Quantification of volcanic CO_2 fluxes in the Azores archipelago based on sequential Gaussian simulations

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1. Degassing areas in the Azores archipelago

Volcanic gas emissions in the azores archipelago are characterized by low-temperature fumarolic fields (maximum 100 ºC outlet temperatures), thermal and cold CO_2-rich springs, as well as diffuse degassing areas.

Main fumarolic grounds are located in the islands of São Miguel, Terceira and Graciosa. Steam emissions are also observed on Pico and Faial islands *(Figure 1)*.

Hydrothermal fumaroles composition is dominated by water vapour (H_2O), followed by carbon dioxide (CO_2).

Volcanic soils may release CO_2 through the so-called **diffuse degassing processes**. In these areas, the gas is released in an imperceptible and permanent way, and detected only using specific instruments (*Figure 2*).

Several areas of the Azores archipelago are characterized by the permanent deep-derived CO_2 emissions, most of them associated to the fumarolic grounds and/or tectonic structures.

Up to the moment, diffuse degassing areas were identified in Terceira, Graciosa, São Jorge, Pico, Faial, and São Miguel islands.

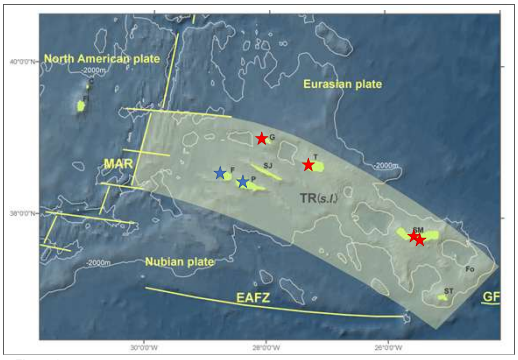

Figure 1 - Location of the main subaerial fumarolic ground in the Azores islands (C – Corvo, Fl – Flores, F – Faial, P – Pico, SJ – São Jorge, G – Graciosa, T – Terceira, SM – São Miguel, ST – Santa Maria). **Red stars** represent the volcanoes with hydrothermal fumaroles, and the **blue stars** the volcanoes with steam emissions.

2. Sampling methodology

Several methodologies may be used to detect the volatiles diffusely released from the soils. The so-known **accumulation chamber method** (Chiodini *et al.*, 1998) has been commonly used in studies carried out in volcanic environments. Both spatial distributions and time series have been recorded using this methodology in the last three decades.

Measurements are carried out not only in the soils (*Figure 2*), but also in the lakes surface (*Figure 3*), to identify anomalous CO_2 emissions and to quantify the volcanic CO_2 emitted to the atmosphere.

Figure 2 - Measurement of soil CO_2 fluxes with the accumulation chamber method.

Figure 3 - Measurement of CO_2 fluxes with a floating device.

3. Statistical approach

Spatial distribution soil CO_2 fluxes have been commonly analysed through **sequential Gaussian simulations (sGs)**, a methodology that maintains the spatial and statistical features of original data and allows estimating uncertainties.

All simulations were performed using the *sgsim* program based on the algorithm from Deutsch and Journel (1998). This program is included in the winGslib software, a toolbox of geostatistical software written for windows that provides a front-end to all the GSLIB programs.

The successive steps used to apply sequential Gaussian simulation to a dataset are displayed in the diagram of figure 4.

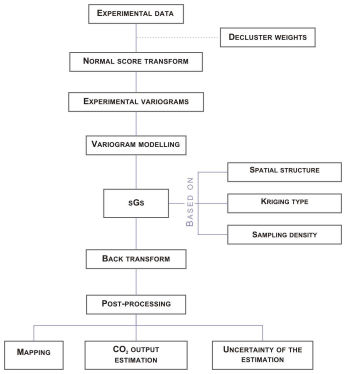

Figure 4 - Box diagram schematizing the sGs procedure used.

4. Results: sequential Gaussian simulation

Sampling sites

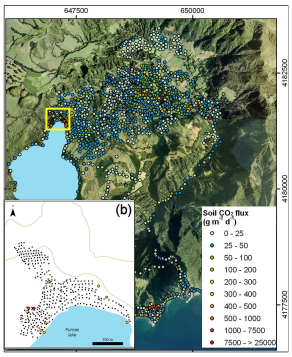

Figure 5 - Sampling sites at Furnas Volcano caldera. Insect b) represents the sampling sites at Furnas Lake fumarolic field (yellow square).

