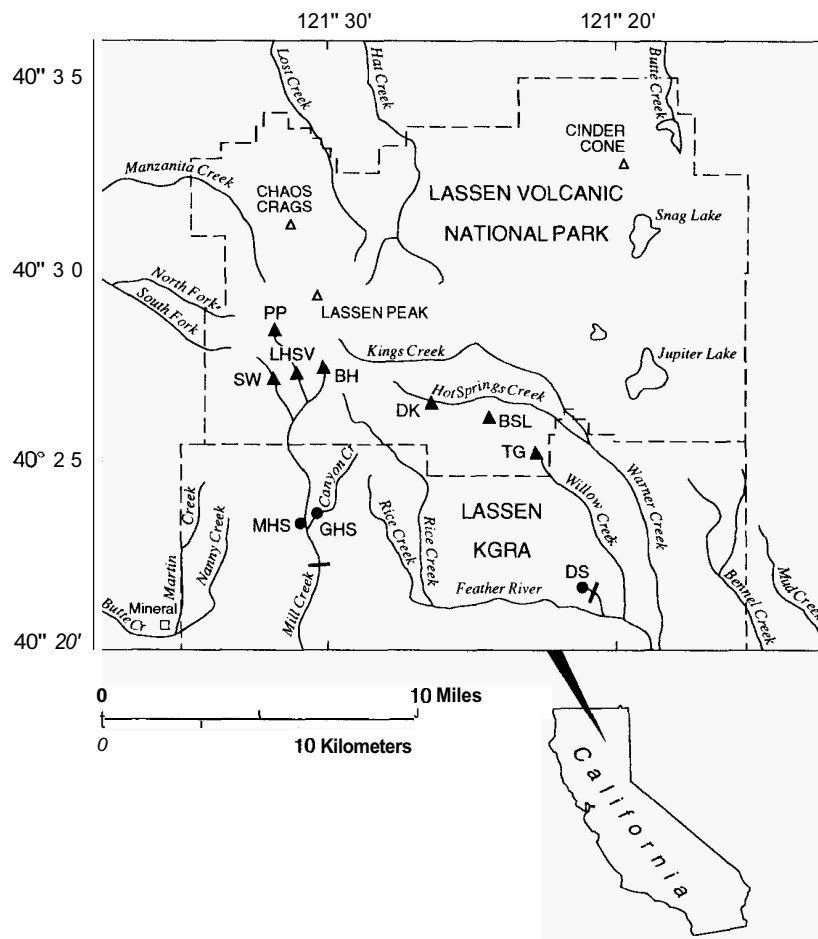


Figure 1. Map showing areas of fluid discharge and major streams in the Lassen region. Open triangles indicate areas of recent eruptive activity. Filled triangles indicate principal steam-heated thermal areas (BH=Bumpass Hell, BSL=Boiling Springs Lake, DK=Devils Kitchen, LHSV=Little Hot Springs Valley, PP=Pilot Pinnacle, SW=Sulphur Works, TG=Terminal Geyser). A small steam-heated thermal area (not shown) also exists on the northwest side of Lassen Peak. Filled circles indicate areas of neutral-pH thermal springs (GHS=Growler Hot Spring, MHS=Morgan Hot Spring) and springs with a thermal-water component (DS=Domingo Springs). Sites along Mill Creek and at Domingo Spring where chloride-flux measurements have been made are indicated by bars.

Lassen region to the north and south are large enough that they could contain substantial thermal components without showing obvious anomalous Na:Cl ratios. For two of these streams (the Pit River and the North Fork of the Feather River), mixing model calculations were applied to late-summer (base flow) Na and Cl data and values of annual average streamflow to estimate the maximum probable component of Lassen-type thermal water (Paulson and Ingebritsen, 1991).

3. RESULTS

Heat-loss measurements for Bumpass Hell exemplify the results for thermal areas inside LVNP (Table 1). At Bumpass Hell, the total heat loss of 29 ± 4 MW results mainly from evaporative heat loss from five thermal pools. Under low-streamflow conditions in the late summer and fall, heat loss from fumaroles amounts to only 2 MW and advective heat loss in the stream that drains the area averages 0.53 ± 0.33 MW. Although it is difficult to reach the high-elevation steam-heated areas before the snow has melted, some measurements of advective heat loss in the streams have been made during high-streamflow conditions in the late spring and early summer. At Bumpass Hell, the late spring-early summer advective heat loss averages 4.4 ± 1.5 MW. Advective heat loss in streams at the other major thermal areas was also found to be significantly greater during high-flow periods than during low-flow periods. We attribute the greater advective heat-loss rates during high-flow periods to removal of heat from shallow soils by cold water that infiltrates locally and eventually discharges in the streams above our downstream measuring sections. This is a transient process that

presumably is followed by a period of heating up of the shallow soils by a combination of steam condensation and heat conduction.

