GRC *Transactions*, Vol. 39, 2015

Cerro Prieto, Mexico—A Convective Extensional Geothermal Play

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Keywords
Geothermal plays, transform margin, extensional, tectonic setting, exploration

ABSTRACT

The Cerro Prieto, Mexico, geothermal field lies in a convective geothermal play type located into an extensional (transtensional) setting, defined by a pull-apart basin in the middle of two strike-slip faults belonging to the San Andreas fault system, which in turn is part of the transform margin between the North America and Pacific plates. The reservoir is of high temperature (250-310°C) and liquid-dominant type with a current production of 41% steam and 59% brine of typical neutral sodium-chloride composition and average of 27,300 ppm of total dissolved solids (TDS). The easternmost wells produce geothermal fluids with lower pH. The steam fraction presents an average of 1.4% in weight of non-condensable gases. The natural recharge to the reservoir is groundwater from a huge, shallow, alluvial aquifer and the Colorado River located to the east. The heat source is a regional thinning of the continental crust producing heat plumes and inferred basic intrusives. Host rocks are Tertiary sandstones interbedded into shales overlying a mainly Cretaceous granitic basement. Reservoir permeability is primary (sandstones matrix for storage) and secondary, with faults driving the geothermal flows. With an installed power capacity of 720 MW (570 MW currently in operation), the field is the second largest worldwide, and has been in production since 1973. There are almost 170 production and injection wells with average depth of 2,400 meters. The field is located at 13 meters above the sea level into a low-relieve topographic framework.

1. Introduction

The proper comparison between different renewable and non-renewable energy sources requires, among other things, consistent methods for assessing and classifying their energy potential. Many non-renewable and renewable energy sectors have defined and adopted standard methodologies for assessing energy potential in a globally consistent manner, like the classification scheme UNFC-2009 (United Nations Framework Classification for Fossil Energy and Mineral Resources 2009) that is currently under development by the United Nations Economic Commission for Europe (UNECE). The resolution 2004/233 of the United Nations Economic and Social Council invited UN's state members, international organizations and regional commissions to take appropriate measures for ensuring worldwide application of the United Nations Framework Classification for Fossil Energy and Mineral Resources. The member states of the UNECE decided work to apply the UNFC-2009 to renewable energy resources. The aim is to reconcile estimates of fossil energy resources with renewable energy resources.

Recently the International Geothermal Association (IGA) and the UNECE Expert Group on Resource Classification signed a Memorandum of Understanding (MoU) for the IGA to provide the commodity-specific specifications for the application of UNFC-2009 to geothermal resources, along with the proper generic specifications and guidelines. In parallel, through its Resources and Reserves (R&R) Committee the IGA Board of Directors approved a working plan with two additional sets of activities that will result in (i) a glossary of definitions for terms related to geothermal resources and reserves, and (ii) a Catalogue of Geothermal Play Types based on geological criteria, which can be used as a basis for discovering geothermal systems and guiding efficient exploration and development of those systems.

That is the general framework for this paper, whose main objective is to present a comprehensive description of the Cerro Prieto geothermal play.

2. Geothermal Plays

In the oil industry, a petroleum play is usually defined as the combination of geological parameters that control the location of a certain type of hydrocarbon accumulation (Mudge and Holdoway, 2005), or as a group of oil fields or prospects in the same region that are controlled by the same set of geological conditions. A specific play type represents a particular stratigraphic or structural geological setting, defined by source rock, reservoir rock and trap. Geothermal plays, for the other hand, can be defined as sets of geological conditions that might support natural or engineered geothermal systems, where the heat source and the geological elements that control the transport and storage capacity of the heat and geothermal fluids are the key elements (Moeck, 2014; Moeck and Beardsmore, 2014). The Australian lexicon indicates that geothermal play can also be used as “an informal qualitative descriptor for an accumulation of heat energy within the Earth’s crust. It can apply to heat contained in rock and/or fluid. It has no connotations as to permeability or the recoverability of the energy, although it implies an intention to investigate those parameters. A Geothermal Play does not necessarily imply the existence of a Geothermal Resource or Reserve and quantitative amounts of energy must not be reported against it” (AGEG-AGEA, 2010).

