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**Author**

Lippmann, M.J.

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M.J. Lippmann, A.H. Truesdell,
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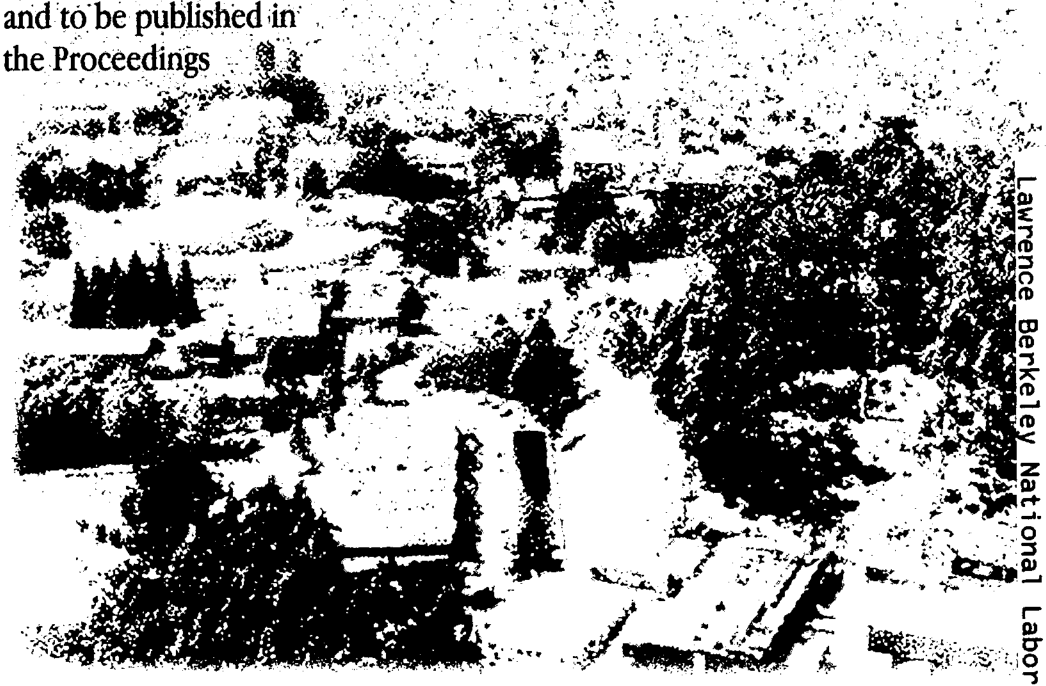

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M.J. Lippmann,[1] A.H. Truesdell,[2] and K. Pruess[1]

[1]Earth Sciences Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

[2]Consultant
Menlo Park, California 94720

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# THE CONTROL OF FAULT H ON THE HYDROLOGY OF THE CERRO PRIETO III AREA

M.J. Lippmann[1], A.H. Truesdell[2] and K. Pruess[1]

1) Lawrence Berkeley National Laboratory, Berkeley, CA 94720
(2) Consultant, Menlo Park, CA 94025
mjlippmann@lbl.gov

## ABSTRACT

Previous studies have shown that Fault H controls a significant part of the fluid recharge in the Cerro Prieto, Mexico geothermal field. The fault is a conduit for the upflow of deep hot fluids into the reservoir, and for the downflow of colder groundwaters from aquifers located above the producing formations. Further examination of the field data supports the hypothesis that under prior natural-state conditions some of the geothermal fluids flowing up Fault H discharged into the overlying groundwater aquifers. When pressures in the system decreased in response to commercial exploitation, fluid flow in the upper regions of the fault (i.e., above the level of the producing formations) reversed direction, that is, colder groundwaters began descending into the geothermal reservoir. Numerical simulation studies of these phenomena show similar physical and chemical changes to those observed. The analysis of the field data and the results of the numerical modeling study of the role of Fault H in the hydrology of the eastern CP-II and CP-III areas of the field are discussed.

## INTRODUCTION

A geologic model of the liquid-dominated Cerro Prieto geothermal field was developed by Halfman et al. (1984) mainly on the basis of geophysical and lithologic well logs. By incorporating downhole-temperature profiles and well-production interval data, these authors postulated geothermal fluid flow paths ("the plumbing") for the system prior to its exploitation. Two normal faults (Faults H and L) were identified as significant features in the hydrogeological model of the field proposed by these authors; this was confirmed by later studies.

