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OVERVIEW OF CERRO PRIETO STUDIES

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ABSTRACT

The studies performed on the Cerro Prieto geothermal field, Mexico, since the late 1950's are summarized. Emphasis is given to those activities leading to the identification of the sources of heat and mass, the fluid flow paths, and the phenomena occurring in the field in its natural state and under exploitation.

INTRODUCTION

The purposes of this paper are: (1) to review the studies conducted on the Cerro Prieto geothermal field, located about 20 miles south of the city of Mexicali, Baja California, Mexico; and (2) to discuss recent models of the processes in the reservoir and the circulation of geothermal fluids in the system.

The Comisión Federal de Electricidad (CFE), which manages and operates the field, carried out the first studies and surveys, and still continues to evaluate the resource as new wells are drilled and data from existing wells are collected and analyzed.

In 1977 a five-year agreement was signed between CFE and the U. S. Energy Research and Development Administration, now the U. S. Department of Energy (DOE), to conduct a cooperative study of Cerro Prieto (Witherspoon et al., 1978). This agreement resulted in a more intensive study of the reservoir; a wide variety of standard and new geological, geochemical, geophysical and reservoir engineering techniques were carried out. Because of the success of this cooperative program preliminary discussions have been held to sign a new DOE/CFE agreement to study Cerro Prieto and other geothermal areas in Mexico.

STUDIES SPONSORED BY CFE

PRE-1977 STUDIES

Exploration for geothermal resources began in the Mexicali Valley in the late 1950's. Photo and field geologic surveys were concentrated near the Cerro Prieto volcano in an area characterized by numerous hot springs, fumaroles and mud volcanos. Between 1959 and 1961 three relatively shallow wells (up to 755 m deep) were drilled east of the volcano. Only one (well M-1A, Figure 1) produced geothermal fluids, but these were of low enthalpy (Alonso, 1966).

To determine the subsurface structure of the Cerro Prieto area, seismic refraction (GEOCA, 1962) and gravimetric surveys (Velasco, 1963) were carried out. These studies indicated a block-faulted basement, with blocks generally becoming deeper towards the east and major faults striking northwest-southeast. Based on the new subsurface interpretation, four deep exploration wells were drilled in 1964 to intercept some of the inferred faults, reach the geothermal resource and penetrate the basement. Well M-3 encountered relatively hot (~270°C) fluids from about 650 to 900 m depth. Only this well reached basement, at 2532 m. Well M-5 was the discovery well for this field; it produced fluids hotter than 300°C from about 1100 to 1300 m depth (Alonso, 1966).

In 1965 fifty shallow wells were drilled for heat flow determination (Mañón et al., 1978a). In 1966 a geochemical study of the hot springs and fumaroles was completed. Between 1966 and 1968, 15 development wells were drilled in the Cerro Prieto area. After successful well tests were completed the first 75 MW plant was planned. Commercial production of electricity from two 37.5 MW turbogenerators began in 1973 (Alonso, 1978).

On the basis of the geochemical study of the surface manifestations and on the geological and geochemical data from the wells completed at that time, Mercado (1968) presented the first hydrogeologic model of the field showing the circulation of geothermal fluids in the subsurface (Figure 2). The model indicated the entrance from the northeast of cold Colorado River water, which was heated by magmatic gases ascending through the center of the field (between wells M-5 and M-10). Then, deflected by a clay cap rock, the heated fluids moved westward towards the area of well M-6, an area of high-permeability sandstones. There, the fluids leaked to the surface through a fault zone.

In 1968 a study began of the ^{18}O, ^{14}C and deuterium contents in the ground waters of the Mexicali Valley and Cerro Prieto, in particular. The data indicated that these waters originated as Colorado River water altered by evaporation (Crosby et al., 1972).

A regional aeromagnetic survey of the area was completed in 1971 to determine the basement configuration of the Mexicali Valley. The location of a number of strike-slip and normal faults was revealed from this study (Evans, 1972).

Between 1972 and 1975 detailed resistivity surveys of the area were made (García, 1976). The results showed that the field was associated with a large resistivity low which later was found to be due to highly conductive and altered sediments near the surface. (Goldstein and Razo, 1978). A number of faults were identified, including a major one striking northwest-southeast, parallel to the railroad tracks.

To replace damaged wells and to find additional steam to increase power production in the future, 14 new wells were drilled at Cerro Prieto between 1972 and 1974. One of the wells (M-53) was located about 1.5 km northeast of the production area at that time. Its purpose was to explore the eastern region where geophysical data indicated a deep extension of the reservoir. A hot (340°C) reservoir was found at about 1900 m depth (about 600 m deeper than in the western area) which seemed to confirm the existence of an important fault parallel to the railroad tracks.

In 1976 Mercado presented a revised model showing the movement of geothermal fluids in the field (Figure 3). It was a refinement of his 1968 model and was based on new geothermometric and reservoir engineering data. The fluid circulation patterns and temperature distributions shown, especially in the western part of the field, in general have been confirmed by subsequent studies.

Passive seismic studies in the area of Cerro Prieto were carried out in 1974-75 using portable stations. In 1977 five permanent stations were established in the area. The results indicated right-lateral strike-slip faulting parallel to the northwest-southeast striking Cerro Prieto-Imperial transform fault system, and dip-slip faulting along some of the faults oblique to that system (Albores et al., 1978).

1977-1982 STUDIES

Geophysics

Because of their success in the limited area southeast of the Cerro Prieto volcano, CFE in 1977 began a series of geophysical studies in the Mexicali Valley to define the extent of the Cerro Prieto field and to locate other geothermal anomalies. Schlumberger resistivity surveys identified in the area of the field a resistivity low which at that time was assumed to be closely associated with the so-called Cerro Prieto basement horst which had been inferred from gravity data (Razo et al., 1978). Later it was shown that this resistivity low was due to surface effects related to highly conductive near-surface materials (Wilt et al., 1978). On the other hand, Lyons and van de Kamp (1980) indicated that there does not seem to be any convincing geophysical evidence for a basement horst underlying the field.

Gravity, magnetic, and reflection seismic surveys carried out in 1977 enabled Fonseca and Razo (1979) to construct a structural map of the basement. There exists now disagreement about this map since some of the data seem to reflect the alteration of the sediments or the presence of volcanic layers in the valley fill (Lyons and van de Kamp, 1980). However, these studies identified a number of northeast-southwest faults which, at least partially, were confirmed by well log correlation studies. The data gathered were very useful for understanding the subsurface geology at Cerro Prieto (e.g. Lyons and van de Kamp, 1980; Majer and McEvilly, 1982). For example, the magnetic study showed a high centered about 5 km east of the power plant, which later was interpreted as evidence of a basalt/gabbro intrusion which might be related to the heat source for the field (Elders et al., 1982, Goldstein et al., 1982b).

After the 1977 surveys, CFE carried out additional geophysical studies in the Mexicali Valley, most of them to locate new geothermal areas. Only a heat flow study (Díaz, 1978) and a few lines of a 1980 seismic reflection survey (Fonseca, et al., 1981) covered parts of the field. All this time, the monitoring and analysis of the seismic activity continued to study the structure and tectonics of the region (Reyes and Razo, 1979, Reyes et al., 1982; Wong and Frez, 1982).

Geology

In 1978 Puente and de la Peña, and in 1979 de la Peña et al., presented a geologic model of the field based mainly on surface geophysical data and well cutting lithologies. They showed a complex horst-and-graben basement structure and faulting of the sedimentary fill. In their analysis, great weight was given to the A/B contact between unconsolidated (Unit A) and consolidated (Unit B) sediments. This contact was used as a stratigraphic marker horizon. Later, it was found that this was misleading since the A/B contact is an induration boundary that cuts across sedimentary layers, suggesting postdepositional alteration (Elders et al., 1978; Lyons and van de Kamp, 1980; Halfman et al., 1982a).

The cuttings from new wells have been carefully studied by CFE, using mainly a binocular microscope to determine the appearance of key minerals which indicate the presence of high subsurface temperatures. These studies, which are useful to establish well completion depths, have produced lithologic columns and cross section showing the distribution of sand percentage and mineral zones in the field (Cobo, 1981; Cobo and Bermejo, 1982).

