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EFFECTS OF PRESSURE DRAWDOWN AND RECOVERY ON THE CERRO PRIETO BETA RESERVOIR IN THE CP-III AREA

Alfred H. Truesdell[1] and Marcelo J. Lippmann[2]

1. Consultant, Menlo Park, CA 94025
2. E.O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720
ahtruesdell@lbl.gov

ABSTRACT

The production characteristics of wells in the northwestern Cerro Prieto III area changed greatly when the CP-III power plant went on line in 1986. Fluid extraction in the field more than doubled and reservoir-wide boiling started immediately, greatly increasing the enthalpy of produced fluids. Some well fluids showed a decrease in chloride due to adiabatic steam condensation in the well and separator, and others were enriched in chloride due to boiling. As reservoir drawdown increased, entrance of cooler and more dilute groundwaters into the reservoir became evident (i.e., condensation stopped, and there was a decrease in enthalpy and chloride in produced fluids). Although some groundwater inflow was from the leaky western margin of the reservoir, the majority is in the northeast, inferred to be local and downward, possibly through more permeable zones associated with the normal fault H. This natural recharge and some reinjection have slowed and possibly reversed pressure drawdown throughout CP-III. Enthalpy has decreased and liquid saturation has increased as the steam-rich zone in the upper part of the reservoir has either disappeared or become thinner.

INTRODUCTION

Cerro Prieto fluids have been produced from two main geothermal reservoirs. The shallow "alpha" reservoir is only encountered in the western part of the field, while the deeper (below about 1600 m) and hotter (310-330°C) "beta" reservoir extends over the entire field (Lippmann et al., 1991; Truesdell et al., 1997). For administrative purposes the eastern wellfield has been subdivided into CP-II (toward the SE) and CP-III (toward the NW). Coincidentally there is a general correspondence between these areas and the geology of the field. CP-II is mostly on the SE downthrown block of the normal, SW-NE striking fault H, and CP-III on the upthrown block. The average depth to the top of the reservoir in the downthrown block is 2600 m, whereas that in the upthrown block is 2000 m (Fig. 1).

Since the initial (natural-state) reservoir temperatures were very similar in both areas (Fig. 2, 1986 Na-K-Ca temperatures), and the average elevation of the beta reservoir in the CP-III area is about 600 m higher than in CP-II (so that the reservoir pressure is some 50 bars lower in CP-III), boiling occurred earlier in CP-III during exploitation. Another important reason why the reservoir tends to boil faster and more extensively in CP-III is that natural (lateral) fluid recharge is much more restricted than in CP-II (Lippmann et al., 1991). While vertical recharge of hot (about 350°C) water upward through the fault H zone was identified in the early 1980s (e.g., Lippmann and Bodvarsson, 1983; Halfman et al., 1984), only recently has the influx of cooler groundwater down the same fault, in response to reservoir drawdown, become evident (Truesdell et al., 1997).

As soon as the exploitation of the Cerro Prieto field started in 1973, changes in the chemistry of the produced fluids related to reservoir pressure drawdown were observed (e.g., Truesdell et al., 1979; Stallard et al., 1987). But much larger changes in fluids from the beta reservoir over the entire Cerro Prieto field began to be observed after 1986, as the installed capacity in the field increased from 180 to 620 MWe (Truesdell et al., 1997). Because of the more significant changes observed in the enthalpy and chemistry of the fluids produced from CP-III, the discussion here will be restricted to this northwestern area of the field. The evolution of particular regions and wells will be followed over the 1986-96 period.

CHANGES OBSERVED IN PRODUCED CP-III FLUIDS

Changes in Inlet Vapor Fraction

Excess reservoir steam (the part of the total steam in excess of that produced by flashing of liquid) results from boiling in the reservoir due to the decrease of pressure (or increase of temperature). A useful

$$IVF = (E_{total} - E_{inlet\ liquid}) / \lambda_{inlet} \qquad (1)$$

where $E_{inlet\ liquid}$ is the enthalpy of the well inlet liquid calculated from the Na-K-Ca geothermometer temperature, E_{total} is the measured total enthalpy, and λ_{inlet} is the enthalpy of evaporation at the inlet temperature (Truesdell et al., 1989).

After three years of production from the shallow alpha reservoir in the CP-I area, high values of IVF (0.3 to 0.5) occurred locally due to near-well boiling. However, the fust wells drilled in 1980-82 into the northwestern upthrown block of the beta reservoir (Fig. 1) quickly developed higher values of IVF (to 0.7 by 1983). This boiling was not limited to the near-well region and resulted in the formation of a steam cap with separate entries of steam and brine to each well (Truesdell et al., 1989). The initial IVF of wells depended on the amount of production during well development and from nearby wells. The most isolated wells showed IVF values from 0 to 0.1 (e.g., M-103, M-53; locations given in Fig. 1), but boiling spread rapidly and most wells in this part of the beta reservoir started with IVF above 0.1. The highest IVF values are found adjacent to the fault H (*see* IVF values for 1989 in Fig. 3).

