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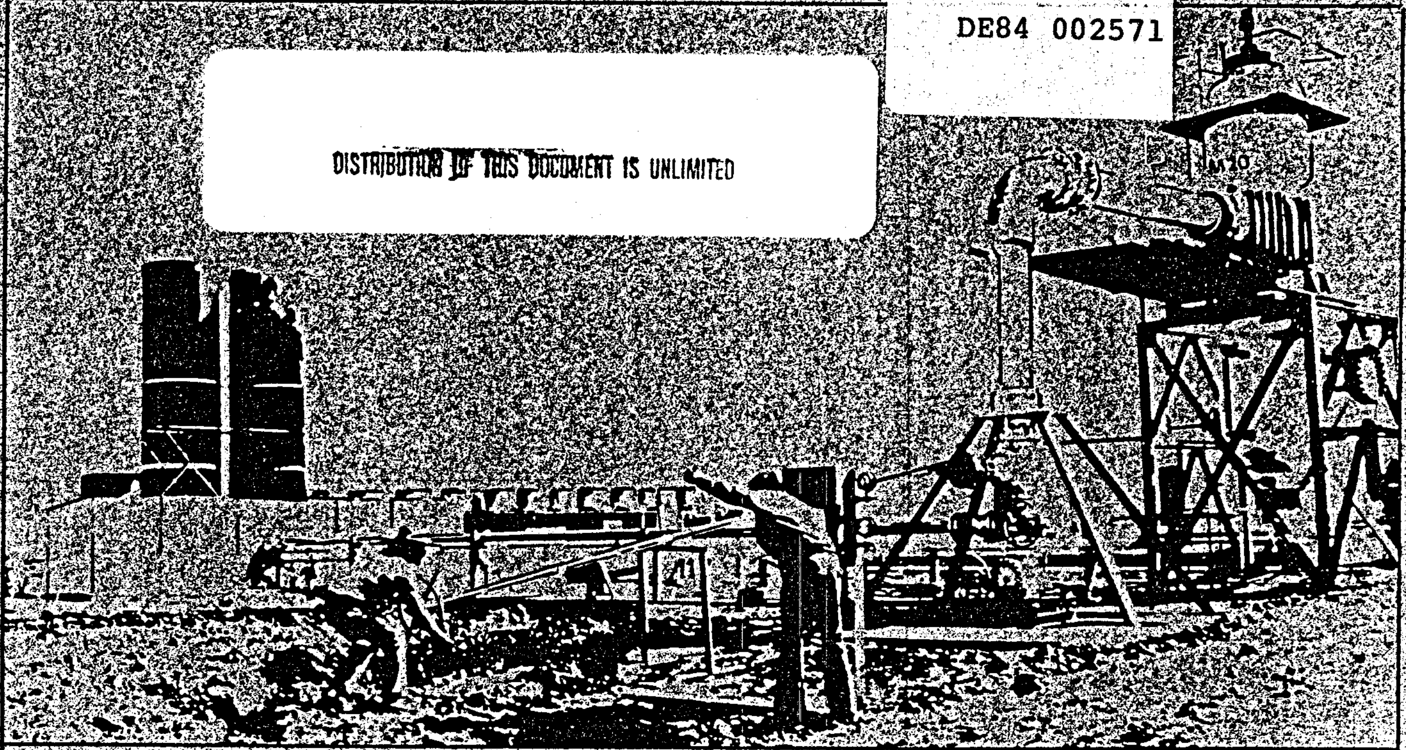

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ABSTRACT

A multidisciplinary effort to locate, delineate, and characterize the geothermal system at Cerro Prieto, Baja California, Mexico, began about 25 years ago. It led to the identification of an important high-temperature, liquid-dominated geothermal system which went into production in 1973. Initially, the effort was undertaken principally by the Mexican electric power agency, the Comisión Federal de Electricidad (CFE). Starting in 1977 a group of U.S. organizations sponsored by the U.S. Department of Energy, joined CFE in this endeavor.

An evaluation of the different studies carried out at Cerro Prieto has shown that: 1) surface electrical resistivity and seismic reflection surveys are useful in defining targets for exploratory drilling, 2) the mineralogical studies of cores and cuttings and the analysis of well logs are important in designing the completion of wells, identifying geological controls on fluid movement, determining thermal effects and inferring the thermal history of the field, 3) geochemical surveys help to define zones of recharge and paths of fluid migration, and 4) reservoir engineering studies are necessary in establishing the characteristics of the reservoir and in predicting its response to fluid production.

INTRODUCTION

The Cerro Prieto geothermal field is located in the Mexicali Valley, Baja California, Mexico, about 30 km south of the U.S. border (Fig. 1). It has been in production since 1973, when it became the first liquid-dominated geothermal system in North America from which significant electrical power was produced.

The general geologic similarity between Cerro Prieto and the geothermal fields of the neighboring Imperial Valley (southern California), and the experience gained by the Comisión Federal de Electricidad of Mexico (CFE) in locating and developing the resource were the main factors that led to the signing, in 1977, of a five-year agreement 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.[1] The Lawrence Berkeley Laboratory (LBL) coordinated U.S. technical activities carried out under the agreement. Because of the success of this cooperative program, discussions are being held to sign a new DOE/CFE agreement to study Cerro Prieto and other geothermal areas in Mexico.

Exploration for geothermal energy in the Cerro Prieto area began in the late 1950's, and the first deep exploration wells were drilled in 1960/61 over the thermal anomaly. By early 1983, about 120 deep wells (up to 3550 m in depth) had been drilled, delineating a good portion of the geothermal reservoir (Fig. 2). Presently, 180 MW of electricity are being generated; CFE, which manages and operates Cerro Prieto, is building two new power plants that will increase the output to 620 MWe by mid 1985.

Over the years, a vast amount of data on the subsurface of the area and on the characteristics of the producing wells have been gathered making Cerro Prieto one of the more thoroughly documented and best understood geothermal systems. The purpose of this paper is to review the exploration effort which led first to the discovery of the field, then to the delineation of the resource, and finally to the definition of the subsurface fluid and heat circulation. Other studies carried out on Cerro Prieto are summarized elsewhere.[2]

GEOLOGIC SETTING OF THE AREA

Cerro Prieto is situated in the southern portion of the Salton Trough, which is an actively developing structural depression filled with sediments. It is the landward continuation of the Gulf of California (Fig. 1) and a region of high seismicity and high heat flow. The Salton Trough-Gulf of California is the result of tectonic activity that has created a series of spreading centers and transform faults which link the East Pacific Rise, an oceanic ridge, with the San Andreas fault system, a transform boundary (Fig. 3).[3,4]

References and illustrations at end of paper.

The Cerro Prieto area is on a spreading center where the crust is being pulled open by right-lateral strike-slip movement. Under such tectonic stresses an extensional sedimentary basin (pull-apart basin)[5,6] would begin to form as the lithosphere thins and begins to subside. Where thinning of the crust and basin development is rapid, there will occur an upwelling of magma from the asthenosphere creating a new oceanic-type crust.[5] The rifting and intrusion generate high heat flows and induce metamorphism of the sedimentary rocks at relatively shallow depths, consolidating the section into new crust.[7]

The Cerro Prieto field is located in a tensional area developed at the end of the right-stepping en echelon strike-slip Cerro Prieto and Imperial faults (Fig. 4).[3,4] The tensional forces produce crustal spreading and thinning; Savino et al.[8] indicate that the crust at Cerro Prieto is about 13.5 km thick, compared to more than 30 km at the margins of the Salton Trough.

An area of seismicity connects the Cerro Prieto and Imperial faults (Fig. 5), corresponding possibly to a zone where magma is intruding to form a complex of dikes and sills[9,10] as described by Hill.[11] Some of these dikes, of basaltic-diabasic composition, have been found in wells drilled in the eastern part of Cerro Prieto.[12,13]

Granodioritic and metamorphic rocks outcrop on the western edge of the Mexicali Valley forming the Sierra de Cucapá. These basement rocks have been intersected in three wells drilled on the western margin of the Cerro Prieto field (M-96, M-3, S-262; Fig. 2). Elsewhere in the field, the wells penetrate alluvial, deltaic, estuarine and shallow marine deposits without reaching the base of the sedimentary column. Seismic studies indicate that at the U.S.-Mexican border near the center of the trough, the basement, possibly consisting of metasediments, is at 4.8 km depth, and that below it, at 10 km depth, there is a subbasement composed possibly of intrusive rocks of basaltic composition.[7]

RECENT GEOLOGIC HISTORY OF THE AREA

About 15 million years before present (Ma b.p.), during the Miocene, extensional tectonism resulted in the formation of a "proto-Gulf of California" which was the first major invasion of marine water preceding the formation of the Gulf proper. The present configuration of the Gulf began to develop by major crustal extension about 5 Ma b.p., during the early Pliocene, when the transform fault along the oceanward side of Baja California "moved" inland, splitting Baja California from the Mexican mainland. Extension has continued at short spreading centers within deep basins separated by long transform faults.[14]

Ingle[15] indicates that Colorado River deltaic sediments, which form the bulk of the Cerro Prieto section, began depositing into the northernmost reaches of the Gulf of California as early as the late Miocene or early Pliocene (7 to 5 Ma b.p.). The progradation of the delta into the Cerro Prieto area began in mid-to-late Pliocene (3 to 2 Ma b.p.). By late Pliocene, the southwesterly advance of the delta was essentially complete, resulting in the conversion of the Salton basin into a nonmarine depositional basin with delta plain sedimentation in the Cerro Prieto area.[16] By mid-Pleistocene time, the marine connection between the Gulf of California to the south, and the Imperial Valley to the north, was severed.[15]