Over the years the interpretation of geophysical well logs has been performed by several Mexican authors with the purpose of developing a geologic model of the system (Abril and Noble, 1978; Prian, 1978, 1979, 1981; Díaz et al.,1981).

An ambitious drilling program to establish new production and to define the extent of the geothermal anomaly started in 1977. Between that year and 1982 more than 75 wells were completed at Cerro Prieto (Cobo and Bermejo, 1982). Thirteen of these were planned to be large step-out wells to help define the field boundaries, i.e., wells M-92, M-96, Prian, G-1 (not indicated in Figure 1) and S-262 are now known to be clearly outside the field; wells M-172, H-2, NL-1, M-189 and O-473 defined approximately the boundaries of the system; wells Q-757 and M-94 are marginal producers; and well E-1, in the western part of the field, discovered a deeper reservoir. This reservoir (B or β) is at about 1550-1800 m depth, and has a temperature of about

335°C, compared to the shallower reservoir (A or α), exploited since 1973, which is about 1000-1400 m depth and has a temperature of about 285°C. After well E-1 was completed, a number of deeper wells (E-series, Figure 1) were drilled in the western part of the field confirming the existence of this excellent geothermal aquifer.

Only two of these 13 exploration wells penetrated basement, well S-262 at 1473 m and well M-96 at 2719 m, even though one well, H-2, was drilled to 3540 m. The cuttings of wells H-2, M-189 and NL-1 indicated that they had drilled through a series of basic and silicic dikes at depths between 2500 and 3540 m (These were also found in production well T-366) Elders et al., 1981; Goldstein et al., 1982b).

Geochemistry

Data on the production characteristics of the Cerro Prieto wells and the chemistry of the fluids produced have been collected and analyzed since the mid-1960's.

Details on the chemical and physical characteristics of the fluids produced by the different wells, the reservoir temperatures computed on the basis of geothermometers, the composition of the reservoir fluids, and their spatial and temporal variations have been discussed by several Mexican authors (Mañón et al., 1978b; Mercado and Samaniego, 1978; Fausto et al., 1979 and 1981; Nieva et al., 1982). A general decrease of reservoir temperatures with time, localized boiling near the wells, and the recharge of colder waters from the west and hot waters from the northeast have been indicated by these studies.

Subsidence

Between 1977 and 1979 three first-order leveling surveys were carried out in the area of Cerro Prieto. The network used in these studies was tied to stations north of the border. In the production area of the field increased ground subsidence was observed. However, it was not clear how much of it was due to fluid extraction and how much to ground shaking related to the strong (6.2 M_L) June 8, 1980 "Victoria" earthquake (de la Peña, 1981).

Reservoir Engineering

In the mid 1970's CFE began carrying out two-rate flow and interference tests in Cerro Prieto wells. A few papers describing the data and results have been published (e.g., Rivera and Ramey, 1977; Rivera et al., 1978; Abril and Molinar, 1979; Abril and Vargas, 1981). The reported permeability-thickness products vary between 3.6 and 40 darcy-meters.

The results of CFE's downhole pressure measurements and the pressure drawdowns observed in the field have been discussed by Bermejo et al. (1979) and Sánchez and de la Peña (1981). The distribution of temperatures in the field have been given by several authors. The latest and most complete set of data is by Navarro et al. (1982), and Rivera et al. (1982).

Over the years CFE has used commercial laboratories to measure hydraulic properties of cores. Recently the Instituto de Investigaciones Eléctricas (IIE) installed a high temperature rock mechanics laboratory for testing samples from geothermal areas. Permeability and porosity data on Cerro Prieto cores have recently been reported by IIE (Contreras et al., 1982a, 1982b).

A number of modeling studies and analysis of production data have been made by CFE and its contractors; part of the results have been reported. Rivera (1977) indicated that the behavior of the Cerro Prieto reservoir and wells could be described using decline curve analysis. In 1978 Rivera described how a graphic procedure could be used for forecasting production. Liguori (1979) simulated the evolution of Cerro Prieto using a mathematical model. He found that a very low heat transfer coefficient between rocks and fluids was adequate to match observed values which he attributed to flow through microfractures as well as pores. His results showed a good match in the steam production rate, but the computed rate of water production was low and the enthalpy too high. Liguori indicated that this was caused by the vertical leakage of colder waters into the reservoir which was not considered by his model.

Saltuklaroglu (1979) analyzed the interference effects between wells. From observation well data he established an average rate of water level drop of 0.56 x 10^{-6} meter/cumulative ton of discharge. Later this value was used by Grant et al. (1981) to suggest that the α reservoir, the shallow reservoir in the western part of the field, is unconfined.

Based on a simplified reservoir model Molinar et al. (1979), calculated a 20-year production life for Cerro Prieto at an electric power production capacity of 1500 MWe. Using standard groundwater analysis techniques, Sánchez and de la Peña (1981) showed that the α reservoir is very permeable and is recharged from all sides. A permeability-thickness value of 3.4 x 10^{-3} m^2/s, equivalent to 353 darcy-meters, is given in the paper. According to their data, these authors maintain that the α and β reservoirs in the western part of the field are not connected, at least not locally. The hydrological model of Halfman et al. (1982b) disagrees with this conclusion.

Reinjection

In August 1979 injection of untreated 175-180°C brines began in well M-9. The rate varied between 8 and 80 tons per hour at about constant wellhead pressure. The injection operation has been described in detail by Cortez et al. (1982). It is worthwhile to indicate that a sudden increase in reinjection rate was observed after the June 1980 earthquake; it jumped from about 30 to 70 tons/hr, slowly decreasing with time.

Previously, several treatment methods for colder (about 100°C) brines were evaluated (Hurtado et al., 1981) for possible future use if larger-scale injection operation should begin.

STUDIES SPONSORED BY DOE

PRE-1978 STUDIES

One of the activities carried out before the signing of the 1977 DOE/CFE agreement was to collect available data on Cerro Prieto to incorporate in an open-file data bank (Lippmann et al., 1977). New information is still being added to this bank, which is being maintained by the Earth Sciences Division of the Lawrence Berkeley Laboratory (LBL).

Geochemical studies on Cerro Prieto also began before the formal agreement was signed. In close cooperation with CFE the geochemical data gathered on Cerro Prieto since 1966 were summarized and interpreted by Mañón et al. (1977), and Mazor and Mañón (1978). On the basis of early CFE and U. S. Geological Survey (USGS) data and fluid samples collected between 1977 and 1978, Truesdell et al. (1978a) concluded that production-related drawdown caused the leaking of lower chloride (colder) fluids into the reservoir from above and boiling, with excess steam reaching the producing wells.

In 1977 a preliminary model of the structure of the field was developed by Noble et al. using geophysical well logs, temperature logs, and production and geochemical data.

A self-potential survey conducted in late 1977 detected a large-amplitude, long-wavelength anomaly over the field. In 1978 a more detailed study defined a dipolar self-potential anomaly running through the center of the production field (Figure 4). The source of it appeared to correspond to a north-trending fault, and be caused, possibly, by a electrokinetic (streaming-potential) mechanism (Corwin et al., 1978; Fitterman and Corwin, 1982).

Other 1977 geophysical studies were restricted to the interpretation of CFE Schlumberger resistivity and gravity data using numerical modeling techniques. The gravity interpretation gave clear evidence of a north-northwest trending fault and several trending northeast. The data showed a "basement" high in the production which was interpreted to be the result of a shallow zone of densified sediments (Goldstein, 1977).

The first paper on the hydrothermal alteration of Cerro Prieto sediments was by Reed (1976) of the USGS. In 1977, Elders and his group at the University of California at Riverside (UCR) began thorough petrological and light isotope studies of well cuttings and cores. A number of regularly distributed metamorphic mineral zones were recognized in the field. The progressive changes in mineralogy indicated a systematic relationship with reservoir temperatures (Elders et al., 1978). They also showed that the A/B contact (Puente and de la Peña, 1978) was a postdepositional feature. The isotope studies indicated that the $\delta^{18}O$ for calcite in sandstones could be used to estimate stable reservoir temperatures and that the same parameter in shales could indicate the extent and distribution of subsurface flow (Olson, 1978). Other results of this work indicated that the Cerro Prieto hydrothermal system is relatively open to fluid flow.

