GEOPHYSICS, VOL. 48, NO. 5 (MAY 1983); P. 618–626, 11 FIGS.

Thermal hydrology and heat flow of Beowawe geothermal area, Nevada

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ABSTRACT

Inflections in temperature-depth profiles from forty 150 m thermal gradient holes define a shallow thermal flow system in the Whirlwind Valley near the Beowawe Geysers. U.S. Geological Survey hydrologic data reveal the vertical and west-to-east components of cold water flow at the water table above the thermal flow system. The temperature inflections break most abruptly in areas with a downward component of flow at the water table. The inflections are thought to indicate the level where the buoyant thermal water maintains a dynamic equilibrium with the overlying cold water. Combining these geophysical and hydrologic data suggests areas away from The Geysers where thermal water may rise from the deep reservoir into the alluvium. These leakage areas may be viable geothermal exploration targets. Even if the temperatures of the leakage were subeconomic, knowledge of where upwelling occurs could be helpful in assessing the potential for energy production. The systematic acquisition of hydrologic data is recommended as a standard component of hydrothermal resource exploration programs.

Measurements of thermal conductivity from chip samples from the shallow holes and from Chevron Resources Company's Ginn 1-13 geothermal exploration hole (2917 m T.D.) enable inferences based on heat flow. The average heat flow east of the Dunphy Pass fault zone, 110 mW/m^2, may be representative of background in this portion of the Battle Mountain high heat flow province. Thermal gradient and conductivity data from the deep well have a wide range of values (65–144°C/km, 1.59–5.95 Wm^{-1}K^{-1}) but produce a relatively constant heat flow of 235 mW/m^2 above a depth of 1600 m. The shallow data indicate that the area with similarly high surficial heat flow extends as far east as the Dunphy Pass fault zone, suggesting that this Miocene rift boundary may form the eastern margin of the Beowawe hydrothermal system.

INTRODUCTION

The geysering action of vandalized wells drilled in the late 1950s for geothermal exploration at Beowawe, Nevada, may have been the most spectacular hydrothermal phenomenon created artificially in the United States. The location of the blowing wells, known as The Geysers, is shown in Figure 1. They were spudded in a 1 km long opaline sinter terrace on the south flank of the Whirlwind Valley in Eureka and Lander Counties, Nevada, approximately 50 km east of the town of Battle Mountain. At this time (spring 1981), The Geysers play intermittently.

Struhsacker (1980) gave the most thorough description of the stratigraphic and structural framework of the Beowawe area. Other recent geologic summaries were given in Zoback (1979) and Garside and Schilling (1979). As shown in Figure 1, The Geysers lie along the Malpais fault zone at the base of the Malpais Rim. The steep fault-scarp slope faces north-northwest towards the Whirlwind Valley. Tertiary lava flows and tuffaceous sediments crop out on the Malpais dip slope. The Malpais scarp exposes an older normal fault system, the Dunphy Pass fault zone, that has a northwest trend. This Oligocene to Miocene fault zone forms the eastern margin of a major northwest-trending graben that is part of the southern extension of a 750 km long linear aeromagnetic and structural feature called the Oregon-Nevada lineament (Stewart et al, 1975).

The Tertiary volcanic section within the graben is approximately 1400 m thick; east of the Dunphy Pass fault zone, it is only 100 m thick. The detailed volcanic stratigraphy of Struhsacker (1980) is included in Figure 2. The underlying Ordovician Valmy formation is a shattered sequence of siliceous eugeosynclinal sediments that are part of the Roberts Mountains thrust sheet. Carbonaceous siltstone, chert, and quartzite of the Valmy formation crop out along the Malpais east of the Dunphy Pass fault zone and are encountered by the deep geothermal test wells in the Whirlwind Valley. Tertiary diabase dikes that intrude both the Valmy and the volcanic rocks are thought to be the source for the pronounced aeromagnetic anomaly associated with the Oregon-Nevada Lineament and

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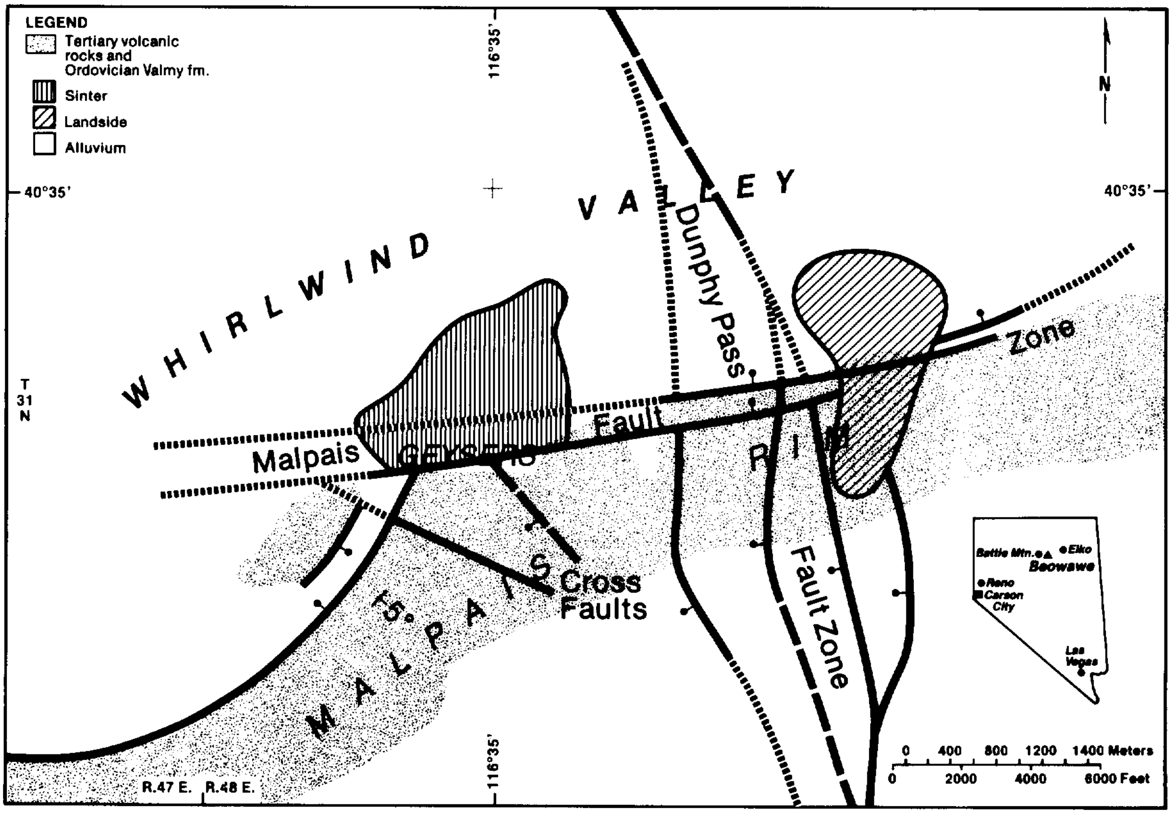

