UCR/IGPP--83/4

DE83 016726

HYDROTHERMAL-FLOW REGIME
AND MAGMATIC HEAT SOURCE OF THE CERRO PRIETO GEOTHERMAL SYSTEM,
BAJA CALIFORNIA, MEXICO

Wilfred A. Elders*

Dennis K. Bird**

Alan E. Williams*

Peter Schiffman*

ACO 7-80 ID 12145

*Institute of Geophysics and Planetary Physics
University of California
Riverside, California 92521 U.S.A.

**Department of Geology
Stanford University
Stanford, California 94305 U.S.A.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.

It has been reproduced from the best available copy to permit the broadest possible availability.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Abstract

Our detailed three-dimensional model of the natural flow regime of the Cerro Prieto geothermal field, before steam production began, is based on patterns of hydrothermal mineral zones and light stable isotopic ratios observed in rock samples from more than fifty deep wells, together with temperature gradients, wireline logs and other data. At the level so far penetrated by drilling, this hydrothermal system was heated by a thermal plume of water close to boiling, inclined at 45° , rising from the northeast and discharging to the west. To the east a zone of cold water recharge overlies the inclined thermal plume. Fission track annealing studies shows that the reservoir reached 170°C only 10^4 years ago. Oxygen isotope exchange data indicate that a 12 km^3 volume of rock subsequently reacted with three times its volume of water hotter than 200°C . Averaged over the duration of the heating event this would require a flow velocity of about 6 m/year through the pores of a typical cross section of the reservoir having an average porosity of 10%.

The heat in storage in that part of the reservoir hotter than 200°C and shallower than 3 km depth is equivalent to that which would be released by the cooling of about one or two cubic kilometers of basalt or gabbro magma. Although this is an extensional tectonic environment of "leaky" transform faulting in which repeated intrusions of basalt magma are likely, for simplicity of computation we have modelled possible heat sources as simple two dimensional basalt intrusions of various sizes, shapes and locations. We have calculated a series of two-dimensional convective heat transfer models, with different heat sources and permeability distributions. The models which produce the best fit for the temperature distributions observed in the field today have in common a heat source which is a funnel-shaped basalt intrusion, 4 km wide at the top, emplaced at a depth of 5 km to 6 km about 40,000 to 50,000 years ago.

Although such forward modelling does not provide a unique solution of the thermal history, it does suggest that the igneous intrusion which supplied the heat to the Cerro Prieto system must be young, large and close. Modelling the hydrothermal system is useful in guiding geothermal resource evaluation, in turn we hope that modelling of the magmatic system will stimulate the search for the parent magma chamber by geophysical means and eventually by deep drilling.

Introduction

The Cerro Prieto geothermal system is one of several high-temperature, water-dominated geothermal fields in the Salton Trough of southern California, U.S.A., and northern Baja California, Mexico (Fig. 1). The Trough is a seismically active, structural depression, forming the landward extension of the Gulf of California, but partially filled by the continental sediments of the delta of the Colorado River. It forms a tectonic regime transitional between the East Pacific Rise to the southeast and the San Andreas Fault System to the northwest (Elders, 1979).

In the Cerro Prieto geothermal field more than 110 deep boreholes penetrate the Plio-Pleistocene deltaic sands and shales and yield brines of up to 18,000 mg/L TDS from wells with temperatures $<350^{\circ}\text{C}$. Because all of the information is in the public domain and because it has been the subject of an extensive international program of collaborative investigations, we believe it is the best studied geothermal field in North America.

The Geothermal Resources group at the University of California, Riverside (UCR), has participated in the investigations of Cerro Prieto since 1977. Our emphasis has been upon petrological and geochemical study of borehole samples

and surface emanations. We have studied hydrothermal mineralogy and petrology, fluid inclusion geothermometry, stable isotope geochemistry, vitrinite reflectance, fluid chemistry, fission track dating and interpretation of wire-line logs. Among the aims of the work of our group were: (1) to assist in making lithological correlations between deep wells; (2) to improve the definition of the shape of the geothermal reservoir, as well as defining the nature of its boundaries; (3) to use a variety of geothermometric and dating methods to determine the thermal history of the field; (4) to determine various patterns of hydrothermal alteration which record the dynamics of fluid flow through the reservoir; and (5) to discuss the location and nature of the heat sources and how they couple with the geothermal system. These data were used as input to modelling the natural circulation in the hydrothermal system as it was before exploitation to supply steam to the power plant. In turn such models are applicable to exploration, to assessment, to development, and to reservoir management.

At this point the hydrothermal system is so well understood that the boundary conditions for modelling the heat source are rather well constrained. We have therefore computed a series of forward models of different magmatic systems and permeability structures to test which of them give rise to conditions close to those observed in the upper 3 km of the reservoir today. The results show that this is clearly a young hydrothermal-magmatic system with a nearby magmatic heat source.

Brief reviews of our earlier work at UCR were presented at the international symposia on Cerro Prieto in 1978, 1979, 1981 and 1982. Two of these reports were published in this journal (Elders et al., 1979; Elders et al., 1981A). This paper is a synthesis and update of the two papers which appeared in the Third and Fourth Symposia (Elders et al., 1981B; Elders et al., 1982).

At the Third Symposium the work of our group in collaboration with other investigators was extended to embrace a comprehensive model of fluid flow for the Cerro Prieto field, as it was in the natural state before production began (Elders et al., 1981B). This model is based upon (a) the location of the natural surface discharges in an arc west of the field (Valette-Silver et al., 1981); (b) the temperature gradients measured in deep boreholes by the engineers of the Comisión Federal de Electricidad (Bermejo et al., 1979); (c) the depths of the production zones in flowing wells (Bermejo et al., 1979); (d) the depths of the first occurrence of specific hydrothermal minerals, especially epidote and biotite (Elders et al., 1981B); (e) isotope and fluid inclusion geothermometry (Williams and Elders, 1981); (f) the relative durations of heating estimated from vitrinite reflectances (Barker et al., 1981); (g) the locations of zones of high and low electrical resistivity, based on downhole wireline electrical logs (Seamount and Elders, 1981); (h) the location of dike rocks in the sedimentary section along the eastern margin of the field (Elders et al., 1981B); (i) correlations with surface surveys of DC electrical resistivity by the geophysics group of Lawrence Berkeley Laboratory (Wilt and Goldstein, 1979); and (j) the results of a detailed study of subsurface geology using wireline logs (Halfman et al., 1982). In the following we will amplify various of these points.

