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Earth Sciences Division

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CERRO PRIETO COLD WATER INJECTION: EFFECTS ON NEARBY PRODUCTION WELLS

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ABSTRACT

The liquid-dominated Cerro Prieto geothermal field of northern Baja California, Mexico has been under commercial exploitation since 1973. During the early years of operation, all waste brines were sent to an evaporation pond built west of the production area. In 1989, cooled pond brines began to be successfully injected into the reservoir along the western boundary of the geothermal system. The injection rate varied over the years, and is at present about 20% of the total fluid extracted. As expected under the continental desert conditions prevailing in the area, the temperature and salinity of the pond brines change with the seasons, being higher during the summer and lower during the winter. The chemistry of pond brines is also affected by precipitation of silica, oxidation of H_2S and reaction with airborne clays.

Several production wells in the western part of the field (CP-I area) showed beneficial effects from injection. The chemical (chloride, isotopic) and physical (enthalpy, flow rate) changes observed in producers close to the injectors are reviewed. Some wells showed steam flow increases, in others steam flow decline rates flattened. Because of their higher density, injected brines migrated downward in the reservoir and showed up in deep wells.

INTRODUCTION

For the first 16 years of commercial operation, all separated waters and excess condensate at the Cerro Prieto geothermal field were discharged into a large man-made evaporation pond located west of the wellfield. In the average, the pond brines have a chlorinity of about 22,000 ppm and a temperature of about 26°C (mean annual temperature in the area). These concentrations and temperatures vary during the year, being higher in the summer and lower in the winter. During the summer the climatic conditions are ideal for evaporating the brine stored in the pond, however in winter the water level tends to rise, sometimes filling the pond to capacity.

As the installed generation capacity at Cerro Prieto rose, fluid production rate as well as waste brine volumes increased, especially after 1986-87 when two large (220 MWe) power plants were put on line. At that time in order to avoid possible infiltration of brine into the alluvium of the

Mexicali Valley, the Comisión Federal de Electricidad (CFE) began to build facilities to inject the brine stored in the evaporation pond into the reservoir.

Long-term injection operations began in April 1989 in wells drilled near the eastern margin of the pond and on berms within it (Gutiérrez Puente and Ribó Muñóz, 1994). Since then, the number of wells and the amount of injected fluid has varied, reaching a maximum of 24 % of the total mass extracted in 1993 (Truesdell et al., 1998); at present, around 20 % is injected. The bulk of the fluid injected is cold brine from the evaporation pond. To date, only minor amounts of hot separated brines have been injected taking advantage of separation pressures. Annual production and injection data for the 1973-97 period obtained from CFE internal reports are quoted in Truesdell et al. (1998).

It is important to note that at the beginning, the main goal of CFE's injection project was disposal of brine to reduce the volume stored in the evaporation pond. As the beneficial effects of injection on some nearby production wells became evident, the emphasis of the operation shifted to finding the optimum injection/production scheme for recharging the geothermal reservoirs (i.e., the Alpha reservoir from 1000 to 1500 m depth and the Beta reservoir below about 1500 m), without premature thermal breakthroughs in production wells.

By injecting pond brine along the western edge of the geothermal reservoir, it is possible to sweep the heat stored in the subsurface rocks toward the producing wells. This reinforces the natural west-to-east fluid recharge and heat sweep that occurs in the reservoir in response to the pressure gradient created by the exploitation of the system (Lippmann and Truesdell, 1990; Truesdell and Lippmann, 1990).

Since the permeability of the Cerro Prieto geothermal reservoir is essentially controlled by primary porosity and not by fractures (although there may be flow paths short-circuiting the connection between some injection and production wells), it is possible to estimate the time it will take for the thermal front to get to a production well from the arrival of the chemical front. It is mainly a function of porosity; the smaller the formation porosity, the longer the time between the chemical and thermal fronts (e.g., Grant et al., 1984). Theoretically in a medium with 20 % porosity, the time before arrival of the thermal front would be about three times longer than that of the chemical front.

The study of the effects of injection on the performance of the field began during the CFE-DOE Cooperative Program (Witherspoon et al., 1978; Hiriart Le Bert, 1990). Initial studies used analytical and semi-analytical models assuming a homogeneous porous medium (e.g., Tsang et al., 1980). Later, numerical codes were applied to study the behavior of the reservoir under different exploitation schemes that included injection. These more sophisticated models incorporated details of the non-homogeneous geologic and permeability structure of the system.

The early numerical studies on injection assumed one-phase liquid reservoir conditions (Tsang et al., 1981). A few years later, a two-phase system was considered (Tsang et al., 1984). Since then, CFE and its contractors have carried out several numerical studies to evaluate reservoir management plans for Cerro Prieto using codes of increasing complexity; the results being available only in internal reports. In the last ten years, several papers in the open literature discuss Cerro Prieto modeling studies (e.g., Ocampo et al., 1989; Halfman-Dooley et al., 1989; Antúnez et al., 1991), but none evaluates the effects of injection on reservoir behavior.

The purpose of this study is to review the effects of injecting cold brine from the evaporation pond on nearby production wells in the western part of the field (Cerro Prieto I area; CP-I); it updates and expands the paper presented by Gutiérrez Puente and Ribó Muñóz at the 1994 GRC Annual Meeting. Most of the injection wells are open to the Alpha reservoir, and some are connected to the deeper Beta reservoir. Emphasis is given to the changes observed in the chemistry and enthalpy of the produced fluids and in the output of the production wells.

COLD INJECTION IN THE WESTERN PART OF THE FIELD

CFE decided to inject waste geothermal brine along the western edge of the Cerro Prieto for several reasons,

1) The evaporation pond west of the CP-I wellfield provided a large supply of "aged" brines with low silica concentrations. Most silica contained in the separated water had time to precipitate as it cooled and circulated within the pond. This reduced the potential problem of silica scaling in the wells and in the injected formation.

2) Injection in the pond area would strengthen the natural groundwater recharge occurring along the western boundary. This flow serves to sweep heat toward centrally located production wells.

3) Hot injection was considered problematic because residual brines separated from the higher enthalpy geothermal fluids in the eastern CP-II and CP-III areas are supersaturated with amorphous silica, possibly leading to wellbore or formation scaling. On the other hand, hot injection would be advantageous because the separation pressure would help inject the brines into the reservoir and more heat would be conserved.

4) Since in the west the Alpha reservoir can be found at shallower depths (below 1000 m) the cost of drilling and completing new injection wells is lower than in the East where the Alpha reservoir is absent and the top of the Beta reservoir is found at depths exceeding 2 km.

5) Because of the advance of the cooler groundwater toward the center of the reservoir, the enthalpy of the fluids produced by some of the wells along the western edge of the geothermal system had decreased (Truesdell et al., 1997). These wells could be transformed into injectors without the need to drill new ones.

