Response of Northeastern Cerro Prieto Wells to Exploitation

Marco H. Rodríguez R.

Residencia General de Cerro Prieto
Comisión Federal de Electricidad
Mexicali, B.C., México

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ABSTRACT

The northeastern Cerro Prieto reservoir has unusual features and responds differently to exploitation than other areas. Intensive exploitation began in the NE Cerro Prieto 4 area (CP4) when a 100 MWe power plant came on line in 2000. Three NE zones with particular characteristics are described, especially the production and chemical evolution of some of their wells. Some show evidence of cool-water recharge, the predominant process in the western part of the field, while others, show an inferred, unusual high-temperature recharge. Most of the NE wells undergo general boiling, and some an increase in wellhead pressure, which is also rare for Cerro Prieto.

The behavior of wells in CP4 and neighboring areas and the underlying reservoir recharge processes are discussed. The information is useful for designing the completion of new wells and the repair and re-completion of existing ones.

Introduction

For administrative purposes, the Cerro Prieto Geothermal Field (CPGF) has been divided into four areas. The Cerro Prieto 4 area (CP4) is in the northeastern part of the field (Figure 1). Initially, a few of the CP4 wells supplied steam to the CP3 power plant. In the year 2000, the 100 MWe CP4 power plant came on line raising to 720 MWe the total installed capacity in the field. There are 20 wells of the so-called "400 series" that send steam to the new plant; they were drilled in the CP4 area between 1998 and 2002. .

The response of a reservoir to exploitation depends on the characteristics of the fluid recharge (i.e., quantity and quality). If the recharging and native reservoir fluids are similar in chemistry and enthalpy, and the recharge is strong enough, little change in the fluids produced by the wells is to be expected with time. However, if the recharge of a liquid-dominated reservoir is weak, a significant pressure drawdown is likely to result, and the formation of a two-phase (i.e., boiling) zone is possible.

The mass recharge in a reservoir depends on differences in fluid pressure (i.e., the hydraulic gradient) and the permeability of the reservoir and surrounding formations. To understand the response of the reservoir to exploitation it is necessary to know the its general characteristics, its permeability, the main fluid recharge paths, the presence of flow barriers and impermeable boundaries, etc.

Two reservoirs have been identified in the CPGF. A shallow Alpha reservoir (at 1,000 m to 1,500 m depth), found only in CP1 area, and the deeper Beta Reservoir (below 1,500 m depth) which extends throughout the entire field (Lippmann et al., 1991).

CP4 Reservoir Characteristics

The shape and size of the reservoir is reflected by the distribution of hydrothermal mineral zones (Elders et al., 1981). The top of the silica-epidote mineralized zone (SEZ) defines the top

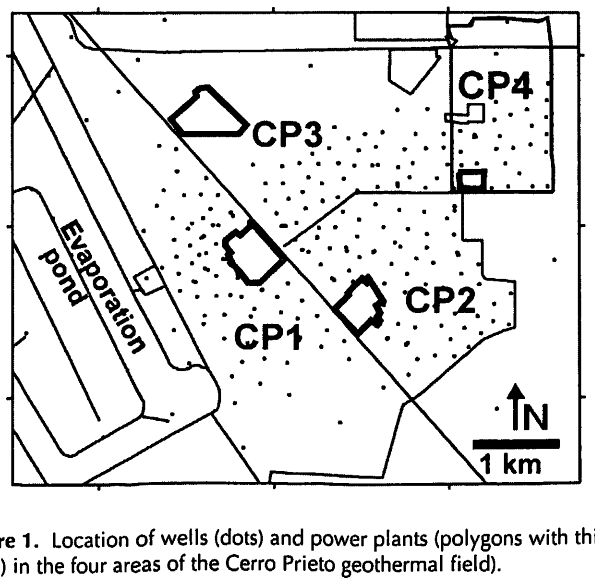

Figure 1. Location of wells (dots) and power plants (polygons with thick lines) in the four areas of the Cerro Prieto geothermal field).

of the Beta Reservoir; production wells are completed below the top of the SEZ.

Figure 2 shows the depth to the top of the SEZ in the NE parts of the CPGF. Note that in this region the deepest wells located to the north, like well 426, while the shallowest is E-43.

In the following three NE areas of the field the behavior of the Beta Reservoir is quite different because of their recharge and depth characteristics.

