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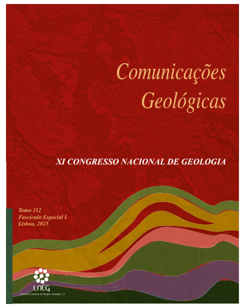
Tephra fallout hazard assessment for Sub-Plinian eruption scenarios at Fogo volcano (São Miguel, Azores)

Avaliação do perigo de queda de cinzas para cenários de erupção Sub-Pliniana no vulcão do Fogo (São Miguel, Açores)



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Abstract: The geological setting of the Azores makes this region prone to volcanic eruptions. A future explosive eruption in the Azores could have a significant socioeconomic impact and affect the North Atlantic airspace. This study aims to assess tephra fallout hazard associated with an explosive eruption of Fogo volcano on the island of São Miguel. Numerical simulations of tephra deposition were performed using an advection-diffusion model and considering the most probable scenario for a future explosive eruption at Fogo, a Sub-Plinian eruption with Volcanic Explosivity Index of 4. The obtained results suggest that the eastern half of São Miguel Island could be the most affected, regardless of the season, and Furnas parish would be the locality with a thicker deposition of tephra (≥2 m). This approach based on the analysis of scenarios is crucial for decision-making by civil protection entities.

Keywords: Sub-Plinian eruption, tephra fallout, numerical simulations, vulcanic hazard.

Resumo: O enquadramento geológico dos Açores torna esta região propícia à ocorrência de erupções vulcânicas. Uma futura erupção explosiva nos Açores poderá ter um impacto socioeconómico significativo e afetar o espaço aéreo do Atlântico Norte. Este estudo tem como objetivo avaliar o perigo de queda de cinzas associado a uma erupção explosiva do vulcão do Fogo na ilha de São Miguel. Foram realizadas simulações numéricas de deposição de cinzas usando um modelo de advecção-difusão e considerando o cenário mais provável para uma futura erupção explosiva no Fogo, uma erupção Sub-Pliniana com Índice de Explosividade Vulcânica 4. Os resultados obtidos sugerem que a metade leste de São Miguel poderá ser a mais afetada, independentemente da estação do ano, sendo as Furnas a freguesia com maior deposição de cinzas (≥2 m de espessura). Esta abordagem baseada na análise de cenários é fundamental à tomada de decisão por parte das entidades de proteção civil.

Palavras-chave: Erupção Sub-Pliniana, queda de tefra, simulações numéricas, perigo vulcânico.

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1. Introduction

Explosive volcanic eruptions, such as Plinian-type eruptions, are among the most powerful and destructive natural phenomena on Earth. Plinian and Sub-Plinian eruptions are characterized by the ejection of large amounts of tephra and volcanic gases into the atmosphere, forming eruption columns from which the erupted material is dispersed by wind, sometimes thousands of kilometres away from the vent (Walker, 1971; Cas and Wright, 1988). Of the wide range of volcanic hazards associated with Plinian and Sub-Plinian eruptions, tephra fallout is the most common and the one with the potential to affect vast areas, threatening critical infrastructure, dwellings, air traffic, agriculture, water resources, human health, and in extreme cases, even affecting the climate (Cas and Wright, 1988; Cioni *et al.*, 2000).

In small territories, such as the Azores archipelago, the impact of explosive eruptions is even greater as people live alongside volcanoes, making local communities highly vulnerable to volcanic hazards. Moreover, the typically small size, irregular topography, and remote location of these oceanic volcanic islands make crisis management and evacuation very challenging.

São Miguel Island is one such case, where three active central volcanoes, namely, Sete Cidades, Fogo, and Furnas, recurrently produced Plinian and Sub-Plinian eruptions during the Holocene. Despite having a lower eruptive frequency than Sete Cidades and Furnas in the last 5 kyr, Fogo is considered one of the most hazardous volcanoes of the Azores because of its location in the centre of São Miguel and its potential to produce large explosive eruptions. From a volcanic hazard perspective, the 1563 eruption of Fogo volcano has been defined as the most probable scenario for a future Sub-Plinian eruption with Volcanic Explosivity Index (VEI) of 4 (Medeiros *et al.*, 2021).

