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Hydrothermal Mineralogy and Microthermometry of Fluid Inclusions in the Cerro Prieto Geothermal Field, Mexico

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Keywords

Cerro Prieto, hydrothermal mineralogy, fluid inclusions

ABSTRACT

The distribution of hydrothermal minerals, common mineral assemblages and microthermometry of fluid inclusion were determined in cuttings from wells located all over the Cerro Prieto Geothermal Field.

Deep samples of cuttings and fragments of cores were studied mainly from the production zone. This zone has been named as the silica epidote zone (SEZ) and it is located mainly in sandstones. The most common paragenetic associations show three ranges of temperature in this zone of the field: 200 °C, 200-250 °C, 250-300°C. The first one is characterized mainly by clays, calcite and quartz; the second one by quartz, epidote, chlorite and micas, and the third one represented by epidote, amphiboles, illite and chlorites. A preliminary study of fluid inclusions in authigenic quartz showed two phase (L +V) fluid inclusions with variable salinity. Homogenization temperatures are over a wide range; for some wells are in good agreement with those recorded by other means.

Introduction

The Cerro Prieto Geothermal Field (CPGF) is a liquid dominated field, located in the northwest part of Mexico close to the United States border (Figure 1). It is hosted mostly in sandstones and shales of the Colorado river delta. It is the largest producing field within Mexico and has 720 Mwe of installed capacity. It is the second largest producer in the world. At present more than 300 wells have

been drilled, some of them are out of order and some others have been repaired.

For administrative purposes the entire field has been divided into four areas known as CP-I (Cerro Prieto I) to the west of

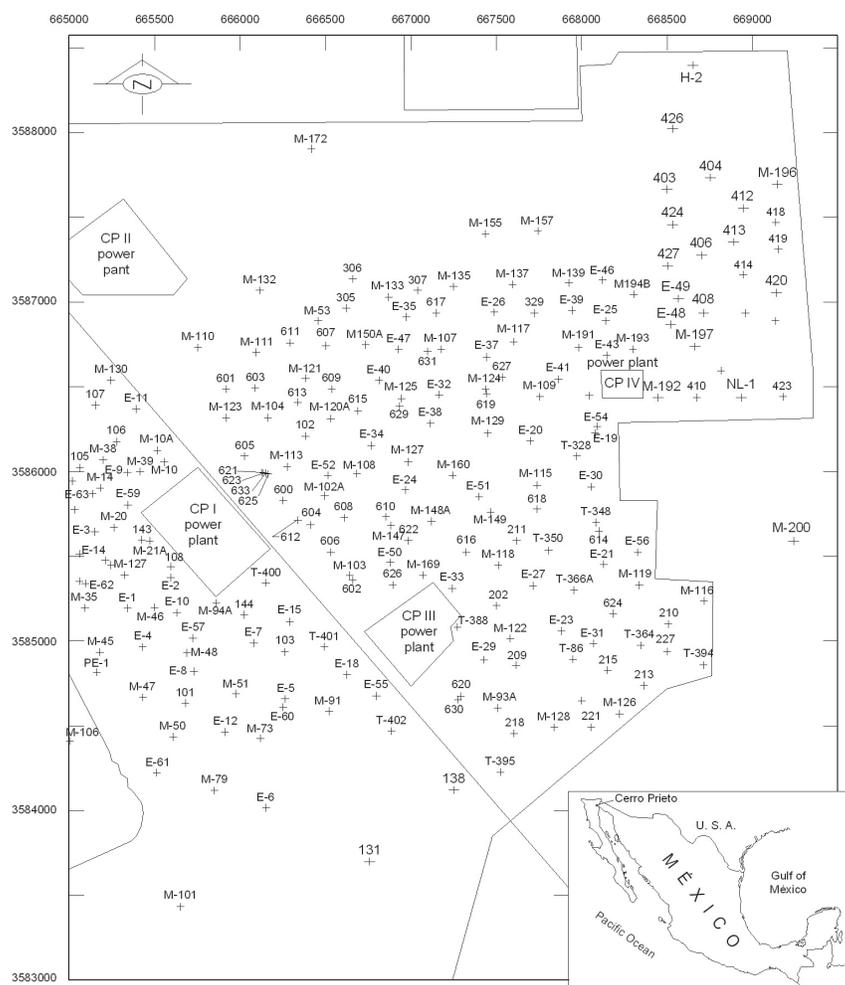


Figure 1. Location of drilled wells in the CPGF. The inset gives the location of the field within the Republic of Mexico.

the railroad, CP-II (Cerro Prieto II) in the southeast area, CP-III (Cerro Prieto III) in the northeast area and CP IV (Cerro Prieto IV) northeast from CP-III.

