Géomorphologie : relief, processus, environnement

3/2007 (2007)
Varia

Nicolau Wallenstein, Angus Duncan, David Chester et Rui Marques

Fogo Volcano (São Miguel, Azores): a hazardous edifice

Avertissement
Le contenu de ce site relève de la législation française sur la propriété intellectuelle et est la propriété exclusive de l'éditeur.
Les œuvres figurant sur ce site peuvent être consultées et reproduites sur un support papier ou numérique sous réserve qu'elles soient strictement réservées à un usage soit personnel, soit scientifique ou pédagogique excluant toute exploitation commerciale. La reproduction devra obligatoirement mentionner l'éditeur, le nom de la revue, l'auteur et la référence du document.
Toute autre reproduction est interdite sauf accord préalable de l'éditeur, en dehors des cas prévus par la législation en vigueur en France.

revues.org

Revues.org est un portail de revues en sciences humaines et sociales développé par le Cléo, Centre pour l'édition électronique ouverte (CNRS, EHESS, UP, UAPV).

Référence électronique
Nicolau Wallenstein, Angus Duncan, David Chester et Rui Marques, « Fogo Volcano (São Miguel, Azores): a hazardous edifice », *Géomorphologie : relief, processus, environnement* [En ligne], 3/2007 | 2007, mis en ligne le 01 octobre 2009, consulté le 14 octobre 2012. URL : http://geomorphologie.revues.org/2853 ; DOI : 10.4000/geomorphologie.2853

Éditeur : Groupe français de géomorphologie
http://geomorphologie.revues.org
http://www.revues.org

Document accessible en ligne sur : http://geomorphologie.revues.org/2853
Ce document est le fac-similé de l'édition papier.
© Groupe français de géomorphologie

Géomorphologie : relief, processus, environnement, 2007, n° 3, p. 259-270

Fogo Volcano (São Miguel, Azores): a hazardous edifice

Le volcan Fogo, un édifice générateur d'aléas indirects

Nicolau Wallenstein*, Angus Duncan**, David Chester*** and Rui Marques*

Abstract

Fogo volcano, the largest of the three active volcanoes of São Miguel Island in the Azores, presents a range of hazards, which are related to non-eruptive processes. Often termed indirect volcano hazards, these are the focus of the present paper and on Fogo volcano are produced by interactions between the unstable volcanic edifice and processes controlled by seismic, hydrothermal, slope instability and hydrological processes. Many houses, roads and bridges are at risk should significant earthquake activity occur. Since the island was settled in the 15th century, earthquakes exceeding IX on the European Macroseismic Scale (i.e. EMS 98) have struck São Miguel in 1522, 1713, 1811 and 1935. An estimated 45,000 people live within the Fogo District and, without action to reduce vulnerability, future losses are inevitable. Gases are emitted from several locations on Fogo, and CO_2 is a dangerous gas when it ponds in depressions. Concentrations of over 15% often lead to asphyxiation and death, and case studies of the hazards posed by gas discharge are presented. São Miguel has been affected by several destructive landslides and flash floods in the last five centuries, triggered by earthquakes, volcanic eruptions or periods of heavy rainfall. A large (X, EMS 98) earthquake in October 1522 generated a debris flow that buried and completely destroyed the town of Vila Franca do Campo. About 5,000 people were killed and an area of ~4.5 km² was covered by millions of cubic metres of debris. Indirect volcanic hazards are an ever-present threat to people living on the Fogo Volcano, yet until recently they have been little researched.

Key words: Fogo, São Miguel, Azores, indirect volcanic hazards, seismic activity, gases, landslides, floods.

Résumé

Le volcan Fogo, le plus grand des trois volcans actifs sur l'île São Miguel dans les Açores, montre une variété d'aléas qui sont liés à des processus non éruptifs. Souvent nommés aléas volcaniques indirects, ils sont, sur le Fogo, le produit d'interactions entre l'édifice volcanique instable et les processus contrôlés par des mécanismes sismiques, hydrothermaux, gravitaires et hydrologiques. Il s'avère que de nombreuses maisons, routes et ponts seraient en danger si une activité séismique importante se manifestait. Or, depuis que l'île a été colonisée, les tremblements de terre supérieurs à IX sur l'échelle européenne macrosismique (EMS 98) ont frappé en 1522, 1713, 1811 et 1935. Environ 45 000 personnes habitent dans le district de Fogo et, si aucune action pour réduire la vulnérabilité n'est mise en place, des dommages seront inévitables dans le futur. Des gaz sont émis à plusieurs endroits sur le Fogo et, parmi eux, le CO_2 est un gaz dangereux quand il se concentre dans des dépressions. Des concentrations supérieures à 15 % conduisent souvent à l'asphyxie et à la mort, aussi les risques induits par les émissions de gaz représentent-ils un danger important pour les habitants du Fogo. Au cours des cinq derniers siècles, l'île São Miguel a été affectée par plusieurs glissements de terrain destructeurs et des crues soudaines qui ont été provoqués par des tremblements de terre, des éruptions volcaniques et des périodes de fortes pluies. Parmi ceux-ci, un événement de grande magnitude (X, EMS 98) en octobre 1522 a produit une coulée boueuse qui a complètement détruit la ville de Vila Franca do Campo. Environ 5 000 habitants furent tués et une surface de 4,5 km² fut recouverte par des millions de mètres cubes de matériel. Les aléas volcaniques indirects sont une menace constante pour les habitants du volcan Fogo, mais ce n'est que récemment que des recherches approfondies leur sont consacrées.

