Conductive Heat Flux in VC-1 and the Thermal Regime of Valles Caldera, Jemez Mountains, New Mexico

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Over 5% of heat in the western United States is lost through Quaternary silicic volcanic centers, including the Valles caldera in north central New Mexico. These centers are the sites of major hydrothermal activity and upper crustal metamorphism, metasomatism, and mineralization, producing associated geothermal resources. We present new heat flow data from Valles caldera core hole 1 (VC-1), drilled in the southwestern margin of the Valles caldera. Thermal conductivities were measured on 55 segments of core from VC-1, waxed and wrapped to preserve fluids. These values were combined with temperature gradient data to calculate heat flow. Above 335 m, which is probably unsaturated, heat flow is 247 ± 16 mW m^{-2}. The only deep temperature information available is from an uncalibrated commercial log made 19 months after drilling. Gradients, derived from uncalibrated temperature logs, and conductivities are inversely correlated between 335 and 737 m, indicating a conductive thermal regime, and component heat fluxes over three depth intervals (335–539 m, 549–628 m, and 628–737 m) are in excellent agreement with each other with an average of 504 ± 15 mW m^{-2}. Temperature logs to 518 m depth with well-calibrated temperature sensors result in a revised heat flow of 463 ± 15 mW m. We use shallow thermal gradient data from 75 other sites in and around the caldera to interpret the thermal regime at the VC-1 site. A critical review of published thermal conductivity data from the Valles caldera yields an average thermal conductivity of ≥ 1 W m^{-1} K^{-1} for the near-surface tuffaceous material, and we assume that shallow gradient values (°C km^{-1}) are approximately numerically equal to heat flow (mW m^{-2}). Heat loss from the caldera is asymmetrically distributed, with higher values (400 mW m^{-2} or higher) concentrated in the west-southwestern quadrant of the caldera. This quadrant also contains the main drainage from the caldera and the youngest volcanism associated with the caldera. We interpret the shallow thermal gradient data and the thermal regime at VC-1 to indicate a long-lived hydrothermal (and magmatic) system in the sothwestern Valles caldera that has been maintained through the generation of shallow magma bodies during the long postcollapse history of the caldera. High heat flow at the VC-1 site is interpreted to result from hot water circulating below the base of the core hole, and we attribute the lower heat flow in the unsaturated zone to hydrologic recharge.

INTRODUCTION

A significant fraction of the heat loss in regions of young tectonic activity is associated with upper crustal magmatism. For example, *Blackwell* [1978] estimates that approximately 5% of the heat loss from the western United States is associated with the Quaternary Yellowstone caldera (see also *Morgan et al.* [1977], *Lachenbruch and Sass* [1977], and *Blackwell et al.* [1986]). Similar, slightly older and smaller silicic thermal systems are associated with the Long Valley caldera in eastern California [*Lachenbruch et al.*, 1976a, b; *Blackwell*, 1985; *Sorey*, 1985] and the Valles caldera in the Jemez Mountains of north central New Mexico [*Kolstad and McGetchin*, 1978; *Laughlin*, 1981; *Heiken and Goff*, 1983]. The thermal characteristics of these systems are important because they represent a major portion of the local thermal budget associated with tectonism, they are the sites of major hydrothermal activity and upper crustal metamorphism, metasomatism, and mineralization, and they are associated with geothermal resources. In this contribution we focus upon the thermal regime of the Valles caldera.

The Valles caldera (Figure 1) is a major silicic igneous center on the western margin of the Neogene Rio Grande rift

and has been the site of essentially continuous igneous activity since 13 Ma [*Gardner and Goff*, 1984]. Major caldera collapse events occurred at 1.4 and 1.1 Ma [*Laughlin et al.*, 1983; *Heiken et al.*, 1986; *Self et al.*, 1986] associated with voluminous (600 km³) eruptions of silicic ash flow tuffs [*Gardner and Goff*, 1984]. Volcanism during the past 1 m.y. has been restricted to the Valles rhyolite, which has formed domes extruded along the ring fractures of the Valles caldera and caused growth of Redondo Peak, a large resurgent structural dome in the caldera [*Smith and Bailey*, 1968]. The youngest unit of the Valles rhyolite is the Banco Bonito obsidian, which was erupted at 0.13 ± 0.10 Ma on the southwestern margin of the caldera [*Marvin and Dobson*, 1979].

The Valles caldera lies on the western margin of a zone of high heat flow associated with the Rio Grande rift (Figure 2). *Reiter et al.* [1976] presented temperature data from 13 drill tests around the Valles caldera with heat flow estimates from four of the sites (Figure 2). These observations suggested a relatively shallow (upper crustal) heat source located beneath the western part of the caldera. Temperature data from a deep geothermal research well (GT-2) at Fenton Hill, approximately 1 km outside the western margin of the caldera (Figure 1), were used by *Kolstad and McGetchin* [1978] to constrain a two-dimensional finite element heat conduction model of the thermal evolution of the caldera, consistent with major crustal heating associated with the last
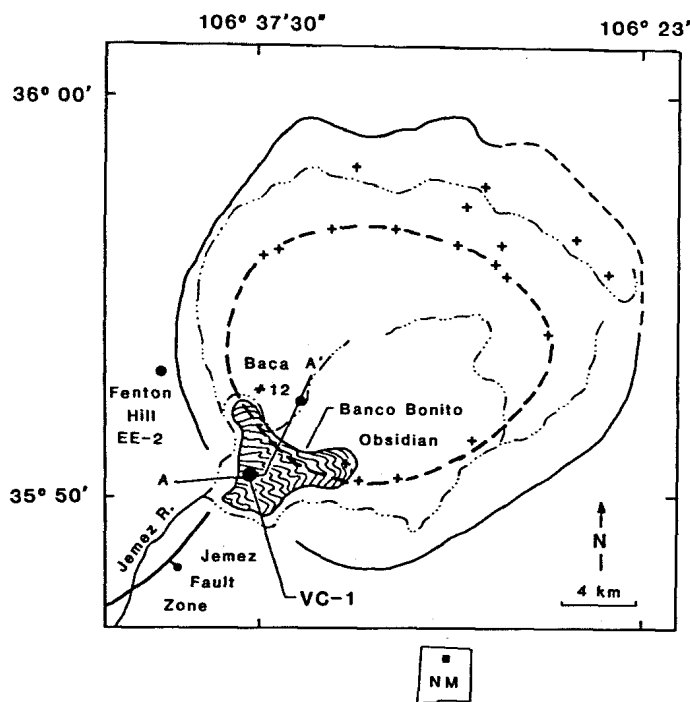
Fig. 1 Location map of the Valles caldera and the VC-1 core hole. Wavy pattern shows Banco Bonito obsidian flow, pluses denote intracaldera rhyolite vents, heavy dashed line shows the inferred position of the Valles ring fracture zone, outer irregular circle shows topographic rim of caldera, and dash-dot lines show main surface drainage within the caldera. Also shown are the locations of deep well Baca 12 and the Fenton Hill site where three wells discussed in the text, GT-2, EE-2, and EE-1, are located (modified from *Goff et al.* [1986]).

caldera collapse event (1.0–1.1 Ma). However, new thermal data and interpretations and $^{40}Ar/^{39}Ar$ age spectra from core samples at this site suggest a heating age of less than 40 ka, probably related to a very young magmatic and/or hydrothermal event in the western segment of the caldera [*Harrison et al.*, 1986]. Temperature data from a number of shallow thermal gradient wells drilled in and around the caldera for geothermal exploration have been used to extrapolate subsurface isotherms for most of the caldera [*Swanberg and Li*, 1982; *Tomczyk and Morgan*, 1987], and these analyses, together with temperature data from deep geothermal test wells within the caldera [*Dondanville*, 1978] indicate the importance of hydrothermal processes at depths less than 2 km within the caldera.

Relatively well-constrained heat flow data from the Valles caldera have been lacking in previous studies. The drilling of Valles caldera 1 (VC-1) has allowed us to collect new temperature and thermal conductivity data which are used to calculate heat flow for the Valles caldera presented and discussed in this contribution. The conductivity data from the core hole are used to estimate heat flow at other sites from which only temperature data are available. We use the thermal structure derived from the new VC-1 data and published thermal data to construct subsurface isotherms and to make an interpretation of the thermal regime of the southwestern Valles caldera.

