Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Review and Update of the Main Features of the Los Humeros Geothermal Field, Mexico

Luis C.A. Gutiérrez-Negrín[1] and Georgina Izquierdo-Montalvo[2]

[1]Geocónsul, SA, Morelia, Mich., Mexico, [2]Instituto de Investigaciones Eléctricas, Cuernavaca, Mor., Mexico

[1]l.g.negrin@gmail.com, 2gim@iie.org.mx

Keywords: Corrosion, geochemical composition, hydrothermal mineralogy, lithology, Los Humeros, Mexico, production zones.

ABSTRACT

Los Humeros is one of the four geothermal fields currently producing electricity in Mexico. This paper presents a review on the main geologic, geochemical and production characteristics of the field and updates them, considering the imminent construction of new production wells for installing an additional power unit. Those characteristics can be summarized as follows. At the subsurface there are four lithologic units, the third of which, composed of Tertiary andesites 1,200 m thick in average, contains the geothermal fluids. These fluids are mainly composed of steam with minor amount of low-salinity water of sodium-chloride to bicarbonate-sulfated type and oversaturated in silica and calcite. Instead of two different reservoirs, as previously proposed, the geothermal system seems to be a single reservoir with several feeding zones and subject to recurrent processes of self-sealing and hydro micro-fracturing. The hydrothermal mineralogy found in the subsurface seems to form three distinct zones: zeolites, epidote and amphiboles with respectively increasing temperatures. The most profitable areas are the Colapso Central and the corridor between the Antigua and Maztaloya faults. Production from deep zones in wells at the Colapso Central has provoked problems of corrosion and scaling in the past, and so these zones have been avoided in the last 15 years. For the new wells it is recommendable, however, try to exploit these deep zones, taking measures to prevent those problems, in order to get a better production of steam.

1. INTRODUCTION

The Los Humeros geothermal field is located between the eastern portion of the state of Puebla and the western part of the state of Veracruz, at central-eastern Mexico (Fig. 1). The field is 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.

Los Humeros is one of the four geothermal fields currently operating in Mexico. It has an installed capacity of 40 MW with eight back-pressure units of 5 MW each, which are fed by an average of 20 production wells that produce around 500 tons of steam per hour. There are also three injection wells in operation. The power units, wells and installations are operated by the Comisión Federal de Electricidad (CFE).

The CFE has planned to increase the installed capacity in 46 MW with the project Los Humeros II in two phases. Phase A consists of one condensing unit of 25 MW and phase B consists of seven binary units of 3 MW each, to be installed in seven of the 5-MW back-pressure units in operation to use the exhausted steam. Even though the current availability of steam is a little higher than the demand of the power units, it will be necessary to drill some additional production wells to complete the supply for the new 25-MW unit. Therefore, it seems appropriate to present a brief review and update of the main geologic and geothermal features of the field, to take the proper decisions on the location and characteristics of the new wells. This is the objective of this paper.

Figure 1: Location of Los Humeros.

2. GEOLOGICAL FEATURES AND EVOLUTION

The oldest outcropping rocks at the surroundings of the field are granites and schists that form the Macizo de Teziutlán of Paleozoic age (De la Cruz, 1985). Over these rocks, limestones started to be deposited during the Jurassic, around 190 Ma ago, when sedimentary processes of transgression and regression occurred, related with the opening of the Gulf of Mexico. In the Cretaceous, around 140 Ma, the process became essentially transgressive. Deposition process during Jurassic and Cretaceous produced a thick series of limestones (micrite and bio-micrite) with minor shales and lenses of flint (Gutiérrez-Negrín, 1982a).

At the subsurface of the Los Humeros Caldera, well H-2 cut fossiliferous limestones (bio-micrite) between 1200 and

1210 m depth, whose organisms were identified by the Mexican Petroleum Institute as *Nannoconus steinmanni, Calpionella alpina, C. elliptica, C. oblonga, Calpionellopsis simplex, C. oblonga, Tintinnopsella longa and T. carpathica*. These fossils correspond to the Berriasian (Early Cretaceous), and the sedimentary rocks cut by the well between 1140 m depth and the total depth (2280 m) were correlated to the Tamaulipas Inferior (Early Cretaceous) and the Pimienta (Late Jurassic) formations (Gutiérrez-Negrín, 1982a). It has been suggested that, besides these formations, subsurface limestones in Los Humeros could include the Tamán and Santiago formations, also from the Late Jurassic (De la Cruz, 1985).

