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Authors
Truesdell, A.H.
Manon, A.
Quijano, L.
et al.

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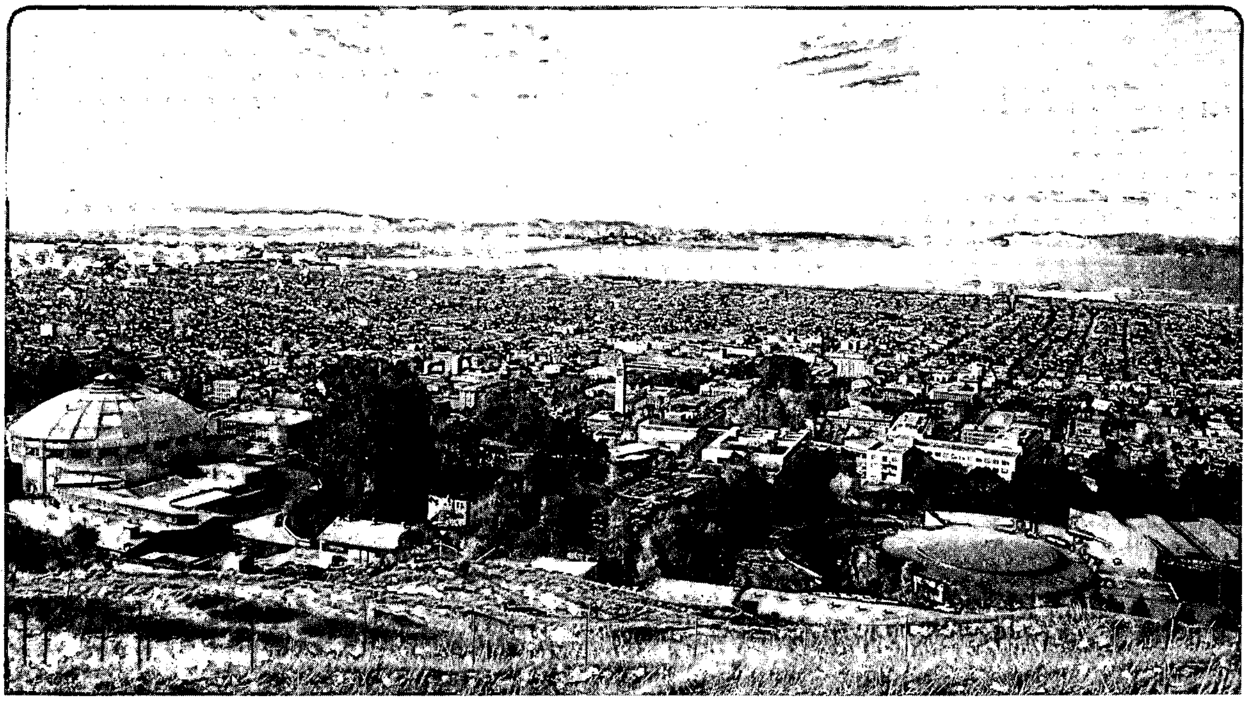

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Alfred Truesdell,[1] *Alfredo Mañón,*[2]
Luis Quijano,[2] *Tyler Coplen,*[3] *and Marcelo Lippmann*[4]

[1]Consultant, Menlo Park, California

[2]Comisión Federal de Electricidad
Morelia, Mexico

[3]U.S. Geological Survey
Reston, Virginia

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

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BOILING AND CONDENSATION PROCESSES IN THE CERRO PRIETO BETA RESERVOIR UNDER EXPLOITATION

by Alfred Truesdell[1], Alfredo Mañón[2], Luís Quijano[2],
Tyler Coplen[3] and Marcelo Lippmann[4]

[1]Consultant, Menlo Park, California
[2]Comisión Federal de Electricidad, Morelia, Mexico
[3]U.S. Geological Survey, Reston, Virginia.
[4]Lawrence Berkeley Laboratory, Berkeley, California.

ABSTRACT

The deep Cerro Prieto (Baja California, Mexico) beta reservoir is offset vertically by the southwest-northeast trending, normal H fault. Under exploitation pressures in the upthrown block have decreased strongly resulting in boiling and high-enthalpy production fluids. Significant differences in fluid chemical and isotopic compositions are observed in the two parts of the reservoir and particularly in an anomalous zone associated with the H fault. These differences result from intense boiling and adiabatic steam condensation, as well as from leakage of overlying cooler water along the fault.

Introduction

The Cerro Prieto geothermal field has three reservoirs developed in sandstones and sandy shales of the Colorado River delta. The shallow (1000 to 1500 m depth) alpha reservoir in the west of the field was developed first and has been partly abandoned because of decreasing fluid temperatures. Most production is now from the deeper (1500 to 2700 m depth) beta reservoir which underlies the whole field. There are a few wells that produce from the yet deeper gamma reservoir. The beta reservoir is offset by the "H" fault of Halfman *et al.* (1986) with the downthrown block mainly exploited by the CP-II power plant and the upthrown block by the CP-III plant. The position of the H fault (top of the upthrown block to the top of the downthrown block) from these authors is shown in Figure 1. After these plants went on line in 1986-7, large quantities of fluids were withdrawn and reservoir pressures decreased more or less strongly depending on initial pressure and degree of isolation from other aquifers. The response to pressure decrease in the alpha reservoir, exploited since 1973 by the CP-I power plant, has been an influx of cooler waters from the sides and above with limited local boiling (Grant *et al.*, 1984; Truesdell *et al.*, 1989). The response to pressure decrease in the beta reservoir is not as well known because a much shorter production record is available.

