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Fluid Inclusion Study from the Tres Virgenes Geothermal Field, Baja California Sur, Mexico

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ABSTRACT

The geothermal field of Las Tres Virgenes is a liquid-dominated system whose wells produce sodium chloride-rich waters. Fluid composition is chemically balanced and suggests that the fluids attained water-rock equilibrium at ca. 280°C, in agreement with the temperatures estimated for gaseous and liquid phases. The gas content is less than 1% in weight and is mostly CO_2 (> 90%). Fluid inclusions studies show that ice-melting temperatures (Tmi) display a vertical evolution. Fluids sampled within the granodiorite basement present a large range of Tmi from -2.1°C to -15.7°C, with corresponding salinities between 3.5 to 19.2 wt.% NaCl eq. In the volcanic cover, Tmi have a much narrower dispersion, from -0.3°C to -2.0°C and associated with clathrates melting at Tm_{clat} = +0.4 to +8.7ºC. The homogenization temperatures indicate a field-scale thermal evolution from 290ºC to 150ºC, delineating an up-flow zone with temperatures constrained between 290 and 260ºC, and an out-flow zone with a mean temperature of 240ºC.

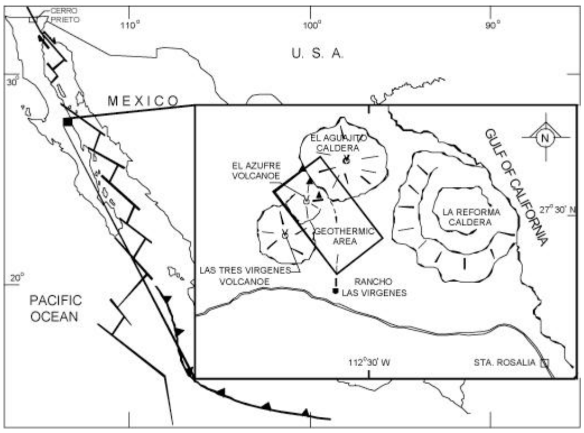

Figure 1. Regional tectonic framework of Baja California with the distribution of the main geothermal zones and the most prominent geological structures.

1. INTRODUCTION

The Tres Virgenes geothermal field is located at the South of Baja California state, 33 Km north of the Santa Rosalía harbor (figure 1). From the geologic point of view, this system is located in a Plio-Quaternary depression that constitutes the western limit of a deformation zone related to the opening of the Gulf of California (Lopez et al., 1995). The western border of the basin is limited by a set of normal faults trending NW-SE. This system originated a series of steps, falling to the NE, which controlled the distribution of the mid-Miocene to mid-Pliocene marine sediments deposits and the present-day aquifer (Ramirez, 1998). The intersection of this system with a more recent N-S faulting trend allowed the formation of three eruptive centers: La Virgen, El Azufre and El Viejo (figure 2). All of them are aligned on the N-S trend and show progressively younger ages southwards (Lopez et al., 1995). The ages span from 0.44 Ma (El Viejo volcano) to the still active Las Tres Virgenes. The chemical composition of their products varies from dacitic (El Viejo) to basaltic-rhyolitic products southwards (Las Tres Virgenes). These centers belong to the calco-alkaline series (Lopez et al., 1993) and are supposed to be the heat source of the geothermal reservoir. All the wells crosscut the granodioritic basement (81±4 Ma; K-Ar, Viggiano G., 1992) at a maximum depth of 1000 meter.

