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UPDATE OF THE HYDROGEOLOGIC MODEL OF THE CERRO PRIETO FIELD BASED ON RECENT WELL DATA

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Abstract

The hydrogeologic model of the Cerro Prieto geothermal field in Baja California, Mexico has been updated and modified on the basis of geologic and reservoir engineering data from 21 newly completed wells. Previously, only two reservoirs had been discovered: the shallow α reservoir and the deeper β reservoir. Recently, three deep wells drilled east of the main wellfield penetrated a third geothermal reservoir (called the γ reservoir) below the sandstones corresponding to the β reservoir in the main part of the field. The new well data delimit the β reservoir, confirm the important role of Fault H in controlling the flow of geothermal fluids, and enable us to refine the hydrogeologic model of the field.

Introduction

The exploration and development of the Cerro Prieto geothermal field of Baja California, Mexico (Figure 1) began in the late 1950s, and continues with the drilling of additional production wells and construction of new power plants. Between January 1984 and February 1986, 21 new wells were added to the approximately 100 existing wells (Table 1; Figure 2). At present (April 1986), the installed generating capacity is 400 MWe; by the end of this year it is expected to reach 620 MWe. Earlier developments at Cerro Prieto have been summarized in several papers (e.g., Mañón, 1984; Lippmann et al., 1984).

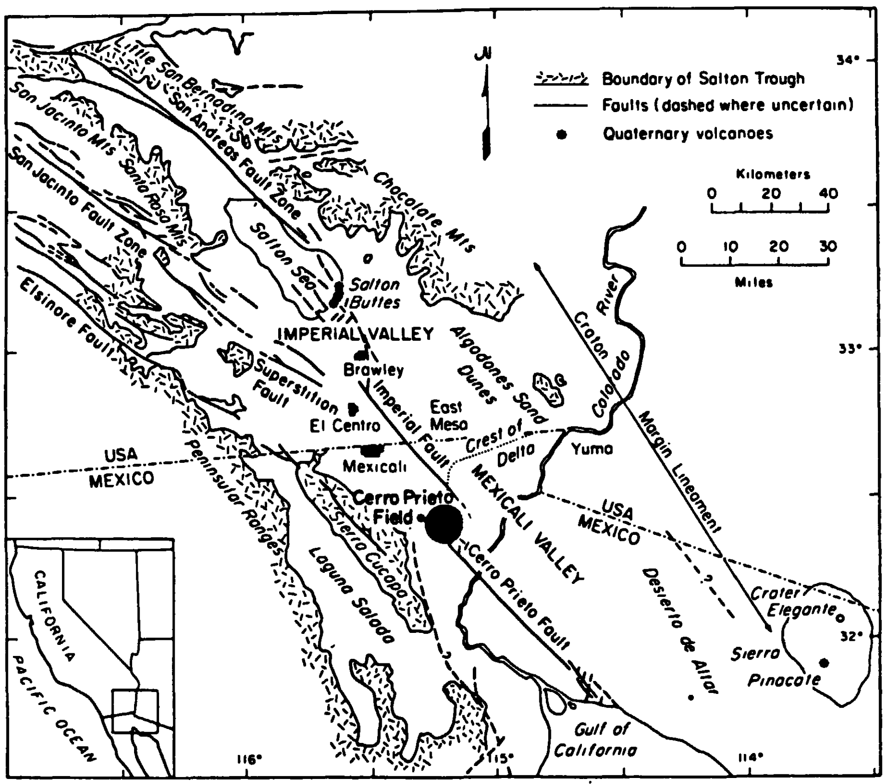

Figure 1. Location of the Cerro Prieto field in the Salton Trough, that includes the Imperial and Mexicali Valleys. XBL 801-6718A

Table 1

Cerro Prieto wells completed between January 1984 and February 1986

Well	Total Depth (m)	Open Interval (depth, m)
E-8	1796	1507-1794
E-9	1714	1479-1702
E-10	1814	1515-1807
E-11	1780	1584-1776
E-12	1319	Obstructed
E-14	1802	1599-1786
E-15	1916	1609-1911
E-18	2403	2137-2398
M-108	2211	1896-2211
M-112	3624	2409-2801 3370-3622
M-148	2305	2053-2302
M-155	2526	2358-2525
M-160	2322	2039-2317
M-200	2841	2482-2834
M-201	3817	3610-3811
M-202	3987	3712-3987
M-203	3995	3537-3993
M-204	4120	Obstructed
M-205	4389	3766-4389
M-206	4024	2285-4024
T-394	3019	2684-3013

