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The Hydrothermal Outflow Plume of Valles Caldera, New Mexico, and a Comparison With Other Outflow Plumes

FRASER GOFF, LISA SHEVENELL, AND JAMIE N. GARDNER

Los Alamos National Laboratory, New Mexico

FRANCOIS-D. VUATAZ

Institut Mixte de Recherches Géothermiques, Bureau de Recherches Géologiques et Minières, Orléans, France

CHARLES O. GRIGSBY

Los Alamos National Laboratory, New Mexico

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Stratigraphic, temperature gradient, hydrogeochemical, and hydrologic data have been integrated with geologic data from previous studies to show the structural configuration of the Valles caldera hydrothermal ouflow plume. Hydrologic data suggest that 25–50% of the discharge of the Valles outflow is confined to the Jemez fault zone, which predates caldera formation. Thermal gradient data from bores penetrating the plume show that shallow gradients are highest in the vicinity of the Jemez fault zone (up to 190°C/km). Shallow heat flow above the hydrothermal plume is as high as 500 mW m^{-2} near core hole VC-1 (Jemez fault zone) to 200 mW m^{-2} at Fenton Hill (Jemez Plateau). Chemical and isotopic data indicate that two source reservoirs within the caldera (Redondo Creek and Sulphur Springs reservoirs) are parents to mixed fluids flowing in the hydrothermal plume. However, isotopic data, borehole data, basic geology, and inverse relations between temperature and chloride content at major hot springs indicate that no single reservoir fluid and no single diluting fluid are involved in mixing. The Valles caldera hydrothermal plume is structurally dominated by lateral flow through a belt of vertical conduits (Jemez fault zone) that strike away from the source reservoir. Stratigraphically confined flow is present but dispersed over a wide area in relatively impermeable rocks. The Valles configuration is contrasted with the configuration of the hydrothermal plume at Roosevelt Hot Springs, which is dominated by lateral flow through a near-surface, widespread, permeable aquifer. Data from 12 other representative geothermal systems show that outflow plumes occur in a variety of magmatic and tectonic settings, have varying reservoir compositions, and have different flow characteristics. Although temperature reversals are commonly observed in wells penetrating outflow plumes, reversals are not observed in all plumes. Less information is available on the absolute age of hydrothermal outflow plumes, although the data show that they can be as old as 10^6 years and display episodic behavior.

INTRODUCTION

Hydrothermal outflow plumes ("lateral" or "horizontal" flow systems) are a characteristic hydrologic feature of many active geothermal systems [*Healy and Hochstein*, 1973]. Although outflow plumes are most commonly recognized at geothermal areas associated with Quaternary volcanism [e.g., *Sorey*, 1985; *Hulston et al.*, 1981], they also occur at lower-temperature geothermal systems associated solely with deep circulation along faults [*Vuataz et al.*, 1984]. Recognition of outflow plumes is important in geothermal exploration because surface hot springs of deep reservoir composition do not invariably occur above the zone of upward convection and the heat source. Commonly, hot springs of deep composition occur near the middle or end of the outflow plume many kilometers from the heat source, and as a result, such hot spring areas make poor drilling targets for geothermal production [*Ingebritsen and Sorey*, 1985]. Recognition of outflow plumes is also important in geothermal exploitation because withdrawal of fluids may affect the discharge of springs downgradient from the geothermal site. The possible effects on spring discharge and the reactions of those who use the springs must be evaluated before production begins.

At Valles caldera, New Mexico, a hydrothermal system at temperatures of 220–300°C resides at depths of 600–2500 m in caldera-fill ignimbrites and precaldera andesites [*Dondanville*, 1978; *Nielson and Hulen*, 1984]. The Valles hydrothermal system contains two drilled reservoirs or subsystems: the Redondo Creek reservoir and the Sulphur Springs reservoir. (In this paper we prefer to use the term Valles caldera hydrothermal system instead of Baca geothermal system or Baca geothermal field (the geothermal lease of Unocal no longer exists). That portion of the Valles system most commonly referred to as the Baca geothermal field is termed by us the Redondo Creek reservoir. The Redondo Creek reservoir and the Sulphur Springs reservoir to the west comprise the two drilled subsystems of the Valles hydrothermal system.) Deep reservoir fluids are neutral-chloride in character and contain approximately 5000–18,000 mg/kg total dissolved solids (TDS). However, no surface hot springs within the caldera resemble the chemical composition of the deep fluids [*Goff and Grigsby*, 1982]. About 10 km outside Valles caldera, two sets of neutral-chloride hot springs discharge along the precaldera Jemez fault zone at Soda Dam and Jemez Springs. These springs have strong chemical similarities to the deep fluids inside the caldera [*Trainer*, 1974]. The obvious conclusion has been that a hydrothermal outflow plume travels out of the caldera in the subsurface along the Jemez fault zone and within adjacent sedimentary rocks toward the springs [*Goff et al.*, 1981; *Trainer*, 1984]. In spite of convincing chemical evidence, there has been considerable disagreement about the

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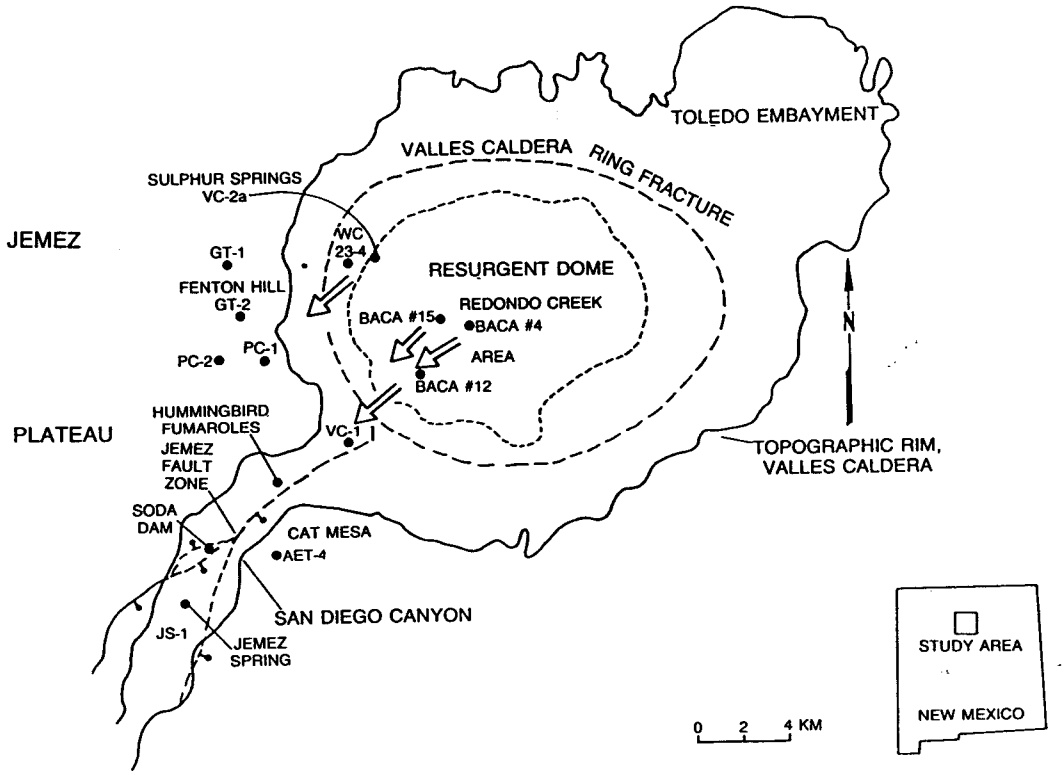

Fig. 1. Sketch map showing the locations of 12 geothermal wells in the Valles caldera region; the short-dashed line outlines the border of the resurgent dome within Valles caldera. Large arrows show the two source reservoirs and direction of lateral flow of the Valles caldera hydrothermal plume.

configuration, discharge, and hydrologic models of this plume [*Faust et al.*, 1984; *Williams*, 1986] and even claims that the plume does not exist, by groups concerned with legal and economic issues of geothermal development [*All Indian Pueblo Council*, 1979; *State of New Mexico*, 1980].

One of the major objectives of Continental Scientific Drilling Program (CSDP) core hole VC-1 was to penetrate the postulated outflow plume of Valles caldera at a point southwest of the Redondo Creek reservoir to verify that the plume exists [*Goff et al.*, 1986; *Rowley et al.*, 1987]. Several other papers in this volume address different aspects of hydrothermal outflow and describe hydrothermal alteration in the VC-1 core and Valles caldera [*Vuataz et al.*, this issue; *Keith*, this issue; *Hulen and Nielson*, this issue; *Sasada*, this issue; *Sturchio and Binz*, this issue]. This paper integrates stratigraphic, temperature gradient, and hydrogeochemical data from VC-1 and the wells and hot springs of the southwestern Valles area to show the structural configuration and chemical characteristics of the Valles outflow plume. We then compare the Valles outflow to the outflow of Roosevelt Hot Springs, Utah, which we believe is representative of a different geologic type of outflow plume. Finally we present data for outflow plumes from several geothermal areas to show the variations in geology, heat source, age, chemistry, etc., that may occur in this realm of hydrologic systems.

General Geology

The Jemez Mountains volcanic field contains a diverse suite of basaltic through rhyolitic rocks that were erupted from >13 to 0.13 Ma, although the field is best known for the Valles caldera (1.12 Ma) and the Bandelier Tuffs [*Smith and Bailey*, 1968; *Bailey et al.*, 1969; *Smith et al.*, 1970; *Gardner et al.*, 1986]. The volcanic pile overlies the western edge of the Rio Grande rift at the intersection of the rift and the Jemez Lineament. Tertiary basin-fill rocks of the rift underlie volcanic rocks on the east side of the field, whereas Paleozoic sedimentary rocks and Precambrian crystalline rocks of the Colorado Plateau underlie volcanic rocks on the west.

San Diego Canyon, where the main subsurface flow of the Valles outflow plume apparently occurs, is controlled by the northeast trending Jemez fault zone (Figure 1) that predates formation of Valles caldera [*Goff and Kron*, 1980; *Goff et al.*, 1981]. The subsurface structure of the Jemez Plateau area north of San Diego Canyon has been presented by *Slemmons* [1975]. Descriptions of the subsurface structure and internal geology of the Redondo Creek reservoir can be found in the work by *Nielson and Hulen* [1984]. The subsurface structure of the southwestern boundary of Valles caldera in the vicinity of the Jemez fault zone is depicted by *Goff et al.* [1986].

