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A TRANSIENT MODEL OF THE GEOTHERMAL SYSTEM OF THE LONG VALLEY CALDERA, CALIFORNIA

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ABSTRACT

The present-day geothermal system underlying the southern one-third of the Long Valley Caldera is discussed, based on interpretation of the complex shapes of temperature-depth curves and the correlation of this interpretation with hydrologic and geologic data. The results give information on the transient nature of the geothermal system operating in the Long Valley caldera. At the present time there is major west-east flow of hot fluid in two aquifers. The first aquifer is just below (and in places may be) the shallow groundwater table aquifer. Water is recharged at a temperature greater than 175°C west of Casa Diablo Hot Springs, and flows eastward at a velocity on the order of 100 to 200 m/yr to exit in the hot springs along Hot Creek and at the edges of Lake Crowley. Temperatures systematically decrease eastward in the shallow aquifer. In order to interpret the temperature data in Long Valley caldera, a model of the thermal effects of flow in a shallow aquifer is discussed, and the results are found to be consistent with geologic and hydrologic information. The shape of overturns of temperature versus depth curves indicate that the age of this aquifer ranges between 200-700 years; the best estimate is 500-700 years. The initiation of hot water flow in the shallow aquifer coincides with intrusive activity associated with the Mono/Inyo Crater chain of rhyolitic centers, which was active over a linear distance of about 40 km during the period 500-600 years ago. A second aquifer occurs just below the top of the Bishop Tuff at a depth of approximately 700 m in hole Mammoth #1. Less is known about the flow velocity and other characteristics of this aquifer. Modeling of the temperature-depth suggests that this aquifer is on the order of 3000 years old. Temperatures associated with both aquifers are evidence for transient events which caused a sudden

input of hot water along the west side of the caldera into an existing geothermal system that was circulating at temperatures below 120°C. Apparently, previous to the input of hot water into these aquifers, the geothermal system in the caldera was in a waning phase. The waning of the system may have been due to loss of porosity and permeability by mineral deposition in the circulation pathways and/or cooling of the caldera and subjacent intrusive rocks and a decrease in the thermal drive. There is no evidence at the present time of a large-scale, high-temperature geothermal system associated with the magma chamber identified by seismic studies beneath the resurgent dome. Whether the high temperatures in the current geothermal system reflect cooling of magma associated with Mono/Inyo Craters, or merely fracturing and reconnection of a pre-existing source of hot water to the shallow subsurface, is not known. Although the shallow flow of hot water is from west to east, deep temperature data suggest deep return flow of cold water from east to west in the caldera fill below the deep aquifer in the eastern part of the caldera. The velocity of this return flow is probably on the order of a meter per year, or two orders of magnitude below the velocity of flow in the shallow aquifers.

INTRODUCTION

The Long Valley Caldera is a 450 km^2 elliptical depression along the eastern front of the Sierra Nevada Mountains in east central California. It occurs along the boundary between the Basin and Range province to the east and the Sierra Nevada province to the west. Cenozoic volcanism in the vicinity began about 3.2 my ago and has continued until very recent times. The caldera was formed about 0.7 my ago by the eruption of approximately 600 km^3 of Bishop Tuff. The eruption of the rhyolitic Bishop Tuff resulted in the collapse of the roof of the magma chamber along steep ring fractures and deposition of about 1 km of infill tuff on the previous basement (Sierra Nevada granite and metamorphic rocks). Subsequent intracaldera volcanism caused resurgence of the west central part of the caldera floor. Extrusion of rhyolite, rhyodacitic and basaltic rocks occurred around the resurgent region between 0.6 and 0.5 my ago. Extrusion of rhyolite domes (Inyo domes) has occurred in the western third of the caldera intermittently to as recently as 500-600 years ago (Miller, 1984). In view of the large size of the caldera and its relatively young age, it is of great practical and theoretical importance to understand the nature of the fluid flow and geothermal systems in the caldera and the mechanisms of cooling of any large magma chamber which might underlie the caldera.

The Long Valley caldera has been extensively studied by the U. S. Geological Survey (see Muffler and Williams, 1976). The geology and the geologic history of the caldera as discussed above were described by Bailey *et al*. (1976). The geophysical studies of the area have been numerous and detailed. In particular, the geometry of the fill of the caldera was described by Kane et al. (1976) and evidence for a contemporary magma chamber was developed from seismic data by Hill (1976) and Steeples and Iyer (1976).

The regional thermal setting of the caldera was discussed by Lachenbruch et al. (1976b) and the convective and conductive heat flow associated with the shallow hydrologic regime was discussed by Lachenbruch et al. (1976a) and Lewis and Sorey (1976). Subsequent studies of the heat flow associated with the hydrothermal system of the caldera have been published by Sorey et al. (1978), Diment et al. (1980) and Sorey (1984). In particular, Lachenbruch et al. (1976a), Sorey et al. (1978) and Diment et al. (1980) discussed in detail data from numerous shallow (less than 30 m) and intermediate (50 to 300 m deep) depth holes drilled for temperature gradient and heat flow studies. Sorey et al. (1978) described the groundwater hydrologic regime in the caldera and discussed some hypothetical models of the geothermal systems within the caldera. Since 1980 there has been extensive seismic activity along the south side of, and south of the caldera (Ryall and Ryall, 1981, 1983; Sherburne, 1980) which may be related to magmatism (Savage, 1983). Hermance (1983) has summarized recent geophysical studies of the caldera.

The heat transport models discussed by Sorey and Lewis (1976) and Sorey et al (1978) are characterized by a magma chamber under the western half of the caldera, major fluid upflow in the system only in the vicinity of Hot Creek gorge, and deep recharge (1-3 km depth) from the east and the west sides of the caldera toward Hot Creek. No significant shallow flow is included in the model, and the activity near Casa Diablo hot springs is not modeled. The magma chamber is assumed to be steady-state, so that the rate of magma influx must match the rate of heat loss in the geothermal system. The consequences of such an assumption in terms of the amount of magma flux are discussed by Lachenbruch et al. (1976b).

At the time of the geothermal studies mentioned in the previous paragraph, no direct information on the deep system within the caldera was available and interpretation of the geothermal system was based on the shallow data. Since these studies, thermal and lithological data from three deep holes in the caldera have become available (Smith and Rex, 1977; Petroleum Information Corporation, 1980; Gambill, 1981). These new data are not consistent with some major features of the models proposed previously.

During the same period of time, a better understanding of heat transfer in geothermal systems has developed. While the influence of lateral fluid flow on the thermal profiles and heat flow associated geothermal systems has long been realized, quantitative analysis has been lacking, in part because of lack of sufficient observations to constrain possible models. However, with the development of more sophisticated modeling techniques and with deep drilling in geothermal systems, a number of types of models have been developed. Several models have been discussed for the Imperial Valley geothermal systems (Goyal and Kassoy, 1980; Lau; 1980, Lippmann and Bodvarsson, 1983). However, the information for application of these numerical techniques usually does not exist until extensive deep drilling has occurred, and simple analytic approximations may be more useful in the early exploration stages of geothermal evaluation.

A very common phenomenon in Basin and Range geothermal systems, and indeed associated with many geothermal systems, is the intermittent injection of warm to hot water into the shallow cold water hydrologic system from a reservoir or circulating system deeper in the geothermal system. Flow patterns in many geothermal systems appear to change on the order of a few hundreds to a few thousands of years. Very often, the transient changes in the flow system result in temperature overturns. These temperature overturns were initially discussed by Bodvarsson (1969, 1973), who derived a one-dimensional temperature-time model for them. Ziagos and Blackwell (1981,

1984) developed a two-dimensional model for such flow systems (see also Bodvarsson et al., 1980, 1982). The object of this paper is to apply the model of Ziagos and Blackwell (1981, 1984) to the Long Valley system to demonstrate the usefulness of the solution, to elucidate the characteristics of the shallow geothermal system in the Long Valley Caldera, and to characterize the overall geothermal system and its history.

The basic geothermal system description might be as follows: a geothermal circulation system exists with relatively great depths of ciruclation and relatively high temperatures (for large scale systems to exist, flow has to occur over periods of tens to hundreds of thousands of years). The lower parts of the circulation system are kept open by solution as the colder waters are drawn toward the heat source and raised in temperature. However, circulation paths in the upper parts of the systems are often sealed by deposition as the rising hot fluids cool and precipitate minerals. Thus the actual paths by which the system exhausts fluid to the surface may vary as a function of time depending on the details of the tectonic and volcanic activity associated with the geothermal system. For example, active faulting may fracture or refracture a conduit which then leaks fluid for a period of a few hundred to a few thousand years until it is resealed. At some later time, the process is repeated. When a fracture is opened, fluid with a positive hydrostatic pressure with respect to cold groundwater rises up the newly opened fracture system to the water table. The hot water then floats on top of or displaces the cold groundwater and flows down the regional hydrologic gradient. As a result, very high temperature gradients exist in the air column above the groundwater, and depending on the age of initiation of the flow, large negative temperature radients exist below the flow zone. The fluid may also be injected into confined permeable horizons (with similar results). If the watertable is near the surface then all or part of the flow is lost as a hot spring. In the model developed by Ziagos and Blackwell (1981, 1984) the thermal effects of the overflow zone are calculated but the effects of the upflow zone are not included and conductive heat transfer is assumed outside of a discrete horizontal aquifer.

In the process of applying the flow model to the shallow geothermal system in Long Valley, three different hypotheses with respect to the deep geothermal system underlying the shallow system will be evaluated. These hypotheses are: 1) that in fact no deep system underlies the caldera and the high temperatures in the geothermal system are associated with warming of water in the west end of the caldera by dikes underlying the very young rhyolite domes; 2) a deep system exists in the central part of caldera with temperatures in excess, perhaps much in excess, of 180-200°C, which feeds the shallow system (this has been the model upon which most of the previous analyses have been based); 3) a deep system exists in the west or southwest end of the caldera with minimum temperatures between 180°C and 200°C, which feeds the shallow system.

TEMPERATURE AND HEAT FLOW PATTERN

The shallow heat flow characteristics of the Long Valley caldera have been discussed extensively by Lachenbruch _et al_. (1976a) and by Sorey _et al_. (1978). These data can be supplemented with information from the three subsequent deep drill holes and one shallow (200 m) drill hole which was not used in the previous discussions. The hole locations have been taken from Sorey _et al_. (1978, Plate I). Heat flow values for holes not discussed in that paper are based on thermal conductivity listed in Table 5 of Sorey _et al_. (1978). The hydrologic properties of the caldera have been discussed in detail by Sorey et al. (1978). Particularly pertinent to this discussion is the shallow hydrology. The water table elevation drops approximately 350 m between the west edge of the caldera and the Owens River - Lake Crowley region. The strike of the water table contours is approximately north-south (Sorey et al., 1978).

Shallow Hole Results Temperature-depth data in shallow holes in the Long Valley caldera have been discussed by Diment et al. (1980). Temperature-depth curves for the southern part are shown in Figure 1. The locations of the holes are shown in Figure 2. Temperature gradients are extremely high near the surface; in some of the holes temperatures exceed 100°C at depths of less than 50 meters. However, most of the holes show a temperature maximum at shallow depths and a temperature decrease below 50 to 100 m, so that temperatures at depths of 200-300 m are much lower than those at shallow depths. Temperatures in other holes in the caldera, particularly to the north of the holes shown in Figure 1 (see Figure 2), show little if any temperature increase to depths of at least 150-300 m.