In this work, we assessed the potential impact of tephra fallout associated with a future Sub-Plinian eruption at Fogo volcano, during the summer and winter periods, using eruption source parameters obtained from the Fogo 1563 deposit (Aguiar, 2018). Two eruptive scenarios were considered in this analysis: (1) a larger eruption, with the parameters of the total deposit, and (2) a smaller eruption, with the parameters of the P2 pumice layer (the largest pulse of the eruption).

2. Geological setting

The Azores archipelago, located in the middle of the North Atlantic, encompasses nine volcanic islands straddling the triple junction of the Eurasian, Nubian, and North American lithospheric plates. The complex geological setting of the Azores makes this region highly susceptible to seismic and volcanic activity, including explosive eruptions (Gaspar *et al.*, 2015).

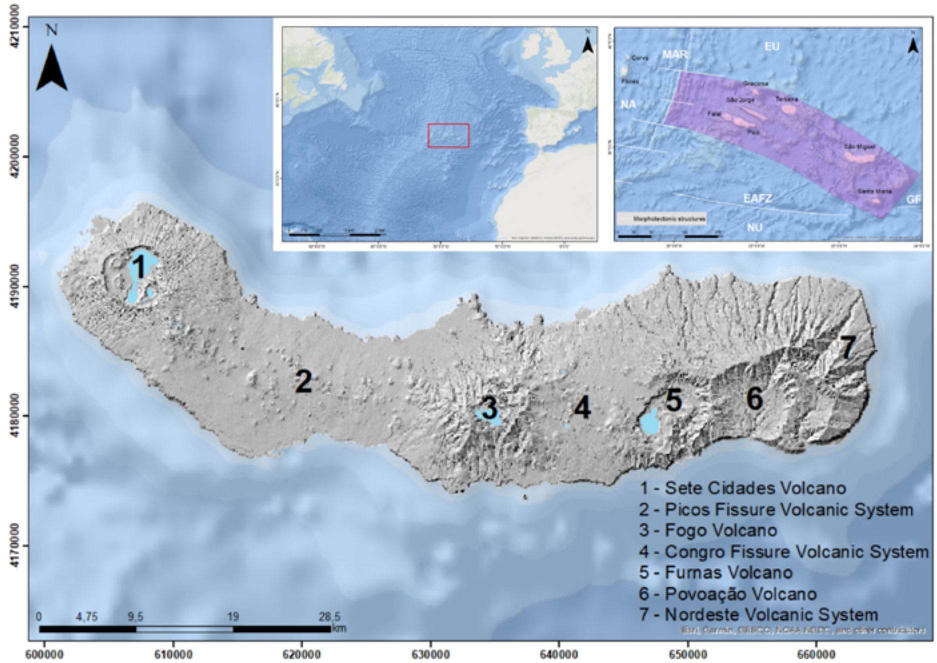

Figure 1. Digital elevation model of São Miguel Island showing the volcanic systems. The left inset illustrates the geographic position of the Azores archipelago in the Atlantic Ocean and the right inset the main morphotectonic structures of the region (MAR – Mid-Atlantic Ridge, EAFZ – East Azores Fracture Zone, GF – GLORIA Fault, EU – Eurasian plate, NU – Nubian plate, NA – North American plate, shaded area corresponds to the Terceira Rift s.l.).

Figura 1. Modelo digital de elevação da ilha de São Miguel mostrando os seus sistemas vulcânicos. A figura superior esquerda ilustra a posição geográfica do arquipélago dos Açores no Atlântico Norte e a figura superior direita ilustra as principais estruturas morfotectónicas da região (MAR – Crista Média-Atlântica, EAFZ- Zona de fratura Este dos Açores, GF- Falha GLORIA, EU- Placa Eurasiatica, NU- Placa Nubia, NA- Placa Norte Americana, A área a sombreado corresponde ao Rifte da Terceira s.l.).

