

ISOTOPIC CHANGES IN THE FLUIDS OF THE CERRO PRIETO β RESERVOIR

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ABSTRACT

Monitoring changes with time of the isotopes of water (¹⁸O and D) in wellhead fluids is an effective way of indicating reservoir changes and processes. Because ¹⁸O concentrations in water are altered by high-temperature exchange with rock oxygen and because both ¹⁸O and D are fractionated in vapor-liquid separation processes at the surface (separators and cooling towers), these isotopes are excellent indicators of inflow and distribution of fluids from outside the reservoir, either natural or injected. Studies of the isotopic compositions of fluids from the Cerro Prieto field in Baja California, Mexico show that pressure drawdown in the major β (beta) reservoir has caused intense boiling followed by inflow of water from outside the reservoir. A method of field exploitation based on this behavior is discussed.

INTRODUCTION

Production of fluid from a geothermal reservoir causes a decrease in reservoir pressure. Unless these fluids are replaced by injection, this drawdown will cause entry of fluid from the outside or boiling in the reservoir. Although in many fields injection is required for waste disposal, injection wells are expensive and may be avoided if other disposal means are available. Without injection the effects of exploitation depend on connections to outside groundwater aquifers and on temperature and permeability. At Cerro Prieto, inflow of cooler water with limited local boiling was characteristic of the early-exploited shallow α (alpha) geothermal reservoir, and widespread boiling was initially characteristic of the lower β reservoir.

The necessity for injection to maintain reservoir pressures and fluid production rates has long been an article of faith for many reservoir engineers. The Geysers, California, where injection of liquid was insufficient to replace reservoir liquid with eventual declines in steam flow and pressure amply reinforces belief in the need for injection. However the case is not proven for hot water fields, particularly those with sedimentary reservoir rocks such as Cerro Prieto and the Imperial Valley geothermal fields.

The effect of natural inflow of water from outside the reservoir is similar to that of artificial injection except that the location of the natural inflow is difficult or impossible to control. Although pressure is maintained, the reservoir is cooled and ultimately the amount of steam generated

decreases. This cooling is, however, slowed by heat contained in the rock and usually proceeds from the margins of the reservoir toward the production area, providing a beneficial sweep of heat to producing zones. If the inflow occurs along fractures that provide direct channels to wells the premature breakthrough may be harmful.

Uncontrolled boiling has other consequences. Initially the decrease in pressure causes fluid boiling and cooling. Some heat contained in the reservoir rock is transferred to the cooled liquid, accelerating boiling and increasing the steam fraction. If reservoir liquid is locally exhausted, the pressure of steam decreases and it becomes superheated. Pressure drawdown causes a decline in total mass flow, but energy production may increase and the decrease in separated water eases disposal. However, production of superheated steam may allow detrimental constituents, previously suppressed by liquid, to be produced. Gas contents in steam may increase, and potentially corrosive HCl gas may be carried to the wells. Complete depletion of liquid in a hot-water reservoir has been observed locally and for short periods, as at Krafla, Iceland in 1980 where serious corrosion from HCl occurred (Truesdell et al., 1989a).

Boiling may be self-limiting in hot-water reservoirs. Pressures are maintained near original values as long as any liquid remains, and will decline rapidly only when that liquid is exhausted. If a system is sufficiently leaky to maintain a high temperature by means of strong upflow of hot water (Lippmann and Truesdell, 1990), large decrease in pressure may produce an inflow of outside water. This process has occurred at Cerro Prieto.

CERRO PRIETO

The Cerro Prieto geothermal field of Baja California, Mexico (Figure 1) is about 60 km. South of the city of Mexicali and the Mexico-California boundary. The field is contained in sandstones and shales of the Colorado River delta and is similar in temperature and reservoir rocks to the geothermal fields of the Imperial Valley immediately to the North. The circulation of geothermal fluids and the properties of the Cerro Prieto reservoirs have been described by Halfman et al. (1984, 1986) and Lippmann et al. (1989, 1991). There are two major exploited geothermal reservoirs located in sandstone and sandy shale units that are fed from depth by fluids rising along the NE-trending, SE-dipping normal fault H of

Halfman et al. (1984). Although faults are important in the vertical movement of fluid between reservoirs and to the surface, intergranular fluid flow, and matrix porosity and permeability dominate reservoir properties.