By the beginning of the Tertiary started the compression phase known as Laramide Orogeny. At Los Humeros and its surroundings this orogeny 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 orogenic stresses produced low to medium regional metamorphism on the sedimentary rocks. Between the end of the Eocene and beginning of Oligocene, around 35 Ma ago, began a distension phase that included late intrusions of syenitic and granitic stocks and dikes into calcareous rocks, which were locally metamorphized to marble, hornfels and skarn.

Volcanic activity in the area started in the Miocene, around 10 Ma ago. It was essentially of fissure type and produced the Alseseca Andesites that outcrop at the northeastern part of the Los Humeros caldera and cover the calcareous rocks (Yáñez and Casique, 1980). There was not more volcanic activity until the Pliocene, when began the volcanism associated with the Mexican Volcanic Belt, and the Teziutlán Andesites were formed between 3.5 and 1.9 Ma.

The caldera process started 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 the Oligocene intrusions. The magmatic chamber produced a flexure on the overlaying volcanic rocks and left a weakness zone circularly shaped through which were erupted a series of rhyolitic domes containing up to 76% of silica. After these peripheral domes were emplaced, around 0.46 Ma some gasification occurred at the upper zone of the magma chamber. The excess of pressure was released as a series of explosive eruptions through a central vent; the eruptive columns collapsed at their lower parts and produced pyroclastic flows stretching over 3000 square kilometers. Cooling and consolidation of these flows formed the Xaltipan Ignimbrite, with an equivalent magma volume estimated in 115 cubic kilometers. These are rhyolitic ignimbrites with silica content between 71 and 77%. The sudden release of that amount of magma triggered the gravitational collapse of the overlaying rocks, giving place to the Los Humeros caldera with a major diameter of 21 km and a minor diameter of 15 km (Yáñez and Casique, 1980; Ferriz and Mahood, 1984).

One hundred-thousand years ago, after a resurgence process, a new gasification occurred in the chamber, whose pressure was also released by sudden explosive eruptions giving place to new pyroclastics flows that formed the Zaragoza Ignimbrite. These rocks are less differentiated presenting andesitic to dacitic composition with silica contents between 56 and 70%. The equivalent magma volume was of around 20 cubic kilometers and the eruptions provoked a new collapse known as the Los Potreros caldera (Fig. 2). This caldera is nested inside Los Humeros caldera, at the south portion, and presents a diameter between 7 and 10 kilometers (Yáñez and Casique, 1980; Ferriz and Mahood, 1984).

Between 40,000-60,000 years after the Los Potreros collapse, other volcanic eruptions produced scarce rhyolitic domes, abundant cinder cones and some andesitic volcanoes and flows through the southern rim of the Los Humeros caldera, including the Arenas and Maztaloya volcanoes, the latter with an explosion crater of 1.7 km in diameter (the Xalapazco Maztaloya; Fig. 2). The local volcanism seems to be finished around 20,000 years ago with 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 active at the subsurface, whose heat source is the magmatic chamber that is at its last, hydrothermal stage.

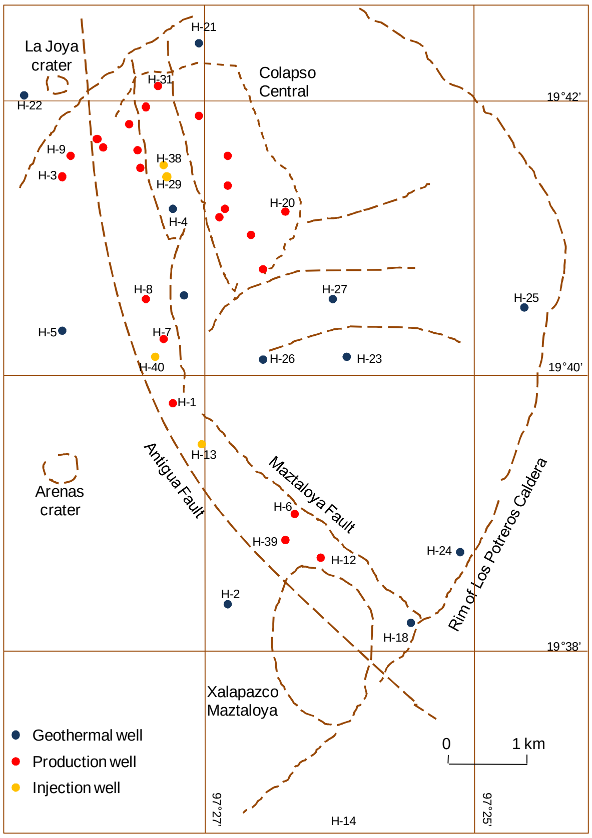

Figure 2: Main geological structures and wells in Los Humeros.

