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Mexican Geothermal Plays

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ABSTRACT

Defining geothermal plays is one of the initial steps for a proper comparison between geothermal energy potential and other renewable and non-renewable sources. Geothermal plays can be defined by the heat source and the geological elements that control the transport and storage of the heat and the geothermal fluids. The main geologic and geothermal characteristics of the Mexican geothermal fields of Cerro Prieto, Los Azufres, Los Humeros, Las Tres Vírgenes and Cerritos Colorados are succinctly described and the fields are defined in terms of their respective geothermal plays, following the initial classification scheme proposed by Moeck and Beardsmore (2014). Using this preliminary scheme, it is proposed that Cerro Prieto might be considered as an extensional domain play, and the other four fields as extrusive magmatic plays.

1. INTRODUCTION

In the oil industry, a petroleum play, or more simply a play, can be defined as the combination of geological parameters that control the location of a 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. Thus, a play type represents a particular stratigraphic or structural geological setting, defined by source rock, reservoir rock and trap. In an analog way, geothermal plays 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 and Beardsmore, 2014).

According to the Australian lexicon, the term 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).

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.

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

Heat transfer	Division / Subdivision		Some examples
Convection dominant	Magmatic	Extrusive	Java (Indonesia), Andes mountains (South America)
		Intrusive	Taupo (New Zealand)
	Plutonic	Recent volcanism	Larederello (Italy)
		No recent volcanism	The Geysers (USA)
	Extensional domain		Great Basin (USA), Western Turkey, African Rift Valley
Conduction dominant	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)

The purpose of this paper is to describe the main features of the geothermal plays into which the currently identified Mexican geothermal fields are located, in the framework of this initial classification.

2. CERRO PRIETO GEOTHERMAL FIELD

This 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 northwestern Mexico (Fig. 1), at around 30 km south of the international border with the US. The field lies within the alluvial plain of the Mexicali Valley, at an average altitude of 13 meters above the sea level (masl).

The tensional tectonics that formed the Basin and Range Province of the western United States and northwestern Mexico during Late Tertiary, in the Cerro Prieto area resulted 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 lies within a pull-apart basin between the Cucapah-Cerro Prieto and Imperial faults that are of strike-slip type and belong to the San Andreas system, and then all the region is subject to transtensional stresses.

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 gray 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 at 220 masl, emplaced on a granitic basement on the alluvial plain of the Mexicali Valley, and is composed of one volcanic cone and several domes of dacitic composition (65-69% by weight of SiO_2) and almost circular shape. It is a small stratovolcano composed of brecciated dacitic lava, epiclastic deposits, dacitic lava, dikes and domes, and air-fall deposits and flow debris deposits of lahar type, formed 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).

The basement seems to be composed of three distinct portions, called by Lira (2005) the North America Terrane, the Baja California Terrane and the Mafic Intrusive. The tectonic-stratigraphic terranes of North America and Baja California are composed of Paleozoic-Mesozoic metamorphic and intrusive rocks (the mentioned gneiss, schists and tonalites) and Cretaceous granites, respectively, 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 and Imperial faults. This basic intrusive is associated with a magnetic anomaly 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 gray shales that form the lithological unit resting directly on the basement. This package is called Lutita Gris Unit 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 2900 m depth in the eastern portion, with an average thickness of 3000 m. The sandstones are arkoses composed of fragments of quartz and feldspar with thickness varying from a few centimeters to 300 m and porosity up to 22% (Lira, 2005). This unit is covered by other shales-sandstones (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 2500 m.

The interaction of geothermal fluids with the host rocks has produced hydrothermal minerals that replace in several grades the original cement of the sandstones. Four hydrothermal zones have been defined 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 gray shale.

The Cerro Prieto system is a dominated liquid reservoir, and the wells produce a mixture of fluids at surface conditions with approximately 60% water and 40% steam. The liquid fraction has a sodium-chloride chemical type with neutral to alkaline pH. It is a diluted brine with an average of 27,400 mg/kg of total dissolved solids (TDS), varying from 20,000 mg/kg in the sector of the field known as Cerro Prieto I (CP-I) to 33,000 mg/kg in Cerro Prieto II (CP-II). The steam fraction contains an average of 1.4% in weight of un-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 most recently developed CP-IV sector, wells produce two-phase fluids at wellhead with heterogeneous steam fraction characteristics. At its 'natural state' fluids presented 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 seems to be a liquid with a temperature of over 300°C with negative or negligible excess steam, and the other seems to be a two-phase fluid with a temperature of about 275°C and an 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 with the boiling of deep reservoir fluid from a pressure drop (Barragán Reyes et al., 2007).

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 regional 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 gray shales.

