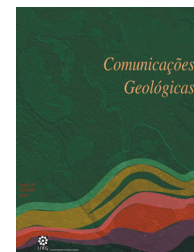


## Non-eruptive geological hazards of dormant volcanoes: São Miguel, Azores

### Perigos geológicos não eruptivos em vulcões adormecidos: São Miguel, Açores

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**Abstract:** São Miguel Island presents a diversity of geological hazards that are related to non-eruptive processes. Frequent seismic swarms and destructive earthquakes, of volcanic and tectonically-related origin, have been recorded on the Island since it was settled in the 15<sup>th</sup> century. Large areas of volcanic edifices of Sete Cidades, Fogo and Furnas are unstable. Steep slopes, unconsolidated and poorly consolidated materials, such as volcanoclastic deposits occasionally weathered by hydrothermal activity, play an important role in landslide activity. Slope instability is mainly triggered by intense rainfall, but also by seismic activity, sea and fluvial erosion and/or anthropogenic activity. Volcano degassing represents a major risk during anomalous gas release and a continuous menace for the public health.

**Keywords:** Hazards, Dormant volcanoes, São Miguel, Azores.

**Resumo:** A ilha de São Miguel apresenta uma diversidade de perigos geológicos associados a processos não eruptivos. Enxames sísmicos frequentes e terramotos destrutivos, de origem vulcânica e tectónica têm sido registados na ilha desde o seu povoamento, no séc. XV. Vastas áreas dos edifícios vulcânicos das Sete Cidades, Fogo e Furnas são instáveis. Vertentes declivosas, materiais pouco ou não consolidados, tais como depósitos vulcanoclasticos, ocasionalmente alterados por atividade hidrotermal, desempenham um papel importante no desenvolvimento de movimentos de vertente. Estes são maioritariamente desencadeados por precipitação intensa, mas também por atividade sísmica, erosão marinha e fluvial e/ou ação antropogénica. A emissão de gases vulcânicos representa um importante risco para as populações, durante períodos de emissões anómalas, constituindo uma ameaça contínua para a saúde pública.

**Palavras-chave:** Perigos, Vulcões adormecidos, São Miguel, Açores.

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## 1. Introduction

São Miguel is the largest island of the Azores with 137,856 permanent inhabitants (INE, 2012), which represents about 56% of the total of the archipelago. The

population varies during the year as tourism and the return of migrants during holidays and festival periods are significant. The population mostly lives in settlements distributed around the coast with a particular focus in the capital city, Ponta Delgada.

There are three dormant central volcanoes on the island: Sete Cidades at the western end of the island, which has not erupted since the first settlement of São Miguel and the youngest dated eruption is around 800 years BP (Moore & Rubin, 1991); Fogo which lies in the central part of the island and last erupted in 1563 (Wallenstein *et al.*, 2005) and, further to the east, Furnas which erupted most recently in 1630 (Guest *et al.*, 1999). Based on their past patterns of activity all of these volcanoes are likely to erupt again in the future.

The hazards posed by these volcanoes in their inactive, dormant state are of importance as a number of villages and towns are situated on their lower flanks (Fig. 1). As discussed below there have been a number of events that have produced casualties during historic times.

## 2. Hazards presented by dormant volcanoes

Though it is natural that attention has been concentrated on eruptions and their hazards, volcanoes in their dormant state can be hazardous landforms.

Youthful volcanic edifices typically comprise interbedded lavas and tephra dipping down slope, and forming inherently unstable landforms. Slope failure is mainly triggered by rainfall (Marques, 2013), but can also result from earthquakes (Marques *et al.*, 2006).

Dormant volcanoes may still continue to discharge gases through fumarolic activity and thermal springs. The dominant gas is normally H<sub>2</sub>O, but CO<sub>2</sub> is a very important component. This CO<sub>2</sub> is likely to be largely mantle derived and under certain conditions can be a major hazard (Viveiros, 2010), also has a <sup>222</sup>Rn carrier (Silva, 2013). For example, on Graciosa island the central caldera volcano has not erupted for a few thousand years, but discharges CO<sub>2</sub> in the intracaldera Furna do Enxofre lava cave (Gaspar, 1996) and caused two casualties in 1992 (Ferreira *et al.*, 2005).

