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THE IMPORTANCE OF NATURAL FLUID RECHARGE TO THE SUSTAINABILITY OF THE CERRO PRIETO RESOURCE

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ABSTRACT

The Cerro Prieto field in northern Mexico has been under commercial exploitation for 25 years. At present its three power plants are generating around 600 MWe (the total installed capacity is 620 MWe). Almost 1800 million tons of fluids have been produced between 1973 and 1997 with only about 140 million tons injected back into the reservoir (injection started in 1989).

In spite of the large net fluid (and heat) extraction from the system, wells continue to supply steam to the power plants. This is largely due to the natural recharge of the reservoir. The inflow of cooler waters does not occur everywhere. Groundwater recharge along the north boundary of the present wellfield seems to be minor, but the lateral influx through the western and southern edges of the field, as well as vertical through two normal faults, has been documented. The amount of natural fluid recharge at Cerro Prieto is estimated based on changes in chloride in the produced fluids.

Because of the pressure support provided by natural recharge, not only has the life of the field been extended, but also that of individual wells. The behavior of wells in areas affected by this fluid inflow contrasts with that of wells located where recharge is only minor, or non existent. Other wells are influenced by the injection of waste geothermal waters.

INTRODUCTION

The importance of fluid recharge in liquid-dominated geothermal systems is well established. Without active circulation (i.e., recharge and discharge) of hot fluids, these systems would not exist or would be short lived (i.e., Donaldson et al., 1983; Lippmann and Truesdell, 1990). The case of vapor-dominated systems is quite different; since they are driven by heat conduction, mass recharge is lacking or tends to be negligible.

Cerro Prieto is a large, hot (320-350°C) field (total capacity at least 780-800 MWe; Hiriart-Le Bert and Gutiérrez-Negrín, 1996) hosted in sedimentary and metasedimentary rocks, but otherwise it is a typical water-dominated system. In a number of papers the evidence for groundwater recharge at Cerro Prieto was discussed. We now review the most relevant results and conclusions reached by these earlier studies.

The reservoir pressure drawdown caused by the exploitation of the field (Bermejo et al., 1979; Pelayo et al., 1989), which started in 1973, resulted in an almost immediate inflow of cooler, more dilute groundwaters into the western, shallower Alpha reservoir. This was evident from changes in the chloride and silica content and isotopic characteristics of the produced fluids (i.e., Truesdell et al., 1979a, b; Grant et al., 1984; Stallard et al., 1987). The paths followed by the groundwater were studied by Truesdell and Lippmann (1986), who showed that the waters invaded the Alpha reservoir horizontally from the west and vertically down the normal, east-dipping Fault L.

Later, as the development of the field proceeded towards the east, studies tended to focus on the much larger Beta reservoir. Initially groundwater recharge to this deeper aquifer was believed to be lateral, along the edges of the system, except perhaps to the north where there is an impermeable boundary (Truesdell and Lippmann, 1990; Lippmann et al., 1991; Truesdell et al., 1995). More recent chloride and isotope data, however, clearly indicate that the major recharge to the Beta reservoir is by groundwater flowing down the normal, SE-dipping Fault H (Truesdell et al., 1997; Truesdell and Lippmann, 1998). These more recent papers also discuss the effects of man-made recharge (i.e. injection) on the chemistry of the produced fluids.

As indicated by Grant et al. (1984) geothermal fluids in the Alpha reservoir mixed with cooler waters even before commercial-scale fluid production began. This mixing was not uniform as shown by the chloride content of fluids produced by different wells. In response to reservoir drawdown caused by exploitation, only local boiling occurs near most Alpha wells (i.e., no extended steam zone is formed). This is due to the lateral and vertical groundwater recharge that provides significant pressure support (essentially the reservoir responds as having a constant-pressure boundary).

The behavior of Beta wells is quite different and varies over the system. Until about 1985, before power plants

CP-II and III came on line more than doubling the installed capacity in the field, production from this deeper reservoir was relatively small. However because temperatures are higher and fluid recharge is more restricted than in the alpha reservoir, an extended boiling zone began to form very early. After 1986, some wells showed adiabatic steam condensation, others produced fluid enriched in chlorides due to boiling (Truesdell and Lippmann, 1998). Other wells in the Beta reservoir present clear indications of the effects of horizontal and vertical groundwater recharge. Still others show mixing with the waters being injected along the western edges of the system (Gutiérrez Puente and Ribo Muñoz, 1994).