1. In the western part of the NE areas, wells E-43 and E-25 are located on a high or cupola of the Beta Reservoir. They encounter the reservoir at depths that are about 300 m shallower than in surrounding wells. Some studies (Verma et al., 1996; Truesdell and Lippmann, 1998) infer that this cupola (or dome) is the location where cooler groundwater from an overlying aquifer infiltrates into the geothermal reservoir.
2. Toward the northern part of CP4, between wells 404 and H-2, the Beta Reservoir is at greater depth. Well 426, located between both wells, showed no clear indication of SEZ although it is the deepest of the 400 series wells, with a depth of 3,192 meters. The depth increase is not as pronounced as in the northern parts of CP3 (Gutiérrez Puente and Rodríguez, 2000).
3. The SW-NE striking H Fault Zone (HFZ) intersects the southern CP4 area (Figure 1). That fault zone is considered to be the most important source of hot fluid recharge of the geothermal system (Halfman et al., 1983; Lippmann et al., 1991).

An interesting characteristic of the NE areas is that they are close to the heat source of the system that seems to be located deep below the NE part of the wellfield. This was inferred by Elders et al. (1984) on the basis of mineral and temperature distributions. Wells NL-1 and M-112 in the southern part of CP4 encountered intrusive (hypabissal) dikes at 3,300-3,315 m (in NL-1) and at 3,324 m (in M-112) depth. None of the 400 series wells drilled through these dikes, probably because they did not reach 3,000 m depth, with the exception of 426.

Total Production in the CP4 Area

Figure 3a shows the change with time of the number of CP4 production wells on line; it grew from 6 wells in 1989 to 22 wells in early 2003. Not all of the wells supply the 100 MWe CP4 plant, some send their steam to the 220 MWe CP3 plant.

The total mass and steam production rates of CP4 wells are given in Figure 3b. Between 2000 and 2003 the total mass rate increased from 900 to 1,400 t/h, while the steam flow rate from 480 to 1,400 t/h. After 1990 the enthalpy of the produced fluids varied between about 1700 and 2000 kJ/kg (Figure 3c), indicating a two-phase zone in the reservoir. Actually, the CP4 area has the highest average production enthalpy in the CPGF.

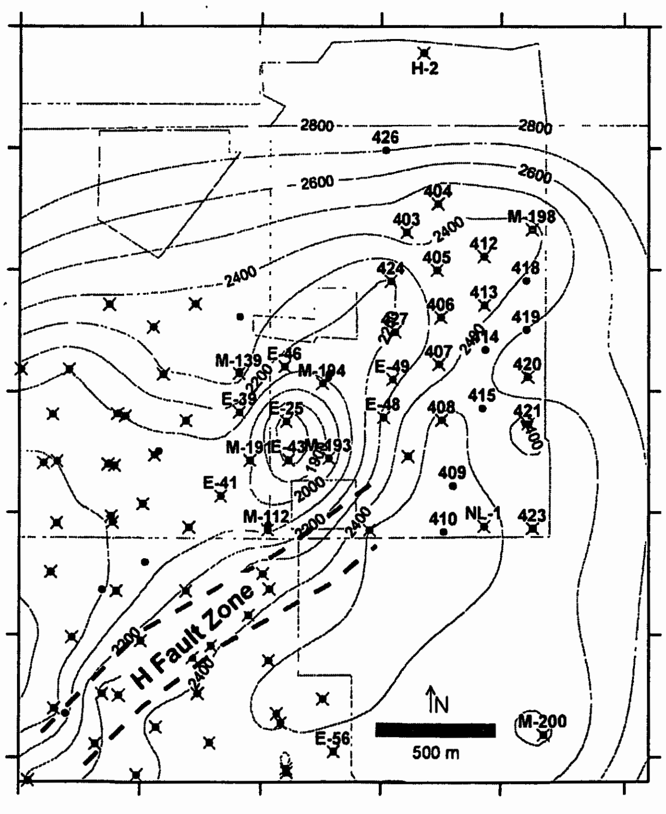

Figure 2. Depth (in meters) to the top of the silica-epidote mineral zone (SEZ) in CP4. Wells that show a continuous SEZ are indicated by an "X". In the other wells that zone seems to be discontinuous, in some cases because no cuttings wererecovered due to loss of circulation during drilling. Labeled wells are mentioned inthe text.

