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Hydrodynamic model of Los Humeros geothermal field, Mexico, based on geochemical, mineralogical and isotopic data

E. Portugal, G. Izquierdo, R. M. Barragán and B. I. Romero
Instituto de Investigaciones Eléctricas, Gerencia Geotermia
Temixco, Mor. México

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RESUMEN

El basamento local del campo geotérmico Los Humeros está formado por un complejo metamórfico del Paleozoico y una secuencia sedimentaria, constituida por lutitas ricas en cloritas y muscovitas del Mesozoico, y una intrusión granítica del Terciario Inferior y andesitas del Plioceno.

La presencia de dos yacimientos geotérmicos fue reconocida con registros de presión realizados en el área del Colapso Central. Un yacimiento de vapor a profundidad y otro menos profundo que produce mezcla de fluidos (líquido + vapor), el cual está claramente relacionado con la mineralogía hidrotermal. Los datos geoquímicos confirman la presencia de dos yacimientos. Uno somero con pH neutro y temperatura alrededor de 280 ºC y otro más profundo con temperatura más alta. La clasificación química de los fluidos muestra aguas tipo cloruradas y bicarbonatadas. Los estudios mineralógicos permitieron identificar ambas zonas productoras: Una con típica alteración hidrotermal considerada de alto rango, y otra donde pozos profundos localizados en la zona del Colapso Central tienen alta temperatura sin alteración. La evidencia mineralógica confirma los límites de los dos yacimientos en el sistema. La dinámica del sistema se estudio a partir de los datos isotópicos de C, H y O del fluido de los pozos productores y de H y O de manantiales circunvecinos, con lo cual se postula un modelo preliminar.

PALABRAS CLAVE: Isótopos estables, mineralogía, geoquímica, campos geotérmicos.

ABSTRACT

The local basement of Los Humeros geothermal field is a Paleozoic metamorphic complex, a Mesozoic folded sedimentary sequence formed by chlorite-muscovite shales, lower Tertiary syenitic and granodioritic intrusions and Pliocene andesites. Based on pressure test logs in the central collapse area two geothermal reservoirs were recognized: A reservoir of low liquid saturation located at depth and a shallow (two phase) reservoir dominated by liquid clearly related to the hydrothermal mineralogy. Geochemical data confirm the presence of two aquifers: An upper, neutral pH aquifer with temperature around 280ºC, and a deeper one with higher temperature. The chemical classification shows that waters are bicarbonate and chloride types. Mineralogical studies identified a zone of typical hydrothermal alteration, considered as high-rank low-intensity, and another zone where deep wells located in the central collapse zone show no alteration but high temperatures. The mineralogical evidence confirms the boundaries of the two reservoirs in the system. Isotopic results of C, H and O in fluids from producing wells and related natural springs were used to study the dynamics of the system. The data allowed a preliminary model to be postulated.

KEY WORDS: Geochemistry, mineralogy, stable isotopes, Los Humeros, geothermal field.

INTRODUCTION

The Los Humeros geothermal field (LHGF) is located in the eastern part of the Mexican Volcanic Belt. The volcanic system has several geological structures where the main feature is the Los Humeros Caldera. This structure has a diameter of 16 km, that contains the 7 km of diameter Los Potreros collapse. Small structures have been recognized as the Central and the Xalapazco collapses, and fault systems such as the Mastaloya and Los Humeros. The geothermal field is located in the State of Puebla, between 19º35'- 19º45' longitudes and 97º24'- 97º30' latitudes (Figure 1). At present, as far as electric generation is concerned, the LHGF is the third geothermal field in México. The geochemical data interpretation shows the presence of two different geothermal reservoirs. A shallower reservoir with temperature close to 280ºC and neutral pH, and a deeper reservoir with temperature as high as 330ºC (Barragán *et al.,* 1988). These occurrences have been confirmed by mineralogy and evaluation of pressure test logs in the production intervals of the geothermal wells (Arellano *et al.,* 1998). The shallower reservoir is liquid-dominated, while the deeper is vapour-dominated.