HEAT FLOW DATA FOR VC-1

Valles caldera core hole 1 (VC-1) was drilled in the southwestern margin of the Valles caldera (Figure 1) to a total depth of 856 m in August and September 1984. The lithologies penetrated by VC-1 with respect to caldera struc-

ture and lithologies penetrated by nearby deep geothermal tests are shown in Figure 3. Planning and drilling histories and initial results from VC-1 have been given by *Goff* [1985] and *Goff et al.* [1985, 1986].

Temperature Data

Seven temperature logs were obtained from VC-1. Four logs were run by Southwest Surveys, a commercial logging contractor. Three of these logs are shown in Figure 4. The fourth log, obtained on August 28, 1986, extends only to 530 m. The well was perforated at about that depth prior to this log and the casing was bridged, so that subsequent access to the lower part of the hole was not possible). The fourth log is virtually identical to the third commercial log (May 1986 on Figure 4). The fifth log was made by Drilling Office personnel from the Sandia National Laboratory, New Mexico, on September 9, 1986, to 518 m. A sixth log was obtained in May 1987 and is essentially identical to the September 1986 log (R. Meyer, personal communication, May 1987). A final log to a depth of 450 m, made on September 5, 1987, using a thermistor based system of the U.S. Geological Survey, confirmed the accuracy of the Sandia logs.

Below 310 m, there is a substantial divergence in gradient between Sandia's and Southwest's logs (Figure 5). We have no information on Southwest's calibration procedures but the positive shift to higher temperatures below 310 m in the August 28 log suggests some kind of instrument malfunction. Commercial temperature logs often yield unreliable absolute temperature as these instruments are rarely calibrated, as their temperature data are normally collected only for temperature corrections to other logs (e.g., resistivity) or to locate thermal pulses associated with cementation. The Sandia log was made with a platinum resistance temperature transducer (RTD) with a four-wire connection to a digital voltmeter (DVM) at the surface (R. Jacobson, personal communication, February 1987). The calibration of such devices is usually very stable. The Sandia log was run as an instrument test rather than as a data gathering exercise; however, when the discrepancy between the two logs was noted, Sandia recalibrated its RTD and found no calibration error (P. Lysne, personal communication, February 1987). Electrical leakage in the Sandia cable head could account for the lower temperatures of the September 9 log if the leakage was systematic and temperature-dependent and produced no erratic readings. The facts that the hole has been relogged with the same probe (May 1987) and that the September log is not significantly different from the later May 1987 log makes this an extremely remote possibility. Our final log (September 1987) confirms that the Sandia logging equipment did not malfunction, and we have used the Sandia data for our best estimate of heat flow in VC-1.

Thermal Conductivity Data

Sections of core from VC-1, each about 0.3 m long, were wrapped and waxed at the site in an attempt to preserve in situ fluids. Samples were taken at intervals of about 3 m (10 feet) resulting in a set of 280 core samples. From this set of waxed cores, 55 samples spaced ~15 m apart (50 feet) were analyzed for pore fluids, thermal conductivity, and other physical properties. Thermal conductivity measurements were performed at the U.S. Geological Survey (USGS) Geothermal Laboratory in Menlo Park, California, and the measurements are described in detail by *Munroe and Sass* [1987]. Depending on the physical state of the core, two
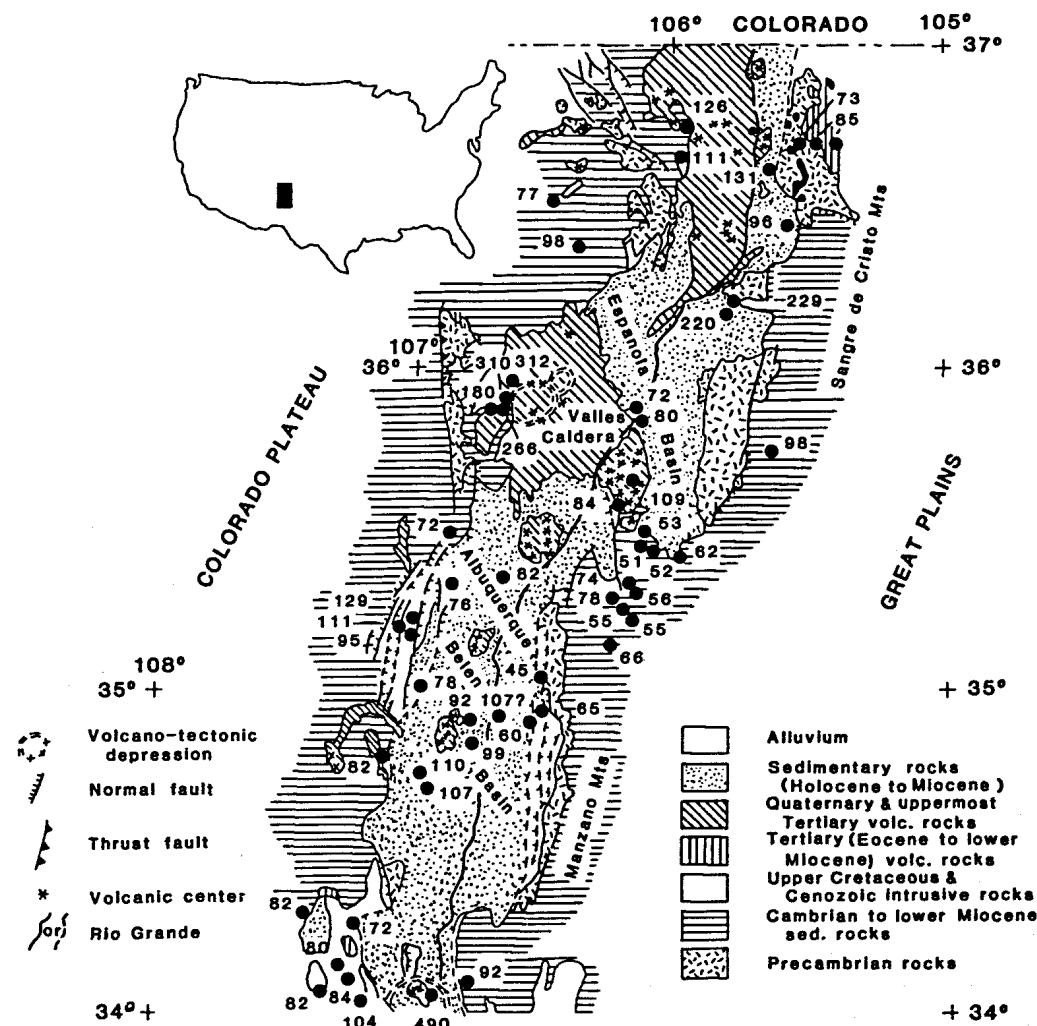
Fig. 2. Heat flow data from the Rio Grande rift in northern New Mexico (modified from *Reiter et al.* [1986]).

methods were used for these measurements. Strong, competent rocks were machined into disks for measurements by the traditional, steady state Birch-type divided-bar apparatus [*Sass et al.*, 1971]. More friable rocks were drilled both parallel and perpendicular to the core axis for measurement using a needle probe (line source) transient heat source method [*Sass et al.*, 1984]. The precision of the two methods is comparable (±5% or better), but an interpretive procedure is required to calculate the vertical component of conductivity of anisotropic rocks when a line source method has been employed [*Grubbe et al.* 1983]. For the vertical VC-1 hole the divided bar apparatus measures the vertical components directly. Postcaldera volcanic rocks in the upper 300 m of VC-1 were thermally isotropic. Below 300 m, the Paleozoic sedimentary rocks encountered were anisotropic. The mean conductivity parallel to bedding is some 20% higher than that perpendicular to bedding [*Munroe and Sass*, 1987].

