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Convective Heat Flow From Hot Springs in the Long Valley Caldera, Mono County, California

MICHAEL L. SOREY

U.S. Geological Survey, Water Resources Division, Menlo Park, California 94025

R. E. LEWIS

U.S. Geological Survey, Water Resources Division, Laguna Niguel, California 92677

The heat discharged by the hot spring system in Long Valley, California, has been estimated from measured spring discharges by using geochemical mixing models. Of the total flow of 1300 l/s from 11 thermal springs in the caldera, approximately 20% or 250 l/s is contributed by the hydrothermal system at depth with temperatures near 210°C. The effects of heat loss by conductive cooling, mixing, and boiling are quantified for the springs in Hot Creek Gorge, which are the major source of hot water discharge in the caldera. The estimated total convective heat discharge is 4.3×10^7 cal/s, which is in agreement with an estimate obtained from the rate of boron discharge from the caldera into Lake Crowley. To supply heat conductively to circulating water of meteoric origin at a rate of 4.3×10^7 cal/s requires a heat flux at depth in excess of 10 μcal/cm²/s.

INTRODUCTION

The natural heat flow in potential geothermal areas is a useful parameter in assessing the potential for energy development. As discussed by *White* [1965, p. 4], the natural heat flow is a first approximation of the minimum rate at which heat can be withdrawn from the system in water or steam and is a reference base for evaluating effects of accelerated withdrawal from a developed geothermal field. The magnitude and distribution of heat flow in a 'hot' area are also useful in attempting to define the characteristics of the underlying heat source.

In the Long Valley area, preliminary temperature measurements indicated that the conductive heat flow in the upper 300 m was about 4 HFU (1 HFU = 1 μcal/s/cm²) near the western rim of the caldera, 4 HFU in the center of the caldera, and 2 HFU near the eastern rim, as discussed by *Lachenbruch et al.* [1976]. The convective heat flow in hot spring water was estimated by *White* [1965, p. 7] to be 7×10^7 cal/s, based on the boron contributed to Lake Crowley from the thermal system. A convective heat flow of this magnitude implies that the total heat flux at depth averaged over the caldera is considerably greater than 4 HFU. This suggests that a more detailed study of the convective heat flow is desirable.

In this paper the rate of heat discharge in each of the major thermal springs in Long Valley is estimated. For the purposes of this paper, springs are classified as thermal if their discharge temperatures are above 10°C. Geochemical techniques are used to separate the surface flow of thermal water into hot water and cold water components. The hot water component is assumed to be contributed by the geothermal reservoir at depth and to have chemical characteristics and temperatures distinctly different from the colder, fresher water which mixes with it. In particular, the hot water has significantly greater concentrations of chloride, boron, and silica than the shallow ground water. The total of dissolved solids of the thermal springs is near 1400 mg/l, and that of the nonthermal springs is near 150 mg/l.

DISTRIBUTION OF HOT SPRINGS

Casa Diablo Hot Springs

In the literature, one of Long Valley's most widely cited areas of geothermal activity is the Casa Diablo area (Figure 1, T3S/R28E-32). Historically, hot spring discharge from the area has been substantial, as is noted by *Russell* [1889], *Lee* [1906], and *Blake and Matthes* [1938], and the springs were once used for bathing by Indians and travelers along the old highway between Bishop and Mono Lake. Presently, very little hot water is discharging from the area, although numerous steam vents and several mud pots are in evidence. In June 1972 an estimated discharge of 0.6 l/s of 82°C water was observed coming from the spring area at Casa Diablo west of the old highway. By June of the following year, however, no discharge was apparent, and the temperature of the water in the marshy spring area was ambient. Chemical characteristics of the spring water suggest that its source may be steam-heated groundwater and the ambient temperature condition noted in 1973 may be the result of the diluting effect of a local perched groundwater body which formed as a result of the above normal recharge.