The initial distribution of temperatures in the subsurface clearly indicated that under natural-state conditions hot fluids recharging the geothermal reservoir flowed up the southeast-dipping Fault H. On the other hand, the east-dipping Fault L provided a path for the discharge of hot fluids from the system. The hydrologic role of the two faults was validated by the results of the Lippmann and Bodvarsson (1983) numerical study. It is inferred that the hot fluid recharge through Fault H continued (and perhaps increased) as the field was developed. Other studies confirmed this type of recharge, as summarized by Lippmann et al. (1991); see Figure 1.

About three years ago, on the basis of data on reservoir chlorides and isotopes in the eastern parts of the Cerro Prieto field (CP-II and CP-III areas*), it became obvious that colder (i.e., less than about 250 °C) groundwaters were flowing into the reservoir down a northeastern sector of Fault H. This was in response to the pressure drawdown resulting from fluid production (Truesdell et al., 1997, 1998; Truesdell and Lippmann, 1998). It is interesting to note that a similar phenomenon has occurred in Fault

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* The CP-III is the eastern area of the field, northwest of Fault H on its upthrown block; CP-II is southeast of the fault on the downthrown block.

L, as described by Truesdell and Lippmann (1986) and depicted in Figure 1.

It is now suspected that initially (i.e., before the start of field exploitation) not all of the hot fluids flowing up Fault H recharged the geothermal reservoir. Instead, a relative small amount kept moving up the fault discharging into aquifers overlying the caprock and mixing with shallower colder (and less saline) groundwaters. Because of their relatively smaller volume, it is inferred that the ascending fluids had only a slight effect on the temperature of the aquifers above the geothermal reservoir.

