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Paul Morgan, John H. Sass, and Ronald D. Jacobson, 1996, pp. 231-236

in:

Jemez Mountains Region, Goff, F.; Kues, B. S.; Rogers, M. A.; McFadden, L. S.; Gardner, J. N.; [eds.], New Mexico Geological Society 47th Annual Fall Field Conference Guidebook, 484 p.

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HEAT FLOW IN VC-2A AND VC-2B, AND CONSTRAINTS ON THE THERMAL REGIME OF THE VALLES CALDERA, NEW MEXICO

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Abstract—Shallow thermal gradient data from the Quaternary Valles caldera in the Jemez Mountains of New Mexico indicate that heat loss from the caldera is concentrated in its western half. The Sulphur Springs area, near the western margin of the resurgent dome, was the site of the earliest intensive exploration for geothermal resources in the caldera. In an earlier study we demonstrated that the conductive heat flow near the western margin of the Valles caldera averages between 300 and 400 mW m^{-2}. A combined total of 150 determinations of thermal conductivity on core segments from research wells VC-1, VC-2A, and VC-2B are sufficient to characterize the thermal conductivity of the major rock types in the area. A high degree of alteration of tuffs from VC-2A and VC-2B relative to VC-1 is reflected by significantly higher thermal conductivities, generally greater than 2 W m^{-1} K^{-1}, for the tuffs in the VC-2 wells relative to an average tuff conductivity of 1 W m^{-1} K^{-1} for VC-1. Temperature data from VC-2A and VC-2B confirm surface indications that the Sulphur Springs area is the locus of vigorous hydrothermal activity. The hydrothermal systems in both wells are capped by relatively thin (12 and 200 m, respectively) near-surface conductive thermal regimes. Heat flows from these near-surface caps are 7200 ± 370 mW m^{-2} (±standard error) for VC-2A and 1340 ± 60 mW m^{-2} for VC-2b, several times the very high background heat flux in the western portion of the caldera of 250 to 350 mW m^{-2}. The probable source of these high heat-flow values is the intrusion of one or more shallow magma bodies during the post-collapse history of the caldera.

INTRODUCTION

Quaternary silicic calderas are the sites of some of the highest measured continental heat flow values. Heat flow values in excess of 1 W m^{-2}, or about two orders of magnitude above typical continental heat flow values have been measured in three such calderas in the western United States, the Yellowstone (Morgan et al., 1977), Long Valley (Lachenbruch et al., 1976a, b), and Valles (Sass and Morgan, 1988) calderas. Of these, the most extensive subsurface temperature data set exists for the Valles caldera, and this data set reveals a spatially complex pattern of heat loss.

Thermal models of the cooling of the Valles caldera by Kolstad and McGetchin (1978) suggested that a large shallow magma chamber, larger in diameter than the caldera, would be required to explain the measured heat flow just outside the caldera margin if the magma had been cooling to the surface conductively since the main most recent caldera-forming event at about 1.1 Ma. Later studies, however, based upon both thermal and argon-release spectra investigations of data and samples resulting from additional drilling, revealed a temporally more complex cooling history (Harrison et al., 1986).

Subsequent compilations of thermal data from the Valles caldera, collected as the result of extensive geothermal research and exploration in and around the caldera, have been interpreted to suggest that both the recent geological evolution of the caldera and topographically driven groundwater flow are significant components of the caldera heat loss (Tomczyk and Morgan, 1987; Sass and Morgan, 1988). These results reveal that cooling of the caldera is much more complex than may be modelled by relatively simple conductive cooling models, and that the source or sources of the caldera thermal anomaly in terms of a large silicic intrusion remains largely unconstrained. Thus, although Quaternary silicic calderas are estimated to represent a significant portion of the present heat loss from the western United States (e.g., Blackwell, 1978), the heat budget of these major systems is poorly constrained.

The Valles caldera lies in the Jemez Mountains of northern New Mexico straddling the western margin of the Rio Grande rift (Fig. 1). It is the type example of a resurgent caldera (Smith and Bailey, 1968), which is the latest major caldera-forming stage in a dynamic and complex tectonomagmatic evolution lasting more than 13 Ma (Gardner et al., 1986; Goff and Nielsen, 1986; Self et al., 1986, 1988; Loeffler et al., 1988; Stix et al., 1988; Turbeville and Self, 1988; Heiken et al., 1990). The youngest age dates from the caldera volcanics are 50 to 60 ka (Reneau et al., 1996), and Wolff and Gardner (1995) have suggested that the caldera is entering a new cycle of activity.

The Valles caldera is also the site of a high-temperature geothermal system (Dondanville, 1978), and the site of the first hot dry rock (HDR) geothermal research experiment (Heiken et al., 1981; Smith, 1983). Drilling associated with this geothermal exploration and research has allowed the collection of the extensive subsurface temperature data set currently available for the Valles caldera, as summarized by Sass and Morgan (1988).

Following the successful completion of VC-1, a Continental Scientific Drilling Program corehole drilled just outside the Valles caldera (Goff et al., 1986), two research wells (VC-2A and VC-2B; Fig. 2) drilled in the west-central moat zone of the Valles caldera in 1986 and 1988 (Goff and Gardner, 1994) have provided the first opportunity for detailed study of heat flow in a portion of the caldera that is dominated by hydrothermal processes. Here, we present new geothermal data from these two wells with estimates of the conductive heat flow in their upper conduction-dominated sections. We integrate these data with existing geothermal data to investigate the thermal regime of the Valles caldera.