Casa Diablo Hot Pool

Variously referred to as Casa Diablo Hot Pool by *Stearns et al.* [1937] and *Waring* [1915] and as Hot Bubbling Pool by the *California State Department of Water Resources* [1967] and *Rinehart and Ross* [1964], this shallow pool, about 650 m² in surface area, is located very near the eastern fault of the central graben mapped by *Bailey* [1974] in T3S/R28E-35. Temperature measured near one of the vents along the northern margin of the pool was 68°C. *Waring* [1915] recorded temperatures of 49°C and 82°C at vents near the margin of the pool. There is no apparent discharge from the pool; however, a small well-defined channel leading in the direction of Hot Creek indicates flow in the past. Calculations based on the work of *Bensemen* [1959] indicate that an inflow of about 6.5 l/s is necessary to maintain a surface temperature near 55°C in a pool of this size. Such a volume of water cannot be accounted

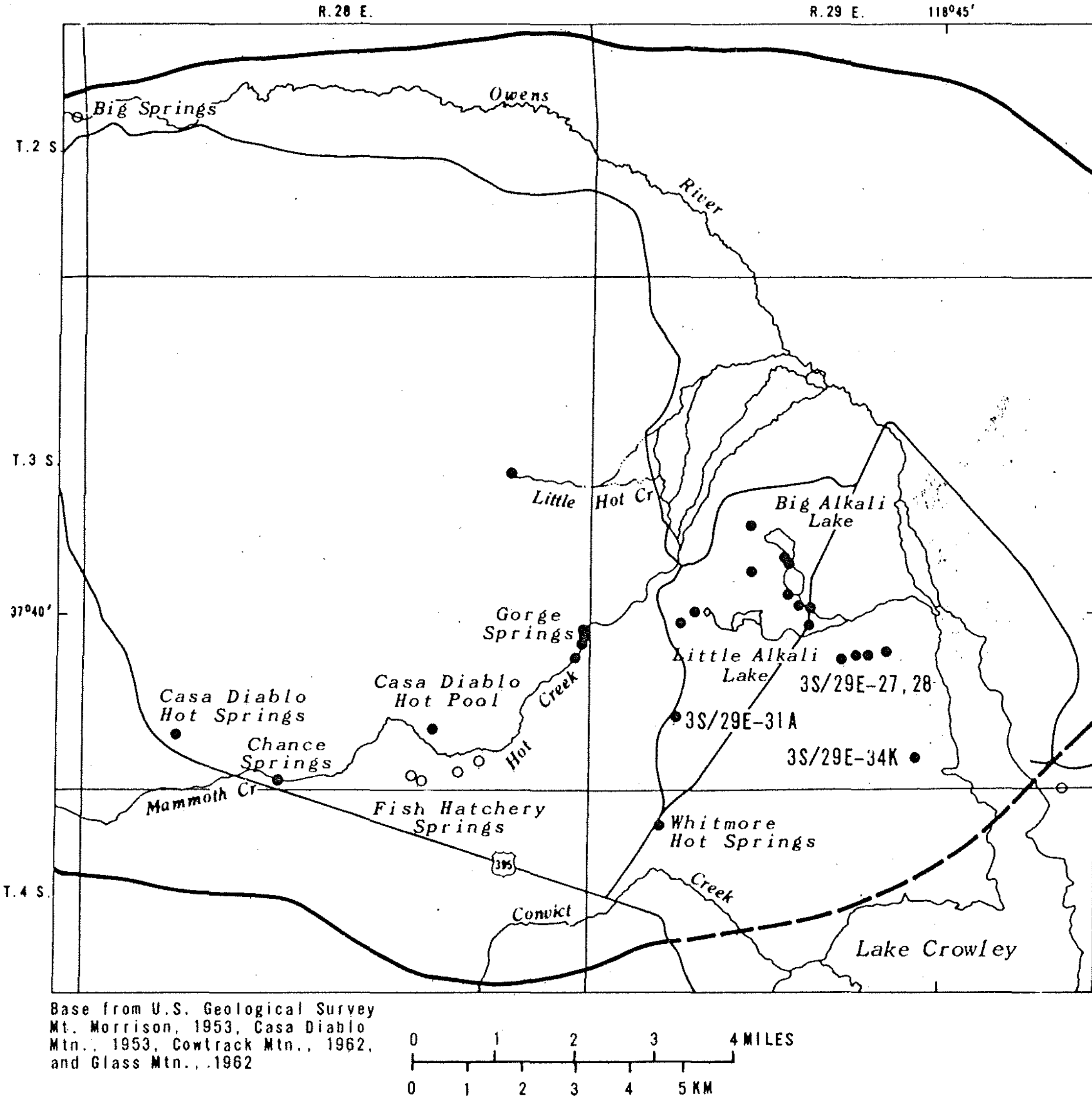

Fig. 1. Map of thermal springs in Long Valley caldera. Solid circles show hot springs or groups of hot springs, and open circles show cold or slightly thermal springs or groups of springs. The thick solid line is the caldera boundary, and it is dashed where the boundary is approximately located.

for by evaporation alone. Thus some combination of subsurface outflow and convective circulation is suggested. Over the bottom of the pool, numerous openings emit bubbles of what is apparently CO_2 gas and possibly some steam. Some carbonate material has precipitated from the water and is deposited along the edge of the pool.