The Cerro Prieto reservoir has been under exploitation more than 40 years. Approximately 3,300 million of metric tons of fluids have been drawn up to 2013, from an area of roughly 18km^2. In the last years, the field experience 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 decision of place out of production the first oldest and less efficient four power units of 37.5 MW each. Thus, although the installed capacity is 720 MW, the running capacity is 570 MW. To feed these units, around 35 million tons of steam are annually produced by 160 production wells. The annual electric generation is around 4,100 GWh.

3. LOS AZUFRES GEOTHERMAL FIELD

Los Azufres is located in the central part of the country (Figure 1), inside the Mexican Volcanic Belt province at an average elevation of 2,850 masl. The field lies in a complex Plio-Pleistocene succession of basalts, andesites, dacites and rhyolites representing three probable volcanic cycles. The second cycle started with basalts and continuing with basaltic andesites, porphyritic and microcrystalline andesites, dacites and rhyolites, each rock type accompanied by its pyroclastic equivalents. The first cycle is represented only by scarce dacites at the bottom of some deepest wells, stratigraphically below of thick andesitic sequences. Some young basaltic and diabase dikes stratigraphically and radiometrically younger than the youngest rhyolites that are the final, acid stage of the second volcanic cycle, represent the third, final volcanic cycle. The geothermal fluids are hosted by the middle and lower parts of the second, more complete cycle, mainly by andesites (Gutiérrez-Negrín and Aumento, 1982).

It has been postulated that the field is located in the southern portion of a large (~80 km in diameter) caldera within the Morelia-Acambay rift (Ferrari et al., 1991), yet more recent studies did not found any evidences for such large caldera (Pérez-Esquivias et al., 2010). In any case this caldera wouldn't be related to the current geothermal system, whose heat source seems to be the magma chamber feeding the San Andrés volcano, the highest peak in the area.

The volcanic rocks un-conformably overlie metamorphic and sedimentary rocks of Late Mesozoic to Oligocene age. This pre-volcanic basement has not been cut by the wells but is supposed to consist of gently folded shales, sandstones, and conglomerates. The oldest volcanic activity reported in the area began as andesite flows about 18 Ma, followed by micro-granular andesites of 5.9 ± 0.6 Ma in age, highly fractured and faulted with layering resembling that of sedimentary rocks in places (Gutiérrez-Negrín and Aumento, 1982; Dobson and Mahood, 1985). More than 2700 m thick interstratified lava flows and pyroclastic rocks of andesitic to basaltic composition, with ages between 18 and 1 Ma, form the local basement where the geothermal fluids are found in its middle and lower portions.

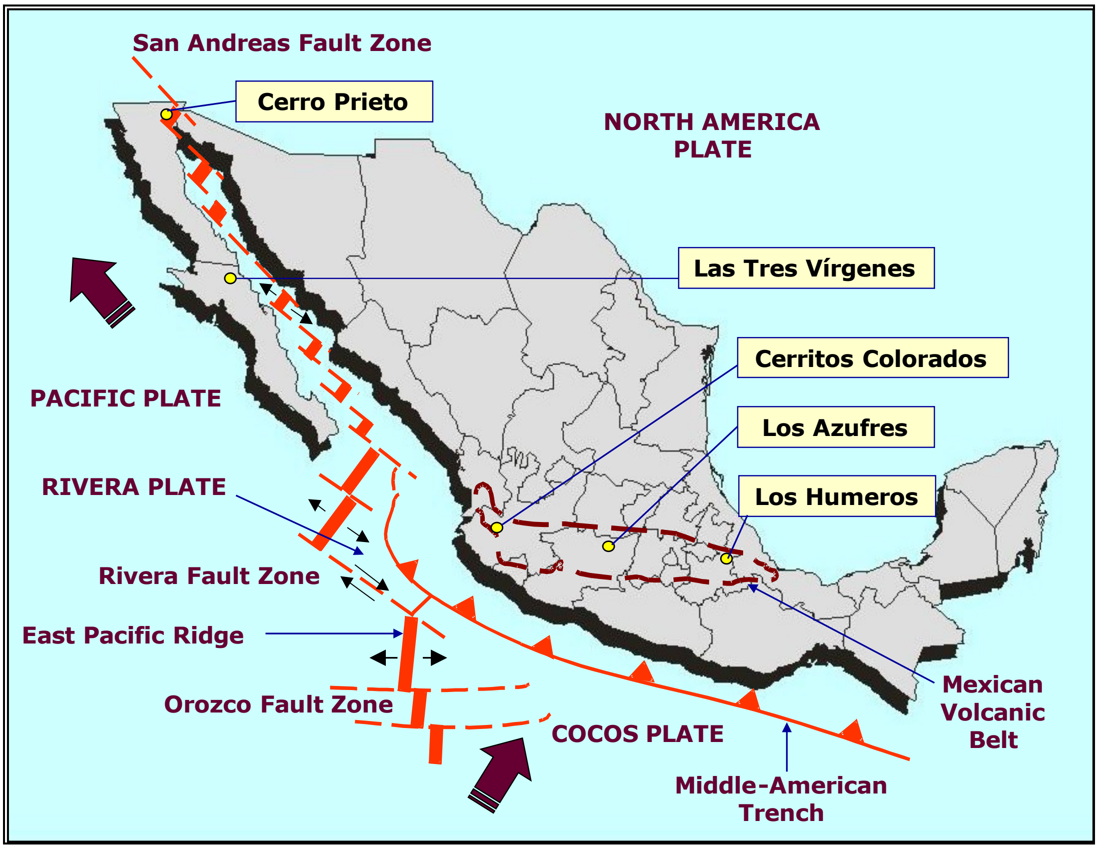

Figure 1: General tectonic setting of Mexico and location of geothermal fields.

