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Surface geochemical and geophysical studies for geothermal exploration at the southern volcanic rift zone of Tenerife, Canary Islands, Spain

Fátima Rodríguez[a,*], Nemesio M. Pérez[a,b,c], Eleazar Padrón[a,b,c], Gladys Melián[a,b,c], Perla Piña-Varas[d,1], Samara Dionis[a], José Barrancos[a,b], Germán D. Padilla[a,b], Pedro A. Hernández[a,b,c], Rayco Marrero[a,b,2], Juan José Ledo[a,d], Fabián Bellmunt[d], Pilar Queralt[d], Alejandro Marcuello[d], Raúl Hidalgo[e]

[a] Instituto Volcanológico de Canarias (INVOLCAN), 38400 Puerto de la Cruz, Tenerife, Canary Islands, Spain
[b] Environmental Research Division, ITER, 38600 Granadilla de Abona, Tenerife, Canary Islands, Spain
[c] Agencia Insular de Energía de Tenerife (AIET), 38600 Granadilla de Abona, Tenerife, Canary Islands, Spain
[d] Departament de Geodinàmica i Geofísica, Facultad de Geología, GEOMODELS Research Institute, Universitat de Barcelona, C/ Martí Franquès s/n, 08028 Barcelona, Spain
[e] EuroGeol, La Esperanza 2, pta 9, 21200 Aracena, Huelva, Spain

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ABSTRACT

A joint geochemistry and magnetotellurics survey was carried out in the southern volcanic rift zone of Tenerife (Canary Islands, Spain) covering an area ~100 km^2 for geothermal exploration purposes. Soil CO_2 and H_2S diffuse effluxes, ^{222}Rn and ^{220}Rn activities, soil He, H_2, N_2, CO_2, O_2 and H_2S concentrations and isotopic composition of CO_2 were measured in 557 selected sampling sites. Magnetotelluric survey (MT) was carried out in the northern part of the study area. A total of 47 MT sites were surveyed and a new 3-D resistivity model was obtained. The observed geochemical anomalies at the soil surface have allowed the detection of areas of deep-seated gas emanations as well as the identification of high vertical permeability volcano-tectonic features in the study area. The resistivity distribution model shows a prominent low-resistivity structure interpreted as a clay alteration cap of variable thickness that might play a role on the mechanism of upward motion of deep-seated gases from the volcano-geothermal system. This is supported by positive correlation between thickness of clay alteration cap and helium emission.

1. Introduction

The Canary Islands, owing to their recent volcanism, are the only Spanish territory with potential high enthalpy geothermal resources (European Commission, 1999). Tenerife (2034 km^2) is the largest island of the archipelago and shows evident geothermal surface manifestations (Teide volcano fumaroles, the only visible discharge of geothermal fluids existing nowadays in the Canary Islands), where gas composition indicates that steam derives from a mature liquid dominated geothermal reservoir with temperatures in the range of 250–300 °C (Hernández et al., 2000). However, very few efforts have been made to develop the potential geothermal energy resources in the archipelago. From the 1970s to the 1990s, the Spanish Geological Survey (IGME) performed intensive research on geothermal resources in the country, due mainly to the oil crisis of the 1970s (Sánchez-Guzmán and García de la Noceda, 2010). Later geothermal research declined sharply and only a few projects on geothermal resources were active in Spain from 1994 to 2006, compared with the many projects carried out during the previous two decades (Sánchez-Guzmán and García de la Noceda, 2010).

The final goal of geothermal exploration in a specific area is to locate and define the size, shape, structure of hidden geothermal resources, and determine their characteristics (fluid type, temperature, chemical composition and ability to produce energy). Exploration methods include a broad range of disciplines such as geochemistry, geophysics, geology and engineering. We report

* Corresponding author at: Instituto Volcanológico de Canarias (INVOLCAN), 38400, Puerto de la Cruz, Tenerife, Canary Islands, Spain. Tel.: +34 922 747770; fax: +34 922747701.
E-mail address: fatima@iter.es (F. Rodríguez).
[1] Present address: Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.
[2] Present address: Laboratorio Nacional de Energia e Geologia (LNEG), Alfragide, 2610-999 Lisboa, Portugal.

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herein the results of detailed soil gas and magnetotelluric surveys performed in the southern part of Tenerife Island with the aim of evaluating the application of these techniques for geothermal exploration. The combination of two techniques (geochemical and geophysical) is used to better characterize the existence of geothermal reservoirs in the subsurface of the southern volcanic rift zone of Tenerife. The study area comprises a large part of the southern volcanic rift zone of Tenerife, with an area of ~100 km^2. During the study period, visible geothermal manifestations in the surface environment (i.e. fumaroles, hot springs) were absent in the study area.

1.1. Soil gas geochemistry

Geochemical studies for geothermal exploration are carried out performing a wide chemical and isotopic characterization of evident geothermal manifestations (i.e. fumaroles, hot springs) existing in an area under investigation. However, at those areas where there is a lack of visible geothermal manifestations in the surface environment, geochemical prospecting of soil gases and volatiles in the soil matrix itself can provide useful information on the location of areas where deep-seated fluids can reach the surface along active tectonic structures (Alparone et al., 2004; Giammanco et al., 2006; Hernández et al., 2000; Padrón et al., 2012; Voltattorni et al., 2010; Hanson et al., 2014). Gases released from active geothermal systems, might freely rise through the overlying cover to be detected in the soil surface. Owing to their high mobility, some gases are good pathfinders for concealed geothermal systems. They can escape towards the surface by diffusion, through convective transportation by rising hot fluids and by advective migration along fractures and faults. Therefore, studies on soil gases and volcanic/hydrothermal volatiles have become an important tool to identify vertical permeability areas for the rise of hydrothermal gases in geothermal exploration at those areas where no obvious surface geothermal manifestations are present. These surveys can also help to delineate the boundaries of a geothermal system, particularly where the interpretation and application of geophysical data is difficult.