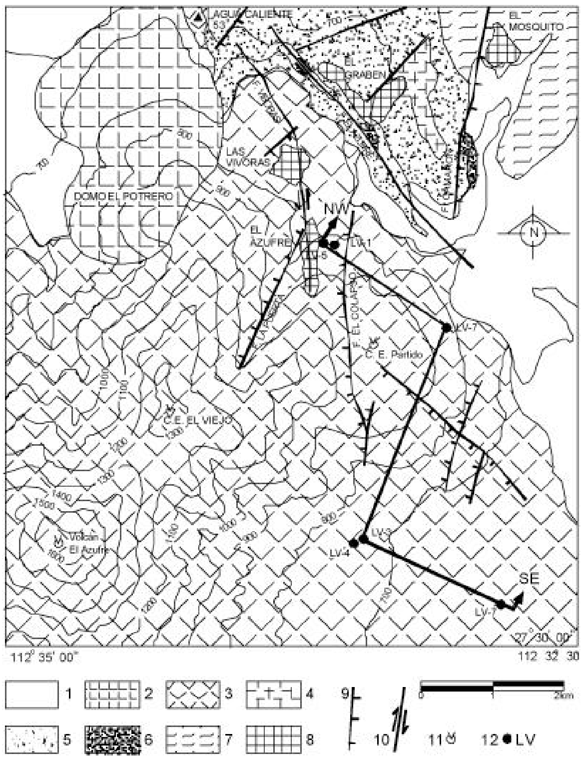

Figure 2. Geological map of the Tres Virgines geothermal field. 1 Alluvium; 2 Potrero Dome; 3 Andesite-dacite; 4 El Aguajito Andesite-dacite; 5 El Aguajito ingnimbrite; 6 La Gloria formation; 7 Cumundu group; 8 Advanced argillic alteration; 9 Normal fault; 10 Strike-slip fault; 11 Eruptive center; 12 Geothermal well.

2. PETROLOGICAL STUDIES

Five lithological units are distinguished (figure 3), namely: (1) andesite/dacite augite porphyric of the Tres Virgenes volcanic complex; (2) La Gloria formation, made up by coarse sand horizons with fossiliferous calcareous sandstone; (3) the Santa Lucia andesite formation; (4) Cumundu Group, composed by greywackes with andesitic horizons, lying unconformably on the Santa Lucia Fm.; and (5) the granodioritic basement. The latter is characterized by presence of biotite and rare hornblende, ilmenite-magnetite and sphene. The degree of alteration of the rock is generally low (1 to 5%) in the shallow levels, gradually increasing with the depth, representing up to 20 to 30% of the rock. The unconformity surface between the granodiorite and the Miocene deposits is marked by the presence of a massive calcite and quartz deposit up to 150m thick. The reservoir displays a vertical mineralogical zoning, whose boundary is defined by the stability of epidote (Figure 4). The alteration in the shallow reservoir is dominated by zeolites (stilbite and mordenite) with quartz + calcite + chlorite + smectite / illite. The deepest part of the reservoir is characterized by a more complex association dominated by epidote + quartz + calcite + chlorite + wairakite + sericite + marcasite + chalcopyrite + pyrite + chlorite/smectite interstratified

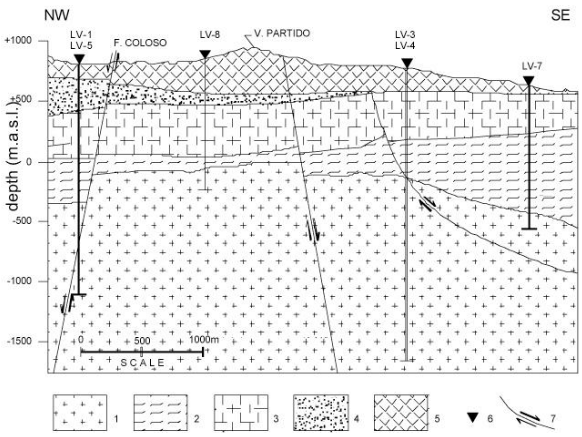

Figure 3. NW-SE geologic cross-section (see figure 2 for location) showing the depth of the analyzed wells at the Tres Virgenes geothermal field.