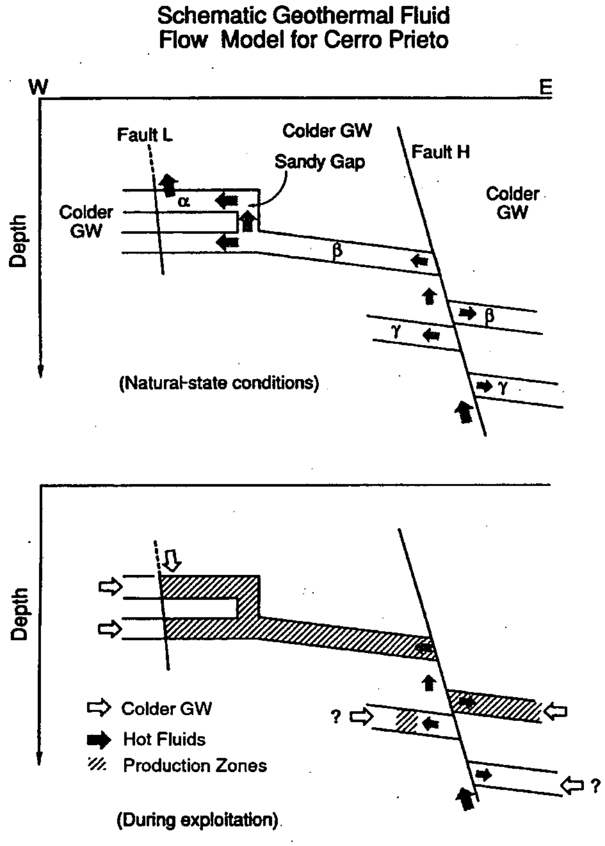


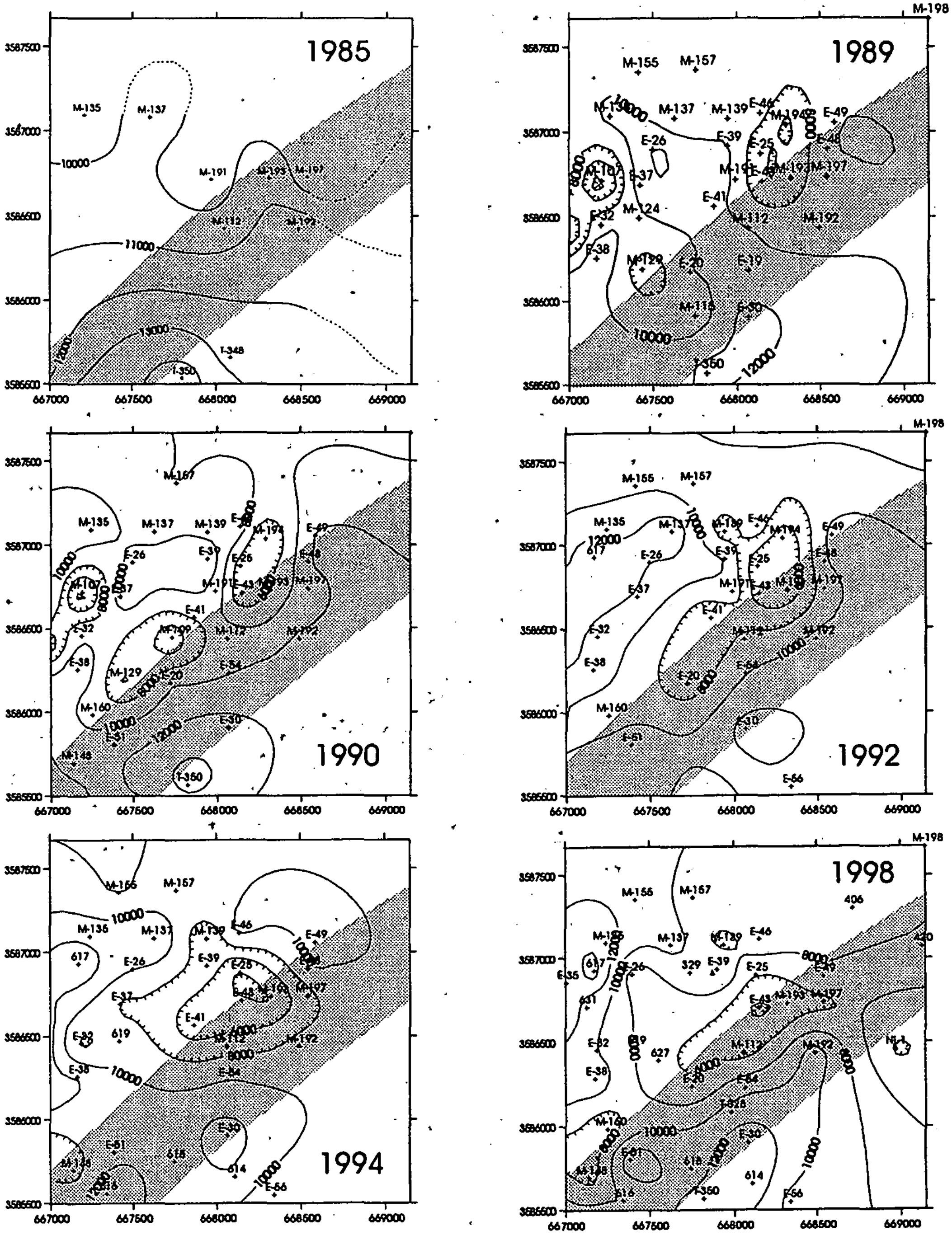
*Figure 1. Early schematic fluid flow model for the reservoir system at Cerro Prieto (GW: groundwater; from Lippmann et al., 1991).*

The purpose of this paper is to describe the approach used to update the natural-state hydrogeological model of the Cerro Prieto geothermal system. The work was mainly focused on evaluating the effects of hot and colder (and less saline) fluids recharging the geothermal reservoir in the CP-III area through Fault H. Field data, especially geochemical and mineralogic information, as well as the results of a numerical simulation study are reviewed.