Figure 2 shows a "shallow" heat flow map similar to that presented by Sorey et al. (1978), but modified by including data from Chance #1, Endogeneous #1, and Clay Pit #1 (see Table 1). Inclusion of these data changes the configuration of the very high heat flow values. Instead of being confined to the area west of Hot Creek (where there are extensive hot springs), the contours of high heat flow extend to the west, and the heat flow anomaly is depicted as a sausage-shaped feature at least 10 km long, 3 or 4 km wide, with heat flow values in excess of 1500 mWm^{-2} over the whole area. In most of the previous discussions and models, major significance has been attached to the Hilton Creek fault zone and to the hot springs in Hot Creek (see Figure 2). It has been generally concluded that significant recharge of hot water into the shallow system is occurring at these positions (Lachenbruch et al., 1976a; Sorey and Lewis, 1976; Sorey et al., 1978). However, the argument for this recharge near Hot Creek is weakened by the presentation of the heat flow data in Figure 2. It is true that maximum heat flow values in the caldera occur in the vicinity of the Hilton Creek fault zone, but high heat flow values extend to the west up the hydrologic gradient. In view of the strong groundwater flow from west to east (see Sorey et al., 1978) it seems unlikely that the shallow geothermal leakage would move up the hydrologic gradient, and in fact, it seems much more likely that the fluid would move in the direction of the hydrologic flow (from west to east).

Deep Hole Results Temperature-depth curves from the three deep drill holes are shown on Figure 3 (P.I., 1980; Smith and Rex, 1977 Sorey, personal communication, 1983) and estimated heat flow values from these holes are shown in Table 1. The data from Union Geothermal Incorporated Clay Pit #1 and Republic Geothermal Incorporated 66-29 do not represent equilibrium temperatures while the data from the second logging of Union Geothermal Incorporated Mammoth #1 do represent equilibrium temperatures. The cooling effect of the drilling is clearly shown on the 8/29/79 log run shortly after completion of drilling. For the purposes of this discussion, however, the holes are probably close enough to equilibrium to constrain the interpretation.

The high temperatures anticipated on the basis of the fluid geochemistry do not occur in the wells (1.5-2.1 km deep) within the caldera fill, which might be expected to represent the porous units that would permit geothermal fluid circulation. In fact, well 66-29 has a sub-regional temperature of only 72°C at a depth of 2100 m (see Table 1).

Heat flow values based on the bottom hole temperature data from these three wells are shown in Table 1 as "deep" heat flow. The thermal conductivity values have been assumed based on measured values (Sorey et al., 1978, Table 5) with upper limit assumed in calculating heat flow. Nonetheless, the heat flow values are significantly lower than might have been anticipated (see Sorey et al., 1978, for example). The actual observed values range from a maximum of 130 mWm^{-2} at the Clay Pit #1 hole to approximately 40-120 mWm^{-2} (depending on the assumptions) for the 66-29 and Mammoth #1 wells. Heat flow values outside the caldera to the east and north are regional to subregional (see Table 2). The highest regional heat flow outside the caldera is observed to the west at Devil's Post Pile ($159mWm^{-2}$).

Thus the heat flow values for the deep holes, with the possible exception of Clay Pit #1, are less than or equal to regional background heat flow. If a major magma chamber has existed and remained uncooled in the western part of the caldera for a period of a 0.5-1 my, then heat flow values at a depth of 2 km could be expected to be 50 to 200% higher than those actually observed (Lachenbruch et al., 1976b; Sorey et al., 1978) unless the temperatures are held low by rapid cold fluid flow along a down or laterally flowing limb of a major convection system. Furthermore, the available drill holes do not locate any major high temperature geothermal system circulating within the caldera fill since the highest observed temperature below 330 m is 106°C (except for the narrow high temperature zone in Mammoth #1 at 700 m).

Based on the data, a conceptual model for the geothermal system is shown in Figure 4. Hot water is charged into a shallow aquifer at a depth of 50 to 100 m, and into a deep aquifer at about 700 m to the west or south of Casa Diablo hot springs. The fluid comes either from groundwater heated by dikes or from geothermal fluid recharge from depth. This model does not include significant thermal fluid input into the shallow system from Hilton Creek fault zone, which has previously been the focus of most of the attention. An analytical model that can be applied to this area will be briefly discussed in the next section.

THE SHALLOW GEOTHERMAL SYSTEM

Mathematical Modeling The temperature-depth curves shown in Figures 1 and 3 dramatically illustrate the temperature overturns observed in all of the holes along an east-west section from Casa Diablo to Lake Crowley. Ziagos and Blackwell (1981, 1984) discuss a model for temperature and heat flow in and above a geothermal system characterized by lateral fluid flow along a thin sub-horizontal aquifer. A similar model with a slightly different boundary condition was presented by Bodvarsson *et al*. (1982).

Of particular interest are the temperatures in the aquifer (assumed to be thin and at depth ℓ) and the conductive temperatures below the aquifer. If the aquifer has been flowing for a long enough period of time so that the temperatures in the aquifer can be considered steady-state, then the temperature in the aquifer as a function of distance from the recharge point (x) is given by:

$$T(x,\ell,t) = T_a \, e^{-\alpha x/\ell} \, \mathrm{erfc} \, \frac{\alpha x}{\sqrt{4kt''}} \qquad (1)$$

where the parameter α is given by $\alpha = {}^{K}/VMC$. In this equation, K is the thermal conductivity of the rock, V is velocity of water flow through the aquifer, C is heat capacity of the water, and M is mass per unit area of water in contact with the rock. The parameter k is thermal diffusivity and $t'' = t - x/V - \alpha\ell x/3k$. At some time (based on the value of the argument of the complementary error function) after the front of the fluid flow has passed a point, the aquifer temperature equation simplifies to:

$$T(x,\ell) = T_a\ e^{-\alpha x/\ell} \quad (2)$$

The approximate solution for the temperature in the half-space below the aquifer ($z \geq \ell$), where z is the depth below the aquifer and ℓ is the depth to the aquifer, is given by

$$T(x,z,t) = T_a\ e^{-\alpha x/\ell}\ \mathrm{erfc}\ \frac{\alpha x + \ell - z}{4kt''} \quad (3)$$

A similar equation applies in the layer over the aquifer ($z \leq \ell$), except that the solution is the sum of the differences of solutions like Equation (3). The major approximations are the assumption of no heat conduction in the x-direction, and conductive heat transfer outside the aquifer. Input data necessary to use this model include an estimate of the parameter α, the aquifer recharge temperature (T_a), the time (t), and the background gradient. Conversely, temperature-depth data may be inverted to estimate T_a, α and t and background gradient (Ziagos and Blackwell, 1984).

Characteristics of Shallow Aquifer Sorey et al. (1978) have discussed in detail the hydraulic characteristics of the shallow geothermal system in Long Valley. The pertinent information from that discussion is summarized in Table 3. Sorey et al. (1978, p. 32-33) indicate the heat loss from this part of the system is about 2×10^8W. They estimate that this heat loss corresponds to a flow of approximately 250 kg/sec of thermal fluid at a temperature of approximately 210°C. They model the system assuming that most of the hot fluid upwells in the vicinity of Hot Creek, while a smaller amount rises above Casa Diablo Hot Springs. Several different models are assumed but they all have similar characteristics. Including all the possible sources, a total heat loss for the Long Valley caldera of 2.8 x 10^8 W was calculated. This value corresponds to an average heat flow for the caldera (an area of approximately 450 km^2) of 600 mWm^{-2}.

The total heat loss of the caldera is quite modest in comparison to some large caldera systems. The mean heat flow for the Taupo graben (Elder, 1965) and the Yellowstone caldera (Fourier et al., 1976) is 2000 mWm^{-2} averaged over the area of the calderas. Because of the larger sizes of these two caldera features, the total heat losses are much greater than Long Valley, but average heat flow values are also much higher.

Heat loss values characteristic of Long Valley are similar to those found in different types of geothermal systems. For example, the Roosevelt Hot Springs system in Utah has a heat loss which is very analogous to Long Valley. The total heat loss at Roosevelt is occurring along a fracture zone approximately 4 km long by 2 km wide, and corresponds to a natural flow of approximately 200 kg/sec of water at a temperature of 260°C (Ward et al., 1978). Other hot spring systems such as Leach Hot Springs, Nevada, and so forth, have heat losses of 10^7-10^8 W. The point of this comparison is that the total heat loss for the Long Valley Caldera is not particularly high when compared to typical heat loss values associated with geothermal systems overlying large, shallow silicic magma chambers. Therefore, either the geothermal system may be in the waning stages, the magma chamber is more deeply buried under rocks less porous than the other caldera systems discussed, or the geothermal system in existence today is not directly related to geothermal systems which might have been associated with the cooling of the magma chamber associated with caldera formation and resurgence. Hence, rather than having one or more widespread high-temperature convection system, the caldera fill geothermal system in the Long Valley caldera may be characterized by a confined system with a relatively small zone of upflow.

Application of Analytic Aquifer Temperature Model As illustrated in Figure 4, the data are consistent with recharge of fluid at the far western end of the caldera and lateral flow of the hot fluid down the hydrologic gradient toward Lake Crowley. The flow takes place in a shallow and a deep aquifer. The parameters in the horizontal flow model discussed in the first paragraph of this section were estimated utilizing the information discussed by Sorey *et al*. (1978). These parameters are shown in Table 3. The aquifer is assumed to be 3.1 km wide, have a thickness of 32 m and an average porosity of 35%. Based on the discussion of Sorey *et al*. (1978), it is assumed that half of the geothermal fluid volume (130 ℓ/sec) is discharged by the springs in and above Hot Creek so that of the total mass flow, only 120 ℓ/sec actually reaches Lake Crowley. Of the total heat loss of 2.8×10^8 W, 1.2×10^8 W is lost by convective heat loss by spring flow (mostly in and above Hot Creek), 1.5×10^8 W is lost by conductive cooling of the hot aquifer, and only 0.1×10^8 W actually reaches Lake Crowley as convective loss at the downstream end of the aquifer. The actual fluid loss at the springs in Hot Creek Gorge is 247 ℓ/sec, so that some dilution by cold groundwater may have occurred either upstream or near the hot springs (up to a factor of about two).

In Table 3, two columns are shown for the groundwater aquifer above Hot Creek. Sorey *et al*. (1978) used a uniform thickness of 32 m for the aquifer below Hot Creek after noting that the thickness ranges from 20 to 46 m. The temperature data from Chance #1 and Endogeneous #1 suggest that the aquifer above Hot Creek may be somewhat thicker. Therefore for the purposes of this discussion, the calculations were made for aquifer thicknesses of 32 and 70 m. If the aquifer is 32 m thick, then the fluid flow rate is on the order of 228 m/yr, and if the aquifer is 70 m thick the velocity is 104 m/yr. In the thicker case the fluid velocity in the aquifer above and below Hot Creek is about the same, whereas if the thickness is constant the velocity is approximately half as fast below as above Hot Creek. In either case, the differences above and below Hot Creek would be accounted for by the loss of fluid at the hot springs in Hot Creek gorge.

