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Evolution of the Cerro Prieto Reservoirs Under Exploitation

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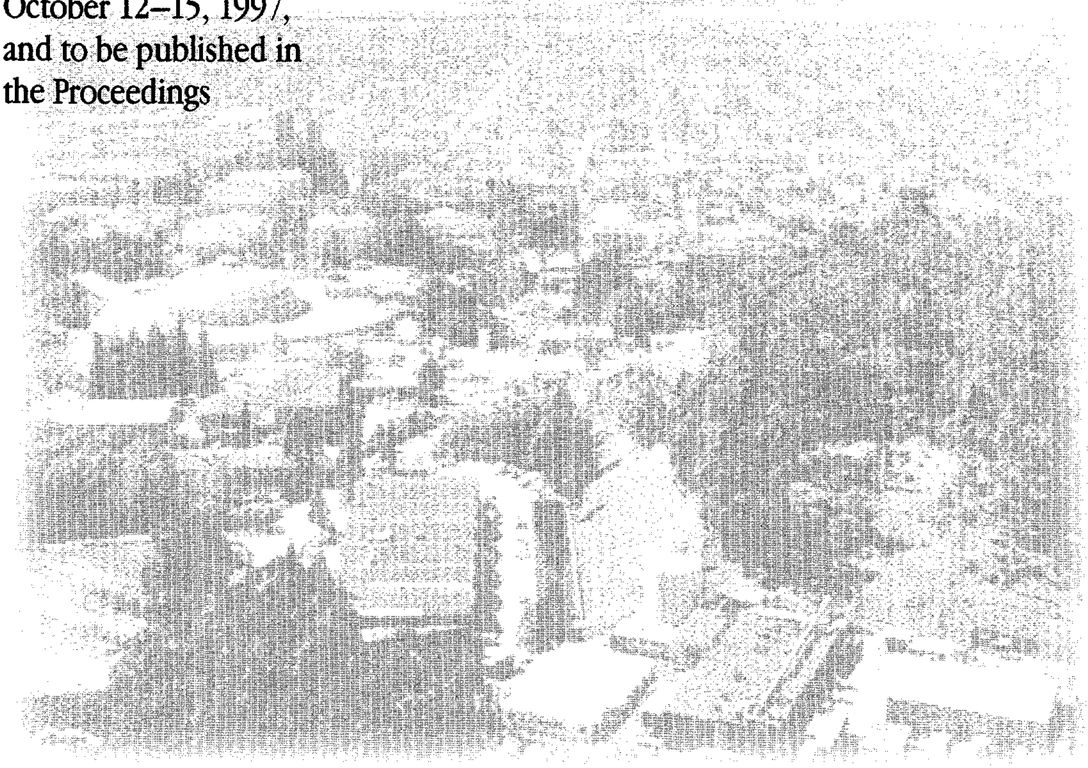

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ABSTRACT

The Cerro Prieto geothermal field of Baja California (Mexico) has been under commercial production to generate electricity since 1973. Over the years, the large amount of geothermal fluids extracted (at present about 12,000 tons per hour) to supply steam to the power plants has resulted in a reduction of pressures, changes in reservoir processes, and increased flow of cooler groundwater into the geothermal system.

The groundwater recharging the reservoir moves horizontally through permeable layers, as well as vertically through permeable fault zones. In addition, the supply of deep hot waters has continued unabated, and perhaps has increased as reservoir pressure decreased. Since 1989, this natural fluid recharge has been supplemented by injection which presently amounts to about 20% of the fluid produced.

Changes in the chemical and physical characteristics of the reservoir fluids due to the drop in pressures and the inflow of cooler groundwaters and injectate have been detected on the basis of wellhead data. These changes point to reservoir processes like local boiling, phase segregation, steam condensation, mixing and dilution. Finally, the study identified areas where fluids are entering the reservoir, as well as indicated their source (i.e. natural groundwater recharge versus injectate) and established the controlling geologic structures.

INTRODUCTION

The Cerro Prieto geothermal area is located in the Mexicali Valley—the southern portion of the Salton Trough—just south of the Imperial Valley of California. The wellfield is about 30 km south of the US-Mexico border. Electrical power generation at Cerro Prieto began in 1973; at the end of that year the installed capacity was 75 MWe. In 1979 it reached 150 MWe and in July 1981, 180 MWe. During 1986 and 1987 four 110 MWe units were put on line, with no additional units added since. Thus the total installed capacity at Cerro Prieto has been 620 MWe since 1987.

