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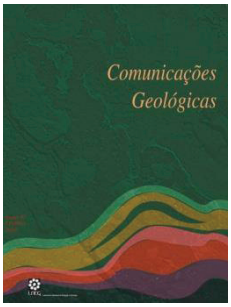
Secondary manifestations of volcanism – an open window to understand geothermal resources in the Azores archipelago



Manifestações secundárias de vulcanismo – uma janela para o conhecimento dos recursos geotérmicos no arquipélago dos Açores

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Abstract: Gas geochemistry techniques applied to fumaroles and soil diffuse degassing areas constitute fundamental tools to understand deep geothermal reservoirs thermodynamic conditions and may provide valuable information both during the exploratory and production phases. Geothermometry applied to fumaroles located at Fogo (São Miguel Island) and Pico Alto (Terceira Island) volcanoes showed maximum feeding temperatures around 256 and 263 ºC, respectively, for each area, which are in general in agreement with the direct temperature measurements performed in the geothermal wells. Soil CO_2 flux degassing maps performed at Caldeiras da Ribeira Grande (Fogo) and Furnas do Enxofre (Pico Alto) fumarolic fields allowed to estimate the CO_2 naturally emitted to the atmosphere as well as the thermal energy released from both degassing areas.

Keywords: Fumaroles, diffuse degassing areas, geothermometers.

Resumo: As técnicas de monitorização geoquímica aplicadas em fumarolas e áreas de desgaseificação difusa constituem ferramentas importantes para compreender as condições termodinâmicas de reservatórios geotérmicos quer durante a fase exploratória, quer durante a fase de produção de energia. Os geotermómetros aplicados aos campos fumarólicos dos vulcões do Fogo (São Miguel) e Pico Alto (Terceira) sugerem temperaturas máximas dos sistemas de alimentação das fumarolas de 256 e 263 ºC, respetivamente. Estes valores concordam, de forma geral, com as temperaturas medidas nos poços geotérmicos em produção nestes sistemas vulcânicos. Campanhas de medição de fluxo de CO_2 com recurso à câmara de acumulação têm sido realizadas em diferentes áreas de desgaseificação do arquipélago dos Açores e permitem calcular quer a emissão natural de CO_2 para a atmosfera, quer a energia térmica associada a essa emissão. No caso das Caldeiras da Ribeira Grande (Fogo) estima-se um valor de 70 t/d para o CO_2 emitido, com uma energia térmica associada de cerca de 8 MW (área com aproximadamente 0,22 km^2). O CO_2 emitido no campo fumarólico das Furnas do Enxofre (Pico Alto) (aproximadamente 0,024 km^2) é de cerca de 3 t/d e a energia térmica de 1,1 MW.

Palavras chave: Fumarolas, áreas de desgaseificação difusa, geotermómetros.

1. Introduction

Existence of permeability and the presence of a heat source are key factors to select an adequate area for geothermal exploration. Due to its geodynamic context, the Azores archipelago constitutes a natural laboratory for the development and use of high enthalpy geothermal energy. The islands are located in the triple junction of the North American, Eurasian and Nubian tectonic plates and are crossed by several tectonic structures with main directions WNW-ESE and NW-SE (Carmo *et al*., 2015). The active volcanic systems that form the archipelago and where occurred at least 28 eruptions in the last 600 years, together with the existence of several secondary manifestations of volcanism, testify the presence of higher thermal gradients in certain areas of the islands. The secondary manifestations of volcanism comprise hydrothermal fumaroles, thermal and cold CO_2-rich springs, as well as soil diffuse degassing areas (Caliro *et al*., 2015 and references therein; Cruz *et al*., 1999; Viveiros *et al*., 2010). The present study shows how these gas emissions, specially fumaroles and soil diffuse degassing areas, may be used to better understand deep processes and identify areas with potential for geothermal exploration. The fumarolic emissions from the Azores archipelago, with outlet temperature below 100 ºC, have a typical hydrothermal composition (*e.g.* Caliro *et al*., 2015) dominated by the presence of water vapour, followed by CO_2, H_2S, H_2, O_2, Ar, N_2, He, CO and CH_4. The main fumarolic fields of the Azores are located in the islands of São Miguel, Terceira, Graciosa, Pico and Faial. Soil diffuse degassing areas are characterized by the permanent emission of gases, mainly CO_2 and radon (^{222}Rn), through the surface of the volcanic systems; the release of gases occur associated to fractured zones, representing in some cases hidden tectonic structures (Viveiros *et al*., 2010 and references therein) and are commonly associated with thermal anomalies (up to 100 ºC).