FIG. 1. Location and generalized structure of the Beowawe area (after Struhsacker, 1980).

the feeders for the Tertiary volcanic sequence filling the graben (Robinson, 1970).

In the 1970s, exploration for a hydrothermal resource capable of sustaining electrical power generation was conducted by Chevron Resources Co. and Getty Oil Co. Much of their geophysical data has been acquired and made available through the Dept. of Energy, Division of Geothermal Energy Industry Coupled Program (Chevron Resources Co., 1979; Getty Oil Co., 1981). Included in these data packages are the temperature-depth profiles and drill-chip cuttings from the forty 150 m thermal gradient holes shown in Figure 3. The temperature-depth profiles provide a three-dimensional (3-D) view of the coupled heat and water flow in the shallow subsurface. Mapping these flows can contribute to the exploration effort by locating upflow zones or widespread horizons with enhanced permeability.

THERMAL HYDROLOGY

The geothermal industry has generally neglected to include groundwater studies in their exploration programs even though water is the resource being sought. The typical program has looked at water only with an eye to its chemistry. Geothermal exploration geophysicists can remedy this omission by including piezometers in their shallow drilling plans.

A piezometer is a small-diameter pipe open to a waterbearing formation at one depth only, generally at the bottom, as schematically shown in Figure 4. The annulus between the drilled hole and the pipe or casing is usually grouted to ensure that there can be no vertical fluid flow within the hole. The elevation at which water stands in the piezometer indicates the total hydraulic head at the point of measurement. The hydraulic head H is the sum of two components, the pressure head $P/\rho g$ and the elevation head z:

$$H = z + \frac{P}{\rho g}, \tag{1}$$

where z is the elevation above an arbitrary datum (usually sea level), P is the fluid pressure, ρ the fluid density at ambient temperature, and g the acceleration due to gravity.

Under nonisothermal conditions, observed head values are corrected for density differences. In most groundwater studies these differences are small enough to be neglected. At geothermal areas with cold water aquifers, the less dense thermal water generally plumes upward to float on the colder water or emerge as hot springs. Where the thermal water is not sufficiently hot and buoyant, the weight of the overlying cold water may hold it down. The result can be a temperature inversion within the aquifer.

Water flows from areas of higher hydraulic head to areas of lower hydraulic head. Figure 4 is a sketch of the relation given

MAP CODE		LITHOLOGIC UNIT	THERMAL CONDUCTIVITY Mean ± Std. Dev. ($W \bullet m^{-1} K^{-1}$)	NUMBER SAMPLES
Qs		Opaline Sinter	——	——
Qls		Landslide	——	——
Qal		Alluvium	1.68 ± 0.11	8
Tv	Tg	Coarse Gravel	1.60	1
Tv	Tb	Basalt	1.60	2
Tv	Twc	Tuffaceous Sediment of White Canyon		
		glassy	1.33 ± 0.12	3
		silty	1.65 ± 0.08	9
Tv	Td	Dacite		
		porphyritic	2.02 ± 0.13	9
		vitrophyric	1.20	2
		argillized	1.67 ± 0.22	4
Tv	Tba	Basaltic Andesite	2.26 ± 0.06	5
Tv	Tts	Early tuffaceous material	1.58 ± 0.01	4
Tv	Tha	Hornblende Andesite	1.90 ± 0.17	5
Tv	Ti	Diabase dikes	2.09 ± 0.17	3
Ov		Valmy Formation	4.44 ± 1.01	6

FIG. 2. Stratigraphy of Beowawe area with measured thermal conductivity values.

by equation (1). The elevations of standing water (corrected for temperature where necessary) in a number of piezometers completed in the same horizon and distributed over an area, as in Figures 5a and 5b, are used to produce maps of hydraulic head. The differences in water levels seen in plan view can be used to compute the horizontal component of hydraulic gradient and, in isotropic media, the direction of water flow.

A cross-section of hydraulic heads can be generated if water levels are measured in adjacent piezometers completed at different depths, illustrated by Figures 5c and 5d. The difference in elevation of standing water in adjacent piezometers can be used to compute the vertical hydraulic gradient. Since elevation is positive upward, a negative vertical hydraulic gradient implies that there is a downward component of groundwater flow at that location. A positive value is computed wherever water rises from depth.