One of the important model parameters for discussion of the aquifer thermal conditions is α. Utilizing the data shown in Table 3, α was calculated for each different situation. For the two cases of flow above Hot Creek, α is 0.00310 and 0.00678. Below Hot Creek, the calculated value for α from the data presented by Sorey *et al*. (1978) is 0.00645.

Using these parameters, the theoretical change in temperature with distance along the aquifer can also be calculated. The short time approximation to aquifer temperature includes the complementary error function term (Equation 1). In the long time behavior, the error function term becomes 1 and the aquifer temperature is given by equation (2). The magnitude of the error function term is estimated by assuming that the flow has been in existence for approximately 500-600 years and evaluating the term at a distance of 14 km from the input point. In this case the value of the complementary error function is 0.944 or within 5.6% of steady state. Thus the long time approximation can be used in this application.

The relation of temperature to distance in the aquifer is shown in Figure 5. The plotted temperature is the maximum temperature in the drill hole as a function of distance from Casa Diablo Hot Springs. The value plotted is obviously not the anomalous temperature, as no background has been subtracted. Of course a quantity of interest would be the background temperatures and the gradients below the aquifer at each point. An argument can be made based on the data below Hot Creek, that the background temperature is approximately constant with distance and so would have no effect on the rate of change of the temperature with distance. Above Hot Creek, the situation is more complicated, but because only two data points exist, not much can be said about that part of the flow system from the temperature distribution as a function of distance.

Using the data from the holes below Hot Creek, a exponential curve was fit to the data shown in Figure 5. The calculated value of α is 0.00582 for the aquifer below Hot Creek compared to the value derived from hydrologic reasoning of 0.00645. The difference is only 10% and since these two analyses are derived from completely different approaches the agreement is remarkable. The results demonstrate that the flow model can be used in other geothermal systems without such complete data if one or the other of the two sets of information were available. In many cases the hydrologic information may be easier to obtain without extensive drilling than the aquifer temperature. The great importance of determining hydrologic conditions for interpretation of the heat flow values, and vice versa, is clearly demonstrated.

The question of the input aquifer temperature (T_a) to be used is not significant below Hot Creek as the aquifer temperature is observed at Hot Creek. On the other hand the initial aquifer temperature (T_a) to be used for the portion of the aquifer above Hot Creek is not known directly. A conservative temperature to use would be just higher than that observed in the wells at Casa Diablo Hot Springs. A more realistic temperature to be used might be that derived from geochemistry (approximately 210°C). If T_a is 210°C, then the exponential curve shown (which was calculated by using the α values as shown in Table 5) can be extrapolated westward. In this case, the temperature of 210°C should occur at a distance of approximately 5 km from Casa Diablo Hot Springs. The most logical direction would be to the west, although there are other possibilities as discussed below. This distance information could be used in a design of an exploration program to determine the upflow zone or deep reservoir for possible geothermal exploitation.

MODELING OF TEMPERATURE-DEPTH CURVES

Deep Holes Other characteristics of the flow involve the length of time of flow and the background temperatures on which the flow is superimposed. In order to evaluate these parameters, theoretical temperature-depth models can be compared to observed temperature-depth data. If temperature-depth data were available from only one position as is the case in some situations, then it would not be possible to unambiguously separate the background temperature effect from the temperature effect of the aquifer (Ziagos and Blackwell, 1984). In Long Valley temperature data are available in the aquifer as a function of distance so that α and T_a can be independently determined. In addition there are temperature data for several holes which penetrate through the aquifer so that a more complete discussion of the background temperature effects and time period of flow is possible. In this section, the long time approximation equation is fit to each of the temperature-depth curves suitable for modeling using flow parameters listed in Table 3. The deep holes are discussed first.

The most informative and interesting hole for this part of the discussion is the Mammoth #1 deep hole at Casa Diablo Hot Springs as it shows the effects of transient flow in two aquifers. Observed and calculated temperature-depth curves are shown in Figures 6 and 7 for two different assumed background temperature characteristics. The equilibrium log is plotted for comparison.

The model of background temperature shown in Figure 6 assumes that the background temperature in the caldera at the site of the drill hole is consistent with a heat flow value of 85 mWm^{-2}. Thus the gradient in the upper part of the hole is consistent with a conductivity of 1.05 $Wm^{-1}K^{-1}$, the gradient in the Bishop Tuff is consistent with a thermal conductivity of 1.7 $Wm^{-1}K^{-1}$, and the gradient in the bottom part of the hole is consistent with an assumed conductivity for quartzite of 4.2 $Wm^{-1}K^{-1}$.

At intermediate depths in the hole (between 200 and 500 m) the effects of the two aquifers interfere and so their effects cannot be independently determined. However, there is no interference in the bottom part of the hole so an estimate of the age of the deeper aquifer can be determined from that part of the hole. The effects of the aquifer superimposed on the background are shown in Figure 6. It can be seen from simple curve comparison that an age of flow for the deeper aquifer of about 4000 years is consistent with the data. If the effects of the deep aquifer are subtracted from the shallow part of the temperature-depth curve, a temperature effect and an age for the shallow aquifer can be determined. The superposition of the effects of the aquifers is shown in Figure 6. Using this background, an age for the upper aquifer on the order of about 1500 years is calculated. In this calculation the same assumed α and T_a have been used for the deeper aquifer as for the shallower aquifer, even though the characteristics of the deeper aquifer are unknown (since only one temperature-depth curve is available). Changes in these parameters would not change the calculated age significantly, however. With the assumed background, the age of both the aquifers would be on the order of thousands of years and both would be considerably older than the age inferred for the groundwater aquifer below Hot Creek (see following section).

Since the argument was made above that there is only one groundwater aquifer at shallow depths, another model of background temperatures was examined, which gave results for the shallow aquifer more consistent with the aquifer below Hot Creek. In this calculation (Figure 7), the background temperature was assumed to be approximately 84°C plus 11°C/km times the depth in km. The superposition of several calculated aquifer ages for both the deep and the shallow aquifer are shown in Figure 7. In this case, best ages for the deep aquifer and shallow aquifer of approximately 3,100 years and 700 years are calculated. A conductivity of 1.05 $Wm^{-1}K^{-1}$ was assumed for the upper aquifer calculation. A conductivity of 1.7 $Wm^{-1}K^{-1}$ was assumed for the lower aquifer calculation.

It might appear that the assumption of the background temperature in the calculation is arbitrary compared to the assumption of conductive heat flow in the first case. However, it is clear that temperatures are subnormal in the eastern part of the caldera, and temperatures in the Clay Pit #1 hole are not compatible with conductive heat flow in the caldera even if the effects of the transient aquifers are ignored.

The fit to the observed temperature-depth curve illustrated in Figure 7 is quite good and the effect of superposition is clearly shown. Comparison of the location of the aquifers to the geology suggests that the shallow aquifer is coincident with or just below the groundwater table aquifer and that the deeper aquifer occurs just below the top part of the Bishop Tuff.

Modeling of Shallow Holes Calculated effects of temperatures based on transient aquifer flow applied to the shallow holes east of Casa Diablo Hot Springs are shown in Figures 8 and 9. As in the case of the Mammoth #1 hole, two different backgrounds are investigated. The first of these consists of a background gradient of 110°C/km and a surface temperature of 10°C (shown in Figure 8). This background gradient implies a conductive heat flow of 80-120

mWm^{-2} given a thermal conductivity of 1.05 $Wm^{-1}K^{-1}$. The difficulty with this model is that it implies successively older ages for the aquifer in drill holes further downslope along the aquifer because the temperatures are constrained to go through the bottom point of holes R-7 and C-5. Furthermore, extension of this gradient to depth is not consistent with the deep data in Republic #66-29. In fact the background temperature in that hole at 1500-2000 m is apparently about 50°C which would be reached at about 350 m using the assumed background gradient.

In the second model a constant background temperature in this part of the caldera of 40°C is assumed. In this case a more consistent set of ages for various holes are obtained. These ages are summarized in Table 4. The results from hole Mammoth #1, discussed above, are also included. In both cases the results obtained using the Model 2 background temperatures are preferred because of their general consistency as a function of distance east of Casa Diablo hot springs. In general the holes north of and including R7 (R7, R2, C7, C10, not including #66-29) have an apparent aquifer age on the order of 150   100 years while the southern holes (R4, R6, and C5) have apparent aquifer ages on the order of 200-500 years.

In fitting calculated temperatures to observed temperatures in these holes, the assumption is made that the temperature in the aquifer is uniform. However, it is quite obvious from consideration of the temperature-depth curves that the temperatures are not exactly uniform and picking a point to match for the conductive effect below the aquifer is subjective. Thus it is possible to change the actual ages of match by a few tens of years depending on the precise point picked to start the comparison. In view of the other assumptions and interpretations, this variation does not significantly affect the results.

The shape of the temperature-depth curve in hole #66-29 is not similar to the shallow holes. However, it is interesting that the maximum temperature observed in the upper part of #66-29 is consistent with its position in the groundwater flow system (see Figure 5). It is not clear whether the groundwater flow system is somewhat deeper at this point or whether it is blocked from the area around the hole site by permeability variations.

There is a significant variation in the calculated age of the aquifer in the different holes. The ages are most consistent for the holes in the northern group. Two southern holes have significantly older ages. Two of the holes (R5 and CH 1) have curves which indicate either a very thick aquifer or vertical leakage (either upward from a deeper aquifer or downward from the groundwater aquifer). Because the temperatures in the holes reflect variations in aquifer characteristics (thickness, three-dimensional permeability, porosity, thermal conductivity, and variations in water table elevation, etc.) as well as the effects of the assumed flow, the agreement of ages may be as good as can be expected. The holes may not be completely grouted, so that intrahole water flow may occur and the holes C7 and C10 are not deep enough for a reliable determination of age.

The results are that an age of several hundred years for the aquifer is reasonable. At a velocity of flow of 100 m/year, it would take over 100 years for temperature changes in the aquifer to propagate from the western input end to the eastern discharge end. The older age of the aquifer at Casa Diablo hot springs is therefore consistent with the expected age progression.

If the background temperature in the eastern part of the caldera is 40°C, the deeper aquifer (along the top of the Bishop Tuff--see Figure 4) observed in Mammoth #1 may also be present in hole #66-29, but considerably reduced in amplitude. In this case the relative temperature amplitude in both aquifers is similar, suggesting similar flow velocities. It is possible that the effects of the aquifers have been considerably smeared by the drilling effect, and if the hole had been allowed to reach equilibrium, then the temperature-depth curve would resemble the one in Mammoth #1 more closely (see Figure 3). As noted by Diment _et al_. (1980, p. 38), the temperatures are not at equilibrium. During the drilling geothermal wells, temperature-depth curves of this type will often be smoothed drastically by the drilling effect, even to the point that the aquifers are not recognized during the initial logging. An example of this particular phenomenon is clearly illustrated by Benoit _et al_. (1983) in the Desert Peak geothermal system in western Nevada. In such cases, the geothermal implications of the hole can be completely misinterpreted unless enough time is allowed for recovery to a more stable temperature configuration. This interpretation for hole #66-29 is speculative, however, in view of the fact that we do not know the equilibrium temperatures in the hole. The temperatures in the hole, though, are nonetheless consistent with the background temperature on the order of 40-50°C below 1000 m. This temperature is much below regional.