The α (alpha) reservoir in the western part of the field is the shallowest and was the first to be exploited. It covers an area of about 4.5 km² west of the railroad tracks (Figure 1) and has been exploited since 1973 by the CPI plant. Pre-exploitation temperatures were from 260 to 310°C at depths between 1000 and 1500 m. The response to pressure decrease in the α reservoir, has been an influx of cooler waters from the sides and above with limited local boiling (Grant et al., 1984; Stallard et al., 1987; Truesdell et al., 1989b). In the natural state, thermal fluids leaked out of the reservoir along its western edge and upward along fault L of Halfman et al. (1984; Figure 1) to form thermal springs west of the field or to disperse into colder groundwater. Under exploitation cold groundwater has entered the reservoir along these pathways (Lippmann et al., 1991).

The deeper β reservoir extends beneath the entire area of the Cerro Prieto field (about 15 km²) at depths from 1500 to >2700 m with temperatures ranging from 300 to possibly 340°C. Ascending thermal fluids flow into the reservoir along fault H (Figure 1) and move laterally to the NW and SE. In the natural state fluids flowed upwards into the α reservoir at a "sandy gap" between reservoirs. Fluids in the western and southwestern parts of the β reservoir connect with outside aquifers, and isotopic and chemical evidence indicates that under exploitation cooler waters have entered the reservoir in these areas. The β reservoir is offset by the normal fault H, with the downthrown block mainly exploited by the CPII power plant and the upthrown block by the CPIII plant. Figure 2 shows the position of fault H (shaded) as indicated by the depth to the top of the reservoir.

After CPII and CPIII plants went on line in 1986-7, large quantities of fluids were withdrawn from the β reservoir and the entire reservoir suffered strong pressure drawdown. The response to pressure decrease has been primarily dependent on the elevation of the exploited block. Although the entire reservoir has nearly the same temperature (about 310-320°C from geothermometers), the downthrown block is about 700 m deeper than the upthrown block and therefore had an original pressure about 50 bars higher. When pressures were drawn down throughout, the southeast block remained below boiling while the northwest block boiled intensely. This difference was accentuated by the relative isolation of the northwest block which has closed boundaries to the North and South and is relatively far (4-5 km) from the western boundary which is open to cool groundwater inflow. The southeast block, in contrast has cold water aquifers on its South and East edges. As described below boiling in the northeast has decreased as connections to outside aquifers have developed since about 1990 as described below.

COLLECTION AND ANALYSIS

Collection of samples for isotopic analysis of fluids from hot-water fields is necessarily of separated phases

available at the surface. Isotopes fractionate strongly during phase separation at the usual separator temperatures, so it is necessary to sample under well-defined conditions and to consider possible problems during collection. At Cerro Prieto the water level in the separators tends to be set low (to keep liquid out of steam lines), so the most reliable samples are of high-pressure steam collected from valves located on the top of steam lines close to separator outlets (Stallard et al., 1987). The high-enthalpy discharge of many wells in CPIII has made separated liquid unavailable. At Cerro Prieto steam (and water) samples from separators were cooled and condensed in coiled stainless steel tubing immersed in ice baths and collected at atmospheric pressure into clean pyrex bottles with leak-proof caps taped to prevent opening.

Samples were analyzed in the laboratories of Tyler Coplen at the USGS (before 1993) and Mahendra Verma at IIE (in 1993 and 1995) using automated preparation lines and computer-run mass spectrometers. Both laboratories have cooperated closely with the International Atomic Energy Agency program for isotopic standardization and produce routine analyses of high quality, with standard errors of ± 0.1 permil in $\delta^{18}\text{O}$ and ± 1 permil in δD . Analytical results were computed to total discharge (TD) concentrations with a computer program that allowed comparison of TD compositions calculated combining steam table data and experimental isotope fractionation factors with compositions of single and multiple phases collected from high- and low-pressure separators and from silencers. In general, the high-pressure vapor calculated to TD composition using experimental fractionations was the most consistent single calculation. For this reason the 1995 and part of the 1993 collections were of high-pressure vapor alone. The effects of salts on isotopic fractionation and on water thermodynamic properties were negligible because Cerro Prieto waters are about half the salinity of seawater. In the case of excess-steam fluids (with both steam and water in the reservoir) the TD compositions do not represent any reservoir fluid, but there is little to gain from further elaboration of the calculations.

1989 CERRO PRIETO ISOTOPES

Until 1986 essentially all production was from the shallow α reservoir. In that year the 220 MWe CPII powerplant in the southeast was put on line and soon after the 220 MWe CPIII powerplant in the northwest. These two plants used steam from the β reservoir and, as the α reservoir declined, the CPI plant also drew on wells completed in the β reservoir in the western part of the field.

