Chemical and physical indicators of reservoir processes in exploited high-temperature, liquid-dominated geothermal fields

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ABSTRACT

Experience in the long-exploited Cerro Prieto (Mexico) and Ahuachapan (El Salvador) geothermal fields shows that monitoring changes with time of fluid flow, enthalpy, reservoir temperatures (from silica and cation geothermometers), and reservoir chloride concentrations, can clearly indicate physical and geochemical processes occurring in the reservoir and wells. These processes include coldwater entry, near-well boiling, reservoir-wide boiling, production of injectate, scaling in the wellbore or in the formation, and entry of fluid through casing breaks or defective joints. The observed fluid changes provide warning of short-term problems related to well maintenance and long-term problems, such as reservoir cooling or drying (i.e. **loss** of liquid superheating of steam), in time to take appropriate corrective actions.

INTRODUCTION

Geothermal reservoirs store both fluid and heat. In order to exploit the heat stored in the reservoir rock and in the fluid, it is necessary to move fluid from the reservoir to the surface. Extraction of fluid causes a deficit in mass and a resulting decrease in reservoir pressure. These effects may cause entry of fluid from the outside or boiling in the reservoir with some of the original fluid replaced by newly formed steam. The effects of exploitation depend on connections to outside aquifers and **on** the temperature and permeability within the reservoir. Entry of outside water is characteristic of hot water reservoirs initially below boiling temperatures, and induced boiling is typical of high-temperature reservoirs initially at or near boiling temperatures.

If the hot water reservoir has leaky boundaries, decrease in pressure will cause flow of water from outside the reservoir. The effect is similar to artificial injection of liquid except that the location of the natural inflow cannot be controlled by the developer. Although pressure is maintained, the reservoir is cooled and ultimately the amount of steam generated decreases. This cooling is slowed by heat contained in the rock and usually proceeds from the margins of the reservoir toward the production area. In addition the cooling and dilution usually decreases the amount of silica scale, although in some circumstances Mg-silicate or calcite scale may increase.

If the reservoir boundaries are closed, the effects are more complicated. Initially the decrease in pressure causes fluid boiling and cooling. Part of the heat contained **in** the reservoir rock is transferred to the cooled liquid, accelerating boiling to produce steam-enriched fluid. If reservoir liquid is locally exhausted, the pressure **of** steam decreases and it becomes superheated. In high-temperature, liquid-dominated fields the increase in fluid enthalpy may cause a decline in total mass flow, but energy extraction efficiency increases and the decrease in separated water eases disposal. Pressure and well flow maintenance depend **on** the amount of liquid remaining in the reservoir. In steam-water mixtures, pressures depend **on** temperatures which are buffered by heat contained in rock. Thus pressure may change only slowly as long as any liquid remains and decline rapidly when that liquid is exhausted.

Complete depletion of liquid has been observed locally in liquid-dominated reservoirs (as at Krafla, Iceland in 1980, Truesdell et al., 1989a). If this happens, detrimental constituents of reservoir steam previously suppressed by the presence of liquid may appear in the steam. Steam from vaporized liquid is low in gas and dilutes gas contained in original reservoir steam. When liquid is exhausted, gas contents in steam increase. Potentially corrosive HCI gas is highly soluble in liquid and once dissolved is neutralized by reaction with rock minerals. When liquid is depleted and steam becomes superheated, HCI is not removed. ***So*** long as steam **is** superheated, HCI is unreactive, but when steam cools and condenses in the casing or wellhead, HCI dissolves in condensate and becomes highly corrosive.

Knowledge of reservoir processes is vital to field management. The state of an exploited reservoir may he indicated by wellhead pressure, temperature and flow measurements, supplemented by chemical analyses of the produced fluid. This paper reviews the applications of chemical and physical measurements using Cerro Prieto, Mexico as an example. Additional examples are from Ahuachapan, El Salvador.

CERRO PRIETO

The Cerro Prieto geothermal field of northern Mexico is contained in sandstones and shales of the Colorado River delta (Figure 1). The Cerro Prieto reservoirs and the circulation of geothermal fluids were described by Halfinan et al. (1984, 1986) and Lippmann et al. (1989, 1991). There are three reservoirs developed in sandstone and sandy shale units that are fed from depth by fluids rising along the NE-trending, SE-dipping normal fault H of Halfinan et al. (1984).