OBSERVATIONS

Contours of reservoir chloride across the area of the reservoir and plots of the changes with time of reservoir chloride (Cl) for individual wells provide indications of the time and amount of groundwater (or injectate) reaching each well. For the Alpha reservoir the earliest maps show a chloride maximum in the middle of the field with lower chloride on all sides except the northwest (Figure 1), and later maps show a strong minimum in the center (Figure 2). A typical central Alpha well, M-35, initially (1974) had reservoir Cl near 10,000 ppm which decreased slowly to 8500 ppm by 1979, when Cl sharply dropped to nearly level out at 4500 ppm (Figure 3). In 1992 injected brine reached this well and Cl increased rapidly. This behavior is interpreted as showing production from reservoir water with a Cl gradient followed by the arrival of a groundwater front and an injectate front. Wells at the northern part of the Alpha reservoir decrease slowly in Cl from their initial values until they are strongly affected by injected brine. Southern wells behave similarly, but do not show injectate.

The response of the Beta reservoir is much more complex as seen in a contour map of reservoir chloride for 1997 (Figure 4). Much of the chloride behavior in Beta wells has been described by Truesdell and Lippmann (1998), here only chloride changes in wells located near reservoir boundaries and points of fluid inflow will be described. The histories of reservoir chloride concentration of these wells are shown in Figures 5-7 and their locations in Figure 4. These wells are typical of their areas, but others show the same changes.

Wells near the margin of the reservoir are considered likely to show evidence of groundwater recharge. In the west, the Beta reservoir rock (sandstone with minor shale) probably interfingers with coarser sediments (Halfman et al., 1984) which could provide an avenue for entry of groundwater. Less information is available about other boundaries. Chloride changes for well E-2 (Figure 5) on the west indeed show groundwater inflow with a gradual decrease from 13,000 to 10,000 ppm, followed by a sharp drop to 4000 ppm and in 1993 a rapid increase. This is interpreted in the same way as the behavior of well M-35 in the Alpha reservoir, although the E-2 pattern is not as clear.

The southern boundary is evidently also leaky to groundwater as illustrated by well T-395 (Figure 5). Chloride in this well has decreased linearly from 10,000 to 7000 ppm. This suggests that there is a gradient in chloride to the south. To the north of the field the system appears closed to groundwater entry as shown by essentially constant chloride in well M-155 (Figure 6). This was suggested earlier because boiling appeared rapidly in the north when the CP-III powerplant went on line (Truesdell et al., 1997). Well T-394 in the east also shows constant chloride (Figure 6), but the reservoir boundary is probably far to the east as indicated by drilling.

Other parts of the Beta reservoir have shown rapid changes in chloride due to the entry of waters from outside. At the northwest part of the intersection of fault H with the top of the upthrown block (Figure 4), lower chloride waters appeared soon after the start of large-scale production. The area with lower chloride has spread 3.5 km east- west and probably along the entire length of the intersection in the drilled field. A typical well at the center of this area is E-41 (Figure 7) which shows a steady decrease in reservoir chloride from 11,000 ppm to about 4000 ppm. A similar decrease was shown by well M-193 (Truesdell and Lippmann, 1998). This was interpreted as showing flow of groundwater down fault H into the upper part of the reservoir. It was estimated that up to 1996 about 100 million tons had flowed into the reservoir in this area.

A strong high-chloride anomaly appears in the south-central part of the field centered on well E-55 (Figure 7). This represents return from brine injected into well E-6 increasing from 0.5 $\times 10^6$ tons in 1990, to 4.3 $\times$ 10^6 tons in 1991 and about 5-6 $\times$ 10^6 tons per year thereafter (unpublished CFE data). The shape of the Cl versus time curve indicates the arrival of a strong front.

METHODOLOGY

Observations of groundwater inflow into the Cerro Prieto reservoirs have been mostly qualitative (see Introduction) or limited to parts of the field. In order to quantify the contribution of groundwater inflow to the total production of the field a mass balance approach was used. Although groundwaters adjacent to the exploited reservoirs have not been sampled *in situ*, some wellfluids consist nearly entirely of groundwater that has displaced the original thermal water (Figure 3).

This groundwater has been altered in temperature and

reactive constituents, but certain unreactive components remain unchanged. In particular these are chloride ion and the hydrogen and oxygen isotopes of water which allow the calculation of the fraction of groundwater in the total produced fluid. Isotopes have great advantages in this calculation because they are less affected by boiling and condensation processes (Stallard et al., 1987; Verma et al., 1996; Truesdell et al., 1997), but the isotope database is sparse, particularly in early years. For this reason it was decided to use chloride ion which the Comisión Federal de Electricidad (CFE), the operator of the field, has analyzed once or twice a year for each well from the start of production. A chloride balance on the reservoir fluid can be written as

$$\mathrm{Cl}_{\text{present reservoir water}} = X \cdot \mathrm{Cl}_{\text{groundwater}} + (1-X) \cdot \mathrm{Cl}_{\text{original reservoir water}} \quad (1)$$

where X is the mass fraction of groundwater. This equation assumes that mixing is the only process affecting chloride. Although mostly true for the shallower Alpha reservoir, it does not apply to large parts of the Beta reservoir in the CP-III area (in the northeastern part of the field) which have undergone strong boiling and phase segregation during production (Truesdell and Lippmann, 1998).

