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GEOTHERMAL FIELD, MEXICO

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M.J. Lippmann and G.S. Bodvarsson

March 1983

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Submitted to Water
Resources Research

NUMERICAL STUDIES OF THE HEAT AND MASS TRANSPORT IN THE CERRO PRIETO GEOTHERMAL FIELD, MEXICO

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ABSTRACT

Numerical simulation techniques are employed in studies of the natural flow of heat and mass through the Cerro Prieto reservoir, Mexico, and of the effects of exploitation on the field's behavior. The reservoir model is a two-dimensional vertical east to west-southwest cross section, which is based on a recent hydrogeologic model of this geothermal system. The numerical code MULKOM is used in the simulation studies.

The steady-state pressure and temperature distributions are computed and compared against observed preproduction pressures and temperatures; a reasonable match is obtained. A natural hot water recharge rate of about 1×10^{-2} kg/s per meter of field length (measured in a north-south direction) is obtained.

The model is then used to simulate the behavior of the field during the 1973-1978 production period. The response of the model to fluid extraction agrees to what has been observed in the field or postulated by other authors. There is a decrease in temperatures and pressures in the produced region; No extensive two-phase zone develops in the reservoir because of the strong fluid recharge; Most of the fluid recharging the system comes from colder regions located above and west of the produced reservoir.

INTRODUCTION

The Cerro Prieto geothermal field is located in the Mexicali Valley, Baja California, Mexico, about 35 km southeast of the city of Mexicali (Figure 1). Presently over 100 deep wells have been drilled on the site ranging in depth from 1200 to 3500 m (Figure 2). The wells have identified the presence of two main hot-water (single-phase) aquifers with temperatures between 280 and 350°C. Fluids tapped from these geothermal reservoirs provide steam for the 180 MW_e that are presently generated at Cerro Prieto. Two additional 220 MW_e power plants are under construction and are scheduled to go into operation before the end of 1984.

The Cerro Prieto geothermal field is a complex geological and hydrologic system. The natural flows through the geothermal reservoirs are controlled by layered sedimentary units (sands and shales), major fault zones, buoyancy effects, and the regional hydrological pressure gradient. All of these factors must be considered in modeling the reservoirs.

A comprehensive effort to understand the behavior of the Cerro Prieto system began in 1977 with the signing of a cooperative agreement between the Comisión Federal de Electricidad of Mexico (CFE) and the U. S. Department of Energy (DOE) (Witherspoon et al, 1978; Lippmann, 1982). The work described here was funded by DOE as a part of this agreement.

Several authors have presented generalized models describing the natural (initial) conditions of the Cerro Prieto field and its evolution under production. A model for the natural flow pattern in the Cerro Prieto system was initially suggested by Mercado (1976) on the basis of geochemical data (Figure 3). Later, Elders et al. (1981, 1982) used mineralogic and isotopic

data from well cuttings and cores to develop flow patterns for the field in its natural state (Figure 4). Both models show similar characteristics. The heat source for the hydrothermal system is located to the east, near well NL-1 (Figure 2), in an area where wells have drilled through basic and silicic dikes. A plume of hot water ascends from the source, boiling as it rises, discharging upwards and horizontally to the west forming hot springs and fumaroles at the surface.

Both models indicate that cold water recharges the system from the east through shallow layers. However, Mercado (1976) also postulates cold water entering the field from the west. Elders et al. (1981, 1982) on the basis of mineralogic data and simple hydraulic computations estimate the average velocity of the geothermal fluids through the field to be between 0.02 and 6 m/yr.

The general dynamics of the α (shallow) reservoir were described by Grant et al. (1983) based on chemical, production, and reservoir engineering data. They concluded that the reservoir is bounded below by low-permeability rocks, and above and at the sides by zones of cooler waters. There seem to be no continuous permeability barriers around or immediately above the reservoir. The dominating cooling process in the natural state is mixing of hot reservoir fluids with colder surrounding fluids. Exploitation causes displacement of hot water by cooler water and consequently, the reservoir temperatures tend to decline. Local boiling occurs near most wells in response to pressure decreases, but there is no indication that a continuous two-phase zone has formed in the reservoir.

Observed chemical and thermal changes in the reservoir were used by Grant and O'Sullivan (1982) to study the recharge characteristics of the old

(western) production field. Based on pressure changes the permeability of the layer overlying the reservoir was calculated. It was found that this layer was considerably less permeable than the producing aquifer but not sufficiently impermeable to exclude inflow of cooler waters from above. The authors concluded that the α reservoir in the old field is best considered as a leaky aquifer. They estimated that one-quarter to one-half of its recharge derives from cooler rock immediately above it.

The results of a limited number of numerical studies of heat and mass flow in Cerro Prieto have been reported. Liguori (1979) simulated the evolution of the geothermal field under exploitation, obtaining a reasonable good match in the steam production rate. However, the computed rate of water production was low and the enthalpy too high. He indicated that this was caused by the vertical leakage of colder waters into the reservoir which was not considered in his finite-difference model.