It has been proposed a third collapse-caldera named the Colapso Central, located inside the Los Potreros caldera (De la Cruz, 1983). However, there are not evidences to support this event, being the Colapso Central a morphologic feature produced by the arrangement of the superficial lava flows (Garduño *et al.*, 1985). Anyway, the areal location of this zone coincides with the upflow of the geothermal system and with the magma chamber at depth.

According to the rocks cut by the geothermal wells, and making a synthesis of the previously proposed groups (Gutiérrez-Negrín, 1982b; Viggiano and Robles, 1988) the subsurface lithology can be grouped into four units that from the top to bottom are as follows (see also Table 1 at the end of the text):

Unit 1. Post-caldera volcanism. Quaternary (<100,000 years). It includes all the volcanic rocks and products formed after the second caldera collapse of Los Potreros, and is composed of andesites (San Antonio Andesites and others), basalts, dacites, rhyolites, flow and ash tuffs, pumices, ashes and materials from phreatic eruptions. The unit contains shallow aquifers, some of them locally thermal.

Unit 2. Caldera volcanism. Quaternary (510,000-100,000 years). This unit is mainly composed of lithic and vitreous ignimbrites from the two collapses (Los Humeros and Los Potreros) which form the Xaltipan and the Zaragoza ignimbrites, respectively. It also includes products of the volcanic events occurred between both collapses, as rhyolites, pumices, tuffs and some andesitic lava flows, as well as the peripheral rhyolitic domes emplaced before the first collapse. This unit acts as an aquitard (Cedillo, 2000).

Unit 3. Pre-caldera volcanism. Tertiary (Miocene-Pliocene, 10-1.9 Ma). It is composed of thick andesitic lava flows, probably from the Alseseca Andesites (~10 Ma) at the bottom and the Teziutlán Andesites (3.5-1.9 Ma) towards the top, with some intercalations of horizons of tuffs. The characteristic accessory mineral of the upper andesites is augite and the lower andesites contain mainly hornblende. Both packages include minor and local flows of basalts, dacites and eventually rhyolites. This unit contains the geothermal fluids.

Unit 4. Basement. Mesozoic-Tertiary (Jurassic-Oligocene, 140-31 Ma). This basement unit is composed of limestones and subordinated shales and flint lenses from the Pimienta and Tamaulipas Inferior formations (and may be others), which were folded and partially metamorphized by the Laramide Orogeny, and then locally metamorphized by Oligocene intrusions. Therefore, this unit 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 endhoreic hydrographic basin of the same name. The northern sector of this graben is a zone of major distension that has favored the rising and emplacement of huge volumes of magma (Pasquaré, 1982).

It has been identified two main structural systems in the field. The oldest one is NE-SW to E-W (strikes NE 40-90° SW, dips ~70° towards N or NW) and includes mainly normal faults. The other is the system NW-SE to N-S (strikes NW 0-45° SE, dips 72-80° towards NE, SW, E and W) and includes also normal faults like the Maztaloya and Antigua faults (Fig. 2), some of which cut faults from the first system (Garduño *et al.*, 1985). The Antigua fault is actually a basement, old structure, which was reactivated later and defines the western limit of the reservoir by putting in contact the Mesozoic rocks with the Tertiary andesites.

2. THERMAL MANIFESTATIONS AND HYDROTHERMAL MINERALOGY

Superficial thermal manifestations in Los Humeros are gaseous in the form of fumaroles, heat steam-soils and alteration (kaolin) zones. This steamy aspect of the area is where the name of Los Humeros comes from. These manifestations release small amount of steam through the porous soils, faults and fractures with superficial temperatures between 50 to 89° C, and all but two (Xalapazco Maztaloya and Tenamastepec) are located in the Colapso Central area.

Analysis by X-ray diffraction of superficial samples from distinct zones of the field shows minerals characteristics of the advanced argillic alteration type: alunite, kaolinite, gypsum and small amounts of jarosite, alunogen, and scarcely potash alum.

During its 20,000 years of activity, the geothermal system in Los Humeros has produced a complex arrangement of hydrothermal minerals, which were emplaced through two main processes: filling of cavities (cracks, micro-fractures, voids, etc.) and metasomatic replacement of primary minerals. First one is predominant, especially at the shallow portions of the system. The main hydrothermal minerals found at subsurface are chlorite, epidote, quartz, calcite, leucoxene and pyrite. In minor proportion are smectite, kaolinite, illite, mixed-layer minerals, biotite, zeolites (including wairakite), anhydrite, amphiboles, garnet, diopside and wollastonite. The latter three minerals could be product of ancient contact metamorphism more than of recent hydrothermal activity, yet all the rest are product of the interaction of sodium chloride waters and pH from neutral to alkaline. Minerals formed at high temperature and low pH fluids like pyrophyllite, dickite, diaspore, andalusite, zunyite, tourmaline, etc., have not been found.