The startup of the CP-III power plant in 1986 caused an increase in fluid production of about 37 million metric tons per year. During the first year the new production was mainly from liquid (*see* Fig. 4 in Truesdell et al., 1997) and there were only small zones where IVF values exceeded 0.5 (Fig. 4). In 1986 IVF values above 0.5 were limited to the area including wells M-104, M-120 and M-121, and three smaller regions around M-84, E-1 and E-15 (Fig. 4). Wells in this area had been producing for several years and had caused a local steam cap to form.

The amount of boiling increased greatly in 1987 (Fig. 4). The area of IVF values greater than 0.5 expanded manyfold forming an irregular area in the upthrown block bounded on the southeast by the intersection of fault H with the top of the reservoir. The location of this zone of boiling and steam segregation was due to a number of factors. It was the shallowest part of the upthrown block, farthest from leaky boundaries to the west that provide pressure support, and had the largest number of producing wells (Figs. 1 - 4).

In the following three years to 1990, the boundaries of this boiling zone moved a bit, but it did not grow significantly in size. After 1992 the area of the reservoir with IVF>0.5 decreased (Fig. 4). As there was no decrease in production or any expansion in the area produced, this decrease in total enthalpy must have been due to increase in pressure, mainly *caused* by inflow of groundwater from outside the reservoir (Truesdell et al., 1995, 1997; Verma et al., 1996). The groundwater inflow was cooler, much less saline and much lower in $\delta^{18}O$ than the reservoir brine.

Changes in Chloride Content

Chloride in produced fluids from hot-water geothermal reservoirs is generally calculated to reservoir concentration in order to eliminate the variable effects of steam removal during separation and collection. The equation for this process is,

$$Cl_{res} = Cl_{sep}(1 - y) \qquad (2)$$

where Cl_{res} is the chloride concentration in the reservoir, Cl_{sep} is the chloride concentration after one stage of separation, and y is the steam fraction in the separation process. The steam fraction is often measured, *or* can be calculated from an enthalpy balance as,

$$y = (E_{res\ liquid} - E_{sep\ liquid}) / \lambda_{sep} \qquad (3)$$

where $E_{res\ liquid}$ is the enthalpy of reservoir liquid, $E_{sep\ liquid}$ is the enthalpy of separated liquid and λ_{sep} is the enthalpy of vaporization at separator conditions. This equation is repeated for each stage of separation before collection; that is, for a weirbox sample this calculation is made for separator pressure and again for atmospheric pressure in the silencer. If the reservoir temperature is known, or can be calculated from the total enthalpy, this is straightforward. However at Cerro Prieto where temperatures are not measured in producing wells and excess steam is common, it is necessary to use temperatures from geothermometers. As discussed earlier (e.g., Lippmann and Truesdell, 1990), where there is a temperature gradient toward a producing well, the Na-K-Ca geothermometer indicates the temperature far from a well, 'and the silica geothermometer, the near-well temperature. However for the CP-III reservoir, Na-K-Ca temperatures were used because silica temperatures are doubtful where both temperatures and IVF values are high due to dilution caused by adiabatic condensation.

Adiabatic condensation

Adiabatic condensation processes due to boiling in the CP-III area were described by Truesdell et al. (1992). This occurs when relatively high-temperature, low-enthalpy, saturated steam is decompressed to a separator pressure at which steam has a higher enthalpy. The steam condensate formed is nearly pure water and mixes with residual brine. If single-phase liquid enters the well and all separation occurs in the well and separator, this process does not affect the properties of the separated brine, however if there is excess steam entering the well, the condensate formed will dilute the brine.

Effects of solute dilution by condensate and concentration due to boiling

The effects of adiabatic condensation are usually minor because the amount of condensate formed is significant only if total fluid enthalpy, and reservoir and separator temperatures are relatively high (see Truesdell et al., **1992).** At CP-III the reservoir temperature is near **310°C** and the separator pressure for most wells is near **15** bara. **Under** these conditions **3%** of the steam will condense. If the IVF is 0.5, the effect of this condensate would be a 3% dilution, near the limit of analytical error, but if the **IVF** is **0.7** or more the effect should be appreciable. In practice significant dilution occurs less often than IVF values above **0.7.** This happens because the parts of the reservoir with high IVF values from intense boiling and steam separation also have highly concentrated residual brines. For most solutes (including chloride) these conditions tend to cancel each other to various degrees and the observed salinity varies widely.

Concentration of solutes due to boiling and loss of steam is similar to the increase of solute concentrations from steam separation in wells and separators, however where there is excess steam the amount of concentration cannot be calculated in a simple way. It is especially difficult for fluids from high-temperature reservoir areas because heat exchange with rocks occurs and, as noted above, adiabatic condensation affects chloride concentrations in separated brines. The observed reservoir liquid chloride concentrations show large variations related to processes in the reservoir.

