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June 1983

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A MODELING STUDY OF THE NATURAL STATE OF THE HEBER GEOTHERMAL FIELD, CALIFORNIA

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ABSTRACT

As a first step in simulating the behavior of the Heber field under exploitation, the system is modeled in its natural (pre-exploitation) state. Using Lawrence Berkeley Laboratory's (LBL) computer code PT and a radially symmetric model, a reasonable match between published and calculated temperature and pressure distributions is obtained.

The results of the study indicate that the Heber geothermal system is created by the upflow of hot water through a central zone of higher permeability. The model shows that in its natural state the system is recharged at depth by a 15 MW(thermal) convective heat source. The existence of a radially symmetric convection pattern, whose axis coincides with that of the Heber anomaly is suggested. At the lower part of the ascending hot water plume, the deep recharge water mixes with colder water moving laterally towards the axis of the system. On the upper part, the rising plume spreads radially outward before reaching the bottom of the caprock, at 550 m depth. The model results suggest that the caprock is quite permeable, with convection controlling the temperature distribution. The low permeability of the upper zones in the outer region of the system may be due to mineral precipitation.

INTRODUCTION

The Heber geothermal system is located in the southern part of the Imperial Valley, California, about 7 km north of the Mexican border (Figure 1). The Heber geothermal anomaly is a circular-shaped, moderate-temperature, low-salinity, liquid-dominated system, that is characterized by high heat flow, an electrical resistivity low, and a positive gravity anomaly (Tansev and Wasserman, 1978). There are no surface manifestations in the area. The exploration and development of Heber has been summarized by Salveson and Cooper (1979). A 45 MW_e (net) binary demonstration power plant has been commissioned by the San Diego Gas and Electric Company; it is expected to be on-line in 1985. The geothermal fluids for this plant will be supplied by Chevron Geothermal which has unitized the field with the other leaseholder, Union Geothermal.

In this paper we develop a coarse model of the natural state of the Heber geothermal field. We use a numerical simulator to calculate steady-state mass and heat flow conditions for various different models. Then the resulting thermodynamic conditions (temperature and pressure) in the reservoir system are compared to field observations. Using a two-dimensional radial model, we are able to match temperature and pressure data from the field reasonably well. The main differences between the observed pressures and temperatures and the calculated ones are due to the two-dimensional approximations used. The best match obtained yields values for the permeability distribution in the field and mass and heat flows through the system in its undisturbed state.

The modeling of a geothermal system in its natural state is a necessary step before simulations of field performance under exploitation are carried out. This type of modeling effort is time-consuming as many iterations are needed before a reasonable match with observed data is achieved. However, the information contained in the natural thermodynamic conditions of a field can, if properly analyzed, help determine the permeability distribution in the field and the natural mass and heat recharge; parameters that can greatly affect the response of the geothermal system to full-scale exploitation. Natural-state modeling studies have been reported by Lippmann and Bodvarsson (1983) on the Cerro Prieto geothermal field, Mexico, and Bodvarsson et al. (1983) on the Krafla geothermal field in Iceland.

AVAILABLE DATA

Relatively little information has been published on the subsurface characteristics of the Heber system.

Tansev and Wasserman (1978) describe the Heber field as part of the Colorado river deltaic environment consisting of interbedded sandstones and shales. The shales are thick and predominant to about 610 m

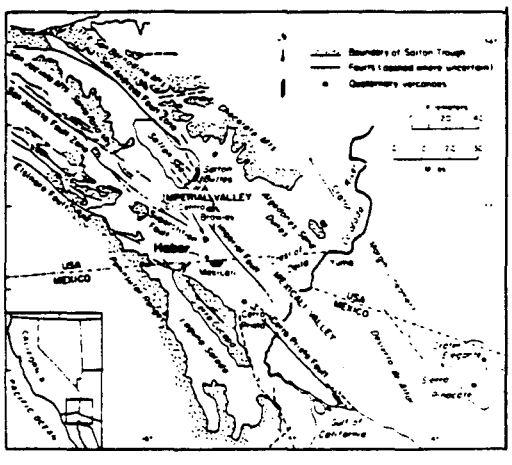


Figure 1. Regional geology of the Salton Trough and location of the Heber field, southeast of El Centro, California.

