NOTICE CONCERNING COPYRIGHT RESTRICTIONS

PATTERNS OF CHANGE IN WATER ISOTOPES FROM THE CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO: 1977-1986

By M.L. Stallard[1], T.L. Winnett[1], A.H. Truesdell[1], T.B. Coplen[2],
C. Kendall[2], L.D. White[1], C.J. Janik[1], and J.M. Thompson[1]

[1]U.S. Geological Survey, Menlo Park, Calif. 94025
[2]U.S. Geological Survey, Reston, Va. 22092

ABSTRACT

Isotopic analyses of Cerro Prieto well waters collected over the last 10 years indicate continued drawdown of cooler, isotopically lighter water from the sides and above the geothermal reservoir. Drawdown from above the reservoir has been most pronounced along a north-striking normal fault that intersects the shallow α reservoir in the western part of the geothermal field. Hot geothermal fluid recharges the system from the northeast, rising through a major normal fault zone and moving out into the surrounding permeable reservoir. In the central region of the field, near the α reservoir boundary, a natural region of two-phase fluid exists between the α reservoir and the deeper β reservoir. Comparison of observed isotopic fractionation between steam and water from production separators on Cerro Prieto wells with experimental fractionation factors indicates steam contamination of most water samples.

INTRODUCTION

The Cerro Prieto geothermal system is located 35 km southeast of Mexicali in Baja California, Mexico (Fig. 1), and is associated with one of several pull-apart basins along the strike-slip boundary of the North American and Pacific plates. The basin is bounded to the northeast by the Imperial Fault and to the southwest by the Cerro Prieto Fault. Thick deposits of Colorado River sands and shales have accumulated in the basin, and two main geothermal aquifers have been identified predominantly in the sand units. The α reservoir located in the western part of the field (Fig. 2) occurs between 1,000 and 1,500 m depth and was originally at temperatures of 260 to 310 °C. The hotter (320 to 340 °C), deeper (>1,500 m) β reservoir underlies the entire area of exploitation shown in Figure 2. These reservoirs are bounded below by low-permeability mineralized rocks and above and to the sides by discontinuous shale beds and an interface with cooler water (Grant et al., 1984). A number of northeast-striking faults transect the Cerro Prieto pull-apart basin, and have been mapped in various locations (for example, Puente and Pena, 1978; Diaz et al., 1981; Rivera et al., 1982). Figure 2 shows the faults identified by Halfman et al. (1984) as displaying substantial offset. These authors suggest that Fault H and Fault L

have an important influence on fluid flow in the system. Exploration of the Cerro Prieto geothermal field began in 1958; and the first power plant, drawing from 20 wells and generating 75 MWe, went on line in 1973. At present, there are three power plants with a total installed capacity of over 600 MWe.

Since April 1977, water and steam samples for isotopic analysis have been collected approximately yearly from all available wells on production. The number of wells sampled has increased from 15 (all producing from the α reservoir) in 1977 to 64 (19 from the α reservoir and 45 from the β reservoir) in 1986 (see Fig. 2 for well locations). Changes in the isotope composition of fluids from the α reservoir are shown by data from the 1977 and 1982 collections (Truesdell et al., 1979, 1984), and are also evident in data from other years with the newer data also showing relationships of β reservoir fluids. Most significant is the continuing drawdown of cooler, isotopically lighter water into the α reservoir from the sides and above in response to lowered reservoir pressure resulting from production. This cooler water extracts heat from the reservoir rocks and has caused lowered enthalpy and temperature in most wells. The β reservoir has been tapped extensively since 1982, and the isotope data from these wells have supplied new information about patterns of recharge in this deeper, hotter, and larger reservoir and have revealed a natural region of two-phase fluid in the central part of the field.

OBSERVED VERSUS EXPERIMENTAL FRACTIONATION

Samples of steam and separated brine were collected from production separators using sampling ports on the bottom of the separator (for brine) and on the steam line as it left the separator. Samples were cooled by passage through stainless-steel coils in water and ice baths and collected in the usual manner. In order to calculate the total fluid isotope composition of the discharge we compared observed oxygen-18 fractionations to fractionation factors calculated from an equation (Bottinga, quoted by Friedman and O'Neil, 1976) based on experimental isotope equilibrium (Bottinga, 1968; Bottinga and Craig, 1968). Observed deuterium fractionations were compared to a curve fit to the same experimental

data (Truesdell, Nathenson, and Rye, 1977). Temperatures of separation were calculated from measured pressures (CFE, written commun., 1977-86) using steam tables (Keenan et al., 1969).

Except for samples taken from the second separator of double-separator wells, we consistently found steam-water fractionations smaller than those predicted by the experimental equations (Table 1). This may be due to one or more of the following: (1) The experimental curves are inaccurate over this temperature range (150 to 200°C) or for brines of this concentration (6,000 to 18,000 mg/kg Cl⁻); (2) the recorded separator pressures are inaccurate (consistently too low); or (3) the steam/brine separation is not complete and the brine is contaminated with steam or vice versa. Of these possibilities the third is the most likely. The water level in centrifugal separators is unstable and the separators are generally adjusted to produce a consistently pure steam fraction by allowing a small amount of steam to be included in the brine fraction. Steam contamination of brine is also indicated by data from the double-separator wells sampled in 1986 (see Table 1). Low-pressure secondary separators produce a much smaller fraction of steam than high-pressure separators or single-stage separators (steam fractions are 0.065 to 0.1 compared to 0.11 to 0.9), and the brine fraction is, therefore, probably contaminated with a proportionately smaller amount of steam. This is reflected in the smaller discrepancy between experimental and observed deuterium fractionation for these wells compared to other wells (Table 1).