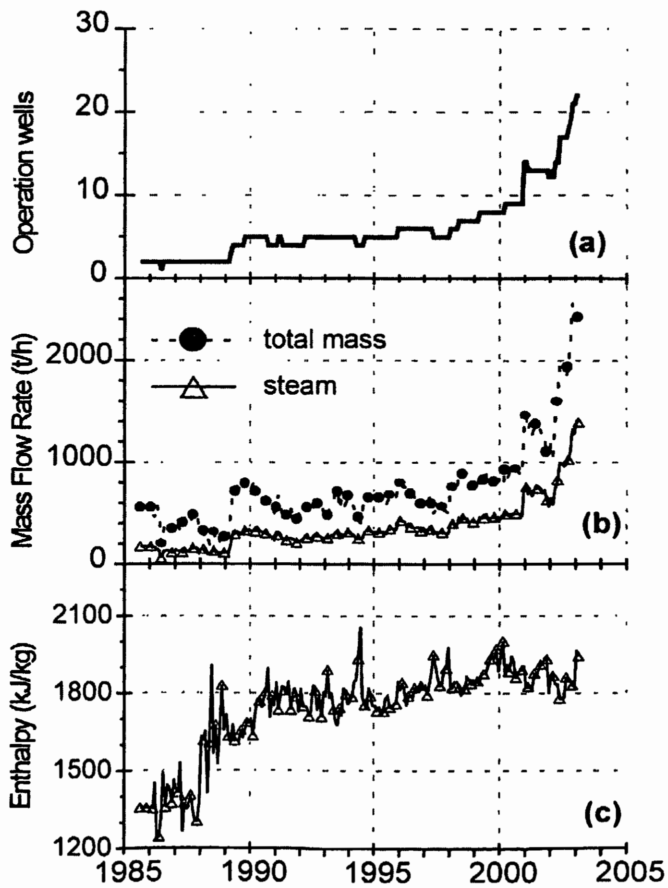

Figure 3. CP4 production history. (a) Number of production wells on line; (b) Total mass and steam flow rates; and (c) Production enthalpy.

Individual Well Behavior

Some of the NE Cerro Prieto wells have quite different responses to exploitation because of their particular recharge characteristics. This is illustrated with the behavior of some wells located in the three different areas of the Beta Reservoir mentioned earlier.

Well 426

Well 426, in the northern region of CP4, began producing in 2000 and was taken out of line in early 2003. It had very low production characteristics. Its reservoir chloride variations are given in Figure 4a. The well did not show evidences of high dilution; chloride content remained at about 9,000 ppm. Some wells located in the dome (cupola) have lower chloride content (i.e., Cl < 4000 ppm).

The temperature history, based on two different geothermometers, is presented in Figure 4b. In 2000, the T-NaKCa was lower than T-SiO_2 (280° and 290°C, respectively), indicating a sweep of cooler water through hotter rock (Truesdell et al., 1989).

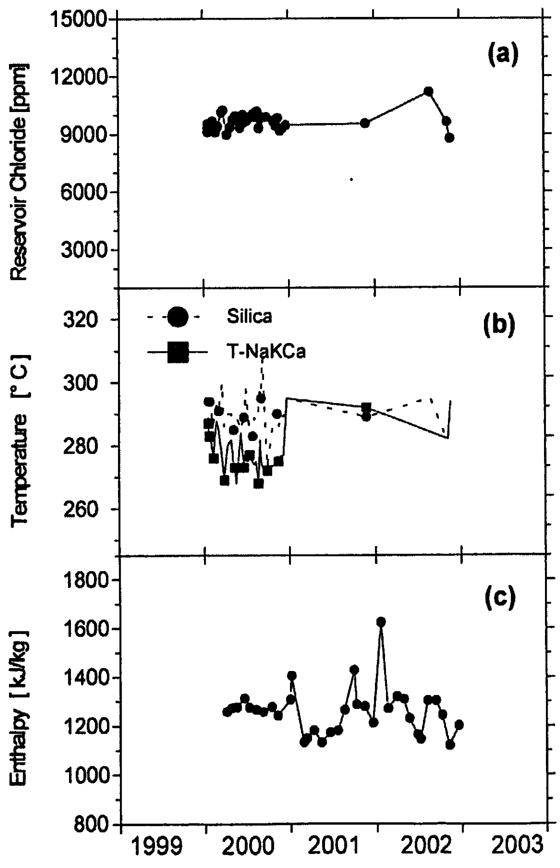

Figure 4. Well 426. (a) Reservoir chloride concentration; (b) Geothermometer temperatures; and (c) Production enthalpy.