## GEOCHEMICAL INDICATORS OF RESERVOIR PROCESSES

The chemistry of production fluids from Cerro Prieto has long been used to show what processes are occurring in the reservoir. In tracing the influence of Fault H on these processes, including the movement of fluid into and within the reservoir, we are helped by the large contrasts in salinity observed in the fluids produced. These include: undisturbed well-mixed reservoir water; high-salinity, hot recharge fluid from below; low-salinity groundwater from outside the reservoir; high-salinity injectate; low- and variable-salinity mixtures of brine and steam condensate formed by adiabatic decompression of high-temperature steam; and finally, high-salinity water in areas of intense boiling. Although most brine constituents show these variations, the most useful species for evaluating reservoir processes is chloride because it is conservative, i. e., it is not contained in or absorbed by the reservoir rock minerals and not affected by processes other than boiling and mixing.

As a base for interpretation, the chloride concentrations in flashed brine were calculated to the original reservoir concentrations using enthalpy derived from NaKCa geothermometer (Fournier and Truesdell, 1973) temperatures. This procedure was necessary because most fluids in the area of study contained variable amounts of excess steam. Large contrasts also exist in oxygen isotope compositions of reservoir water with groundwater and injectate, but isotope analyses of Cerro Prieto fluids are made only every second year while twice yearly chemical analyses are available for most wells.



Reservoir Chloride Concentrations
in the CP-II and CP-III areas

*Figure 2. Reservoir chloride concentrations in parts of CP-II and CP-III from 1985 to 1998. Location of the area depicted is given in Figure 3; producing wells are indicated by the crosses; distances in meters.*

The distribution of chlorides and boiling in the producing (Beta) reservoir of the CP-II and III areas, and its changes with time suggest that several processes are ocurring in response to exploitation. They are mainly boiling resulting in steam and brine segregation, steam condensation, increased salinity in residual brines, as well as hot and colder fluid recharge, and mixing of different fluids. Some resulting changes in chloride are shown in Figure 2. Data on the evolution of boiling and chloride content in the Cerro Prieto reservoir brines are discussed and analyzed in detail in several recent papers (e.g., de León Vivar, 1988; Truesdell et al., 1997, 1998; Truesdell and Lippmann, 1998).

## COMMUNICATION OF THE PRODUCING RESERVOIR WITH THE OVERLYING GROUNDWATER AQUIFERS

There is clear geochemical evidence that in response to reservoir pressure drawdown, localized colder groundwater recharge occurs down a northeastern part of the Fault H in the CP-II and CP-III areas (e.g., Truesdell et al., 1998). Considering that there is hydraulic communication between the producing (Beta) reservoir and the overlying groundwater aquifers during the exploitation of the geothermal field, we decided to investigate whether this connection existed earlier under natural-state conditions.

No detailed maps showing the initial (pre-production) temperature distribution above the geothermal reservoir in the easternmost areas of the field could be found. This is partly due to the fact that in 1986-87, when power plants CP-II and CP-III came on line, a relatively small number of wells had been drilled in the area of interest (shown in the upper right NW corner of Figure 3). In addition, it is suspected that the initial distribution of temperatures in the geothermal system had already been disturbed