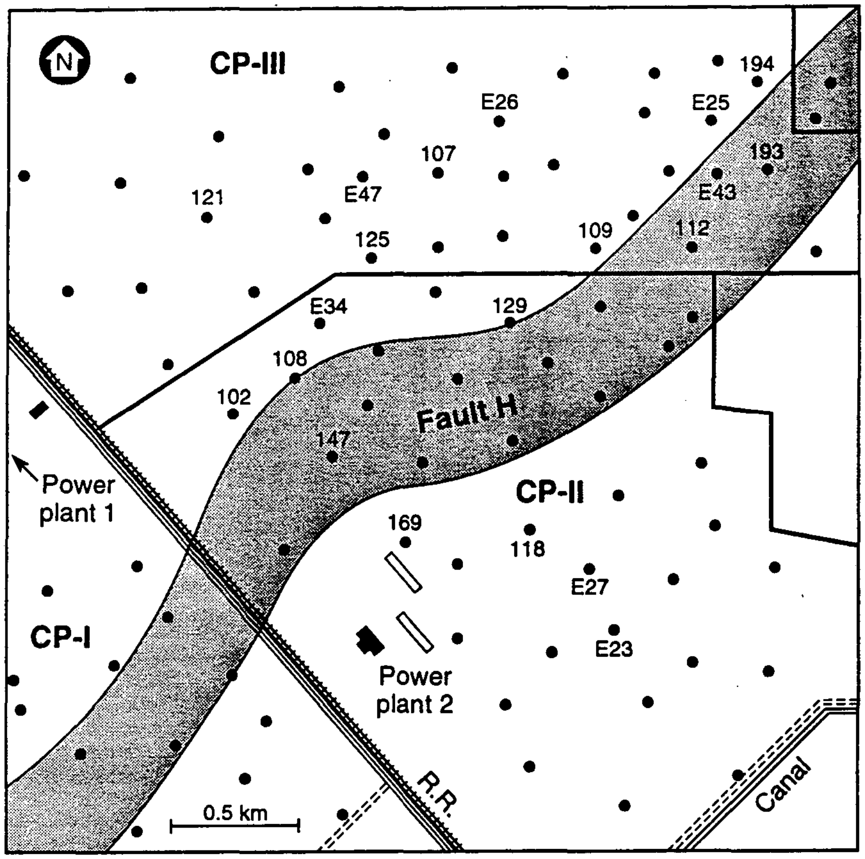
The beta reservoir is not well connected to cooler water aquifers except on the western margin (in the CP-I area) and possibly in the south. The upthrown block (CP-III) shows strong boiling (de León Vivar, 1988) apparently because it is closed to the north by an undefined barrier and has only limited connections with cooler aquifers in the west at a distance of 2-3 kilometers. Boiling in the CP-III area appears to occur generally throughout the reservoir with a gravity segregation of steam and water resulting in separate entries of steam and water in producing wells (Truesdell *et al.*, 1989; Truesdell and Lippmann, 1990). Simulation studies (Lippmann and Truesdell, 1990) show that the general CP-III boiling results from closed reservoir boundaries or restricted recharge while localized near-well boiling observed in the shallow reservoir of the CP-I area is related to constant pressure boundaries.

Anomalous fluids related to boiling in the CP-III area were described by Stallard *et al.* (1987), who showed that some high-enthalpy, high-deuterium, low-chloride fluids did not fall on the chloride-deuterium (or chloride-oxygen 18) mixing line that characterized most of the field. All of these observations are consistent with boiling, phase segregation and preferential steam flow to the wells. In some fluids a small increase of oxygen-18 (up to 0.5 permil) was observed which is not consistent with increased steam entry. At the time of the 1987 study, this anomaly could not be examined in detail because most CP-III wells had been in production for only one year . With two or three years more of production and geochemical data available we have reexamined processes in the beta reservoir related to continued production.

Data collection and analysis

Water samples were collected by the staff of the Comisión Federal de Electricidad (CFE) and by members of the U.S. Geological Survey (USGS) from production separators after one or two stages of steam separation and cooled or flashed to atmospheric pressure. Chemical analyses of flashed water samples were made in the laboratories of CFE at Cerro Prieto. Isotope analyses were made at the USGS Laboratories in Reston, Virginia, on samples of steam and separated water cooled without flashing. In most cases total fluid enthalpy (H_{total}) measurements were made within less than 15 days of the time of sample collection. Aquifer liquid temperatures and enthalpies were calculated by the use of geothermometers and steam tables based on pure water. Near-well aquifer chloride concentrations ($Cl_{aquifer}$) were calculated from analysis of flashed samples using aquifer liquid enthalpy (H_{total})

Figure 1. Map of the Cerro Prieto geothermal field showing the boundaries of the CP-I, CP-II and CP-III areas, the position of the H fault at reservoir level and the locations of wells mentioned in the text.



calculated from Na/K temperatures (Fournier, 1979). The equation used is

$$Cl_{aquifer} = Cl_{water}(sep) \times \frac{H_{steam}(sep) - H_{total}}{H_{steam}(sep) - H_{water}(sep)}$$

for a single separation and repeated for each additional stage of separation including flashing during collection. Data at separation conditions are denoted by (sep); enthalpy values for separator conditions are from steam tables. These calculated aquifer chloride concentrations (rather than analytical concentrations) are used throughout the paper.

The fraction of "excess" steam entering the well from reservoir two-phase fluid (the inlet vapor fraction or IVF) was calculated from the equation (Truesdell *et al.*, 1989),

$$IVF = \frac{H_{total} - H_{water}(inlet)}{H_{steam}(inlet) - H_{water}(inlet)}$$

with inlet temperatures based on Na/K rather than silica because some waters may become diluted near to or in the well (discussed below).

Results

Maps of 1990 excess steam fractions (IVF), chloride concentrations in the aquifer liquid, Na/K geochemical temperatures and total-discharge isotope compositions (for 1989) show similarities and differences between fluids from the CP-II and CP-III parts of the beta reservoir (Figures 2-6). The northeast-striking, southeast-dipping, normal H fault divides the beta reservoir into two blocks. The fault at reservoir level approximately follows the boundary between CP-II and CP-III (Figure 1). Compared with fluids of the southeast block, those of the northwest upthrown block show higher excess steam, generally lower and variable reservoir chloride, higher oxygen-18 concentrations but similar deuterium concentrations and chemical (Na/K) temperatures. There is a more or less well-defined anomalous zone of low temperatures, low aquifer chloride concentrations and somewhat lighter isotope compositions approximately along the trace of the H fault at reservoir level (Figures 3-6). The general character of fluids from the southeast and northwest parts of the reservoir are considered first and the anomalous area later.