São Miguel is the largest and the most densely populated island (133.000 inhabitants) of the archipelago, hosting five active volcanic systems: three central volcanoes – Sete Cidades, Fogo (also known as Água de Pau), and Furnas, and two fissure volcanic systems – Picos and Congro. Additionally, the eastern part of the island is composed of two older and inactive volcanic systems, namely, Povoação volcano and Nordeste volcanic system (Figura 1).

Fogo volcano (the focus of this study) dominates the central part of the island. It is the largest among the three active central volcanoes, rising to a maximum altitude of 947 m above sea level. Its summit caldera (3.2 km wide) was formed by several collapse episodes and explosive eruptions, and today is partially occupied by a lake. The most recent activity of Fogo volcano (*i.e.*, the last 5 kyr) was marked by four Hawaiian-Strombolian eruptions, five Sub-Plinian eruptions (Pisão, Fogo B, Fogo C, Fogo D, and the 1563 eruption) and one Plinian event (Fogo A) (Wallenstein, 1999; Wallenstein *et al.*, 2015).

The 1563 explosive eruption was the latest and largest Sub-Plinian eruption at Fogo volcano in the last 5 kyr and it has been used as a reference for volcanic hazard scenarios. The eruption has been well-documented in historical records, and its deposit has been studied by several authors over the years. Walker and Croasdale (1971) provided the first physical characterization of the deposit, followed by Wallenstein (1999), and Aguiar (2018), who reconstructed the eruption history and source parameters in detail. The Fogo 1563 deposit is characterized by a sequence of coarse-grained and fine-grained pumice lapilli layers interbedded with fine ash layers, which were mostly dispersed toward the eastern part of the island because of the predominant WSW-blowing wind at the time of the eruption. The internal stratigraphy of the deposit suggests that the eruption started with a hydromagmatic phase, followed by the establishment of a Sub-Plinian eruption column up to a height of 19 km, which was mostly dominated by magmatic activity but with repeated hydromagmatic pulses.

3. Material and methods

To assess the tephra fallout hazard at Fogo volcano, we used the 1563 explosive eruption as a reference to define the most probable scenarios for a future Sub-Plinian eruption with VEI of 4. The dispersion of tephra was simulated with an advection-diffusion model that assumes that above the vent particles are distributed along a vertical line and far from the vent, the transport of particles is controlled by the advective effect of the wind, diffusion due to atmospheric turbulence, and settling velocity of the particles (Felpeto *et al.*, 2007). This model is part of VORIS (Volcanic Risk Information System) version 2.0.1 (Felpeto *et al.*, 2007), a tool for volcanic hazard assessment implemented in a geographic information system (ArcGIS 9.1 from ESRI, Environmental Systems Research Institute).

Eruption source parameters, such as tephra volume, column height, and particle size, were obtained from field data of the Fogo 1563 deposit (Aguiar, 2018). Numerical simulations of tephra deposition were performed for two eruptive scenarios. In the first case, we simulated a large Sub-Plinian eruption (VEI 4) with the same characteristics as the 1563 explosive eruption (using the parameters of the total deposit). In the second case, we simulated a smaller Sub-Plinian eruption (also VEI 4), similar to the other recent Sub-Plinian eruptions of Fogo, using the parameters obtained from the P2 pumice layer (representative of the largest pulse of the eruption) (see Table 1). In both cases, we considered a vent located in the centre of the Fogo caldera.

Wind parameters (direction and intensity) were selected from a compilation of the Integrated Global Radiosonde Archive dataset of the National Centers for Environmental Information (for details see

Pimentel *et al.*, 2006). Simulations were performed using the most probable wind conditions for different vertical heights during the summer and winter periods (Table 2).