On the basis of geological and geophysical data, Lyons and van de Kamp[16] concluded that during the late Pleistocene (about 0.11 Ma b.p.) a new faulting episode began at Cerro Prieto, which seems to have been synchronous with the induration of sediments by hydrothermal alteration and the onset of volcanism at the Cerro Prieto volcano, northwest of the field. Since that time, there have been at least five eruptive phases of that volcanic complex.[17] Contemporaneously, repeated faulting and the emplacement of a plexus of dikes and sills into the sediments occurred which resulted in fracturing and sealing of fractures by hydrothermal alteration, and development of secondary porosity in altered sandstones. The age of the dikes encountered in some of the wells has not been determined, but the present-day seismic activity might be related to continued crustal extension and magma movement. Another indication of recent magmatic-hydrothermal activity are the phreatic explosions (?) in the area of Laguna Volcano described by newspaper accounts (the latest possibly on January 1, 1927).[18]

EARLY EXPLORATION AND FIELD DEVELOPMENT ACTIVITIES (1959-1975)

In 1959, studies of aerial photographs were followed up by field geologic surveys in the Mexicali Valley to determine the geothermal energy potential of the area.[19,20] The studies were concentrated near the Cerro Prieto volcano, a Quaternary rhyodacitic complex rising about 210 m above the valley floor, and at the nearby Laguna Volcano, consisting of low hills built up by continued hot springs and phreatic activity surrounded now by conspicuous geothermal surface manifestations (i.e., hot springs, fumaroles, and mud volcanoes) (Fig. 6). Between 1959 and 1961, three exploration wells (up to 755 m deep) were drilled east of the Cerro Prieto volcano. One well (M-1A, Fig. 2) produced geothermal fluids but of low enthalpy.[21]

Basement configuration and fault patterns were determined initially from early seismic refraction and gravity studies. A block-faulted basement, with blocks generally becoming deeper toward the east and major faults striking northwest-southeast, was indicated by early seismic refraction and gravimetric surveys.[22,23] On the basis of subsurface data, four deep exploration wells were drilled in 1964. Well M-3 encountered relatively hot (~270°C) fluids between 650 and 900 m depth; it reached granodioritic basement at 2532 m. Well M-5, the discovery well for the field, produced fluids hotter than 300°C from about 1100 and 1300 m depth.[21] In 1965, 50 shallow temperature gradient wells (about 50 m deep) were drilled.[19] This study was later extended when 11 additional wells, up to 102 m deep, were completed.[24] The distribution of maximum temperatures measured in these wells is shown in Figure 7. The "hottest" areas correspond to places with abundant surface manifestations (see Fig. 6), and not to the geothermal reservoir at depth; the trend of the isotherms reflects the faults controlling the leakage of geothermal fluids to the surface.

Based on the temperature contours given in Figure 7 and assuming an average 75-m depth to the isotherms, an average annual surface temperature of 24.5°C[25], and a thermal rock conductivity of 3×10^{-3} cal/cm^{2}sec°C, it was calculated that the conductive heat losses to the surface amount to about 45 MW over the 61.5 km^2 area encompassing temperatures 25°C or higher.

In 1966, a geochemical study of the hot springs and fumaroles was completed. Mercado[26] found that the temperatures of the manifestations correlated with the Na/K and Cl/SO_4 ratios in the hot-springs. He estimated that the total flow of the surface manifestations was about 5×10^6 m^3/yr and their heat output to be about 40 MW. Based on results of this work and on geological and geochemical data from the few deep wells drilled in the area, Mercado[26,27] developed a model of the field showing the circulation of fluids in the subsurface. The model indicated the entrance of cold water from the northeast and the southwest. These waters are heated in the eastern part of the field by a deep heat source, and move westward toward the area of well M-6. There, the fluids leak to the surface via a fault zone (Fig. 8). The general fluid circulation pattern and temperature distribution in the field given by Mercado's model, based mainly on measured values and Na/K ratios in the fluids, have been confirmed by later studies, especially in the western part of the field.

Between 1966 and 1968, 15 development wells were completed in the area west of the railroad tracks. After successfully testing the wells, CFE ordered the first two 37.5 MW turbo-generators which went on line in 1973[28], and continued exploration activities to ascertain the dimensions and other parameters of the resource.

A number of strike-slip and normal faults were located by a regional aeromagnetic survey carried out in 1971.[29] Between 1972 and 1975 detailed electrical resistivity surveys of the area showed that the field was associated with a large NW-SE elongated resistivity low.[30] Because of the low power of the equipment used to emplace current, and the high conductivity of the surface materials it was not possible to achieve sufficient depth of exploration to determine the true dimensions of the field. These surveys also indicated a number of faults including a major normal fault, downthrown to the NE, parallel and near the railroad tracks, (later called Michoacán Fault; Fig. 9).

The depth and the production intervals of the first wells drilled at Cerro Prieto were based mainly on temperature logs, geophysical well logs and well cuttings. In some instances, wells perforated at various depths resulted in the scaling of the production casing because of chemical reactions between the different waters entering the well bore. In other cases, the hottest zones indicated by the temperature logs produced little fluid. From these experiences, CFE placed greater importance on lost circulation zones, temperature of the returning drilling mud and the percentage of sandstone in the cuttings for selecting production intervals.[31]

Fourteen new wells were drilled at Cerro Prieto between 1972 and 1974. The purpose of exploration well M-53 (Fig. 2), located about 1.5 km northeast of the production area at that time, was to study the eastern region. A hot (340°C) reservoir was reached at about 1900 m depth (about 600 m deeper than in the western area). This seemed to confirm the existence of the major normal fault parallel to the railroad.

A geologic model of the field developed by CFE mainly on the basis of well-cutting lithologies and surface geophysical data, showed a complex horst-and-graben basement structure and faulting of the sedimentary fill (Fig. 10).[32] In preparing this model, the A/B contact between unconsolidated (Unit A) and the underlying consolidated (Unit B) sediments was used as a stratigraphic marker horizon. Later, it was found that this contact was the result of postdepositional alteration. This finding has led to the reinterpretation of the geology of the area.

RECENT EXPLORATION AND RESERVOIR DEFINITION STUDIES

After 1975, with the expansion of power production in mind, CFE increased its exploration effort at Cerro Prieto. In 1977 the DOE-sponsored groups began studying the field. A discussion of these recent studies, and an evaluation of their impact on the exploration and development of Cerro Prieto follow.

Geochemistry

Geochemical studies have played an important role in the exploration and development of Cerro Prieto. The data and interpretations have been reviewed by Truesdell et al.[33] Some of the results are summarized below.

Isotopic studies indicated local recharge from the area immediately to the west of the field, leakage of shallower waters into the reservoir, and a suggested age for the fluids between 50 and 10,000 years.[34] On the basis of computed deuterium and chloride concentrations in the reservoir brines and Cl/Br ratios it was concluded that the geothermal fluids at Cerro Prieto are a mixture of Colorado River water and a saline brine of marine origin.[35] 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.[36]

Geology and Geophysics

Passive seismic studies, which began in 1974, indicated NW-SE striking right-lateral, strike-slip faults of the Cerro Prieto-Imperial transform fault system, and dip-slip faulting along some of the NE-SW striking Volcano system (Fig. 9).[9]

Self-potential surveys conducted in 1977 and 1978 defined a dipolar voltage anomaly whose axis runs through the center of the production field (Fig. 11). The source of the electrical anomaly may correspond to a north-trending fault, along which moving fluid produces a streaming potential.[37] The existence of this upflow zone has been indicated by various authors.[12,26,27,38]

Starting in 1977, CFE began a renewed program of geophysical investigations consisting of deeper Schlumberger resistivity soundings, gravity, magnetic and reflection seismic studies to define the extent of the field.[39,40,41] These studies showed that the Cerro Prieto field is not associated with either gravity or magnetic anomalies (Figs. 12 and 13). However, it is now agreed that large-scale gravity and magnetic effects can be interpreted in terms of the spreading center concept, including contributions from igneous intrusion, basement structure and hydrothermal metamorphism. The gravity highs observed over a portion of the field were originally interpreted as reflecting a basement horst.[39,40] However, later it was shown that the gravity anomalies could be explained by a combination of hydrothermal metamorphism of the sediments[42,43], and local basement highs found from drilling. Lyons and van de Kamp[16] reviewed the seismic and other data and did not find any convincing geophysical evidence for a major Cerro Prieto horst. They did find, however, that the gravity high could be reasonably explained by hydrothermal densification of the shale units below the A/B contact.

The hydrothermal alteration of Cerro Prieto sediments was first reported by Reed[44], and a systematic mineralogic study of well cuttings and cores began in 1977 which led to the recognition and description of hydrothermal mineral zonation around the reservoir.[12,45] At the top of the reservoir detrital or authigenic clay minerals, like montmorillonite and kaolinite, are progressively replaced by pore-filling chloride, illite, and calcite. This sealing process causes the sediments to be highly indurated at the top of the reservoir. In the main production zone, above 225°C, there is a zone of progressive decarbonation and calcium aluminum silicates are formed. At the highest temperatures so far measured, hydrothermal biotite and vermiculite form. This zonation (Fig. 14) could be correlated to present-day formation temperatures and chemistries of both brines and recharge waters. This work led CFE to include results from their well cutting analyses in designing well completions.[31] The presence of carbonate or silica cement, and the appearance of key minerals like epidote ($T > 230$-$250°C$) are now carefully studied and recorded.[46]

The mineralogic studies by Elders et al.[45] and the analysis of geophysical well logs[16,38] indicated that the A/B contact which has a dome-like configuration similar to the temperature distribution in the field (Figs. 15 and 16), is an induration boundary that cross-cuts sedimentary layers, confirming that postdepositional alteration is the cause of this boundary.