Hot Creek Springs

Along a 1.6-km reach of Hot Creek, in the gorge in T3S/R28E-25, about 18 springs discharge nearly 250 l/s of thermal water into the creek. This discharge represents about 20% of the discharge of thermal water (above 10°C) in the caldera and is a mixture of shallow groundwater and hot water from the geothermal system. Springs along this reach of Hot Creek are among the hottest found in the Long Valley caldera and are the source of the greatest discharge of hot water from the geothermal system, accounting for 80% of the total (see Table 3). Most of the low-discharge springs along this reach are located on the banks above the creek and can be readily measured and sampled. Their combined discharge, however, is minor in relation to the total spring discharge into Hot Creek. Most of the thermal water contributory to Hot Creek discharges beneath the water surface. Techniques for estimating this flow are described in the next section.

Little Hot Creek

The springs of Little Hot Creek (Figure 1, T3S/R28E-13) are located in a small narrow canyon near the head of the creek; above the springs there is no perennial flow in the channel. Four main spring orifices discharge a total of about 12 l/s of thermal water at 68°C to 82°C into Little Hot Creek. Most of the flow disappears beneath the ground surface within about 0.8 km downstream from the hot springs and continues as underflow along a broad channel until it mixes with water from Hot Creek flowing toward the Owens River. Some variation in the flow of these springs has been observed during the period of this investigation, possibly in response to continuing tectonic activity or seasonal hydrologic events.

Fish Hatchery Springs

About eight main spring orifices make up the spring group at the California State Fish Hatchery (Figure 1, T3S/R28E-35). These springs are classified as thermal with temperatures between 12.5°C and 17°C throughout the year and are ideally suited for the raising of rainbow trout at the hatchery. The fish hatchery springs discharge about 570 l/s and comprise about 74% of the total thermal spring discharge in Long Valley. The actual amount of hot geothermal water contributed by these springs is small, however, and amounts to only about 7% of the total (see Table 3).

Alkali Lakes Springs

Springs in the vicinity of Big Alkali Lake and Little Alkali Lake (Figure 1) generally show low discharge between 0.07 and 2.5 l/s and moderate temperatures between 39°C and 63°C. Many of the very low discharge springs do not discharge at the surface but form seeps, and the entire area is one of broad flat grass-covered sometimes marshy terrain. Even in some of the moderately discharging springs, surface flows are not apparent for any great distance as the water quickly percolates into the unconsolidated sediments and joins the shallow groundwater in its movement toward Lake Crowley.

The existence of the Alkali lakes is evidently due in part to the near-surface water table in that area. The total measured and estimated warm spring discharge of about 12.7 l/s is insufficient to sustain the lake levels, particularly during the summer months. The high groundwater table remains fairly constant, being replenished by the subsurface discharge from the hot springs and subsurface inflow from Hot Creek.

Whitmore Hot Springs

Whitmore Hot Springs is located about 1.6 km from U.S. Highway 395 along the road to Owens River (Figure 1, T4S/R29E-6). Referred to in the early description of *Waring* [1915] as Whitmore Tub, the springs were later developed into a spa with the construction of several concrete pools, a bath house, and several other structures. With the development of bathing facilities at Hot Creek the Whitmore spa was shut down and has remained closed since. In the Whitmore group there are two large main spring openings and two small ones. The temperature and discharge of these springs have remained constant over the years. In the two large pools, *Waring* [1915] measured a maximum temperature of 38°C and a discharge of 28 l/s at the same time that the two smaller spring openings had equal discharge of 0.5 l/s and temperatures of 23.5°C and 37.8°C. Recent data by *Lewis* [1974] indicate a combined discharge of 25 l/s and temperatures of 32.5°C and 34.5°C in the two large springs and a discharge of 0.8 l/s and temperatures of 27°C and 35°C in the two small springs.