The alpha (α) reservoir in the W part of the field is the shallowest and was the first to be exploited. It is found at depths between 1000 and 1500 m; pre-exploitation temperatures ranged from 260 to 310°C. The α reservoir covers about 4.5 km^2 W of the railroad tracks and is exploited by the CP-I powerplant. In the natural state, thermal fluids leaked **out** of the reservoir along its W edge and upward along fault L of Halfman et al. (1984; Figure 1) to form thermal springs W of the field or to disperse into colder groundwater. Under exploitation cold groundwater has entered the reservoir along these pathways.

The deeper beta (β) reservoir extends underneath the entire area of the Cerro Prieto field (about 15 km^2) at depths of 1500 to >2700 m with temperatures ranging from **300** to 340°C. Ascending thermal fluids flow into the reservoir along fault H (Figure 1) and move laterally westward with limited flow to the S. Fluids in the SE and SW regions of this reservoir connect with permeable aquifers outside the reservoir and in the natural state feed hot springs or disperse as noted for the α reservoir. Chemical evidence presented here indicates that under exploitation colder waters have invaded the reservoir in these areas. There is no evidence that cold waters have entered the β reservoir by way of fault L. The β reservoir to the N of fault H has less connection with colder water and appears **to** boil under exploitation. The deepest gamma reservoir (Halfinan et al., 1986) is poorly **known** and not yet exploited **on** a large scale.

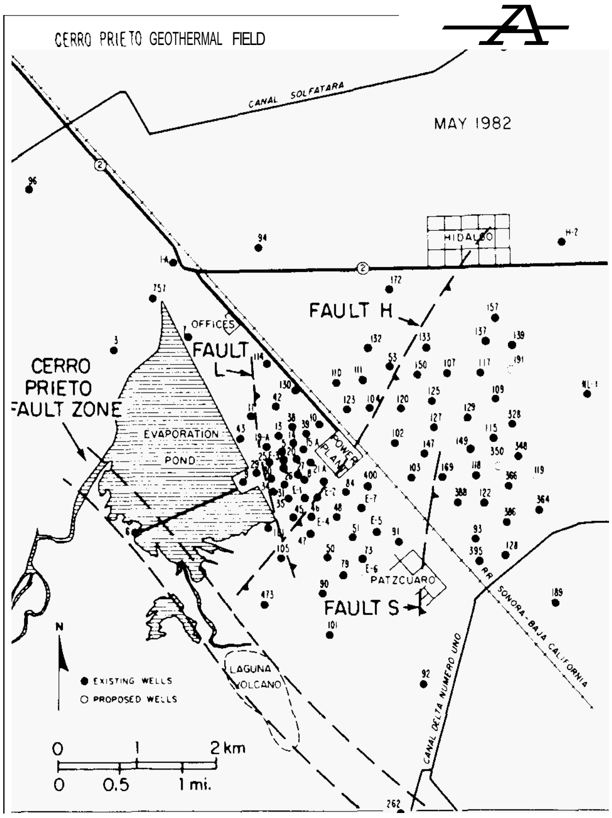

Figure 1. The location of the Cerro Prieto field taken from Halfman et al. (1984). Fault H, L and S locations are shown extrapolated to the surface.

The electrical generation capacity of the Cerro Prieto geothermal field has been progressively enlarged from 75 MWe in 1973 to 620 MWe today. The quantity of fluid required for the present power plants exceeds 10,000 metric tons per hour and must cause significant reservoir drawdown. Decrease of reservoir pressure in a high-temperature geothermal system results in boiling and/or cold water entry. The effect of exploitation on fluid flow in the system has recently been described by Lippmann et al. (1989, 1991) and Truesdell et al. (1989b); the mechanism of cold-water entry into the a reservoir was described by Grant et al. (1984); and the effects of induced near-well boiling were discussed by Truesdell et al. (1984).