The Cerro Prieto geothermal system is associated with one of several pull-apart basins found along the strike-slip boundary between the Pacific and North America Plates. The basin is located at the end of the right-lateral, strike-slip Imperial and Cerro Prieto faults (Elders et al., 1972). Rapid, voluminous deposition, keeping pace with the subsidence of the pull-apart basin, has resulted in thick accumulations of sediments of primarily Colorado River origin.

Recent well data have enabled us to update the hydrogeologic model of the field presented by Halfman et al. (1984). In the development of the original model, the lithologic sequences determined from geophysical and lithologic well logs were classified into three lithofacies groups: sandstone, sandy-shale, and shale. The sandstone group is composed of well-defined, thick, permeable sandstone beds with some interbedded shales; the sandy-shale and shale groups have increasingly thin and less permeable sandstones with a higher percentage of intercalated shale. On the basis of this simplified lithology, a geologic model was constructed and displayed in five cross sections. By superimposing temperature profiles and production intervals on these sections, the natural-state (prior to the start of exploitation in 1973) movement of the hot fluids in the system was inferred, and lithologies were correlated to the two geothermal reservoirs identified at Cerro Prieto. In both this and our present study, a geothermal reservoir is assumed to exceed temperatures of 250 °C.

In the 1984 model, the deepest identified geothermal aquifer (β reservoir) is in Sand Unit Z, at a depth of about 2650 m in well NL-1 (located at the eastern edge of cross section A-A' in Figure 3). The shallower α reservoir is associated with a sandy-shale group within Sand Unit O and is restricted to the western part of the system, west of the railroad tracks.

The model showed that the subsurface movement of hot fluids in Cerro Prieto is controlled by stratigraphic and structural features. The permeable sandstones (especially Sand Unit Z) and faults are the conduits, and the discontinuous densified shales (particularly Shale Unit O) form the local cap rocks. According to the natural-state model, the geothermal fluids originate in a deep reservoir in the downthrown portion of Sand Unit Z (Figure 3) and then flow upward along Fault H, westward through Sand Unit Z (from M-191 to M-123), up into the sandy gap (in the vicinity of M-10A), westward through the sandy-shale group in Shale Unit O (between M-14 and M-25), up Fault L, and westward through a shallower sandstone between M-29 and M-9. Finally, the geothermal fluids either mix with cold ground waters or discharge at the surface as mudpots, fumaroles, and hot springs.

In this paper, from the addition of the new well data, a third deeper geothermal reservoir (γ reservoir) has been identified. We will show how this new data integrate into and generally confirm the 1984 hydrogeologic model of the Cerro Prieto field.

Analysis of the New Well Data

Lithologic logs are available for all of the 21 new wells; geophysical logs are available only for wells M-205 and M-206. Data from the 15 new wells drilled in the main portion of the field (all new wells except M-201 through M-206; see Table 1) have confirmed the hydrogeologic model by Halfman et al. (1984). Of these 15 wells, only E-11 did not encounter Shale Unit O. Well E-11 shows a thick sequence of sandstones between 1200 and 1490 m corresponding to the sandy gap encountered earlier in M-10A (Figure 3). Twelve of the 15 wells have been completed in the β reservoir. Exceptions are E-15 (the producing interval partially penetrates a shallow sandstone layer holding hot fluids from Fault H; see below), E-12 (obstructed), and M-155 (located north of the β reservoir; Figure 4). Well M-112 not only penetrated the β reservoir but also encountered a third deeper geothermal reservoir, which we named γ reservoir, in Sand Unit K (Figure 5). A shaly zone separates these β and γ reservoirs. A study of logs from earlier wells suggest that Sand Unit K might also be penetrated by well M-189, located in the southern end of cross section E-E' (Figure 6). However the temperatures measured in this unit are below 300 °C, indicating that the γ reservoir does not spread extensively toward the south.