Another complication with the application of Eq. 1 is that concentrations are referred to the liquid phase in the reservoir rather than to the total discharge. This is necessary for wells that produce excess enthalpy fluids as commonly found at CP-III. Therefore additional chloride and enthalpy balances were used to calculate Cl in reservoir liquid for both all-liquid and excess steam reservoir fluids. These equations are

$$\mathrm{Cl}_{\text{reservoir water}} = \mathrm{Cl}_{\text{separator water}} \frac{1 - Y_{\text{separator}}}{1 - Y_{\text{reservoir}}} \quad (2)$$

$$Y_{\text{separator}} = \frac{H_{\text{total fluid}} - H_{\text{separator water}}}{H_{\text{separator steam}} - H_{\text{separator water}}} \quad (3)$$

and

$$Y_{\text{reservoir}} = \frac{H_{\text{total fluid}} - H_{\text{reservoir water}}}{H_{\text{reservoir steam}} - H_{\text{reservoir water}}} \quad (4)$$

where Y is the steam (mass) fraction and H is enthalpy. Production enthalpy (H total fluid) is measured monthly for each well by CFE, reservoir enthalpy values were based on Na-K-Ca geothermometer temperatures, and thermodynamic data for pure water were used (Keenan et al., 1969). The reservoir quantities used in Eqs. 1 to 4 apply strictly only to fluid at the inlet to the well, but "reservoir" is used here due to common practice.

In order to calculate the mass fraction of groundwater (X), using Eq. 1 the chloride concentrations in groundwater and original reservoir water must be known or estimated. Groundwater chloride was estimated from the chloride histories of wells like M-35 (Figure 3) in which original reservoir water has been completely replaced by groundwater, or nearly so. Wells used for this estimation include M-26, M-31, M-35 and M-90 producing from the Alpha reservoir, and M-193, E-4, E-27 and E-41 producing from the Beta reservoir. The concentrations of chloride in groundwater indicated from these wellfluids range from near 3500 to 4000 ppm. For the computations, a value of 4000 ppm was assumed for both reservoirs.

Obtaining concentrations of chloride in original reservoir water is somewhat more difficult. Chloride gradients in the earliest Alpha fluids suggest that the edges of the reservoir were affected by groundwater inflow and mixing before the start of production. The data for 1973 (the first year of production) show four wells in the center of the drilled area with 10,000 ± 500 ppm Cl. Away from this area the chloride drops off to about 8500 ppm (Figure 1). For the Beta reservoir, 1986 data (before the start of intense boiling in the CP-III area) show an elongated area in the east-central part of the field with five wells with reservoir Cl above 12,000 ppm, while the rest of the wells show reservoir Cl of 11,000 ±1000 ppm (Truesdell and Lippmann, 1998). Based on these data the original geothermal fluid is assumed to have a reservoir chloride of 10,000 ppm in the Alpha reservoir and 11,000 ppm in the Beta reservoir.

RESULTS

Applying Eqs. 1 to 4 to waters produced from the Alpha reservoir is straightforward. Chloride concentrations of 10,000 ppm and 4000 ppm were used as the original compositions of the reservoir water and the entering groundwater, respectively. Figure 8 shows the evolution of Cl in the reservoir, with a line for each well connecting the yearly average concentrations. The spread in Cl concentrations at the start of production apparently results from mixing with groundwater which started before the plant went on line. The slope of the change in chloride is similar for most wells, and some wells near the center of the reservoir that started with higher Cl, cross over to the trend of the low-Cl wells (Figure 8). This resulted from the entry of groundwaters (flowing down fault L) into the Alpha reservoir near its center (Figure 2). Many wells show upturns after 1991 due to increasing mixture with brine from the evaporating pond injected into the reservoir along the western edge of the field; injection began in 1989, becoming important after 1991 (Table 1). The results of these calculations are presented in Table 1 which shows, for each year, the total production from the Alpha reservoir and the part originating from groundwater. Note that after 1983, more than half of the total Alpha production was from

groundwater recharging the system.

