Origin of fluids in Las Tres Vírgenes Geothermal Field

Mario A. Hernández Hernández^{1,2}, Daniele L. Pinti^{1,*}, M. Clara Castro³, Aída López-Hernández², Orfan Shouakar-Stash^{4,5,6}, Luc Richard¹, Sandra Núñez-Hernández⁷, Chris M. Hall³, Miguel A. Ramírez Montes⁸, and Carlos Sánchez-Cornejo⁸

¹GEOTOP-Research Centre on the dynamics of the Earth System, UQAM, Quebec, Canada

²Facultad de Ingeniería Civil, UMSNH, Morelia, Mich., México

³Dept. of Earth and Environmental Sciences, Univ. of Michigan, Ann Arbor, Michigan, USA

⁴Isotope Traces Technologies Inc., Waterloo, ON, N2V 1Z5, Canada

⁵Dept. of Earth and Environmental Science, Univ. of Waterloo, Waterloo, ON, N2L 3G1, Canada

⁶School of Engineering, University of Guelph, Guelph, ON, N1G 2W2, Canada

⁷Facultad en Ciencias de Ingeniería Química, UMSNH, Morelia, Mich., México

⁸Comisión Federal de Electricidad, GPG, México

Abstract. A geochemical survey of fluids in the Las Tres Vírgenes geothermal field (LTVGF) in Baja California Sur, Mexico, was carried out to describe their origins and evolution within the reservoir. Major and minor elements and noble gas isotopes (He, Ne, Ar, Kr, and Xe) were measured in fluids from three production wells, one injection well, and one fumarole (El Azufre). Stable isotopes of water (δD and $\delta^{18}O$) show mixing between Quaternary recharge, lighter than present-day rainfall, and a deep fluid of andesitic origin. The Na/Br and Cl/Br ratios indicate that deep brines from the LTVGF are seawater having leached evaporite deposits (i.e., halite). These deposits are presently absent in the area, but likely occurred during the Miocene, prior to the breakup of the Gulf of California, suggesting that the saline fluid end-member of the LTVGF is several million year old. Measured $^3He/^4He$ ratios of greater than 6.5 Ra (where Ra is the atmospheric ratio of 1.384×10^{-6}) show that LTVGF fluids are a mixture of meteoric waters and deep magmatic fluids, with the hotter and more pristine mantle fluids found in the southern part of the exploitation zone.

1 Introduction

The Las Tres Vírgenes Geothermal Field (LTVGF) is the smallest high-enthalpy geothermal field exploited by the Comisión Federal de Electricidad (CFE) in Mexico. It is located in the central portion of the Baja California Peninsula (Baja California Sur; Fig. 1A), 34 km NW of the town of Santa Rosalía, within a magmatic complex that includes La Reforma Caldera, the Aguajito complex, and the Las Tres Vírgenes volcano (Fig. 1B).

*Corresponding author: pinti.daniele@uqam.ca

Commercial exploitation began in 2001, with a 10 MW power plant and two back-pressure 5 MW generator units. As of December 2013, 11 wells had been drilled, with depths ranging from 1291 to 2505 m. Currently, there are four producing wells, three reinjection wells, and four exploratory wells [1]. The LTVGF presents numerous challenges related to low permeability, low recharge, and intense carbonate scaling. Nevertheless, efforts to develop this challenging geothermal field are ongoing due to the lack of conventional energy resources in the area, rendering geothermal energy one of the cheapest and most feasible sources available.

To assess the current state of LTVGF fluids (Fig. 1C), a geochemical survey was carried out in November 2016. During these studies, three production wells (LV-6, LV-11, and LV-13), a reinjection well (LV-8), and the El Azufre fumarole were sampled for major and trace elements, halogens (Cl and Br), water stable isotopes (δD and $\delta^{18}O$), and noble gas isotopes (He, Ne, Ar, Kr and Xe). The main results of halogen, He isotope, and stable isotopes of water analyses are presented in this paper.

Fig. 1. A) Location of the Las Tres Virgenes Geothermal Field (LTVGF) in Mexico; B) simplified geology of the region; C) detailed location of the production and injection wells.

2 Geology of the LTV geothermal field

The LTVGF is located in a NW-SE-oriented Plio-Quaternary rift, the Santa Rosalía Basin [2], which is related to the deformation zone created by the opening of the Gulf of California [3]. This geodynamic setting favours high heat flow and has led to favourable conditions for the occurrence of numerous geothermal areas along the coast, where normal faults act as flow channels that allow meteoric waters and/or seawaters to penetrate deep into the crust and to be heated by the anomalously high geothermal gradient of the region [3]. Three volcanic centers are located in the region: La Reforma caldera (3.5 to 0.8 Ma), the Sierra de Aguajito (0.7-0.45 Ma), and Las Tres Vírgenes volcano (0.44 Ma- 30 ka), where the geothermal field is located [2] (Fig. 1B). Their products vary from basaltic to andesitic and rhyolitic [4]. The western border of the basin comprises a system of regional normal faults, with evidence of recent lateral displacement. Trending NW-SE faults, such as the El Azufre fault (Fig. 1C), control both the reservoir permeability and the hydrothermal activity [2].