In summary, cold injection in the west was considered safer and cheaper than injecting hot separated brines of high silica content which might form silica scale in the wells and reservoir.

EFFECTS OF INJECTION ON INDIVIDUAL WELLS

Even though much of the injection at Cerro Prieto was into shallow wells in the western part of the field far from the area of production, injection into several wells along the western margin of the CP-I area have affected the flow and chemistry of fluids produced from nearby wells. The effects of injection wells 303 in the northwest and E-6 in the southeast are discussed here in detail.

Shallow Injection in the Northern CP-I Area: Injection Well 303

Well 303 is located next to the evaporation pond at the northern end of CP-I (Figure 1). Experiments with injection of cooled pond brine into well 303 were started in late 1990 (Figure 2). At first, seasonal operation was planned with injection in the winter, when the evaporation pond was nearly overflowing, and production in the summer, when power demand was at its maximum. This operating scheme proved impractical because the well, once used as an injector, took more than a year to heat up again and become a potential producer. Because of this, 303 was refitted as an injection well and has been receiving pond brine continuously since January 1993.

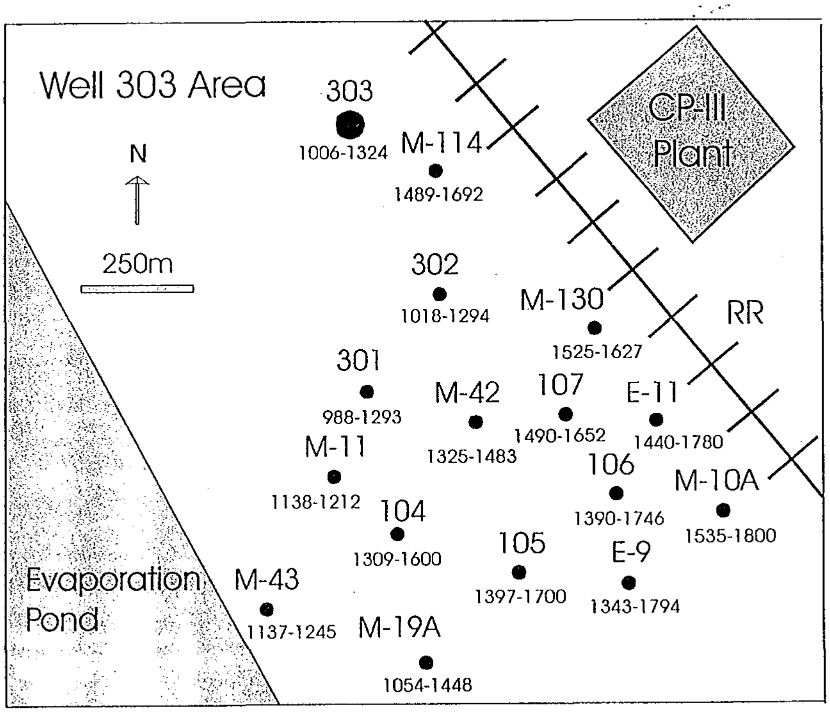


Figure 1. Map of the northernmost part of the CP-I area of Cerro Prieto. Locations of the major injection well 303, a minor injection well 104, and producing wells that could be affected by injection into 303 are shown with their open intervals in meters.

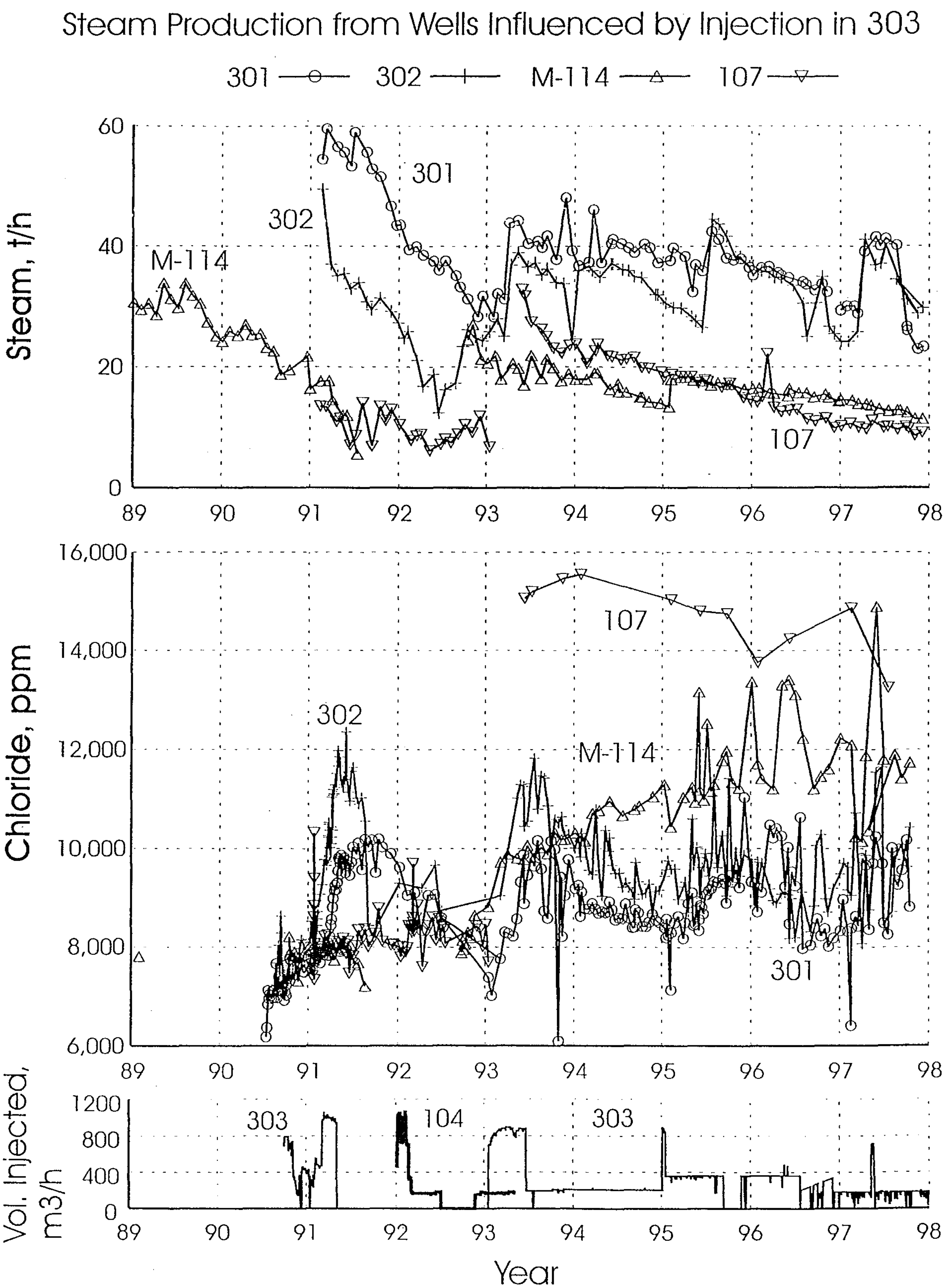


Figure 2. Changes with time of steam flows and of chloride concentrations in flashed, separated waters from producing Alpha reservoir wells close to injection wells 303 and 104 along with the volumes of brine injected.

