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Geochemical survey of geothermal systems in northern Chile

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Introduction

Hydrothermal activity in northern Chile not necessarily associated with volcanic structures [1] is related to an anomalous geothermal gradient produced by the subduction process thrusting the oceanic Nazca Plate beneath the South America Plate [2]. Preliminary investigations [3] indicated that several areas area characterized by extended hydrothermal systems, such as El Tatio, Puchuldiza and Surire, although the local economic conditions did not allowed a systematic geothermal exploitation. This study presents and discusses the compositional data of thermal fluid discharges of Puchuldiza-Tuya, Surire, Pampa Lirima, Pampa Apacheta, El Tatio and Torta de Tocorpuri hydrothermal systems (Fig. 1). The aim is to investigate the chemical-physical conditions acting on the fluid reservoirs to provide information useful for the evaluation of the geothermal potential of these systems.

Regional setting

The main hydrothermal systems of northern Chile are located within NS-, NW-trending grabens at the western side of the Pliocene–Holocene Central Andean Volcanic Zone (CAVZ) [4]. This wide area is characterized by a homogeneous geological setting, consisting of Lower Miocene-Pleistocene ignimbrite deposits and andesitic–rhyolitic volcanic products overlying Middle Cretaceous-Upper Miocene volcano–sedimentary formations. The latter, likely hosting the main hydrothermal reservoirs, are formed mainly by andesitic lava and pyroclastic flows, conglomerates, and occasionally by breccias, sandstones, siltstones, limestones, marls and evaporites [5,6]. Evaporitic surficial deposit, locally named "salar", constituted by borates (mostly ulexite), and subordinate sulphates, carbonates and chlorinates, are locally present [7].

Water geochemistry

The chemical composition of the El Tatio and Puchuldiza-Tuya water discharges is characterized by a Na^+-Cl^- composition, high TDS (Total Dissolved Solids) values (up to 10,829 mg/L), and relatively high concentrations of geochemical tracers commonly enriched in mature waters (B and Li^+). These features are related to contribution of steam produced by relatively high enthalpy geothermal reservoirs. Surire waters, although marked by similar characteristics, display significant SO_4^{2-}-enrichment that may be caused by i) H_2S dissolution and ii) leaching of evaporitic rocks that are extensively present in the area. At Pampa Apacheta, low-temperature (<90 °C) fumaroles discharging low-pH (<3.57), SO_4^{2-}-dominated fluids, typical of meteoric water heated by H_2S-bearing steam. The Torta de Tocorpuri fluid discharges, having a Ca^{2+}-SO_4^{2-}(HCO_3^-) composition and low outlet temperatures (<28 °C), are likely related to presence of a thick meteoric aquifer affected by dissolution of relatively low amounts of a CO_2-H_2S-rich gas phase. Eventually, Pampa Lirima thermal waters are characterized by a Na^+-Cl^-(SO_4^{2-}) composition and relatively low TDS values (<1,250 mg/L), indicating that the origin of these thermal discharges are fed by low contribution of both hydrothermal fluids and solute from gas-water-rock interactions.

In the δD vs. $\delta^{18}O$ diagram (Fig. 2), the Na^+-Cl^- waters plot out of the Local meteoric Water Line (LMWL) [8], likely because of different processes: 1) loss of vapour, 2) water-rock interaction, and 3) mixing between meteoric and "andesitic" water [9]. The water isotopic signature of the Pampa Apacheta, Pampa Lirima and Torta de Tocorpuri waters confirms that the contribution of magmatic water to these discharges is negligible.

Geothermometric calculations based on the composition of the main cations indicate that: 1) mature waters, i.e. those from fluid discharges of El Tatio and Puchuldiza Tuya, equilibrated at about 230 °C; 2) Surire and Pampa Lirima waters did not attain a complete chemical equilibrium; 3) Pampa Apacheta and Torta de Tocorpuri waters are completely immature (Fig. 3).