The vertical components of thermal conductivity for individual samples are summarized in Table 1. The USGS laboratory is not equipped to measure thermal conductivity at elevated temperature on a routine basis. Thus most measurements were performed at or near 25°C. For a few samples of Madera limestone, crude measurements of conductivity at temperatures up to 100°C were made [see *Munroe and Sass*, 1987, Table 1]; the experimental error in these higher-temperature conductivity determinations was greater than that

for room temperature measurements (about ±10-15%), so that the temperature variation of conductivity, which is expected to be of the same magnitude as this error over the temperature range observed in VC-1, is not well characterized.

The high-temperature conductivity determinations are shown in Figure 6 as a percentage of the thermal conductivity at room temperature. For one sample (diamonds, Figure 6) the low relative conductivities suggest that the sample was physically altered by heating. For the other samples there is considerable scatter, but the results are consistent with those of *Birch and Clark* [1940] for either Pennsylvania limestone or Vermont marble. We have used the temperature coefficient of conductivity for Pennsylvania limestone to correct the Madera limestone conductivities measured at room temperature to conductivities at in situ temperatures because the metamorphic grade of the Madera limestone is not sufficiently high for it to be classified as marble. We used the same temperature coefficient to correct conductivities of the Abo formation which is largely arkosic sandstone. This was justified because these coefficients apply equally well to rocks of granitic composition [*Birch and Clark*, 1940].

Heat Flow at VC-1

Despite the discrepancies between the commercial (Southwest) log of May 1986 and the Sandia log and the likelihood that the May log was in error, we have estimated heat flow
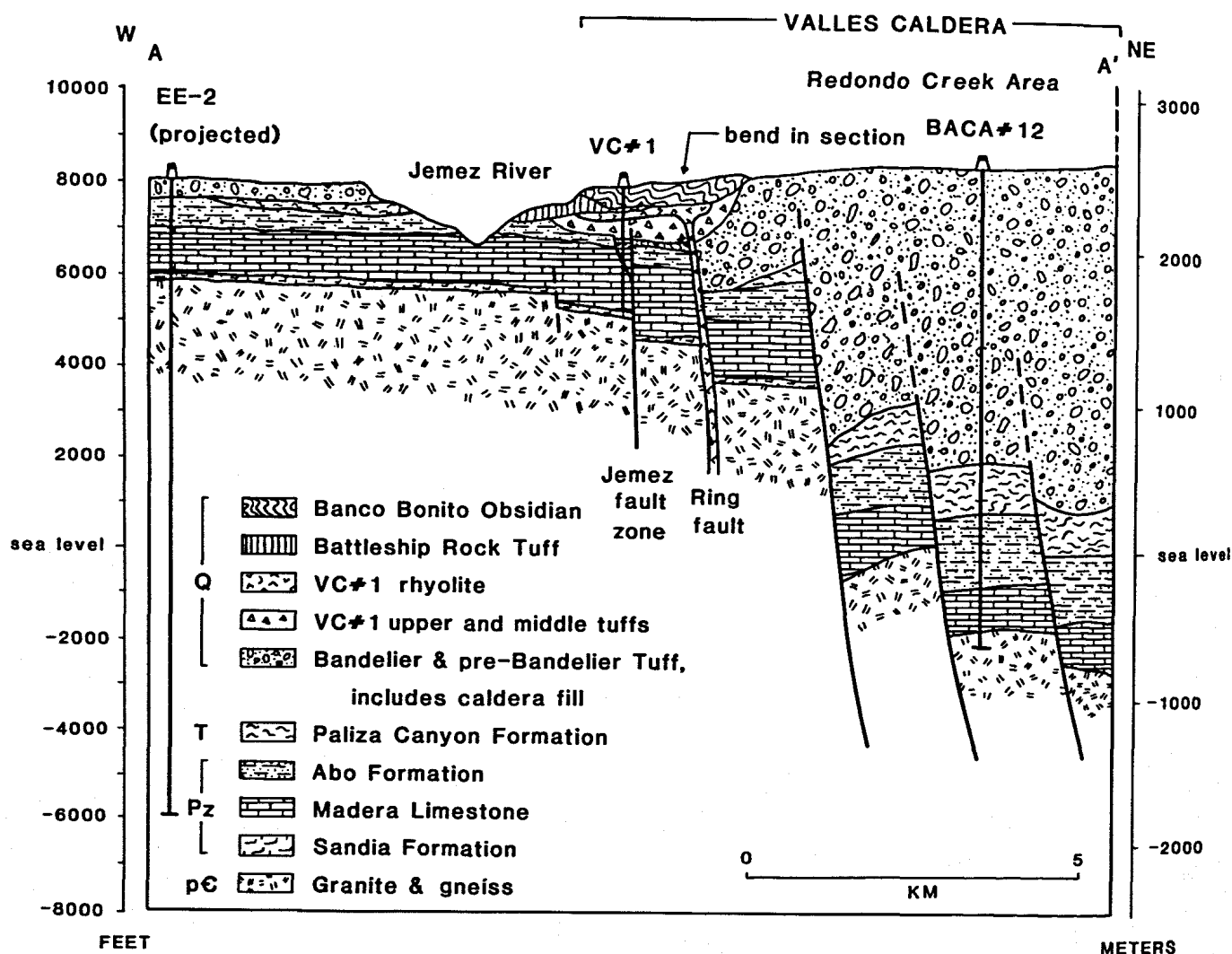
Fig. 3.   Schematic cross section of the southwestern Valles caldera showing stratigraphy, structure, and relative well locations. Position of section is shown by line A-A' in Figure 1 (modified from *Goff et al.* [1986]). Q, Quaternary; T, Tertiary; PZ, Paleozoic; Pℂ, Precambrian.
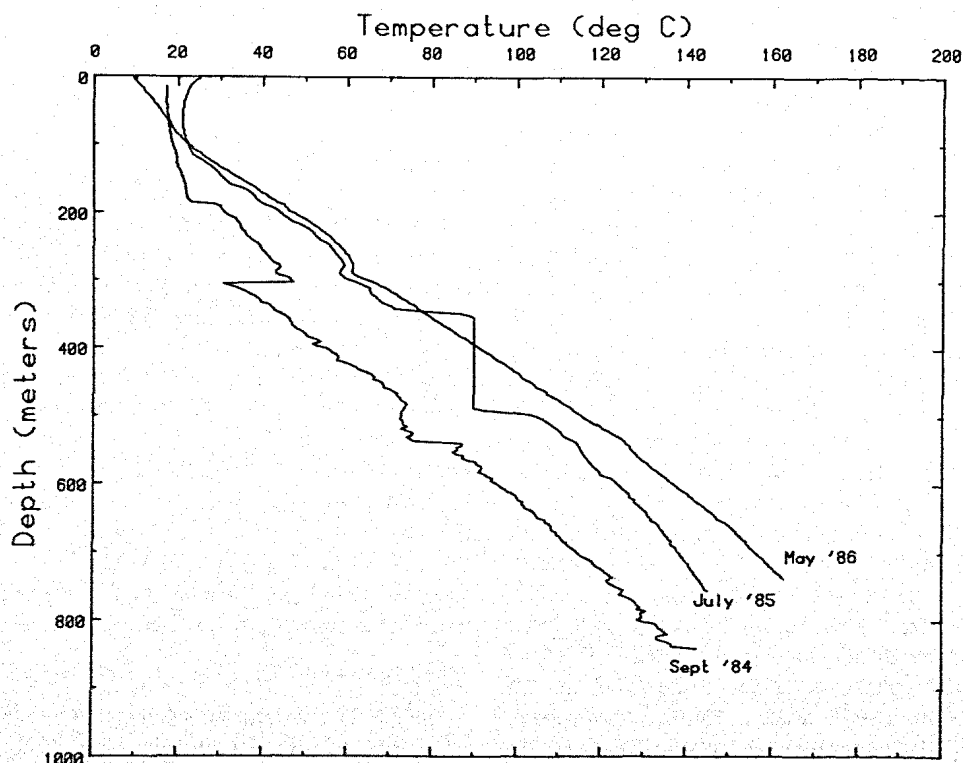

