IOP Conference Series: Earth and Environmental Science



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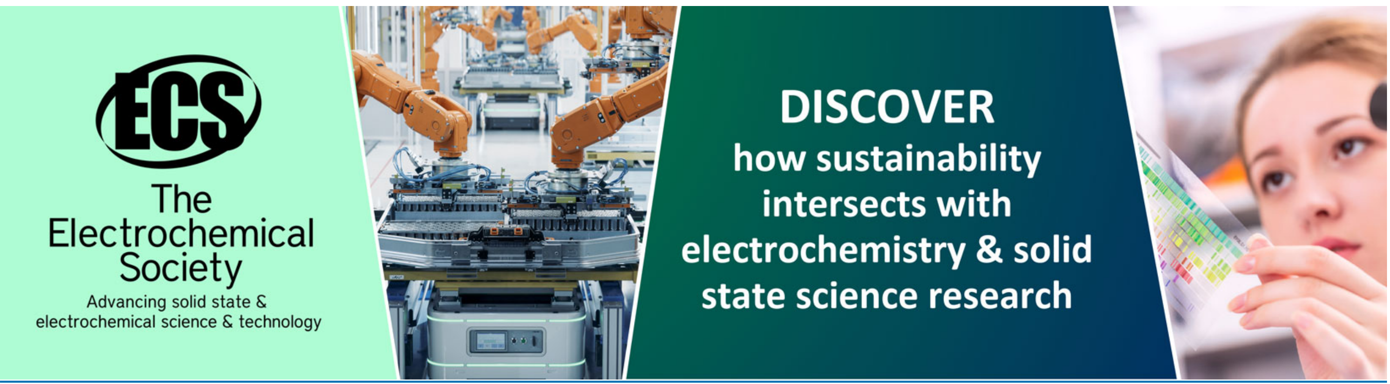
To cite this article: E González-Partida *et al* 2008 *IOP Conf. Ser.: Earth Environ. Sci.* **3** 012012





# Hydro-geochemical and isotopic fluid evolution of the Los Azufres caldera geothermal field, central Mexico

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**Keywords**: geothermal reservoir, fluid inclusions, melting temperatures, boiling.

## Summary

Hydrothermal alteration at Los Azufres geothermal field is mostly propylitic showing progressive dehydration and temperature increase with depth. Regular argillic and advanced argillic zones overlie the propylitic zone due to intense gas activity of the hydrothermal system. The deepest fluid inclusions (proto-fluid) are liquid-rich and with low salinity, with NaCl as the dominant fluid type and ice melting temperatures (Tmi) near 0 °C, and salinities of 0.8 wt% NaCl-equivalence. The homogenization temperature (Th) is 335±5 °C. The boiling zone has a Th of ± 300 °C and apparent salinities between 1 and 4.9 wt% NaCl-equivalence, implying a vaporization process and a very important participation of non-condensable gases (NCGs), mostly $CO_2$. We interpret the evolution of this system as deep liquid water that boils during ascension through fractures connected to the surface. Boiling is caused by a drop of pressure, which favors an increase in the steam phase within the brine ascending towards the surface. During the ascent, the fluid becomes steam-dominant in the shallowest zone and mixes with meteoric water in perched aquifers. Stable isotope compositions ($\delta^{18}O$ – $\delta D$) of the geothermal brine indicate mixing between meteoric water and a minor magmatic component. The enrichment in $\delta^{18}O$ is due to the rock–water interaction at relatively high temperatures.

IOP Conf. Series: Earth and Environmental Science **3** (2008) 012012 doi:10.1088/1755-1307/3/1/012012

# 1. Introduction

The geothermal reservoir of Los Azufres is located in the eastern central portion of the Michoacan State, central Mexico and within the Trans-Mexican Volcanic belt (Fig. 1). It was discovered in 1972, and actually, the geothermal field has an installed capacity of 88 MW in an area of 35 $km^2$. There are 67 drilled wells, from which 37 are productive, with an average production of 39 t/h of steam. The depth of the productive wells ranges from 627 to 3544 m. The 88 MW are generated with 7 units of 5 MW each, a condensation unit of 50 MW, and two units of binary cycle of 1.5 MW each. There are plans to expand the capacity of the geothermal field to 128 MW with the installation of two more units of 20 MW.

