PROCEEDINGS. Twenty-First Workshop on Geothermal Reservoir Engineering
Stanford University. Stanford. California. January 27-29, 1997
SGP-TR-155

WHAT WILL A 6 KM DEEP WELL AT CERRO PRIETO FIND ?

M.J. Lippmann (+), A.H. Truesdell(#) and H. GutiCrrez Puente(*)

(+) E.O. Lawrence Berkeley National Laboratory, Berkeley, California, **USA**
(#) Consultant, Menlo Park, Califonia, USA
(*) Comisidn Federal de Electricidad, Mexicali, BCN, Mexico

ABSTRACT

This paper reviews geological, geochemical and geophysical data on the deeper parts of the high-temperature, water-dominated geothermal system of Cerro Prieto in Baja California, Mexico. It also speculates about the lithology, temperature, pressure and fluid chemistry that might be encountered in a deep (about **6** km) exploration well being considered for the eastern part of this field. Based on the depths of observed seismic activity, it is possible that the proposed well could penetrate below the brittle-ductile transition zone. Above the transition pressures should be hydrostatic and temperatures in the 350-400°C range, with production occurring largely from fractures. Below the brittle-ductile transition fractures would tend to be sealed both by precipitation of silica and the plasticity of the rocks. In such a region fluid pressures could exceed hydrostatic and heat flow would be conduction-dominated, leading to higher temperatures but lower permeabilities.

INTRODUCTION

Recent encouraging results in deepening Cerro Prieto production wells (i.e., increased fluid production, higher wellhead pressures) have prompted Comisidn Federal de Electricidad de México (CFE) - the operator of the geothermal field - to consider the possibility of drilling a six-kilometer deep exploration borehole in the eastern part of the present production area (Alvarez-Rosales, 1996). The purpose of the well would be to characterize the lower parts of the geothermal system, determine the bottom of the (commercial) reservoir and identify drilling and production problems associated with deep (> 4 km) wells at Cerro Prieto.

Several groups have indicated interest in the deep well project from commercial and scientific points of view. CFE plans to pay for the drilling costs, while the Office of Geothermal Technologies of the Department of Energy and other organizations might support the associated scientific studies. At present, CFE's funding for the project seems quite likely. Those interested in the project should contact Ing. Héctor GutiCrrez Puente (hgutierrez@cfe.gob.mx).

This paper will review what is known and what is inferred about the deeper Cerro Prieto regions which have not been reached by the drillbit.

REVIEW OF RELEVANT INFORMATION

The Cerro Prieto geothermal field is located in the southern portion of the Salton Trough, an actively developing rift basin. 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, serving as a transform boundary (Fig. 1).

Cerro Prieto is in the spreading center (tensional area) developed between the ends of the right-stepping, ***en echelon,*** strike-slip Cerro Prieto and Imperial faults, which are part of the San Andreas system (Figs. 1 and 2). As the crust is being pulled open, it thins and begins to subside forming a sedimentary basin ("pull-apart" basin). Savino et al. (1977) 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.

Where thinning of the crust and basin development is rapid, there will occur an upwelling of magma from the asthenosphere creating new oceanic-type crust. We assume that the mechanical model of Lachenbruch et al. (1985) developed for the Imperial Valley (northern part of the Salton Trough) is also valid for Cerro Prieto. According to this model the extended crust is being intruded by gabbroic magma from the mantle, while subsidence is accompanied by rapid sedimentation that keeps the surface at (or near) sea level and isostatic balance is maintained. The rifting and gabbroic intrusion result in high heat

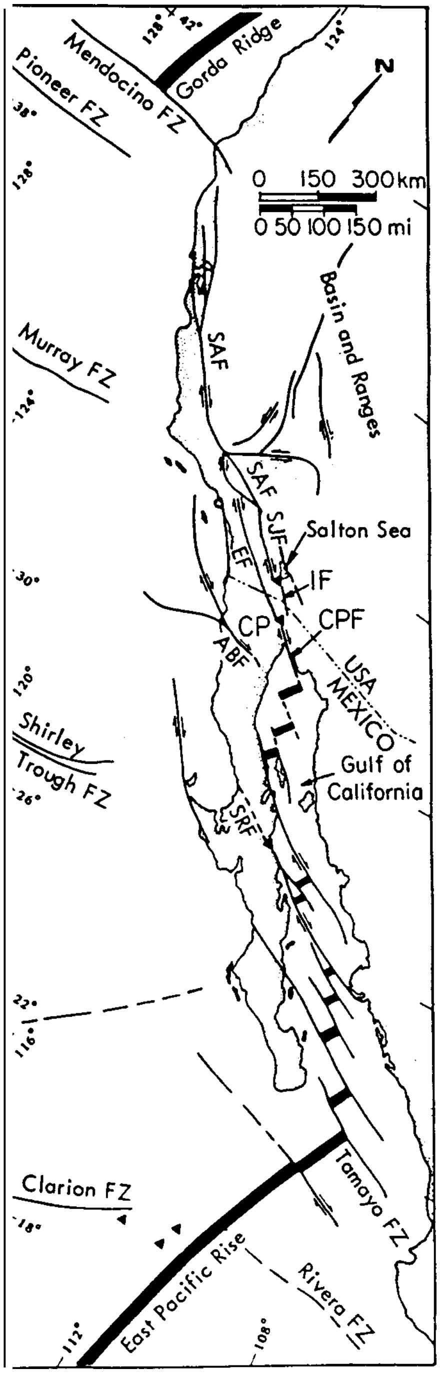


Fig. 1. Fractures and spreading centers along part of the Pacific coast of North America. Oceanic fracture zones (FZ) and continental faults (F) are solid black lines. ABF, Agua Blanca Fault; CPF, Cerro Prieto Fault; EF, Elsinore Fault; IF, Imperial Fault; SAF, San Andreas Fault; SJF. San Jacinto Fault; 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 Elders et al., 1972).