Well 303 is perforated from 1006 to 1324 m depth, penetrating about half to three quarters of the production thickness in the area. The open interval of this injection well overlaps that of six nearby producing wells, but is shallower than nine other neighboring production wells (Figure 1). The difference between the bottom of 303 and the top of the open interval of several of these nearby wells is small.

Injection well 104 is included in Figure 1 because its area of influence overlaps that of 303. Well 104 was used as an injector for only a short time in 1992-93. Its effects on neighboring production wells (particularly well 107) was much more immediate than that of 303, so its use as an injector was stopped.

Figures 2 and 3 show the injection histories of wells 303 and 104 and changes in steam flow and brine chloride from nearby producers. (Data for M-130 is not shown because it was abandoned in early 1991, before most injection in well 303 took place). Wells closest to 303 (except possibly M-114) all show increases in chloride and steam flow that can be attributed to 303 injection. Although wells 303 and M-114 are only 200 m apart, M-114 steam flow showed no effect of the 1990-91 injection into 303. The increased steam flow in late 1992 must be due to the workover in M-114 and not to 303 injection which started a few months later. A small increase in M-114 steam flow in 1995 might be related to a 1995 pulse of injection in 303 followed by a higher sustained injection rate.

The poor connection between these two wells probably results from the deep completion of M-114 (1489-1692 m) with the top of the open interval 165 m below the bottom of 303. Despite this, chloride in M-114 fluid increased from 8,000 ppm to nearly 10,000 ppm in early 1993 followed by irregular increases to about 12,000 ppm (with peaks to 13,000 ppm). These changes occurred after injection into well 303 started (with 800 m^3/h from January to June 1993) and fell back to 9,000-10,000 ppm when the injected volume dropped to 200 m^3/h. Apparently the 303 injectate (with up to 20,000 ppm chloride) was dense enough to flow at least 165 m downwards in the reservoir and contribute to fluids feeding M-114.

The next closest wells, 301 and 302, showed changes in chloride and steam flow following periods of injection into 303, with high values when the wells were started in 1991 (along with 303 injection), and again in 1993. The large steam flows and rapid declines of these wells in 1991 represent the normal declines after startup combined with the effects of the short pulse of injection in well 303.

Well 107 is relatively far (about 750 m) from wells 303 and 104, with completion deeper than 303 but similar to 104 (original open interval from 1344 to 1544 m depth changed in 1993 to 1491-1652 m). Well 107 showed a small increase in steam in 1993, probably due to its deepening, and a large and sustained increase in chloride starting in mid-1993. This rise in chloride was too much delayed and too lasting to be due to the limited injection into 104 in early 1992, and is more likely to have resulted from downward migration of the large quantity (about 850 m^3/h for four months) of brine injected into 303 in early 1993.

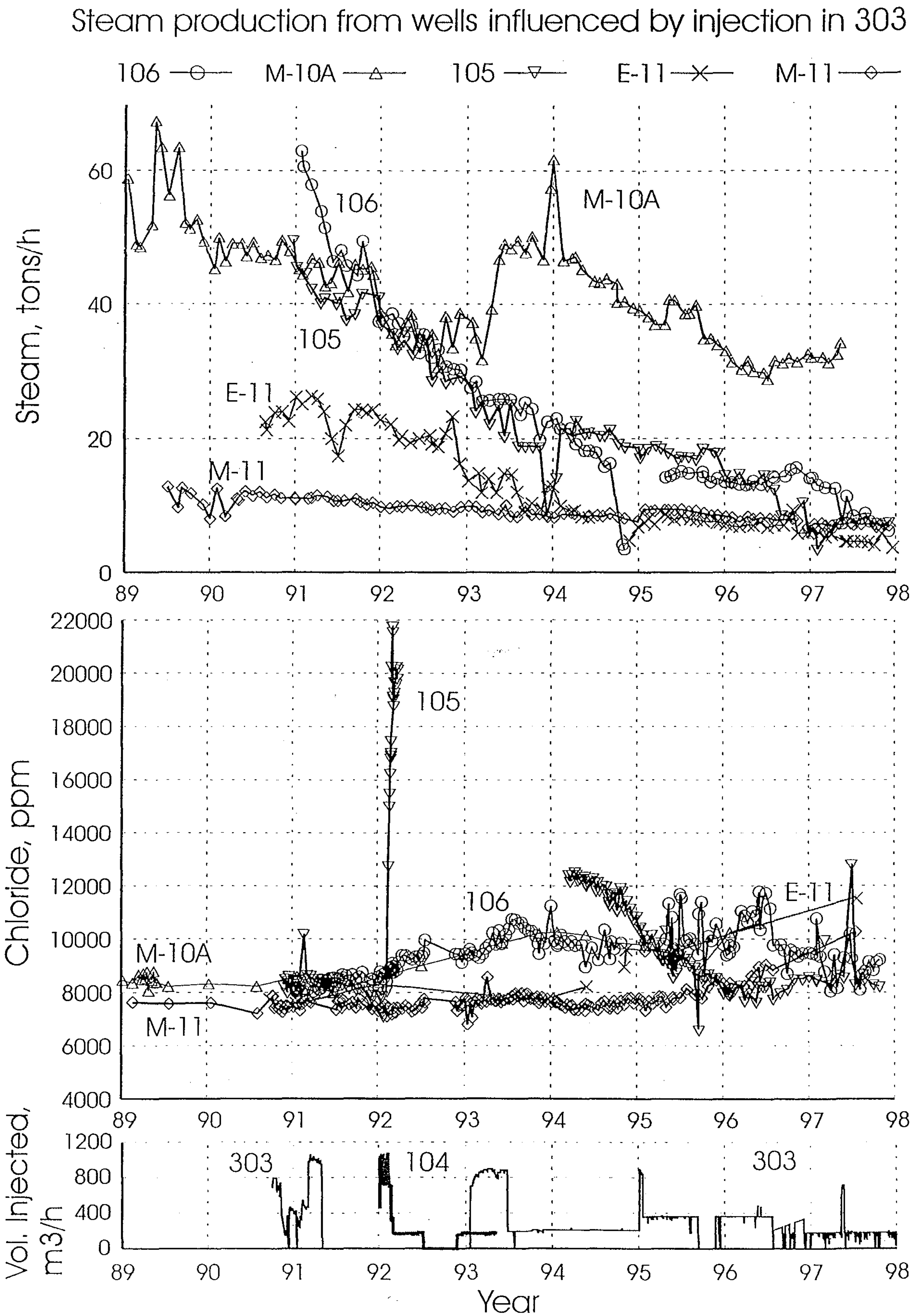


Figure 3. Changes with time in steam flow and chloride for alpha wells farther from injection well 303. Quantities shown are the same as in Figure 2.