Fig. 4.   Temperature profiles obtained by Southwest Surveys in VC-1. Offsets in log of September 1984 and isothermal zone in log of July 1985 are thought to be instrumental in origin (see text).
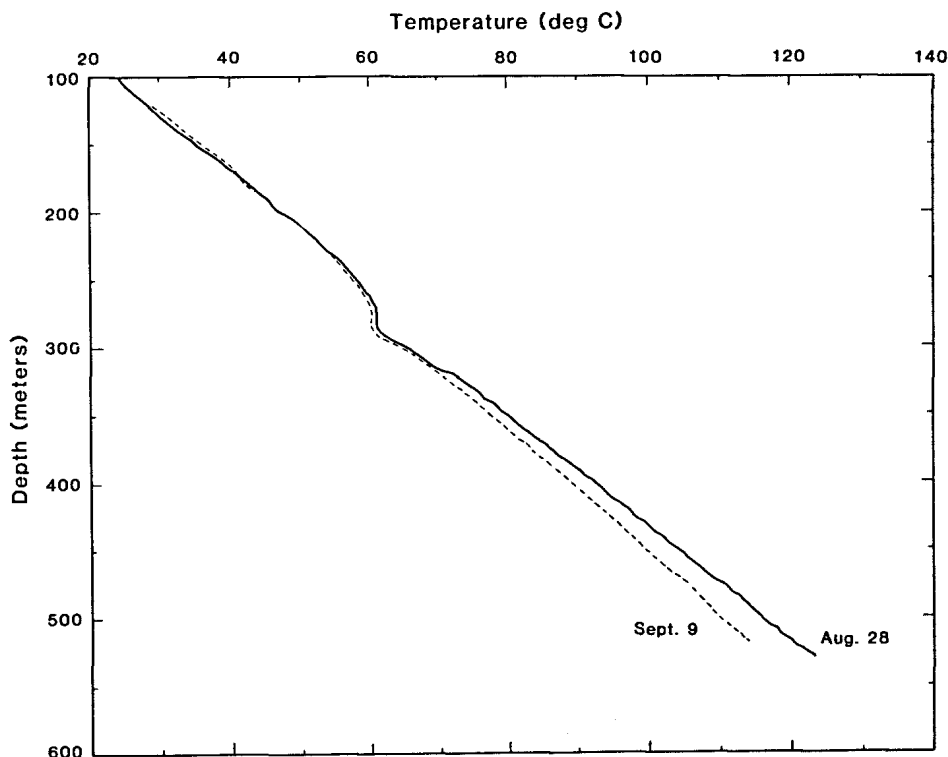
Fig. 5. Temperature profiles obtained by Southwest Surveys (August 28) and Sandia National Laboratory (September 9) in VC-1.

from the May log because it is the only one for which at total depth, temperatures approach equilibrium. Above the water table, there is a linear segment of the temperature profile corresponding to the VC-1 Tuffs. Calculation of heat flow over this interval yields a value of 247 $\pm$ 16 mW m^{-2} (Table 2). Below 335 m, component heat flows are in good agreement, with range of 482–525 and mean (weighted for length of interval) of 504 $\pm$ 15 mW m^{-2} (Table 2). The disagreement between heat flow in the unsaturated zone and that below the water table may be explained in a number of ways: (1) Logging speed was about 0.17 m s^{-1} (2000 feet h^1) (this speed is acceptable in a water-filled hole for most state-of-the-art temperature transducers, but it introduces a substantial temperature lag in air), (2) the effect of recharge in the unsaturated zone would be to lower the observed heat flux above the water table, and (3) two-phase fluid movement in the unsaturated zone could also lower the observed heat flux, although there is no direct evidence to support this latter hypothesis. If we assume that the Sandia log of September 9, 1986 (Figure 5), is correct, we may recalculate heat flow for the uppermost interval of the saturated zone. In this case, the least squares gradient is 217.5 $\pm$ 0.08 °C km^{-1}, and the resulting heat flow is 463 $\pm$ 15 mW m^{-2}.

From the rough inverse correlation between gradient and thermal conductivities (Figure 7) and the resulting agreement among component heat flows below the water table (Table 2) we may conclude that the thermal regime of VC-1 is indeed conductive. Owing to the apparent systematic error in temperature gradient in the May 13 log, we adopt the rounded value of 460 mW m^{-2}, based on the latest Sandia log, as the most plausible value of heat flow for the VC-1 site.

HEAT FLOW AT OTHER SITES IN AND AROUND VALLES CALDERA

Published contour maps of the thermal gradient data from the Valles caldera give a useful indication of the distribution of heat loss from the caldera [e.g., *Swanberg and Li*, 1982; *Tomczyk and Morgan*, 1987]. However, quantitative analyses of the thermal regime of the caldera cannot be made without converting these gradients to heat flow. We have therefore compiled all published thermal conductivity data for the Valles caldera and used these data and the VC-1 data to estimate heat flux at the published thermal gradient sites in and around the caldera.

Thermal Conductivity Data

Thermal conductivity data for the Valles caldera are available from three published sources, and these data are summarized in Tables 1 and 3. Conductivity data from VC-1 (Table 1) [*Munroe and Sass*, 1987] are discussed above. *Reiter et al.* [1976] report data from four sites in Pleistocene Bandelier Tuff on the western flank of the Valles caldera (Table 3). These conductivities are generally higher than conductivities for comparable lithologies reported for VC-1, and reported conductivity changes with depth in the holes are not complemented by gradient changes, indicating variations in conductive vertical heat flow with depth and/or errors in the conductivity values. As the conductivities were generally based upon estimated porosity corrections, the VC-1 data are preferred. *Sibbitt et al.* [1979] report conductivities as a function of temperature for Precambrian basement samples from two sites on the western flank of the caldera, and with the exception of the deepest samples from GT-2 (Table 3), for which conductivities perpendicular to the core axis were reported for samples that may be anisotropic, the values should be useful for heat flow estimates from basement gradients.

Temperature Gradient Data

To place the VC-1 temperature data in context, we have plotted these data on a graph with data from EE-3 at Fenton Hill (wells GT-2, EE-2, and EE-3 are all at the Fenton Hill

TABLE 1. Vertical Component of Thermal Conductivity of 48 Waxed Core Samples From Borehole VC-1, Valles Caldera, New Mexico

Stratigraphic Unit and Lithology*	Depth, m	Conductivity K, W m^{-1} K^{-1}	In Situ Temperature, °C	Corrected K, W m^{-1} K^{-1}	Method†
Banco Bonito Obsidian	14.4	0.96	11	0.96	np
	29.6	1.09	13	1.09	np
	47.7	1.16	14	1.16	np
	60.6	1.53	17	1.53	np
	79.7	1.93	19	1.93	db
	91.9	1.58	21	1.58	np
	105.7	1.91	24	1.91	db
	119.8	1.26	26	1.26	np
Battleship Rock Tuff	153.8	0.78	35	0.78	np
VC-1 Rhyolite	170.4	1.18	39	1.18	np
Upper VC-1 Tuff	182.5	0.96	43	0.96	np
	201.9	0.84	47	0.84	np
Middle VC-1 Tuff	214.2	1.02	51	1.02	np
	231.2	1.11	55	1.11	np
	245.6	1.22	57	1.22	np
	258.0	1.24	60	1.27	np
	276.2	1.12	61	1.12	np
	289.8	1.03	61	1.03	np
Volcaniclastic Breccia	304.5	1.62	67	1.62	np
	318.8	1.84	71	1.84	np
Abo Formation	335.0	3.27	76	2.92	db
	348.6	2.11	79	1.98	np
	364.8	2.06	83	1.92	np
	383.8	1.99	88	1.85	np
	395.6	2.16	91	2.00	np
	411.6	2.18	94	2.01	np
Madera Limestone	425.0	2.76	97	2.53	np
	444.1	2.28	102	2.08	np
	456.1	2.52	105	2.29	np
	477.8	2.54	111	2.30	np
	515.8	2.73	120	2.44	np
	532.4	2.53	125	2.25	np
	551.6	2.28	128	2.02	np
	568.8	2.28	131	2.02	np
	581.6	3.06	133	2.70	np
	504.0	2.97	136	2.61	np
	608.0	2.58	139	2.26	np
	626.9	3.04	143	2.65	np
	639.4	3.11	146	2.71	np
	653.0	3.15	148	2.74	np
	672.5	3.03	152	2.62	np
	684.6	3.10	154	2.67	np
	704.1	3.27	157	2.81	db
	715.5	2.87	159	2.46	np
	732.9	3.57	162	3.05	db
	749.5	3.07	~164	2.62	db
	762.0	3.25	~165	2.77	np
	777.9	4.31	~170	3.66	db

* Designation refers to all depths between it and succeeding designation.
† Method: np, needle probe; db, divided bar.

site), just outside the caldera, and from Baca 12, within the caldera (Figure 8). Locations of these wells are plotted in Figure 1, and lithologies are indicated in Figure 3. Both of these deep logs indicate considerable variation in gradient with depth and differences between the shallow and deeper thermal regimes. The gradient is very high at shallow depths in Baca 12, which is just south of the peak temperature gradient anomaly in the caldera (Figure 9) but decreases with depth. The gradient is relatively high at shallow depths at Fenton Hill but decreases abruptly at the crystalline basement surface and increases with depth within the basement (Figure 8).