Resistivity, density and sonic velocity logs in the altered zone indicate a sudden reduction in shale porosity and an increase in density at the top of the altered zone. On the other hand, some sandstone units increase in porosity below the A/B contact, implying secondary porosity development due to chemical dissolution of unstable grains and cement.[16] These alteration effects were confirmed by Vonder Haar and Howard[6] who studied porosity variation by means of scanning electron microphotographs of well cuttings and cores.

The induration of the shales also resulted in a decrease in drilling rate.[47] Generally in Cerro Prieto wells the production intervals straddle or underlie the top of the high-resistivity, high density shales. Sandstones in the altered zone commonly have fair to good porosities (15% to 35% or higher). Fractures often appear to be sealed by hydrothermal mineralization. According to Lyons and van de Kamp[16] secondary matrix permeability in the Cerro Prieto reservoirs is more important volumetrically than fracture permeability. (Well tests performed at Cerro Prieto indicate that the reservoir permeability is in the order of tens of millidarcies).

The hydrothermal alteration dome was also detected by means of surface electrical measurements. The dipole-dipole dc resistivity method with 1-km-electrode separations was used along two NE-SW lines; one directly over the reservoir and a subparallel line several kilometers to the north near the Cerro Prieto volcano. Careful data collection and interpretation for the line E-E' over the production zone in 1978 revealed, to everyone's initial surprise, that the production intervals correlated with a more resistive zone (4 ohm-m) than the surrounding rock (1 to 2 ohm-m).

The dipole-dipole survey was repeated in 1979 using better instruments and improved survey techniques to reduce statistical errors in the field measurements. This work resulted in a more reliable subsurface resistivity model for the eastern part of the field.[43] The model (Fig. 17) revealed that the 4 ohm-m body associated with the producing zone dips eastward at 30 to 50° to a depth greater than 2 km. The narrow, steeply dipping 1.5 ohm-m zone immediately to the east was interpreted as a possible fault zone and conduit for ascending hot waters. The conductive production intervals within the 4 ohm-m dome are undetectable by means of the dc resistivity method for various reasons of geometry and physical parameters involved.

Over a period of three years starting in 1978, a number of magnetotelluric (MT) stations were occupied 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. Later MT studies were conducted to help delineate a possible boundary on the south side of the thermal area.[48,49]

Another important contribution of Lyons and van de Kamp's study[16] was their start on a detailed geologic model of the field using available well sample descriptions and regional geology integrated with geophysical well logs and surface geophysical data. These authors proposed a lithofacies and depositional model for the region that showed a transition from a deltaic environment in the east, to a marine environment in the west. They found evidence for three groups of faults of different ages based on well logs, air photo lineaments and surface geophysical data (seismic, gravity and magnetic). They also showed that the reservoir is not overlain by a continuous low-permeability layer, but that colder and less saline ground water were entering the reservoir from above, a process also indicated by the geochemical studies.[50] Their analysis of available geophysical data indicated that there seemed to be a general deepening of the basement in a SE direction across the field and no evidence for the much debated underlying basement horst. Lyons and van de Kamp did note a zone of chaotic reflections coincident with the hydrothermal alteration zone, suggesting that the seismic reflection method may be a good technique for detecting altered rock. However, other geophysical data are necessary to eliminate other sources of reflection-poor zones.

A broad magnetic high and a general gravity low about 5 km east of the power plant are shown in Figures 12 and 13. These anomalies were interpreted as indicating the presence of volcanics and/or dikes and sills within the basin fill.[16] This interpretation was confirmed by the intersections of mafic and minor rhyodacitic dikes at depths between 2500 and 3540 m depth in wells drilled in the eastern part of the field (e.g. H-2, NL-1, T-366, and M-189).

Recently, Goldstein et al.[13] analyzed this magnetic anomaly. 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, 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 9-10 km depth, as determined from seismic (earthquake) observations and a Curie isotherm analysis.

In a related study based on thermal modeling Elders et al.[12] fitted the present subsurface temperature distribution determined from deep wells to a single stage of magmatic intrusion in the form of a funnel-shaped gabbroic body whose top is some 4 km across and at a depth of 5 km. The model age for such an event is 40,000 to 50,000 years, which is in the range of the age for the volcanic activity at Cerro Prieto.[17] The depth of the thermal model body is deeper than the main intrusive body inferred by Goldstein et al.[13] from magnetic data, but the thermal model assumes a two-dimensional source and a single phase of magma emplacement. These assumptions greatly affect the size, depth, and age of the model heat source.

As part of an aggressive drilling program, started in 1977, to establish new production and define the extent of the geothermal field, an exploratory well (E-1), drilled in the western part of the field discovered in 1980 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 at about 1000-1400 m depth and has a present average temperature of about 285°C. A number of additional wells (e.g. E-series, Fig. 2) have tapped this hot aquifer.

On the basis of geophysical and lithological well logs, the geologic model of Lyons and van de Kamp[16] has been recently extended and improved by Halfman et al.[38] The newer model shows an interconnection between the reservoir in the eastern part of the system (also called B or β) and both reservoirs in the west, and confirmed the lack of a laterally continuous cap rock over the field.

By superimposing, downhole temperature, and well completion data on the geologic model, Halfman et al.[38] were able to determine the natural movement of geothermal fluids in the region prior to exploitation (Figs. 18 and 19). In general, the fluid circulation system discerned agrees with that of earlier models developed mainly from geochemical and mineralogical data.[12,26,27] Halfman's model, based on detailed analyses of structure and stratigraphy showed that the hot fluids enter the system from the southeast, from the area where igneous dikes have intruded into the sedimentary fill of the valley. Then, moving westward through permeable layers, and upwards through faults and sandy gaps in the shaly layers, the hot fluids gradually reach shallow depths. Eventually, in the western margin of the field, part of the geothermal fluids leak to the surface and the rest mix with local colder groundwaters.

This model seems to indicate that the Michoacán fault (Fig. 9), parallel to the railroad track, does not exist in the area of the field 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 Figs. 18 and 19) which seem to control the movement of geothermal fluids in the subsurface. Reflection seismic data, the location of boiling zones in the field, and the results of numerical studies provide independent confirmation on the existence of these faults.[51,52,53]

Reservoir Engineering

Since the mid 1970's, a number of two-rate flow and interference well tests have been carried out. The reported permeability-thickness products obtained from these tests vary between 3.6 and 40 darcy-meters. Moreover, the data of one of the tests clearly indicated communication between the α and β reservoirs.[54]

Reservoir modeling studies confirmed the open-nature of the Cerro Prieto field.[53,55,56] It was shown that in its natural state the field is recharged from the east by hot (about 355°C) deep water and from both the east and west by colder (between 50° and 150°C) waters from shallower aquifers. 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 (Fig. 19). 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.[53]

Since 1979-1980 CFE's exploration activity at Cerro Prieto was confined mainly to new development drilling to the east. These step-out wells will eventually help to establish the hydrogeologic boundaries of the field. CFE has also devoted considerable effort toward locating and evaluating other geothermal areas in the Mexicali Valley and neighboring areas.

RESERVOIR CHANGES DUE TO PRODUCTION

The Cerro Prieto field has been under large-scale production since 1973. The rate of fluid extraction has increased over the years as new generators were added to the power plant (i.e.: June 1975 (75 MWe): 2000 tonnes of steam-water mixture per hour; June 1982 (180 MWe): 4400 tonnes/h). As a result of this exploitation changes have occurred in the reservoir(s) which have been detected and monitored downhole, at the wellhead and over the field.

Geochemistry

The geochemical data indicating changes in the reservoir due to production have been discussed in detail by Truesdell et al.[33] A general decrease in reservoir temperature has been observed. According to Fausto et al.[57] the Na-K-Ca geothermometer indicates that between 1973 and 1978 the temperature in the α reservoir has dropped by up to 30°C.

Production-related drawdown caused the leaking of lower-chloride (colder) fluids into the reservoir and boiling, with excess steam reaching the producing wells.[50] No extended vapor zone has formed. Only local boiling occurs near most wells because ample recharge of colder waters from shallower aquifers and from the western margins of the field helps maintain pressure.[58]

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.[58] Other changes in the characteristics of the produced fluids and interference effects between wells have also been detected and are discussed elsewhere.[33]

A study of the composition of the gases produced from the wells seem to indicate that the boiling zone is not expanding.[52] On the other hand, Semprini and Kruger[59], show that based on the concentration of radon and ammonia in the produced fluids the two-phase zone is expanding in the northeastern part of the field and is decreasing in the southeast.

Reservoir Engineering

The pressure in the α reservoir decreased about 330 psi between June 1973 and December 1979.[60] Lately, a partial pressure recovery has been observed in this aquifer as fluid production has shifted increasingly to the deeper β reservoir.[61]

A study of the production characteristics of the Cerro Prieto wells over the 1973-1980 period indicated that production from 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.[62]

Geophysics

Repetitive high-precision, dipole-dipole resistivity measurements taken since 1979 along line E-E' showed a consistent pattern of apparent resistivity changes. A zone of increasing resistivity is related to the region of the α reservoir and presumed caused by decreasing temperature and salinity. Above and flanking this region, resistivities show a systematic decrease with time. These changes are more difficult to explain, but there seems to be a component related to ascending hot, more saline, fluids at the eastern edge of the producing zone.[63]

Detailed seismological studies conducted in the area showed 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. During a 1980 study the 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.[51]

Subsidence Monitoring

First-order leveling surveys performed between 1977 and 1979 indicated subsidence over the production area of the field. 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.[64] Between 1978 and 1981 inward ground-surface movement toward the production area was detected by resurveying horizontal control networks. This movement was considered to result from the exploitation of the field.[65]

Precision gravity surveys conducted over the field since 1978 seem also to indicate production-induced subsidence.[66,67] The interpretation of the data is complicated by the ground deformation resulting from the natural earthquake activity characteristic of the Salton Trough area.

