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Authors
Truesdell, A.H.
Lippmann, Marcelo J.

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A.H. Truesdell and M.J. Lippmann

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Alfred H. Truesdell[†] *and Marcelo J. Lippmann*[‡]

[†]U.S. Geological Survey
Menlo Park, California 94025

[‡]Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Alfred H. Truesdell† and Marcelo J. Lippmann‡

†U.S. Geological Survey
Menlo Park, California, 94025, USA

‡Lawrence Berkeley Laboratory
Berkeley, California, 94720, USA

Abstract

Cerro Prieto geothermal reservoirs tend to exhibit good hydraulic communication with adjacent cool groundwater aquifers. Under natural state conditions the hot fluids mix with the surrounding colder waters along the margins of the geothermal system, or discharge to shallow levels by flowing up fault L. In response to exploitation reservoir pressures decrease, leading to changes in the fluid flow pattern in the system and to groundwater influx.

The various Cerro Prieto reservoirs have responded differently to production, showing localized near-well or generalized boiling, depending on their access to cool-water recharge. Significant cooling by dilution with groundwater has only been observed in wells located near the edges of the field. In general, entry of cool water at Cerro Prieto is beneficial because it tends to maintain reservoir pressures, restrict boiling, and lengthen the life and productivity of wells.

Introduction

The Cerro Prieto geothermal field in northern Baja California, Mexico, is developed in the deltaic sands and shales of the southern Salton trough (Fig. 1). Extensive drilling by the Comisión Federal de Electricidad (CFE), has provided fairly detailed information concerning lithology and temperatures from about 800 to 3000 m depth in the upper part of the system. Cerro Prieto has two thoroughly explored geothermal reservoirs and another that is less well known. These reservoirs differ from some other exploited reservoirs (The Geysers, Wairakei) in having "leaky" boundaries where the hot geothermal fluids exist in dynamic equilibrium with much cooler waters. Originally the boundaries of the system were maintained by an upward flow of hot water that eventually emerged at the surface or dispersed into surrounding cold aquifers.

In the natural state, heat in high-temperature hot-water reservoirs is supplied by an upward flow of hot fluid. This fluid must cool by boiling or by mixing with cooler water (dilution) to eventually reach surface temperatures. These processes have been described for the shallow Cerro Prieto α (alpha) reservoir and for Wairakei and Broadlands by Grant *et al.* (1984). At Wairakei boiling occurred at the top of the reservoir but dilution was prevented by relatively well-sealed margins. At Broadlands boiling took place throughout the reservoir and dilution was very limited. In contrast, the α Cerro Prieto reser-

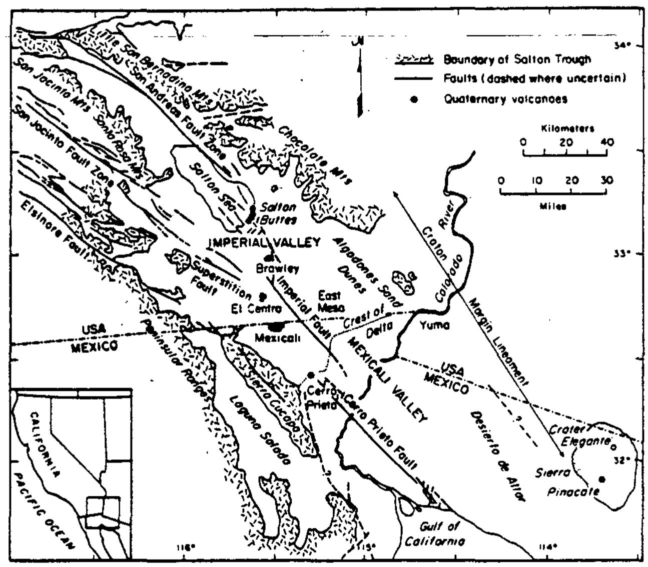

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Figure 1. Regional geological map of the Salton trough, showing the location of the Cerro Prieto field, SE of the city of Mexicali.

voir showed strong dilution which produced temperature and salinity gradients and limited boiling. This reservoir, unlike the New Zealand systems, was not well sealed and connections to cooler aquifers must have been relatively open. Bixley (1990) showed that under exploitation Wairakei and other New Zealand reservoirs were increasingly invaded by cooler water entering along conduits that originally fed surface discharges.