The objective of this work is to provide a better understanding of the hydrodynamic processes occurring in the Los Humeros geothermal system.

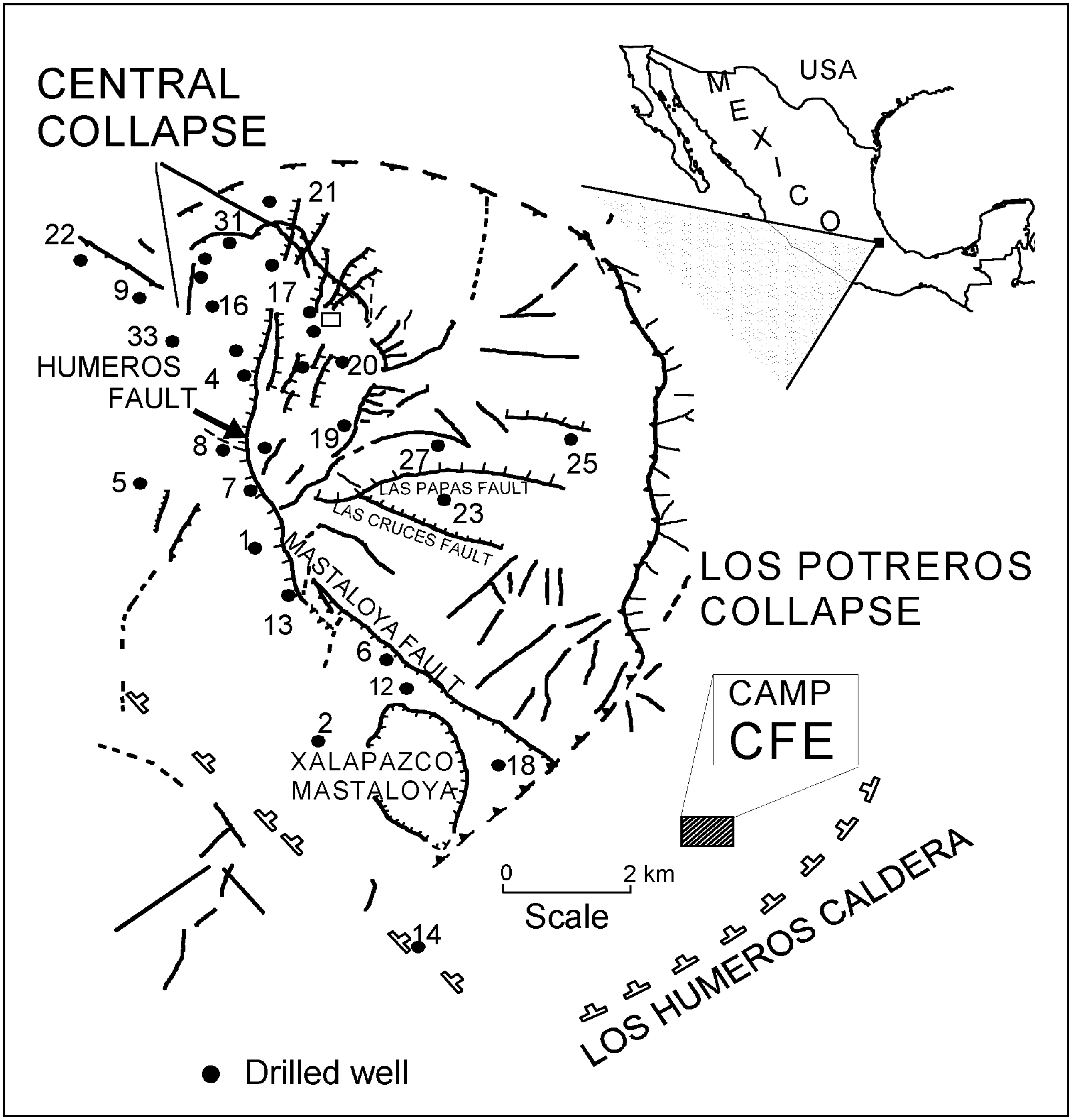

Fig. 1. Location map of the Los Humeros geothermal field and main structures in the field, including geothermal wells (details of springs location in Portugal *et al.,* 1994).