Estimated Discharge Rate of Hydrothermal Plume

The total discharge rate of the Valles hydrothermal plume is difficult to measure because much of the flow is confined to subsurface aquifers north and south of San Diego Canyon (and the Jemez fault zone). Several of these subsurface aquifers have been penetrated by deep wells as discussed below. Only in San Diego Canyon do hot springs discharge in the immediate region outside the caldera depression. As a result, several workers have estimated the amount of discharge from the hydrothermal plume into the Jemez River. The best estimates use ion balance calculations made from river samples taken upstream and downstream of thermal water inflow areas be-

TABLE 1. Stratigraphic and Temperature Data for 10 Bores in the Southwestern Valles Caldera Region, New Mexico

	Bore									
	GT-1	GT-2	PC-1	PC-2	WC 23-4	Baca-4	Baca-12	VC-1	AET-4	JS-1
Latitude	54′10″	52′49″	52′35″	52′33″	54′33″	53′21″	52′24″	50′27″	47′34″	46′20″
Longitude	40′16″	40′26″	39′43″	41′01″	37′54″	34′13″	35′27″	37′15″	39′13″	41′25″
Surface elevation, m	2584	2649	2567	2629	2627	2841	2570	2497	2439	1889
Total depth, m	785	2930	664	558	1965	1916	3219	856	1221	251
Top of unit*										
Alluvium			2567			2841	2570			1889
Banco Bonito Rhyolite								2497		
Battleship Rock Tuff								2351		
VC-1 Rhyolite								2338		
VC-1 Tuffs								2320		
San Antonio Mt. Rhyolite					2627					
Redondo Creek Rhyolite					2566					
Bandelier Tuffs	2584	2649	2564	2629	2502	2800	2521		2439	
Paliza Canyon Fm.		2543		2596		1017	590		2380	
Abiquiu Fm.	2566	2528	2536	2530					2242	
Abo Fm.	2535	2509	2508	2509	2459		288	2166	2134	
Madera Lmst.	2258	2275	2260	2284	2212		−213	2078	1713	1868
Sandia Fm.	2030	1999	1954		1951			1692	1466	1691
Arroyo Penasco Gp.										1666
Precambrian	1942	1920	1912		1889		−506	1658	1442	1651
Maximum temperature, °C	100	186	84	54	233	300	343	163	129	73
Depth to maximum temperature, m	785	2930	639	558	1890	1699	3100	738	893	24
Depth to isotherm, m										
50°C	350	250	355	518	73			210	274	‡
100°C	785	1494			295	100	244	430	716	‡
150°C		2301†			493	201	390	640		‡
200°C		3550†			737	350	588			‡
300°C		4100†				1699	2515			‡

Stratigraphic and temperature data from the following sources: GT-1, *Purtymun* [1973] and *Kolstad and McGetchin* [1978]; GT-2, *Purtymun et al.* [1974] and *Pettitt* [1975]; Baca-4 and Baca-12, *Nielson and Hulen* [1984] and *White* [1986]; JS-1, *Goff et al.* [1981]; PC-1, PC-2, WC 23-4, AET-4, and VC-1, *Shevenell et al.* [1988].

All latitudes are 35°N and all longitudes are 106°W.

*Top of unit is listed as elevation above sea level.

†Depths listed are from the EE-1 and EE-2 HDR wells located at the same site as GT-2 [*Laughlin et al.*, 1983].

‡No temperature log exists for this well; the temperature of surface hot springs ranges from 75° to 40°C.

cause much thermal input occurs below river level. Even so, estimates vary. *Erickson* [1977] obtained a value of 620 L/min of thermal water entering the Jemez River from the caldera margin to a point downstream of Jemez Springs, but his estimate relies solely on As, a less conservative ion. *Balleau* [1980] estimated 1380 L/min for the same stretch of the river considered by Erickson. The latter author relied heavily on Cl and other more conservative ions. *Trainer* [1984] estimated 1500 L/min of discharge from only the Soda Dam group of hot springs during 1973–1974. He also pointed out that discharge rate was somewhat seasonal from year to year.

The only group to estimate the total discharge rate of the Valles hydrothermal plume has been *Faust et al.* [1984] in their analysis of production strategies for the "Baca geothermal system." Using a three-dimensional model based on finite difference approximations, they concluded that the (calibrated preproduction) discharge rate of thermal water from the Valles geothermal system is 3077.5 L/min. If the estimate by *Faust et al.* [1984] is accurate, it means that a significant fraction of thermal water (up to 50%) from the Valles hydrothermal plume issues at the hot springs at Soda Dam and Jemez Springs. Noncoincidentally, these springs occur on or very near the main trace of the Jemez fault zone in San Diego Canyon.

BOREHOLE DATA

Table 1 shows pertinent stratigraphic and temperature data for 10 boreholes located in the southwestern sector of the Valles caldera region (Figure 1). (See Figure 2 for a key to the stratigraphic units described in Figures 3–5.) The data in Table 1 and the geologic reports discussed above were used to draw the cross sections of Figures 3–5. Isotherms shown on the cross sections are based on measurements made in the various boreholes. Depths to selected isotherms are also tabulated in Table 1.

As mentioned above, one of the primary objectives of core hole VC-1 was to test the model of hydrothermal outflow from Valles caldera. Structurally, VC-1 is located near the intersection of the Valles ring-fracture zone and the Jemez fault zone, about 7 km southwest of the center of the Redondo Creek reservoir. Because this area is buried by the most recent moat volcanics of the caldera [*Geissman*, this issue; *Self et al.*, this issue], this structural intersection is impossible to see in the field. Preliminary observations of the core [*Goff et al.*, 1986] and detailed work on the breccia zone at the bottom of the core hole [*Hulen and Nielson*, this issue] show that VC-1 penetrated a faulted zone within Paleozoic and Precambrian rocks just outside the ring fracture of the caldera. Overlying

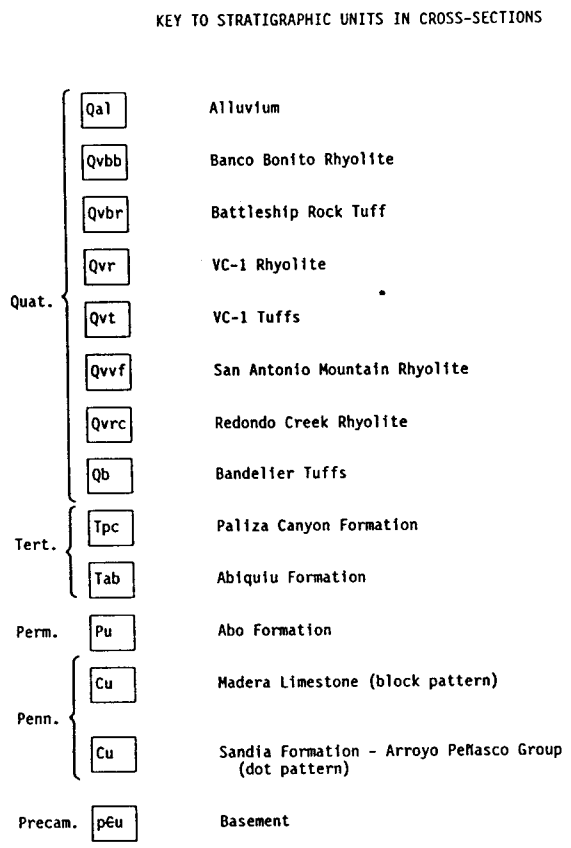

Fig. 2. Key to stratigraphic units used in cross sections in Figures 3, 4, and 5.

volcanic rocks (≤ 0.6 Ma) do not display significant faulting or fracturing.

The other wells listed in Table 1 were drilled by a variety of organizations to obtain information on or production from geothermal resources, either conventional or hot dry rock. All wells drilled outside the southwest margin of the caldera except VC-1 and JS-1 were drilled away from known fault zones. All wells drilled outside the caldera strike thermal aquifers in the lower Paleozoic section (aquifers are shown by large dots on wellbores of Figures 3–5). These aquifers are consistently nonartesian and were never tested because they were either too insignificant from a production standpoint (i.e., AET-4 well) or of no interest to the project (i.e., Fenton Hill wells). In most cases, the thermal aquifer probably could not be produced without some difficulty due to limited permeability. Examination of Figures 3–5 shows that the thermal aquifers do not occur in a unique stratigraphic horizon. Generally, the thermal aquifers flow in the lower Madera Limestone or underlying Pennsylvanian sedimentary rocks. These units are notoriously nonhomogeneous in their lithology from location to location beneath the Jemez Plateau (D. Wachs and J. N. Gardner, unpublished data, 1985; see also *Keith* [this issue]). In other words, there is not one unique thermal aquifer beneath the southwestern plateaus outside Valles caldera. There are many, poorly connected zones of lateral flow generally in the lower Paleozoic section and always above Precambrian basement.

A glance at well locations in Figure 1 shows that thermal aquifers constituting the hydrothermal plume of Valles caldera occur beneath not less than 120 km^2 of land surface outside the southwestern caldera margin. San Diego Canyon and the Jemez fault zone constitute liberally only 10% of that area, yet 25–50% of the thermal discharge of the hydrothermal plume issues in the canyon, as noted in the previous section.

Using the borehole data, the general configuration of the hydrothermal plume can be visualized by examining the cross sections of Figures 3–5. The section in Figure 3 runs west from the Sulphur Springs area inside the caldera across the caldera margin to the Jemez Plateau. The section then bends south semiparallel to the caldera margin and then cuts across San Diego Canyon and the Jemez fault zone to tie into the AET-4 well. Isotherms shown on the section show the effects of convective heat flow inside the caldera and a sharp change to more conductive heat flow outside the caldera beneath the Jemez Plateau. As shown, the isotherms rise (particularly the 50° and 100° isotherms) as the section crosses San Diego Canyon and the Jemez fault zone, reflecting the observed temperature reversal in the AET-4 well and the presence of low-temperature fumaroles and 74°–47°C hot springs in the canyon. Rising isotherms and increasing temperature gradient near the fault zone are best explained by convective flow of more hot fluid in the vicinity of the fault than in stratigraphic horizons away from the fault.

The contrasting distribution of isotherms is more dramatically portrayed in the section of Figure 4 which runs semiparallel to the caldera margin from the Jemez Plateau into the Jemez fault zone at core hole VC-1. Obviously, the temperature of hydrothermal fluids channeled along the fault zone and vicinity is much greater than the temperature of fluids stratigraphically confined near the bottom of the Paleozoic section beneath the plateau. Because the temperature of source reservoir fluids inside the caldera is everywhere greater than 200°C and we observe rising isotherms in the vicinity of the fault, a relatively large volume of hydrothermal fluid leaves the caldera along the fault zone compared with the volume of fluid leaving by way of semipermeable strata adjacent to the rest of the caldera margin. Such an explanation reflects the known and modeled discharge rates of the Jemez fault zone and the Valles hydrothermal system overall.

Figure 5 shows a radial cross section that runs from the heart of the Redondo Creek reservoir (Baca-4) across the caldera wall and semiparallel to the Jemez fault zone to Jemez Springs (JS-1). The distribution of isotherms clearly shows the change from convective upflow in the heart of the Redondo Creek reservoir, to lateral fluid flow toward the caldera wall. Fluids leave the caldera by way of permeable horizons in Paleozoic rocks and the Jemez fault zone. No lateral flow is known in Precambrian rocks. Small temperature reversals occur in the Paleozoic section of wells AET-4 and JS-1 (too small to show in Figure 5). The isotherms reflect the loss of heat in the Paleozoic section as distance from the caldera increases.

HYDROGEOCHEMICAL DATA

Representative hydrogeochemical data from reservoir fluids inside the caldera and from thermal fluids within the hydrothermal outflow plume are shown in Table 2. The samples were obtained in a variety of ways, and the quality of samples varies.