Natural-State Boiling and Dilution

Boiling and dilution in the natural state differ from the same processes during exploitation. In the natural state steam resulting from boiling may remain with liquid or separate to form a steam zone. The flow of mixtures of steam and water through pores (or small fractures) may be restricted by relative permeability effects and possibly by permeability reduction due to mineral precipitation. The results of these processes is to hinder fluid flow. Under exploitation high-enthalpy fluids may be locally generated by boiling and removed through drill holes, so long-distance transport of steam-water mixtures does not occur.

In the natural state, dilution within a reservoir requires that cooler water enters along the same permeable connections through which hot fluids discharge. This counterflow of hot and cold fluids was shown in the natural state simulations of Cerro Prieto by Lippmann and Bodvarsson (1983). The competition of boiling and dilution may act to hold temperatures at the boiling point to depth without much boiling. Hotter, less-diluted liquid would boil and its upward flow would be impeded by relative permeability and mineral deposition. Fluids diluted just enough not to boil would not be hindered by these effects but would be more buoyant than cooler, more-diluted fluid. This could explain the adherence to boiling temperatures in the shallow α reservoir (Grant *et al.*, 1984) even though little boiling occurs.

Natural-State Hot and Cold Aquifers at Cerro Prieto

Halfman *et al.* (1984, 1986) and Lippmann *et al.* (1989) have described the natural state hydrology of Cerro Prieto. These descriptions are based on lithologic and temperature logs and on modeling of heat and fluid flows. The general pattern of circulation in each of the Cerro Prieto reservoirs is similar. Hot fluids enter each reservoir from below and flow upward and toward the margins.

In the natural state the Cerro Prieto reservoirs are fed by hot brine from a deep source. These fluids appear to be heated by intrusion of igneous dikes into the sediments. A complex of mafic and silicic dikes have been intercepted in deep wells in the E part of the field (Elders *et al.*, 1984).

It has been suggested from geochemical arguments, that the deep recharge to the Cerro Prieto system is formed from hypersaline brines of marine origin that mix with Colorado River water in several stages (Truesdell *et al.*, 1981). This mixing was, as will be described later, the major process for cooling the Cerro Prieto brines in the natural state.

The hot brine (at 350°C where first encountered) flows up normal fault H (Fig. 2) and, as discussed next, enters the deep γ (gamma) and β (beta) reservoirs and then flows through part of the β reservoir to the shallow α reservoir. Each of these reservoirs has complex connections through more or less permeable interbedded sandstones and shales to the hot brine and in most parts to cooler water.

The γ reservoir has been found only SE of fault H at depths greater than 3300 m. Very few wells produce from this aquifer. We do not know its extent and have no information on connections with cold-water aquifers. The entry of hot water suggests connection and flow to cold aquifers to maintain temperatures.

The β reservoir is the largest in the exploited field. It underlies the entire α reservoir and extends 3–4 km to the NE of the railroad (Fig. 2). The depth to this reservoir is about 1500 m in the W to more than 2700 m in the E. It is divided by the SE dipping fault H into upthrown and downthrown blocks. Fluids ascending along fault H flow NW and SE into these two parts of the β reservoir. About two thirds of the β reservoir lies in the upthrown block. Fluid temperatures range from 320° to 340°C in the central reservoir and decrease to 240°C toward the margins.

The β reservoir residing in sand unit "Z" (Fig. 3) is connected with cold-water aquifers to the S and W. Wells near

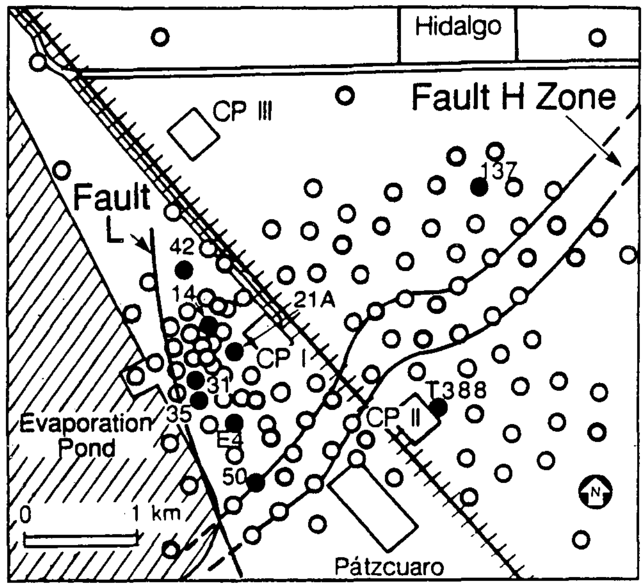

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Figure 2. Location of Cerro Prieto wells discussed in the paper (darkened circles) and faults H and L. Fault H zone is shown at the β reservoir level; fault L is subvertical (after Halfman *et al.*, 1986).