Figure 3 shows the effects of injection on deeper wells producing from the Beta reservoir and at a greater distance from 303. Of these wells only M-10A showed a clear increase in steam flow that can be attributed to 303 injection, with a jump in early-to-mid 1993 that appears to correlate with the second period of injection, not the first. Other wells perhaps show a more subtle effect. The slope of steam flow decline for wells 105, 106 and E-11 decreased over the period from mid-1993 to the end of 1994, but note that the original declines were so steep that without change they would have reached zero steam flow. The observed change may be the normal decline to minimum flow. Well M-11 showed no change in slope except a very slight increase in 1995 that might be related to the increase in 303 injection at the same time.

The chloride record is more interesting. All wells presented some increase in chloride, but well 105 showed a sudden jump to more than 20,000 ppm and a swift decline in 1992 (Figure 3). This well and injector 104 are located close together (about 500 m), and their open intervals are nearly at the same depths (Figure 1), so it is reasonable that the brine flowed between them. However, the injection into 104 was brief and did not significantly increase steam flow in 105. The reservoir chloride concentrations for other wells increased slowly over a long period. Again the response of well M-11 was the least apparent. This is probably due to its shallow producing interval (1138-1212 m); the other wells were all completed much deeper. As noted above, brine tends to flow downward and outward in the reservoir and can appear in distant wells that show no increase in steam flow. Although we did no simulation of this phenomenon, it seems that the pressure effects were limited by the high compressibility of the two-phase (boiling) fluids in the exploited Cerro Prieto Alpha reservoir.

Deep Injection in the Southern CP-I Area: Well E-6

In the southern part of CP-I the deeper Beta reservoir was exploited to maintain steam production as the older, shallower Alpha wells declined. One of the deepest of these wells, E-6, was chosen to receive excess brine from the evaporation pond (Figure 4; note that the area shown in this figure is southeast of that of Figure 1). E-6 is completed in part of the Beta reservoir that is to the southeast of normal fault H in the downthrown block, and as a result has higher pressure than wells in the upthrown block (Truesdell et al., 1997). Fluid production from CP-I Beta reservoir wells is all liquid at wellbottom which has resulted in more direct effects of injection on both steam flow and reservoir chloride (Figure 5).

The three wells most rapidly and strongly affected by injection into E-6 are E-55, E-18 and T-402 (in order of decreasing effect). Chloride from these wells started to increase in mid-to-late 1992, about 20 months after injection began in E-6 (Figure 5). The initial chloride from T-402 was lower (9,000 ppm) than that from the other wells (10,500 to 11,000 ppm), probably due to the location of T-402 nearer sources of natural low-chloride groundwater recharge (Truesdell et al., 1998). The rate of reservoir chloride increase in the three wells was about the same and they all leveled off in mid-to-late 1994, but at different values. The most direct flowpath for high-chloride brine was apparently to well E-55 (the deepest producer in CP-I) which reached the

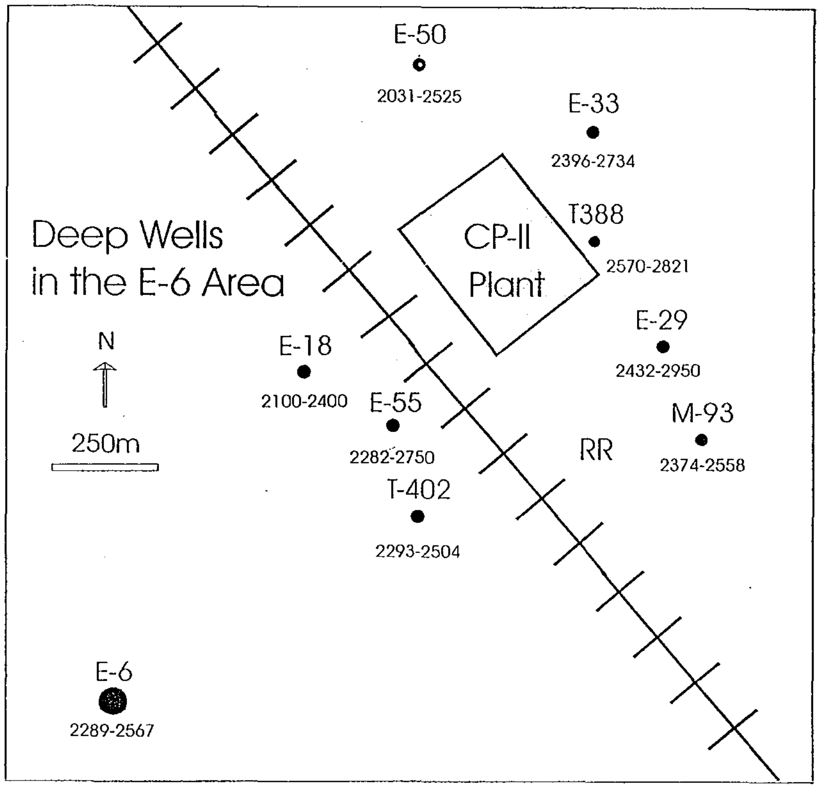


Figure 4. Map of the southernmost part of the CP-I unit of Cerro Prieto. Locations of injection well M-6 and producing wells that could be affected by injection into well M-6 are shown with their open intervals in meters.

highest reservoir chloride at 17,000 to 20,000 ppm. This direct path may have been provided in part by the fractured zone along the Fault H which both wells intersect at the same depth (see figure of the depth to the Beta reservoir in papers cited earlier). Well E-50, much farther from E-6 (Figure 4) shows a very small increase in reservoir chloride that may be locally caused by boiling (Figure 5).

The effects of injection on steam production from these three wells has been significant (Figure 5). The initial trends of steam flow decline for wells E-55 and E-18 are similar (shown by labeled straight lines) and showed a rapid rise in early 1992, about a year after injection started in E-6. The slope of the later steam flow decline in E-18 is similar to the initial slope, but that of E-55 is flatter, suggesting stronger pressure support. The initial decline rate of T-402 was much slower than those of E-55 and E-18, and its response to injection occurred about a year-and-a-half later and was much less pronounced than those of the other wells. This behavior may have resulted from the pressure support given by the natural groundwater recharge mentioned earlier.