Lippmann and Goyal (1979) used a simplified three dimensional geological model of the field, and integrated finite different methods to compute the preproduction distribution of temperatures in the system. Only partial matching with the temperatures reported by Mercado (1976) was obtained. It was felt that a better agreement could be achieved only after a more realistic geologic model of Cerro Prieto was available.

Lippmann et al. (1980) carried out modeling studies to examine the influence of fluid recharge from over and underlying aquifers on the temperature of the Cerro Prieto producing reservoir. Appreciable variations in the temperature changes and amount of recharge were observed, depending mainly on the leaky aquifer conditions assumed for the geothermal reservoir.

Westwood and Castanier (1981) applied to Cerro Prieto a lumped-parameter model to gain insight into the physical processes in the reservoir and its response to production. The results suggested that the producing zone became two-phase early in the production history of the field and that strong recharge of 260°C water exists.

The response of the field to fluid reinjection was simulated numerically by Tsang et al. (1981, 1983). In the latest work these authors incorporated into the integrated finite difference model some of the geologic features of Cerro Prieto described by Halfman et al. (1983). The results showed that significant pressure-sustaining effects can be obtained in the producing reservoir by injecting as little as 30% of the fluid extracted.

Recently, Halfman et al. (1983) have developed a hydrogeologic model of the Cerro Prieto system on the basis of well log and reservoir engineering data. They identify permeable and less permeable zones, and postulate the flow pattern for the geothermal fluids. Some of their results are illustrated on Figure 5. This cross section along the line indicated on Figure 2 shows the distribution of sandstones, sandy-shales and shales, the temperature logs of various wells (the thicker lines indicate where the temperature is equal to or more than 300°C), production intervals, and postulated flow paths. The hot fluids move through a thick sandstone unit (Reservoir β) from the north-east, ascend through a gap in the shale layers, and flow towards the west through the more permeable units (Reservoir α at about 1200 m and Reservoir β at about 1700 m depth). The fluid flow pattern in this cross section are similar to those suggested by Mercado (1976) and Elders et al. (1981). Halfman's model, however, is much more detailed with respect to depths and location of the geothermal aquifers.

METHODOLOGY

In the present work numerical techniques are employed to estimate first the natural heat and mass flows through the reservoirs, using measured values of temperature and pressure at different depths as a basis for comparison. Then the model developed for the natural state of the reservoir is used to examine phenomena that occur during exploitation. The effects of exploitation on pressure and temperature decline, the rate of recharge of cold water, and the extent of the two-phase zone in the reservoir are considered.

RESERVOIR MODEL

A two-dimensional reservoir model, based on Halfman's hydrogeologic model, has been developed for the numerical simulation studies (Figure 6). The locations of three selected wells are shown in Figure 6 for comparison with the cross section shown in Figure 5. The grid blocks used in the simulations are also shown in Figure 6; the hatched zones indicating layers of lower permeability. The mesh consists of 60 "internal" elements and 25 boundary elements. The flow region modeled extends from east to west-southwest at a depth of 800-2000 m, and with a thickness of 1 m.

The elements in the mesh can be grouped into different zones depending upon their material properties (Figure 7). The "S1" zone corresponds to the cooler aquifer overlying the main geothermal reservoirs in the western region. In the same region, the "C1" zone represents the shaly layer above the α reservoir (zone "S2"). The shaly zone "C2" separates in the western region the α and β reservoirs, the latter represented by the zone "S3". The zone "C3" is a low-permeability layer underlying the β reservoir. The zone "F" represents a fault zone (Fault L of Halfman et al., 1983) that is postulated between wells M-25 and M-29.

In the eastern region, the "S4" zone represents a thick sandy unit overlying the thick shaly "C4" zone. Underlying the latter zone there is the sandy zone "S5" which corresponds to the eastern portion of the β reservoir which extends upwards communicating with the sandy zones "S2" and "S3".

The zone "C5" represents a region of low permeability assumed to be formed by the precipitation of calcite as cooler water comes in contact with hotter rocks.

ROCK PROPERTIES

For the simulation studies, the single most important reservoir parameter is its permeability. Analysis of well test data indicates that the permeability of the Cerro Prieto reservoirs lies in the range of tens to a few hundred millidarcies (Schroeder et al., 1980; Rivera et al., 1980; Abril and Vargas, 1981).

Values of transmissivity reported by the same authors vary between 3.6 and 40 darcy-meters. On the other hand, laboratory core analyses give permeabilities of tenths or few millidarcies (Abou-Sayed et al., 1979; Schatz, 1981) possibly because their measurements indicate vertical permeabilities obtained along the axis of the cores. No measurements have been made on relative permeabilities of Cerro Prieto rocks.

Rock porosity, compressibility, heat conductivity, and heat capacity data are also needed for simulation studies, although the effects of these parameters are not as great as those of permeability.

