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Publication Date

1986-06-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

To be presented at the 1986 Geothermal Resources Council Annual Meeting, Palm Springs, CA, September 29 - October 1, 1986; and to be published in the Proceedings

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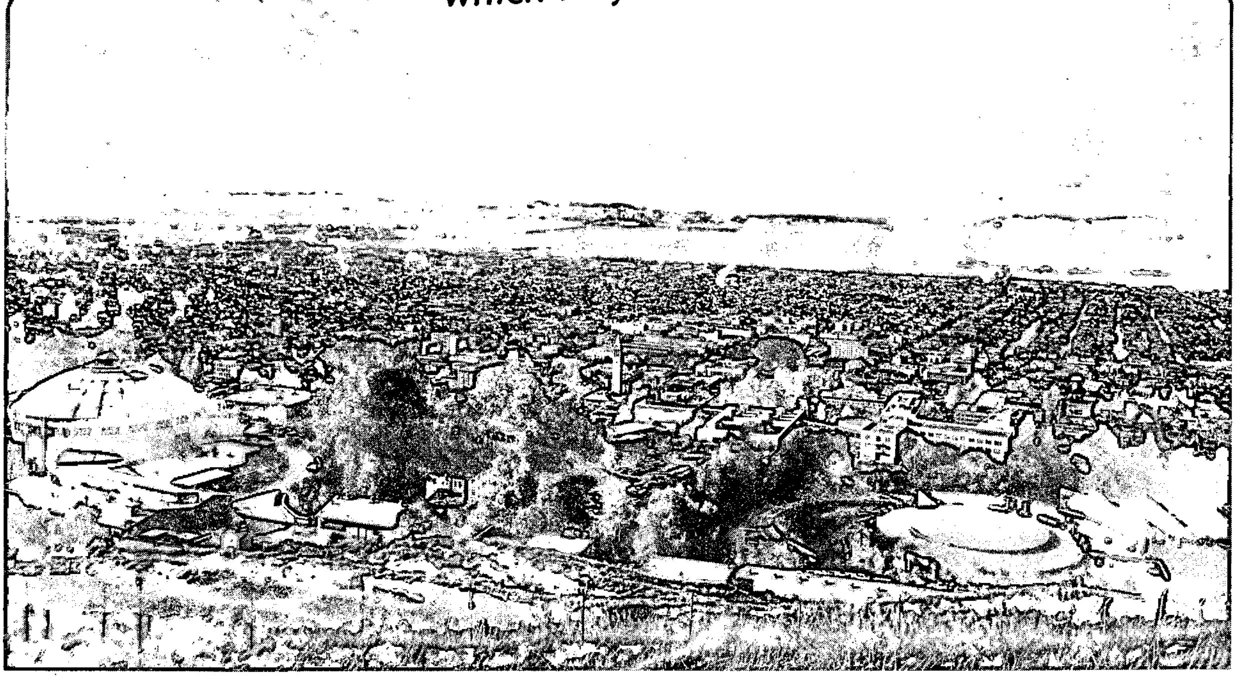

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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This work was supported by the U.S. Geological Survey under an Interagency Agreement with the U.S. Department of Energy and by the Lawrence Berkeley Laboratory under U.S. Department of Energy Contract No. DE-AC03-76SF00098.

The Lack of Immediate Effects from the 1979-80 Imperial and Victoria Earthquakes on the Exploited Cerro Prieto Geothermal Reservoir

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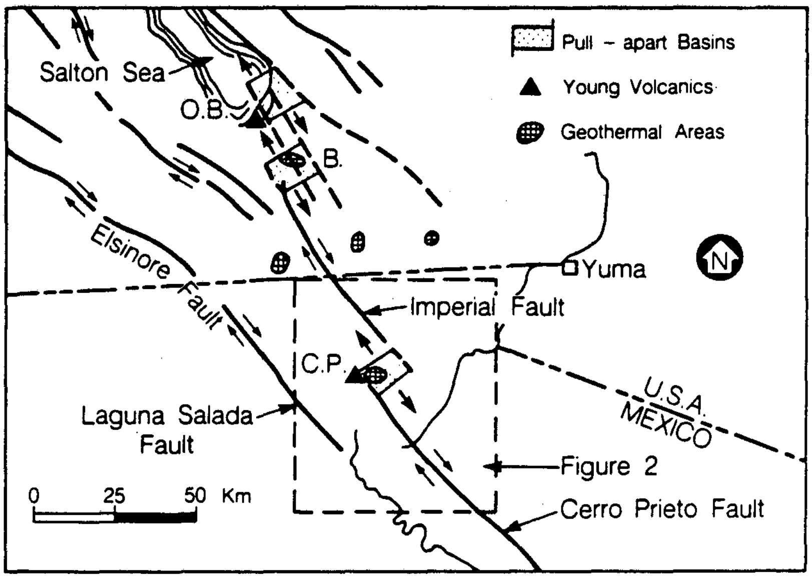
ABSTRACT

In 1979-80 two large earthquakes of local magnitude (M_L) greater than 6.0 occurred near the Cerro Prieto geothermal field. It has been suggested that related to these seismic events there was an abrupt temperature increase in the wells completed in the shallow (alpha) reservoir. A careful study of the geochemistry of the produced fluids, as well as a cursory reservoir engineering analysis, cannot confirm either the data or the hypothesis of a massive influx of hot water into the system related to those events. Our study shows that the cold water recharge of the alpha reservoir in response to the production-induced drawdown continued, unaffected by the two earthquakes.