DISCUSSION AND CONCLUSIONS

One object of this paper is to investigate the characteristics of the shallow geothermal aquifer in Long Valley caldera in order to illustrate the application of the model developed by Ziagos and Blackwell (1981, 1984) and to use this model to determine some characteristics of the shallow flow system. It is concluded that transient thermal conditions are present in two major aquifers in the southern half of the Long Valley caldera. The first of these aquifers involves hot fluid flow along or just below the groundwater table, and it is this system that is responsible for most of the geothermal manifestations presently observed in the southern half of the caldera. Hot water is recharged from some point west or south of Casa Diablo Hot Springs and flows down the regional hydrologic gradient to exit at Lake Crowley. Along the way approximately half the original volume of the hot fluid is lost in the geothermal manifestations such as those along Hot Creek, at Casa Diablo and between Hot Creek and Lake Crowley. Geothermal flow in the aquifer was initiated 500-700 years ago. This age is in remarkable agreement with the age of the last major activity along the Inyo Crater zone of 500-600 years (Miller, 1984). A second transient thermal aquifer occurs below the top of the Bishop Tuff. This aquifer has been in existence for a longer period of time (on the order of 3000 years).

Based on this discussion, the second objective of this paper can be discussed: the three hypotheses describing possible geothermal systems in the caldera. These hypotheses are: 1) that in fact no deep system underlies the caldera and the high temperatures in the geothermal system are associated with warming of water in the west end of the caldera by dikes underlying the very young rhyolite domes; 2) a deep system exists in the central part of the caldera with temperatures in excess, perhaps much in excess of 180-200°C, which feeds the shallow system (this has been the model upon which most of the previous analyses have been based); 3) a deep system exists in the west or southwest end of the caldera with temperatures above 180°C to 200°C which feeds the shallow system. The evidence from the temperatures in the deep holes, and the consistency of the interpretation based on transient aquifer flow with the temperature and hydrologic evidence indicate that hypothesis number 2 can be disregarded as the major controlling part of the geothermal system. Thus only hypotheses 1 and 3 remain as possibilities.

If the shallow aquifers are charged from a deep source at a temperature near 210°C, as implied by the geochemistry, the input point would be 4-6 km from Casa Diablo hot springs. The distance uncertainty is quite large, however, as we know very little about the actual flow characteristics of the aquifer above Casa Diablo. The recharge might be from ring fractures along the southwest or northwest, or from faults or fractured intrusive conduits in the western third of the caldera. The deep recharge might be associated with fractures related to the zones along which seismic activity has recently occurred (which are the right distance from Casa Diablo hot springs). In any case the first indications of temperature changes would be observed at Casa Diablo hot springs. Fumaroles exist on Mammoth Mountain (Sorey et al., 1978) and these manifestations might be related to the source of the hot fluid.

An interesting speculation is that the shallow geothermal system might be associated with only shallow fluid flow and in fact no deep flow is involved. If the ages of these aquifers correspond to the ages of a possible intrusive associated with the Inyo domes, the shallow systems may merely be groundwater heated by flow past a shallow silicic intrusive underlying these young domes. Thus the presence of the geothermal system would imply that a still hot silicic magma underlies the west side of the caldera at very shallow depths. The heat loss value for the geothermal system of 2.0×10^8 W could be supplied by complete cooling of about .003 km^3/year of liquid dacite. Thus, over a period of a 1000 years the shallow cooling of about 3 km^3 of intrusive material could supply the geothermal system with heat. Such a volume is not unreasonable given the amount of extrusive activity associated with the Inyo Domes.

A final objective is to remove effects of the shallow flow system so that the background characteristics of temperature in the Long Valley caldera can be evaluated. The analytical model seems to be applicable to the shallow data, although some uncertainties are involved because of the many geologic and hydrologic complexities. Thus we conclude that the section shown in Figure 4 represents the present conditions in the southern half of the caldera.

If the transient effect of hot water flow in the two shallow aquifers is removed from the temperature-depth section shown in Figure 4, the temperatures in the caldera before recent changes in the aquifer flow are as shown in Figure 10. The background temperatures inferred from the analyses discussed with reference to Figures 7 and 9 were used to construct the isotherms shown in Figure 10. Previous to 3000 years ago, there was a large scale, low temperature geothermal flow system in the south half of the caldera having maximum temperatures on the order of 100-120°C. Along the section studied, major downflow is along the east side of the caldera, lateral circulation occurs in the lower parts of the caldera fill (Bishop Tuff), and major upflow occurs at the west side of the caldera. In addition mixing with cold groundwater at shallow depths may occur along the west side (see Table 3 footnote). The flow system is three-dimensional, and in the vicinity of the resurgent dome, either the flow system is being heated more effectively, some upflow is occuring, or flow is less rapid due to reduced permeability (as indicated by the high temperatures at depth in Clay Pit #1).

The correspondence of this inferred temperature-depth-distance distribution in the caldera to some of the calculated convective systems is rather remarkable. Because of the geometry, however, it is more like a regional flow system than a local geothermal system (the aspect ratio of the system may be as much as 10:1). This large-scale flow system was modeled using an approximate formulation of the fluid flow and heat transfer equations discussed by Lau (1980). Flow patterns and temperatures were calculated for a heat source in the west side of the caldera, a fluid flow system approximately corresponding to the limits of the caldera, and a Rayleigh number of 200. Calculated results were very similar to those actually observed and/or postulated. Temperatures in the flow system were initially in excess of 200°C. However, after period of approximately 100,000 years, temperatures in the flow system decreased to about 100°C and remained at that temperature for an additional several hundred thousand years. The maximum calculated flow velocities were on the order of 1 m/yr. Additional useful discussions of this sort of model are given by Norton and Knight (1977) and Cathles (1977).

Based on these observations and numerical results, the evolution of geothermal systems in Long Valley caldera can be discussed. During formation, the caldera was filled with almost a thousand meters of very hot Bishop Tuff. Extensive and very active geothermal systems developed associated with the cooling of the Bishop Tuff. This phase of the caldera geothermal system might have lasted for 100,000 to 200,000 years. Subsequently, long-term geothermal flow developed with the flow being driven by the presence of a rejuvenated magma system under the resurgent dome and/or west side of the caldera. Fluid recharge was from the east side of the caldera and discharge occurred along the west side of the caldera. This or a similar flow system has been in existence for several hundred thousand years and resulted in cooling of any magma on the west side of the caldera, the intrusive associated with the resurgent dome and shallow intrusive feeders for the 0.1-0.6 MY volcanism. It is this geothermal system that is probably responsible for the extensive saline deposits observed near Crowley Lake and for which a long period flow is required (as discussed by Sorey *et al.*, 1978 and Sorey, (1984)). By 5000 years ago the activity of the fluid flow had diminished as the cooling had proceeded to the point that the flow was no longer effective and/or mineral deposition had sealed off many of the channelways and fluid flow temperatures were quite low. Somewhere in the system, fluid with temperatures on the order of 210°C+ may still have been available, however. The previous flow system had homogenized temperatures over distances of kilometers and must have existed for several tens or hundreds of thousands of years. Within the last few thousand years, the hot fluid has been injected at least twice into shallow aquifers as a result of tectonic and/or intrusive/thermal events. As a consequence, shallow penetration of hot water with two orders of magnitude greater fluid flow velocities has been superimposed on the existing convection pattern. This aquifer flow represents circulation on a relatively small scale, however, compared to the much larger distributed flow system associated with the caldera as illustrated in Figure 10.

From the point of view of geothermal exploration, the major enigma of Long Valley is the location of the possible high temperatures in a geothermal system and the question of whether or not an exploitable geothermal system exists. Obviously production of geothermal fluid from the thin aquifers, even though temperatures are relatively high, would not be very effective. It is clear that the west side of the caldera holds the key to the understanding of the source of the hot fluid and to the potential location of geothermal systems of commercial exploitable temperatures. The remainder of the caldera is either too old, too well sealed or too cooled by convection flow to offer attractive targets for geothermal exploitation.

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Table 1. Heat flow values calculated for holes drilled in Long Valley not discussed by Lachenbruch et al., (1976b) and Sorey et al., (1978). For calculation of the deep and shallow gradients the surface temperature was assumed to be 10°C. The assumed mean thermal conductivity for each deep hole is $1.7 Wm^{-1}K^{-1}$ (a maximum value). The shallow thermal conductivity was assumed to be $1.05 Wm^{-1}K^{-1}$.

Hole Name	Location	Depth m	Bottom Hole Temperature °C	Mean Gradient °C/km	Mean Heat Flow mWm^{-2}	Maximum Shallow Temp °C	Shallow Heat Flow mWm^{-2}
Long Valley #66-29	3S/29E-29db	2130	72	28.2	≤ 48	70	289
Mammoth #1	3S/28E-32bdb	1585	102	58.0	≤ 99	169	1368
Clay Pit #1	3S/28E-15add	1808	147	75.8	≤ 129	113	557
Endogeneous #1	3S/28E-32b	200		-	-	172	1546
Chance #1	3S/28E-35b	210	125	-	-	134	2170

Table 2. Measured heat flow outside of, but in the vicinity of, the Long Valley Caldera (data from Lachenbruch et al., 1976b)

	Elevation m	Gradient °C/km	Heat Flow mWm^{-2}	Distance from Rim (Direction) km
Devils Postpile	2316	51.4	157	3 (WSW)
Aeolian Buttes	2240	31.2	91	13 (NNW)
Waterson Canyon	2133	30.0	93	0 (SE)
Waterson Trough	2316	78.1	88	1 (E)
Waterson Trough	2393	25.0	70	3 (E)
Round Mountain	2225	24.0	79	6 (E)
Johnny Meadow	2637	6.1	17	6 (N)
Sagehen Meadow	2560	9.3	30	11 (N)

Table 3. Parameters of the groundwater aquifer in the southern part of the Long Valley Caldera. Aquifer characteristics below Hot Creek are from Sorey et al. (1978). The flow rate was calculated from the amount of fluid at 210°C required to release 2×10^8 W of heat upon cooling (Sorey et al., 1978).

	Above Hot Creek		Below Hot Creek
	Case 1	Case 2	
Aquifer Input Temperature (°C)	210	210	120
Heat Loss (cal/gm)	214	214	
Flow Rate (l/sec)	250*	250*	120**
Width of Aquifer (km)	3.1	3.1	3.1
Thickness of Aquifer (m)	32	70	32 (20-46)
Depth To Aquifer (m)	60	60	30
Porosity of top of Aquifer (%)	35	35	35
Velocity of Flow (m/yr)	228	104	109
Thermal Conductivity($Wm^{-1}K^{-1}$)	1.05	1.05	1.05
Flow Parameter, $\alpha = {}^{K}/MVC$	0.00310	0.0678	0.00645

*Assuming no dilution of the input hot fluid. In fact dilution may occur as the measured flow rate at the Hot Creek hot springs is 247 l/sec (Sorey et al., 1978, p. 33).