According to the location of the areas and production depth, three reservoirs have been inferred; all of them developed in sandstones and sandy shale units that are fed from depth by fluids rising from fractures (Lippmann *et al.*, 1991). The Alpha reservoir in the west part of the field is the shallowest and was the first to be exploited. It is found at depths between 1000 and 1500 m (Cerro Prieto I). The deeper Beta reservoir extends underneath the entire area of the Cerro Prieto (about 15 km²) at depths between 1500 and 2700 m with temperatures higher than those in Alpha reservoir (CP II, CP III, CP IV). The inferred deep Gamma reservoir has not been reached yet.

The Beta reservoir is located in high porosity, permeable sandstones underlying the low porosity, relatively impermeable brown shale unit.

The study of alteration minerals as indicators of physical and chemical conditions in geothermal systems has received special attention by very few researchers. For Cerro Prieto the work done by Elders *et al.*, (1979, 1981) has been taken as reference for the field and also as a model to represent the alteration mineralogy in several geothermal fields. Izquierdo *et al.*, (2000, 2001) carried out petrographic and X-ray analysis of the SEZ in wells located in CP-IV. Optically rock alteration was estimated to be close to 40 % with respect to primary minerals; it was defined as high rank and moderate intensity. The rocks are terrigenous being shales more abundant than sandstone.

Minerals identified by X-ray diffraction in the clay fraction were: Na-smectite, Ca-smectite, illite, chlorite and scarce interstratified minerals. Minerals like quartz, plagioclase and amphibole were also identified. Optically calcite, quartz, epidote, illite, chlorite, smectites, wairakite, pyrite, amphiboles and scarce biotite were recognized. These minerals occur in active hydrothermal systems where sodium-chloride fluids of neutral to alkaline pH are present.

In the past, because of the size of secondary minerals, the study of fluid inclusions was not possible. In this work it could only be possible with the help of recent technology that permits observation of microthermometric changes in tiny inclusions. This study has given information about temperature and salinity of fluids circulating in the production zone (SEZ) before production began

The purpose of this study has been to study in detail the hydrothermal mineralogy, to determine the rock conforming the production zone, to infer temperatures through mineral assemblages. The new and detailed information will give support to the Comision Federal de Electricidad to update the geologic model of the field.

Geological Setting

Tectonically, the Salton Trough-Gulf of California area is a zone of transition between the divergent boundary of the East Pacific Rise and the transform boundary of the San Andreas Fault system.

The sediments at Cerro Prieto were deposited mainly in alluvial, deltaic, estuarine and shallow-marine environments during Pliocene to middle Pleistocene times (Halfman *et al.*, 1984).

From petrographic data from more than 300 drilled wells five lithologic units have been identified (Lira, 2005) from the oldest to the latest: The first unit is the basement, represented by metamorphic and granitic rocks, and an intrusive of basaltic composition located at depth.

The gray shale is the second unit, formed by shale and sandstone interbedded in different proportions. Both together give an average thickness of 3000 m. The top of this unit is almost 400 m deep at the west of the field and 2847 m in well deep M-201 located at the east of the field. The thickness of sandstone in gray shale varies from a few meters to 300m; it has been designated as the silica epidote zone (SEZ) considered as the production zone.

The third unit is known as brown shale and overlies the gray shale. This unit is composed of shale and silt; sandstone is also found between them. The top of this unit is found at 600 m to the west and at 2500 m to the east (well M-205).

The fourth is the siltstone unit. It has a random distribution. It is found mainly to the east of the field. Layers of sandstone are also found in it.

Non indurated clastic sediments conform the fifth unit which overlies the other units. It is composed of sand, gravel, silt and clay. It is of variable thickness, thin at the west and thicker to the east.

Results

Petrographic and X-ray diffraction analysis were carried out in deep samples from the production zone. Depending of the well location and availability of material samples were analyzed every 200 or 250 m within the SEZ. The theoretical formation temperature of mineral paragenetic sequences has been estimated having as a reference data for other geothermal fields. As in other geothermal systems, epidote has been considered as a temperature indicator.

In the studied samples the intensity of hydrothermal alteration may be considered as medium to low; few samples showed almost 50 % of alteration. In sandstones alteration is mainly in material cementing grains; grains also have been altered

By transmitted light minerals like clays, mixed layer clay minerals, mica, chlorite, calcite, quartz, epidote were identified; also in minor amounts amphiboles (tremolite-actinolite, gedrite), vermiculite, anatase and sphene were observed. Opaque minerals were identified by reflected light; magnetite, hematite, pyrite, chalcopyrite, pyrrotite and sphalerite were identified in varying proportion but always in small amounts relative to the total of the sample.