In well E-50 the response of steam flow due to injection is muted, similar to that of T-402 (Figure 5), although the distance to E-6 is nearly twice as great (Figure 4). Possibly distance had similar effects as groundwater recharge.

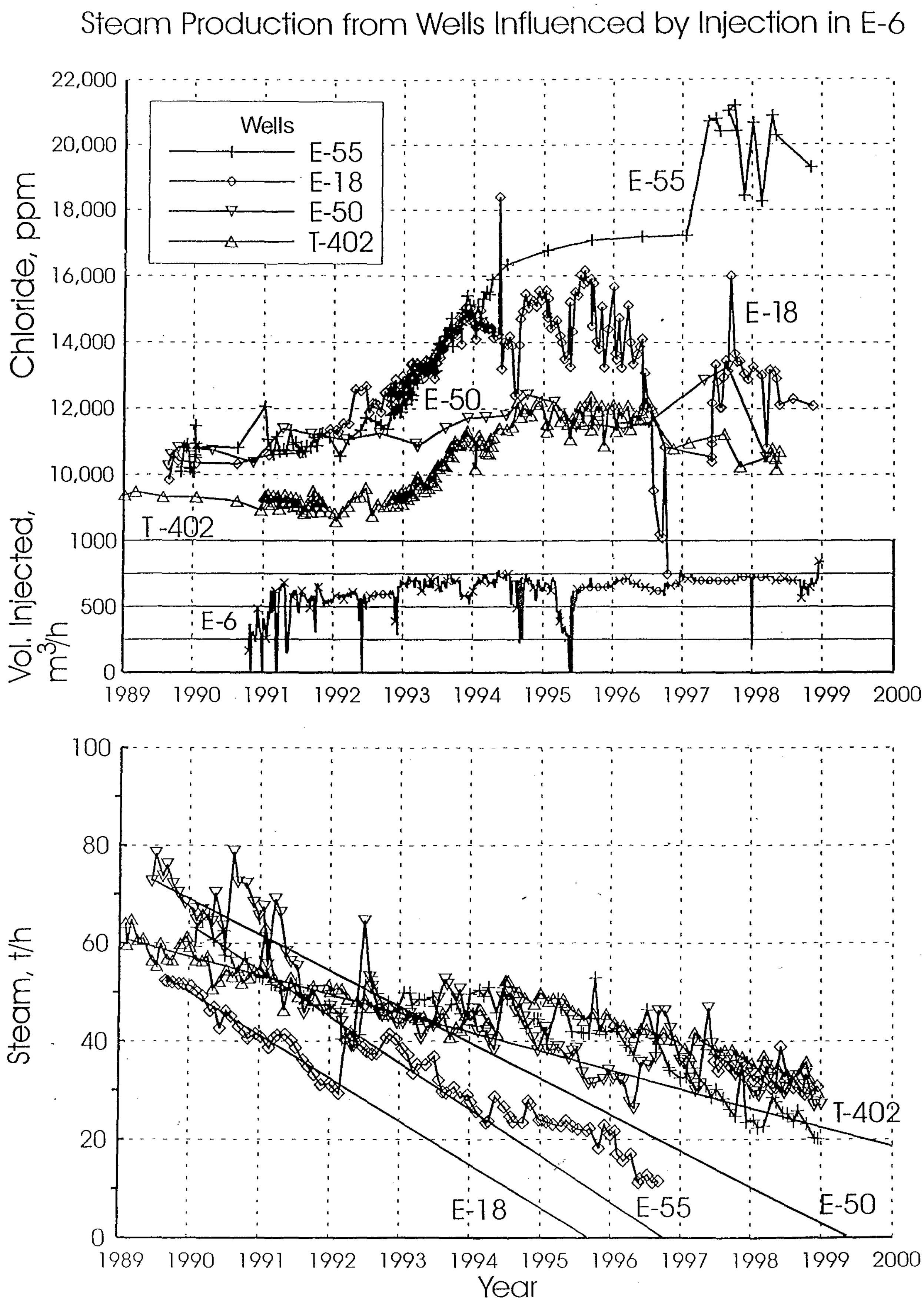


Figure 5. Changes with time of steam flows and chloride concentrations in flashed, separated waters from producing Beta reservoir wells close to injection well E-6 along with the volumes of brine injected.

Data from another set of deep wells at a similar distance from E-6 as E-50 were examined for injection effects (Figure 6). These wells showed slow increases in chloride after 1995, but little or no rises in steam production. The wells that apparently produced more steam had undergone workovers that seem more likely to have caused the improvements. This pattern is similar to that observed for the area of injector 303; that is, increases in chloride due to brine injection occur beyond the area where changes in steam flow are observed.

Well E-55: A Special Case of Injection Influence

Well E-55 showed the most intense effects of injection returns and was chosen for further study. Some of these data are given in Figure 7. The flashed chloride concentrations of 17,000 to 20,000 ppm are similar to the average chloride concentrations injected into E-6, suggesting that much of the reservoir fluid produced from E-55 came from E-6. This reflects chemical breakthrough which should be followed by thermal breakthrough. However the situation is complicated. The only ways of detecting the thermal breakthrough (short of frequent downhole temperature measurements) are through changes in geothermometer temperatures and measured total enthalpy. However, the injected brine has such high concentrations of all major constituents (except silica) that geothermometers based on cations (normally the most reliable) may not equilibrate significantly after injection. Thus, temperatures calculated for the E-6 injectate are nearly the same as those for produced E-55 brine (Table 1). The NaKCa geothermometer temperatures for E-55 (Figure 7) do show a slow decline after 1993, decreasing from 310° to 295°C in 1997, then to 280°C and becoming erratic.

Table 1. Analyses of injection and production waters with calculated geothermometer temperatures. Data in °C and ppm. I: Injection; P: Production; Silica temperatures are: TQZ, quartz saturation calculated for injection (for I wells) and aquifer (for P wells) conditions; TAM, amorphous silica saturation for injectate. Analyses are from CFE.

Well	Type	Date	Temp	pH	Li	Na	K	Ca	Mg	Cl	HCO_3	SO_4	SiO_2	TNKC	TQZ	TAM
303	I	9/94	30	7	57	27000	6000	1380	17	49500	22	180	147	303	160	38
303	I	3/95	20	8	32	13800	3170	675	10	25200	29	83	80	297	126	6
107	P	2/91	-	8	18	7080	1620	322	1.1	13000	109	11	905	289	277	-
107	P	7/93	-	8	26	12000	2050	960	0.8	2100	51	22	690	265	254	-
E-6	I	5/95	28	8	37	17100	1830	1000	33	29900	83	244	100	239	138	17
E-6	I	3/96	25	8	19	8520	1840	561	7	15800	76	66	86	281	129	9.6
E-55	P	7/91	-	8	25	10100	2610	527	0.2	19100	39	1	1090	302	295	-
E-55	P	1/96	-	8	34	15600	3420	876	0.5	28800	32	7	610	293	244	-

Unlike cations, silica was precipitated in the evaporation pond and not carried over into the injected brines, and quartz should be saturated at reservoir temperatures. E-55 silica temperatures have been erratic and low suggesting near-well boiling, which is consistent with the observed increase in total enthalpy (Figure 7). The average silica temperatures dropped from 290° to 280°C in 1993 and possibly lower in 1996, remaining near 280°C after 1997.