The other six new wells, M-201 through M-206, were drilled east of the main field and to a greater depth (>3800 m) than the other wells. The lithologic logs of M-201, M-202, and M-203 indicate that these wells penetrate Shale Unit O and Sand Unit Z. Below these units they penetrate a shale zone and Sand Unit K (Figure 5). In this part of the system, the fluids in Sand Unit Z have temperatures estimated to be less

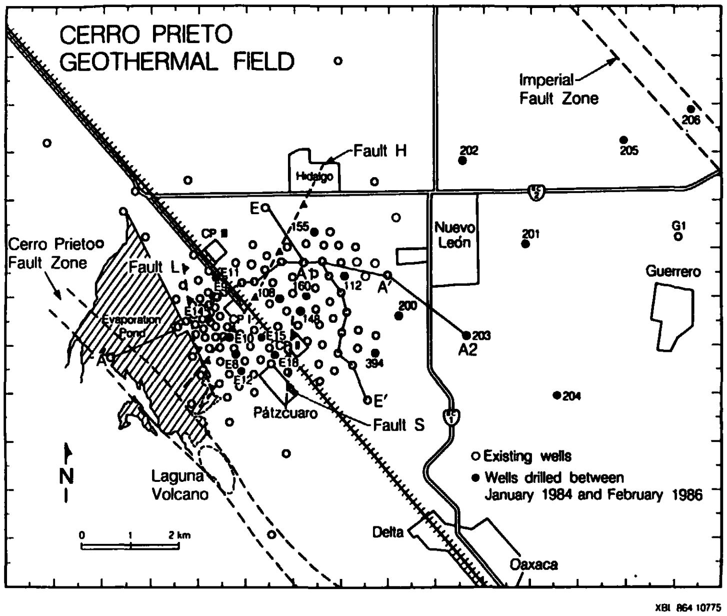

Figure 2. Location of old and new wells, principal faults, and cross sections A-A', A1-A2, and E-E'. The faults are projected to the surface.