GEOLOGICAL SETTING

The geology has been studied by Yáñez and García, (1982), Cedillo, (1984), Ferriz and Mahood, (1984), Campos and Garduño, (1987) and Cedillo, (1987). The local basement of the Los Humeros geothermal field is formed by a Paleozoic metamorphic complex, a Mesozoic folded sedimentary sequence formed by chlorite-muscovite shales and lower Tertiary syenitic and granodioritic intrusions and Pliocene andesites. The latter flowed through faults in the boundary of the field. The deeper productive reservoir is related to basalts and andesites with hornblende, while the upper productive reservoir is located in augite andesites (Figure 2). The recent volcanism (Quaternary) corresponds to acid to basic flows and pyroclastics from several emission sources within the Los Humeros volcanic center. Within the pyroclastic material of the Xaltipan Ignimbrites lithic tuff and pumice are also found with low permeability. According to Cedillo, (1997) the permeability and porosity of the basaltic flows, dacites and pumice are high. In Los Humeros collapse, outcrops of basaltic flows are observed which have moderate capacity of water infiltration. The pumice absorbs approximately 80% of pluvial precipitation.

Phreatic aquifer

Lithological and hydrogeological results of piezometric wells, (between 200 and 400 m) drilled inside and outside of the Los Humeros Caldera, indicate that two (cold and warm) shallow aquifers exist. Temperature gradient data provide evidence for the existence of a single aquifers body, since groundwater temperature values increase as depth increase (Cedillo, 2000). This occurrence can possible be due to the existence of the fault system.

The shallow subsurface geology was interpreted from petrologic and geophysical data. The geological formation, which hosts the shallow aquifers, consists of basalts, tuffs and andesites with high permeability, and is limited at the bottom by Xaltipan Ignimbrite and laterally by Los Potreros and Los Humeros collapses, which confine the groundwater. Therefore, it has been suggested that groundwater discharge is through faults and fractures toward deeper zones reaching the geothermal reservoir (Cedillo 2000).

GEOCHEMISTRY

The Los Humeros system has been the subject of several geochemical studies (Barragán, 1988). The geochemistry of the fluids indicates that geothermal wells located along the Mastaloya fault produce bicarbonate-type waters, while chloride-type fluids are produced by deeper wells. The separated liquid phase has low salinity and almost neutral pH. According to the Na-K-Mg diagram (Giggenbach, 1988) the chemical composition of the fluids from the initial production stage has a partial equilibrium. Chemical variations have been observed with time during exploitation of the field, which have been related to well operation conditions as some wells are fed either by shallower or deeper thermal aquifers.

HYDROTHERMAL MINERALOGY

The hydrothermal alteration of the subsurface rocks of the LHGF can be recognized as neutral to basic pH alteration and according to Browne (1991), can be defined as of high rank and low intensity. The low intensity of calc-silicates and carbonates alteration caused by the hydrothermalism in cores and cuttings from drilled wells is an indication of the low water-rock ratio of the hydrothermal system. The relative highest alteration percentages are found in the lithological unit formed by augite andesites. The main hydrothermal minerals found in the alteration zones of the system are chlorite, epidote, quartz, calcite, low proportion of leucoxene and pyrite. Apart from these minerals, clays (smectite, kaolinite, illite/smectite, chlorite/smectite, and