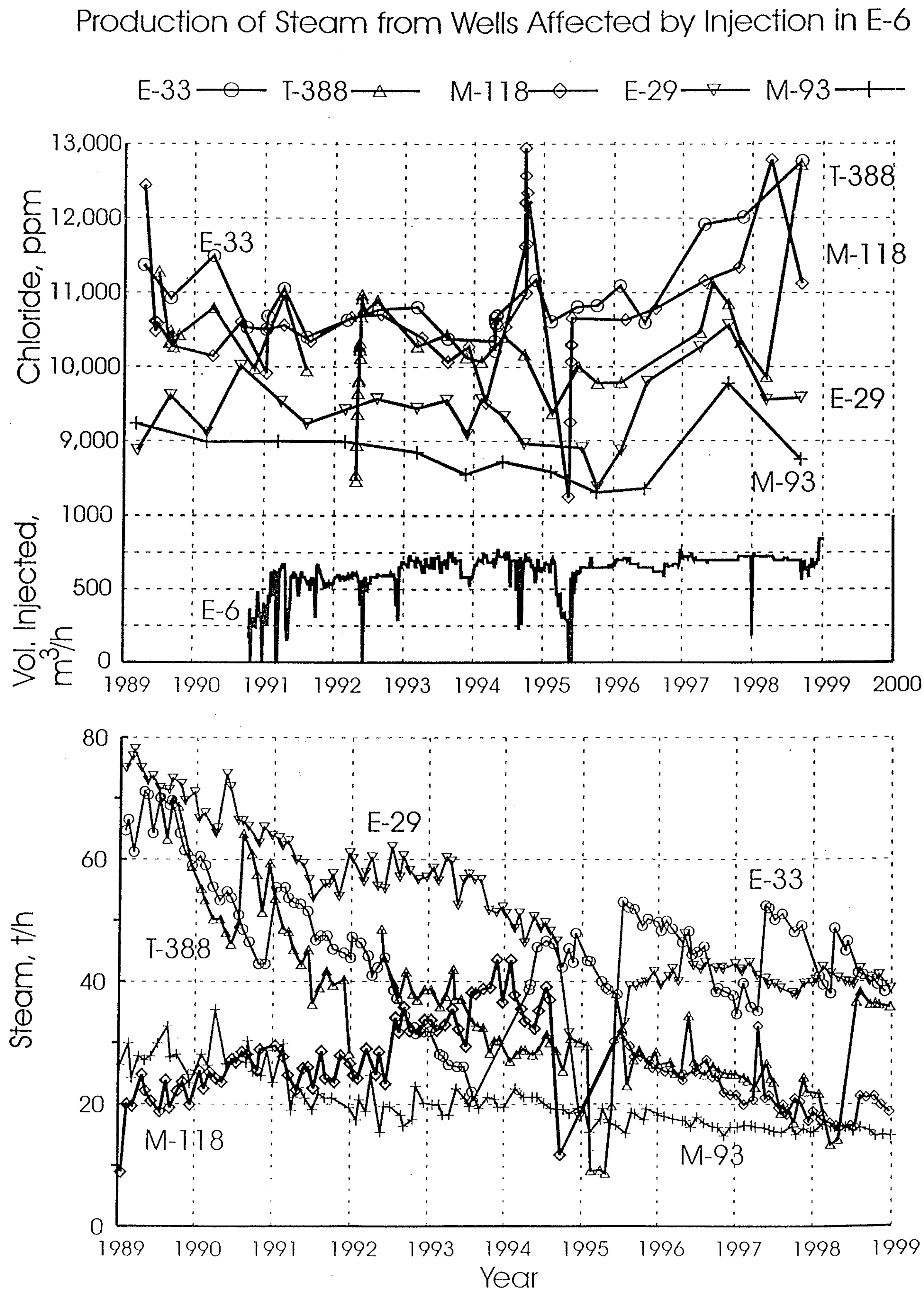


Figure 6. Changes with time in steam flow and chloride for beta wells farther from injection well E-6. Quantities shown are the same as in Figure 5.

