GEOCHEMICAL MODELS FOR RESERVOIR PROCESSES AT CERRO PRIETO, MEXICO

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INTRODUCTION

Cerro Prieto, located 20 miles SE of Mexicali in Baja California, is the world's largest producing hot-water geothermal field (620 MWe capacity). In the mid 1950's The Comision Federal de Electricidad de Mexico (CFE) began geological and geochemical surveys of the area of natural manifestations near the Cerro Prieto volcano; in 1959 they started exploratory drilling. The early wells were successful and the best, well M-5, produced large quantities of fluid hotter than 300°C from 1100 m to 1300 m depth. New wells were drilled near M-5 and by 1968 nearly all wells that were used for initial electrical generation had been drilled and tested, and their produced fluids analyzed. The field went on line with 75 MWe in 1973-74 and drilling continued in preparation for field expansion. In 1977 an agreement was signed by CFE and the U.S. Department of Energy (DOE) for a 5 year cooperative study of the field, which has resulted in extensive geological, geophysical, geochemical, and reservoir studies reported in the Cerro Prieto Symposium volumes I-IV (CFE-DOE, 1978-82). These studies were reviewed by Lippmann (1983); the geochemical component of the CFE-DOE and earlier CFE studies will be discussed here. The geochemistry of Cerro Prieto was previously reviewed by Truesdell et al. (1984a).

CHEMISTRY OF SURFACE AND DEEP FLUIDS

Mercado (1968) described the survey of numerous hot springs and fumaroles west and south of the field (fig. 1). Spring temperatures and flow rates indicated convective heat flow of $3x10^{14}$ cal/yr. Spring chemistry (Na/K and Cl/SO_4 ratios) correlated with spring temperature and discharge intensity. Chloride concentrations (interpreted later) indicated that some waters had boiled, some had mixed with surface waters, and some had cooled conductively to retain the reservoir concentration of about 9000 ppm Cl. Fournier (1979) used this data to calculate a maximum reservoir temperature of 335°C similar to that found earlier in deep wells of the field. A model for the origin of Cerro Prieto waters from Colorado River water mixed with marine hypersaline brine (fig. 2) was proposed by Truesdell et al. (1981).

CHEMICAL THERMOMETRY

Mercado (1976) proposed a model based on Na/K ratios (which are insensitive to variable amounts of cooling by boiling and conduction), very similar to present natural-state models of the field (fig. 3). In this model the highest temperature fluids (Na/K = 3) flow up and to the west, cooling (Na/K = 5-8) and mixing with cooler recharge waters (Na/K = 30-100) flowing from east and west. Reservoir gases (CO_2, H_2S, H_2, CH_4, N_2 and NH_4) were found to be in equilibrium chemically (Nehring and D'Amore, 1984) and for CO_2, CH_4, H_2O and H_2, isotopically (Shigeno et al., 1988). The recent use of solute geothermometers in reservoir studies is described below.

CHANGES DUE TO PRODUCTION

Production-caused changes in reservoir processes and fluid flow are most easily followed by geochemical study. Fluid collection does not disrupt production and provides indications of temperature and source of fluids not available from wellhead physical measurements. Frequent chemical analyses of fluids were made by CFE; yearly isotopic, water and gas analyses by the U.S. Geological Survey were begun in 1977. These studies were used to indicate fieldwide processes of cold-water influx and boiling induced by drawdown as well as to identify upflow areas and field margins. At the same time, detailed study of the changes in fluid chemistry with time of single wells were used to indicate details of local processes of boiling and heat transfer, mixing with steam or cooler water, and migration of fluids within the reservoir.

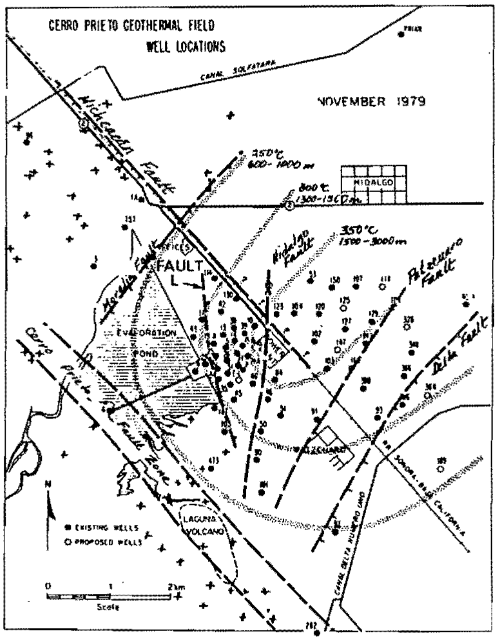

Figure 1. Map of Cerro Prieto showing well locations, faults (heavy dashed lines), simplified isotherms for variable depths (stippled), and locations of surface manifestations (pluses).