Shallow temperature gradient data in and around the Valles caldera are available from geothermal test and exploration wells. The locations of these wells are shown in Figure 9, and the pertinent thermal data are given by *Tomczyk and*

Morgan [1987]. Reasonably linear temperature profiles were obtained in most of these wells in the depth range 23–76 m (75–250 feet), and contours of these gradients for the central and western portions of the caldera are also given by *Tomczyk and Morgan* [1987, Figure 2]. These shallow temperature gradients range from 19 to 620 °C km^{-1} and indicate a very pronounced westward displacement of the peak gradients from the center of the caldera. Shallow gradient data from all the wells are contoured in Figure 9.

Heat Flow Estimates

Accurate thermal conductivity determinations local to each gradient site are needed for precise heat flow determinations. Lateral variations in thermal conductivity are expected within formations, especially in association with
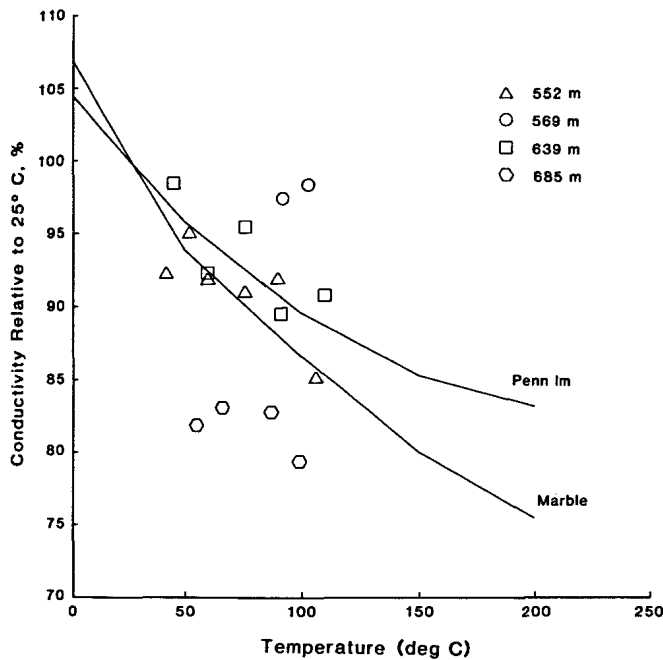
Fig. 6. Relative thermal conductivity of the Madera limestone as a function of temperature. Reference lines are from *Birch and Clark* [1940] for Pennsylvania limestone (Penn lm) and Vermont marble (marble).

variations in composition and degree of welding in the proximal and distal portions of the ash flow units and in association with hydrothermal alteration of local areas. Lacking this information, we use a mean shallow conductivity for all units with which to estimate the shallow heat flow field. As most of the shallow gradient sites are represented

TABLE 2. Heat Flow Parameters for VC-1

Depth Range, m	Gradient, °C km^{-1}	n^*	K,† W m^{-1} K^{-1}	Heat, Flow, mW m^{-2}
128–229	257 ± 1	6	0.96 ± 0.06	247 ± 16
335–530	246.6 ± 0.6	11	2.13 ± 0.06	525 ± 16
549–628	206.1 ± 1.4	6	2.11 ± 0.12	482 ± 30
628–737	173.9 ± 1.8	11	2.77 ± 0.08	482 ± 19
335–737				504 ± 15‡

* n = is number of thermal conductivity measurements.
† K is harmonic mean thermal conductivity.
‡ Weighted mean.

by tuff lithologies [see *Smith et al.* 1970], we have taken a mean conductivity of the tuff units measured by *Munroe and Sass* [1987]. The mean conductivity of the Battleship Rock, upper and middle VC-1 tuffs is 1.02 ± 0.18 W m^{-1} K^{-1} (n = 9). Heat flow values have been computed using this conductivity and from the thermal gradient data given by *Tomczyk and Morgan* [1987]. This conductivity is probably a minimum estimate for many of the sites [cf. *Reiter et al.*, 1976], and thus heat flow values are considered to be minimum estimates and may be locally low by as much as a factor of 2. However, without detailed thermal conductivity data it is convenient to assume a uniform shallow thermal conductivity of 1 W m^{-1} K^{-1} giving a numerical equality between gradient (in °C km^{-1}) and heat flow (in mW m^{-2}). Estimated shallow heat flow varies from 19 mW m^{-2} on the eastern flank of the caldera to 635 mW m^{-2} about 1 km inside the western rim of the caldera, and the shallow gradient data contoured in Figure 9 are numerically equivalent to our shallow heat flow estimates.
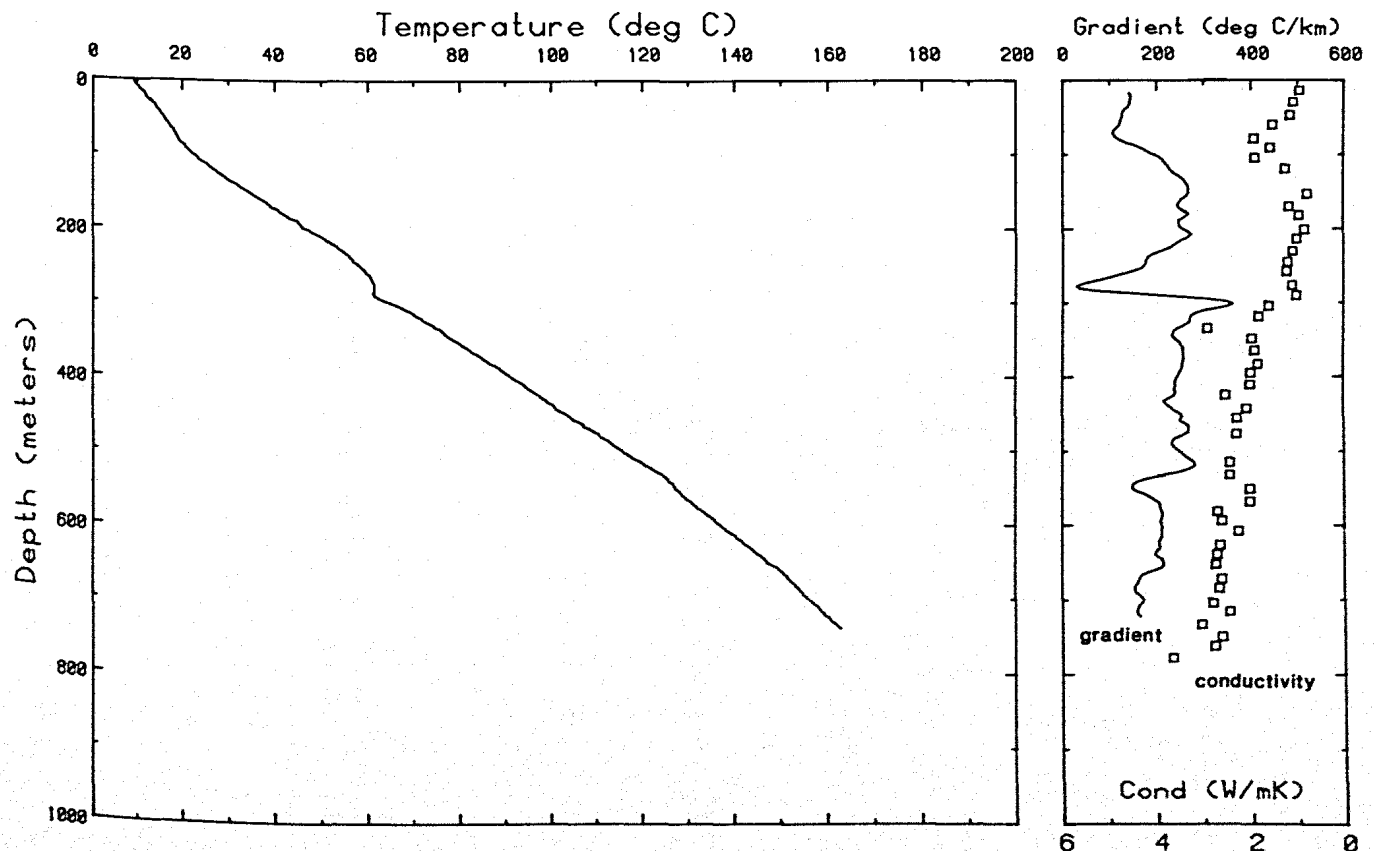

Fig. 7. Temperature profile in VC-1 on May 13, 1986, with thermal gradient and conductivity profiles.