flows, metamorphism of the sedimentary rocks at relatively shallow depths (Elders et al., 1984), consolidation of the section into new crust, and generation of the volcanism and current hydrothermal activity at Cerro Prieto (Reed, 1984).

An area of seismicity connects the Cerro Prieto and Imperial faults (Fig. 2), corresponding possibly to a zone where magma is intruding to form a complex of dikes and sills. Some of these dikes, mainly of mafic composition, have been found in wells drilled in the eastern part of Cerro Prieto (Figs. 3-6; Elders et al., 1984; Goldstein et al., 1984).

The structural picture of Cerro Prieto is complex. The strike-slip Cerro Prieto and Imperial faults are easily recognized from their surface expressions. Mainly on the basis of geophysical and well data, several normal faults of different age and strike were located by Lyons and van de **Kamp** (1980). Halfman et al. (1984) identified three normal faults (faults H, L, and S; Fig. **3).** The role of faults H and L in controlling geothermal fluid flow in the reservoir have been confirmed by several studies (e.g., Lippmann et al., 1991; Verma et al., 1996).

The Mesozoic crystalline rocks which crop out at the Sierra de Cucapá, some 5 km west of the field, have

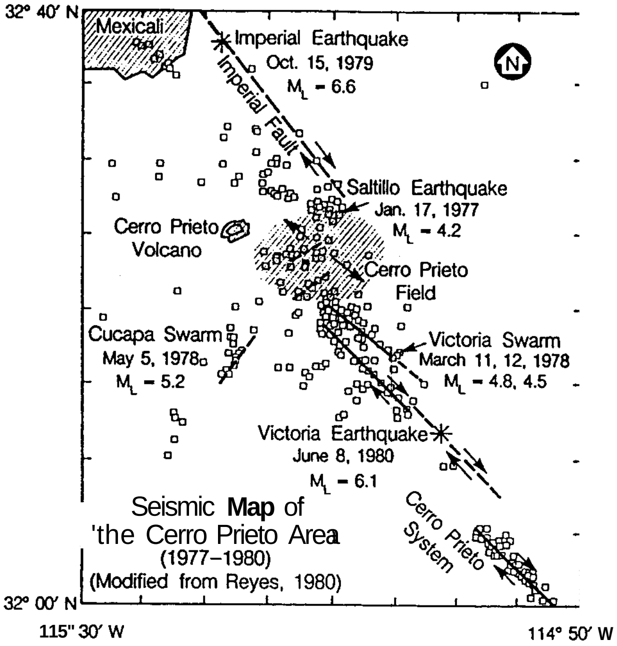
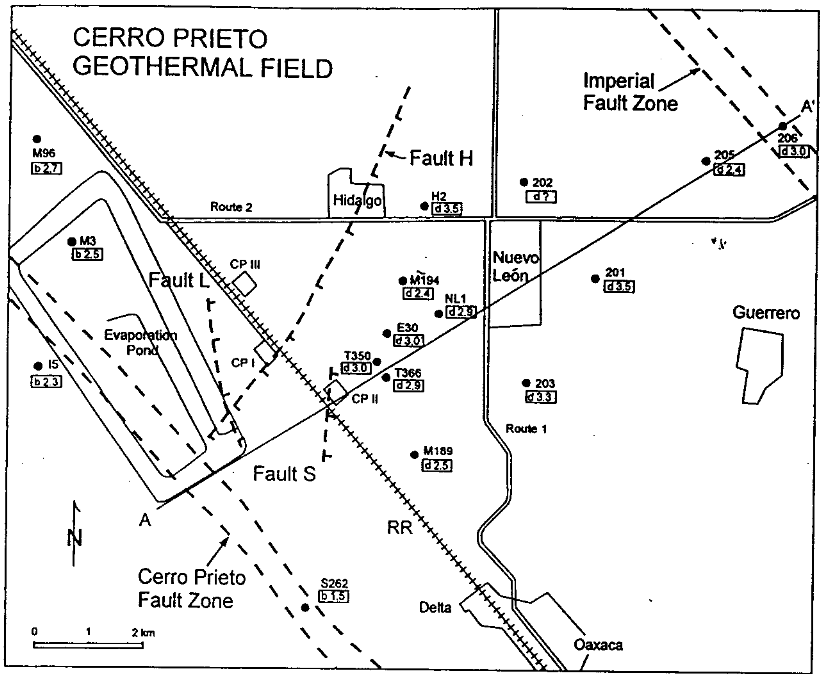


Fig. 2. Seismic map of the Cerro Prieto area (1977-1980 events).