Observed changes in CP-III fluids

Before the CP-III power plant was put on line, the reservoir chloride varied relatively little within the CP-III area. In **1986** (Fig. **5),** the first year of plant operation, there was only limited boiling and almost all of the CP-III area produced from fluid with reservoir chloride near **10000** ppm. The **8000** ppm Cl contour in Fig. **5** shows the boundary of the lower-chloride CP-I area to the southwest, and a **12000** ppm Cl zone near the boundary with CP-II. This higher salinity zone may be related to upflow along fault H, but this is rather speculative. When the CP-III plant went on line, the apparent chloride distribution changed rapidly. The **1987** contours show several low-Cl anomalies, one around wells **M-102, M-103** and **M-147,** and a larger one around wells **M-120, M-121, M-150, E-35** and **M-107** (Fig. **5; see** Fig. 1 for well locations). Two smaller negative anomalies occur, one at wells **M-194, E-25** and **M-193,** and another at well **T-348.** The **M-194** anomaly will grow, but the **T-348** anomaly disappeared when this well was shut in at the end of **1987. The** positive anomaly at the boundary with CP-II became shorted and wider.

The large low-Cl anomalies occur where intense boiling produced high IVF values (see Figs. **3-5).** By **1990,** the **8000** ppm Cl contour at the boundary with CP-I moved northeast to merge with the low-Cl anomaly at well **M-102** and **M-147** (Fig. **5). This** may indicate increased flow of low-Cl groundwater from the west. The low-Cl anomaly at **M-194** increased in size to include **E-43.** Low $\delta^{18}O$ in fluids from these wells (see Figs. 8 and **11** in Truesdell et al., **1997)** showed that **this** anomaly was not due to dilution by condensate (which is isotopically similar to the separated brine), but represented groundwater **drawn** into the reservoir because of the strong pressure drawdown. **These** wells encountered the beta reservoir at a relatively shallow depth (Fig. **1)** which may have contributed to the occurrence of inflow at this location. The low-Cl anomaly in the zone of high IVF values decreases in size and is replaced in the west by a high-Cl zone, and a small low-Cl zone **appears to** the southeast. These high- and low-Cl anomalies are related to the increased salinity caused by boiling masked in part by condensate dilution. The low-Cl zones occur where high IVF and boiling continued and the high-Cl zones to a decrease in boiling and condensate dilution.

Between **1990** and **1992** the zone of groundwater inflow grew larger and included wells **L-41** and **E-20** (Fig. **5).** In **1992,** a few wells in the northern area of the reservoir showed less than **8000** ppm Cl, but this occurred in only one year. From **1992** to **1996** there was an increase in size of the low-Cl zone in the northeast as inflow of groundwater continued (Fig. 5) and IVF values decreased along with the amount of dilution by condensate (Fig. **4).** With less masking by dilution, the area of high chloride increased in the area of boiling. The **12000** ppm Cl contour reflects this change in the north central part of the field, but in the south it also shows the arrival of injectate in wells **E-18, E-55** and **T-402**

Changes in IVF and chloride in individual wells

Although the fieldwide contour maps indicate reservoir-wide changes, they do not show clearly the relationships of changes in IVF and Cl for different parts of the reservoir. For this purpose, time-series graphs of IVF, Cl and fluid production have been drawn for representative wells (Fig. **6).**

Well **M-104** (location given in Fig. **1)** is typical of wells that were on line before the startup of the CP-III power plant (Fig. 6). The IVF of this well was influenced by production of liquid from nearby wells **M-120** and **M-102** which started up at about the same time but were drilled 250 and 300 m deeper, respectively. These wells started production with IVF values of about 0.1, but well M-104, producing from the shallower liquid-depleted zone, *started* with an IVF of 0.5 which was nearly constant until 1986. The increased flow with the startup of the CP-III plant caused IVF to increase to 0.6 and 0.7 in 1986 and then to >0.9 in 1987 where it remained to the present. The calculated reservoir chloride varied between 9000 and 10000 ppm (with a few outliers) until 1987 when Cl dropped to 8000 ppm as IVF increased. The well was shut down for repairs and afterward Cl started below 6000 ppm and increased to 9000 ppm as IVF decreased from nearly 1 to 0.85-0.9. The changes in chloride are probably due to the balance of dilution with condensate and concentration from boiling. As is common for wells with extensive reservoir boiling, wellbore scaling occurred and fluid flows decreased after the start of production and after each repair. Therefore, the flows did not clearly reflect reservoir pressure.

Some wells showed strong increases in chloride concentration from boiling and steam segregation apparently without large effects of condensate dilution. One of these wells, M-108 (Fig. 6), had a relatively low IVF until 1987 when it climbed to >0.9 in 1989 and remained high until 1994 (later workovers led to scattered values). The chloride climbed from about 10000 ppm in 1986-89 to >15000 ppm in 1992-94. The reservoir Cl may have been much higher if the produced brine contained as much condensate as suggested by the IVF values. Liquid flow from this well is variable as a result of intense boiling and scaling, but note that the flow of steam is relatively constant.