The oxygen-18 compositions (Figure 3) show the effects of the fault H offset (Figure 3). The SE part of the β reservoir (in CPII) is characterized by fluids with oxygen-18 compositions between -8.5 and -10 permil SMOW which changes to values between -7.5 to -8.5 in the area to the NW with high excess steam. This is something of a paradox because at equilibrium steam is 0.7 to 1.0 permil lower in $\delta^{18}\text{O}$ than liquid water at the temperature of the Cerro Prieto reservoirs (320-340°C), thus light isotopes

(i.e. lower $^{18}\text{O}/^{16}\text{O}$ ratios) should accompany higher-enthalpy discharge. This may result from adiabatic condensation with high-temperature condensate, which is little changed isotopically from the original liquid, carried into producing wells (Truesdell et al., 1992). It is also possible that the heavier fluids in the northern part of CPIII represent the deep inflow to the field which has elsewhere been altered by mixing with lighter groundwaters. The lack of distinctive temperatures or chloride concentrations in this area argues against this hypothesis. The western side of the reservoir has much lighter isotopes with $\delta^{18}\text{O}$ as low as to -11.5. These low values represent the influence of lower temperature waters entering the reservoir through subsurface sandy units found west of the field.

Deuterium shows little experimental liquid-vapor fractionation at 320 to 340°C (steam is less than 2 permil enriched in deuterium) and there are few large changes throughout the CPII reservoir (Figure 4) with southern fluids about 1 to 2 permil lighter than central CPII fluids (-97 permil compared with -95 permil SMOW). The relatively small liquid-vapor fractionation factors for deuterium above 200°C and the lack of a "deuterium shift" from exchange with rock minerals, make deuterium a less sensitive indicator of boiling and mixing processes in geothermal systems than oxygen-18. Although oxygen-18 isotopes are influenced by boiling processes at high temperatures, the "oxygen isotope shift" resulting from oxygen-18 exchange between water and rock may also produce variations in isotope compositions. Fluids with lower deuterium (to -97 permil), similar to the low ^{18}O fluids described above, are found in part of the zone of anomalous fluids along the excess enthalpy boundary at fault H.

1991 CERRO PRIETO ISOTOPES

The total discharge $\delta^{18}\text{O}$ map for 1991 (Figure 5) is incomplete because relatively few samples were collected that year. The data show a fairly uniform gradient from -10.5 in the SW to -7.5 in the NE except for an elongate zone of fluids depleted in O-18 (as low as -10.5). The lowest $\delta^{18}\text{O}$ fluids are also low in chloride and temperature (wells M-193, E-25 and E-43), but not all low-temperature, low-Cl fluids are low in $\delta^{18}\text{O}$ (well M-102) and vice-versa (well E-41). The strong $\delta^{18}\text{O}$ low in the NE of CPIII (wells M-193, E-25 and E-43) was barely evident in 1989 (only E-43 was low in both $\delta^{18}\text{O}$ and δD), but strongly developed in 1991. This low is located in part of the upthrown block that is not only at the intersection of fault H with the top of the β reservoir, but also where production occurred 300 m higher than adjacent parts of the upthrown block. Because this area is also low in chloride and temperature, it seems to represent cooler, less-saline, isotopically-lighter groundwater flowing down the H fault, similar to the cooler groundwater that entered the α reservoir along the L fault (Lippmann et al., 1989). The deuterium data (Figure 6) shows a less pronounced low in the same location and a high centered on well M-120. This well had a high enthalpy in 1991 but was not otherwise distinctive. The high value may be from an analytical or computational error.

In 1991 the average enthalpy of production was near its maximum. The wells just NW of fault H produced exceptionally high-enthalpy fluids with 0.4 to >0.9 inlet vapor fraction (IVF) while almost all fluids from wells southeast of the fault had <0.1 IVF (Truesdell et al.; 1992). Fluids from the fault itself had intermediate values. In 1991 reservoir chloride concentrations in the downthrown block were uniformly high (10,000 to 12,000 mg/kg except for two wells) and reservoir temperatures ranged between 300 and 320°C. In the upthrown block both temperatures and chloride varied widely. The maximum values (14,000 mg/kg Cl and >310°C) were similar to or slightly above those in the southeast block, but several parts had low chloride and temperature (down to 6000 mg/kg Cl and 280°C) due to dilution from high-temperature adiabatic steam condensation.