TABLE 3. Published Thermal Conductivity Data From Sites on the Western Flank of the Valles Caldera

Site	Lithology	Temperature, °C	Depth, m	n^*	Conductivity, W m^{-1} K^{-1}	Comments†	Source‡
Hole A	Bandelier Tuff		70–110	2	2.18	1,2	R+76
			120–170	2	2.06	1,2	R+76
Hole B	Bandelier Tuff		40–110	3	1.14	1,2	R+76
			110–140	1	1.77	1,2	R+76
			140–160	1	2.10	1,2	R+76
Hole C	Bandelier Tuff		60–90	3	1.38	1,2	R+76
			90–150	7	1.67	3	R+76
			150–210	3	2.21	4	R+76
Hole D	Bandelier Tuff		20–60	2	1.79	1,2	R+76
			70–140	3	2.35	4	R+76
Barley Canyon, GT-1	granite, adamellite	25	745	1	3.29	5	S+79
		100			2.95		
		150			2.76		
		200			2.62		
		250			2.48		
	gneissic granite, adamellite	25	758	1	2.87	5	S+79
		100			2.63		
		150			2.50		
		200			2.40		
		250			2.31		
	gneissic biotite-granodiorite	25	766	1	2.87	5	S+79
		100			2.63		
		150			2.49		
		200			2.38		
		250			2.28		
	biotite-amphibolite	25	769	1	2.42	5	S+79
		100			2.30		
		150			2.24		
		200			2.18		
		250			2.14		
	biotite-amphibolite	25	778	1	2.21	5	S+79
		100			2.11		
		150			2.05		
		200			1.99		
		250			1.95		
	biotite-amphibolite	25	783	1	2.35	5	S+79
		100			2.24		
		150			2.18		
		200			2.12		
		250			2.08		
Fenton Hill, GT-2	leucocratic monozogranite gneiss	25	786	1	3.62	5	S+79
		100			3.21		
		150			3.00		
		200			2.82		
		250			2.68		
	leucocratic monozogranite gneiss	25	1499	1	3.62	5	S+79
		100			3.21		
		150			2.98		
		200			2.80		
		250			2.65		
	anphibolite	25	1818	1	2.80	5	S+79
		100			2.57		
		150			2.44		
		200			2.34		
		250			2.26		
	leucocratic granodiorite gneiss	25	1875	2	3.30	5	S+79
		100			2.96		
		150			2.79		
		200			2.65		
		250			2.54		
	granodiorite gneiss	25	1876	1	2.87	5	S+79
		100			2.63		
		150			2.50		
		200			2.39		
		250			2.29		
	biotite granodiorite	25	2615	1	3.02	6	S+79
		100			2.85		
		150			2.75		
		200			2.66		
		250			2.60		

TABLE 3. (continued)

Site	Lithology	Temperature, °C	Depth, m	n*	Conductivity, W m^{-1} K^{-1}	Comments†	Source‡
	biotite granodiorite gneiss	25	2929	1	3.0₁	6	S+79
		100			2.73		
		150			2.59		
		200			2.47		
		250			2.38		

* n is number of samples.

† Comments: 1, fragment samples (method of Sass et al. [1971]); 2, conductivity corrected for estimated porosity; 3, average of five fragment samples with estimated porosity correction and two saturated core samples (method described by Sass et al. [1971]); 4, average of two fragment samples with estimated porosity correction and one saturated core sample; 5, core samples measured by divided bar method (described by Sass et al. [1971]), parallel to core axis; 6, core samples measured by needle probe [Sass et al., 1984], perpendicular to core axis.

‡ Sources: R+76, Reiter et al. [1976]; S+79, Sibbitt et al. [1979].

Deeper temperature gradient data from the Baca 12 and Fenton Hill sites indicate changes in conductive heat flow with depth. At the Baca 12 site the gradient between 30 and 300 m is approximately 315 °C km^{-1} but decreases by an order of magnitude to approximately 30 °C km^{-1} in the lower half of the hole. This large gradient change cannot be explained in terms of a conductivity variation with depth and, in accordance with the high temperatures encountered at this site and the geothermal tests, must result from upward convection of hydrothermal fluids within the Valles caldera (Baca) geothermal system.

Heat flow at the Fenton Hill site has been extensively discussed by Harrison et al. [1986]. Gradient variations with depth at this site are not as great as at the Baca 12 site and are in part compensated by conductivity variations. For example, at Fenton Hill the gradient drops from about 100 °C km^{-1} in the Phanerozoic sediments and volcanics above 730 m to about 30 °C km^{-1} in the uppermost section of the Precambrian basement, with a corresponding decrease in thermal conductivity of about a factor of 2 (Tables 1 and 3).

Thus a significant fraction of the gradient change is attributable to thermal conductivity structure, but a variation in vertical heat flow is also indicated. The most likely mechanism for this vertical variation is lateral transfer of heat by water flow on the Precambrian basement surface. The gradient increases with depth to about 95 °C km^{-1} at 4.35 km (Figure 8), and again, although there is a corresponding decrease of up to 30% in thermal conductivity (Table 3 and Harrison et al. [1986], the gradient increase cannot be explained completely by conductivity variations. The vertical component of conductive heat flow increases by a factor of about 2 with depth in the Precambrian basement. Some of this increase may be associated with lateral heat flow from the caldera, apparent in the data because of deviation of the wells toward the caldera: However, as interpreted by Harrison et al. [1986], the curvature of the geotherm (Figure 8) and ^{40}Ar/^{39}Ar age spectra data indicate a transient thermal regime at this site heating at the top of the Precambrian and at the bottom of the well during the last 40 kyear or less.
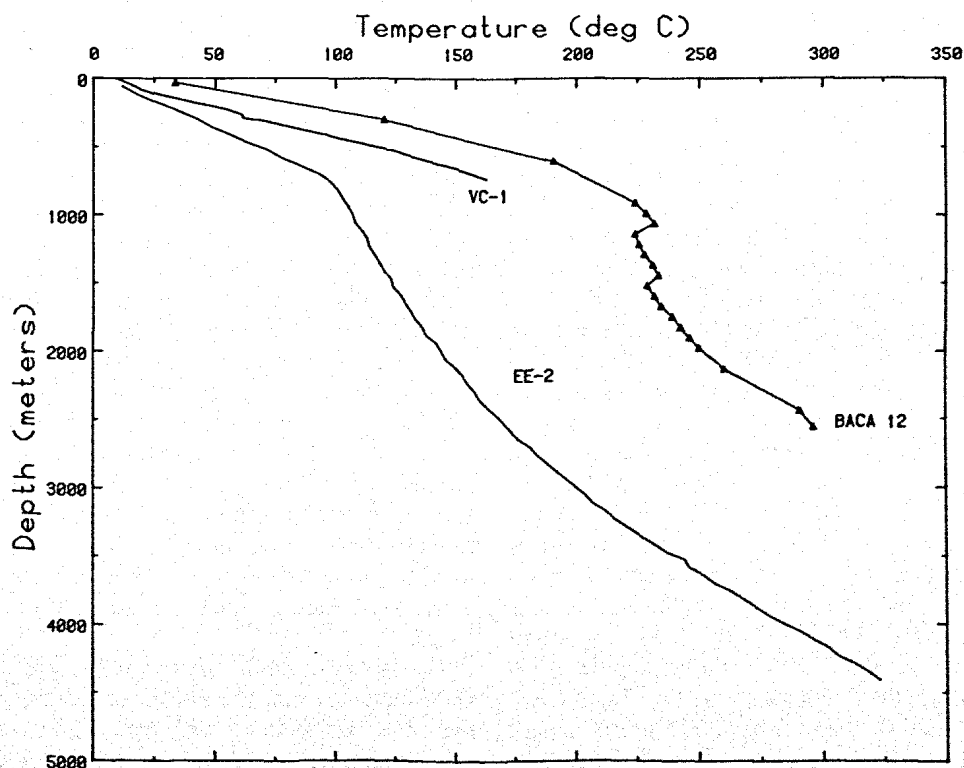