We used the results of our late summer-fall measurements to compute total heat loss from each steam-heated thermal area. The uncertainty in heat loss from each area was computed from the sum of the squares of the measured or estimated standard deviations for each component of heat loss (as shown in Table 1 for Bumpass Hell). The corresponding relative standard deviations (RSD) range from 11-30 percent (Table 2). Under late summer-fall conditions, the total heat loss from all thermal areas in LVNP is 115 MW (Table 2). Using the same sum of squares procedure to compute the uncertainty in this total yields an RSD of 8 percent. However, considering that additional uncertainty in total heat loss is introduced by seasonal variations in heat loss at each area and possible undetected subsurface outflow of heated ground water, we estimate that the uncertainty in the total heat loss is closer to ± 20 percent, or 20-25 MW.

The calculated rates of steam upflow (enthalpy 2,800 kJ/kg) required to support the heat loss at each thermal area range from 0.1 kg/s to 13 kg/s and total 41 kg/s (Table 2). About half of the total heat loss and steam upflow occurs at the five thermal areas situated on the flanks of Lassen Peak, and half occurs at the three areas located to the southeast along or near Hot Springs Creek.

Repeated measurements of chloride flux in Mill Creek and from Domingo Springs (Figure 1) over the period 1983-1994 yield an average value of total thermal-water discharge of 22 ± 4 kg/s. Only

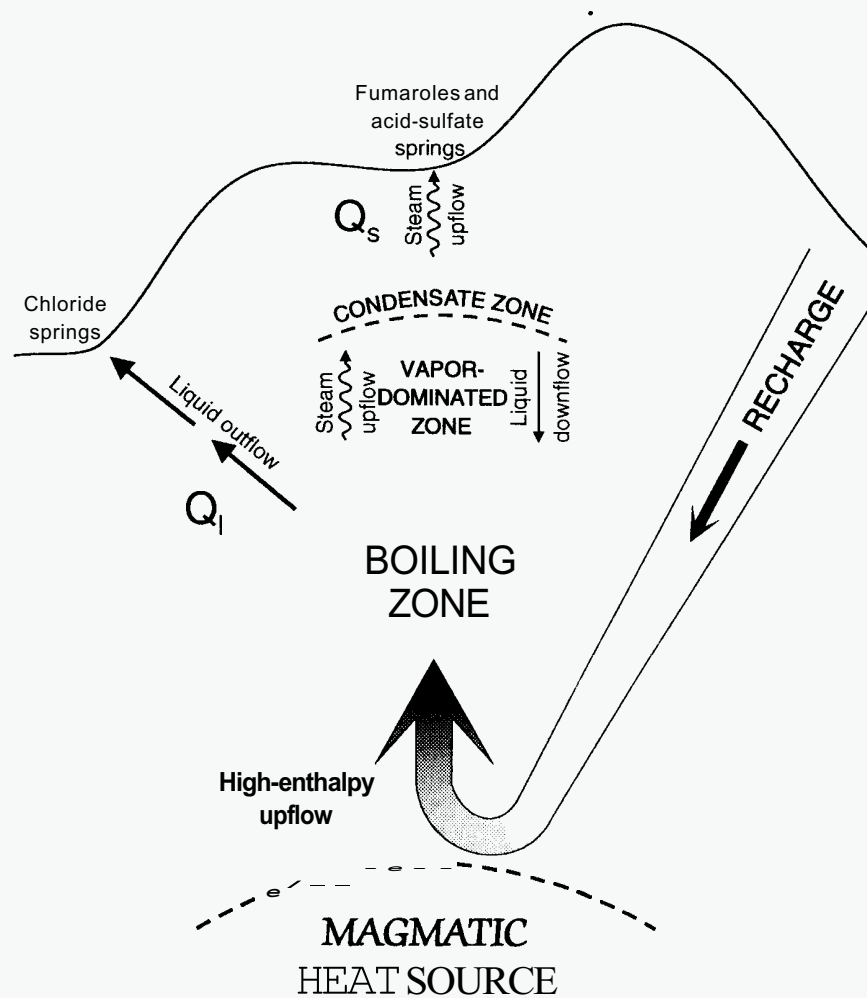


Figure 2. Conceptual model of a Lassen-like geothermal system, referred to as being liquid-dominated with a parasitic vapor-dominated zone. Q_s and Q_l refer to rates of mass flow of steam and liquid, respectively.

about 1 kg/s of this total comes from Domingo Springs. Chloride-flux measurements in Mill Creek in August 1994 indicate that an additional 5 kg/s of Lassen-type thermal water may enter this stream between the gaging site shown in Figure 1 and a site ~30 km downstream. The component of Lassen-type thermal water in the Pit River to the north of LVNP and the North Fork of the Feather River to the south, neither of which is obviously Cl-enriched, is estimated at 0-15 kg/s (Paulson and Ingebritsen, 1991). Thus, we would place the total liquid discharge from the Lassen system at ≤ 40 kg/s.