A number of authors have presented data on porosity (Martínez, 1978; Abou-Sayed et al., 1979; Lyons and van de Kamp, 1980; Schatz, 1981); the values reported vary between 4 and 39%. The porosity does not only depend on the rock type, but also changes with depth. Lyons and van de Kamp (1980) consider that while fractures may be an important contributor to reservoir permeability locally, secondary matrix porosity and permeability are more important volumetrically in the Cerro Prieto reservoirs. Grant et al. (1983) also conclude that the permeability within the reservoirs is predominantly intergranular.

Measurements of deformation properties of Cerro Prieto cores were made by Somerton (1980), Abou-Sayed et al. (1979) and Schatz (1981, 1982). These studies indicate that the rock compressibility is on the order of 10^{-10} Pa⁻¹. Martínez (1980) measured thermal conductivities of Cerro Prieto rocks obtaining values between 0.5 and 4.6 W/m°C for sandstones, and between 1.4 and 3.1 W/m°C for shales and silts. No measurements have been made on the heat capacities of these rocks.

In the present simulation studies, seven different materials were used (Table 1). These materials differ mainly in permeability with only slight variations in density, thermal conductivity and heat capacity. The rock porosity and compressibility was assumed to be the same for all materials, or 20% and 5×10^{-10} Pa⁻¹, respectively. The interrelations between the different zones in the model and the different materials are given in Table 2. One should note that the permeability of most of the materials is assumed anisotropic because of the layered nature of the sediments at Cerro Prieto. All of the zones shown in Figure 7 consist of shale and sand sequences in different proportions. The only material which was assumed to be isotropic is

material 4 which represents the fault zone located between wells M-25 and M-29.

Relative permeabilities of the two-phase (liquid and vapor) zones were calculated using the Corey curves. In functional form, these curves are represented by the following equations:

$$k_{rl} = \begin{cases} [S^*]^4 & S < S_{rl} \\ 0 & S \geq S_{rl} \end{cases} \quad (1)$$

$$k_{rv} = \begin{cases} [1-S^*]^2[1-(S^*)^2] & S > S_{rv} \\ 0 & S \leq S_{rv} \end{cases} \quad (2)$$

$$\text{where } S^* = \frac{1 - S_{rl} - S}{1 - S_{rl} - S_{rv}}.$$

All of the symbols are defined in the nomenclature.

In the present work we used $S_{rl} = 0.30$ and $S_{rv} = 0.05$.

TEMPERATURE AND PRESSURE MEASUREMENTS

The temperature distribution of the western portion of the Cerro Prieto field in its natural state is given by Mercado (1976) (Figure 8). Recently, Navarro et al. (1982) and Rivera et al. (1982) presented the temperature distribution for the entire geothermal system; the reported temperatures may have been affected by the exploitation of the field which began in 1973. During exploitation, wells at Cerro Prieto have shown a decline in temperature of the produced fluids. Fausto et al. (1981) and Grant et al. (1983) show, for selected

wells, temperature changes with time based on the Na-K-Ca geothermometer (Figure 9).

Pre-exploitation pressures in the α reservoir (1200 m depth) are shown in Figure 10 (mid-1973 data) and Figure 11 shows the pressure contours at the same datum in 1979 (Bermejo et al., 1979). The pressure decline in the reservoir with time is shown in Figures 12 and 13 (Bermejo et al., 1979). Limited data have been published on the pressure distribution in the β reservoir. Sánchez and de la Peña (1981) give a partial piezometric map for this reservoir.

BOUNDARY CONDITIONS

The boundary nodes, nodes B1 to B25 in Figure 6, have constant temperatures and pressures. All of them are open to heat flow, but only selected ones are open to fluid flow. The temperatures of the boundary nodes were varied to some degree until a reasonable match between observed and calculated pre-production temperature data was obtained. The best match was obtained when the values given in Table 3 were used.

During the simulations of the system under natural conditions (preproduction), only the boundary elements B1, B4, B5, B16 and B25 were assumed open to fluid flow. The pressure in these nodes was calculated based on the average fluid density of the overlying fluids and the depth to the midpoint of the boundary node. The values used are given in Table 3. The pressure in element B25, controlling the influx of 355°C water into system, was adjusted during the simulations until a reasonable match with observed pressure and temperature data was obtained.

Later, while modeling the field under production, all lateral boundary nodes (B1 to B10, and B16 to B25) were assumed to have constant pressures and be open to fluid flow. The pressures assigned to the nodes were equal to those corresponding to the natural state.

COMPUTER MODEL

In this study, the three-dimensional, multiphase, multicomponent simulator MULKOM (Pruess, 1983) was used. This program was developed at Lawrence Berkeley Laboratory for modeling the flow of water/steam mixtures in porous and fractured rock masses. The thermophysical properties of water are accurately represented by the steam table equations given by the International Formulation Committee (1967). MULKOM is an advanced version of the geothermal reservoir simulator SHAFT79 (Pruess and Schroeder, 1980), which has been extensively validated both analytically and numerically (Stanford University, 1980).