Table 1. Eruption source parameters used for the simulations of two eruptive scenarios considered in this study.

Tabela 1. Parâmetros eruptivos utilizados para a simulação de dois cenários eruptivos considerados neste estudo.

Eruption source parameters		**Total deposit**	**P2 layer**
	Volume (km^3)	0.421	0.128
	Column height (m)	19,000	19,000
Particles size	Medium (φ)	-1.51	-2.51
	Standard deviation (φ)	3.08	1.61
	Maximum (φ)	-5.5	-4.0
	Minimum (φ)	5.5	4.5
Particles density (kg/m^3)	Large φ <1	800	
	Medium φ <1 & <3	1200	
	Small φ >3	2400	
	Vent location	M: 634294; P: 4180724	

Table 2. Wind parameters used in simulations for the summer and winter periods (Pimentel *et al.*, 2006).

Tabela 2. Parâmetros de vento utilizados nas simulações para os períodos de verão e inverno. (Pimentel et al., 2006).

	Summer Period		**Winter Period**	
Column height (m)	Wind direction (°)	Wind intensity (m/s)	Wind direction (°)	Wind intensity (m/s)
4000	W 270	9	W 270	17
12,000	W 270	17	W 270	20
17,000	W 270	8	W 270	18
20,000	E 90	5	W 270	8

4. Numerical-simulation Results

4.1. Tephra fallout from a large Sub-Plinian eruption (VEI 4)

The simulation of a large Sub-Plinian eruption with VEI of 4, using the parameters of the Fogo 1563 total deposit and the most probable wind conditions for the summer period (Figura 2a), shows that the deposition of tephra occurs mainly in the eastern part of the island. The