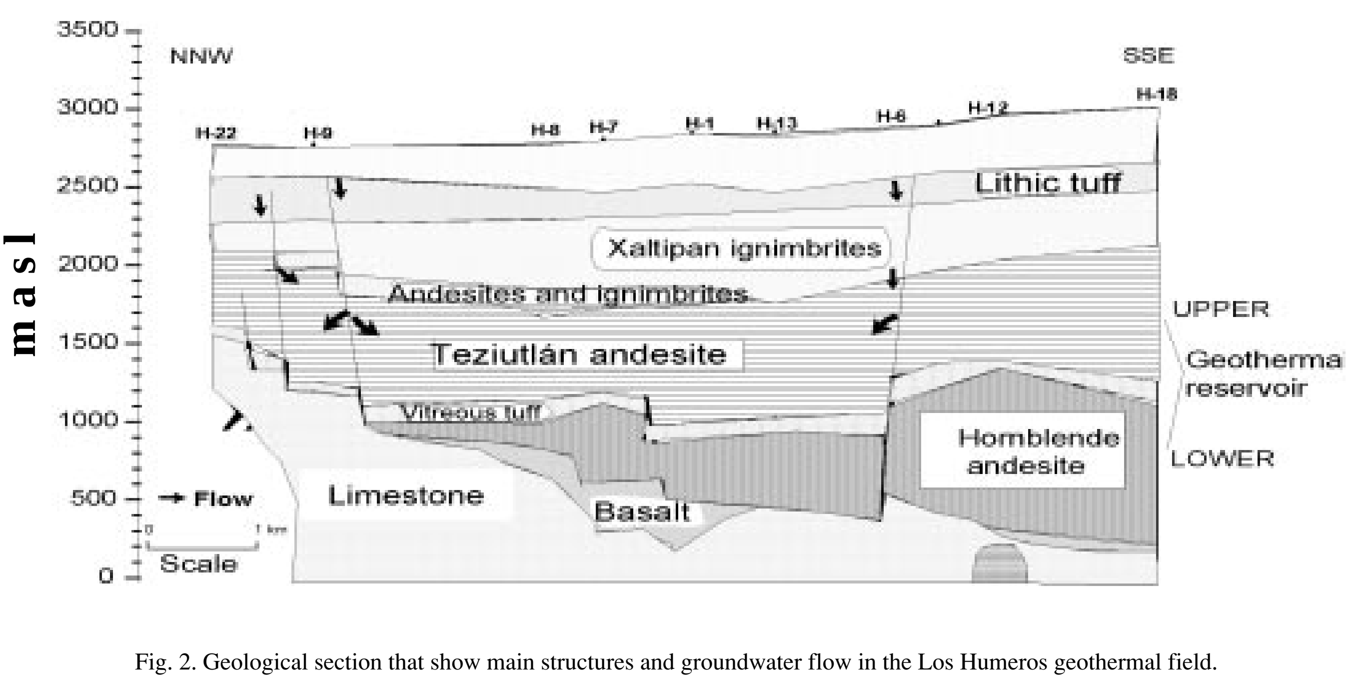

Fig. 2. Geological section that show main structures and groundwater flow in the Los Humeros geothermal field.

scarce kaolinite/smectite), biotite and in minor amount zeolites, anhydrite, amphibole, garnet, diopside and wollastonite have been recognized (Izquierdo, 1993). The pH conditions, in which these minerals are formed are neutral to alkaline environments. The distribution of epidote, amphibol, diopside, garnet and biotite in several geological sections of the field indicates high temperature zones. In wells drilled in the Central Collapse, the occurrence of these minerals indicates ascent of hotter fluids than in adjacent zones. The distribution of calcite and epidote increases from shallow depths to the augite andesite zone. At greater depth, below the augite andesite zone, both minerals are scarce in wells that produce fluid mixtures and are absent in wells producing vapour. The absence of hydrothermal mineralogy at depth is the result of the low water-rock ratio that exists in the vapour zone.