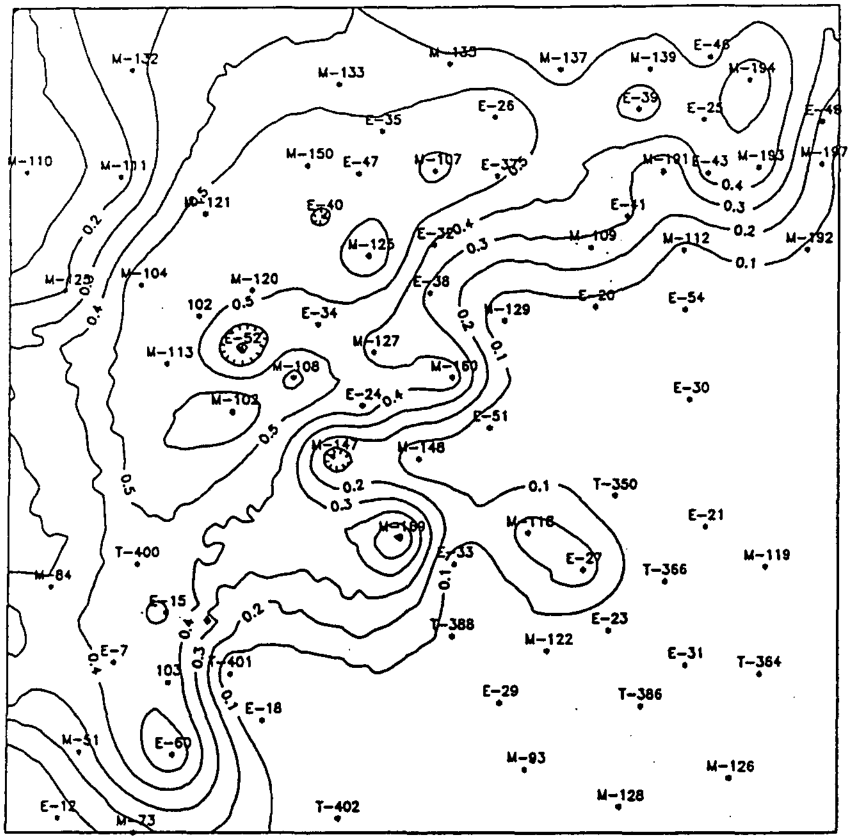


Figure 2. Inlet vapor fraction (excess steam) for Cerro Prieto wells producing in 1990. Measured enthalpy values and chemical analyses are from CFE. The area and scale of this and following maps are the same as Figure 1.

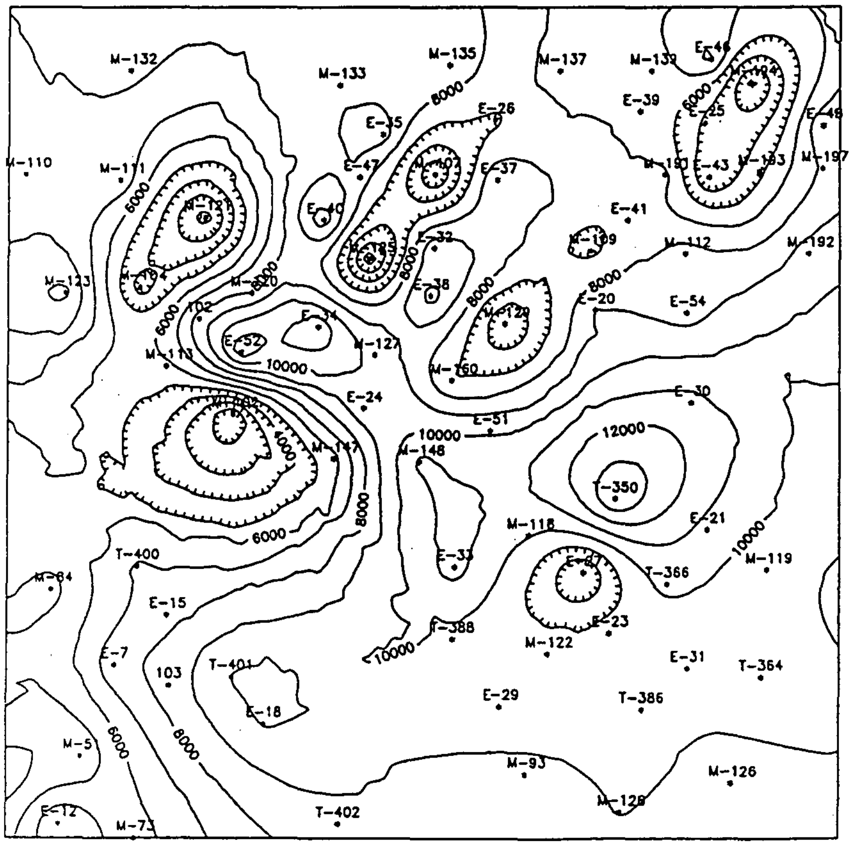


Figure 3. Aquifer liquid chloride concentrations (in mg/kg) for Cerro Prieto wells producing in 1990. In equation 1 (text), aquifer liquid enthalpy values have been calculated from Na/K temperatures. Analyses are from CFE.

Figure 4. Na/K geothermometer temperatures (in °C) for 1990 Cerro Prieto fluids, calculated using the equation of Fournier (1979). Water analyses are from CFE. The locations of the eastern and western lines of anomalous wells are indicated.