Surface and Subsurface Hydrothermal Alteration

Hydrothermal alteration of surface rocks accompanies the natural surface emissions which occur in an arc northwest, west and southwest of the present production field (Valette-Silver et al., 1981). The chemistry of these surface emissions is made complex by the competing effects of boiling, steam con-

densation, evaporation, dilution by meteoric water, and oxidation at the surface (Valette and Esquer-Patiño, 1979). Among the several types of surface emission observed, the hot springs have a chemistry close to the brine produced from deep wells which penetrate the geothermal reservoir indicating leaking of the reservoir fluids to the surface. Comparison of samples of altered surface sediments within the hot springs with fresh sediments outside the springs documents the mineralogic reactions produced by the reservoir fluid at the surface. Quartz, feldspar and illite are increased and kaolinite, montmorillonite, calcite and dolomite are destroyed (Valette-Silver et al., 1981). These observations are consistent with simple solubility considerations.

Comparison of the minerals associated with the surface discharges with minerals observed in subsurface samples recovered from deep boreholes in the geothermal reservoir, reveals certain similarities and major differences. Fig. 2 shows the progressive zones of hydrothermal alteration minerals in sandstones at temperatures up to the maximum encountered, based on our study of more than 50 deep wells, of the 110 which have penetrated the reservoir. Shallow sediments above the reservoir appear to be uncemented and rather permeable; there is no continuous shallow sedimentary caprock. At the top of the reservoir detrital or authigenic clay minerals, like montmorillonite and kaolinite, are progressively replaced by pore-filling chlorite, illite, and especially calcite. This self-sealing process causes the sediments to be highly indurated at the top of the reservoir. In the main production zone, above 225°C there is a zone of progressive decarbonation where carbonates are destroyed and calcium aluminum silicates are formed. At the highest temperatures so far measured, hydrothermal biotite and vermiculite form.

Textures in sandstones within the production zone are highly variable, ranging from highly recrystallized hornfels, with low porosity, to local regions of appreciable secondary porosity. However, water/rock reactions have reduced the net porosity compared to that found at comparable depths outside the field. The physical properties of the mudstones and shales are even more susceptible than those of sandstones to induration induced by mineralogical changes with increasing temperature (Seamount and Elders, 1981).

Duration of Heating

Sanford and Elders (1981) dated the heating at Cerro Prieto, using the annealing of ^{238}U fission tracks in detrital apatite. The well T-366, towards the eastern side of the field, has had an apparently simple thermal history. Apatites in this well lose their fission tracks at approximately 170°C , corresponding to a duration of heating of 10^3 to 10^4 years (Sanford and Elders, 1981). In contrast, the well M-94, on the northern extremity of the field, has cooled by 50° to 100°C from the maximum temperatures previously present, which is indicated by fluid inclusions and isotopic geothermometry. Based on fission track annealing, the high temperatures recorded by geothermometers in this well had durations of only 10^0 to 10^1 years. Thus it appears that the main part of the geothermal field has been heating for some 10^4 years, and that, on the periphery, some rocks have a "memory" of very short-lived incursions of hotter water.

Temperature Distribution

The shape and size of the reservoir is reflected in the distribution of hydrothermal mineral zones (Elders et al., 1981A). Fig. 3A shows the depth of the first occurrence of hydrothermal epidote in sandstones of the reservoir,

which corresponds to an equilibrium temperature of approximately 225°C. This datum forms an elongate broad thermal dome with a gentle dip to the northeast. Fig. 3B shows the depth to the first occurrence of biotite and vermiculite in sandstones which we believe occurs at 325°C. This shows a similar asymmetric thermal dome, shifted to the east relative to the epidote surface. These observations are consistent with a thermal plume ascending from the east towards the west, inclined at 45° (Elders et al., 1981B).

They are also consistent with a published SW-NE thermal profile across the field from well M6 to M53 based on direct measurements of temperature gradients in wells (Mercado, 1976, Fig. 3). However, light stable isotope ratios in calcite provide a more convenient tool to determine variations in temperature across the field before production. This method is independent of the problems of downhole temperature measurements using mechanical recorders and the disturbance of temperature gradients due to the drilling and flowing of geothermal wells. This ^{18}O isotopic geothermometer does not necessarily indicate the ambient temperature of the reservoir at this moment, but records the temperature at which calcite equilibrated isotopically. It is therefore not subject to short term fluctuations. The pattern of isotherms based on these data also describes an asymmetric thermal dome, deepening gradually to the northeast (Williams and Elders, 1984). For example, Fig. 4 is a thermal profile from southwest to northeast across the field showing much more detail than published profiles based on downhole temperature measurements (e.g., Mercado, 1976). It shows a broad area of temperature inversion in the southwest due to a zone of horizontal flow.

Patterns of Fluid Flow

As a test of our hypothesis, we examined the distribution of different hydrothermal mineral zones around the reservoir. Fig. 5 shows how the

hydrothermal mineral zones in sandstones of Fig. 2 correlate with those found in mudstones and shales. Because of differences in permeability, given hydrothermal minerals tend to appear first at lower temperatures in sandstones than in shales. When we examine the spacing of mineral zones penetrated by different boreholes in the field, four different cases are apparent (Fig. 5). In a normal prograde sequence (P) mineral zones are fairly evenly spaced with depth. In other boreholes (case R in Fig. 5), lower temperature mineral zones extend to a greater depth, where high temperature zones are penetrated in a narrow depth range. A third type of relationship is shown by curve D where the highest temperature mineral zones are absent and low to moderate temperature zones persist to the bottom of the well. Curve H illustrates the fourth kind of mineral spacing observed. It shows reversals of mineral zones with depth produced by a horizontal flow regime.