Phyllosilicates identified by X-ray diffraction in the clay fraction of cores and cuttings from wells H-14, H-15, H-16, H-17 and H-29 were formed in a neutral to basic environments: smectite, kaolinite, illite/smectite, chlorite/smectite, scarce kaolinite/smectite, illite, biotite and chlorite (Libreros, 1991; Izquierdo, 1993). There was no evidence of pyrophyllite (Izquierdo *et al.*, 2000), the only clay mineral formed at high temperature in an acid environment.

The hydrothermal minerals can be grouped into three zones (Viggiano and Robles, 1988; Gutiérrez-Negrín and Viggiano-Guerra, 1990), even though they are not uniformly defined. These are: zeolites zone, characterized by calcic zeolites like stilbite and heulandite, with temperatures between 50 and 150° C; epidote zone, defined by the first appearing of this mineral in the wells and the presence of deeper wairakite, with present temperatures of 150-300° C; and amphiboles zone, characterized by the first occurrence of hydrothermal hornblende and/or some tremolite-actinolite, at present temperatures higher than 300° C.

Some hydrothermal and metamorphic minerals present microscopic evidences of strain, like undulant extinction of secondary quartz, some anisotropy in garnets and undulant cleavage, which means they underwent strains after their formation. These stresses seem to have been produced by the reservoir pressure instead of tectonic stresses. It seems to have been processes of hydraulic micro-fracturing over zones previously self-sealed by mineral deposition, which probably occurred in more than one episode. The simplified process can be outlined as follows: a) flow of geothermal fluids through planes of fracture and fault zones; b) deposition of secondary minerals from the periphery to the center of the structural plane, as the temperature and pressure drop until sealing the conducts; c) increase of the reservoir pressure as the flow stopped; d) hydraulic micro-fracturing of the deposited minerals and re-opening of the conducts. Then the process can start again.

Comparing the subsurface paleo-temperatures, as deduced from mineralogy and some data from homogenization temperatures obtained in fluid inclusions, with the current temperatures, it can be observed some parts of the reservoir that have been cooled, other than have been heated and other more or less stable. Over a plain view, at the east of the Colapso Central cooling seems to have occurred, which disappears towards the west. Over a vertical section, inside the Colapso Central the shallower zones of the reservoir presented higher temperatures in the past, while the deeper parts present currently higher temperatures.

The distribution of epidote at depth seems outline two upflow areas of the reservoir. One would be located in the Colapso Central near the wells H-9 and H-22, at the northern-northwestern area of the field, and the other outside the Colapso Central at the central-south-eastern area, near the well H-6. The first one could be related with the intersection of the Los Potreros rim and the Antigua Fault, and the second with the Maztaloya Fault.

3. GEOTHERMAL FLUIDS AND PRODUCTION

At the surface, fluids produced by the wells are a mixture of low salinity fluids, classified as bicarbonate, sulphate and sodium-chloride type, oversaturated in silica and calcite (Barragán *et al.*, 1991; López, 2006). Furthermore, most of the wells are fed from different strata and so the discharge is composed of mixture. Well H-1 is the only one that from the beginning of exploitation has shown the major liquid fraction.

Wells mainly produce steam with high enthalpy (more than 2000 kJ/kg) excepting the well H-1 that produces mainly water with enthalpy of 1100-1300 kJ/kg. Water is chemically homogeneous of type sodium-chloride to bicarbonate-sulfated with high content of boron, ammonia and arsenic. Average chloride content in the reservoir is between 25 and 75 ppm, with a maximum of 533 ppm in the well H-19 (GENZL-SIHASA, 1993). However, the chemical composition of the liquid phase varies through time and depends on the depth of the well and the diameter of the production orifice. In general terms, it is low-salinity with partial equilibrium with rocks at temperatures between 280 and 310° C estimated by Na/K geo-thermometers (Barragán *et al.*, 2008). These characteristics have been considered as resulting of boiling and lack of chemical equilibrium in the fluids (Tello, 1992; Prol-Ledesma, 1998), or as resulting of mixing of the original liquid phase with steam condensate, rich in sulfates and carbonates (Barragán *et al.*, 2008).

All the production wells produce from andesites of the Unit 3, particularly from the lower hornblende andesites, approximately between 1100 and 2800 m depth. The permeability in the reservoir is controlled by structures that have formed permeable zones, especially those belonging to the NW-SE and E-W system.