When discussing geothermal plays, it is important to take into account the similarities and differences with petroleum plays. Although the exploitation of geothermal resources has many similar characteristics to extraction of petroleum resources, there are of course important differences. While oil and gas resources are the fluids themselves, geothermal resources are more related to the thermal energy contained in the fluid and in the host rock, whose extraction involves thermodynamic processes not observed in petroleum extraction. In hydrothermal systems, geothermal resources differ also from petroleum (and mineral) resources by their renewable nature through recharge –providing that it is faster than the extraction of energy. Petroleum products have a defined and worldwide value in dollars, while electrical energy tariffs prices vary widely from place to place and are highly country and region specific (AGEG-AGEA, 2010). And, finally, in contrast to the straight definition of hydrocarbon play systems, clearly defined by the source rock, common reservoir and trap, geothermal play systems lack of such clear set of geological features, since they may appear everywhere. That is so because heat is available everywhere, and where the specific heat demand of the potential end-user of geothermal energy at site is relevant (Moeck, 2014).

Moeck and Beardsmore (2014) recently added that a geothermal play may be defined as a preliminary model “in the mind of a geologist of how a number of geological factors might generate a recoverable geothermal resource at a specific structural position in a certain geologic setting”, and proposed an initial classification scheme, summarized in the Table 1 (taken from Gutiérrez-Negrín, 2015).

Table 1. Preliminary classification of geothermal plays (prepared with data based on Moeck and Beardsmore, 2014).

Heat Transfer	Division / Subdivision		Some Examples
Convection dominated	Magmatic	Extrusive	Java (Indonesia), Andes mountains (South America)
		Intrusive	Taupo (New Zealand)
	Plutonic	Recent volcanism	Larderello (Italy)
		No recent volcanism	The Geysers (USA)
	Extensional domain		Great Basin (USA), Western Turkey, African Rift Valley
Conduction dominated	Intracratonic basin		Paris Basin (France), Neustadt-Glewe (Germany)
	Orogenic belt with adjacent foreland basins		Bavarian Molasse Basin (Germany), North Dakota (USA)
	Basement/Crystalline rocks		Habanero (Australia)

3. The Cerro Prieto Field

Cerro Prieto is the oldest and largest field in operation in Mexico, and the second largest worldwide after its installed capacity of 720 MW (570 MW in operation). It is located in north-western Mexico, at around 30 km south of the international border with the US (Fig. 1). The field lies within the alluvial plain of the Mexicali Valley, at an average altitude of 14 meters above the sea level (masl), and is owned and operated by the state utility Comisión Federal de Electricidad (CFE), which also owns and runs the power plants.

During the last 50 years about 430 geothermal wells have been drilled in the field and its surroundings, with an average depth of 2,400 m and maximum depth of 4,400 m. The Cerro Prieto reservoir has been under exploitation more than 40 years, and approximately 3,300 million of metric tons of fluids have been drawn up to 2013, from an area of roughly 18 km^2 (estimate after data from Aguilar Dumas, 2010). In the last years, the field has experienced problems related to a lower steam production, mainly due to pressure, enthalpy, and temperature drops, which in turn come from over-exploiting the geothermal resource. That situation resulted in the CFE's decision of place out of production the first oldest and less efficient four power units of 37.5 MW (megawatts) each. Thus, although the installed capacity is still 720 MW, the running capacity is only 570 MW.

In average, 159 production wells were in operation along 2014 producing 35.6 million of metric tons of steam, at an annual average rate of 4,060 tons per hour (t/h). There were nine power units in operation, all of flash type: four of 110 MW each, one of 30 MW and four of 25 MW each. The power units in operation produced around 4,000 GWh (gigawatts-hour) at an annual capacity factor of 84.5%.

