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# THE MOVEMENT OF GEOTHERMAL FLUID IN THE CERRO PRIETO FIELD AS DETERMINED FROM WELL LOG AND RESERVOIR ENGINEERING DATA

S. E. Halfman, M. J. Lippmann, and R. Zelwer

Earth Sciences Division
Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

## ABSTRACT

A hydrogeologic model of the Cerro Prieto geothermal field in its undisturbed state, developed on the basis of well log and reservoir engineering data, is discussed.

According to this model, geothermal fluid enters the field from the east through a deep (>10,000 ft) sandstone aquifer which is overlain by a thick shale unit which locally prevents the upward migration of the fluid. As it flows westward, the fluid gradually rises through faults and sandy gaps in the shale unit. Eventually, some of the fluid leaks to the surface in the western part of the field, while the rest mixes with surrounding colder waters.

## INTRODUCTION

The Cerro Prieto liquid-dominated geothermal field is located in Baja California, Mexico, about 20 miles south of the US-Mexico border (Figure 1). A vast amount of subsurface geologic and reservoir enginnering data have been gathered from over 100 wells (some as deep as 11,600 ft) completed in this field (Figure 2).

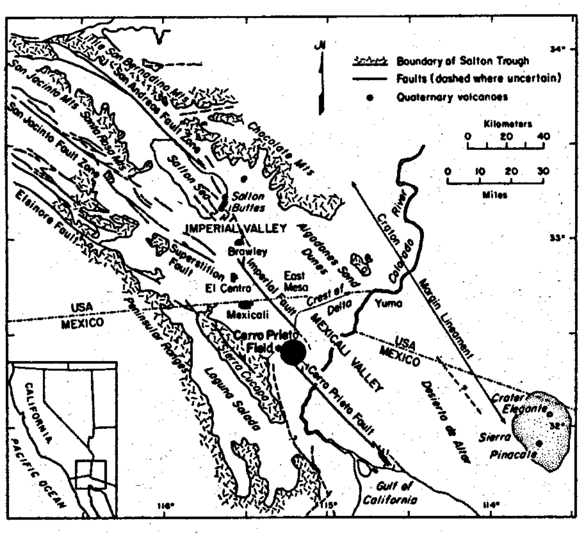


Figure 1. Regional geology of the Salton Trough (i.e., Imperial and Mexicali Valleys) and location of the Cerro Prieto area.

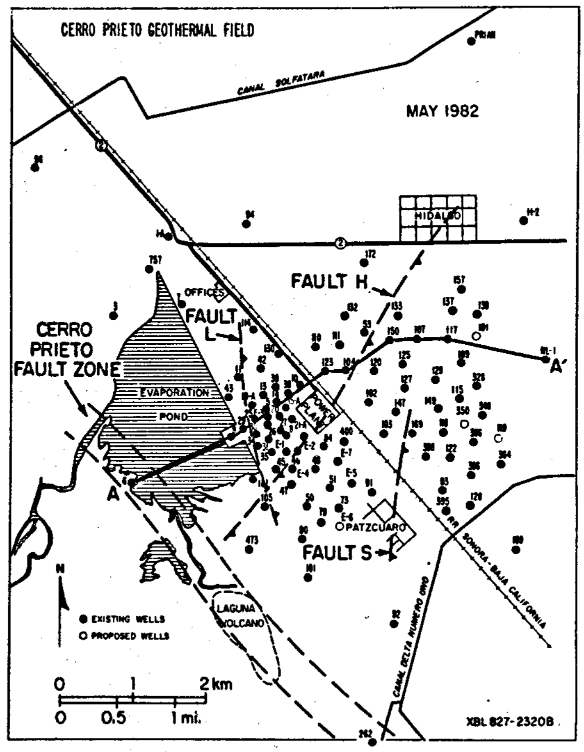


Figure 2. Location of wells, principal faults, and cross section A-A' at Cerro Prieto.