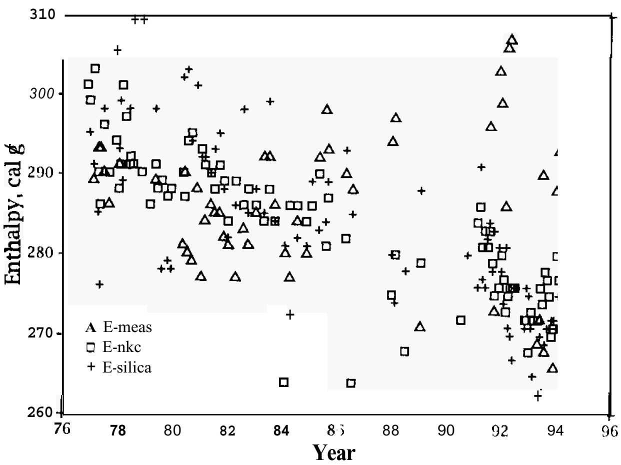

Figure 2. Cerro Prieto well M-42. Changes with time of measured total fluid enthalpy and liquid enthalpy calculated using the Na-K-Ca and quartz saturation geothermometers. The pattern before 1986 is E-meas = E-nkc = E-silica indicating equilibrated liquid with no boiling or mixing.

INDIVIDUAL WELLS

Characteristic changes with time of geochemical indicators for individual wells provide clear indications of near-well reservoir processes. The different rates of response of the quartz and Na-K-Ca geothermometers combined with the measured fluid enthalpy provide indications of fluid state and of fluid temperature at distances near and far from wells. Aquifer chloride provides additional indications of dilution and boiling processes. These indicators are most useful when a long history is available with water samples collected at frequent intervals and analysed at least for Na, K, Ca, Cl and SiO_2. These data are needed for the interpretation of certain processes such as cold-water sweep and allow errors to be estimated. Using steam table data for pure water, temperatures are converted to enthalpy of reservoir liquid for comparison with measured enthalpy values. These quantities are abbreviated as E-meas, E-silica and E-nkc, indicating enthalpy values from wellhead measurements, quartz, and Na-K-Ca geothermometer temperatures, respectively. The reservoir processes inferred from the geochemical patterns have been simulated numerically by Lippmann and Truesdell (1990).

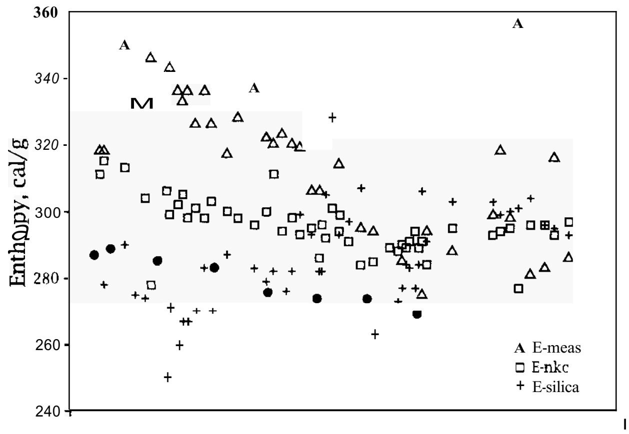

Figure 3. Cerro Prieto well M-31. Changes with time of fluid enthalpies as in Figure 2. The pattern before 1980 is E-meas > E-nkc > E-silica indicating localized near-well boiling.

1. E-meas = E-nkc = E-silica indicates all-liquid, fully equilibrated reservoir fluid. Fast and slow geothermometer reactions are in equilibrium at the inlet temperature. Excess steam is not present and temperatures have not been affected by mixing. Cerro Prieto well M-42 showed this behavior fiom 1977 to 1986 with subsequent periods of boiling and cool water entry (Figure 2).

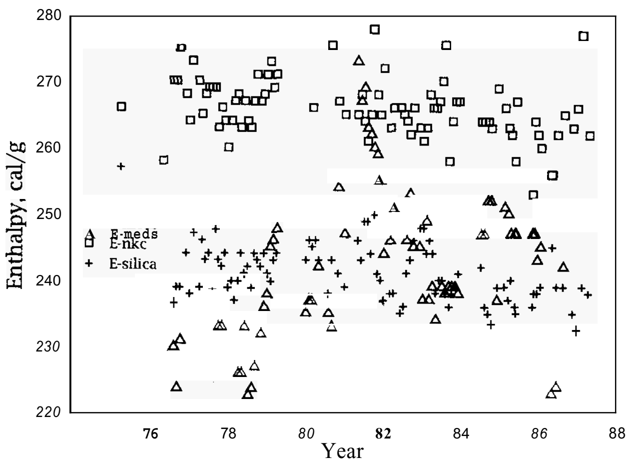

Figure 4. Ahuachapan well AH-21. Changes with time of fluid enthalpy values as in Figure 2. The pattern is E-nkc > E-meas = E-silica indicating mixing with cooler water close to the well.