4. DISCUSSION

Heat-loss values for the principal thermal areas in LVNP vary from 10-37 MW (Table 2). Heat-loss estimates for the steam-heated summit regions of other volcanoes in the Cascade Range are close to 10 MW under quiescent conditions (Frank, 1985; Friedman and Frank, 1980; Friedman *et al.*, 1982; and Sorey and Colvard, 1994). The other volcanoes (Mt. Rainier, Mt. Baker, and Mt. Hood) are dominantly andesitic stratocones fed by a single magmatic conduit, and higher heat loss from the Lassen thermal areas may reflect the presence of a larger, more silicic magmatic system. Steam-heated thermal areas on New Zealand's Mt. Tongariro, a complex andesite volcano of Quaternary age near the southern end of the Taupo Volcanic Zone, are more similar in size and activity to the Lassen thermal areas. The estimated heat-loss rate for three such areas on Mt. Tongariro, including Ketetahi Hot Springs, is ~60 MW (Hochstein, 1985; Hochstein and Bromley, 1979).

Calculated rates of steam upflow (Q_s) and liquid outflow (Q_l) from the Lassen geothermal system imply a Q_s/Q_l ratio of 1.0. In contrast, numerical simulations of fluid and heat flow in the

conceptual model pictured in Figure 2, with a deep-fluid upflow temperature of 258°C, resulted in Q_s/Q_l values of <0.1 (Ingebritsen and Sorey, 1985). It now seems unlikely that the actual Q_s/Q_l ratio could be significantly less than 1.0 unless (1) some of the thermal water emanating from the Lassen system is much less saline than water sampled from Morgan Hot Springs and the well at Terminal Geyser or (2) we have failed to detect a large amount of thermal-water discharge.

Under steady-state conditions, the factor that controls Q_s/Q_l in the model pictured in Figure 1 is the enthalpy of the deep upflow. The following relation can be developed from heat- and mass-balance equations for a system with liquid upflow and liquid and steam outflow under adiabatic conditions:

$$Q_s/Q_l = (h_{up} - h_l) / (h_s - h_{up})$$

where h is steam-outflow enthalpy, h_l is liquid-outflow enthalpy, and h_{up} is liquid upflow enthalpy. An important constraint in modeling the Lassen system is that the temperature in both the vapor-dominated zone and in the underlying boiling zone should be close to the value of 230°C indicated by geochemical and isotopic characteristics of hot-spring and fumarolic gas samples (Muffler *et al.*, 1982; Ingebritsen and Sorey, 1985). Thus, h_s and h_l should be about 2,800 and 990 kJ/kg, respectively. The relation shown above then yields values of Q_s/Q_l ranging from 0.08 to 1.6 for values of h_{up} corresponding to liquid temperatures of 258°C to 374°C (1,120 to 2,100 kJ/kg). Only for upflow temperatures near and above the critical point would there be sufficient heat to generate steam fractions close to those measured at Lassen.

Table 1. Heat loss from different types of features at Bumpass Hell (upper and lower basins). Double dash indicates no data.

¹ Type of Feature	Number of Features	² Area (m ²)	³ Heat Loss (MW)	⁴ Period of Observation {number}
Fumaroles	30	--	2 f 1	1987-90 {5}
Water surfaces	5	1,600	⁵ 20 ± 2	1986-88 {4}
Bare ground		44,000	⁶ 6 ± 3	1986 {1}
Streamflow	1	--	⁷ 0.53 ± 0.33	1984-93 {17}
Totals	--	46,000	29 ± 4	--

¹ Fumaroles include steam vents, drowned steam vents, and frying pans; Water surfaces include 5 small lakes containing thermal water and Bumpass Creek; Streamflow refers to Bumpass Creek at a flume installed in 1984 at a site 30 m below the boardwalk.

² Total area of heated ground equals the anomalously warm area determined from infrared photos analyzed by Friedman and Frank (1978). Area of water surfaces determined from visual inspections and stadia measurements averaged over four sets of observations.

³ Calculated or estimated 1 σ uncertainties shown with \pm . Uncertainty for total heat loss calculated from the square root of the sum of squares of O's for each type of feature.

⁴ Years during which one or more visits were made; {number} is the number of observations of heat loss from each set of features.

⁵ Average of four separate determinations of total heat loss by evaporation, conduction, and radiation from all five pools plus an average heat loss of 0.7 MW from the streams draining these pools.

⁶ From Sorey and Colvard (1994), based on heat flows of 10 mW/m² over 20 percent of total area, 40 mW/m² over 60 percent of total area, and 300 mW/m² over 20 percent of total area.

