Title
THE HYDROGEOLOGIC-GEOCHEMICAL MODEL OF CERRO PRIETO REVISITED

Authors
Lippmann, M.J.
Truesdell, ft. H.
Manon, A.

Publication Date
1989

LBL-26819 c. 2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

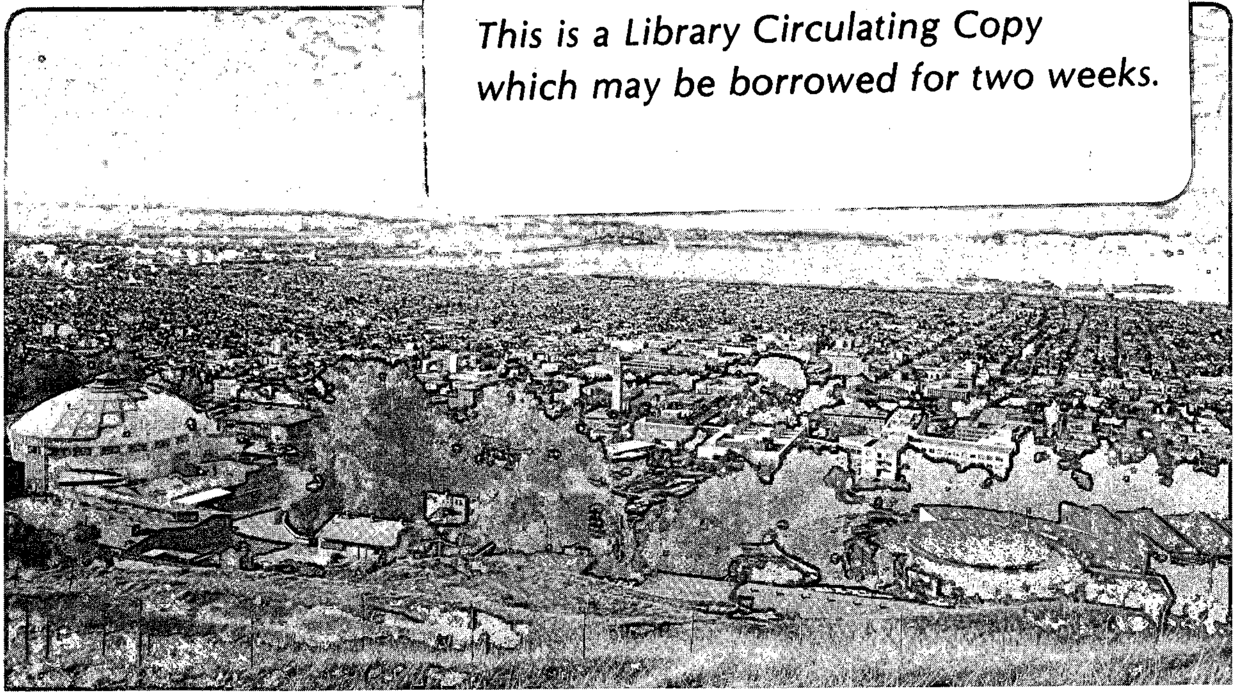
EARTH SCIENCES DIVISION

Presented at the Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford, CA, January 24–26, 1989

The Hydrogeologic-Geochemical Model of Cerro Prieto Revisited

M.J. Lippmann, A.H. Truesdell, A. Mañón M., and S.E. Halfman

January 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-26819

The Hydrogeologic-Geochemical Model of Cerro Prieto Revisited

M.J. Lippmann and S.E. Halfman
Earth Sciences Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

A.H. Truesdell
U.S. Geological Survey
Menlo Park, CA 94025

A. Mañón M.
Comisión Federal de Electricidad
Mexicali, BC, Mexico

January 1989

THE HYDROGEOLOGIC-GEOCHEMICAL MODEL OF CERRO PRIETO REVISITED

M. J. Lippmann, A. H. Truesdell,† A. Mañón M.,‡ and S. E. Halfman,**

*Lawrence Berkeley Laboratory
Berkeley, CA 94720

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

‡Comisión Federal de Electricidad,
Mexicali, BC, Mexico

ABSTRACT

As the exploitation of the Cerro Prieto, Mexico, geothermal field continues, there is increasing evidence that the hydrogeologic model developed by Halfman et al. (1984, 1986) presents the basic features controlling the movement of geothermal fluids in the system. At the present time the total installed capacity at Cerro Prieto is 620 MWe requiring the production of more than 10,500 tonnes/hr of a brine-steam mixture. This significant rate of fluid production has resulted in changes in reservoir thermodynamic conditions and in the chemistry of the produced fluids.

After reviewing the hydrogeologic-geochemical model of Cerro Prieto, some of the changes observed in the field due to its exploitation are discussed and interpreted on the basis of the model.

INTRODUCTION

The Cerro Prieto field has been extensively studied by the Comisión Federal de Electricidad (CFE) of Mexico and by various U.S. groups participating in cooperative agreements between CFE and the U.S. Department of Energy (DOE).

The exploration and development of the Cerro Prieto field and the early changes resulting from its exploitation have been discussed in numerous papers and reports; a recent summary is given by Lippmann and Mañón (1987). The purpose of this paper is to review generally accepted hydrogeologic and geochemical models developed for the Cerro Prieto geothermal system and illustrate how these models can explain the changes being observed as the exploitation of the field continues.

NATURAL STATE HYDROGEOLOGICAL MODEL

The hydrogeological model of Cerro Prieto that best describes the movement of geothermal fluids in the system under natural state conditions is that of Halfman et al. (1984, 1986). The model developed on the basis of electric, lithologic and temperature well logs, as well as on information on well completion, demonstrates the importance of lithology and faults in controlling fluid circulation.