Other Spring Discharge

Several other springs or spring groups exist in the Long Valley caldera which have significant flow but contribute little water from the geothermal system because of the dilute nature of their waters. The Chance Springs (Figure 1, T3S/R28E-33) issue along the bank of Mammoth Creek several hundred meters downstream from U.S. Highway 395. About 23 l/s of water at 22.5°C discharge from three orifices formed by cooling joints in the basalt.

Between the Alkali lakes and Lake Crowley, about 17 springs discharge along a nearly east-west line (Figure 1, T3S/R29E-27, 28). The discharge of these springs is low, between 0.1 and 3.2 l/s, and the temperatures range between 18°C and 49°C. In addition to the springs, numerous seeps exist along the same line between the road and the lake. This broad grassy area is similar in appearance to the area around the Alkali lakes.

Big Springs (Figure 1, T2S/R27E-25) discharges water at about 11°C which flows into the upper Owens River near the northwest rim of the caldera. Although not measured in recent investigations, the discharge was estimated at about 6 l/s. Samples from this spring and other cold water springs provided data on the chemical characteristics of the shallow groundwater which mixes with the hot spring water.

MIXING MODELS

Variations in the chemical composition and temperature of thermal spring waters in Long Valley suggest that the hot water rising from depth is mixed with and diluted by cooler water from shallow aquifers before being discharged at the land surface. In addition, surface discharge conditions are affected by boiling in the upflowing column and heat conduction in the surrounding rocks. Thus to evaluate the amount and heat content of the hot water moving through the system, the effects of mixing, boiling, and conduction must be accounted for.

Methods

Several chemical techniques have been described by *Fournier and Truesdell* [1973, 1974] and *Fournier et al.* [1974] for estimating the temperature of water in geothermal reservoirs and the fraction of hot water mixed with cold water in hot spring systems. *Mariner and Willey* [1976] discuss the geochemistry of thermal water in Long Valley and the application of geothermometers on the basis of concentrations of silica and the cations sodium, potassium, and calcium. Their results show that calculations of reservoir temperatures based on the cation ratios were consistently higher and hence less affected by mixing than were the silica temperatures.

Mixing calculations based on the model of *Fournier and Truesdell* [1974] require data on the silica concentration and temperature of the mixed spring water and the cold fresh water. Results for samples from springs in Hot Creek Gorge and along Little Hot Creek give temperature estimates ranging from 170°C to 225°C [*Mariner and Willey*, 1976]. The range in temperature is due in large part to uncertainty as to the characteristics of the fresh water component.

An alternative mixing model, proposed by *Truesdell and Fournier* [1975], utilizes the ratio of the chloride concentration in the mixed water to the chloride concentration in the unmixed hot water to correct the silica geothermometer temperature and compute the mixing ratio. From a chloride balance the mixing ratio or the fraction of the total discharge which is from the hot water source is computed as

$$X = (\mathrm{Cl}_m - \mathrm{Cl}_c)/(\mathrm{Cl}_h - \mathrm{Cl}_c) \qquad (1)$$

where X is the mixing ratio, Cl_m is the chloride concentration of mixed spring water, Cl_c is the chloride concentration of the cold water component, and Cl_h is the chloride concentration of the hot water component. If the spring is boiling, the chloride concentration at the surface must be corrected for the concentrating effect of boiling to obtain Cl_m. Otherwise, Cl_m is equal to the chloride concentration at the surface. In the Long Valley area the concentration of chloride in the nonthermal springs ranges from 1 to 6 mg/l compared with 280 mg/l in the hot water, as is discussed in the next section.

The enthalpy of the hot water source is computed as

$$h_h = (h_m - h_c)/X + h_c \qquad (2)$$

where h_h is the enthalpy of the hot water source, h_m is the enthalpy of the mixed spring water, and h_c is the enthalpy of the cold water component. The enthalpy of the mixed spring

TABLE 1. Geochemical Data From Samples of Long Valley Hot Springs

Spring or Spring Area	Discharge, l/s	Surface Temperature T, °C	Boron, mg/l	Chloride, mg/l	T_{Si}, °C	$T_{Na-K-Ca}$, °C
Hot Creek Gorge*	6.7	90	10.3	225	153	192
Little Hot Creek	12.0	80	10.6	200	143	172
Casa Diablo Hot Pool	6.5†	60	13.0	250	209	189
Whitmore Hot Springs	26.0	34	3.5	74	75	...
Big Alkali Lake‡	8.8	56	7.7	150	196	200
Little Alkali Lake	3.8	66	8.8	200	150	...
Chance Spring	23.0	20	1.8	40	100	...
T3S/R29E-27, 28	3.8	49	8.6	150	193	200
T3S/R29E-34K	1.8	41	6.2	130	182	184
T3S/R29E-31A	1.5	58	8.1	176	161	176