Based on geochemical, mineralogical, and downhole temperature logs, it has been shown that the geothermal fluid enters the field from the east, gradually flowing to the west as it ascends to shallower depths (Mercado, 1968 and 1976; Bermejo et al., 1979; Elders et al., 1981). However, in the models developed by these authors, the movement of hot fluids in the subsurface is shown only schematically. We will discuss a hydrogeologic model for the Cerro Prieto reservoir in its natural (pre-production) state (Halfman et al., 1982). The model provides details on the westward and upward flow of geothermal fluids in the field and the geologic features controlling this movement.

## METHODOLOGY

First, a geologic model of the Cerro Prieto field was constructed based on geophysical and

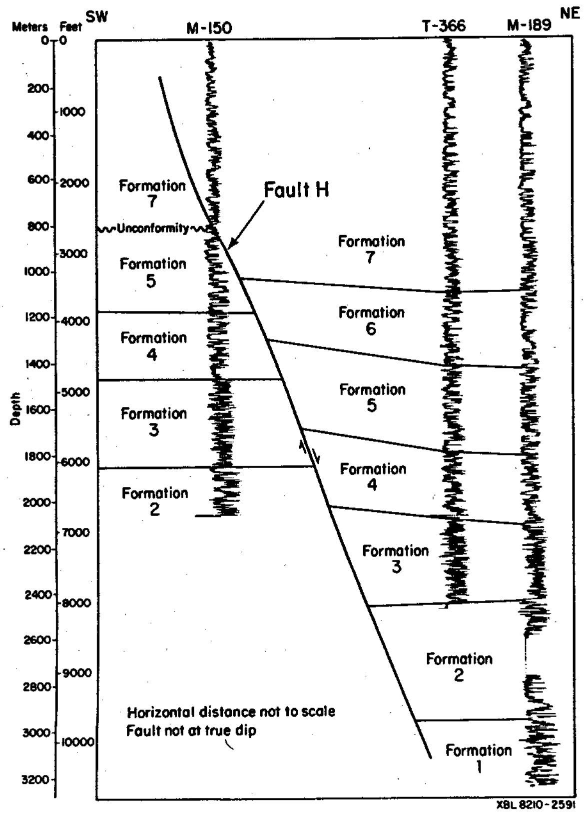


**Figure 3.** Simplified stratigraphy of the Cerro Prieto field. The traces correspond to gamma-ray (GR) logs.

lithological well logs. Downhole temperature profiles and well production interval data were then incorporated into the geologic model to develop a geothermal fluid flow model that would show the actual fluid flow paths. This model was then used to identify the lithologic and structural features that control the movement of the geothermal fluid.

From the geologic model, we were able to identify faults on the basis of significant vertical displacements of formations and by recognizing that sections or entire formations were missing in some wells (Figure 3). Seven distinct formations were defined, based mainly on the interpretation of gamma-ray (GR), spontaneous potential (SP), deep induction (ILD), and formation density gamma-gamma (RHOB) logs (Halfman et al., 1982).

Using a different approach, the beds were categorized into three lithofacies groups (sandstone, sandy-shale, and shale) on the basis of the well log analysis criteria followed by Lyons and van de Kamp (1980). Basically, the sandstone group is comprised of thick, permeable, and well defined sandstone beds (with some interbedded shales); the sandstone beds in the sandy-shale group are thinner and less permeable (with a higher percentage of intercalated shales), and are yet thinner (<10 ft) in the shale group. After assigning the beds to the different lithofacies groups, lithofacies cross sections were constructed incorporating the faults previously defined.