The Halfman et al. natural state model shows that in the Cerro Prieto system there is circulation of geothermal fluids generally from east to west. Hot (about 350°C) fluids enter the system from the east-southeast, and are discharged in the area of surface manifestations located west of the wellfield (Figs. 1 and 2). The geothermal fluids seem to ascend from depth through the SE-dipping, normal fault H. (The results of recent isotope and self-potential surveys have given further evidences of fluid movement through this fault; Stallard, et al., 1987; Goldstein et al., this volume).

As the hot fluids flow up fault H, they tend to move laterally into the more permeable layers (Figs. 2 and 3). An unknown amount recharges the deepest reservoir identified so far (gamma reservoir); it corresponds to layer K found below 3300 m depth (Fig. 3). The bulk of the hot fluids flow westward into layer Z (beta reservoir) following the general east-west gradient prevalent in the system; only a smaller fraction seem to penetrate layer Z east of the fault (Fig. 3).

The westward movement of the geothermal fluids has an upward component since it follows the bottom of the less permeable shale layer O, which is dipping toward the northeast. In the region of well M-10A (Fig. 2) a significant part of the fluids manages to ascend because of the absence of a shale caprock; this region has been called the "sandy gap". The rest of the fluids move into the western continuation of the beta reservoir (below 1600 m depth in the western area of the field).

The movement of fluids through the sandy gap was reflected by the self-potential anomaly observed in 1977 over the Cerro Prieto field (Goldstein et al., this volume). As the hot fluids ascend through the gap, boiling occurs. The vertical flow of the geothermal fluids is eventually stopped at about 1000 m depth by the presence of low permeability sandy materials sealed by mineral precipitation (Lippmann and Bodvarsson, 1983). At this point, the fluids continue to flow westward through a shallower permeable layer (alpha reservoir), between about 1000 and 1500 m depth. The alpha reservoir is restricted to the western region of the field, i.e., west of the railroad tracks (Fig. 1). It generally corresponds to the hatched region shown in the west-central part of Figure 2. Under natural state conditions the westward movement of hot fluids in

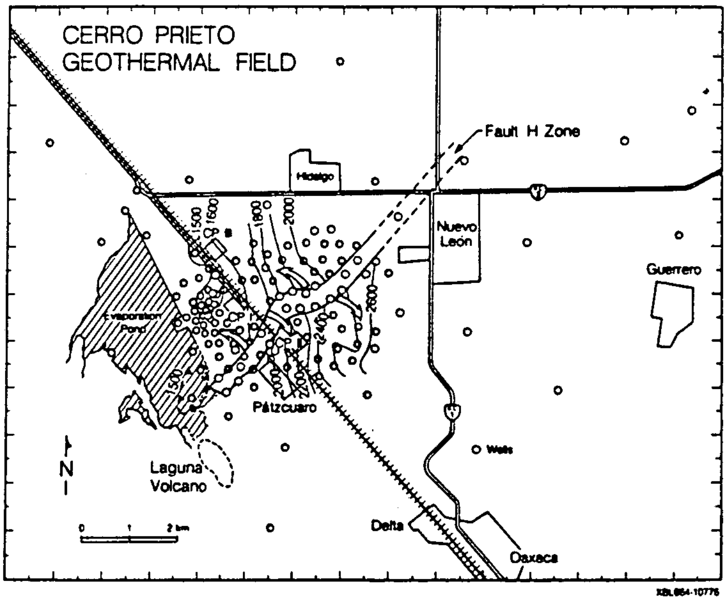


Figure 1. Cerro Prieto. Depth (in meters) to the top of the Sand Unit Z (see Fig. 2). The arrows indicate the direction of geothermal fluid flow away from fault H. The fault zone is shown at the beta reservoir level (from Halfman et al., 1984)

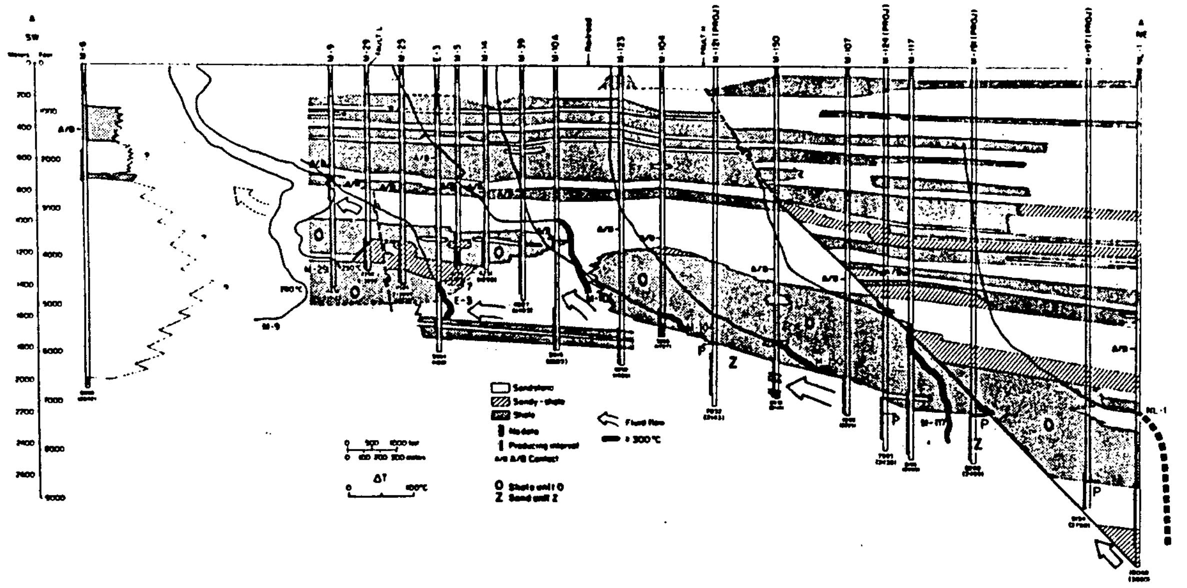


Figure 2. Southwest-northeast geologic cross section of the Cerro Prieto field showing schematically the lithology and the flow of geothermal fluids (from Halfman et al., 1984)

the alpha reservoir continues somewhat west of the normal fault L. However, most of the fluids flow up this fault (Fig. 2), reaching a shallower aquifer where mixing occurs with colder ground waters. Some of the hotter fluids leak to the surface west of the wellfield.