*New spring discharging from bank.
†Calculated from evaporation rate.
‡Sample 3S/29E-21 PS1 [*Mariner and Willey*, 1976].

water is based on the temperature obtained from the silica geothermometer calculation, when no mixing is assumed. Where the mixing ratio is greater than about 0.7, the enthalpy of the cold water component in (2) can be neglected to yield

$$h_h = h_m/X \quad (3)$$

In the case of the springs along Hot Creek Gorge, most of the discharge occurs below the stream surface, a situation making discharge measurements and sampling impractical by standard techniques. Consequently, a seepage gain technique was used in this area and for the springs at the fish hatchery. Measurements of water discharge, temperature, and concentrations of boron and chloride were made above and below the hot springs to compute the net gain of boron and chloride by using

$$B_m = (B_2Q_2 - B_1Q_1)/(Q_2 - Q_1) \quad (4)$$

$$Cl_m = (Cl_2Q_2 - Cl_1Q_1)/(Q_2 - Q_1) \quad (5)$$

where B_1 and Cl_1 are the boron and chloride concentrations of the stream above the springs, respectively, B_2 and Cl_2 are the boron and chloride concentrations of the stream below the springs, respectively, Q_1 is the volumetric flow rate of the stream above the springs, and Q_2 is the volumetric flow rate of the stream below the springs. Boron and chloride were chosen as the constituents to be used because they are characteristic of water of volcanic association [*White*, 1957*a*, *b*] and are least likely to be affected by chemical precipitation, base exchange, and other factors [*White*, 1968, p. 83]. As is seen in subsequent tables, calculations of boron and chloride concentrations from the seepage gain technique agree well with data from a spring sample taken along the bank in Hot Creek Gorge.

In the results that follow, the component of the spring discharge which is of geothermal origin is computed from (1) by using boron and chloride concentrations for each of 11 spring systems with significant discharges. With the exception of the Hot Creek Gorge springs the discharge temperatures of these springs are well below 90°C, and hence the effects of boiling have been neglected. The magnitude of the boiling effect is considered later for the Hot Creek springs. Hot water temperatures were first computed from the silica and cation geothermometers and then corrected by using the mixing models as indicated in Table 3.

Thermal Water

Hot waters discharging in the Long Valley springs may originate from one regionally continuous reservoir or from several zones at various depths. In the course of this investigation a core hole to 305 m was drilled inside the caldera about 1.6 km northeast of Hot Creek Gorge. No evidence of a permeable reservoir with hot water was found. However, extrapolation of the measured temperature gradient of about 200°C/km indicated that water with temperatures in excess of 200°C might be found at depths near 1 km.

Ten geothermal wells were drilled at Casa Diablo hot springs by the Magma Power Company between 1959 and 1964 to a maximum depth of 324 m. Maximum temperatures of 177°C were found at a depth of 120 m [*McNitt*, 1963, p. 28]. Temperatures decrease below 120 m, a fact suggesting that the wells penetrate a fault underlying the Casa Diablo area and that hot water moving up the fault is intercepted by the wells at the 120-m depth. Thus water sampled from these wells may be relatively unmixed, although the measured temperatures may be below temperatures in the reservoir because of conductive cooling as the water moves up the fault.

Water sampled from one of the wells during the course of this investigation contained 280 mg/l of chloride and 15 mg/l of boron [*Willey et al.*, 1974]. The temperature of this water at depth, based on its silica content, is 220°C. Earlier analyses reported 276 mg/l [*McNitt*, 1963] and 285 mg/l of chloride and 13 mg/l of boron [*California State Department of Water Resources*, 1967] as average values for 11 samples. For the purposes of this paper it will be assumed that the geothermal waters underlying the hot spring areas in the caldera average 14 mg/l of boron and 280 mg/l of chloride. Constant Cl/B ratios [*Mariner and Willey*, 1976] and hot water temperatures from mixing model calculations consistently near 200°C indicate that the same hot water aquifer supplies each of the