The observed mineralogy has shown the association of minerals formed by interaction of the rock with hot fluids of alkaline to neutral pH. There was not evidence of minerals formed in an acidic environment. Some of the common associations and their estimated temperature in Cerro Prieto may be established as follows:

Ep - Cl - Ca - Op	> 220 °C
Ep - Cl - Ca - Sph	> 220 °C
Ep - Cl - Amp	250 > 300 °C
Ep - Qtz - Cl - Amp	250 > 300 °C
Qtz - Ca - Cl - He	150 - 200 °C
Qtz - Ca - Ep - Op	> 200 °C
Qtz - Ep - Amp	> 300 °C
Cl - Op	~ 150 °C
Cl - Ca - Ep - Qtz - Op - Sph	200-250 °C
Cl - Ill - Ca - Sph - Ep	200- 250 °C
Cl - Ep - Amp - Qtz - Ca - Es	250 - 300 °C
Ca - Cl - Qtz	< 200 °C
Ca - Sph - Op - Ep	>200 °C
Ca - Cl - Ep - Sph -Op - Amp	250 - 300 °C

Within the SEZ three thermal zones may be inferred depending on the proportion of shale and sandstone: <200 °C, 200-250 °C, 250-300°C. Very few deep samples show the presence of amphiboles indicating temperatures above 300°C. To find three thermal ranges in a relative short range of depth is a clear indication that fluid do not move to less permeable zones. The mineral assemblages near the border between sandstones and gray shale always indicate temperature less than 200 °C. High or low mineral assemblages depend mostly on the nature of the strata; it has been observed that low and high hydrothermal minerals may be preserved in low porosity and relatively impermeable zones (shale and siltstone). In some wells like M-105 at 996 m the sample is classified as siltstone-shale (65%) and sandstone (35%); mineral assemblage indicates temperature less than 200 °C. At 1248 m sample is classified as sandstone (98%); incipient epidote is observed the temperature could higher than 250 °C. Finally at 1587 the sample is mainly shale (93%) and again the mineral assemblage indicates temperature <200 °C.

Using the representation of Elders et al., (1981) the hydrothermal mineralogy in all CPGF may be illustrated as a function of temperature (Figure 2). Wairakite is a common mineral in wells located in CP IV but not in other areas of the

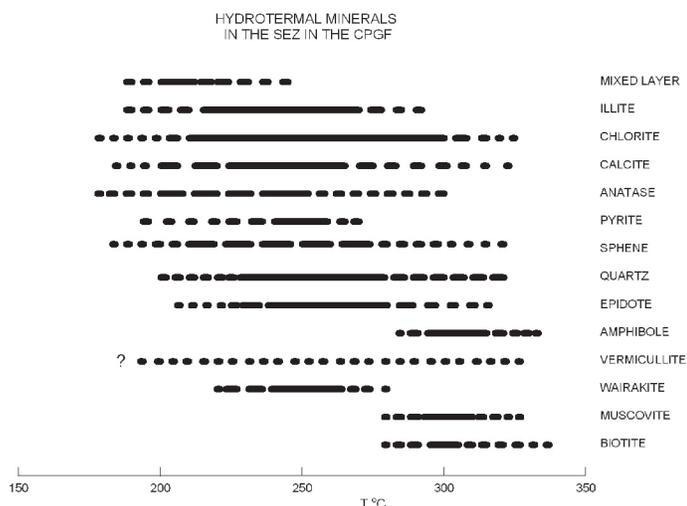


Figure 2. Minerals in the silica epidote zone at Cerro Prieto as a function of temperature (includes the mineralogy found all over the field).

field. Vermiculite is found in deep samples from the west part of the field but not in the east part (CP IV).

Seven cross sections were drawn for the field in NE-SW direction. Each section includes at least 7 wells, in that way more than 50 wells over the field were studied. As representative of the new data, only one NE-SW cross section is shown in Figure 3; lithofacies are indicated as well as the distribution of hydrothermal minerals in the silica epidote zone. Epidote is fix with a rhombus, the size of the rhombus represents the relative percentage of the mineral. As in other cross sections of the field, the presence of epidote gives a profile of a permeable horizon in the sandstone included in the gray shale. Its presence indicates permeability and circulation of hot fluids. The large amount of amphiboles at depth in well E22A indicates temperature higher than 300°C. Homogenization temperature for this well at a depth between 2400 and 2667 is in the range between 302 and 336 °C. Same behavior of epidote was observed in the other cross sections not shown in this work.