Mot clés : *Fogo, São Miguel des Açores, aléas volcaniques indirects, activité sismique, gaz, glissements de terrain, crues.*

Version française abrégée

Le plus grand des trois volcans de São Miguel, le Fogo (fig. 1 et fig. 2) domine le centre de l'île, avec un sommet à presque 1 000 m d'altitude. Une caldera sommitale s'est formée à la suite de plusieurs effondrements, le plus récent ayant eu lieu pendant l'éruption de 1563. La formation du Fogo a commencé il y a plus de 200 000 ans, mais des pro-

* Centro de Vulcanologia e Avaliação de Riscos Geológicos, Universidade dos Açores, 9501-801 Ponta Delgada, Portugal. E-mail: Nicolau.MB.Wallenstein@azores.gov.pt
** Research Institute for Applied Natural Sciences, University of Bedfordshire, Luton, LU1 3JU, United Kingdom. E-mail: angus.duncan@beds.ac.uk
*** Department of Geography, University of Liverpool, Liverpool L69 3BX, United Kingdom. E-mail: jg54@liverpool.ac.uk

duits plus anciens, quoique rares, sont préservés sur le flanc nord grâce à l'effondrement d'un graben (Moore, 1990). Une stratigraphie complète a été établie pour les derniers 40 000 ans, fondée en grande partie sur les affleurements du flanc sud. Trois grandes éruptions pliniennes de type trachytique, incluant Fogo A, ont eu lieu depuis 15 000 ans (Wallenstein, 1999). L'éruption explosive la plus récente, de type subplinien, a eu lieu en 1563 et a déposé une épaisseur considérable de cendres sur la moitié est de l'île.

Les aléas volcaniques sur le Fogo ont été récemment discutés par Wallenstein et al. *(2005). Cet article s'intéresse aux aléas provoqués par les processus non-éruptifs, souvent nommés aléas volcaniques indirects (Tilling, 2005). Ces aléas majeurs sont produits par les interactions entre l'édifice volcanique instable et les processus sismiques, hydrothermaux, gravitaires et hydrologiques.*

São Miguel est situé dans une région tectoniquement active (fig. 3) ; environ 80 % des constructions bâties dans la région étudiée du volcan Fogo sont construites en moellons, ce qui les rend extrêmement vulnérables aux secousses sismiques. Ces résultats ont été confirmés lors d'une étude sur la stabilité de l'autoroute, des routes d'évacuation et des types d'habitations dans le District du Fogo. L'investigation a aussi révélé qu'un grand nombre de routes et de ponts sont menacés par l'activité sismique, une grande partie d'entre eux restant aussi sous la menace des glissements de terrain et de crues soudaines d'où la prise en compte de cet aspect de la vulnérabilité. L'étude a révélé des dangers supplémentaires dans certaines régions habitées. Ainsi, un certain nombre de villages et de villes ont des rues étroites, dont certaines sont des routes stratégiques desservant d'autres parties de São Miguel. Celles-ci seraient bloquées par des éboulements à la suite d'un tremblement de terre.

Gomes et al. *(2006) ont démontré que des tremblements de terre supérieurs à IX (Échelle Européenne macrosismique-EMS 98) ont frappé l'île en 1522, 1713, 1811 et 1935 et, avec des secousses de moindre intensité, en 1810, 1848, 1852, 1932 et 1952. Environ 45 000 personnes vivent aujourd'hui dans le District du Fogo (INEP, 2002) ; comme aucune action n'est entreprise pour réduire la vulnérabilité des habitations, des dégâts matériels et des pertes en vies humaines seront inévitables en cas de fortes secousses.*

À plusieurs endroits sur São Miguel, des émanations de gaz sont liées aux systèmes hydrothermaux (Ferreira, 2000). Sur le Fogo, ces systèmes coïncident avec les zones d'activité des fumerolles et sont associés aux failles de distension NO-SE sur le flanc nord (Ferreira, 2000). Le CO_2 est un gaz dangereux, car il s'accumule dans les dépressions où les concentrations supérieures à 15 % entraînent souvent l'asphyxie et la mort (Baxter et al., *1999). Une zone proche du lit de la rivière Ribeira Seca (fig. 4) est connue comme le site d'émission importante de CO_2 et il y a quelques années, le décès d'un fermier fut attribué à l'asphyxie par le CO_2.*

En 1997, le centre de volcanologie de l'Université des Açores a détecté des émissions de vapeur dans le village de Ribeira Seca (Ferreira, 2000 ; Ferreira et al., *2005). En 1998 et 1999, ces émissions de vapeur ont atteint une température maximale de 50 °C et une concentration en CO_2 de 13,5 %, juste en dessous du niveau dangereux d'asphyxie défini par Baxter (Ferreira* et al., *2005). Comme cette anomalie était située dans une zone résidentielle, quatre maisons furent évacuées. La figure 5 représente la carte des risques fondée sur cette étude.*

Au cours des cinq derniers siècles, l'île São Miguel a été affectée par plusieurs glissements de terrain destructeurs qui ont été déclenchés par des tremblements de terre, des éruptions volcaniques et par des épisodes de fortes précipitations. Un exemple récent des effets des pluies a eu lieu le 21 octobre 1997 sur le volcan Furnas (fig. 1). Le glissement fut déclenché par des pluies de l'ordre de 220 l/m² : 36 maisons furent détruites, 29 personnes tuées, 114 habitants sont restés sans abri et le village de Ribeira Quente a été coupé du reste de São Miguel pendant plus de 12 heures (Wallenstein et al., *2005 ; Malheiro, 2006). Le volcan Fogo possède une topographie contrastée, potentiellement instable, avec une proportion significative de matériel pyroclastique. Ses pentes raides inscrites dans ce matériau meuble sont fortement disséquées et les glissements de terrain deviennent ainsi un aléa volcanique indirect fréquent, comme le montre le réseau dense des cicatrices dues aux glissements de terrain (Valadão* et al., *2002). L'exemple d'un glissement de terrain dû à une secousse sismique et ayant causé un maximum de dommages a eu lieu le 22 octobre 1522, lorsque qu'une coulée boueuse a enterré et complètement détruit la ville de Vila Franca do Campo (fig. 7). Environ 5000 personnes périrent et une surface d'environ 4,5 km² (fig. 7) a été recouverte de millions de mètres cubes de matériaux.*

Les crues soudaines, normalement associées à des facteurs hydrologiques spécifiques, sont engendrées par des précipitations intenses. Sur l'île de São Miguel, les bassins versants sont de petite taille, ce qui entraîne, avec leurs profils longitudinaux raides, une montée des eaux fulgurante, consécutive à des abats d'eau abondants. Les barrages naturels créés par les sédiments et la végétation augmentent la menace de crue soudaine et, en décembre 1998, un événement de ce genre a balayé le village de Praia sur la partie basse du flanc sud du volcan (fig. 6). Praia est situé au débouché de la vallée dont le bassin hydrographique s'étend juste en dessous de la limite sud du lac de caldera du Fogo. Praia n'est qu'un exemple extrême d'une zone résidentielle sous la menace de crues soudaines (tab. 2), car de nombreuses implantations similaires à Praia existent sur la partie basse des flancs sud et nord du Fogo (fig. 4 et fig. 6).