In areas where water flow affects heat flow, hydraulic head data should be able to delineate zones of upwelling hot water. Since hot water is the hydrothermal resource, water levels and vertical hydraulic gradient data should be gathered as part of any geothermal exploration program. Data from Beowawe demonstrate the utility of incorporating groundwater hydrology into thermal gradient surveys.

BEOWAWE GROUNDWATER

The U.S. Geological Survey, Water Resources Division, has drilled piezometers at several northern Nevada geothermal areas (e.g., Welch et al, 1981). Their data for the water table in the Whirlwind Valley are shown in Figure 3. The elevation of the water table appears to decrease systematically down the valley from west to east, reflecting the topography. It is within a few meters of the surface in the center of the valley. Much of the groundwater in the valley is presumably discharged by evapotranspiration at a playa lake beyond the eastern edge of Figure 3. Some may reach the Humboldt River farther to the east.

Water levels in the paired piezometers allow the computation of the vertical hydraulic gradient. Near The Geysers the vertical gradients are negative; water at the water table flows downward as well as toward the center of the valley. The

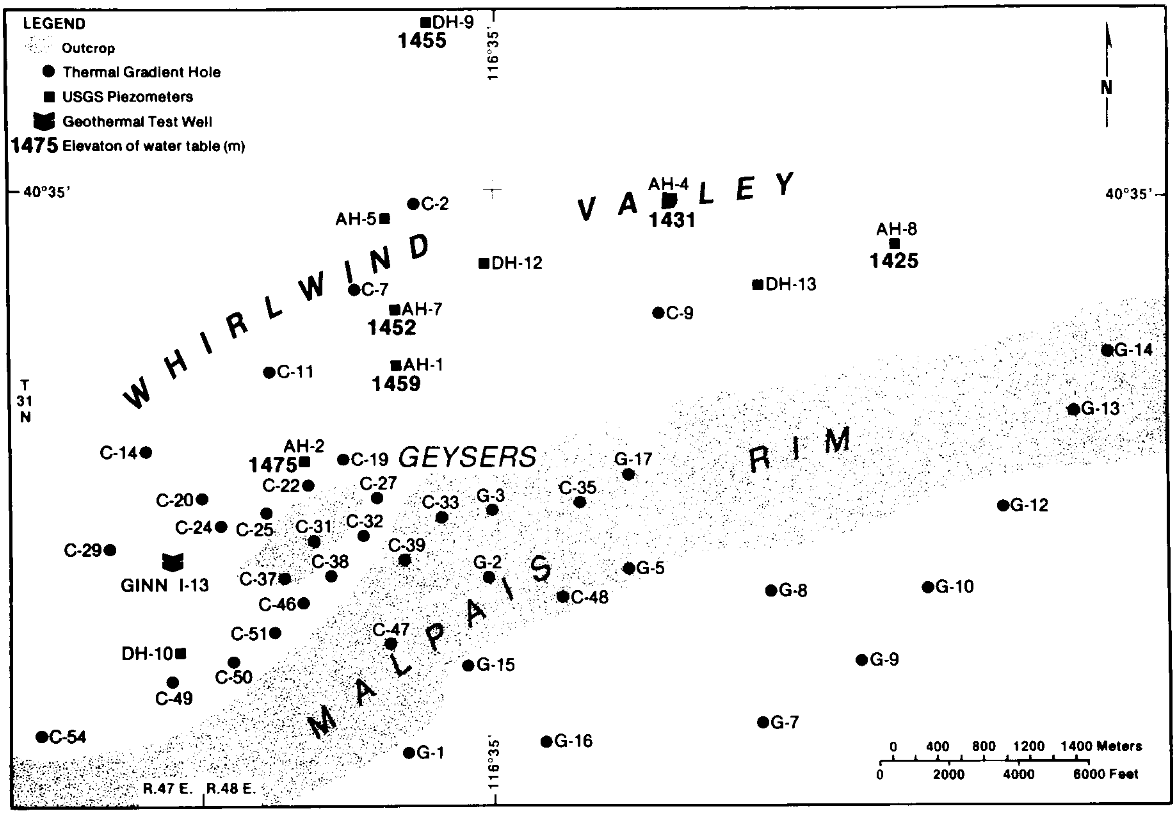

FIG. 3. Map of Beowawe area showing thermal gradient holes, piezometers, and elevation of water table.

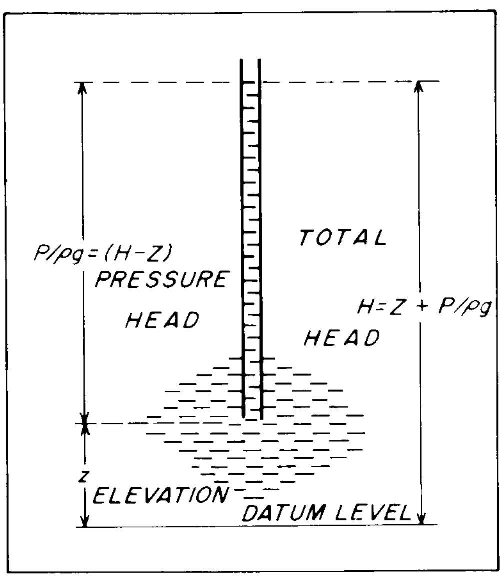

FIG. 4. Relation between total head, pressure head, and elevation (after Hubbert, 1940).