According to their isotopic behavior, the geothermal fluids are a mixing between "andesitic" water and meteoric fluids of light isotopic composition ($\delta\ ^{18}O$: -14.5, and δD: -105) or paleo-fluids. The fraction of andesitic component has been estimated between 0.35 and 0.5. The general tendency is considered to be resulting of a convective process produced by separation and rising of steam with descent of condensate. Profiles of CO_2 and $\delta\ ^{18}O$ in the liquid phase show that condensate seem to follow a preferential path toward the central part of the field (Barragán *et al.*, 2008).

Based on geochemical and production data that allowed to obtain pressure and temperature profiles for the unperturbed fluids, it has been proposed the existence of two reservoirs at depth: one upper reservoir composed of dominant liquid with hydrostatic pressure profile, and other lower reservoir composed of dominant steam with steam-static pressure profile (CFE, 1986; Barragán *et al.*, 1991; Arellano *et al.*, 1998, 2003). Cedillo (2000) proposed that both reservoirs are separated by a low permeability vitreous tuff layer that acts as an aquitard.

The upper reservoir was proposed to be between 1400 and 900 masl (approximate average depths of 1400 and 1900 m) with temperatures of 290-320° C, and the lower reservoir was proposed deeper than 700 masl (more than 2100 m depth) with temperatures of 330-360° C (Torres, 1993). Based on the calculation of stabilized temperatures by the sphere method adjusted by the PPEP (pressure-profile versus depth) method, which were assumed as the most probable initial reservoir temperatures, García-Gutiérrez (2009) proposed the upper reservoir to be between 1650 and 1000 masl (approximately 1150-1800 m depth) with temperatures of 290-330° C, and the lower reservoir between 900 and 0 masl (2100 and 2800 m depth) with temperatures of 300-400° C, as apparently shown by two clusters of wells in the Fig. 3.

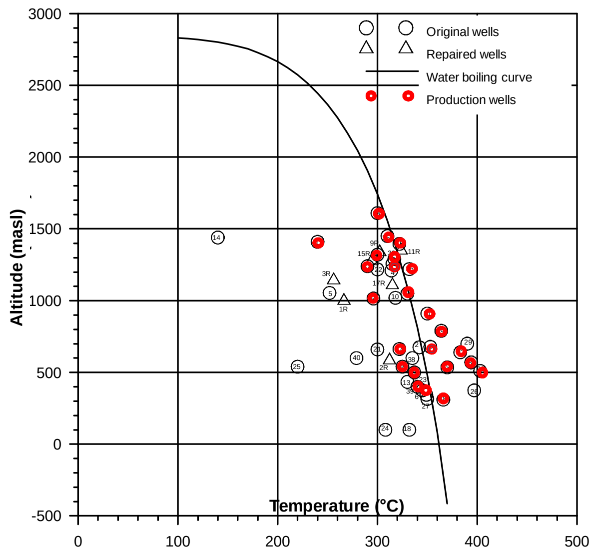

Figure 3. Water boiling curve with depth and stabilized temperatures of Los Humeros wells (slightly modified from García-Gutiérrez, 2009).

However, several wells included in that figure never were producers. If are taken into account only the actual production wells (highlighted in red in the figure), instead of two distinct reservoirs it seems to be one single reservoir with several feeding zones, defined mainly by structural conditions, that tend to be heater as they are deeper –which happens to be usual in geothermal reservoirs. Moreover, there is no any physical separation between both proposed reservoirs, since the vitreous tuff layer (Cedillo, 2000) has not been cut by most of the wells and then cannot be considered as a continuous layer at the subsurface of Los Humeros. Neither there is a registered volcanic episode that could be originated that layer of tuffs, which had to be occurred between 10 and 3.5 Ma.

One special feature in the Los Humeros wells is the occurrence of fluids of low pH in those drilled in the area of the Colapso Central, particularly at more than 1800 m depth. It was proposed that acid fluids came from a deep acid geothermal reservoir, probably located in the hornblende andesites, but this has been discarded (Izquierdo *et al.*, 2000). Instead, the formation of low pH fluids is explained as a post-exploitation process related to the migration of deep magmatic volatile species, which is induced by the extraction of fluids. The volatiles such as CO_2, H_2S, Cl, F, etc., react in their way to the surface with aqueous fluids, producing aqueous corrosive species.

HCl is usually formed at deep parts of geothermal reservoirs by reaction between alkaline chlorides with silica. When a well starts to produce, HCl can be transported associated to the preferential flow of steam toward the well. Near the well or inside it, when partial condensation of the steam occurs, HCl passes from the steam phase to the water phase as the fluid expands itself in an iso-enthalpic way. This condensate of low pH is usually neutralized by the surrounding rocks containing calcium and magnesium, but when temperatures are very high and near the critical point the amount of water in the steam decreases, HCl can corrode the metal of the casings. Additionally, if this acid condensate is mixed with fluids of higher pH coming from shallower strata, formation of scaling is induced by precipitation of iron sulfides (IIE, 1989; GENZL-SIHASA, 1993).

