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Reservoir Simulation and Geochemical Study of Cerro Prieto I Wells

Marcelo J. Lippmann† and Alfred H. Truesdell‡

†Lawrence Berkeley Laboratory
Berkeley, CA 94720

‡U.S. Geological Survey
Menlo Park, CA 94025

ABSTRACT

Combined reservoir simulation and geochemical data analysis are used to investigate the effects of recharge and other reservoir processes occurring in the western part of the Cerro Prieto, Mexico, geothermal field (i.e., Cerro Prieto I area).

Enthalpy-based temperatures and bottomhole temperatures are calculated based on simplified models of the system, considering different reservoir boundary conditions and zones of contrasting initial temperatures and reservoir properties. By matching the computed trends with geothermometer-based temperature and enthalpy histories of producing wells, the main processes active in the western area of Cerro Prieto are identified. This part of the geothermal system is strongly influenced by nearby groundwater aquifers; cooler waters readily recharge the reservoirs. In response to exploitation, the natural influx of cold water into the shallower alpha reservoir is mainly from the west and down Fault L, while the recharge to the deeper beta reservoir in this part of the field, seems to be only lateral, from the west and possibly south.

INTRODUCTION

Geothermometers should be applied to geothermal systems not only to determine subsurface fluid temperatures but also to establish reservoir changes and infer reservoir processes. A typical field case study is that of Cerro Prieto, located in the Mexicali Valley of northern Baja California, Mexico. This high-temperature geothermal system has been studied and monitored for many years. The methodology described below offers an alternative "window" on reservoir processes that confirms and complements earlier geochemical and reservoir engineering evidence.

In about 1977, some four years after the first power plant came on line, the geochemistry of the fluids produced by many Cerro Prieto wells began reflecting an encroachment of cold water into the shallower alpha reservoir (Truesdell *et al.*, 1979, 1989). With time, additional data confirmed that more-dilute groundwaters were recharging the geothermal system and that heat was being swept by the colder waters as they moved toward the producing wells (Grant *et al.*, 1984).

Initial fluid production began from the shallower alpha reservoir found only in the western part of the field (i.e., the Cerro Prieto I area located west of the railroad tracks; see Fig. 1). Large-scale production from the deeper beta reservoir which extends over the entire field, started only in the early 1980s; by 1986 most fluids at Cerro Prieto were extracted from this reservoir.

At the beginning, it was not clear whether the fluid recharge into the alpha reservoir was vertical, through a leaky caprock, or lateral from neighboring aquifers. Presently, it is evident that groundwater recharges this reservoir both horizontally from the west and south and vertically through the normal Fault L (see Fig. 1; Stallard *et al.*, 1987; Truesdell *et al.*, 1989; Lippmann *et al.*, 1990).

Because of its later development, less data is available on the beta reservoir. Our present understanding indicates that it is recharged by groundwaters from the west, east and southeast. There seems to be no significant colder fluid influx from above or from the north (Halfman-Dooley *et al.*, 1989; Truesdell *et al.*, 1989; and Lippmann *et al.*, 1990).

Data on the physical and chemical properties of the fluids being produced at the Cerro Prieto field are being routinely collected by the personnel of the Comisión Federal de Electricidad, operator of the field and three power plants. Based on this information we can monitor the effects of production on the wells and reservoirs by following the evolution of geothermometer and enthalpy data. Since some geothermometers respond more slowly to changes in reservoir temperature than others it is possible to resolve the thermal history of the produced fluids as they flow toward the wells, and thus develop conceptual models of the phenomena active in the subsurface (Truesdell *et al.*, 1984, 1989).

The Na-K-Ca geothermometer equilibrates slowly in the moderate salinity waters of Cerro Prieto, thus the computed temperatures (TNaKCa) indicate those of waters at a distance from the producing wells. On the other hand, the quartz-saturation geothermometer equilibrates rather quickly, and the corresponding temperatures (TSil) reflect those at, or near, the bottom of the wells. Another usually reported parameter is the enthalpy temperature (TE), defined as the temperature of saturated liquid water that has the same enthalpy as the measured total fluid enthalpy.

As discussed by Truesdell *et al.* (1989), at Cerro Prieto there are several processes active in the reservoir which

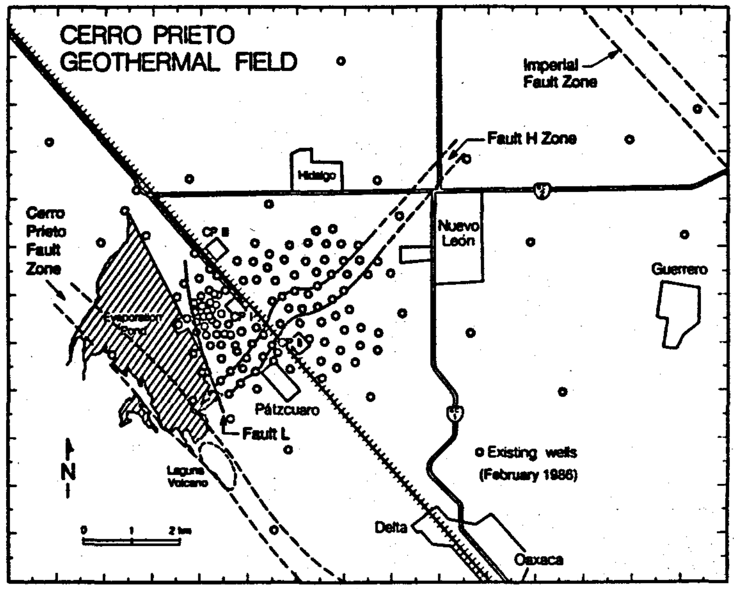

Figure 1 Location of geothermal wells and faults at Cerro Prieto. Fault H zone is shown at the beta reservoir level; Fault L is subvertical (after Halfman *et al.*, 1986).