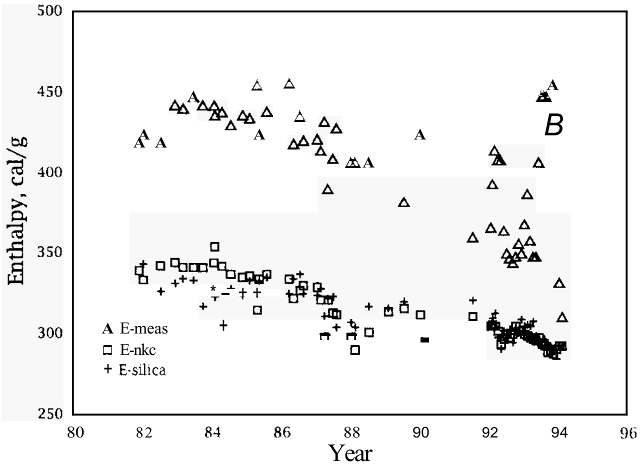

Figure 5. Cerro Prieto well E-4. Changes with time of fluid enthalpies as in Figure 2. The pattern is E-meas > E-nkc = E-silica indicating general reservoir-wide boiling.

2. E-meas > E-nkc > E-silica indicates fluid boiling during flow to the well in response to decrease in well-bottom pressure. Boiling lowers near-well fluid temperatures and causes heat transfer from (now hotter) rocks to increase E-meas values. Silica equilibrates, so E-silica values decrease, but slower equilibration of cations with aluminosilicate minerals does not occur, particularly because conduits are lined with quartz, thus E-nkc is not affected. If pressures are controlled by a constant pressure boundary, well-bottom pressures gradually stabilize and expansion of the boiling zone slows and stops. Within the stabilized boiling zone, temperatures equilibrate and heat is no longer transferred so excess enthalpy decreases slowly and disappears. E-silica is still depressed because near-well boiling and temperature decrease continues. The order then becomes E-meas = E-nkc > E-silica. Well M-31 showed local boiling from 1973 which stabilized in 1980 (Figure 3). Flows declined rapidly in 1980 probably due to localized near-well scaling and the well became unstable. The dots in Figure 3 show bottomhole fluid enthalpy based on results from wellbore flow model calculations (Goyal et al., 1981). These data support the assumption that the silica geothermometer yields near-well temperatures.

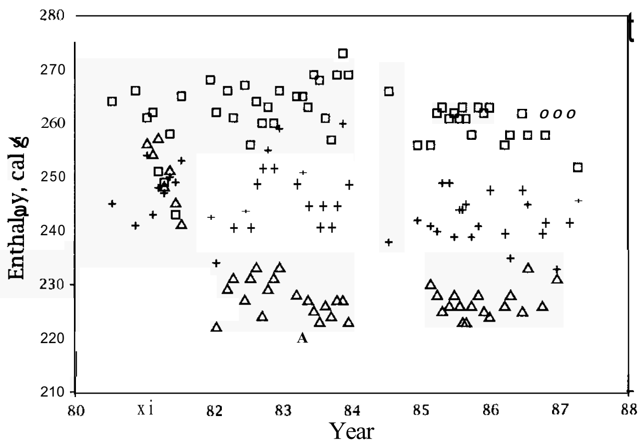

Figure 6. Ahuachapan well AH-28. Changes with time of fluid enthalpies as in Figure 2. The pattern is E-nkc > E-silica > E-meas indicating mixing in the wellbore.

3. E-nkc > E-meas = E-silica results from mixing with cooler water near the well with reequilibration of E-silica but not E-nkc. This is not observed at Cerro Prieto but well AH-21 at Ahuachapan, El Salvador, is a good example (Figure 4; see Truesdell et al., 1989c).

4. E-meas > E-nkc = E-silica indicates mixture of equilibrated liquid with steam formed by boiling away from the well. This pattern usually indicates widespread (not localized) boiling with phase segregation and separate entries of steam and water. This is characteristic of many wells in the Cerro Prieto beta reservoir; E-4 is typical (Figure 5).