The reservoir and production zone are located at depths of ca. 1000 m, in a fractured Cretaceous granodiorite, which comprises the regional basement in the area. The reservoir has secondary permeability associated with NW-SE and N-S faults, which varies from 0.3 to 3.0 mD, and an effective porosity ranging from 0.4 to 5 %. The granodiorite production zone is capped by a 750m-thick volcano-sedimentary sequence of Oligocene-Miocene age, known as the Comondú Group, followed by 300 m-thick Miocene-Quaternary age shallow marine deposits, corresponding to the Santa Rosalía Basin [2]. According to geological, geochemical, reservoir, and production characteristics, the field is divided into two areas: north and south (Fig. 1C). The highest temperatures, of up to 275°C, are observed in the southern area, where four wells are currently exploited: LV-4A, LV-6, LV-11, and LV-13D. Although the reservoir is liquid-dominated, the fluid reaches saturation conditions in producing wells, leading to a steam-water mixture [1].

2.1 Fluid geochemistry

Fluids exploited at the LTVGF are of sodium-chloride type, with the highest salinity found in the southern production area, which also shows the highest temperature. The non-condensable gas phase is dominated by CO₂ (average value of 98.1±1.1 % m/m), followed by H₂S (1.4 % m/m), and N₂ (1% m/m) [5]. Based on the element geochemistry and the stable isotopic composition of the geothermal fluids and the surrounding cold and hot springs, numerous authors have concluded that the LTVGF fluids are a mixture of at least two fluids, but their origins remain unclear [4, 5, 6].

The stable isotopic composition of the fluids suggests that magmatic waters contribute approximately 30% of the LTVGF fluid composition, whereas meteoric waters represent the main component (70%) [4]. Because of present-day arid conditions, and because the calculated stable isotopic composition of the meteoric recharge is lighter than that of modern precipitation, it is suggested that the meteoric water component is fossil, with recharge having taken place during the wetter Quaternary period [4, 6]. The ¹⁴C and U/Th/⁴He calculated ages of 4-31 ka appear to support this hypothesis [6].

While some authors have excluded seawater as part of the LTVGF deep fluid composition [4], others have suggested that seawater infiltrated into the reservoir from the nearby Gulf of California, based on the Na/Cl ratio [5]. More recently, a mixture of seawater (25 to 42%) and fossil meteoric waters were assumed to explain the composition of the LTVGF fluids [6].

3 Results and discussion

3.1 Major ions and halogens

The Na-Cl-Br systematics of the brines (Fig. 2), graphically presented as Cl/Br and Na/Br molar ratios, is helpful to identify the solute sources [7]. During seawater evaporation and halite precipitation, Na and Cl concentrations decrease relative to Br, the latter sparingly incorporated into halite. In contrast, during halite dissolution, both Na and Cl concentrations increase by equimolar amounts relative to Br concentration [7]. In Figure 2, the data plots to the left of the seawater composition, based on a 1:1 molar halite line, as is often observed in sedimentary formation waters [7, 8]. This shift results from water-rock interactions (i.e., the WRI-path in Fig. 2), with Na exchanged for another cation. The LTVGF brines plot above seawater, indicating halite dissolution as the origin of these formation waters, or at least a significant impact from halite dissolution.

Evaporitic deposits of Miocene age exist in the Santa Rosalía Basin, but are mainly composed of gypsum, not halite, while other authors have suggested that the Santa Rosalía gypsum beds formed on the fringe of a much thicker evaporite deposit currently located 280 km southeast of the LTVGF, in the Guyamas basin [9]. These evaporites formed a unique body 7Ma ago, prior to the breakup of the Gulf of California. If the salinity charge of the LTVGF brines derives from such deposits, then the primary LTVGF saline brine could be of Late Miocene age.

Fig. 2. Na/Br vs. Cl/Br molar ratios of production and injection wells in the LTVGF. The “halite precipitation line” and the “halite dissolution line” are reported as tracers of seawater evolution during the evaporation and dissolution of evaporites respectively.

3.2 Stable isotopes

The measured stable isotopes show very consistent δD values (average $\pm$ STDEV), -51.45 $\pm$ 0.26‰, while $\delta^{18}O$ is more variable, ranging from -2.80 to 3.07‰. The δD vs $\delta^{18}O$ diagram plots the results for LTVGF fluids sampled at both production and injection wells (Fig. 3). The stable isotopic composition of groundwater and geothermal waters measured by [4] in the Las Tres Vírgenes region are also reported. The recharge of the LTVGF is expected to have an initial δD value of -67.3‰ and a $\delta^{18}O$ value of -9.7‰. A regression line, estimated using both recharge and values measured from the fluids of the geothermal

wells, indicates mixing between meteoric water [6] and a deep magmatic fluid. The stable isotopic composition of geothermal waters plots on a different straight line, which can be interpreted as resulting from the related surface evaporation processes [4]. The estimated LTVGF recharge has a much lighter isotopic composition than that of modern rainfall (Fig. 3), suggesting that the system was recharged in older periods [4, 6].