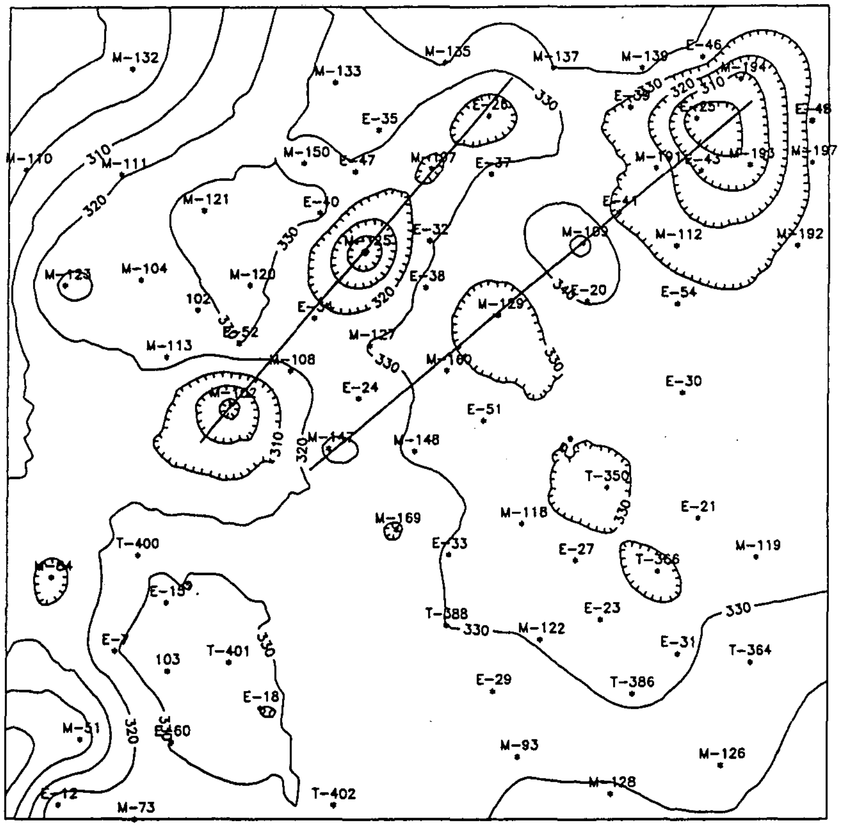
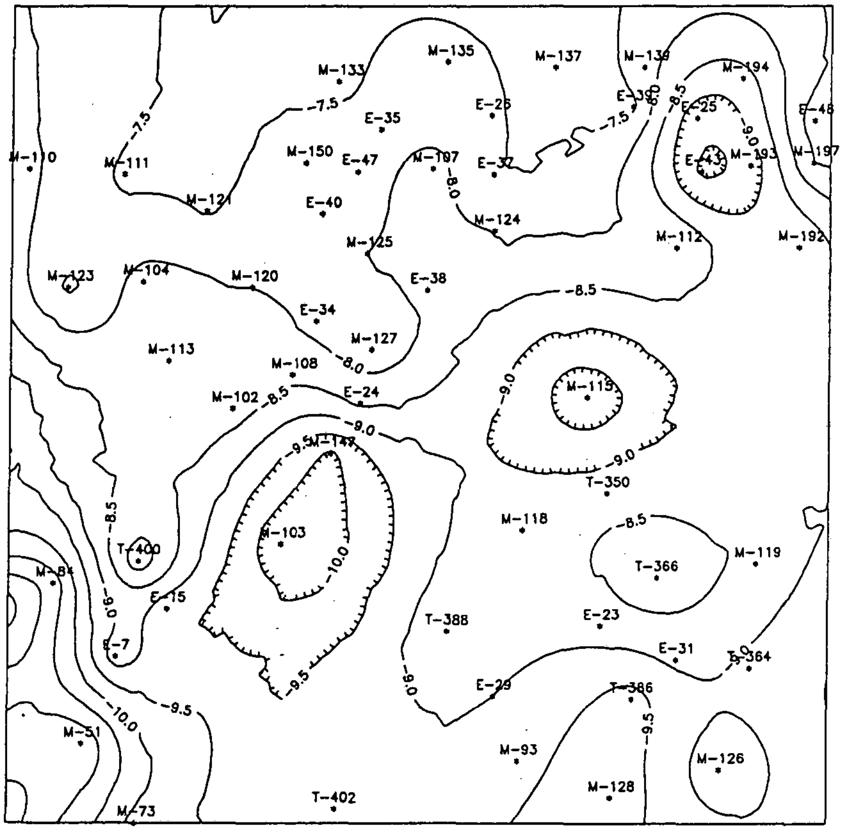


Figure 5. Total discharge oxygen-18 compositions of Cerro Prieto well fluids collected in 1989. Calculated values are from steam and water analyses by the USGS. Units are permil SMOW.