INTRODUCTION

The Cerro Prieto geothermal field is located in a pull-apart basin or dilational jog (Elders et al., 1972; Sibson, 1985) of the San Andreas fault system (Fig. 1). Movement along the bounding en-echelon strike slip faults is right lateral and the jog is to the right, producing a dilational basin that is essentially an inland part of the East Pacific Rise. The occurrence of earthquakes along each of its bounding faults suggests that a spreading event occurred in 1979-80 (Fig. 2).

Several phenomena of geothermal interest could be associated with these earthquakes and spreading events. For example, at depth, fracturing of geologic formations would tend to enhance the permeability of the rocks in the geothermal reservoir and surrounding formations, and increase the porosity that might have been reduced earlier because of mineral precipitation. Igneous dikes could intrude the sedimentary fill of the pull-apart basin, thus thermally recharging the geothermal system. At the surface, sandblows emitting hot water and hydrothermal explosions might occur. The first historical account of the latter type of event at Cerro Prieto was given by Lt. Sweeney of the U.S. Army who, while stationed in Yuma wrote in his journal for December 12, 1852: "The effects of the earthquake (of November 29, 1852) are seen around in every direction . . . a large column of smoke or steam was observed . . . about 25 or 30 miles (to the southwest) in Lower California . . ." Other hydrothermal explosions occurred at Cerro Prieto in 1915 and possibly 1927 (Bureau of Reclamation, 1976, p. 14, 36 and 49).



XBL 865-10805

Figure 1. Inferred transform faults and pull-apart basins in the Salton Trough; O. B. Obsidian Butte; B. Brawley geothermal area; C. P. Cerro Prieto geothermal area (modified from Elders et al., 1972).

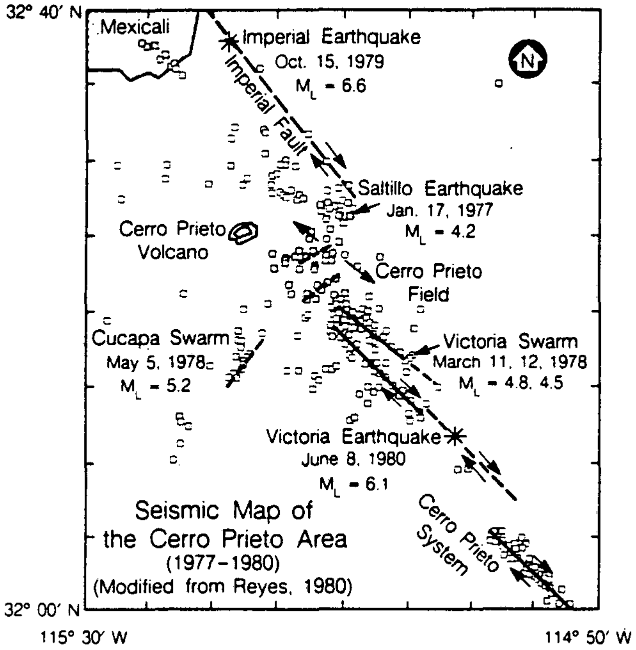


Figure 2. Seismicity of the Cerro Prieto area (modified from Reyes, 1980). XBL 865-10806

Stefánsson (1981) recently described the effects of a spreading event on the nearby Krafla geothermal field in Iceland. The analogy is not complete, because unlike Cerro Prieto, this field is in oceanic crust, with no thick sedimentary cover. The spreading, inflation and eruption tilted the power plant and produced large pressure surges in the geothermal wells. At Cerro Prieto the depth of intrusion (if any) was much greater and such direct responses were not observed.

The epicenter of the Imperial earthquake of October 15, 1979 ($M_L = 6.6$) was located on the Imperial fault about 20 km NNW of Cerro Prieto (Fig. 2). The earthquake propagated northwestward, with aftershocks and surface ruptures, with up to 40 cm of right-lateral movement, extending 35 km into the Imperial Valley (U.S. Geological Survey, 1982). The Victoria earthquake of June 9, 1980 ($M_L = 6.1$) on the Cerro Prieto fault was centered about 20 km southeast of the field. Movement during this earthquake did not produce a strike-slip surface trace, although some surface collapse and cracking occurred (Suárez et al., 1982). Neither of these earthquakes produced any significant damage to the wells or surface structures of the geothermal field, but there may have been some changes in the shallow (900 - 1400 m) alpha reservoir, as suggested by Valette-Silver et al. (1985). It is our purpose to examine the evidence and possibility of reservoir changes caused by these earthquakes.