Cerro Prieto continues to be the largest liquid-dominated geothermal system under exploitation. Note the three "administrative areas" into which the field has been divided (CP-I, CP-II and CP-III; Figure 1); a new area (CP-IV), northeast of CP-III is being considered for future development (e.g., Hiriart-LeBert and Gutiérrez-Negrín, 1994).

At the present time, the Comisión Federal de Electricidad de México (CFE), the operator of the field and power plants, has ambitious plans to increase the total capacity and electrical generation at Cerro Prieto to reduce the amount of fossil fuels being used to produce electricity in Baja California.

CFE has also begun a program to improve the steam transmission system and to use the geothermal steam more efficiently.

Among the most significant plans to expand production at Cerro Prieto is the installation of another 100 MWe in the northeastern part of the field. CFE is now evaluating bids for four 25 MWe units and a decision is expected by the end of this year. Construction of the plants will begin in mid-1998, with the first one on line expected by January 2000. The 800 tons (metric tons) per hour of steam needed for this project will be produced from the eastern region of the field; drilling of production wells has already started.

By re-powering the turbogenerators in power plant CP-I, two of which have been in service since 1973, and by improving the steam transmission and purification systems, CFE expects within the next two years to increase the steam available in the field by up to 8%. This alone will increase the power output at Cerro Prieto by some 40 MWe.

With the installation of small biphase turbines—at present in an experimental stage—CFE expects to add

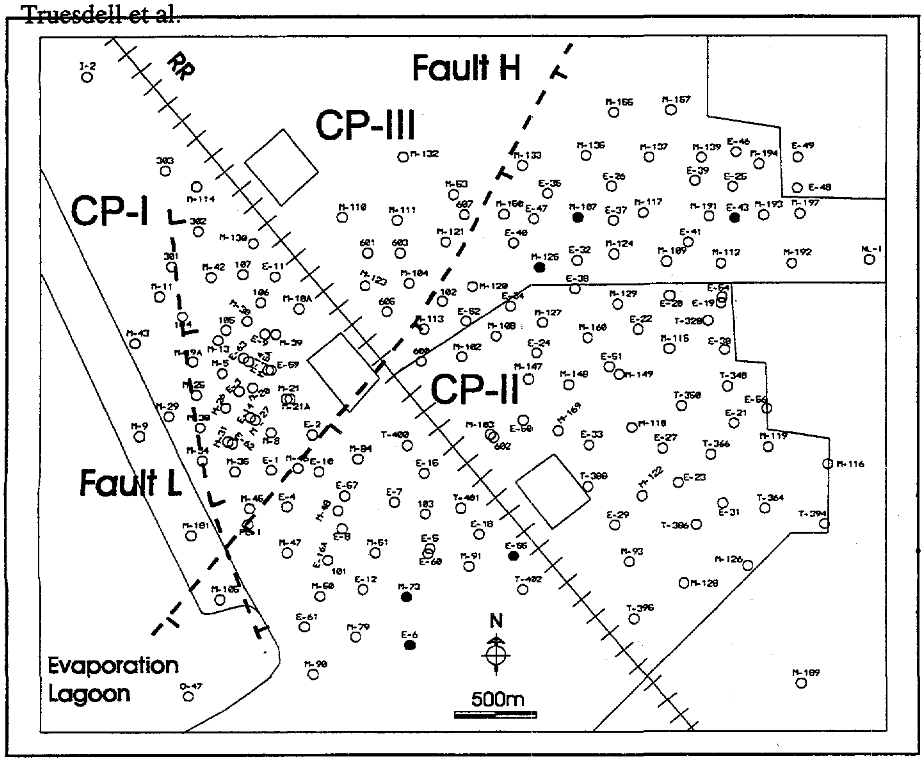

Figure 1. Location of production wells in the Cerro Prieto field. Also shown are the three power plants (open quadrilaterals), the CP-I, CP-II and CP-III areas (the railroad is one boundary), and the normal faults H and L which control the movement of fluids in the system (the fault traces are shown where they would intersect the ground surface). Wells mentioned in the text are shown with solid circles. After an unpublished 1990 well map by Emilio Antúnez with fault locations from Halfman et al. (1984;1986).

out 30 MWe to the installed plant capacity without increasing total steam consumption. In the next few years, binary plants that will use the hot waste brines now being disposed of might increase the field's output by another 10 MWe or so.

The Residencia de Cerro Prieto, the organizational unit in charge of the field, continues to lobby within CFE for the drilling of a deep (up to 6 km) scientific exploration well in the eastern part of the field (Alvarez-Rosales, 1996; Lippmann et al., 1997). It is believed that modular projects of up to 80 MWe, independent from the present geothermal development, might be possible in the eastern regions of Cerro Prieto.