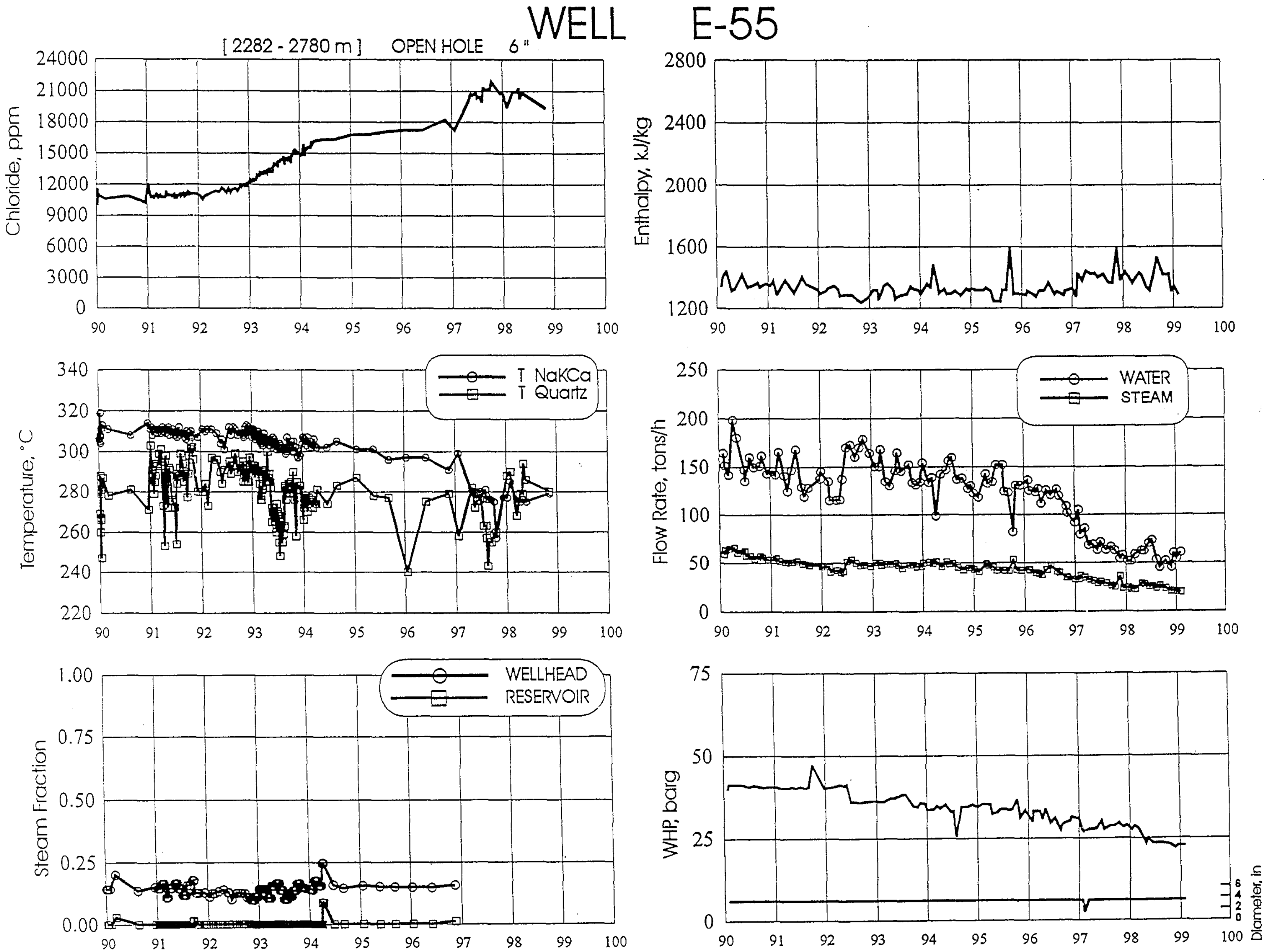


Figure 7. Changes with time in characteristic quantities for well E-55 which showed the greatest effects from injection into E-6 (See text for discussion).

Decreases in E-55 wellhead pressure and in water and steam flows starting in mid-1996 may have resulted from boiling with localized mineral deposition in the formation outside the wellbore. Usually the precipitated scale is mostly quartz, but these waters are probably also saturated with anhydrite. Sulfate, not normally found above trace levels in Cerro Prieto reservoir waters, is present in E-6 injection water at 50 to 200 ppm and when heated will react with calcium (500 to 1000 ppm in the injectate) to precipitate anhydrite ($CaSO_4$). This scale should form near the injection well because this is where the heating of the injectate occurs, and should, therefore, affect the injectivity of the well. These chemical and thermal changes deserve further study.

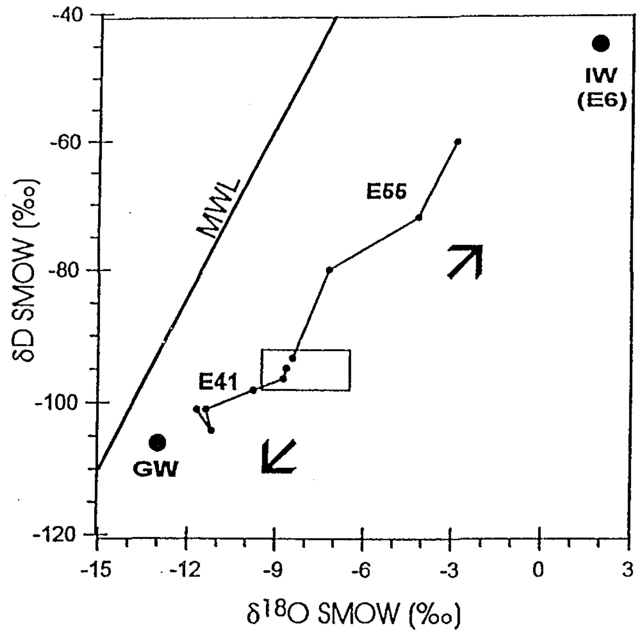
ISOTOPE STUDIES OF INJECTION

Analyses of oxygen-18 and deuterium ($\delta^{18}O$ and δD) of Cerro Prieto production fluids have been made yearly or semi-yearly since 1977 (e.g., Truesdell et al., 1979; Stallard et al., 1987; Verma et al., 1996). These analyses (particularly $\delta^{18}O$) have been very useful in distinguishing fluids from outside the reservoir (either injectate or groundwater) because their isotopic compositions are very different from reservoir brine. In addition, isotopes have been found to be little affected by reservoir processes that influence the interpretation of chloride concentrations. The changes in $\delta^{18}O$ and δD for mixing of reservoir brine with groundwater and injection water are shown in Figure 8, along with changes in chloride concentrations and NaKCa geothermometer temperatures.

The groundwater mixing example is for well E-41 which is in the center of the area where groundwater enters the deeper Beta reservoir along the northeast part of Fault H (Truesdell et al.,1998) and the injection example is for well E-55 discussed earlier. The changes in isotopes and chloride are almost diametrically opposed. As expected, groundwater mixing results in lower numbers and injection, in higher. The Na-K-Ca geothermometer-chloride changes are interesting. Mixture with groundwater produces nearly straight lines for chloride and temperature between the assumed end members, while mixing with highly saline injection brine results in widely variable Na-K-Ca geothermometer temperatures that have little relation to the original temperatures in either the injector or the producer. This seems to result from incomplete reequilibration of cations in the highly concentrated brine with reservoir aluminosilicate minerals.

CHEMICAL CHANGES IN BRINE DURING EVAPORATION AND INJECTION

Processes in the evaporation pond are not limited to the removal of water. Gases dissolved in the separated water include H_2S which oxidizes to SO_4. Silica is supersaturated at surface temperatures and precipitates, probably accompanied with small amounts of aluminosilicate minerals. Dust blown into the pond contains particles derived from deltaic sediments and clays which add solutes to the pond brine. Organic materials are added from salt-tolerant algae and bacteria and hapless birds and insects. In Table 1 we compare major elements in typical analyses of separated production water, pond brine as injected, and produced water containing injectate.