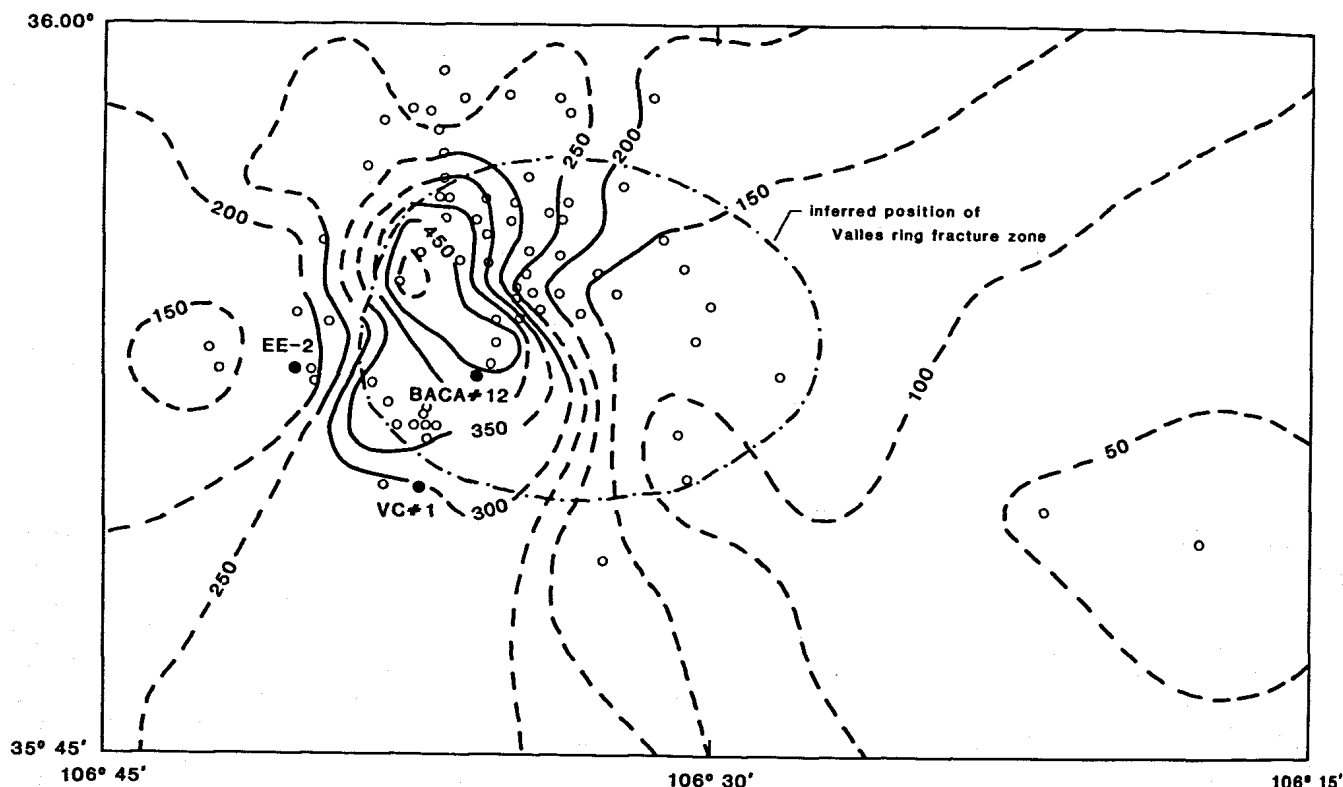Fig. 8. Temperature profiles from EE-2 (Fenton Hill), VC-1, and Baca 12.

Fig. 9. Contour map of shallow temperature gradients (°C km^{-1}) in and around the Valles caldera. Open and solid circles show locations of data points. These gradients are numerically equivalent to the shallow heat flow estimates for the caldera (in mW m^{-2}), assuming a thermal conductivity of 1 W m^{-1} K^{-1} for all the shallow tuffs associated with the caldera. This assumption provides a minimum estimate of condictive heat flow.

THERMAL REGIME OF VALLES CALDERA

As deduced by previous studies [e.g., Kolstad and McGetchin, 1978; Tomczyk and Morgan, 1987], very high heat flow values associated with the Valles caldera, which we estimate to be in excess of 500 mW m^{-2}, or about an order of magnitude above the continental mean, are related to a magmatic heat source associated with the caldera. In an early analysis of the thermal regime of the Valles caldera, Kolstad and McGetchin [1978] interpreted the thermal gradient measured down to 3 km (the maximum depth of the wells at that time at the Fenton Hill site) to be consistent with the conductive cooling of a major magma chamber, larger in diameter than the caldera, and with its top just below 3 km, emplaced at 1.0–1.1 Ma during the most recent caldera-forming event. Using more recent data from Fenton Hill, however, Harrison et al. [1986] have shown that heating at this site is probably a very recent event. In addition, the asymmetric distribution of the surface heat flow relative to the caldera suggests that the heat source is correspondingly asymmetric and/or heat transfer is in part nonconductive (as is confirmed by data from the deeper wells).

New heat flow data from VC-1 presented here indicate higher heat flow at depth than near the surface on the southwestern margin of the caldera, with a break somewhere near the water table but no measurable change in apparent heat flow with depth in the lower section of the hole (504 ± 15 mW m^{-2} between 335 and 737 m from uncalibrated logs or 463 mW m^{-2} from the calibrated September 1986 Sandia log). Over a similar depth range at the Fenton Hill site (data from well EE-3), the geotherm is approximately linear (Figure 8), indicating essentially constant heat flow over the interval. However, heat flow increases below this

depth and appears to be associated with a 40 ka or younger heating event [Harrison et al., 1986].

VC-1 is located in the main surface drainage outflow of the caldera which includes both surface and subsurface flows (Figure 1). The outflow follows Jemez River and is responsible for extensive travertine deposits at Soda Dam, approximately 2 km downstream from VC-1. Goff and Shevenell [1987] interpret age dates from this deposit to indicate essentially continuous subsurface flow of hydrothermal fluids over the past million or so years, or roughly continuous since the last major caldera-forming event. Heat flow data from VC-1 do not indicate groundwater flow below the water table in the formations penetrated by the core hole. We interpret high heat flow at this site to result from heating by a thermal groundwater plume flowing out of the caldera below the base of the core hole. F. Goff (personal communication, 1987) has suggested that this plume may be flowing in brecciated Precambrian Sandia Formation beneath the core hole. If, as seems likely, this flow is part of the Soda Dam hydrothermal system, the hydrothermal heat source for VC-1 has been active continually over the past million years or so and is still active today (see also Goff et al. [this issue]). Homogenization temperatures from secondary fluid inclusions from the VC-1 core indicate that the present temperatures in VC-1 were established when these inclusions were formed, giving additional evidence for a continual heat source at the VC-1 site for an extended period of time [Sasada, this issue].