Among soil gases, a special attention has been addressed to CO_2, Rn, He and H_2. CO_2 is the most abundant gas, after water, in the volatile phase exsolved from magma and hydrothermal systems due to its low solubility in silicate melts (Giggenbach, 1992; Stolper and Holloway, 1988). Different sources can explain the presence of CO_2 in the surface environment: biogenic CO_2, deep seated CO_2 of magmatic and/or hydrothermal origin, crustal carbon including marine limestone and organic carbon from sedimentary rocks and atmospheric CO_2 (Irwin and Barnes, 1980). Helium is considered as an almost ideal geochemical indicator due to its geochemical characteristics (Ciotoli et al., 2004): it is chemically inert, physically stable, sparingly soluble in water under ambient conditions and almost non-adsorbable. Due to its characteristics and its deep origin, helium appears as a powerful pathfinder for crustal discontinuities, faults and fractures (Padrón et al., 2012). Helium enrichment in soil gases is related to migration of fluids from deep sources, controlled by the tectonic characteristics of the studied area (Padrón et al., 2012; Walia et al., 2005). ^{222}Rn is a short-lived decay product derived from the ^{238}U decay series, with a half-life of 3.8 days. Due to its noble characteristics, the spatial pattern of radon contents in the soil gas is useful to unveil active fault zones and vertical permeability structures (Padilla et al., 2013). In volcanic-geothermal systems, the interpretation of soil ^{222}Rn data is often complicated because of the wide variety of factors influencing the source and transport of this gas. In this context, variations in soil ^{222}Rn concentration can be produced by fluid release from new magma injection, crustal micro-fracturing, changes in the temperature and depth of the hydrothermal system and variations in rock permeability because of the opening or sealing of gas conduits, cracks and fissures (Del Pezzo et al., 1981; Hernández et al., 2004; Semprini and Kruger, 1984; Whitehead, 1984). Finally, the low solubility of H_2 in groundwater, coupled with its low atmospheric concentration (~530 ppb, Novelli et al., 1999), make H_2 an excellent tracer for processes operating deep in the crust. High concentrations of H_2 have been often detected in soil and dissolved gases in faulted zones (Sugisaki et al., 1980; Wakita et al., 1980). H_2 can be generated abundantly by several chemical reactions induced by a water–rock interaction.

1.2. Geophysical exploration (magnetotelluric method, MT)

The MT method uses naturally occurring electromagnetic (EM) field variations as a source for imaging the electrical resistivity structure of the earth (Vozoff, 1991). Electrical resistivity is a physical property dominated by the presence of minor phases in the host rock matrix and is complementary to bulk properties determined by seismic and potential field methods. Magnetotelluric data involve simultaneous measurements of temporal variations in the electric and magnetic fields at the Earth's surface (Chave and Jones, 2012). The penetration of the electromagnetic field is a function of the electrical resistivity of the subsurface (ρ; Ωm) and the frequency (f; Hz) of the incident field, referred to as the skin depth: $\delta \approx 500(\rho/f)^{1/2}$ (m). Electric and magnetic fields decay exponentially within the earth over this characteristic distance δ. High-frequency waves penetrate a relatively short distance and low-frequency waves penetrate deeper, averaging over a larger volume. The measured fields are transformed into the frequency domain, and the transfer functions, which relate the electric (E) and magnetic (H) fields, can be estimated:

$$[E] = [Z][H],$$

where Z is the impedance, a frequency-dependent 2×2 complex tensor containing information on the electrical conductivity of the subsurface. The magnetotelluric response functions can be obtained from each impedance tensor element: apparent resistivity (ρ_a) and phase (φ). The appearance of the impedance tensor is related to the dimensionality of the electromagnetic field, which reflects the complexity of the distribution of subsurface conductivity. Structural dimensionality of the dataset requires appropriate multi-dimensional inversion algorithm, since if the MT responses have an intrinsically higher dimension than is being used in the interpretation, the final model will be incorrect (Chave and Jones, 2012).

In volcanic areas with hydrothermal circulation, a clay cap (smectite, smectite–illite) is commonly developed by the alteration of the volcanic rocks (Cumming, 2009; Pellerin et al., 1996). This alteration layer is expected to have a very low permeability, so any gap in this layer could be related with surface manifestations of gases. Magnetotelluric surveys have been used in volcanic areas for structural investigation, geothermal evaluation and hydrothermal circulation (García and Jones, 2010; Heise et al., 2008; Ingham et al., 2009; Uchida and Sasaki, 2006). Five MT surveys have been performed in Tenerife (Coppo et al., 2008, 2010; Ortiz et al., 1986; Piña-Varas et al., 2014; Pous et al., 2002). In this island, the existence of a clay cap was pointed out by Piña-Varas et al. (2014), and its morphology follows the topography at relatively shallow depths (about 1500 m).

In this work, the resistivity structure of the southern volcanic rift zone of Tenerife was determined by a 3-D MT data inversion at 47 sites. This new electrical resistivity model will be correlated with the soil gases distribution presented in this work, since the bulk resistivity is sensitive to factors as fluids content and/or temperature at the surface.