These different spacings of mineral zones are also characterized by different isotopic signatures (Fig. 6). The $\delta^{18}O$ of calcites from sandstones plotted against depth for the well M84 are typical of a well of the prograde type. The data show a narrow range of values and a sharp inflection point at shallow depth, below which temperatures are close to boiling. In contrast, data for well M53 are typical for wells of type R. They show a wider range of values, a deeper inflection point, and negligible isotopic exchange at shallow depth. In wells of type D there is a wide range of isotope values, an absence of a steep inflection point, and a temperature at depth considerably below boiling, as illustrated by data from well M92 in Fig. 6. Finally, well M3 is an example of wells of type H showing reversals of isotopic ratios with depth.

When the four types of wells are plotted on a map, a systematic geographic clustering into distinct areas is revealed (Fig. 7). Wells of type

P are in the main production field, type R wells all occur to the northeast, whereas types D and H occupy the western and southwestern quadrants, surrounding the area of type P wells.

We suggest that, in the region marked P on the map (Fig. 7), the boreholes penetrate an inclined upwelling thermal plume at only moderate depth. Furthermore in the region marked R, the boreholes traverse a cold water recharge system before entering the hot reservoir at depth. We suggest the area marked D is a discharge zone, where the upper part of the thermal plume discharges upwards into a shallow aquifer. Similarly, the region designated H represents a region of shallow horizontal flow of hot water and discharge to the surface. All of the natural surface emissions described by Valette-Silver and Esquer-Patiño (1979) lie in the areas marked H or D.

Fig. 8 shows a cross-section from southwest to northeast, from the general vicinity of borehole M6 to borehole M53, to illustrate our hypothesis for natural convective flow before the borefield was developed. We suggest that the heat source for the hydrothermal system lay to the east or northeast. A thermal plume rose from it, which ascended to the west or southwest inclined at an angle of approximately 45°. It boiled in places and precipitated minerals, causing local self-sealing. This plume discharged upwards and horizontally to the west and southwest, forming hot springs and fumaroles, and shallow zones of temperature reversals. Downward flow of cold groundwater permitted recharge from the northeast in the region marked R in the diagram. Recharge may also have been accompanied by self-sealing as the recharge water was heated it would precipitate carbonates.

Supporting Evidence

We believe it significant that the only subsurface intrusive dike or sill rocks we have seen from the Cerro Prieto field occur in the eastern part of

the field in wells H2, NL-1, T366 and M189. Fig. 9 is a lithologic column for the well NL-1 (Bruno Weist, personal communication, 1980) showing the occurrence of both silicic and mafic intrusive rocks in this region. Such rocks are absent in the central and western parts of the field.

Another line of supporting evidence comes from the study of the downhole logs (Seamount and Elders, 1981). Deep induction resistivity logs show some highly resistive zones in sandstones, with resistivity up to 40 ohm meters. These appear to be zones of fresh water in the sandstones. They occur as deep as 1500 m in well T-366, and are restricted to wells in the area marked R in Fig. 7. Their existence requires rapid downward flow of cold, low salinity water, the mass recharge for the inclined thermal plume.

Similarly the vitrinite reflectance study of Barker et al. (1981) shows a pattern consistent with our proposed fluid flow model. The optical reflectance of vitrinites depends on both the temperature and the duration of heating. Thus variations in reflectance from samples of rocks which are now at the same temperature give information on the relative duration of heating. This concept is illustrated in Fig. 10. This cartoon shows, in cross-section, progressive positions of an isotherm at four successive times t_1 , t_2 , t_3 and t_4 . Where isotherms moved relatively quickly, i.e., heating was rapid, we would expect relatively low vitrinite reflectances and high water to rock ratios. Where the isotherms moved slowly, i.e., heating was protracted, we would expect high vitrinite reflectances and low water to rock ratios. Barker et al. (1981) applied this concept by studying vitrinite reflectances in shale samples from well cuttings selected at the 250°C isotherm at Cerro Prieto. Their data are consistent with our model. They suggest that heating to 250°C began in the northeast and spread southwesterly at shallower depth.

This model of an inclined plume of hot saline water, overlain by colder fresher water, can also be tested by comparison with the dipole-dipole resistivity surveys of Wilt and Goldstein (1979). These authors (1979, Fig. 3) show an apparent resistivity pseudo-section in which the main part of the reservoir has a resistivity of 4.0 ohm-m; this is overlain to the east by an inclined zone of resistivity of 1.5 ohm-m, dipping east, which in turn is overlain by inclined zones of 5.0 and 8.5 ohm-m, further east. The apparent coincidence between these inclined zones of varying resistivity and the features shown in Fig. 8 is striking. To a first approximation, the 4.0 ohm-m zone appears to correspond to the hot saline plume where induration has reduced porosity, especially by destruction of clay minerals in the shales. The 1.5 ohm-m zone is a more conductive zone presumably because of higher porosities, and higher concentrations of conductive clays. Within this zone salinity appears to be less than in the 4.0 ohm-m zone, as recognized on the electric logs (Seamount and Elders, 1981). This 1.5 ohm-m layer is, in turn, overlain by aquifers in the recharge system of resistivities 5.0 to 8.5 ohm-m, containing colder, lower salinity water.

Finally, the best confirmation for this flow model came from a very detailed investigation of subsurface geology of the field based on well log interpretation (Halfman et al., 1982). These authors extended the earlier work of Lyons and van de Kamp (1980) to consider logs from 90 wells. They were able to correlate formations and lithofacies across this field and locate faults more precisely. When these results were compared with information on production intervals and on temperature gradients, they were able to infer the details of the paths of fluid flow. Their study, (Halfman et al., 1982), confirmed that the hot fluids ascended from a deep heat source in the east and

moved laterally westwards through the sandstone units. Locally, shale units acted as barriers to the convective heat transport and faults acted as conduits between the aquifers to permit hot brines to escape to the surface in the southwest along the Cerro Prieto fault (Halfman et al., 1982).

Our Hydrothermal Flow Model

In summary, a key feature of this model is that the field is divided into four regions: (1) an area of cold water recharge to the northeast; (2) a zone of upward flowing boiling water in the center; (3) a region of surface discharge lying to the west; and (4) an aquifer in which flow of hot water is primarily horizontal, which lies at the extreme western boundary of the field. We infer that this pattern was produced by hydrothermal convection in which a buoyant hydrothermal plume, dipping at 45° to the east, discharged to the southwest. Mass flow was recharged by cold water from the northeast which descended and was heated by a deep magmatic heat source in that direction (Elders et al., 1981B).