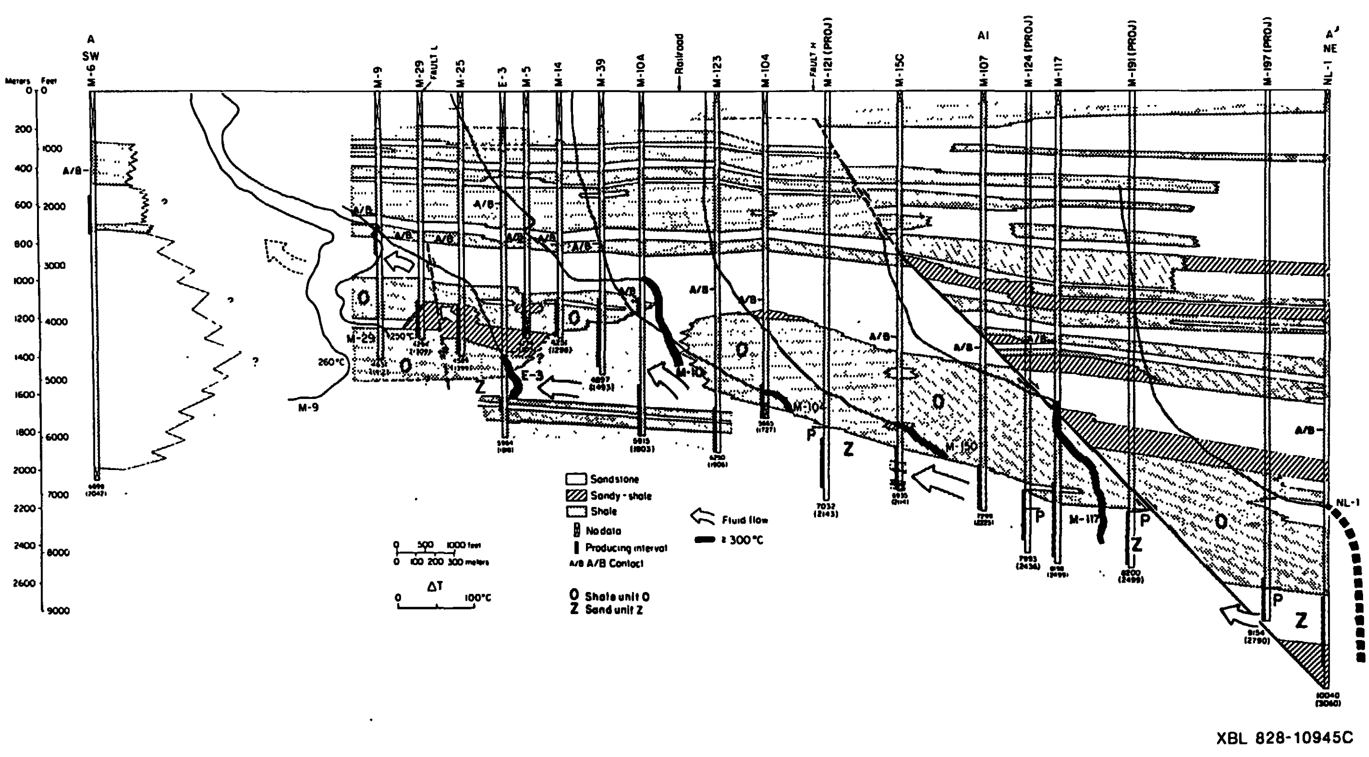

Figure 3. Lithofacies cross section A-A' showing well locations, lithofacies groups, faults, temperature profiles, producing intervals, Shale Unit O, Sand Unit Z, and arrows indication direction of geothermal fluid flow according to the hydrogeologic model of Halfman et al. (1984). On the temperature profiles, the points corresponding to 300°C are located below the respective wells. The parts of the temperature profiles shown by heavy lines indicate temperatures of 300°C or greater.

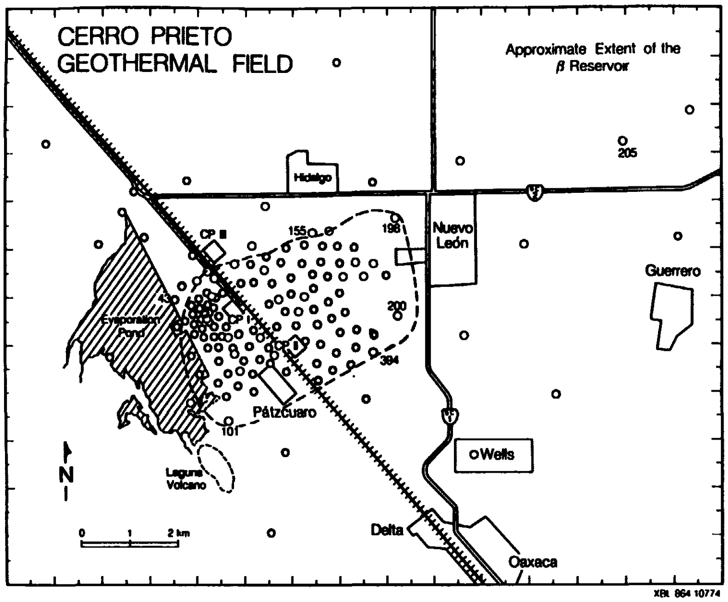

Figure 4. Approximate extent of the hot β geothermal reservoir as inferred from well data.