depth; below that, relatively thick sand layers prevail and shale layers become thinner. From about 2400 to 3000 m, sands are predominant with minor shale breaks. The continuity of several sand layers has been confirmed by well tests. A few faults have been identified, but according to these authors, any faults present in the more sandy section would not significantly hamper fluid flow. Measurements in Heber wells indicate that the pressure gradient in the reservoir is approximately 95.01 bar/km (0.42 psi/ft) which is the hydrostatic pressure gradient for 170°C liquid water. As the temperatures in the main thermal anomaly at Heber are close to 190°C, this indicates upflow from depth in the center of the anomaly.

Salveson and Cooper (1979) show that temperature data from Heber wells outline a convective plume of hot water of 190°C temperature, or higher, rising from depths below 3000 m. Above 1350 m, horizontal fluid flow shifts the plume northerly. The hot plume centers near well Nowlin #1 at about 600 m but shifts about 800 m towards the south at 1200 m depth (Fig. 2). These authors state that the caprock (predominantly shales) at Heber extends down to a depth of 600 m, and that in the caprock heat flow is predominantly conductive. Sands dominate (50-80%) below 600 m with intergranular porosities of 15 to 30%. To our knowledge, no other values of reservoir parameters at Heber have been published.

The heat source at Heber has not been identified. One well (Holtz #1, about 900 m southwest of J. D. Jackson #1) penetrated a diabase dike or sill of probable Pleistocene age at a depth of 1335 to 1366 m. However, such a small rock body could not be the heat source for the present Heber geothermal anomaly (Browne, 1977). It can be postulated that at the Heber field, similar to the East Mesa field (Goyal and Kassoy, 1981), mass and heat is recharged through a more permeable zone, associated perhaps with one of the identified faults or with an intersection of these faults. However, it is difficult to confirm this hypothesis since a fault map for this system has not been published.

Mineralogic studies of well cuttings (Browne, 1977) indicate that temperatures have changed in the field during its evolution. Fluid inclusion data indicate that, at least locally, the reservoir has been cooling at an undetermined rate, from a maximum temperature of 240°C, and that there were at least two significant pulses of hot fluids.

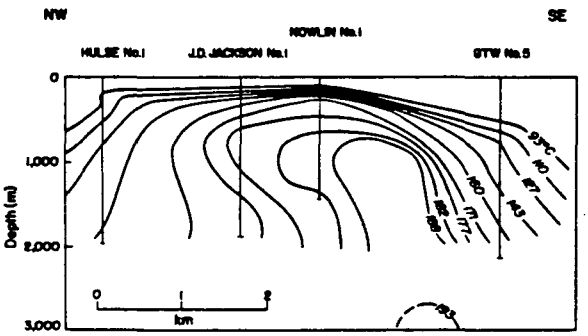


Figure 2. Temperature distribution in the Heber geothermal field (modified from Salveson and Cooper, 1979).

METHODOLOGY

In this study the computer code PT (Bodvarsson, 1982) was used. This program was developed at Lawrence Berkeley Laboratory for modeling heat and mass transport in fully saturated fractured and/or porous media rocks.

A simplified model of the Heber field was developed based on data published in the literature (see below). The temperatures and pressures at the boundaries, the rock properties of the different zones in the model, and the amount of hot water recharging the system were varied in order to match the computed values with the pressure gradient indicated by Tansev and Wasserman (1978), i.e., 95.01 bar/km, and the temperature distribution given by Salveson and Cooper (1979), see Figure 2.

It was assumed that the field was under steady-state conditions in its natural (pre-exploited) state. Therefore, the gradual cooling of the reservoir as indicated by mineralogic studies (Browne, 1977) was neglected.