After the corrosion and scaling problems experienced by the well H-4 and particularly the well H-16 (Gutiérrez-Negrín and Viggiano-Guerra, 1990), the CFE repaired this well and others in similar conditions by plugging the deep production zones with cement, so isolating these zones to prevent the mixing of deep and shallow fluids. The CFE also decided that further wells to be drilled in the area of the Colapso Central shall be shallow enough to avoid the deeper production zones. Since then (ca. 1993), this prevented more corrosion and scaling cases but also reduced the production rate of the wells by more than a half. For instance, well H-16 produced initially 48 t/h of steam and 3.6 t/h of water, and after repaired produced finally 10 t/h of steam and 11 t/h of water.

Now, when additional wells are necessary to supply steam for the new projected 25-MW unit, it is convenient to consider drilling of deeper wells in the Colapso Central area to reach the deep feeding zones despite the transport of HCl, taking measures to neutralize this acid to get better production rates. Anyway, the shallow feeding zones must be avoided by isolating them during drilling to prevent the fluid mixing and the resulting scaling problems. Also it is a good idea to leave the smallest diameter hole of the well without casing, as suggested some time ago (Gutiérrez-Negrín and Viggiano-Guerra, 1990). Something like that was tried by the CFE in the recent well H-43, completed in January 2008, that was finished without casing between 1250 and 2200 m depth, though the stretch of open-hole seems to be too long since allows the production of the shallow zones, identified around 1600 m (Sánchez and Torres, 2008). CFE is also considering implement some type of neutralization based on NaOH in this well and in other further wells susceptible to present corrosion problems (Flores-Armenta *et al.*, 2008).

4. CONCLUSIONS

The outcropping and subsurface lithology at the Los Humeros field and its surroundings, is very complex and includes sedimentary, metamorphic, intrusive and volcanic rocks dated from Paleozoic to Quaternary. At the subsurface, these rocks can be grouped into four lithologic units (Gutiérrez-Negrín, 1982b; Viggiano and Robles, 1988) formed from the Jurassic (~140 Ma) to the Quaternary (<100,000 years). Geothermal fluids are hosted by the Unit 3, composed of pre-caldera volcanic rocks (mainly hornblende and augite andesites from Alseseca and Teziutlán formations, respectively) with a mean thickness of 1200 m and age between 10 and 1.9 Ma. Unit 2, composed of caldera volcanic rocks (mainly ignimbrites of the Xaltipan and Zaragoza formations coming from the Los Humeros and Los Potreros collapses, respectively), presents a mean thickness of 600 m, age between 510,000 and 100,000 years and acts as an aquitard (Cedillo, 2000), preventing the escape of the underlying geothermal fluids.

The geothermal system is at least 20,000 years old and has produced hydrothermal minerals emplaced by filling of cavities and by metasomatic replacement of primary minerals as a product of the interaction of sodium chloride waters and pH from neutral to alkaline. They include chlorite, epidote, quartz, calcite, leucoxene, pyrite, smectite, kaolinite, illite, mixed-layer minerals, biotite, zeolites (including wairakite), anhydrite, and amphiboles. There are also garnet, diopside and wollastonite probably products of ancient contact metamorphism. These minerals can be grouped into three zones (Viggiano and Robles, 1988; Gutiérrez-Negrín and Viggiano-Guerra, 1990): zeolites zone (50-150° C), epidote zone (150-300° C) and amphiboles zone (>300° C). Minerals formed at high temperature and low pH fluids have not been found.

The geothermal fluids are mainly steam with high enthalpy and low volume of water, which is a mixture of low-salinity fluids of sodium-chloride to bicarbonate-sulfated type, high content of boron, ammonia and arsenic and oversaturated in silica and calcite (Barragán *et al.*, 1991; López, 2006). The chemical composition of the liquid phase tends to vary depending on the depth of the well and the diameter of the production orifice, and is in partial equilibrium with rocks at temperatures of 280-310° C as estimated by geo-thermometry (Barragán *et al.*, 2008).