Les aléas volcaniques indirects sont une menace constante pour les personnes vivant sur les flancs du volcan et dans certains cas, dans le District du Fogo. Le glissement de terrain de 1522, les coulées boueuses et le tsunami ont provoqué la mort de 5 000 personnes, mais aujourd'hui, plus de 11 000 personnes habitant dans le « concelho » de Vila Franco do Campo sont en danger. D'après le recensement de la population en 2001, le District du Fogo abrite environ 45 000 personnes alors que l'île São Miguel est devenue une destination touristique de plus en plus populaire (INEP, 2002), ce qui augmente l'exposition à des phénomènes indirectement liés au volcan.

Une recrudescence des précipitations accentuerait les menaces de glissements de terrain et de crues et aggraveraient les processus d'érosion des côtes, qui provoquent déjà quelques difficultés sur le flanc sud de Fogo (Malheiro, 2006). Le changement climatique pourrait rendre critique une situation qui, à l'heure actuelle, reste sous contrôle. Les interactions entre l'édifice volcanique et les activités sismiques et hydrothermales (gaz), les glissements de terrain et les crues soudaines créent des risques majeurs et une étude détaillée et intégrée serait nécessaire afin de pouvoir élaborer des plans d'urbanisation appropriés (Wallenstein et al., *2005).*

Introduction

Volcanic eruptions are a major natural hazard and even when inactive a volcanic construct often presents a range of hazards. Volcanic edifices are constructive features that can build up rapidly but are, as a consequence, often unstable. Mount Etna was built to an altitude of around 3,000 m in about 100,000 years (Chester *et al*., 1985) and the eastern flank has shown instability and episodes of collapse (Calvari *et al.,* 2004). Constructs made up of a high proportion of pyroclastic material are particularly prone to failure. Slope failure can be triggered by heavy rainfall and/or earthquakes. In October 1998 a hurricane in Nicaragua caused avalanches and lahars on Casita volcano, which has no record of historic activity, and around 1600 people were killed (Rodolfo, 2000; Scott *et al*., 2005). This report is concerned with those hazards posed by non-eruptive processes, which are often termed indirect volcano hazards (Tilling, 2005). Such non-eruptive hazards include seismicity, gas emissions, landslides, flooding and tsunamis. Many indirect hazards are, however, smaller in scale and are associated with interactions between volcanoes, which are essentially rapidly growing-intrinsically unstable landforms, and processes within the subterranean and sub-aerial environments. Examples from volcanoes around the world are listed in table 1 and for the Azores as a whole Malheiro (2006) has recently considered the relationships between potentially unstable volcanoes and human vulnerability. The impact on the coastlines of the Azores of historical tsunami produced by tectonic and others causes has recently been discussed by Andrade *et al*. (2006). Fogo volcano, São Miguel in the Azores, provides good examples of the types of hazards described above. It is the purpose of this paper to provide an analysis of the hazards posed by Fogo volcano when it is not volcanically active.

Fogo volcano

Fogo is the largest of the three central volcanoes on São Miguel and dominates the centre of the island (fig. 1). With a complex morphology the volcano rises to almost 1000 m and a summit caldera has formed as a result of numerous collapses and explosions, the most recent occurring during the sub-plinian eruption of 1563 and the hydromagmatic explosive event of 1564. The northern and southern flanks