Modified from Lippmann et al., 1991

Fig. **3**. Cerro Prieto. Location of main faults (from Halfman et al., 1984), wells that encountered crystalline basement (b) and igneous dikes (d) and of cross section **A-A'** (see Fig. 4). "b 1.5" indicates that the well penetrated basement at about 1.5 km depth; "d 2.9," that the shallowest dike was found at about 2.9 km depth. Faults locations are shown extrapolated to the surface.

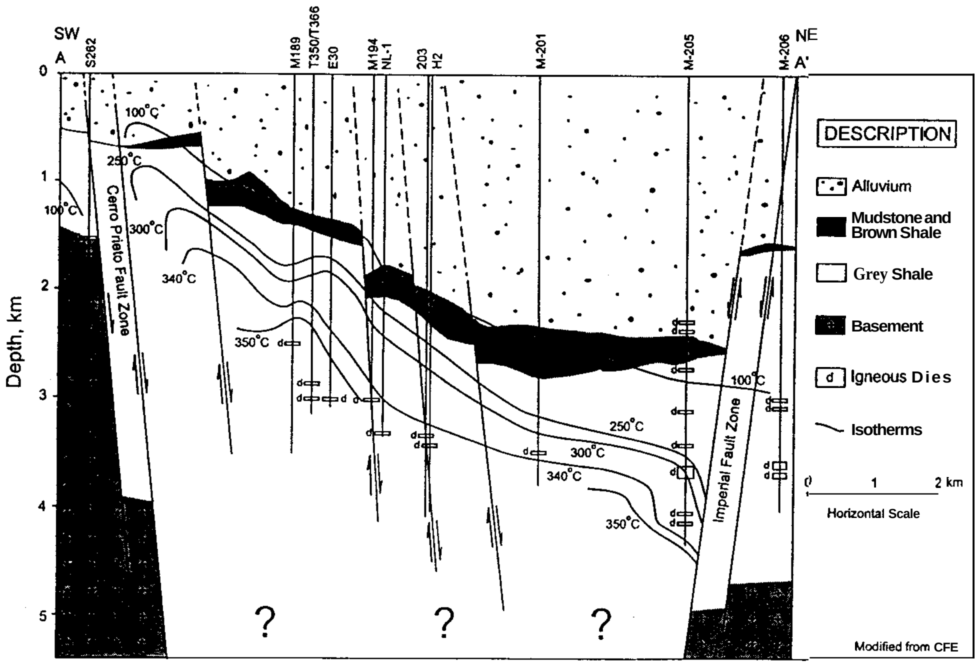


Fig. 4. SW-NE geologic section across Cerro Prieto (see location in Fig. **3)** showing main lithologic units, faults, wells that encountered crystalline basement and igneous dikes, and isotherms (modified after CFE promotional brochure).

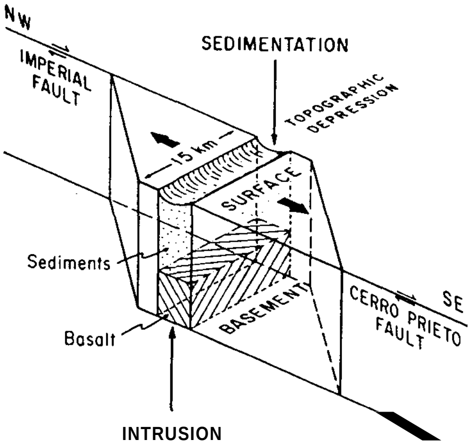


Fig. 5. Block diagram of a pull-apart basin between the Imperial and Cerro Prieto faults. The area of new crust formation is arbitrarily indicated as a central vertical slice (from Elders et al., 1984).

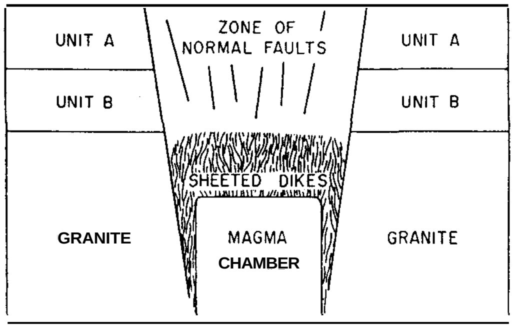


Fig. 6. Very schematic NW-SE section across the Cerro Prieto area parallel to the major strike-slip faults. The figure is intended to suggest a heat source and the different geologic regimes likely to be present at depth, rather than inferring exact geometrical relations. Unit **A,** unconsolidated sediments; Unit B, consolidated sedimentary rocks (from Elders et al., 1984).