MODEL STUDIES

The mass and heat flow through the Cerro Prieto system in its natural state, and the effects of exploitation on pressures, temperatures and boiling patterns in the system were studied. By employing a two-dimensional model, the important assumption was made that the mass and energy fluxes in the third dimension are negligible. In the case of natural flows, it is believed that this approximation is quite reasonable, as the model is approximately oriented in the direction of the primary flow components, inferred from Halfman et al. (1983) work. However, in studies of the behavior of the field under exploitation, the two-dimensional assumption becomes much more critical. Massive exploitation will invariably lead to three-dimensional

flow patterns. Therefore, the studies of the reservoir behavior during exploitation can only yield qualitative results.

MODELING OF THE NATURAL STATE

Several models were considered; they differed in prescribed material properties, boundary conditions and geologic features. The analyses of five of the models studied is described elsewhere (Lippmann and Bodvarsson, 1982). The model discussed here is one of the models which better reproduces the initial distribution of temperature and pressure in the field.

It is assumed that the field is under steady state conditions in its natural state, neglecting the very slow temporal changes in the thermal or fluid flow regime that have been suggested by some mineralogic studies (Elders et al., 1981). The initial thermodynamic conditions in the model used for the natural state computations were assumed to depend only on depth. The temperature and pressure increased linearly with depth, with single-phase liquid conditions everywhere. Steady-state conditions were generally reached after 10-100 thousand years of simulation.

The model represents the geologic formations between 800 and 2000 m depth, as shown schematically in Figure 6. At the top of the model (800-1000 m depth), there is a shallow cooler aquifer which extends all across the system (zones S1 and S4, Figure 7) and which is assumed to be overlain by an impermeable layer at 800 m depth. Cold (50°C) water is recharging this aquifer from the east (through node B16, Figure 6). Hot (about 240°C) water is flowing into this aquifer from depth through the fault zone (zone F) located between wells M-25 and M-29 (node 8). This shallow aquifer discharges

fluids to the west (through node B1) feeding the surface manifestations that are observed in that area. Based on geologic data it is assumed that the western part of the aquifer is more permeable than the eastern part.

In the western region, a permeable shaly layer (zone C1) separates the shallow cooler aquifer from the α reservoir (1200-1400 m depth). As mentioned earlier, this shaly layer is cut by the fault between M-25 and M-29 (zone F) which allows the upward movement of hot fluids.

Below this shaly layer the α reservoir (zone S2) is recharged from the east with hot waters which ascend through the vertical gap existing between the shaly layers east of well M-10 (Figure 5). Cooler waters (150°C) recharge the α reservoir from the west. Under natural conditions both hot and cold water move towards the fault zone, and then upwards along the fault zone.

In the western region the α reservoir is separated from the deeper β reservoir (zone S3) by a continuous but leaky shaly layer (zone C2). It is assumed that the fault zone has been sealed by mineral deposition between 1400 and 1600 m depth, so that it does not allow rapid transport of hot water to the α reservoir. In the western part of the system this reservoir is considered to be in hydraulic equilibrium with colder (150°C) waters.

A low-permeability, low-conductivity layer (zone C3) is assumed to underlie the β reservoir. Because of the lower temperature prevailing in boundary nodes B13 and B14 (Table 3), there is a decrease of temperature with depth, as observed in the western region below the β reservoir.

In the eastern region below the cold shallow aquifer discussed earlier, there is a thick shaly, low-permeability unit (zone C4) which acts as a confining

layer to the underlying β reservoir (zone S5). The depth to the β reservoir increases towards the east where it is recharged with 355°C liquid water (through node B25). This fluid is believed to be heated at depth by a swarm of intruded dikes (Elders et al., 1982).

The vertical gap between the shaly units (Figure 5, east of well M-10) could allow fluid flow between the shallow cold aquifer and the geothermal reservoirs. If the vertical permeability of the sandy materials in this gap were high, the cold water could move downward because of its higher density and gradually cool the geothermal resource. However, the vertical permeability of the gap is probably not very large, because the ascending hot water, tends to precipitate minerals as it boils (Elders et al., 1981).

It is considered that the fluid flow between the shallow aquifer (zones S1 and S4) and the geothermal system below is restricted by the existence of a low-permeability zone (zone C5, node 16) created by the self-sealing of the sediments as the cold recharge water is heated (Elders et al., 1981).

Results

Figure 14 and 15 show the computed steady state temperature distribution and fluid flow pattern in the system. The hatched regions represent the lower permeability zones and the dotted regions the areas where boiling occurs. Some of the results are summarized in Table 4.

The temperature of the α reservoir (nodes 21 and 27 in Figure 6) varies between 291 and 299°C. The pressure at 1250 m depth (node 21) is 11.52 MPa. At 1200 m it would be about 11.11 MPa, which compares well with the 1973 pressures shown in Figure 10.

The temperatures in nodes 45 and 51, representing the β reservoir in the western part, are 330 and 329°C, respectively. The pressure in node 51 (1750 m depth) is 15.93 MPa. This value is slightly higher than the pressure reported by Prian (1981) for well E-1 (15.30 MPa). However, the pressure in well E-1 was measured in January 1981, about two years after fluid extraction started in the β aquifer in the southwestern and eastern parts of the field.