may be identified by comparing the evolution of the different temperatures (i.e.: TNaKCa, TSil and TE). The following cases have been observed in the field:

(1) TE = TNaKCa = TSil : Indicates overpressured fully equilibrated liquid (no reservoir boiling). Example: well M-42.

(2) TE > TNaKCa > TSil : Indicates near-well boiling and ongoing heat transfer from the reservoir rocks to the fluid (expanding boiling zone). Example: well M-31 up to mid-1979.

(3) TE = TNaKCa > TSil : Indicates near-well boiling after fluid and rock have reached thermal equilibrium (stabilized boiling zone). Example: well M-31 after 1979.

(4) TE > TNaKCa = TSil : Indicates mixing near, or in, the well of steam from generalized reservoir (not near-well) boiling and thermally equilibrated liquid. Example: well E-4.

(5) TE = TSil > TNaKCa : Indicates cool water sweeping heat from hotter rocks without the water reaching complete chemical equilibrium. Example: well M-35.

Several of these cases have been observed in a single well during its production history.

Temperature histories based on geothermometer and fluid enthalpy data have been developed for all Cerro Prieto I production wells. This allowed us to characterize the wells on the basis of their geochemical and thermal behavior. The various well histories reflect differences in the amount and characteristics of the recharging fluids and in the processes that arise in response to reservoir exploitation (Truesdell *et al.*, 1989).

The purpose of this paper is to investigate what type of initial and boundary conditions, and reservoir properties can explain the observed enthalpy and chemical changes observed in some of the wells in the western Cerro Prieto area.

APPROACH

Temperature changes in porous medium, radially-symmetric reservoir models were computed using the heat and mass transfer numerical code MULKOM (Pruess, 1988). The calculated trends in produced fluid enthalpies and bottomhole temperatures were compared respectively against observed well histories of enthalpy (TE) and silica (TSil) temperatures. Changes in NaKCa-temperatures were not computed since presently MULKOM does not have a particle-tracking module. However, the latter temperatures can be inferred from the assumed initial reservoir temperature distribution.

We consider that a reasonable match between the observed and calculated trends indicates that the simulated characteristics and processes in the model approximate those of the geothermal reservoir. No exact correspondence is expected since simple radial models cannot reproduce the complexities of a real wellfield under exploitation.

Constant mass rate production is assumed in the simulations. There are no significant differences in the results if the flow rates are allowed to vary with time in response to changes in reservoir pressure and fluid mobilities (assuming similar average rates). In all cases thermal conduction is neglected.

In three simulations the reservoir is represented as a 100 m-thick isotropic permeable layer, but in one case it is subdivided into four 25 m-thick anisotropic layers. The production well is assumed to be totally penetrating the reservoir and having a one-meter effective radius. In the multi-layer case the fluid is extracted from each of the layers, the individual contributions being a function of the reservoir pressure and fluid mobility. The computational mesh is very fine near the well ($\Delta r = 0.6$ m) and becomes coarser with radial distance (e.g. $\Delta r = 20$ m at $r = 100$ m; $\Delta r = 25$ km at 125 km, the last element in the mesh).

The radially symmetric computational mesh has a no-flow boundary (i.e., it is closed) at $r = 125$ km. However the system behaves like an infinite one, since for the conditions and time of simulation, the radius of influence is smaller than 125 km.

The rock properties used in the computations are indicated below in the figures that show the simulation results. For all materials the relative permeability curves are linear, with residual saturations of 0.4 and 0.05 for liquid and steam, respectively. The fluid is assumed to be pure water.

CASES STUDIED

The locations of the Cerro Prieto I wells whose geothermometer temperature trends were numerically simulated are shown in Fig. 2.

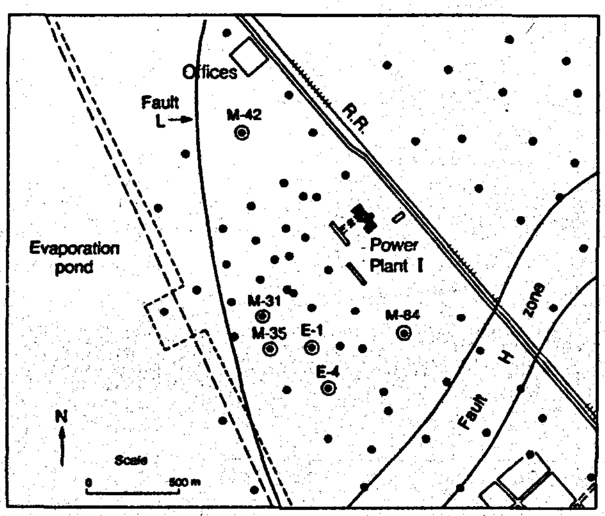

Figure 2 Location of Cerro Prieto I wells mentioned in the paper.