Several studies have proposed the existence of two reservoirs at depth (CFE, 1986; Barragán *et al.*, 1991; Torres, 1993; Arellano *et al.*, 1998, 2003; García-Gutiérrez, 2009), separated by a low permeability vitreous tuff layer (Cedillo, 2000). However, the updated available information on the field points out that there is one single reservoir with several production zones defined by local structural conditions, and that there is no such continuous layer of vitreous tuffs. This single reservoir seems to have been subject to recurrent episodes of self-sealing and hydraulic micro-fracturing provoked by the movement of fluids, as suggested by microscopic evidences of strain on hydrothermal and metamorphic minerals. Thus, some parts of the reservoir present currently higher or lower temperatures than in the past, which is quite evident in the Colapso Central area.

The most profitable areas of the field are the Colapso Central and the corridor formed between the Antigua and Maztaloya faults (Fig. 2). Wells located at the Colapso Central and drilled deeper than ~1800 m presented problems of corrosion and scaling. More than a deep acid geothermal reservoir in that area, corrosion has been explained by the HCl formed at depth, dragged by the steam phase, passed to the liquid phase when the steam is condensed, and unable to be neutralized by the host rocks due to the unusually high temperatures and the consequent scarcity of water. Scaling was explained by the mixing of that acid condensate with neutral, shallower fluids (IIE, 1989; GENZL-SIHASA, 1993).

Anyway, all of the present wells in the Colapso Central are shallower than ~1800 m depth. For additional production wells to be drilled in this area to supply the new projected unit, it is convenient to go deeper looking for the deeper production zones, adopting measures to prevent corrosion and scaling. This will result in better production rates per well.

REFERENCES

Arellano G., V., A. García G., R.M. Barragán R., G. Izquierdo M., A. Aragón A., D. Nieva G., E. Portugal M., e I. Torres A., 1998. Desarrollo de un modelo básico actualizado del yacimiento geotérmico de Los Humeros, Pue. Internal report of the Instituto de Investigaciones Eléctricas, number IIE/11/11459/01/F. Unpublished.

Arellano, V.M., A. García, R.M. Barragán, G. Izquierdo, A. Aragón, and D. Nieva, 2003. An updated conceptual model for the Los Humeros geothermal reservoir. *Journal of Volcanology and Geothermal Research*, Vol. 124, pp. 67-88.

Barragán, R.M., D. Nieva, E. Santoyo, M.P. Verma and E. González, 1991. Geoquímica de fluidos del campo geotérmico de Los Humeros, Pue. (México). *Geotermia*, Vol. 7, No. 1, pp. 23-47.

Barragán Reyes, R.M, V.M. Arellano Gómez, M. Ramírez Montes, and R. Tovar Aguado, 2008. Geoquímica isotópica (δ ^{18}O, δ D) inicial de fluidos de pozos del campo de Los Humeros, Pue. *Memorias de la III Reunión Interna de Mejora Continua*, CFE, Marzo 2008, Xalapa, Ver., pp. 185-194.

Cedillo R., F., 2000. Hydrogeologic model of the geothermal reservoirs from Los Humeros, Puebla, México. *Proc. World Geothermal Congress 2000*, Kyushu-Tohoku Japan, May-June 2000, pp. 1639-1644.

Comisión Federal de Electricidad (CFE), 1986. Descripción del comportamiento geoquímico del campo de Los Humeros. CFE, internal report number 132-004. Unpublished.

De la Cruz Martínez, V., 1983. Estudio geológico a detalle de la zona geotérmica de Los Humeros, Pue. CFE, internal report No. 10-83. Unpublished.

Ferriz, H., and G.A. Mahood, 1984. Eruption rates and compositional trends at Los Humeros volcanic center, Puebla, Mexico. *Journal of Geophysical Research*, 89, pp. 135-148.

Flores-Armenta, M., M. Ramírez-Montes y J.M. García Cuevas, 2008. Propuesta para la neutralización de fluidos ácidos provenientes de pozos del campo geotérmico de Los Humeros, Pue. *Memorias de la III Reunión Interna de Mejora Continua*, Xalapa, Ver., Marzo de 2008, pp. 56-65.

García-Gutiérrez, A., 2009. Estado térmico inicial del campo geotérmico de Los Humeros, Puebla. *Geotermia*, Vol. 22, No. 1, pp. 59-69.

Garduño Monroy, V.H., F. Romero Ríos y R. Torres Hernández, 1985. Análisis estructural del campo geotérmico de Los Humeros, Pue. CFE internal report number 26-85. Unpublished.

GENZL-SIHASA, 1993. Evaluación del potencial energético del yacimiento geotérmico de Los Humeros, Puebla. Internal report prepared for the CFE. Unpublished.

Gutiérrez-Negrín, L.C.A., 1982(a). Petrografía del pozo H-2 del campo geotérmico de Los Humeros, Pue. CFE, internal report number 22-82. Unpublished.