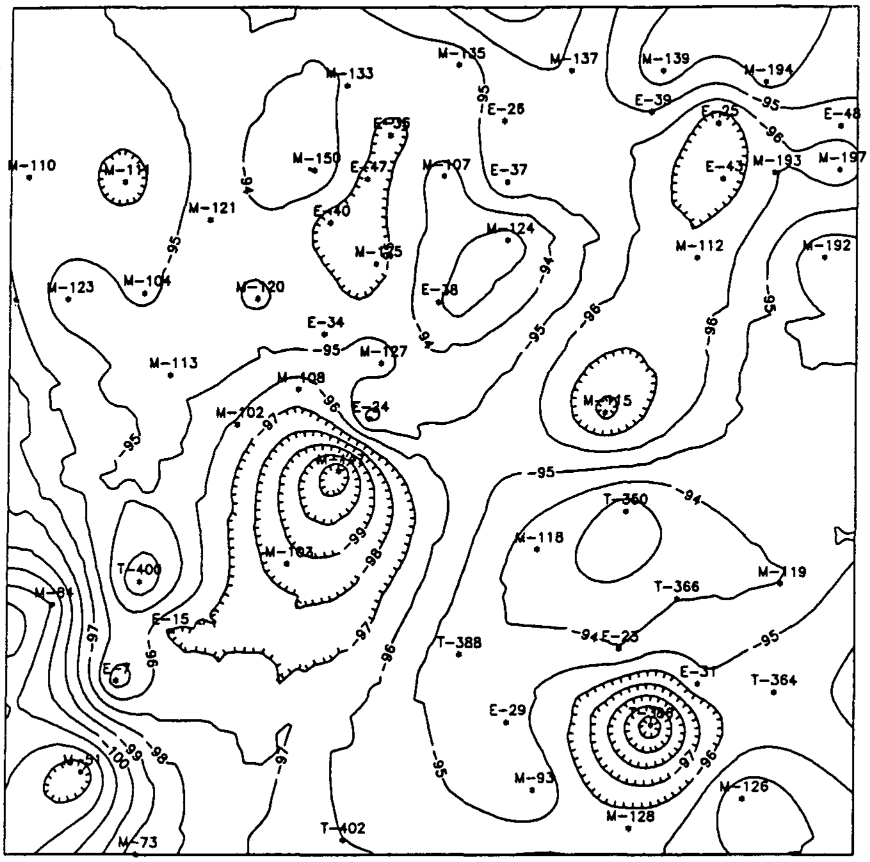


Figure 6. Total discharge deuterium compositions of Cerro Prieto well fluids collected in 1989. Calculated values are from steam and water analyses by the USGS. Units are permil SMOW.

Cerro Prieto II fluids

As was described earlier (e.g. Truesdell *et al.*, 1989; Lippmann *et al.*, 1991), the downthrown block of the beta reservoir shows only limited boiling because of its great depth and possibly because of connections with cooler fluids to the south. The lack of reservoir boiling is seen in the excess steam (IVF) map (Figure 2) in which almost all fluids southeast of a line between wells M-129 and M-169 show inlet vapor fractions less than 0.1. The exceptions are wells M-118 and E-27 which showed IVF values greater than 0.2 in 1990. The low values of IVF are confirmed by detailed enthalpy and chloride histories of typical well fluids (Figure 7) which show neither near-well boiling (which would lower silica enthalpy) nor general boiling and steam-water phase segregation (which would increase measured enthalpy). The O-18 isotope map (Figure 5) shows decreases to the southwest and (less strongly) to the south. These trends in O-18 and excess steam together with the decrease toward the south of aquifer chloride from greater than 10,000 ppm to less than 9000 ppm (Figure 3) suggest mixing with somewhat less saline water. The temperature effect of this mixing is less well defined (Figure 4) with 1990 Na/K temperatures near 320°C along the boundary, only 10-15°C cooler than elsewhere. The location of the H fault at the boundary with the northwest block is clearly shown in the excess steam (Figure 2) with near zero IVF values changing to greater than 0.4 IVF within a distance of 250-500 m.

The oxygen-18 compositions show almost exactly the same location for the H fault (Figure 5). The southeastern part of CP-II is characterized by fluids with oxygen-18 compositions between -8.5 and -10 permil SMOW which changes to values between -7.5 to -8.5 in the area with high excess steam. This is something of a paradox because at equilibrium steam is 0.7 to 1.0 permil lower in O-18 than liquid water at the temperature of the Cerro Prieto reservoirs (320-340°C), thus light isotopes (i.e. lower O-18/O-16 ratios) should accompany higher-enthalpy discharge.

Deuterium shows little experimental liquid-vapor fractionation at 320 to 340°C (steam is less than 2 permil enriched in deuterium) and there are few large changes throughout the CP-II reservoir (Figure 6) with southern fluids about 1 permil lighter than central CP-II fluids (-96 permil compared with -95 permil SMOW). The relatively small liquid-vapor fractionation factors for deuterium above 200°C and the lack of a "deuterium shift" from exchange with rock minerals make deuterium a less sensitive indicator of boiling and mixing processes in geothermal systems than oxygen-18. Although oxygen-18 isotopes are more sensitive to boiling processes at high temperatures, the "oxygen isotope shift" resulting from oxygen-18 exchange between water and rock, depends on temperature, rock type and duration of contact and may also produce variation in isotope compositions. Fluids with lower deuterium (to -97 permil) are found in part of the zone of anomalous fluids along the excess enthalpy boundary (the H fault). These are discussed below.

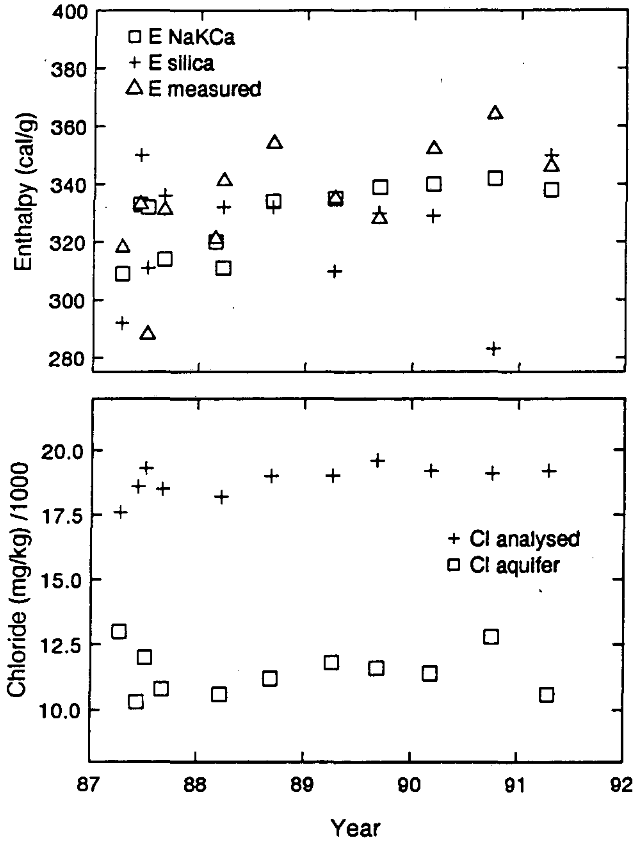


Figure 7. Geochemical history of E-23, a typical CP-II well. This includes measured total fluid enthalpy and calculated aquifer liquid enthalpy from silica and NaKCa geothermometers, along with measured and calculated aquifer liquid chloride based on silica temperatures. Enthalpy measurements and water analyses are from CFE.