**The difference in the two flow rates is the volume of hot fluid lost along and west of Hot Creek.

TABLE 4. Age of intiation of hot water flow in the groundwater table and Top-of-Bishop aquifers in the southern part of Long Valley. The Model 1 and Model 2 ages are based on different assumptions of the background temperatures (see text). The model 2 ages are preferred.

Groundwater Table Aquifer

	Model 1		Model 2 (best)	
	Age (years)	#T(°C)	Age (years)	#T (°C)
Mammoth #1	3000	150	700	82
Chance #1	"old"	55	"old"	
C 10	250	90	250	55
C 7	"young"		"young"	
R 7	200-300	57	50-200	35
R 5	"old"	55	"old"	33
C 5	300-500	52	200-300	30
R 2	350-450	40	50-200	15
R 4	600-700	40	400-500	15

Top-of-Bishop Aquifer

Mammoth #1	5000	92	3100	61
#66-29	-	-	-	18(?)

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Figure Captions

Figure 1. Shallow temperature depth curves from the Long Valley, California data from Diment et al. (1980) and McNitt (1973) (Endogeneous #1). The locations of the holes are shown in Figure 2.

Figure 2. Location of holes and shallow heat flow map in the Long Valley caldera. The outline of the physiographic edge of the caldera is shown as a solid line. The dotted line represents the outline of the resurgent dome; dashed lines represent mapped normal faults (the Hilton Creek fault zone) and the ruled pattern indicates the young rhyolite domes of the Inyo domes complex. Locations and identifying numbers for each hole are shown. Locations of the major hot springs are also shown. Contours of heat loss from the shallow aquifer are in units of mWm^{-2} (1×10^{-6} cal/cm^2 sec = 41.84 mWm^{-2}).

Figure 3. Temperature-depth curves from deep and shallow holes in the Long Valley caldera (locations are given in Figure 2). The Clay Pit #1 and Long Valley 66-29 holes are probably not represented by equilibrium temperature measurements.

Figure 4. Conceptual model of the geothermal system in the southern half of the Long Valley caldera. The lithologic data are taken from published reports by Smith and Rex (1977), Petroleum Information, Inc. (1980) and Gambill (1981). Location and sense of displacement along the normal faults associated with the Hilton

Creek fault zone are shown. The presence of two temperature overturns associated with the groundwater aquifer and the "top of the Bishop" aquifer are shown. The presence of subnormal temperatures in the eastern part of the caldera is indicated by comparison with the regional isotherms (see extreme right hand side of figure) based on an assumed typical heat flow of $80mWm^{-2}$.

Figure 5. Plot of maximum temperature in the shallow groundwater aquifer as a function of distance from Casa Diablo hot springs. The Hot Creek hot springs are associated with the change in slope of the temperature vs. distance curve. The line shows a least squares fit to the temperature-distance data below Hot Creek. The calculated value of the flow parameter α from this fit (0.00582) can be compared to the independent calculation of the value of α determined from the hydrologic data in Table 3 (0.00645).

Figure 6. Comparison of observed and calculated temperatures in Mammoth #1 (and Endogenesus #1) at Casa Diablo hot springs based on an assumed heat flow of $85mWm^{-2}$ and a surface temperature of 10°C. Theoretical curves calculated for the two different aquifers for different flow periods are shown. Calculated shallow aquifer temperatures are indicated by the dashed lines and calculated deep aquifer temperatures are indicated by dot-dash lines.

Figure 7. Same as Figure 6, but with an assumed "surface" temperature of 84°C and a background gradient of 11°C/km.

Figure 8. Comparison of calculated and observed temperatures from shallow holes east of Hot Creek. The background temperature assumed for this model is 100°C/km with a surface temperature of 10°C. The numbers shown in each curve refer to the age of the flow at each point. Hole C-4 is actually east of the area in consideration.

Figure 9. Same as Figure 8, but with an assumed background temperature of 40°C below a depth of 30m (constant with position). All other parameters are the same.

Figure 10. Hypothetical temperature-depth-distance model for the southern half of the Long Valley caldera if the effect of shallow overflow in the transient aquifers is removed. The temperatures were reconstructed by interpolation from background temperatures for Mammoth #1 and the holes east of Hot Creek (Figures 7 and 9).

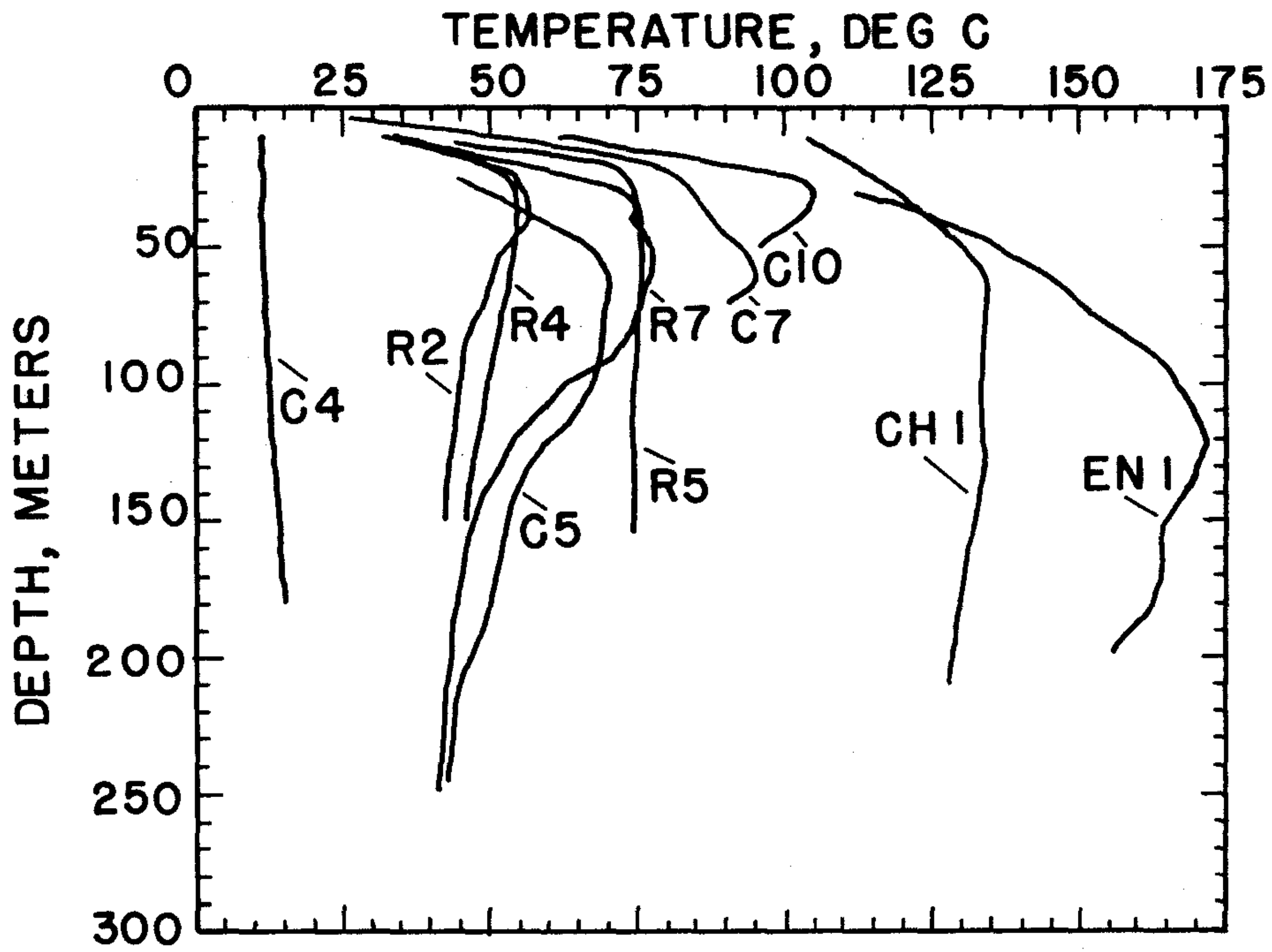
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Fig 1