Well M-42

Well M-42 began commercial fluid production in November 1976 and is still on line today. It is completed in the northern region of the alpha reservoir, an area of relatively low well density. Because of sufficient fluid recharge and a general lack of well interference, M-42 has shown reservoir boiling only at early times. Near-well boiling (Case 2, see above) has occurred up to about the end of 1978 (see Fig. 3). From then on, the reservoir has been producing fully equilibrated liquid (Case 1). Careful observation shows that there is a slight drop in temperatures with time.

Considering that the well is located near the northwestern edge of the geothermal anomaly, we assume in the numerical simulations that initially there is a gradual temperature decrease away from the well. The properties, initial conditions and assumed flow rate are indicated in Fig. 4. This figure also shows the two computed temperature histories for a well completed in this quasi-infinite radial system. Here, as well as in the other simulations described below, the enthalpy temperatures [T (enthalpy)] are calculated on the basis of the computed enthalpies of the produced fluids, and the bottomhole temperatures (B.H.T.) correspond to the average temperature in the simulated well, at reservoir level.

The initial conditions in the model assume the presence of liquid water throughout the entire reservoir. As production begins, the fluid recharge toward the well is not sufficient and boiling occurs; indicated by T (enthalpy) > T (initial) > B.H.T. However, after about a year, an adequate pressure gradient (and fluid recharge) is established in the reservoir, and the near-well boiling zone collapses; i.e., T (enthalpy) = B.H.T. As production continues, cooler waters from neighboring reservoir regions begin to affect the well temperatures and the model shows a gradual temperature decrease (The rate of temperature change is a function of the size of the inner 300°C zone and the temperature of the outer regions).

This example shows the behavior of a well located in an area with significant mass recharge (or of low exploitation) whose temperature is slightly affected by the encroachment of somewhat cooler water. There is only a short period of near-well boiling and a small but continuous decrease in temperature (and in chloride; see Truesdell *et al.*, 1989).

Well E-4

E-4 is a well producing from the deeper and hotter beta reservoir. It came on line in November 1981 and continues to supply fluids to power plant I. Figure 5 indicates that for about five years the well showed constant excess enthalpy [i.e., T (enthalpy) > T (initial)]; then a slight decrease. On the other hand, TNaKCa was almost constant for about four years and only then decreased. These data suggest colder-water recharge into the beta reservoir, possibly entering from the west and south, and a delay between the breakthrough of the chemical and thermal fronts. The colder fluid influx is also indicated by a drop in reservoir chlorides (Truesdell *et al.*, 1989).

Well E-4 is one of the shallowest wells completed in the beta reservoir. The data suggest that it is producing from zones of different initial thermodynamic properties. The upper zone had initially a high steam saturation, even before the well was put on line at the end of 1981. The initial boiling seemed to be related to a general pressure drawdown in the reservoir because of production from surrounding beta wells (e.g., M-84, 515 m away, began

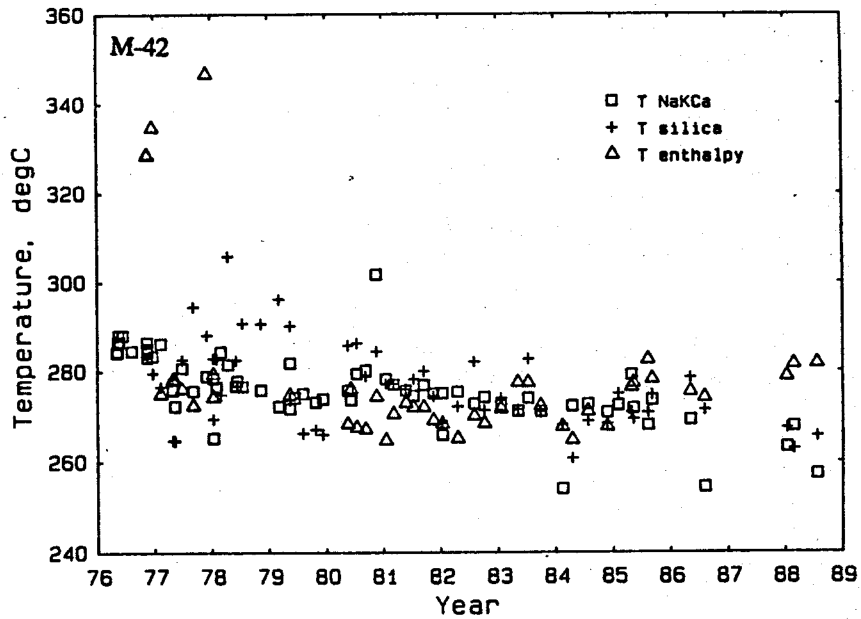

Figure 3 Indicated aquifer temperatures for well M-42.