The production enthalpy history for 426 is given in Figure 4c. Enthalpy stayed at about 1,200 kJ/kg, the lowest in CP4. The initial (2000) steam flow rate was 25 t/h; it was 20 t/h in January 2003.

The well was affected by cooler fluid recharge coming from the northern margin of CP4. The drop of water level in well H-2, north of CP4 (Figure 2), might be showing the effects of this recharge. Well 426 does not show reservoir boiling because of the high pressures in the production zone (about 200 bars at 3,100 m depth). This results from the deep (from 2,580 to 3,192 m) open interval. Gradually the wellhead pressure, enthalpy and steam flow rate declined until the well was shutdown in January 2003.

The most import reservoir process affecting the behavior of 426 is a lateral groundwater recharge. The cooler fluids heat up as they flow through the hotter rocks.

Since well 426 downhole logs do not show significant temperature changes below 2,450 m depth, the well could be worked over by opening it at shallower depths (i.e., between 2,450 and 2,750 m). In that case, the re-completed well might undergo reservoir boiling and an enthalpy increase when produced.

Wells E-43 and E-49

Wells E-43 and E-49 were selected because they have been on line continuously for more than 14 years. Both are in the western part of CP4, at and near the SEZ dome (see Figure 2 above). Due to the heterogeneity of the reservoir, neighboring wells (i.e., E-25, E-39, E-41, E-46, E-48, M-112, M-139, M-191, M-193 and

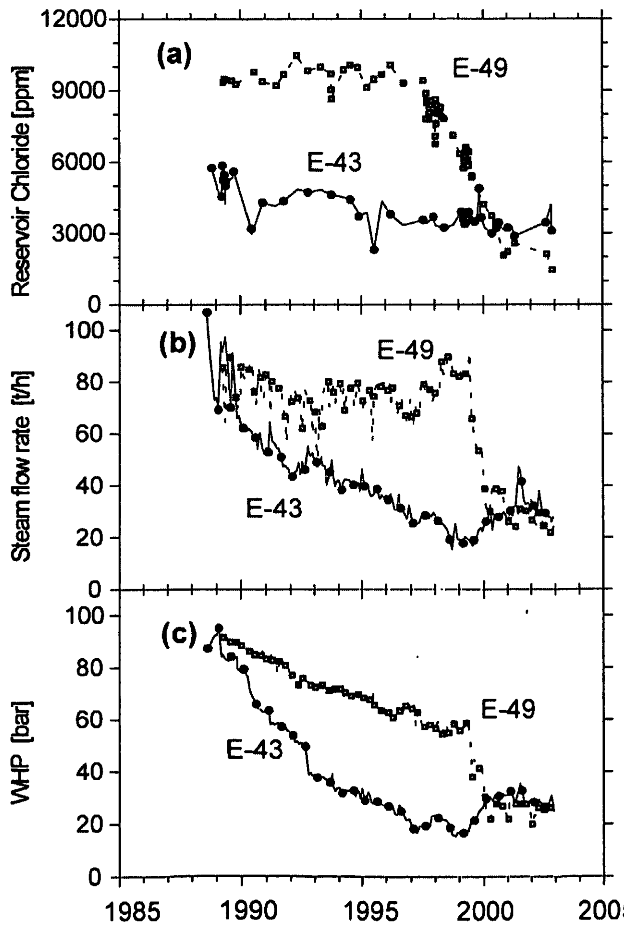

Figure 5. Wells E-43 and E-49. (a) Reservoir chloride concentrations; (b) Steam flow rates; and (c) Wellhead pressures.

M-194) react differently to exploitation. Over the years, some of these wells had to be repaired and some stopped producing altogether (i.e., their production period was shorter than that of E-43 and E-49). A number of the neighboring wells show cooler, diluted water inflow (e.g., E-41; Truesdell et al., 1998).

Well E-43 is located near the top of the SEZ dome (i.e., it has a shallower production interval than neighboring wells; from 1,811 to 2,145 m depth). When production began in 1988, relatively low-chloride (about 5,000 ppm) fluids were observed. The chloride concentration slowly declined with time; after 14 years of production (by the end of 2002) it was only about 3,000 ppm (Figure 5a). On other hand, in well E-49 the initial (1989) chloride concentration was 9,000 ppm. Until 1997 there was little change, at which time chloride began decreasing. In 2000, the concentration had dropped to about 2,000 ppm.