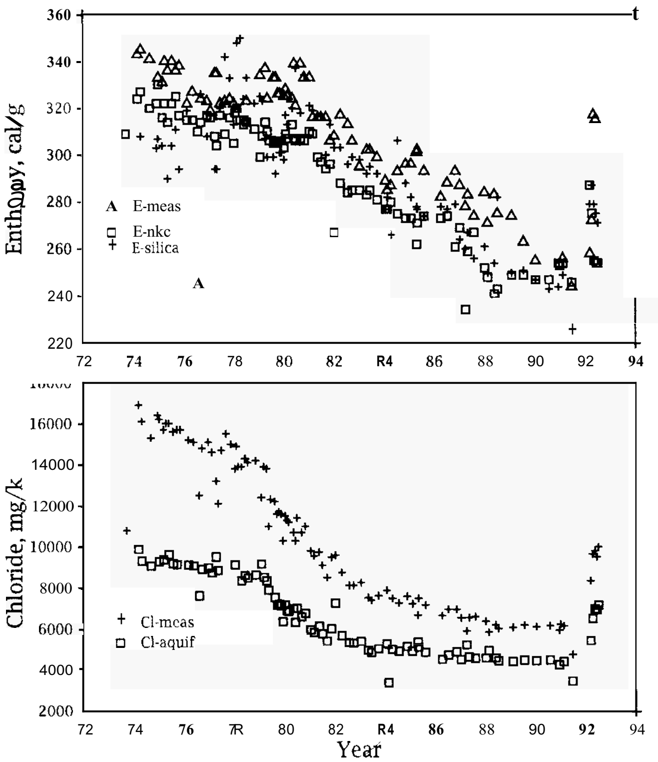

Figure 7. Cerro Prieto well M-35. Changes with time of fluid enthalpies as in Figure 2 and chloride concentrations as measured and calculated for aquifer conditions. The pattern is E-meas = E-silica > E-nkc indicating breakthrough of cooler water.

5. E-nkc > E-silica > E-meas shows mixture in the well of cooler more dilute water with equilibrated liquid. Lower E-silica values result from dilution without reequilibration and E-nkc is not significantly affected. Inflow of shallow cooler water into a well with multiple fluid entries could produce this pattern. Ahuachapan well AH-28 exhibits this pattern (Figure 6). Leakage of cool water into the well from a casing break or bad joint can give similar indications.

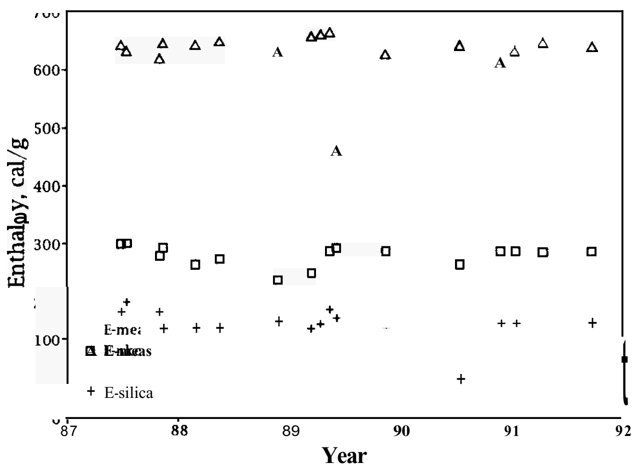

Figure 8. Cerro Prieto well M-107. Changes with time of fluid enthalpies as in Figure 2. The pattern is E-meas >> E-nkc >> E-silica indicating high-temperature condensation in the wellbore.

6. E-meas = E-silica > E-nkc indicates thermal breakthrough of cooler water. E-nkc still partly retains the memory of equilibration at lower temperatures although the fluid has been heated by flow through hot rock. Changes in aquifer chloride will indicate hydraulic

(or chemical) breakthrough, which precedes thermal breakthrough. Cerro Prieto well M-35 shows this pattern after thermal breakthrough in 1980-81, and eventual replacement of the original brine with cooler water about half as saline (Figure 7). Although chemical breakthrough was complete, temperatures were still declining when M-35 was shut-in in 1992.

7. E-meas >> E-nkc >> E-silica is an unusual pattern that, along with discharge of very dilute brine, indicates that high-temperature steam condensation is occurring in well casings and separators, and possibly in reservoir conduits. The condensation occurs at constant enthalpy and does not cool produced fluids but dilution of brine with the condensate produced lowers apparent silica temperatures. Wells with high enthalpy discharges in the NW Cerro Prieto area show this behavior (Truesdell et al., 1992). Well M-107, for example, has accompanying liquid with chloride concentrations as low as 1000 mgikg chloride and silica temperatures below 150°C. The Na-K-Ca temperatures are probably nearly correct.