The important control of fault H on the recharge of geothermal fluids to the Cerro Prieto system is made evident by the high production rates being observed in wells with open intervals within, or near the fault zone. As an example, Figure 4 illustrates the excellent production characteristics of well M-147; the initial enthalpies of the

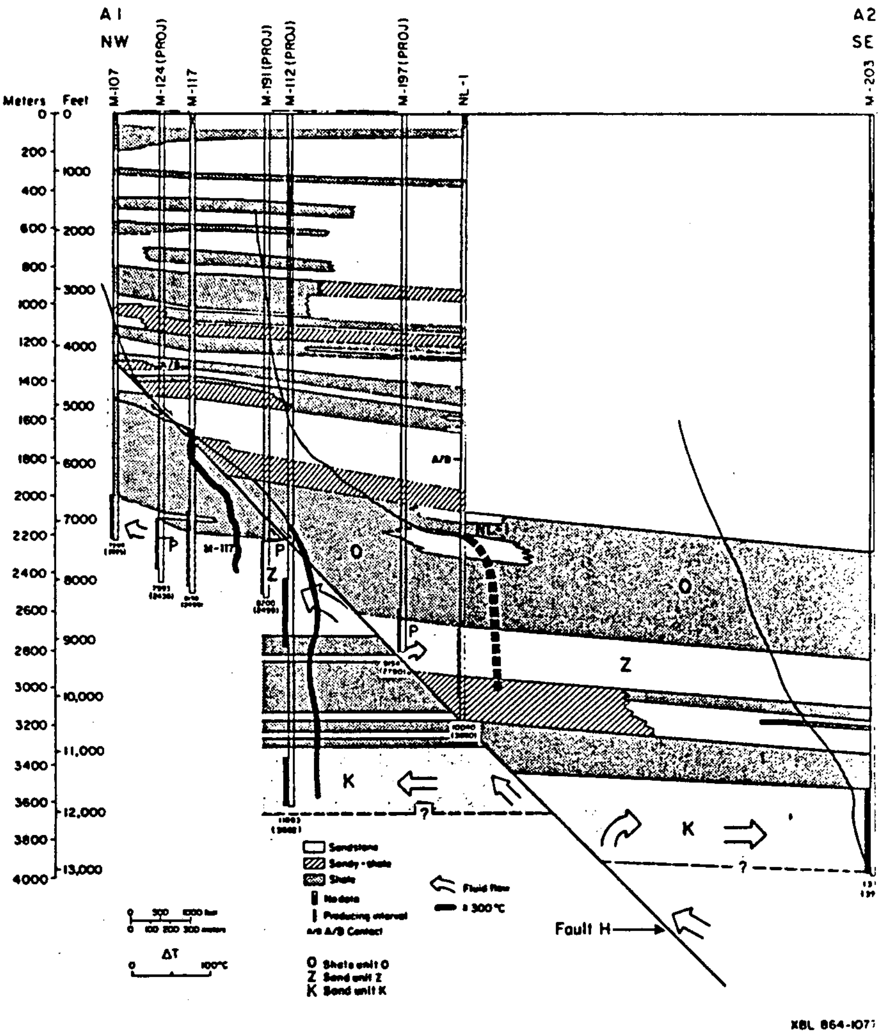


Figure 3. Northwest-southeast cross section of the eastern Cerro Prieto wellfield showing geothermal fluid flow pattern (after Halfman et al., 1986)

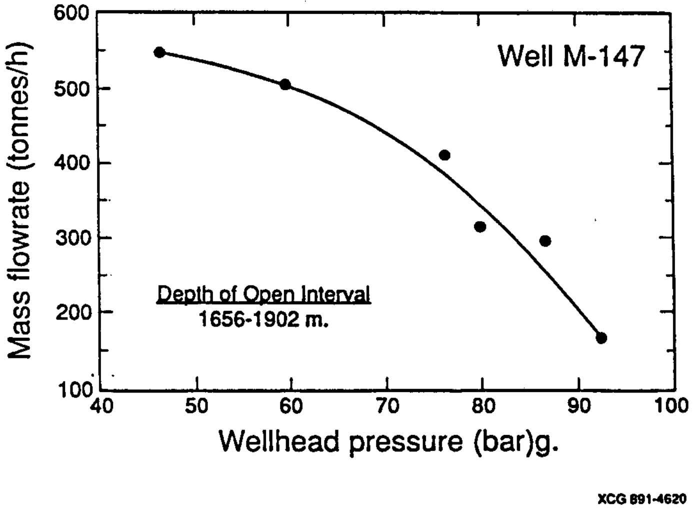


Figure 4. Characteristic curve for well M-147 (after Mercado and Bermejo, 1987).

produced fluids exceeded 2000 kJ/kg. The high production rates, enthalpies and wellhead pressures recorded in M-147 have led Mercado and Bermejo (1987) to postulate that it is fed by a fracture connected to a steam chamber located below the producing reservoir. We do not necessarily agree with their hypothesis of a deep steam chamber; we consider that the behavior of M-147 is related to its proximity to fault H through which hot compressed liquid recharges the system.

NATURAL STATE GEOCHEMICAL MODEL

The original temperatures and sources of the Cerro Prieto field reservoir fluids, as well as the processes active in the system mainly after the start of fluid production, have been discussed in several papers and summarized by Truesdell et al. (1984b) and Truesdell (1988).