Production, wellhead and fluid chemistry data are here analyzed to show changes in reservoir fluid enthalpy (based on geothermometry), and chemistry (mainly chloride and isotope compositions). These changes are interpreted taking into consideration the chemistry of the geothermal fluids, cooler groundwaters and injectate, the subsurface geology (especially faults), and the production/injection history of the field.

HYDROGEOLOGY OF THE CERRO PRIETO FIELD

The geothermal system at Cerro Prieto is developed in deltaic sands and shales of the southern Salton Trough. Three reservoirs (or producing regions) have been identified: the shallow alpha (α) reservoir, between about 1000 and 1500 m depth, restricted to the western

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part of the field; the deeper beta (β) reservoir (below about 1500 m depth) which seems to extend over the entire system; and the gamma (γ) reservoir, to date only found in the eastern regions at depths of about 3300 m (Halfman et al., 1986). The α and β (and possibly the γ) reservoirs have more or less “leaky” boundaries. This type of boundary allows the hot geothermal fluids to exist in dynamic equilibrium with the surrounding cooler groundwaters; thus the system is relatively “open”.

The geothermal system is fed by hot brine from a deep source. This approximately 350°C brine flows up the NE-striking, SE-dipping, normal fault H (Figure 1), to enter the γ and β reservoirs. In the natural state the brine flowed through part of the β reservoir into the shallow α reservoir (Halfman et al. 1984; 1986). Eventually the hot fluids left the geothermal system through the N-striking, E-dipping, normal fault L in the western part of the field (Figure 1). The discharged fluids mixed with the surrounding groundwaters and flowed to the surface creating the geothermal manifestations that alerted locals and geologists to the area.

When commercial fluid extraction from the α reservoir began in 1973, the resulting pressure drawdown in the reservoir created localized boiling zones around the producing wells (Grant et al., 1984). Wells near the western edge of the field showed chemical and thermal breakthroughs of cooler, lower-Cl waters, and wells near fault L presented sharp breakthroughs indicating the entrance of cooler groundwaters vertically down fault L and horizontally from the west. These phenomena and their evidences have been discussed in detail by Truesdell and Lippmann (1986; 1990).

FLUID AND ELECTRICITY PRODUCTION

The actual megawatts on line at Cerro Prieto are given in Figure 2, indicating that the plants seldom reached their total installed capacities (i.e., CP-I, 180 MWe; CP-II, 220 MWe and CP-III, 220 MWe), especially power plant CP-I. Seasonal variations are clearly shown, reflecting lower power consumption during the winters and equipment maintenance periods during those times.

The fluid produced from the Cerro Prieto liquid-dominated geothermal reservoir has increased with time (Figure 3) as new turbogenerators were installed in the field. The figure illustrates how total fluid production jumped when power plants CP-II and III came on line in 1986-1987 and large-scale exploitation of the β reservoir began. After that, for about three years, water production tended to decrease while steam production increased as a result of boiling in the reservoir, especially in the area of CP-III (see below). After 1989 the water flow began to increase and steam flow reached a maximum and then slowly decreased. This is assumed to be related to the natural recharge and the injection of colder waters into the reservoir and lately to the deepening of production wells into a zone of the reservoir with higher water saturation.

In some cases, the recent deepening of several existing production wells resulted in higher wellhead pressures, increased mass production, and lower fluid enthalpies. For example, when in 1996 well 615 was deepened from 2149 to 2600 meters, the wellhead pressure, which had declined from 42 to 21 bar (abs) in 4 years of production, rose to 56 bar (abs) and the steam production increased from 22.4 (just before deepening) to 74 tons/hr and that of water from 1.4 to 63 tons/hr (at a separation pressure of 13.8 bars abs; i.e., 200 psia), while the enthalpy of the produced fluid decreased from 2669 to 1880 kJ/kg.