STABLE ISOTOPES

The values of $\delta^{18}O$ and δD of water samples from springs located around the field, as well as samples from Los Humeros wells were taken from Portugal *et al.* (1994) and are plotted in Figure 3. The continuous line corresponds to the world meteoric water line (Craig, 1961). In general, the isotopic composition of the spring is close to the world meteoric water line, while the points corresponding to the geothermal wells are grouped to the right of the spring data as a result of interaction between fluid and the host rock. This behavior suggests the occurrence of meteoric water recharge to the system. However, as discussed later, this occurrence cannot be explained exclusively by water-rock interaction. Figure 4 shows the $\delta^{18}O$ content vs. elevation in the fluid feeding zone of the well. This figure shows that the deepest fluid contains greater abundance of heavy isotopes. Values fit a negative linear correlation, indicated on the figure by the dashed line. Also, the shallow fluids from H-16 and H-1 are dispersed in the plot. Values of ^{13}C from CO_2 from the vapour phase are in the narrow range between –4.2 ‰ and –6‰. The isotopic data dispersion is 2.4 units. The heavy value corresponds to the well H-8, while the lightest was measured in well H-12. Figure 5 depicts the plot of $\delta^{13}C_{CO2(gas)}$ data vs. the production zone for the year 1991, where the distribution of isotopic values is shown for the field. According to the ^{13}C classification from CO_2 (Hoefs, 1980), values of $\delta^{13}C$ from $CO_{2(gas)}$ are within the composition range of solid carbonates and carbonates dissolved in water. The accepted ^{13}C values for carbonates are close to 0 ‰, while those surface organic matter present values near –25 ‰ (Hoefs, 1980). Therefore, the generation mechanism for CO_2 in the system can be through thermal decarbonatation of the limestone or by dissolution of carbonates. CO_2 of magmatic origin has values between –8‰ and -5‰ (Omotho, 1972). Therefore, the $\delta^{13}C$ values from Los Humeros geothermal system may also result from a mixture between CO_2 of magmatic origin and CO_2 from carbonates. It is feasible that in the deeper strata, a major contribution of mag-