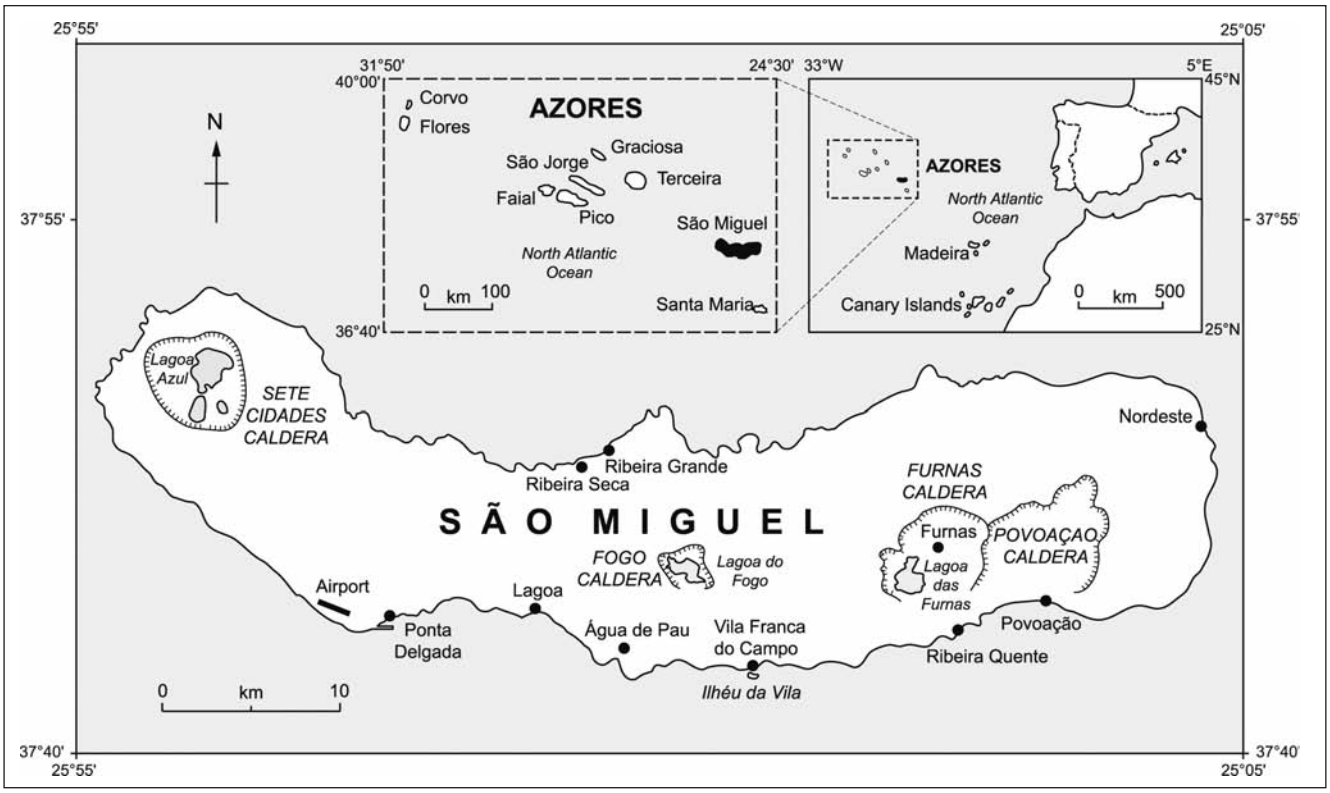

Fig. 1 – **Location of Fogo volcano within the Island of São Miguel.**

Fig. 1 – ***Localisation du volcan Fogo au sein de l'île de São Miguel.***

Processes	Examples
Tectonic	Many volcanoes are located in tectonically active regions where major earthquakes occur. In AD 62, 17 years before the Plinian eruption of AD 79, Pompeii and other Roman cities around the flanks of Vesuvius were damaged by a major earthquake (Guest *et al.*, 2003). In 1693 the city of Catania on the slopes of Mount Etna was devastated by an earthquake in eastern Sicily that left 18,000 people buried in rubble and up to 100,000 dead (Chester *et al.*, 1985). In historic accounts there has often been a blurring of the impacts of seismic and volcanic activity sometimes leading to a misinterpretation of the processes involved. For instance, this has led to some sources attributing deaths from the 1169 Sicilian earthquake to the volcanic activity of Etna (Chester *et al.*, 1985). Examples of tsunami include: Krakatau (1883), when nearly 300 coastal villages were destroyed and more than 30,000 people were killed (Simkin and Fiske, 1983); and the waves generated in 1792 when the Mayuyama dome (Unzen Volcano, Japan) collapsed into the sea generating a tsunami that killed 15,000 people (Tilling, 2005).
Hydrothermal/ volatiles	Volcanoes which have not been active for hundreds or indeed thousands of years may continue to release volatiles, in particular CO_2, to the atmosphere. These gases are released, not only through solfataric activity in crater regions but also in leaks from fractures on the flanks of edifices. The Monticchio craters on Vulture volcano in Italy, which were formed around 132 ka ago, discharge CO_2 and Vulture is famous for its naturally carbonated groundwaters (Guest *et al.*, 2003). Discharge of CO_2 may represent a serious hazard because the gas is denser than the atmosphere and ponds in topographic depressions. In 1992 on the island of Graciosa in the Azores two visitors from the Portuguese Navy were asphyxiated by higher than normal levels of CO_2 which collected in the fumarole situated in the intra-caldera Furna do Enxofre lava cave in the Caldera Volcano (Ferreira *et al.*, 2005), which has not been active in the last few thousand years (Gaspar, 1996). The most famous example of the impact of CO_2 discharge from an inactive volcano was at Nyos in Cameroon, where there is a flux of CO_2 into the floor of the crater lake. In 1986 there was a gas burst from the crater lake and CO_2 poured down slope. Over 1,700 people were killed. The exact mechanism that caused the CO_2 to be released from the gas-rich bottom waters of the lake is not yet fully understood (Delmelle and Bernard, 2000).
Sub-aerial	Volcanic edifices are constructive features that build up rapidly but are, as a consequence, immature and unstable. Constructs made up of a high proportion of pyroclastic material are particularly prone to failure. Slope failure may be triggered by heavy rainfall and/or earthquakes. For example: in October 1998 a hurricane in Nicaragua caused avalanches and lahars on Casita volcano, which has no record of historic activity, and around 1,600 people were killed (Rodolfo, 2000; Scott *et al.*, 2005). In 1999 at Cordillera de la Costa Volcano in Venezuela, landslides and debris flows caused the deaths of 30,000 people (Larsen *et al.*, 2001).

Table 1 – **Examples of volcanoes showing interactions between unstable edifices, and tectonic and geomorphological and hydrological processes**.

Tableau 1 – ***Exemples de volcans montrant des interactions entre les édifices instables et les processus tectoniques, géomorphologiques et hydrologiques.***

of the volcano have been extensively dissected by deep valleys that reach the coast, whilst to the north the volcano has been down-faulted by a northwest to southeast trending graben (Moore, 1990).

Fogo began to form more than 200,000 years ago, but older products are poorly exposed. A more complete stratigraphy, mainly based on exposures on the southern flank, has been established for the last 40,000 years and three large trachytic plinian eruptions are recognised: Roída da Praia (*c*. 15 ka); Ribeira Chã (*c*. 8-12 ka) and Fogo A (*c*. 4.6 ka) (Wallenstein, 1999). The most recent explosive eruption from the caldera, which was sub-plinian in size, took place in 1563 and deposited a considerable thickness of tephra on the eastern half of the island, with 0.5 m of tephra on the east coast and 2 m within 5 km of the summit (Booth *et al*., 1978). Four days after this event an effusive basaltic eruption on the lower western flank produced a lava flow that severely damaged the village of Ribeira Seca and reached the north coast (fig. 2). The volcanic hazards of Fogo have been discussed previously (Wallenstein *et al.,* 2005) and include pyroclastic fall and pyroclastic flows from explosive sub-plinian and plinian eruptions, and lava flows, much more localised, from effusive eruptions. This report is concerned with those threats posed by non-eruptive processes.