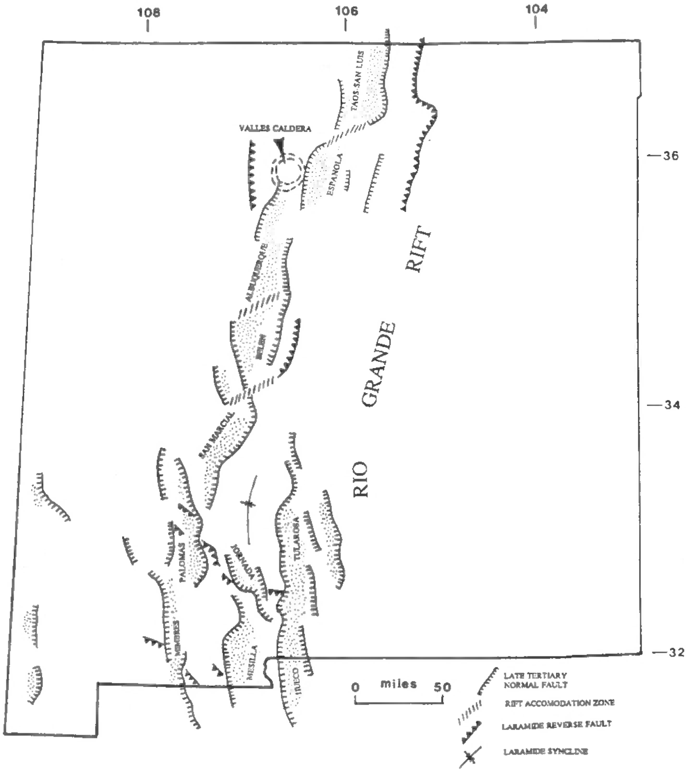

FIGURE 1. Location map showing the basins of the Rio Grande rift in New Mexico and the location of the Valles caldera on the western margin of the rift.

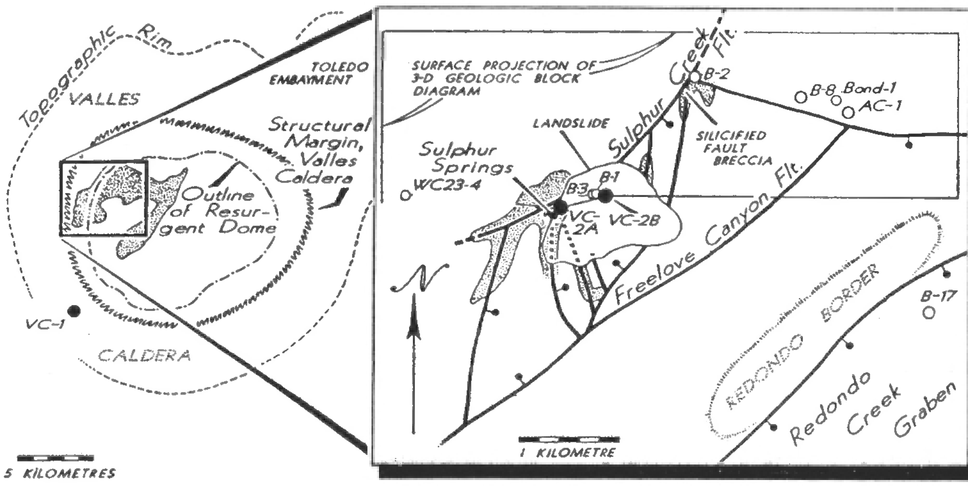

FIGURE 2. Map showing the locations of the Continental Scientific Drilling Program coreholes VC-2A and VC-2B relative to the Sulphur Springs area of the Valles caldera. Stippled areas show the extent of phyllic, argillic, and advanced argillic acid-sulphate alteration. From Hulen et al. (1988), modified from Goff and Garner (1980) and Charles et al. (1986).

NEW GEOTHERMAL DATA

VC-2A was designed to penetrate a postulated vapor cap in the main spring and fumarole area of Sulphur Springs, the largest area of geothermal manifestations in the Valles caldera (Musgrave et al., 1989). VC-2B was designed to investigate the deeper reaches of the Sulphur Springs hydrothermal system, and was drilled approximately 450 m east-northeast of VC-2A, outside the area of the main surface hydrothermal manifestations (Gardner et al., 1989).

VC-2A

VC-2A was a corehole drilled in the west-central moat zone of the Valles caldera (Fig. 2) and was completed at a depth of 527.6 m on 28 September 1986 after 28 days of drilling. This well penetrated the vapor cap and an impermeable zone transitional into the top of the liquid-dominated hydrothermal reservoir. The well encountered pervasive and intensive hydrothermal alteration (Goff et al., 1987). The temperature profile in VC-2A evolved from quasi-linear shortly after the completion of drilling on September 27, 1986, to distinctly curved on November 10, 1986 (Fig. 3A). The November 10 temperature profile shows many local disturbances and is not completely in thermal equilibrium, but it appears to best represent the undisturbed rock temperatures at this site.