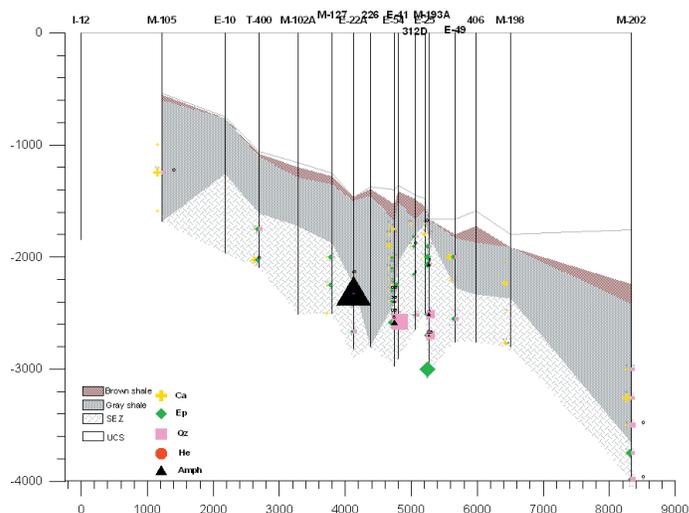


Figure 3. NE-SW cross section showing well location, lithofacies and mineral distribution in the SEZ.

Fluid inclusions were analyzed in authigenic quartz as isolated crystals filling holes in the sandstone matrix. A Linkam THMSG600 heating and cooling stage was used for the microthermometry study of fluid inclusions.

Fluid inclusions are of the vapor-liquid type with low proportion of vapor. Melting temperatures indicate variable salinities. All observed inclusions homogenize to the liquid phase. As samples analyzed come from the deep production zone, homogenization temperatures (T_h) are high; except those coming from wells located at the margins of the field as it is the case of wells I-3 and M-92 More samples need to be studied in order to conduct a proper interpretation of the meaning of microthermometric data of fluid inclusions in Cerro Prieto and compare data with present day data and some other temperature data.

Table I contains fluid inclusion data for deep samples of wells aligned in one of the NE-SW cross sections. It can be observed that for the same depth (E-49), T_h is constant and the salinity variable; for some wells T_h is variable and salinity con-

stant. This could indicate that the heating regime was constant with flow of fluids of different nature or flow of fluids from the same source and the temperature was variable. Additional work has to be done in order to give the proper interpretation of microthermometric data in Cerro Prieto.

Table 1. Fluid inclusion data for deep samples.

Well	Depth (m)	T _h °C	T _{im} °C	Eq.W % NaCl
I-3	1206.3	170	-1	1.16
M-202	3986	326	-0.4	0.66
M-198	2496	338	-0.1	0.16
M-198	2768	320	-5.7	8.78
E-49	2547	321	-5.3	8.24
E-49	2547	320	-9.0	0.82
T-400	2025	300	-0.1	0.17
M-105	1587	327	-3.7	6.08

Conclusions

Analysis of fluid inclusions in CPGF has provided information about temperatures of the system before exploitation started. At present microthermometric data can be used only for comparative purposes. Additional work is needed to set enough data on homogenization temperature and salinity of fluids that once circulated in the system.

Homogenization temperatures are in good agreement with temperatures assigned to mineral assemblages. Actual temperature data for the studied wells are required to give an interpretation of processes that have occurred in the reservoir.

In CPGF the percentage of hydrothermal alteration is not so high (less than 50% in a few deep samples). However because of the presence of minerals like epidote or amphiboles it is assumed that hot fluids were in contact with hot rocks. Low intensity of hydrothermal alteration at the time of drilling could be evidence of a young hydrothermal system.

By analogy with other geothermal fields temperature has been inferred for some common mineral assemblages found in the silica epidote zone. In a relatively short depth range at least three isotherms can be drawn; for some wells they are not always progressive because of the interstratifications of sandstones and shales.

For CPGF it is clear that hydrothermal mineralogy is dependent on temperature and permeability of the rocks. In

the gray shale, sandstones give the conditions to form high temperature alteration minerals. Epidote is an example and a good indicator of temperature. In fact its occurrence had been taken as a guide during drilling of wells.

All minerals identified are formed in neutral to alkaline environments; there is not mineralogical evidence of interaction of reservoir rocks with low pH fluids.

Acknowledgements.

The authors wish to express their indebtedness to the authorities of the Comisión Federal de Electricidad, Residencia General de Cerro Prieto for their support and assistance during these studies; which were part of the contract CFE 9400017183. Also, we want to express our gratitude to Mr. Salvador Antunez A. and the technical personnel of the Instituto de Investigaciones Eléctricas for their support during execution of these studies.

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