Initial hydrogeologic models of the Cerro Prieto field were mainly developed on the basis of geochemical information (e.g., Mercado, 1976). Later models, like the one discussed above, had to show the "subsurface plumbing" inferred from the interpretation of the chemistry of the initially produced fluids. Thus, there is general agreement between the natural state circulation models developed for Cerro Prieto by geologists, reservoir engineers and geochemists.

Geochemical studies established the origin of the geothermal brines as mixtures of Colorado River water and marine hypersaline brine contained in the deltaic sediments of the Mexicali Valley (Fig. 5). These studies also showed that N_2 and Ar originate from the atmosphere, CO_2, H_2S, HC, ^4He and NH_3 from thermal metamorphism of sediments, and a minor amount of ^3He from magmatic sources.

EXPLOITATION HISTORY OF CERRO PRIETO

Before the initial 37.5 MWe unit began operating in April 1973, long-term production tests of wells completed in the alpha reservoir had been carried out. Very little data are available for this early period. However, starting in 1973 careful records have been kept on the rate of production and on the chemistry of the produced fluids.

The present installed electrical generating capacity at Cerro Prieto is 620 MWe. Initially the total capacity at the field grew slowly, but in 1986-87 it expanded substantially, as indicated in Table 1. Accordingly, the rate of fluid production has significantly increased (Fig. 6). To date only small-scale reinjection tests have been carried out; all the separated brine is being disposed into a evaporation pond located west of the wellfield (Fig. 1). Recently, the pond has been expanded to cover an area of about 16 km^2 (Mercado and Bermejo, 1988).

Table 1

Installed electrical generating capacity at Cerro Prieto

Date	Total installed capacity (MWe)
April 1973	37.5
October 1973	75
January 1979	112.5
March 1979	150
November 1981	180
January 1986	400
September 1986	510
June 1987	620

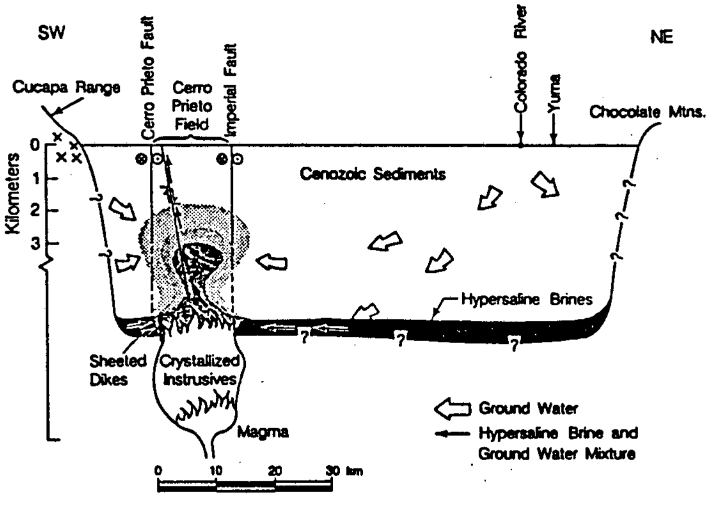
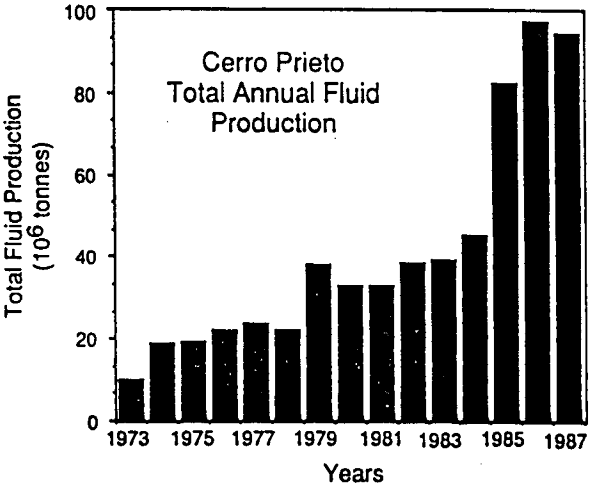


Figure 5. Schematic diagram of the geology and fluid flow across the Mexicali Valley (from Halfman et al., 1986).



XBL 891-7423

Figure 6. Total annual fluid production at Cerro Prieto.

Due to the large fluid extraction rate, significant changes have been observed in the reservoirs and production wells. The bulk of available information on reservoir changes is on the alpha reservoir, the first one to be exploited. Even though fluid production from the beta reservoir began in the late 1970s, only a few studies have dealt with the changes occurring in this reservoir. There are no data on the evolution, if any, of the gamma reservoir; only a few wells (e.g., M-112) are producing from it.

For administrative purposes the present wellfield has been divided into three areas: CPI (Cerro Prieto I), west of the railroad tracks; CPII, the southeastern area; and CPIII, the northeastern area.

Response of the alpha reservoir to production

As indicated earlier, the alpha reservoir is restricted to the region west of the railroad tracks (CPI). Between 1973 and 1980 most of the fluids produced at Cerro Prieto came from this, the shallowest (1000-1500m depth), hot water aquifer. Exploitation of the alpha reservoir continues but on a smaller scale as a reduced production enthalpy (i.e., steam/water ratio) make some of the wells uneconomical. These are being replaced by new wells completed in the deeper beta reservoir ("E-wells").