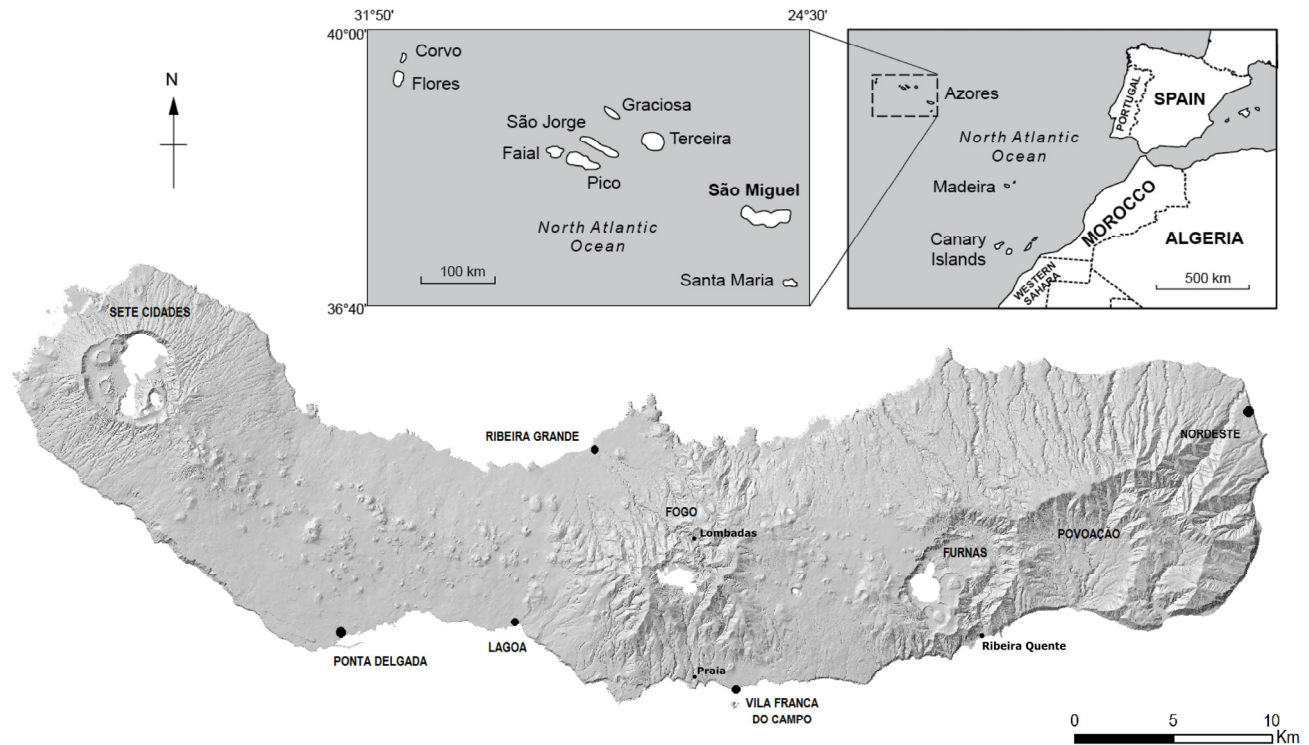


Fig. 1. General location map of São Miguel Island with localities and sites referred on the text.

Fig. 1. Mapa de localização geral da ilha de São Miguel, com as povoações e locais referidos no texto.

### 3. The dormant volcanoes of São Miguel island

Sete Cidades, Fogo and Furnas are central volcanoes which have all been active within the last 1000 years. Between Sete Cidades and Fogo volcanoes lies the Picos Fissural Volcanic System, a zone of monogenetic cones that is typically basaltic, with the last eruption occurring in 1652 AD (Ferreira, 2000).

#### 3.1. Sete Cidades

Sete Cidades has a classical shape with a clear cone profile which forms the western end of the island. It is a polygenetic volcano with slopes averaging  $12^\circ$  rising to  $18^\circ$  on its upper slopes where there is a higher proportion of pyroclastic material. On its southeastern side lavas of the Picos Fissural Volcanic System abut against the cone. The volcano rises to a height of 845 m asl with the summit being truncated by a caldera. The Mosteiros graben, a continuation of the Terceira Rift, cuts the northwest flank of the volcano through the caldera wall (Queiroz, 1997).

Though there have been no recorded subaerial eruptions since the settlement of São Miguel in the 15th century, in 1638 and 1811 there were basaltic surtseyan eruptions in the ocean, a few km from the shore in the western quadrant. These impacted the Sete Cidades area and produced short-lived islands that were quickly washed away (Agostinho, 1960, Chaves, 1960, Queiroz *et al.*, 2008). Seismicity associated with the off-shore eruptions

of 1811 caused considerable damage to the villages on the southwest coast of Sete Cidades.

On the Landslide Susceptibility Map (Marques *et al.*, in press), the lower northwest and northeast slopes of Sete Cidades are particularly risk prone. A number of damaging events have been recorded in the last 300 years and more recently a magnitude 5.8 earthquake with its epicentre 20 km west of the island, caused numerous landslides that cut the main roads at the foot of the volcano has happened recently, in 2002 and 2003, but just triggered by intense rainfall and strong winds (Gomes *et al.*, 2005).

The only hydrothermal activity associated with Sete Cidades occurs below the high tide level on the shore at Mosteiros and Ferraria.

#### 3.2. Fogo

Fogo volcano is the largest of the three central volcanoes, rises to 947 m asl and has a summit caldera which formed as a result of a number of collapse events. The southern side of the volcano is heavily dissected by erosion, whereas the northern side has been down-faulted by a northwest-southeast trending graben (Moore, 1990).

The most recent eruptive activity of Fogo was in 1563/1564 and began with a subplinian eruption from the summit caldera. Four days later an effusive basaltic eruption on lower northwest flank produced a lava flow that reached the north coast by the village of Ribeira Seca.