Of greater interest to the development of the field is the amount of low-chloride groundwater entering the reservoir. The wells located in and around the shallow production zone (centered on well E-43) at the northeastern part of the intersection of fault H with the top of the beta reservoir (Fig. 1) show the most dramatic decrease in chloride and IVF due to groundwater inflow. Well M-193 is one of these wells and its calculated reservoir chloride has steadily declined from near 11000 ppm in 1985 to 4000 ±500 ppm from 1992 to 1996 (Fig. 6). The inflow of cooler water has lowered the IVF from a maximum of about 0.7 in 1987 to about 0.2 from 1993 to 1996. The Na-K-Ca temperature has decreased from 310 to 280°C which is probably higher than the original groundwater temperature because of heating by reservoir rocks. Total fluid production from this well has been constant or increased somewhat from 1987 to 1996. This suggests that pressures remained constant, possibly due to the groundwater inflow.

The inflow of groundwater into the beta reservoir is not limited to the northeastern part of the reservoir. Although the affected area is not as large, groundwater inflow in the western part of the beta reservoir (CP-I area) also caused changes in chloride and flows. Production from these wells dates from 1980 and many of them have shown a decrease in IVF and chloride. E-59 is a more recently drilled well relatively unaffected by boiling in the vicinity of the well. The IVF of E-59 has decreased steadily from 0.8 in 1992 to 0.3 in 1996 as chloride decreased from 7000 to 6000 ppm (Fig. 6). The total flow and flow of water have increased while steam flow remained constant, possibly due to an increase in reservoir pressure.

CALCULATION OF THE AMOUNT OF GROUNDWATER INFLOW

Based on conservation of chloride, a simple order-of-magnitude calculation (Eq. 4) was made of the amount of cooler groundwater flowing down fault H into the beta reservoir in the region centered in the vicinity of wells E-43 and E-41 (Fig. 1; Fig. 4, 1994-1996). In that area of about 1.2 x 10^6 m^2, the average reservoir chloride content in the geothermal reservoir dropped from about 10500 ppm to about 7000 pm and the IVF changed from approximately 0.7 to 0.3 between 1986 and 1996.

$$[1-(IVF)_0]\,\rho_w\,\phi\,V\,C_0 + M_R C_R - \Sigma M_P C_P = [1-(IVF)_1]\,\rho_w\,\phi\,V\,C_1 \qquad (4)$$

ORIGINAL *AMOUNT* + RECHARGE - PRODUCTION = FINAL *AMOUNT*

IVF = inlet vapor fraction
ρ_w = density of geothermal liquid
ϕ = reservoir porosity
V = reservoir volume
M = mass of liquid
C = chloride concentration

Subscripts
0 = initial (1986)
1 = final (1996)
R = recharge
P = production

Assuming a reservoir thickness of 500 m, a porosity of 10%, an average hot liquid water density of 750 kg/m^3 and a chloride content in the inflowing groundwater of 4000 ppm, we estimated that about 100 million tons of groundwater recharged that part of the CP-III beta reservoir during this eleven year period.

One should remember that the yearly fluid production over the entire field is of the same order. That is, on the average this downward groundwater recharge through fault H is about one eleventh of the total mass of fluid being extracted every year from the geothermal system, and about one half of the fluid being reinjected in both reservoirs at present (see Figs. 3 and 5 in Truesdell et al., 1997). Eventually, a better estimation of this recharge should be made by modeling the Cerro Prieto system using numerical simulation techniques.

CONCLUSIONS

The use of inlet vapor fraction and calculated reservoir chloride concentrations has increased our understanding of the complex changes that occurred in the upthrown beta reservoir in the area of CP-III. When the CP-III power plant went on line, the strong pressure drawdown initially produced intense boiling with high flows of steam and relatively little reservoir brine. After about 5 years, pressures have stabilized or increased and the relative amounts of steam declined as groundwater was drawn into the reservoir. The estimated average rate of downward groundwater recharge through fault H is about half the present rate of total injection into both the alpha and beta reservoirs at Cerro Prieto. Groundwater entry and brine injection, and deepening of production wells (Beall et al., 1997; Ocampo et al., 1997), have helped the CP-III area to maintain its present high rate of fluid (and electrical) production.