As a consequence of production, the pressure in the alpha reservoir has dropped, resulting in localized boiling around some of the wells and an increased influx of colder, less saline water (Grant et al., 1984; Truesdell et al.; 1984a). Large excesses in enthalpy temperatures and deficiencies in silica temperatures compared to Na-K-Ca temperatures indicate initial boiling around some wells (Janik et al., 1982; Nehring and D'Amore, 1984; Truesdell et al., 1984a; 1989). With time, these boiling zones tend to expand and stabilize; the history of well M-31 illustrates such behavior (Fig. 7). This type of well response can be simulated by a radially symmetric system showing a constant pressure boundary at a given distance from the well (Fig. 8). Boiling has deposited large amounts of quartz and calcite in the near-well region resulting in flow declines, sometimes leading to the loss of wells (Truesdell et al., 1984a)

As the alpha reservoir is bounded below by low permeability rocks, and above and to the west by an interface of colder waters (Fig. 9), pressure drawdown results in cold recharge from the west and/or through fault L (Fig. 2) that breaches the overlying shale layer. Once in the reservoir, the cooler waters tend to sweep the hot waters as they move toward the producing wells (Grant et al., 1984; Truesdell and Lippmann, 1986). Because of their location near the natural recharge areas or in less exploited parts of the field, some of the alpha wells never developed a boiling zone (e.g., M-42; Grant et al., 1984).

Fault L, which under natural state conditions allowed the upward leakage of geothermal fluids, now acts as conduit to the downward flow of colder groundwater into the reservoir. The evolution of the chemistry of the fluids produced by wells completed in the alpha reservoir clearly indicates the importance of this fault in the cold-water recharge of this aquifer (Truesdell and Lippmann, 1986; Stallard et al, 1987).

Response of the beta reservoir to production

The beta reservoir is officially considered to have been discovered in 1974 in the eastern part of the field with the drilling of well M-53. It was not until later studies by Halfman et al. (1984) that it became evident that some earlier wells in the southern region of CPI had partially penetrated this reservoir (e.g., M-51 completed in 1972). The beta reservoir extends over most of the Cerro Prieto field. It is found below about 1600 m depth, deepening towards the east (layer Z in Figs. 1 and 2).

Even though fluid production from this reservoir began in the late 1970s in the southwestern (i.e., southern CPI) and southeastern (i.e., CPII) regions of the field, it increased markedly with the completion of the deeper E-wells in CPI (started in 1980) and more recently with the start up of the new CPII and CPIII power plants (Table 1).

Only a small number of studies have been made on the response of the beta reservoir to production. However, a general picture of its behavior can be obtained from the available wellhead data. Because of its significant depth, and with its top and bottom sealed boundaries (Figs. 2 and 3), the beta reservoir has restricted natural fluid recharge. This is especially true in the eastern areas which presently are being heavily exploited. In the CPI region lateral influx from the west seems to be readily available; a similar situation could exist along the southeastern edge of the field.

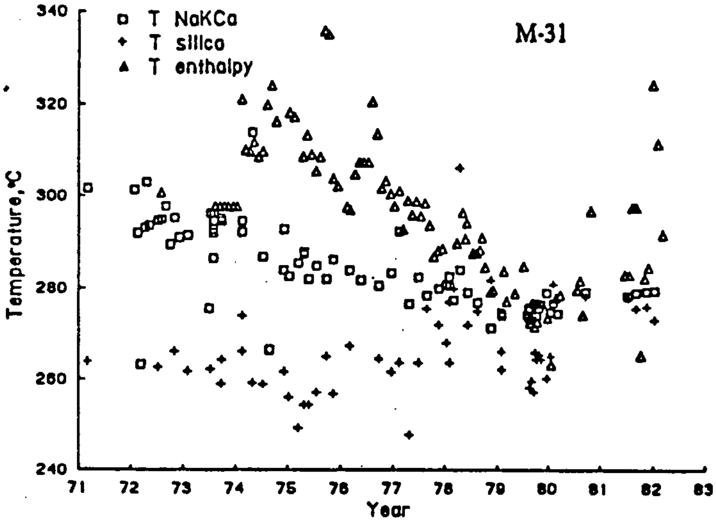


Figure 7. Chemical and enthalpy temperature history of well M-31. (from Truesdell et al, 1984a)

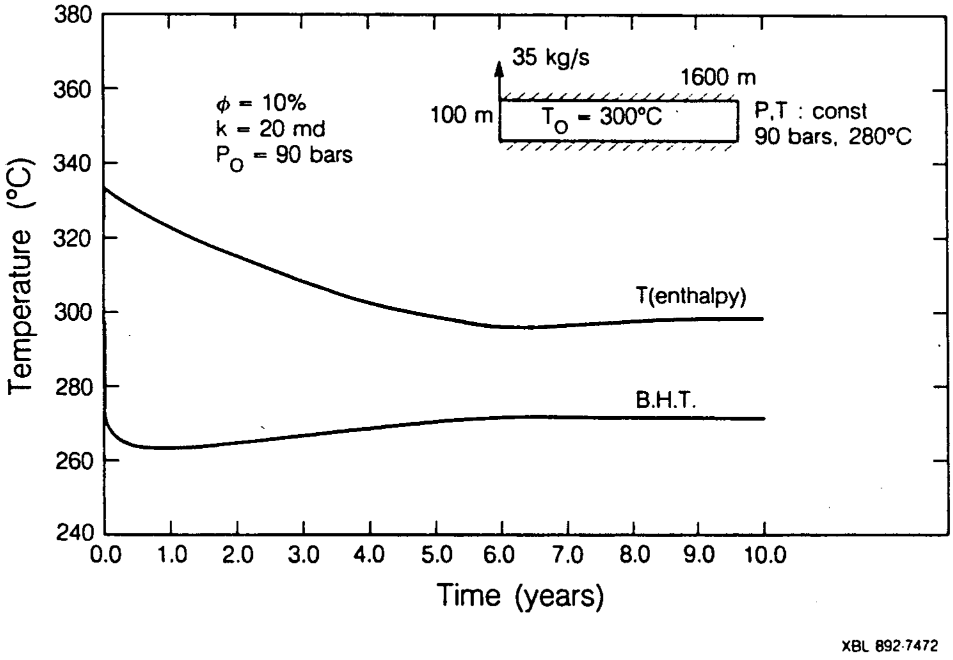


Figure 8. Numerically simulated enthalpy and bottomhole temperatures (B.H.T.) for a radially symmetric system with a constant pressure and temperature boundary.