Finally in 1564 a phreatic explosion occurred in the summit caldera (Wallenstein *et al.*, 2007).

The worst natural disaster to strike São Miguel occurred on October 1522 in the Fogo southern flank, when an earthquake with a maximum intensity X (EMS-98) (Silveira *et al.*, 2003) triggered several landslides over the island, one of which was a debris-flow (Fig. 2), of about  $6.75 \times 10^6 \text{ m}^3$  that covered an area of  $4.5 \text{ km}^2$  (Marques *et al.*, 2009), killing 5000 people and destroying the entire village of Vila Franca do Campo (Frutuoso, 1522-1591†), then capital of the island. More recently the village of Praia, located at the foot of a valley and whose catchment extends to just below the southern margin of the caldera, was damaged by flash floods caused by heavy rain in December 1998. This village is at particular risk from any overflow from the caldera lake which might be, for example, be generated by landslides on the lake-side cliffs (Wallenstein, 1999). In 2005 the Fogo-Congro seismic swarm produced over 22,000 shallow earthquakes between Fogo and Furnas, causing over 250 shallow translational slides (Fig. 3) in the Lombadas and Ribeira Seca valleys, blocking some streams and rural roads (Marques *et al.*, 2006, Wallenstein *et al.*, 2007).



Fig. 2. Detail of the deposit of a debris flow associated with the October 1522 earthquake which reached the coast near Vila Franca do Campo.

Fig. 2. Detalhe do depósito de uma escoada de detritos associada ao terramoto de outubro de 1522, o qual atingiu a costa perto de Vila Franca do Campo.

Fogo has an active hydrothermal system with several associated areas of fumarolic activity. Large volumes of  $\text{CO}_2$  are discharged at these fumarolic sites, as well as diffuse emissions through the soil and dissolved in water. An area of high  $\text{CO}_2$  discharge occurs near the river bed at Ribeira Seca. A peak discharge was measured in 1998-1999, with a temperature of  $50^\circ\text{C}$  and a 13.5%  $\text{CO}_2$  concentration, just below the asphyxiation danger level (Ferreira *et al.*, 2005).

### 3.3. Furnas

Furnas has been the most active of the three volcanoes in historic times with the most recent event being the major sub-plinian eruption of 1630 which caused major devastation and loss of life (Guest *et al.*, 1999).



Fig. 3. Aerial view of Lombadas valley where the landslides associated scars triggered by the 2005 seismic swarms can be observed.

Fig. 3. Vista aérea do vale das Lombadas onde é possível observar-se as cicatrizes associadas aos movimentos de vertentes desencadeados pelos enxames sísmicos de 2005.

Landslides in the steep caldera walls pose a threat to settlements on the caldera floor. In April 1996 a rotational slide that evolved downslope to a debris flow collapse travelled as far as the football pitch at the edge of Furnas village and some cattle were killed. If landslides were to propagate into Furnas lake, then overflow could have devastating consequences for the village. The most recent disaster was on October 1997 when numerous landslides were triggered by intense rainfall in the Furnas area, including at the small coastal village of Ribeira Quente (Fig. 4) where 29 people were killed by debris flows. In addition the landslides destroyed the access road and power supply, with Ribeira Quente village being isolated for over 12 hours. This event emphasized not only the risk to settlements from landslides but also the disruption to communications which hinders any immediate response.



Fig. 4. Landslides triggered intense rainfall that affected Ribeira Quente village on October 2007.

Fig. 4. Movimentos de vertente desencadeados por queda de chuva intensa que afetaram a freguesia da Ribeira Quente em Outubro de 2007.

There are several vigorous fumarolic fields inside Furnas Caldera and fumaroles are distributed along the Ribeira



Quente valley to the coast. There have been occasional phreatic blasts from the fumarole field at the edge of Furnas village which pose a hazard as these features are major tourist attractions.

A survey of soil gas emissions in Furnas village by Baxter *et al.* (1999), later updated by Viveiros *et al.* (2010) (Fig. 5), showed that when higher CO<sub>2</sub> emissions occur overall and increased discharge in the inhabited zone, there was a risk that people sleeping in ground floor bedrooms could be asphyxiated. Although no deaths have been recorded in the village which may be attributable to CO<sub>2</sub>, there have been issues of workers digging trenches for pipes and cables being affected (Baxter *et al.*, 1999).



Fig. 5. CO<sub>2</sub> soil degassing flux survey in the Furnas village fumarolic field.

Fig. 5. Cartografia do fluxo de desgaseificação de CO<sub>2</sub> no campo fumarólico da freguesia das Furnas.

#### 4. Conclusions

Consideration of the hazard posed by these volcanoes demonstrates that they represent a significant threat to their associated communities even whilst they are dormant.

These trachytic central volcanoes with edifices composed of interbedded tephra and lava flows are unstable landforms, to which frequent volcano tectonic seismic swarms are also associated. Fumarolic activity and soil gas emissions of carbon dioxide also present a hazard in some dormant volcanoes.

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