DESCRIPTION OF THE MODEL

The model used in the simulations was radially symmetric. The outer boundary, 10 km from the axis, was assumed to be open to heat and mass flow and have constant temperatures and pressures. The temperatures at the outer boundary were assumed to increase linearly with depth with a gradient of 50°C/km. The pressures used at the outer boundary were hydrostatic for the assumed temperature distribution.

The top boundary was considered open only to heat flow; it was kept at a constant temperature of 22°C (about the mean annual temperature in the area; Imperial Irrigation District, 1978). The bottom boundary, at 4950 m depth, was assumed to have a constant temperature of 269.5°C, computed from the assumed geothermal gradient and surface temperature. An upflow zone feeding hot water to the reservoir system was assumed to exist over a 1000 m radius at the bottom of the reservoir system. The amount and temperature of the fluids recharging the system through the upflow zone were varied during the simulations. The remainder of the bottom boundary was closed to fluid flow.

The model was divided into 5 zones with different rock properties, primarily different permeability values (Fig. 3). Zones 1 and 2 are 550 m thick and represent the caprock. Zone 3, representing a cylinder of 1000 m radius, is the hot water upflow zone. Zones 4 and 5 correspond to the outer regions of the field.

The single most important reservoir parameter controlling steady-state distribution of temperature and pressure in the system is the permeability. The permeability values were changed for the different cases studied, and it was found that the best match between computed and observed temperature values were obtained when the permeability anisotropy (k_{hor}/k_{vert}) in zones 1, 3, and 5 was kept at 10 and in zones 2 and 4 at 100.

The anisotropic nature of the permeability of the different regions seems reasonable when one con-

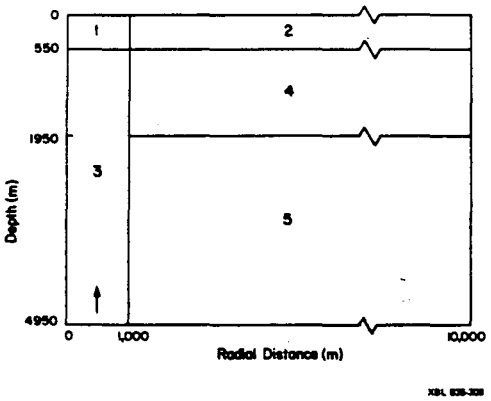


Figure 3. Different zones used in the model.

siders the general intercalation of sandstones and shales in the lithologic column at Heber. The lower anisotropy of zones 1 and 3 could be due to a higher density of vertical fractures/faults; perhaps the faults postulated with the upflow region. On the other hand, in zone 5, below the bottom of the deepest wells at Heber, the lower anisotropy could be related to a larger sand percentage. This is consistent with an apparent increase of sandstone abundance with depth reported by Tansev and Wasserman (1978).

The thermal conductivity of the materials is another important parameter that greatly affects the steady-state thermodynamic conditions computed. Since no values of thermal conductivity of the various formations at Heber are available, we assumed a value of 2 W/m °C. This value seems reasonable for sandstone and shale. However, for the materials in zones 1 and 2 (shallow layers), a lower value was assigned (1.088 W/m °C) based on the average thermal conductivity reported by Combs (1977) for forty samples from 150-m-deep wells drilled in the Imperial Valley. It should be emphasized that the thermal conductivity values assigned to the shallow zones (zones 1 and 2) are much more important than those assigned to deeper reservoir zones because of the predominantly conductive heat losses to the surface.

The results presented in this paper are not dependent upon rock parameters such as the porosity, rock density, heat capacity, thermal expansivity, or compressibility. These are storage-type parameters that do not affect steady-state solutions.

RESULTS

Several cases were studied; not all are discussed here. They differ in the permeability distributions used, boundary conditions, and strength of the heat source. We will first discuss the model that best reproduces the reported temperature distribution and pressure gradient in the Heber system, then consider the sensitivity of the model to various parameters. When evaluating the results one should keep in mind that the radial model used in the simulations cannot replicate the horizontal groundwater flow which distorts the shape of the convective plume into a lopsided mushroom (Salveson and Cooper, 1978). When matching values, the computed results are centered on well Nowlin #1 (Fig. 2).