Table 1. Differences between experimental and observed water-steam isotope fractionations (10^3 ln α experimental − 10^3 ln α observed; 10^3 ln $\alpha \approx \delta$water − δsteam). n = number of samples.

Year	Oxygen	n	Deuterium	n
1977	.309	15	1.97	14
1978	.291	11	—	
1979	.362	22	1.96	20
1980	.346	16	2.49	16
1982	.235	27	2.08	27
1984	.250	17	1.89	17
1985	.181	27	1.65	26
1986	.197	27	1.63	30
1986*	-.107	30	1.08	30

*Second separator

Based on the results described above, the total fluid isotopic composition for each well discharge was calculated using the measured steam isotopic composition, the measured steam fraction (obtained as close in time to the water collection as possible), and a calculated brine isotopic composition based on the steam composition and experimental fractionation factors. Total fluid isotopic compositions were also calculated using the measured brine composition for comparison. Oxygen-18 results obtained from these calculations typically differ by 0.2 or 0.3 per mil and deuterium results differ by 2 or 3 per mil. General trends, however, remain the same.

ISOTOPIC CHANGES WITH TIME: 1977-1985

Although the isotopic compositions of fluids from Cerro Prieto were not measured before 1977, the fluid in the shallow α reservoir was probably about -8.0 to -8.3 in $\delta^{18}O$ based on several lines of evidence. Truesdell et al. (1979) found that in 1977 wells in the northern part of the field (comparatively unaffected by drawdown as shown by constant chloride and enthalpy) had total fluid isotope compositions between -8.3 and -8.1 per mil. Wells in the south-central part of the exploited field produced lower chloride, lower ^{18}O fluids(to -10.1 per mil) apparently influenced by fluid drawdown into the production aquifer from above. Olson (1979) found that calcite from drill cuttings appeared to have equilibrated at observed temperatures with a reservoir fluid $\delta^{18}O$ near -8.3 with no evidence of lighter fluids. A few later produced well fluids were slightly heavier (e.g., M20 with $\delta^{18}O$ = -7.7) but they were also deeper and probably contained some contribution from the β reservoir. Fluid from M48 (producing from the α reservoir) when first sampled in 1979 had $\delta^{18}O$ = -8.0, similar to the heaviest total fluid composition of 1977.

Only two wells were sampled in 1978 that had not been on line in 1977, and the oxygen isotope pattern was virtually unchanged (Fig. 3a). Drawdown of low-chloride, low-$\delta^{18}O$ water was centered on wells M26 and M27 and dropped off sharply to the northwest of these wells. Wells in the northwest and south had experienced little or no dilution by this time, suggesting that only vertical drawdown and horizontal flow from the northeast had occurred. Deuterium distribution showed the same general area of drawdown, but not as clearly because the total spread in data (4 per mil) was small relative to analytical error (± 1 per mil).

Oxygen isotope data for waters collected in 1979 (Fig. 3b) covered a much larger area than the previous two years. The central area of -9 per mil waters had expanded and water from M26 was considerably lighter than -10 per mil. Other areas of pronounced dilution to the north and southeast of the central zone had also developed. These areas of dilution define a line which coincides with a fault suggested by Halfman et al. (1984) to be a major conduit for fluids (Fault L, Fig. 2; dashed on Fig. 3b). The coincidence of isotopically light waters with Fault L suggests that vertical drawdown along this fault occurred in the central area and that vertical and/or horizontal flow along the fault occurred in the north and south areas. The areas of less dilution may correspond to less permeable segments of the fault or to areas where cross-cutting faults are supplying hot geothermal waters.

By 1980 the drawdown of isotopically light water in the southern part of the α reservoir had nearly caught up to drawdown in the center of the field (Fig. 3c). Results from 1982 and 1985 collections (Figs. 3d and 3e) show continued development of these two areas of most intense drawdown in the α reservoir. By 1985, waters in these two areas had $\delta^{18}O$ values well below -11 per mil and waters from the rest of the α reservoir had $\delta^{18}O$ values that were generally less than -9 per mil. In the meantime, the two wells to the north that had shown marked dilution in 1979 remained constant (M42) or became 1 per mil heavier (M114), indicating a new influx of isotopically heavier water.

The 1982 collection included the first samples taken from wells that tap only the deeper β reservoir (all wells located northeast of the railroad tracks plus those shown in parentheses· southwest of the tracks). These waters are generally isotopically heavier than those from α reservoir wells, presumably because they have been less mixed with cooler, isotopically lighter waters or have equilibrated with minerals at higher temperatures. β reservoir waters are heaviest in the northeast and get lighter toward the α reservoir in the southwest.