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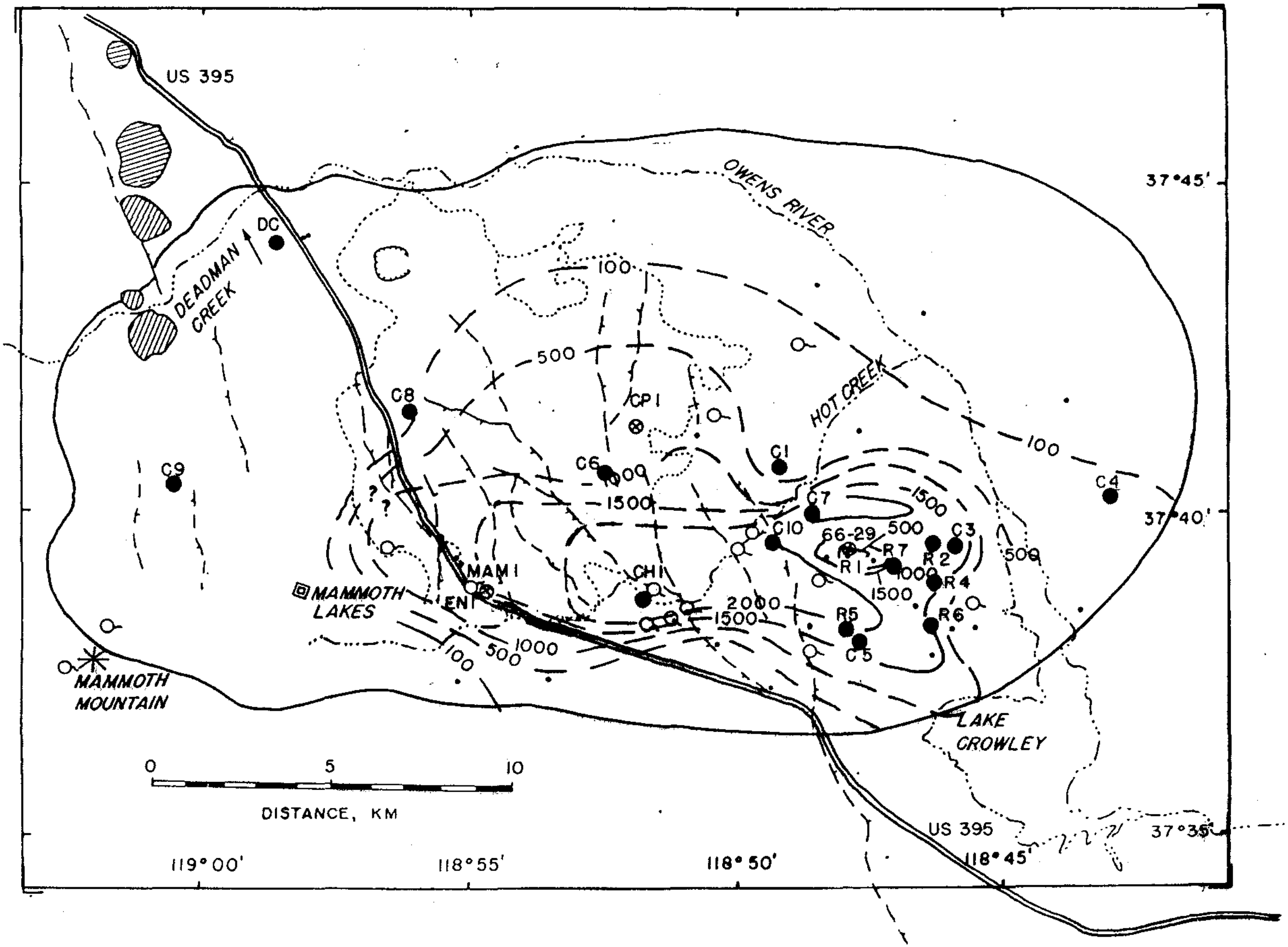
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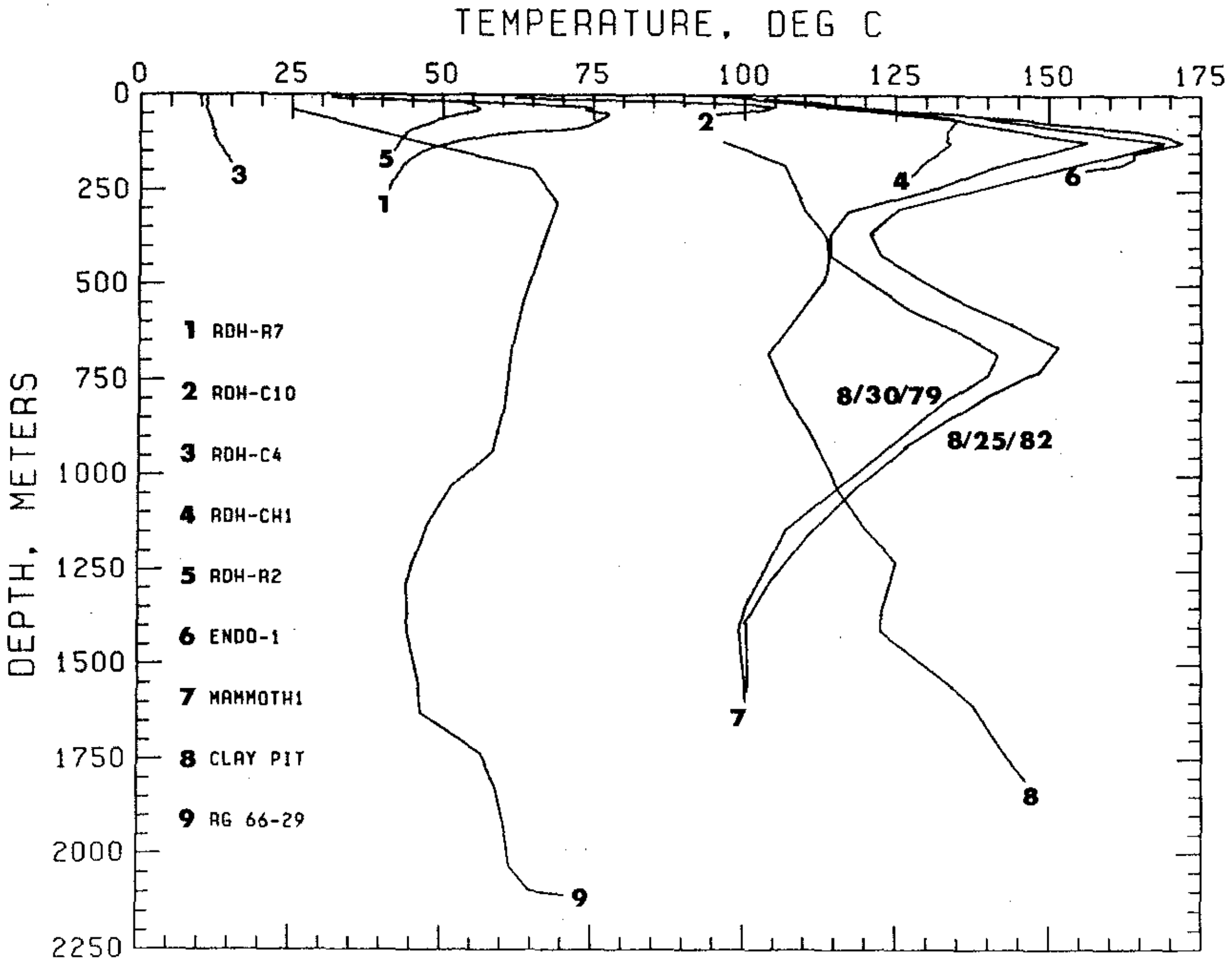
Fig 2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2 RDH-C10
3 RDH-C4
4 RDH-CH1
5 RDH-R2
6 ENDO-1
7 MAMMOTH1
8 CLAY PIT
9 RG 66-29
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Fig 3

④

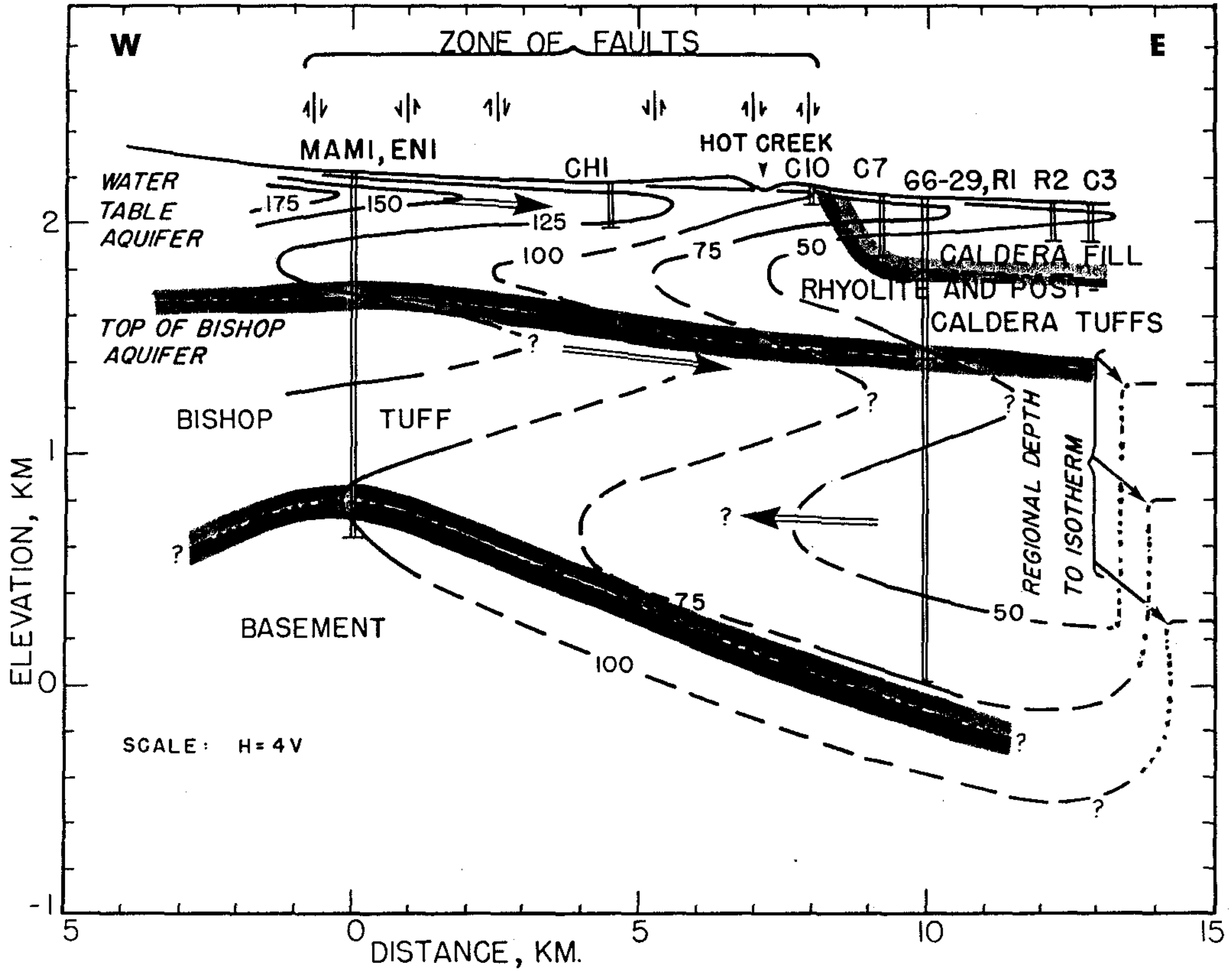
W
E
ZONE OF FAULTS
MAMI, ENI
CHI
HOT CREEK
C10
C7
66-29, RI
R2
C3
WATER TABLE AQUIFER
175
150
125
100
75
50
CALDERA FILL
RHYOLITE AND POST-CALDERA TUFFS
TOP OF BISHOP AQUIFER
BISHOP TUFF
?
REGIONAL DEPTH TO ISOTHERM
BASEMENT
75
100
50
SCALE: H=4V
ELEVATION, KM
DISTANCE, KM.
2
1
0
-1
5
0
5
10
15