Subsequent temperature profiles show little change in the temperature profile below about 140 m, but are near-isothermal above 100 m due to flow of hot water or steam from about 120 m to the surface (Fig. 3B). Some of the earlier temperature logs have a negative temperature spike between 120 and 140 m, which we interpret to indicate an inflow of colder water at this depth. The temperature profile in the uppermost 20 m of the November 10, 1986, log is approximately linear, and we use this section of the temperature log to estimate a conductive heat flow to the surface at this site.

Thermal conductivity measurements on core samples from VC-2A were difficult to make due to the intensely altered nature of these samples. Thirty-five core samples were waxed upon retrieval from the core barrel to reduce drying and atmospheric alteration, and their thermal conductivities were measured (Fig. 4) at a mean temperature of approximately 25°C with a line source in either the needle-probe or half-space configuration (Sass et al., 1988).

Rock thermal conductivities are temperature dependent and as in situ temperatures of the samples were considerably higher than their mean measurement temperatures, these results were adjusted to their in situ temperatures using temperature coefficients of thermal conductivity from Birch and Clark (1940). Recent measurements of water-saturated rocks at elevated temperatures indicate that the Birch and Clark coefficients cause the adjustment to be overestimated; thus, our adjusted thermal conductivity values may be underestimated by a few percent (Pribnow et al., 1996; Williams and Sass, 1996). Nevertheless, we believe that the conductivities plotted in Figure 4 are representative of the in situ values.

We have also applied an adjustment for in situ porosity as determined from well-log data, which reduces both the magnitudes and the scatter of the conductivity data (Fig. 4). The adjusted data indicate a thermal conductivity of approximately 2.5 W m^{-1} K^{-1} in the upper 100 m of VC-2A, decreasing to approximately 2.0 W m^{-2} K^{-1} in the lowermost 300 m of the hole. The primary lithology of the VC-2A core samples is a quartz-rich

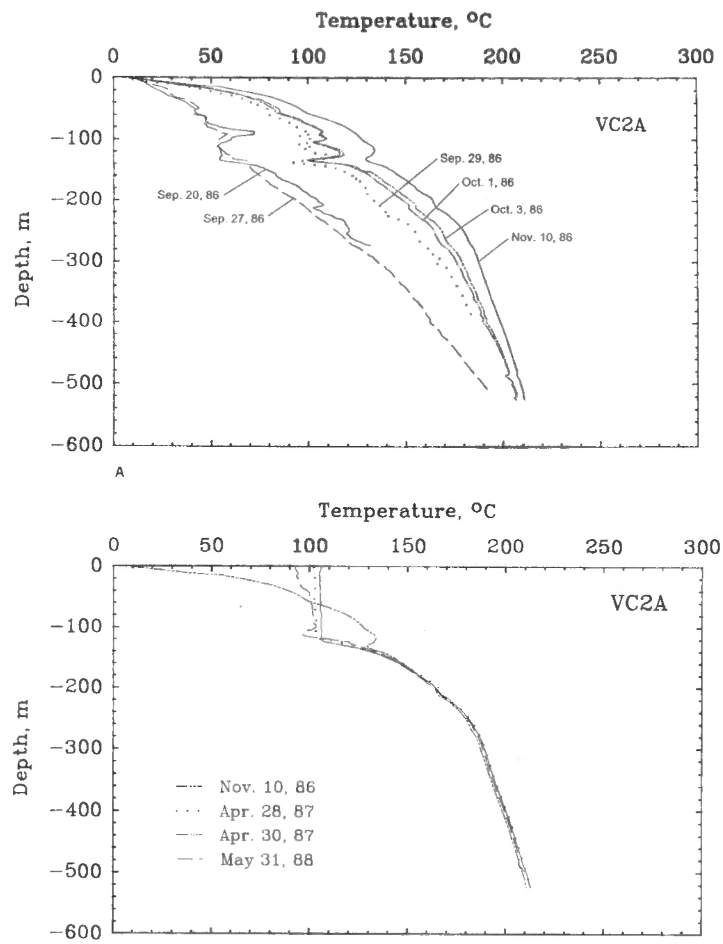

FIGURE 3. Temperature logs from VC-2A. A, logs between September 20, 1986 and November 10, 1986; B, logs between November 10, 1986 and May 31, 1988.

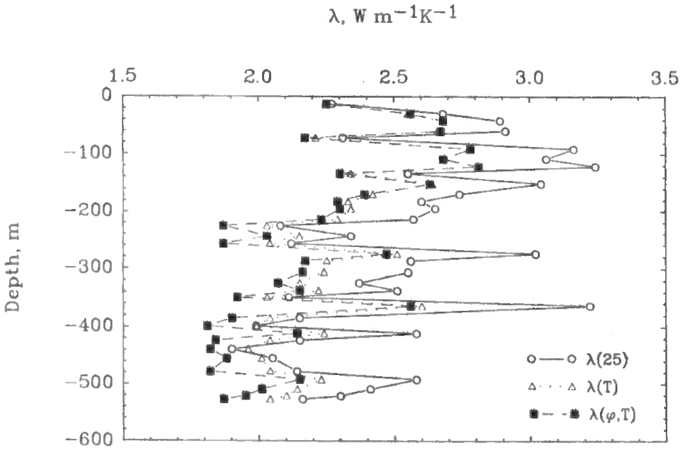

FIGURE 4. Thermal conductivity data (λ, W m^{-1} K^{-1}) from VC-2A as a function of depth (m). Open circles show conductivities at room temperature (25°C). Open triangles show conductivities corrected to in situ temperature. Closed squares show conductivities corrected to in situ temperature and porosity.