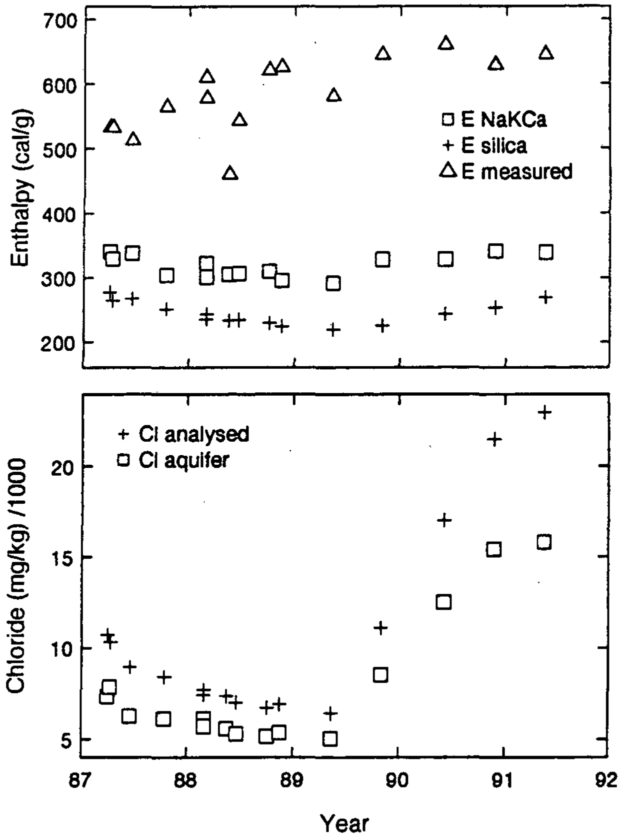


Figure 8. Geochemical history of M-121, a typical CP-III well. Quantities are as in Figure 7.

Cerro Prieto III fluids

The CP-III area (Figure 1) is very interesting geochemically. As mentioned earlier, fluids from this part of the field have high excess steam resulting from widespread boiling and phase segregation with steam entering wells separately from the liquid. This steam-rich fluid should show depletion of oxygen-18 on a total fluid basis and increase of chloride in the liquid (but not in the total fluid) as a result of boiling. CP-III fluids have, however, enriched total discharge oxygen-18 (Figure 5) and low (but highly variable) aquifer liquid chloride concentrations (Figure 3) compared with CP-II fluids. High oxygen-18 in CP-III fluids may be unrelated to boiling and result instead from oxygen isotope shift enhanced by limited fluid circulation. Although Na/K temperatures (Figure 4) show no significant differences between CP-III and CP-II, CP-III silica temperatures are typically lower by 25-50°C (Figure 8). This could result from near-well boiling and quartz deposition, but in the absence of the exponential decline of excess steam characteristic of near-well boiling (Lippmann and Truesdell, 1990), another explanation is suggested (see below). The fluids produced from wells at the boundary between CP-II and CP-III are anomalous in one or more of these quantities compared to either part of the reservoir.

Anomalous fluids

A number of wells along two northeast-southwest trends near the CP-II/CP-III boundary have shown anomalous behavior in 1988-1990. The map of Na/K temperatures for 1990 (Figure 4) shows that fluids from the anomalous wells (marked by lines) have temperatures 10 to 40°C lower than adjacent wells. The anomalous wells form two lines and include M-102, M-125, M-107 and E-26 in the western line and M-194, E-25, E-43, M-193, M-109, M-129 and M-147 in the eastern line. A few wells (M-147, M-109) did not have anomalous temperatures but were abnormal in other ways. Other wells along the same lines show no anomalies (for example M-108 and E-34) and some of the abnormal wells show only small temperature deficits in 1990 but showed large ones in previous years (e.g. M-129 in 1988). Some other wells off the trend had anomalous fluid temperatures for short periods (e.g. E-47 in 1988, M-169 in 1989). Some (but not all) wells with low 1990 temperatures show low aquifer chloride (M-102, M-194 and adjacent wells, and M-129). Some of the wells (E-25, E-43, M-193 and M-147) had low oxygen-18 (Figure 5) and deuterium (Figure

6). Finally, most of the anomalous wells (but not E-26, M-109 and M-129) showed high excess steam in 1990 (Figure 2) with IVF values greater than 0.5 in the western line (usually more than 0.1 higher than adjacent wells). Wells in the eastern line have lower but still elevated IVF values (>0.4).

Interpretation of anomalous fluid compositions

The wells with the most consistently anomalous fluids are M-102 and the group including M-194, E-25, E-43 and M-193. A map of the top of the producing interval (Figure 9) shows that this group of wells (except M-102 and M-194) have unusually shallow production intervals, as much as 250 m above adjacent wells (E-43 at 1900 m depth has the shallowest production in the western half of CP-III). Wells M-129 and M-147 also have shallow production and anomalous fluids, but in M-127 shallow production did not lead to anomalous fluids. This partial correlation of fluid anomalies and shallow production suggests that part of these fluids may have been produced in or migrated to the upper parts of the reservoir. Note that a band of steep gradient in production depth runs from northeast to southwest almost coincident with the position of the H fault determined by Halfman *et al.* (1986) from well logs.

Two possible causes of anomalous fluids at the top of the reservoir are gravity-induced steam segregation after extensive boiling, and recharge of cooler water from above. Some observations (high excess enthalpy, low total chloride) suggest steam segregation while others (low geothermometer temperatures, low liquid chloride) imply cool recharge. It is important to note that in 1989 light isotopes were associated only with the eastern line of anomalous fluids (wells in the M-194 group, and M-147; data for M-109 and M-129 are not available for that year).