1986 DATA

Sixty-three wells were sampled and their waters nalyzed for isotopic composition in 1986. This is more than twice the number sampled during any other year, and includes a number of new wells producing from the deep (up to 3,000 m) eastern part of the β reservoir.

The oxygen isotope distribution for 1986 is shown on Figure 4. With the exception of a few wells (discussed below), the entire field could be contoured as one system, suggesting some communication between the α and β reservoirs. The narrow, northwest-trending, -8 to -9 per mil strip marks the edge of the α reservoir and reflects the steepening $\delta^{18}O$ gradient to the northeast of the railroad tracks where only β reservoir fluids are produced. The contours for the α reservoir show a pattern similar to the 1985 pattern, but with significant expansion of the -11 region in the southwestern part of the field, which may be a result of increased drawdown in response to the opening of a number of new deep wells to the east.

Contours in the β reservoir open to the northeast and the heaviest waters are found in this corner of the exploited area. This suggests that the hot geothermal brine originates somewhere to the northeast of the field in agreement with Elders et al. (1984) and Goldstein et al. (1984), who suggest that the heat source for the Cerro Prieto system might be associated with a swarm of dikes intruded into the eastern regions of the field. The geothermal brine has apparently moved upward and to the southwest, where it mixed with lighter, cooler waters and reequilibrated at lower temperatures with reservoir rock. The tight curvature of the contour in the northeastern part

of the field and the double-bullseye pattern in the southwestern part of the field both suggest that recharge to the field is controlled to some extent by the prominent northeast-striking normal faults that transect the pull-apart basin. Halfman et al. (1984, 1986) have suggested that the geothermal fluids rise from depth and enter the β reservoir along Fault H, a major northeast-striking normal fault (surface projection shown on Fig. 2).

With only 1986 samples for much of the β reservoir, it is difficult to project back to pre-exploitation conditions. If it is assumed, as was discussed earlier for the α reservoir, that the β reservoir had a uniform composition prior to exploitation and that since it has been diluted with isotopically lighter water, then the pre-exploitation fluid must have had a uniform $\delta^{18}O$ at least as heavy as -6.9 per mil (see Fig. 4). This seems unlikely for several reasons. For one, the α and β reservoirs have been demonstrated to communicate with one another and originally there was probably a gradational change in fluid $\delta^{18}O$ (rather than a sudden jump from -8.0 per mil in the α reservoir to -6.9 per mil). Also, the temperature derived from this oxygen composition for β reservoir water and the oxygen composition of calcite from M127 and M132 (~-4 per mil, from Williams, 1982) is 410°C, unreasonably high for the β production zone. In fact, even the 1986 oxygen values for M127 and M132 well waters (-7.9 and -7.5 per mil, respectively) give unreasonable temperatures of 360° and 380°C with a calcite oxygen of -4 per mil. It may be that while draw-down of cool isotopically light water is occurring in the western part of the field in response to exploitation, the eastern fluids are actually getting heavier due to increased recharge from the deep hot source to the northeast. More definite indication of the isotopic evolution of these waters in response to fluid production must await future collections.

Deuterium data for waters collected in 1986 show a pattern of distribution very similar to that of the oxygen. The fieldwide deuterium and oxygen-18 distribution can be explained by dilution to varying degrees with cooler ground-water (δD = -103, $\delta^{18}O$ = -13; Truesdell et al., 1979) over most of the field (Fig. 5). Using this model, the least diluted waters (found in wells M133, M135, and M137), with $\delta^{18}O$ of -6.9 per mil and δD of -93 per mil, have been mixed with 70 percent groundwater (75 percent if oxygen-18 data are used) to form the -11.5 per mil ($\delta^{18}O$), -100 per mil (δD) water found in the most diluted wells (M35, M50, M90, and M105). Mixing calculations based on oxygen-18 are probably less accurate because exhange with rock oxygen must occur both before and after mixing.

Comparing oxygen and deuterium data from α reservoir wells in 1986 with data for the same wells in 1977 reveals the extent of drawdown and dilution by cooler water that occurred over that ten-year period. Percent dilution over this period ranges from 10 percent dilution for well M19A to 70 percent dilution for well M35. In the

southern area of intense drawdown, well M105 experienced 65% dilution between 1979 and 1986.

ANOMALOUS FLUIDS

Assuming all variations in the isotopic compositions of Cerro Prieto waters are due solely to mixing hot brine with a cooler water of constant composition works fairly well in general. However, if this mixing is the only process involved in forming Cerro Prieto waters, then contour patterns for oxygen-18, deuterium, and chloride should coincide. While this is reasonably true for the α reservoir, these contours diverge somewhat in the central part of the β reservoir (shaded area of Fig. 4). Waters in this area show the highest deuterium values (up to -91 per mil) and yet relatively low chloride (as low as 500 mg/kg).

A plot of deuterium versus oxygen-18 defines a reasonably clear mixing line with cooler groundwater (Fig. 5). The three points falling farthest off the line are from wells at the eastern edge of the field which may have encountered slightly different diluting waters moving in from the east. A plot of deuterium versus chloride (Fig. 6) shows most waters defining a mixing line with the same groundwater shown in the deuterium/oxygen-18 plot (δD = -103, Cl = 500 mg/kg). A number of waters, however, all with δD greater than -96 per mil, fall well to the left of this line, indicating anomalously low salinity. All of the wells producing these anomalous waters, with the exception of well M193, draw from the β reservoir and fall in the center of the field (shaded area on Fig. 4).