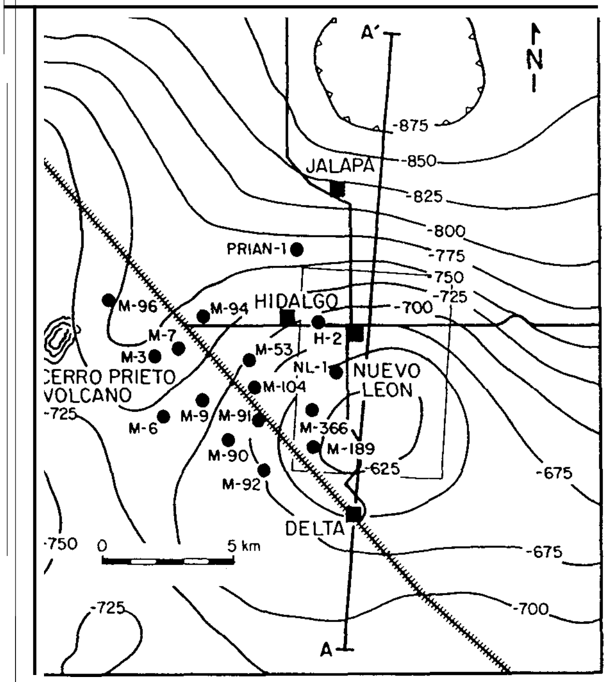
been intersected only in a few wells along the western margin of the Cerro Prieto field. They have not been found towards the center of the field and axis of the trough (Figs. *3* and 4). There, the wells penetrate alluvial, deltaic, estuarine and shallow marine deposits without reaching the base of the sedimentary column. Seismic studies indicate that at the US-Mexican border, some 30 km north of the field 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 sub-basement possibly composed of intrusive rocks of basaltic composition (Fuis et al., 1984).

The upper part of the sedimentary column, mainly of Colorado River provenance, consists of non-indurated and semi-indurated sediments (Unit **A** of Puente C. and de la Peiia L., 1979), mostly sands, silts and clays; the lower part, of sediments indurated by post-depositional hydrothermal alteration (Unit **B** of Puente C. and de la Peña L., 1979), mainly sandstones and clays. **A** much more detailed picture of the Cerro Prieto sedimentary column was developed by Halfman et al. (e.g., 1984, 1986), however it is not relevant here.

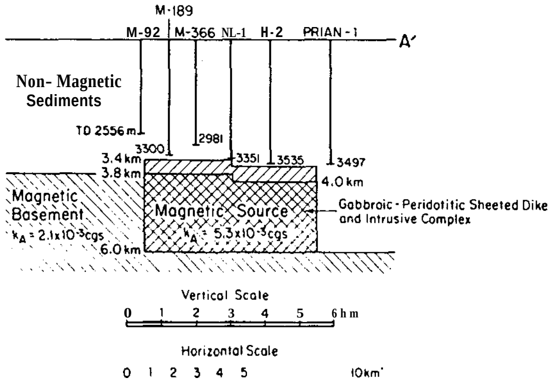
Below the A/B contact, shales show a sudden reduction in porosity and an increase in density, while sandstones increase in porosity, implying development of secondary porosity due to dissolution of unstable grains and cements (Lyons and van dc Kamp, 1980). With increasing temperatures and depth and progressive water-rock interaction there is probably a transition to fracture-dominated permeability (Elders et al., 1984).

In the eastern regions of Cerro Prieto the location **of** the bottom of the sedimentary/metasedimentary column can only be inferred. The deepest well, M-205 drilled in 1985 (see Fig. **3),** is about 4400 meters deep and bottoms in a shale/sandstone sequence (its temperature at total depth is about **350°C).** Seismic profiling techniques have not been successful in imaging deep reflectors because of the attenuation zone that coincides with the geothermal reservoir (Blakeslee, 1984). Crystalline basement could only be detected by seismic reflection methods in the western parts of the field (Fonseca López and Razo Montiel, 1979).

The mafic and silicic igneous dikes that have intruded the sediments in the eastern part of Cerro Prieto may be related to the broad magnetic high (the "Nuevo Ledn Magnetic Anomaly") about 5 km east of power plant CP-I (Fig. 7). **A** detailed fit of the computer model to the observed magnetic field indicates that the source may be approximated by a tabular block, 3.7 km in depth and **2.3** km thick, dipping slightly to the north (Fig. 8; Goldstein et al., 1984). The bottom of the magnetic source, at a depth of about **6** km, is presumed to be at or near that of the Curie isotherm (575°C) for magnetite, the principal ferromagnetic mineral in peridotitic-gabbroic rocks. The earthquake data suggest dike injection is occurring at 6-11 km depth in an area beneath the magnetic source (Goldstein et al., 1984).



ig. 7. The “Nuevo León Magnetic Anomaly” in the astern part of the Cerro Prieto field. The rectangle orresponds to the approximate surface projection of he inferred magnetic mafic rocks. Solid circles, vells; solid squares. villages. Also given is the ocation of the A-A’ line shown in Fig. 8 (from oldstein et al., 1984).



ig. 8. Inferred subsurface model and magnetic ource for the “Nuevo Ledn Magnetic Anomaly” ased on modelling results. The location of the ross-section is given in Fig. 7, wells are projected into this section (from Goldstein et al., 1984).

Recently, Nielson (1996) suggested that the transition from brittle to ductile rock in response to applied stress probably occurs gradationally over a depth interval in the subsurface. He indicated that the location of the transition zone determines the depth to which fluids freely circulate in a geothermal system.

In the brittle zone, rocks tend to fracture, while in the ductile zone, they deform plastically. Where fractures exist fluids may circulate and heat transfer is mainly by convection. If there are no fractures, heat conduction dominates (Fig. 9). Fournier (1991) indicates that the transition from brittle to ductile behavior may occur at 370-400°C. Sealing by hydrothermal quartz would result in above-hydrostatic pressures below the brittle zone.