On Fogo, major hazards are posed through interactions between the unstable volcanic edifice and a number of seismic, hydrothermal, slope instability and fluvial processes. The 2001 census showed that the Fogo District was home for ~45, 000 people and that the island of São Miguel as a whole was becoming an important holiday destination, not only for Azorean expatriates returning home for summer, but also for tourists from mainland Portugal, the European Union and North America. After decades of decline the population of São Miguel increased by over 4% between the 1991 and 2001 and today stands at over 131,000 (INEP, 2002). Exposure to volcano-related phenomena is increasing. In this paper interactions are first described and then discussed both with reference to the vulnerability of the towns and villages in which the people of Fogo reside and the ability of people to move freely about São Miguel by means of the road network.

Seismicity

São Miguel is located in a tectonically active region, with the Terceira Rift, which runs from the Mid Atlantic Ridge through Terceira to the Gloria Fault, crossing the western part of the island. There is significant seismicity on São

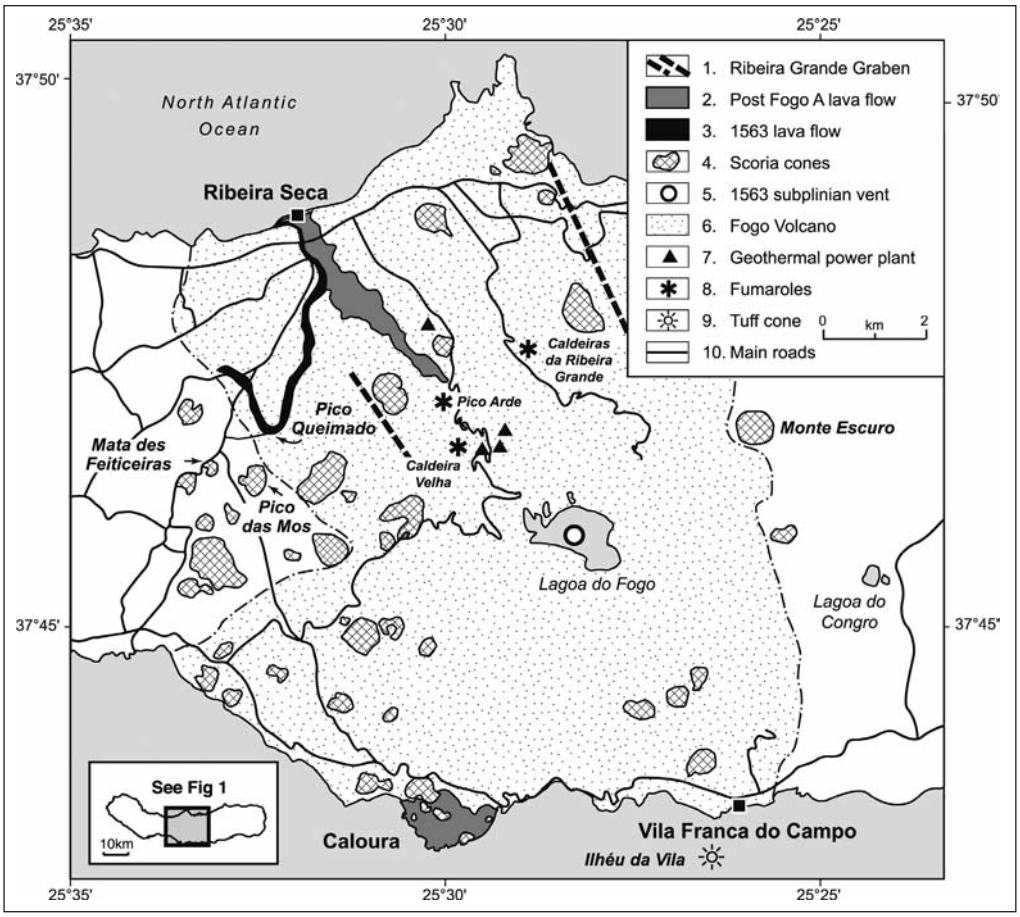

Fig. 2 – **Fogo volcano: a morphostructural sketch.** 1: Ribeira Grande graben; 2: post Fogo A lava flow; 3: A.D. 1563 lava flow; 4: scoria cones; 5: A.D. 1563 subplinian vent; 6: Fogo volcano; 7: geothermal power plant; 8: fumaroles; 9: tuff cone; 10: main roads.

Fig. 2 – ***Le volcan Fogo : un schéma morphostructural.*** *1 : graben de Ribeira Grande ; 2 : coulée de lave postérieure à Fogo A ; 3 : coulée de lave en 1563 AD ; 4 : cônes de scories ; 5 : cratère subplinien de 1563 AD ; 6 : volcan Fogo ; 7 : usine géothermique ; 8 : fumerolles ; 9 : cône de tuf ; 10 : routes principales.*

Miguel associated with these NW–SE structures (Queiroz, 1997; Ferreira, 2000) which is typified by the activity that occurred between 1997 and 2003 (fig. 3). Although associated with all São Miguel's active volcanic systems, between 1997 and 2003, seismicity was mainly concentrated in the central part of the island between Fogo and Furnas volcanoes and involved regional tectonic earthquakes as well as seismic swarms associated with the volcanic systems of this region.