Boiling is restricted to the eastern region of the field, in the upflow zone and part of the β aquifer. The flow patterns shown in Figure 15 indicate a significant cold water recharge from the west and an even larger upward flow through the fault zone near well M-29. The ascending water eventually discharges at the upper left corner of the model.

In the western part of the β reservoir some hot water enters from the east, part of which leaks upwards through the confining layer, while some moves westward where it cools in a not very well-defined convection cell.

In the α reservoir east of the fault zone, the major component of flow is to the west, a small amount of colder water flows to the east in the lower part of the reservoir. Both waters mix and flow upwards through the fault.

In Figure 15 and a later figure, the length of the arrows is scaled with respect to the largest flow rate. Consequently, in regions where the flow is small, no arrows are present. The rates of fluid recharge and discharge, and the velocities in the α reservoir are given in Table 4. These velocities (0.4 and 1.4 m/yr) are in the range computed by Elders et al., (1981, 1982).

Furthermore, Mercado (1968) estimated the volume of the natural flows of the surface manifestations to be $5 \times 10^6 \text{ m}^3/\text{yr}$ along a 10 km-long zone. Assuming a fluid density of 1000 kg/m^3 , this outflow is about $1.6 \text{ kg} \times 10^{-2} \text{ kg/s}\cdot\text{m}$. This value compares reasonably well with the calculated natural flow rates through the Cerro Prieto system. For example, the inflow of hot fluids into the β reservoir from the east (node 60) is $1.01 \times 10^{-2} \text{ kg/s}\cdot\text{m}$, and the outflow through node 1 is $2.28 \times 10^{-2} \text{ kg/s}\cdot\text{m}$ (Table 4).

Sensitivity Studies

Slight changes were made in the distribution of materials, boundary conditions and geologic features of the model, to gain insight to their effects on the steady-state mass and heat flows in the system.

By lowering the permeability of the shaly layer (zone C2), i.e. changing it from material 3 to material 7, the vertical leakage of hot waters though it is significantly reduced. This decreases the flow of hot water into the western region of the β reservoir, markedly reducing the temperature and increasing the pressure in this reservoir; (285°C and 17.57 MPa in node

51). On the other hand, the temperature in the α reservoir is slightly increased (297°C in node 21 and 302°C in node 27).

Because of the low temperatures and high pressures obtained in this case for the western part of the β reservoir, it is concluded that the permeability, especially the vertical permeability, of zone C2 should not be reduced.

If the fault zone between well M-25 and M-29 is opened in nodes 32 and 38, allowing a direct connection between the α and β reservoirs in the western region of the field, a significant drop in the steady state temperatures and pressures is observed in the α reservoir. In the β reservoir, the temperature is almost unchanged but the pressure is considerably lower (15.19 MPa in node 51); this value is lower than the one measured in well E-1 in early 1981 (15.30 MPa).

Since the low temperature and pressure in the α reservoir and the low pressures in the western part of the β reservoir are not consistent with the measured data, this permeable gap in the shaly zone C2 is considered to be unrealistic.

When the pressures in boundary nodes B4 and B5 are decreased to 11.278 and 12.180 MPa, respectively, there is not only a reduction in the influx of 150°C water into the α reservoir, but also a decrease in pressures throughout the system. The temperature in the α reservoir rises to 297°C in node 21, and 308°C in node 27. This agrees more closely with the temperatures given by Mercado (Figure 8) and also best reproduces the temperature reversal observed in the western part of field. The pressure in node 21 is now 11.33 MPa, and

at 1200 m depth it would be about 10.95 MPa, a value similar to those shown in Figure 10. On the other hand, the pressures and temperatures in the β reservoir have slightly dropped. This increases somewhat the extent of the boiling zone in the eastern regions of the β reservoir.

The good matches obtained in the α reservoir seem to indicate that a reduction of pressures in the western boundary nodes of the model might be realistic.

When the permeability of node 16 (zone C5) is increased, i.e. changing it from material 3 to material 2, the influx of colder water from the shallow aquifer into the reservoir also increases. This results in a significant cooling of the upper region of the ascending hot water plume (254°C in node 22). The rest of the system is only slightly affected.

The relatively low temperatures in the upper eastern part of the α reservoir (in the region near M-10) agree well with values reported by Mercado (1976) (see Figure 8). This indicates that the sealing of the sediments of zone C5 is not complete. In other simulations the permeability of this zone, was increased even further, thus eliminating the self-sealing zone on top of the rising hot water plume, but the results showed an inordinate cooling of the α reservoir.

A brief study was conducted to examine the effects of the relative permeability curves used on the steady state temperature and pressure distribution in the Cerro Prieto system. Linear relative permeability curves were used and the results were compared with those obtained using the Corey curves. The

results showed no significant differences, primarily because of the small volume of the two-phase zone.