EFFECTS OF SPREADING

The earthquakes of 1979-80 indicated dilation (or spreading) of the area between the faults. The geometry of the dilational jog requires spreading at the same rate as movement along the San Andreas fault system, suggesting average dilation of 5 to 10 cm per year. This spreading is partly accommodated by sedimentation from the Colorado River and partly by the intrusion of mantle material. The intrusions carry heat toward the surface and undoubtedly the formation of the geothermal system is made possible by this heat. If, somehow, this thermal energy were immediately available to reheat a geothermal system that has been cooled by heavy exploitation, we would have, at least in part, a renewable energy source. This is unlikely despite the arguments of Valette-Silver et al. (1985), who suggest that there was a 10°C average temperature increase over the whole alpha reservoir (with some well temperatures increasing 30°C) as a direct result of the 1979-80 earthquakes. Let us examine the evidence.

CHANGES AT CERRO PRIETO

The Cerro Prieto alpha reservoir fluid was originally 260 to 310°C, with proportional chloride concentrations between 6,000 and 10,000 mg/kg (Grant et al., 1984). This reservoir is restricted to the western part of the field, and is partially fed by fluids from a deeper reservoir (beta) with higher temperatures and chloride contents (from 320 to 340°C, and from 9,000 to 12,000 mg/kg, respectively). Based on the results of the two-dimensional natural state modeling study of Cerro Prieto by Lippmann and Bodvarsson (1983), and assuming a 3 km north-south dimension for the alpha aquifer, this deep recharge would amount to about 100 tonnes/hr.

In response to exploitation this hot water influx does not change significantly. It seems to be limited by the presence of a two-phase zone in the permeable gap connecting the alpha and beta reservoirs (Fig. 3, modified from Halfman et al., 1984 and 1986). The associated fluid mobility decrease due to relative permeability effects restricts the mass recharge from the deeper (eastern) parts of the geothermal system. Lippmann and Bodvarsson (1983) estimated that only 3% of the fluids produced between 1973 and 1978 came from the beta reservoir. The alpha aquifer is also recharged from the side (west) and above with cold water that enters the reservoir in response to lower pressures due to exploitation. This influx of cold water produces a cold sweep that has resulted in a steady decrease in reservoir fluid temperature and chloride content, with temperature decline retarded by heat conduction from reservoir rocks (Grant et al., 1984; Grant and O'Sullivan, 1982).

The connections of deep hot water and shallow cold water to the alpha reservoir near the wells can be investigated using fluid chemistry. If the 1979-80 dilation opened deep fractures, then higher-temperature, higher-chloride fluid might move upward, causing increases in temperature and salinity; if shallow fractures were opened, there might be cooling and dilution. Fortunately, from the earliest tests of Cerro Prieto wells there has been an established Comisión Federal de Electricidad (CFE) program of monthly or bimonthly sampling and chemical analysis of brine after steam separation, and monthly measurements of fluid flows and enthalpy. These analyses and measurements may be used to calculate reservoir temperatures, using chemical geothermometers, and reservoir fluid chloride concentrations, using measured enthalpy, reservoir temperatures, and chloride analyses of flashed brine. Valette-Silver et al. (1985) used Na/K geothermometer temperatures processed using a "matched filter" to "enhance" the evidence for a thermal event, and concluded that some well temperatures had risen by as much as 30°C, with an average for the whole field of 10°C.

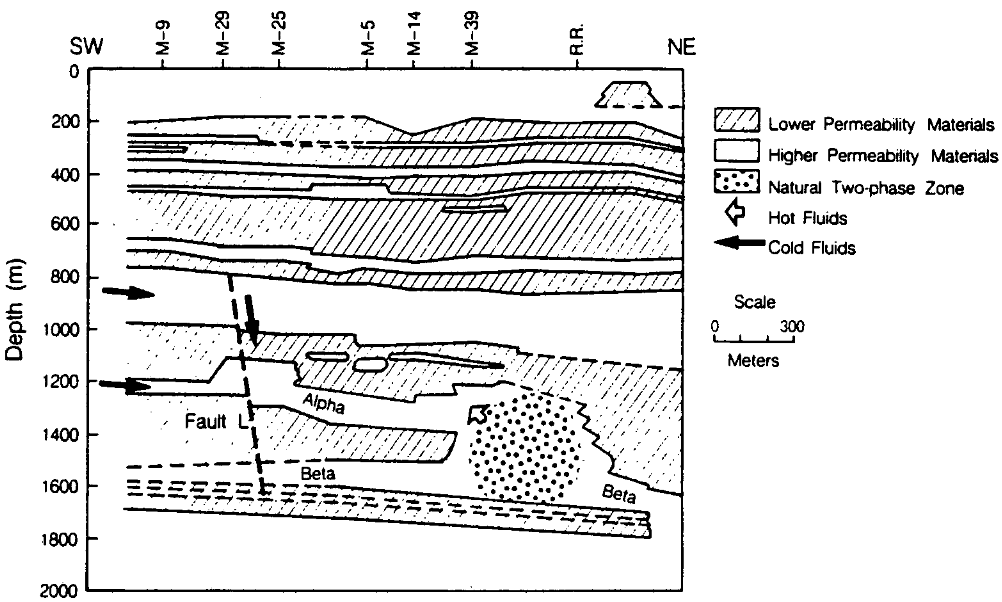


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Figure 3. Postulated fluid recharge pattern in the Cerro Prieto alpha reservoir resulting from its exploitation (geology based on Halfman et al., 1984 and 1986).