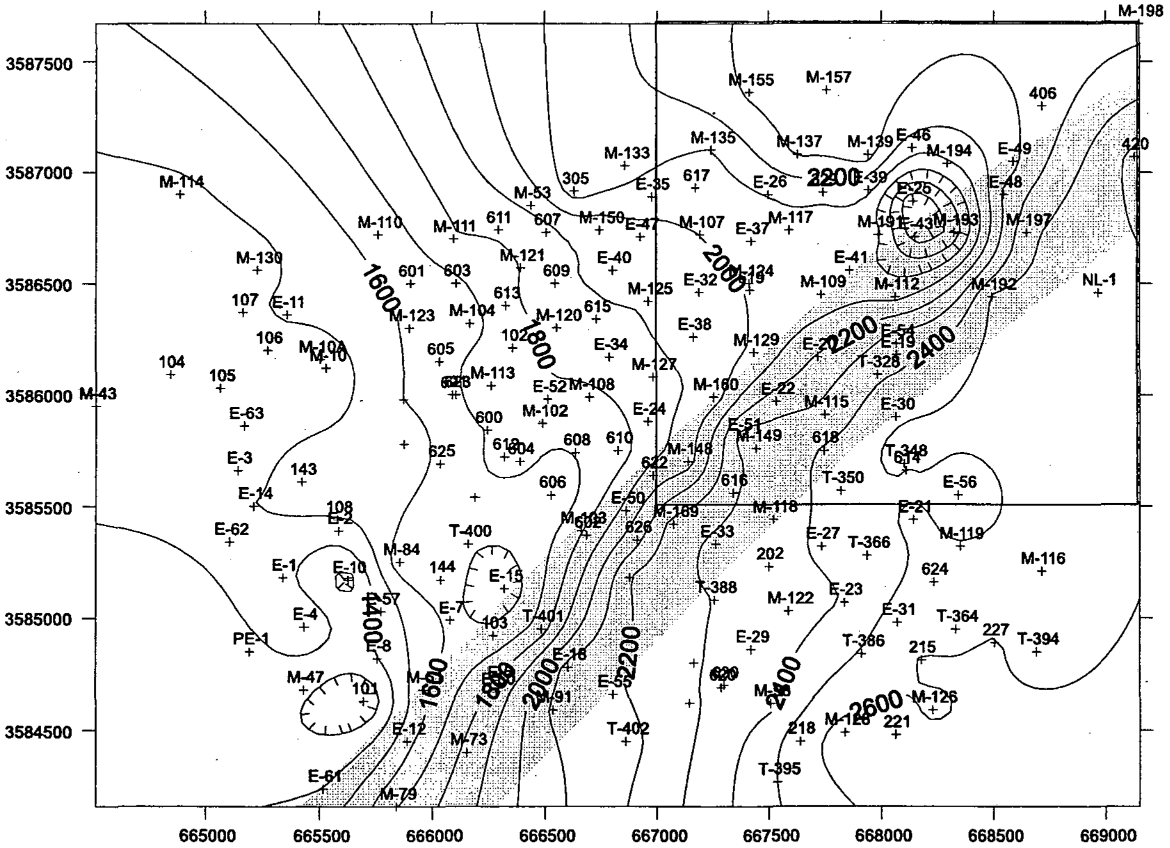


*Figure 3. Depth, in meters, of the top of the Silica-Epidote Zone in CP-II and CP-III. The area of interest is delimited by the box shown in the upper right corner of the figure. The location of Fault H at the reservoir level is shaded; wells are indicated by the crosses; distances in meters.*

by the exploitation of the western region of the field (CP-I) and the westernmost parts of the CP-II and CP-III areas, which began in 1973.

However, some temperature data that indicate the local ascent of geothermal waters to shallower levels have been published. For example, Rivera et al. (1982) in their Figs. 5A, 8 and 10 show that around well M-109, located near Fault H (see Figure 3), the 300°C isotherm is found at about 1700 m depth, at least 200 m higher than in surrounding wells. Also, Halfman-Dooley et al. (1989) present a figure (their Fig. 10A) indicating that in the same general area and depth the temperature was about 50°C higher than in nearby wells.

Because of a lack of natural-state temperature information adequate to indicate geothermal fluid discharge into groundwater aquifers located above the producing reservoir, it was necessary to rely on mineralogical data and numerical modeling results to support this hypothesis.

### Mineralogical Data

The Comisión Federal de Electricidad (CFE), operator of the field, uses the top of the Silica-Epidote Zone (SEZ; Cobo R., 1979) as a pragmatic definition for the top of the producing (Beta) reservoir. This mineralogical zone is characterized by the continuous (versus sporadic elsewhere) occurrence of both of these minerals in well cuttings and cores. The SEZ is below the depth of the first appearance of hydrothermal epidote. Detailed petrologic studies of Cerro Prieto by Wilfred Elders and his group at the University of California Riverside defined several prograde metamorphic mineral zones. In general, the Cobo's SEZ matches the calc-aluminum silicate zone of Elders et al. (1979), which corresponds to temperatures of 230-250°C to 350°C.

Figure 3 shows the depth to the top of the SEZ in the CP-II and CP-III areas. A cupola (i.e., shallower top of the SEZ) is clearly seen near wells E-43 and M-193, both located within the Fault H area. Note that this figure is slightly different from those presented in previous papers (e.g., Truesdell et al., 1992, 1997, 1998) which displayed the top of the well production intervals. Since the top of the SEZ corresponds to that of the Beta reservoir (see above), the upper parts of the production intervals tend to be (slightly) deeper than the tops of the SEZ, but the general picture of the shape of the depth contours is very similar.