these boundaries show evidence of chemical breakthrough of lower Cl, lower $\delta^{18}O$ waters (Stallard *et al.*, 1987; Truesdell *et al.*, 1989) indicating dilution. Wells in the N and NE, however, do not show dilution but present high excess steam indicating reservoir boiling. Modeling by Lippmann *et al.* (1989) shows that most of the fluid entering the β reservoir from fault H enters the upthrown block (to the NW). A large proportion of this fluid flows into the α reservoir but part is dispersed into cold aquifers within the thick sandstones present along the western edge of the field (Halfman *et al.*, 1985). Probably all of the flow out of the downthrown block is into an adjacent cold-water aquifer. The edge of the β reservoir is defined by decreases in temperature and alteration (Elders *et al.*, 1984). There is no evidence of self sealing by mineral deposition at any of the lateral boundaries.

Most of the hot fluid leaving the E part of the β reservoir flows upward through a sandy gap in shale "O" into the α reservoir (Fig. 3; Halfman *et al.*, 1984). Modeling by Lippmann and Bodvarsson (1983) indicates that the fluid boils as it ascends through the sandy gap. Flow into the α reservoir is from both fault H and the E part of the β reservoir (S.E. Halfman-Dooley, pers. commun., 1990).

The shallow α reservoir is found in the W part of the field (W of the railroad in Fig. 2). It extends from 1000 to 1500 m depth and originally had temperatures from 260° to 310°C. Unlike the β reservoir, the α reservoir is not confined to a single sand unit but resides in mixed sands and shales in the upper part of shale "O". Flow upward may be limited by more shaley layers or by precipitation of calcite or quartz. The sandstone above it carries cooler waters with temperatures <100°C in the E, increasing to 250°C in the W where hot waters enter from fault L (Fig. 3). Fault L is the major outflow conduit for fluids from the α reservoir, as indicated by the pattern of cold-