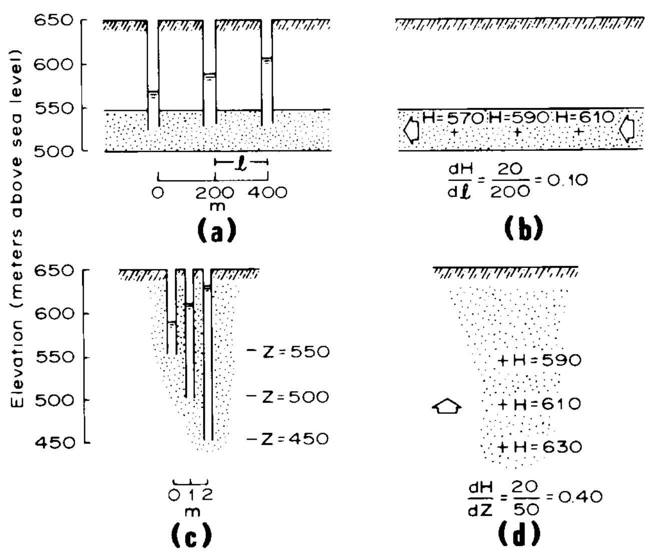

FIG. 5. Theoretical cross-section showing piezometers, head distribution, flow pattern, and hydraulic gradients (after Freeze and Cherry, 1979).

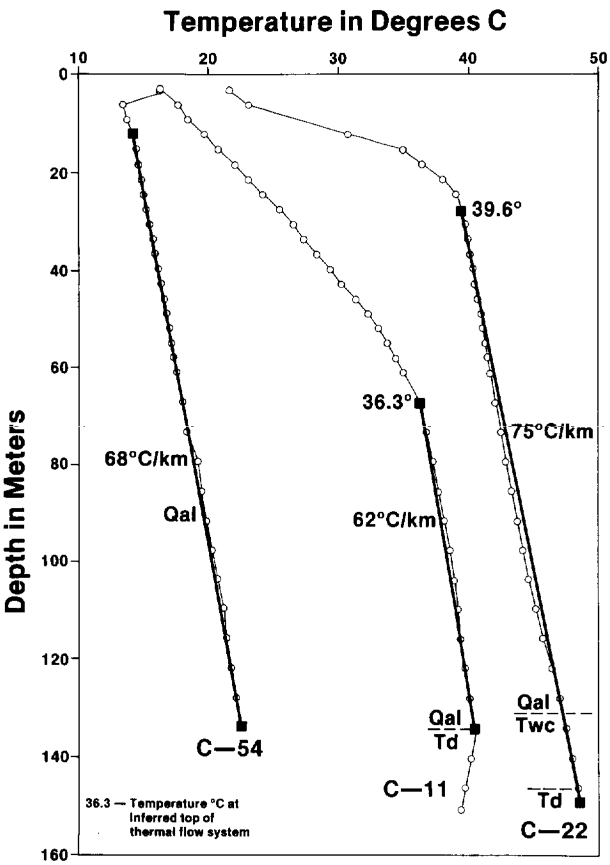

FIG. 6. Temperature-depth profiles with similar thermal gradients, Whirlwind Valley, with inferred depths to top of thermal flow system. Lithologic symbols given in Figure 2.

vertical gradient is positive in the piezometer pairs in the center of the valley. In this area, water flows upward as well as eastward, perhaps responding to evaporation at the water table.

The vertical flow measured in the shallow piezometers is indicated at greater depths by curvature and inflections in temperature-depth profiles. Figure 6 presents examples. Hole C-22 is near piezometer pair AH-2 which has a strong negative gradient; its temperature profile is concave upward, reflecting the downward flow of water (Sorey, 1971). Upward fluid flow is shown by the concave downward profile of hole C-11 near the center of the valley.

The 68°C/km gradient in hole C-54 is similar to those in holes C-11 and C-22, but its linearity for the length of the hole and low temperature are unlike the other profiles in Figure 6. The temperature-depth profile in hole C-54 is one of the few in the Whirlwind Valley that shows little disturbance by groundwater flow and may be representative of regional conductive heat flow. If 68°C/km were a background gradient in alluvium, the regional conductive heat flow would be approximately 118 mW/m^2. This heat flow is within the range of values given by Sass et al (1971a) for this portion of the Basin and Range province, allowing hole C-54 to serve as the reference for an arbitrary definition of *cold* and *thermal* for the Beowawe area: water less than 7°C above the temperature in C-54 at the same