The method used to group the different beds, based mainly on the GR log, is illustrated in Figure 4. This figure (well M-150, a typical

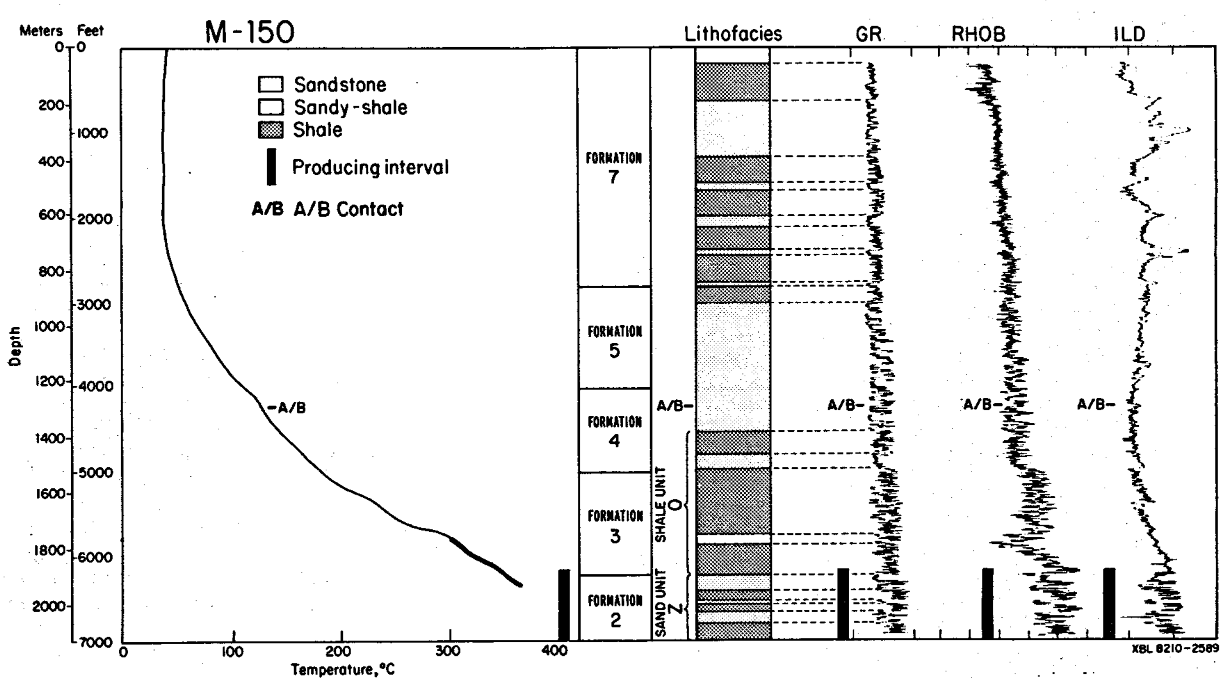


**Figure 4.** Well M-150, showing temperature profile; interpreted formation and lithofacies columns; and gamma-ray (GR), formation density gamma-gamma (RHOB), and deep induction (ILD) logs.