As indicated earlier, the Beta reservoir evolution is more complex. The extreme boiling in the northwestern CP-III part of the reservoir caused wellfluids to fluctuate in chloride as dilution with adiabatic condensate occurred in wells with the largest amounts of excess steam, followed in the same wells by high-chloride waters residual to the earlier boiling. These processes have been described at length elsewhere (Truesdell and Lippmann, 1998). As a result of these processes (and the large number of wells producing from the Beta reservoir), the diagram of changes in reservoir chloride for single wells is confusing and relatively uninformative (Figure 9). Only at the NE end of the intersection of fault H with the top of the upthrown Beta reservoir (in the CP-III area) did groundwater entry and strong boiling coincide. In any case boiling in this area did not last long because it was quenched by the increase in reservoir pressure caused by the entry of groundwater.

At first we considered removing wells from the computation if they had unusually low or high reservoir chloride. However the groundwater fractions calculated with and without these wells differed little, probably because they are few. The concentration changes were short lived and partly compensatory. We therefore left them in the calculation, but for the calculation of the fraction of groundwater we did remove wells strongly affected by injection of brine from the pond, for the reason that there was no compensating dilution process. Although only three wells are strongly affected by injectate, the inclusion of these wells lowered the average groundwater fraction by about 10%.

The fraction of groundwater was calculated for each Beta well on a yearly basis (usually there are only one or two chloride analyses in a year) using original reservoir water and groundwater chloride concentrations of 11,000 and 4000 ppm, respectively. The results of these calculations summed for each year are given in Table 1. The part of total production due to groundwater is much smaller than in the Alpha reservoir. Initially the results fluctuate from a thirtieth to a quarter of the total, but after 1985 the relative amount is stable at between a fourth and a fifth of the total production. Note the amounts injected shown in the last column are about the same or somewhat less than the groundwater recharge into both reservoirs.

DISCUSSION

Mixture with groundwater was emphasized by Grant et al. (1984) as the dominant reservoir process in both the natural and exploitation states for the Cerro Prieto Alpha reservoir. These authors infer from the natural state enthalpy-chloride gradient that mixing with cooler water acted as the dominant natural-state cooling mechanism, and that exploitation was dominated by "heat sweep" by inflowing groundwater with minor boiling. This behavior is quite different from Wairakei and Broadlands, New Zealand in which boiling is the dominant cooling mechanism.

Chloride-time plots for central Alpha reservoir wells (e.g., Figure 3) show two regions, a gentle decline in chloride lasting a few years and a rapid drop indicating the arrival of a chemical front (Grant et al., 1984; Truesdell and Lippmann, 1986). Moderate chloride groundwaters entered from the sides of the Alpha reservoir producing the gentle chloride gradient in the initial and early exploitation state. Later on, when reservoir pressures declined sufficiently, much lower salinity groundwaters from above flowed down Fault L into the reservoir producing the sharp change in water chemistry.

On the basis of the distribution of isotherms in the subsurface, we estimated that the volume of the reservoir at temperatures at and above 250°C is about 49.7 km^3 (CFE unpublished data). Assuming an average porosity of 0.15 and an average fluid density of 750 kg/m^3, the estimated initial (pre-exploitation) mass of geothermal brine in the reservoir at these high temperatures is about 5.6×10^9 metric tons. This amounts to about three times the mass that has been produced from the system since 1973 (Table 1). In other words, considering the heat stored in the rock, the reservoir water in place, the natural groundwater recharge, and the injection of waste geothermal liquids, the Cerro Prieto field will be able to sustain production for a long time. A more precise estimation of the commercial lifetime of the field, could only be obtained using numerical modeling techniques, which will also permit consideration of different exploitation and injection scenarios.

The advantages of "leaky" boundaries in the formation and exploitation of geothermal reservoirs were emphasized by Lippmann and Truesdell (1990) and Verma et al. (1996). The latter authors state that induced inflow of cooler groundwaters is an efficient way of exploiting heat stored in fluids and rocks of a geothermal system, because reservoir pressures are maintained and heat is swept to producing wells without the necessity of drilling wells for injection. Considering the data shown in Table 1, it seems likely that the large and stable production of Cerro Prieto has been largely supported by the inflow of groundwater. The produced groundwater constitutes about one quarter of total production, without which the level of liquid saturation would drop below the bottom of most wells. Thus, without this inflow most wells would eventually produce entirely or mostly steam and would decrease in flow as observed in the CP-III zone of intense boiling (see discussion of well 615 in Truesdell et al., 1997).

Leaky reservoir boundaries help sustain production and extend the commercial lifetime of a geothermal field, but since recharge is mainly from cooler groundwater, the temperature of the reservoir rocks and fluids must progressively decrease. Thus, power plant design should allow for the use of lower separation pressures as the exploitation of a geothermal field proceeds.