Elders et al. (1979, 1981, 1984) indicate that the distribution of hydrothermal mineral assemblages is related to the pattern of fluid flow and heat transfer in a geothermal system under natural-state conditions (i.e., before the distribution is affected by production and injection operations). Hydrothermally altered rocks are records of the temperature and fluid flow, which they have experienced. In their 1981 paper, these authors used the arrangement of hydrothermal mineral zones (and that of light stable isotopic ratios) within the field, to develop a general (versus detailed) three-dimensional model of the natural flow regime in the Cerro Prieto geothermal system.

Applying this concept to a more detailed level, the "topography" of the top of the SEZ would indicate to what depths the geothermal fluids were able to ascend in the system during geologic times. It is assumed that the mineralogy of the hydrothermally altered zones would only slowly change in response to temperature variations (i.e., not during the first years of field development).

Therefore, the cupola seen in the SEZ near E-43 and M-193 would indicate an area where hot (above 250°C) fluid moved up Fault H and discharged into the overlying aquifers. Considering the large volume of water-saturated sediment fill of the Mexicali Valley, the effects of this hot fluid recharge on the temperature of the shallower groundwater aquifers is assumed to be minor and localized.

Without good and detailed natural-state temperature distribution data for Mexicali Valley groundwaters above the geothermal reservoirs, it is impossible to calculate the rate of this hot fluid recharge. However, numerical simulation studies could give a general estimate on what proportion of the deep geothermal recharge ascending through the fault this hot discharge into the shallow groundwater aquifers represents.

## Numerical Simulation Study

The system used to study the effects of geothermal and groundwater recharge through Fault H is a two-dimensional vertical section of one-meter thick that runs perpendicular to the fault in a NW-SE direction (Figure 4a). The fault is modeled as a 20-m wide zone of high (200 md) permeability which dips to the SE at an angle of 45 degrees.

In the model, hot fluid flows up Fault H from a depth of 3100 m, where constant pressure and temperature conditions (P= 200 bars; T= 340°C) are maintained. The fault intersects the shallow, cooler, less saline, groundwater aquifer at 1000 m depth, where constant pressure and temperature conditions of P= 78.47 bars and T= 200°C are assigned. At the NW (left) boundary of the CP-III reservoir, pressures were specified as three bars below hydrostatic equilibrium relative to the upflow-aquifer pressures. Reservoir parameters are: porosity = 20%, horizontal permeability = 100 md, and vertical permeability = 10 md. Grid spacing for the numerical simulation was chosen as 50 m near the fault, and 100 m at some distance from it, with fine gridding in the fault itself (see below). All simulations were run with the numerical simulator TOUGH2 (Pruess, 1991), using the "two waters" option to be able to distinguish aquifer water from deep hot upflow.

The system is run to steady state, corresponding to natural-state conditions prior to large-scale production. By matching the temperature distribution, it was estimated that the upflow in Fault H occurs at a rate of $2.05 \times 10^{-2}$ kg/s, of which 90% flows into the CP-III reservoir and exits at the NW boundary, while the remaining 10% of the upflow enters the aquifer. (Recall that a one-meter thick section is being modeled, so the upflow rate is per meter of fault length).

Subsequently, production is applied uniformly across the top of the CP-III reservoir at a mass flux of $2.28 \times 10^{-5}$ kg $s^{-1}$ $m^{-2}$. Different conditions at the left boundary were tried for the production simulations, including constant pressure over the entire boundary (or only part of it), and assuming it to be closed. Production rapidly causes strong boiling across the top reservoir layers, with large increases in vapor saturation and produced enthalpy, and declining pressures and temperatures. Boiling also occurs in the shallower portions of Fault H, above the CP-III reservoir. This leads to rising vapor saturation in the fault, accompanied by increased upflow of steam that discharges into the overlying colder aquifer. Hot liquid also continues to flow up the fault and out into the groundwater aquifer.