Samples from the WC 23-4 well near Sulphur Springs were obtained using a gas-tight downhole sampler [*Archuleta et al.*, 1978]. Samples from the Baca reservoir were obtained during flow tests conducted by Union Oil Company in 1982 [*Truesdell and Janik*, 1986; *White*, 1986]. The sample from the

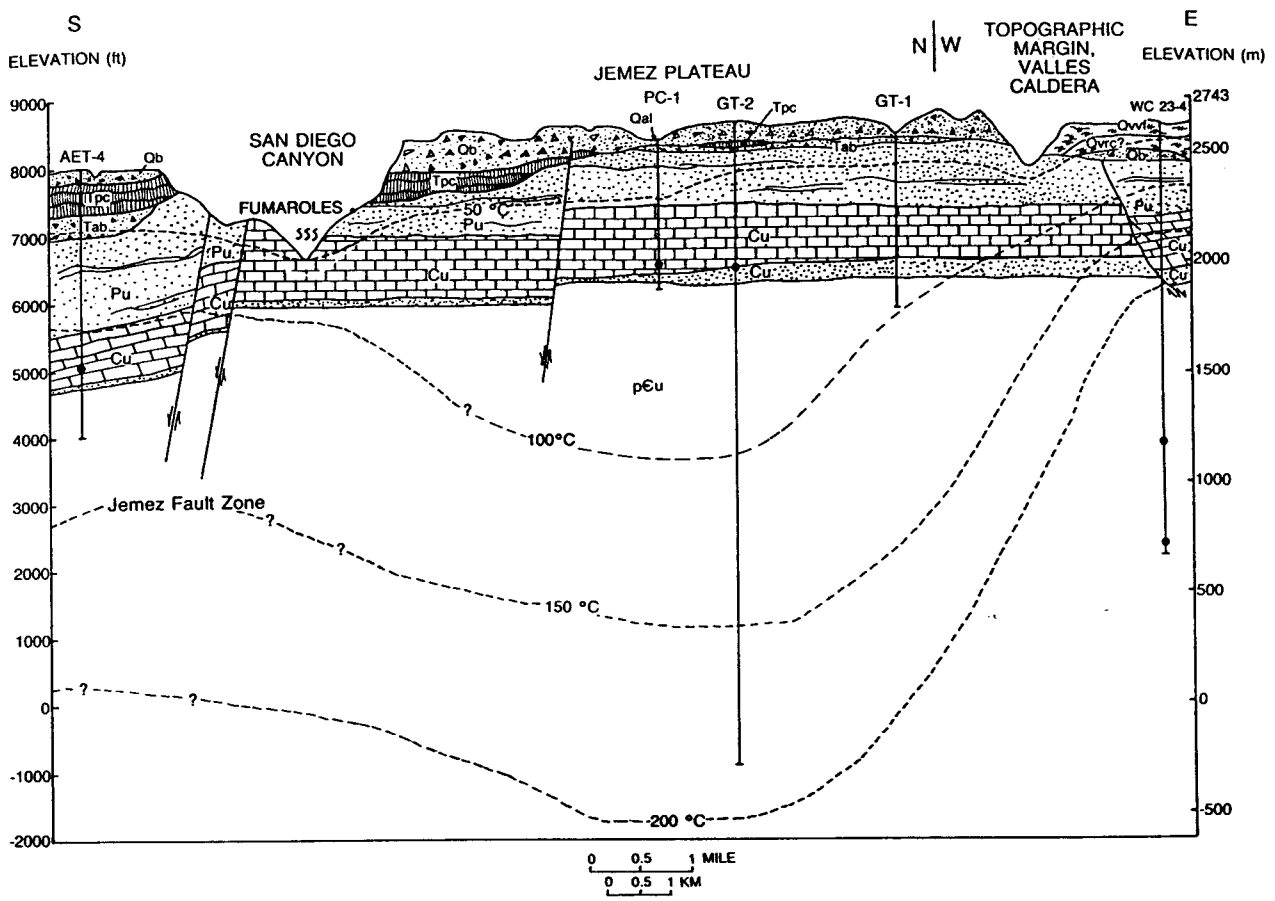

Fig. 3. Cross section showing stratigraphy, structure, and isotherms along the section defined by wells AET-4, PC-1, GT-2, GT-1, and WC 23-4 (vertical exaggeration 3.5×). Dots along wellbore show locations of thermal aquifers of the hydrothermal outflow plume. The geology of the GT-2 well has been described by *Purtymun et al.* [1974] and *Pettitt* [1975], while temperature logs were provided by Schlumberger International. The geology of GT-1 has been described by *Purtymun* [1973]. Stratigraphy and temperature data for AET-4, PC-1, and WC 23-4 are from *Shevenell et al.* [1988].

Madera Limestone aquifer in the GT-2 well at the Fenton Hill hot dry rock site was obtained during drilling and is contaminated with sodium carbonate and probably sulfate from drilling fluids. The PC-1 well which was drilled for the hot dry rock project encountered several aquifers in the Paleozoic section [*Shevenell et al.*, 1987], but the samples are variably contaminated with drilling fluids. The sample listed in Table 2 (PC1-1) is the least contaminated sample that was collected.

Samples from core hole VC-1 were obtained by using a downhole sampler at two different horizons in the bore. The data listed are from the least contaminated and diluted samples that were taken. Wellhead samples from the JS-1 well in Jemez Springs were collected soon after drilling. The well was allowed to flow, and the two aquifers listed were isolated by casing. Hot spring samples from Soda Dam and Jemez Springs are examples of 13 and 7 samples, respectively, collected from 1978 to 1984 [*Shevenell et al.*, 1987]. Samples from the PC-2 and AET-4 wells are so contaminated with drilling fluids that their analyses are useless and are not reported. All analyses given in Table 2, except the sample from the Madera Limestone aquifer in the GT-2 well, were determined at the Fenton Hill laboratory according to procedures described by *Trujillo et al.* [1987].

The first person proposing that the hot springs in San Diego Canyon were derived from the reservoir inside Valles caldera was *Dondanville* [1971], and his ideas were supported by *Trainer* [1974]. Both authors noticed the chemical similarity of the ratios B/Cl, Br/Cl, and Li/Cl between the hot springs and reservoir fluids. *Goff et al.* [1981] provided isotopic support for these arguments and data from the GT-2 and JS-1 wells to draw mixing lines such as those shown in Figure 6. The latter authors also stressed, from geologic considerations, that the outflow plume was channeled principally along the Jemez fault zone but that subordinate flow occurred near the base of the Paleozoic sedimentary section. *Pearson and Goff* [1981] used Schlumberger resistivity surveys to show that shallow conductive zones, suggesting the presence of thermal fluids, occur in San Diego Canyon from the caldera boundary to Jemez Springs.

Detailed sampling of five Baca wells in 1982 provided more data that indicated a link between the reservoir fluids and the hot springs in San Diego Canyon [*White et al.*, 1984; *White*, 1986]. *Trainer* [1984] added hydrologic arguments in favor of the hydrothermal plume concept. *Goff and Shevenell* [1987] showed that the voluminous travertines of the Soda Dam area began deposition soon after formation of Valles caldera (1.12 Ma), indicating that the plume has been part of the Valles hydrothermal system for approximately 10^6 years.

The data of Table 2, which include chemistry of five recently sampled thermal fluid horizons intersected by the WC 23-4, PC-1, and VC-1 bores, provide more evidence for the existence of a plume because all fluids have relatively constant

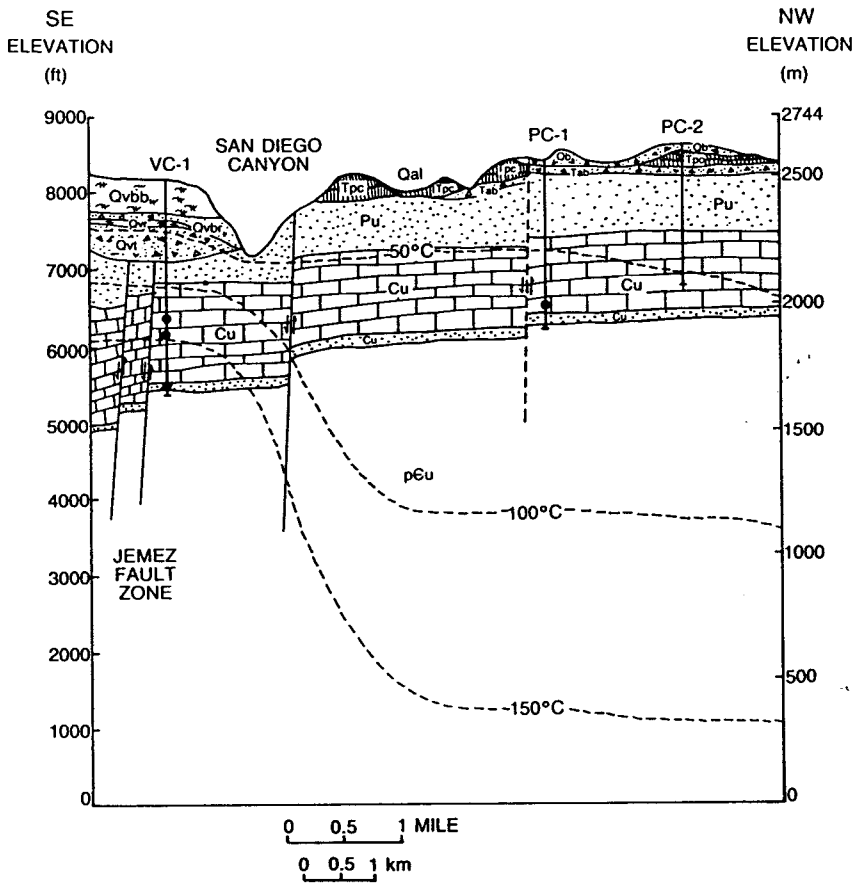

Fig. 4. Cross section showing stratigraphy, structure, and isotherms along the section defined by wells VC-1, PC-1, and PC-2 (vertical exaggeration 3.5 ×). Dots along wellbore show thermal aquifers. Lithology and temperature data for the three wells are from *Shevenell et al.* [1988].

ratios of the conservative species B/Cl, Br/Cl, and Li/Cl (Figure 6). These near-constant ratios are maintained even though the waters circulate in a variety of rock types at temperatures ranging from about 50°C to 300°C and have TDS from approximately 18,000 to only 1200 mg/kg. Consequently, hydrothermal fluids outside the caldera must be derived from reservoir fluids inside the caldera because the ratios of conservative components are nearly constant. Variations in TDS among samples outside the caldera reflect mixing with dilute groundwaters.

Reservoir and Mixing Processes

Although hydrothermal fluids outside the caldera are derived from reservoir fluids inside the caldera, it is incorrect to assume there is one reservoir fluid or one dilute aquifer involved in mixing. From the data obtained during the 1982 flow tests of five Baca wells, both *Smith and Kennedy* [1985] and *Truesdell and Janik* [1986] showed that there are at least two subtly different reservoir fluids in the Redondo Creek reservoir. Fluid A (represented by Baca-15) has a reservoir temperature between 260°C and 280°C, has chlorinity around 2500 mg/kg (corrected for steam flash), is isotopically heavy, is low in radiogenic gases, CO_2 and HCO_3, and is relatively high in Ca. Fluid B (represented by Baca-4) has a reservoir temperature of 290°–300°C, a chlorinity of 1900 mg/kg (corrected for steam flash), is isotopically light, is higher in radiogenic gases, CO_2 and HCO_3, and is relatively low in Ca. Some of these differences can be seen in the data of Table 2 and the plot of δD versus $\delta^{18}O$ in Figure 7.