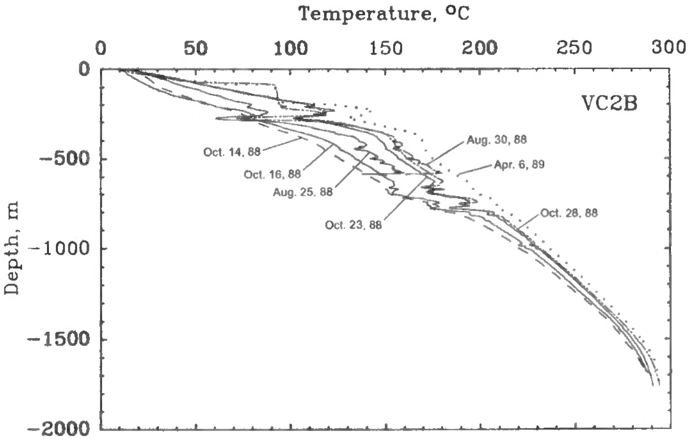

FIGURE 5. Temperature logs from VC-2B between August 25, 1988 and April 6, 1989.

welded tuff, somewhat similar to the tuff lithology in the moat volcanic section of an earlier research hole, VC-1. Adjusted thermal conductivities for tuff samples from VC-1 were much lower, however; typically ranging from 1 to 1.2 W m^{-1} K^{-1} (Sass and Morgan, 1988). Higher thermal conductivities in VC-2A result from the high degree of hydrothermal induration of the samples at this site.

Both the temperature gradient and the adjusted thermal conductivity in VC-2A decrease with depth. In a steady-state conductive thermal regime, temperature gradient and thermal conductivity are expected to be inversely correlated and thus the temperature profile in VC-2A cannot be interpreted in terms of a steady-state conductive thermal regime. The thermal gradient decreases from over 3000°C km^{-1} in the uppermost section of the hole to around 100°C km^{-1} below 300 m, and over the same depth range the thermal conductivity decreases by about 20%. Conductive heat flow is given by the product of temperature gradient and thermal conductivity, and thus a decrease down the hole in the conductive heat flow of >95% is indicated by these data. We interpret this result to indicate that ~95% of the heat is transferred by hydrothermal convection in the lower section of the hole. Using data from the uppermost section of VC-2A (3–12 m), we estimate a thermal gradient of 2858±22°C km^{-1} (±standard error, n = 6), a harmonic mean conductivity of 2.52±0.11 W m^{-1} K^{-1} (n = 4), and the conductive heat loss from this site to be 7200±370 mW m^{-2}.

VC-2B

Research drill hole VC-2B was drilled to the east-northeast of VC-2A in the west-central caldera moat and was completed at a depth of 1762 m on October 22, 1988 (Gardner et al., 1989). This well penetrated caldera fill to about half its depth, then pierced pre-caldera rocks, terminating in what appears to be a Precambrian quartz monzonite.

As with VC-2A, the temperature data from VC-2B (Fig. 5) indicate a more linear temperature profile shortly after drilling than six months later. The section above 200 m, which appeared to have a near-linear temperature profile one to six days after drilling, was disturbed, as indicated by a near-isothermal section between about 100 and 200 m, in the temperature log of April 6, 1989. We interpret this disturbance to be evidence for upflow of water in the hole, at a temperature near the surface boiling temperature, in the depth range of the isothermal section of the log. Similar behavior was observed in the upper section of VC-2A right to the surface, but in VC-2B the hot fluids only appear to rise to a depth of approximately 100 m.

Thermal conductivities of the rocks penetrated by VC-2B were measured in the laboratory at room temperature in the same manner as the samples from VC-2A. Fifty-six samples yielded thermal conductivity measurements (Fig. 6) with the conductivity determinations adjusted for in situ temperature and for in situ temperature and porosity. As with VC-2A, the adjustments significantly reduce the scatter in the measured thermal conductivities. There is no significant trend in the adjusted conductivity values as a function of depth and the arithmetic mean conductivity is 2.16±0.03 W m^{-1} K^{-1} (±standard error, n = 56).

VC-2B penetrated tuff from 168 to 742 m (Hulen and Gardner, 1989), and significantly higher thermal conductivities were measured in these units than in similar tuff in VC-1 (Sass and Morgan, 1988), indicating greater hydrothermal induration of tuff inside the caldera than outside. No significant correlation exists between conductivity and lithology in the sedimentary units penetrated by VC-2B between 742 and 1558 m, and only the Precambrian quartz monzonite, the lowest unit in the hole below 1558 m, is distinctive with its small scatter in conductivities (arithmetic mean = 2.26±0.02 W m^{-1} K^{-1}, n = 6).