We do not find this treatment convincing. In particular we distrust the use of the matched filter, which has a "step rise in temperature" that appears to cause processed data to show a rapid rise and fall of temperature just at the time of the earthquakes. We examined the fluid temperature-time curves, based on the Na-K-Ca geothermometer, for all Cerro Prieto wells in production between 1978 and 1981 and found that: (1) very few wells show apparent temperature increases that are in every case coincident with extreme decreases in flow and increases in enthalpy, probably caused by choking due to near-well mineral precipitation (Truesdell et al., 1984a); and (2) many wells show decreases in temperature with time, with the rate of temperature decline increasing between 1979 and 1981. After processing with the matched filter, the increasing decline in temperature was apparently interpreted as a local maximum. As discussed later, the increased decline probably represents thermal breakthrough of encroaching cold water which may have been telescoped by the increase of production that started between late 1978 and early 1979. Production increased from about 2,500 to 4,300 tonnes/hr in order to increase electrical output from 75 to 150 MWe. For many wells there was no change in the rate of temperature decrease but calculated temperatures varied randomly due to variations in sampling and analysis. For these wells positive fluctuations in calculated temperatures were taken by Valette-Silver et al. (1985) to represent real temperature increases. (It is important to avoid connecting data points when considering data containing random errors. Without connecting lines, random fluctuation can be seen for what it is; with connecting lines, the variation appears real.) The consideration of changes in aquifer chloride concentration, flow rate, and enthalpy clarifies what has occurred at Cerro Prieto. Let us take these in turn.

AQUIFER CHLORIDE CALCULATION

The interpretation of the temperature changes in the wells can be checked by calculating reservoir chloride. For an all-liquid reservoir fluid that flashes only in the wellbore, the reservoir chloride is equal to the total discharge chloride. This is also true of fluids that boil in the formation local to the well so long as all steam and water flow to the well. These aquifer chlorides can be calculated from

$$\mathrm{Cl_{aq}} = \mathrm{Cl_{sep}} \times \mathrm{WF_{sep}} \tag{1}$$

and

$$\mathrm{WF_{sep}} = \frac{(\mathrm{H^{sep}_{stm}} - \mathrm{H_{tot}})}{(\mathrm{H^{sep}_{stm}} - \mathrm{H^{sep}_{wat}})} \tag{2}$$

where WF is the water fraction. If the sample flashes to the atmosphere after separation, the equation becomes

$$\mathrm{Cl_{aq}} = \mathrm{Cl_{atm}} \times \mathrm{WF_{atm}} \times \mathrm{WF_{sep}} \tag{3}$$

The water fractions are calculated using measured enthalpy of total discharge and steam-table enthalpies at separator and atmospheric pressures (salinity corrections are insignificant). Excess steam in the discharge may also originate from general reservoir boiling away from the well, with the steam and water entering the well from separate sources. In this case, the equation is

$$\mathrm{Cl_{aq}} = \mathrm{Cl_{atm}} \times \mathrm{WF_{atm}} \times \frac{\mathrm{WF_{sep}}}{\mathrm{WF_{res}}}, \tag{4}$$

with the water fraction in the reservoir calculated from total discharge enthalpy, and enthalpies of water and steam at the reservoir temperature estimated from geothermometers. Most wells at Cerro Prieto appear to exhibit local, near-well boiling, but where the near-well zones coalesce the boiling may become more general.

AQUIFER CHLORIDE AND TEMPERATURE

A positive linear correlation between original fluid enthalpies (as indicated by Na-K-Ca temperatures), and original chloride concentrations was observed at Cerro Prieto by Grant et al. (1984). Thus the entry of fluid into the alpha reservoir from a higher- or lower-temperature aquifer would be indicated by an increase or decrease in both chloride concentration and temperature. Because temperatures are buffered by heat contained in the rock, the chemical change (or breakthrough) should preceed the thermal change (or breakthrough) by an amount depending on the porosity. This relationship was the basis for the prediction of reservoir cooling between 1980 and 1985 made by Truesdell et al. (1979) based on a model by Nathenson (1975).

Careful inspection of the changes in aquifer temperature and chloride with time shows the following: (1) only wells with erratic flow and enthalpy (Wells M-20, 31, 21A) have increases in Na-K-Ca temperature, with some increases appearing years before the 1979 Imperial earthquake; (2) many wells have no evidence of breakthrough of chloride or temperature; (3) in other wells chloride breakthrough preceeded thermal breakthrough (taken as the point of inflection on each curve) by about 3 to 27 months (Table 1) as expected; and (4) chloride breakthrough in some wells preceeded the 1979 Imperial earthquake. These observations suggest that the actual effect of the earthquakes on the alpha aquifer was small or nonexistent and that observed changes in chloride and temperature were due to breakthrough of cooler water into the alpha reservoir from the side and from above, which by coincidence occurred within about the same period as the earthquakes. This breakthrough was the natural result of heavy production of fluid from a reservoir with leaky boundaries (Grant and O'Sullivan, 1982, and other papers cited).