Most beta wells show high production rates and temperatures initially. The enthalpy of the produced fluids tends to increase immediately due to reservoir boiling (indicated by excess steam). Evidences of boiling in the beta reservoir have been reported by Semprini and Kruger (1984), Stallard et al. (1987), de León Vivar (1988), and Truesdell et al. (1989).

In many wells of the eastern region (e.g., M-147 discussed above) a decrease in flowrate has been observed, that has been generally attributed to casing problems, but may be also due to mineral deposition in and around the well because of reservoir boiling, especially in CPIII (a more careful analysis of downhole data is needed). On the other hand, the precipitation of silica in the wellbores and/or wellhead separators is a significant problem in the southeastern region of the field (CPII). This indicates that in this region reservoir boiling is not yet extensive.

In some E-wells of CPI a decrease of fluid chloride content has been observed that could be explained by the advance of cold water entering the beta reservoir from

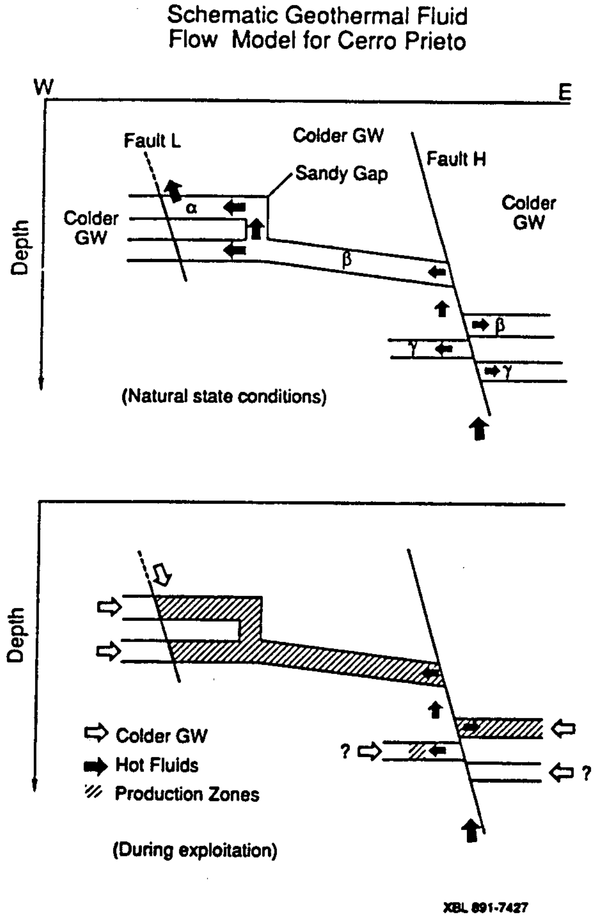


Figure 9. Schematic fluid flow model for Cerro Prieto.

the western edge of the field (A cold water sweep similar to the one occurring in the alpha reservoir; Truesdell et al., 1989).

There is a remarkable spatial correlation between the boiling zone in the beta reservoir and the location of fault H. Semprini and Kruger (1984) and Stallard et al.(1987) have shown boiling zones that generally agree with the position of this fault. More striking is the correspondence between de León Vivar's (1988) distribution of wells showing reservoir boiling and Halfman et al.'s (1986) trace of the fault H at reservoir level (Fig. 10). There is clear evidence that the boiling beta wells are located near the fault zone or in the upthrown block of fault H. A simplified model of the beta reservoir simulating its natural recharge and response to production (Fig. 11), shows that because of relative elevation, location of producing areas, and restricted recharge, the boiling in this reservoir tends to start in the upthrown block of the fault.

Figure 11a shows a schematic two-dimensional (x - z plane), one-meter thick (y axis) numerical simulation model of the Cerro Prieto beta reservoir system. Zone 1 correspond approximately to CPI and CPII, and Zone 2 to CPIII. Figure 11b describes the assumed conditions that were used to compute the pre-exploitation mass flow and temperature distributions. No heat and mass transfer was allowed between the reservoirs and surrounding formations. LBL's MULKOM code (Pruess, 1988) was used in the calculations.

For these particular conditions, 87.5 % of the recharged water flows into the upthrown Zone 1; only 12.5% into Zone 2. The computed temperatures are quite uniform