The new data from the WC 23-4 well in the Sulphur Springs area suggest that there is at least one more reservoir fluid in the caldera (at 210°–240°C) that has considerably heavier isotopic composition and considerably greater bulk concentration than fluids in the Redondo Creek reservoir. The isotopic enrichment in $\delta^{18}O$ of the most concentrated sample from WC 23-4 is at least 5‰ and it is enriched in δD by at least 10‰ in comparison with other Valles reservoir fluids. Although it has not been established that the WC 23-4 fluids are representative of all fluids in the Sulphur Springs reservoir, it is no surprise that other reservoir fluids should exist in the caldera, because the Sulphur Springs area is isolated structurally from the Redondo Creek area [*Goff et al.*, 1985], and *Swanberg* [1983] has shown from thermal gradient data that the Sulphur Springs and Redondo Creek areas represent separate zones of convective upflow within the caldera. Most production from both areas of convective upflow occurs from thick sequences of intracaldera Bandelier Tuff and underlying volcanics, which probably help fix the ionic ratios of different reservoir fluids to constant values.

Although the ratios of B, Br, and Li with respect to Cl remain nearly constant in all reservoir fluids regardless of location, isotopic differences between reservoir fluids and derivative waters indicate that no single reservoir fluid and no single diluting fluid are parents of the derivative hydrothermal

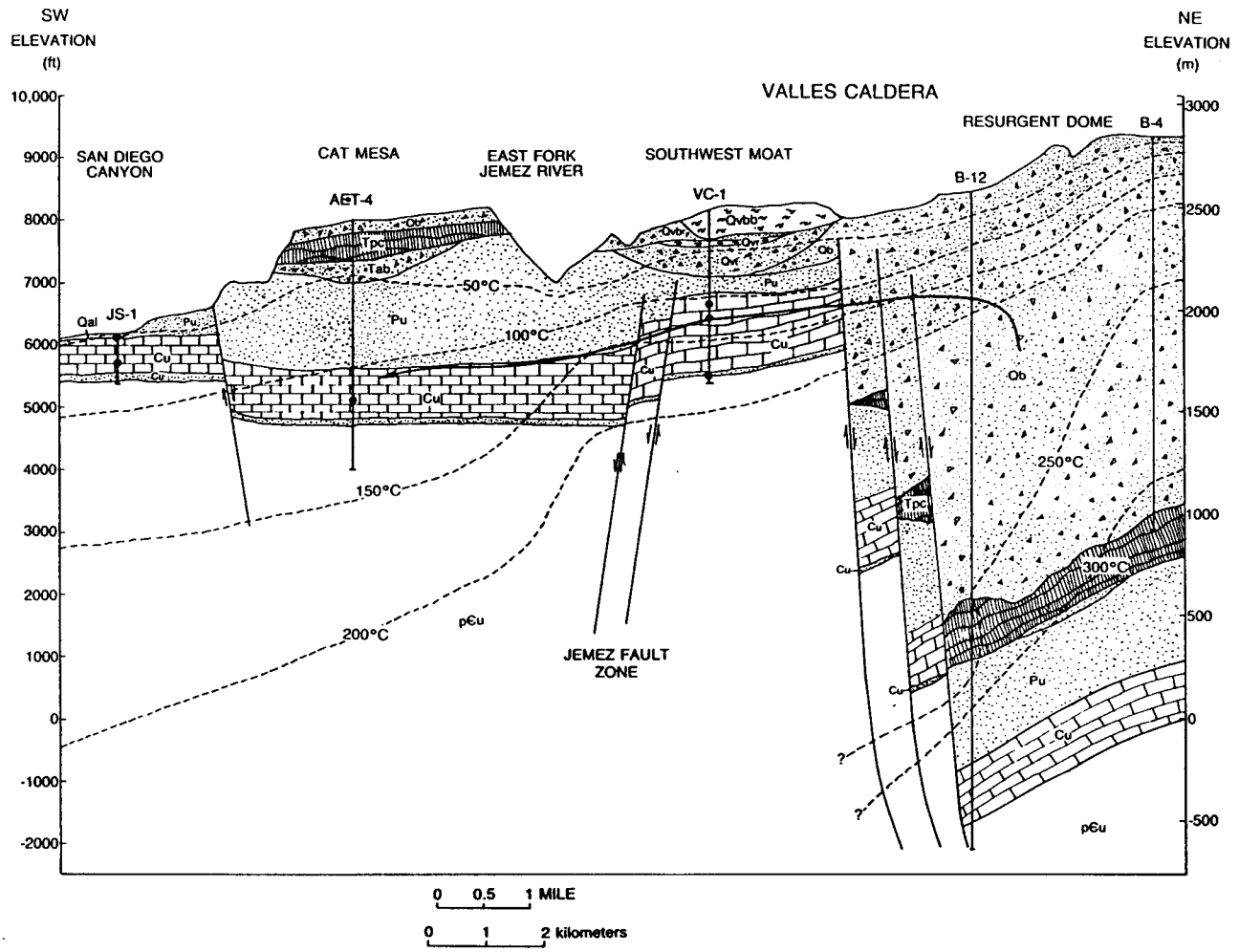

Fig. 5. Cross section showing stratigraphy, structure, and isotherms along the section defined by wells JS-1, AET-4, VC-1, Baca-12, and Baca-4 (vertical exaggeration 3.5 ×). Dots along wellbore show thermal aquifers. The line and arrow identify a possible path of thermal fluid flow. The lithology of the Jemez Springs well is from *Goff and Kron* [1980]. Lithologic data of the two Baca wells are from *Nielson and Hulen* [1984], while temperature data are from *White* [1986] and *Hulen and Nielson* [1986].

waters flowing outside the caldera (Figure 7). The isotopic data do not display one trend. Instead they form a belt of compositions with derivative waters generally lying between reservoir compositions and the Jemez Mountains meteoric line [*Vuataz and Goff*, 1986].

Cold meteoric waters in the Jemez Mountains have $\delta^{18}O$ values ranging from −14.25 to −10.90‰ and δD values ranging from −99.1 to −75.7‰ [*Vuataz and Goff*, 1986]. Because of the large variation of isotopic values in cold meteoric waters, it is impossible to determine which reservoir fluid is mixing with which diluting fluid to form the derivative thermal waters found at Soda Dam, Jemez Springs, VC-1, etc. (a more involved discussion of this problem is found in *Vuataz and Goff* [1986]). Yet another complexity is suggested by *Phillips et al.* [1984], who found very low ^{36}Cl values in both Redondo Creek reservoir fluids and Soda Dam hot spring water. This could mean that small amounts of old Cl are leached out of either minerals or pore fluids (of unknown isotopic composition) in the Paleozoic section. The data of Figure 7 could be interpreted such that all fluids are derived from the most isotopically enriched fluid samples in the 1921-m aquifer of the WC 23-4 well. Poor productivity from this horizon and the geologic isolation of the well beneath the western edge of the Sulphur Springs reservoir would argue against this extreme scenario. Many mixing scenarios are possible, but no unique trends are identifiable.

From previous work in the San Diego Canyon area, *Goff et al.* [1981] pointed out that the two groups of hot springs must originate from isolated flow paths of the hydrothermal plume. How else could Soda Dam, which issues 2 km closer to the caldera than Jemez Springs, have such high discharge (1500 L/min) and have higher Cl (~1500 versus ~900 mg/kg) yet have lower discharge temperature (47°C versus 73°C)? Fluid samples from core hole VC-1, even closer to the caldera, indicate the same conclusion. Thermal waters in VC-1 could not supply the hot spring system at Soda Dam because they have less Cl than the Soda Dam waters. VC-1 aquifers more closely resemble the fluids at Jemez Springs in chemistry, yet the two sampling points are distinct isotopically. Yet another mixed thermal fluid circulates at 152-m depth below Jemez Springs in well JS-1 that is cooler in temperature (61°C), lower in TDS, and distinct isotopically from the hot springs at the surface. These unusual patterns can only result from isolated paths of fluid flow and different mixing histories along the

TABLE 2. Chemical and Isotopic Data for Selected Production Zones, Hydrothermal Aquifers, and Hot Springs in the Southwestern Valles Caldera Region, New Mexico

	Sulphur Springs Area		Redondo Creek Reservoir		Jemez Plateau		Jemez Fault Zone					
	WC 23-4	WC 23-4	Baca-4	Baca-15	GT-2	PC-1	VC-1	VC-1	Soda Dam	Main Jemez Spring	JS-1	JS-1
Sample	VA-113	VA-116	BA-5*	BA-7*	GT-2a	PC1-1	VA-209	VA-242	VA-140	VA-216	VA-19	VA-15
Date	Jan. 4, 1983	Jan. 4, 1983	July 2, 1982	July 23, 1982	Feb. 1974	April 1984	Sept. 5, 1985	Aug. 26, 1986	Feb. 1, 1984	Oct. 4, 1985	Jan. 1979	Jan. 1979
Depth, m	1463	1921	>1000	>800	670	522	483.2	536.6			24	152
Temperature, °C	214	233	295	270	≤76	70	111	125	46.8	73.7	68	60.5
*p*H (field)	8.03	7.10	7.20	7.61	8.8	7.21	7.06	6.68	6.71	6.90	6.64	6.69
SiO_2	395	450	760	680	115	225	74	90	47	91	70	24
Ca	80.5	46.0	3.7	13.6	2.0	762	49	47.8	342	137	122	120
Mg	2.89	0.45	<0.01	<0.01	2.0	52.8	17.8	11.9	21.9	5.1	5.76	9.31
Sr	2.29	1.98	0.10	0.25		3.52	1.33	1.03	2.84	0.64	0.54	0.40
Na	2800	5890	1560	1950	6300?	1390	883	804	960	638	546	185
K	470	1020	280	330	350	153	85	84	160	68	61.6	29.9
Li	37.4	68.0	20.0	23.1	25.0	10.8	8.00	7.27	13.8	8.90	6.96	2.27
HCO_3	360	382	190	89	6820?	1133	942	919	1488	745	642	479
SO_4	33	95	49	45	2110?	2157?	56.8	74	34	40.8	45.0	38.0
Cl	4350	9960	2670	3257	3500	1602	964	853	1480	917	705	243
F	6.90	13.8	6.8	6.9		1.06	3.94	4.74	3.33	4.99	4.42	3.30
Br	14.0	27.0	7.83	9.59		4.30	2.80	2.20	4.60	2.40		
B	39.3	96.2	20.0	25.4	25.0	13.4	8.55	10.1	12.1	7.34	6.10	2.20
As	4.1	7.8	2.8	3.4			<0.1	<0.1	1.5	0.7		
B/Cl	0.0090	0.0097	0.0075	0.0078	0.0071	0.0084	0.0089	0.0118	0.0082	0.0080	0.0087	0.0091
Br/Cl	0.0032	0.0027	0.0029	0.0029		0.0027	0.0029	0.0026	0.0031	0.0026		
Li/Cl	0.0086	0.0068	0.0075	0.0071	0.0071	0.0067	0.0083	0.0085	0.0093	0.0097	0.0099	0.0093
δD, ‰	−80.4	−71.5	−86.6	−83.9	−78.9		−88.0	−88.3	−84.9	−81.9	−84.0	−85.9
$\delta^{18}O$, ‰	−7.80	−5.05	−9.97	−8.61	−8.12		−11.35	−11.33	−10.56	−10.46	−11.3	−11.8

Values listed are in mg/kg except where noted. All chemical analyses were done by P. E. Trujillo, Jr., and D. Counce (Los Alamos National Laboratory), except sample GT-2a.