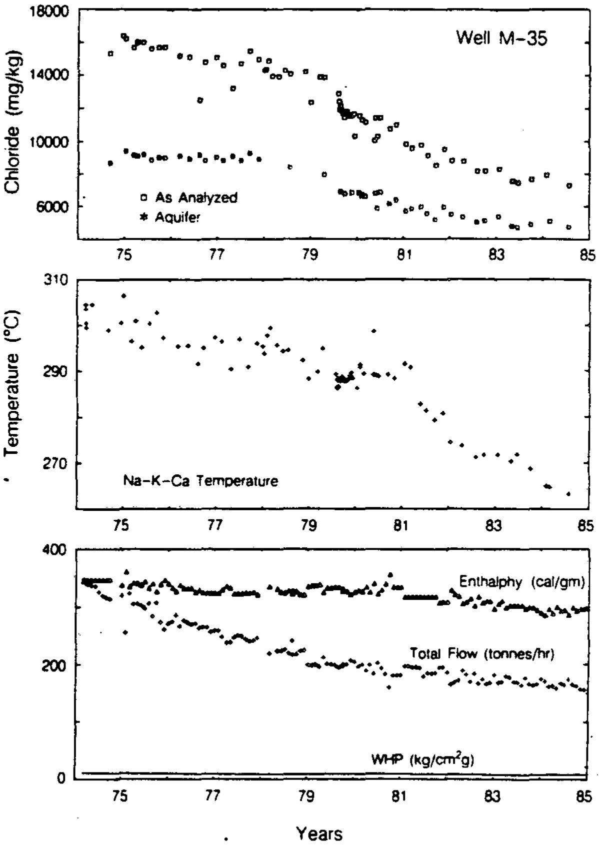

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Figure 4. History of well M-35. Aquifer chloride calculated from Eq. 3.

Table 1

Cerro Prieto Wells that Show Definite Breakthrough

Well	**Approximate Breakthrough Dates Indicated by Chloride Content**	**Approximate Breakthrough Dates Indicated by Temperature**
M-5	12/78	3/81
M-9	1973 ?	1973 ?
M-19A	6/79	12/79 ?
M-25	6/80	12/80
M-26	12/74	9/75
M-29	9/79	?
M-30	12/80	3/81
M-35	12/77	3/80
M-50	3/80 ?	3/81
M-105	?	3/81

Examples of wells showing thermal and chemical breakthrough (M-35), no breakthrough (M-14) and erratic changes (M-20) are given in Figures 4 through 6. Other examples have been presented in Truesdell et al. (1978 and 1984a). It should be noted that the breakthrough of cooler water can be demonstrated by changes in any conservative chemical component, of which chloride is the most frequently analyzed (see for example data for $\delta^{18}O$ in Truesdell et al., 1984b).

Wells choked by aquifer scaling show unusual behavior that is not fully understood. The constricted flow results in lower pressures between the blockage and the well, with increased boiling and excess enthalpy due to increased conductive heating from the rock. The boiling causes increased calcite deposition and decreased calcium in the produced fluids. This explains the behavior of most wells but the behavior of well M-20 has some additional features. The Na/Ca ratio for fluids from M-20 increased from 13 to 24 with a flow decrease from about 100 to 20 tonnes/hr (Figs. 6 and 7). The calculated Na-K-Ca temperatures increased due to the decrease in calcium. These chemical changes can be explained by choking due to aquifer scaling. However, at the same time as the Na/Ca ratio increased, the Na/K ratio

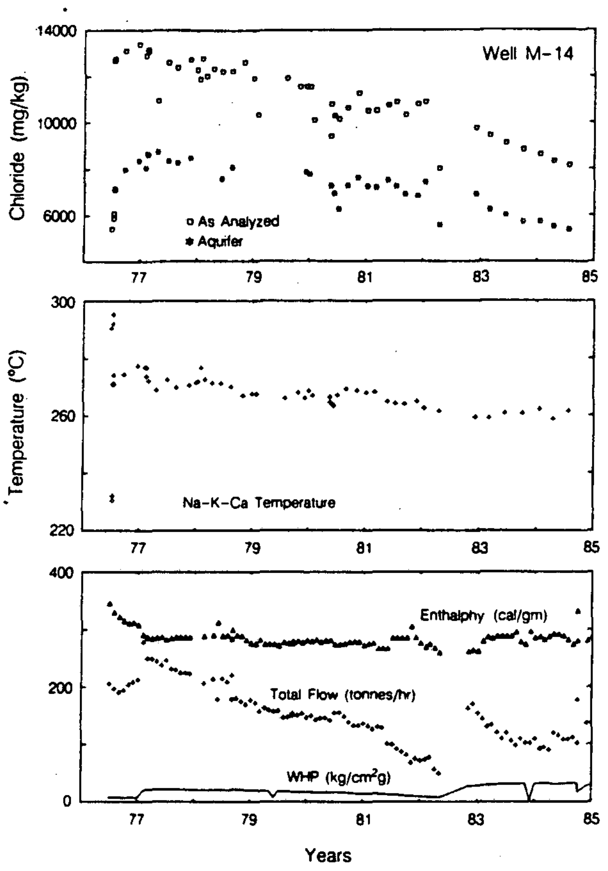

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Figure 5. History of well M-14. Aquifer chloride calculated from Eq. 3.