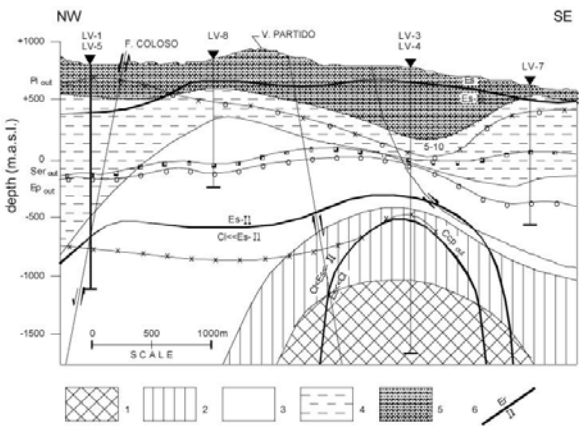

Figure 4. Distribution of the hydrothermal alteration (AH-clay fraction) and limit of distribution of: pyrite (py), sericite (ser), epidote (ep) and chalcopyrite (ccp); (1) 30-40 % AH; (2) 15-20% AH; (3) 15-10 % AH; (4) 5-10% AH; (5) 1-5 % AH; (6) limit of the distribution of the clay fraction.

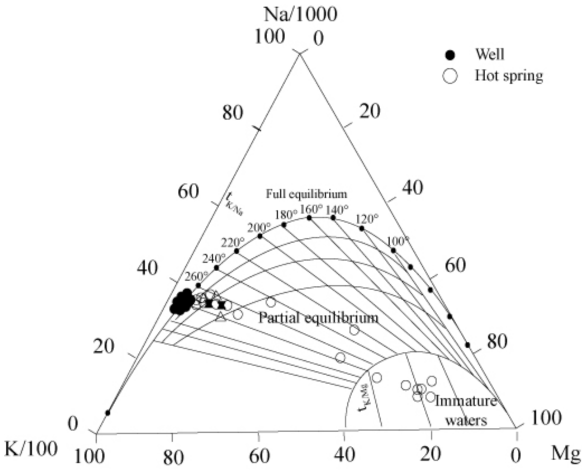

Figure 5. Na-K-Mg diagram (Giggenbach, 1991) showing equilibrium temperature and conditions for the geothermal brine of the Tres Virgenes geothermal field.

3. CHEMICAL CHARACTERISTICS OF THE PRESENT DAY BRINE

Present day brine is a balanced fluid with Cl/B molar relation close to 12, comparable to typical geothermal brine. The low values of Cl/B and Mg concentration indicate a high temperature water rock interaction. Temperatures calculated for water samples using the K/Na geothermometer (Giggenbach, 1991) from wells LV-1, LV-3, LV-4 and LV-5 are homogenous and around 280ºC. These waters, on the Na-K-Mg diagram of Giggenbach (1991; figure 5), show a similar equilibrium temperature at around 280ºC, also indicating an immature tendency of these geothermal waters. The gas phase geothermometer (H_2/Ar molar relation vs TºC) allowed us to estimate a maximum temperature of around 280ºC (González et al., 2001), in perfect agreement with the temperatures calculated for the liquid phase. Molar ratio of H_2/Ar vs CO_2/Ar (figure 6) also suggests temperatures of gas/liquid phase equilibrium for the wells LV-1, LV-3, LV-4 at around 280ºC.

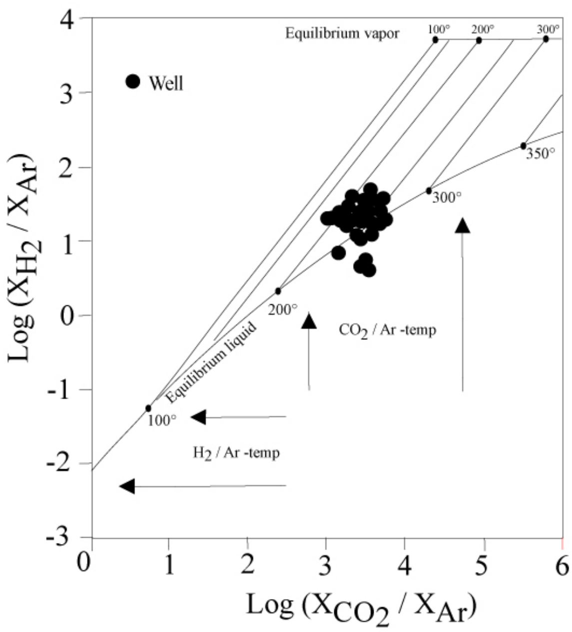

Figure 6. H_2 vs CO_2/Ar plot to evaluate the equilibrium conditions evaluation for the gas phase at the Tres Virgenes geothermal field.