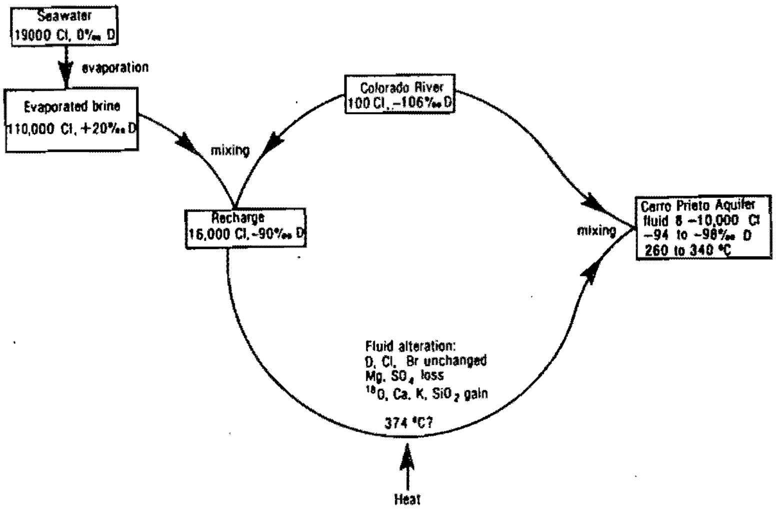

Figure 2. Schematic geochemical history of Cerro Prieto fluids showing evaporation of seawater to a hypersaline brine, mixture with Colorado River water, high-temperature reaction of the mixture with deltaic sediments to form a geothermal brine, and further mixture with river water to form the observed range of reservoir fluids.

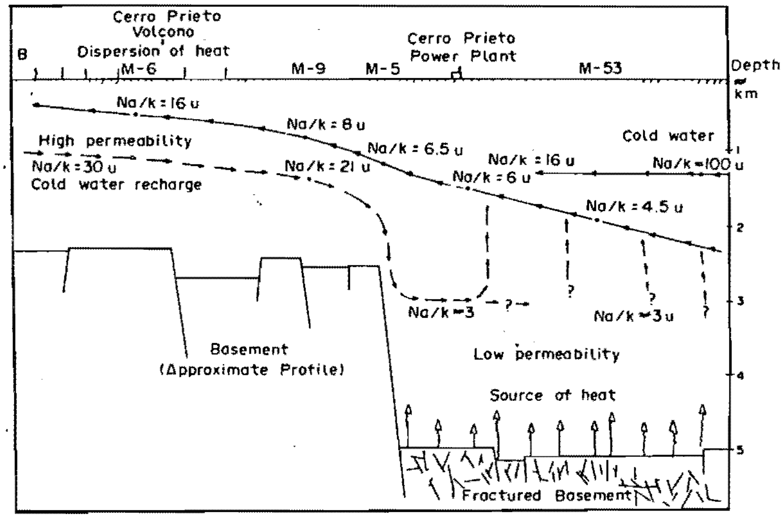

Figure 3. The Mercado (1976) model of fluid flow in the Cerro Prieto reservoir. The ratio of Na/K is used to indicate temperatures; Na/K = 3u is about 350°C and Na/K = 30u is about 50°C. The model does not locate the geothermal brine described in fig. 2.

FIELDWIDE CHANGES

Studies by CFE (Manon et al., 1979; Fausto et al., 1979, 1981) used Na-K-Ca geothermometry and concentration patterns to indicate changes in fluid temperature and composition due to exploitation. From 1973 to 1977 they found decreases in temperature of 10-20°C and in chloride of 370-670 ppm per year. The margins of the field to the south and west were indicated by chloride dropoff but the eastern margin was not defined. Changes in chloride (Truesdell et al., 1979a and unpublished data) and isotopes (Truesdell et al., 1979b; Stallard et al., 1987) show similar patterns (fig. 4), with lower chloride and lighter isotopes at the field margins, and also show drawdown of more dilute, isotopically lighter water in the center of the field along fault L (fig. 1) located by Halfman et al. (1984). This drawdown has increased from 1977 to the present. Cold waters are also entering the field from the southeast and probably the west, although interpretation of western inflow is complicated by lack of wells and close proximity to the central drawdown. A zone of upflow in the northeastern part of the field is indicated in recent isotope surveys by isotopically heavier fluids (fig. 4).

RESERVOIR PROCESSES NEAR INDIVIDUAL WELLS

Geothermometers differ in their rate of equilibration and these differences may be used to indicate processes that have heated or cooled fluids during their passage to the well. The Na-K-Ca geothermometer (T_{NKC}) which equilibrates relatively slowly in fluids of moderate or high salinity, indicates fluid temperature away from the influence of the well; and the quartz saturation geothermometer (T_{SIL}) which equilibrates relatively quickly, indicates well-bottom