Silveira *et al*. (2003) show that since the island was settled earthquakes exceeding IX (EMS 98*)* have struck São Miguel in 1522, 1713, 1811 and 1935, with slightly lower intensity events occurring in 1810, 1848, 1852, 1932 and 1952. The largest historic earthquake to have affected São

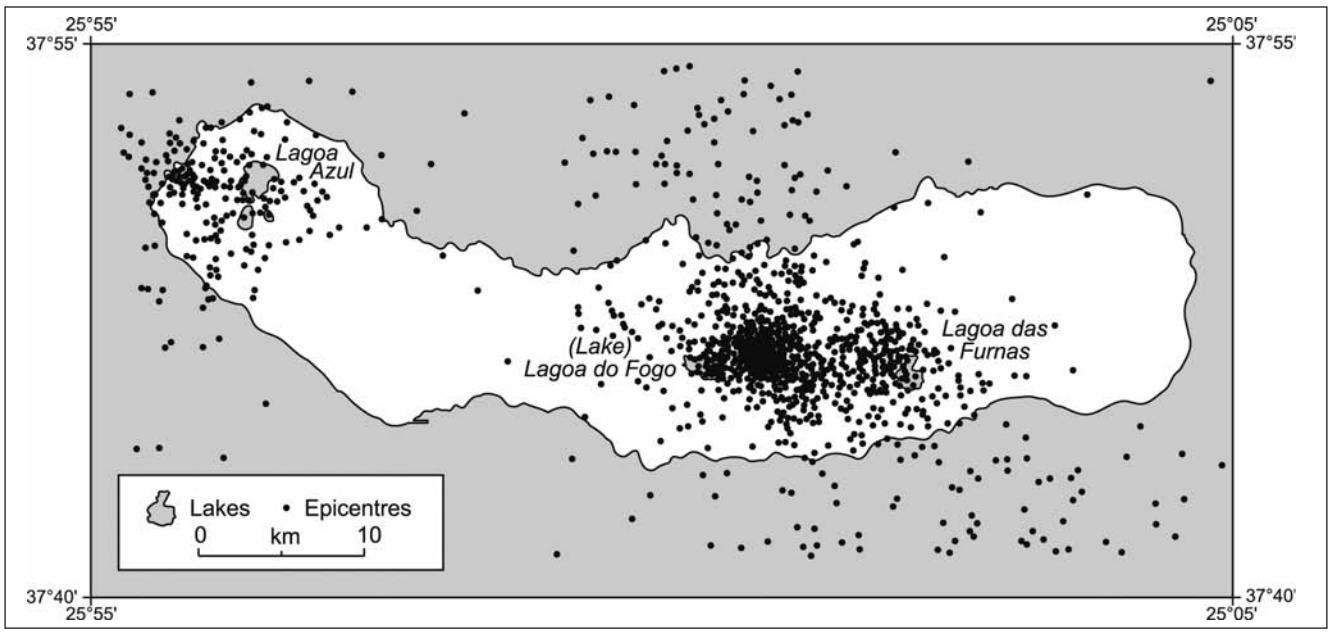

Fig. 3 – **Location of earthquake epicentres, 1997-2003.**

Fig. 3 – ***Localisation des épicentres des séismes survenus entre 1997 et 2003.***

Miguel had a maximum intensity of X (European Macroseismic Scale EMS 98) (Silveira *et al*., 2003) and occurred on 22 October, 1522 (Fructuoso, 1522-1591†; Machado, 1959). It has been suggested that this event had its epicentre on the lower flanks of Fogo, a few kilometres NNW of the town of Vila Franca do Campo (Silveira *et al*., 2003). The 1522 earthquake caused around 5,000 deaths as a result of building collapse and two devastating landslides. At the time Vila Franca do Campo (fig. 1) was the capital of the island, but after the earthquake the seat of government was moved to Ponta Delgada where it remains to this day. Seismic swarms are very common in the area between Fogo, Congro and Monte Escuro (fig. 2) where a major seismic crisis occurred in 1989. A new series of increasingly energetic seismic swarms began in the same area at the end of 2002 and reached a maximum on September 20, 2005. Several thousand earthquakes were located in the tectonic structures that surround Fogo's geothermal reservoir and in the vicinities of Congro and Monte Escuro volcanoes (fig. 2).

Some of the principal characteristics of the seismic swarms that have been associated with the Fogo-Congro-Monte Escuro area are typified by the events that occurred between April and July 2003. These events were closely monitored by the permanent seismic stations established by the Azores Seismological Surveillance System (SIVISA), complemented by a network of 14 portable stations and 3 seismic arrays deployed on behalf of e-Ruption (a European Union sponsored project) and over 1,000 seismic events were recorded between April and July. During this period of time magnitudes never exceeded 3 (M_L) and focal depths ranged from 2 and 6 km (Silva *et al*., 2004; Saccorotti *et al*., 2004). Two main groups of seismic events were identified and occurred north-east of the Fogo Caldera and north-west of Furnas caldera (fig. 1; Saccorotti *et al*., 2004; Bonagura *et al*., 2004).

Between May and December 2005, more than 46,000 earthquakes were registered by SIVISA. On May 10, 2005 a seismic swarm began in the Fogo-Congro-Monte Escuro area (fig. 2), the two strongest earthquakes occurring on September 20 and 21, 2005, with respective magnitudes of 4.1 and 4.3 (M_L). Epicentres were located in the central part of the island and a maximum intensity of V/VI (EMS 98) was recorded in the closest villages. Despite the magnitude of these earthquakes, they did not cause severe damage or casualties, though they were responsible for extensive slope failure in the central part of São Miguel and some aligned superficial ruptures were observed between Fogo and Monte Escuro volcanoes (Marques *et al*., 2005, 2006) (fig. 2).

Several writers have shown that the traditional 'rubble stone' buildings of São Miguel are extremely vulnerable to earthquake shaking, because they lack resistance to horizontal motions. Gomes *et al*. (2006) have calculated that an earthquake with an EMS-98 intensity of IX would destroy between 57 and 77% of the dwellings located around Sete Cidades volcano in the western part of the island (fig. 1), whilst some 80% of buildings in that part of the Fogo volcano which was surveyed by Pomonis *et al*. (1999) were of similar construction. These findings are confirmed by a study by the present authors into highway stability, evacua-