The inconsistent nature of the anomalies suggests that more than one factor may apply. In general wells in the western anomaly (M-102, M-125, M-107 and E-26) have very high excess steam and no evidence of light isotopes, while those in the eastern anomaly have light isotopes with low (M-147, M-112, M-109) or moderate (wells near M-194) excess steam. Of these factors, low total discharge deuterium values are clearly related to cooler, less-saline waters (which have a larger fraction of Colorado river water, low in salts and deuterium; Stallard *et al.*, 1987). High excess steam is probably related to segregation of steam and its preferential flow to wells. The M-194 group has both low deuterium and moderately high excess steam, with shallow feed zones. Thus these wells may have both influences. The addition of cooler water to the western wells is strongly indicated by their low Na/K temperatures and aquifer chloride concentrations, but they show no anomalies in total-fluid isotope compositions. It seems likely that because these wells have such high excess steam, the composition of the liquid fraction has little influence on the total-discharge isotope compositions. Thus it is possible that cooler recharge could cause low geothermometer temperatures and aquifer chloride concentrations, because these quantites are related to liquid compositions, but isotope compositions remain strongly influenced by high excess steam. The high excess steam could also contribute to lower aquifer chloride and silica-geothermometer temperatures in the manner discussed next.

High excess steam and low chloride in CP-III fluids

As mentioned above, the CP-III area generally has high excess steam (Figure 2) and low variable aquifer chloride concentrations (Figures 3 and 8). Intuitively, since boiling and steam separation should leave residual water enriched in chloride, high rather than low aquifer chloride would be expected. In addition the extreme range in chloride (e.g. 5000 to 15,000 mg/kg in M-121; Figure 8) is not consistent with these waters starting with 11,000-12,000 mg/kg chloride as found in CP-II, and becoming more concentrated by boiling off steam. A possible explanation of the low and variable chloride found, lies in the boiling and condensation processes that may be expected for very high-temperature waters. This sort of argument was used by James (1968) to explain the preference of vapor-dominated reservoirs for 240°C, the temperature corresponding to the enthalpy maximum of steam.

The processes suggested can be understood by considering the enthalpy-pressure diagram for water constructed from steam table data (White *et al.*, 1971). This diagram is for pure water, but can be applied to Cerro Prieto waters which all have less than 2% NaCl equivalent concentration. Figure 10 shows an outline of the two-phase region, and isotherms for 150, 200 (partial) and 300°C along with the hypothesized boiling and condensation processes.

The generalized initial state of Cerro Prieto III water before exploitation is shown at point A. This fluid is compressed liquid at supercritical pressure but subcritical temperature. At the start of exploitation the liquid undergoes decompression along the 350°C isotherm with temperature buffered by heat in the rock, to reach the two-phase region at point B. From B to C the liquid boils at constant enthalpy with phase separation at C to form residual liquid of composition L1 and vapor, V1. The fraction of vapor formed is about 0.14 and if the initial chloride concentration is about 10,000 mg/kg (as in CP-II), then the concentration in residual liquid would be 11,600 mg/kg. This process is similar to boiling in a separator except that heat may be transfered from the rock as the fluid decreases in pressure and temperature from B to C. Initially this heat transfer must increase the fluid enthalpy so that the steam fraction is higher than 0.14 and the residual chloride, greater than 11,600 mg/kg. With time, rock temperatures equilibrate with boiling fluid temperatures and the process becomes isoenthalpic.

The CP-III reservoir has very low recharge (i.e. is nearly closed) and the pressure drop from exploitation would have propagated widely causing widespread boiling. Since boiling is not limited to the near-well region,

Figure 9. Map of the top of the producing intervals (depths in meters) of Cerro Prieto wells in the beta reservoir (Ricardo Márquez, CFE Cerro Prieto; personal commun., 1991).

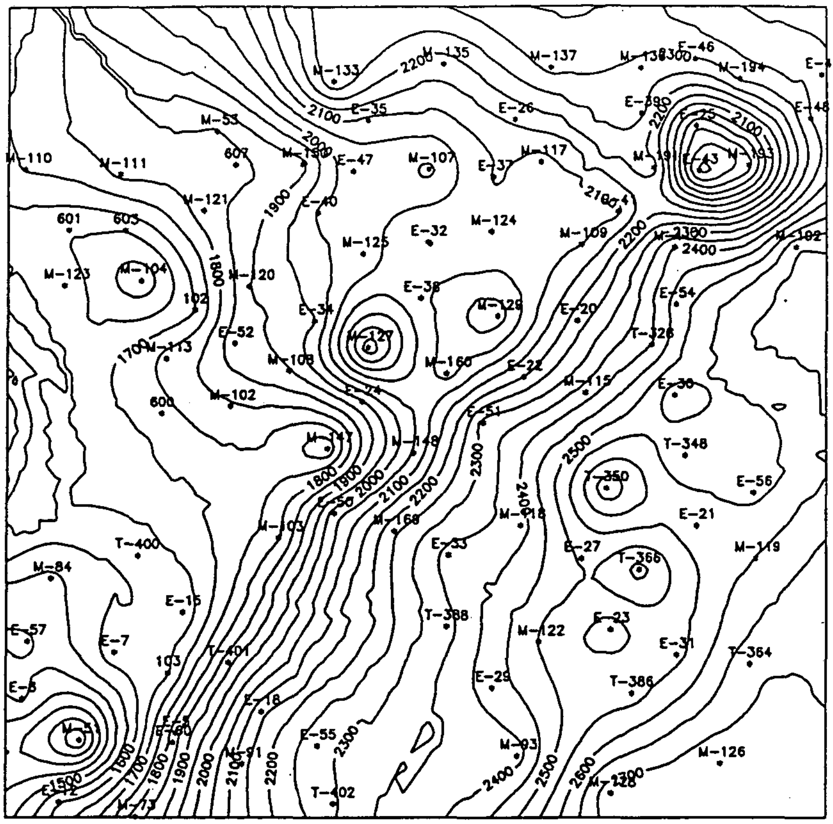
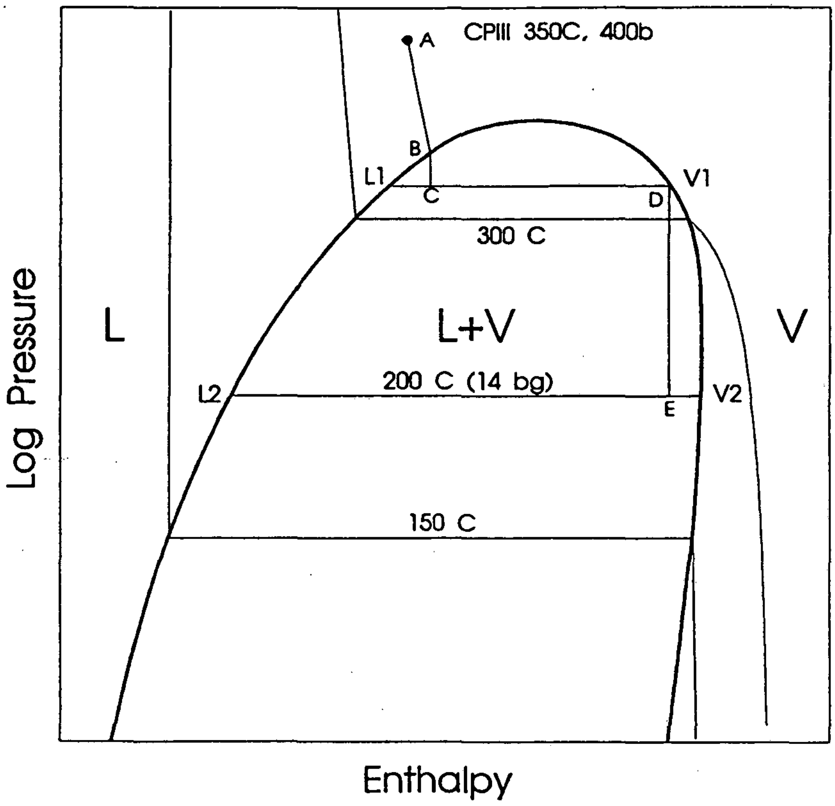