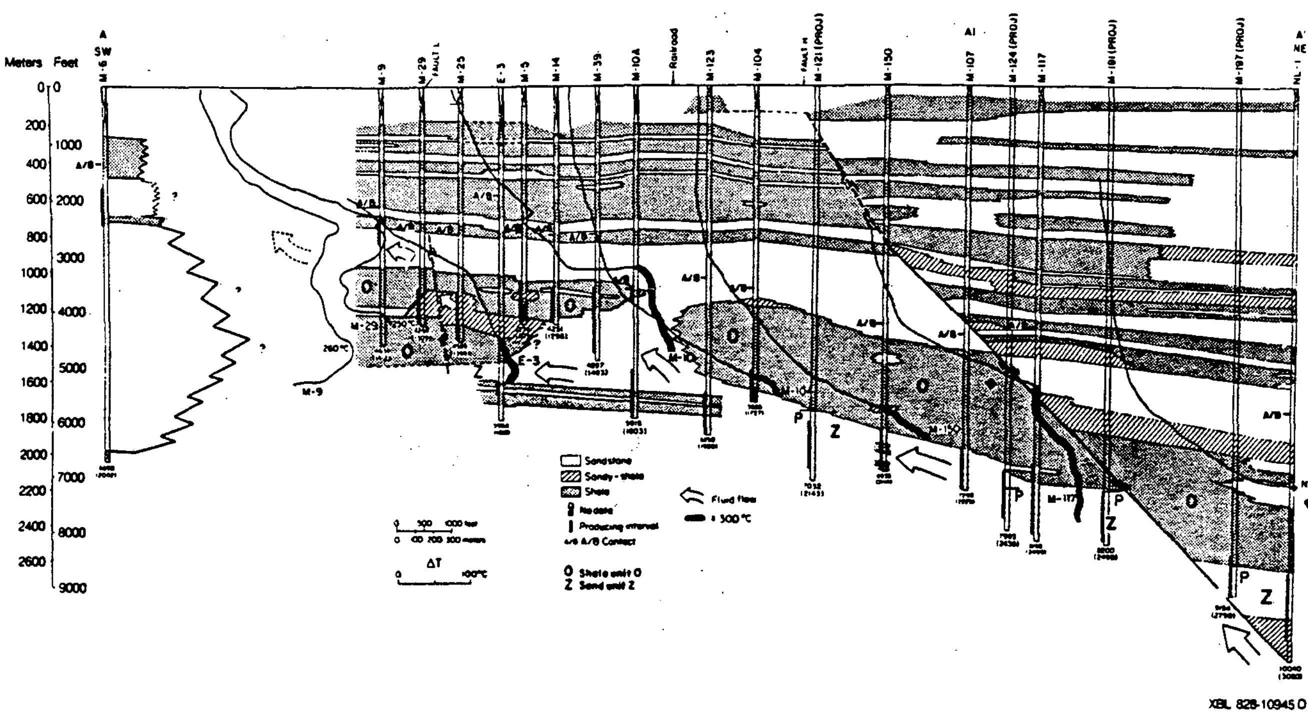

Figure 3. Cross section of the Cerro Prieto field from SW to NE showing faults, lithofacies groups, downhole temperature profiles, production intervals, and geothermal fluid flow directions. On the temperature profiles, the points corresponding to 300°C are located below the respective wells. The heavy lines on these profiles indicate temperatures of 300°C or greater (after Halfman *et al.*, 1986).

water entry under exploitation (Stallard *et al.*, 1987; Lippmann *et al.*, 1989).

From the α reservoir some fluids flow to the W and S margin but probably most flow up the subvertical normal fault L into the overlying cooler sandstone aquifer. At shallower depths the path is not certain but eventually most of the hot fluid feeds the springs and fumaroles W of the field. Solute concentrations in the spring waters suggest boiling and dilution of hot brine originally at a temperature and chloride concentration (300°C and 9000 mg/kg) similar to brine in the α reservoir (Mercado, 1968).

In systems such as Cerro Prieto where the hottest fluids are significantly saline and cooler fluids are more dilute, most ascending fluid is cooled by dilution. Complex exchange between hot and cold aquifers occurs in the natural state. Cold water must enter hot aquifers and mix with hot fluid to produce the gradients in temperature and chlorinity observed in the earliest samples from the field (Truesdell *et al.*, 1979; Grant *et al.*, 1984). Cooling by dilution rather than boiling must be favored by effective permeability decrease in zones of boiling. Relatively free access of cooler water aquifers to geothermal reservoirs in the natural state has provided a mechanism for the throughflow of hot water to maintain reservoir temperatures and has limited boiling through cooling by dilution.

Response of Cerro Prieto Reservoirs to Exploitation

Production of fluid from the α reservoir causes pressure drawdown and a deficit of mass. Without injection of liquid to replace the fluid deficit and maintain pressures, surrounding cooler water will be drawn into the reservoir or fluid will boil so that the volume of fluid removed is filled by vapor or cooler liquid.

At Cerro Prieto the chemistry of produced fluids along with measured enthalpy has been used to indicate processes in the reservoir (Truesdell *et al.*, 1989; Lippmann and Truesdell, 1990). Near-well fluid temperatures are indicated by the quartz-saturation geothermometer and distant temperatures by the Na-K-Ca geothermometer. The comparison of these temperatures (or equivalent liquid enthalpies) with measured total enthalpy indicates excess steam. Changes in aquifer chloride indicate dilution and boiling.

Exploitation of Cerro Prieto reservoirs started in 1973 with the α reservoir supplying steam to the CPI power plant. Electrical power production from this part of the field increased from 75 MWe initially to 180 MWe in 1981. Declining production from the α reservoir led to drilling the deeper E-series wells that produce from the β reservoir in the same area. Production from E-wells within the CPI area started in 1981. The CPII and CPIII power plants (each 220-MWe capacity) went on line in 1986–1987. These plants were fed with fluids from the β reservoir (and to a small extent, the γ reservoir) in the E part of the field (E of the railroad in Fig. 2). Thus, experience with reservoir behavior is longest for the α reservoir, shortest for the β reservoir in the E, and intermediate for wells in the W part of the β reservoir.