Data from the following sources: sample GT-2a, *Trainer* [1978]; samples VA-209, VA-216, and VA-242 unpublished; all other samples from *Shevenell et al.* [1987]; isotope data of Baca-4 and Baca-15 from *Truesdell and Janik* [1986].

*Chemical data are not corrected for flashing; isotope data are corrected for flashing.

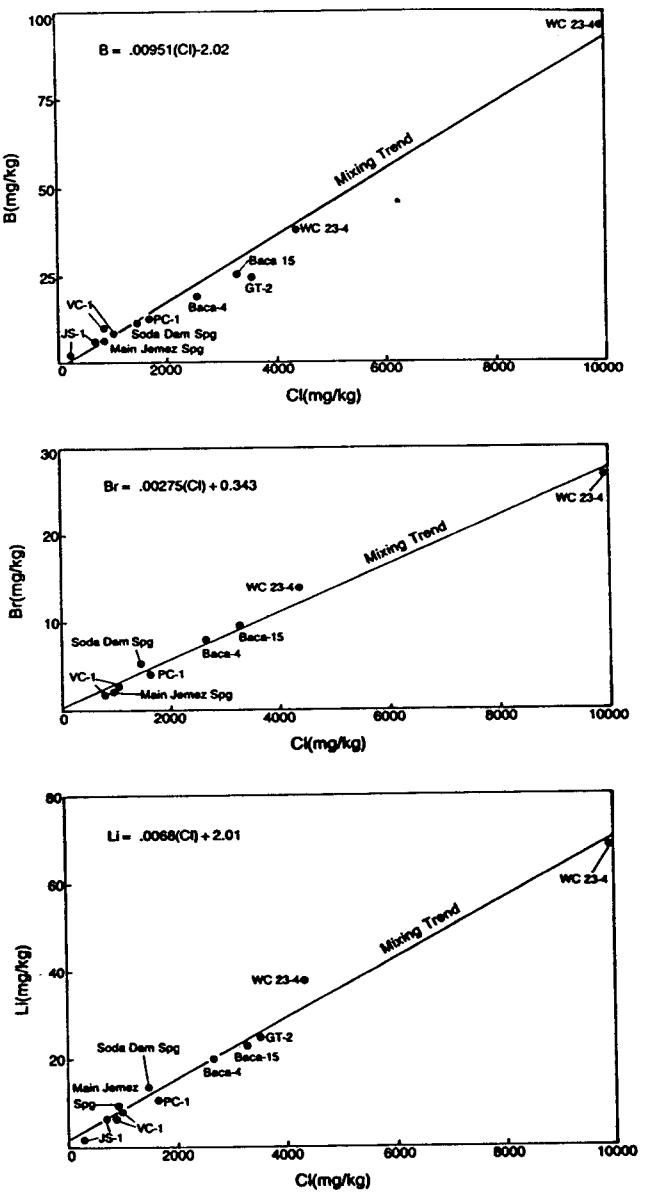

Fig. 6. Plots of B, Br, and Li versus Cl for the data listed in Table 2.

paths. The hydrothermal outflow plume of Valles caldera cannot be a homogeneous aquifer having only one concentrated and one dilute end-member. It is a plume made up of many flow paths in which end-member thermal fluids from at least two reservoirs mix with different dilute meteoric waters at different points along the Jemez fault zone and adjacent strata.

Based merely on proximity, it is most likely that fluids from the Redondo Creek reservoir are the parents for most derivative waters along the Jemez fault zone, whereas fluids from the Sulphur Creek reservoir supply derivative waters beneath the Jemez Plateau. Using the chemical data of Table 2 and Figure 6, Soda Dam would be composed of roughly 50% reservoir water, whereas Jemez Springs and VC-1 would be composed of roughly 30% reservoir water. Fluids from wells PC-1 and GT-2 could contain as little as 15% and 25% reservoir water if the most concentrated fluid in the WC 23-4 well is assumed to be the end-member reservoir fluid. We hasten to add, however, that it is still not known how representative WC 23-4 fluids are of the Sulphur Springs reservoir overall.

THERMAL GRADIENT DATA AND RELATIVE HEAT FLOW

Figure 8 displays the thermal gradients of the five bores shown in the cross section of Figure 5. A detailed analysis of thermal conductivity and thermal gradient in VC-1 is given by *Sass and Morgan* [this issue]. Thermal gradients of other wells discussed in this report can be found in the work by *Laughlin et al.* [1983] and *Shevenell et al.* [1988]. A thermal transient analysis of the temperature gradients of wells EE-2 and AET-4 is presented by *Harrison et al.* [1986]. The five gradients of Figure 8 show the varied effects of convective and conductive thermal environments. The convective gradient of Baca-4, in the heart of the Redondo Creek reservoir, displays a shape that parallels the boiling point curve for pure water. The absolute temperature of the well slowly approaches 300°C with increasing depth. The gradient of Baca-12 measured soon after the well was deepened in 1982 shows an isothermal zone at about 220°C from 1700 to 1100 m above mean sea level (msl) in the Bandelier Tuffs. A temperature reversal occurs at an elevation of 750 m near the base of the tuffs, and another occurs at 250 m in the Permian Abo Formation (red beds). According to D. Nielson (personal communication, 1986) of University of Utah Research Institute, these apparent reversals are considered to be lost circulation zones that were greatly cooled with drilling fluids and never recovered during the short time interval between deepening and temperature logging. A rather linear gradient of about 75°C/km occurs from about 150 to 500 m below msl in the Pennsylvanian Madera Limestone beneath the geothermal reservoir. According to *Nielson and Hulen* [1984] and *Hulen and Nielson* [1986], the Madera in Baca-12 has been metamorphosed into a diopside-actinolite marble. In addition, these authors indicate an absence of porosity and permeability below the Abo Formation, which may account for the observed conductive gradient in the bottom of Baca-12.

VC-1 displays a rather linear gradient of 190°C/km (as of the summer of 1986) from 1980 to 1760 m above msl in the Paleozoic section. The initial temperature log obtained in the summer of 1984 showed two small positive excursions in the above depth range which result from small hydrothermal inflow zones whose chemistry is described above (Table 2). The 1984 log also showed a dramatic temperature increase in the bottom of the well, suggesting yet another hydrothermal aquifer was present in the breccia zone at the bottom of the bore. By extrapolation of the present gradient, the temperature of this lower aquifer would be approximately 185°C. Unfortunately, this aquifer was not sampled due to a parted linear above the bottom of the well. The thermal gradient in VC-1 is much higher than the deep conductive gradient in Baca-12, suggesting that the VC-1 gradient is a reflection of conductive heat flow above a hydrothermal aquifer whose temperature is approximately 185°C or possibly greater.

Further away from the caldera, well AET-4 shows a conductive gradient of 140°C/km from an elevation of 1940–1555 m above msl in the Paleozoic section. A temperature reversal and a zone of nearly isothermal temperatures occur below this depth in Precambrian rocks [*Shevenell et al.*, 1988]. The absolute temperature of this reversal was 115°C soon after drilling [*Harrison et al.*, 1986] and 129°C in 1986 [*Shevenell et al.*, 1988]. Water samples were obtained from the zone causing the temperature reversal but were highly contaminated with drilling fluid additives (mostly NaOH and Na_2CO_3).

An estimated temperature profile is shown for the JS-1 well

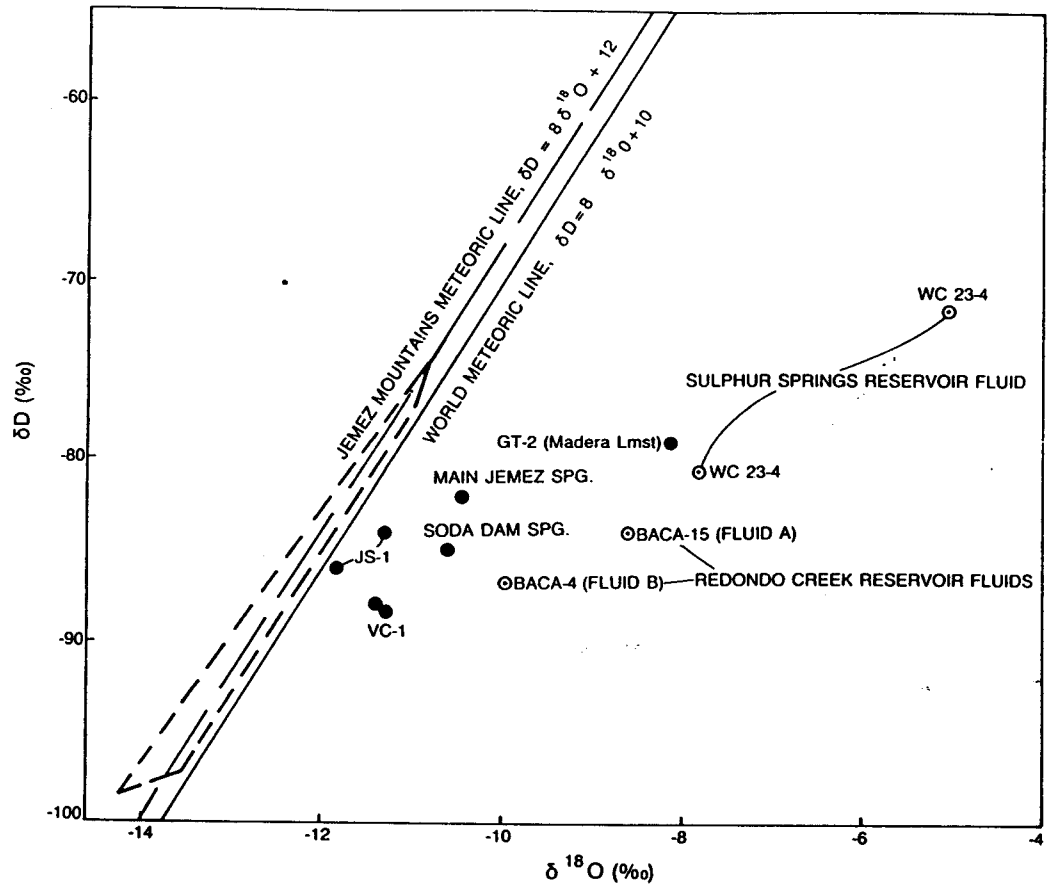

Fig. 7. Plot of δD versus $\delta^{18}O$ for the data listed in Table 2; Jemez Mountains meteoric line is from *Vuataz and Goff* [1986]. Short-dashed line encloses the range in δD and $\delta^{18}O$ of meteoric waters in the Jemez mountains.