Figure 10. Part of the enthalpy - pressure diagram for pure water from White *et al.*(1971) showing hypothetical boiling and condensation processes.



gravity segregation could occur and it is likely that before or during flow to the wells, the residual liquid would flow to lower zones and steam would flow toward upper zones. Steam at point D (composition V1) would continue to decrease in pressure and temperature as it flowed toward the wells and, because it has a temperature well above 240°C (and therefore less than maximum enthalpy), it can condense at constant enthalpy to form a low-enthalpy liquid (L2) and higher-enthalpy steam (V2). The condensation process shown in Figure 10 is for final separation at 200°C and 14 bars gage, typical of the high pressure separators at CP-III. The decompression process shown from D to E occurs at least partly in the wellbore and separator (at constant enthalpy), but is likely to also occur partly in the reservoir.

The liquid L2 is steam condensate which contains negligible chloride and represents about 0.06 of the total fluid separating from L1. If all of this condensate is carried into the well (or formed in the well) and the excess vapor fraction (IVF) of the well is high (as for most CP-III wells), then this condensate could significantly dilute brine from the lower reservoir zones. If the condensation ocurred partly in the reservoir as the steam flows toward the well, then a smaller fraction might enter the well and the remainder might mix with and partially dilute the brine outside the well.

These processes allow for a great variety in apparent aquifer liquid chloride with all or nearly all fluids showing some dilution. The degree of dilution depends on conditions that would not be consistent from well to well or with time in a single well. This agrees with the observed variation in aquifer chloride concentrations of CP-III reservoir fluids (Figures 3 and 8). Dilution with condensate would also affect calculated silica temperatures and produce the greatly depressed silica temperatures observed in CP-III fluids. Low chloride and silica concentrations associated with the CP-III fluids also characterize anomalous well fluids along the western line. These fluids have extremely high excess steam and must also show the effects of these boiling and condensation effects. However the low Na/K temperatures of these fluids could not be produced by condensation and near-well dilution, but must result from the entry of cooler waters.

Summary

The beta reservoir at Cerro Prieto shows several types of production mechanisms. Fault-H divides the reservoir into a deeper block in the southeast and a shallower block in the northwest. The southeast part, producing steam mainly for powerplant CP-II, shows limited boiling due to its greater depth and higher initial pressure, and probably because pressures are maintained by its connections to cooler aquifers. The northwest part supplying steam mainly to powerplant CP-III shows intense boiling with phase segregation and preferential steam flow to wells resulting in high excess steam. The fluids from the CP-III area have aquifer chloride concentrations about 20% lower than those from the central CP-II area and are relatively enriched in oxygen-18.

Near the trace of the H fault at reservoir level, there are two lines of wells with anomalous fluids. The western line shows high excess steam with low aquifer liquid chloride, low Na/K temperatures and total-discharge deuterium concentrations similar to most other fluids from the beta reservoir. The eastern line shows lower excess steam, low chloride, low Na/K temperatures and low deuterium values. These anomalous fluids appear to result in part from cool water recharge from above and in part from exceptionally large amounts of excess steam (high IVF values). The generally lower aquifer chloride in CP-III fluids may be due to isoenthalpic condensation of very high-temperature steam with resulting dilution of reservoir liquids with condensate. This process also may contribute to the low chloride of the western anomalous fluids. The high oxygen-18 in CP-III fluid probably results from oxygen isotope shift.

If cooler water is entering the beta reservoir along the line of anomalous wells, then it is probably moving down the H fault. Not only is the fault zone a possible conduit, but because of the offset of the shale layer overlying the beta reservoir, the distance from the hot reservoir to overlying cooler groundwater is the least along the fault trace. Inflow of cooler water into the greatly decompressed northwest block of the beta reservoir would be beneficial providing it is dispersed through the reservoir and not concentrated in a limited area.

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