# 2. Surface geology

The local basement includes a sequence of andesitic and basaltic lavas and interbedded volcanic agglomerates and paleosoils. Unconformably overlying this sequence are silicic volcanic rocks (Agua Fría rhyolite), lake sediments, dacitic lavas (San Andrés dacite), ignimbrites and domes (Yerbabuena rhyolite). The last volcanic stage at Los Azufres is represented by basaltic lavas and pyroclastic deposits and cinder cones in the east and west of the geothermal field.

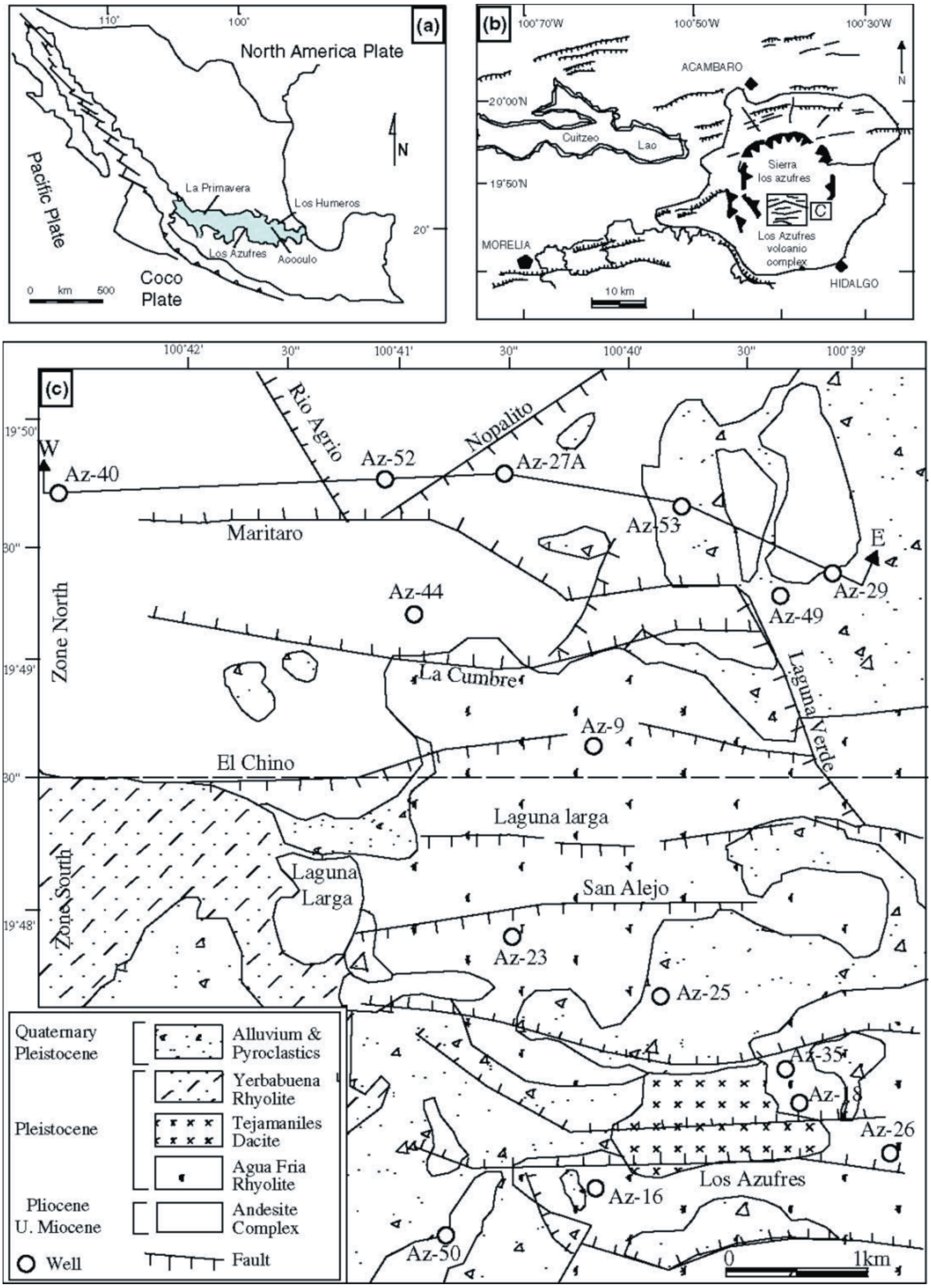
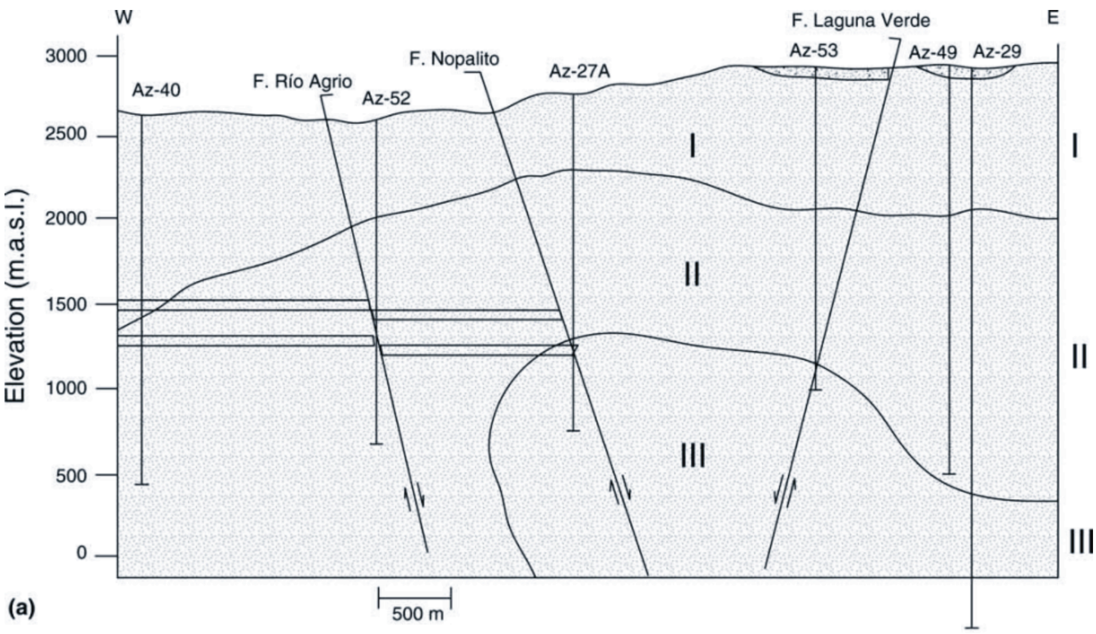