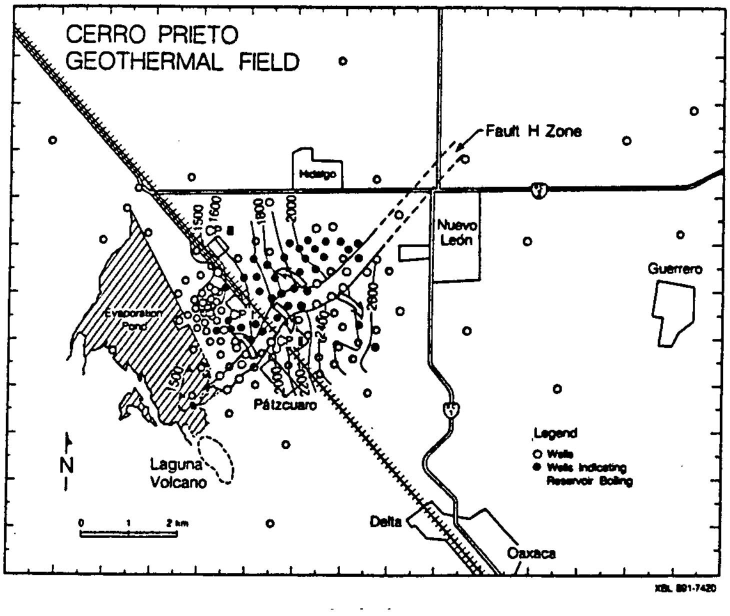


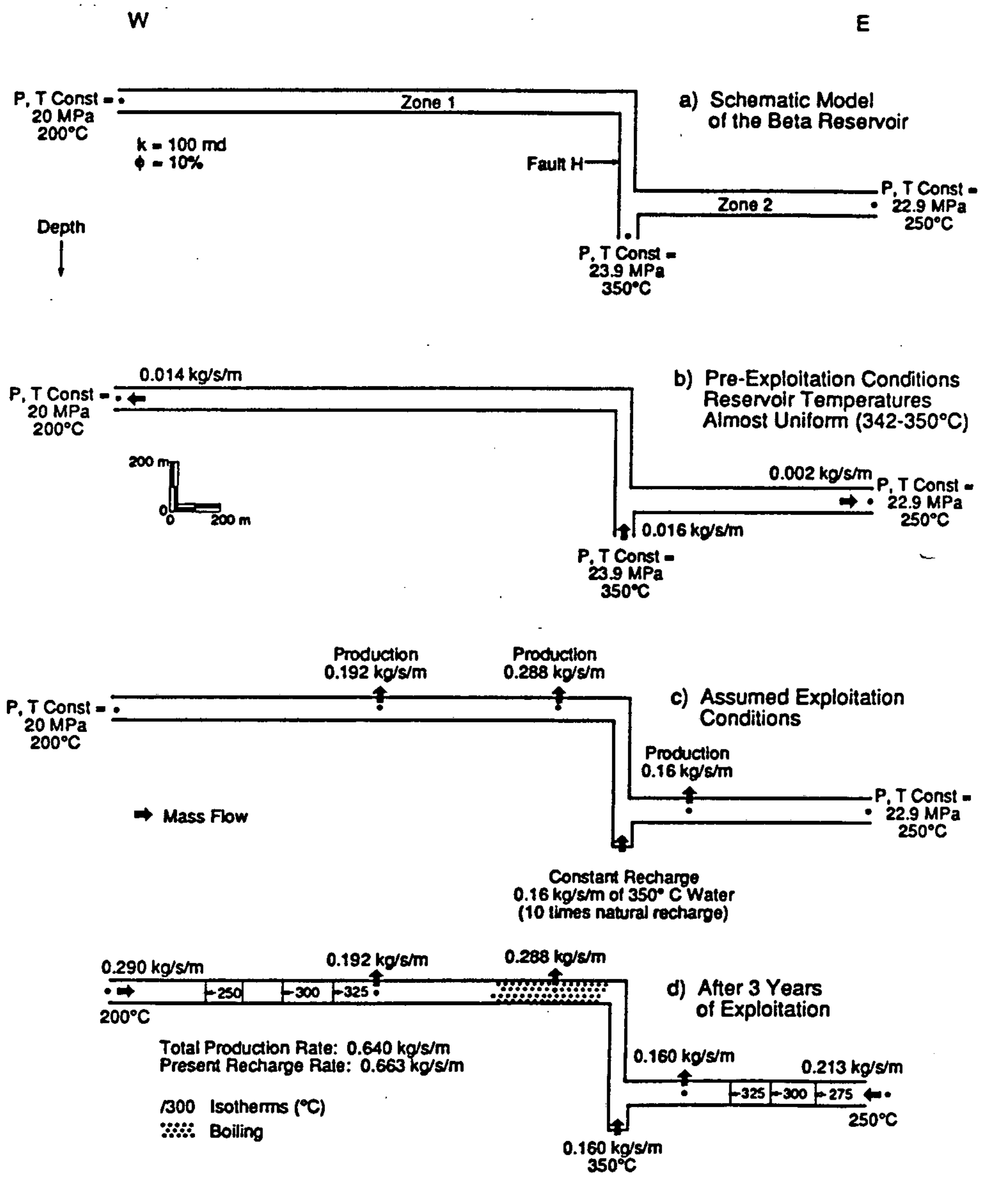
Figure 10. Location of wells indicating reservoir boiling (de León Vivar, 1988) and of the fault H zone (see Fig. 1).

under these "natural state" conditions, varying between 342 and 350 °C; no boiling is observed.

Figure 11c describes the exploitation conditions that were assumed for the model. The system is produced at a total rate 40 times the natural recharge, while the hot (350 °C) recharge is assumed to be 10 times the natural value because of pressure drawdown. Figure 11d shows the temperature distribution and location of the boiling zone in the system after three years of production. The effects of lateral cold-water recharge are reflected by the isotherms; thermal fronts are advancing toward the producing areas, but have not yet reached them. The boiling is restricted to the upthrown block near the fault since this particular region is isolated from the recharge areas.

The model shows that the boiling zone collapses with time because of increasing system recharge and cooling. Note that at 3 years (Fig. 11d) the total recharge slightly exceeds total production.

Even though models like the one described in Figures 9 and 11 are very schematic, they can reproduce some of the behavior of the beta reservoir. These simple models may be used to outline a production/injection program at Cerro Prieto that could reduce the boiling and induced cold water recharge, and the related reservoir plugging and cooling.



XBL 893-7487

Figure 11. (a) Schematic vertical cross-sectional flow model of the Cerro Prieto beta reservoir system.
(b) Pre-exploitation (initial) flow and temperature conditions.
(c) Assumed exploitation regime.
(d) Temperature distribution, fluid flows and location of boiling zone after 3 years of production.

CONCLUSIONS

We find a surprisingly clear control of fluid circulation in the Cerro Prieto field by faults and lithology. The simple geothermal fluid flow model given in Figure 9, describes in very general terms the natural state circulation of hot fluids in the system, as well as the recharge that results from pressure drawdown due to exploitation.