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Table 1. Groundwater (GW) contribution to production from the Cerro Prieto Alpha and Beta reservoirs, compared to total injection (quantities given in millions of metric tons)

Year	Alpha Reservoir		Beta Reservoir		Injection
	Total	GW	Total	GW	Total
1973	23.35	4.35			
1974	22.79	3.24			
1975	21.42	3.90			
1976	26.18	6.53			
1977	25.79	8.73			
1978	26.86	7.40	1.02	0.29	
1979	29.58	7.98	7.20	2.19	
1980	25.21	7.75	8.79	1.79	
1981	24.69	9.36	15.00	0.56	
1982	22.35	8.97	23.31	0.31	
1983	21.07	8.83	22.84	1.85	
1984	19.33	8.74	20.41	2.28	
1985	16.74	8.54	24.93	3.10	
1986	15.81	8.64	90.38	14.59	
1987	15.64	9.02	90.69	18.98	
1988	13.34	8.46	84.04	21.06	
1989	12.85	8.17	90.38	18.41	1.48
1990	19.41	12.54	99.29	18.90	4.50
1991	18.15	10.82	100.00	23.70	10.03
1992	15.16	10.00	95.64	20.95	19.35
1993	15.16	8.67	95.29	12.20	24.23
1994	15.36	9.24	94.48	16.34	20.08
1995	15.17	9.46	92.74	20.37	22.27
1996	12.20	7.43	97.41	25.60	18.30
1997	8.63	5.71	98.28	26.67	20.22
Totals	482.24	202.48	1252.12	250.14	140.46

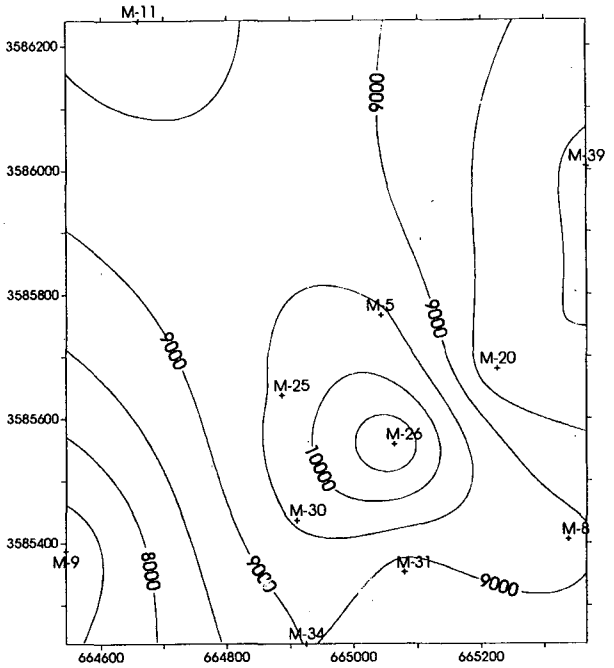

Figure 1. Map of reservoir chloride concentrations for the Alpha reservoir in 1973 (in ppm).

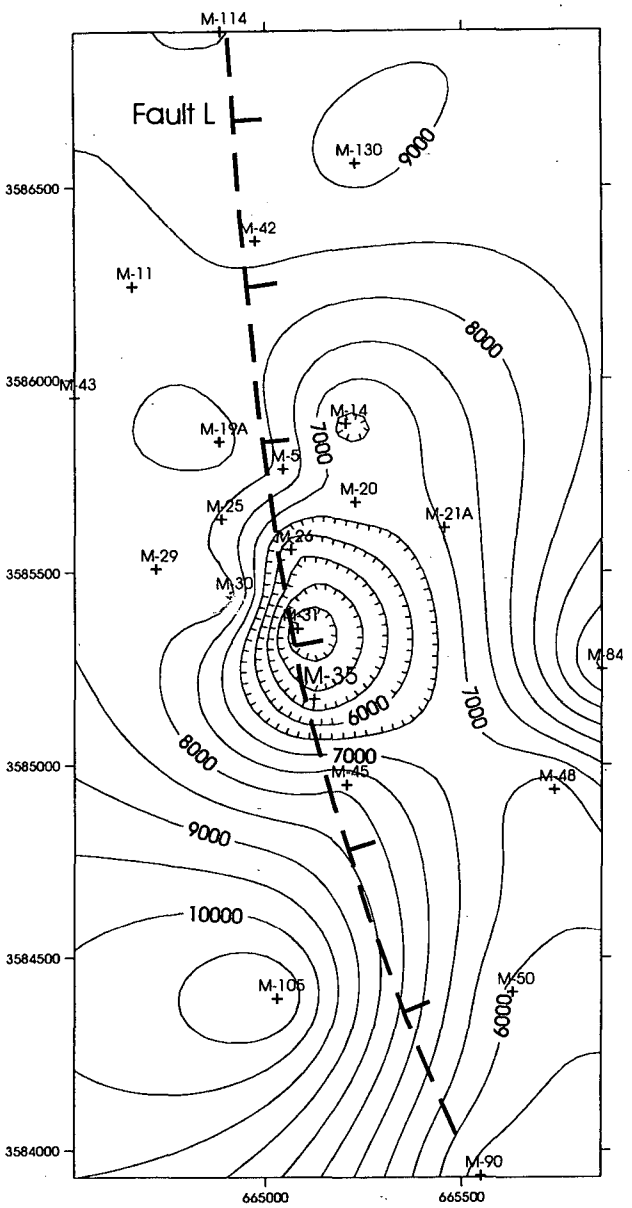

Figure 2. Map of reservoir chloride concentrations (ppm) for the Alpha reservoir in 1983 with the position of fault L (Halfman et al., 1984) shown at reservoir level.