The Cerro Prieto reservoirs have shown quite different behavior under exploitation. The α reservoir presented strong localized drawdown within a short time after the start of production. Almost all wells showed near-well boiling with excess steam that decreased exponentially with time. After this initial boiling, wells in the N part of the α reservoir away from intense exploitation showed no boiling or dilution with near-constant liquid and total enthalpies (Fig. 4).

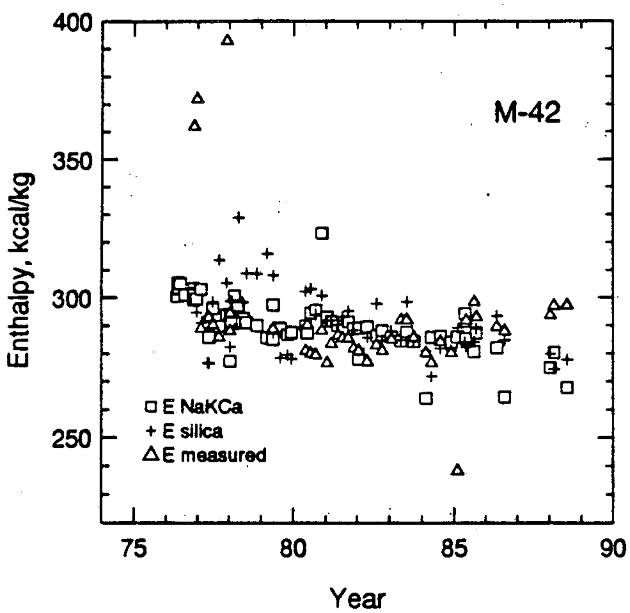

Figure 4. Indicated aquifer liquid enthalpy values and measured wellhead total fluid enthalpy values for well M-42. E Na-K-Ca is the enthalpy of liquid calculated from the Na-K-Ca geothermometer temperature; E silica is the enthalpy of liquid calculated from the quartz saturation geothermometer temperature.

Wells near the edge of the field show chemical and thermal breakthrough of cooler, lower-Cl waters. Wells near fault L show sharp breakthrough (Fig. 5), but wells in the W and S of the α reservoir and in the downthrown S block of the β reservoir show more gradual decreases in temperature and Cl (Figs. 6 and 7).

Wells with pronounced near-well boiling exhibit significant excess steam that decreases exponentially and lowered near-well temperatures (Fig. 8). This has been shown by Lippmann and Truesdell (1990) to result from boiling in a reservoir with a constant pressure boundary. This near-well boiling in the α reservoir was characteristic of the first six years of production of wells in the central part of this reservoir, where connection to cooler aquifers through fault L probably provided the constant pressure. Near-well boiling and resulting mineral deposition may lead to formation plugging (Truesdell *et al.*, 1984).

Boiling of a different sort is shown by wells in the β reservoir. These wells are not as closely connected to cool aquifers and boiling is more widespread, not limited to individual wells.

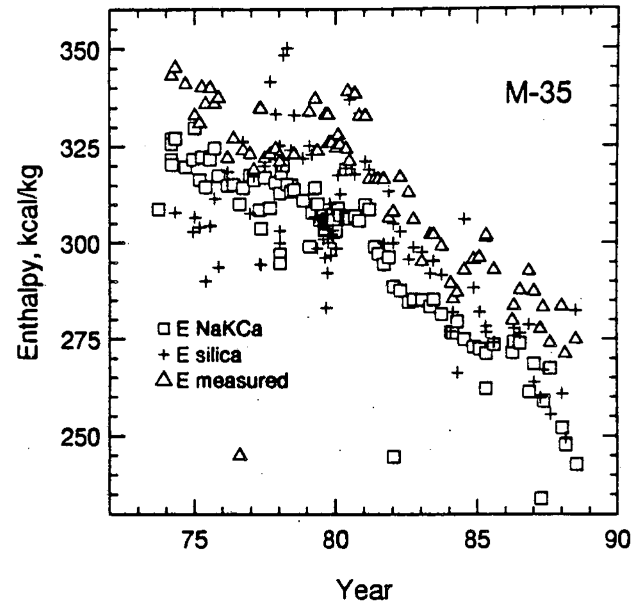

Figure 5. Indicated aquifer liquid enthalpy and wellhead total fluid enthalpy values for well M-35 (see caption of Fig. 4).