Examining patterns of isotopic change over time also reveals that these wells are anomalous in showing slight increases of $\delta^{18}O$ with time. Most wells have shown continuously decreasing ^{18}O, D, and chloride concentrations. A minor number of wells show different behavior: A few show small, probably insignificant, fluctuations in $\delta^{18}O$ (<0.3 per mil); others show erratic behavior, with large increases in ^{18}O during certain periods of their histories probably related to change in fluid entry; and some, mostly in the central zone, have shown an overall increase in ^{18}O from when they first were opened to the present.

Wells M20, M45, and M91 are wells that have all shown large increases (>.5 per mil) in $\delta^{18}O$ in a one-year period, although they are from the western part of the field rather than the anomalous central region. Since the year of increase was different for all three wells, these appear to be isolated events relating to individual wells. Well M20 has been demonstrated to draw on fluids from both the α and β aquifers (Grant et al., 1984; Truesdell and Lippmann, 1986). Wells M45 and M91 are deep enough that they too may be drawing on both the α and β reservoirs. These wells may discharge different proportions of α and β liquid at different times with lower flow rates favoring the hotter (and isotopically heavier) reservoir fluid (Grant et al., 1984). Note that the year during which each of these wells experienced a marked increase in the oxygen-18 content of discharged fluids was also the year that the flow rate dropped the most.

Wells M102, M103, M104, and M114 are from the central region and have shown an overall increase in oxygen-18 since the beginning of production. M102 increased by .5 per mil from 1980 to 1986, M103 increased by .5 per mil between 1979 and 1986, well M104 increased by .6 per mil between 1980 and 1984 (and has decreased by .5 per mil since then), and well M114 increased by .95 per mil between 1979 and 1985. These wells all fall in the anomalous central region of the β reservoir and, except for the E-series wells, are the only wells in this area that have been sampled more than once.

The wells in the central part of the field have shown slight increases in $\delta^{18}O$ and δD over time, while the rest of the field has been getting steadily lighter. Fluid enthalpies in the central zone are high and have increased with time while chloride concentrations have shown dramatic decreases (for example, M102 dropped from 9,300 mg/kg Cl$^-$ in 1980 to 500 mg/kg Cl$^-$ in 1986, M103 dropped from 9,500 mg/kg Cl$^-$ in 1979 to 6,300 mg/kg Cl$^-$ in 1986). The increase in deuterium, decrease in chloride, and high (and increasing) enthalpy of these wells are consistent with excess steam in the well due to boiling at temperatures greater than 220°C. A plot of enthalpy versus chloride (Fig. 7) also indicates mixing with steam in these wells. It has been suggested (Lippmann and Bodvarsson, 1983) that a natural two-phase zone exists in this region where the α and β reservoirs connect, and the deuterium, chloride, and enthalpy data support this suggestion. The general increase in oxygen-18, however, is contradictory and suggests more complicated reservoir processes. A different mixing water with heavier oxygen, possibly due to more extensive water-rock interaction, may be recharging this area to some extent, and may be coming up from below the reservoir. Since the increases in oxygen-18 are small, however, these results may simply indicate localized boiling in which essentially all the water is vaporized and the isotopic composition is near constant. The fact that these waters conform to the reservoir mixing line (see Fig. 5) suggests that this may be the case. This region is of considerable interest because of its anomalous behavior and the indications that it taps a consistently two-phase section of the reservoir. It will be interesting to see how this area evolves in response to continued exploitation.

CONCLUSIONS

Isotopic analyses of Cerro Prieto well waters collected over the 10-year period from 1977 to 1986 indicate continuing drawdown of cooler, isotopically lighter water from above and to some extent from the sides of the geothermal reservoir. Infiltration by cooler waters affects both the α and β reservoirs, but has been most pronounced in two areas tapping the shallower α reservoir. These areas lie along a north-northwest-striking fault, which Halfman et al. (1984, 1986) suggest

is a major conduit for fluid recharge into the reservoir. Contours in the eastern part of the β reservoir open to the northeast and the least diluted geothermal waters are found in this corner of the field. This pattern is also consistent with the Halfman et al. model, which calls for a heat source to the east of the field, with geothermal recharge moving away from the source, up and to the southwest along a major normal fault that cuts through the center of the Cerro Prieto geothermal field. Deuterium, chloride, and enthalpy data for the central part of the field indicate boiling and excess steam production in this region. The small increases in oxygen-18 are apparently inconsistent but may reflect localized boiling in which essentially all the water is vaporized and isotopic composition is near constant.

REFERENCES

Bottinga, Y., 1968. Calculation of fractionation factors for carbon and oxygen exchange in the system calcite-carbon dioxide-water, J. Phys. Chemistry, v. 72, p. 800-808.

Bottinga, Y., and Craig, H., 1968. High-temperature liquid-vapor fractionation factors for $H_2O-HDO-H_2O^{18}$, EOS (Am. Geophy. Union Trans.), v. 49, p. 356.