TABLE 2. Results of Seepage Gain Measurements for Springs at Hot Creek Gorge and the Fish Hatchery

	Discharge, l/s	Calculated Concentration, mg/l: Boron	Calculated Concentration, mg/l: Chloride
Hot Creek Gorge			
October 17, 1972	303	9.23	199
January 17, 1973	218	12.28	221
March 25, 1973	227	9.33	220
April 17, 1973	275	9.06	225
September 25, 1973	212	15.29*	248
Average	247	11.04	223
Fish Hatchery			
October 17, 1973	843	0.25	4.8
September 25, 1973	1085	0.23	4.6
Average	964	0.24	4.7

*Calculated concentration exceeds upper limit established for boron in Long Valley thermal water.

major thermal springs in the caldera. However, the extent of regional continuity to this reservoir is as yet unknown. The area of present hot spring activity covers only about 15% of the total caldera area.

Geochemical Data

Table 1 presents pertinent geochemical data from samples of the major hot springs in Long Valley. Geothermometer calculations for springs with discharge temperatures greater than 90°C assume adiabatic cooling by boiling, whereas for springs with temperatures less than 90°C, conductive cooling is assumed.

Results of the seepage gain measurements for the springs at Hot Creek Gorge and the fish hatchery are shown in Table 2. The averages of calculated concentrations of boron and chloride for the Hot Creek springs are in close agreement with measured concentrations in Table 1 for the sample from the new spring along the bank.

Table 3 lists the results of mixing calculations for thermal water discharges and temperatures. The estimate of total discharge of hot water is 248 l/s from both boron and chloride calculations. Of this, approximately 80% is contributed by the springs in Hot Creek Gorge. Calculated temperatures of the hot water range from 184°C to 225°C and average 204°C.

CONVECTIVE HEAT DISCHARGE

Heat Content of Thermal Water

Hot water discharging in the Long Valley thermal springs is primarily of meteoric origin [*White*, 1968]. The water must be heated from approximately mean annual air temperature to temperatures in excess of 200°C by conduction from the surrounding rocks as it moves through the system. When a mean annual air temperature of 10°C and a reservoir temperature of 210°C are assumed, on the basis of the data in Table 3, the gain in heat content of the water can be calculated as

$$C = \rho_{210°}(h_{210°} - h_{10°})$$
$$= 0.86 \text{ g/cm}^3 \, (214 - 10) \text{ cal/g} = 175 \text{ cal/cm}^3$$

where C is the gain in heat content per unit volume, ρ is fluid density, and h is fluid enthalpy.

As this water moves upward toward the discharge areas, heat is removed from the thermal reservoir at a rate given by

TABLE 3. Summary of Hot Water Discharge From Long Valley Hot Springs

Spring	Discharge of Hot Water, l/s: With 14.0 mg/l B	Discharge of Hot Water, l/s: With 280 mg/l Cl	Temperature of Hot Water, °C
Hot Creek Gorge	195.0	197.0	210*†
Fish hatchery	16.5	16.2	...
Little Hot Creek	9.0	8.5	214*
Whitmore Hot Springs	6.8	6.7	...
Casa Diablo Hot Pool	6.0	5.8	189‡
Big Alkali Lake	4.8	4.7	200‡
Chance Springs	3.2	3.2	...
Little Alkali Lake	2.7	2.5	210*
T3S/R29E-27, 28	2.0	2.0	200‡
T3S/R29E-34K	0.8	0.8	184‡
T3S/R29E-31A	0.8	0.8	225†
Total	248	248	

*Based on Si-Cl mixing model (A. H. Truesdell, personal communication, 1974).

†Based on Si mixing model [*Fournier and Truesdell*, 1974].

‡Based on Na-K-Ca geothermometer [*Fournier and Truesdell*, 1973].