Almost all wells in the NW part of the β aquifer (N of fault H) show high excess enthalpy, which has increased with time rather than decreasing exponentially (Fig. 9). Although these wells have been produced for only three years, it appears that declining pressure has caused nearly reservoir-wide boiling with gravity segregation of steam and brine. As the brine level drops and steam flow to the wells increases, both enthalpy and whole-fluid gas concentrations increase (L. Quijano, pers.

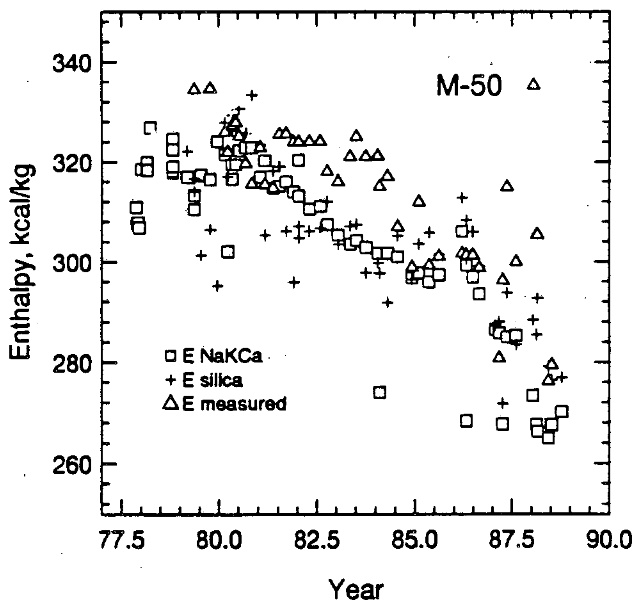

Figure 6. Indicated aquifer liquid enthalpy and wellhead total fluid enthalpy values for well M-50 (see caption of Fig. 4).

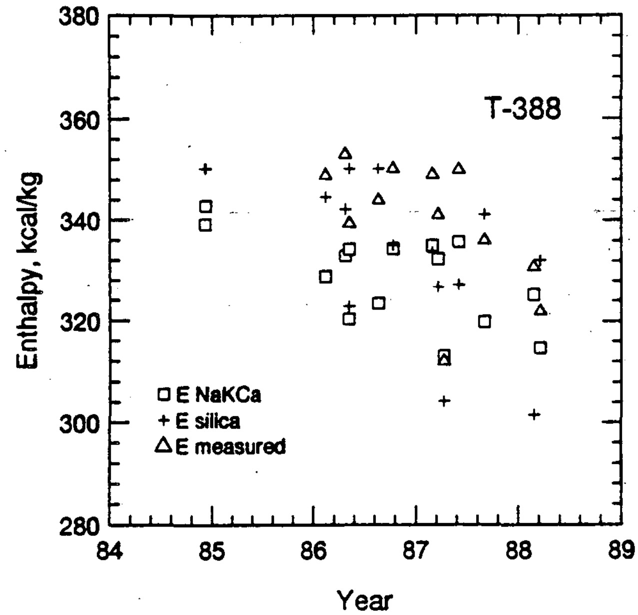

Figure 7. Indicated aquifer liquid enthalpy and wellhead total fluid enthalpy values for well T-388 (see caption of Fig. 4).

commun., 1989). The β reservoir wells in the W part of the upthrown block (CPI area) also show general boiling but with cold sweep superimposed (Fig. 10). Temperature and enthalpy decrease with the arrival of the thermal front, presumably as a result of replacement of vapor with cooler water.

Effects of Cool-Water Entry on Production

Cerro Prieto has been a very productive field. This productivity has been achieved without liquid injection and with wells located on a grid pattern. We suggest that this success is due in part to the entry of cooler waters that have maintained pressures, prevented boiling, and swept heat to the wells. Only in the N part of the β reservoir, where access of cool water is most limited, could liquid injection benefit the field.