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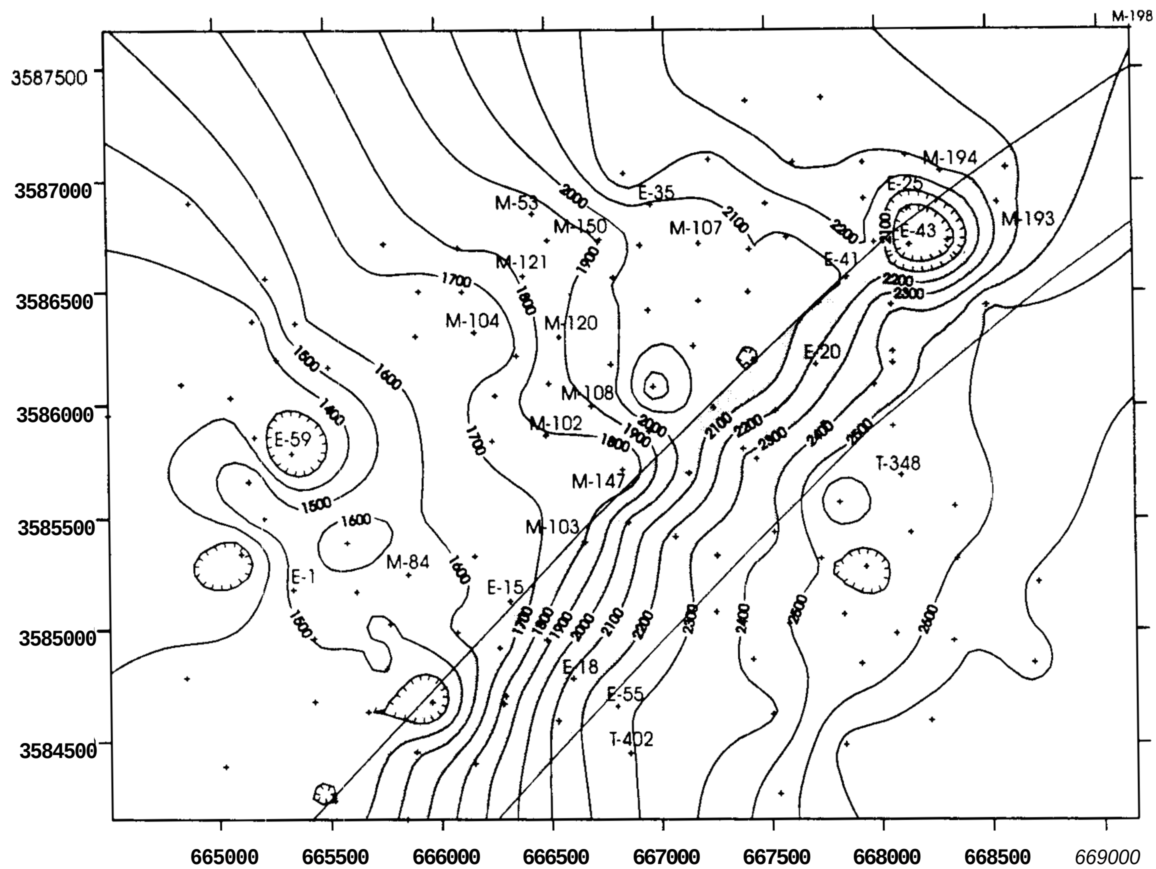

Figure 1. Depth in meters to the top of production in the Cerro Prieto beta reservoir. The intersection of fault H with the top of the reservoir **as** inferred from the contours is shaded. Coordinates are in meters. Well locations are shown by crosses, and wells mentioned in the text are named..

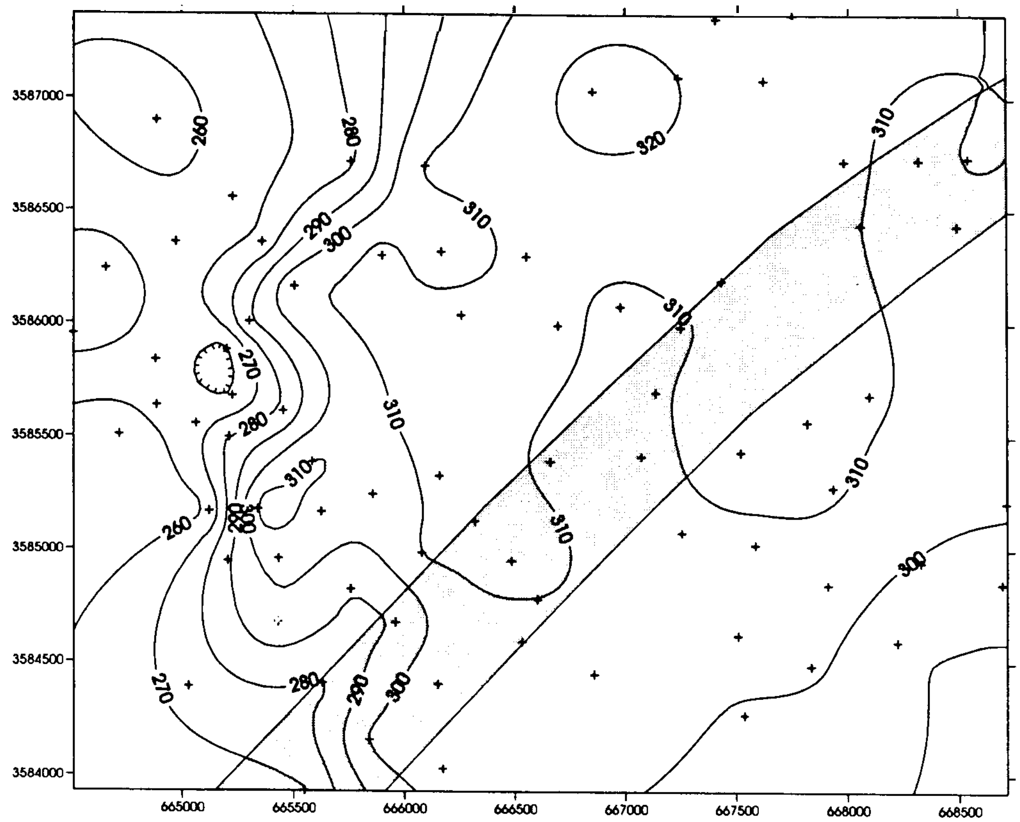

Figure 2. Contours of 1986 Cerro Prieto reservoir temperatures calculated from the Na-K-Ca geothermometer. Locations of 1986 producing wells are shown as crosses. See Fig. 1 for additional details.

