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Fluid geochemistry and soil gas fluxes (CO_2–CH_4–H_2S) at a promissory Hot Dry Rock Geothermal System: The Acoculco caldera, Mexico

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ABSTRACT

The Acoculco caldera has been recognized by the Mexican Federal Electricity Company (CFE) as a Hot Dry Rock Geothermal System (HDR) and could be a potential candidate for developing an Enhanced Geothermal System (EGS). Apart from hydrothermally altered rocks, geothermal manifestations within the Acoculco caldera are scarce. Close to ambient temperature bubbling springs and soil degassing are reported inside the caldera while a few springs discharge warm water on the periphery of the caldera. In this study, we infer the origin of fluids and we characterize for the first time the soil degassing dynamic. Chemical and isotopic ($\delta^{18}O$–δD) analyses of spring waters indicate a meteoric origin and the dissolution of CO_2 and H_2S gases, while gas chemical and isotopic compositions (N_2/He, $^3He/^4He$, ^{13}C, ^{15}N) reveal a magmatic contribution with both MORB- and arc-type signatures which could be explained by an extension regime created by local and regional fault systems. Gas geothermometry results are in agreement with temperature measured during well drilling (260 °C–300 °C). Absence of well-developed water reservoir at depth impedes re-equilibration of gases upon surface. A multi-gas flux survey including CO_2, CH_4 and H_2S measurements was performed within the caldera. Using the graphical statistical analysis (GSA) approach, CO_2 flux measurements were classified in two populations. Population A, representing 95% of measured fluxes is characterized by low values (mean: 18 g m^{-2} day^{-1}) while the remaining 5% fluxes belonging to Population B are much higher (mean: 5543 g m^{-2} day^{-1}). This low degassing rate probably reflects the low permeability of the system, a consequence of the intense hydrothermal alteration observed in the upper 800 m of volcanic rocks. An attempt to interpret the origin and transport mechanism of these fluxes is proposed by means of flux ratios as well as by numerical modeling. Measurements with CO_2/CH_4 and CO_2/H_2S flux ratios similar to mass ratios of sampled gases were considered as reflecting advective transport. A numerical model of CO_2 migration in the subsoil system under fully water and gas saturated conditions was performed using the TOUGH2 code in order to reproduce semi-quantitatively field measurements. The main results show that high flux values produced by advective geothermal degassing can be very localized and that low and heterogeneous permeability conditions can induce low advective CO_2 flux values. Therefore, in this case the populations discriminated by the GSA method should not be interpreted in terms of origin and/or transport mechanism but rather in terms of permeability conditions.

1. Introduction

For the last years, Hot Dry Rock (HDR) geothermal systems have been the center of attention in the geothermal community. Also referred as hidden geothermal systems, HDR systems differ from the classical convective geothermal systems by the lack of water reservoir at depth due to low permeability wall-rock, and therefore the quasi-absence of thermal manifestations at the surface. If an artificial reservoir can be created by hydraulic fracking of the HDR system, an Enhanced (or Engineered) Geothermal System (EGS) is created. Due to the far most abundance of HDR systems compared to convective geothermal systems, the potential of producing electricity by EGS is considered as very promising. For example, Blackwell et al. (2006) stated that the exploitation of only 2% of the EGS resource in the USA would be enough to supply 2500 times the annual national consumption of primary energy.

In Mexico, no current estimations of EGS resources are available but exploration of potential areas is under process. One ideal target site for developing EGS is the Acoculco Caldera located at 130 km northeast of Mexico City (López-Hernández and Castillo-Hernández, 1997; Lorenzo Pulido et al., 2011; Fig. 1A). The presence of extensive argillic alteration at the surface and a few bubbling springs motivated a series of geochemical and geophysical exploration studies mostly lead by the

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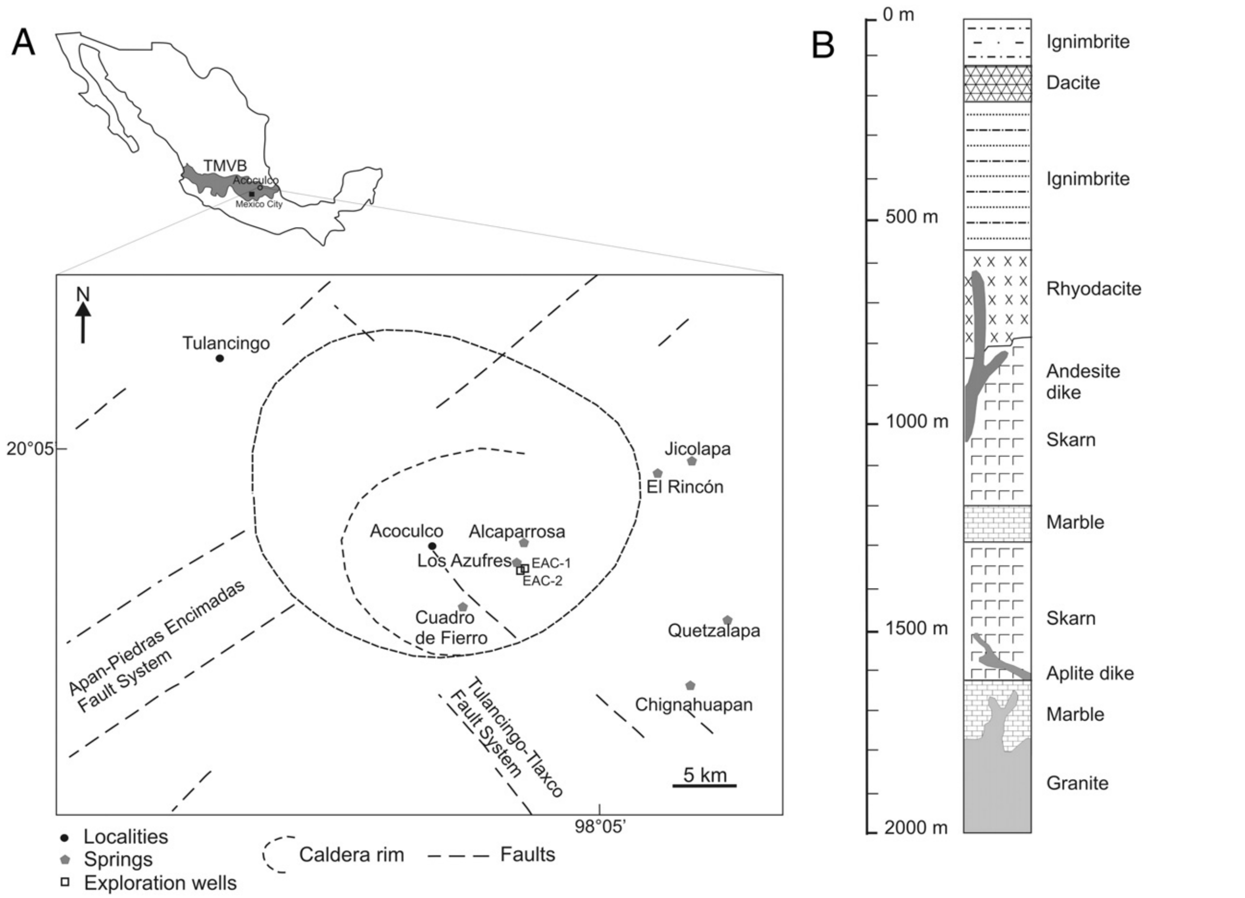