The steam flow rate in E-43 declined gradually between 1989 and 1999, from 80 to 20 t/h. After that, however, the steam rate showed a slight increase (Figure 5b). On other hand, in E-49 the steam flow rate was a relatively stable, at about 75 t/h, during the first 10 years of production. However, in 1999-2000 it dropped to 25 t/h, staying almost constant after that.

The wellhead pressures (WHP) for E-43 and E-49 are given in Figure 5c. There is a clear correlation between these pressures and the wells' steam flow rates. That is, in E-49 after a decline in 2000, steam flow rates and WHPs became quite stable. Note that E-43 showed slight increases in these quantities.

One could speculate about what caused the change in behavior around 2000. Perhaps there was a decrease in the amount of cooler and less saline groundwater recharge in the area of the reservoir where these two wells are located. The slight increase in steam flow rate and pressure in E-43 may be caused by a combination of smaller cool groundwater recharge and a somewhat larger steam recharge.

NL-1 and Neighboring Wells

Wells NL-1, M-198 and M-200 were drilled between 1979 and 1984 for exploration purposes. Since they encountered good reservoir conditions they were put under production, M-198 in 1989; NL-1 in December 1996 (after a workover), and M-200 in December 1999.

After its workover, NL-1 produced from 2,296 to 2,649 m depth. The well's initial fluids had very low chloride concentrations, but these increased from 800 to 5,000 ppm between 1996 and 2002 (Figure 6a).

The temperature history of NL-1 based on the Na-K-Ca and silica geothermometers is presented in Figure 6b. Initially, T-NaKCa was higher that T-Silica, but T-Silica increased from 190° to 240°C between 1999 to 2002. The well's production enthalpy history is shown in Figure 6c; the enthalpy reached values up to 2,400 kJ/kg.

The initial conditions for well NL-1 are similar to those of some wells in the northwestern part of CP3 when the installed capacity in the field was expanded from 180 to 620 MWe, which gave rise to intense reservoir boiling. That behavior was interpreted by Truesdell et al. (1992) as due to pressure drawdown with intense boiling, gravity induced steam-brine phase separation. In some wells this resulted in partial adiabatic condensation of vapor during decompression. The amount of residual brine that reached the well's inlet varied from nearly zero to nearly 100 per cent resulting in a wide range of effects. The temperature of the steam is also critical because the amount of adiabatic condensation decreases rapidly as the temperature decreases, and is zero at 240 °C (Alfred Truesdell, pers. comm., 2003).

The increase in chloride concentration and the unusual rise in geothermometer temperatures observed in well NL-1, may suggest a deep higher temperature recharge, although could be other