1978-1982 STUDIES

The work pace under the DOE/CFE cooperative program increased in 1978 and did not slow down until quite recently at the expiration of the agreement in July 1982.

Geology

The analysis of cuttings and cores continued at UCR over the entire five-year cooperative program adding vitrinite, fission-track annealing and geophysical well log studies to the petrologic and light isotope work begun earlier (Elders et al., 1979; Barker et al., 1981; Sanford and Elders, 1981; Seamount and Elders, 1981; Williams, 1982). Mainly on the basis of the results of these studies, Elders et al. (1981) developed a model for the natural (pre-production) flow regime at Cerro Prieto (Figure 5). A heat source for the hydrothermal system was suggested to lie to the northeast in an area where wells drilled through basic and silicic dikes. From that source an inclined plume of hot water ascends toward the southwest, boiling in places and precipitating minerals which tend to seal the rock pores. The plume discharges upward and horizontally to the southwest creating surface manifestations and shallow zones of temperature reversals. The model also shows cold water recharge from the northeast which may also seal the reservoir pores as these waters are heated.

In 1978, a study of the paleomagnetism of the rhyodacitic rocks of the Cerro Prieto volcano was made. Magnetic polarity and paleopole position data suggested that the volcanism was initiated about 110,000 years ago. The youngest volcanics reaching the surface cooled about 10,000 years ago (De Boer, 1979).

The analysis of geophysical well logs was conducted during the entire length of the program as new wells were completed. Noble and Abril (1978) described the problems found in interpreting logs obtained from Cerro Prieto wells. Later, and along the same line Ershaghi et al. (1978), Lyons and van de Kamp (1980), Ershaghi and Ghaemian (1980a, 1980b, 1981), and Seamount and Elders (1981) studied the effects of salinity and mineralogy in estimating the parameters of the Cerro Prieto reservoir.

Using mainly wireline well logs and surface geophysical data Lyons and van de Kamp (1980) developed a geologic model of the area that was significantly more detailed than any of the earlier models. They proposed three groups of faults of different ages, and presented a depositional model for the reservoir that showed a transition from a delta environment in the east, to a marine environment in the west. These authors gave well log evidence that disputed the basement-horst structural model; they showed that the gravity high over the reservoir is due to the high densities of the indurated shales of Unit B. They also showed that the reservoir is not overlain by a laterally continuous low-permeability layer, that the reservoir sandstones present secondary porosity, and that the production intervals in the wells generally straddle or underlie the top of the high-density (and high-resistivity) shales. Lyons and van de Kamp seem to have been the first to suggest that the positive magnetic anomaly, about 5 km east of the power plant, was related to the presence of igneous dikes within the basin fill.

The structural framework of the Mexicali Valley and the Cerro Prieto field was analyzed by Vonder Haar and Howard (1979). The degree and distribution of hydrothermal alteration, and the origin and distribution of dissolution (secondary) porosity in the field were discussed by Vonder Haar (1980, 1981). In 1981, Teilman and Cordon briefly described how the geologic model of Cerro Prieto evolved as new exploration data became available.

A fault map for the field was developed during an internal DOE/CFE workshop (Figure 6) (Lippmann and Mañón, 1980). It showed two types of faults: (1) the NW-SE Cerro Prieto system of strike-slip faults, and (2) the NE-SW Volcano system of normal faults. The existence of a continuous fault near and parallel to the railroad tracks (Michoacán fault) was considered doubtful. On the basis of new data, this map was somewhat modified during a second workshop (Zelwer, 1982).

Recently a micropaleontological analysis of 30 core samples was completed (Ingle, 1982). The distributed patterns of ostracodes and foraminifera together with the lithofacies studies of Lyons and van de Kamp (1980) indicated that the sediments at Cerro Prieto represent a complex of alluvial, deltaic, estuarine and shallow marine environments. These sediments were deposited along the front of the Colorado River delta as it prograded across the Salton Trough during the Pliocene and Pleistocene. Tentative correlation of the Cerro Prieto section with the Palm Spring Formation of the Imperial Valley suggests that the Pliocene/Pleistocene boundary occurs at about 2000 m depth in the area of well M-93. Ingle also found evidence that a sand/shale unit usually present between 700 and 1100 m depth represents a significant mid-Pleistocene marine incursion. The existence of reworked Cretaceous specimens confirmed that a significant part of the deltaic sediments in the area derived from the Colorado Plateau.

After an extensive analysis of geophysical and lithological well logs, Halfman et al. (1982a, 1982b) have recently extended and improved the geologic model developed by Lyons and van de Kamp (1980). By superimposing on the model downhole temperature and well completion data it was possible to establish the movement of the geothermal fluid in the field, prior to its exploitation (Figure 7). The hot fluid appears to enter the system from the southeast, from the area where igneous dikes are believed to have intruded into the valley fill (Lyons and van de Kamp, 1980b; Elders et al., 1982; Goldstein et al., 1982b). Then, the fluid moving westward through permeable layers ascends gradually to shallower depths by flowing upward through faults and sandy gaps in shaly layers acting as local cap rocks. Eventually, in the western part of the field, part of the geothermal fluid leaks to the surface and the rest mixes with colder groundwaters.

Halfman's model seems to indicate that the Michoacán fault (Figure 6), assumed to run parallel to the railroad tracks, does not exist or does not continue southeast of the general area of well M-114. This study has identified three faults (called H, L, and S on Figure 8) which have an important role in controlling the subsurface flow of geothermal fluids. Reflection seismic data (Majer and McEvilly, 1982), the location of boiling zones in the reservoir (Nehring and D'Amore, 1982), and the result of numerical modeling studies (Lippmann and Bodvarsson, 1982) have substantiated the existence of these faults.

The model has also shown, confirming the conclusions of others, that there is no laterally continuous cap rock at Cerro Prieto which prevents the leakage of geothermal fluids from the reservoir. The model indicates that in the general area of well M-10, reservoirs α and β are communicating through a sandy gap in the shale layers.

Geophysics

In 1978, the first LBL detailed seismological study was conducted at Cerro Prieto; two others were made in 1980 and 1981 (Majer and McEvilly, 1979, 1981, 1982). In addition, in late 1980 a downhole geophone was installed in a 100-meter-deep well near well M-6. The purpose of this work was to determine the relation of wave propagation characteristics and microearthquake activity to the production zone, recharge areas, heat source and general lithology and structure of the field. It was found that in the immediate production zone seismicity had increased from 1-2 events/day ($M_L > 1$) in 1978 to 7-8 events/day in 1981, and that these events appeared to be production related. The events registered in 1978 indicated strike-slip movement along northwest-southeast trending faults. The results of later surveys did not permit establishing the type of faulting associated to the monitored events.

The 1980 seismic events were clustered near the center of the production area, at depths from 2 to 5 km, on a fairly well defined north-south plane extending from well M-101 to the power plant. On the other hand, the 1981 events were distributed in a rather diffuse pattern concentrated on the western edge of the field. The diffuse pattern of the 1981 events and the increase in seismicity may indicate that the area is undergoing a transformation from aseismic creep to stick-slip behavior, which is accelerated by the extraction of fluids from the field (Majer and McEvilly, 1982).

During the 1978-1981 period four precision gravity surveys were conducted at Cerro Prieto to study the possibility of geothermally induced subsidence (Chase et al., 1978; Grannell et al., 1981, 1982). Comparison of results from year to year showed subsidence clearly associated with the June 1980 earthquake. Also, significant changes were observed at several stations in the western (older) part of the field. The pattern of these latter changes is elliptical in a northwest-southeast direction parallel to the structural grain and faulting in the region. By correlating precision gravity and leveling data, Zelwer and Grannell (1982) concluded that changes in gravity and surface elevation correlate well, and were primarily produced by compaction that occurred in response to the June 1980 earthquake. However, Grannell et al. (1982) also suggest that this subsidence is probably of geothermal origin because they considered that the natural recharge of the field is not keeping pace with production. Zelwer and Grannell (1982) also indicated that a density increase is taking place in the reservoir zone because of mineral precipitation or the entrance of cooler, denser, waters. Further analysis of the data will be required to clarify the importance of fluid extraction on the subsidence observed at Cerro Prieto.