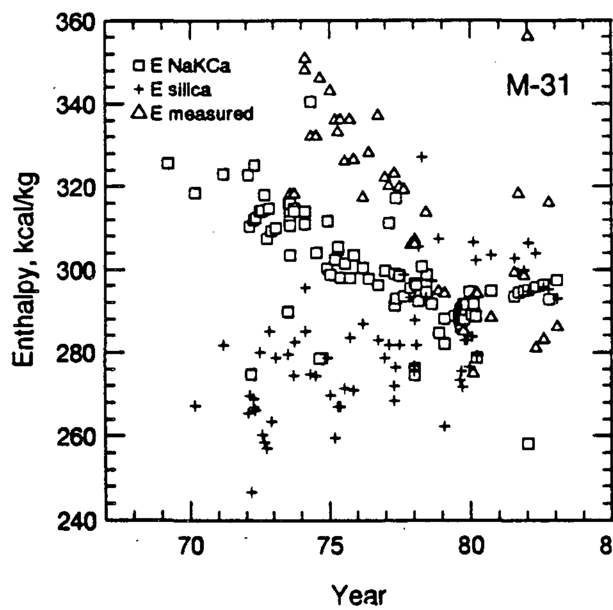

Figure 8. Indicated aquifer liquid enthalpy and wellhead total fluid enthalpy values for well M-31 (see caption of Fig. 4).

The comparison of well productivity and longevity in different parts of the Cerro Prieto reservoirs is instructive. The α reservoir has been produced for the longest time and in the S and W has the strongest connections to cooler aquifers. Wells in this part of the field have shown early chemical and thermal breakthrough and little boiling. The enthalpy of the wells has decreased slowly, however, and these wells have produced high steamflow over long lifetimes (Table 1).

Wells in the N part of the α reservoir show little drawdown because this area has not been extensively drilled. These wells show only slight initial boiling and no dilution. They have relatively long lives with moderately low steam flow (Table 1).

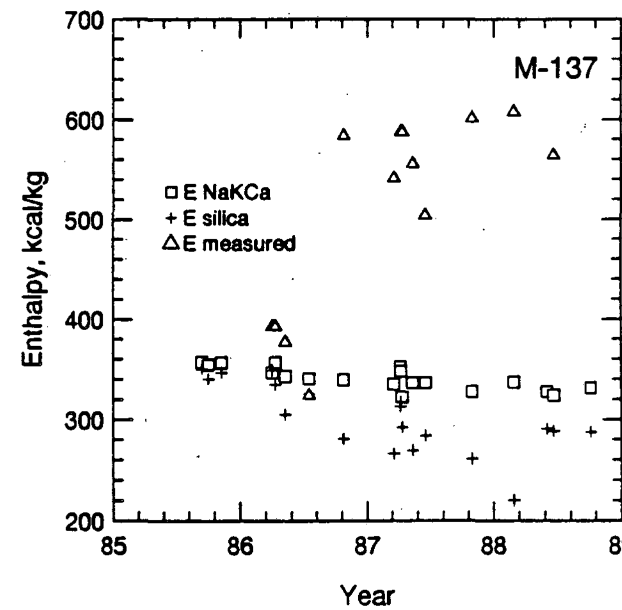

Figure 9. Indicated aquifer liquid enthalpy and wellhead total fluid enthalpy values for well M-137 (see caption of Fig. 4).

The behavior of wells in the central, heavily exploited zone of the α reservoir has been varied. Some wells on the N edge of this zone (e.g. M-14) behave as those in the N part of the reservoir. Others are close to the L fault and have shown early chemical and thermal breakthrough, sometimes combined with moderate initial boiling. Their steam production has been high and their longevity has been exceptional (Table 1). Other wells (e.g. M-31, M-21A), perhaps less well connected to cool water, have high excess enthalpy and reduced fluid silica contents, indicating near-well boiling and mineral precipitation in the reservoir. These wells were initially high steam producers but have shown rapid declines and relatively short lives (Table 1).