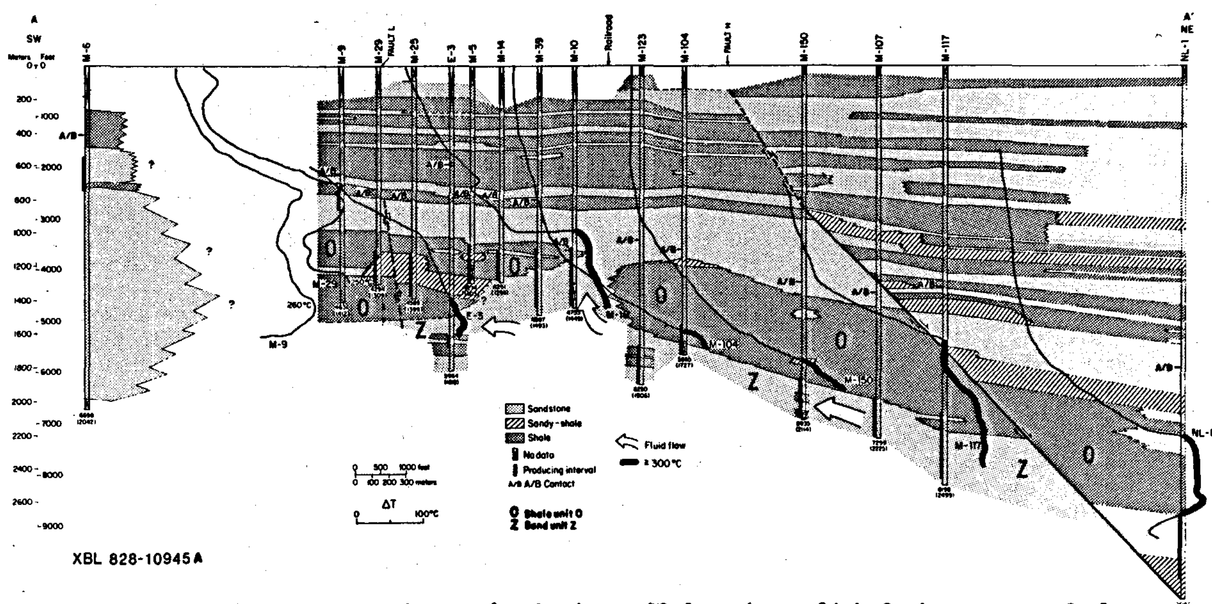


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Figure 5. Lithofacies cross section A-A', showing well locations, lithofacies groups, faults, temperature profiles (the parts of the temperature profiles shown by heavy lines indicate temperatures 300°C or greater), producing intervals, A/B contacts, Shale Unit 0, Sand Unit Z, and arrows indicating direction of geothermal fluid flow.

Cerro Prieto well) shows the GR, RHOB, ILD and temperature logs, as well as the interpreted formation column, A/B contact, Shale Unit 0 and Sand Unit Z, which will be discussed below.

## RESULTS

### Geologic Model

Three concealed normal faults (Faults H, L, and S), believed to have an important impact on the natural (pre-exploitation) circulation of geothermal fluid in the system, were identified (Figure 2). All three faults have a northeast-southwest strike, dipping to the southeast. Fault H has displacements as great as 1650 ft in the northeastern areas and as small as 1000 ft in the southwest. Faults L and S have displacements of about 200 and 400 ft, respectively (Halfman et al., 1982). The existence of these faults have also been inferred from geophysical and mineralogical data (Majer and McEvilly, 1982; Williams, 1982).

In Figure 5, the three types of lithofacies distinguished in this study are shown correlated across section A-A'. Two main sedimentary units, one comprised mostly of the shale group (Shale Unit 0), and another comprised of mostly the sandstone group (Sand Unit Z) were identified. These two units, along with the faults, will be shown to play an important role in controlling the flow of the geothermal fluid.

The well log readings indicate that some of the sediments in the Cerro Prieto field have been hydrothermally altered. The sandstones and shales above Shale Unit 0 show fairly normal log readings for a sedimentary environment (Figures 4 and 5). The high ILD readings in the upper 3,000 feet, which may look unusual, are actually only due to fresh water sandstones (Lyons and van de Kamp, 1980; Seamount and Elders, 1981). Shale Unit 0 and the underlying Sand Unit Z, however, show some anomalous log values because they have been affected by the heat and fluid moving through the subsurface.

Shale Unit 0, especially its lower part, acts as a barrier to the upward migration of geothermal fluid and convective heat flow. This is substantiated by the lithology, temperature and low porosity readings obtained from the logs (Figure 4). The lower portion of Shale Unit 0 consists mainly of thinly bedded sandstones and shales and lacks any thick permeable sandstone beds that would permit fluid flow. This is confirmed by the general sharp rise in temperature gradient observed near the top of Shale Unit 0 (Figure 5), indicative of strata through which heat is transferred by conduction rather than convection. Furthermore, the unusually high RHOB (shales generally >2.6 gm/cm$^3$) and ILD (shales generally >6.5 ohm-m) values commonly found near the base of Shale Unit 0 indicate low porosity, especially in wells southeast of Fault H. The density values have been shown by Seamount and Elders (1981) to be much higher than expected from normal compaction of sediments at these depths. Ershaghi and Ghaemian (1980) explain that the unusual high resistivity readings may be due to porosity loss resulting from chemical reactions and also to drastic reduction in clay conductivity. Thus Shale Unit 0 is a thick, relatively impermeable, low-porosity body that acts as a local cap rock, as will be shown below. By a local cap rock, we mean a geologic unit of lower permeability which overlies the reservoir, locally preventing the upward migration of fluid.