Fig 4

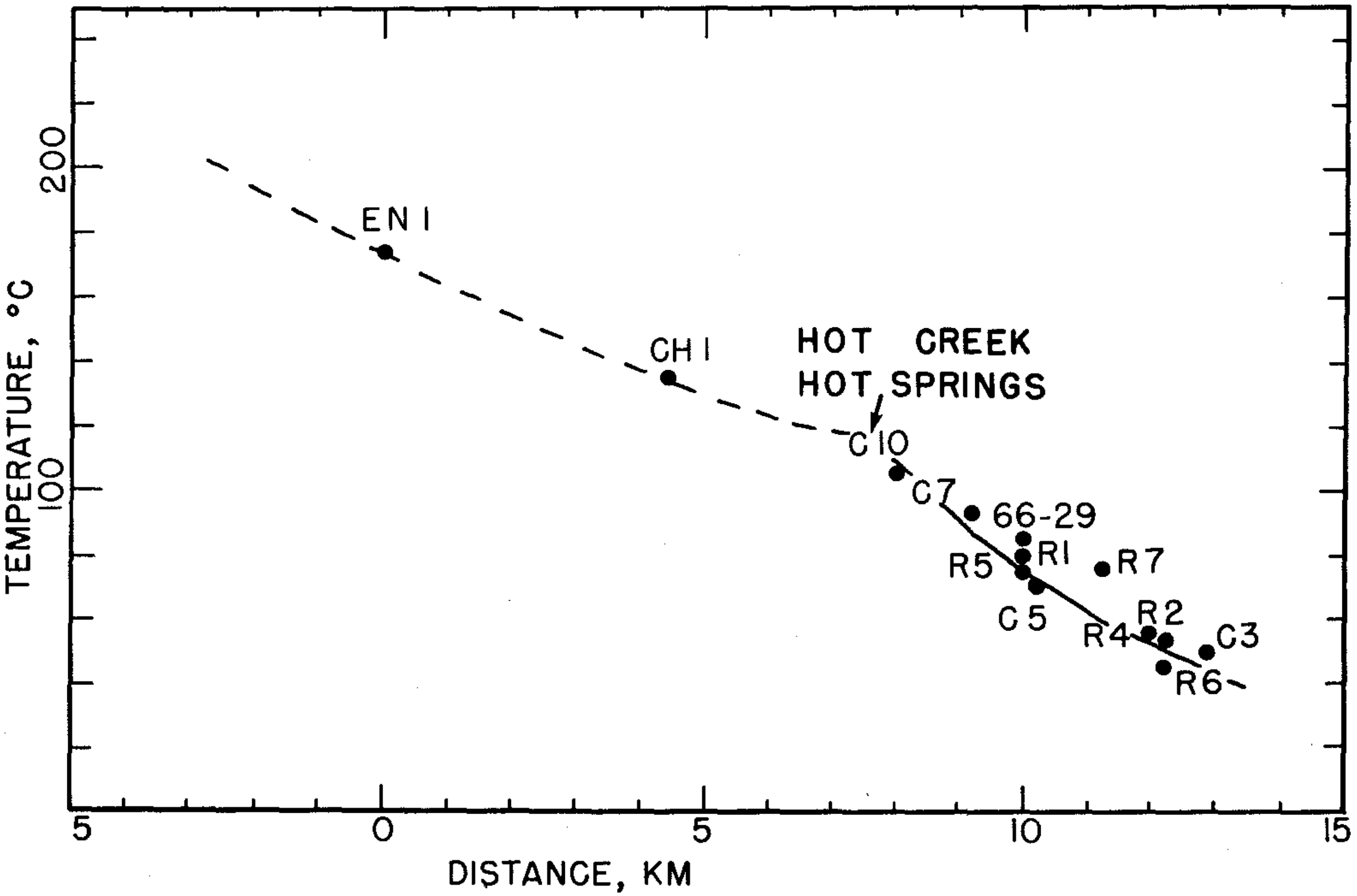
TEMPERATURE, °C
200
100
DISTANCE, KM
5
0
5
10
15
EN I
CH I
HOT CREEK
HOT SPRINGS
C10
C7
66-29
R1
R5
C5
R7
R4
R2
C3
R6

Fig 5

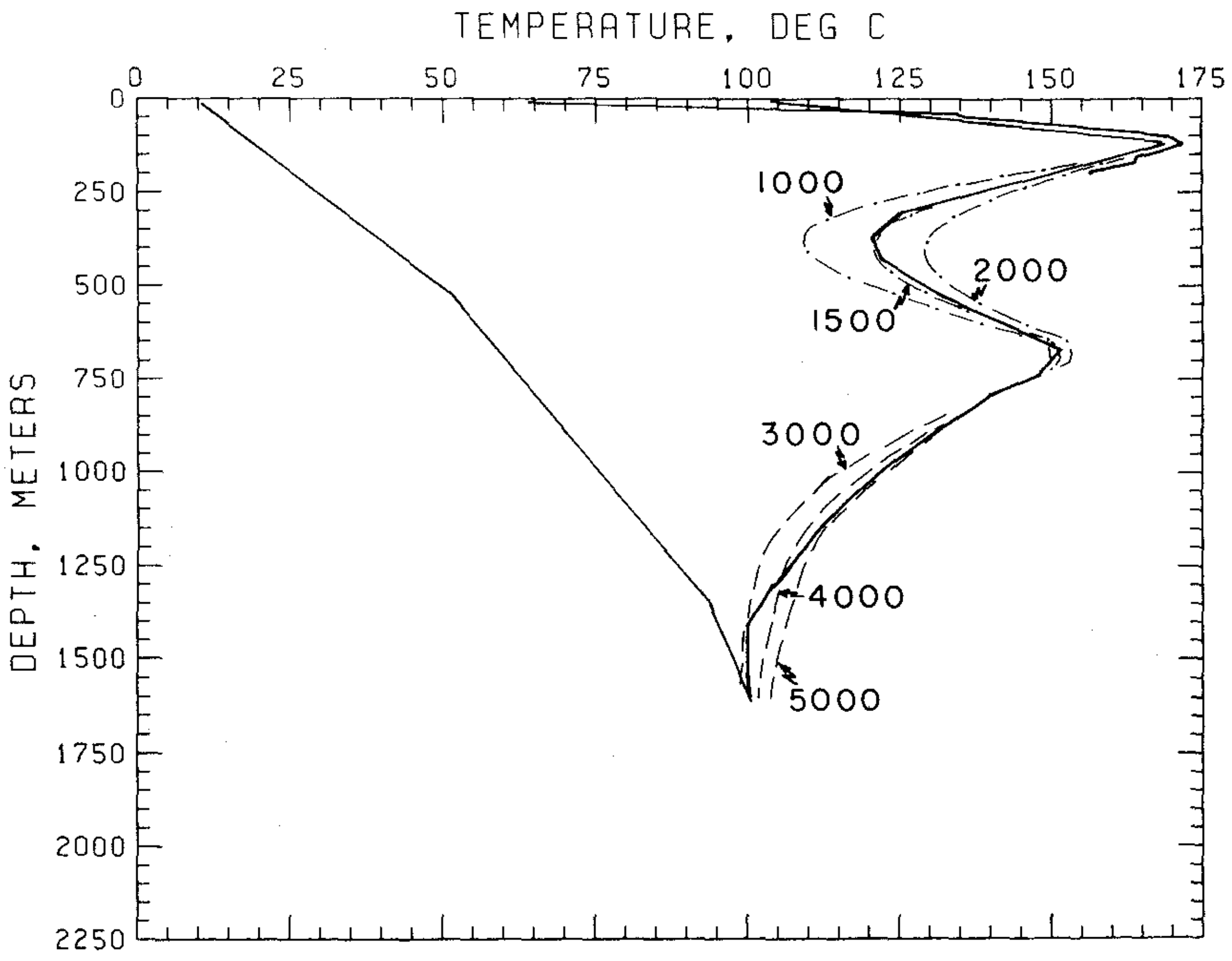
TEMPERATURE, DEG C
0
25
50
75
100
125
150
175
DEPTH, METERS
0
250
500
750
1000
1250
1500
1750
2000
2250
1000
2000
1500
3000
4000
5000

Fig 6

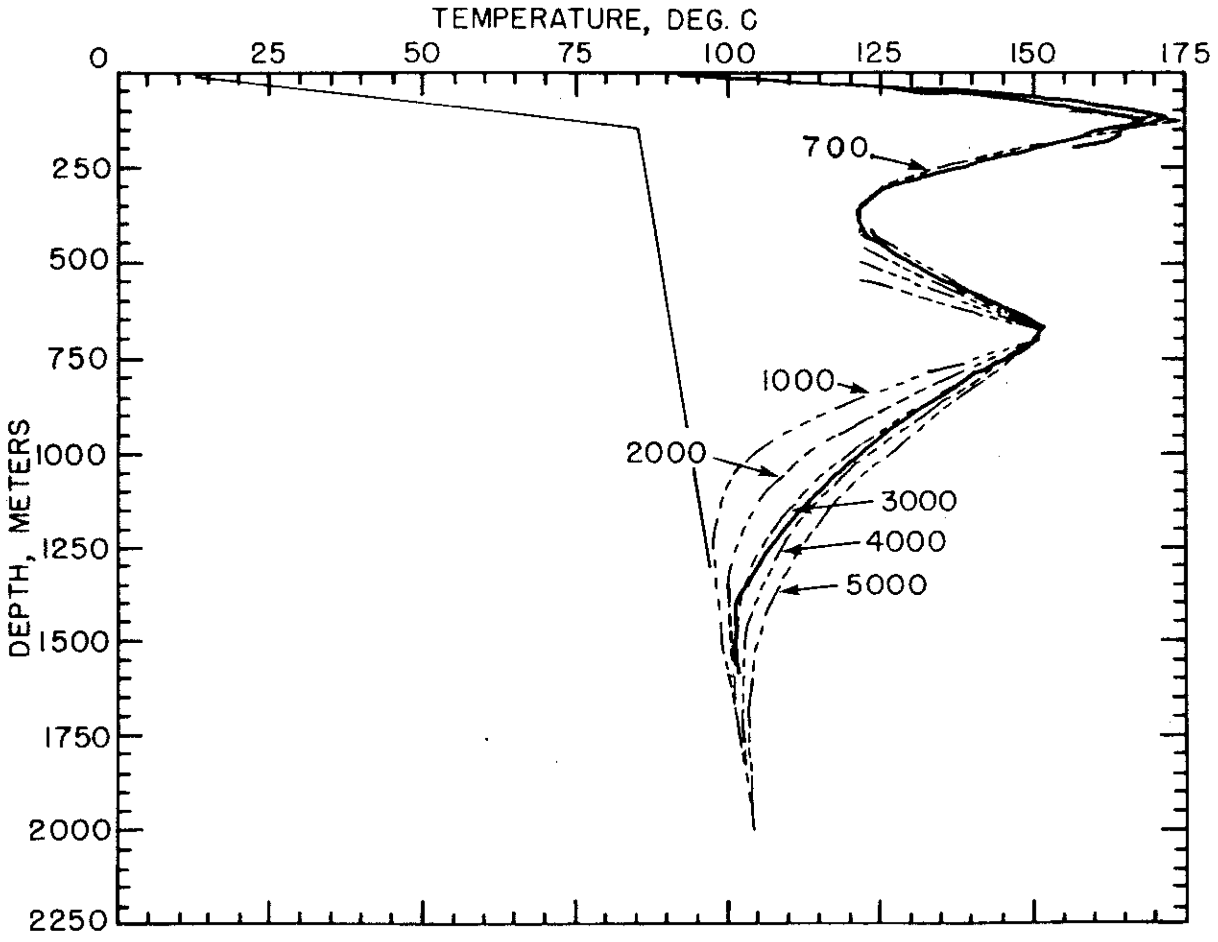
TEMPERATURE, DEG. C
0
25
50
75
100
125
150
175
DEPTH, METERS
250
500
750
1000
1250
1500
1750
2000
2250
700
1000
2000
3000
4000
5000