Best Model

The best match between observed and computed values was obtained when the following parameters were used:

(1) The caprock (zones 1 and 2, Fig. 3) has a horizontal permeability of 5 md; the upflow zone (zone 3) 125 md; the upper outer region (zone 4) 10 md; and the lower outer region (zone 5) 115 md. As mentioned earlier, a thermal conductivity of 2.0 W/m °C was used everywhere, except in zones 1 and 2 where a value of 1.1 W/m °C was used.

(2) The recharge rate from below into the upflow zone (zone 3) is 14.6 kg/s of 244.5°C water, or equivalent to 15 MW thermal energy.

The computed temperature distribution in the system is shown in Figure 4 (only half of the cross section is depicted because of the radial symmetry of the model). The figure shows the typical mushroom shape due to the outward flow of hot fluids in the upper part of the reservoir system and the inflow of colder fluids below. Consequently, one finds large temperature inversions in wells drilled outside the main upflow zone.

The comparison between observed and calculated temperatures is shown in the cross section given in Figure 5. The match obtained is reasonable when one considers the radial model used in the simulations. The calculated isotherms are symmetrical whereas the observed data show some nonsymmetrical behavior, probably due to regional groundwater flow and variations in the permeability distribution in the various reservoir regions. Figure 5 shows that the calculated isotherms spread too far to the SE in the upper regions of the reservoir but not far enough to the NW. Similarly, the calculated temperature

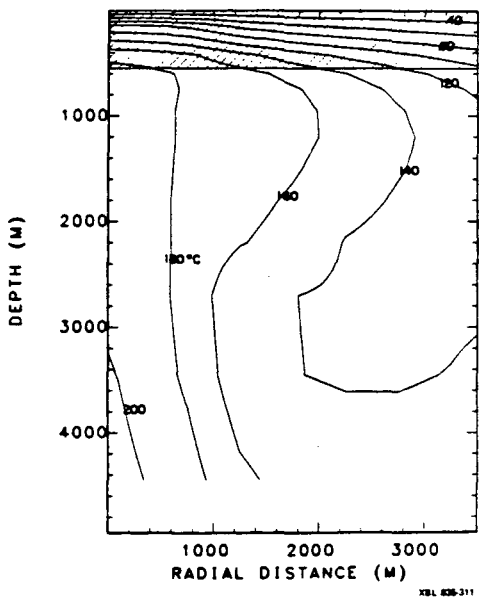


Figure 4. Best model. Computed steady-state temperature distribution. Hatched layer represents the caprock (zones 1 and 2, see Fig. 3).

inversions are too large in the lower part of the reservoir to the SE but are less than those observed to the NW. Overall, the calculated temperatures are close to those observed so the actual energy input into the system must be close to that used in the simulation.

Figure 6 shows the comparison between observed shallow temperatures (146 m depth) reported by Salveson and Cooper (1978) and our calculated values. The agreement is reasonable, indicating that heat losses to the surface are adequately modeled.

The computed pressure distribution in the upper 3000 m of the upflow zone is shown in Figure 7. The match with the observed pressure gradient (95.01 bar/km) is good. The overall gradient from the ground surface to 1200 m depth is 98.16 bar/km; to 1800 m, 95.44 bar/km; and to 3450 m, 93.23 bar/km. Thus, on the average, the calculated pressure gradient is very close to the observed value (95.01 bar/km).

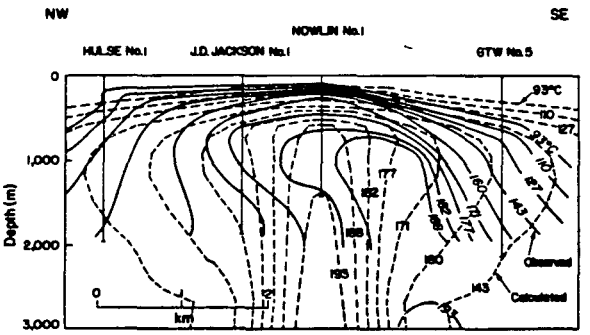


Figure 5. Best model. Comparison between observed and computed temperature distributions (see Figs. 2 and 4).