2. Methods and results

The application of geothermometers to the gas species associated with the fumarolic emissions may be useful to infer deep reservoir temperatures and changes on the equilibrium status of the system (Arnorsson, 2000). Several gas geothermometers have been applied

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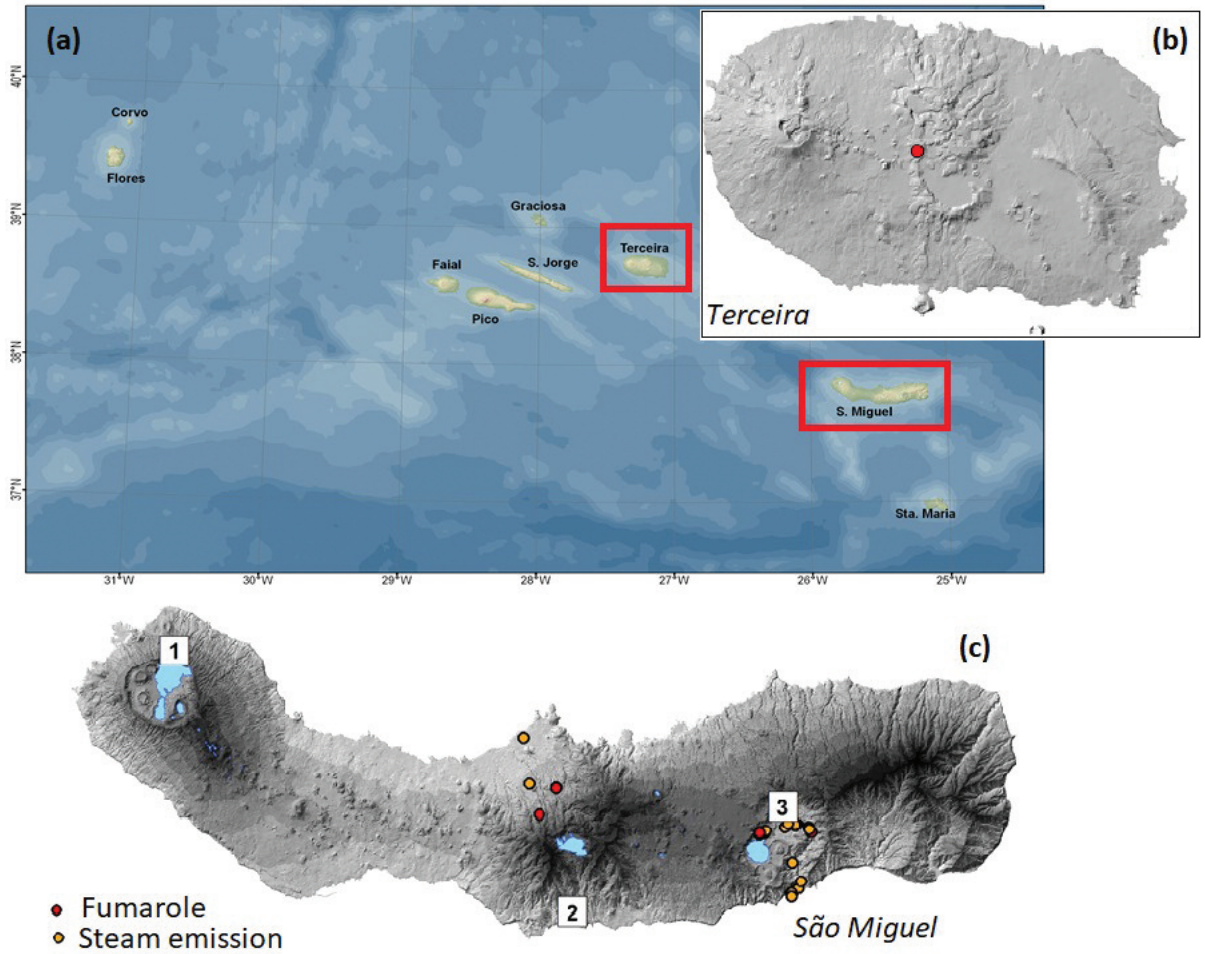