⁷ Average value of H_{adv} based on measurement of streamflow and temperature during late summer and fall when flow was <10 L/s. A reference temperature of 4°C was assumed.

To generate and sustain such high upflow temperatures in a hydrothermal system with total throughflow rates on the order of 100 kg/s requires a potent magmatic heat source. Steady-state heat-balance relations indicate that intrusion rates on the order of 2 km³/1,000 yrs and conduction lengths on the order of 10's to 100's of meters are required, depending on the lateral dimensions of the flow system where heating takes place. Furthermore, the modeling work of Ingebritsen and Sorey (1985) suggests that the current hydrothermal system at Lassen took perhaps 10,000 years to develop, and that high-temperature fluid circulation has been ongoing for most of that period.

However, the possibility of strong transient effects cannot be ruled out. For example, intrusive activity associated with the 1914-1917 eruptive period at Lassen Peak may have caused a temporary increase in steam upflow and heat loss. Longer-term effects associated with other volcanic episodes that have occurred in the Park during the past few thousand years may also influence the current steam-liquid discharge ratios. A few earlier heat-loss measurements are available for comparison, including advective heat-loss measurements made at Devils Kitchen in the 1920's (Day and Allen, 1925) and in 1974 (Friedman and Frank, 1978). Although the earlier values of advective heat loss were significantly greater (21-29 MW) than those measured during our study (~10 MW), streamflows during the earlier measurements were also much higher, so that seasonal heat mining may have contributed to the higher heat losses.

Alternative conceptual models for the Lassen system might also be considered. For example, there could be a regional-scale convection cell underlying part of the Park and adjacent regions in the KGRA. The rising limb of such a cell might boil beneath the Park, supporting the observed steam upflow; the majority of the liquid

would recirculate and be reheated, with a relatively minor fraction leaking away to feed the thermal springs in the KGRA. A fossil system involving such regional-scale convection has been proposed for the Creede caldera in Colorado (Hayba, 1993). This model allows much lower Q_s/Q_l ratios in the boiling region than would be calculated from surficial fluid-discharge conditions. However, total magmatic heat requirements would be similar to those for the single-pass boiling system shown in Figure 2

Separate liquid- and vapor-dominated systems may also exist in the Lassen region, in which case there would be no constraints on the relative rates of steam and liquid discharge. Both flow systems could conceivably share the same magmatic heat source but not be in hydraulic communication. On a smaller scale, such a model may account for conditions encountered at thermal areas located to the southeast of Lassen Peak. For these areas, it seems unlikely that the rates of steam upflow indicated by the observed heat-loss rates could be generated by boiling from underlying liquid reservoirs, which appear to be at temperatures below 200°C (Beall, 1981). However, on a more regional scale, the geochemical evidence summarized by Muffler *et al.* (1982) and Ingebritsen and Sorey (1985) seems to indicate that the principal zone of hot-water outflow to hot springs south of the Park is hydraulically connected with the vapor-dominated zone that supplies steam to the thermal areas on the flanks of Lassen Peak.

More information on subsurface conditions in the Lassen region will probably be needed before a unique model can be delineated. Although it is unlikely that additional drilling for geothermal exploration will take place in this region in the near future, data do exist from test holes previously drilled by private industry in the KGRA to depths close to 1 km. These data, currently held as

Table 2. Summary of total heat loss, heat flow, and inferred rate of steam upflow at thermal areas in Lassen Volcanic National Park, listed in order of decreasing heat loss and steam upflow. nm indicates not measured.

Thermal Area	¹ Size (m ²)	² Heat Loss (MW)	³ Heat Flow (W/m ²)	⁴ Steam Upflow (kg/s)
Boiling Springs Lake	14,300	37 ± 5	2,600	13
Bumpass Hell	46,000	29 ± 4	630	10
Devils Kitchen	40,900	21 ± 4	510	8
Little H.S. Valley	79,000	15 ± 3	190	5
Sulphur works	58,000	10 ± 3	120	4
Pilot Pinnacle	7,500	2 ± 1	300	0.7
Terminal Geyser	900	1 ± 0.5	1,000	0.4
Lassen Peak	3,500	0.3 ± 0.2	Y0	0.1
Totals	--	115 ± 9	--	41

¹ Area of heated ground.

² 1 σ uncertainties shown with \pm . Uncertainty in total heat loss calculated from the square root of the sum of squares of σ 's for heat loss from each area.

³ Average heat loss divided by the area of heated ground.

⁴ Average heat loss divided by 2800 kJ/kg.

proprietary, may provide useful constraints on the distribution of thermal-water outflow and possible heat sources. Numerical modeling to simulate some or all of the alternative hypotheses discussed above could also prove useful in constraining possible models. Largely because of its simplicity, we continue to favor a model similar to that shown in Figure 2, but with a much higher-enthalpy upflow than that invoked in our earlier numerical simulations.

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