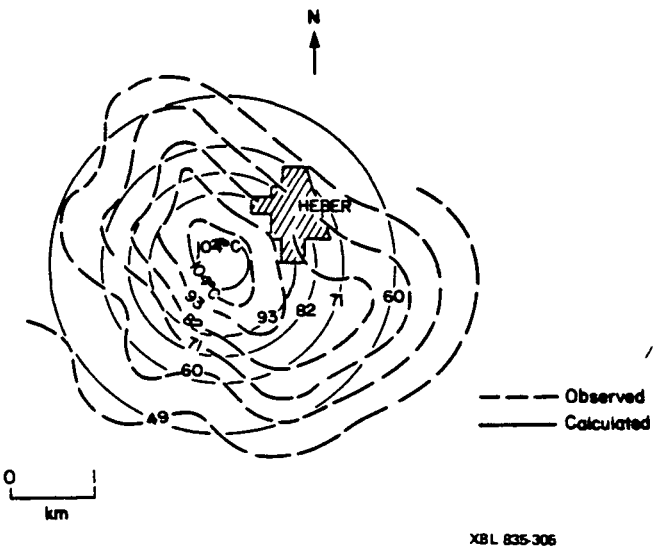


Figure 6. Best model. Comparison between observed temperatures at 146 m depth (from Salveson and Cooper, 1979) and computed steady-state temperatures at 150 m.

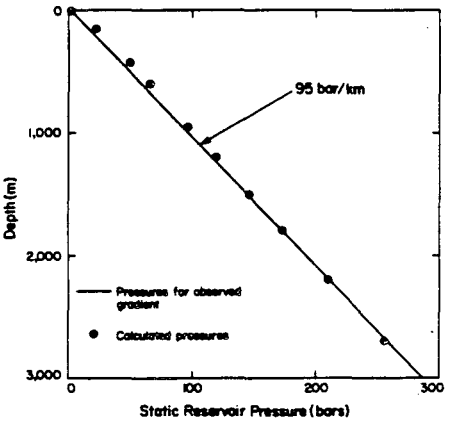


Figure 7. Best model. Comparison between pressures computed based on the reported gradient and those calculated near the axis of the model.

The computed flow patterns are shown in Figure 8. Hot water from the convective heat source ascends through the central upflow region (zone 3) and spreads laterally outwards into the upper part of the system. Colder water surrounding the geothermal anomaly, because of its higher density, flows inward toward the upflow zone. This cold water inflow is slowed down significantly by the relatively low permeability of the upper outer region (zone 4). This is indicated by the blank zone in Figure 8. (The length of the arrows is scaled with respect to the largest velocity computed in the system.) In the more permeable, deeper outer zone (zone 5) the cold water is more mobile and moves more rapidly toward the inflow zone. Near the bottom of the system, the high pressures created by the fluids recharging the upflow zone cause gradual outward fluid movement. Some fluid mixing occurs in the bottom of the upflow zone reducing the temperature of the upwelling water.

The influx of colder water from beyond the geothermal anomaly creates the marked reversals of temperature in the outer regions of the system (Fig. 4). This model seems to indicate that the

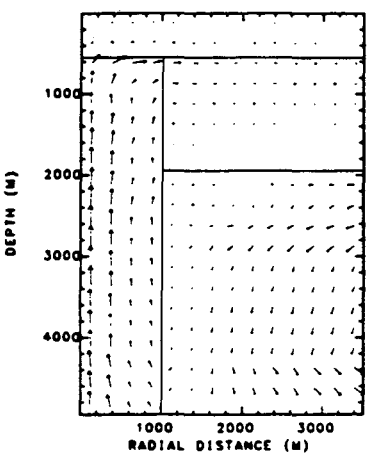


Figure 8. Best model. Computed steady-state mass flow pattern (length of arrows is scaled with respect to the largest computed velocity).

so-called caprock (zones 1 and 2) is quite permeable (5 md). If its permeability is decreased significantly, the shallow temperatures (150 m depth) would drop below those reported by Salveson and Cooper (1979). This drop could be lessened by further decreasing the thermal conductivity of zones 1 and 2. However, for the caprock a thermal conductivity value below 1 W/m °C seems unrealistic.