Our study of oxygen isotope data and of subsurface temperatures indicated that a reservoir volume of about 12 km³ has exchanged its oxygen isotopes with water at temperatures greater than 200°C (Williams and Elders, 1981; 1984). Based upon the measured isotope shifts between unreacted sediments and hydrothermally altered sediments, and upon the $\delta^{18}\text{O}$ of the waters, we calculated a water to rock mass ratio of 1.33 to 1. This implies a volume ratio of approximately 3 to 1. Thus 36 km³ of water hotter than 200°C reacted with the 12 km³ of the so far explored reservoir, causing the observed isotopic exchanges.

As indicated earlier, fission track annealing studies suggest that a well on the east side of the field reached 170°C only 10⁴ years ago. If this age

can be generalized to the whole reservoir, it implies that the flux of >200°C water occurred in less than 10,000 years (Sanford and Elders, 1981). This in turn requires a flow of more than $3.6 \times 10^6 \text{ m}^3$ of hot water a year through the whole reservoir in the natural state for approximately 10,000 years. If this volume were to flow through a cross-section of the reservoir with an average area of 6 km^2 the specific discharge would be 0.6 m/year. For an average porosity of 10%, the velocity would have then been 6 meters/year averaged over 10^4 years. In an earlier report (Elders et al., 1981B) it was suggested that the inclination of the thermal plume might be due to the regional hydrologic gradient on the delta of the Colorado River. In order to cause the resultant flow of the thermal plume to be inclined at 45°, the vertical momentum of the buoyant plume and the horizontal momentum of the cold river subflow must be equal. The subflow of the delta is recharged where the Colorado River enters the Salton Trough at Yuma, Arizona (Fig. 1). Yuma lies 57 km to the northeast and 33 m higher than the surface elevation of the Cerro Prieto field. Following the suggestion of J. Tremblay (personal communication, 1981), we assumed that ρ , the density of cold water, is 1.0 gm cm^{-3} , that μ , the coefficient of viscosity, is $0.0054 \text{ gm/cm} \cdot \text{sec}$ (pure H_2O at 50°C and 200 bars), and that the delta has a uniform permeability, k , of 50 md. We then calculated the specific discharge of the horizontal Darcy flow as

$$q = k \left(\frac{\rho}{\mu} \right) g \frac{\Delta z}{\Delta x} = 5.25 \times 10^{-8} \text{ cm/sec} = 1.66 \text{ cm/year.}$$

Assuming a uniform porosity of 10% the horizontal velocity of this groundwater through the pores would be 16.6 cm/year. Thus the average time for regional groundwater to traverse a 2 km horizontal distance would be about 1,200 years with this hydraulic gradient and permeability. If we assume the mean

density of the hydrothermal water to be 0.7 gm cm^3 (ρ at 300°C with saturation pressure of 86 bars), for the horizontal velocity of the cold water given above, the vertical pore velocity of the thermal water must be only 24 cm/year, an order of magnitude less than the velocity we estimated from our isotopic exchange and fission track annealing study. As we shall indicate later, it now seems unlikely to us that the indication of the thermal plume is caused solely by the interaction of the vertically flowing hot water and the horizontally flowing regional groundwater. This would require that the high horizontal permeability assumed persists to an unlikely great depth. The inclination of the plume is more strongly affected by the permeability variations in the reservoir as described by Halfman and her co-workers (Halfman et al., 1982).

The Magma-Hydrothermal System

Our rough estimates of the heat stored in that part of the explored geothermal reservoir hotter than 200°C , down to a depth of 3 km, showed that it is equivalent to the enthalpy which would be released by the cooling of at least 1.5 cubic kilometers of molten magma. For such a large amount of heat to be transferred into the sediments in 10^4 years by conduction and convection requires that the source of heat is both large and close. Therefore, the Cerro Prieto geothermal field should be considered as an active magma-hydrothermal system.

Although the nearby Quaternary volcano of Cerro Prieto is a rhyodacite dome (Elders et al., 1978), we believe there are two compelling reasons for assuming that the heat source for the field is basaltic magma. Firstly, the dikes encountered in deep boreholes in this field and in other fields in the Salton Trough are largely diabbases. Secondly, in this tectonic setting of crustal spreading associated with "leaky" transform faults of the San Andreas

fault - Gulf of California system, basalt or gabbro intrusions are likely (Fig. 11).

More than ten years ago it was pointed out that this geothermal anomaly lies in a tensional zone between the Cerro Prieto and Imperial faults, similar tectonically to the submarine "pull-apart" basins in the Gulf of California (Elders et al., 1972). If these faults move at rates comparable to the plate-edge deformations measured at the mouth of the Gulf on the East Pacific Rise, they have a half spreading rate of about 5 cm/year, implying a pull-apart rate of 10 cm/year for the "pull-apart" basin or spreading center (Elders, 1979). A "basin" elongating in this way extends 1 km each 10,000 years. As the distance from the Cerro Prieto fault to the Imperial fault is about 15 km, this would require addition of a prism of new crust 1 km wide, 15 km long and up to 20 km deep (the approximate Moho depth) each 10,000 years (Fig. 11). We assume that this new crust is supplied from below by deep-seated magma and from above by deltaic sediments of the Colorado River. Of course not all of this new crust need be confined to a narrow central slot like that depicted in Figure 11; more likely new crust would be formed over a broad region of the tensional zone or "rhombochasm" between the transform faults. Furthermore if only a small fraction of this new crust were basaltic magma, this would be more than enough to be the heat source for the Cerro Prieto hydrothermal system, as the following rough calculation shows. If the 12 km^3 of the explored reservoir which is between 200°C and 350°C has an average heat capacity of $0.25 \text{ cal/gm}^\circ\text{C}$ and porosity of 10%, then the thermal energy required to heat this rock and water from its initial temperatures is approximately 1.7×10^{18} calories. This is roughly equivalent to the heat released by cooling of 1.6 km^3 of basalt magma.