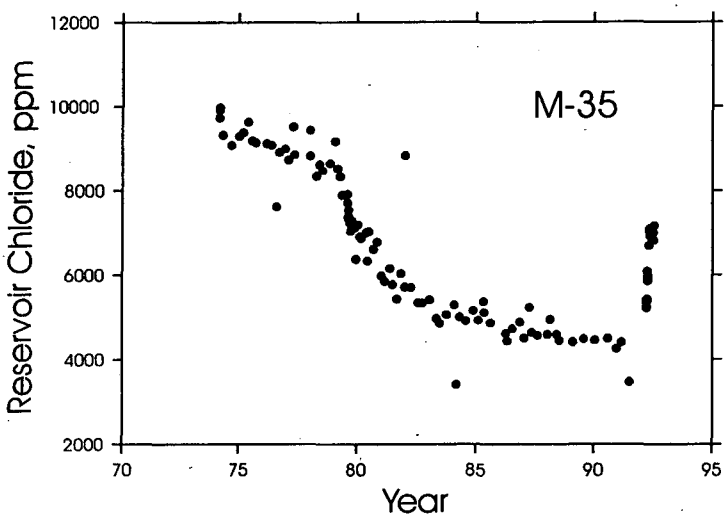

Figure 3. Reservoir chloride concentration history for Alpha reservoir well M-35.