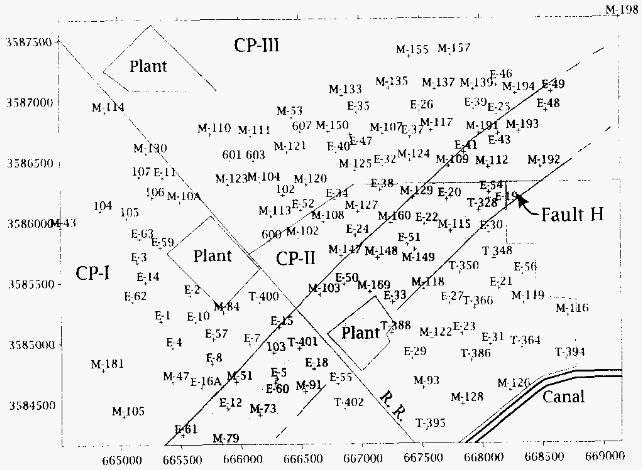

Figure 9. The location of the H-Fault at the level of the top of the Cerro Prieto β reservoir based on data from Halfinan et al. (1986) and on the depth to the reservoir (Figure 10). Coordinates shown are in meters.

Other cases can occur by combination of these processes; for example, boiling in the reservoir could be accompanied by cool water entry into the well. Some of these combinations produce ambiguous indications. Consideration of changes in aquifer chloride is of value in interpretation of these reservoir processes.

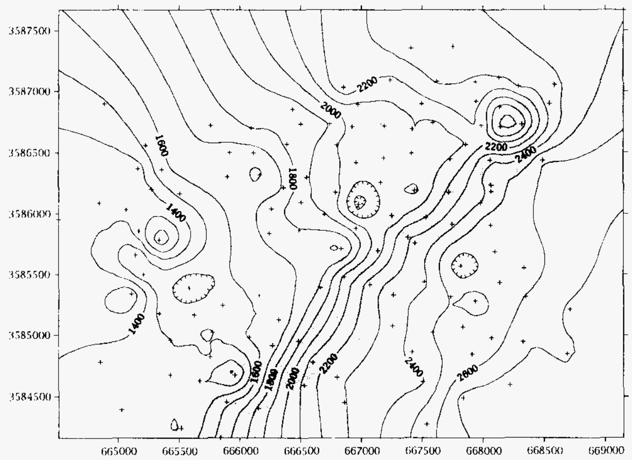

Figure 10. The depth to the top of the Cerro Prieto β reservoir based on drilling data (in meters). Note the change in slope represented by the plane of the H-fault (shaded) and the cupola in the NE.

FIELDWIDE PROCESSES

Although study of individual wells reveals details of near-well processes such as local boiling or the passage of a chemical or thermal front, and indicates problems such as scaling or casing leakage, the development of a resource management plan depends on the behavior of the entire reservoir. Field-wide response to exploitation is best

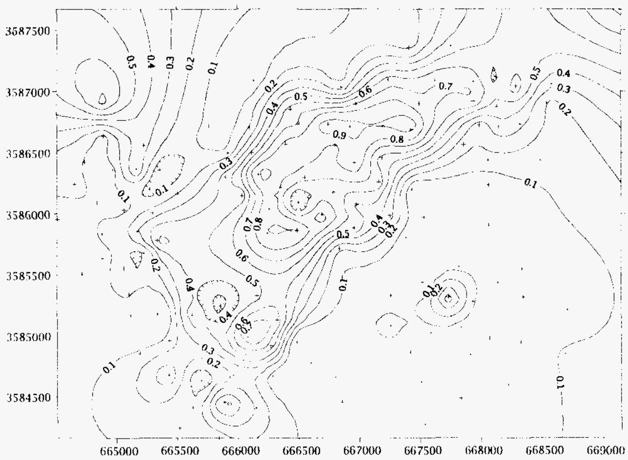

Figure 11. Inlet vapor fraction (IVF) for 1991 Cerro Prieto production. IVF is a measure of excess enthalpy. See text for explanation

shown by the use of contour maps of chemical and physical parameters including reservoir fluid temperature, enthalpy, and chloride and isotope concentrations. These quantities can be calculated from a combination of wellhead physical measurements and analyses of produced fluid (these methods are described in Henley et al., 1984, and Truesdell et al., 1989b and 1992).