The 1-m.y. or so history of hydrothermal activity at Soda Dam indicates that the subsurface drainage of the caldera hydrothermal system was established to the southwest shortly after caldera formation [Goff and Shevenell, 1987]. The effect of this drainage must be to transfer heat laterally
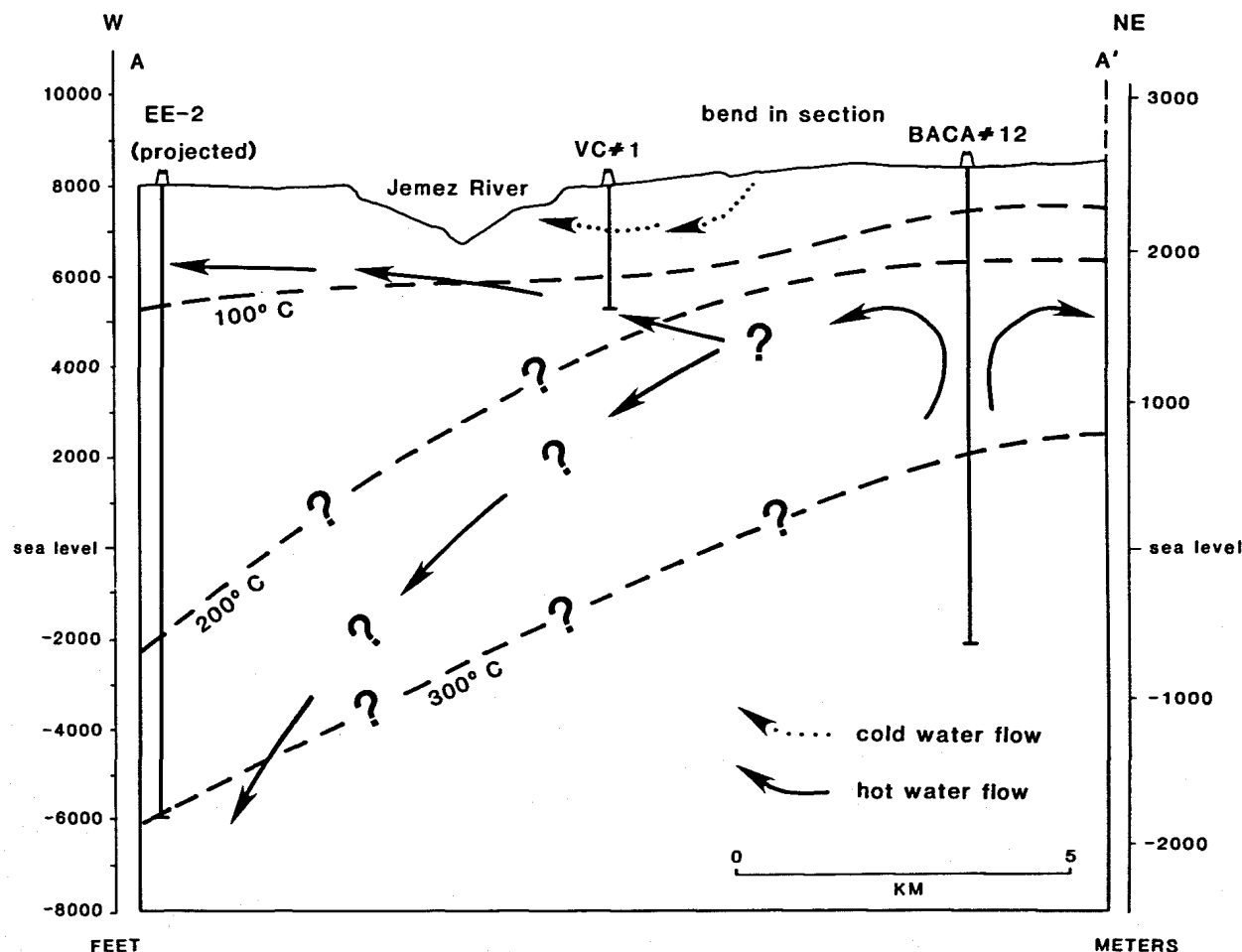
Fig. 10. Schematic cross section of the southwestern Valles caldera showing subsurface flow patterns inferred from thermal regime. Section corresponds to Figure 3. At Baca 12, hot hydrothermal fluids rise or are flowing laterally from the main hydrothermal system. In the upper portion of VC-1, temperatures are suppressed by groundwater recharge. The source of high heat flow at the VC-1 site is subsurface flow from the hydrothermal system below the base of the corehole. High heat flow in the upper section of EE-2 is caused by lateral flow of hydrothermal fluid at a depth of about 730 m. Heating in the lower portion of EE-2 is thought to be caused by deep flow from the hydrothermal system [see *Harrison et al.*, 1986].

to the southwest, and it is likely to be a factor in the asymmetric distribution of near-surface heat flow from the caldera. In the eastern portion of the caldera, stable isotope data indicate that heat flow is suppressed by the downward percolation of cold recharge waters that fill broad valleys of the north and northeast caldera and that supply water to the deep hydrothermal system [*Vuataz and Goff*, 1986; F. Goff, personal communication, 1987]. Very low heat flow to the east of the caldera suggests the effects of a complementary subsurface drainage system outside the caldera to the east, down into the Española Basin of the Rio Grande rift (Figure 2), and that heat from the caldera may be contributing to geothermal anomalies downflow at groundwater constrictions in the rift basins [*Morgan et al.*, 1986]. We lack sufficient constraints upon the hydrology of the Jemez Mountains to make quantitative calculations of the thermal effects of the regional groundwater flow.

Extensive volcanism has occurred in the southwest moat of the Valles caldera during the last 0.5 m.y. (F. Goff, personal communication, 1987), including the 0.13±0.10 Ma Banco Bonito obsidian, which suggests a deep source contributing to the asymmetric near-surface heat flow from the caldera. The large area (approximately 35 km^2) of heat flow

in excess of 400 mW m^{-2} in the western portion of the caldera is inconsistent with pluton conductive-cooling models of the last caldera-forming eruption at 1.0–1.1 Ma [*Kolstad and McGetchin*, 1978], unless it is associated with a transient convection system much younger than the caldera. The long history of deposition at Soda Dam suggests that convective heat loss from the caldera has occurred for at least 1 m.y., perhaps episodically, and high heat flow in the western caldera probably requires recurrent postcaldera magmatic heat sources (cf. discussion of the Long Valley caldera by *Lachenbruch et al.* [1976a]). Thus both the subsurface hydrothermal drainage pattern and young magmatic activity are likely to contribute to the asymmetric heat flow pattern.

Our interpretation of the present hydrothermal regime in the southwestern quadrant of the Valles caldera is illustrated in Figure 10. Temperature data from Baca 12 indicate that hot hydrothermal fluids from the main caldera geothermal system are either ascending or flowing laterally at this site. These fluids drain out of the caldera to the southwest with recharge from the east (see Figure 9, and *Goff et al.* [this issue]. The effects of cold water infiltration are indicated by the temperature data at the VC-1 site, but high heat flow at depth is interpreted to result from hot hydrothermal fluid

flowing out of the caldera below the base of the VC-1 corehole. Evidence for a shallow and recent (<40 ka) branch of this thermal plume is given by temperature data from wells at the Fenton Hill site [*Harrison et al.*, 1986]. At this site the deep temperature data and $^{40}Ar/^{39}Ar$ age spectra data indicate that heating thought to be associated with the deep thermal plume is also similarly recent [*Harrison et al.*, 1986].

Conclusion

New data from VC-1 give the first reliable conductive heat flow determination from the Phanerozoic sediments and moat volcanics of the southwestern Valles caldera. This heat flow of 463 ± 15 mW m^{-2} is very similar to the peak local heat flow from the coeval Long Valley caldera in eastern California [*Lachenbruch et al.*, 1976a, b] and about half the regional conductive heat flow from the younger Yellowstone caldera in northwestern Wyoming [*Morgan et al.*, 1977]. The new data support earlier interpretations that near-surface heat loss from the caldera is skewed to the west or southwest and that heat flow distribution results from a combination of hydrothermal convection associated with subsurface drainage of the caldera to the southwest and postcaldera magmatic heat sources in the western/southwestern portion of the caldera. Deeper drilling and a variety of other studies will be required near the western margin of the caldera to ascertain whether a Holocene thermal event has occurred near VC-1, as seems to be the case at Fenton Hill on the caldera rim.

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