Gas geochemistry

The dry fraction of the gas phases discharged at El Tatio, Puchuldiza-Tuya and Surire has a chemical composition typical of hydrothermal fluids, being dominated by CO_2 with significant concentrations of N_2, CH_4, H_2S and H_2, and showing low atmospheric contribution. At Pampa Apacheta, the presence of SO_2 and HCl suggests a direct contribution of magmatic-related fluids. The gas samples from all these systems are characterized by mantle isotopic signature for CO_2 ($\delta^{13}C$-CO_2), whereas the $\delta^{13}C$-CH_4 and δD values indicate that CH_4 is mainly thermogenic. On the contrary, the CO_2-rich gases from Pampa Lirima and Torta de Tocorpuri show relatively high Ar and O_2 concentrations, suggesting that these discharges strongly depend on the influence of shallow environment. Accordingly, the carbon isotopic signature of CO_2 points to significant organic contribution, and the isotopic features of CH_4 are related to biogenic processes. Gas geothermometry in the H_2-CO_2-CH_4 system (Fig. 4), consistently with the cation geothermometers (Fig. 3), indicate that the El Tatio, Surire and Puchuldiza-Tuya fluids equilibrated at temperatures of 200-250°C, assuming redox conditions more oxidizing than those typical of hydrothermal fluids. Equilibrium temperatures of the Pampa Apacheta gases are significantly higher (up to 345 °C), whereas Pampa Lirima and Torta de Tocorpuri gases seems to be affected by severe H_2-depletion, likely caused by re-equilibrium at lower temperature during the fluid ascent toward the surface.

Concluding remarks

Chemical and isotopic compositions of fluids discharges from the El Tatio, Puchuldiza-Tuya and Surire hydrothermal systems seem to be related to liquid-dominated reservoirs that may be considered promising for geothermal exploitation. However, a reliable estimation of the production capability of these systems can only be obtained on the basis of further detailed geophysical and geochemical investigations. The Pampa Apacheta fumaroles are fed by a still active magmatic system, thus a geothermal prospection could be successfully carried out in the areas surrounding the volcano. On the contrary, at both Torta de Tocorpuri and Pampa Lirima thick shallow aquifers mask possible clues related to presence of well developed geothermal systems.

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Fig. 1. Location of the hydrothermal systems of northern Chile

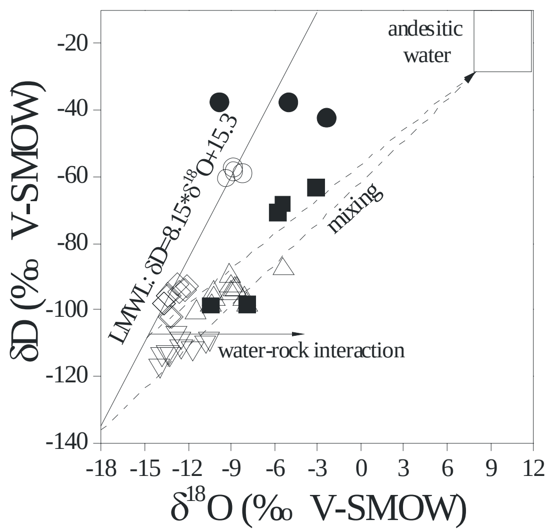

Fig. 2. δD vs. δ^{18}O binary diagram

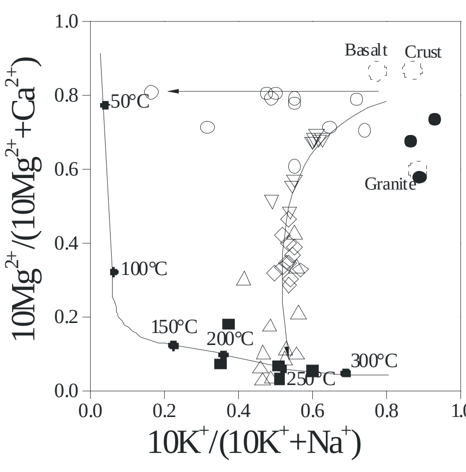

Fig. 3. 10Mg/(10Mg+Ca) vs. 10K/(10K+Na) binary diagram

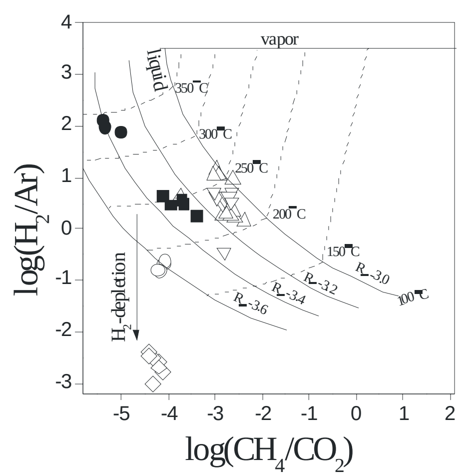

Fig. 4. log(CH_4/CO_2) vs. log(H_2/Ar) binary diagram