During the first 15 years or so of production, no fluid was injected back into the reservoir; brine separated at the wellheads and condensate from the cooling towers were sent to the large (14 km^2) evaporation lagoon, west of the wellfield (Figure 4). In order to slow the rate of reservoir pressure drawdown resulting from the large masses being extracted and avoid or reduce its effects on

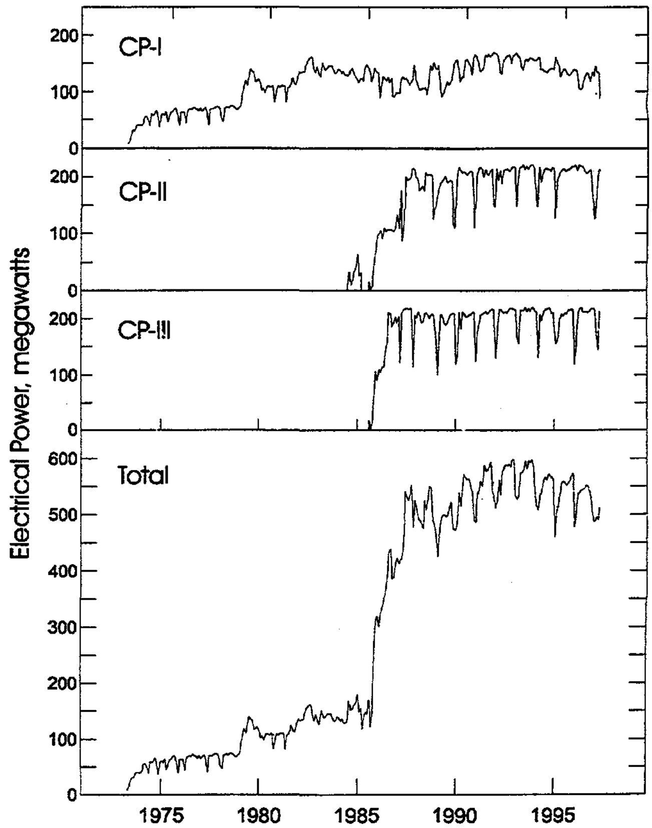


Figure 2. Cerro Prieto. Average monthly power on line.

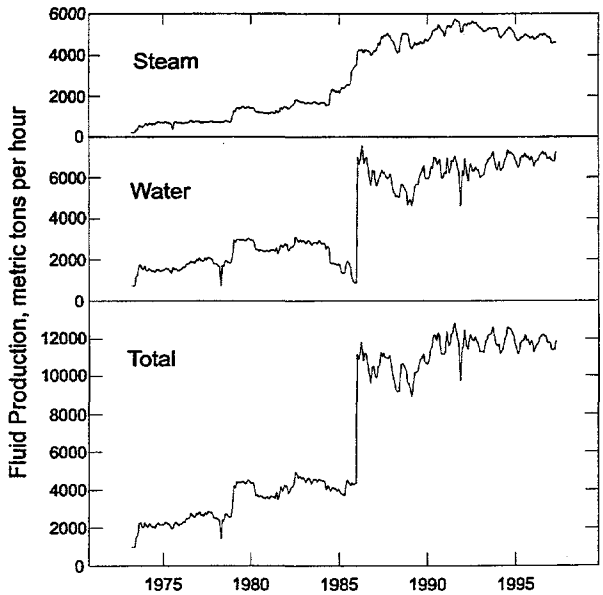
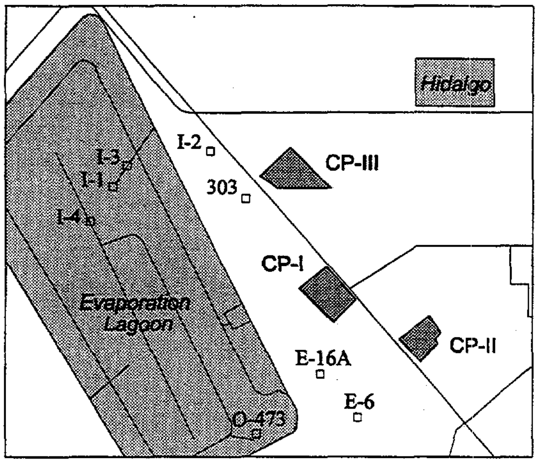


Figure 3. Cerro Prieto. Fluid production history.



Well	Well Diam. (in)	Completion		
		Depth (m)		Type
		from	to	
O-473	4½	1981	2252	Sloted
E-6	7	2289	2567	Sloted
E-16A	4½	1392	1592	Sloted
I-1	9 ⅝	595	807	Sloted
	7	849	1247	Sloted
I-2	4½	1118	1394	Sloted
I-3	9 ⅝	642	981	Sloted
I-4	9 ⅝	592	1145	Sloted
303	9 ⅝	1006	1324	Sloted

Figure 4. Location and completion of Cerro Prieto injection wells presently on line.