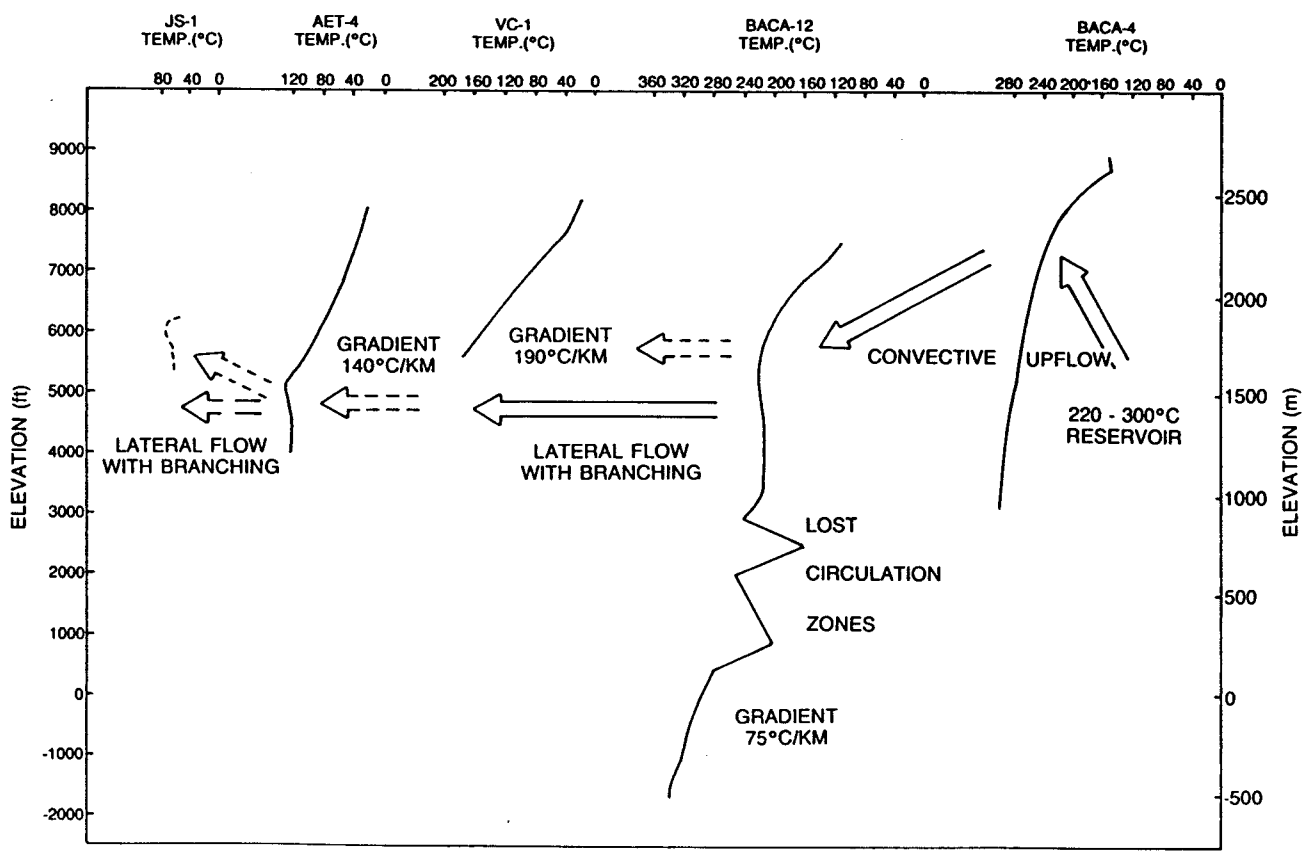

Fig. 8. Temperature gradients of Baca-4, Baca-12, VC-1, AET-4, and JS-1 wells adjusted for elevation with respect to sea level; data from *Hulen and Nielson* [1986], *Nielson and Hulen* [1984], *Shevenell et al.* [1988], *White* [1986], and *Goff et al.* [1986].

TABLE 3. Comparison of Deep Conductive Heat Flow and Near-Surface Conductive Heat Flow Associated With Valles Caldera and the Valles Hydrothermal Outflow Plume

Borehole	Intracaldera Baca-12	Southwest Caldera Margin (Jemez Plateau)		Hydrothermal Plume		
		EE-3	Model*	VC-1	AET-4	EE-3
Distance from center of system, km†	3.2	8.8	16	7.2	12	8.8
Temperature gradient, °C/km	75	≤90‡	40	190	140	100
Depth interval of gradient, m	2550–3040	3800–4400	>800	518–740	500–884	0–730
Rock type	limestone and sandstone	granite	granite	limestone and sandstone	limestone and sandstone	volcanics over limestone and sandstone
Conductivity, W m^{-1} K^{-1}	3.3¶	2.2§	2.2§	3.3¶	3.3¶	2.0**
Heat flow, mW m^{-2}	248	≤198	88	627	462	200

*Data estimated from thermal model of *Kolstad and McGetchin* [1978].
†Center of system assumed to be beneath head of Redondo Creek in the central resurgent dome.
‡*Laughlin et al.* [1983]; EE-3 is at the same location as well as GT-2, Tables 1 and 2.
¶Conductivity estimated from *Rybach* [1981] assuming limestone has been metamorphosed to marble and has the highest conductivity listed.
§Conductivity from *Sibbitt et al.* [1979] is average of six analyses of granite core run at 250°C from well GT-1.
**Computed from *Harrison et al.* [1986].

located in San Diego Canyon in the village of Jemez Springs. No thermal gradient log was ever obtained for the well, but two aquifers were encountered. Temperatures were recorded at the wellhead by isolating and flowing the aquifers separately. The upper aquifer (~73°C) is hotter than the lower one (~62°C) [*Goff et al.*, 1981]. Both aquifers occur in Paleozoic rocks.

The temperature reversals displayed by the JS-1 and AET-4 wells are the only reversals presently documented from wells in the vicinity of the Valles outflow system. The presence of temperature reversals is commonly accepted as proof of lateral flow [*Healy and Hochstein*, 1973]. Both wells are located southeast of the main trace of the Jemez fault zone. Wells northwest of the Jemez fault zone show a pronounced decrease in gradient going from Paleozoic rocks into Precambrian rocks (i.e., well EE-3 at Fenton Hill [*Laughlin et al.*, 1983]) but no true temperature reversal. The change in gradient is due in part to the difference in thermal conductivity between Paleozoic sedimentary rocks and Precambrian crystalline rocks, but some of the change must be due to the presence of hydrothermal fluids near the base of the Paleozoic section [*Laughlin*, 1981]. The lack of pronounced temperature reversals in the Valles outflow plume is best explained by the relatively old absolute age of the plume as discussed below.

Based on many thermal gradient wells located inside and outside the caldera, *Kolstad and McGetchin* [1978] were able to calculate heat flow in Precambrian rocks outside the caldera depression to aid in their thermal cooling models of the Valles caldera pluton. *Heiken and Goff* [1983] used these data with other thermal gradient data to show the radial distribution of deep conductive gradients around the southwest caldera area. The various differences in gradients and heat flow are summarized in Table 3. Using values of thermal conductivity determined for Precambrian rocks outside the caldera [*Sibbett et al.*, 1979], we calculated approximate values for deep conductive heat flow with increasing distance from the caldera (Table 3). Assuming a value for the thermal conductivity of marble such as now exists in the Madera Limestone at the bottom of Baca-12, the conductive heat flow beneath the Redondo Creek reservoir is probably not less than 250 mW m^{-2}. Deep conductive heat flow beneath the Jemez Plateau varies from about 200 mW m^{-2} at the caldera margin (Fenton Hill) to about 90 mW m^{-2}, another 7 km further from the caldera center. The shallow heat flow associated with the hydrothermal plume in the Fenton Hill area is also about 200 mW m^{-2} [*Harrison et al.*, 1986], even though the temperature gradient is high (100°C/km), because thermal conductivity of Phanerozoic rocks is low. In contrast, the shallow heat flows associated with the thermal gradients above hydrothermal aquifers in the VC-1 and AET-4 wells are roughly 600–450 mW m^{-2}, considerably more than the deep conductive heat flow or the shallow heat flow at Fenton Hill. Hence the hydrothermal outflow plume, particularly near the Jemez fault zone, has a pronounced effect on the shallow heat flow distribution outside the caldera depression.

OUTFLOW PLUME OF ROOSEVELT HOT SPRINGS, UTAH

The geology and hydrogeochemistry of the hydrothermal outflow plume of Roosevelt Hot Springs, Utah, are briefly described here because the Roosevelt plume is stratigraphically controlled, whereas the Valles plume is primarily fault controlled. The Valles outflow is dominated by lateral flow down a zone of vertical conduits (Jemez fault zone) striking away from the hydrothermal reservoir, while the Roosevelt outflow plume reflects lateral flow in a horizontal permeable layer of relatively great areal extent. Hydrothermal fluids in this horizontal layer are fed from a highly fractured graben in which the main reservoir resides [*Vuataz and Goff*, 1987].

The Roosevelt Hot Springs geothermal system is located in southwestern Utah near the eastern edge of the Basin and Range tectonic province. This region is characterized by thin earth crust (25–30 km), active seismicity, extensional tectonics, and high regional heat flow (92 mW m^{-2} [*Ward et al.*, 1978; *East*, 1981]). The geothermal system circulates in a graben of fractured crystalline rocks on the west side of the Mineral Mountains (Figure 9). The west boundary to the reservoir is the Opal Mound Fault which trends NNE semiparallel to the trend of the mountains. A string of rhyolite vents occurs along the crest of the range east of the geothermal system ranging

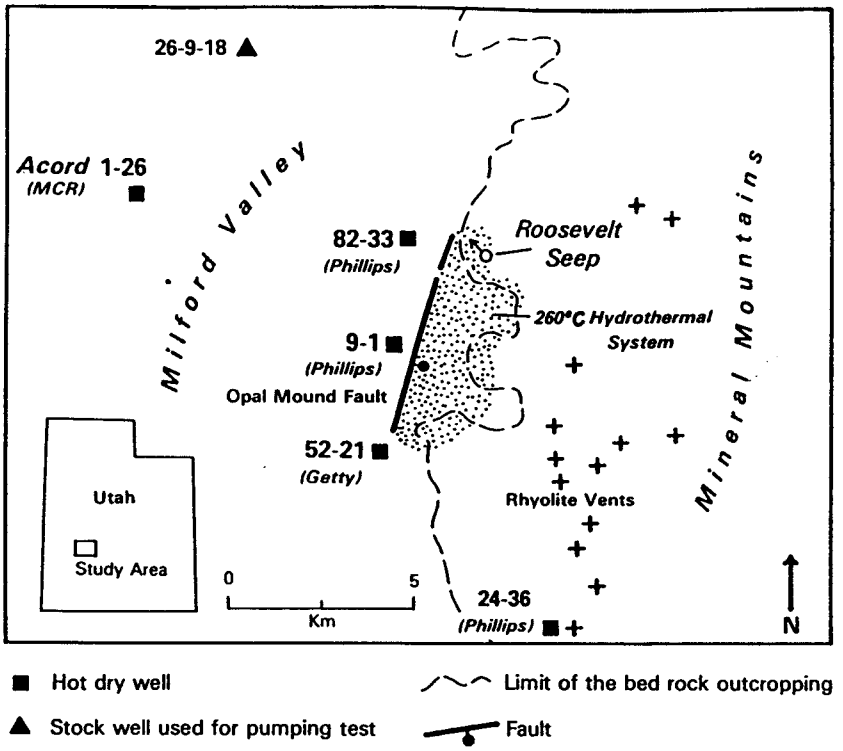

Fig. 9. Location map of the Roosevelt Hot Springs geothermal system.

from 0.8 to 0.5 Ma and mafic lavas occur east of the range varying from 1.0 to 0.3 Ma. The heat source driving the present system may have regional tectonic as well as magmatic contributions because the volume of silicic lavas is small and the mafic lavas have short residence time in the crust [*Smith and Shaw*, 1979]. About 20 MW(*e*) are presently produced from the field.