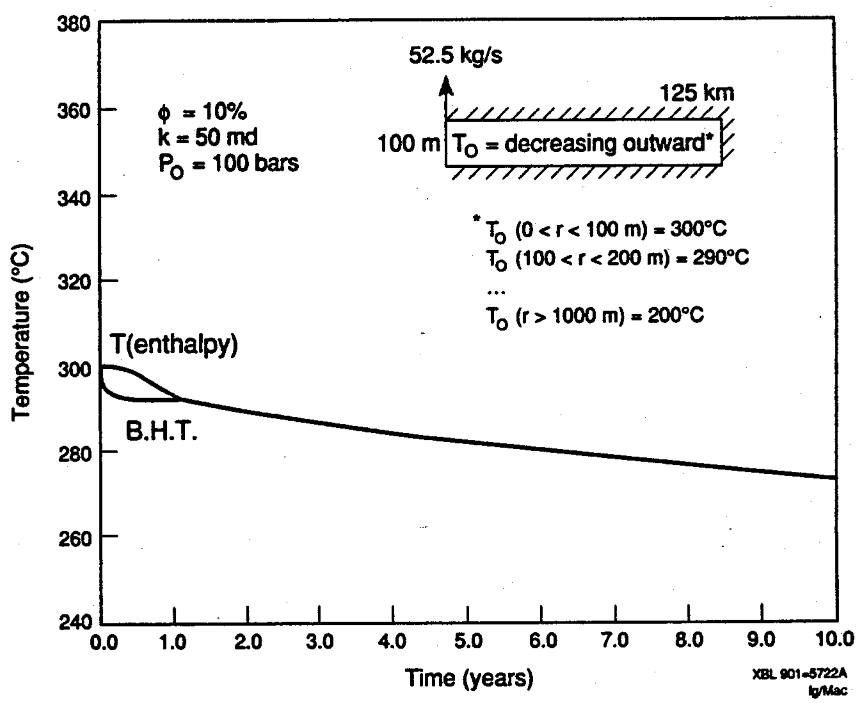

Figure 4 Calculated temperature histories for the model shown in the insert (compare trends against those in Fig. 3).

producing in March 1979, and E-1, 240 m away, in August 1981; Fig. 2).

On the other hand, the lower reservoir layers contained initially compressed liquid. With exploitation a small stabilized near-well boiling zone is observed in the deeper layers (Case 3). Thus, the chemical characteristics of the fluids produced at the wellhead are a mixture of steam, resulting from generalized reservoir boiling, and thermally equilibrated liquid (Case 4). The effect of colder water encroachment followed later.

The early behavior of E-4 can be simulated using a two-zone model of quasi-infinite radial extent (Fig. 6). The upper, 25-m thick, higher-permeability zone is assumed to have an initial high-steam (80 percent) saturation. The lower zone, divided into three 25-m thick layers, presents initially only liquid water. The permeability of both zones

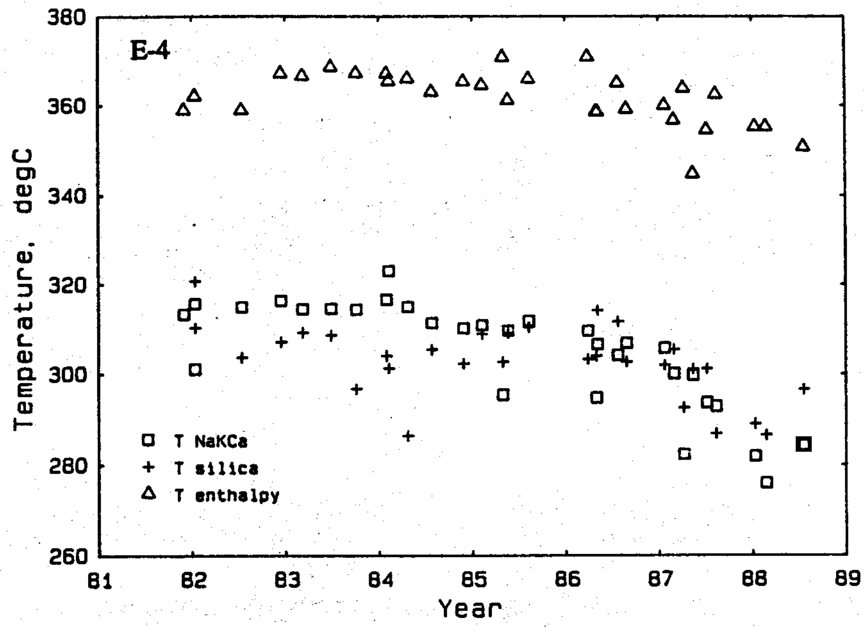

Figure 5 Indicated aquifer temperatures for well E-4.