The andesites are overlain by flow-structured rhyolites of 1.2 ± 0.4 Ma in age, which include obsidian flows and perlite structures in some sites. Rhyolites are also fractured and present wide areas of superficial kaolin as results of hydrothermal alteration by geothermal fluids discharging at the surface. The silicic volcanism also includes rhyodacites and dacites with ages up to 0.15 Ma and a thickness of up to 1,000 m, with five different units: the Agua Fría rhyolite, Tejamaniles dacite, Cerro Mozo and San Andrés dacites, and Yerbabuena rhyolite. They form domes and short lava flows with glassy structures, and are generally fractured on the surface. Close to hydrothermal manifestations, they show a very intense alteration, characterized by strong kaolinitization and silicification. The more recent outcropping rocks include porphyritic andesites, glassy and pumicitic rhyolites, and basalt flows and cinder cones on the western field, product of the youngest volcanic activity in the area (Gutiérrez-Negrín and Aumento, 1982; Dobson and Mahood, 1985).

Three main fractures trends NNW-SSE, NE-SW, and E-W have been identified in the field and its surroundings. The first trend corresponds to a Miocene deformation with semi-vertical geometry affecting the basement. The two other trends were formed as part of the Mexican Volcanic Belt and present semi-vertical and sub-horizontal geometry in regionally affected Miocene basement rocks and Quaternary rocks outcropping in the geothermal field (Pérez Esquivias et al., 2010).

Hydrothermal manifestations are represented by hot springs, some with temperatures up to 90°C –especially through faults where the fluid surpasses the vadose zone--, fumaroles, steaming soil, mud pools and even small thermal lakes. The thermal features are mostly located along faults or lineaments suggesting a fracture control (Viggiano-Guerra and Gutiérrez-Negrín, 1995).

In general, hydrothermal alteration has affected most rocks in the Los Azufres geothermal field. The hydrothermal alteration of primary minerals and rock matrix, as well as vesicle and fracture filling, ranges from incipient to complete. The subsurface hydrothermal activity can be divided into two types: acid sulfate (near surface) and alkali chloride, below the water table, which is located at about 400 m depth. Separation of steam from the boiling alkali chloride water provides steam to some shallow wells in the Southern Zone of the field. Three main calc-silicate alteration zones have been defined. The shallower is the zeolite zone, located below 400 m depth and composed of calcite ± anhydrite + pyrite + smectite + chlorite + quartz (chalcedony) and zeolites (heulandite and laumontite). Below is the epidote zone, composed of epidote + wairakita + chlorite (penninite) + quartz + illite/smectite + illite + calcite + pyrite ± prehnite. It is located between 400 and 2000 m depth on average, and is the most important because it contains the producing reservoir, with temperatures between 250 and 285°C. Finally is the amphibole zone, presenting amphibole + epidote ± wairakite + biotite ± illite ± chlorite ± garnet ± diopside. This zone is located below 2,200 m depth with temperatures up to 285°C and pressures over 170 bars. Porosity is less than 3% and anhydrous minerals appear, and thus the thermal regime is forced convective or almost conductive. No well drilled into this zone is producer. It has been assumed this zone acts as an aquitard with alternating regimes from conductive to convective or vice versa, but also channels fluids to the upper reservoir (Viggiano-Guerra and Gutiérrez-Negrín, 1995).

Deep geothermal fluids in Los Azufres are sodium chloride-rich waters with high CO_2 contents, and pH around 7.5. Although fluid temperatures can reach as high as 320ºC, 240 to 280ºC are commonly measured in the field. Geochemical studies have shown that chemical reactions between the volcanic rocks and geothermal fluids are close to equilibrium (Verma et al., 1989).

Analysis of production, chemical and isotopic (δ18O, δD) data in the northern zone of the field showed interference effects of fluids reinjected in some wells. In the southern zone the long-term response is more complex, and the following patterns were identified: pressure and mass flow-rate drop, boiling, cooling, vapor production and—in some wells affected by injection—an increase in both pressure and mass flow rate. The isotopic results of well fluids in the southern zone showed the occurrence of two processes. The first, with a positive slope, indicates a mixing of reservoir and injection fluids affecting some wells. The second, with a negative slope, results from the original processes of reservoir steam separation and partial condensation (Arellano et al., 2004, 2005).