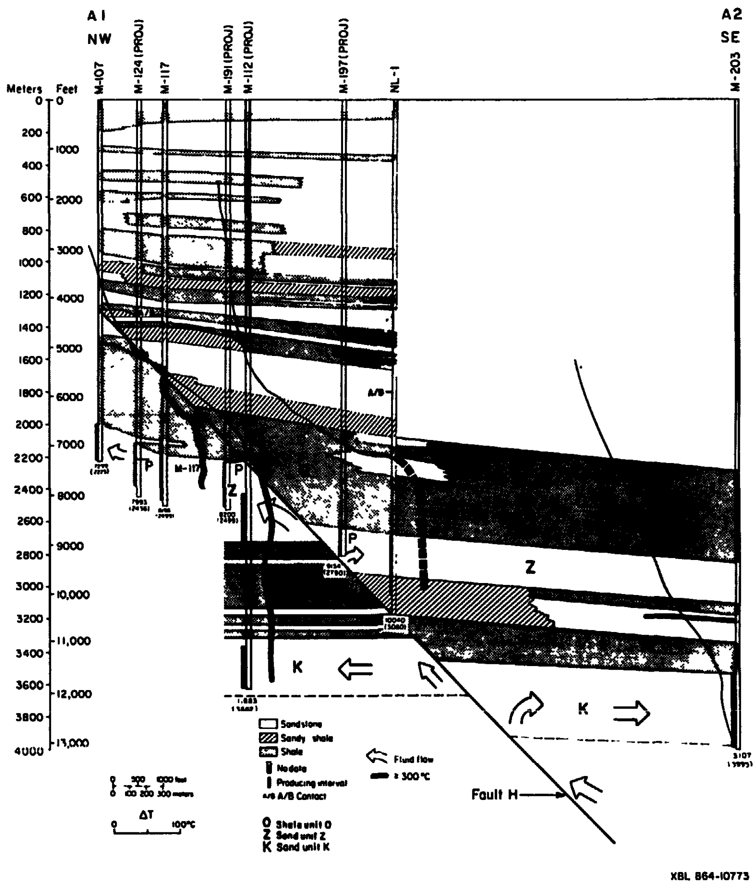

Figure 5. Lithofacies cross section A1-A2 showing the updated geothermal fluid flow pattern.