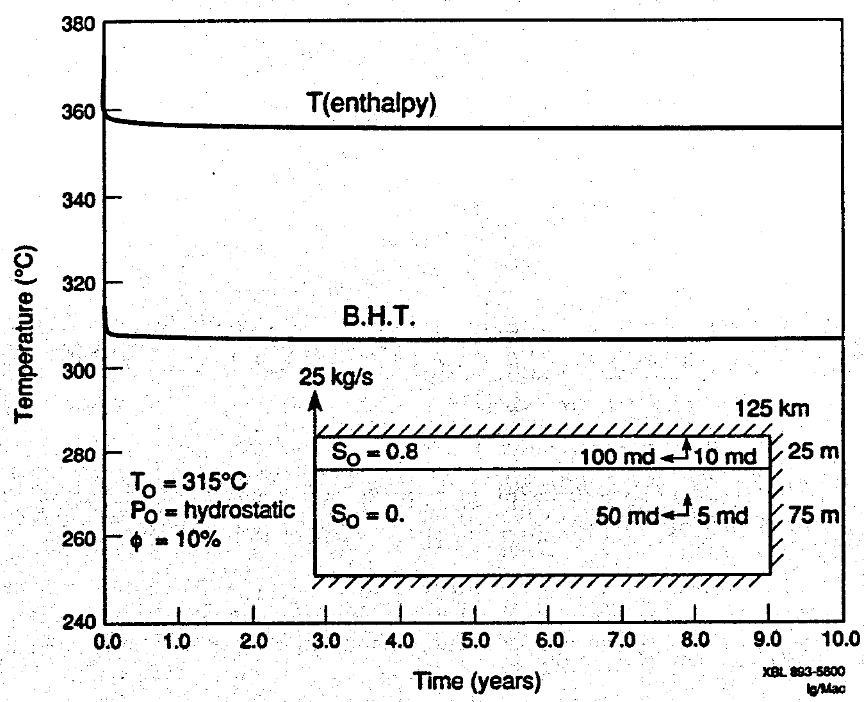

Figure 6 Calculated temperature histories for the model shown in the insert (compare trends against those in Fig. 5).

is assumed to be anisotropic, with horizontal permeabilities ten times larger than the vertical ones.

Figure 6 illustrates the response of this two-layer system to production. Because of the relatively low flow rate/permeability-thickness ratio, the excess steam and the bottomhole temperatures remain almost constant over the ten years of simulation; only a very slight negative slope in both curves is observed.

As indicated earlier, in the model mass is extracted from all four levels, the individual amounts depend on the reservoir and downhole pressures, and on the mobility of the fluid in each layer. At about 6 years, 23 percent of the total flow (0.99 quality steam) is extracted from the upper zone, while from the layers below, 25 percent (0.03 quality), 26 percent (0.02 quality) and 26 percent (0.02 quality), are produced respectively.

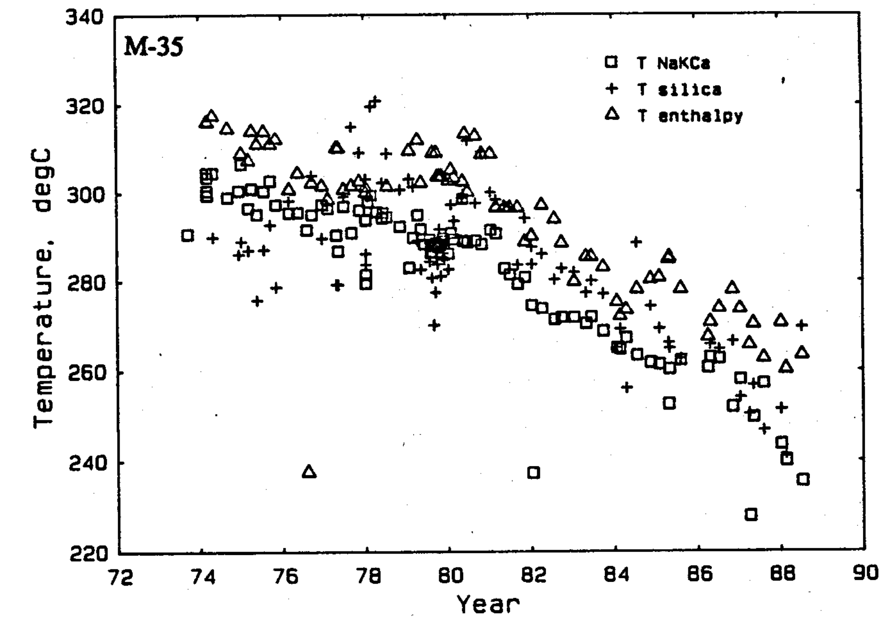

Figure 7 Indicated aquifer temperatures for well M-35.