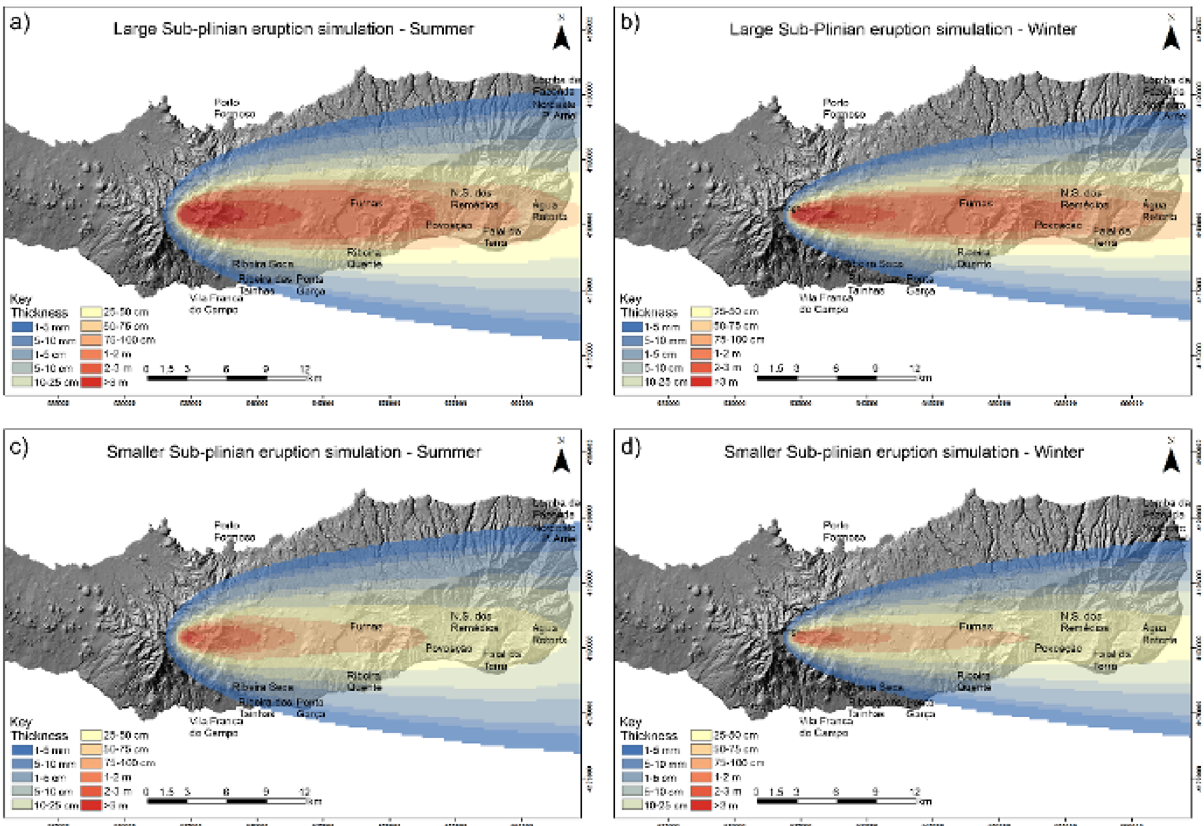

Figure 2. Tephra deposition maps from a) a large Sub-Plinian eruption (VEI 4) at Fogo volcano during the summer period; b) a large Sub-Plinian eruption (VEI 4) at Fogo volcano during the winter period; c) a smaller Sub-Plinian eruption (VEI 4) at Fogo volcano during the summer period; d) a smaller Sub-Plinian eruption (VEI 4) at Fogo volcano during the winter period.

Figura 2. Mapas de deposição de tefra. a) de uma grande erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de verão; b) de uma grande erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de inverno; c) de uma pequena erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de verão; d) de uma pequena erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de inverno.

area affected by tephra fallout includes the parishes along the south coast, from Ribeira Seca to Água Retorta, the entire eastern end of the island, up to Nordeste, as well as a large portion of the rural areas of the parishes of the north coast, between Porto Formoso and Lomba da Fazenda. However, Furnas parish would be the most affected locality, with a thickness of tephra between 1 and 2 m (Figura 3a). Other localities, such as Povoação (0.75 to 1 m), Faial da Terra and Água Retorta (0.5 to 0.75 m), and Ribeira Quente (0.1 to 0.25 m), would also be affected.

The simulation for the winter period (Figura 2b) also shows the deposition of tephra towards the eastern half of São Miguel. The impacted area encompasses the parishes of the south and east coasts, from Ponta Garça to Nordeste, and the entire central part of the island to the east of Fogo volcano. Similar to the summer simulation, Furnas is expected to be the most impacted locality, where tephra fall may reach between 1 and 2 m in thickness (Figura 3b). At Povoação and Nossa Senhora dos Remédios, tephra deposition may reach between 0.75 to 2 m in thickness, while at Faial da Terra and Água Retorta the expected thicknesses may range from 0.5 to 1 m.

4.2. Tephra fallout from a smaller Sub-Plinian eruption (VEI 4)

The simulations of a smaller Sub-Plinian eruption (VEI 4), using the parameters of the P2 pumice layer, showed similar dispersion patterns to the previous eruptive scenario. For the summer period (Figura 2c), the affected localities are the parishes between Ribeira Seca and Nordeste, including the central part of the island (east of Fogo volcano), and the rural areas of the parishes of the north coast. However, the most impacted would be Furnas parish, with tephra thicknesses ranging from 0.25 to 0.75 m (Figura 3c). The communities of Povoação, Nossa Senhora dos Remédios, Faial da Terra, and Água Retorta, would also be affected with thicknesses in the order of 0.25 to 0.50 m.

The simulation for the winter period (Figura 2d) shows that the area affected by tephra fallout includes all parishes extending from Ponta Garça to Ponta do Arnel. The thicker deposition of tephra would be at Furnas parish (0.25 to 0.75 m), followed by Povoação, Nossa Senhora dos Remédios, Faial da Terra, and Água Retorna, with thicknesses between 0.25 and 0.50 m (Figura 3d).