In response to continuing pressure decline, eventually a reversal of liquid flow takes place at the top of the fault. Once fluid from the aquifer (i.e., groundwater) enters the fault, downflow increases rapidly due to the larger gravitational body force of the cooler, denser waters. For the case with the closed left boundary, flow reversal occurs after about four years, and leads to a rapid increase in the groundwater recharge fraction and a decline of produced enthalpy near the fault. The influx of the fresher groundwater reduces the salinity in the producing reservoir.

After 10 years the model shows widespread boiling throughout the CP-III reservoir, and a tongue of lower vapor saturation near the intersection with the fault (Figure 4b), due both to upflow of hot fluid from below and downflow of colder groundwater from above. Figure 4c shows the enthalpy and recharge fraction history for two elements located 100 m and 825 m from the fault, respectively. For the element farther from the fault, cooler groundwater recharge is slower to arrive and no effects on produced enthalpy are noted within 10 years after start of production.

Test calculations showed that very fine gridding of the order of one meter was required near the top of the fault, in order to properly resolve the flow reversal caused by production. A simulation in which part of the NW boundary of the CP-III reservoir was specified as a constant pressure boundary, generated less reservoir boiling and pressure decline, with recharge down the fault occurring at later time and smaller rates.

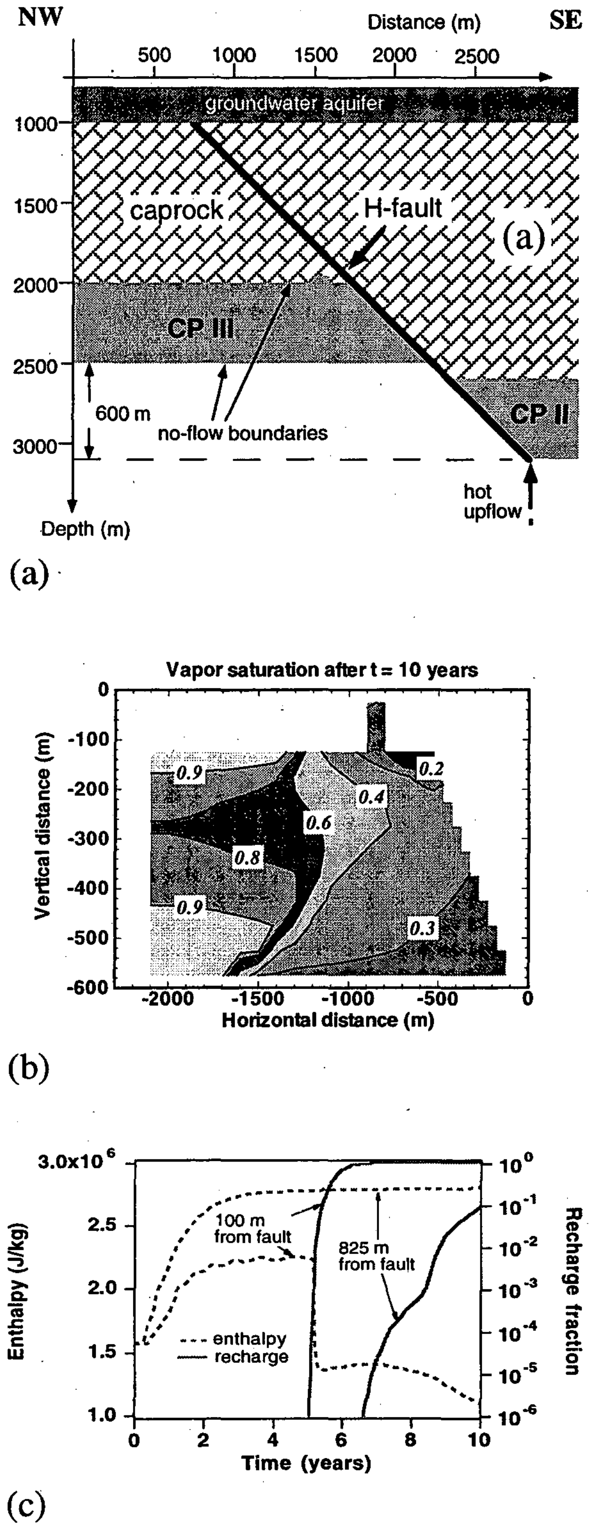


*Figure 4. Numerical simulation study of effects of geothermal and groundwater recharge of CP-III through Fault H. (a) Two-dimensional vertical model used. Computed results for the case when the left (NW) boundary of the model is assumed to be closed, (b) vapor saturations in the model's CP-III reservoir area 10 years after start of production (note the vertical exaggeration); and (c) enthalpy and groundwater recharge fraction histories for two elements of the model located at 100 m and 825 m from the fault, respectively.*