Our conceptual model of the heat source resembles the intrusive bodies in ophiolite complexes, formed at ocean spreading centers where they are responsible for submarine hydrothermal systems (Pallister and Hopson, 1981; Coleman, 1981). An important difference is that the intrusion beneath Cerro Prieto was probably initially emplaced into continental crust rather than into crust of oceanic affinity.

Fig. 12 illustrates the concept. Following the example of our Mexican colleagues (de la Peña et al., 1979), we consider a simplified upper crust consisting of three layers - Unit A or unconsolidated sediments, unit B or consolidated sedimentary rocks, and the granitic basement. The cross section in Fig. 12 is drawn parallel to the transform faults showing the three layers of crust being rifted apart and basaltic magma being emplaced in the tensional zone. If the analogy with an ophiolite is apt, the intrusion would consist of a gabbro/peridotite grading upwards into a sheeted basaltic dike swarm formed by repeated minor intrusions into cold wet crust. Extrusive pillow basalts would of course be absent as the magma complex is overlain by several kilometers of deltaic sediments rather than by sea water.

Modelling Heat and Mass Transfer

Perhaps in the future a predictive model may lead to success in drilling into the parental magma chamber responsible for the Cerro Prieto system. Until then we believe the best test of numerical analog models of heat and mass transfer is that they successfully replicate the timing and temperature distribution observed in the explored part of the hydrothermal system. We therefore first evaluated the thermal energy in the reservoir more exactly. Next we made simplifying approximations to constrain the nature of the heat source and the rock permeability at depth. With these assumed initial con-

ditions we then computed numerical finite element models of conductive and convective heat transfer using a series of different heat sources and associated permeability structures. With the insight gained we were then able to refine the model conditions to improve the match with known conditions in the explored reservoir.

Such forward modelling does not, of course, lead to unique solutions. However by choosing a range of different initial conditions we could test the sensitivity of the model to different parameters and refine it in stages. For simplicity of computation we restricted the calculations to two dimensions and considered only heat sources emplaced as single intrusive events rather than considering multiple or continuous intrusions (Elders et al., 1982).

Thermal Energy in the Reservoir

In calculating the heat in storage in the reservoir we chose two orthogonal cross-sections across the field, each covering a lateral distance of 7 km and a vertical depth of 2 km, and each divided into a 15 by 20 grid. One cross-section, that shown in Fig. 4, was chosen to be parallel to the inferred flow direction in the thermal plume. The second cross-section was chosen to be perpendicular to this flow and to the various dip-slip faults which have been proposed to occur within and near the production zone (Fig. 13). Because this second cross section is nearly perpendicular to the assumed regional groundwater flow in the delta, complications of this hydrologic gradient are also minimized for these preliminary calculations. As is seen in Fig. 13, the pattern of isotherms in this cross-section is approximately bilaterally symmetrical.

The observed and inferred stratigraphy, structure and temperature distributions for this cross-section are also summarized in Fig. 13. Note that the

high angle normal faults are centered about the shallow subsurface thermal anomaly, and that these faults apparently offset the major geologic units, Unit A, Unit B, and granite basement. The location of the basement is based upon the work of Fonseca and Razo (1979) and the seismic basement is after that shown by Prian (1979). The 300°C isotherm is locally within 2 km from the surface. It can be inferred from Fig. 13 that at 2.5 km depth this isotherm extends over a horizontal distance of about 4 km or more in the cross section.

Because we are interested in modelling the heat in storage in the reservoir before wells were drilled and production began, and because there is a somewhat subjective element in interpreting downhole temperature logs, we constructed subsurface isotherms using the calcite-water oxygen isotope geothermometer (Williams and Elders, 1984).

In addition to temperature data, density, porosity and heat capacity values were determined for each grid point. An average grain density value was computed using a typical sand composition from Cerro Prieto drillhole cuttings, and mineral density values from Clark (1966). Both altered and unaltered grain densities averaged 2.7 gm/cm^3 which shows the dominance of quartz and feldspar in the sand composition.

Measured values for porosity of cores as a function of depth were reported for several drillholes at Cerro Prieto (Lyons and van de Kamp, 1980). These values range from 5% to 40% between surface and 2 km depth. Using the porosity-depth trends in wells M-96 and M-127 reported in Lyons and van de Kamp (1980), a grid of porosity values was determined for the cross-sections.

Similarly we chose values of the heat capacity for rock as a function of temperature and rock composition, using published heat capacity data (Helgeson

et al., 1978). The temperatures from the oxygen isotope and other geochemical data (Williams and Elders, 1984) were input to a program which retrieves fluid properties. Thermodynamic data for water were calculated using saturation pressures for the temperature values (Keenan et al., 1969; Helgeson and Kirkham, 1974). We then calculated the total energy contained in the volumes of rock and fluid-filled pores of the two cross-sections, both considered as vertical slices of the reservoir 1 cm thick, by integrating the sum of the fluid energy and rock energy. The total anomalous thermal energy was referenced to a background geothermal gradient of 25°C/km at each grid point.

Preliminary Numerical Analysis

Our preliminary calculations of heat and mass transfer presented below were designed to approximate a geologic cross-section 16 km long and 10 km deep along an approximate NW-SE section through the geothermal field, east of the Cerro Prieto fault. This numerical section was chosen to be parallel to the regional tensional stresses and perpendicular to the horizontal component of the regional groundwater flow (Fig. 13).

In order to evaluate rapidly and inexpensively the nature of possible magmatic heat sources and the subsurface permeability distribution, the computational mesh was initially divided into only forty internal grid points. Each point represents the volume averaged thermodynamic and transport properties of a representative elementary volume of rock and fluid 1 cm thick and either 2 by 2 km or 1 by 1 km in area. Calculations are made using the computer program FLOW51 and the graphics support developed at the University of Arizona (Norton and Knight, 1977). All boundary conditions were chosen to be conductive to heat transfer with various combinations of open or closed boundaries to convective fluid flow. The surface temperature was chosen to be

20°C and the initial regional temperature gradient was set at 25°C per kilometer.