The annual average production rate per well in Cerro Prieto in 2014 was 25.5 t/h. There were also 16 injection wells operating in the field to partially dispose ~60 million tons of separated brine. Most of the brine was disposed in the solar evaporation pond. According to the steam and electric output produced in Cerro Prieto, the gross steam specific consumption during 2014 was of 8.9 tons per MWh (megawatts-hour) in average.

4. Geologic and Tectonic Setting

Cerro Prieto lies into a pull-apart basin formed as result of two active strike-slip faults from the San Andreas Fault System. The heat source seems to be a basic intrusion producing a thermal anomaly, which in turn has been produced by the thinning of the continental crust in the basin. A sequence of sedimentary rocks (sandstones interbedded into shales) with a mean thickness of ~3,000 meters is hosting the geothermal fluids.

The Basin and Range Province of the western United States was formed during Late Tertiary as a consequence of mainly tensional tectonic movements. This same tectonics in north-western Mexico resulted in the Cerro Prieto region in the formation of a couple of half-graben tectonic basins between the Cucapah and Cerro Prieto faults and the Michoacán and Imperial faults (Lira, 2005; Gallardo et al., 2012). Currently, the geothermal field is located within a pull-apart basin between the faults of Cucapah-Cerro Prieto (at west) and Imperial (at east) that are of strike-slip type and belong to the San Andreas system. The region is presently subject to transtensional stresses (Fig. 1).

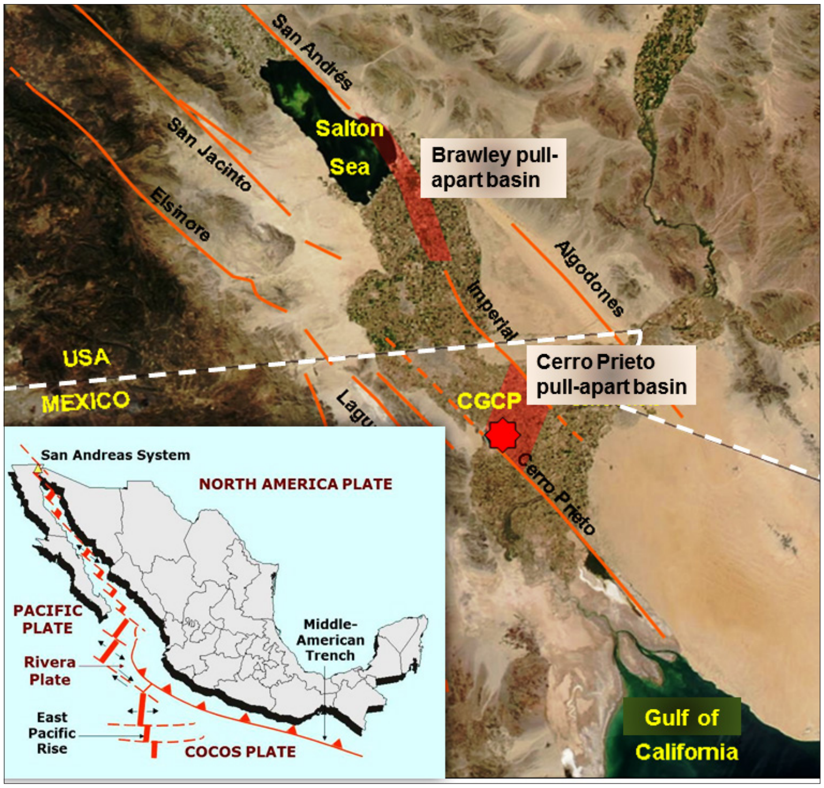

Figure 1. Location and tectonic frame of the Cerro Prieto geothermal play.