The monitoring of the field will continue and will be further expanded into the eastern areas of Cerro Prieto; e.g. recently a new NW-SE dipole-dipole resistivity line crossing these areas has been established. This effort will allow to continue to study the response of the reservoir(s), especially as the extraction of fluids is significantly increased to supply steam to the new power plants due to come on line in the next few years.

CONCLUSIONS

The Cerro Prieto case study demonstrated the value of a multidisciplinary effort for exploring and developing a geothermal field.

There was no problem in recognizing the geothermal potential of the Cerro Prieto area because of the many obvious surface manifestations. However, the delineation of the geothermal reservoir at depth was not so straightforward. Wells drilled near the abundant surface manifestations only produced fluids of relatively low enthalpy. Later it was determined that these zones of high heat loss corresponded to discharge areas where faults and fractures allowed thermal fluids to leak to the surface, and not to the main geothermal reservoir.

The early gravity and seismic refraction surveys provided important information on the general structure of the area. Unaware of the existence of a higher density zone of hydrothermally altered sediments capping the geothermal reservoir, CFE interpreted a basement horst in the western part of the field and hypothesized that the bounding faults were controlling the upward flow of thermal fluids. Attempting to penetrate the sedimentary column to reach the "basement horst", CFE discovered the α geothermal reservoir (in well M-5). The continuation of the geothermal aquifer (actually the β reservoir) east of the original well field was later confirmed by a deep exploration well (M-53).

The experience of Cerro Prieto showed the importance of chemical ratios, and geothermometers in general, in establishing the subsurface temperatures and fluid flow patterns. Fluid chemical and isotopic compositions have also been helpful to determine the origin of the fluids, fluid-production mechanisms and production induced effects on the reservoir.

The mineralogic and petrographic studies of well cuttings and cores established the hydrothermal alteration of the sediments due to temperature-dependent rock-fluid interactions. The mineral zonation and isotopic ratios in the rocks helped to define the shape of the reservoir, the preproduction fluid flow patterns in the system, and its thermal history. The appearance of key hydrothermal minerals reflecting high subsurface temperatures was important in the design of well completions.

Interpretation of temperature, geophysical and lithological well logs allowed CFE to improve the completion of Cerro Prieto geothermal wells. The analyses of these logs were also very useful in the development of a hydrogeological model of the geothermal system. Well tests and reservoir modelling studies determined reservoir parameters, and helped to define the role of certain geologic features in the transport and recharge of heat and mass in the geothermal system.

Resistivity, gravity and magnetic field surveys were used extensively to help define anomalies in the region. Although these data permitted simple initial interpretations, it was generally found that these contained flaws. Experience at Cerro Prieto showed that the analyses of electrical resistivity (dipole-dipole and magnetotelluric) data were useful in defining the (resistivity) structure of the field and the location of faults and fronts of waters of different properties. These studies indicated that the reservoir region had higher resistivity than the surroundings because of the hydrothermal alteration of the shales in the reservoir area. The low resistivity zone associated with the field was shown to be due to highly conductive near-surface sediments, particularly in the discharge areas.

Self-potential surveys were useful for identifying a permeable zone allowing the upflow of geothermal fluids. Gravimetry seems better than magnetometry to define the zone of hydrothermal alteration/metamorphism associated with the geothermal field. No magnetite and only sparse pyrrhotite has been observed in cutting and cores, explaining the lack of a magnetic anomaly coincident with the reservoirs.

The occurrence of chaotic seismic reflections coincident with the hydrothermal alteration zone suggests that seismic reflection can be a useful exploration method. However, other geophysical data will be necessary to eliminate alternate sources of reflection-poor zones.

Summarizing, self-potential, dc resistivity and magnetotelluric surveys were useful for locating the reservoir regions, but the full significance of these data was not appreciated until they could be compared to seismic reflection, gravity and geophysical and geological well logging results. After the first wells had been completed, fluid geochemistry, mineralogy of cuttings and cores, geophysical well logs and reservoir engineering studies played important roles in understanding the nature of the geothermal system, such as origin of the geofluids, fluid circulation, dilution, and location of the heat source.

The usefulness of fluid geochemistry and reservoir engineering studies, as well as electrical resistivity, passive seismic, precision gravity and ground-surface deformation surveys, for monitoring the behavior of a geothermal field under production has been proven at Cerro Prieto.

ACKNOWLEDGEMENTS

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REFERENCES

1. Witherspoon, P.A., Alonso, H., Lippmann, M.J., Mañón, A., and Wollenberg, H.A.: "Mexican-American Cooperative Program at the Cerro Prieto Geothermal Field," Lawrence Berkeley Laboratory Report LBL-7095 (1978).

2. Lippmann, M.J.: "Overview of Cerro Prieto Studies," Geothermics (1983) 12, in press.

3. Lomnitz, C., Mooser, F., Allen, C.R., Brune, J.N., and Thatcher, W.: "Seismicity and Tectonics of the Northern Gulf of California Region, Mexico - Preliminary Results," Geofísica Internacional (1970) 10, 37-48.

4. Elders, W.A., Rex, R.W., Meidav, T., Robinson, P.T., and Biehler, S.: "Crustal Spreading in Southern California," Science (1972) 178, 15-24.

5. McKenzie, D.P.: "Some Remarks on the Development of Sedimentary Basins," Earth and Planetary Sc. Letters (1978) 40, 25-32.

6. Vonder Haar, S. and Howard, J.H.: "Intersecting Faults and Sandstone Stratigraphy at the Cerro Prieto Geothermal Field," Geothermics (1981) 10, 145-167.

7. Fuis, G.S., Mooney, W.D., Healey, J.H., McMechan, G.A., and Lutter, W.J.: "Crustal Structure of the Imperial Valley Region," U.S. Geol. Survey Prof. Paper (1982) 1254, 25-49.

8. Savino, J.M., Rodi, W.L., Goff, R.C., Jordan, T.H., Alexander, J.H., and Lambert, D.G.: "Inversion of Combined Geophysical Data for Determination of Structure Beneath the Imperial Valley Geothermal Region," U.S. Department of Energy Report SAN-1313-1 (September 1977).

9. Albores, A., Reyes, C.A., Brune, J.N., González, J., Garcilazo, L., and Suárez, F.: "Seismicity Studies in the Region of the Cerro Prieto Geothermal Field," Geothermics (1980) 9, 65-77.

10. Johnson, C.E. and Hutton, L.K.: "Aftershocks and Preearthquake Seismicity," U.S. Geol. Survey Prof. Paper (1982) 1254, 59-76.

11. Hill, D.P.: "A Model for Earthquake Swarms," J. Geoph. Res. (1977) 82, 1347-1352.

12. Elders, W.A., Bird, D.K., Williams, A.E., and Schiffman, P.: "Hydrothermal Flow Regime and Magmatic Heat Source of the Cerro Prieto Geothermal System, Baja California, Mexico," Geothermics (1984) 13, in press.

13. Goldstein, N.E., Wilt, M.J., and Corrigan, D.J.: "Analysis of the Nuevo León Magnetic Anomaly and its Possible Relation to the Cerro Prieto Magmatic-Hydrothermal System," Geothermics (1984) 13, in press.

14. Saunders, A.D., Fornari, D.J., and Morrison, M.A.: "The Composition and Emplacement of Basaltic Magmas Produced During the Development of Continental-Margin Basins: The Gulf of California, Mexico," J. Geol. Soc. London (1982) 139, 335-346.

15. Ingle, J.C.: "Microfaunal Evidence of Age and Depositional Environments of the Cerro Prieto Section (Plio-Pleistocene), Baja California, Mexico," Lawrence Berkeley Laboratory Report LBL-13897 (1980).

16. Lyons, D.J. and van de Kamp, P.C.: "Subsurface Geological and Geophysical Study of the Cerro Prieto Geothermal Field, Baja California, Mexico," Lawrence Berkeley Laboratory Report LBL-10540 (1980).

17. de Boer, J.: " Paleomagnetism of the Quaternary Cerro Prieto, Crater Elegante, and Salton Buttes Volcanic Domes in the Northern Part of the Gulf of California Rhombochasm," Proc. 2nd Symp. Cerro Prieto, Comisión Federal de Electricidad, Mexicali (1979), 91-98.

18. Bureau of Reclamation: "Record of Earthquakes in the Yuma Area. Yuma County, Arizona; Imperial County, California," U.S. Dept. Interior, Bureau of Reclamation, Special Report (July 1976).

19. Mañón, A., de la Peña, A., and Puente, I.: "El Campo Geotérmico de Cerro Prieto (Estudios Realizados y Programas Futuros)," Organ. Lat. Amer. de Energía (1978) Serie Docum. 2, 219-262.

20. Fonseca, H.L.: "The Cerro Prieto Geothermal Field. Geophysical Studies," Proc. 4th Symp. Cerro Prieto (1982), Comisión Federal de Electricidad, Mexicali, in press.

21. Alonso, H.: "La Zona Geotérmica de Cerro Prieto, Baja California," Bol. Soc. Geol. Mex. (1966) 29, 17-47.

22. GEOCA: "Levantamiento Sismológico de Refracción en la Zona Geotérmica de Cerro Prieto," Internal Report Comisión Federal de Electricidad, Mexicali (1962).

23. Velasco, J.: "Levantamiento Gravimétrico. Zona Geotérmica de Mexicali, Baja California," Internal Report Consejo Recursos Naturales No Renovables, Mexico City (1963).

24. Díaz, E.: "Pozos de Gradiente Cerro Prieto Oeste," Internal Report Comisión Federal de Electricidad, Mexicali (1978).