The first LBL dipole-dipole resistivity survey at Cerro Prieto was completed in 1978. A two-dimensional vertical resistivity model along a northeast-southwest line across the field (line E-E') was developed (Wilt et al., 1978). It showed that the production region is characterized by high resistivity (4 ohm-m) relative to the surrounding region (1 to 2 ohm-m). The higher resistivity is assumed to be related to the densification of the shales in Unit B.

The 1979 studies improved the resistivity model for the eastern part of the field (Wilt and Goldstein, 1979). It revealed that the 4 ohm-m body associated with the producing zone dips eastward at 30 to 50 degrees to a depth greater than 2 km (Figure 9). A narrow, steeply dipping 1.5 ohm-m zone immediately to the east was interpreted as a possible zone of recharge or faulting.

Repetitive high-precision dipole-dipole resistivity measurements taken during the period 1979-1981 over line E-E' showed a consistent pattern of apparent resistivity changes. A zone of increasing resistivity is related to the production region; above and flanking this region are zones of decreasing resistivities. These changes were interpreted as near-surface effects due to changing irrigation patterns and deeper effects due to lateral recharge of cooler, less saline fluids into the shallow western α reservoir. There is also an unresolved component that might relate to ascending hot fluids at the eastern edge of the producing zone (Wilt and Goldstein, 1982).

The changes in apparent resistivities detected at Cerro Prieto from the dipole-dipole monitoring surveys were studied by Pruess et al. (1982) and Goldstein et al. (1982a) using reservoir modeling techniques combined with dc resistivity calculations. Based on schematic one- and two-dimensional reservoir simulations, assuming the existence of waters of different salinity and temperature, changes in formation resistivity were computed which were then transformed into changes in apparent resistivity that would be observed at the surface.

Over a period of three years starting in 1978, three magnetotelluric (MT) studies were made in the area of the field. The initial purpose of the MT soundings was to provide additional and deeper subsurface resistivity data to supplement the dipole-dipole and Schlumberger surveys conducted in the region. Subsurface resistivity models developed jointly from the dipole-dipole resistivity and MT data sets helped define the deep resistivity structure of the field. The models also showed: (a) the inferred position of faults in the system; (b) a front of cooler, less saline Colorado River water entering from the east; and (c) the A/B contact between nonconsolidated and consolidated sediments (Gamble et al., 1979; Goubau et al., 1981). Later MT studies were conducted to help delineate a possible boundary on the south side of the thermal area.

Recently Goldstein et al. (1982b) analyzed the broad magnetic anomaly observed about 5 km east of the power plant. Their modeling studies, coupled with the analysis of cuttings of mafic dikes recovered from well NL-1, and viewed in conjunction with other geological and geophysical data, gave further support to the hypothesis that Cerro Prieto is located in a pull-apart basin like others in the Salton Trough and the Gulf of California (Lomnitz et al., 1970; Elders et al., 1972), into which igneous basic rocks are being emplaced. These authors estimate that the top of the main magnetic source body is about 3.5 km below the surface, and that the present melt zone may be at 10-12 km depth, as determined from seismic (earthquake) observations and a Curie isotherm analysis.

On the basis of preliminary thermal modeling results, Elders et al. (1982) suggested that the present subsurface temperature distribution determined from deep wells can be fitted approximately to a single stage of magmatic intrusion in the form of a funnel-shaped gabbroic body, some 4 km across at the top at a depth of 5 km. The model age for such an event is 30,000 to 40,000 years, which is in the range of the age for the volcanic activity at Cerro Prieto (de Boer, 1979). The depth is quite shallower than the 10-12 km depth of the present magma inferred by Goldstein et al. (1982b). Above the intrusive, Elders postulated the existence of a sheeted dike complex which would correspond to the dikes found in some of the deep wells in the eastern part of the field.

Subsidence

Measurement of horizontal ground-surface movements in the northern part of the Mexicali Valley and around Cerro Prieto began in 1978 (Massey, 1978, 1979, 1981). Inward movement toward the center of the production area was observed during the 1978-81 study period. The movement, probably not exceeding 6 or 7 cm, occurred mainly between 1978 and 1979 and was confined to the production area. A consistent change in the length of the survey lines crossing the well field, similar to the general shortening detected in 1978-79, was not observed over the 1978-81 period.

Massey (1981) indicated that the ground-surface movements in the production area were due to fluid extraction. However, an increase in the rate of deformation resulting from the continuous exploitation of the field was not evident for the longer time period. Outside the well field ground deformation, excluding earthquake related movements, was small.

Lisowsky and Prescott (1982) studied ground deformations near the epicenter of the June 1980 ($M_L = 6.2$) Victoria earthquake, located about 30 km southeast of Cerro Prieto. Their analysis showed that production-induced deformations at the field could not be observed or were masked by earthquake-related changes.

In 1978 cores from Cerro Prieto were studied in the laboratory to determine the permeability, thermal conductivity and deformation properties of reservoir rocks. The tests made at that time indicated large changes in properties occurring with temperature and stress (Somerton, 1978, Martínez, 1978). Later, cores were tested under simulated in situ conditions to measure porosity reduction and establish short- and long-term compaction triggered by reservoir drawdown (Abou-Sayed et al., 1979; Schatz, 1982).

It was found that the rocks behaved as expected with respect to instantaneous compaction, and that they present a tendency to compact further with time (creep). The results obtained when extrapolated to a reservoir life of 20 to 30 years showed that reductions of several percent in porosity and several tens of percent in permeability are possible. Instantaneous compaction-related subsidence might be small; however, creep-related subsidence might be significant at Cerro Prieto (Schatz, 1982).

Geochemistry

The scope of geochemical studies on Cerro Prieto geothermal fluids also increased in 1978 as a result of the DOE/CFE agreement. A review of the studies carried out both by U. S. and Mexican scientists has been made by Truesdell et al. (1982).

The 1978 isotopic studies indicated local recharge from the area immediately to the west of the field and leakage of shallower waters into the reservoir. The tritium and ^{14}C contents in the fluids could only suggest an average age between 50 and 10,000 yrs. (Truesdell et al., 1978b).

The work by Mazor and Mañón (1978) indicated regularities and correlations between different ions in the Cerro Prieto fluids, indicating concentration-dilution processes, such as steam loss or mixing with condensed steam and possibly fresher waters from shallower aquifers. The data also suggested that the deep brine has a chloride content of about 10,000 ppm, that no significant reactions occur during the ascent of fluids through the wells, and that temperature zonation existed in the reservoir. This zonation makes the reactive K and SiO_2 ions useful as geothermometers at Cerro Prieto.

The study of the composition of the gases produced from the wells began in 1977 (Nehring and Fausto, 1978). By analyzing the spatial distribution of different gases in the field and using gas geothermometers, Nehring and D'Amore (1982) interpreted that in 1977 a large boiling zone existed in the center of the production area. Changes between 1977 and 1982 seem to indicate that some colder groundwater is leaking into the reservoir, and that the boiling zone is not expanding and possibly receding because some of the wells have been taken out of production.

On the basis of computed deuterium and chloride concentrations in the reservoir brines and measured Cl/Br ratios, Truesdell et al. (1979) concluded that the geothermal fluids are a mixture of Colorado River water and a saline brine of seawater origin. The study showed that this mixture circulated deeply and was extensively altered compositionally by high-temperature reactions involving reservoir rocks.

The surface manifestations were studied by Valette-Silver and others. Five types of surface emissions, each of different chemical characteristics, were identified along the western edge of the production area. A similarity in isotopic composition and ratios of major elements was observed between the hot springs and the producing wells, suggesting that the geothermal reservoir and the springs are closely related. This relationship is also indicated by the chemical changes observed in the hot springs after fluid production began in the field (Valette and Esquer-Patiño, 1979).