The depth of the brittle-ductile (BD) transition zone is a function of temperature, rock properties, stress orientation and strain rate (Sibson, 1982). According to Sibson's model, shear resistance increases with depth, reaching a maximum at that zone. Below it, resistance decreases as well as the number of earthquakes (Fig. 9).

The vertical distribution of hypocenters of seismic events recorded at Cerro Prieto between August 1994 and August 1996 (Fabriol and Glowacka, 1997) shows a clear reduction in numbers below the 4-6 km depth interval (Fig. 10). Based on this, we might conclude that the BD transition zone occurs around 5 km depth at Cerro Prieto. One should note, however, that the depths are model-dependent and that the vertical error for the hypocenter locations is up to 2 km.

The physical and chemical character of fluids at the total depth of the planned drillhole would depend on its position relative to the interface of fractured, brittle rock representing the maximum depth of circulation of waters originating from the surface (including connate brines and meteoric waters; Fig. 11), and ductile rock without fractures that can carry heat and fluids from intruding magmas.

Cerro Prieto waters originating at the surface include rainwater, Colorado River water, seawater and probably highly-evaporated brines of marine origin. The geothermal reservoir waters have high salinities (to 3/4 that of seawater) and extraordinarily light hydrogen isotopes (to δD of -110). These production brines have been described as being a complex mixture of a hypersaline marine brine and Colorado River waters (Truesdell et al., 1981). The processes

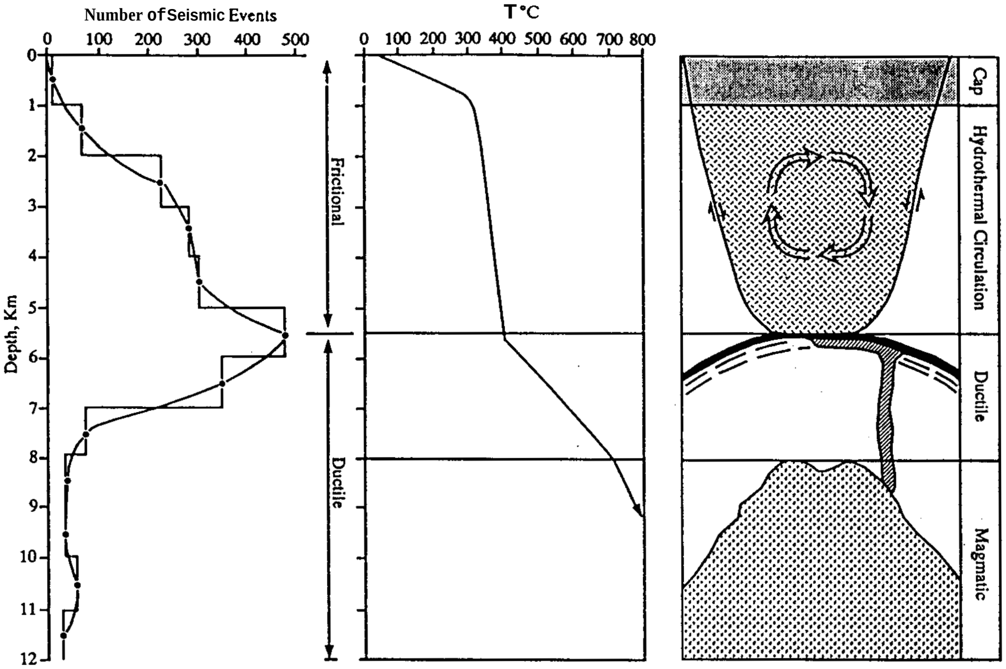


Fig. 9. Schematic model for zonation within an active hydrothermal system (from Nielson, 1996).

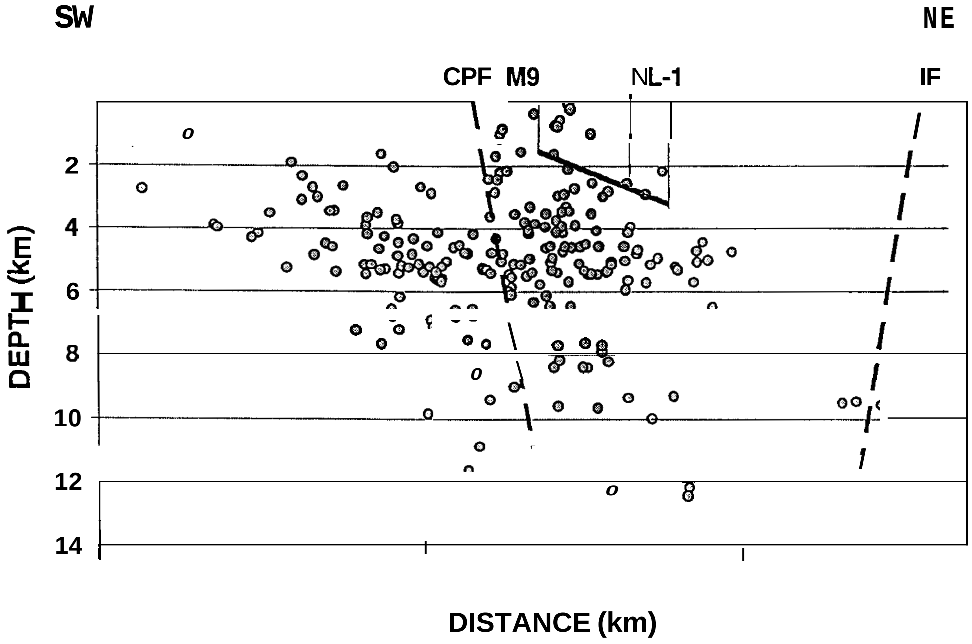


Fig. 10. Distribution of hypocenters monitored between August 1994 and August 1996 along a SW-NE plane across the Cerro Prieto field. CPF, Cerro Prieto Fault; IF, Imperial Fault; M9, M133 and NL-1, geothermal wells. The gray line roughly corresponds to the top the geothermal reservoir. The traces of the faults are approximate (modified after Fabriol and Glowacka, 1997).