It was shown that simple models can explain the behavior of individual wells and large regions of the Cerro Prieto geothermal system. Development of a reservoir management plan for this highly-productive field requires more detailed numerical simulations. This effort is being carried out in parallel by CFE and LBL scientists who are studying the system using three-dimensional numerical models that are quite sophisticated. The basic understanding of geothermal field processes obtained here from analyzing simplified models is providing valuable guidance in the development of more detailed numerical simulation models of Cerro Prieto.

ACKNOWLEDGEMENTS

We wish to thank Norman Goldstein and Karsten Pruess of LBL for discussing and reviewing the paper. Special thanks are due to our colleagues of the Superintendencia General de Estudios of the Coordinadora Ejecutiva de Cerro Prieto of CFE for providing the field data used in this study. Finally, we want to acknowledge the assistance of Diana Parks in producing the paper. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technologies, Division of Geothermal Energy of the U.S. Department of Energy under contract DE-AC03-76SF00098.

REFERENCES

de León Vivar, J., 1988. "Presencia de dos fases en el yacimiento del campo geotérmico de Cerro Prieto," *Geotermia, Rev. Mex. de Geoenergía, 4,* 1, 203-211.

Goldstein, N.E., Halfman, S.E., Corwin, N.E., and J. Martínez R., 1989. "Self-potential anomaly changes at the East Mesa and Cerro Prieto geothermal fields," (this volume).

Grant, M.A., Truesdell, A.H., and Mañón M., A., 1984. "Production induced boiling and cold water entry in the Cerro Prieto geothermal reservoir indicated by chemical and physical measurements," *Geothermics, 13,* 1/2, 117-140.

Halfman, S.E., Lippmann, M.J., Zelwer, R., and Howard, J.H., 1984. "Geologic interpretation of geothermal fluid movement in Cerro Prieto Field, Baja California, Mexico", *Amer. Assoc. Petroleum Geologists Bull., 68,* 1, 18-30.

Halfman, S.E., Lippmann, M.J., and Gilreath, J.A., 1985. "Cerro Prieto case history: Use of wireline logs to characterize a geothermal reservoir," *Soc. Pet. Eng. Jour., 25,* 6, 793-803 (LBL-12379).

Halfman, S.E., Mañón, A., and Lippmann, M.J., 1986. "Update of the hydrogeologic model of the Cerro Prieto field based on recent well log data," *Geothermal Resources Council Trans., 10,* 369-375.

Janik, C.J. et al., 1982. "Carbon-13 variations in fluids from the Cerro Prieto geothermal system," Proc. Fourth Symposium on the Cerro Prieto Geothermal Field, 535-541, Comisión Federal de Electricidad, Mexico.

Lippmann, M.J. and Bodvarsson, G.S., 1983. "Numerical studies of the heat and mass transport in the Cerro Prieto geothermal field, Mexico," *Water Resources Research, 19,* 3, 753-767.

Lippmann, M.J. and Mañón, A., 1987. "The Cerro Prieto geothermal field," *Geothermal Science and Technology, 1,* 1, 1-38.

Mercado, S., 1976. "Movement of geothermal fluids and temperature distribution in the Cerro Prieto geothermal field, Baja California, Mexico," Proc. 2nd UN Symp. Development and Use of Geothermal Resources, 487-492.

Mercado, S. and Bermejo, F.J., 1987. "Mecanismo de producción del pozo M147 de la central geotermoeléctrica de Cerro Prieto II," Proc. Internat. Symp. on Develop. and Exploit. of Geothermal Resources, Oct. 5-9, 1987, Cuernavaca, Mexico, 214-220.

Mercado S. and Bermejo, F.J., 1988. "Ecological aspects on Cerro Prieto geothermal field," *Trans., Geothermal Resources Council, 12,* 95-99.

Nehring, N.L. and D'Amore, F., 1984. "Gas chemistry and thermometry of the Cerro Prieto, Mexico, geothermal field," *Geothermics, 13,* 1/2, 75-89.

Pruess, K., 1988. "SHAFT, MULKOM AND TOUGH: A set of numerical simulators for multiphase fluid and heat flow," *Geotermia, Rev. Mex. de Geoenergía, 4,* 1, 185-202.

Semprini, L. and Kruger, P., 1984. "Relationship of radon concentration to spatial and temporal variations of reservoir thermodynamic conditions in the Cerro Prieto geothermal field," *Geothermics, 13,* 1/2, 103-115.

Stallard, M.L. et al., 1987. "Patterns of change in water isotopes from the Cerro Prieto geothermal field, Baja California, Mexico," *Geothermal Resources Council Trans., 11,* 203-210.

Truesdell, A.H., 1988. "Geochemical models for reservoir processes at Cerro Prieto, Mexico," Proc. Intern. Symp. on Geothermal Energy, Nov. 10-14, 1988, Kumamoto and Beppu, Japan, 59-62.

Truesdell, A.H., D'Amore, F., and Nieva, D., 1984a. "The effects of localized boiling on fluid production at Cerro Prieto," *Geothermal Resources Council Trans., 8,* 223-229.

Truesdell, A.H. and Lippmann, M.J., 1986. "The lack of immediate effects from the 1979-1980 Imperial and Victoria earthquakes on the exploited Cerro Prieto geothermal reservoir," *Geothermal Resources Council Trans., 10,* 405-411.

Truesdell, A.H., Nehring, N.L., Thompson, J.M., Janik, C.J. and Coplen, T.B., 1984b. "A review of progress in understanding the fluid geochemistry of the Cerro Prieto geothermal system," *Geothermics, 13,* 1/2, 65-74.

Truesdell, A. H., Terrazas, B., Hernández, L., Janik, C., Quijano, L. and Tovar, R., 1989. "The response of the Cerro Prieto reservoir to exploitation as indicated by fluid geochemistry," paper to be presented at the April 4-5, 1989, Symposium on Cooperative Geothermal Research of the United States and Mexico, San Diego, CA.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720