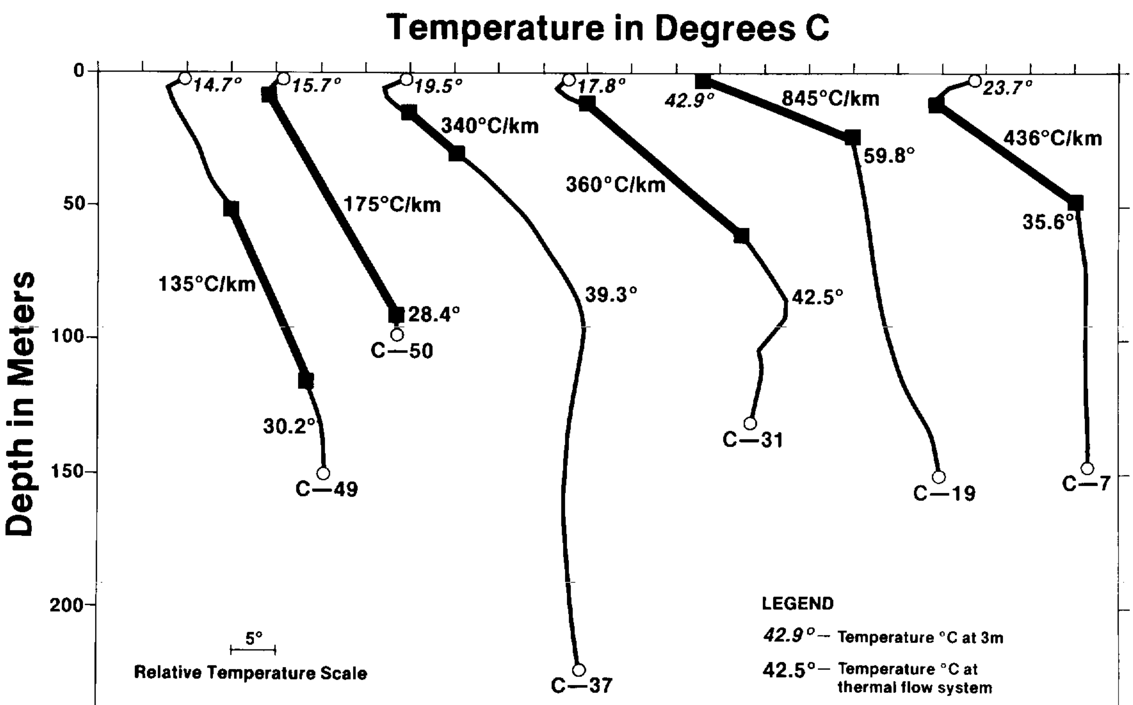

FIG. 7. Representative temperature-depth profiles in Whirlwind Valley.

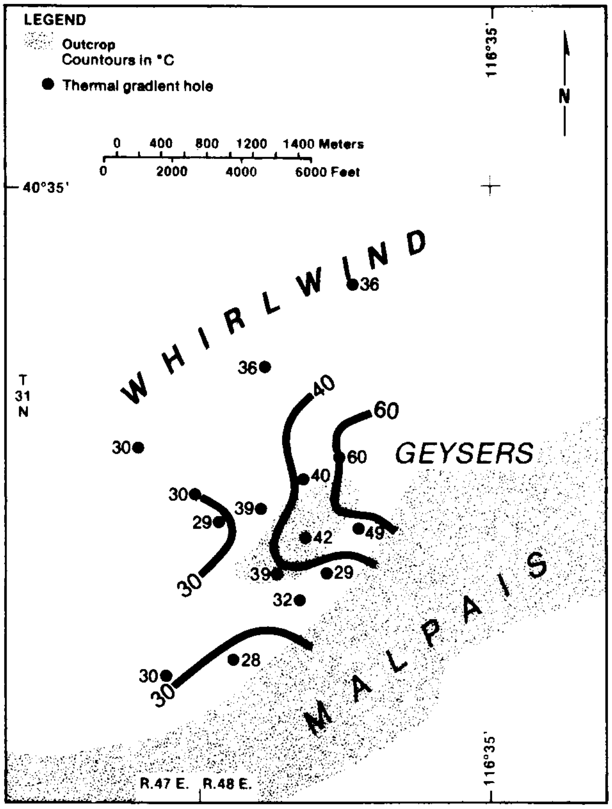

FIG. 8. Map of temperature at top of thermal flow system, contours in °C.

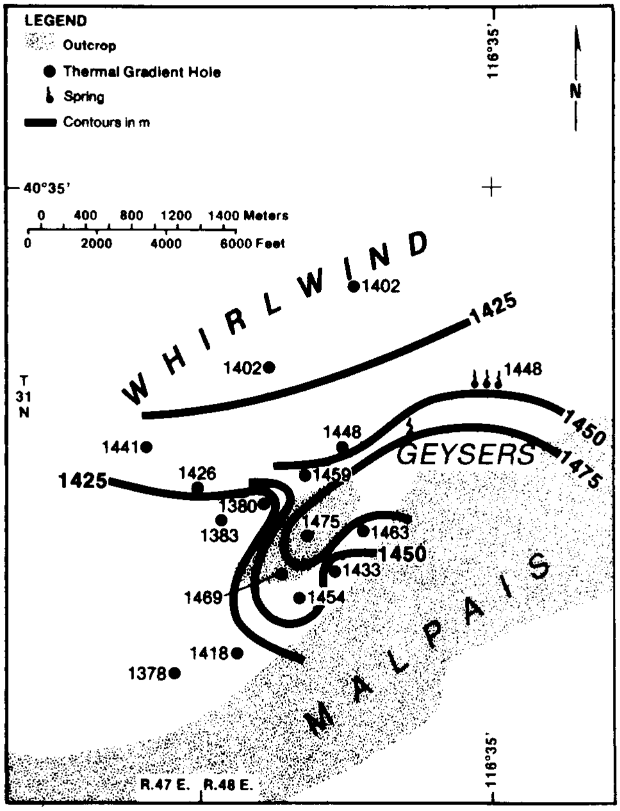

FIG. 9. Map of elevation at top of thermal flow system, contours in meters.

depth is said to be cold; water at higher temperatures is thermal.

Many of the temperature-depth profiles in the Whirlwind Valley contain abrupt downward inflections that are diagnostic of vertical transport of heat by groundwater. The inflections occur at depths ranging between 24 and 134 m and at temperatures from 28°C to 60°C. The relative temperature scale of Figure 7 is used to avoid overlap of several of these profiles. The inflections are keyed with their temperatures. Including the measured temperature at the shallowest depth permits the reconstruction of the actual temperature profiles.

The inflections in the temperature profiles are caused by fluid flow largely within the open annulus of these economically completed exploration holes. To minimize drilling costs, the annulus between the 0.12 m (4.75 inch) drilled hole and the 0.03 m (1 inch) pipe was not grouted. This method of hole completion is not recommended because the open hole forms a conduit for vertical flow. The annulus becomes a poor piezometer, open to the formation over the length of the hole instead of at one isolated interval. Differences in hydraulic head within the formation drive the vertical flow. The temperature inflections are interpreted to occur where the buoyant head of thermal water balances the gravitational head of the column of cold water above. They indicate the level where a dynamic equilibrium is maintained in the hole between rising thermal water and heavier cold water. Their depths probably do not strictly correlate to the top of a particular aquifer or to a true hydraulic head. These data are not optimal but they are usable. They form a mappable horizon interpreted to represent the top of the thermal flow system.