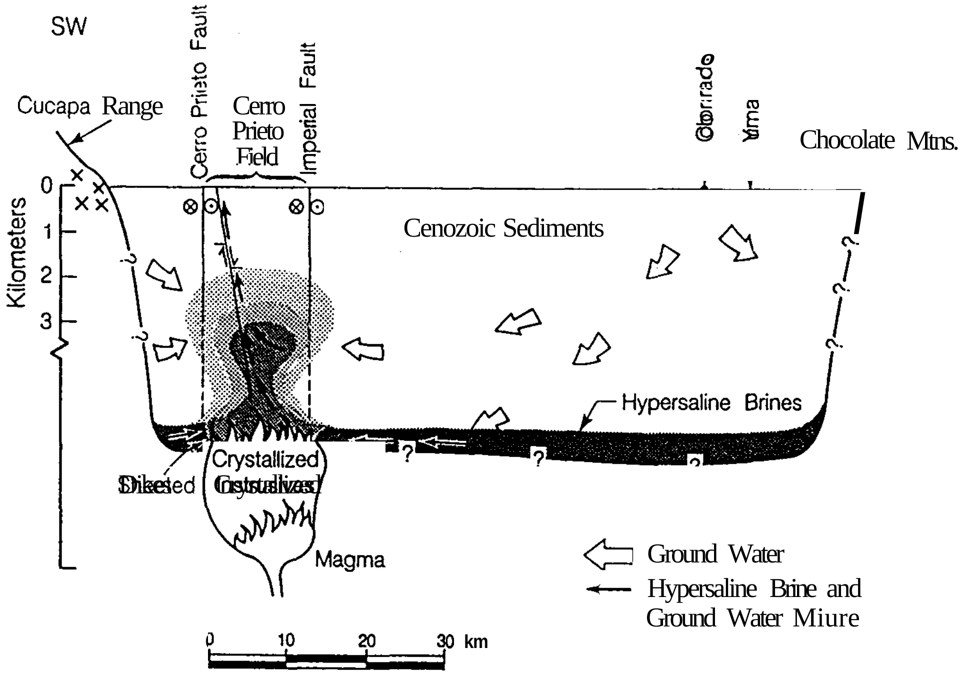


Fig. 11. Schematic diagram of the geology and fluid flow across the Mexicali Valley (from Halfman et al., 1986).

inferred are shown in Fig. 12. Although this model does not feature a magmatic component, a moderate fraction of magmatic water would not significantly change the final compositions and is certainly indicated by the high ^{3}He/^{4}He (R/Ra= 5.5 to 7.2) found in **Cerro** Prieto fluids (Welhan et al., 1979; Mack Kennedy, pers. com., 1996).

However at the BD transition (i.e., conditions which could be encounter by the proposed well) temperatures and pressures must be higher than those hypothesized in the Truesdell et al. (1981) model, which assumes circulation of surface-related waters. There is a large literature discussing these conditions as related to the formation of ore deposits (and to a lesser extent geothermal systems). Most of the ideas in the following discussion are taken from this literature, but it would be impractical here to refer to individual papers.

The BD transition has been discussed above. It is reasonable to hypothesize that mainly heat is carried through the ductile zone to drive fluid (and mineral) metamorphism in the overlying fractured zone, and that the ascending magmatic fluids may be altered before they mixed with overlying brines.

Quartz in pure and saline waters exhibits a solubility maximum at temperatures not far below the critical point of the solvent. For pure, steam-saturated water this maximum is at about 340°C. At higher temperatures the solubility decreases rapidly, reaching half its maximum at **370°C** and is near zero at the critical point (experimental data are few). With increasing salinity and pressure, the solubility maximum is displaced to higher temperatures. The effect of rapid solubility decline is to prevent downward circulating waters from reaching near-critical temperatures except under conditions of high pressure. When water at the quartz solubility maximum enters a fracture at higher temperatures and is heated, quartz becomes supersaturated and precipitates tending to seal the fracture. This may account for the lack of geothermal production at temperatures above 340 to 360°C.