25. Vilchis, M.A., pers. comm. (1983).

26. Mercado, S.: "Localización de Zonas de Máxima Actividad Hidrotermal por Medio de Proporciones Químicas, Campo Geotérmico de Cerro Prieto, B.C.," paper presented at the III Cong. Mex. Quím. Pura y Aplicada, Guadalajara, Mexico, March 21-23, 1968.

27. Mercado, S.: "Movement of Geothermal Fluids and Temperature Distribution in the Cerro Prieto Geothermal Field, Baja California, Mexico," Proc. 2nd U.N. Symp. Devel. and Use Geoth. Resour., U.S. Printing Office, Wash., D.C. (1976), 487-492.

28. Alonso, H.: "The Cerro Prieto Geothermal Field - Present and Future," Geothermics (1979) 8, 151-153.

29. Evans, K.R.: "Aeromagnetic Study of the Mexicali-Cerro Prieto Geothermal Area," M.S. thesis, Univ. Arizona, Dept. Geosciences, Tucson (1972).

30. García, S.: "Geoelectric Study of the Cerro Prieto Geothermal Area, Baja California, Mexico," Proc. 2nd U.N. Symp. Devel. and Use Geoth. Resour., U.S. Printing Office, Wash., D.C. (1976), 1003-1011.

31. Domínguez, B.: "Well Completion and Development at Cerro Prieto," Geothermics (1980) 9, 101-131.

32. Puente, I. and de la Peña, A.: "Geology of the Cerro Prieto Geothermal Field," Geothermics (1979) 8, 155-175.

33. Truesdell, A.H., Nehring, N.L., Thompson, J.M., Janik, C.J., and Coplen, T.B.: "A Review of Progress in Understanding the Fluid Geochemistry of the Cerro Prieto Geothermal System," Geothermics (1984) 13, in press.

34. Truesdell, A.H., Rye, R.O., Pearson, F.J., Jr., Olson, E.R., Nehring, N.L., Whelan, J.F., Huebner, M.A., and Coplen, T.B.: "Preliminary Isotopic Studies of Fluids from the Cerro Prieto Geothermal Field," Geothermics (1979) 8, 223-229.

35. Truesdell, A.H., Thompson, J.M., Coplen, T.B., Nehring, N.L., and Janik, C.J.: "The Origin of the Cerro Prieto Geothermal Brine," Geothermics (1981) 10, 225-238.

36. Valètte, J.N. and Esquer-Patiño, I.: "Geochemistry of the Surface Emissions in the Cerro Prieto Geothermal Field," Proc. 2nd Symp. Cerro Prieto, Comisión Federal de Electricidad, Mexicali (1979), 241-250.

37. Fitterman, D.V. and Corwin, R.F.: "Inversion of Self-Potential Data from the Cerro Prieto Geothermal Field, Mexico," Geophysics (1982) 47, 938-945.

38. Halfman, S.E., Lippmann, M.J., Zelwer, R., and Howard, J.H.: "A Geological Interpretation of the Geothermal Fluid Movement in the Cerro Prieto Field, Baja California, Mexico," Amer. Assoc. Petrol. Geol. Bull. (1983) 67, in press.

39. Fonseca, H. and Razo, A.: "Gravity, Magnetics, and Seismic Reflection Studies at the Cerro Prieto Geothermal Field," Proc. 2nd Symp. Cerro Prieto, Comisión Federal de Electricidad, Mexicali (1979), 303-328.

40. Razo, A., Arellano, F., and Fonseca, H.: "CFE Resistivity Studies at Cerro Prieto," Geothermics (1980) 9, 7-14.

41. Fonseca, H., de la Peña, A., Puente, I., and Díaz, E.: "Extension of the Cerro Prieto Field, and Zones in the Mexicali Valley with Geothermal Possibilities in the Future," Proc. 3rd Symp. Cerro Prieto (1981), Lawrence Berkeley Laboratory Report LBL-11967, 384-421.

42. Grannell, R.B., Tarman, D.W., Clover, R.C., Leggewie, R.M., Goldstein, N.E., Chase, D.S., and Eppink, J.: "Precision Gravity Studies at Cerro Prieto," Geothermics (1980) 9, 89-99.

43. Wilt, M.J. and Goldstein, N.E.: "Resistivity Monitoring at Cerro Prieto," Geothermics (1981) 10, 183-193.

44. Reed, M.J.: "Geology and Hydrothermal Metamorphism in the Cerro Prieto Geothermal Field, Mexico," Proc. 2nd U.N. Symp. Devel. and Use Geoth. Resour., U.S. Printing Office, Wash., D.C. (1976), 539-547.

45. Elders, W.A., Hoagland, J.R., McDowell, S.D., and Cobo, J.M.: "Hydrothermal Mineral Zones in the Geothermal Reservoir of Cerro Prieto," Geothermics (1979) 8, 201-209.

46. Cobo, J.M. and Bermejo, F.J.: "Analysis of the Exploration Wells in the Cerro Prieto Field and Mexicali Valley," Proc. 4th Symp. Cerro Prieto (1982), Comisión Federal de Electricidad, Mexicali, in press.

47. Prian, R.: "Drilling Rate for the Cerro Prieto Stratigraphic Sequence," Proc. 3rd Symp. Cerro Prieto (1981) Lawrence Berkeley Laboratory Report LBL-11967, 77-87.

48. Gamble, T.D., Goubau, W.M., Goldstein, N.E., Miracky, R., Stark, M., and Clarke, J.: "Magnetotelluric Studies at Cerro Prieto," Geothermics (1981) 10, 169-182.

49. Goubau, W.M., Goldstein, N.E., and Clarke, J.: "Magnetotelluric Studies at the Cerro Prieto Geothermal Field," Proc. 3rd Symp. Cerro Prieto (1981), Lawrence Berkeley Laboratory Report LBL-11967, 357-367.

50. Truesdell, A.H., Mañón, A., Jiménez, M.E., Sánchez, A., and Fausto, J.J.: "Geochemical Evidence of Drawdown in the Cerro Prieto Geothermal Field," Geothermics (1979) 8, 257-265.

51. Majer, E.L. and McEvilly, T.V.: "Seismological Studies at the Cerro Prieto Field: 1978-1982," Proc. 4th Symp. Cerro Prieto (1982), Comisión Federal de Electricidad, Mexicali, in press.

52. Nehring, N.L. and D'Amore, F.: "Gas Chemistry and Thermometry of the Cerro Prieto, Mexico, Geothermal Field," Geothermics (1984) 13, in press.

53. Lippmann, M.J. and Bodvarsson, G.S.: "Numerical Studies of the Heat and Mass Transport in the Cerro Prieto Geothermal Field, Mexico," Water Resour. Res. (1983) 19, 753-767.

54. Schroeder, R.C., Goranson, C.B., Benson, S.M., and Lippmann, M.J.: "Well Interference Tests at the Cerro Prieto Geothermal Field," Geothermics (1980) 9, 179-187.

55. Westwood, J.D. and Castanier, L.M.: "Application of a Lumped Parameter Model to the Cerro Prieto Geothermal Field," Proc. 7th Workshop Geoth. Reserv. Engr., Stanford Geothermal Program Report SGP-TR-55 (1981), 23-28.

56. Grant, M.A. and O'Sullivan, M.J.: "The Old Field at Cerro Prieto Considered as a Leaky Aquifer," Proc. 4th Symp. Cerro Prieto (1982), Comisión Federal de Electricidad, Mexicali, in press.

57. Fausto, J.J., Jiménez, M.E., and Esquer, I.: "Current State of the Hydrothermal Geochemistry Studies at Cerro Prieto," Proc. 3rd Symp. Cerro Prieto (1981), Lawrence Berkeley Laboratory Report LBL-11967, 188-220.

58. Grant, M.A., Truesdell, A.H., and Mañón, A.: "Production Induced Boiling and Cold Water Entry in the Cerro Prieto Geothermal Reservoir Indicated by Chemical and Physical Measurements," Geothermics (1984) 13, in press.

59. Semprini, L. and Kruger, P.: "Relationship of Radon Concentration to Spatial and Temporal Variations of Reservoir Thermodynamic Conditions in the Cerro Prieto Geothermal Field," Geothermics (1984) 13, in press.

60. Bermejo, F.J., Navarro, F.X., Castillo, F., Esquer, C.A., and Cortez, C.: "Pressure Variations at the Cerro Prieto Reservoir During Production," Proc. 2nd Symp. Cerro Prieto, Comisión Federal de Electricidad, Mexicali (1979), 473-496.

61. Mañón, A., pers. comm. (1983).

62. Goyal, K.P., Miller, C.W., Lippmann, M.J., and Vonder Haar, S.P.: "Analysis of Cerro Prieto Production Data," Proc. 3rd Symp. Cerro Prieto (1981), Lawrence Berkeley Laboratory Report LBL-11967, 496-500.

63. Wilt, M.J. and Goldstein, N.E.: "Interpretation of Dipole-Dipole Resistivity Monitoring Data at Cerro Prieto," Geothermics (1984) 13, in press.

64. de la Peña, A.: "Results of the First Order Leveling Surveys in the Mexicali Valley and at the Cerro Prieto Field," Proc. 3rd Symp. Cerro Prieto (1981), Lawrence Berkeley Laboratory Report LBL-11967, 281-291.

65. Massey, B.L.: "Measured Ground-Surface Movements, Cerro Prieto Geothermal Field," Proc. 3rd Symp. Cerro Prieto (1981), Lawrence Berkeley Laboratory Report LBL-11967, 299-305.

66. Grannell, R.B., Wyman, R.M., Leggewie, R.M., and Randall, G.A.: "Subsidence Detection at the Cerro Prieto Geothermal Field by Precision Gravity Studies," Proc. 4th Symp. Cerro Prieto (1982), Comisión Federal de Electricidad, Mexicali, in press.