## CONCLUSIONS

During the 1980s, analysis of geological, geochemical and temperature data, as well as numerical modeling studies, established that deep hot fluids ascend through Fault H recharging the Cerro Prieto geothermal system.

Later work, especially during the last five years, determined on the basis of the chemical and physical characteristics of the produced fluids that Fault H allows the leakage of shallower, colder groundwaters into the geothermal reservoir as drawdown results from field exploitation.

The present study, based mainly on the chemical changes, the depth distribution of the top of the silica-epidote zone, scant temperature data and supporting simulation studies, concludes that under natural-state conditions (i.e., before the start of the commercial development of the system), some of the geothermal fluids ascended through the fault and discharged in the overlying groundwater aquifers (Figure 5).

When the eastern areas of the field (CP-II and CP-III) were put on full production in 1986-87, the strong pressure drawdown caused intense boiling in the higher parts of the (Beta) reservoir and, in addition, the reversal of the flow direction in the upper regions of Fault H (i.e., reversing the initial upward flow of hot water which discharged into the overlying groundwater aquifers). This was not immediately apparent because other processes created low-chloride anomalies, but by 1989 it was clear that there was increasing cooler groundwater flow down Fault H. This leakage into the reservoir is sufficient to partially replace the fluid extracted and decrease the amount of intense boiling across all of the CP-III area.

The modeling study provided descriptions and added constraints to the reservoir processes associated with the upward and downward flow of fluids through Fault H (i.e., boiling, mixing and condensation). The history of aquifer recharge and changes in reservoir steam saturation calculated by the model are similar to those inferred to occur at Cerro Prieto under natural-state conditions and to those observed during the exploitation of the system.

In summary, Fault H is an important feature in the hydrogeology of Cerro Prieto before and after the field began to be exploited for electrical power generation. The work described here, part of the Cerro Prieto field case study, confirms the significance of multidisciplinary approaches when trying to understand and predict the behavior of complex geothermal systems, especially if the available data set is not as complete as one would wish.

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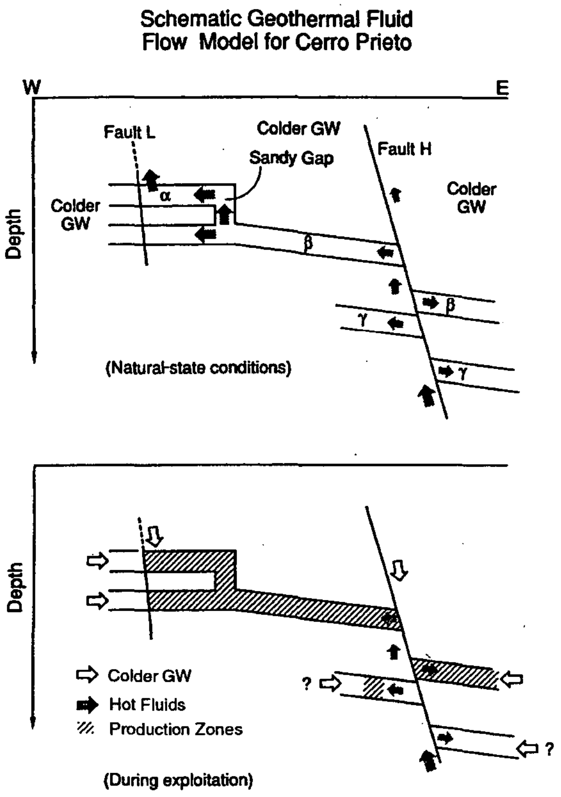

*Figure 5. Updated schematic fluid flow model for the reservoir system at Cerro Prieto (compare to that of Figure 1; GW: groundwater).*

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ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

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