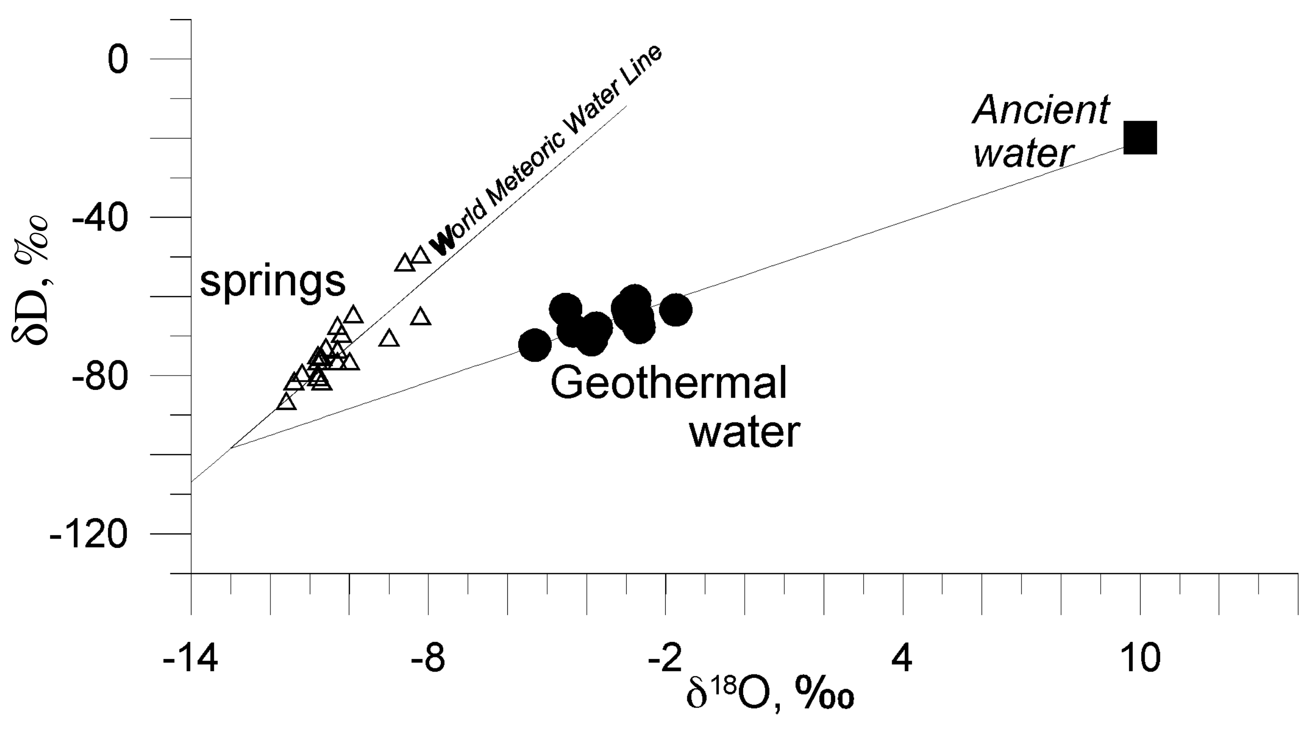

Fig. 3. $\delta^{18}O$ vs. δD plot that shows the waters of the Los Humeros geothermal field.

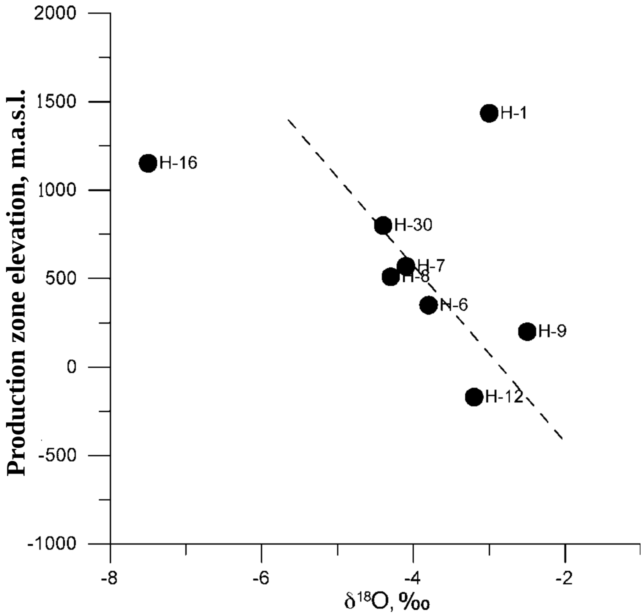

Fig. 4. Distribution of the $\delta^{18}O$ geothermal wells data vs. production zone in Los Humeros geothermal field.

matic CO_2 occurs, while in the shallower strata, CO_2 could be supplied mainly by the carbonates. No ^{13}C data of the carbonates are available to confirm this hypothesis.

DISCUSSION

The dispersion of the isotopic values of well H-1 and H-16 from the linear trend has been explained by different water-rock ^{18}O exchanges in shallow strata and is due to recent meteoric water infiltration (Portugal *et al.,* 1994). This behavior is also observed by the linear correlation (mixing line in Figure 5), where the fluids of the wells H-6, H-7 and H-9 are the resulting component between two end members, wells H-12 and H-8. The $\delta^{13}C$ values from shallow wells H-33, H-16 and H-1 are outside of this regression line as shown in Figure 5. The deviation may be due to the influence of meteoric water, as explained above for ^{18}O. Isotopic data for carbonates dissolved in groundwater show negative $\delta^{13}C$ values, as a result of interaction with organic matter (Presley and Kaplan, 1968). Mixing between groundwater and geothermal fluids may explain the light $\delta^{13}C$ values of shallow wells. The hypothesis of groundwater infiltration agrees with hydrogeological information that supports warm groundwater flowing towards deeper strata (Cedillo, 2000). However, a mixing line involving H-12 and H-1 fluids is also possible. Based on these assumptions, the following preliminary conceptual hydrodynamics model is proposed (Figure 2).