67. Grannell, R.B., pers. comm. (1983).

68. Mañón, A., Mazor, E., Jiménez, M., Sánchez, A., Fausto, J., and Zenizo, C.: "Extensive Geochemical Studies in the Geothermal Field of Cerro Prieto, Mexico," Lawrence Berkeley Laboratory Report LBL-7019 (1977).

69. Rivera, R., Bermejo, F., Castillo, F., Pérez, H., and Abraján, A.: "Update of Temperature Behavior and Distribution in Cerro Prieto II and III," Proc. 4th Symp. Cerro Prieto (1982), Comisión Federal de Electricidad, Mexicali, in press.

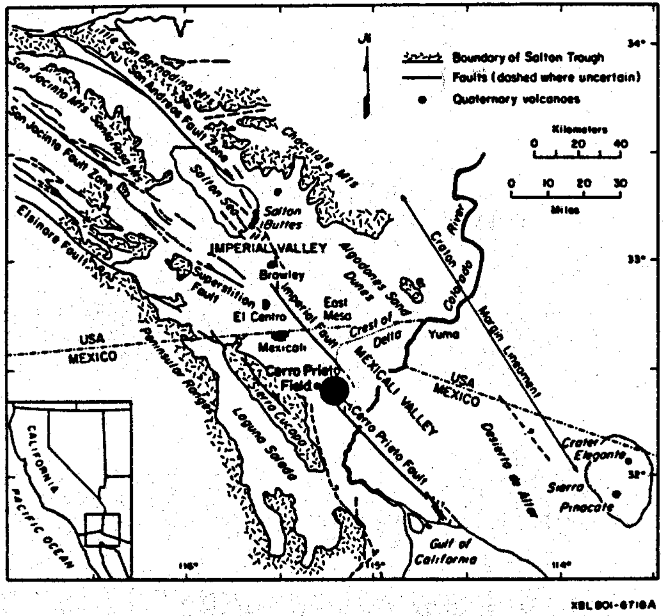


Fig. 1: Regional geology of the Salton Trough and location of the Cerro Prieto field.

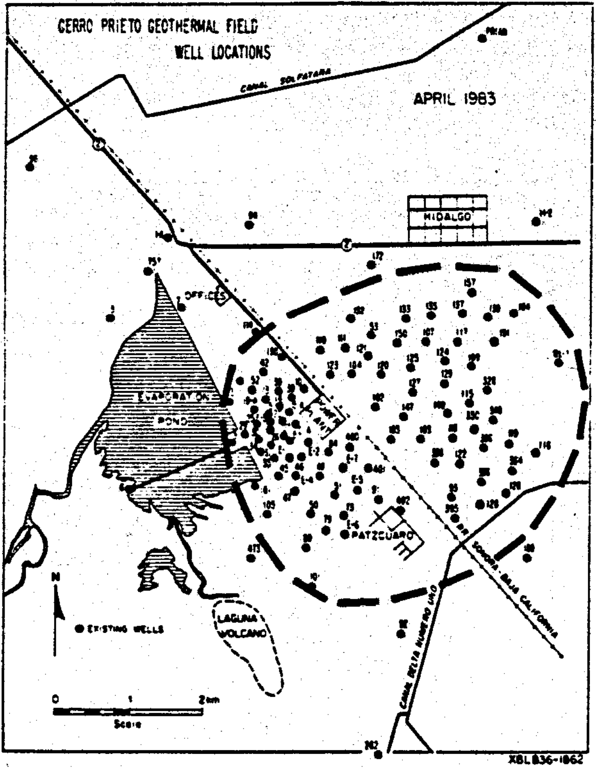


Fig. 2: Location of wells in the Cerro Prieto field; the dashed lines approximately outlines the geothermal anomaly.

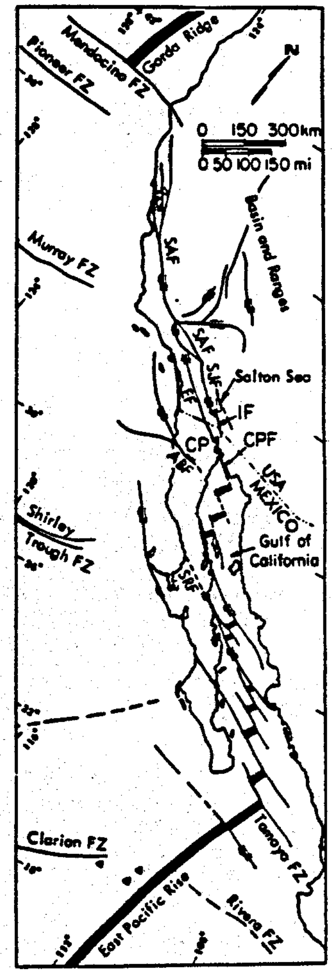


Fig. 3: Fractures and spreading centers along part of the Pacific Coast of North America. Oceanic fracture zones (FZ) and continental faults (F) are solid black lines. ABF, Agua Blanca Fault; CPF, Cerro Prieto Fault; EF, Elsinore Fault; IF, Imperial Fault; SAF, San Andreas Fault; SJF, San Jacinto Fault; SRF, Santa Rosa Fault. Postulated spreading centers in the Gulf of California are shown in black. Black triangles are Holocene or recent volcanoes: CP: Cerro Prieto (after Ref. 4).

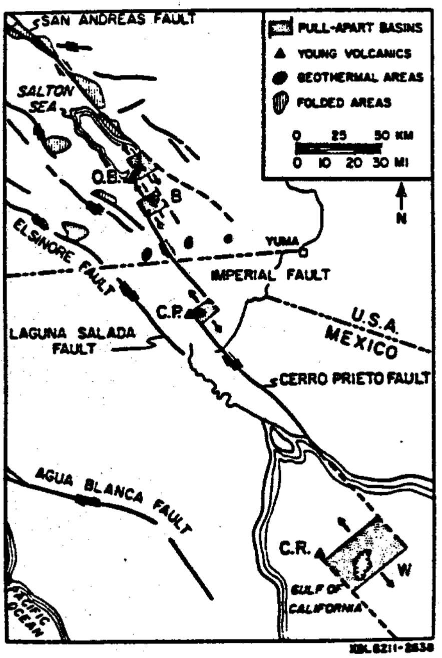
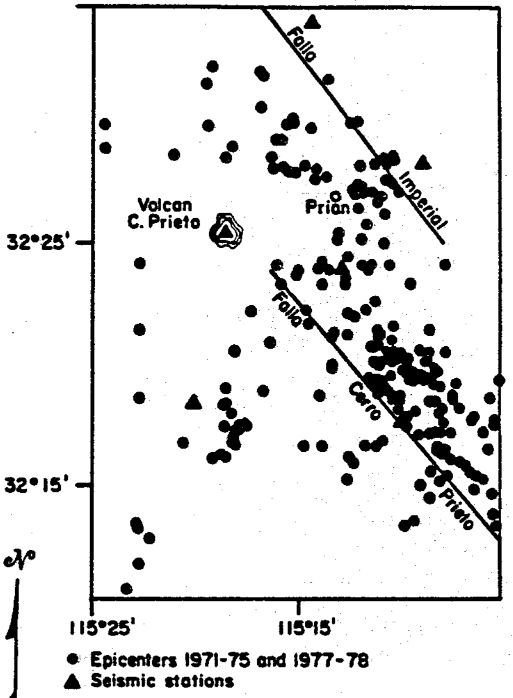


Fig. 4: Postulated system of transform faults and pull-apart basins in the Salton Trough area; O.B., Obsidian Butte; B, Brawley geothermal area; C.P., Cerro Prieto geothermal area; C.R., Consag Rock; W, Wagner Basin (after Refs. 3 and 4).



XBL 797-7516

Fig. 5: Seismicity of the Cerro Prieto area for 1971-75 and 1977-78 (after Ref. 9).

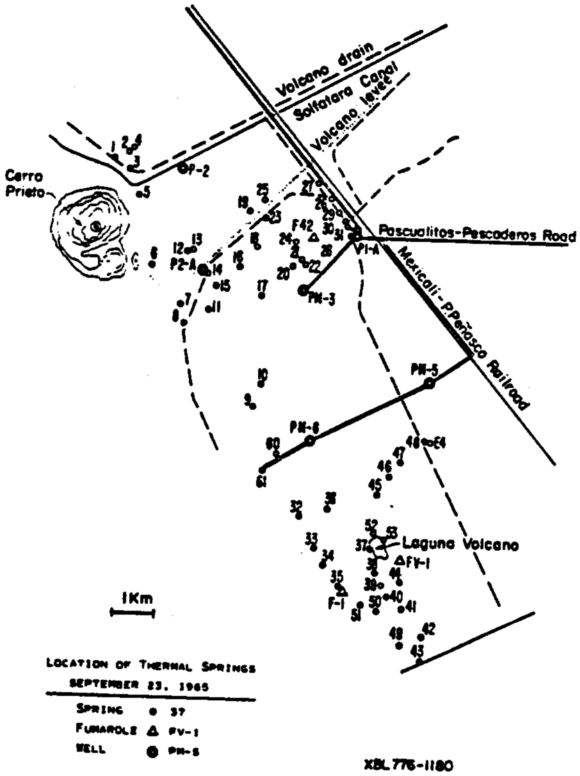


Fig. 6: Location of surface manifestations in the Cerro Prieto area (Ref. 68).