Main un-condensable gases in the separated steam are CO_2 (94% in volume), with H_2S (2.5% in volume) and minor concentrations of H_2, CH_4, N_2 and NH_3 (combined 3.5% in volume). In general, production wells have shown a decrease in the temperature of the fluids and an increase in the steam fraction of the reservoir (Barragán-Reyes et al., 2012).

There are currently 37 production and 6 injection wells in operation, producing more than 14 million tons of steam per year, accompanied by 4.3 million tons of brine. The first power plants were commissioned in 1982, and the present installed capacity is 194 MW. One additional 50-MW flash power unit is under construction, expected to be operating in early 2015.

4. LOS HUMEROS GEOTHERMAL FIELD

The Los Humeros geothermal field is located at the eastern state of Puebla and the western state of Veracruz, at central-eastern Mexico (Fig. 1), at an average elevation of 2,800 masl. The field has been developed inside the Los Humeros volcanic caldera, which lies at the eastern end of the Mexican Volcanic Belt, near the limit of this province with the Sierra Madre Oriental province.

The oldest outcropping rocks at the surroundings of the field are granites and schists of Paleozoic age (De la Cruz, 1983). By the beginning of the Tertiary started the Laramide Orogeny that gave place to two distinct strain styles: folds on basin limestones towards the north and folds and thrusts on shelf limestones towards the south (Garduño et al., 1985). The orogeny produced also low to medium regional metamorphism on the sedimentary rocks.

Volcanic activity in the area started in the Miocene, around 10 Ma ago, and continued in the Pliocene between 3.5 and 1.9 Ma. The caldera process began 0.51 Ma ago when a highly differentiated magmatic chamber was emplaced into the Mesozoic calcareous package, which was already partially metamorphized by the Laramide Orogeny and some Oligocene intrusions. A series of explosive eruptions produced pyroclastic flows stretching over 3,000 km^2 and triggered a gravitational collapse. The equivalent erupted magma was 155 km^3 and produced the Los Humeros caldera with 15-21 km in diameter. A second caldera collapse occurred 100,000 years ago, due to other sudden explosive eruptions giving place to new pyroclastic flows with an equivalent magma volume of 20 km^3. This was the Los Potreros caldera, nested inside Los Humeros caldera with diameter between 7 and 10 km (Yáñez and Casique, 1980; Ferriz and Mahood, 1984).

The last volcanic activities occurred at 60,000, 40,000 and 20,000 years ago producing scarce rhyolitic domes, abundant cinder cones and some andesitic volcanoes and flows, including two volcanoes and an explosion crater of 1.7 km in diameter, as well as the last andesitic, basaltic and dacitic lava flows and some phreatic and phreatic-magmatic explosions with deposits of ashes and sand. Since then a geothermal system has been forming at the subsurface, whose heat source is the magmatic chamber that is at its last, hydrothermal stage.

The subsurface lithology cut by the wells can be grouped into four units (Gutiérrez-Negrín, 1982, Viggiano and Robles, 1988). Geothermal fluids are contained in the third one (Unit 3), composed of thick andesitic lava flows, with some intercalations of horizons of tuffs. This unit is cover by the ignimbrites produced by the two calderas that form the Unit 2 and act as an aquitard, and overlies the Jurassic-Oligocene (140-31 Ma) basement (Unit 4), composed of limestones, subordinated shales and flint lenses, which were folded and partially metamorphized by the Laramide Orogeny, and then locally metamorphized by Oligocene intrusions. Basement includes also intrusive rocks (granite, granodiorite and tonalite) and metamorphic (marble, skarn, hornfels), and eventually some more recent (Miocene?) diabasic to andesitic dikes.

From a tectonic view point, Los Humeros caldera is situated at the northern border of the graben of Libres-Oriental, a NNE-SSW and roughly triangular deep formed by a distension stage that gives place to the endorheic hydrographic basin of the same name. It has been identified two main structural systems in the field, the oldest NE-SW to E-W and the more recent NW-SE to N-S (Garduño et al., 1985).

Superficial thermal manifestations in Los Humeros are gaseous in the form of fumaroles, heat steam-soils and alteration (kaolin) zones. These manifestations release small amount of steam through the porous soils, faults and fractures with superficial temperatures between 50 to 89°C. The hydrothermal minerals can be grouped into three zones (Viggiano and Robles, 1988), even though they are not uniformly defined. These are: zeolites zone with temperatures between 50 and 150° C, epidote zone with current temperatures of 150-300°C, and amphiboles zone at present temperatures higher than 300°C. There seem to be two up-flow areas of the reservoir (Gutiérrez-Negrín et al., 2010).