**Figure 1**. a) Regional tectonic framework of Mexico and distribution map of the main geothermal zones. b) General structural map of the Los Azufres caldera and geothermal field. c) Detailed geologic map of Los Azufres, location of the geothermal wells and location of the cross-section W–E (wells Az-40, Az-52, Az-27A, Az-53 and Az-29). Modified from González-Partida et al. (2000 a, 2000 b).



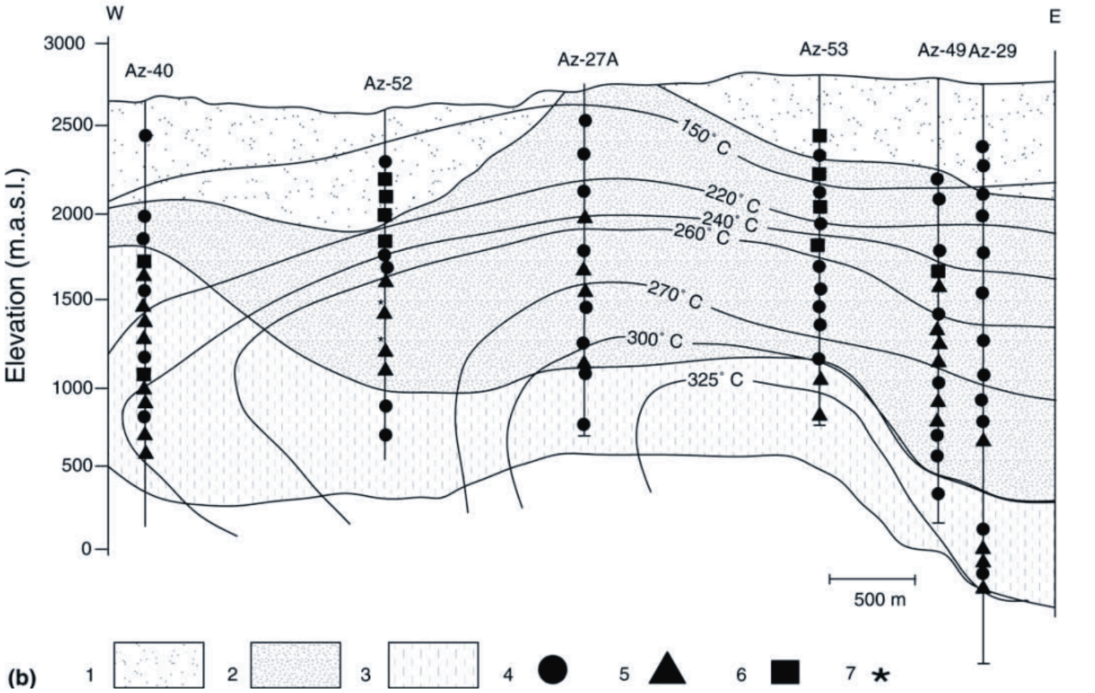




**Figure 2**. a) Paragenetic zones I, II and III, which were determined with regard to petrologic considerations. Zone III (deepest) is situated in the 300–325 °C range; it is characterized by the assemblage epidote + clinozoisite + actinolite + tremolite ± garnet and smectite+illite+chlorite in the clay fraction (more chlorite than illite and smectite). Zone II is situated in the 220–300 °C range, with the mineral assemblage

epidote+laumontite wairakite, and within the clay fraction illite+ smectite+chlorite. Zone I is situated in the 150–220 °C range and is defined by the predominance of laumontite. b) W–E cross-section indicating isoconcentration zones of the paleo-brine (fluid inclusions) and isotherms obtained from microthermometric analyses of fluid inclusions. Continued lines correspond to average homogenization temperatures zones, where (1) clathrate positive fusion temperaturas, (2) fusion temperatures from 0.7 to 2.4 °C, (3) fusion temperatures from 0.5 to 0.7 C, (4) microthermometric analysis of quartz (d), (5) microthermometric analysis of epidote (m), (6) microthermometric analysis of calcite (j), (7) microthermometric analysis of prehenite (*). Modified from González-Partida et al. (2000 a, 2000 b).

## 3. Hydrothermal alteration.

A generalized zoning of the calc-silicate assemblage can be observed in the alteration zones, with zeolites in the upper part and epidote–clinozoisite in the deepest levels (González-Partida, 2000). An argillic alteration zone overlies the calc-silicate zone and is the dominant surface manifestation of the hydrothermal alteration. In some parts, there is a mineral assemblage composed of kaolinite–alunite–S–quartz (advanced argillic zone) formed by the interaction of steam and shallow groundwater.