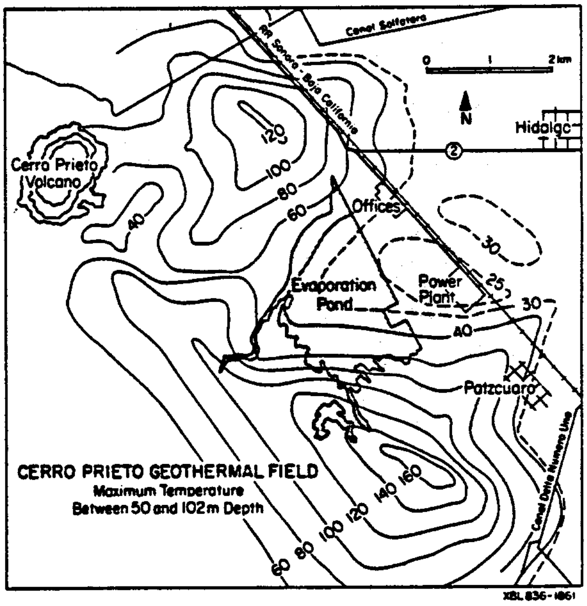


Fig. 7: Isotherm map for the Cerro Prieto area showing maximum temperatures measured between 50 and 102 m depth (after Ref. 24).

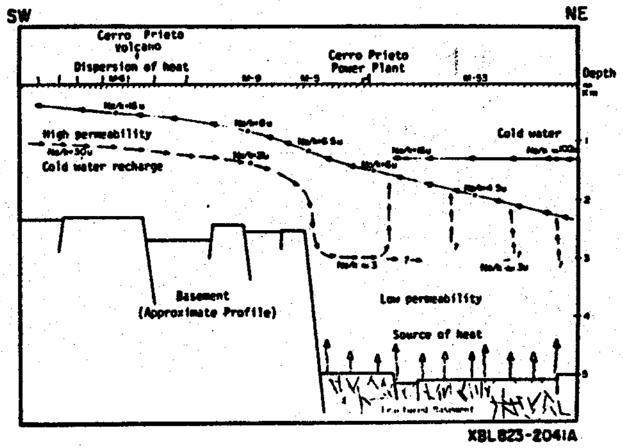


Fig. 8: Mercado's[27] convective model for the Cerro Prieto system.

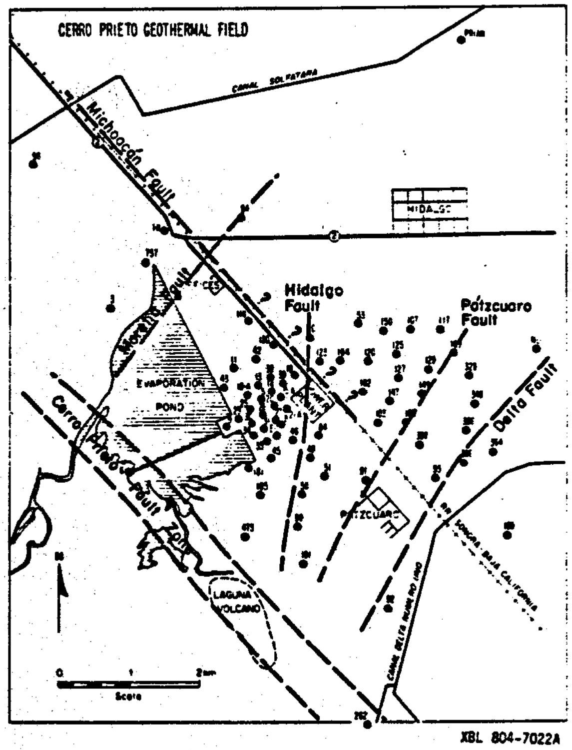


Fig. 9: Schematic fault map for the Cerro Prieto area developed in 1980.

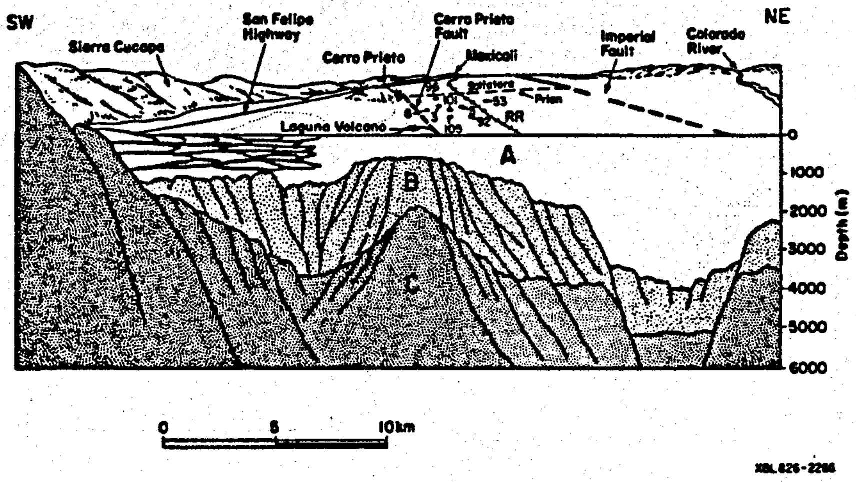


Fig. 10: Puente and de la Peña's[32] geologic model of Cerro Prieto.

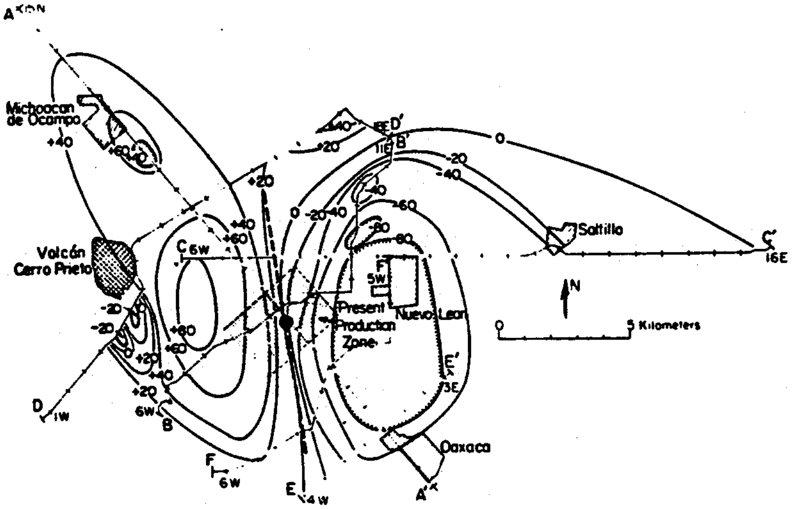


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Fig. 11: Self-potential anomaly over the Cerro Prieto field. The dashed line indicates best estimate of the source plane location (Ref. 37).

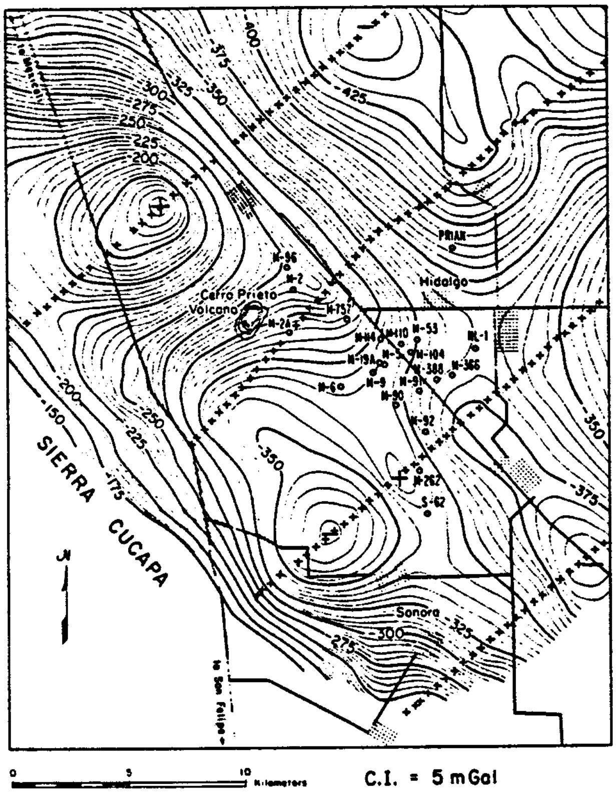

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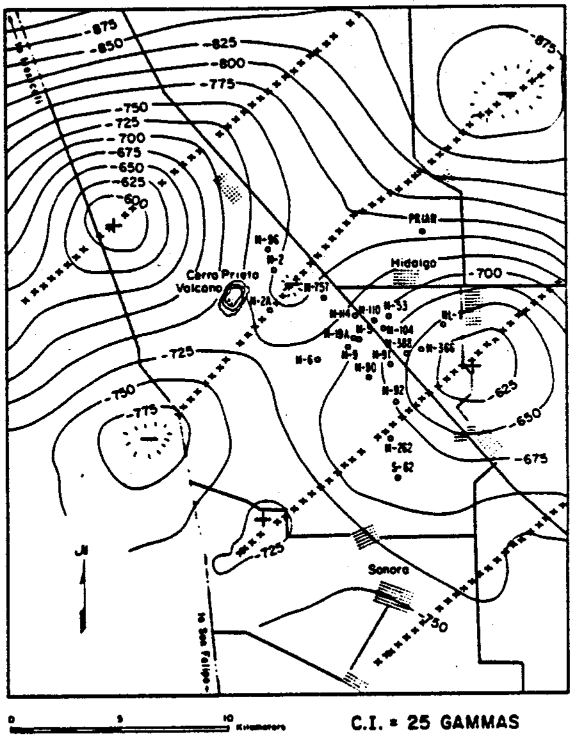
Fig. 12: Bouguer anomaly map for the Cerro Prieto area (after Ref. 39).



XBL 805-7068

Fig. 13: Magnetic anomaly map for the Cerro Prieto area (after Ref. 39).