The production area extends to approximately 17 km^2. The geothermal wells are located into the Los Potreros Collapse, where fault systems occur. Increased permeability is found at shallow depths between 200 to 400 m. The main materials are pumice, basalts and andesites. These units host a cold and a hot phreatic aquifers. Below 400 m, a medium permeability unit there exists, which is formed by lithic tuffs with the possible occurrence of an aquifer. Deeper units have low permeability and form the top of the shallower thermal reservoir. The hydraulic system acts through secondary permeability (faults and fractures), which allows the groundwater to flow towards deeper strata. Hydraulic changes due to exploitation of the shallower thermal reservoir have possibly occurred, causing the groundwater recharge from phreatic aquifer. The geological unit formed by vitreous tuff is considered to be the sealing layer, where low fluid flow between geothermal reservoirs occurs. According to the stable isotope data, regional recharge should have occurred (Figure 2). However, regional geological structures formed by granitic rocks and clay limestone seem to act as a barrier, obstructing regional lateral recharge. The deep geothermal fluids can be the result of two components, regional ancient meteoric water and magmatic water (Figure 3). The interception of the mixture line with the meteoric line result to be –13 ‰ for ^{18}O and –78.5‰ for deuterium. This isotopic composition is lighter than the present day meteoric water, indicating an ancient meteoric water input. The contribution of fossil meteoric water in the geothermal mixture is estimated to be approximately 60%.

CONCLUSIONS

Previous studies have shown the occurrence of two reservoirs in the LHGF. The structural characteristics show low

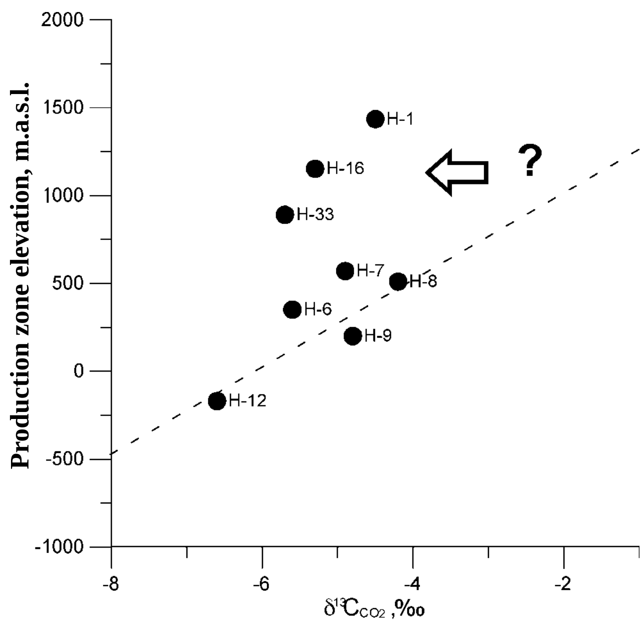

Fig. 5. Distribution of the $\delta^{13}C$ geothermal wells data vs. production zone in Los Humeros geothermal field.

permeability of the system, indicating little flow migration. The hydraulic communication between the geological formations is due to secondary permeability originated by fractures and fault systems. Stable isotopic data from reservoir and springs indicate an ancient meteoric origin for the geothermal fluid, which has been perturbed in the shallow strata by hydraulic changes due to exploitation of the reservoir. It is assumed that the infiltration of the groundwater reaches the production zone of the shallow wells through faults of the system. This hypothesis is in agreement with hydrogeological observations.

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E. Portugal, G. Izquierdo, R. M. Barragán and B. I. Romero
Instituto de Investigaciones Eléctricas,
Gerencia Geotermia
Reforma 113, Col. Palmira, 62490 Temixco, Mor. México.