There is no correlation between the thermal gradient and thermal conductivity values in VC-2B, an order of magnitude decrease in gradient with depth corresponding to constant thermal conductivity. As with VC-2A, therefore, we conclude that most of the heat is transferred at depth by thermal convection, and only the uppermost thermal gradient (excluding the upflow effects evident in the April 6, 1989) represents the total thermal budget as conductive heat flow. Using the uppermost section of the data (15–200 m), we have calculated a gradient of 483±1°C km^{-1} (n = 120), a harmonic mean conductivity of 2.12±0.12 W m^{-1} K^{-1} (n = 5), and a heat flow of 1034±60 mW m^{-2}.

DISCUSSION AND CONCLUSIONS

The shallow temperature gradient data presented by Sass and Morgan (1988) are shown in Figure 7 with the locations of the new data sites, VC-2A and VC-2B indicated. The new data do not significantly modify the temperature gradient contours on this map, and they confirm the intensity of the sharp peak of thermal gradients on the western margin of

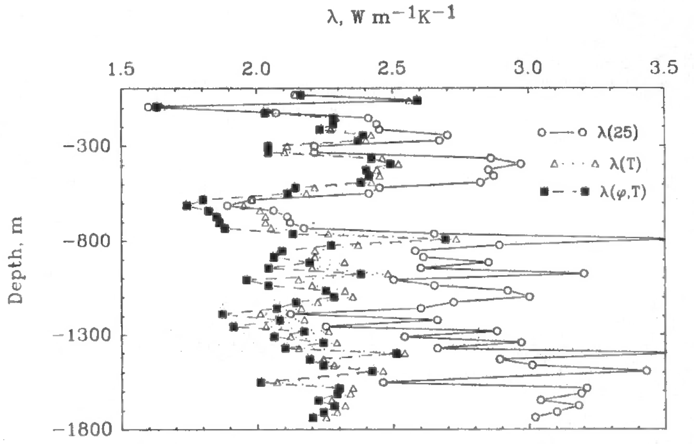

FIGURE 6. Thermal conductivity data (λ, W m^{-1} K^{-1}) from VC-2B as a function of depth (m). Symbols as for Figure 4.

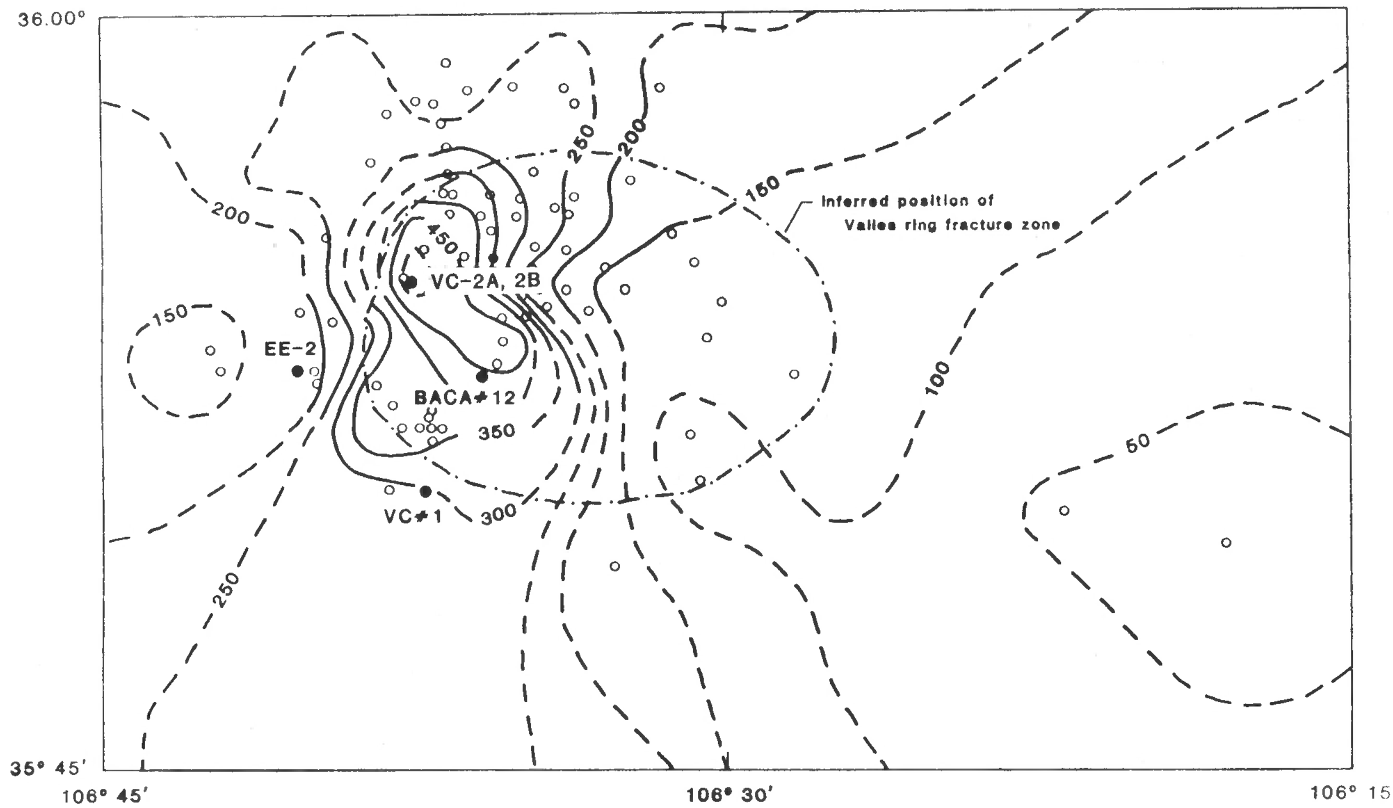

FIGURE 7. Shallow thermal gradients in and around the Valles caldera and the locations of VC-2A and VC-2B, modified from Sass and Morgan (1988).