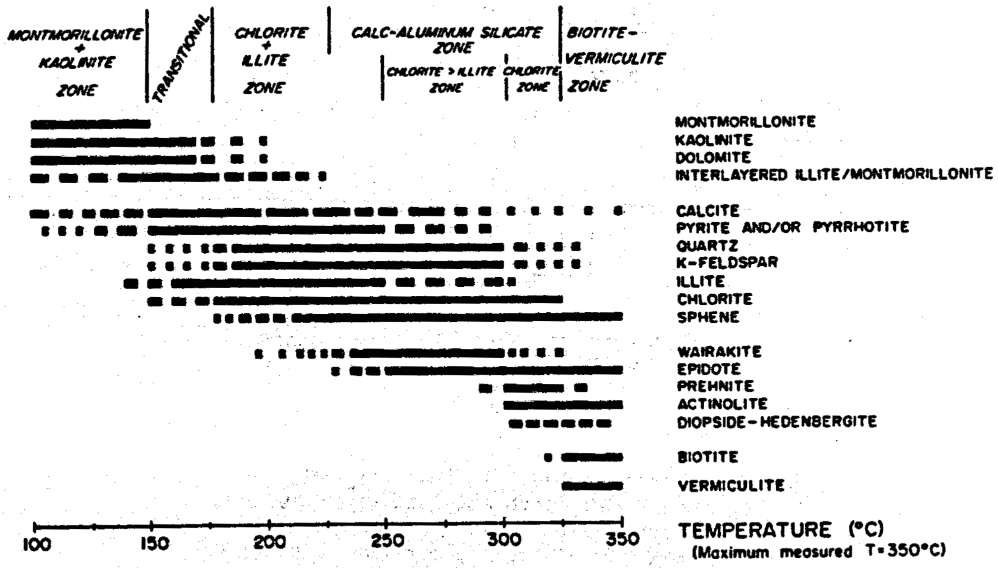


Fig. 14: Temperature ranges of hydrothermal alteration mineral zones in Cerro Prieto sandstones (Ref. 12).

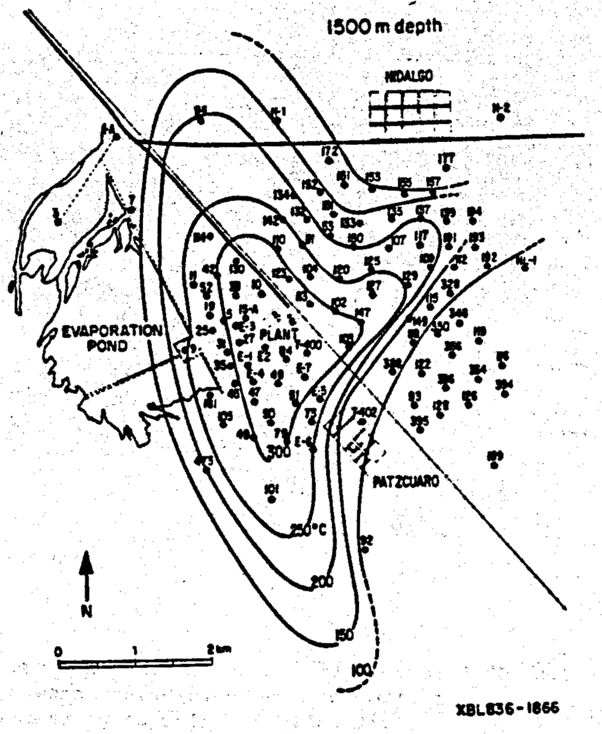


Fig. 15: Isotherms at a depth of 1500 m at Cerro Prieto (after Ref. 69).

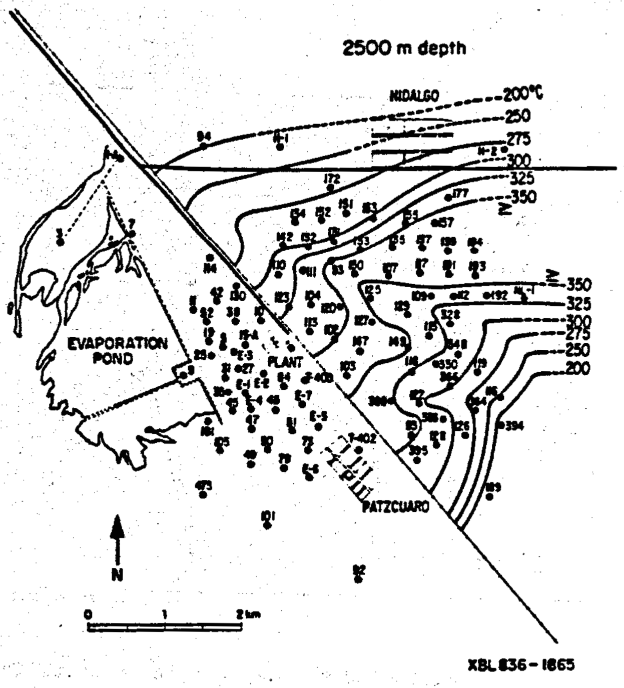


Fig. 16: Isotherms at a depth of 2500 m at Cerro Prieto (after Ref. 69).

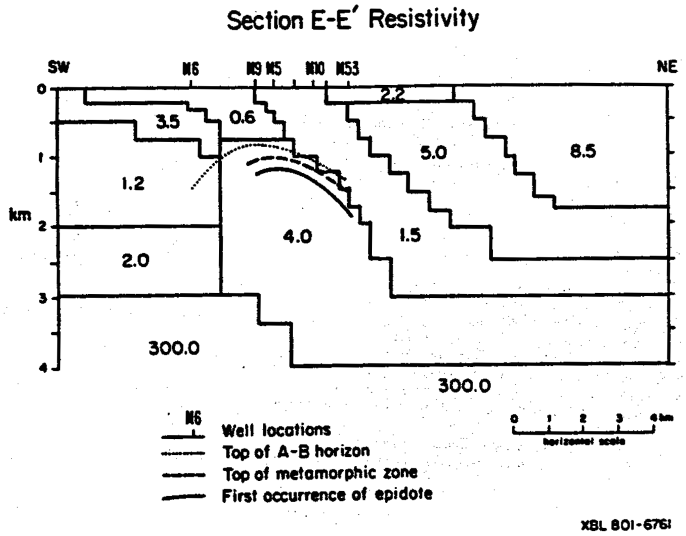
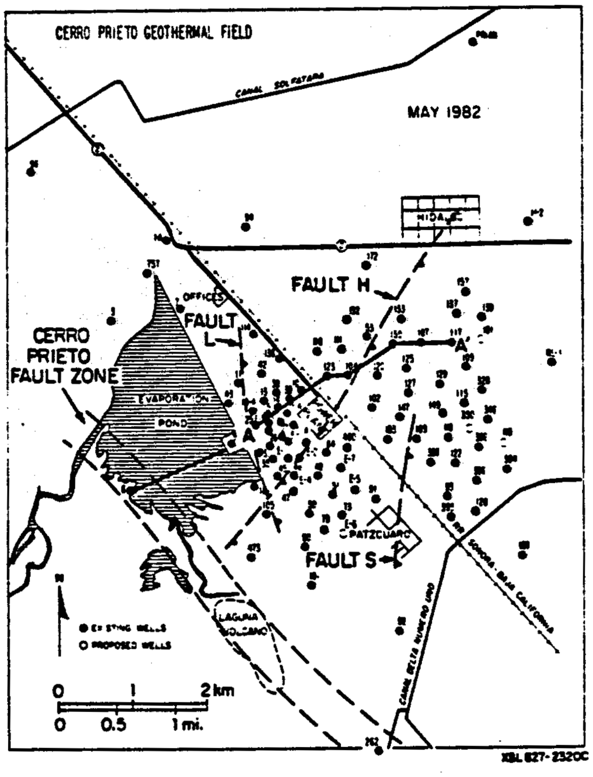


Fig. 17: Two-dimensional resistivity model for a southwest-northeast line crossing the Cerro Prieto field. Shown are also the position of the A/B contact, the top of the metamorphic zone, and the first occurrence of the mineral epidote (Ref. 43).



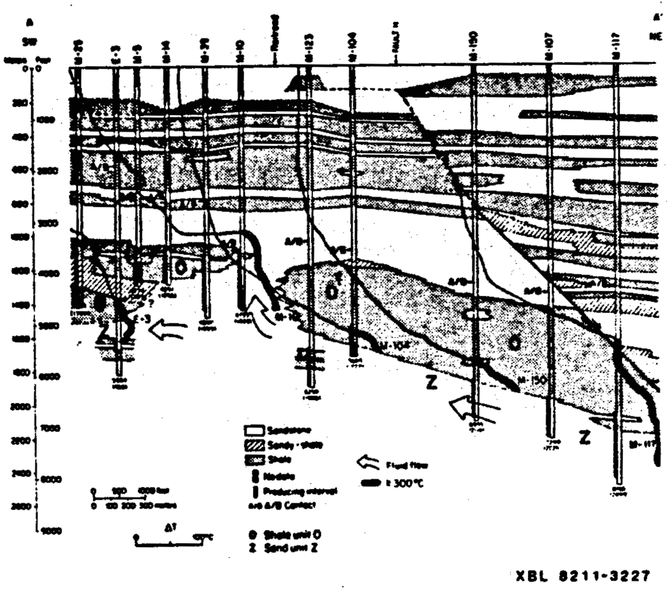


Fig. 18: Location of the main faults controlling the subsurface flow of geothermal fluids in the Cerro Prieto field. Also shown is the position of cross section A-A' given in Figure 19 (after Ref. 38)

Fig. 19: Southwest-northeast geologic cross section of the Cerro Prieto showing schematically the flow of geothermal fluids (Ref. 38).