5. Discussion

The simulations performed for the different scenarios allowed the assessment of the potential impact of tephra fallout associated with a future explosive eruption at Fogo volcano on the island of São Miguel. For these simulations, we used eruption source parameters obtained from the Fogo 1563 deposit; however, we did not intend to reconstruct the fall deposit of the 1563 eruption or any of its units. Instead, the aim was to produce tephra fallout maps from Sub-Plinian eruption scenarios for volcanic hazard analysis.

In the first eruptive scenario, we simulated a large Sub-Plinian eruption (VEI 4), like the Fogo 1563 eruption, using the eruption

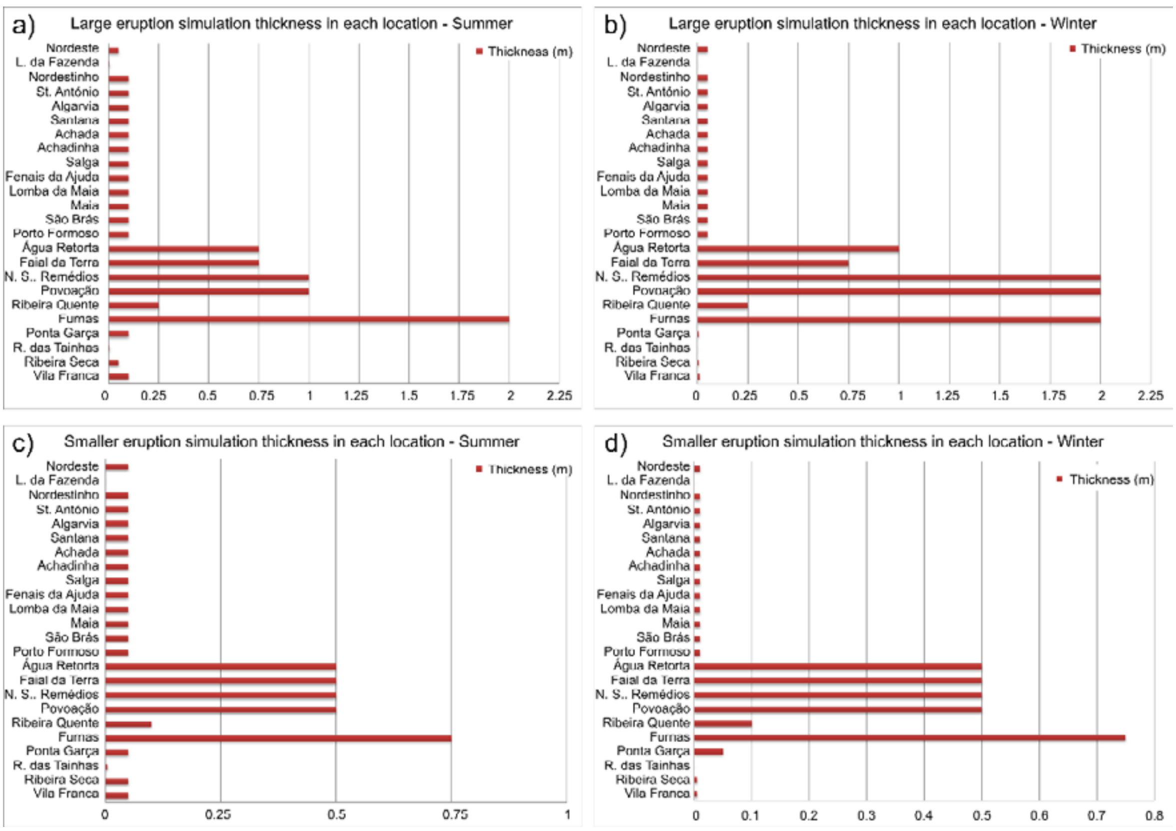

Figure 3. Maximum expect thickness of tephra in the parishes of the eastern part of São Miguel for a) a large Sub-Plinian eruption (VEI 4) at Fogo volcano during the summer period; b) a large Sub-Plinian eruption (VEI 4) at Fogo volcano during the winter period; c) a smaller Sub-Plinian eruption (VEI 4) at Fogo volcano during the summer period; d) a smaller Sub-Plinian eruption (VEI 4) at Fogo volcano during the winter period.