Gutiérrez-Negrín, L.C.A., 1982(b). Litología y zoneamiento hidrotermal de los pozos H-1 y H-2 del campo geotérmico de Los Humeros, Pue. CFE, internal report number 23-82. Unpublished.

Instituto de Investigaciones Eléctricas, 1989. Caracterización del fenómeno de corrosión-obturación de pozos de Los Humeros, Puebla. Internal report of the Instituto de Investigaciones Eléctricas, number IIE-11-3753-I-15F prepared for CFE.

Izquierdo, G. 1993. Difracción de rayos-X en la caracterización de especies arcillosas: un caso de aplicación en el pozo H29 del campo de Los Humeros, Pue. *Geofísica Internacional* Vol. 32, No. 2, pp. 21-329.

Izquierdo, Georgina, Víctor Manuel Arellano, Alfonso Aragón, Enrique Portugal and Ignacio Torres, 2000. Fluid acidity and hydrothermal alteration at the Los Humeros geothermal reservoir, Puebla, México. *Proc. World Geothermal Congress 2000*, Kyushu-Tohoku Japan, May-June 2000, pp. 1301-1306.

Libreros, P. 1991. Caracterización de filosilicatos en el campo geotérmico de Los Humeros, Pue., por medio de difracción de rayos-X. Tesis de Licenciatura. Escuela de Ciencias Químicas. Universidad Autónoma de Puebla. Unpublished.

López Romero Oscar (2006). Actualización del modelo geoquímico de Los Humeros, Pue., México. *Geotermia*, Vol. 19, No. 1, pp. 23-32.

Pasquaré, G., 1982. Informe preliminar sobre la zona geotérmica de Los Humeros, Pue. CFE, internal report. Unpublished.

Prol-Ledesma, R.M., 1998. Pre- and post-exploitation variations in hydrothermal activity in Los Humeros geothermal field, Mexico. *Journal of Volcanology and Geothermal Research*, 83, pp. 313-333.

Sánchez-Luviano, M., y M.A. Torres Rodríguez, 2008. Análisis y diagnóstico de las pruebas durante la perforación del pozo H-43 de Los Humeros, Pue. *Memorias del XVI Congreso Anual de la Asociación Geotérmica Mexicana*, Morelia, Mich., 14 de noviembre de 2008.

Tello H., E., 1992. Características geoquímicas e isotópicas de los fluidos producidos por los pozos de Los Humeros, Puebla. *Geotermia*, Vol. 8, No. 2, pp. 3-48.

Torres R., Marco Antonio, 1983. Caracterización del yacimiento contenido en el campo geotérmico de Los Humeros, Pue., a partir de la ingeniería de yacimientos. CFE, internal report number OIY-HU-10/93. Unpublished.

Viggiano, J.C., y J. Robles, 1988. Mineralogía hidrotermal en el campo geotérmico de Los Humeros, Pue. I: Sus usos como indicadora de temperatura y del régimen hidrológico. *Geotermia*, Vol. 4, No. 1, pp. 15-28.

Yáñez García, C., y J. Casique Vázquez, 1980. Informe geológico del proyecto geotérmico Los Humeros-Las Derrumbadas, estados de Puebla y Veracruz, México. CFE, internal report. Unpublished.

Table 1. Main lithologic units and characteristics of the subsurface at Los Humeros.

Unit	Description	Age	Thickness	Characteristics
1	Post-caldera volcanism. Andesites, basalts, rhyolites, dacites, tuffs, ashes, pumices.	Quaternary (<100,000 years)	Minimum: 90 m Maximum: 1010 m Average: 340 m	It forms shallow hot and cold aquifers. High-medium permeability.
2	Caldera volcanism. Ignimbrites Xaltipan and Zaragoza, with andesites, pumices, rhyolites, tuffs.	Quaternary (510,000-100,000 years)	Minimum: 185 m Maximum: 880 m Average: 600 m	It forms an aquitard and acts as a seal-cap. Low permeability.
3	Pre-caldera volcanism. Hornblende andesites (Alseseca?) and augite andesites (Teziutlán), with tuffs, basalts, dacites, rhyolites.	Tertiary (Miocene-Pliocene) (10-1.9 Ma)	Minimum: 90 m Maximum: 2600 m Average: 1200 m	It contains the geothermal fluids. Medium-low permeability.
4	Basement. Limestones and subordinated shales (Pimienta and Tamaulipas Superior formations), marble, skarn, hornfels, granitic rocks and minor diabasic and andesitic dikes.	Mesozoic-Tertiary (Jurassic-Oligocene) (140-31 Ma)	Minimum: 13 m Maximum: Unknown Average: 210 m	Low permeability, high temperature. Several wells did not cut the top.