the caldera. In geothermal areas in which the thermal gradients are much more variable than thermal conductivities, the thermal gradient map is commonly used as an indication of the distribution of conductive heat loss from the area. The new thermal conductivity data collected from VC-2A and VC-2B, however, suggest that the heat flow from the peak of the anomaly may be underestimated by a factor of two based on temperature gradients alone. Induration of the tuff units over the peak of the thermal anomaly, and almost certainly by geothermal fluids, has doubled their thermal conductivities compared to flanking tuff units off the anomaly peak. This result highlights the importance of both thermal gradient and thermal conductivity determinations in making reliable heat flow and energy budget calculations for geothermal systems.

The effect of induration of the tuff units may be understood from the temporal succession of temperature logs in VC-2A and VC-2B (Figs. 3, 5). Logs obtained during breaks in drilling or shortly after drilling show the effects of cooling of the hole by the circulating drilling fluid. The general form of the temperature profile becomes more convex upward as time increases after drilling, indicating the effects of upward convection of heat by ascending fluids in the formation. Some cooling of the fluids as they ascend from reservoir temperatures, probably in excess of 300°C, to the measured temperatures is indicated. As solubility generally decreases with decreasing temperature, we may expect the precipitation of dissolved solids from the ascending fluids, thus decreasing porosity and permeability. Precipitation is also aided by subsurface boiling. This effect would be greatest near the surface where the temperature gradient is the steepest, and precipitation at these levels may eventually reduce permeability to a level at which convection becomes insignificant unless new fracture permeability forms, resulting in the domination of heat transfer by conduction. The vertical transfer of heat by convection is also less efficient near the surface because, unless there is artesian or geyser activity, water flow is predominantly lateral and does not transfer heat vertically.

Temperature logs in both VC-2A and VC-2B suggest that the drill holes created artificial conduits for ascending geothermal fluids by breaching low-permeability zones at shallow depths. Immediately after drilling, the fluid pressures in the wells appear to have been sufficiently disturbed for the shallow conductive regimes in the uppermost sections of the holes to have been preserved. Shortly thereafter, however, the convective regimes were reestablished, the low impedance pathways produced by the drill holes were exploited by the ascending geothermal fluids, and the steep temperature gradients in the shallow conductive caps appear to have been perturbed by fluids ascending in the drill holes. This suggests that the uppermost portions of the sections were relatively impermeable and blocked ascending fluids prior to breaching by the drill holes.

The new thermal conductivity data from VC-2A and VC-2B allow us to make a quantitative estimate of heat flow from the western part of the Valles caldera. From the thermal gradient map (Fig. 7) we calculated an average gradient of 342°C km^{-1} for the western "half" of the caldera with an area of 98 km^2. Using a thermal conductivity of 2.1 W m^{-1} K^{-1}, this average gradient represents a heat flow of 720 mW m^{-2}, or a total constant of steady-state heat loss of 70 MW over the western portion of the caldera. By comparison, Fournier et al (1976) measured the present rate of heat loss for the hydrothermal convection system in the Yellowstone caldera as 1.2 x 10^9 cal/s (5000 MW); Sorey and Lewis (1976) calculated a present convective heat discharge from the Long Valley caldera of 4.3 x 10^7 cal/s (180 MW).

Kolstad and McGetchin (1978) produced a series of thermal models of the caldera based on the conductive cooling of a circular pluton intruded at 1.0 Ma, with its top at a depth of 3 km and its base at 23 km. Using their results for plutons with radii of 8 and 12 km, we calculate present heat losses for the two models of 74 MW and 96 MW, respectively, out to a radial distance of 12 km from the center of the plutons, an area of 452 km^2. These heat losses are comparable to the heat loss indicated by the thermal gradient data for just the western portion of the caldera. Water flow is a significant factor redistributing heat in and around the caldera (e.g., Harrison et al., 1986; Sass and Morgan, 1988), but, using the Kolstad and McGetchin (1978) models of cooling 1 Ma plutons, almost all of the heat from a 450 km^2 area would need to be concentrated in the 98 km^2 area of the western portion of the caldera.

Gradient contours outside the western portion of the caldera range from 100 to 250°C km^{-1}. Taking a conservative average gradient of 150°C km^{-1} and a conservative thermal conductivity of 1.1 W m^{-1} K^{-1}, an average heat flow of 165 mW m^{-2} is estimated for the adjacent regions. To compare this value to the Kolstad and McGetchin models, we apply this heat flow over an area of 354 km^2 to add to the heat loss from the western portion of the caldera, because our estimate of heat loss for the western portion covers only part of the area of heat loss calculated for the cooling pluton model. A 'background' heat loss of 58 MW is calculated. Thus, the total heat loss from the western portion of the caldera and the adjacent regions in an area equivalent to the 24 km diameter circle used for the Kolstad and McGetchin heat loss calculations is 128 MW, significantly greater than the heat loss predicted by the 1 Ma pluton models.