Figure 8 is an illustration of the temperature at the top of the thermal flow system as inferred from inflections like those in Figures 6 and 7. The hot springs around the base of the sinter terrace at The Geysers provide additional data. The near radial symmetry of the temperature distribution suggests that the area of The Geysers contains the principal source of thermal water flowing into the alluvium of the Whirlwind Valley. This symmetry also suggests that the temperature inflections reveal a single, laterally continuous flow system.

The elevation of the top of the thermal flow system is shown in Figure 9. These elevations cannot be corrected for density since the thermal gradient holes are not true piezometers and the inflections are not true hydraulic heads. The contours of Figure 9 reveal the levels to which the buoyant water rises. They reflect neither the radial pattern of the temperature map nor the west-to-east hydraulic gradient of the water table. Thermal water levels are higher within the bedrock southwest of The Geysers than they are in the adjacent alluvium. The high water levels may indicate that upwelling occurs in this area. It is also possible that water from The Geysers is perched above a less permeable horizon of volcanic rock.

Relatively high thermal water levels are sustained within the alluvium along the buried extension of the Malpais fault zone to the west of The Geysers (Smith, 1979). Since water level and vertical hydraulic gradient data are not available there, it is not possible to decipher the hydrologic system that sustains the high thermal water levels. One plausible flow system would limit the source of thermal water to The Geysers and suggest that it preferentially flows laterally along the fault zone. If this were the case, vertical hydraulic gradient data would probably show only a small vertical component of groundwater flow.

An alternative flow system that would account for the high thermal water levels in the alluvium suggests that the western extension of the Malpais fault zone may be a channel for rising thermal water. If this buried structure were a local source of thermal water, vertical hydraulic gradients along its trace would indicate an upward flow of water.

A few strategically placed piezometers could determine whether the western extension of the Malpais fault zone allows water to rise from depth. If it does, it may prove to be a viable geothermal exploration target or the key to the location of a deep permeable reservoir.

HEAT FLOW

Figure 2 summarizes the mean and standard deviations of the measured thermal conductivities for each of the major rock units in the Beowawe area. All thermal conductivity values were determined using a modified divided bar apparatus at the University of Utah (Chapman et al, 1981). Computations of the thermal conductivities of the 61 drill-chip samples were made using the cell technique of Sass et al (1971b) but were not corrected for in-situ porosity. Uncertainty about the in-situ porosity is the major source of error in the computation of surface heat flow. The porosity of the alluvial and tuffaceous materials may exceed 30 percent; if so, the conductivities mea-

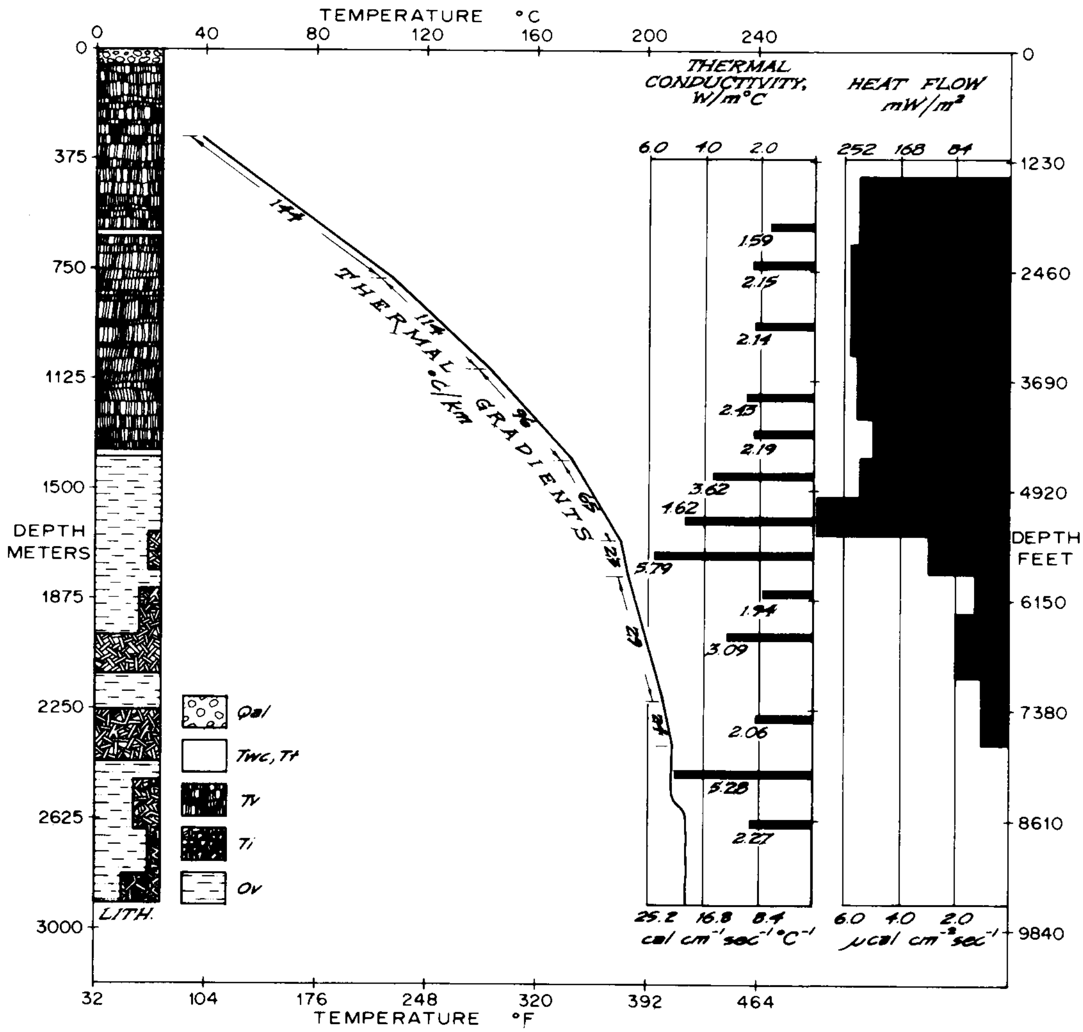

FIG. 10. Generalized lithology, thermal gradients and conductivities, and computed heat flow, Chevron Resources Co. Ginn 1–13 geothermal test well, Whirlwind Valley. Lithologic symbols given in Figure 2.