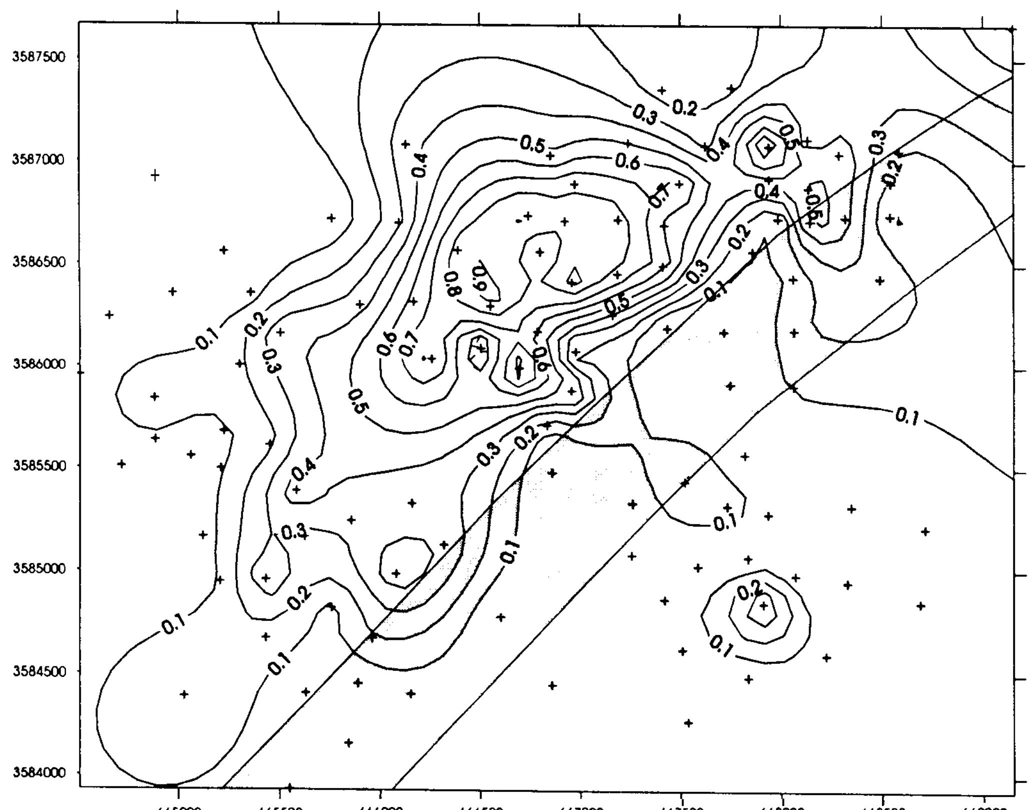

Figure 3. Contours of the inlet vapor fraction (IVF) for Cerro Prieto in 1989. Locations of wells producing in 1989 are shown as crosses. See Fig. 1 for additional details.