While we recognize that changes in the parameters of the Kolstad and McGetchin (1978) conductive cooling pluton models may result in better agreement between the modelled heat loss and the heat loss calculated from the gradient data above, we believe that these changes are likely to be geologically unrealistic: the top of the pluton is already unrealistically shallow, the 12 km radius model is already larger than the caldera, and the age is constrained by caldera collapse. A more likely explanation for the high heat loss in the western portion of the caldera is younger intrusions associated with uplift of the resurgent dome in the caldera, the rhyolite domes intruded into the ring fractures of the caldera, and the eruption of the southwestern moat rhyolite. Detailed modelling of the thermal effects of these intrusions is beyond the scope of the present study, but our results suggest one or more post-1 Ma intrusions beneath the western portion of the caldera. New geochronologic studies of the young volcanics within the caldera give ages as young as 50 to 60 ka (Reneau et al., 1996), and are consistent with a new cycle of magmatism in the Valles caldera (Wolff and Gardner, 1995). This young magmatism may be the primary sources of the present geothermal manifestations and high heat flow in the western portion of the caldera.

ACKNOWLEDGMENTS

We thank Fraser Goff, Jeff Hulen and Jamie Gardner for providing access to the holes for logging and for providing core samples for thermal conductivity measurements. Gene Smith is thanked for his assistance with the thermal conductivity measurements. Fraser Goff and Wendell Duffield provided constructive reviews of this manuscript.

REFERENCES

Birch, F. and Clark, H., 1940, The thermal conductivity of rocks and its dependence on temperature and composition: American Journal of Science, v. 238, p. 529–558, 613–635.

Blackwell, D. D., 1978, Heat flow and energy loss in the western United States: Geological Society of America, Memoir 152, p. 175–208.

Charles, R. W., Vidale-Buden R. and Goff F., 1986, An interpretation of the alteration assemblages at Sulphur Springs, Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, p. 1887–1898.

Dondanville, R. F., 1978, Geologic characteristics of the Valles geothermal system, New Mexico: Geothermal Resources Council Transactions, v. 2, p. 157–160.

Fournier, R. O., White, D. E. and Truesdell, A. H., 1976, Convective heat flow in Yellowstone National Park; *in* Proceedings of the 2nd United Nations Symposium on the development and use of geothermal resources, v. 1: U. S. Government Printing Office, Washington, D. C., p. 731–740.

Gardner, J. N., Goff, F., Garcia, S. and Hagan, R. C., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 91, p. 1763–1778.

Gardner, J. N., Hulen, J. B., Lysne, P., Jacobson, R., Goff, F., Nielson, D. L., Pisto, L., Criswell, C. W., Gribble, R., Meeker, K., Musgrave, J. A., Smith, T. and Wilson, D., 1989, Scientific core hole Valles caldera #2b (VC-2B), New Mexico: drilling and some initial results: Geothermal Resources Council Transactions, v. 13, p. 133–139.

Goff, F. and Gardner, J. N., 1980, Geologic map of the Sulphur Springs area, Valles caldera geothermal system, New Mexico: Los Alamos Scientific Laboratory, Map LA-8634-MAP, 2 sheets, scale 1:5000.

Goff, F. and Gardner, J. N., 1994, Evolution of a mineralized geothermal system, Valles caldera, New Mexico: Economic Geology, v. 89, p. 1803–1832.

Goff, F. and Nielsen, D. L., 1986, Caldera processes and magma-hydrothermal systems: Continental Scientific Drilling Program—thermal regimes, Valles caldera research, scientific and management plan: Los Alamos National Laboratory, Report LA-10737-OBES, 163 p.

Goff, F., Nielsen, D. L., Gardner, J. N., Hulen, J. B., Lysne, P., Shevenell, L. and Rowley, J. C., 1987, Scientific drilling at Sulphur Springs, Valles caldera, New Mexico: core hole VC 2A: Eos, Transactions of the American Geophysical Union, v. 30, p. 649, 661–662.

Goff, F., Rowley, J., Gardner, J. N., Hawkins, W., Goff, S., Charles, R., Wachs, D., Maassen, L. and Heiken, G., 1986, Initial results from VC-1, first Continental Scientific Drilling Program core hole in Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, p. 1742–1752.

Harrison, T. M., Morgan, P. and Blackwell, D. D., 1986, Constraints on the age of heating at the Fenton Hill site, Valles caldera, New Mexico: Journal of Geophysical Research, v. 91, p. 1899–1908.

Heiken, G., Goff, F., Gardner, J. N., Baldridge, W. S., Hulen, J. B., Neilsen, D. L. and Valiman, D., 1990, The Valles/Toledo caldera complex, Jemez volcanic field, New Mexico: Annual Reviews of Earth and Planetary Science, v. 18, p. 27–53.

Heiken, G., Murphy, H., Nunz, G., Potter, R. and Grigsby, C., 1981, Hot dry rock geothermal energy: American Scientist, v. 69, p. 400–407.