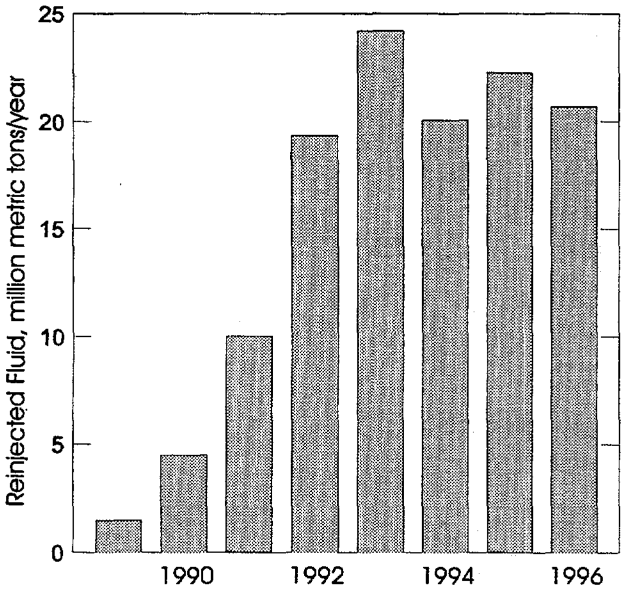


Figure 5. Cerro Prieto. Reinjection history.

production and on the field in general, an injection program was begun in 1989 (Gutiérrez Puente and Ribó Muñoz, 1994). Up to 15 wells, located mainly along the western edge of the field, have been used in the injection operations (the eight wells presently in operation are shown in Figure 4). Injection rates have changed with time and season. The maximum rates occurred in 1993 (Figure 5) corresponding to approximately 24% of the fluid (steam and brine) produced; in 1996 injection rates had decreased to about 20% of the total mass extracted.

STUDIES OF CERRO PRIETO RESERVOIRS

In addition to CFE's regional geology and geophysical surveys, study of drill cuttings, downhole temperature measurement, and some downhole geophysical logging, Cerro Prieto was studied jointly by Mexican and US scientists as part of several multidisciplinary investigations (e.g. DOE-CFE Proceedings, 1979-1989). These studies provided a necessary background for the understanding of the rock properties and indications of the origin of the system. In more recent studies the chemical and physical data on produced fluids have been used as indicators of the present state of the reservoirs and the processes occurring naturally and in response to production. Due to close cooperation between the geochemists and reservoir engineers of CFE, the U.S. Geological Survey and the Lawrence Berkeley National Laboratory, Cerro Prieto has been the main field area for the development of these interpretive methods (Truesdell et al., 1979; 1989; 1995).

One method used for individual wells depends on the changes with time of reservoir chloride, and of enthalpy values measured at the wellhead and calculated for reservoir liquid from NaKCa and quartz-saturation geothermometer temperatures. If there is a temperature gradient toward the well, the slow-reacting NaKCa geothermometer will indicate the temperature away from the well and the rapid-reacting quartz geothermometer, the bottomhole temperature. Applied to Cerro Prieto this method has shown that there are distinct responses to pressure drawdown in different parts of the reservoir and local to certain wells.

A complementary method uses contoured maps of indicators of reservoir processes for a particular time period. These maps are useful for demonstrating fieldwide processes and the interrelations of wells. Because processes such as inflow of groundwater or spreading of injectate move from a line or out from a center, predictions of future changes to nearby wells are possible. Useful indicators for these maps, in addition to the reservoir chloride and temperature, include the inlet vapor fraction (IVF) derived from measured and geothermometer enthalpies, and the total discharge oxygen-18 compositions.

INDICATORS OF RESERVOIR RESPONSE TO DRAWDOWN

In the shallow Cerro Prieto α reservoir, some wells present no effects of drawdown, others initially boiled locally, and almost all producing wells eventually showed inflow of water from outside the reservoir. In wells without boiling or outside inflow, total and reservoir-liquid enthalpy values were the same, and reservoir chloride was constant or showed a small decrease due to a gradient toward the reservoir margins. Production from wells in reservoir regions with lower permeability, produced boiling around the wellbore with transient excess enthalpy and depressed near-well temperatures indicated by low quartz temperatures. Wells completed entirely in the α reservoir tended to show inflow of cooler, less-saline groundwater from a leaky boundary along the intersection of the fault L with the top of the reservoir. This behavior was indicated by changes in reservoir chloride (tracking the chemical front) and enthalpy (tracking the thermal front). The position of the leaky fault L in the α reservoir can be clearly seen from contours of reservoir chloride or total discharge isotopes (e.g., Stallard et al., 1987).