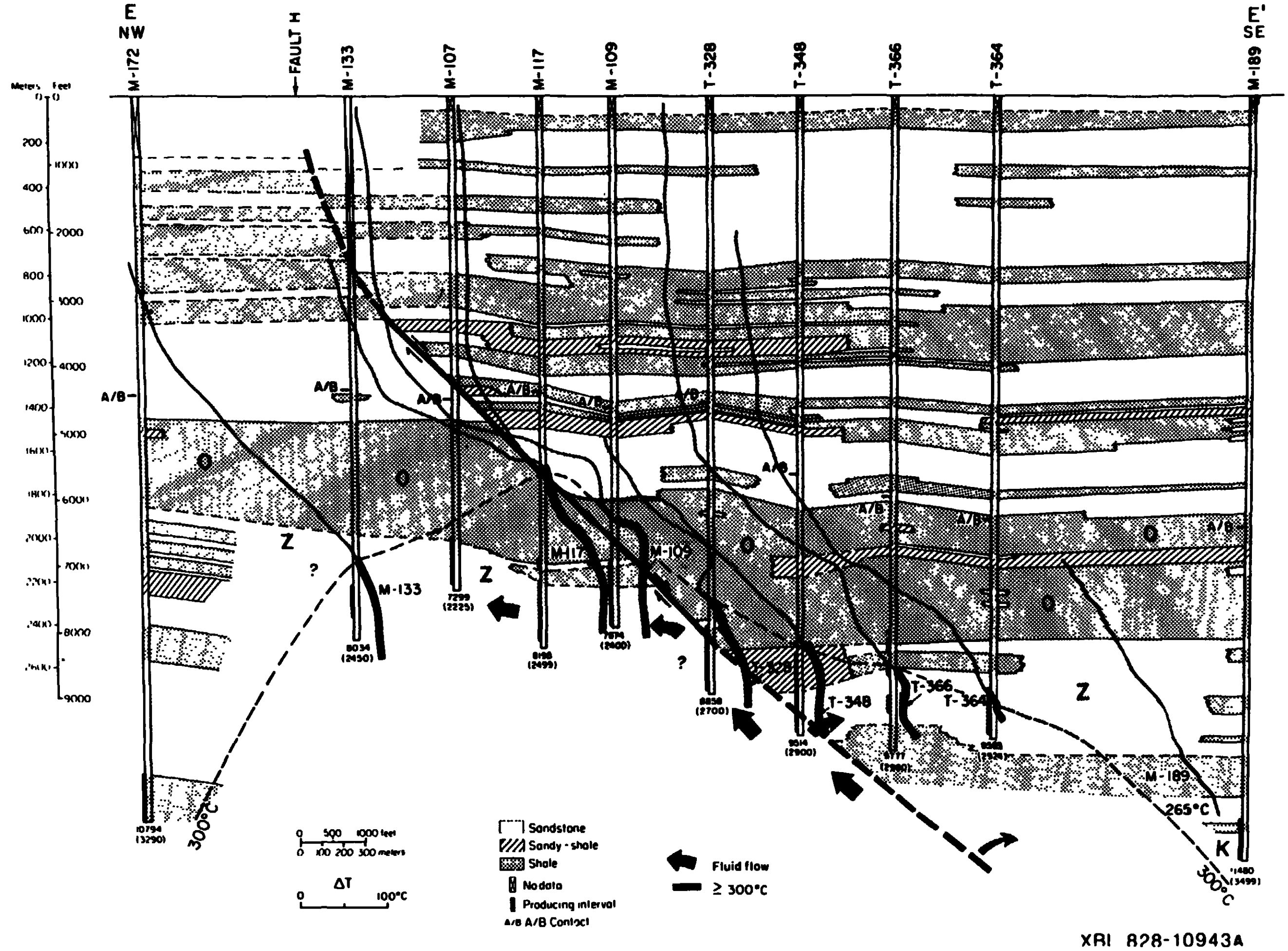

Figure 6. Lithofacies cross section E-E' showing the updated geothermal fluid flow pattern.

than 240 °C, indicating that the hot β reservoir (temperatures >300 °C) does not extend this far east (Figure 4). These eastern wells have been completed only in Sand Unit K, which corresponds to the downthrown equivalent of the γ reservoir encountered in M-112.

The lithologic log of M-204 shows that the sedimentary column becomes sandier east of the main well field. The temperature profile extends only to about 3750 m; measured values do not exceed 220 °C.

Well M-205 was drilled just west of the Imperial fault (Figure 2), within the pull-apart basin. The upper part of the sedimentary sequence is composed of coarse materials (sands and gravels), similar to those found in well G-1 (Figure 2; Cobo and Bermejo, 1982). The available lithologic log (2500-4390 m) shows a predominance of sandstones, with a few thin, interbedded gravel beds between 2550 and 2980 m. Well M-205 encountered high temperatures (>300 °C) below 3600 m. Although the depths of the open interval (3766-4389 m) appear to be within the approximate depths of the γ reservoir, the lithology of wells M-201, M-202, and M-203 cannot be correlated with that of M-205 with any certainty.

Well M-206 is believed to have been drilled within, or east of, the Imperial fault zone. Again, coarse materials predominate in the well. The lithologic log (1564-4024 m) shows several thick gravel sections at depths between about 1900 and 2020 m, and between 2360 and 2560 m. At other depths mainly sandstones are encountered. The highest recorded temperature is a relatively cool 240 °C, at approximately 3800 m. This low temperature indicates that the identified geothermal reservoirs do not extend this far east, suggesting that the Imperial fault is the eastern boundary of the pull-apart basin and the Cerro Prieto geothermal system.

Since wells M-205, M-206, and G-1 are located just west of the present Colorado River, it is reasonable to assume that the thick column of coarse sediments found in these wells represent a series of paleochannels of that river.

Updated Hydrogeologic Model

Our updated hydrogeologic model of the Cerro Prieto circulation system assumes that geothermal fluids ascend from depths greater than the deepest well drilled to this date (>4400 m). Truesdell et al. (1981; 1984) suggest that the geothermal fluids are Colorado River water that have circulated deeply (below 2500 m) and mixed with a hypersaline, oceanic brine. As they ascend, the fluids mix with more Colorado River water. During the subsurface circulation the composition of the fluids change as they re-equilibrate, under changing conditions, with the rocks they contact. The heat source is thought to be related to a thinner crust and the intrusion of igneous dikes into the sediments filling the pull-apart basin associated with the Cerro Prieto field (Figure 7; Goldstein et al., 1984; Elders et al., 1984).

Based on the new and old well data, we suggest that the geothermal fluids rise from depth along Fault H (Figure 5), a major normal fault in the pull-apart basin. Most of the hot fluids flow into the upthrown portion of the β reservoir (upthrown Sand Unit Z) and continue to move westward and upward, as explained in the original hydrogeologic model. Lesser amounts seem to leak into the γ reservoir (Sand Unit K), and the downthrown portion of the β reservoir (downthrown Sand Unit Z).