There are currently 22 production and 3 injection wells in operation in the field, to feed an installed capacity of 93.4 MW (running capacity 68.4 MW). The wells produce more than 5 million metric tons of steam annually, accompanied by 0.7 million tons of brine. The produced fluids are mainly steam with high enthalpy (more than 2000 kJ/kg), yet the well H-1 produces mainly water with enthalpy of 1100-1300 kJ/kg. Water is sodium-chloride to bicarbonate-sulfated with high content of boron, ammonia and arsenic. The chemical composition of water varies through time and depends on the depth of the well and the diameter of the production orifice. In general, it is low-salinity with partial equilibrium at temperatures of 280-310°C. According to their isotopic behavior, geothermal fluids are a mixing between 'andesitic' water and meteoric fluids of light isotopic composition (δ18O: -14.5, and δD: -105) or paleo-fluids. The fraction of andesitic component has been estimated between 0.35 and 0.5 (Barragán et al., 2008).

Fluids of low pH were produced by wells drilled in the area of the field known as Colapso Central, particularly at more than 1,800 m depth. The formation of low pH fluids has been explained as a post-exploitation process related to the migration of deep magmatic volatile species, which is induced by the extraction of fluids. Volatiles such as CO_2, H_2S, Cl, F, etc., react in their way to the surface with aqueous fluids, producing aqueous corrosive species (Gutiérrez Negrín et al., 2010). CFE repaired all wells in that area by plugging the deep production zones with cement, so isolating these zones to prevent the mixing of deep and shallow fluids. Further wells in the same area are shallow enough to avoid the deeper production zones. This prevented more corrosion and scaling cases but also reduced the production rate of the wells by more than a half. More recent wells have been finished with no casing at depth, and adding some type of neutralization (Flores-Armenta et al., 2008).

5. LAS TRES VÍRGENES GEOTHERMAL FIELD

Las Tres Vírgenes is located in the middle of the Baja California peninsula, 46 kilometers northwest of the Santa Rosalía town (Fig. 1). The field is within a Quaternary volcanic complex, composed of three volcanoes aligned north-south and related to the NW spreading of the Baja California Peninsula. Las Tres Vírgenes is the most recent of the three volcanic centers in the area, being La Reforma caldera and El Aguajito complex the others.

The geothermal field lies within a NW-SE trending Pliocene to Quaternary depression known as the Santa Rosalía Basin that seems to be the western limit of a deformation zone related to the opening of the California Gulf. The field is at an average altitude of 750 m, with volcanic peaks up to 1,850 masl. The geothermal system is clearly structurally controlled and is located near the northern edge of the volcanic complex. This, in turn, is emplaced into a system of right strike-slip faults of low and high angle related to a tension zone, and some left strike-slip lateral faults (Macías and Jiménez, 2012).

The oldest lithological unit is a Late Cretaceous (99.1 ± 0.8 Ma) granodioritic intrusion, part of the California Batholith (López et al., 1993; Macías and Jiménez, 2012). This is the host rock of the geothermal fluids, and its top is found at depths of 900 to 1000 m in the geothermal wells.

The intrusive rock is overlain by the Upper Miocene-Middle Oligocene volcano-sedimentary sequence known as the Grupo Comondú. This sequence mainly consists of andesites and sandstones, and has an average thickness of 750 m in the wells. Overlaying the Grupo Comondú, are shallow marine deposits belonging to the Santa Rosalía Basin of Late Miocene to Early Quaternary age. The upper member is interbedded with volcanic rocks that preceded the most recent volcanic activity. The maximum thickness of this unit is 300 m. The rocks (conglomerates, sandstones and some pyroclastics) of the Santa Rosalía Basin are overlain by the more recent volcanic products of the La Reforma, El Aguajito and Las Tres Virgenes centers.

The youngest volcanic activity in La Reforma center occurred at 0.8 Ma, while in the El Aguajito center the youngest andesites and some dacitic domes were erupted at 0.5 Ma (López et al., 1989). The Las Tres Vírgenes eruptive center consists of three volcanoes aligned along N-S trend: El Viejo-El Partido (0.44-0.2 Ma), El Azufre (0.28 Ma) and La Virgen (last eruption in 1746) (López et al., 1993). The volcanic rocks range from olivine basalts up to dacites including basaltic andesites and andesites, and are sub-alkaline rocks of calc-alkaline type and mid-content of potassium. They were originated by rhyolitic magma chambers stationed at 7-9 km depth (Macías and Jiménez, 2012).

The superficial hydrothermal activity is represented by fumaroles and several acid-sulfate springs with superficial temperatures ranging between 53 and 98°C. Most of the associated alteration is aligned along a NW-SE trend. One area of alteration lies along a NW-SE structure with strike slip, and another along a N-S fault with normal displacement (López et al., 1989). The superficial hydrothermal alteration is dominated by kaolinite + chalcedony (silica residue) + sulfur and minor alunita (or natroalunite), hematite, jarosite, kaolin and pyrite (Viggiano-Guerra and Gutiérrez-Negrín, 2000).