Gallardo et al. (2012) have applied the rifting model detailed by Bosence (1998, cit. by Gallardo et al., 2012), starting by a detachment that produced the thinning of the crust and the isostatic rising of the basement units, as well as elongated basins that were filled by syn-sedimentary deposits and by evaporitic facies during a posterior marine transgression. These evaporitic and transitional delta deposits could be the cause of marine water and acid fluids in some portions of the Cerro Prieto field. During the subsequent transtensional phase the area experienced subsidence and some deltaic sediments with facies changes were deposited to form the unit that currently hosts the geothermal fluids –the so-called Grey Shale Unit, composed of shales with interbedded sandstones. Some regression periods occurred too, producing the deposit of fluvial-deltaic sediments from the Colorado River that currently form the un-consolidated clastic sediments unit (Fig. 2).

The oldest rocks identified in the area are gneiss and biotite-schists of Permian-Jurassic age and tonalites of Jurassic-Cretaceous age in contact with Cretaceous granites, all representing the regional basement. The lithological column in the subsurface of the Cerro Prieto basin is formed by the intrusive basement; an argillaceous package resting on the basement composed of grey shales with interbedded sandstones, brown-shales and mudstones; and clastic sediments of Quaternary age deposited mainly by the Colorado River and alluvial fans of the Cucapah Range, composed of gravel, sands and clays (Lira, 2005).

The Cerro Prieto volcano is the only volcanic structure in the area. It is a stratovolcano at 220 masl, emplaced on the granitic basement in the alluvial plain of the Mexicali Valley. It is composed of one volcanic cone and several domes of dacitic composition (65-69% by weight of SiO_2) and almost circular shape. Among its rocks are brecciated dacitic lavas, epiclastic deposits, dacitic lavas, dikes and domes, and air-fall deposits and flow debris deposits of lahar type. Volcanic activity started around 80,000 years ago. There is some fumarole activity with surface temperatures of 42-52°C on the western portion of the volcano (Macías and Rocha, 2012).

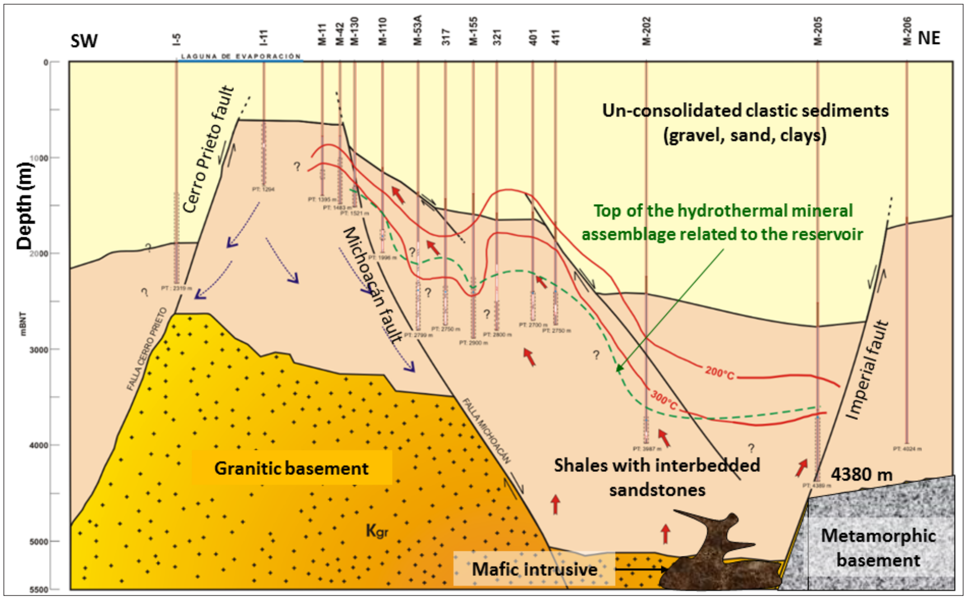

Figure 2. Schematic model of the Cerro Prieto geothermal play (adapted from Lira, 2005, and Aguilar-Dumas, 2010).