Sand Unit Z, below Shale Unit 0, permits the flow of geothermal fluids. This is confirmed by its lithology, temperature profile, high porosity indicated by the logs, and the depths of the producing intervals. The upper portion of this unit consists of thick sandstone beds interbedded with some shales. The vertical temperature profiles in Sand Unit Z usually show a fairly constant temperature of about 300°C or slightly greater (Halfman et al, 1982). This constant temperature is indicative of circulating fluids; i.e., a region where heat is transferred by convection rather than conduction. Most of the producing intervals in wells east of the railroad tracks and deeper ones west of them (Figures 2 and 5) are located in Sand Unit Z. The low ILD and RHOB values of the sandstone beds of this unit indicate high porosity, possibly due to secondary (dissolution) porosity (Lyons and van de Kamp, 1980). Thus Sand Unit Z has thick, permeable, high-porosity sandstone beds that act as conduits for the geothermal fluid.

Also shown in cross section A-A' (Figure 5) are the A/B contacts, and the producing intervals. The A/B contact separates the unconsolidated (Unit A) from the underlying indurated (Unit B) sediments (Puente and de la Peña, 1978). The induration of the sediments is believed to be due to post-depositional thermal effects which modified the deeper materials (Unit B) leaving the shallower ones (Unit A) relatively unaffected (Elders et al., 1978).

Based on the depths of the producing layers, the Comisión Federal de Electricidad has identified two liquid-dominated reservoirs at Cerro Prieto. The shallower one, designated A by Prian (1979) and α by Sánchez and de la Peña (1981), is restricted to the area west of the railroad tracks and corresponds to the sandier layers of the upper part of Shale Unit 0 (Figure 5). The deeper and hotter reservoir, designated B or β by the same authors, is found in Sand Unit Z throughout the field.

## Geothermal Fluid Flow Paths

Using an approach suggested by Howard (1981), it was found that the actual fluid flow paths become readily apparent when downhole temperature profiles and well production intervals (Bermejo et al., 1979; personal communication, 1982) were superimposed on the lithofacies cross section A-A' (Figure 5). In this section, the portions of the temperature profiles shown by heavy lines indicate temperatures of 300°C or greater. The maximum temperatures of cooler wells are indicated next to the corresponding curve.

From Figure 5, it can be seen that the temperature profiles show sharp increases in gradient near the A/B contact, and that the depth of the A/B contact (Cobo, 1981), producing intervals, and increases in temperature gradient are observed at progressively greater depths towards the east. Well M-117 does not conform to this trend, however, and will be discussed below.

Comparison of the temperature profiles with the lithology of wells M-104, M-150, and NL-1 (Figure 5) indicates that the sharp increases in temperature gradient occur near the boundary between Shale Unit 0 and the overlying sandstone group. In wells E-3, M-29, and M-9, this increase is observed near a shallower shale, which is found in well M-29 at the same depth as the A/B contact. The increase in temperature gradient, therefore, suggests that the shale units must be barriers to convective heat transport; i.e., they are essentially acting as local cap rocks.