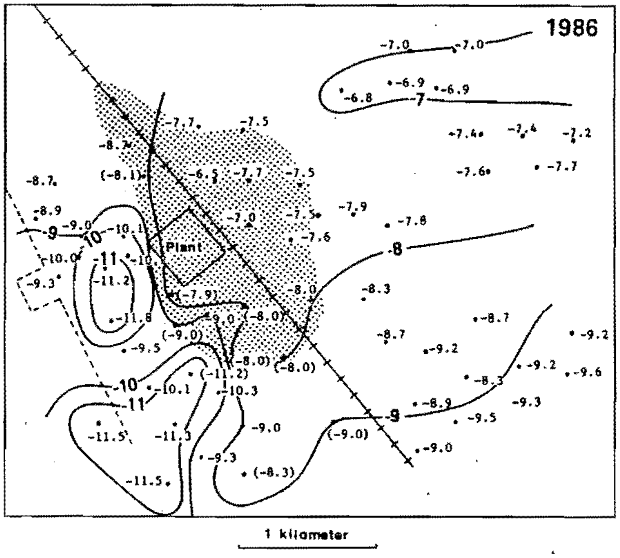

Figure 4. The distribution of oxygen isotope compositions of total discharge from Cerro Prieto wells in permil SMOW. Stippling shows an area of boiling. Note the western area where cold water enters along fault L (< -11 permil), the area of dilution (< -9 permil), and the upflow area in the northeast (< -7 permil).

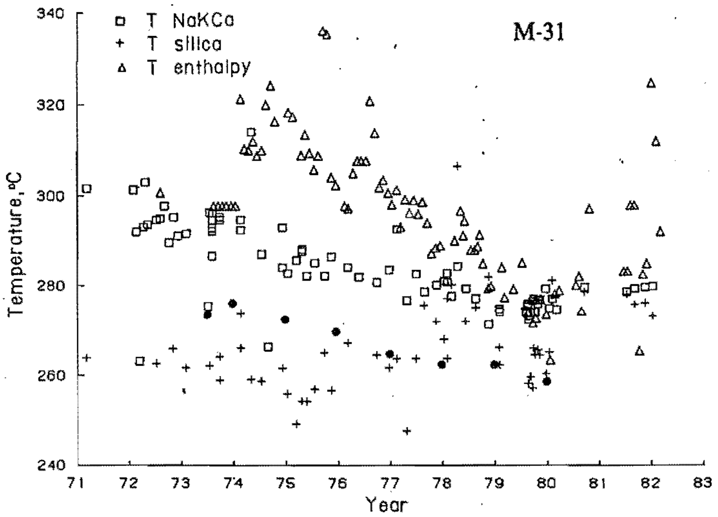

Figure 5. The temperature - enthalpy history of fluids from Cerro Prieto well M31. The rapid increase and exponential decline of T_E indicates near-well boiling and heat transfer with a constant pressure boundary due to a "leaky" caprock. The boiling zone stabilized and excess enthalpy disappeared in 1980. The dots show calculated well bottom temperatures which are similar to values of T_{SIL}.

temperature. These temperatures, along with the "enthalpy temperature" (T_E, the calculated temperature of liquid having the same enthalpy as the measured total fluid enthalpy) give clear indications of near-well reservoir processes. Many of the following cases have been observed at Cerro Prieto and Ahuachapan (El Salvador): $T_{NKC} = T_{SIL} = T_E$ indicates all-liquid, fully equilibrated fluid; $T_E > T_{NKC} > T_{SIL}$ results from near-well boiling with fluid cooling and transfer of heat from rocks (fig. 5 shows exponential enthalpy decline characteristic of near-well boiling with a constant pressure boundary); $T_E = T_{NKC} > T_{SIL}$ results when near-well boiling continues but rock and fluids equilibrate thermally; $T_{NKC} > T_{SIL} = T_E$ results from mixing near the well with cooler liquid and subsequent reequilibration of silica; $T_E > T_{NKC} = T_{SIL}$ results from mixing of steam with equilibrated liquid in or near the well; $T_{NKC} > T_{SIL} > T_E$ from mixing of cooler water in the well with lowering of T_E and apparent lowering of T_{SIL} due to dilution; $T_E = T_{SIL} > T_{NKC}$ results from sweep of cooler water through hotter rock; and $T_{NKC} = T_{SIL} > T_E$ results from conductive cooling in the wellbore during reduced flow. These processes may be combined such as boiling in the reservoir and mixing with cooler water in the well. Changes in calculated aquifer chloride indicate processes of concentration (boiling) and dilution (mixing). Mineral deposition and formation plugging that results from localized aquifer boiling (Truesdell et al., 1984b), and the "cold sweep" of cooler water heated by reservoir rock in the first-exploited CPI reservoir (Grant et al., 1984; Truesdell and Lippmann, 1986) have been demonstrated using these methods.

SUMMARY

Geochemical monitoring of the shallow Cerro Prieto I reservoir shows that although highly productive, it has in part suffered from decrease of fluid temperature and flow due to cold water entry and localized boiling in aquifer rocks. These processes are to be expected in a reservoir initially at boiling temperatures with cold inflow favored by leaky boundaries and boiling by tight ones. Cold-water heat sweep and localized near-well boiling are also encouraged by the dominance of matrix rather than fracture porosity and permeability. The behavior of the deeper Cerro Prieto reservoirs exploited since 1986 is still insufficently known. A new CFE-DOE agreement is in force and geochemical studies are continuing.

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