The general flow pattern for the geothermal fluids described by the 1984 hydrogeologic model is still valid. The three geothermal reservoirs identified to date in Cerro Prieto have different properties and are restricted to different areas of the field. The α reservoir, originally at temperatures of 260 to 310 °C, is located in the western part of the field, between approximately 1000 and 1500 m depth, in the upthrown block of Fault H (in the sandy-shale group of Shale Unit O). This aquifer does not extend to the upthrown section east of the railroad tracks, because of the disappearance of permeable layers within Shale Unit O. In addition, mineral precipitation, caused by the inflow of cooler groundwater from shallower aquifers, has significantly reduced the permeability of the rocks. In the downthrown block of Fault H, a small quantity of geothermal fluids enter a few permeable layers within and above Shale Unit O. However, the geothermal fluids do not migrate far from the fault (as evidenced by well E-15 for example) possibly because of a lack of hydraulic gradient (in the southern area of the field there are no continuous permeable conduits allowing discharge of geothermal fluids to the surface).

The hotter and deeper β reservoir (320 to 340 °C; below 1500 m) is present in both blocks of Fault H (in Sand Unit Z; Figure 8). Because of the general east-to-west direction of geothermal fluid flow, the extension of this reservoir towards the northwest and southeast is limited. This can be seen by the abrupt drop-off of the 300 °C contour in Figure 6. (This contour reflects the shape of the plume of geothermal fluids, mainly in the eastern part of Cerro Prieto.) The hot fluids rise through Fault H into this aquifer, move mainly toward the west, and eventually discharge at the surface along the western margin of the field.

Little is known about the γ reservoir. Although it is deeper it seems to have temperatures similar to those of the β reservoir. We believe that the γ reservoir fluids are below the boiling point to depth curve and are less likely to boil as a result of exploitation. Eventually, the characteristics of the γ aquifer will have to be determined by testing the deep wells of the M-200 series.

Acknowledgments

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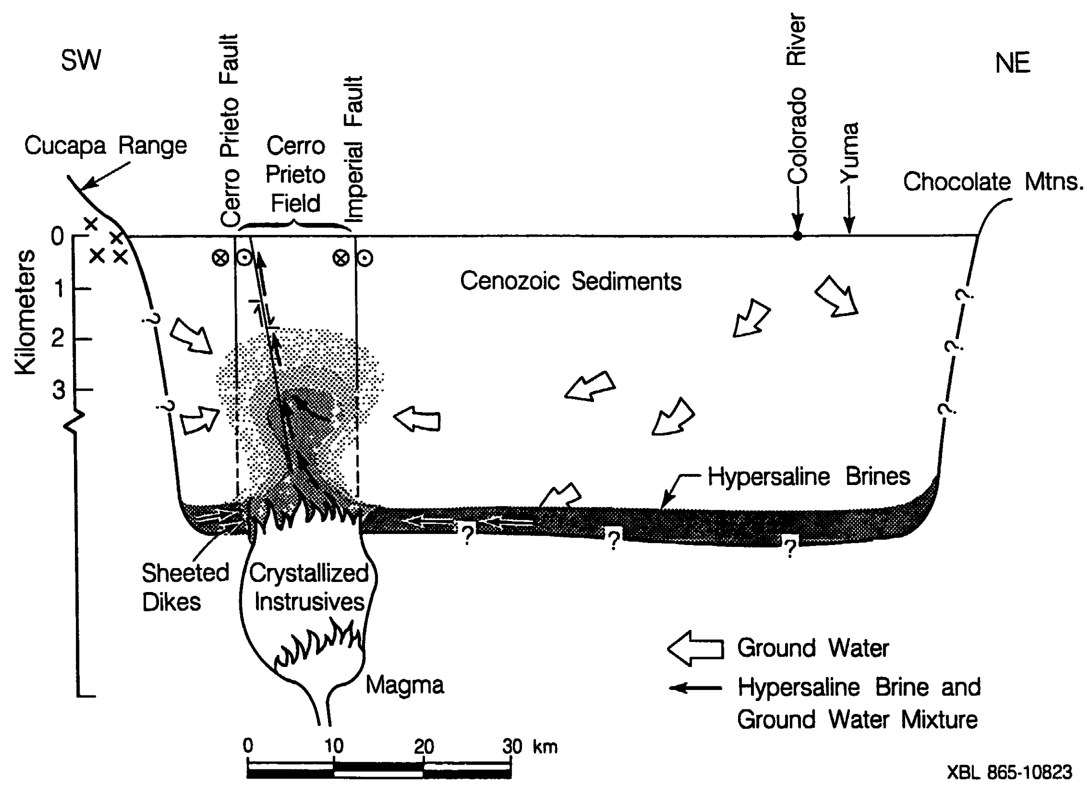

Figure 7. Schematic diagram of the geology and fluid flow across the Mexicali Valley.