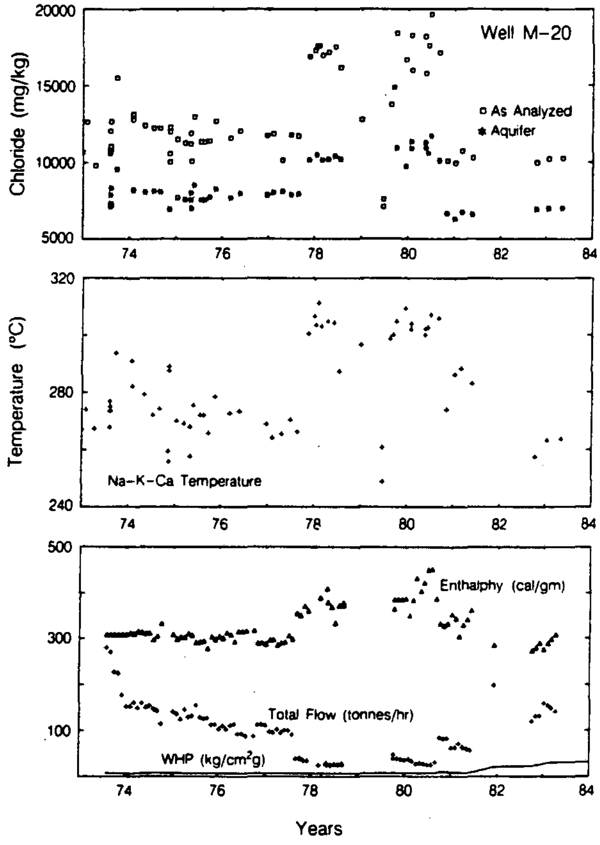

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Figure 6. History of well M-20. Aquifer chloride calculated from Eq. 4.

decreased from 5 to 3.7 (Fig. 7) and the aquifer chloride increased from 8,000 to 11,000 mg/kg (Fig. 6). This suggests a real temperature and chloride increase in the fluids feeding the well. The most reasonable explanation is that well M-20 originally had multiple feed zones that differed in temperature and salinity. When the well was choked by mineral deposition the balance of the inflow changed, with the high-temperature flow increasing. Note that the change of flow regime in this well must be unrelated to the earthquakes because it started in mid-1977, two years before the October 1979 Imperial earthquake. Other wells with flow reduction due to aquifer scaling (M-21A, 26 and 31) also show increases in Na/Ca, higher Na-K-Ca temperatures, and elevated enthalpy but do not show decreases in Na/K or increased aquifer chloride. For these wells, choking with increased near-well boiling and mineral precipitation appears to explain the changes.

INTERPRETATION

As mentioned earlier, the shallow alpha reservoir at Cerro Prieto is connected to both hotter, more saline water, and cooler, less saline water. We have shown that the alpha aquifer temperature and chloride content were either unchanged or showed increased declines before, during and after the period of the 1979-80 earthquakes (Table 1). This seems to strongly suggest that the fluid recharge regime in the alpha reservoir was not significantly affected by this seismicity and the probable related crustal spreading.

Let us examine in more detail the possibilities of increased recharge to the reservoir of hotter and cooler water. The relations of the Cerro Prieto alpha reservoir to the deeper, higher temperature beta reservoir and to cold water aquifers were shown by Halfman et al. (1984 and 1986) and simulated numerically by Lippmann and Bodvarsson (1983). These studies indicate that there are two connections to cooler water, one in permeable sandstones to the west of the alpha reservoir and the other along a fault (Fault L, Figs. 3 and 8) connecting this reservoir to an overlying groundwater aquifer. It was through the leaky upper connection that cooler, less saline influx occurred soon after production started in 1973. This flow was favored by both gravity and the reduced pressure in the exploited aquifer. The temperature of this recharge water is unknown because no wells have been drilled to produce this aquifer; however, the salinity is probably about one-half that of the alpha brine. This is based on the salinity-temperature relationship in wells producing from the alpha reservoir and on the minimum salinity of wells strongly affected by cooler influx. The connection to the deeper beta reservoir is through a permeable zone on the eastern side of the alpha reservoir where boiling and higher steam saturation conditions diminish fluid recharge (Fig. 3).