The Cerro Prieto basement is composed of three distinct parts called by Lira (2005) the tectonic-stratigraphic terranes of North America and Baja California, and the so-called Mafic Intrusive. The tectonic-stratigraphic terrane of North America is composed of Palaeozoic-Mesozoic metamorphic and intrusive rocks (the mentioned gneiss, schists and tonalites). The Baja California Terrane is composed of Cretaceous granites, while the Mafic Intrusive seems to have been emplaced during the Late Tertiary (Lira, 2005) as a consequence of the thinning of the continental crust due to the rifting process occurring between the Cerro Prieto-Michoacán and Imperial faults (Fig. 2). This basic intrusive of diabasic composition is apparently associated with a magnetic anomaly known as Nuevo León and is considered to be the heat source of the current geothermal system, apparently fed by new magma.

The geothermal fluids are contained in sandstones interbedded into the grey shales that form the lithological unit resting directly on the basement. This package is called the Grey Shale Unit (Unidad Lutita Gris) and is Middle to Late Tertiary in age. Its top is found at 400 m depth in the western part of the field and at ~2,900 m depth in the eastern portion, with an average thickness of 3,000 m. The sandstones are arkoses composed of fragments of quartz and feldspar with thickness varying from a few centimetres to 300 meters, and porosity up to 22% (Lira, 2005). This unit is covered by other shales-sandstones (the Brown Shale or Lutita Café Unit) and mudstones, which in turn are covered by the un-consolidated clastic sediments unit of Quaternary age, with thickness from 400 to 2,500 m (Fig. 2).

Superficial thermal manifestations used to be hot springs, mud ponds, fumaroles and the Laguna Volcano, which is a hot pond with hot soils and mud-volcanoes. All of them are located in the west of the geothermal field, and most are presently covered by the solar evaporation pond. Hot springs presented temperatures around 90°C, pH between 6.5 and 8, total dissolved solids (TDS) of ~15,000 mg/kg and sodium-chloride composition. Mud ponds showed temperatures over 90°C, pH < 8, TDS lower than 5,000 mg/kg and sodium-sulphate-bicarbonate composition. The temperatures in Laguna Volcano are around 45°C, pH is acid (1-5), TDS is ~30,000 mg/kg and the composition is calcium-sulphate-chloride. Fumaroles presented two temperature ranks, one around 45°C and other between 80 and 100°C, with condensates of pH between 3 and 8 and TDS lower than 1,000 mg/kg, composed mainly of sulphates (all data from CFE, 1989).

5. Main Features of the Geothermal Reservoir

The Cerro Prieto system is a dominant liquid reservoir. The wells produce a mixture of fluids at surface conditions with approximately 65% water (currently 60%) and 35% (currently 40%) steam. The liquid fraction is diluted brine with sodium-chloride chemical composition and neutral to alkaline pH. The brine presents an average of 27,400 mg/kg of total dissolved solids (TDS), varying from 20,000 mg/kg in the western sector of the field known as Cerro Prieto I (CP-I) to 33,000 mg/kg in the Cerro Prieto II (CP-II) section. The steam fraction contains an average of 1.4% in weight of non-condensable gases, ranging from 1% in CP-I to 1.8% in CP-III, being CO_2 the main component (89% of total gases) (Portugal et al., 2005).

In the CP-IV sector, located in the easternmost part of the field, wells produce two-phase fluids at wellhead conditions with heterogeneous characteristics of the steam fraction. At its 'natural state' fluids used to present reservoir temperatures from 275 to 310°C and excess steam values from -1 to 50%. The well discharges consist of a mixture in different proportions of two end-members. One is a liquid with temperature of over 300°C and negative or negligible excess steam, and the other seems to be a two-phase fluid with temperature of about 275°C and excess steam fraction of about 0.5. Wells drilled after year 2000 suggest the presence of a steam phase in the reservoir, which could be generated due to the boiling of deep reservoir fluid from a pressure drop (Barragán Reyes et al., 2007). The deepest wells in CP-IV have produced low-pH fluids causing corrosion problems in the well casings.

The isotopic composition of the liquid phase goes from -5.5 to -11.5‰ for oxygen-18 and from -80 to -102‰ for deuterium. The natural recharge of the reservoir is groundwater from the alluvial aquifer and the Colorado River located to the east of the field. The fluids feeding the geothermal reservoir are heated as they pass through the zone where the basic intrusive is located (the heat source) and migrate through NE-SW faults toward the permeable layers of sandstone located within the grey shales (Fig. 2).