Diaz, S., Puente, I., and de la Pena, A., 1981. Proposed geologic model based on geophysical well logs, in Proc., 3rd Symp. the Cerro Prieto Geothermal Field, Comisión Federal de Electricidad, Mexicali, Mexico, p. 46-58.

Elders, W.A., Williams, A.E., Bird, D.A., and Schiffman, P., 1984. Hydrothermal flow regime and magmatic heat source of the Cerro Prieto geothermal system, Baja California, Mexico, Geothermics, v. 13, no. 1/2, p. 27-47.

Friedman, I., and O'Neil, J.R., 1976. Compilation of stable isotope fractionation factors of geochemical interest, U.S. Geol. Surv. Prof. Paper 440-KK, 49 figs.

Goldstein, N.E., Wilt, M.J., and Corrigan, D.J., 1984. Analysis of the Nuevo León magnetic anomaly and its possible relation to the Cerro Prieto magmatic-hydrothermal system, Geothermics, v. 13, no. 1/2, p. 3-11.

Grant, M.A., Truesdell, A.H., and Manon, A., 1984. Production induced boiling and cold water entry in the Cerro Prieto geothermal reservoir indicated by chemical and physical measurements, Geothermics, v. 13, no. 1/2, p. 117-140.

Halfman, S.E., Lippmann, M.J., Zelwer, R., and Howard, J.H., 1984. Geologic interpretation of geothermal fluid movement in the Cerro Prieto field, Baja California, Mexico, Am. Assoc. Petrol. Geol. Bull., v. 68, p. 18-30.

Halfman, S.E., Manón, A., and Lippmann, M.J., 1986. Update of the hydrogeologic model of the Cerro Prieto field based on recent well data, Geoth. Res. Counc. Trans., v. 10, p. 369-375.

Keenan, J.H., Keyes, F.G., Hill, P.G., and Moore, J.G., 1969. Steam tables - thermodynamic properties of water including vapor, liquid, and solid phases, Wiley, New York, 162 pp.

Lippmann, M.J., and Bodvarsson, G.S., 1983. Numerical studies of heat and mass transport in the Cerro Prieto geothermal field, Mexico, Water Res. Res., v. 19, no. 3, p. 753-767.

Olson, E.R., 1979. Oxygen and carbon isotope studies of calcite from the Cerro Prieto geothermal field, Geothermics, v. 8, no. 3/4, p. 245-252.

Puente, I., and de la Pena, A., 1979. Geology of the Cerro Prieto geothermal field, Geothermics, v. 8, no. 3/4, p. 155-175.

Rivera, R., Bermejo, F.J., Castillo, F., Pérez, H., Abraján, A., 1982. Study update of temperature behavior and distribution in Cerro Prieto II and III, in Proceedings, Fourth Symp. Cerro Prieto Geothermal Field, Comisión Federal de Electricidad, Mexicali, Mexico, v. 1, p. 281-306.

Truesdell, A.H., and Lippmann, M.J., 1986. The lack of immediate effects from the 1979-80 Imperial and Victoria earthquakes on the exploited Cerro Prieto geothermal reservoir, Geoth. Res. Counc. Trans., v. 10, p. 405-411.

Truesdell, A.H., Nathenson, M., and Rye, R.O., 1977. The effects of subsurface boiling and dilution on the isotopic compositions of Yellowstone thermal waters, J. Geophys. Res., v. 82, no. 26, p. 3694-3704.

Truesdell, A.H., Nehring, N.L., Thompson, J.M., Janik, C.J., and Coplen, T.B., 1984. A review of progress in understanding the fluid geochemistry of the Cerro Prieto geothermal system, Geothermics, v. 13, no. 1/2, p. 65-74.

Truesdell, A.H., Rye, R.O., Pearson, F.J., Olson, E.R., Nehring, N.L., Whelan, J.F., Huebner, M.A., and Coplen, T.B., 1979. Preliminary isotopic studies of fluids from the Cerro Prieto geothermal field, Geothermics, v. 8, no. 3/4, p. 223-279.

Truesdell, A.H., Thompson, J.M., Coplen, T.B., Nehring, N.L., and Janik, C.J., 1981. The origin of the Cerro Prieto geothermal brine, Geothermics, v. 10, no. 3/4, p. 225-238.