The deeper and much larger β reservoir is intersected and divided into two parts by the normal fault H (Figure 6) described by Halfman et al. (1984; 1986). The vertical displacement on the fault is approximately 600 m and, as a result, the top of the downthrown SE (CP-II) block is 600 m deeper and has a pressure about 50 bars higher than the top of the upthrown NW (CP-III) block. Because the original temperature in both parts of the reservoir was about the same (310-320°C at the top), each part responded quite differently to pressure drawdown due to exploitation (Lippmann et al., 1991).

The first wells in CP-III produced from entirely liquid at well bottom and total enthalpy was equal to liquid enthalpy calculated from geothermometers. Within 1 to 3 years these wells and others drilled later produced high-enthalpy discharges while liquid enthalpy values calculated from quartz and NaKCa temperatures showed little change. This resulted from widespread boiling with phase segregation and separate entries of steam and water. Since boiling was not limited to the wellbores, the liquid enthalpy values were unchanged. This progression from all-liquid to two-phase production is also shown in the changes in relative production of liquid and steam after units CP-II and CP-III went on line (Figure 3). Anomalous low salinity (and low quartz temperatures) occurs in some wells with the very high enthalpy because these wells produce little brine, and water from isoenthalpic wellbore condensation mixes with and dilutes the brine (Truesdell et al., 1992). The strong boiling near the fault H in the upthrown block can be seen in a contour map of 1989 IVF values (Figure 7).

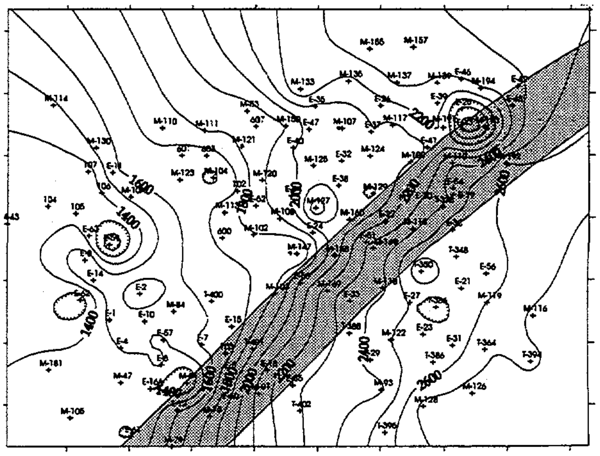


Figure 6. Location of the fault H (shaded) at the level of the top of the Cerro Prieto β reservoir. Depths to the top of the reservoir are given in meters. Note that areas with hachures are shallower.

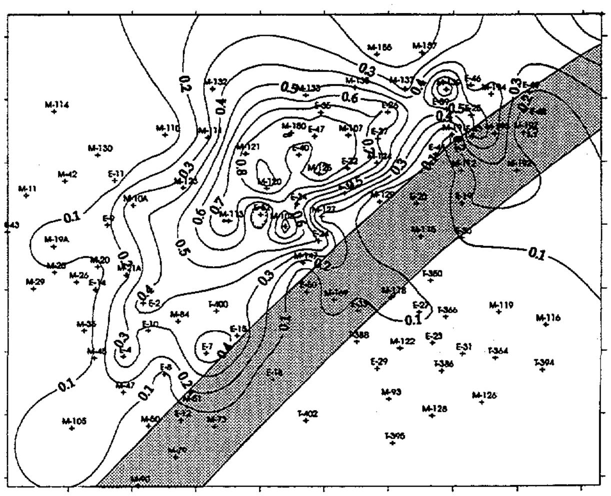


Figure 7. Inlet vapor fraction (IVF) for 1989 Cerro Prieto production with fault H shaded. Note high IVF in the upthrown block and low IVF along fault H and in the downthrown block. See text for further description.

The SE downthrown block of reservoir β produces from liquid with little or no reservoir steam. As a result total fluid and reservoir liquid enthalpy values remain very similar and most IVF values are near zero (Figure 7). This behavior results from the initial relatively high pressure in this block. With continued production, this part of the reservoir will boil and develop a steam layer as in the upthrown block.

In the NW upthrown block, the strong decrease in pressure due to production has caused overlying groundwaters to flow down the fault H in the area of the shallow cupola located near well E-43 at the NE end of the fault (Figure 6). This groundwater influx was visible on maps of total discharge $\delta^{18}O$ (and δD) as early as 1989, three years after large-scale exploitation of the eastern β reservoir began (Figure 8). Because of dilution by condensate in high enthalpy discharges, a low chloride anomaly in this area was less diagnostic (Figure 9). Later isotope and chloride maps showed that by 1995 this anomaly had expanded to include over 12 wells in an area of about one square kilometer. (1995 data is used because this is the last year with $\delta^{18}O$ analyses; 1996 chloride data is similar to that for 1995.)