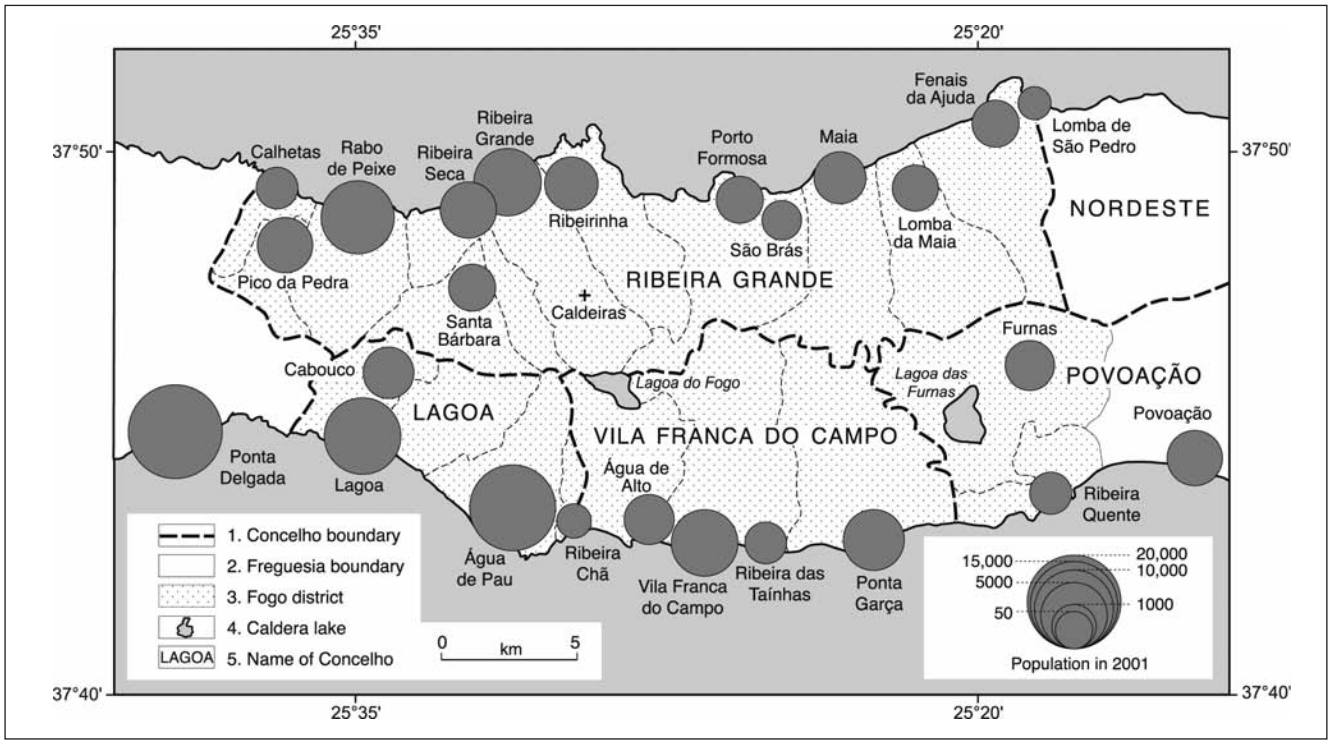

Fig. 4 – **The location of, and population concentrations within, towns and villages of the Fogo District (Population data from INEP, 2002)**. 1: Concelho boundary; 2: Freguesia boundary; 3: Fogo district boundary; 4: caldera lake; 5: name of concelho.

Fig. 4 – ***Localisation et concentration de la population dans les villes et villages du District du Fogo (données démographiques d'après INEP, 2002).*** *1 : limite du Concelho ; 2 : limite de la Freguesia ; 3 : limite du district de Fogo ; 4 : lac de caldera ; 5 : nom du concelho.*

tion routes and housing types found in what was defined as the Fogo District. Fogo District comprises the municipalities (*concelhos*) and parishes (*freguesia*) that are in close proximity to Fogo. The survey showed similar levels of seismic vulnerability within all the settlements of the Fogo District (fig. 4) and also revealed that many roads and bridges within the district were vulnerable should significant earthquake shaking occur. Many of these routes are also threatened by landslides and flash floods and this aspect of vulnerability is considered later in the paper. Seismic vulnerability is not just a question of building safety and the survey revealed additional dangers within particular settlements. For instance the villages and/or towns of Ribeira Seca, Ribeira Grande, Furnas, Vila Franca do Campo, Ribeira Chã, Água de Pau, Cabouco, and Santa Bárbara (fig. 4) all have narrow streets some of which are also strategic roads serving other parts of the island. These streets would be blocked with rubble following an earthquake, not only impeding escape by the residents of these towns and villages, but also blocking evacuation routes serving other settlements. An estimated 45,000 people live within the Fogo District (INEP, 2002) and without action to reduce housing vulnerability, future losses to buildings and many of those living in them are inevitable.

Hydrothermal activity and gas emissions

Volcanoes which have not erupted for hundreds – or indeed thousands – of years can continue to act as conduits releasing volatiles, in particular CO_2, to the atmosphere. These gases are released not only through the crater regions but also leak from fractures on the flanks of volcanic edifices. Discharge of CO_2 can represent a serious hazard as the gas is denser than the atmosphere and ponds in topographic depressions. In the Azores, in 1992, on the island of Graciosa two visitors from the Portuguese Navy were asphyxiated by higher than normal levels of CO_2 in the fumarole situated in the intracaldera Furna do Enxofre lava cave in the Caldera Volcano (Ferreira *et al*., 2005), which has not been active in the last few thousand years (Gaspar, 1996).

São Miguel has areas where gases are emitted and related to hydrothermal systems (Ferreira, 2000). Fogo volcano has an active geothermal field on its northern flank and annually over 100 GWh of electricity are generated from geothermal power plants, which represent ~35% of the electricity requirements of the island. Associated with the hydrothermal system are areas of fumarolic activity at Caldeira Velha, Pico Vermelho and Caldeiras da Ribeira Grande (fig. 2) and these are associated with the distensive NW-SE faults of the northern flank (Ferreira, 2000). At Caldeiras da Ribeira Grande a small spa has been developed and, in addition to water, large volumes of CO_2 are emitted. Diffuse emissions of carbon dioxide also leak more generally through faults and fractures on the flanks of the volcano and include cold emissions of CO_2 from a spring in the Lombadas valley (fig. 2), and diffuse soil degassing as in the *freguesia* of Ribeira Seca (figs. 2 and 4) (Ferreira, 2000; Ferreira *et al*., 2005).