Figura 3. Espessura máxima esperada de tefra nas freguesias da parte Este da ilha de São Miguel considerando: a) uma grande erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de verão; b) uma grande erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de inverno; c) uma pequena erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de verão; d) uma pequena erupção Sub-Pliniana (VEI 4) no vulcão do Fogo durante o período de inverno.

source parameters of the total deposit and the most probable wind conditions for the summer and winter periods. This allowed the estimation of the maximum area expected to be affected by tephra fallout. In the second eruptive scenario, we simulated a smaller Sub-Plinian eruption (also VEI 4), similar to other recent Sub-Plinian eruptions of Fogo (*e.g.* Pisão, Fogo B, Fogo C, Fogo D), using the eruption source parameters of the P2 pumice layer (the largest pulse of the Fogo 1563 eruption) and the predominant winds during the summer and winter periods.

The tephra deposition maps obtained for the two eruptive scenarios shows similarities. This is because we used the same column height and wind parameters in both the cases. The observed differences are mainly related to the tephra volumes used (0.421 vs. 0.128 km^3), which translate into variations in thickness and area covered. From this, we can conclude that even a smaller-scale Sub-Plinian eruption would have a significant impact on the eastern side of São Miguel Island. However, there are differences in the crosswind distance between the summer and winter periods, which are due to the higher wind intensities typical of winter months.

The simulation of a large Sub-Plinian eruption (VEI 4) during the summer period suggests that the most affected locality would be the parish of Furnas, where the tephra fall deposit could reach a thickness of 2 m. During the winter period, besides Furnas, also Nossa Senhora dos Remédios and Povoação could be affected by 2 m of tephra fall deposit. The simulations of a smaller Sub-Plinian eruption (VEI 4) during the summer and winter periods suggest that, in both cases, Furnas parish could be the most affected with tephra fall deposits up to 0.75 m thick.

In all simulations, the population centres located within the dispersion area, as well as critical infrastructure, ground transportation network, water resources, and agricultural areas, among others, would be vulnerable to tephra fallout, and the degree of impact would depend on the thickness of tephra deposition in each location.

6. Conclusions

This study presents a scenario-based approach to assess the potential impact of tephra fallout associated with Sub-Plinian eruptions at Fogo volcano, which is considered the most probable scenario for a future explosive eruption. Two eruptive scenarios were considered for analysis: (1) a large Sub-Plinian eruption (VEI 4) using source parameters of the Fogo 1563 total deposit, and (2) a smaller Sub-Plinian eruption (VEI 4) using source parameters of the P2 pumice layer (the largest pulse of the Fogo 1563 eruption). The simulations were performed using the most probable wind conditions during the summer and winter periods.

Numerical simulations showed tephra dispersion and deposition towards the eastern part of São Miguel Island due to the prevailing winds in the Azores that blow from west to east. The obtained tephra fallout maps suggest that if a large or smaller Sub-Plinian eruption were to occur in the future, it would affect all the parishes of the eastern part of the island. However, regardless of the season, the most affected locality would be Furnas parish, with tephra thicknesses ranging from 0.75 to 2 m.

Although the frequency of explosive eruptions in the Azores archipelago is relatively low, the possibility of future large Sub-Plinian eruptions such as the 1563 eruption of Fogo should not be underestimated. A Sub-Plinian eruption would have long-term socioeconomic consequences for the entire archipelago and could affect the North Atlantic airspace. This approach, based on the analysis of scenarios, can provide important information for hazard assessment and disaster risk management in the case of future volcanic crises.