The horizontal permeability of the upper outer regions of the field (zone 4) seems very low (10 md) when one considers the relatively high horizontal permeability in the upflow zone (125 md). However, if we use a significantly larger permeability in this zone the inflow of cooler fluids from the outside floods the system and causes much greater temperature reversals than those observed. The low permeability of this predominantly sandy zone could be explained either by the precipitation of silica in the rock pores as the geothermal waters flow outward and cool, or by the precipitation of carbonates from the heating up of cold water during the evolution of the system.

The conductive heat losses at the surface are significantly lower than those to the upper outer boundaries where both conductive and convective losses occur. The surface heat losses for the central 1-km-radius circle amount to 1.75 MW (equivalent to 13.3 HFU); for the 3-km circle, 8.63 MW (7.3 HFU); and for the entire 10-km-radius system, 36.6 MW (2.8 HFU). Heat is not only recharged at the bottom of the upflow zone via the 15 MW thermal convective source, but is also transferred by conduction from the lower boundary.

Sensitivity Studies

Sensitivity studies were carried out in order to examine the effects of various key model parameters on the steady-state pressure and temperature distributions in the system. The parameters varied in these studies were the recharge rate to the upflow zone and the permeability values of the caprock and different reservoir zones. The results obtained are given below.

Recharge rate from below. By decreasing the strength of the convective heat source to 10 MW, a significant drop of the steady-state temperatures is observed in the system (Fig. 9).

The lower rate of mass recharge also causes a slight decrease in pressures in the upflow zone (0.3 bars at 1800 m depth). Comparison of Figures 4 and 9 shows that the inflow of cooler waters is greater in the case of the lower recharge rate and temperatures are much lower than those observed in the field (Fig. 2).

By increasing the strength of the heat source, opposite effects are observed.

Permeability of the caprock. A decrease in the horizontal permeability of zones 1 and 2 to 0.1 md (keeping the anisotropy unchanged) results in a slight increase in the pressure of the system (about 0.2 bars at 1800 m depth) since a smaller amount of water can flow upwards. This reduces the temperature in the caprock greatly (Fig. 10) in comparison with the best model (Fig. 4).

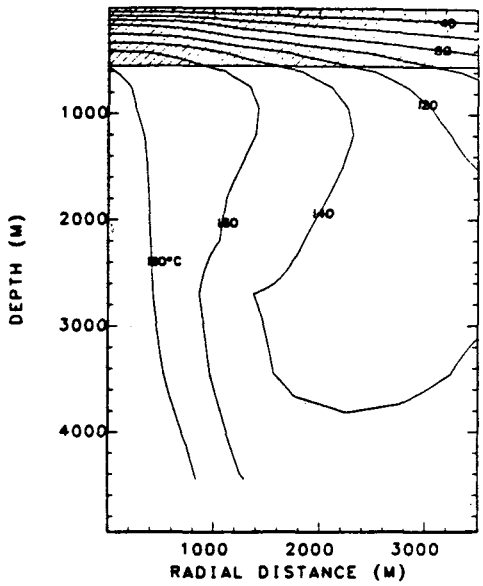


Figure 9. Sensitivity studies. Recharge rate from below: 10 MW (thermal). Computed steady-state temperature distribution.

The higher pressure in the reservoir reduces the inflow of cold water and consequently raises the reservoir temperatures, especially below 1000 m depth. The temperatures in the upper outer region (zone 4) are slightly lower than in the best model because of the downflow of cooler fluids from the caprock. In this case the low temperatures in the caprock suggest that the permeability of the caprock at Heber is significantly higher than 0.1 md.