Figure 1. Location of the study sites. (a) Location of Terceira and São Miguel islands on the Azores archipelago; (b) Terceira Island DEM with the location of Furnas do Enxofre fumarolic field; (c) São Miguel DEM with the location of the main fumarolic emissions at Fogo (number 2) and Furnas (number 3) volcanoes. No fumarolic emission is present at Sete Cidades volcano (number 1).

Figura 1. Localização dos locais de estudo. (a) Localização das ilhas de São Miguel e Terceira no arquipélago dos Açores; (b) modelo digital do terreno da ilha Terceira com a localização do campo fumarólico das Furnas do Enxofre; (c) modelo digital do terreno da ilha de São Miguel com a localização das principais emissões fumarólicas nos vulcões do Fogo (número 2) e das Furnas (número 3). Não existem emissões fumarólicas no vulcão das Sete Cidades (número 1).

in the current study to the fumaroles of Fogo (Caldeiras da Ribeira Grande and Caldeira Velha) and Pico Alto (Furnas do Enxofre) volcanoes (Fig. 1), being these the volcanic systems where the geothermal power plants are located, respectively at São Miguel and Terceira Islands (Rangel *et al*., 2015; Franco *et al*., 2017). The application of the geothermometer H_2-Ar (Arnórsson, 2000 and references therein) suggests equilibrium temperatures around 231 ºC and 256 ºC for Caldeira Velha and Caldeiras da Ribeira Grande, respectively (Tab. 1). These values are in agreement with the conceptual model proposed for Ribeira Grande geothermal area

Table 1. Geothermometers, soil CO_2 fluxes and thermal energy for the fumarolic fields located at Fogo and Pico Alto volcanoes.

Tabela 1. Geotermómetros, fluxo de CO_2 e energia térmica libertada nos campos fumarólicos dos vulcões do Fogo e Pico Alto.

Fumarolic field	Volcano	H_2/Ar		Soil CO_2 flux			Thermal energy released (MW)
		Eq. Temperature (ºC)	Sampling period	Emission (t/d)	Sampling period	Sampled area (km²)	
Caldeiras da Ribeira Grande	Fogo	256	2017	70	Feb-16	0.22	8
Caldeira Velha	Fogo	231	2017	-	-		-
Furnas do Enxofre	Pico Alto	263	2017	3	Aug-14	0.024	1.1

(Rangel *et al*., 2015). Same geothermometer applied at Furnas do Enxofre fumaroles suggests temperatures around 263 ºC, which are also in the range of the temperature defined for the geothermal resource in Pico Alto area (Franco *et al*., 2017). Soil CO_2 flux mapping has been performed in several Azorean areas using the accumulation chamber method (Viveiros *et al*., 2010). Surveys performed at Caldeiras da Ribeira Grande and Furnas do Enxofre degassing fields allowed to estimate, respectively, about 70 t/d and 3 t/d of CO_2 from each of the areas. These estimations together with data from the gases emitted through the fumaroles allow to calculate 8 MW and 1.1 MW for the thermal energy released for each area, following the methodology described by Chiodini *et al*. (2001).

3. Discussion and conclusions

Geothermometers applied to the gases emitted from fumaroles and production of soil diffuse degassing maps may provide valuable information about the feeding geothermal reservoir temperatures, the existence of permeability and the potential thermal energy of an area, constituting relevant information during the exploratory phase of a geothermal power plant. Monitoring gases during the production phase allows also to detect possible variations that may be correlated with deep thermodynamic and permeability changes in the systems.

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