References

Aguiar, S., 2018. Contribuição para o estudo da estratigrafia dos vulcões Fogo e Furnas (S. Miguel, Açores): implicações para a sua história eruptiva recente, MSc thesis, Universidade dos Açores, Portugal.

Booth, B., Croasdale, R., Walker, G. P. L., 1978. A quantitative study of five thousand years of volcanism on Sao Miguel, Azores. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **288** (1352): 271-319.

Bursik, M. I., Sparks, R. S. J., Gilbert, J. S., Carey, S. N., 1992. Sedimentation of tephra by volcanic plumes: I. Theory and its comparison with a study of the Fogo A Plinian deposit, São Miguel (Azores). *Bulletin of Volcanology*, **54** (4): 329–344.

Cas, R. A. F., Wright, J. V., 1988. Volcanic Successions- Modern and Ancient. A geological approach to processes, products and successions.

Cioni, R., Pistolesi, M., Rosi, M., 2000. Plinian and subplinian eruptions. In: Sigurdsson, H., Houghton, B. F., McNutt, S. R., Rymer, H., Stix, J. (eds). Encyclopedia of Volcanoes, Academic, San Diego, 477–494.

Felpeto, A., Martí, J., Ortiz, R., 2007. Automatic GIS-based system for volcanic hazard assessment. *Journal of Volcanology and Geothermal Research*, **166**: 106-116.

Gaspar, J. L., Queiroz, G., Ferreira, T., Medeiros, A. R., Goulart, C., And Medeiros, J., 2015. Earthquakes and volcanic eruptions in the Azores region: geodynamic implications from major historical events and instrumental seismicity. In: Gaspar, J. L., Guest, J. E., Duncan, A. M., Barriga, F. J. A. S., Chester, D. K. (eds.), Volcanic Geology of São Miguel Island (Azores Archipelago). *Geological Society London Memoire*, **44**: 33-49. https://doi.org/10.1144/M44.4.

Medeiros, J., Carmo, R., Pimentel, A., Vieira, J.C. And Queiroz, G., 2021. Assessing the impact of explosive eruptions of Fogo volcano (São Miguel, Azores) on the tourism economy. *Natural Hazards and Earth System Sciences*, **21**: 417–437.

Jenkins, S. J., Wilson, T., Magill, C., Steward, C., Blong, R., Marzocchi, W., Boulton, M., Bonadonna, C., and Costa, A. (2015). *Global volcanic hazard and risk, chap. Volcanic ash fall hazard and risk*. Cambridge University Press.

Pimentel, A., Pacheco, J. M., Felpeto, A. ,2006. Influence of wind patterns on the dispersal of volcanic plumes in the Azores region: test study of the 1630 eruption of Furnas Volcano (S. Miguel, Azores). European Geosciences Union 3rd General Assembly, Vienna, Austria.

Walker, G. P. L., 1971. Grain-size characteristics of pyroclastic deposits. *The Journal of Geology*, **9**(6): 696-714.

Walker, G. P. L., Croasdale, R., 1971. Two plinian-type eruptions in the Azores. *Journal of the Geological Society*, **127**(1): 17-55

Wallenstein, N., 1999. Estudo da história recente e do comportamento eruptivo do vulcão do Fogo (S. Miguel, Açores). Avaliação preliminar do "hazard". PhD thesis, Universidade dos Açores.

Wallenstein, N., Duncan, A., Guest, J. E., Almeida, M. H., 2015. Eruptive history of Fogo Volcano, São Miguel, Azores. In: Gaspar, J. L., Guest, J. E., Duncan, A. M., Barriga, F. J. A. S., Chester, D. K. (eds). Volcanic Geology of São Miguel Island (Azores Archipelago). *Geological Society London Memoir*, **44**: 105–123.

Wilson, L., Walker, G. P. L., 1987. Explosive volcanic-eruptions - VI. Ejecta dispersal in Plinian eruptions: the control of eruption conditions and atmospheric properties. *Geophysical Journal of the Royal Astronomical Society*, **89** (2): 657–679.