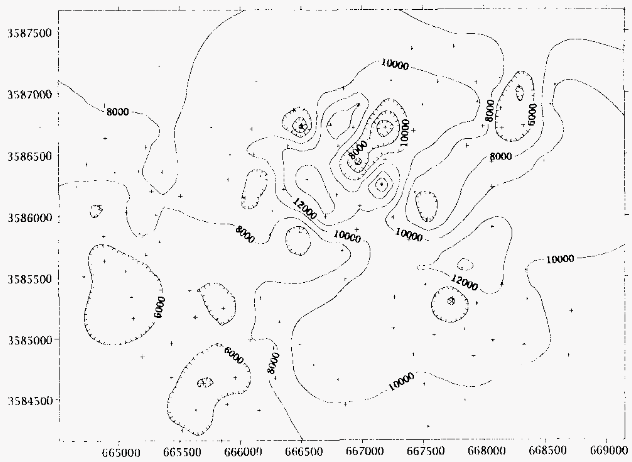

Figure 12. Calculated 1991 chloride concentrations in the Cerro Prieto β reservoir based on Na-K-Ca geothermometer temperatures (in mgikg).

The most useful indicator of reservoir temperature is the Na-K-Ca geothermometer which is little affected by near-well boiling or mixing with condensate or cooler water (e.g., Figure 2). These temperatures can be used with total fluid enthalpy to calculate the inlet vapor fraction (IVF) which is a measure of reservoir steam saturation. Na-K-Ca temperatures can be used with chloride analyses to indicate reservoir chloride concentrations (e.g., Figure 7). Analyses of isotopes in separated steam can be used alone or with separated liquid to calculate total discharge isotope compositions. Oxygen-18 is generally more useful than deuterium as a tracer of water origins because no deuterium isotope shift occurs, and high- and low-temperature waters are not distinguished.

For the Cerro Prieto β (beta) reservoir the most interesting maps show the influence of the **H** fault of Halfman et al. (1984) on the properties of the reservoir. The position of this SE-dipping fault at reservoir level is **shown** in Figure 9. Movement along the H fault has elevated the NW upthrown block (containing the **CP-III** part of the β reservoir) by about 700 meters relative to the SE downthrown block as indicated by the depth to the top of the reservoir (Figure 10). Most **wells** of CP-II are in the downthrown block but some are in the hanging wall of the fault or in the upthrown block. There is a radical difference in the behavior of the β reservoir in the NW and SE blocks.

In 1991 wells just NW of the fault produced high-enthalpy fluids with from 0.4 to >0.9 inlet vapor fraction (IVF) while almost all fluids from wells SE of the fault had <0.1 IVF (Figure 11). Fluids from the fault itself had intermediate values. Other quantities also differ between the upper and lower parts of the reservoir. 1991 reservoir chloride concentrations in the downthrown block were uniformly high (10.000 to 12,000 mgkg except for two wells) and reservoir temperatures ranged between 300 and 320°C (Figures 12 and 13). In the upthrown block both temperatures and chloride vary widely. The maximum values (14,000 **mgkg Cl** and >310°C) are similar to or slightly above those in the SE block but several parts have low chloride and temperature (to 6000 mg/kg Cl and 280°C). These lower values are aligned along the upper fault intersection (wells M-193 and E-22) **or** in the zone of highesi IVF values (wells M-107, M-125 and **M-102).** Some of these wells have normal temperatures with **very** high enthalpy and very low chloride due to adiabatic steam condensation (see Figure 8 and discussion). The total discharge $\delta^{18}O$ map (Figure 14) shows a gradient from -12.5 in the SW to -7 in the NE except for an elongate zone of fluids depleted in 0-18 (to -10.5) and a zone in the S enriched in $\delta^{18}O$. The lowest $\delta^{18}O$ fluids are also low in chloride and temperature (wells M-193, E-25 and M-107), but not all low temperature, low Cl fluids are low in $\delta^{18}O$ (well M-102) and vice-versa (well E-41).