Fig. 3. δD vs. $\delta^{18}O$ of sampled LTVGF production and injection fluids, as well as of groundwater and geothermal waters [4].

3.3 Helium isotopes

The $^3\text{He}/^4\text{He}$ ratios (R), normalized to that of the atmosphere ($R_a = 1.384 \times 10^{-6}$), range from 2.90 to 6.38 R_a . R/R_a ratios, corrected for the air component (R_c/R_a) using the $^4\text{He}/^{20}\text{Ne}$ ratio as proxy for atmospheric He [10], yield values ranging from 4.77 to 6.57 R_a .

Fig. 4 shows the measured R/R_a values as a function of $^4\text{He}/^{20}\text{Ne}$ ratios for all fluid samples collected in this study. R/R_a values are distinct from air ($R/R_a = 1$), crust ($R/R_a = 0.02$), and mantle ($R/R_a = 8$) end-members. Similarly, the terrigenic (i.e., crust and/or mantle) $^4\text{He}/^{20}\text{Ne}$ value is much higher (~ 10000) than that of the air (0.318), rendering this elemental ratio useful to discriminate between atmospheric and terrigenic noble gas contributions.

The LTVGF fluids display helium isotopic compositions compatible with mixing between recharge water (Air Saturated Water; ASW) at 22°C, the Mean Annual Air Temperature of 0.270, and a magmatic fluid. Two main hypotheses are proposed as the origin of the observed helium isotopic values (Fig. 4): 1) if one assumes that the mantle fluid has an isotopic composition similar to that of the upper mantle ($R/R_a = 8$), the presence of radiogenic helium is required (17.5% to 29% of the mixture), possibly from connate water, which may have accumulated radiogenic helium over time; 2) inversely, the expected R/R_a values for mixing range from 5.7 R_a to 6.6 R_a , and are compatible with the subcontinental lithospheric mantle reservoir ($R/R_a = 6.1 \pm 1.9$) or arc volcanism ($R/R_a = 5.37 \pm 1.89$). This second hypothesis, however, is not compatible with the present extensional tectonic context in which the LTVGF formed. Indeed, the area is currently part of the deformation zone related to the opening of the Gulf of California. However, there are several lines of evidence indicating that, during the Miocene, this area corresponded to the Farallon plate subduction zone that formed the so-called Comondú volcanic arc [11]. The

concomitant helium ($^3\text{He}/^4\text{He}$) and C ($\delta^{13}\text{C}$) isotopic signatures present in the LTVGF are also compatible with mixing between a pure mantle source (MORB-type), which is presently the heat source of the field, and the assimilation of ^4He -rich, $\delta^{13}\text{C}$ -lighter sediments from this fossil subducted plate [12].

It is worth noting that the isotopic composition of LV-13D yields the highest mantle helium contribution. Assuming mixing between the three sources (i.e., air, crust, and mantle) leads to a mantle helium contribution to the LV-13D fluid of between 74% and 78% of the total helium. This confirms that the southern region of the LTVGF, which displays the highest temperatures, contains the more pristine and higher enthalpy magmatic fluids of the entire field.

Fig. 4. The $^3\text{He}/^4\text{He}$ ratio (R) normalized to that of the atmosphere (R_a), plotted against the $^4\text{He}/^{20}\text{Ne}$ ratio. The isotopic composition of the upper mantle, the crust, and the ASW are reported for comparison.

4 Conclusions

In this study, the origins of brines and mantle volatiles are revealed through: (1) the conservative solute elements, Cl and Br, (2) the stable isotopic composition of water (δD and $\delta^{18}\text{O}$), and (3) helium isotopes. Firstly, the conservative elements show that the deep LTVGF brine is not evaporated seawater, but instead derives from the dissolution of halite deposits. Since halite deposits are not currently present in the Santa Rosalía Basin, it is likely that they occurred in the Miocene, prior to the breakup of the Gulf of California. This hypothesis suggests that the exploited brines are very ancient, but were diluted by more recent Quaternary or Holocene recharge, as suggested by the stable isotopic composition of the sampled waters. On the other hand, the observed helium ratios confirm that the southern portion of the LTVGF shows the highest temperatures and displays the highest enthalpy of the exploited area, as indicated by the large amount of mantle-derived ^3He .

This work is funded by a CeMieGEO P-20 project from the CONACYT (Convocatoria SENER-CONACYT. 2013-01, Proyecto No. 207032), in collaboration with the Postdoctoral Research Project No. 272697 of CONACYT-SENER-Sustentabilidad Energética. We thank the Comisión Federal de Electricidad (CFE) in Morelia and Los Azufres, as well as Colin Ferguson for assistance during

sampling. DLP is supported by a NSERC Discovery Grant. Financial support from the NSF Instrumentation & Facilities award EAR-1049822 is greatly appreciated.

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