The hydrothermal alteration of the sediments associated with the surface manifestations appears to be controlled by the type of emanation. However, most of the sediments in contact with the geothermal fluids show an increase in quartz and potassium feldspar. Below 180°C similar trends in mineralogy changes are observed in the reservoir and in the surface manifestations (Valette-Silver et al., 1981a). Preliminary attempts at modeling the chemical processes and study the reactions between sediments and fluids of the surface manifestations using chemical equilibrium calculations were made by Valette-Silver et al. (1981b).

Nehring and Valette-Silver (1982) studied the differences in gas composition between well and surface manifestation samples. They found that with respect to the wells the surface features show a loss of H_2S because of reaction with metal ions or air and an increase of nitrogen due to mixing of ground and geothermal waters as the latter move toward the surface.

Mazor and Truesdell (1981) used radiogenic and atmospheric noble gases as tracers to develop a dynamic model for the field. They suggested that the geothermal fluids are dominated by meteoric waters which have penetrated to more than 2500 m depth and then mixed with radiogenic helium and argon-40 formed in the reservoir rocks. Afterwards small amounts of steam are lost by continuous removal as it forms (a Raleigh process) and mixing occurs with shallow colder waters.

The radon and ammonia concentrations in the produced fluids were analyzed by Semprini and Kruger (1981, 1982). The data show that a correlation exists between the radon content and the specific volume of the reservoir fluids. They studied the variations in time and space of the radon concentration to determine changes in the field due to exploitation. Supported by other reservoir data, their analysis indicates an expansion of the two-phase zone in the northeastern part of the field and a decrease in the southeast.

Grant et al. (1981) analyzed chemical, production and reservoir engineering data to study the processes within the relatively shallow western α reservoir. Their model indicates that this reservoir is bounded below by low-permeability rocks and above and to the sides by an interface with cooler water; there is no continuous permeability barrier around or immediately above the reservoir, and permeability within the reservoir is predominantly intergranular. They also show that in the natural state, reservoir cooling takes place mainly by mixing of cooler water with the hot water, rather than by boiling. Production has caused displacement of hot water by cooler water rather than by vapor. Local boiling occurs near most wells in response to pressure decreases, but no extended vapor zone has formed (Figure 10).

Recently on the basis of stable water isotopes, tritium values and chemical composition data Makdisi et al. (1982) concluded that: (1) groundwater in the northern and central regions of the Mexicali Valley originates from the Colorado River; (2) near Cerro Prieto, groundwater originates from a mixture of Colorado River water and geothermal brines; (3) other western groundwaters reflect a mixture of Colorado River water and water from a paleoequivalent to the present Salton Sea; (4) variations in the groundwater chemistry within a given region results from mineral-water reactions dependent on the lithology of the reservoir rocks, as well as evaporation and mixing; and (5) higher groundwater temperatures in the southern and western areas of the Mexicali Valley probably increase rates of ion exchange reactions that produce higher salinities.

The chemical equilibrium between Cerro Prieto geothermal fluid and detrital and alteration minerals of the reservoir were studied by Truesdell and Henley (1982). The fluid appears to be in equilibrium with aquifer minerals. On the other hand, the dissolved gases CO_2, H_2S, H_2, N_2, and NH_3 are in equilibrium with each other, although CH_4 equilibria are apparently frozen in at temperatures somewhat above those of the reservoir.

The variations of ^{13}C in Cerro Prieto fluids were studied by Janik et al. (1982). It was found that the changes in the ^{13}C content in CO_2 over time and location within the field indicated the deposition of calcite in near-well boiling zones and subsequent re-solution. They indicated that the source of the carbon may be of magmatic or sedimentary origin, and that the CO_2 from some surface manifestations is heavily influenced by decomposition of organic matter.

Des Marais et al. (1982) measured the hydrocarbon abundance and stable carbon isotope composition in fluids from various Cerro Prieto wells. Parallel measurements were made on gases from laboratory pyrolysis of coal obtained from samples of one of the wells, in an attempt to simulate the production of the geothermal hydrocarbons. The best correlation between the laboratory and well data was obtained when laboratory produced gases from experiments at 400°C and 600°C were mixed. This suggested that the wells are sampling hydrocarbons produced over a range of depths and temperatures in the sediments.

Reservoir Engineering

The only long-term well-interference and build-up tests conducted by DOE-sponsored groups at Cerro Prieto were described by Schroeder et al. (1978). In one of these tests, interference was observed between wells M-10 and M-53, completed in the α and β reservoirs, respectively. The communication between these aquifers was confirmed by the geological model of Halfman et al. (1982b).

In 1979 a two-rate flow test was carried out using a downhole tool modified by Sandia Laboratories for high-temperature wells. No results were reported as the tool failed after 12 hours in a 340°C well. Castañeda and Horne (1981) described the use of pressure gradient techniques to locate feed zones and internal flows in Cerro Prieto wells.

Since 1979 the characteristics of the Cerro Prieto production wells have been studied at LBL. Using known wellhead data, Goyal et al. (1980, 1981) calculated downhole pressures, temperatures, and saturations in flowing wells. The data show that during the period 1973 to 1980 the pressures and temperatures decreased by about 15 bars and 20°C, and the steam saturations had increased slightly in the near-well regions. The studies confirmed the fact that computed downhole pressures are very sensitive to measured wellhead conditions and to changes in inside well diameter.

Heat and mass production data for the period 1973 to 1980 were analyzed by Goyal et al. (1981). It was found that the production of individual wells generally decreased with time due to relative permeability effects, a reduction in permeability, and/or a reduced pressure gradient in the reservoir. The average enthalpy of the produced fluids has varied over the years. The increases in enthalpy were usually the result of bringing higher-enthalpy wells on line. The decrease in the average enthalpy was thought to be due to the mixing of relatively colder water with the geothermal reservoir fluids.

Goyal et al. (1982) studied the distribution of heat and mass production in the field to determine the initial state of the α and β geothermal reservoirs and the behavior of these aquifers under exploitation. They also analyzed the changes in production characteristics in different wells and the interference effects between wells, establishing the existence of flow barriers and cold boundaries in the reservoirs.

Preliminary reservoir modeling studies of the field's behavior were carried out by Lippmann et al. (1978) and Lippmann and Goyal (1979). Westwood and Castanier (1981) used a lumped-parameter model to gain insight into the physical processes in the reservoir and its response to production. The results suggested that the producing zone became two-phase early in the production history of the field and that strong radial, or spherical, recharge of 260°C water exists.

On the basis of the temperature data given by Castillo et al. (1981), Lippmann (1982) computed the amount of heat stored in the field. A mineable heat of 23.8×10^{13} kcal was obtained using 200°C as the lowest temperature of interest, 3000 m as maximum depth, and assuming that 25% of the total heat stored could be extracted. Taking into consideration the efficiency for electrical conversion (Brook, et al., 1979), a total capacity of 3.16×10^4 MWe-yr, or about 1050 MWe for 30 years, was calculated. This value is similar to the one given by Molinar et al. (1979).

Observed chemical and thermal changes in the reservoir were used by Grant and O'Sullivan (1982) to study the recharge characteristics of the old (western) production field. Based on pressure changes the permeability of the layer overlying the reservoir was calculated. It was found that it was considerably less permeable than the producing aquifer but not sufficiently impermeable to exclude inflow of cooler waters from above. The authors concluded that the α reservoir in the old field is best considered as a leaky aquifer. They estimated that one-quarter to one-half of its recharge derives from cooler rock immediately above it.

A two-dimensional distributed-parameter model was used by Lippmann and Bodvarsson (1982) to study the natural flow of heat and mass through the Cerro Prieto system and the impact of fluid production on the behavior of the field. The results indicated that the Halfman et al. (1982a, 1982b) hydrogeological model is reasonable and consistent with the mass and heat flows in the system. It is shown that the field in its natural state is recharged from the east with hot (about 255°C) water as well as with colder (between 50° and 150°C) waters from shallower aquifers, especially from the west. Some boiling occurs as the hot water ascends through a sandy gap in the shaly layers.