Not all the host rocks are dissolved or replaced, but some silica from them remains as silica residue. Many of the rocks have been only partly altered, unlike the more extensive alteration in many other geothermal systems. Secondary minerals occur as replacement of primary phases. Veining, or direct deposition, does not seem to have been abundant, yet there are some veins of quartz, calcite and chlorite, with varying proportions of adularia, illite, sphene (titanite), pyrite, hematite, wairakite, and anhydrite. All of the alteration minerals at Las Tres Vírgenes were produced by alkali chloride waters of near neutral pH. The partial replacement of K-feldspar by illite, however, indicates that there was a slightly more acid fluid circulating deep in the reservoir after the geothermal system had developed. Deeper in the reservoir, calcite seems to be less abundant and the epidote dominates among the silicates (Viggiano-Guerra and Gutiérrez-Negrín, 2000).

The un-boiled parent fluid of the Las Tres Vírgenes geothermal system is not of marine origin. It seems to be of magmatic origin, produced in the hydrothermal stage of magmatic cooling. This parent fluid could be related to an old, fossil geothermal system, and its salinity was more than 20 weight percent NaCl equivalent (Viggiano-Guerra and Gutiérrez-Negrín, 2000).

The reservoir is liquid dominated (more than 3 parts of brine and 1 part of steam) with temperatures ranging from 250 to 275°C. According to the geochemical changes shown by the produced fluids, there has been a mixing of processes in the reservoir between two main components. One component seems to be the characteristic reservoir fluid (274°C with a Cl content of ~6745 ppm) produced by the deepest well in the field at 2,414 m depth, and the other component showing lower temperatures and salinity (171-202°C and a Cl content of ~500 ppm), is similar to the fluid once produced by the shallowest well in the field, at 1,270 m depth. Geothermal fluids apparently consist of mixtures with different proportions of the two primary fluids. Estimates of well-enthalpy show multiple entrances of fluids into the wells, and thus the fluid mixing is probably occurring inside the wells, which favors mineral deposits and scaling processes observed in the field (Barragán et al., 2010).

Currently there are three production wells in operation producing 0.8 million tons of steam and 2.4 million tons of water per year. The water is reinjected to the reservoir by 2 injection wells. There are two 5-MW each flash power plants in operation, which generates around 55 GWh per year.

6. CERRITOS COLORADOS GEOTHERMAL FIELD

Formerly known as La Primavera, this field is located at the western portion of the Mexican Volcanic Belt, practically in the outskirts of Guadalajara City in the western state of Jalisco (Fig. 1). The field is near the confluence of three major continental structural elements: the Colima Graben oriented N-S, the Chapala Graben oriented E-W, and the Tepic-Zacoalco Graben oriented NW-SE. Some studies have deemed these regional structures as extension zones, along which the western portion of continental Mexico is moving towards northwest, thus becoming the Tepic Graben a transform fault and the Colima Graben an extension basin (Luhr et al., 1985). The volcanic activity in La Primavera complex seems to be more related to this extensional framework than to any subduction process (Gutiérrez-Negrín, 1988).

The geothermal field is inside the La Primavera forest and on a rhyolitic complex of per-alkaline chemical type of rhyolitic lavas and domes (comenditic rhyolites) that forms the present Sierra La Primavera (Mahood, 1980), at around 1,850 masl. The excess of silica presented by some of the rhyolitic units of this sierra is a typical chemical feature of volcanism in zones under tensional strains, not in subduction regimes.

The La Primavera complex is a rhyolitic caldera whose formation began 120,000 years ago, when an ascending magma chamber extruded the first rhyolitic domes and lavas. Around 95,000 years ago a series of explosive eruptions produced huge pyroclastic flows that finally formed the Toba Tala ignimbrites that presently cover an area estimated at 700 km^2 and represents an estimate of 20 km^3 of magma. After these eruptions a roughly circular area of 11-13 km in diameter was collapsed, giving place to the La Primavera caldera, inside of which a lake was formed. During 25,000 years lacustrine sediments covered the lake floor, and then, 70,000 years ago, a differential resurgence took place in the magma chamber, so forming the present sierra and extruding additional domes and lava flows (Mahood, 1980).

The magma chamber entered in its hydrothermal, last stage of evolution, and produced a geothermal system, whose superficial evidences are fumaroles at the central-south part of the caldera and hot springs on the western rim, the latter with a combined mass flow of approximately 400 kg/s. Water from these springs is at 65°C and presents sodium-bicarbonate geochemical type indicating mixture of meteoric water of recent infiltration with deep waters from geothermal origin.