Our calculations evaluated the effects of various permeability distributions in the upper 10 km of the earth's crust on the dispersion of thermal energy from a tholeiitic basaltic magma intrusion whose dimensions were arbitrarily chosen. The initial temperature of the intrusion was set to be 1150°C so that it would crystallize during a temperature drop of about 100 to 150°C to release about 100 cal/gm due to the heat of crystallization (Clark, 1966; Norton and Taylor, 1979). For a time and volume averaged heat capacity of a basalt of 0.25 cal/gm°C the intrusion would release a total of about 330 cal/gm to cool from an initial temperature of 1150°C to an average ambient temperature of 220°C. We then varied the dimensions and locations of the intrusion and observed the propagation of heat into the Cerro Prieto reservoir at successive time steps.

Initially we calculated the cooling history of vertical diabase dikes intruding the sediments at various levels. This analysis showed that dikes rapidly lose most of their heat by horizontal conduction. Even a dike 1 km thick would contain much too little heat and would cool too fast to be the heat source for the Cerro Prieto reservoir. Next we considered a series of gabbro plutons measuring 4 km by 4 km by 1 km emplaced at various depths ranging from 4 km to 6 km. The cooling of such a pluton would release about 1.6×10^{14} cal. We considered various models with heat sources of this size with different permeability distributions. However none of them could reproduce the temperature distribution observed in the field for any reasonable values of permeability. Therefore the heat source must be even larger.

This result caused us to expand the numerical grid to evaluate a series of larger heat sources. These models had 80 internal grid points, each

denoting a representative elemental volume of 1 km by 1 km by 1 cm. Several different larger heat sources emplaced at different depths from the surface were considered. Fig. 14 (model CPP5) is an example where we considered a pluton measuring 4 by 6 km with a brecciated top of higher permeability and a surrounding dike swarm. The high permeability of the sedimentary section above the intrusion was chosen to represent a faulted zone. An important difference in this model is that the top boundary was chosen to be impermeable, i.e., one of no-flow (Fig. 14).

It is apparent from the calculated isotherms given in Fig. 14 that the closed top boundary condition results in a very wide dispersal of heat in the upper 2 to 3 km of the numerical sections. The temperature gradient reversals in the upper 3 km are a consequence of the lateral migration of fluids due to the impermeable top boundary and mass recharge by cold groundwater at depths of 2.5 to 3 km. Because in this model heat can only be transferred by conduction through the top boundary, high temperatures occur in the shallow subsurface over a very large portion of the cross-section. For example, the 200°C isotherm extends for >10 km in width at <1 km deep 100,000 years after intrusion in three different models with an upper boundary of no flow. The width of the 300°C isotherm is also instructive. Its maximum width in the upper 3 km is >4.5 km as opposed to the 3 km actually observed today at Cerro Prieto. It would appear therefore that the heat source must be smaller or deeper than that represented in Fig. 14.

Model CP43 (Fig. 15) depicts a more realistic shape for a smaller and deeper gabbro/basalt intrusion. Such plutons are commonly funnel shaped (Norton and Taylor, 1979; Wager and Brown, 1967; Pallister and Hopson, 1981; Coleman, 1981). Various similar models with different boundary conditions

were calculated with the top boundary open to flow, partially closed and closed to flow. In all these cases the width of the thermal plume is approximately correct after 30,000 years of cooling. A model with a low permeability zone, which acts as a leaky caprock, gives a thermal plume of approximately the correct width and rise time. However, the model CP43 (Fig. 15) which has an impermeable caprock, seems to give an even better fit. A further point of the kind of model shown in Fig. 15 is that the asymmetry of the pluton and of the permeability of the sediments reproduces the inclined thermal plume.

Since we developed these numerical models, independent evidence for a mafic pluton beneath Cerro Prieto has been put forward (Goldstein et al., 1984). These authors have interpreted a broad dipolar magnetic anomaly 5 km east of the power plant Cerro Prieto I as being due to a tabular block 4 by 6 km in area with a top at 3.7 km depth and 2.3 km thick. They further infer that this body has a magnetic susceptibility greater than that of the diabase dike or sill rocks so far encountered in boreholes. These authors believe that the magnetic source is a deeper, magnetite-rich assemblage of peridotite-gabbro plutons. They further infer that the bottom of the magnetic source body at 6 km is at the Curie isotherm (575°C) for magnetite, the principal ferromagnetic mineral present. These inferences are also consistent with other geophysical data. For example, hypocenters of microseisms suggest that the north-northwest border of the magnetized zone is the locus of present extension and possibly of dike injection at depths of 6 to 11 km. Goldstein et al. (1984) also point out that, "A linear extrapolation of temperature data from well logs and the estimated depth to the magnetite Curie isotherm suggests a melt zone at a depth of 9 to 10 km." Our model CP43 shows the upper kilometer of the pluton cooling below 800°C in 50,000 years at 6 km

depth. It would be possible now to use the 575°C at 6 km suggested by Goldstein et al. (1984) to be a further constraint on our heat transfer models. Models with a 500 m grid spacing would also help to give a higher degree of resolution of the permeability structure in the sedimentary section. Similarly models including a component of regional groundwater flow are possible.

Conclusions

We have developed a qualitative model of fluid flow in the Cerro Prieto reservoir as it was before the field was exploited, based upon petrological and geochemical evidence. We suggest that a thermal plume fed from a heat source to the east or northeast is inclined at 45° as it rises to the southwest, discharging in that direction, and being recharged by cold water from the northeast. This model is quantifiable and testable by numerous lines of evidence.

The very high temperatures at shallow depth and youth of the Cerro Prieto geothermal field require that its heat source is a young, large, nearby igneous intrusion. Our preferred model at present is that it is a funnel-shaped gabbro intrusion, probably 30,000 to 50,000 years old, some 4 km across with a top at a depth of 5 to 6 km. Above it there is probably a sheeted dike complex as is typical of ophiolite complexes in ocean spreading centers. Our numerical models for simplicity assumed that there was a single intrusive event which is now cooling. If, as it likely in a tectonic setting of crustal spreading, there have been repeated incursions of magma for a long period, then the intrusion must be even larger and older. Whatever its form, the existence of the igneous intrusion seems to us to be inevitable. It should be detectable geophysically as a recent study suggests. Perhaps in the future it

may be found to be accessible by deep drilling and prove to be an even more valuable source of energy than the geothermal field currently being developed.