Williams, A.E., 1982. Stable isotope systematics of oxygen and carbon in and around the Cerro Prieto geothermal anomaly, Baja California, Mexico, in Proc. 4th Symp. on Cerro Prieto Geothermal Field, Comision Federal de Electricidad, v. 2, p. 571-582.
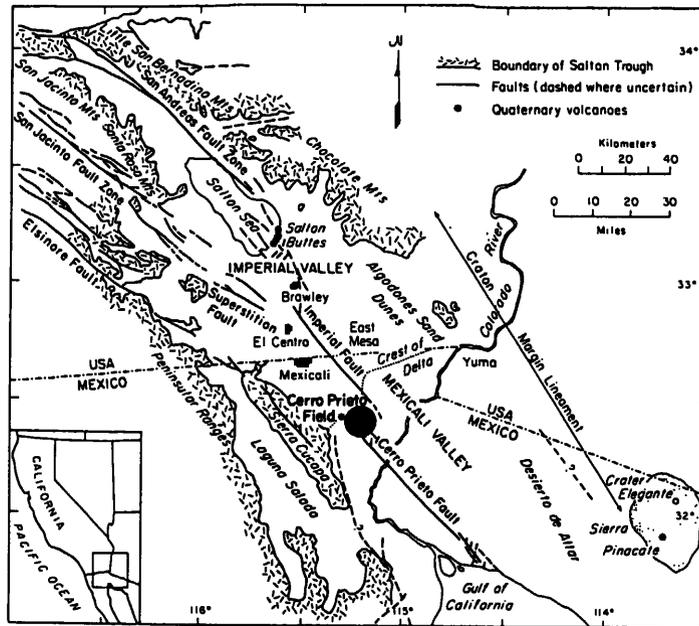
Figure 1. Regional geology and location of the Cerro Prieto geothermal area (from Halfman et al., 1984).
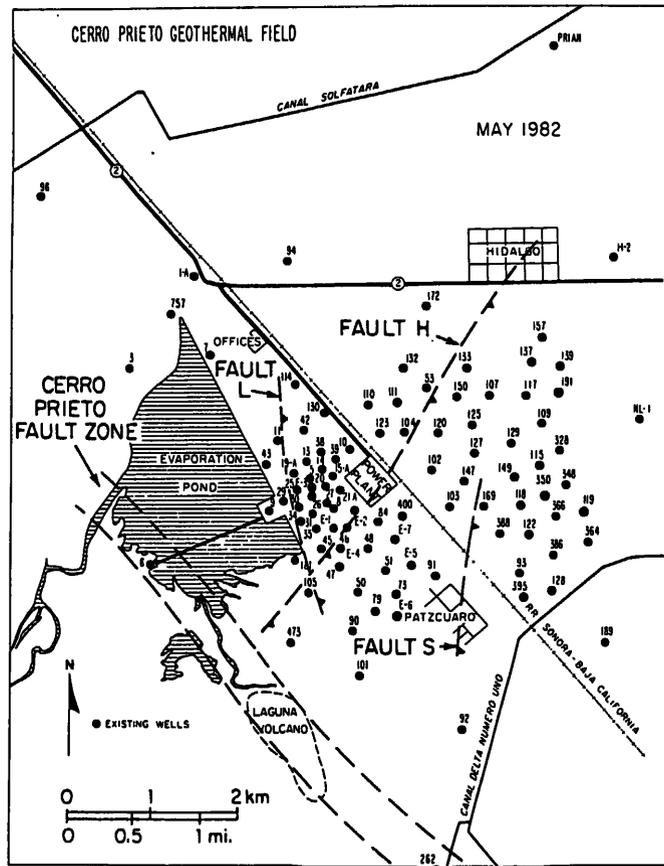