The study of the reservoir response to exploitation showed that most of the fluid recharge to the α reservoir comes from the west and from shallow waters flowing through Fault L. The recharge from the east seemed to be minor due to the presence of a two-phase zone in the sandy gap communicating the α and β reservoirs, near well M-10. Because of the large fluid recharge no extensive two-phase zone develops in the shallow α reservoir.

<u>Reinjection</u>

In support of CFE reinjection tests, the chemistry of silica in Cerro Prieto brines was studied theoretically and in the laboratory (Iglesias and Weres, 1979; Weres et al., 1980). It was established that part of the dissolved silica quickly polymerizes to form suspended colloidal silica. Raising the pH of the brine and stirring produces a rapid and complete flocculation and settling; these results were confirmed by field tests (Hurtado et al., 1981). Weres and his colleagues also developed a simple preinjection treatment for the Cerro Prieto brines, analyzed their equilibrium chemistry and studied the rate of deposition of silica scale from synthetic brines.

The response of the Cerro Prieto field to reinjection was simulated numerically by Tsang et al. (1978, 1979, 1981, 1982). These studies confirmed that the breakthrough of the injected cold water into the production zone is strongly dependent on the location and completion of the injection wells, indicating the need of a carefully planned and monitored production-injection operation to optimize the extraction of the heat stored in the reservoir rocks.

Tsang et al. (1982) incorporated into their model some of the geologic features desribed by Halfman et al. (1982b). The results showed that significant pressure-sustaining effects can be obtained in the producing reservoir by injecting 30% of the fluid extracted.

SUMMARY AND CONCLUSIONS

The present model for the natural (pre-exploitation) circulation of geothermal fluids in Cerro Prieto can be summarized as:

- Waters of Colorado River and seawater origin penetrate deeply into the sedimentary fill of the Mexicali Valley.

- These brines are heated by a thermal source consisting of diabase dikes and gabbroic cummulates presumed to have intruded the eastern part of the field 10^3 to 10^4 years ago. A melt zone and magmatic injection at 10 to 12 km depth may be active presently.

• In response to pressure gradients and bouyancy effects the hot fluids move toward the west through a sandy unit (Reservoir β) overlain by a thick shaly layer.

• The geothermal fluids hydrothermally alter the sedimentary rocks, decreasing their primary porosity. In sandstones some of this effect is offset by the removal by solution of unstable grains and cements (Lyons and van de Kamp, 1980).

• During circulation the composition of the fluids is extensively altered by high-temperature reactions with reservoir rocks.

• As they move westward toward the present production area, the geothermal fluids tend to flow upward through faults and permeable gaps in the overlying shaly layers. During the ascent and because of pressure reduction, some boiling and mineral deposition occurs.

• In the general area of well M-10, where a major sandy gap interrupts the lateral continuity of the shaly materials, some of the geothermal fluids mix with colder waters at shallower depths causing secondary mineral precipitation and porosity reduction. However, most of the hot fluids move into the α and β reservoirs in the western part of Cerro Prieto.

• Along the western edge of the field colder groundwaters are in lateral contact and mix with the geothermal fluids; precipitation of minerals occurs.

• Also in the western areas of the field some of the hot fluids ascend to shallower depths through fault zones, eventually reaching ground level. This is evidenced by the abundant surface manifestations observed along the western edges of the producing area.

A general decrease of pressure and temperature has been observed in the reservoir since fluid production began in 1973. However, because of the open nature of the reservoir, only localized boiling has occurred near the wells. An extensive two-phase zone does not develop, as ample recharge of colder, less saline waters from shallower layers and from the western edges exists. The near-well boiling causes enthalpy excesses in the produced fluids that decrease or disappear with time as the boiling front stabilizes. The boiling results in silica deficiencies in the produced fluids and deposition of quartz near the wells (Grant et al., 1981). Other changes in the characteristics of the produced fluids and interference effects between wells have also been detected (Truesdell et al., 1982).

Great advances have been made toward understanding Cerro Prieto. We hope that many of the studies initiated under the 1977-1982 DOE/CFE agreement will continue and add important new information as the field is expanded. (CFE plans to increase the electrical power output from the present 180 MWe to 620 MWe before the end of 1984.) For example, more needs to be known about the hydraulic properties of the sandy and shaly layers; the hydrogeological model should be updated as new results and field data become available; and the general monitoring of the behavior of the field should continue, especially as new areas come under production.

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CPIII: Proceedings of the Third Symposium on the Cerro Prieto Geothermal Field, March 24-26, 1981, San Francisco, California; Lawrence Berkeley Laboratory report LBL-11967.

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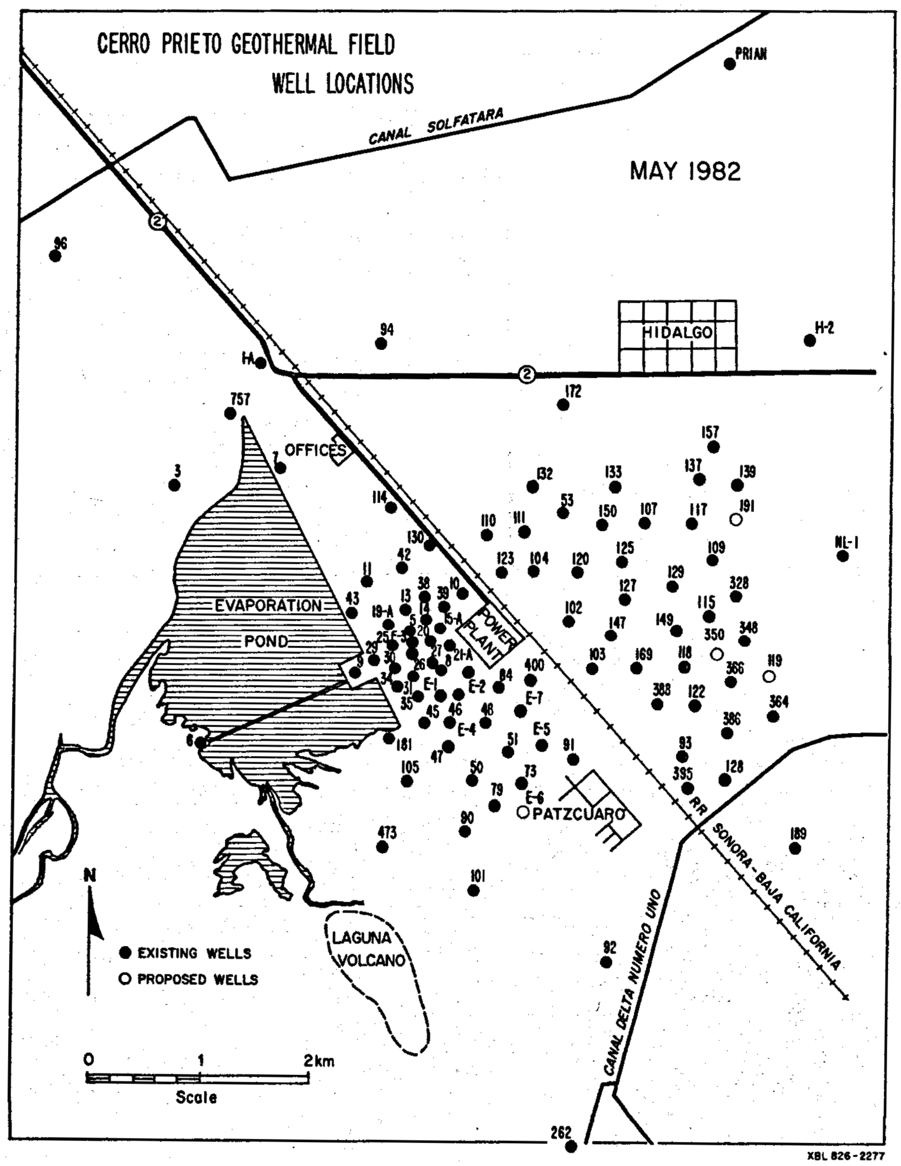

Figure 1. Location of geothermal wells in the Cerro Prieto field.