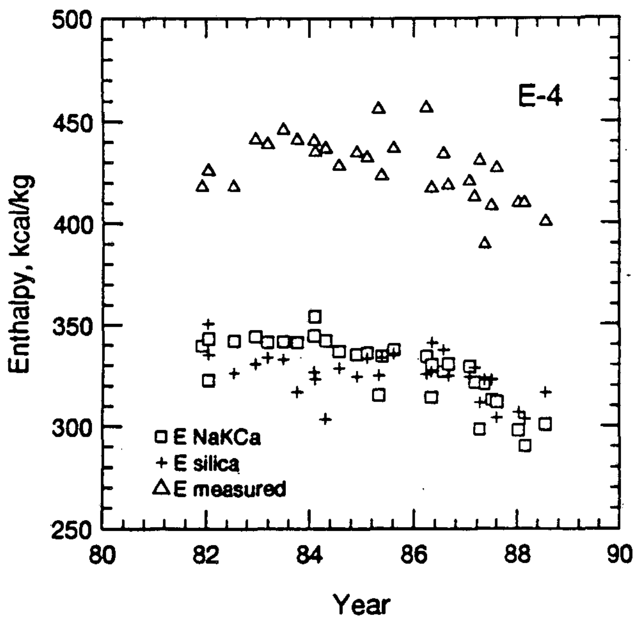

Figure 10. Indicated aquifer liquid enthalpy and wellhead total fluid enthalpy values for well E-4 (see caption of Fig. 4).

The deeper E-wells in the CPI area are on the average more productive than the shallower M-wells but only because they are younger (Table 1). Some of the E-wells show excess enthalpy after a few years and some almost immediately upon start of production (Fig. 10). The excess enthalpy generally does not decrease but remains high or increases, except in the few wells that show thermal breakthrough. None of these wells were produced before 1981 so we cannot compare their longevity to that of M-wells. Silica in the fluid from the E-wells is not depressed, suggesting that mineral deposition and plugging may not become a problem.

Wells in the eastern CPII and CPIII areas have been producing in most cases from 1986 or 1987 but many only from 1988 or 1989, and as a result the average steam production is high. The record is too short to show clearly the influence of cool-water access on longevity. As in the α reservoir, the downthrown block of the β reservoir (S of fault H in the CPII area) shows progressive dilution but no excess enthalpy (boiling). The wells in the center of the CPII area show high steam productivity but a few of those in the far S show low enthalpy and low steam.

Finally, considering the upthrown block of the β reservoir N of fault H in the CPIII area, we find unusually high excess enthalpy that has increased in the few years of production. Wells adjacent to fault H produce unusually large flows (Table

Table 1. Steam Flow and Production Life for Wells and Average Values for Different Cerro Prieto Areas

Wells	Reservoir	Average Steam Flow (tonnes/h)	Maximum Steam Flow (tonnes/h)	Years Produced	Processes
Average	Alpha	40.3	139.4	9.3	—
M-42	Northern Alpha	42.0	72.4	13.2*	No boiling or dilution
M-50	Southern Alpha	59.0	99.9	11.1*	Gradual dilution
M-35	Central Alpha	55.5	120.0	15.8*	Distinct dilution
M-31	Central Alpha	46.2	85.0	9.7	Local boiling
Average E-wells (CP I)	Western Beta	52.1+	126.4	3.8	—
E-4	Western Beta	59.7	126.4	8.2*	General boiling
Average	Eastern Beta (CPII and CPIII)	63.1+	178.4	3.0	—
T-388	Southern Beta (CPII)	57.8+	76.1	4.0*	Gradual dilution
M-137	Northern Beta (CPIII)	75.8+	111.7	4.0*	General boiling

* Production continues (as of January 1990)

\+ High average flow is partly related to short duration of production period

1). The lack of cool-water entry and the intense boiling in this part of Cerro Prieto suggest that liquid injection might be advantageous.

Conclusions

The observations presented here suggest that cool-water entry has increased the average longevity of Cerro Prieto wells. Some wells at the extreme edges of the field have been cooled so that they now produce less steam, but pressures throughout the α reservoir and the S part of the β reservoir have been maintained. In these areas boiling has been prevented in most wells, and the total amount of heat extracted from the reservoir has probably been increased relative to the amount expected without natural recharge. The future productivity of the N part of the β reservoir, which shows little or no cool water recharge, will be an interesting test of these ideas. The present management of the Cerro Prieto field has produced good results that probably could not have been improved upon. A question for the future is the behavior of the β reservoir in the N part of the field that might benefit from liquid injection. Reinjection into other parts of Cerro Prieto might be less cost-effective since there is already natural recharge of groundwater, mainly from the W and S.

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