Figure 2. Location of wells and principal faults at Cerro Prieto. The faults are projected to the surface. (Modified from Halfman et al., 1984.)
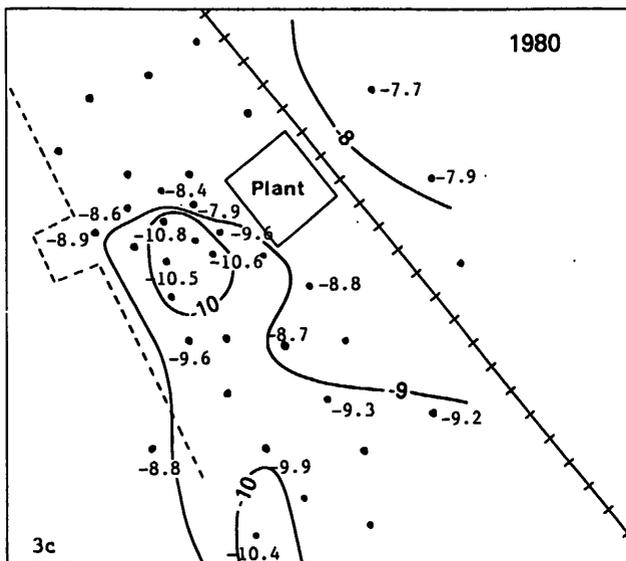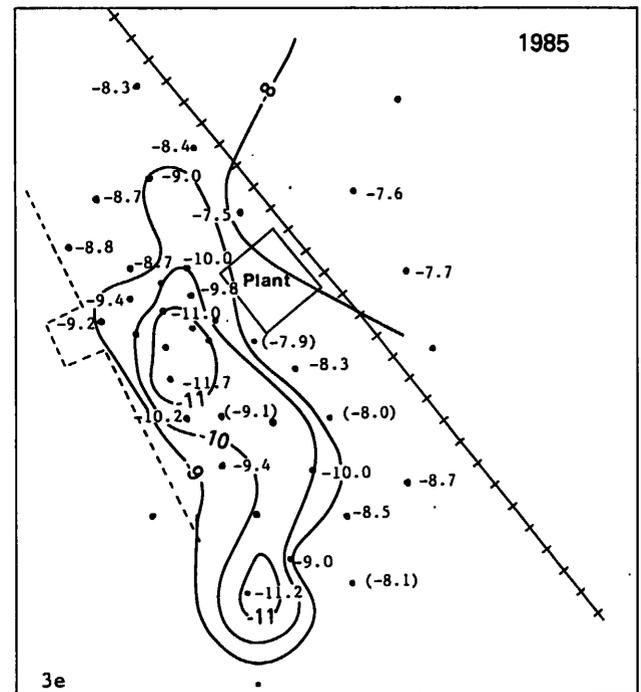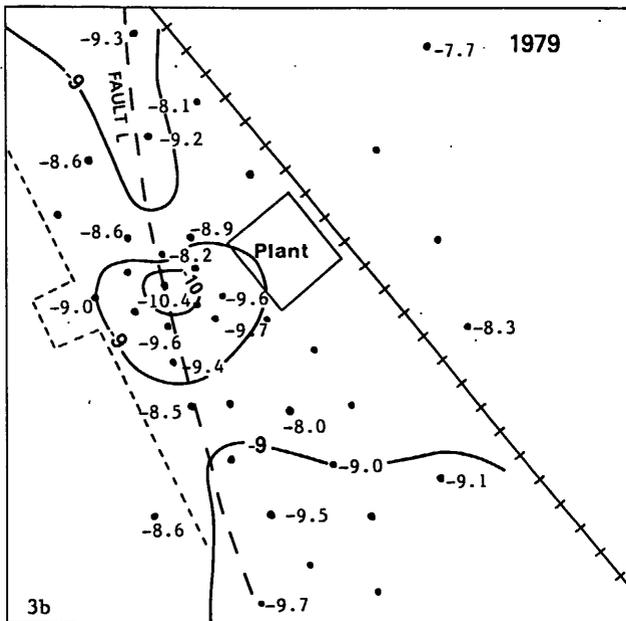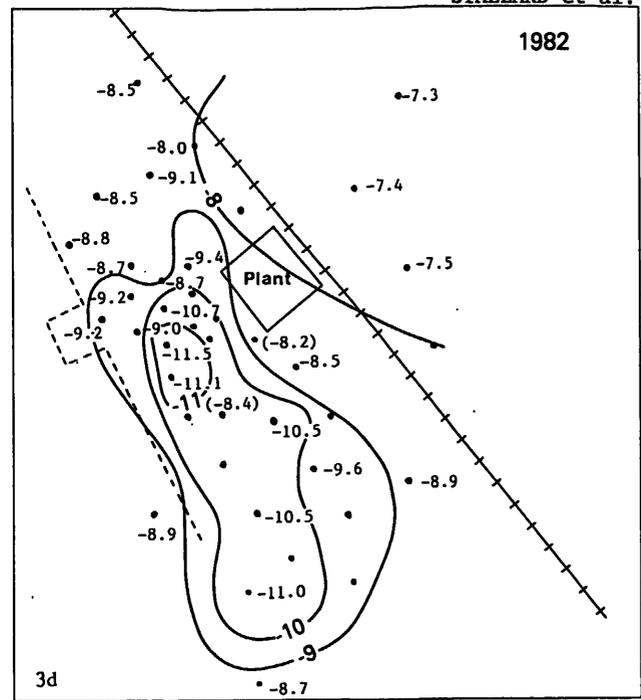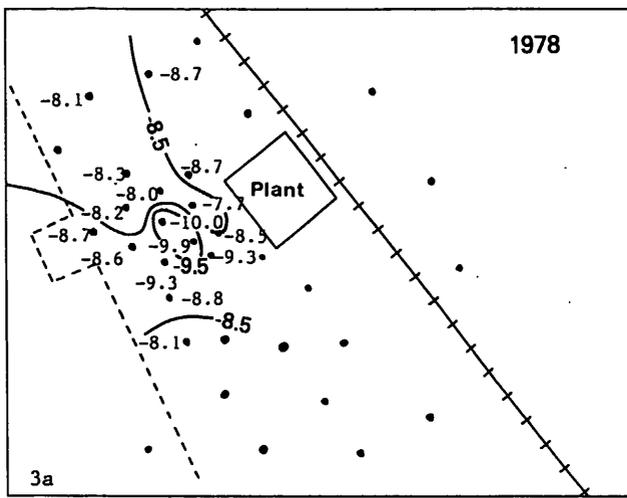
Fig. 3a-e. Distribution of $\delta^{18}O$ in the fluid feeding production wells from 1978 to 1985. Numbers shown to the northeast of the railroad tracks and those shown in parentheses represent β aquifer wells. All others represent α aquifer wells. Contour interval is 1 per mil.
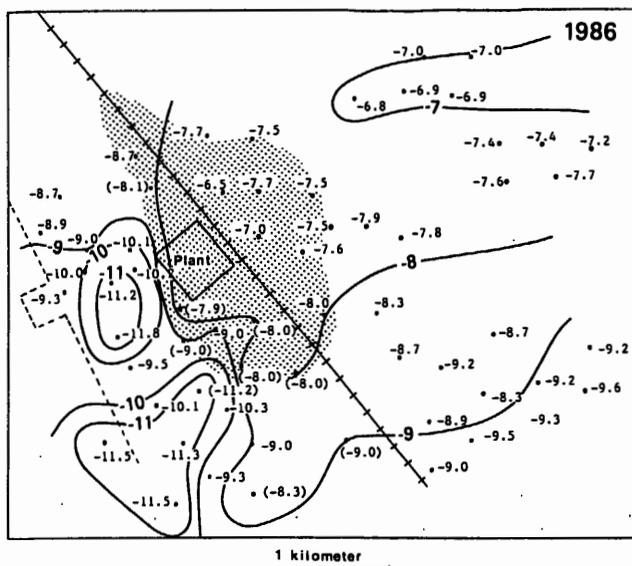
Fig. 4. Distribution of $\delta^{18}O$ in the fluid feeding production wells in 1986. Numbers in parentheses and those northeast of the railroad tracks represent β aquifer wells. Shading indicates area of aquifer boiling. Contour interval is 1 per mil.
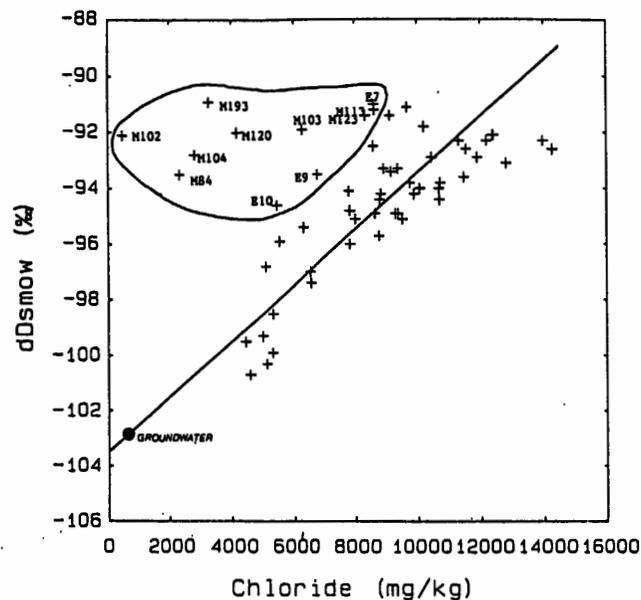