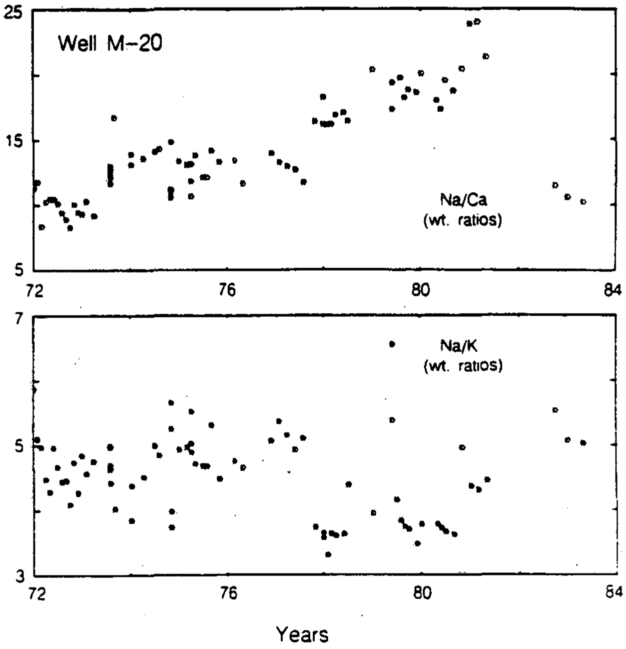

Figure 7. Changes in Na/Ca and Na/K ratios in well M-20 fluids.

Valette-Silver et al. (1985) suggest that the spreading event associated with the Imperial and Victoria earthquakes produced a massive influx of hot water into the alpha reservoir, raising its temperature by 10 to 30 ° C. The analysis of well data does not support this idea. There is no evidence of increased chloride content and/or temperature in the alpha reservoir. Furthermore, a simple calculation shows that the large influx of hot water needed to raise the temperature of the reservoir by even 10 ° C would have been easily detected in the field. Assuming conservative values, that is: (1) a temperature rise of 10 ° C (from 290 to 300 ° C); (2) a 1.2 km^3, 0.2 porosity alpha reservoir; and (3) a constant 340 ° C water influx during a one-year period, one finds that the required hot water influx is about 20,000 tonnes/hr. This recharge would be almost 5 times larger than the average fluid withdrawal rate at Cerro Prieto during the 1979-80 period. This enormous influx would have significantly increased the alpha reservoir pressure, as well as wellheld pressures and well production rates. In addition it would probably have raised groundwater levels and greatly increased hot spring flows. None of this was reported by CFE. If higher temperature fluids were injected, the required mass would be smaller but the pressure increase would still be large and easily detectable. This would be similar to events recently observed at Krafla, Iceland.

In the late 1970s a series of rifting events associated with volcanic activity began near the Krafla geothermal field. During these events significant pressure pulses, resulting in water level increases of up to 80 m, were observed in some of the wells (Stefánsson, 1981). Sigurdsson and Tiab (1983) considered that magma was injected into a fracture causing water in the fracture and the adjacent formation to boil. The phenomena was compared to a steam injection process. These pressure changes probably were not accompanied by significant heating of the geothermal reservoir, and declined rather rapidly (in a matter of days).

CONCLUSIONS

This analysis indicates that there were no observable effects on the alpha reservoir at Cerro Prieto from the two large 1979-80 earthquakes that occurred in the area. The mass influx into this reservoir did not change, and there was no increase in the temperature or amount of recharge. The aquifer continued to be invaded by cooler waters moving horizontally from the west and vertically downwards through Fault L. Although the 1979-80 earthquakes probably indicated a spreading event in which some intrusion of magma may have occurred at great depth under the field, this event did not measurably affect the temperature or chemistry of the reservoir fluid. The existence of the Cerro Prieto field is undoubtedly due in part to the frequent occurrence of such spreading events, and to the incremental heating by igneous intrusions of deep fluid that slowly convects upward through the system. Significant changes in a geothermal system of such ponderous size cannot happen quickly and the resultant heating up and (thankfully) cooling down must occur slowly.

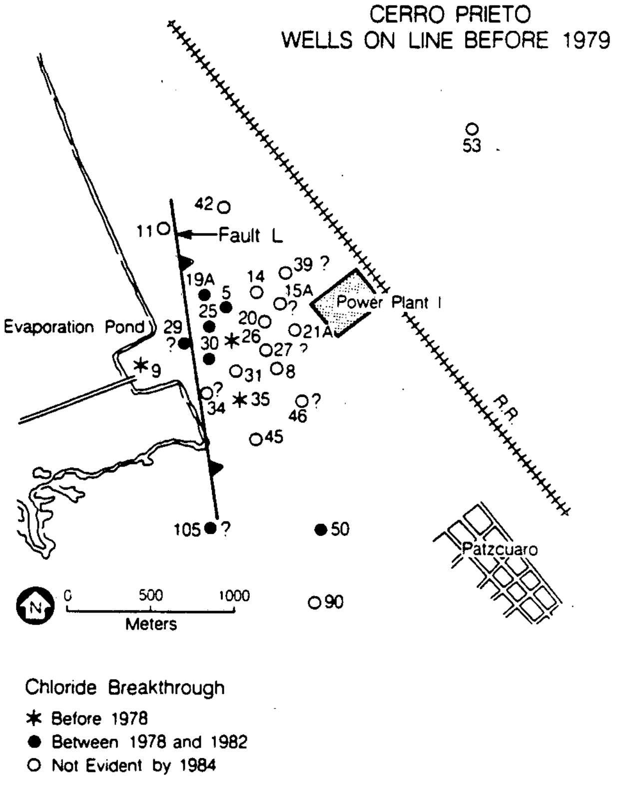

Figure 8. Chloride breakthrough in Cerro Prieto wells that were on line before 1979. The location of Fault L is based on Halfman et al. (1984).