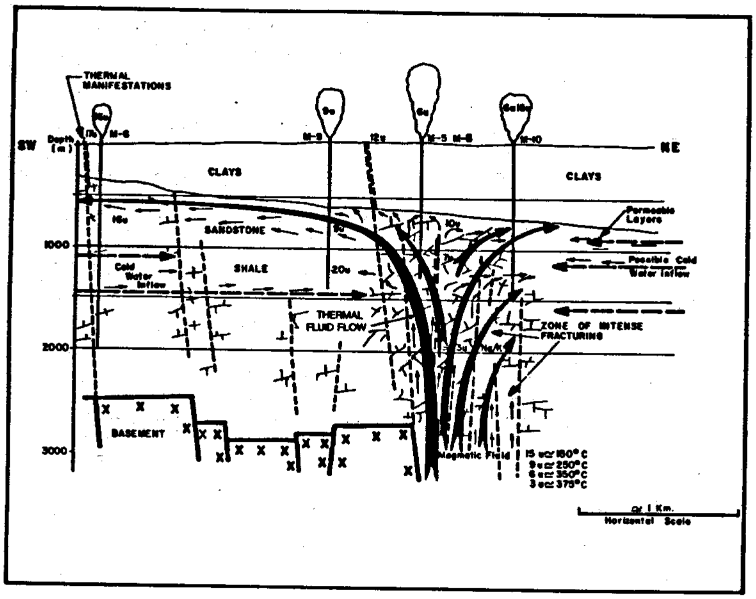

Figure 2. Mercado's (1968) convective model for the Cerro Prieto field.

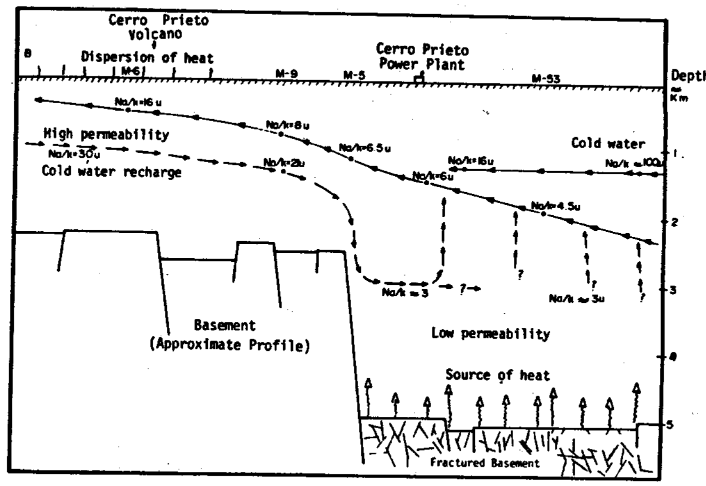

Figure 3. Mercado's (1976) convective model for the Cerro Prieto field.

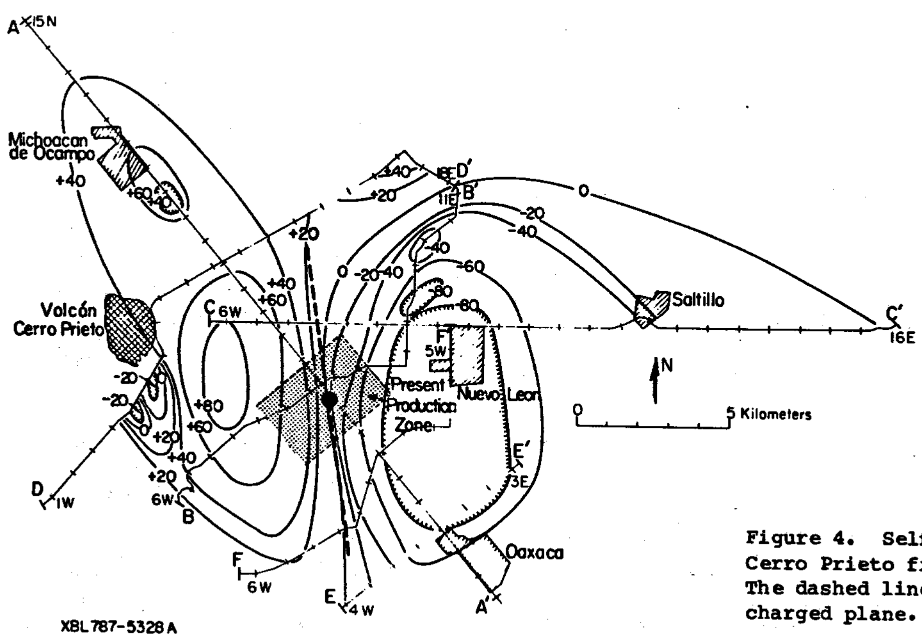

Figure 4. Self-potential anomaly over the Cerro Prieto field (from Corwin et al., 1978). The dashed line indicates the position of the charged plane.

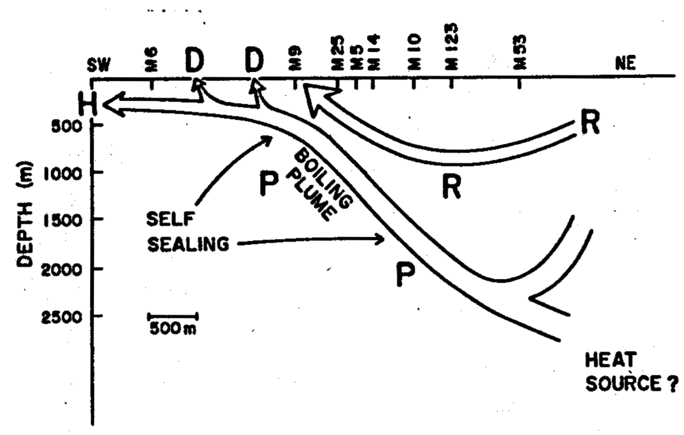

Figure 5. Southwest-northeast section across the Cerro Prieto field showing the flow regime proposed by Elders et al. (1981). R: recharge zone; P: thermal zone; D: discharge zone; H: horizontal flow zone.

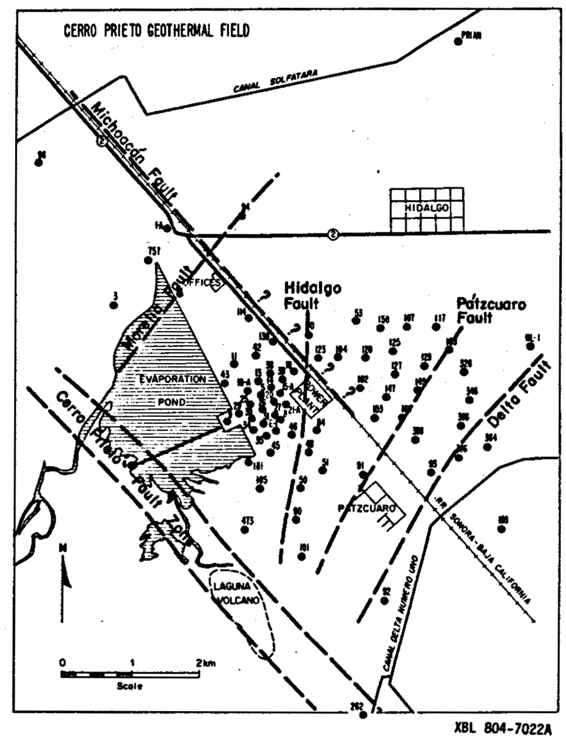

Figure 6. Fault map for the Cerro Prieto region developed at the first DOE/CFE workshop (Lippmann and Mañón, 1980).