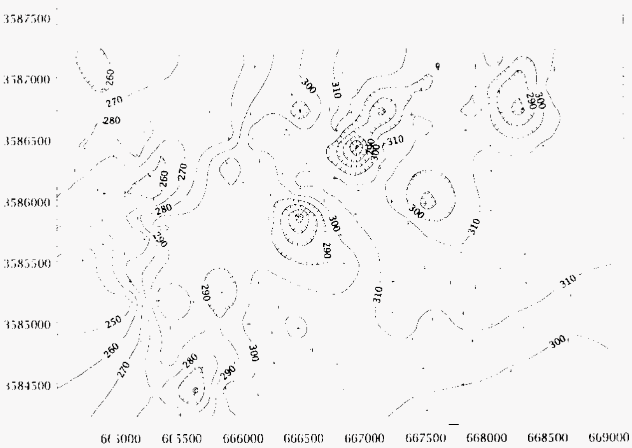

Figure 13 Calculated 1993 temperatures in the Cerro Prieto β reservoir from the Na-K-Ca geothermometer (in degrees Celsius)

The interpretation of these observations on the Cerro Prieto β reservoir is quite straightforward. The 700 m difference in elevation between the blocks must result in lower pressure in the upper block than in the lower one. Before exploitation, the fluid in the shallower hlock was probably at the boiling point and that in the deeper block, significantly below boiling. In addition the upper block probably has closed boundaries related to the displacement of the H fault preventing flow from the SE. The NE part of this block is also relatively distant from the W edge of the reservoir, where lower $\delta^{18}O$, temperature and chloride suggest a leaky boundary. The downthrown block may connect to cooler aquifers to the S as suggested by lower $\delta^{18}O$ and chloride, and more importantly is at greater depth and has higher pressures. These factors have combined to produce general boiling (not **just** near wells) in the upthrown, NW block (high IVF), and little boiling in the SE block (IVF near 0). The highest IVF values are near the fault intersection, with lower values to the W and N probably as a result of pressure support from entry of cooler fluids at the reservoir margin.

The localized occurrence of cooler, less-saline, isotopically-depleted waters at the NE end of the fault H intersection and in a parallel zone to the NW is most probably due to the entry down the fault of cooler waters from above the β reservoir. This is similar to the observed entry of cooler waters down the **L** fault (Halfman et al., 1984) into the shallow a reservoir, which started soon after the ***start*** of production (Stallard et al., 1987, Lippmann et al., 1989, Truesdell et al., 1989b). The entry of this cooler water will ultimately cool the reservoir, but will also recharge fluids and decrease the amount of boiling. The increase in reservoir liquid will maintain pressures, decrease **gas** and prevent the production of corrosive **HCl** (Truesdell et al., 1989a).

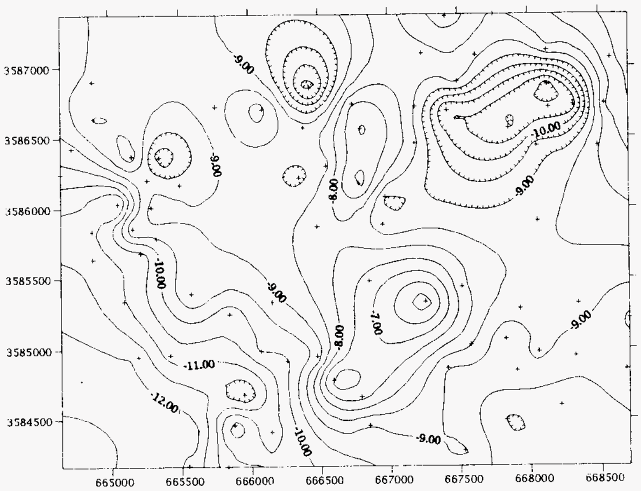

Figure 14. Calculated total discharge $\delta^{18}O$ values in permil SMOW for fluids from the Cerro Prieto β reservoir. Note that the scale is slightly different from that of other maps.

SUMMARY

At Cerro Prieto, extensive drilling, and frequent wellhead measurements, and collection and analysis of chemical and isotopic samples have allowed a good understanding of both near-well and reservoir-wide production mechanisms over its 20 year history. The response to pressure drawdown in **the** shallow ***a*** reservoir was principally entry of cooler water, with boiling limited to the vicinity of certain wells. In the deeper β reservoir drawdown has caused mainly general boiling in the upthrown NW block as a result of its lower pressure and relative isolation. In the downthrown block and at the W margin of the upthrown block much **less** boiling is observed, probably because cooler waters *are* being drawn in at reservoir margins. The increasing entry of cooler water down fault H into the NE end of the upthrown block is reducing boiling and may locally reduce the need for injection to maintain reservoir pressures.

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