Fig. 6. Chloride (mg/kg) versus δD_{SMOW} (per mil) for fluids collected in 1986. Note mixing with local groundwater. Circled wells are mostly from shaded region of Fig. 4.
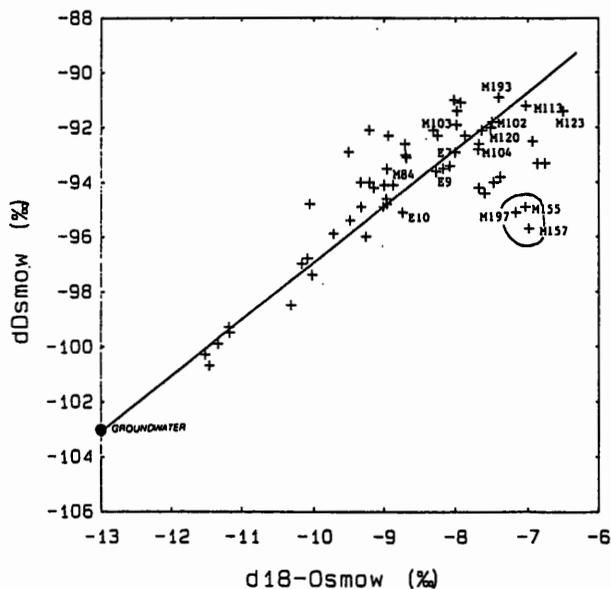

Fig. 5. $\delta^{18}O_{SMOW}$ (per mil) versus δD_{SMOW} (per mil) for fluids collected in 1986. Note mixing with cooler groundwater. Three circled wells are from eastern edge of exploited field.
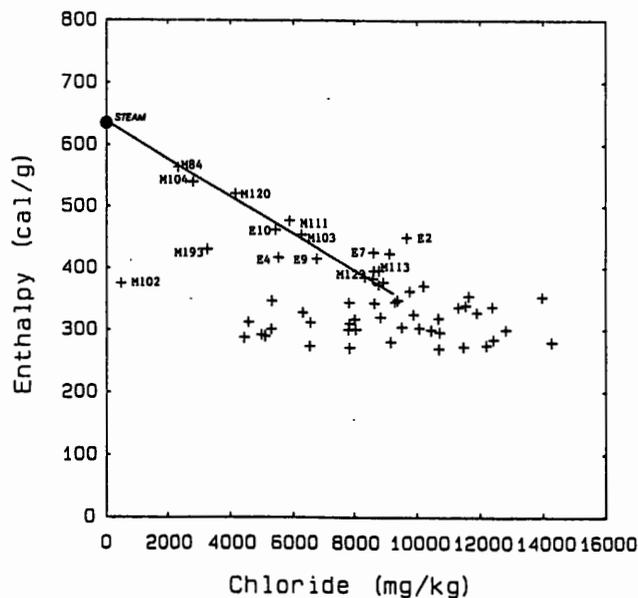

Fig. 7. Chloride (mg/kg) versus enthalpy (cal/g) for fluids collected in 1986. Note evidence of excess steam in wells from shaded region in Fig. 4.

210