Acknowledgements

We thank our colleagues at UCR, the Comisión Federal de Electricidad, Lawrence Berkeley Laboratory and elsewhere, too numerous to mention, with whom we have had the pleasure and privilege of being associated in this cooperative study of Cerro Prieto. Our work has been funded by the generous support of the U.S. Department of Energy. Specifically these modelling studies were performed under contract no. DE-FC07-80ID12145 of that agency. This is report no. UCR/IGPP-83/4 of the Institute of Geophysics and Planetary Physics of the University of California, Riverside (UCR).

REFERENCES

- Barker, C. E., Pawlewicz, M. J., Bostick, N. H., and Elders, W. A. (1981) Evolution of the Cerro Prieto Geothermal System as interpreted from vitrinite reflectance under isothermal conditions. Proceedings of the Third Symposium on Cerro Prieto, March 1981, San Francisco, 88 - 101.
- Bermejo M., F. J., Navarro O., F. X., Castillo B., F., Esquer, C. A. y Coretz A., C. (1979) Variacion de Precision en el yacimiento de Cerro Prieto durante su explotacion. Actas del Segundo Simposia sobre el Campo Geotermico de Cerro Prieto, Baja California, Mexico, Octubre 1979, Mexicali, 473 - 496.
- Clark, S. P. (1966) Handbook of geophysical constants, Revised Edition. Geol. Soc. Am. Memoir 97.
- Coleman, R. G. (1981) Tectonic setting for ophiolite obduction in Oman. J. Geophys. Res. 86, 2497 - 2508.
- De la Peña L., A., Puente C., I., y Diaz C., E. (1979) Modelo del campo geotermico de Cerro Prieto. Actas del Segundo Simposio sobre el Campo Geotermico de Cerro Prieto, Baja California, Mexco, Octubre 1979, Mexicali, 2, 29 - 56.
- Elders, W. A. (1979) Geology and Geothermics of the Salton Trough. Guidebook No. 7. Geological Society of America 92nd Annual Meeting, San Diego, November 1979. University of California, Riverside Campus Museum Contribution No. 5, 106 p.
- Elders, W. A., Rex, R. W., Meidav, T., Robinson, P. T. and Biehler, S. (1972) Crustal spreading in southern California. The Imperial Valley and Gulf of California formed by rifting apart of a continental plate. Science 178, no. 4056, 15 - 24.

- Elders, W. A., Hoagland, J. R., Olson, E. R., McDowell, S. D. and Collier, P. (1978) A comprehensive study of twenty-three wells in the Cerro Prieto Geothermal Field, Baja California, Mexico. University of California, Riverside/Institute of Geophysics and Planetary Physics report 78/26.
- Elders, W. A., Hoagland, J. R., McDowell, S. D. and Cobo, J. M. (1979) Hydrothermal mineral zones in the geothermal reservoir of Cerro Prieto, B.C., Mexico. *Geothermics* 8, 201 - 209.
- Elders, W. A., Hoagland, J. R. and Williams, A. E. (1981A) Distribution of hydrothermal mineral zones in the Cerro Prieto geothermal field of Baja California, Mexico. *Geothermics* 10, 245 - 253.
- Elders, W. A., Williams, A. E. and Hoagland, J. R. (1981B) An integrated model for the natural flow regime in the Cerro Prieto geothermal field, B.C., Mexico, based upon petrological and isotope geochemical criteria. Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, March 1981, Berkeley, Lawrence Berkeley Laboratory report LBL-1197, 102 - 109.
- Elders, W. A., Bird, D. K., Williams, A. E., Schiffman, P. and Cox, B. (1982) A model for the heat source of the Cerro Prieto magma-hydrothermal system, Baja California. Proceedings of the Fourth Symposium on the Cerro Prieto Geothermal Field, August 1982, Guadalajara, Comisión Federal de Electricidad (in press).
- Fonseca L., H. L. y Razo M., A. (1979) Estudios gravimétricos, magnetométricos y de sísmica de reflexión en el Campo Geotérmico de Cerro Prieto. Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Baja California, October 1979, Mexicali 2, Comisión Federal de Electricidad, 303 - 328.
- Goldstein, N. E., Wilt, M. J. and Corrigan, D. J. (1984) Analysis of the Nuevo Leon Magnetic Anomaly and its possible relation to the Cerro Prieto magmatic hydrothermal system. *Geothermics* 13.

- Halfman, S. E., Lippmann, M. J., Zelwer, R. and Howard, J. H. (1982) Fluid flow model of the Cerro Prieto geothermal field based on well log interpretation. Proceedings of the Fourth Symposium on the Cerro Prieto Geothermal Field, August 1982, Guadalajara, Comisión Federal de Electricidad (in press).
- Helgeson, H. C., Delany, J. M., Nesbitt, H. W. and Bird, D. K. (1978) Summary and critique of the thermodynamic properties of rock-forming minerals. Am. J. Sci. 278-A.
- Helgeson, H. C. and Kirkham, D. H. (1974) Theoretical prediction of the thermodynamic behaviour of aqueous electrolytes at high pressures and temperatures. Am. J. Sci. 274, 1089 - 1198.
- Keenan, J. H., Keyes, F. G., Hill, P. F. and Moore, J. G. (1969) Steam Tables: Thermodynamic Properties of Water Including Vapor, Liquid and Solid Phases. John Wiley & Sons.
- Lyons, D. J. and Van de Kamp, P. C. (1980) Subsurface geological and geophysical study of the Cerro Prieto geothermal field, Baja California, Mexico. Lawrence Berkeley Laboratory report LBL-10540.
- Mercado, G., S. (1976) Migración de flúidos geotérmicos y distribución de temperaturas en el subsuelo del Campo Geotérmico de Cerro Prieto, Baja California, México. Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, May 1975, San Francisco, 1, 487 - 494.
- Norton, D. and Taylor, H. P. (1979) Quantitative simulation of the hydrothermal systems of crystallizing magmas on the basis of transport theory and oxygen isotope data: An analysis of the Skaergaard intrusion. J. Petrol. 20, no. 3, 421 - 486.
- Norton, D. and Knight, J. (1977) Transport phenomena in hydrothermal systems: Cooling plutons. Am. J. Sci. 277, 937 - 981.