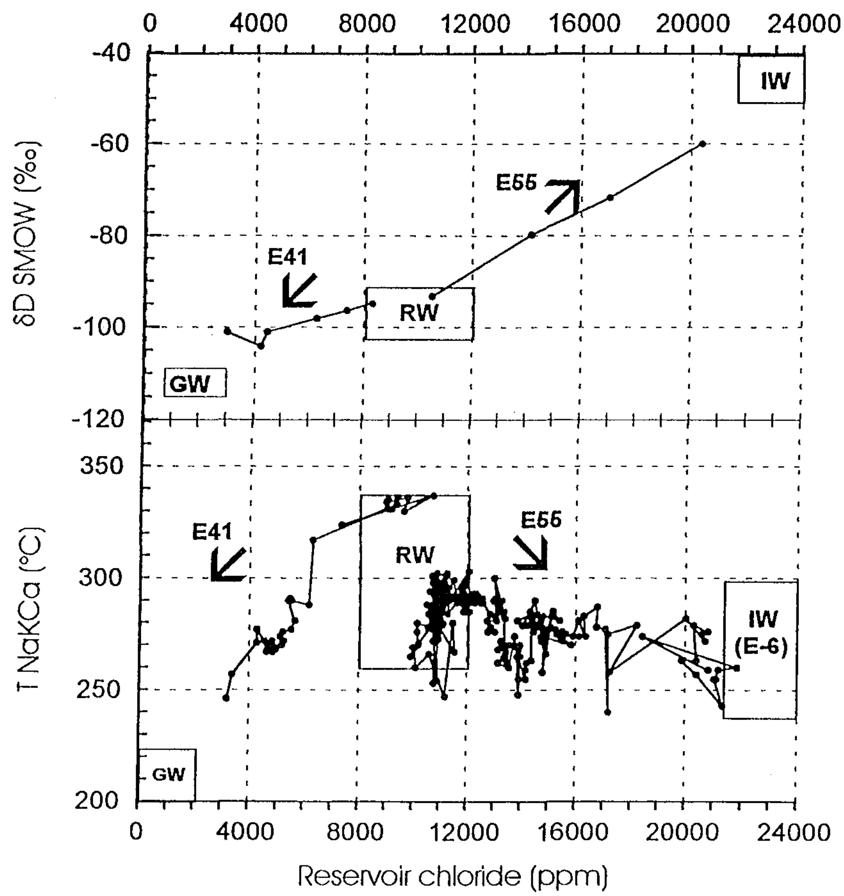


Figure 8. Evolution of the isotopic and chloride compositions along with NaKCa geothermometer temperatures for brines produced from wells E-55 and E-41. These wells show mixture with pond brine and groundwater, respectively. Isotope data is for total production and chloride data is for flashed brine. IW: injection water; GW: groundwater; RW: reservoir water.

Table 1 presents typical analyses of summer and winter brines injected into wells 303 and E-6, analyses of production brines (flashed to atmosphere after steam separation) from wells strongly affected by injection collected before and after injection started, and geothermometer temperatures. Note that since pond brines are evaporated mixtures of many well discharges, the comparison of well and pond brine analyses given here is quite imperfect. The summer and winter injection brines show the typical range of concentrations taken from the evaporation pond. There are also variations from year to year. The seasonal and annual variations of chloride in brine injected into well E-6 are shown in Figure 9.

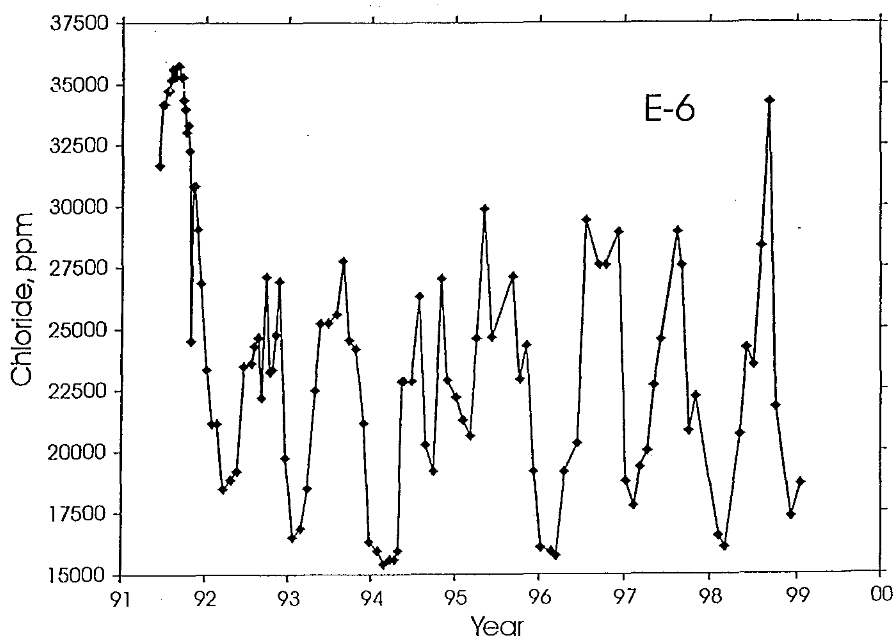


Figure 9. Chloride concentrations of brines injected into well E-6 from mid-1991 to early 1999. The effects of seasonal and annual changes in the rate of evaporation can be seen. Over this period the average chloride concentration was 22,300 ppm.

The pond has dikes directing internal circulation from the inlet to the center, so salt concentrations differ at the various injection intake points. Brine feeding well 303 is more concentrated in conservative constituents than that feeding E-6. The NaKCa geothermometer temperatures of pond brine are similar to those calculated for reservoir brines indicating that little re-equilibration occurs in the pond.

All pond brines are much higher in Mg and SO_4 and lower in SiO_2 than would be expected by simple evaporation. The decrease in silica is due to precipitation of amorphous silica (note the near equilibrium amorphous silica saturation temperatures). Magnesium probably enters the pond from windblown surface clays and sediments. Sulfate is generated by the oxidation of H_2S dissolved in separated brine. Since this oxidation requires sulfur-oxidizing bacteria and these bacteria are more active at higher temperatures, the summer concentrations of SO_4 are much higher than those in the winter.

CONCLUSIONS

Brine from the evaporation pond west of the Cerro Prieto production area has been injected into deep wells along the western edge of the field and into shallow wells farther to the west. The cooled pond brines have lost silica and as a result no silica precipitation affecting well injectivities has been observed. Although the injection wells are not close to many producers, some of the closest wells with open intervals matching those of the injectors have shown increases in steam flow or flattening of steam flow decline rates. These wells, and deeper ones with no changes in steam rates, have shown increases in chloride and other brine constituents.

The calculated NaKCa cation geothermometer temperatures show little significant change during concentration by evaporation in the pond at ambient temperatures, and after reheating in the reservoir. Silica in the brine decreases to near equilibrium with amorphous silica and after injection re-equilibrates with quartz in the reservoir.

Some cooling of the reservoir has occurred near well E-55 which produces the highest proportion of injected brine. In addition to evaporative concentration the pond brines have changed their chemistry through silica precipitation, oxidation of H_2S and solution of airborne clays.

Injection of cooled waste geothermal fluids should continue along the western boundary of the Cerro Prieto field since it has given positive results to date. The injection of hot separated brines in other areas should also be considered. On-going monitoring of the chemical and physical characteristics of producing wells should be expanded with the growth of the injection operations.

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