The 1995 fluid compositions of the most affected wells were lower than 4000 ppm in chloride and -11 permil in $\delta^{18}O$ (Figures 10 and 11). These well fluids are similar to the groundwaters that entered the α reservoir down fault L (Stallard et al., 1987).

In addition to this zone of low $\delta^{18}O$ and chloride, 1993 and later data showed a strong anomaly of high $\delta^{18}O$, δD and chloride along the trace of the fault H in the south central part of the field. By 1995 this anomaly covered a half square kilometer and reached an intensity of 6000 ppm chloride and 5 permil in $\delta^{18}O$ (Figures 10 and 11; Verma et al., 1996). The source of this anomaly was the injection by 1993 of nearly 16 million tons (and nearly 27 million tons by 1995) of brine from the evaporation lagoon into nearby well E-6. This brine is highly enriched in heavy isotopes and salts from steam separation in production separators and ambient temperature evaporation in the lagoon. The composition of the brine varies with season but is typically about zero permil in $\delta^{18}O$ and over 20,000 ppm chloride in the summer (M. Verma, pers. comm., 1996). E-6 is a 2289 m deep well (Figure 4) and the injectate first showed up in well E-55 with a similar depth (2370 m), one kilometer distant. Nearer but shallower wells, such as M-73 (1883 m depth, 600 m from E-6), were in 1995 still unaffected by injection in E-6.

In summary, colder groundwaters are recharging the reservoir, not only horizontally through permeable layers but also vertically through permeable fault zones (fault H

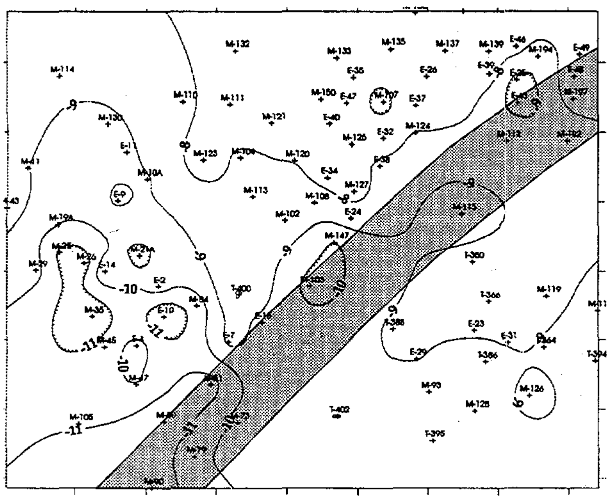


Figure 8. 1989 total discharge $\delta^{18}O$ compositions for Cerro Prieto well fluids and the location of fault H (shaded) where it displaces the reservoir. Note the small negative anomaly at the intersection of the fault and top of the upthrown block centered on well E-43 and the lack of anomalies along the intersection of the fault and the top of downthrown block. Values are in permil SMOW.

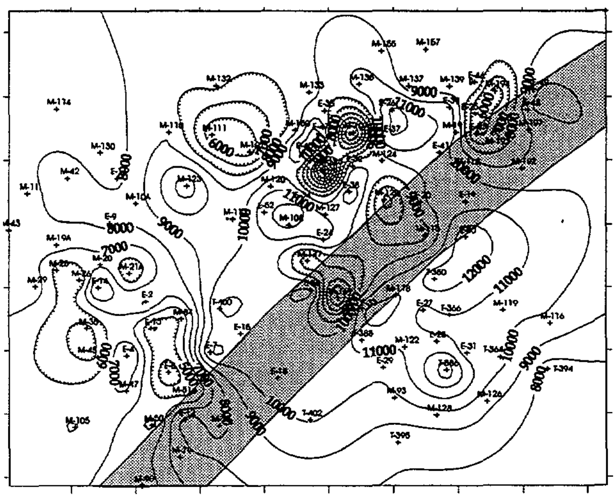


Figure 9. 1989 reservoir concentrations of chloride in the Cerro Prieto β reservoir calculated from analyses of flashed fluids, measured enthalpy and NaKCa reservoir temperatures. Note the low-chloride anomalies centered on well E-43, M-107 and M-125. The E-43 anomaly indicates inflow of groundwater; the other (larger) anomalies are from wellbore condensation (see text). Values are in ppm.

in the east and fault L in the west), structures that before the start of field exploitation allowed the discharge of geothermal fluids from the system, especially fault L.