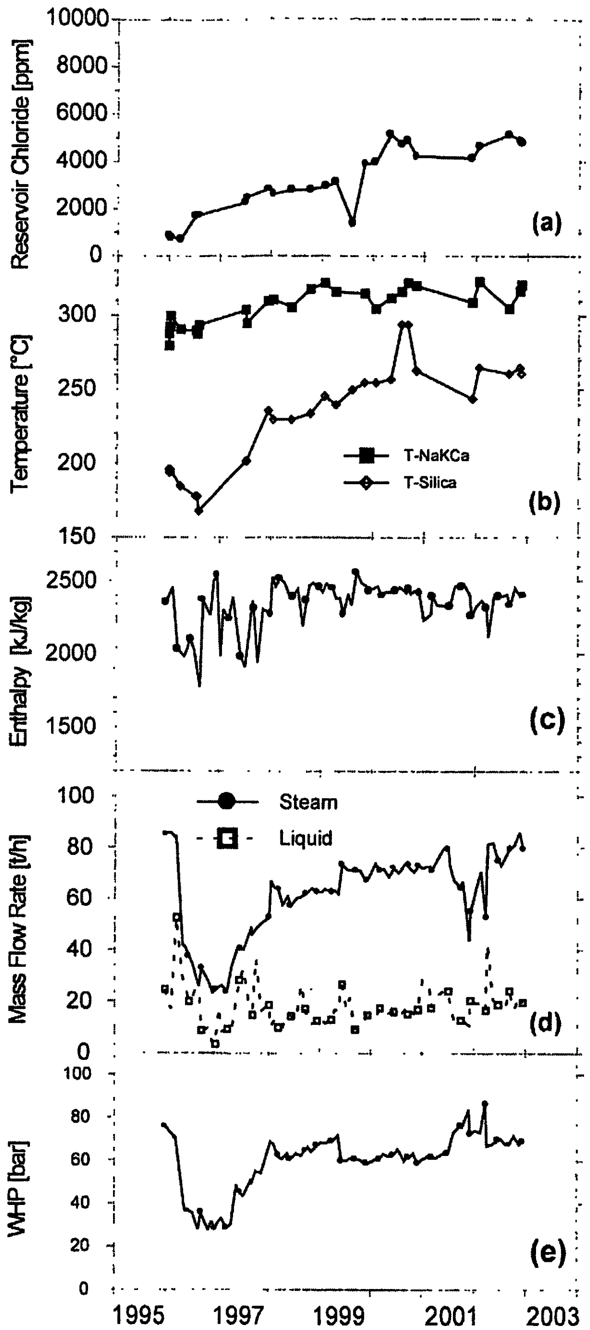

Figure 6. Well NL-1. (a) Reservoir chloride concentrations; (b) Temperatures given by the NaKCa and silica geothermometers; (c) Production enthalpy; (d) Steam and liquid flow rates at the separator; and (e) Wellhead pressure.

reasons. For example, the interpretation of Alfred Truesdell (pers. comm., 2003) is as follows: "With time there was a small increase in production of residual liquid and the enthalpy decreased so that there was drop in the amount of adiabatic steam condensation. This resulted in less dilution of solutes, and the reservoir chloride and silica temperature increased. There was probably also less dissolution of Na and Ca by acid condensate, so that T-NaKCa increased to the initial rock temperature of 310°C."

The steam flow rate and WHP of NL-1 are shown in Figures 6d and 6e, respectively. During the first year of production (1996) the well showed a drastic decline in WHP (from 75 to 30 bars) and in steam production (from 85 to 25 t/h), but in subsequent years has shown unusual increases. For example, in April 2003 its steam flow rate was 76 t/h and its WHP, 72 bar.

High WHPs are also reported in wells close to NL-1 (e.g., 409, 410 and 423; Figure 2). Well 409 came on line in November 2002 with a WHP of 72 bar and a steam flow rate of 85 t/h, values similar to those observed in NL-1 at present. Well 410 began production in December 2000. Its average 2001 wellhead conditions were, WHP: 108 bar; steam flow rate: 65 t/h; and enthalpy: 2,285 kJ/kg. Because of problems with its surface equipment, well 410 was shutdown in 2002. Well 423, located about 300 m east of NL-1, came on line in January 2003 with a steam flow rate of 152 t/h, WHP of 85 bar and enthalpy of 2285 kJ/kg.

Downhole logs in wells 409, 410 and 423 showed temperatures of up to 359°, 360° and 357°C, respectively. The average static pressure in the producing zone (at 2,800 m depth) was about 171 bars in 2001. Summarizing, at present wells in this part of the NE Beta Reservoir (i.e., close to the H Fault Zone) show similar behavior: high production enthalpy (more than 2,200 kJ/kg), higher WHP (as mentioned early) and high measured reservoir temperature (> 350°C). NL-1, the well with the longest history in this zone, showed an unusual increase in WHP and steam flow rate.

Wells M-200 and E-56

Wells E-56 and M-200 (Figure 2) were included in this study, because of their unusual behavior and their location close to the H Fault Zone. These wells did not show a clear increase of reservoir chloride and geothermometers, like NL-1. After being under production during 1991-93, E-56 was repaired in 1994. It has been on line continuously since 1995. The well is open between 2,515 to 2,855 m depth. On the other hand, M-200 has been under commercial exploitation since December 1999; its production interval extends over the 2,482-2,841 m depth interval. Its WHP shows an increase with time (Figure 7e).

The reservoir chloride concentration in E-56 (Figure 7a) shows dilution from 10,000 to 3,000 ppm between 1991 to 2002, which could be due to steam condensation. Temperatures given by the NaKCa and silica geothermometers (Figure 7b) also show a slight decrease, T-NaKCa from 340 to 300°C with some erratic values to 285°C, and T-Silica from 310° to 240°C. On other hand, M-200 well exhibits a slight increase in reservoir chloride (Figure 7a), while NaKCa and silica temperatures show a slight decrease, from 320° to 280°C, although there are not enough data to confirm this trend.