Permeability of zone 4. By increasing the permeability of the upper outer region to 50 md (the anisotropy is kept unchanged), a larger influx of cold water into the reservoir is observed, as indicated by the 120° and 140°C isotherms (Fig. 11).

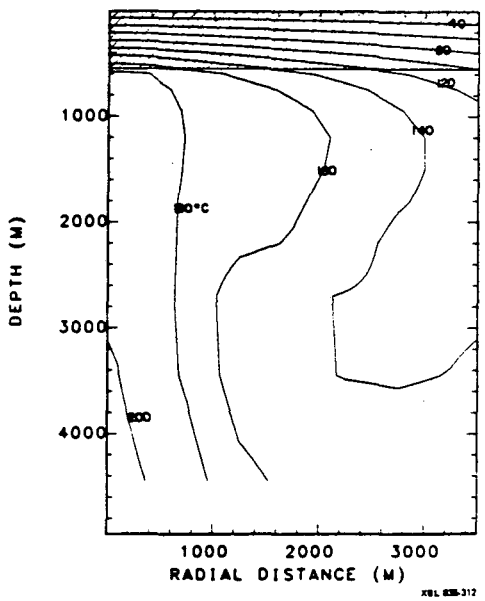


Figure 10. Sensitivity studies. Permeability of the caprock: 0.1 md. Computed steady-state temperature distribution.

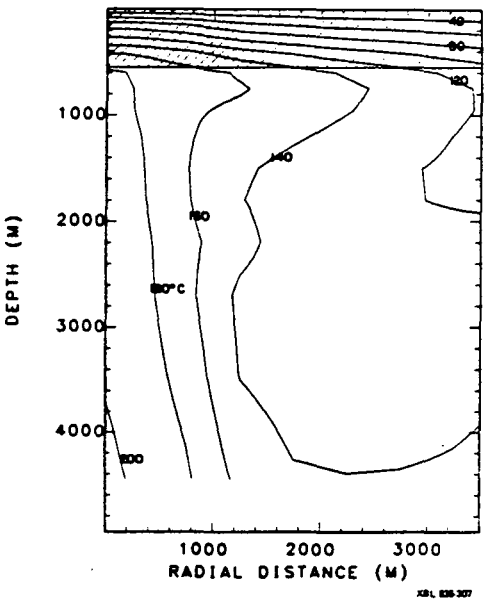


Figure 11. Sensitivity studies. Permeability of the upper outer zone: 50 md. Computed steady-state temperature distribution.

This is caused by the reduced pressure in the upflow zone (the pressure drops 0.8 bars at 1800 m depth) and the higher mobility of the fluids flowing through zone 4. The pressure in the upflow zone is lower because, due to the increase in permeability of zone 4, a smaller pressure gradient is required to push the recharged hot water into the upper part of the outer region. In comparison to the best model, the larger influx of cold water results in lower temperatures in the system.

Opposite effects are observed when the permeability of the lower outer region (zone 5) is decreased. Both pressure and temperature increase and the lateral influx of colder water is reduced.

CONCLUSIONS

Our simulation studies of the natural state of the Heber geothermal field indicate the following:

1. The upflow zone at Heber is a region of relatively high permeability with an anisotropy of approximately 10. In this zone hot waters upwell from depth and ascend to shallower layers where they spread laterally. At depth, colder waters move laterally into this zone and mix with the hot recharged waters.

2. The strength of the convective heat source is equivalent to about 15 MW (thermal). No speculations can be made on the nature of this heat source before more field data becomes available.

3. Outside the central upflow zone, temperature reversals should be encountered by deeper wells.

4. The caprock is quite permeable (approximately 5 md) at least in the lower part. The high temperatures between 150 and 600 m depth cannot be explained by conduction only. This suggests that when exploited, colder fluids from the caprock may recharge the reservoir and cause gradual cooling of the reservoir fluids.

5. The upper part of the outer region has a relatively low permeability (about 10 md). This low-permeability zone could be the result of mineral precipitation in the pores of the rock matrix.

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