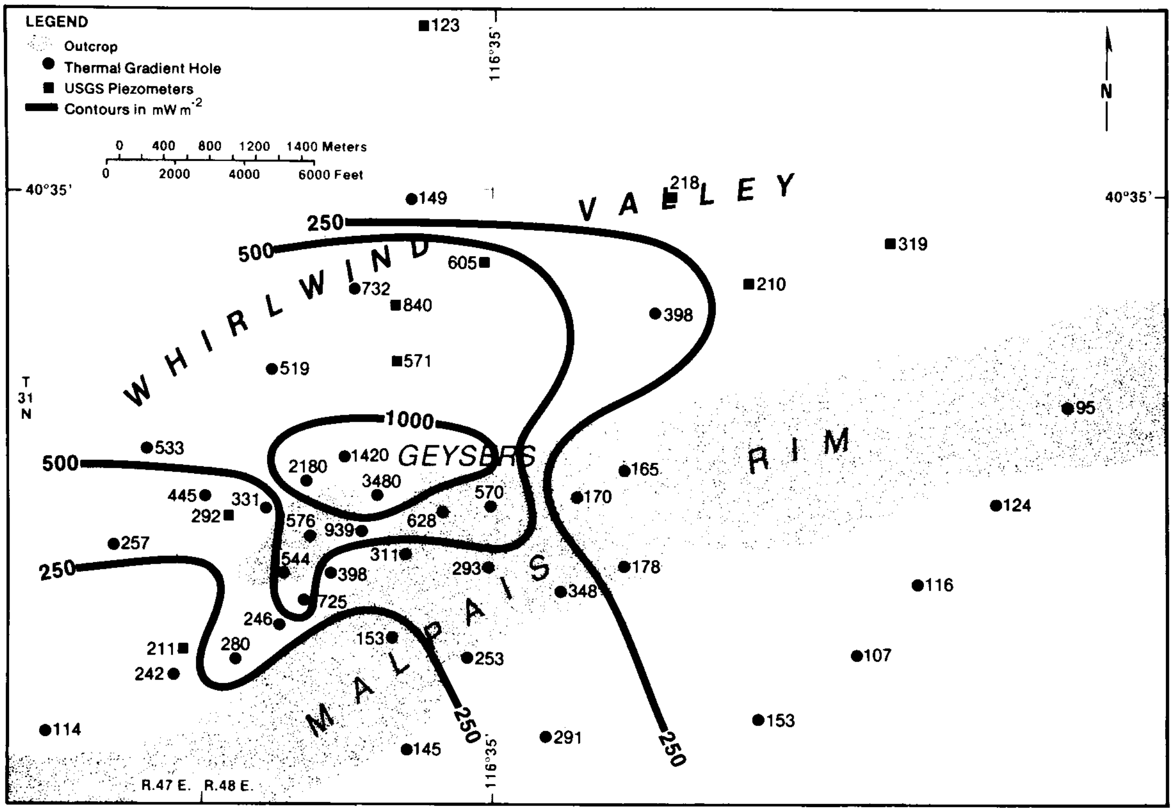

FIG. 11. Map of shallow heat flow, with generalized, variable contour interval in mW/m^2. Discrepancies among neighboring values have been ignored. These differences may be due to the wide range of depths over which the thermal gradient is calculated.

sured for these sedimentary units may be 20–30 percent too large. The matrix porosity of the competent rocks probably averages less than 10 percent and the required correction less than 15 percent.

The low thermal conductivities of the vitrophyric dacite flow and shard-rich tuffaceous sediments reflect their high glass content. The thermal conductivities of the volcanic flow and intrusive rocks cluster around 2 Wm^{-1}K^{-1}, but argillization of some of the dacite flows reduces their conductivity significantly. The high thermal conductivity and standard deviation computed for the Valmy formation reflect the preponderance of quartzite in the measured sample and a highly variable lithology.

An equilibrium temperature log of the Ginn 1-13 geothermal test well is shown in Figure 10 (Chevron Resources Co., 1979). The total depth of the well is approximately 2900 m and the bottom-hole temperature 213°C. It is essentially isothermal below a depth of 2400 m within the Valmy formation. Between 1600 and 2400 m, the temperature gradient decreases systematically. The hole either penetrates a hot water-bearing structure or a permeable formation. Given the fractured character of the Valmy (Evans and Theodore, 1978), it is likely that it could contain a high-temperature hydrothermal reservoir.

Above 1600 m, thermal gradients range from 23 to 144°C/km and thermal conductivities from 1.59 to 5.79 Wm^{-1}K^{-1}. The inverse relationship between the gradients and conductivities produces a nearly constant conductive heat flow averaging 235 mW/m^2. The uniformity of the heat flow above the inferred deep reservoir indicates that the Tertiary volcanic section acts as a relatively impermeable cap. The thermal water must find permeable structures to rise from depth.