Natural State - Conclusions

From the results of modeling the natural state of the Cerro Prieto system it is concluded that:

- (1) The Halfman et al. hydrogeological model is reasonable and consistent with mass and heat flows in the Cerro Prieto reservoir;
- (2) The average natural rate of hot water recharge into the eastern part of the Cerro Prieto system is approximately 1×10^{-2} kg/s per meter of width (measured in a north-south direction);
- (3) The fault zone between wells M-25 and M-29 permits flow of fluids between the α reservoir and the shallow colder aquifer, but not between the α and β reservoirs;
- (4) The hot water plume boils as it ascends through the permeable gap existing in the shaly layers;
- (5) There exists a lower permeability zone at the top of the vertical gap between the shaly layers which inhibits, or reduces, the influx of shallow cooler waters into the geothermal system from above.

SYSTEM UNDER EXPLOITATION

In the second part of the simulation studies, the model developed for the natural state was used to simulate the behavior of the Cerro Prieto system during exploitation.

It was assumed that during exploitation half of the fluid mass is extracted from node 21 and the other half from node 27 (see Figure 6); both nodes represent the main producing zone of the α reservoir. The fluid production rates (Q_T) at the Cerro Prieto field between March 1973 and the end of 1979 are given in Table 5. Initially, these rates were divided by 1500 m (the approximate width of the production area in the western region) to take into consideration the two-dimensional nature of the models. This resulted in pressure drawdowns in the α reservoir (nodes 21 and 27) which were about twice as large as those reported by Bermejo et al. (1979). This discrepancy is caused mainly by the two-dimensional nature of the model, i.e., lack of recharge from the third dimension.

Several rate reductions were tested and are discussed elsewhere (Lippmann and Bodvarsson, 1982). It was found that dividing the total rates (Q_T) by 3000 or 4000 m gave some agreement with the observed pressure changes. On the other hand, by studying the temperature changes in node 21 using different flow rates, it was determined that the 4000 m case gave too slow a temperature decline. Based on the pressure and temperature response it was decided to use an effective width of 3000 m in the simulations of the response of Cerro Prieto to exploitation. (i.e., $Q = Q_T/3000 \text{ m}$).

Results

Figure 16 shows the computed temperature in nodes 21 and 27, representing the production zone in the α reservoir. Between March 1973 and December 1978 the temperature decreases 20.9 and 23.5°C in nodes 21 and 27, respectively; these changes are similar to those observed in the field. The Na-K-Ca geothermometer indicates that between 1973 and 1978 the temperature in the α reservoir has dropped by up to 30°C (Figure 9). An average drop of 20°C over this period is a reasonable value (A. Truesdell, 1982, personal communication).

The cause for the temperature decline in the α reservoir is obvious when one compares the energy inflow into the production nodes (nodes 21 and 27) to the energy produced (Figure 17). The fluid flow into these nodes is dominated by inflow of cooler waters from the west. The low energy content of this recharge results in a net energy loss in the production nodes of about $.5 \times 10^5$ J/s·m; consequently, the temperature declines. The bumps in the curves shown in Figure 17 are due to the variable production rate (Table 5).

The plot of pressure change versus time also present bumps (Figure 18) resulting from changes in production rate. The shape of the curve shows that soon after a rate change occurs the pressure tends to stabilize, reflecting the permeable nature of the system.

It is of interest to examine the cause of the pressure declines in the α reservoir. Reservoir pressure reduction is often attributed to density changes due to limited recharge. However, as shown in Figure 19, the results indicate that during the simulation the recharge rate is generally higher than the

extraction rate. Fluid density increases as the reservoir cools during exploitation. Thus, the pressure reduction is primarily caused by fluid contraction because of the temperature decline.

The computed initial pressure drop is much larger than that reported by Bermejo et al. (1979). This could be explained by the two-dimensional nature of the model which does not allow for recharge from all directions. Also we do not take into account the presence of CO₂ in the reservoir fluids, which facilitates boiling in the reservoir by lowering the boiling temperature of the water. Assuming 0.5% (by mass) of CO₂ in the Cerro Prieto fluids, and using Henry's law, the partial pressure of CO₂ at 300°C is estimated as 0.55 MPa.

A more extensive two-phase zone in the reservoir caused by the presence of CO₂ would significantly increase the compressibility of the system and consequently slow down the pressure reduction. Therefore, it is possible that the computed initial pressure decline is too large because the effects of non-condensable gases were neglected.

Figures 20, 21, and 22 show the computed pressure changes, temperature changes, and mass flow patterns at the end of 1978. Simulation of production after 1978 was not carried out due to a lack of data on the pressure history of the α reservoir and because at that time new wells, located in the southwestern and eastern part of the field, were put on line. It is felt that only a model that considers the three-dimensional nature of the geology and of the flow pattern is appropriate for simulating the behavior of the reservoir after 1978. The development of a three-dimensional model of the field is one of our future objectives.

These last figures illustrate the importance of the western boundary and the fault located between wells M-25 and M-29 (Fault L of Halfman et al, 1983) in the recharge of the produced α reservoir. At the end of 1978, 89% of the recharge into nodes 21 and 27 (representing the α reservoir under exploitation) comes from the west and the fault, 3% from the east and the vertical gap between the shaly units, 6% from the underlying layer, and the remaining 2% from the overlying layer.