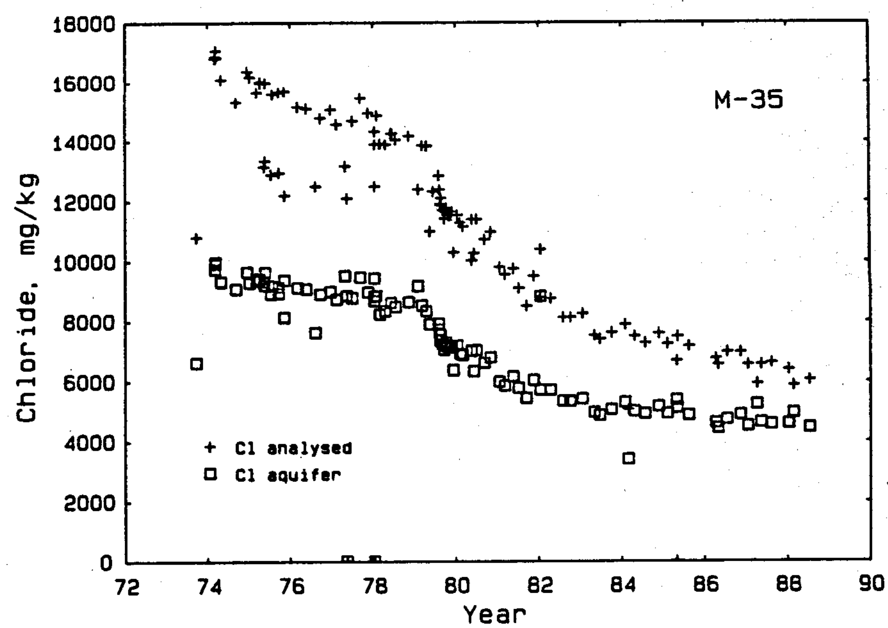

Figure 8 Chloride concentrations in well M-35. Symbols: plus, analyzed chloride concentrations after flashing to 1 atm.; square, calculated aquifer chloride concentrations.

The effects of cold water recharge observed starting about 1986–87 have not been considered in the model. However, this phenomenon is discussed below when simulating the behavior of well M-31.

Well M-35

Well M-35 is completed in the alpha reservoir and is one of the oldest producing Cerro Prieto wells. In March 1973 it started delivering steam to the only turbine installed at that time in the field (unit 1 of power plant I), and today still continues to be on line.

Early geothermeter data (Fig. 7) suggest near-well boiling (Case 2). The collapse of the boiling zone might have happen as early as 1977 (TE ≈ TSil). As this occurred, chemically non-equilibrated cooler waters (TSil ≠ TNaKCa) began sweeping heat from the reservoir rock (Case 5). Changes in the chloride contents of the produced fluids clearly indicate that the chemical front broke through in 1979 (Fig. 8). Around 1980 a gradual thermal degradation of the produced fluids began, which still con-

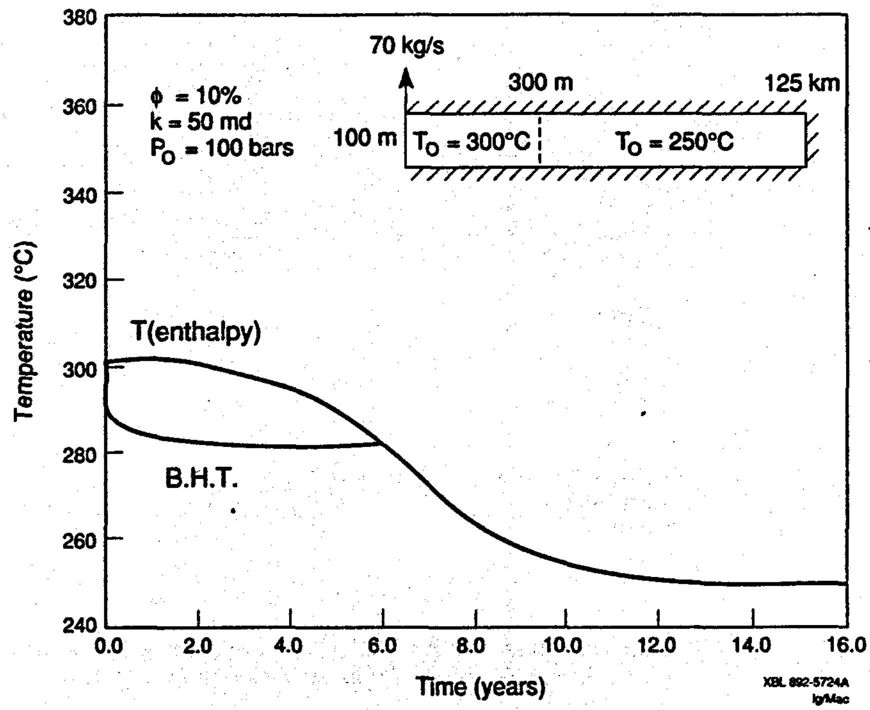

Figure 9 Calculated temperature histories for the model shown in the insert (compare trends against those in Fig. 7).

tinues today.

The behavior of M-35 was simulated by a radial model presenting initially only compressed liquid with a thermal discontinuity 300 m away from the well (Fig. 9). Upon production near-well boiling lowers the bottomhole temperature and heat transferred from the rock raises the total enthalpy above that of the initial liquid. Later, the boiling zone stabilized as Case 2 is reached. With the appearance of cooler waters the boiling zone collapses (at about 5.5 years). From then on, the well only produces liquid of gradually decreasing temperatures. After about 10 years the temperature of the produced water stabilizes at 250°C, which is that of the outer, cooler zone in the model.

We also modelled the response of a two-layer system in order to study the effect of vertical recharge into the producing reservoir. A 50-m thick, 200°C, less permeable layer was added above the original model, simulating a caprock. The impact of vertical colder water influx on the temperature history of the simulated well is minimal, unless the permeability of the caprock is similar to that of the reservoir, which would transform the situation in that of a well partially penetrating a 150 m-thick aquifer.