According to Elders et al. (1982) and Goldstein et al. (1982), the heat source for the Cerro Prieto system is in an area of current mafic rock intrusion beneath the eastern regions of the field. The invaded rocks heat the circulating fluid, which is thought to enter the field from the east through Sand Unit Z (Reservoir β) after which it moves westward toward Fault H (the arrows in Figure 5 indicate the flow of geothermal fluid). The fluid then moves up Fault H until it encounters Sand Unit Z once again. A small portion of the fluid continues up Fault H, resulting in a temperature of 300°C at a relatively shallow depth in well M-117. Most of the fluid, however, moves westward through Sand Unit Z in the upthrown block, west of Fault H. This essentially horizontal flow continues to the area near well M-10, where there exists a sandy gap in Shale Unit 0 which permits the communication between the reservoirs α and β. In this area, the geothermal fluid flows upward, resulting in high temperatures at shallow depths in well M-10. Some of the fluid enters the southwestern part of Shale Unit 0, which is sandier here than in the east, and constitutes the Reservoir α. Then the fluid moves westward until encountering Fault L near well M-29. There, the fluid flows upward through the fault and then westward through the sands above Shale Unit 0. Fluid that does not enter Shale Unit 0 continues to flow westward through the underlying Sand Unit Z (Reservoir β). Eventually, some fluid leaks to the surface through the Cerro Prieto Fault Zone, which bounds the field to the west (see Figure 2), and the rest mixes with the colder waters that surround the geothermal anomaly.

Based on cross section A-A' and other sections given by Halfman et al. (1982), it is inferred that most of the geothermal fluid flows through high porosity, permeable sandstone beds in Sand Unit Z (Reservoir β), underlying the low-porosity, impermeable Shale Unit 0, which acts as a local cap rock. Figure 6 shows a contour map of the top of the β reservoir; the postulated direction of geothermal fluid flow through these sandstone beds is indicated by the arrows. As shown in this figure, the fluid is generally believed to enter the field (at great depth) from the east, gradually moving westward (and rising to shallower depth), and finally reaching the surface in the western regions of the field. Several wells to the southeast are cooler (i.e., M-189). This suggests that these wells are bypassed by the hot fluids entering the field.

## SUMMARY AND CONCLUSIONS

By integrating the geologic model of Cerro Prieto with downhole temperature profiles and well production intervals, we have identified the geothermal fluid flow paths in the field. It has been shown that the movement of hot fluids in the subsurface is strongly controlled by stratigraphic and structural features. Our model indicates that a continuous cap rock does not exist at Cerro Prieto which would prevent the upward migration of geothermal fluids to the surface. This supports the conclusion of Grant et al. (1981) and Grant and O'Sullivan (1982) that the reservoir, especially its western part, is a leaky aquifer.

The results of our model are consistent with mineralogical observations and interpretations (Elders et al., 1981), and with reservoir engineering and geochemical studies (Mercado, 1976; Grant et al., 1981) carried out on this geothermal system, and was used to simulate the behavior of the Cerro Prieto field in its natural state and under exploitation (Lippmann and Bodvarsson, 1982; Tsang et al., 1982).

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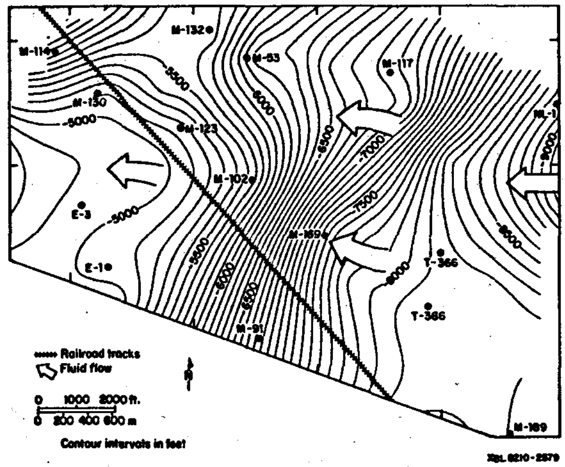


Figure 6. Contour lines indicate the top of Reservoir β. Arrows indicate the direction of geothermal fluid flow through this unit.

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