The presence of the two-phase zone in the permeable gap which connects the α and β reservoirs, the associated mobility decrease due to relative permeability effects, and the low vertical permeability limit the mass recharge to the α reservoir from deeper (eastern) parts of the system.

Some authors (Bermejo et al., 1979, and Sánchez and de la Peña, 1981) have suggested that there is significant recharge to the α reservoir from the east (e.g., see Figure 13). The results of our modeling studies indicate that only a very small fraction of the recharge comes from that direction. Our work, in agreement with that of other authors (e.g., Fausto et al., 1981; Grant and O'Sullivan, 1982; Grant et al., 1983) indicates that most of the recharge to the α reservoir comes from the west and from shallower zones.

Because of the high permeability of the system the extent of the two-phase zones increases only slightly, or not at all, in our simulations of the exploited field. Furthermore, no boiling occurs in the production nodes located in the α reservoir. This agrees with the findings of Grant et al. (1983) that boiling occurs only near the wells and that no extensive two-phase zone has developed in the α reservoir during exploitation.

CONCLUSIONS

The results indicate that the field in its natural state is recharged from the east with hot water (about 1×10^{-2} kg/s per meter width) as well as with colder waters from shallower aquifers, especially from the west. The hot waters flow upwards through a permeable gap in the shaly layers (east of well M-10) and move into the western α and β reservoirs. Some boiling occurs as the hot waters ascend.

The α reservoir is fed from the east by hot waters and from the west by cooler waters. As these waters move towards the fault zone located between wells M-25 and M-29 (Fault L of Halfman et al., 1983), they tend to mix and then flow upwards through the fault zone to a shallow aquifer. This aquifer discharges to the west and the water eventually feeds the surface manifestations at the western region of the field.

In the area near well M-10 mineral deposition, causing partial self-sealing of the porous sediments, could explain the minimal influx of cold water under natural conditions into the geothermal reservoirs from the shallow aquifer overlying the system. The results show that the fault between wells M-25 and M-29 does not permit much fluid flow between the α and β reservoirs, but does connect the α reservoir with the shallow aquifer.

These studies of the reservoir response to exploitation show that most of the fluid recharge to the α reservoir comes from the west and from shallow layers above the fault zone. Recharge from the east seems to be minor due to the presence of a two-phase zone in the vertical gap between the shaly layers.

Because of the large fluid recharge during the 1973-1978 period, no extensive two-phase zone develops in the α reservoir.

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NOMENCLATURE

- h Reservoir thickness, m.
- k Absolute permeability, md.
- k_{rl} Relative permeability of liquid phase.
- k_{rv} Relative permeability of vapor phase .
- Q Production rate used in the simulations, kg/s·m.
- Q_T Total production rate, kg/s.
- S Vapor saturation.
- S_{rl} Residual (immobile) liquid saturation.
- S_{rv} Residual (immobile) vapor saturation.
- ϕ Porosity.

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FIGURE CAPTIONS

- Figure 1. Regional geological map of the Salton Trough showing the location of the Cerro Prieto field, southeast of the city of Mexicali.
- Figure 2. Cerro Prieto. Location of geothermal wells and of the WSW-E cross-section shown on Figure 5.
- Figure 3. Mercado's (1976) convective model for the Cerro Prieto field.
- Figure 4. Southwest-northeast section across the Cerro Prieto field showing the flow regime proposed by Elders et al. (1981). R = recharge zone; P = thermal plume zone; D= discharge zone; H = horizontal flow zone.
- Figure 5. Southwest-northeast cross-section of the Cerro Prieto field showing schematically the flow of geothermal fluids in the system (from Halfman et al., 1983).
- Figure 6. Two-dimensional model of the field used in this work. Grid blocks, grid block numbers, and location of three wells are shown. The hatched zones indicate layers of lower permeability.
- Figure 7. Different zones used in the model.
- Figure 8. Preproduction temperature distribution in the Cerro Prieto field along a southwest-northeast cross-section (adapted from Mercado, 1976).

- Figure 9. Changes in the Na-K-Ca temperatures in some Cerro Prieto wells (from Fausto et al., 1981).
- Figure 10. 1973 pressures (in bars) in the α reservoir, at 1200 m depth (adapted from Bermejo et al., 1979).
- Figure 11. 1979 pressures (in bars) in the α reservoir, at 1200 m depth (adapted from Bermejo et al., 1979).
- Figure 12. Pressure changes (in bars) in well M-30 at 1200 m depth (adapted from Bermejo et al., 1979).
- Figure 13. Pressure changes (in bars) in the α reservoir from 1973 to 1979 (at 1200 m depth) and postulated direction of fluid recharge (adapted from Bermejo et al., 1979).
- Figure 14. Natural state. Computed steady-state temperature distribution; countour interval: 20°C. Hatched areas represent layers of lower permeability; dotted areas, two-phase zones.
- Figure 15. Natural state. Computed steady state mass flow pattern. Length of arrows is scaled with respect to the largest flow rate (in kg/s·m²).
- Figure 16. System under exploitation. Evolution of the temperatures of nodes 21 and 27.
- Figure 17. System under exploitation. Energy extracted and recharged to the production region (nodes 21 and 27).