Subsurface lithology of the field, as indicated by 13 wells drilled by the CFE in the eighties, can be grouped into five units. From the top, the first one is composed of lacustrine sediments and pumice post-caldera deposits of Quaternary age and mean thickness of 33 m. The second unit is composed of the Toba Tala ignimbrites, 95,000 years old and average thickness of 366 m. The third unit, underlying the ignimbrites, is composed of 0.12 Ma rhyolites showing 64 meters as average thickness. The fourth unit is 2,300 m thick and Late Miocene to Early Pliocene in age and is composed of a sequence of andesites and tuffs, a thin layer of rhyolites and another sequence of andesites with minor basalts. All these units are related to the early basement of the Mexican Volcanic Belt or the late volcanic activities of the Western Sierra Madre. This unit rests on a granodiorite basement, cut by the deepest well at 2,780 m depth (Gutiérrez-Negrín et al., 2002).

A deep fault system of NW-SE trend is affecting rocks of the fourth unit and apparently does not present superficial expression. Some shallower systems, mainly due to the collapse and resurgent processes, are represented by some ring caldera fractures and some high angle fractures and normal faults of a NW-SE and NE-SW trends (Gutiérrez-Negrín et al., 2002).

High temperature geothermal fluids are contained in the andesites, tuffs and rhyolites of the fourth lithological unit, whose permeability is mainly secondary, due to local and regional faults and fractures. Under this unit, granodiorite basement presents a much lower permeability.

Several wells were evaluated and produced a mix of two thirds of water and one third of steam, with an average temperature of 305°C and maximum of 356°C. Water is diluted brine with 3,600 mg/kg of total dissolved solids, of sodium-chloride type and up to 128 mg/kg of boron and 16 mg/kg of arsenic.

The natural thermodynamic state of the system corresponds to a compressed liquid reservoir. The vertical pressure profile is almost hydrostatic at shallow depths and higher than hydrostatic below 1,750 meters depth. At shallow depths, fluids flash in the formation adjacent to wells, and then flow in as two phases inside the holes. At deeper depths, fluids come into holes in liquid phase and flash inside it (data from Gutiérrez-Negrín et al., 2002).

Host rocks have been moderate to intensely altered presenting hydrothermal mineral assemblages including calcite, quartz, clay minerals, chlorites and pyrite, and scarce epidote was found in some of the wells (Gutiérrez-Negrín, 1988). The up-flow of the geothermal system is located around the wells PR-1, PR-8 and PR-9, from where geothermal fluids tend to move towards west.

No power plants have been installed in the field, yet the steam produced by six of the 13 wells drilled by CFE was enough to install a 25-MW power plant. CFE estimates a minimum of 75 MW in the field.

7. CONCLUSIONS

In all the five mentioned geothermal plays the main heat transfer process is convection, and then all of them lie in the first domain of convection-dominated systems, like the vast majority of the geothermal fields currently in operation in the world. In general, convection-dominated geothermal play types include the hydrothermal systems also referred to as viable, active, high-temperature geothermal systems, as highlighted by Moeck and Beardsmore (2014). They also indicate that these geothermal plays lie near to plate tectonic margins or in regions of active tectonics or volcanism, magmatic intrusions of less than 3 Ma in age, "…or regions with elevated heat flow due to crustal thinning during extensional tectonics… In convection-dominated geothermal plays, heat is transported efficiently from depth to shallower reservoirs or the surface by the upward movement of fluid along permeable pathways. Laterally extensive, porous high-permeability formations act as the primary reservoirs." (Moeck and Beardsmore, 2014) Furthermore, Moeck (2014) points out that the structural control has a major effect on the fluid flow pathways in this type of convection-dominated systems.

Place those Mexican convection-dominated geothermal plays under one or other division and subdivision of Table 1 is not so easy. To do that, the main features composing the mentioned five geothermal plays can be summarized as shown in Table 2.

Table 2: General features of the five Mexican geothermal fields.