The geology in the vicinity of the production zone (Figure 10) consists of Precambrian metamorphic rocks intruded by Tertiary granitic rocks 25 to 9 Ma [*Nielson et al.*, 1986]. These crystalline rocks have been cut by low-angle gravity slide faults of regional extent. Basin and Range style faulting presently dominates the tectonic picture of the area. Tertiary to Quaternary alluvium, shed off the developing Mineral Mountains block, fills in Milford Valley to the west. This fill is as thick as 3000 m a few kilometers west of the Opal Mound Fault [*Shannon et al.*, 1983] but is considerably thinner in the vicinity of the production zone (Figure 10). The uppermost layer of fill is predominantly unconsolidated alluvial fan debris [*Vuataz and Goff*, 1987].

Phillips Geothermal Company, the original discoverer and developer of the geothermal field, recognized that a hydrothermal outflow plume discharged from the reservoir into the alluvium and flowed west over the shallow horst of crystalline rocks adjacent to the Opal Mount Fault toward the axis of Milford Valley (R. Lenzer, personal communication, 1982). By examining the chemistry of groundwaters tapped by many stock wells and observation wells in the alluvium west

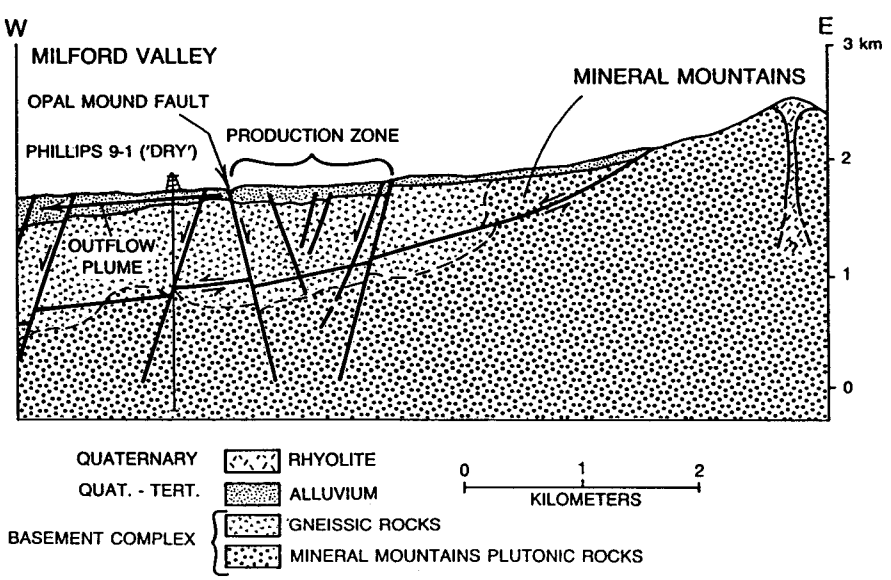

Fig. 10. Schematic cross section of the Roosevelt Hot Springs geothermal system [modified from *Nielson et al.*, 1978].

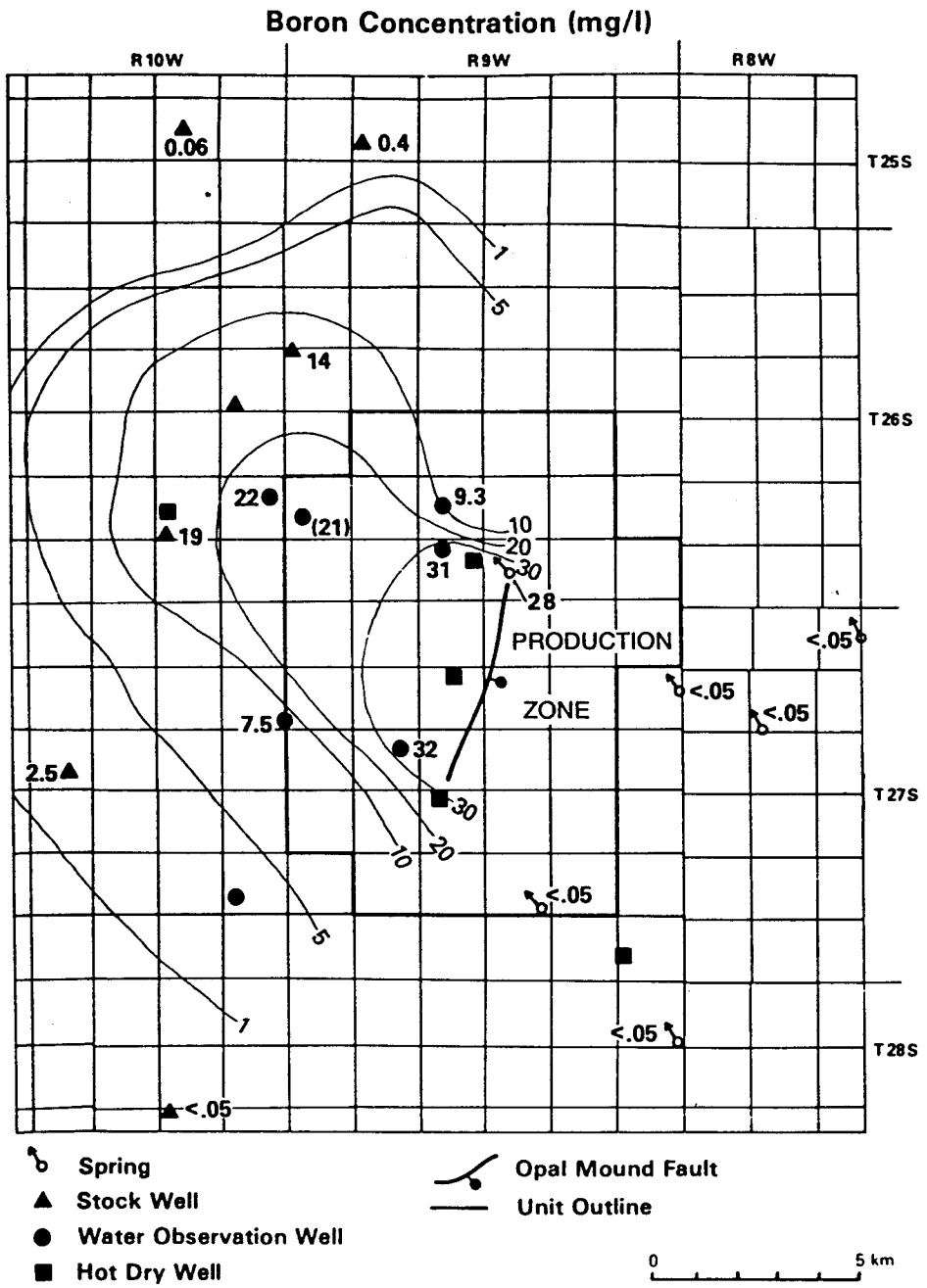

Fig. 11. Contour map of B content in the shallow hydrothermal plume of Roosevelt Hot Springs geothermal system, Utah [from *Vuataz and Goff*, 1987].

of the Opal Mount Fault, *Vuataz and Goff* [1987] created a contour map of B concentration that shows the shape, lateral extent, and amount of dilution in the hydrothermal plume (Figure 11). Although there are very good mixing trends on plots of B, Li, TDS, etc., versus Cl between dilute shallow groundwater and deep hydrothermal fluid, there are subtle complexities in mixing behavior on isotope plots. Just as in the Valles system, the isotopic data from the Roosevelt Hot Springs system [*Vuataz and Goff*, 1987] indicate variations in the reservoir fluids and variations in dilute groundwaters involved in mixing. Interestingly, similar styles of chemical and isotopic variations noted at both the Valles and Roosevelt systems indicate that the variations are not necessarily dependent on structural configuration of the hydrothermal plume.

The hydrologic behavior of the horizontal aquifer at Roosevelt was further studied during pumping tests on one of the wells in the outflow plume [*Vuataz and Goff*, 1987]. Transmissivities in the area range from ≥ 200 m^2/d in the plume to as high as 3700 m^2/d near the axis of Milford Valley due to lithologic variations in the aquifer. Geothermal fluid literally flows west in the permeable alluvial fan deposits as a hot, concentrated tongue of water that mixes with shallow groundwater systems in Milford Valley.

EXAMPLES OF HYDROTHERMAL OUTFLOW PLUMES

The Valles caldera and Roosevelt Hot Springs hydrothermal outflow plumes are considered herein as different types of plumes because of their contrasting hydrogeological controls. In Table 4 we have listed more examples of geother-

TABLE 4. Comparative Data on Hydrothermal Outflow Plumes at 14 Geothermal Systems Around the World

System Name	Heat Source[a]	Maximum Age,[b] Ma	Source Reservoir Temperature, °C	Measured Reservoir Chloride, mg/kg	Outflow Springs	Measured Outflow Chloride, mg/kg	Length of Outflow, km	Outflow Rock Type	Outflow Temperature Reversals	Age of Outflow	References
						United States					
Valles caldera, N. M.[c]	M	1.12	300	2500	Soda Dam, Jemez Springs	1500–200	>20	limestone	small where present	~1 m.y.	This report, *Goff et al.* [1981], *Trainer* [1984], *Goff and Shevenell* [1987]
Roosevelt Hot Springs, Utah	M and T	0.70	270	3600	none[f]	2800–50	15	alluvium	none known; probably small if present	?	*Capuano and Cole* [1982], *Vuataz and Goff* [1987]
Long Valley, Calif.	M	0.70[d]	220[e]	≥280	Casa Diablo, Hot Creek, etc.	300–50[l]	22	rhyolite tuff and allivium	major along most of plume	≤40 kyr	*Sorey* [1985], *Blackwell* [1985], *Wollenberg et al.* [1986], F. Goff and L. Shevenell (unpublished data, 1986)
Lassen, Calif.	M	0.60	240[g]	2500	Morgan and Growler Hot Springs	2400–2200	≥12	andesitic tuffs and lavas	observed (major) in one well only	≤11 kyr	*Beall* [1981], *Muffler et al.* [1982], *Thompson* [1985], *Ingebritsen and Sorey* [1985]
Mt. St. Helens, Wash.	M	0.04	≤200[h]	≥1050	Loowit Hot Springs; Harry's Spa	1050–180	5	andesitic tuffs and lavas	probable but none known	≤5 years	*Mullineaux and Crandell* [1981]; *Thompson et al.* [1985]; F. Goff and L. Shevenell (unpublished data, 1985, 1986, 1987)
Ojo Caliente, N. M.	T	?	85[i]	250	none[j]	240–130?	≥2	gneiss and alluvium	none known; probably small if present	?	*Vuataz et al.* [1984]
Desert Peak, Nev.	T	?	215	3500	none	3300–?	10	alluvium and volcanics	major along most of plume	2 kyr?	*Benoit et al.* [1982]
						Other Countries					
El Tatio, Chile	M	<1.0?[k]	265	5600	Rio Salado Hot Springs	>8000–500[l]	≥15	rhyolite tuff and lavas	major along entire plume	?	*Healy and Hochstein* [1973], *Lahsen and Cusicanqui et al.* [1976]
Miravalles, Costa Rica	M	<0.3	240	3000	Salitral Bagaces; San Bernardo Abajo	2600–160	≥15	rhyolite tuffs and andesite	probable but none known	?	R. Corrales (personal communication, 1985); C. Grigsby, F. Goff and T. Grant (unpublished data, 1986)
Aluto-Langano, Ethiopia	M	≤0.08?[k]	300	280	Langano Hot Springs	400?–250[l]	13	peralkaline lavas and tuffs; basalt	major along part of plume	≤140? kyr	*Lloyd* [1977], *Belaineh* [1983], *Mekuria* [1983], *Govt. of Ethiopia* [1984], *Giday* [1987]
Bacon-Manito, Philippines	M	<0.3[k]	290	5800	Pawa and Naghaso Hot Springs	5000–750	20	andesite lavas and tuffs	major along most of plume	?	*de Leon* [1983], *Tolentino et al.* [1985]
Mokai, New Zealand	M	0.3	300	2300	North Mokai Springs	1500–90	14	rhyolite tuffs and lavas	major along most of plume	≤13 kyr?	*Lloyd* [1978], *Hulston et al.* [1981], J. Hedenquist (unpublished data, 1984)