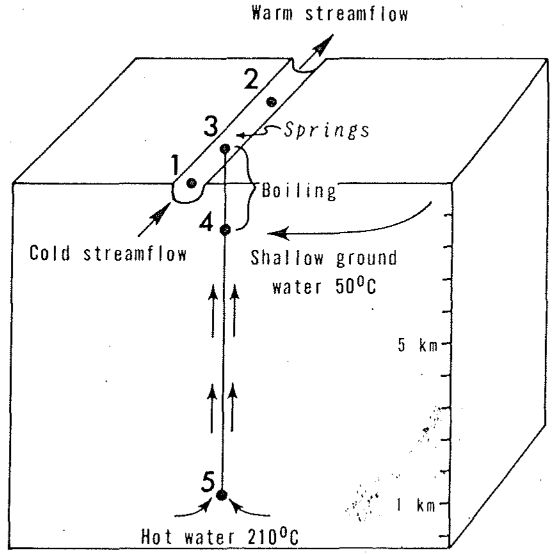

Fig. 2. Diagram of Hot Creek Gorge spring system.

CQ, where Q is the volumetric flow rate of hot water. From Table 3, Q = 248 l/s. Thus our estimate of the convective heat discharge from the system is 4.3 × 10^7 cal/s. *White* [1965, p. 7] used an estimate of the annual discharge of boron into Lake Crowley of 181 metric tons per year and assumed a boron concentration of 11 mg/l to compute a discharge of thermal water equal to 520 l/s. He then assumed a conservative reservoir temperature of 150°C to compute a total convective heat flow from the Long Valley springs of 7 × 10^7 cal/s. The difference between the two estimates of heat flow is due in part to subsurface discharge of hot water which was not measured in the present study. However, data obtained from the Los Angeles Department of Water and Power for the period 1960–1973 show an average discharge of boron from sources within the caldera of 136 metric tons per year. If we use this figure and a concentration of 14 mg/l, the hot water discharge would be 306 l/s. If we assume a reservoir temperature of 210°C, the convective heat flow estimate would be 5.4 × 10^7 cal/s or about 25% greater than the estimate based on measurements at individual hot springs.

Heat Balance for Hot Creek Gorge Springs

Because approximately 80% of the convective heat discharge from the caldera is from the springs along Hot Creek Gorge, it is of interest to consider this particular system in more detail. We wish to quantify the effects of conductive cooling, mixing, and boiling on the heat content of the upflowing water. A simplified diagram of the system is shown in Figure 2. From the seepage gain measurements at points 1 and 2 we have calculated an average spring flow of 247 l/s at a boiling temperature of 90°C at point 3 (Table 2). We also have an estimate of 196 l/s of hot water with a temperature of 210°C at point 5 (Table 3). The corresponding heat fluxes are 3.4 × 10^7 cal/s at point 5 and 1.9 × 10^7 cal/s at point 3. Thus a net loss of 1.5 × 10^7 cal/s occurs as the water flows to the land surface.

Considering first the conductive heat loss to the surrounding rocks, we note that the amount of heat lost and the resultant temperature drop in the fluid depend strongly on the geometry of the upflow channel. At one extreme would be a conduit whose lateral dimensions have been limited, say, by mineral deposition to an area similar to that of the spring discharge area. At the other extreme would be the slab configuration in

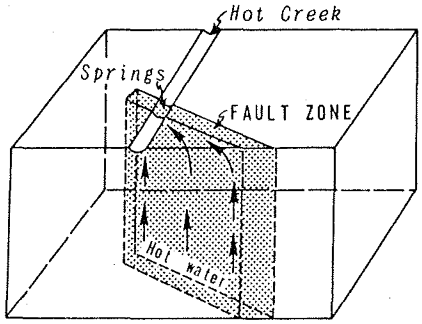

Fig. 3. Slab model for spring flow in Hot Creek.

Figure 3 which is suggested by the surface expression of the faults intersecting the gorge area and the evidence of hydrothermally altered rock along the faults at some distance from the gorge [*Bailey*, 1974]. With a lateral extent to the fault plane of 1 km and a depth of 1 km the heat loss from the plane would be considerably greater than that from the conduit.

From hydraulic considerations the fault plane model seems more likely. For example, Table 4 lists pressures in excess of hydrostatic pressure necessary to yield an upflow of 200 l/s for various combinations of area and permeability. The total head difference from artesian (elevation) and thermal artesian (density) effects is of the order of 300 m, although it is likely that only a fraction of this is available at point 5. From Table 4, unless the permeability of the fractured zone is considerably larger than 10 darcys, the available head would be insufficient for the cylindrical model but adequate for the slab model.