Fig 7

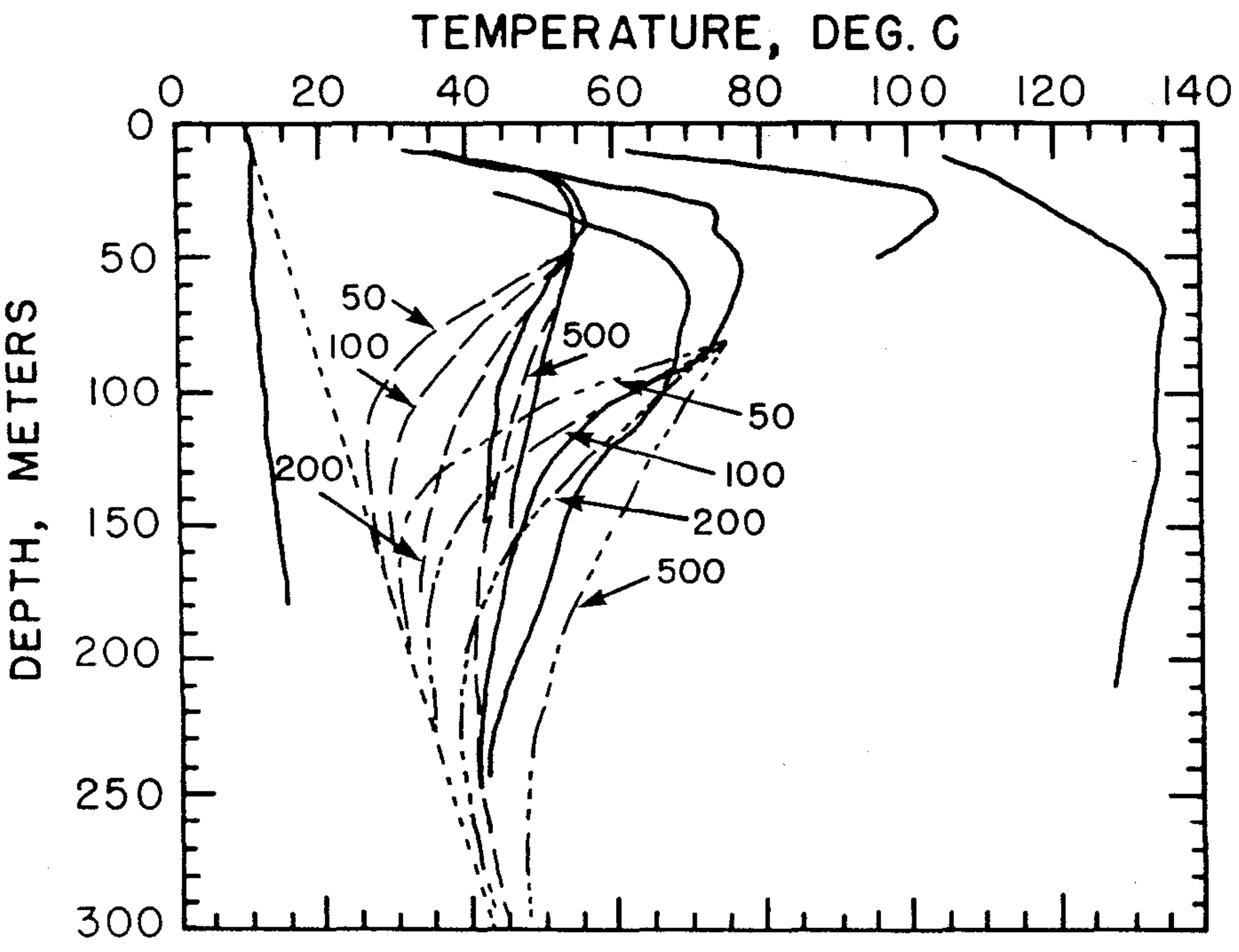
TEMPERATURE, DEG. C
0
20
40
60
80
100
120
140
DEPTH, METERS
0
50
100
150
200
250
300
50
100
500
200
50
100
200
500

Fig 8

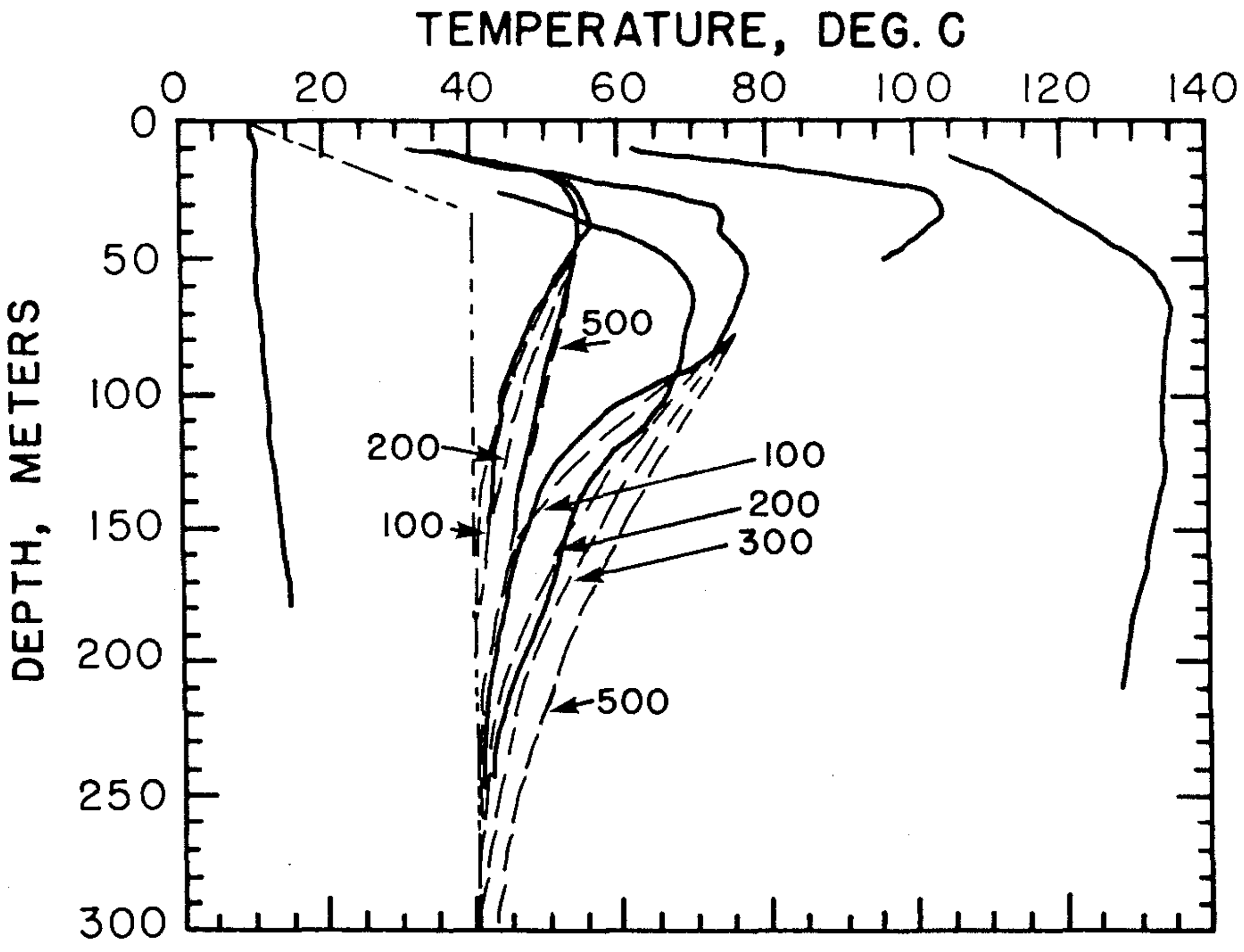
TEMPERATURE, DEG. C
0
20
40
60
80
100
120
140
DEPTH, METERS
0
50
100
150
200
250
300
500
200
100
100
200
300
500

Fig 9

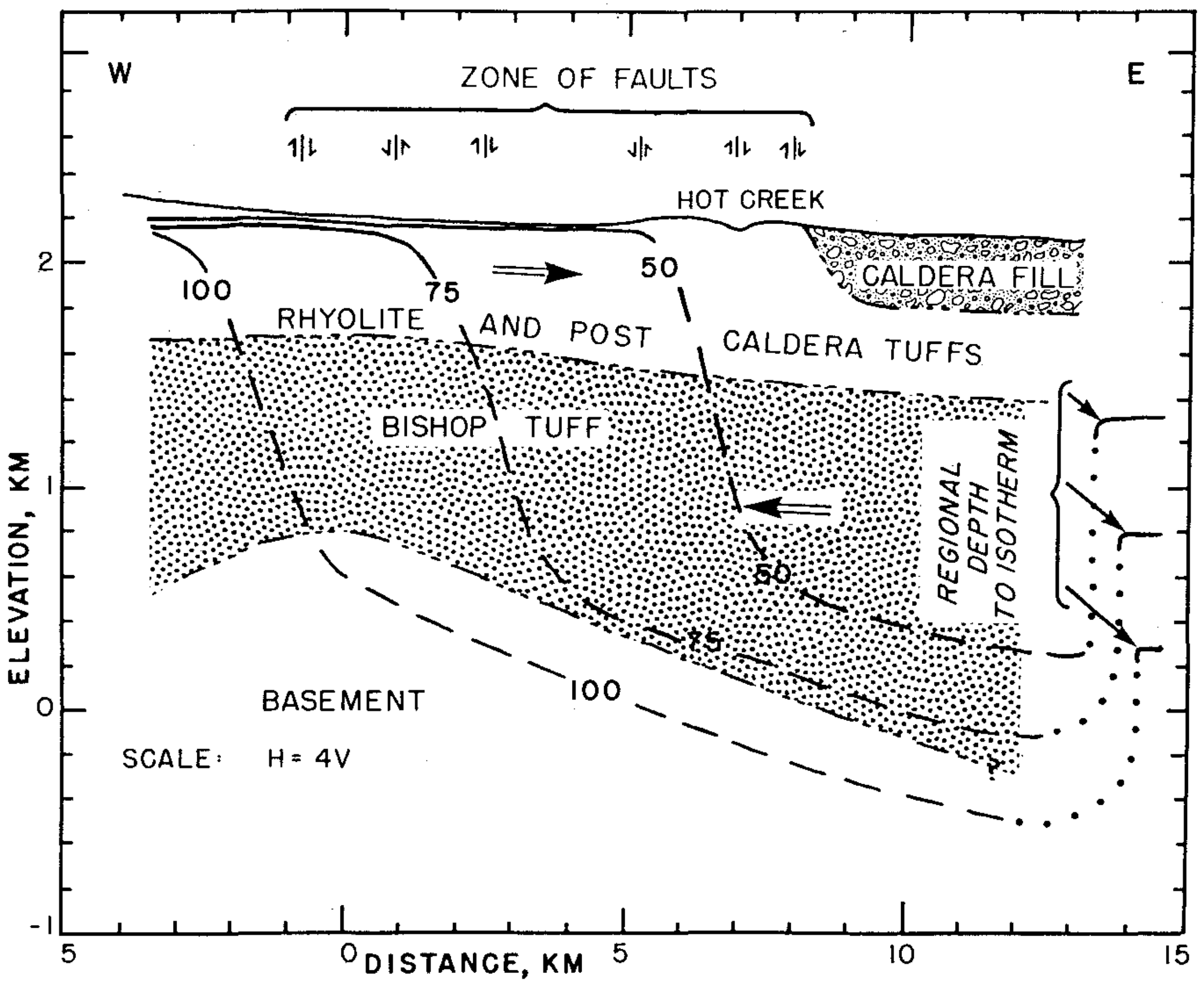
W
E
ZONE OF FAULTS
HOT CREEK
CALDERA FILL
100
75
50
RHYOLITE AND POST CALDERA TUFFS
BISHOP TUFF
REGIONAL DEPTH TO ISOTHERM
50
75
100
BASEMENT
SCALE: H = 4V
ELEVATION, KM
2
1
0
-1
5
0
5
10
15
DISTANCE, KM

Fig 10