Waiotapu, New Zealand	M	0.16?	295	1250	Reporoa Hot Springs	1200–600	>15	volcanic and volcaniclastic	major along most of plume	?	*Healy and Hochstein* [1973], *Hedenquist* [1982]
Platanares, Honduras	T	0.25[n]	225[m]	36	Rio Lara Hot Springs	25–10	≥2	rhyolite tuffs	observed (minor) in one well only	?	*Heiken et al.* [1987], *Goff et al.* [1987], *Truesdell et al.* [1987]

[a]M, magmatic; *T*, tectonic.
[b]The maximum age of the primary magmatic heat source (caldera formation, dome building, etc.) is given.
[c]Data given for the Valles system are for the Redondo Creek/Jemez fault zone segment of the outflow plume.
[d]Data given are for Long Valley caldera, although the primary heat source is now believed to be the Mammoth Mountain/Inyo Dike Chain magma system (age 0.30 m.y. to 600 years).
[e]Temperature is based on chemical geothermometry; maximum drilled temperature in this flow system is 202°C.
[f]Roosevelt seep discharges near source of outflow system (Cl = 3400 mg/kg).
[g]Temperature is based on chemical geothermometry; maximum drilled temperature is 176°C.
[h]Temperature is based on chemical geothermometry; few data are available on this system.
[i]Temperature is based on chemical geothermometry; maximum drilled temperature is 55°C.
[j]Ojo Caliente discharges near source of outflow system (Cl = 240 mg/kg).
[k]Very few dates are available for volcanoes of this region.
[l]Boiling in outflow causes some hot springs to be more concentrated than parent fluid.
[m]Temperature is based on chemical geothermometry; maximum drilled temperature is 165°C.
[n]Age of system determined on U-Th disequilibrium dates on calcite veins (F. Goff, unpublished data, 1987).

mal systems having hydrothermal outflow plumes to accent other differences that may exist in heat source, reservoir chemistry, etc. Generally, outflow plumes are best known at geothermal systems that have magmatic heat sources. This fact probably results because the magmatic systems tend to be hotter and have had more exploration and production drilling. The Roosevelt system is an example of a system that may be in part tectonic, whereas the Ojo Caliente, Desert Peak, and Platanares systems are entirely tectonic. The maximum age of systems driven by magmatic heat sources (generally the oldest date of a large volcano or caldera) may be as old as ~1 m.y. (Valles caldera) or as young as 0.04 m.y. (Mount St. Helens). Source reservoir temperatures may exceed 300°C or be <100°C. Reservoir chloride concentrations of the examples in Table 4 vary by more than 2 orders of magnitude and probably vary by several orders of magnitude on a worldwide scale.

Characteristics of outflow plumes associated with geothermal systems display other interesting variations as well. Some plumes in dry climate areas have no associated hot springs downgradient from the source reservoir (Roosevelt Hot Springs and Desert Peak), although most do. Outflow chloride contents can show little dilution with respect to the source reservoir or considerable dilution. At some systems, outflow chloride contents may exceed those in the source reservoir due to subsurface boiling along the outflow plume (i.e., El Tatio). Length of traceable outflow can be as short as 2 km or greater than 20 km. The configuration (or geometry) of outflow plumes most commonly resembles the Roosevelt Hot Springs type (when enough data are available) in which hot fluid leaves the reservoir as a relatively thin, horizontal tongue. This configuration dominates the El Tatio, Waitapu, Mokai, and Long Valley caldera outflow plumes, where hydrothermal fluids enter laterally extensive deposits of layered ignimbrites or other tuffaceous deposits. In contrast, the outflow plume at Bacon-Manito resembles the Valles caldera type, in which hydrothermal fluids are channeled primarily along a major fault zone striking away from the source reservoir and cutting interbedded andesitic flows and pyroclastics [*Tolentino et al.*, 1985]. Two areally distinct hydrothermal plumes occur at Lassen Volcanic Park that each exhibit a combination of fault and stratigraphic control [*Ingebritsen and Sorey*, 1985]. Presumably, configurations other than the Valles and Roosevelt types must occur.

Temperature reversals in geothermal wells are widely considered to be one of the best criteria for recognizing whether or not a well has penetrated an outflow plume [*Healy and Hochstein*, 1973]. Major temperature reversals occur in most of the lateral flow systems listed in Table 4 but do not occur at all systems. At Valles caldera, small temperature reversals occur only near the end of the plume, and no temperature reversals are seen in the wells penetrating the near-source portion of the Roosevelt Hot Springs outflow plume. The magnitude of temperature reversals must depend primarily on the source temperature, flow rate, volume of hydrothermal fluid, and relative age of the system. When a hydrothermal plume first starts, hot water generally flows into relatively cold country rock. As age of the plume increases, the temperature contrast between water and country rock tends to decrease. Increased age of the plume will eventually be associated with decreases in flow rate, in volume of fluid, and in source reservoir temperature, which will further decrease the temperature contrast between water and country rock. Mixing of hot and

cold fluids and configuration of the flow system (i.e., horizontal layer, vertical conduit) also affect the temperature contrast as functions of time. In general, the higher the temperature, larger the flow rate, larger the volume of fluid, and younger the system, the greater probability that there will be major temperature reversals beneath the plume.

Perhaps the least information is known about the absolute age (or "start-up" time) of the outflow system. At Valles caldera, dates on travertine deposits formed at hot springs discharging from the outflow plume indicate an age of about 1 m.y. for initiation of lateral flow, although the dates indicate at least three distinct episodes of deposition [*Goff and Shevenell*, 1987]. *Harrison et al.* [1986] conclude from thermal modeling that the youngest "pulse" of lateral flow in the Valles region is about 10 kyr. Thermal modeling was used by *Hochstein et al.* [1983] to estimate an age of ≤ 140 kyr for the hydrothermal system at Aluto-Langano, Ethiopia. The age of the caldera hosting the geothermal system is ≤ 80 kyr [*Giday*, 1987]. *Blackwell* [1985] has used thermal modeling to estimate ages of 500–600 and 3000 years, respectively, for the two thermal aquifers now comprising the youngest Long Valley lateral flow system. In contrast, *Sorey* [1985] estimates an age of 40 kyr for start-up of the present Long Valley hydrothermal system by examination of the record of saline deposits at Searles Lake. Both authors discuss the complexity of dating various components of the Long Valley hydrothermal system. The hydrothermal system at Mount St. Helens was newly created after the eruptions of 1980, which modified the summit of the mountain and caused emplacement of a central dacitic dome and plug. A lateral flow system apparently discharges in permeable pyroclastic deposits and lava flows in the breached area on the northeast crater wall (F. Goff and L. Shevenell, unpublished data, 1985–1987). The ephemeral nature of hot springs and hydrothermal systems in the geologic record makes it difficult to directly assess the maximum age of an outflow plume unless hot spring deposits or some other deposit clearly linked to the outflow system can be dated. Analysis of transients in thermal gradient logs is valuable in estimating the age of an existing horizontal flow system [*Ziagos and Blackwell*, 1981, 1986]. However, transient analysis is probably not capable of estimating the maximum age of a hydrothermal plume system that has responded through time to repeated pulses of magmatic, seismic, and hydrothermal activity.

CONCLUSIONS

The basic requirements for creation of a hydrothermal outflow plume are convective upflow above a deep source reservoir and lateral flow into a permeable conduit or layer adjacent to or above the region of upflow. Existence of outflow plumes is not dependent on type of heat source, tectonic setting, age, reservoir temperature, or other parameters usually used to assess and compare geothermal systems (Table 4). Hydrothermal plumes commonly display temperature reversals in wells that penetrate the flow system, but reversals are not universally observed in all systems. The magnitude of temperature reversals in a given plume depends on age of the system, source reservoir temperature, volume and flow rate of thermal fluids, geometry of rock units and faults, and mixing history with cooler waters.

Core hole VC-1 verifies the existence of the Valles hydrothermal outflow plume through hydrogeochemical data from the aquifers sampled. When combined with various geologic, geophysical, and geochemical data for the southwestern caldera region, the wells and hot springs show that the Valles outflow is complex in detail, having at least two major sources of reservoir fluids (Redondo Creek and Sulphur Springs areas) and many dilute fluids involved in mixing. Discharge rates, thermal gradient profiles, relative heat flow estimates, and mixing relationships indicate that 25–50% of the lateral flow is channeled along vertical conduits associated with and adjacent to the Jemez fault zone, even though this zone comprises not more than 10% of the area affected by the lateral flow system. Subordinate flow occurs in horizontal, semipermeable Paleozoic strata above the contact with Precambrian crystalline rocks distributed for several kilometers on either side of the fault zone. Flow paths along the Jemez fault zone must be partly distinct and unconnected to produce the unique variations observed in temperature, bulk chemistry, and isotopic composition of individual springs and aquifers.

The Valles caldera and Roosevelt Hot Springs outflow plumes have similar chemical and isotopic variations but are contrasted herein because of their geohydrologic differences. The Valles outflow geometry is dominated by a belt of vertical conduits striking away from the source of convective upflow, whereas the Roosevelt outflow geometry consists primarily of a permeable, horizontal layer that overlies the source reservoir. Other systems, such as those listed in Table 4, fall into either the Valles or Roosevelt categories or into some intermediate type.

Hydrothermal outflow plumes can be long-lived features (~ 1.0 m.y. at Valles caldera) but can evolve rapidly after magmatic and tectonic perturbations (≤ 5 years at Mount St. Helens). Although geochemistry, geophysics, and temperature gradient wells can individually suggest the presence of hydrothermal outflow from a geothermal system, all three methods in combination with basic geology are needed to clearly define the geometry of the outflow plume and the evolution of fluids within the plume.

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J. N. Gardner, F. Goff, C. O. Grigsby, and L. Shevenell, ESS-1, MS D462, Los Alamos National Laboratory, Los Alamos, NM 87545.

F.-D. Vuataz, Institute Mixte de Recherches Géothermiques, BRGM, BP 6009, 45060 Orléans, Cedex 2, France.

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