Numerical simulations of conductive cooling in upflowing hot spring systems, as described by *Sorey* [1975], can be used to estimate the temperature drop as a function of mass flow rate for the cylindrical conduit and fault plane models. For a flow rate of 200 l/s and the same dimensions as those used in Table 4 the temperature drop in the cylinder would be negligible, whereas the temperature drop in the fault plane would be about 10°C, with a corresponding conductive heat loss of 10^6 cal/s. Under steady state conditions this heat flows out at the land surface within a distance equal to about one conduit depth away from the spring.

On the assumption, then, that the hot water cools from 210°C to 200°C as it flows up to the shallow groundwater system, boiling would begin at a depth of about 160 m. There is evidence from cores and geophysical logs in the test well, located 1.6 km northeast of Hot Creek Gorge, of a permeable zone at 140 m which could provide water for mixing at point 4 in Figure 2 [*Lachenbruch et al.*, 1976]. The temperature at this depth in the test well is about 50°C. If this zone is the source of fresh water which dilutes the spring water and its boron and chloride concentrations are close to those in the nonthermal springs, we can calculate a mixing ratio of 0.80, using (1) and the boron and chloride concentrations in Table 2. The temperature of the mixture at point 4 would then be 160°C. Above this point, boiling would reduce the liquid flow rate by about 13%, and the formation of steam would account for about 1.8 $\times 10^7$ cal/s of heat loss from the water as its temperature drops from 160°C to 90°C at the surface (point 3). This leaves a convective heat flow with the liquid discharge at point 3 of 1.9 $\times 10^7$ cal/s, as was indicated previously. The fate of the steam which forms is uncertain. If it recondenses in the stream, then the heat added at this point would be closer to 3.9 $\times 10^7$ cal/s. However, temperature and discharge measurements downstream at point 2 average 25°C and 1270 l/s in the fall and winter and 16°C and 3680 l/s during the spring runoff period. This represents a heat flow of between 1.9 $\times 10^7$ cal/s and 2.2 $\times 10^7$ cal/s and suggests that the steam either discharges as vapor at the land surface or recondenses in the shallow groundwater below the creek.

Conductive Heat Flow Requirements

Before considering the significance of our estimate for the convective heat discharge from the Long Valley thermal springs we first note some inherent assumptions in the chemical methods used in its derivation. Essentially, we have assigned a quantity of heat to various ions in the thermal spring waters and assumed a degree of regional continuity to a reservoir at depth in terms of uniform concentrations of B and Cl in the hot water underlying the area of hot spring discharge. Further, we refer to this estimate as the gain in heat content, assuming that the source of water was meteoric. In this regard it is possible that the thermal water includes a component of magmatic origin to account for the high concentrations of elements such as boron, chloride, and arsenic, as discussed by *White* [1968] for the Steamboat Springs, Nevada, area and by the *California State Department of Water Resources* [1967] for the Long Valley area. Thus an unknown portion of the heat gained by the circulating meteoric water could be supplied by this fluid of magmatic origin.

With these assumptions in mind, we note that our estimate for the convective heat discharge of 4.3 $\times 10^7$ cal/s is somewhat less than the estimates based on boron discharge in Lake Crowley, a result suggesting that 4.3 $\times 10^7$ cal/s is a minimum value which does not account for some subsurface discharge of hydrothermal water. The significance of this estimate can be seen by calculating from a simple hot plate model that if the heat gained by the circulating fluid at a rate of 4.3 $\times 10^7$ cal/s were supplied conductively to a reservoir covering the entire caldera area of 450 km², an average heat flux of about 10 HFU would be required. For a reservoir of smaller lateral extent the required heat flux would be correspondingly greater. If similar rates of heat removal have persisted for a significant portion of the eruptive history of the caldera, the above calculations place constraints on the nature and intensity of the conductive heat source underlying the caldera, as is discussed by *Lachenbruch et al.* [1976]. Further test drilling to obtain

TABLE 4. Pressures Required to Cause Flow of 200 l/s Through Hot Creek Gorge Spring System

Model	Area Cross Section, m²	Permeability, darcys	Pressure Above Hydrostatic, bars	Head,* m
Cylinder	176	1	1,600	19,000
(diameter, 15 m)	176	10	160	1,900
Plane	16,000	1	17	210
(1.6 km × 10 m)	16,000	10	1.7	21

The depth of the spring system is 1 km, and its temperature is 210°C.
*Head is defined as pressure/ρg.

additional thermal, hydrologic, and geochemical information is needed before a satisfactory model of the hydrothermal system and its related heat source is possible.

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