Changes in the chemical and physical characteristics of the reservoir fluids indicated reservoir processes like local boiling, phase segregation, steam condensation, mixing and dilution, and allowed identification of the sources of the colder waters recharging the geothermal system (i.e. natural groundwater recharge versus injectate).

CONCLUSIONS

This study illustrates the usefulness of monitoring wellhead data to detect reservoir changes as the exploitation of a geothermal system proceeds. Being aware of these changes will allow the field operator to modify reservoir management procedures to avoid possible negative effects on fluid production. For example, the detection of the arrival of a chemical front associated with the natural recharge of cooler groundwater or the advance of injectate toward nearby producers, would indicate that injection in some of the wells should be reduced (or stopped) and part of the injectate rerouted to other wells.

In the case of Cerro Prieto, the value of keeping track of the evolution of reservoir (geothermometer) temperatures, inlet vapor fraction (IVF), $\delta^{18}O$, and fluid chemistry (especially chloride) in the reservoir fluids, parameters calculated from wellhead data (i.e., enthalpy, separation pressure, production rates), has been demonstrated. Interpreting these data, taking into account information on the geology of the field and well completion, and plotting the data areally over the wellfield has pinpointed not only the processes taking place in the exploited reservoir, but also the sources of the colder water influx and the role of the faults in this recharge.

The Cerro Prieto geothermal field has been remarkably productive and with sound management should continue with the same (or greater) output for many years. The area of the field exploited is only about part of that explored. There are indications that the wells in the eastern regions produce mainly from the upper part of the geothermal resource. This has resulted in a significant reservoir drawdown to maintain maximum output. It is believed that further exploration and evaluation of the deeper NE regions of Cerro Prieto should be carried out. If a good producing reservoir is found and developed there, it would reduce the drawdown in the central regions of the geothermal system and the associated boiling and inflow of cooler groundwaters.

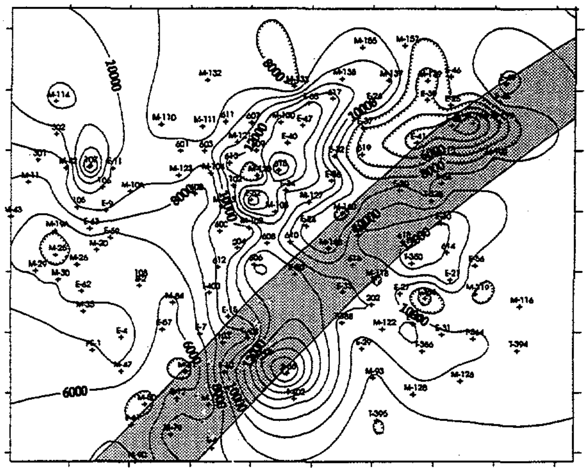


Figure 10. 1995 Cerro Prieto reservoir concentrations of chloride calculated from analyses of flashed fluids, measured enthalpy and NaKCa reservoir temperatures. Note positive and negative anomalies along the intersection of fault H with the top of the displaced β reservoir. Values are in ppm.

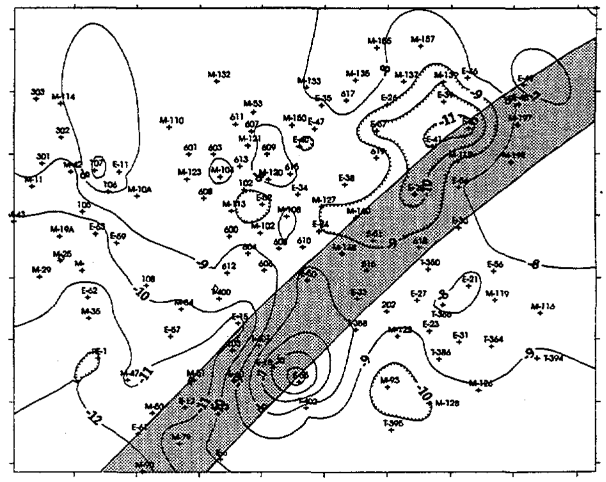


Figure 11. 1995 total discharge $\delta^{18}O$ compositions for Cerro Prieto (fault H shaded). Note the large negative anomaly at well E-43 and the large positive anomaly in the south of the field centered on well E-55. The location of well E-6, one of the largest injection wells in the field, is shown southwest of this anomaly. Compare the pattern of $\delta^{18}O$ with the chloride pattern in the preceeding figure. Values are in permil SMOW.

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