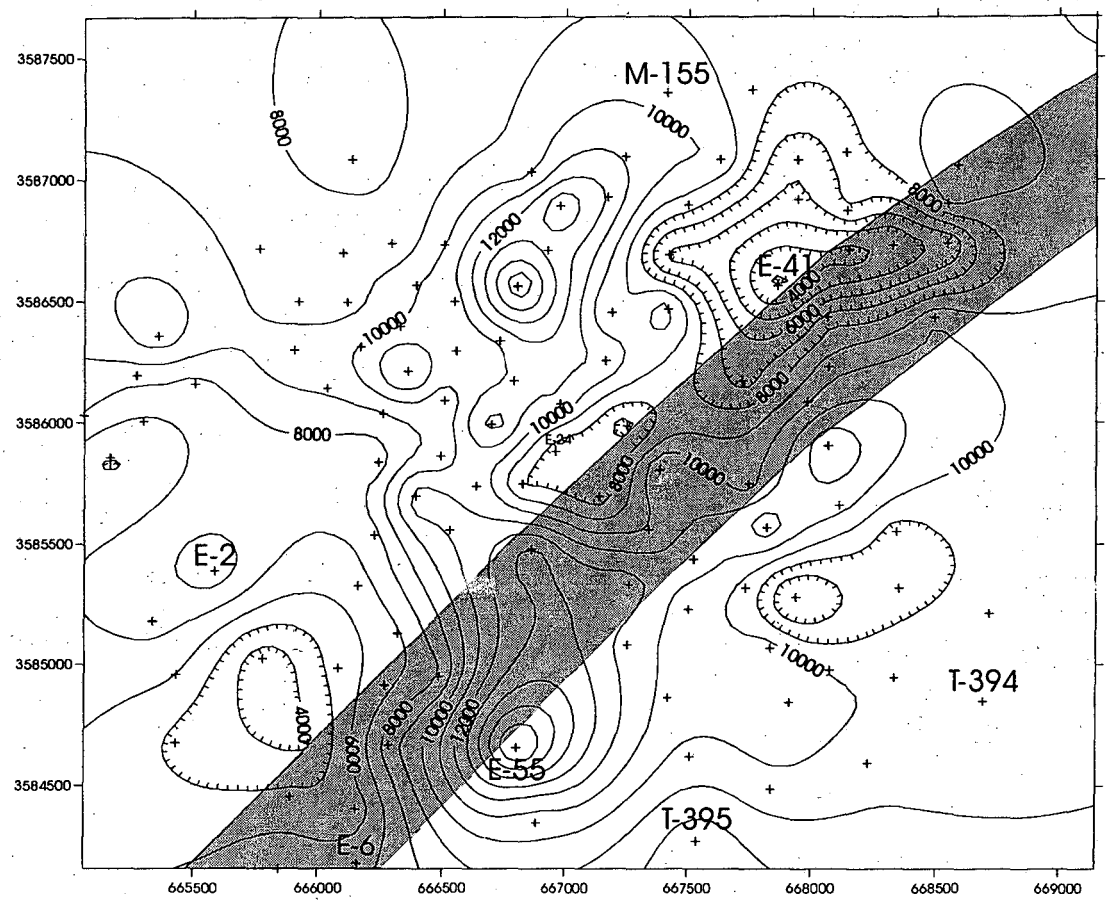

Figure 4. Map of reservoir chloride concentrations for the Beta reservoir in 1997 (in ppm). The location of fault H (Halfman et al., 1984) at the reservoir level is shaded; producing wells are shown by crosses with typical wells (in Figures 5-7) named.

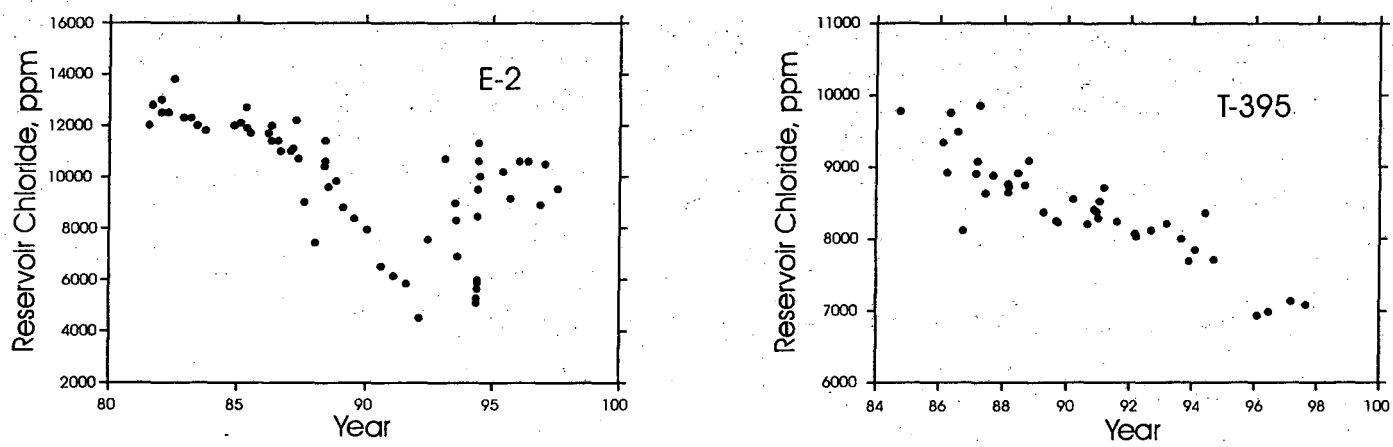

Figure 5. Reservoir chloride changes(in ppm) for wells near the western (E-2) and southern (T-395) margins of the Beta reservoir showing groundwater inflow.

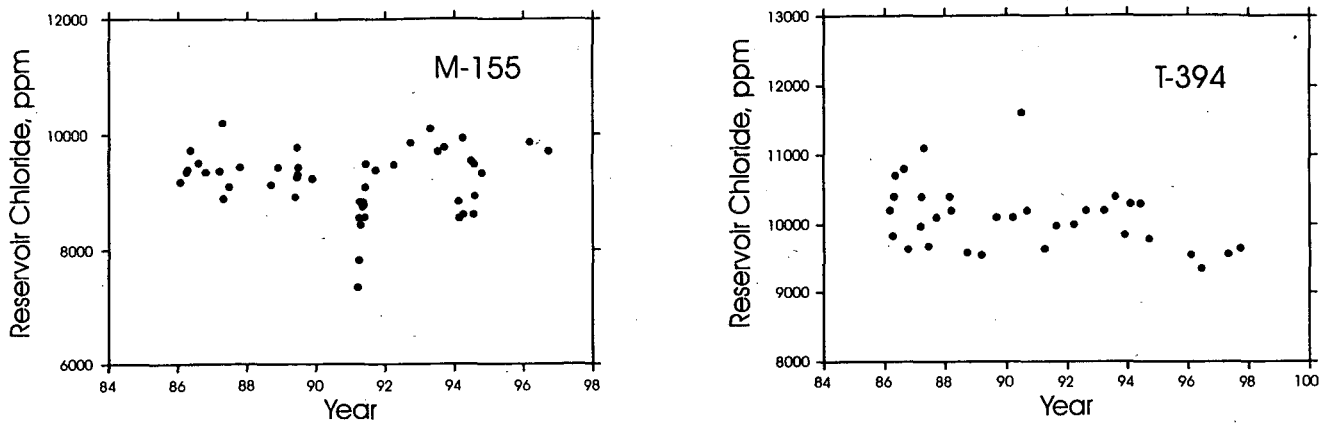

Figure 6. Reservoir chloride changes in (ppm) for wells near the northern (M-155) and eastern (T-394) margins of the Beta reservoir showing no inflow of groundwater.