1993 CERRO PRIETO ISOTOPES

The $\delta^{18}\text{O}$ and δD maps for 1993 are based on a large amount of data (Figures 7 and 8). The division of the reservoir with lower isotope values in the South, which was evident on the 1989 and 1991 maps, is still visible, but the pattern is distorted by the growth of the light isotopic zone in the NE and the appearance of a heavy isotope zone in the center (including wells E-18, E-55, E-33, E-50 and M-118). This zone may have existed in 1991, but there were few samples collected in this area (only E-18 which does show a high value). Heavy isotopes could indicate deep fluid possibly similar to the -7.5 permil $\delta^{18}\text{O}$ values in the NE in 1989 and 1993. However although this central, high- ^{18}O zone has high chloride it also has low indicated temperatures (CFE, unpublished data, 1995). The low temperatures and their position along fault H just NE of injection well E-6 suggest that the high ^{18}O and high chloride are due to mixing with injection water.

The deuterium map for 1993 is almost as featureless as that for 1989, but does show a low in the NE and a high in the center located near the equivalent $\delta^{18}\text{O}$ features. In the NE the -100 δD contour extends to the East to include the wells E-25 and E-43, and in the center there is a δD high of -90 around wells E-18 and E-55. Lower temperature fractionation processes (evaporation or steam separation) are indicated because these well fluids are enriched in both ^{18}O and D with both isotopes behaving similarly rather than showing opposite enrichments as would occur at high temperatures.

1995 CERRO PRIETO ISOTOPES

In 1995 the trends that were indicated in earlier data intensified. The isotopic low in the northeast spread toward the center of the field in the upthrown block and along the trace of fault H (Figures 9 and 10). The isotopic high in the center of the field spread to the northeast along the fault and in the downthrown block. The deuterium map shows a somewhat larger isotope high and a smaller isotope low, but these differences are probably artifacts due to the choice of contour intervals. The enlarged 1995 anomalies give a more detailed indication of the fluid flow patterns. The low for both isotopes is centered on well E-43 which is at the top of the cupola or structural

high shown in Figure 2. The isotopic low has grown mainly toward the center of the field in the direction of greatest fluid production. Comparison with the position of fault H (shaded in Figure 1) shows that the isotopically lighter fluid has spread to the northeast in the upthrown block and a somewhat greater distance along the fault to the southeast. This is probably mainly due to the reservoir fluid flow set up by the location of producing wells, but there may be some effect of higher permeability within the fault zone.

In contrast the center of the isotopic high has migrated from E-33 in 1993 to E-55 in 1995. Both of these wells are near the intersection of the fault with the top of the downthrown block as is injection well E-6, the probable source of the isotopically heavy water, but neither E-33 or E-55 is close to E-6. It seems that the flow of the injectate was to the NE from the exit point on E-6. The area of greatest fluid production has drawn both injectate and groundwater inflow toward the center of the field with much of the flow occurring parallel to the fault zone. This is similar to the flowpath of isotopically-light exotic fluid into the α reservoir from fault L (Truesdell and Lippmann, 1986; Stallard et al., 1987). The flow was initially along the fault zone and then to the east toward the area of highest fluid extraction. Investigations by CFE (unpublished data, 1996) have shown that flow of the injected water in the β reservoir was largely horizontal due to permeability differences.

DISCUSSION

The geochemical observations on Cerro Prieto fluids clearly show that the major reservoir processes resulting from exploitation were influenced strongly by the presence and offset of normal fault H. The evolution of boiling and fluid inflow has been entirely in response to pressure drawdown. This is a simple picture, but it raises interesting questions about the efficient exploitation of hot-water geothermal reservoirs.

The necessity for fluid circulation in maintaining high temperatures in hot water geothermal reservoirs was discussed by Lippmann and Truesdell (1990). They argue that under natural conditions hot water in geothermal reservoirs is in dynamic equilibrium with surrounding cooler groundwaters and that outflow from these reservoirs into cooler aquifers or to the surface is necessary to allow continued inflow of hotter water from below to maintain reservoir temperatures. It is only a small extension of these arguments to suppose that all geothermal reservoirs maintained by inflow of hot fluid must ultimately respond to production-related pressure drawdown by inflow of cooler waters, usually down permeable zones that in the natural state carried water out of the reservoir. This statement does not apply to vapor-dominated reservoirs which receive heat at their base by conduction and transfer heat upwards by boiling and condensation (i.e., heat pipes). There may be hot-water reservoirs which can transfer heat by conduction without discharging fluid, but field evidence is sparse.