The critical point of water is also important to the character of ascending magmatic waters. At supercritical pressures and temperatures water exists as a dense gas or as a liquid depending on its pressure, with properties that are more liquid-like at higher pressures and more gas-like at lower pressures. Because explored geothermal systems

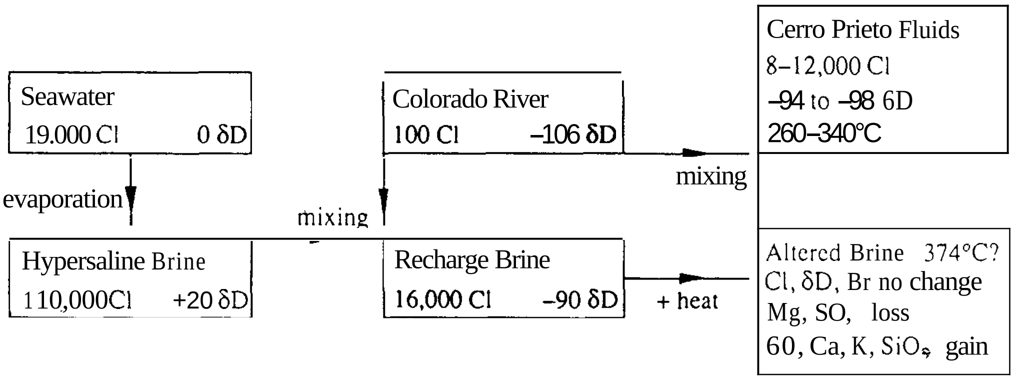


Fig. 12. Schematic geochemical history of the Cerro Prieto fluids showing evaporation of seawater to a hypersaline brine, mixture with Colorado River water, high-temperature reaction of the mixture with deltaic sediments to form a geothermal brine, and further mixture with river water to form the observed range of reservoir fluids (from Lippmann et al., 1991).

have high temperatures at relatively shallow depths, associated supercritical fluids are generally gas-like. When water behaves as a gas, it is not an ionizing solvent and carries only molecular species in solution. This means that H' is nonexistent and only uncharged species and gases (CO_2, SO,, HCl°, HF°, NaCl", and minor N,, KCI", HBO, and SiO_2) are carried into the base of geothermal systems. These species do not significantly react with rock minerals. When subcritical conditions are reached, HCl° and HF° ionize to H', Cl⁻ and F⁻ ions, and SO, disproportionates and reacts with water to form H_2S, and H' and SO; ions. These acid waters are neutralized by reaction with rock and mix (along with the gases) with meteoric waters and connate brines to form normal, near-neutral geothermal waters.

In the BD transition zone, the ascent of subcritical waters would not be impeded by the precipitation of quartz because as these waters cool by passing through cooler rock or mixing with cooler waters, quartz is dissolved rather than precipitated. However the upward flow of these waters may be slowed or prevented by the lack of fractures caused by the ductile nature of rocks at high temperatures. The rheology of rocks in the ductile zone may allow fractures resulting from large earth movements to close slowly, and during this time fluids may be briefly released.

Although temperatures greater than the critical point of pure water (374°C) have been encountered in a few geothermal exploration wells, the salinities in each case were very high and, because the critical point increases with salinity, original conditions may not have been supercritical (summarized in Fournier, **1991).** The pressure at 6 km at Cerro Prieto is calculated to be near 420 bars and extrapolation of temperatures (probably only valid above the BD transition) suggests less than 400°C. These conditions are below the critical point for the saline waters expected, which means that neutralization of acid volatiles is possible and probably depends on the availability of unaltered rock surfaces. Such surfaces will be rare below the BD transition and little alteration and neutralization would be expected. During tectonic episodes there will be more fractures but also more acid fluid. Neutralization above the BD transition may be rapid if there are numerous fractures and in a highly tectonic area such as the Salton Trough, fractures may be plentiful. However open fractures and large scale circulation may not occur until above both the BD transition and the level where temperatures are at or below that of maximun quartz solubility.

Thus the character of the fluid at 6 km will depend on a number **of** factors, the most important of which **is** the position of the drillhole relative to the BD transition and the critical point **for** the ascending magmatic fluid. If the new well bottoms above the BD transition, the rocks are expected to be fractured, fluid circulation will dominate, and the fluids will be near neutral geothermal brines. If the well reaches the BD transition zone, fractures will be limited and acid fluids derived from magmatic HCl and SO, could occur.

SUMMARY

On the basis of the data reviewed above, we conclude that a six-kilometer deep well drilled in the eastern region of the Cerro Prieto field may reach the brittle-ductile transition zone. If this is the case, at total depth there would be little circulation of fluids.

In the brittle region fractures will tend to exist and remain open. Circulation of hydrothermal fluids would occur at hydrostatic pressures and temperatures would tend to remain in the 350-400°C range. Below, in the transition zone, fractures would tend to be closed because of rock plasticity and mineral deposition. Fluid pressures would exceed hydrostatic values, and temperature gradients would be higher since transfer of heat from depth would be dominated by conduction.

Between 4000 meters and total depth, the well should remain in metasediments intruded by sheeted basic dikes; no crystalline basement should be expected.

The fluids encountered at total depth are expected to be near-neutral as long as the rocks are extensively fractured and fluid circulation is dominated by convecting surface-derived brine present at the bottom of the trough (Fig. 11). If fractures are limited, acid fluids derived from magmatic HCI and SO, could occur locally. The acidity of upflowing fluids depends on the amount of neutralizing rock minerals encountered by deep fluids after H^+ ions are produced by ionization at sub-critical temperatures.