Fig. 1. A. Location of the Acoculco caldera within the Trans-Mexican Volcanic Belt and schematic map of the Tulancingo–Acoculco caldera complex with the position of the main fault systems, springs and the two exploration wells. B. Lithologic column from exploration well EAC-1 (depth in m). Both figures were modified after López-Hernández et al. (2009).

Mexican Federal Electricity Company (CFE). Two exploration wells were drilled and promising temperatures of ~300 °C were measured at a depth of 2000 m with a corresponding gradient of 14 °C/100 m, three times higher than the baseline gradient measured within the Trans-Mexican Volcanic Belt (Ziagos et al., 1985). The absence of water reservoir at depth is attributed to the low permeability of the wall-rock. The upper 800 m rock layer is intensely hydrothermally altered and probably impedes the recharge of the system by meteoric waters (López-Hernández et al., 2009).

In this study, exploration geochemical techniques were applied at Acoculco in order to infer the origin of the spring fluids (water and gases), to discuss the conditions of temperature in the subsurface, and to characterize the soil degassing dynamic at the locations of Los Azufres and Alcaparrosa sites where most of the surface manifestations are localized. Waters and gases were sampled for chemical (major components) and isotopic analyses ($^3He/^4He$, ^{13}C, ^{15}N), and a multi-gas soil flux survey (CO_2, CH_4, H_2S) using the accumulation chamber method was performed for measuring soil gas fluxes. CO_2 soil flux surveys have been widely used to quantify gas emission in active volcanoes and geothermal areas, to identify the main tectonic structures controlling the upflow of deep gases and to estimate the heat flux released through soil degassing (e.g. Chiodini et al., 1998; Toutain and Baubron, 1999; Bergfeld et al., 2001; Lewicki et al., 2005; Werner and Cardellini, 2006; Chiodini et al., 2007; Viveiros et al., 2010; Inguaggiato et al., 2011; Mazot et al., 2011). Such measurements are also suggested for the detection of hidden geothermal systems (Lewicki and Oldenburg, 2005). Measurements of CH_4 fluxes in volcanic–geothermal areas are now also relatively common and aim to quantity the contributions of 'geological' CH_4 within the worldwide CH_4 emissions (Etiope et al., 1999; Etiope and Klusman, 2002; Cardellini et al., 2003a; D'Alessandro et al., 2009). Unlike CO_2 and CH_4, H_2S flux measurements are less common probably because of the low fluxes encountered. The reason invoked is that most of H_2S is lost due to dissolution and oxidation in groundwater and formation of sulfur rich mineral encrustations (Werner et al., 2008; Bergfeld et al., 2012; Bloomberg et al., 2012). Werner et al. (2008) reported estimations of the CO_2 (410 T day^{-1}) and H_2S fluxes (2.4 T day^{-1}) at the Hot Spring Basin (Yellowstone National Park) based on measurements with the accumulation chamber and observed that no H_2S flux can be detected when CO_2 fluxes are low. Previously reported geochemical data of Acoculco water and gas samples (data from Tello-Hinojosa, 1986 and cited in López-Hernández et al., 2009) are integrated in this study and discussed together with present data.

Finally, a numerical model was performed to simulate the migration of CO_2 towards the surface through: (1) a fully water saturated shallow aquifer and (2) a fully gas saturated subsoil system. The first scenario situation is supported by the presence of shallow aquifers at Acoculco, which most probably attenuate and affect the migration of deep CO_2 towards the surface. The model is constrained by injecting CO_2 fluxes similar to the ones measured at Acoculco. By changing the properties of the modeled domain (depth, permeability and porosity), it is shown how advected CO_2 fluxes can cover a large range of values. It should be noted that this model only aims to reproduce semi-quantitatively field observations in order to understand the distribution gas fluxes. Further modeling investigations including more detailed characteristics of the surveyed area (e.g. water vapor condensation, mineralogy and chemical reactions) are ongoing and not within the scope of the present study.