If exploitation of most hot water reservoirs will eventually cause inflow of outside water then this can be used as an efficient way of exploiting the geothermal resource. Exploratory wells would be drilled to provide information on reservoir dimensions and temperature distribution. Production wells would be located in the highest temperature zone leaving a buffer zone between them and the edge of the reservoir. The exploitation of the hot zone may cause boiling, but is unlikely to dry it out. Before that happens water from the cooler margins will flow toward the center sweeping heat stored in water and rocks to production wells. Compared to development by wells drilled throughout the reservoir and waste water injected outside the reservoir, a field developed in this way will produce energy more slowly but over a longer period and at much lower cost in well drilling and plant construction. Disposal of waste fluid could be done into surrounding, possibly unconnected, aquifers. This obviously will not work for hot water fields in which fluids flow exclusively through fractures (where short circuiting may occur), but should be considered for fields with sedimentary host rocks similar to those at Cerro Prieto.

SUMMARY

Reservoir processes at Cerro Prieto are reflected in isotope compositions and in other geochemical indicators. In the Cerro Prieto β reservoir, drawdown has caused intense boiling in the upthrown northwest block as a result of its lower pressure and relative isolation. In the downthrown block and at the western margin of the upthrown block much less boiling is observed due to higher initial pressures and cooler water drawn in at reservoir margins. The increasing entry of cooler water down fault H into the northeastern end of the upthrown block is reducing reservoir boiling and may reduce the need for injection to maintain reservoir pressures. Isotopically heavy injectate from a well drilled into area of fault H is being produced from other wells in that area. The induced entry of outside water into the zone of strong boiling caused by pressure drawdown suggests a novel way of exploiting some hot water geothermal reservoirs.

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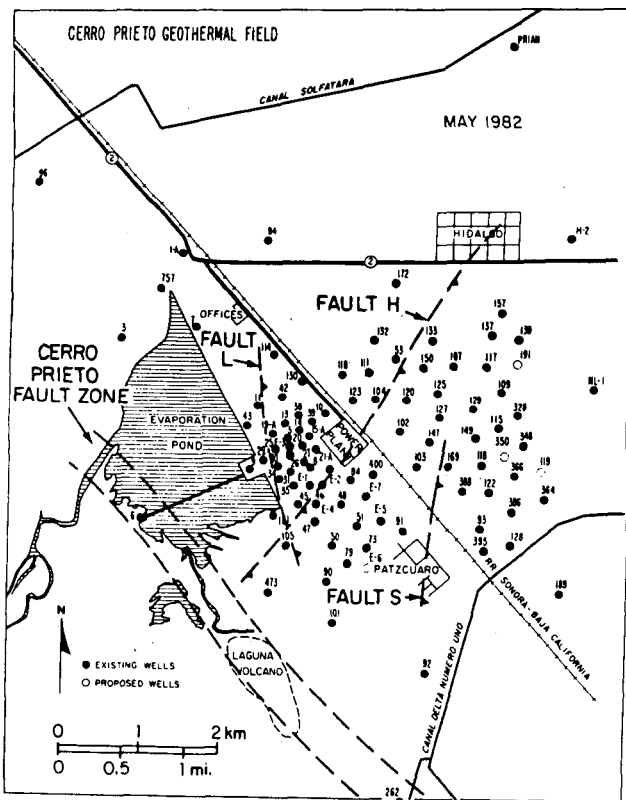


Figure 1. The Cerro Prieto field in 1982. Fault H, L and South locations are shown extrapolated to the surface (from Halfman et al. 1984).

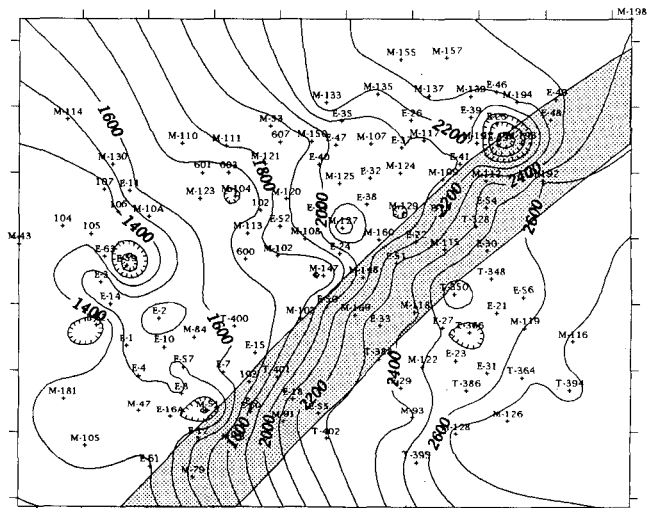


Figure 2. The location of fault H (shaded) at the level of the top of the Cerro Prieto β reservoir based on the depth to the reservoir (data from CFE). Depths and coordinates are in meters.