## 4. Geochemistry of present day fluids

Los Azufres geothermal area is dominated by Cl and Na. The Cl concentration ranges between 1485 and 7297 mg/L, and Na concentration varies between 914 and 4442 mg/L. The next highest dissolved species are $SiO_2$ and K. Boron concentration is relatively high but the Ca and Mg concentrations are relatively low (González-Partida et al., 2000 a, 2000 b). The water from all the geothermal wells is ''mature'' water type (Cl-rich), which is characteristic of deep geothermal water. Water from the hot springs, is heated by geothermal steam ($SO_4$ rich). Water from the periphery is mainly meteoric water with little or no geothermal influence. Samples from hot springs fall in the Cl-rich type suggesting that this geothermal water reaches the surface through faults and fractures. The acid $SO_4$ - rich water is meteoric water that interacts with geothermal steam. The $SO_4$-rich water is present in geothermal and volcanic systems where steam condensate interacts with shallow meteoric water causing oxidation of $H_2S$ to $SO_4$. The high concentrations of B in this type of water (B = 0.08 and 7.97 mg/L) and the relatively low concentrations of Mg (Mg = 0.03 and 112.5 mg/L) suggest a deep circulation. Furthermore, the water/rock interaction must have taken place at relatively high temperature because chlorite solubility decreases with increase in temperature, thus lowering the concentration of Mg. All other waters from the springs fit a $HCO_3$-Cl and $HCO_3$ Cl-poor trend (<12 mg/L), with a low B concentration (<1 mg/L). However, the Ca and Mg concentrations of these intermediate waters are high, suggesting that they are meteoric waters with shallow circulation through volcanic rocks. The gases in the steam dominant zone are mostly composed of $CO_2$ (80–98% of all the gases). Other gases present are: $H_2S$ (1.16%), $H_2$ (0.026%), $N_2$ (0.77%), and $CH_4$ (0.01%). Well samples show a positive $\delta^{18}O$ compared to the meteoric line, which is a characteristic of geothermal fluids. This enrichment in $\delta^{18}O$ ‰ is due to water–rock interaction at relatively high temperatures (Arnold and González-Partida, 1987, Birkle et al., 1997). Most of the spring samples plot close to the global meteoric water line.

## 5. Fluid inclusions composition

At Los Azufres, fluid trapped in inclusions during the growth of hydrothermal minerals in veins (calcite, prehnite, wairakite, anhydrite, quartz and epidote) give a record of the earliest known fluids in this active hydrothermal system.

The iso-concentrations of the proto-fluid and the average Th are indicated in Fig. 2, which is a cross-section based on 6 geothermal wells. The fluid inclusions have an initial ice melting temperature (eutectic temperature, Te), Te= 21.5 ± 0.5 °C, which implies a NaCl rich brine. The final ice melting temperatures (Tmi) reveals a zoning distribution: (a) deepest zone, close to the base line 0 (zone 3 in Fig. 2), where Tf = 0.5 to 0.7 °C, with salinities between 0.88 and 1.23 wt% equivalent NaCl; (b) intermediate zone, located between 1000 and 2500 m.a.s.l. (zone 2 in Fig. 2), with a mixture of L + V and V fluid inclusions, and Tmi = 0.7 to 2.4 °C, which corresponds to apparent salinities of ap.1.2–4.9 wt% NaCl; and (c) shallowest zone located between the surface and the steam-rich zone (steam cap or ‘‘clathrate cap’’ zone 1 in Fig. 2), with positive values for the fusion temperature, indicating a strong chemical change in the paleo-brine (proto-fluid). The fusion temperatures in this zone are Tmi = +0.1 to +7 °C, which implies an invasion of $CO_2$ with some $CH_4$,$N_2$, CO, $H_2$ and $H_2S$. The measured homogenization temperatures, plotted as isotherms (Fig. 2), show an ascending zone between wells Az-29 and Az-27A, and a descending zone in well Az-40 (this well has a thermal inversion at depth). Boiling processes start at the Th = ±300 °C isotherm, which coincides with an increase in the apparent salinity determined, and an increase of gas concentrations in the fluid.

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