If we assume reservoir and caprock permeabilities of 50 and 5 md, respectively, at t = 5 years and over a circular area of 500 m radius around the well, less than 4 percent of the fluid being produced (about 2.9 kg/s) leaks from the caprock into the reservoir. This suggest that in the alpha reservoir the downward influx of colder groundwater is mainly through Fault L (Figs. 2 and 10), and that the areally distributed vertical leakage is of less importance than previously hypothesized (e.g. Grant *et al.*, 1984).

The groundwaters flowing down Fault L after reaching the alpha reservoir, move eastwards towards M-35 located about 250 m away. The descending waters might mix near the fault with other groundwaters encroaching into the aquifer from the west.

Well M-31

M-31 is an alpha well which was under production between August 1973 and April 1983, when it was taken off line because of scaling problems. Cleaning of the wellbore, carried out around 1981, did not significantly increase the flow rate. It is inferred that mineral (mainly silica) deposition greatly reduced the reservoir permeability around the well (Truesdell *et al.*, 1984).

Figure 11 indicates that immediately after M-31 began commercial production a near-well boiling zone developed, which kept expanding until mid-1979 (Case 2). A stabilized boiling zone (Case 3) existed after that.

The response of well M-31 to production is simulated by using a radial model of uniform initial properties, with a constant pressure and temperature boundary at r = 1600 m. Initially the reservoir fluid is 300°C compressed liquid; the temperature of the outer boundary has little effect on the computed results.

The model shows significant boiling upon the start of production (Fig. 12). Initially the enthalpy temperature reaches about 335°C, while the bottomhole temperature drops to 265°C. Then, T (enthalpy) slowly decreases and B.H.T. increases. After about seven years both temperatures stabilize because of the influence of the constant pressure and temperature boundary. This boundary dom-

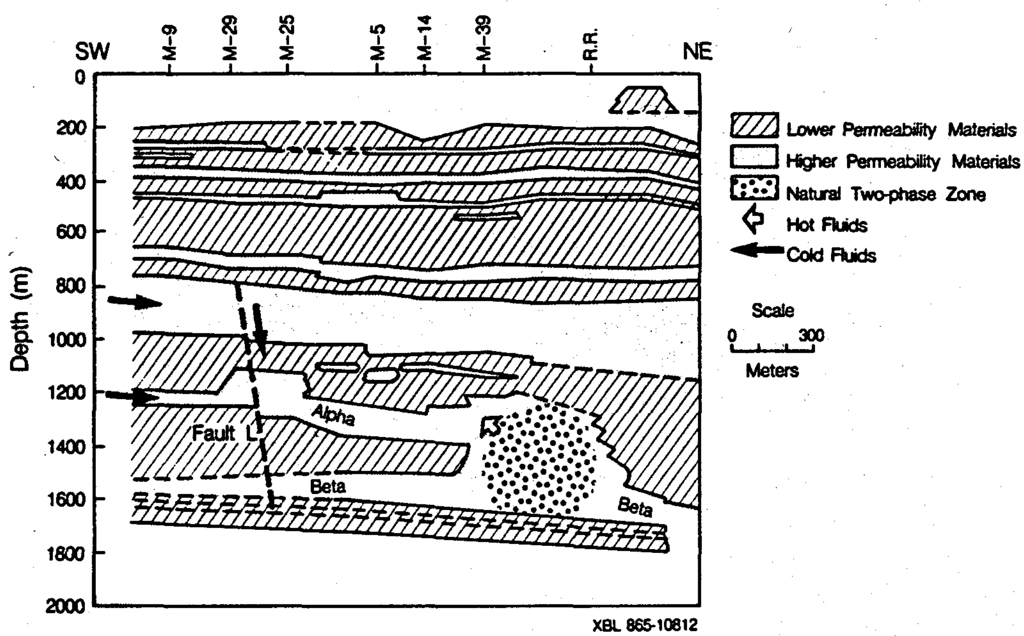

Figure 10 Postulated fluid recharge pattern in the Cerro Prieto alpha reservoir resulting from its exploitation (from Truesdell and Lippmann, 1986).

inates the later behavior of the simulated well; at early times the reservoir properties are more important. The bottomhole temperature stabilizes at about 27°C lower than the initial fluid temperature showing that near-well boiling continues. However, the stabilized T(Ent) is equal to the initial fluid temperature indicating that throughout the system fluid and rock have reached thermal equilibrium.

In the model the boiling around the model is continuous over the 10 year simulated period, because of the large assumed ratio between the production rate and the permeability-thickness product. We expect that the boiling zone will eventually collapse as the cooler waters continue to advance towards the well.

The behavior of M-31 suggests that the particular interval within the alpha reservoir from which the well is producing is strongly connected to an extensive aquifer, possibly the shallow groundwater body of the Mexicali Valley. It is not clear to us why the response of this well is different from that of M-35, which is only about 185 m away. Both wells are completed at similar depths and are at similar distances from Fault L (Fig. 2). It might be possible that because of the geologic heterogeneity of the alpha reservoir (Halfman *et al.*, 1984, 1986), M-31 has lower permeability (and more boiling) near the well but strong hydraulic communication with local groundwater aquifers at greater distances.