Both wells show a general increase of enthalpy (Figure 7c) and steam flow rate (Figure 7d) after 1999-2000, while their liquid production has remained fairly stable. In a producing water-dominated field, wellhead enthalpies depend on the liquid to steam ratios in the production stream. In Cerro Prieto, the enthalpy increases either because of a decrease in liquid flow rate while the steam rate remains nearly constant, or when steam rates

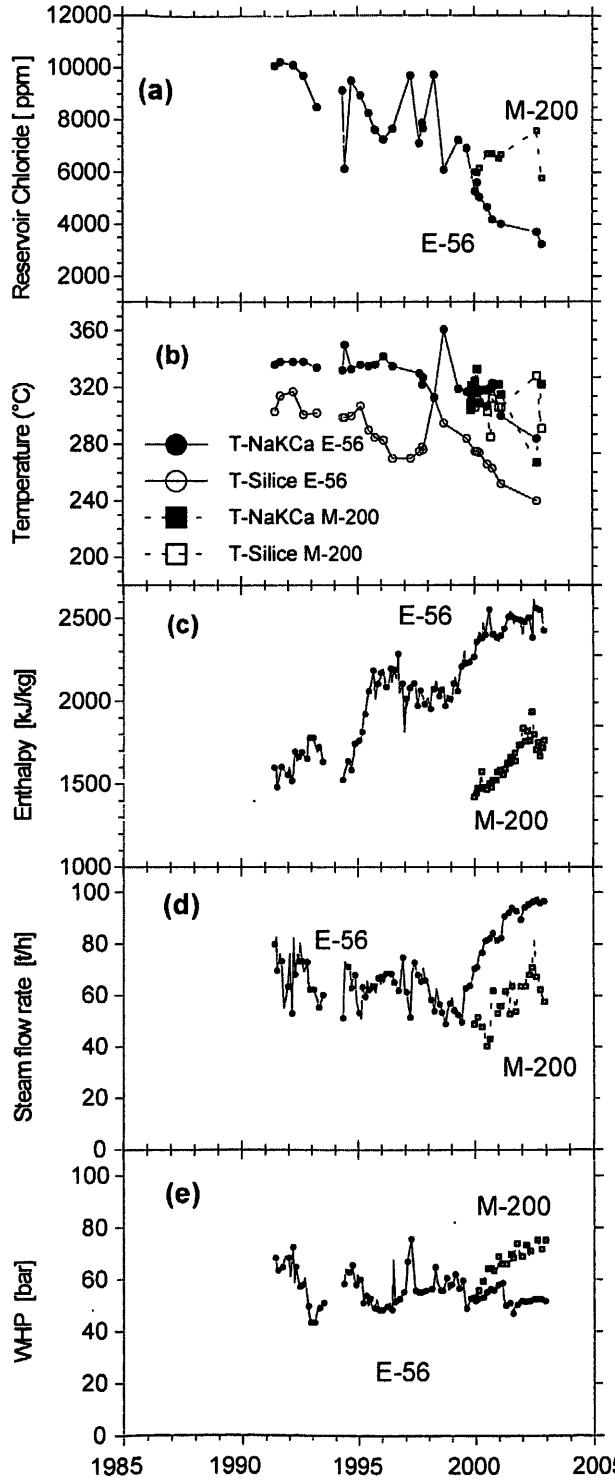

Figure 7. Wells E-56 and M-200. (a) Reservoir chloride concentrations; (b) Temperatures given by the NaKCa and Silica geothermometers; (c) Production enthalpies; (d) Steam flow rates; and (e) Wellhead pressures.

decline proportionally less than the liquid rates. The enthalpy increases observed in wells NL-1, M-200 and E-56 are mainly due to increased steam outputs, while liquid production rates remain stable. In well E-56 the WHP has varied over time, but on average it remained constant, however, M-200 showed a continuous increase in pressure (Figure 7e).

Is There Deep Steam Recharge in NE Cerro Prieto?

For a production well to have high-temperature steam recharge from deep regions of the geothermal system there needs to be (1) significant vertical permeability, (2) a zone of lower pressure near the bottom of the well, (3) higher temperature at depth and (4) no, or very little, cooler groundwater recharge in the area. These conditions are present in the eastern margins of the Cerro Prieto field, close to the H Fault Zone.

In general, the permeability of a geothermal reservoir in or close to a major fault zone is expected to be larger than away from it. Cerro Prieto wells NL-1, 409, 410 and 423 are in the downthrown block of the Beta Reservoir and penetrate the H Fault Zone, so high vertical permeability is expected. Although M-200 and E-56 wells are not as close to the HFZ as NL-1, a similar mechanism of recharge is expected.