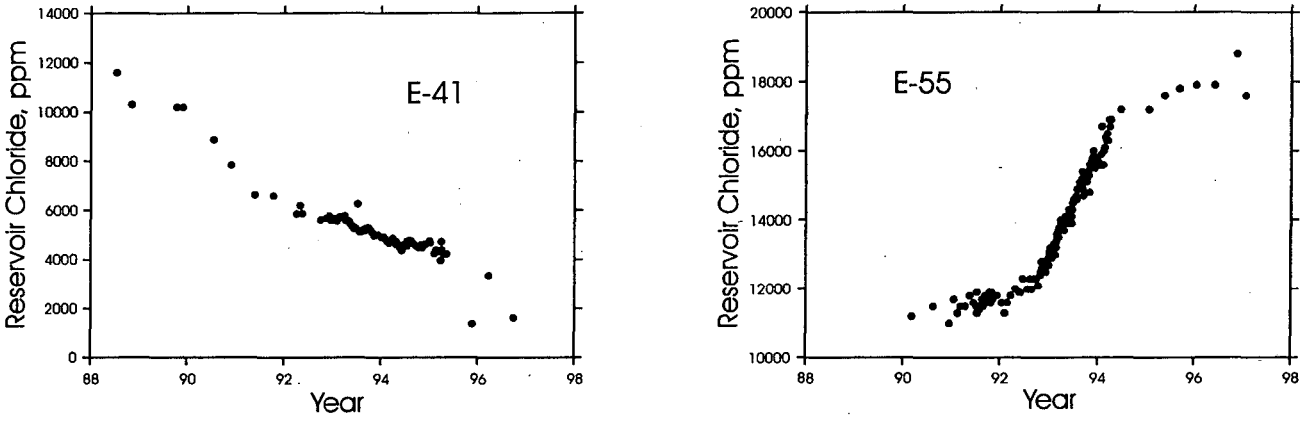

Figure 7. Reservoir chloride changes (in ppm) for wells that show entry of waters from outside the reservoir. Well E-41 is at the center of the area affected by groundwater flowing down fault H into the Beta reservoir. Part of well E-55 production is from brine injected into well E-6.

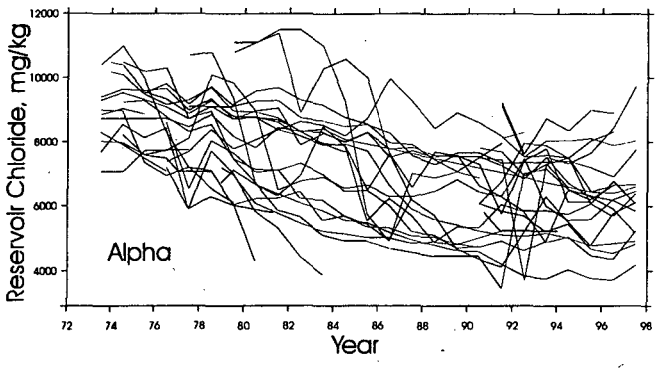

Figure 8. Changes of reservoir chloride concentrations for wells of the Alpha reservoir to 1997 (in ppm).

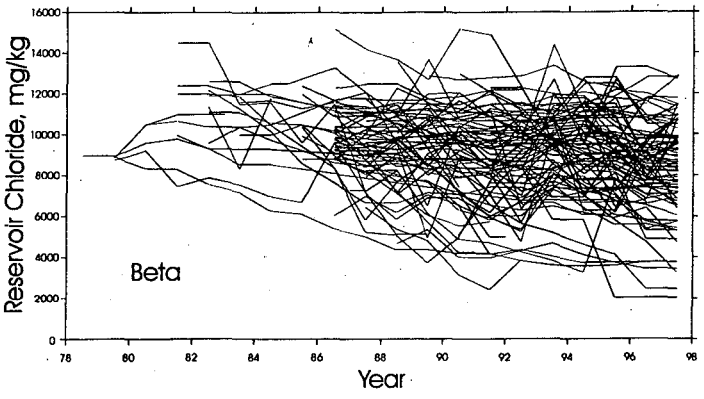

Figure 9. Changes of reservoir chloride concentrations for wells of the Beta reservoir on line in 1986 (in ppm). Inclusion of all wells would render the plot unreadable without adding significant information.

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