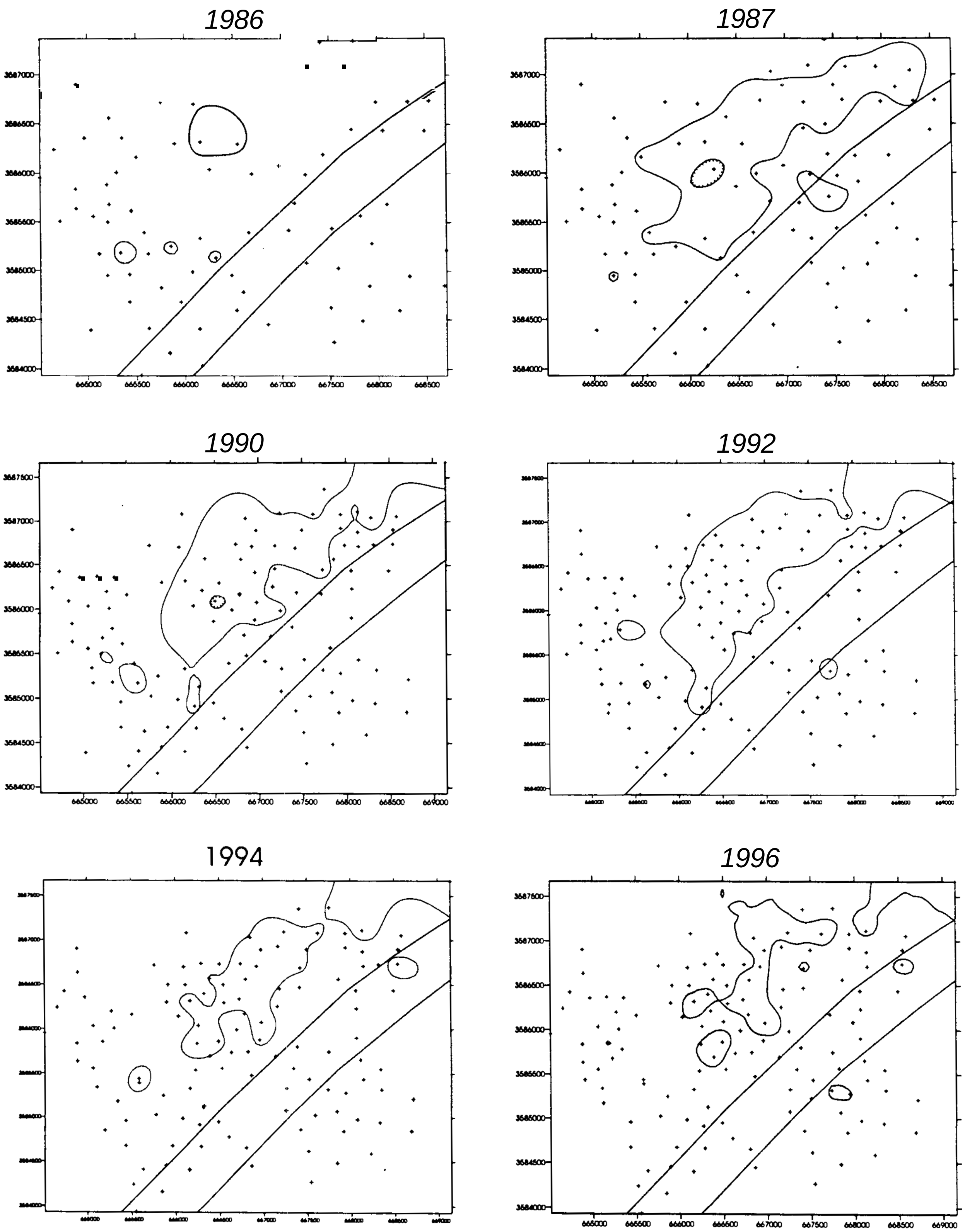

Figure 4. Contours of 0.5 inlet vapor fraction (IVF) for Cerro Prieto production from 1986 to 1996. The locations of wells in production each year are shown as crosses. See Fig. 1 for additional details.