- Pallister, J. S. and Hopson, C. A. (1981) Samail ophiolite plutonic suite: field relations, phase variation, cryptic variation and layering, and a model of a spreading ridge magma chamber. *J. Geophys. Res.* 86, 2593 - 2644.
- Prian C., R. (1979) Posibilidades de desarrollo del area geotérmico de Cerro Prieto, Baja California Norte. Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Oct. 1979, Mexicali 2, Comisión Federal de Electricidad, 146 - 161.
- Sanford, S. J. and Elders, W. A. (1981) Dating thermal events by fission track annealing in wells M-94 and T-366 at Cerro Prieto. Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, March 1981, Berkeley, Lawrence Berkeley Laboratory report LBL-1197, 114 - 119.
- Seamount, D. T., Jr. and Elders, W. A. (1981) Well log use at Cerro Prieto in identification of hydrothermally altered zones, correlation with reservoir temperature and interpretation of reservoir porosity. Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, March 1981, Berkeley, Lawrence Berkeley Laboratory report LBL-1197, 123 - 133.
- Valette, J. N. and Esquer-Patiño, I. (1979) Geochemistry of the surface emissions in the Cerro Prieto geothermal field. Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Oct. 1979, Mexicali, Comisión Federal de Electricidad, 241 - 250.
- Valette-Silver, J. N., Esquer-Patiño, I., Elders, W. A., Collier, P. C. and Hoagland, J. R. (1981) Hydrothermal alteration of sediments associated with surface emissions from the Cerro Prieto geothermal field, Baja California, Mexico. Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, March 1981, Berkeley, Lawrence Berkeley Laboratory report LBL-1197, 140 - 145.
- Wager, L. R. and Brown, G. M. (1967) Layered Igneous Rocks. W. H. Freeman and Co., San Francisco.

- Williams, A. E. and Elders, W. A. (1981) Oxygen isotope exchange in minerals from the Cerro Prieto geothermal system: Indicator of temperature distribution and fluid flow. Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, March 1981, Berkeley, Lawrence Berkeley Laboratory report LBL-1197, 149 - 158.
- Williams, A. E. and Elders, W. A. (1984) Stable isotope systematics of oxygen and carbon in rocks and minerals from the Cerro Prieto geothermal anomaly, Baja California, Mexico. Geothermics 13.
- Wilt, M. J. and Goldstein, N. E. (1979) Resistivity modelling at Cerro Prieto. Proceedings of the Second Symposium on the Cerro Prieto Geothermal Field, Oct. 1979, Mexicali, Comisión Federal de Electricidad, 419 - 436.

FIGURE CAPTIONS

- Fig. 1. The geologic setting of the Cerro Prieto geothermal field.
- Fig. 2. Temperature ranges of zones of hydrothermal alteration minerals in the sandstones at Cerro Prieto.
- Fig. 3. Depth in meters for the first occurrence of specific hydrothermal minerals in sandstones at Cerro Prieto: 3A - epidote ($>225^{\circ}\text{C}$); 3B - biotite and vermiculite ($>325^{\circ}\text{C}$). Filled circles are well locations with a selection of the identifying well numbers indicated. The barbed straight line is a railroad and the rectangle is the location of the power plant Cerro Prieto I.
- Fig. 4. Isotherms on a SW-NE profile across the field, based on the calcite water isotopic geothermometer.
- Fig. 5. (Top) - Correlation of hydrothermal mineral zones in sandstones and those in shales with temperature in the Cerro Prieto reservoir. (Bottom) - Curves showing four different characteristic patterns of hydrothermal mineral zones with depth corresponding to four different temperature gradients.
- Fig. 6. Ranges of $\delta^{18}\text{O}$ in calcites from sandstone samples recovered from four different wells characteristic of Cerro Prieto. The shaded areas between roughly parallel curves for each well show the range of values measured at the various depths. The curve labeled "boiling" shows the $\delta^{18}\text{O}$ of calcite in equilibrium with boiling water with $\delta^{18}\text{O} = -8.33 \text{ ‰}$.
- Fig. 7. The geothermal field can be divided into regions with different patterns of mineral zones, characteristic of different flow regimes. R = recharge zone, P = thermal plume, D = discharge zone, and H =

horizontal flow zone. Open circles show well locations and filled circles are selected wells whose identifying numbers are shown.

Fig. 8. The proposed flow pattern at Cerro Prieto shown on a southwest to northeast profile from well M6 to well M53.

Fig. 9. Lithological column in well NL-1 showing the depths of dike or sill rocks encountered.

Fig. 10. A hypothetical cross-section showing the successive positions of the same isotherm at different times t_1 , t_2 , t_3 and t_4 . V = vitrinite reflectance; W/R = water/rock ratio.

Fig. 11. Block diagram of a pull-apart basin" or rhombochasm between the Imperial and Cerro Prieto faults. The area of new crust formation is arbitrarily indicated as a central vertical slice.

Fig. 12. Schematic cross-section showing the various components of our numerical models; each component has characteristic permeability and other physical properties. Unit A is unconsolidated deltaic sediments and Unit B is consolidated sedimentary rocks.

Fig. 13. Schematic geologic cross-section from northwest to southeast across the field. After de la Peña et al., 1979; Fonseca and Razo, 1979; Prian, 1979; Lyons and Van de Kamp, 1980).

Fig. 14. Model CPP5 - Initial condition and isotherms for four successive time steps. Permeability in millidarcies. The top surface is shown as impermeable. The upper part of the pluton has been given a fracture permeability and is surrounded by a more permeable sheeted dike swarm.

Fig. 15. Model CP43 - Initial condition and isotherms for four successive time steps. The top surface is again chosen to be impermeable. The

pluton is chosen to have an assymmetric funnel-shape. The permeability of the overlying sediments is also chosen to vary laterally. Such factors lead to a rough approximation of an inclined plume and a temperature distribution after 40,000 to 50,000 years similar to that observed today.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

CONDUCTIVE: NO FLOW

Figure 15