Data distribution

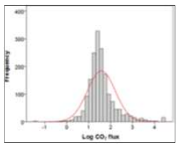

Figure 6 - Histogram plot of $\log_{10}$ soil CO_2 fluxes measured at Furnas Volcano caldera. Red line represents Gaussian distribution.

A total of 3253 sites were sampled at Furnas Volcano (São Miguel Island) (*Figure 5*). Resulting data do not show normal distribution (*Figure 6*) and were normal scored transformed to apply sGs.

Variograms showed various structures, in some cases nested (*Figure 7*).

Variograms

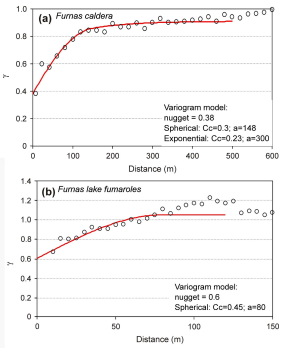

Figure 7 - Experimental and modelled variograms of the soil CO_2 flux normal scores for the two datasets. Legend: Cc (partial sill); a (range, m).

E-type map

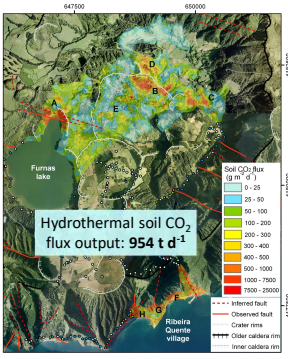

Figure 8 - E-type soil CO_2 flux map for Furnas Volcano resulting from 100 sequential Gaussian simulations.

Probability maps

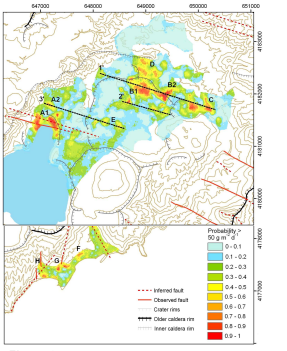

Figure 9 - Probability maps for soil CO_2 flux at Furnas Volcano. The colour scale shows the probability of soil CO_2 flux exceeding 50 g m^{-2} d^{-1}.

CO_2 estimation uncertainties

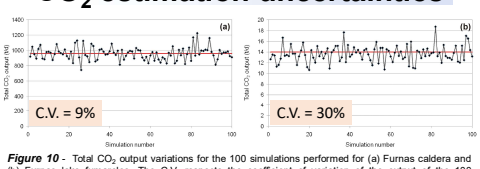

Figure 10 - Total CO_2 output variations for the 100 simulations performed for (a) Furnas caldera and (b) Furnas lake fumaroles. The C.V. respects the coefficient of variation of the output of the 100 simulations.

CO_2 output

Table 1 - Hydrothermal CO_2 output estimated in different degassing areas of the Azores archipelgo

Volcano	Island	Sampling site	Hydrothermal CO_2 flux (t d^{-1})	Type of degassing
Furnas	São Miguel	Furnas Volcano	**954**	Soil diffuse degassing
Fogo		Caldeiras da Ribeira Grande	**40**	
Fogo		Pico Vermelho	**23**	
Fogo		Caldeira Velha	**14.5**	
Sete Cidades		Ferraria	**5.2**	
Pico Alto	Terceira	Furnas do Enxofre	**2.54**	
Furnas	São Miguel	Furnas Lake	**280**	Lake diffuse degassing
Sete Cidades		Santiago Lake	**0.0007**	
Caldeira	Graciosa	Furna do Enxofre	**6.1**	

1039 t d^{-1} deep-derived CO_2 released from soils, and **286 t d^{-1}** from lakes

Total hydrothermal CO_2 flux estimated: 1325 t d^{-1}

5. Final considerations

Application of **geostatistical tools** to spatial CO_2 fluxes allows to:

- **Discriminate anomalous CO_2 degassing areas**
- **Quantify CO_2 emitted to the atmosphere**
- **Identify potential correlations with tectonics**
- **Evaluate uncertainties and the adequacy of the sampling strategy ...**

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