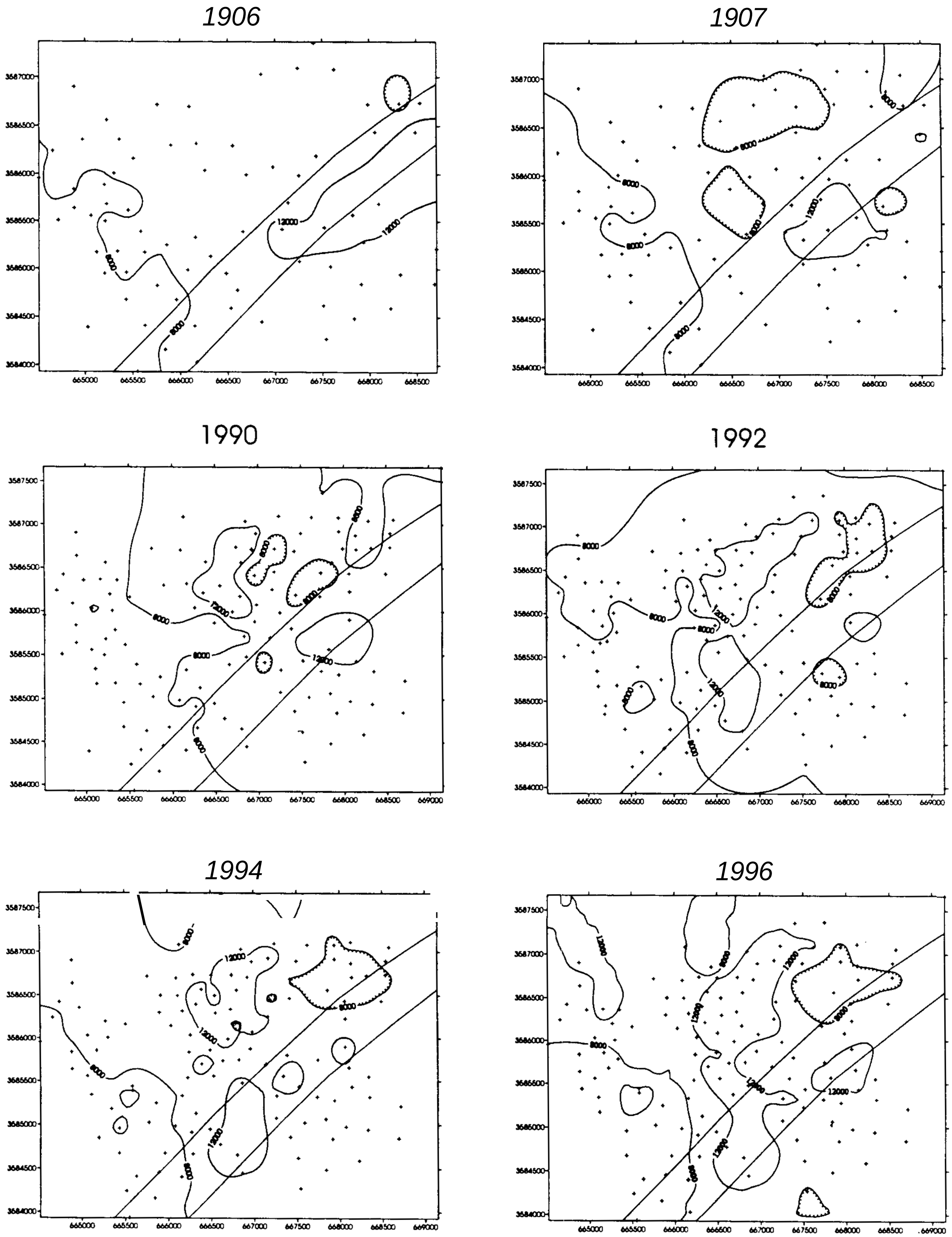

Figure 5. Contours of reservoir chloride concentrations of 8000 and 12000 ppm for the years 1986 to 1996. The locations of wells in production each year are shown as crosses. See Fig. 1 for additional details.

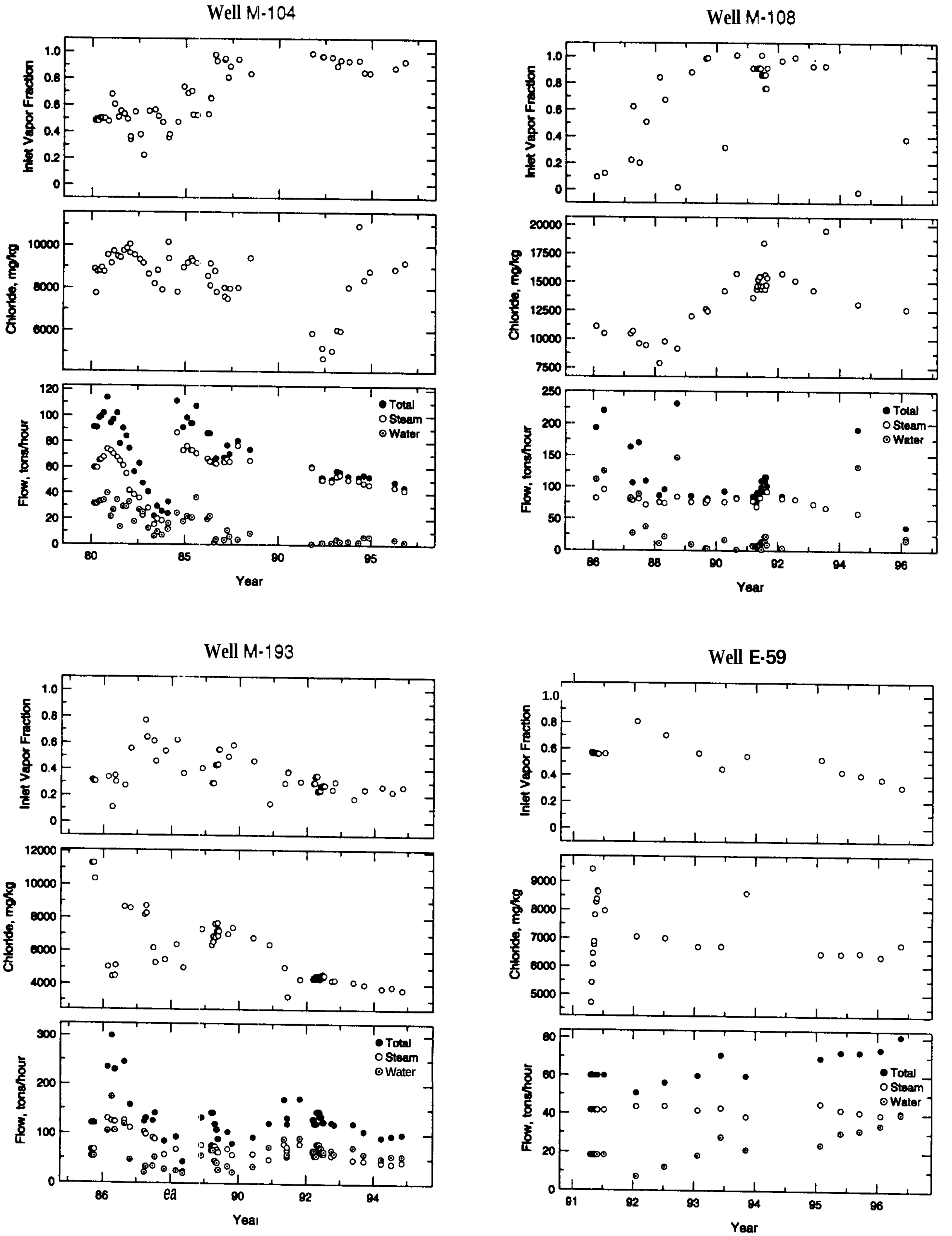

Figure 6. Changes with time of inlet vapor fraction, calculated reservoir chloride (ppm) and fluid flows (tons/hr) for selected Cerro Prieto wells.