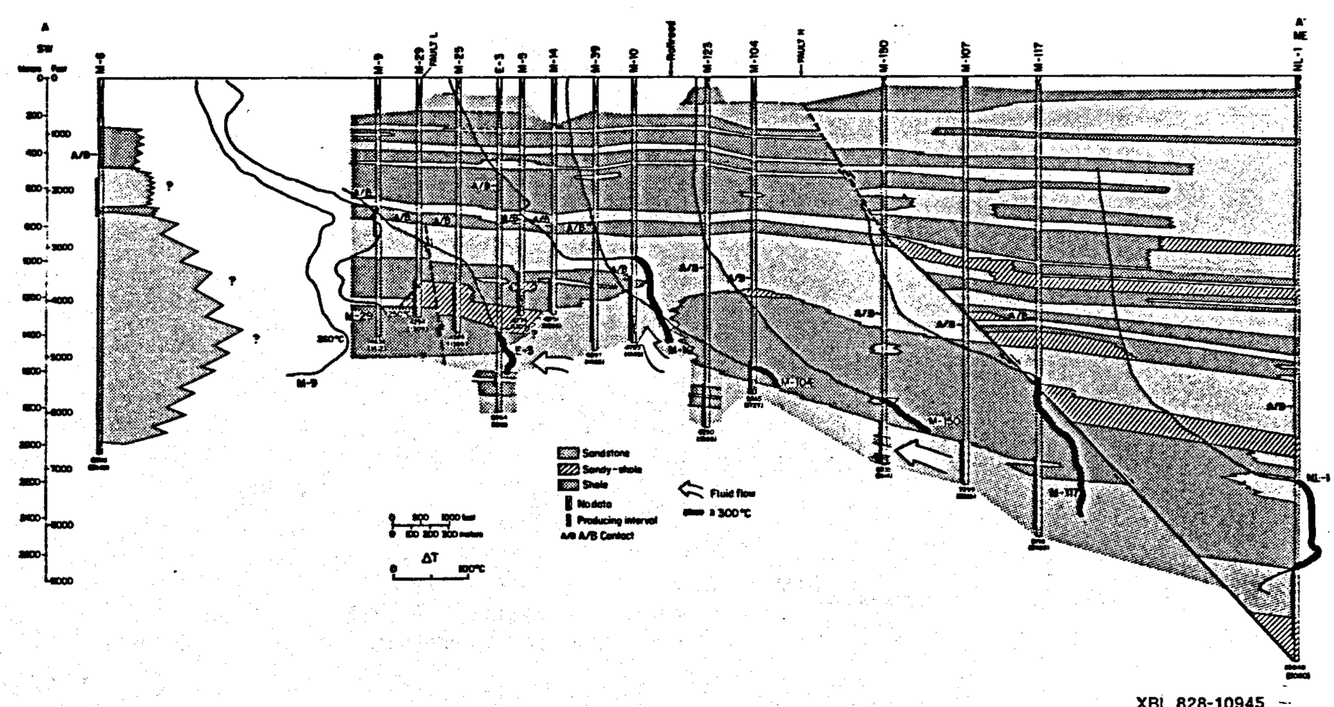

Figure 7. Southwest-northeast cross section of the Cerro Prieto field showing schematically the flow of geothermal fluids in the system (from Halfman et al., 1982a).

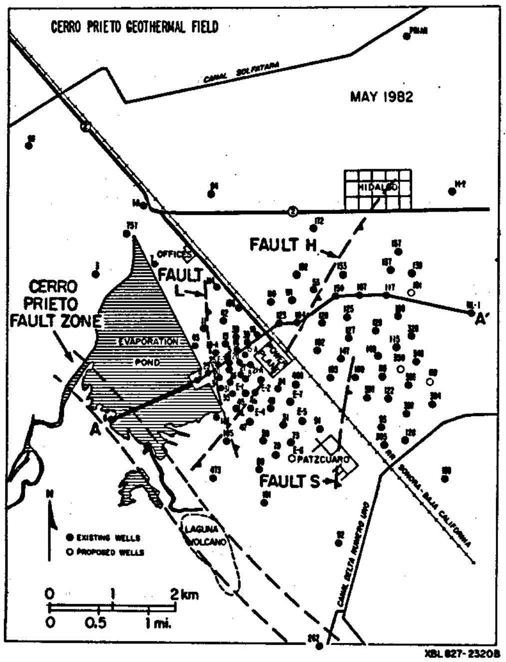

Figure 8. Location of the main faults controlling the subsurface flow of geothermal fluids in the Cerro Prieto field (from Halfman et al., 1982a). Also shown is the position of cross-section A-A' given in Figure 7.

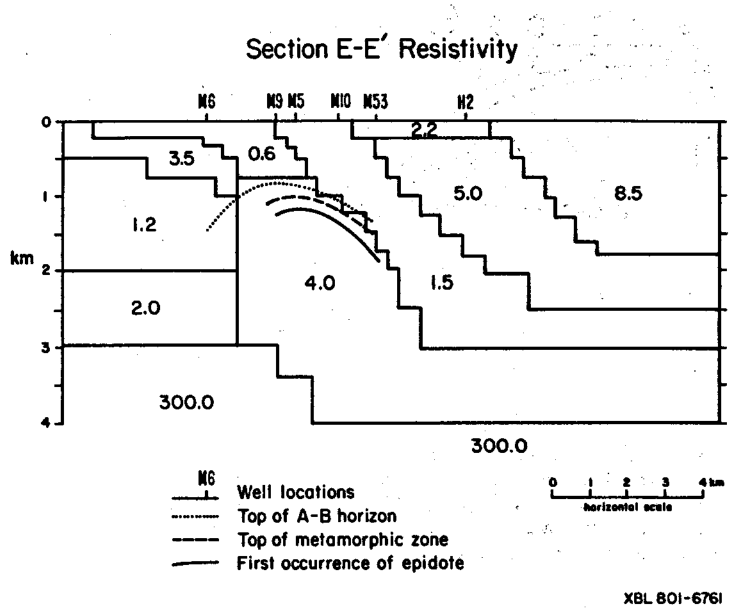

Figure 9. Two-dimensional resistivity model for a southwest-northeast line crossing the Cerro Prieto field (Line E-E'; Wilt and Goldstein, 1979). Shown are also the position of the A/B contact, the top of the metamorphic zone, and the first occurrence of the mineral epidote.

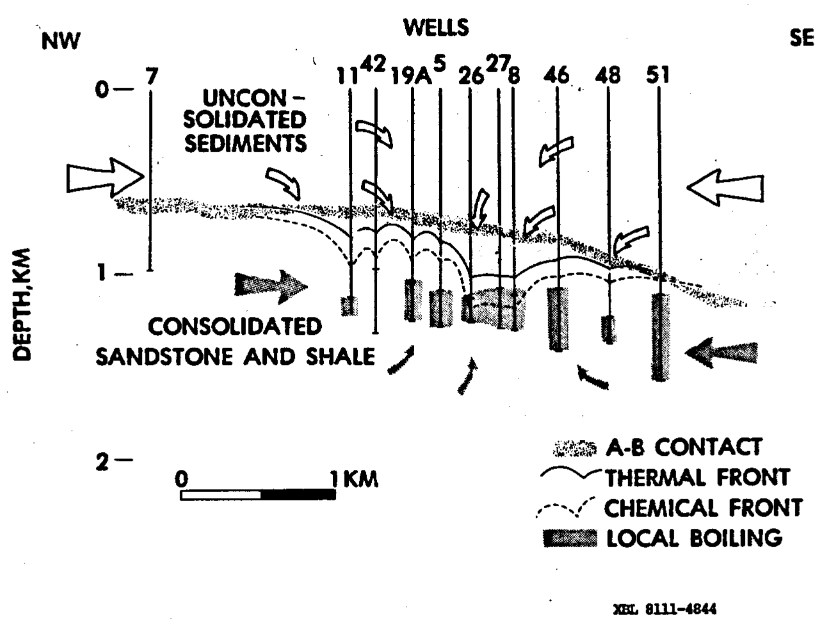

Figure 10. Schematic section across the western part of the Cerro Prieto field, showing movement of hot water (gray arrows) and cold water (white arrows) toward the producing wells, the chemical and thermal fronts, and zones of near-well boiling (from Grant et al., 1981).