Values of surficial heat flow were computed using linear segments of the shallow temperature-depth profiles like those shown in Figures 6 and 7. As shown in Figure 11, the heat flow generally exceeds the 235 mW/m^2 found in the Ginn test well. Most of the Whirlwind Valley and much of the Malpais Rim appear to receive heat not only from the deep reservoir but also from additional shallower sources. In the Whirlwind Valley, the shallow thermal flow system is a supplemental source of heat.

Along the Malpais Rim, the shallow heat flow exceeds the value from the Ginn well in the area between the two southeast-striking cross faults shown in Figure 1. While it is possible that this area contains conduits for upwelling thermal water, hydraulic head data would be required to resolve whether the fault zone channels water to or away from The Geysers.

A different thermal regime is apparent east of the Dunphy Pass fault zone. Four of the values of heat flow along the Malpais Rim average 110 mW/m^2, near the background value given by Sass et al (1971a) for this portion of the Basin and Range province. The Dunphy Pass fault zone appears to form the eastern margin of the Beowawe hydrothermal system. The 110 mW/m^2 average value may be realistic for background heat flow.

RECOMMENDATIONS

The hydraulic head of the shallow thermal flow system at Beowawe and most other hydrothermal exploration targets could be readily obtained by converting existing thermal gradient holes to piezometers. The conversion would consist of perforating the casing below the top of the thermal aquifer. In addition, a shallower companion piezometer open below the water table would make it possible to compute the vertical hydraulic gradient at these locations. Even if conduits for upwelling hot water were not located, the hydrologic data would surely augment the existing thermal data and refine the conceptual model of the resource.

Converting ungrouted thermal gradient holes to piezometers may not provide reliable hydraulic head values because of the difficulty of ensuring that the perforated interval is open to only an isolated portion of the aquifer (Benson et al, 1980). However, it should be possible to obtain both hydrologic and thermal data from piezometers that are later converted to thermal gradient holes. In areas where shallow drilling is planned, holes that intersect an aquifer could be initially completed as piezometers. A screen and a wellpoint would be attached to pipe and set at the bottom of the hole, the annulus filled with gravel to the top of the screen and grouted to the surface. After the static hydraulic head is obtained, the screen could be plugged with cement and the hole filled with water, converting it to a thermal gradient hole. Companion piezometers would be needed to obtain vertical hydraulic gradient data. This procedure is recommended as an integral part of future hydrothermal exploration programs.

At any geothermal prospect where drilling encounters water, the water is a source of data. The hydrologic-thermal field procedure recommended here requires repeated site visits and the drilling and completion of additional shallow, thin holes. This expanded exploration program is predicated on the assumption that it is worthwhile to gather as much meaningful data as possible at a reasonable price. The possibility of locating viable deep drilling targets with groundwater hydrology should encourage geothermal exploration managers to incorporate hydrologic data acquisition in their exploration plans.

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REFERENCES

Benson, S., Goranson, C., Noble, J., Schroder, R., Corrigan, D., and Wollenberg, H., 1980, Evaluation of the Susanville, California geothermal resource: Lawrence Berkeley lab rep. LBL-1187, 100 p.

Chapman, D. S., Clement, M. D., and Mase, C. W., 1981, Thermal regime of the Escalante Desert, Utah, with an analysis of the Newcastle geothermal system: J. Geophys. Res., v. 82, p. 11735–11746.

Chevron Resources Co., 1979, Open-file data released by Earth Science Laboratory, Salt Lake City.

Evans, S. G., and Theodore, T. G., 1978, Deformation of the Roberts Mountains allochthon in north-central Nevada: U.S.G.S. prof. paper 1060, 18 p.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, New Jersey, 604 p., Prentice-Hall, Inc.

Garside, L. J., and Schilling, J. H., 1979, Thermal waters of Nevada: Nevada Bur. Mines Geol., Bull. 91, 163 p.

Getty Oil Co., 1981, Open-file data released by Earth Science Laboratory, Salt Lake City, Utah.

Hubbert, M. K., 1940, The theory of groundwater motion: J. Geology, v. 48, p. 785–944.

Oesterling, W. A., 1962, Geothermal power potential of northern Nevada: Southern Pacific Co. report.

Robinson, E. S., 1970, Relations between geologic structure and aeromagnetic anomalies in central Nevada: GSA Bull., v. 81, p. 2045–2060.

Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W., and Moses, T. H., Jr., 1971a, Heat flow in the western United States: J. Geophys. Res., v. 76, p. 6376–6413.

Sass, J. H., Lachenbruch, A. H., and Munroe, R. J., 1971b, Thermal conductivity of rocks from measurements on fragments and its application to heat flow measurements: J. Geophys. Res., v. 76, p. 3391–3401.

Smith, C., 1979, Interpretation of electrical resistivity and shallow seismic reflection profiles, Whirlwind Valley and Horse Heaven areas, Beowawe KGRA, Nevada: Univ. of Utah Research Inst., Earth Science Lab, rep. no. 25, 43 p.

Sorey, M. L., 1971, Measurement of vertical groundwater velocity from temperature profiles in wells: Water Resources Res., v. 7, p. 963–970.

Stewart, J. H., Walker, G. W., and Kleinhampl, F. J., 1975, Oregon-Nevada lineament: Geology, v. 3, p. 265–268.

Struhsacker, E. M., 1980, The Geology of the Beowawe geothermal system, Eureka and Lander counties, Nevada: Univ. of Utah Research Inst., Earth Science Lab, rep. no. 37, 78 p.

Welch, A. H., Sorey, M. L., and Olmsted, F. H., 1981, The hydrothermal system in Southern Grass Valley, Pershing County, Nevada: U.S.G.S. open-file rep. 81-915, 193 p.

Zoback, M. L. C., 1979, A geologic and geophysical investigation of the Beowawe geothermal area, north-central Nevada: Stanford Univ. Publ., Geological Sciences, v. 16, 79 p.