Hulen, J. B. and Gardner, J. N., 1989, Field geologic log for continental scientific drilling program corehole VC-2B, Valles caldera, New Mexico: Earth Science Laboratory, Report DOE/ER/13196-4, ESL-89025-TR, University of Utah Research Institute, Salt Lake City, Utah, 92 p.

Hulen, J. B., Gardner, J. N. Goff, F. and the Valles Scientific Drilling Team, 1988, Site-specific science plan for Continental Scientific Drilling Program, Corehole VC-2B Sulphur Springs area, Valles caldera, New Mexico: Earth Science Laboratory, Report ESL-88004-TR, University of Utah Research Institute, Salt Lake City, Utah, 98 p.

Kolstad, C. D. and McGetchin, T. R., 1978, Thermal evolution models for the Valles caldera with reference to a hot-dry-rock geothermal experiment: Journal of Volcanology and Geothermal Research, v. 3, p. 197–218.

Lachenbruch, A. H., Sass, J. H., Monroe, R. J. and Moses, T. H., 1976b, Geothermal setting and simple heat conduction models of the Long Valley caldera: Journal of Geophysical Research, v. 81, p. 1769–1784.

Lachenbruch, A. H., Sorey, M. L., Lewis, M. L. and Sass, J. H., 1976a, The near-surface hydrothermal regime of Long Valley caldera: Journal of Geophysical Research, v. 81, p. 763–768.

Loeffler, B. M., Vaniman, D. T., Baldridge, W. S. and Shafiqullah, M., 1988, Neogene rhyolites of the northern Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 93, p. 6157–6167.

Morgan, P., Blackwell, D. D., Spafford, R. E. and Smith, R. B., 1977, Heat flow measurements in Yellowstone Lake and the thermal structure of the Yellowstone caldera: Journal of Geophysical Research, v. 82, p. 3719–3732.

Musgrave, J. A., Goff, F., Shevenell, L., Trujillo, P. E., Counce, D., Luedemann, G., Garcia, S., Dennis, B., Hulen, J. B., Janik, C. and Tomei, F. A., 1989, Selected data from Continental Scientific Drilling Core Holes VC-1 and VC-2a, Valles caldera, New Mexico, Los Alamos National Laboratory, Report LA-11496-OBES, 71 p.

Pribnow, D., Williams, C. F., Sass, J. H. and Keating, R., 1996, Thermal conductivity of water-saturated rocks from the KTB pilot hole at temperatures of 25 to 300°C: Geophysical Research Letters, v. 23, p. 391–394.

Reiter, M., Eggleston, R. E., Broadwell, B. R. and Minier, J., 1986, Estimates of terrestrial heat flow from deep petroleum tests along the Rio Grande rift in central and southern New Mexico: Journal of Geophysical Research, v. 91, p. 6225–6245.

Reneau, S. L., Gardner, J. N. and Forman, S. L., 1996, New evidence for the age of the youngest eruptions in the Valles caldera, New Mexico: Geology, v. 24, p. 7–10.

Sass, J. H. and Morgan, P., 1988, Conductive heat flux in VC-1 and the thermal regime of the Valles caldera, New Mexico: Journal of Geophysical Research, v. 93, p. 6027–6039.

Sass, J. H., Kennelly, J. P., Smith, E. P. and Wendt, W. E., 1984, Laboratory line-source methods for the measurements of thermal conductivity of rocks near room temperature: U. S. Geological Survey, Open-file Report 84-91, 21 p.

Self, S., Goff, F., Gardner, J. N., Wright, J. V. and Kite, W. M., 1986, Explosive rhyolitic volcanism in the Jemez Mountains: vent locations, caldera development, and relation to regional structure: Journal of Geophysical Research, v. 91, p. 1779–1798.

Self, S., Kircher, D. E. and Wolff, J. A., 1988, The El Cajete series, Valles caldera, New Mexico: Journal of Geophysical Research, v. 93, p. 6113–6127.

Smith, M. C., 1983, A history of hot dry rock geothermal systems: Journal of Volcanology and Geothermal Research, v. 15, p. 1–20.

Smith, R. L. and Bailey, R. A., 1968, Resurgent cauldrons: Geological Society of America, Memoir 116, p. 613–662.

Sorey, M. L. and Lewis, R. E., 1976, Convective heat flow from hot springs in the Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, p. 785–791.

Stix, J., Goff, F., Gorton, M. P., Heiken, G. and Garcia, S. R., 1988, Restoration of compositional zonation in the Bandelier silicic magma chamber between two caldera-forming eruptions: geochemistry and origin of the Cerro Toledo rhyolite, Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 93, p. 6129–6147.

Tomczyk, T. and Morgan, P., 1987, Evaluation of the thermal regime of the Valles caldera, New Mexico, U. S. A., by downward continuation of temperature data: Tectonophysics, v. 134, p. 339–345.

Turbeville, B. N. and Self, S., 1988, San Diego Canyon ignimbrites: pre-Bandelier Tuff explosive rhyolitic volcanism in the Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 93, p. 6148–6156.

Williams, C. F. and Sass, J. H. (in press), The thermal conductivity of rocks under hydrothermal conditions: measurements and applications: Proceedings, 21st Stanford Geothermal Workshop.

Wolff, J. A. and Gardner, J. N., 1995, Is the Valles caldera entering a new cycle of activity? Geology, v. 23, p. 411–414.