Figure 18. System under exploitation. Computed pressures changes in nodes 21 and 27.

Figure 19. System under exploitation. Mass extracted and recharged to the production region (nodes 21 and 27).

Figure 20. System under exploitation. Pressure changes between 1973 and 1978; contour interval: 5 bars (0.5 MPa).

Figure 21. System under exploitation. Temperature changes between 1973 and 1978; contour interval: 5°C.

Figure 22. System under exploitation. Mass flow pattern at the end of 1978. The two dots indicate where the fluids are extracted from the system.

Table 1. Properties of the materials used in the models.

Material	Rock density (kg/cm ³)	Permeability		Matrix Heat conductivity (W/m°C)	Rock Heat Capacity (J/kg°C)
		Horizontal (md)	Vertical (md)		
1	2650	100	1	3	820
2	2650	10	1	3	820
3	2550	0.5	0.005	2	920
4	2650	50	50	3	820
5	2700	0.05	0.005	1.5	920
6	2650	100	10	3	820
7	2550	1	0.1	2.5	920

Table 2. Material assigned to the zones shown in Figure 3.

Zone	Material
S1	6
S2	6
S3	6
S4	2
S5	1
F	4
C1	7
C2	7
C3	5
C4	3
C5	3

Table 3. Constant temperature and pressure at boundary nodes.

Node	Temperature (°C)	Pressure (MPa)
B1	220	8.300
B2	150	9,687 (1)
B3	150	10,591 (1)
B4	150	11.523
B5	150	12.445
B6	150	13,331 (1)
B7	150	14,352 (1)
B8	150	15,217 (1)
B9	150	15.963 (1)
B10	150	17.100 (1)
B11	150	6.800 (2)
B12	50	6.800 (2)
B13	230	18.223 (2)
B14	300	16.800 (2)
B15	360	16.800 (2)
B16	50	8.815
B17	75	10.034 (1)
B18	100	10.959 (1)
B19	125	11.875 (1)
B20	150	12.772 (1)
B21	250	13.620 (1)
B22	300	14.501 (1)
B23	315	15.329 (1)
B24	340	16.086 (1)
B25	355	19.250 (3)

- (1) These nodes were assumed to be closed to fluid flow while modeling the natural state considering that they were in pressure equilibrium with the internal part of the system. When simulating the exploitation of the field, these nodes had constant pressures and were open to fluid flow.
- (2) These nodes were closed to fluid flow, but were open to heat flow (conduction).
- (3) The pressure in node B25 was adjusted to allow the inflow of about 10^{-2} kg/s·m of 355°C water into the system.

Table 4. Natural State - Summary of Results

AQUIFER α

Node 21	Temperature ($^{\circ}\text{C}$)	291.0
	Pressure (MPa)	11.52

Node 27	Temperature ($^{\circ}\text{C}$)	298.6
	Pressure (MPa)	12.24

Fluid Velocity (m/yr)	
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Between Nodes 21-22	0.4
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Between Nodes 27-28	1.4
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AQUIFER β

Node 45	Temperature ($^{\circ}\text{C}$)	329.9
	Pressure (MPa)	15.28

Node 51	Temperature ($^{\circ}\text{C}$)	328.8
	Pressure (MPa)	15.93

Node 59	Temperature ($^{\circ}\text{C}$)	351.7
	Pressure (MPa)	17.06

BOUNDARIES

Node 60	Influx of 355°C water (kg/s)	1.01×10^{-2}
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Node 19	Influx of 150°C water (kg/s)	3.65×10^{-3}
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Node 25	Influx of 150°C water (kg/s)	7.88×10^{-3}
---------	--	-----------------------

Node 6	Influx of 50°C water (kg/s)	1.18×10^{-3}
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Node 1	Outflow of hot water (kg/s)	2.28×10^{-2}
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Table 5. Cerro Prieto Fluid Production.

Dates	Production Rates (kg/s)
3/73-12/73	459
1974	590
1975	603
1976	695
1977	751
1/78-6/78	671
7/78-12/78	761
1979	1210

XBL 801-6718

FIGURE 1

FIGURE 2

XBL 823-2041

FIGURE 3

FIGURE 4

FIGURE 5

XBL 827-2324

FIGURE 6

XBL 828-2333

FIGURE 7

FIGURE 8

XBL 822-1825

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

XBL 829-2400

FIGURE 13

XBL 829 - 1116

FIGURE 14

XBL 831-1660

FIGURE 15

FIGURE 16

XBL 828-2344

FIGURE 17

XBL 828-2336A

FIGURE 18

XBL 828-2343

FIGURE 19

XBL 929 -1120

FIGURE 20

XBL 929 - 1121

FIGURE 21

FIGURE 22

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