In 2001, the static downhole fluid pressures and temperatures of wells around NL-1 at 2,600 m depth were about 150 bars and up to 350°C, respectively. When production started, downhole pressures dropped at least 10 bars, thus the flowing downhole pressures were less than 140 bars. Under these pressure and high temperatures, and assuming pure water properties, boiling and phase segregation will occur and a steam-rich fluid will flow towards the wells (according to steam tables, at 350°C the water saturation pressure is 165 bars). Because of relative permeability effects, steam is expected to be more mobile than liquid.

The heat source of the geothermal system has been suggested to be in the eastern part of the field (Elders et. al., 1984). Possibly wells NL-1, 409, 410, 423, M-200 and E-56 are closer to the heat source. Finally, in this zone of the reservoir inflow of cool water from the top of the reservoir has not been found.

Wells NL-1, 409, 410 and 423 have the highest WHPs in the field (around 110 bar during the initial well testing stage). The increase of WHP in NL-1, E-56 and M-200 may be evidence of the deep vertical steam recharge in the NE regions of Cerro Prieto. To confirm this hypothesis, additional geochemical (especially of non-condensable gases) and reservoir engineering studies are needed.

Conclusions

In the northeastern part of the Cerro Prieto, the processes in the Beta Reservoir vary.

In the northern margin of CP4, lateral (horizontal) cooler groundwater recharge occurs (e.g., well 426). These fluids have higher chloride concentrations than those entering the reservoir in the SEZ dome area (e.g., wells E-43 and E-49).

In the area of the dome two competing recharge processes seem to occur. Groundwater from the shallower cooler water aquifer is flowing down the H Fault Zone, recharging the reservoir from above, and steam-rich fluid is entering the area from the east. In some wells (e.g., E-43) the former seems to predominate.

The unusual behavior of some of the NE Cerro Prieto wells (e.g., NL-1, E-56 and M-200) is related to their high-temperature steam recharge. The steam-rich fluid originates from a zone near the heat source of the geothermal system, which is inferred to be located in the SE part of CP4 and the NE part of CP2.

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References

Elders, W.A., D.K Bird, A.E Williams and P. Schiffman, 1984. "Hydrothermal flow regime and magmatic heat source of the Cerro Prieto geothermal system Baja California, Mexico." Geothermics, 13, 27-47.

Elders, W.A., J.R. Hoagland, and A.E. Williams, 1981. "Distribution of hydrothermal mineral zones in the Cerro Prieto geothermal field of Baja California, Mexico." Geothermics, 10, 245-253.

Gutiérrez Puente, H. and M.H. Rodríguez R., 2000. "Development history of Cerro Prieto (1973-2000)." Geothermal Resources Council Trans., 24, 427-431.

Halfman, S.E., M.J. Lippmann, R. Zelwer and J.H. Howard, 1983. "Geologic interpretation of geothermal fluid movement in Cerro Prieto geothermal field, Baja California." American Association Petroleum Geologists Bull., 68, 18-30.

Lippmann, M.J., A.H. Truesdell, S.E. Halfman-Dooley and A. Mañón M., 1991. "A review of the hydrogeologic-geochemical model for Cerro Prieto." Geothermics, 20, 39-52.

Truesdell, A.H. and M.J. Lippmann, 1998. "Effects of pressure drawdown and recovery on the Cerro Prieto Beta Reservoir in the CP-III area." Proc. 23rd Workshop on Geothermal Reservoir Engineering, Stanford, CA, p. 90-98.

Truesdell, A.H., M.J. Lippmann, H. Gutiérrez P. and de J.S. de León V., 1998. "The importance of natural fluid recharge to the sustainability of the Cerro Prieto resource." Geothermal Resources Council Trans., 22, 529-536.

Truesdell, A.H., A. Mañón, L. Quijano, T. Coplen and M.J. Lippmann, 1992. "Boiling and condensation processes in the Cerro Prieto beta reservoir under exploitation." Proc. 17th Workshop on Geothermal Reservoir Engineering. Stanford, CA, p. 205-214.

Truesdell, A., B. Terrazas, L. Hernández, C. Janik, L. Quijano and R. Tovar, 1989. "The response of the Cerro Prieto reservoir to exploitation as indicated by fluid geochemistry." Proc. CFE-DOE Symposium in Field of Geothermal Energy, DOE CONF 8904129, p. 123-132.

Verma, M., L. Quijano, H. Gutiérrez, E. Iglesias and A.H. Truesdell, 1996. "Isotopic changes in the fluids of the Cerro Prieto Beta reservoir." Proc. 21th Workshop on Geothermal Reservoir Engineering, Stanford, CA, p. 93-99.