ACKNOWLEDGEMENTS

We want to thank Wilfred Elders and Dennis Nielson for their useful comments and suggestions, as well as Carol Taliaferro for the preparation of the manuscript. The work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Geothermal Technologies, of the **US** Department of Energy under contract No. DE-AC03-76SF00098.

REFERENCES

Alvarez-Rosales, J. (1996). Perforación profunda en el campo geotérmico de Cerro Prieto (abstract). GEOS, Unión Geofísica Mexicana, 16,238.

Blakeslee, **S.** (1984). Seismic discrimination of a geothermal field: Cerro Prieto. Geothermal Resources Council Trans., 8, 183-188

Elders, W.A., Bird, D.K., Williams, A.E. and Schiffman, P. (1984). Hydrothermal flow regime and magmatic heat source of the Cerro Prieto geothermal system, Baja California, Mexico. Geothermics, **13,** 27-47.

Elders, W.A., Rex, R.W., Meidav, T., Robinson, P.T. and Bielher, **S.** (1972). Crustal spreading in southern California, Science, 178, 15-24.

Fabriol, H. and Glowacka, E. (1997). Seismicity and fluid reinjection at the Cerro Prieto geothermal field: Preliminary results. Proc. 22nd. Workshop **on** Geothermal Reservoir Engineering, Stanford, CA, Jan. 27-29 (in press).

Fonseca López, H.L. and Razo Montiel, A. (1979). Gravity, magnetics and seismic reflection studies at the Cerro Prieto geothermal field. Proc. 2nd. Symposium on the Cerro Prieto geothermal field, Baja California, Mexico, October 17-19, Mexicali, BC, Mexico, pp. 303-328.

Fournier, R.O. (1991). The transition from hydrostatic to greater than hydrostatic fluid pressure in presently active hydrothermal systems in crystalline rocks. Geophys. Res. Letters, 18,995-958.

Fuis, G.S., Mooney, W.D., Healy, J.H., McMechan, G.A. and Lutter, W.J. (1984). A seismic refraction survey of the Imperial Valley, California. J. Geophys. Res., 89, 1165-1189.

Goldstein, N.E., Wilt, M.J. and Corrigan, D.J. (1984). Analysis of the Nuevo Ledn magnetic anomaly and its possible relation to the Cerro Prieto magmatic-hydrothermal system. Geothermics, 13, 3-11.

Halfman, S.E., Lippmann, M.J., Zelwer, R. and Howard, J.H. (1984). A geologic interpretation of geothermal fluid movement in Cerro Prieto field, Baja California, Mexico. Amer. Assoc. Petrol. Geol. Bull, 68, 18-30.

Halfman, S.E., A. Mañón and Lippmann, M.J. (1986). Update of the hydrogeologic model of the Cerro Prieto field based on recent well data. Geothermal Resources Council Trans., 10,369-375.

Lachenbruch, A.H., Sass, J.H. and Galanis, S.P., Jr. (1985). Heat flow in southernmost California and the origin of the Salton Trough. **J.** Geophys. Res., 90, B8, 6709-6736.

Lippmann, M.J., A.H. Truesdell, Halfman-Dooley, S.E. and Mañón M., A. (1991). A review of the hydrogeologic-geochemical model for Cerro Prieto. Geothermics, 20, 39-52.

Lyons, D.J. and van de Kamp, P.C. (1980). Subsurface geological and geophysical study of the Cerro Prieto geothermal field, Baja California, Mexico. Lawrence Berkeley Laboratory report LBL-10540.

Nielson, D.L. (1996). Natural analogs for enhanced heat recovery from geothermal system. Proc. 21st Workshop on Geothermal Reservoir Engineering, Stanford, CA, pp. 43-49.

Puente C., I. and de la Peiia L., A. (1979). Geology of the Cerro Prieto geothermal field. Geothermics, 8, 155-175.

Reed, M.J. (1984). Relationship between volcanism and hydrothermal activity at Cerro Prieto, Mexico. Geothermal Resources Council Trans., 8,217-212.

Reyes , C.A. (1980). Reporte preliminar del sismo “Victoria,” Baja California Norte, del 8 de junio de 1980 (M_L=6.7). Internal technical report GEO80-02, CICESE, June 1980.

Savino, J.M., Rodi, W.L., Goff, R.C., Jordan, T.H., Alexander, J.H. and Lambert, D.G. (1977). Inversion of combined geophysical data for determination of structure beneath the Imperial Valley geothermal region. Report SAN-1313-1, U.S. Department of Energy, Oakland, CA.

Sibson, R.H. (1982). Fault zone models, heat flow and the depth distribution of earthquakes in the continental crust of the United States. Bull. Seismol. Soc. Amer., 72, 151-163.

Truesdell, A.H., Thompson, J.M., Coplen, T.B., Nehring, N.L. and Janik, C.J. (1981). The origin of the Cerro Prieto geothermal brine. Geothermics, 10, 225-238.

Verma, M., Quijano, L., GutiCrrez, H., Iglesias, E. and Truesdell, A. (1996). Isotopic changes in the fluids of the Cerro Prieto β reservoir. Proc. 21st Workshop on Geothermal Reservoir Engineering, Stanford, CA, pp. 93-99.

Welhan, J.A., Poreda, R., Lupton, J.E. and Craig, H. (1979). Gas chemistry and helium isotopes at Cerro Prieto. Geothermics, 8,241-244.