4. FLUID INCLUSION STUDIES

Microthermometric determinations were made on well cuttings and core samples containing veins filled up by hydrothermal epidote, quartz and calcite mainly, collected at depths from 110m to 2452m. The fluid inclusions are L+V type, with liquid phase dominating. The distribution of the melting temperatures (Tmi; figure 7) on the geothermal field indicates the presence of two distinct zones. The first zone span from surface to the limit with the granodioritic basement, with Tmi ranging from -2 to -0.3ºC and clathrate evidences with melting temperatures from +0.4 to +8.7ºC. The second zone corresponds to the reservoir installed within the granodiorite basement, and is characterized by a Tmi ranging from -15.7 to -2.1ºC. The distribution of the homogenization temperatures and isotherms (figure 7) illustrate the presence of an “up-flow” zone close to the wells LV#3 and LV#4 with a range of temperatures from 260 to 290ºC, moving as an thermal plume to the wells LV#5 and LV#1 (Th=240ºC). The distribution of the hydrothermal argillic alteration compared to the structural network reveal the major role that plays the strike-slip fault as a channelway for the geothermal fluids. The fast vertical cooling detected at the basement-cover unconformity, dropping temperatures from 190 to 150ºC, associated with a drastic fall on salinities, degassing of CO_2 and the presence of a massive quartz-calcite layer, is interpreted as the result of a mixing between upwelling geothermal fluids with meteoric waters.

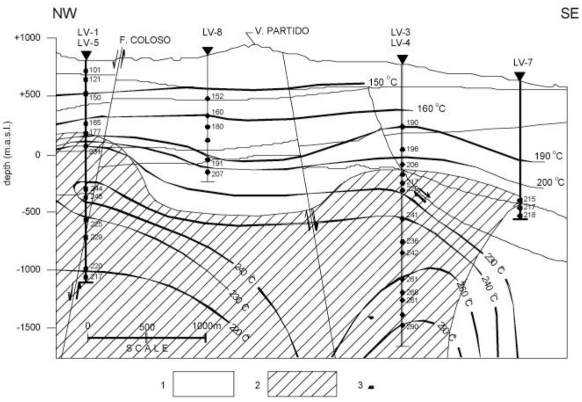

Figure 7. Distribution of the isotherms calculated from microthermometric analyses of fluid inclusions

5. CONCLUSION

The Tres Vírgenes geothermal field is located in an active tectonic zone associated with the opening of the California. The propylitic alteration detected affecting the granodioritic basement at depth, passes to an argillic alteration zone as we move upwards to the shallowest levels of field. The geothermal field of Tres Virgenes is a liquid-dominated system with a well-balanced composition and in equilibrium with the host rock. This equilibrium allowed us to estimate temperatures using geothermometers based in the liquid phase chemistry, resulting in temperatures around 280ºC. The gas/liquid phase equilibrium geothermometer also indicates a temperature of around 280ºC. Fluid inclusion studies reveal a vertical evolution. At depth the fluids present a range of salinities from 3.5 to 19.2 wt.% NaCl eq. Whitin the volcanic cover, salinities present a narrower variation from 0.53 to 3.4 wt.% NaCl eq., respectively associated with the melting of clathrates, (Tm_{cla} = +0.4 to +8.7ºC). Homogenization temperatures (Th) present a vertical evolution from 150ºC to 290ºC. The distribution of the Th suggests an upflow zone with temperature range from 290°C to 260°C, and an outflow zone with a mean temperature of 240 °C. The paleo and present day isotherms distribution in the reservoir is comparable and suggests that the geothermal exploitation do not affect the reservoir thermicity.

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