Feature	Cerro Prieto	Los Azufres	Los Humeros	Las Tres Vírgenes	Cerritos Colorados
Tectonic setting	Transform margin: Pull-apart basin between two strike-slip faults.	Subduction-related (Mexican Volcanic Belt)	Subduction-related (Mexican Volcanic Belt)	Transform margin: tectonic basin	Subduction-related (Mexican Volcanic Belt) and pre-rifting (?)
Tectonic regime	Transtensional	Compressive with local extension	Compressive, with local extension	Tensional	Extensional
Structural setting	Right lateral and normal faults	Normal faults NNW-SSE, NE-SW and E-W trends	Normal faults, NE-SW (old) and NW-SE (recent).	Right and left strike-slip, and local normal faults	Normal, high-angle faults, NW-SE and NE-SW
Topographic relief	Low	High	High	High	High
Average altitude	~13 masl	~2,850 masl	~2,800 masl	~750 masl	1,850 masl
Volcanic activity (age of youngest volcanism)	Scarce, only the Cerro Prieto volcano (0.08 Ma)	Abundant, calc-alkaline, rhyolitic domes (0.15 Ma)	Abundant, calc-alkaline, andesitic volcanoes (0.02 Ma)	Abundant, sub- to calc-alkaline (last eruption in 1746)	Abundant, per-alkaline rhyolites (0.025 Ma).
Volcanic structure	None	Volcanoes, cones & domes	Two calderas	Aligned volcanoes	Caldera
Superficial manifestations (Max. temp)	Mud volcanoes, fumaroles and steamy soils (95°C)	Hot springs, fumaroles, mud pools (90°C)	Fumaroles, steamy soils (89°C), no hot springs	Fumaroles & acid sulfate springs (98°C)	Fumaroles and hot springs (95°C)
Heat source	Regional heat plumes & basic intrusive	Magma chamber	Magma chamber producing two nested calderas	Magma chamber at 7-9 km depth	Magma chamber producing a caldera
Host rock	Tertiary sandstones interbedded into shales	Tertiary andesites (18-6 Ma) with minor tuffs and basaltic andesites	Tertiary andesites with horizons of tuffs	Late Cretaceous granodiorite	Late Miocene-Early Pliocene andesites and tuffs
Cap-rock	Shales and mudstones	Upper portions of the host rock unit	Quaternary ignimbrites	Oligo-Miocene volcano-sedimentary rocks	Quaternary ignimbrites
Basement	Cretaceous granitic and Paleozoic-Mesozoic metamorphic	Inferred Late Mesozoic-Oligocene sedimentary rocks	Sedimentary, metamorphic and intrusive rocks of 140-31 Ma	Granodiorite (99 Ma), part of the California Batholith	Pre-Tertiary (?) granodiorite
Reservoir - Type (steam fraction in %) - Temperature - Average depth - Permeability	Liquid-dominant (steam: 40.6%) 250-310°C ~2,400 m Faults & lithofacies	Vapor-dominant (steam: 73.4%) 240-320°C ~2,000 m Faults, fractures	Vapor-dominant (steam: 84.8%) 210-340°C ~2,200 m Faults, fractures	Liquid-dominant (steam: 23.4%) 250-275°C ~2,050 m Faults, fractures	Liquid-dominant (steam: 33.6%) 280-356°C ~1,800 m Faults, fractures
Liquid phase - Type - Source	Sodium-chloride, neutral pH (acid in CP-IV) Regional aquifer &	Sodium-chloride, pH ~7.5 Regional shallow	Sod.-chl. to bi-carbonate-sulfate (locally acid) Regional shallow	Sodium chloride, neutral pH Local shallow	Sodium chloride, neutral pH Regional & local

	Colorado River	aquifers	aquifer	aquifer	shallow aquifers
Hydrothermal alteration	High. Replacing of original cement in sandstones, 4 well defined zones	High. Both replacing and filling cavities and fractures, 3 zones	High. Both replacing and filling cavities and fractures, 3 zones	Moderate. More replacing than filling of cavities and fractures.	Moderate-High. Replacing and filling cavities and fractures
Highest temp. alteration minerals	Epidote, amphibole, muscovite, biotite	Epidote, amphibole, biotite, diopside, garnet	Epidote, amphibole, diopside, biotite	Wairakite, anhydrite, epidote	Chlorite, calcite, epidote
Installed (running) capacity (MW)	720 (570)	194 (193)	93 (68)	10 (10)	0

Based on Table 2, the Cerro Prieto field is clearly located in an extensional domain, which can be deemed as the key factor for the very existence of the heat source and then for the geothermal reservoir. The field also shows some typical features of intrusive magmatic geothermal plays proposed by Moeck and Beardsmore (2014, Table 1), since the basic intrusive considered as the Cerro Prieto heat source is supposed to be relatively young (less than 3 Ma) and it has intruded beneath flat terrain with (almost) no volcanism. However, since the tectonic setting plays in this case the determinant role, Cerro Prieto would be sub-classified as an extensional domain geothermal play.

Los Azufres and Los Humeros geothermal fields seem to be typical examples of extrusive magmatic plays. Las Tres Vírgenes and Cerritos Colorados would be also extrusive magmatic plays, although not as typical as the other two. The regional tectonic framework of Las Tres Vírgenes is more like that of Cerro Prieto than that of the Mexican Volcanic Belt, since it is related to a spreading process and not to subduction. In the case of Cerritos Colorados, the volcanic activity seems to be more related to a proto-rifting extensional framework than to any subduction process. However, the key factor in both geothermal fields is the magma chamber and not their tectonic location. Thus, also Las Tres Vírgenes and Cerritos Colorados can be initially classified as extrusive magmatic geothermal plays.

The geothermal play scheme proposed by Moeck and Beardsmore (2014) is just an initial proposal that will surely be refined and modified. It is likely more divisions and subdivisions might be necessary to classify geothermal fields similar to the Mexican ones, and more importantly to explore new ones. But even with this preliminary character, it seems to work and is a good foundation to go ahead.

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