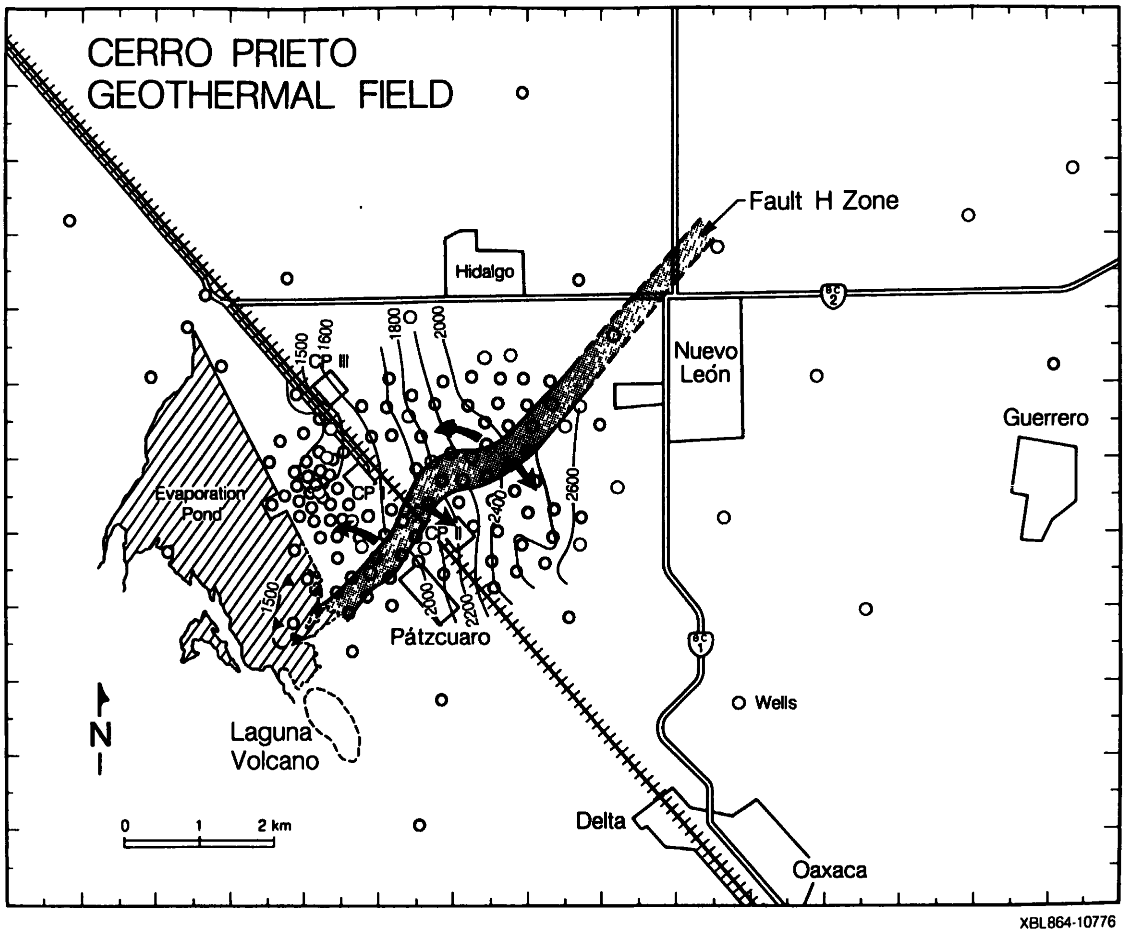

Figure 8. Depth (in meters) to the top of the Sand Unit Z. The arrows indicate the direction of geothermal fluid flow away from the Fault H zone into the β reservoir. The fault is shown at the β reservoir level.

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