CONCLUSIONS

This study illustrates the advantages of combining geochemical data interpretations with numerical geothermal reservoir simulations. The comparison between the changes observed in the fluids produced by Cerro Prieto I wells against the results of modeling studies allowed us to further characterize the producing reservoirs, especially their recharge and boiling processes.

The cold water recharge to the alpha reservoir does not seem to be related to extensive leakage through the overlying less permeable layers. Instead, groundwater from surrounding aquifers tend to descend through Fault L, as well as to move horizontally towards the producing wells.

In most (or all?) alpha wells localized boiling is observed at least during part of their production history. The rate and thermal characteristics of the recharge control the longevity and extent of the boiling zone. It could collapse rapidly if the recharge is strong (well M-42), or expand, stabilize and then collapse (wells M-35 and M-31). The behavior of well M-31 seems to be a good evidence of the strong hydraulic communication between the alpha reservoir and the high-permeability groundwater aquifers of the Mexicali Valley.

Cerro Prieto I wells completed in the deeper beta reservoir seem to be fed by different zones; an upper boiling zone and underlying liquid zones. The two-phase region appears to have developed before well E-4 began producing and be related to general reservoir boiling (not near-well boiling). Lateral colder water recharge into this reservoir also seems to occur in the western part of Cerro Prieto.

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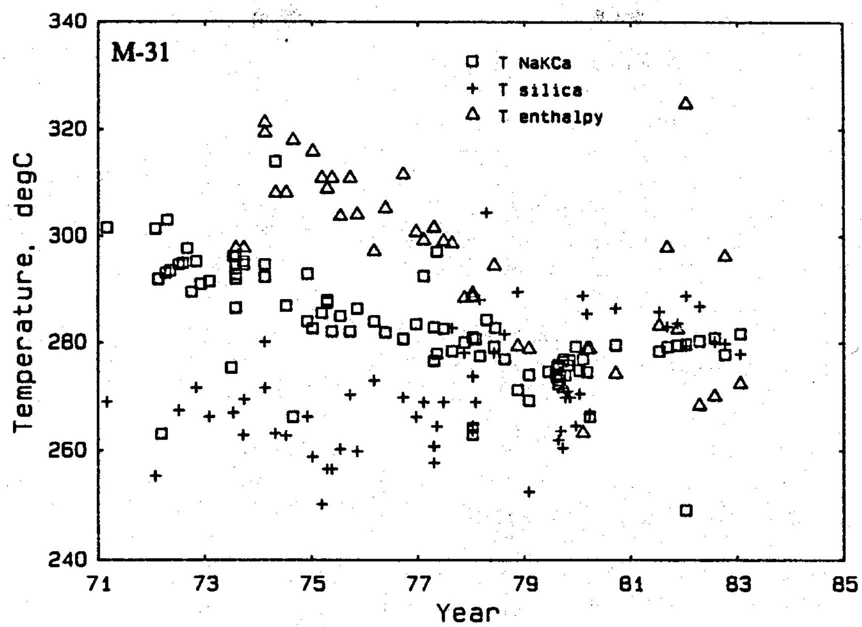

Figure 11 Indicated aquifer temperatures for well M-31.

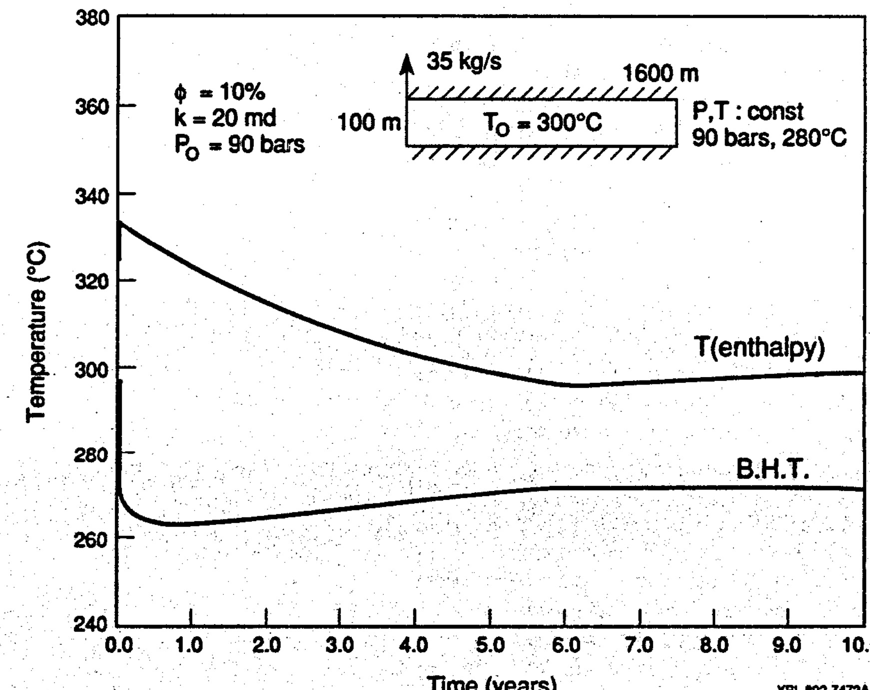

Figure 12 Calculated temperature histories for the model shown in the insert (compare trends against those in Fig. 11).

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