ACKNOWLEDGEMENTS

We are indebted to our colleagues at the Comisión Federal de Electricidad for providing the field data used in this paper. We give special thanks to Karsten Pruess (LBL), Mike Sorey (USGS), and Don White (USGS) for their helpful reviews of the manuscript. This work was supported by the U.S. Geological Survey under an Interagency Agreement with U.S. Department of Energy, and by the Lawrence Berkeley Laboratory under U.S. Department of Energy Contract No. DE-AC03-76SF00098.

REFERENCES

Bureau of Reclamation, 1976. Record of earthquakes in the Yuma area, Yuma County, Arizona; Imperial County, California, 1776-1976, Special Report, U.S. Department of the Interior, Bureau of Reclamation, Yuma, Arizona, July 1976, 206 p.

Elders, W. A., Rex, R. W., Meidav, T., Robinson, P. T., and Biehler, S., 1972. Crustal spreading in Southern California, *Science*, vol. 178, pp. 15-24.

Grant, M. A., and O'Sullivan, M. J., 1982. The old field at Cerro Prieto considered as a leaky aquifer, Proceedings of the Fourth Symposium on the Cerro Prieto Geothermal Field, Comisión Federal de Electricidad, Mexicali, Mexico, pp. 123-132.

Grant, M. A., Truesdell, A. H., and Mañón, A., 1984. Production induced boiling and cold water entry in the Cerro Prieto geothermal reservoir indicated by chemical and physical measurements, *Geothermics*, vol. 13, no. 1/2, pp. 117-140.

Halfman, S. E., Lippmann, M. J., Zelwer, R., and Howard, J. H., 1984. Geological interpretation of geothermal fluid movement in Cerro Prieto field, Baja California, Mexico, *American Association of Petroleum Geologists Bulletin*, vol. 68, no. 1, pp. 18-30.

Halfman, S. E., Mañón, A., and Lippmann, M. J., 1986. Update of the hydrogeologic model of the Cerro Prieto field based on recent well data, this volume.

Lippmann, M. J., and Bodvarsson, G. S., 1983. Numerical studies of the heat and mass transport in the Cerro Prieto geothermal field, Mexico, *Water Resources Research*, vol. 19, no. 3, pp. 753-767.

Nathenson, M., 1975. Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas: U.S. Geological Survey Open-File Report 75-525, 35 p.

Reyes, C. A., 1980. Reporte preliminar del sismo "Victoria", Baja California Norte, del 9 de junio de 1980 ($M_L=6.7$), Centro de Investigación Científica y de Educación Superior de Ensenada, Departamento de Geofísica, report GEO 80-02, 13 p.

Sibson, R. H., 1985. Stopping of earthquake ruptures at dilational fault jogs, *Nature*, vol. 316, no. 6025, pp. 248-251.

Sigurdsson, O. and Tiab, D., 1983. Analysis of pressure pulses resulting from magmatic activity in the vicinity of geothermal wells, paper SPE-11751 presented at the 1983 California Meeting of the Society of Petroleum Engineers, Ventura, CA, March 23-25, 1983.

Stefánsson, V., 1981. The Krafla geothermal field, northeast Iceland, *Geothermal Systems*, L. Rybach and L. J. P. Muffler (eds.), John Wiley & Sons, pp. 273-294.

Suárez, F., Sieh, K. E., and Elders, W. E., 1982. A review of geological effects and damage distribution of the June 9, 1980 Mexicali Valley earthquake, *Newsletter Earthquake Engineering Research Institute*, vol. 16, no. 3, pp. 99-105.

Truesdell, A. H., D'Amore, F., and Nieva, D., 1984a. The effects of localized aquifer boiling on fluid production at Cerro Prieto, Geothermal Resources Council Transactions, vol. 8, pp. 223-229.

Truesdell, A. H., Mañón, A., Jiménez, M.-E., Sánchez, A., and Fausto, J. J., 1979. Geochemical evidence of drawdown in the Cerro Prieto geothermal field, *Geothermics*, vol. 8, no. 3/4, pp. 257-265.

Truesdell, A. H., Nehring, N. L., Thompson, J. M., Janik, C. J., and Coplen, T. B., 1984b. A review of progress in understanding the fluid geochemistry of the Cerro Prieto geothermal system, *Geothermics*, vol. 13, no. 1/2, pp. 65-74.

U. S. Geological Survey, 1982. The Imperial Valley, California, earthquake of October 15, 1979, U.S. Geological Survey Professional Paper 1254, 451 p.

Valette-Silver, N. J., Silver, P. G., and Márquez, M. R., 1985. The effect of a tectonic disturbance on the Cerro Prieto geothermal field (B. C., Mexico), Geothermal Resources Council Transactions, vol. 9, no. I, pp. 515-520.