Four hydrothermal zones have been identified in the subsurface of Cerro Prieto, called zone with cement of calcium carbonate (100-200°C), zone with cement of calcium carbonate and silica (150-250°C), transition zone (~250°C) and zone with cement of silica and epidote (~300°C) (Elders et al., 1978, cit. by Lira, 2005). The last one is related to the production zone of the wells, and is located in the deep part of the Grey Shale Unit (see Fig. 2). All of these mineral assemblages are replacing in several degrees the original cement of the sandstones.

It is worth to mention that the exploration surveys conducted by the CFE in Cerro Prieto to locate the first exploration wells, included regional and local geological studies, mainly focused on the structural and geo-hydrological features of the Mexicali Valley and the geothermal field, in particular. Sampling and analysis of the superficial manifestations and their geochemical interpretation was systematically used during the exploration stage. Among the geophysical studies, the CFE performed superficial thermometry to map and locate the thermal manifestations, superficial isotherms and heat flow. Reflection and refraction seismological surveys, along with gravimetric and magnetometric surveys were also carried out to locate the main structures and the depth of the intrusive basement. Mainly based on these studies, the first four exploration wells were located and drilled in 1964, with depths up to 2,500 m. Two of these wells were successful. Since 1969 onwards, more seismological surveys were performed (including passive seismic), as well as aeromagnetic studies, resistivity surveys (VES: Vertical Electric Sounds in dipole-dipole and Schlumberger arrangements), electric natural potential, a magnetotelluric survey in 1978, and more gravimetric and magnetometric studies. All of these studies allowed locate new wells to the east of the first ones, and eventually extend the field up to its current limits. In fact, the deep reservoir extends to the east more than the current limits of the field. Most appropriate geophysical surveys in this type of geothermal play seem to be thermometric, seismic, gravimetric-magnetometric, and resistivity (CFE, 1989).

6. Conclusions

Based on the classification given in Table 1, the Cerro Prieto geothermal play is of course convective. Among the three convection-dominant subtypes, the field is clearly located in an extensional domain, although it shows some features typical of the magmatic-intrusive subtype included in the Table 1. Such features are the basic intrusive deemed as the heat source of the Cerro Prieto geothermal system, which is supposed to be relatively recent, as well as the flat terrain (the Mexicali Valley) where the field is located with almost no volcanism. However, it seems to be clear that in

Table 2. Main features of the Cerro Prieto extensional geothermal play.

Feature	Description
Tectonic setting / regime	Transform margin. Pull-apart basin between two strike-slip faults / Regime transtensional
Structural setting	Right lateral and normal faults
Relief / Altitude	Low / ~13 masl
Volcanic activity / Age	Scarce, only the Cerro Prieto volcano / 80,000 years
Surface manifestations	Hot springs, fumaroles, mud volcanoes, hot ponds (95°C)
Heat source	Regional heat plumes and basic intrusive
Host rock	Tertiary sandstones interbedded into shales
Cap-rock	Shales and mudstones
Basement	Cretaceous granitic and Paleozoic-Mesozoic metamorphic
Reservoir	Liquid-dominant (steam: 41%), at 250-310°C and ~2,400 m depth
Permeability	Faults and lithofacies (sandstones)
Liquid phase	Sodium chloride coming from regional aquifer and the Colorado River
Hydrothermal alteration	High. Replacement of the original cement of sandstones
Best exploration tools	Geophysics: Thermometry, seismic, gravimetry-magnetometry, resistivity

this case the tectonic setting is the key factor for the very existence of the geothermal resource. Thus, Cerro Prieto can be sub-classified as an extensional domain geothermal play, according to the preliminary classification proposed by Moeck (2014) and Moeck and Beardsmore (2014).

The main characteristics of the play are presented in Table 2 (taken and adapted from Gutiérrez-Negrín, 2015).

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