CO_2 is a dangerous gas and concentrations of over 15% often lead to asphyxiation and death (Blong, 1984; Baxter *et al*., 1999). In fact the only deaths attributed to the large-scale explosive eruption of Fogo in 1563 occurred after it had ended when two people are reported to have died when visiting the vent area where they were overcome by gas, almost certainly CO_2 (Wallenstein *et al*., 2005). The hazard of gas discharge exists even when the volcano is inactive. An area near to the riverbed of the Ribeira Seca is known as a site of high CO_2 discharge and a few years ago the death of a farmer was attributed to CO_2 asphyxiation. There are now warning signs advising people of the hazard. In 1997 the *Centro de Vulcanologia e Avaliação de Riscos Geológicos da Universidade dos Açores* noted vapour discharge in the village of Ribeira Seca (fig. 2) (Ferreira, 2000; Ferreira

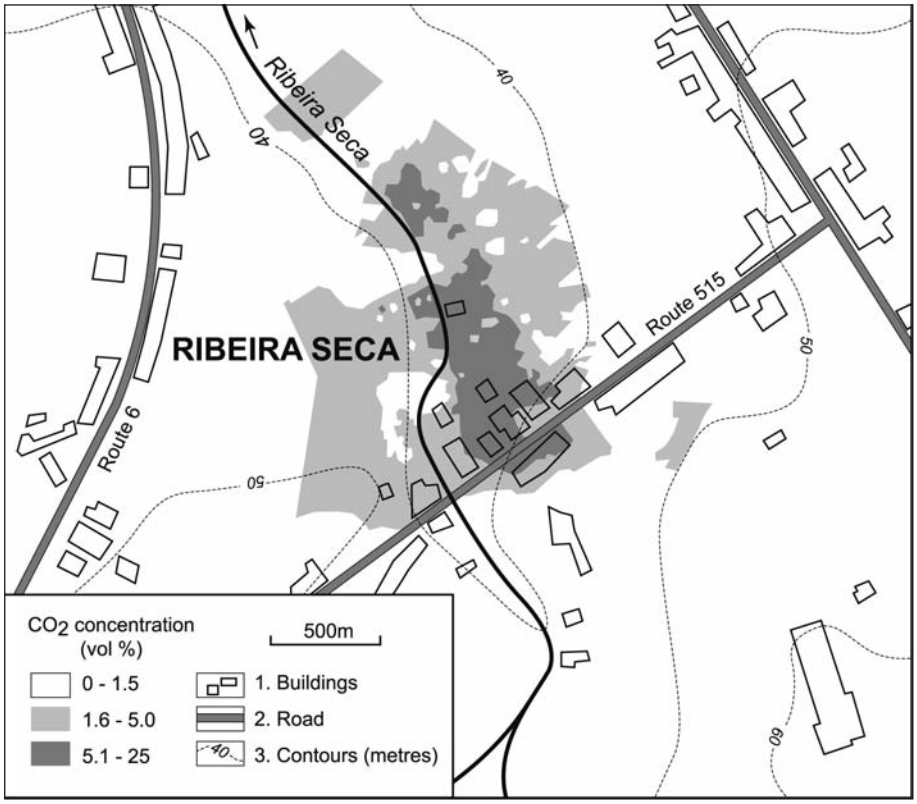

Fig. 5 – **Hazard posed by the CO_2 gas emission at Ribeira Seca during 1998 and 1999 (Ferreira *et al.* 2005).** 1: buildings; 2: roads; 3: contours in metres.

Fig. 5 – ***Aléa engendré par l'émission de CO2 à Ribeira Seca en 1998 et 1999 (Ferreira** et al.**, 2005).*** *1 : constructions ; 2 : routes ; 3 : courbes de niveau en mètres.*

et al., 2005). During 1998 and 1999 the thermal and CO_2 anomalies associated with these emissions reached a peak of 50 °C and 13.5% concentration, only just below Baxter's asphyxiation danger level (Ferreira *et al.,* 2005). Peak values were only recorded in a localized area of ~1 m^2, but the general area of anomaly was ~200 m^2. As this area of anomaly was within a residential area it posed a significant risk and led to the evacuation of four houses. Figure 5 is a hazard map based on this study and points to the need for a systematic investigation of gas emission within other settlements. It is already known, for instance, that high levels of gas discharge occur in Furnas village (fig. 1) where concentrations of over 15% are to be found over an extensive area (Baxter *et al*. 1999, their fig. 2).

Landslides and Flash Floods

Landslides

São Miguel has been affected by several destructive landslides in the last five centuries. Triggered by earthquakes, volcanic eruptions and/or heavy episodes of intense rainfall, these have been responsible for many casualties and extensive economic losses. In a study of Povoação *concelho* (fig. 4), it is shown that landslides are highly probable when precipitation exceeds 200 l.m^{-2} and that risk is exacerbated by the occurrence of soils composed of volcanic ash, high slope angles and particular landuse and vegetation conditions (Valadão *et al*., 2002). However, some more recent important landslides have been triggered by lower levels of precipitation, around 120 l.m^{-2} (Marques *et al*., 2005) and with regard to this, Malheiro (2006) has shown that two factors are important. First, areas devoid of vegetation are particularly prone to erosion and, second, the frequent occurrence of storms together with high winds can uproot trees which are shallow-rooted. *Cryptomeria japonica*, an introduced tree now common on São Miguel is particularly prone to being easily uprooted and has often triggered large-scale slope failures.

One recent example of the effects of rainfall on slope failure occurred on October 31, 1997 on Furnas volcano (fig. 1). Landsliding was triggered by rainfall of up to 220 l.m^{-2} (Gaspar *et al*., 1997) strong southeast winds, volcanic soils and earlier saturation of the ground all being aggravating factors. Landslides were dominated by mobile debris flows, which carried lava blocks with a calibre of up to 3 m. Several roads and bridges were extensively damaged over a wide area and thirty six houses were destroyed, 29 people were killed, 114 residents were left homeless mainly in the village of Ribeira Quente, which was cut off from the rest of São Miguel for more than 12 hours (Gaspar *et al*., 1997). The total financial loss was estimated at more than €20 million (Cunha, 2003).

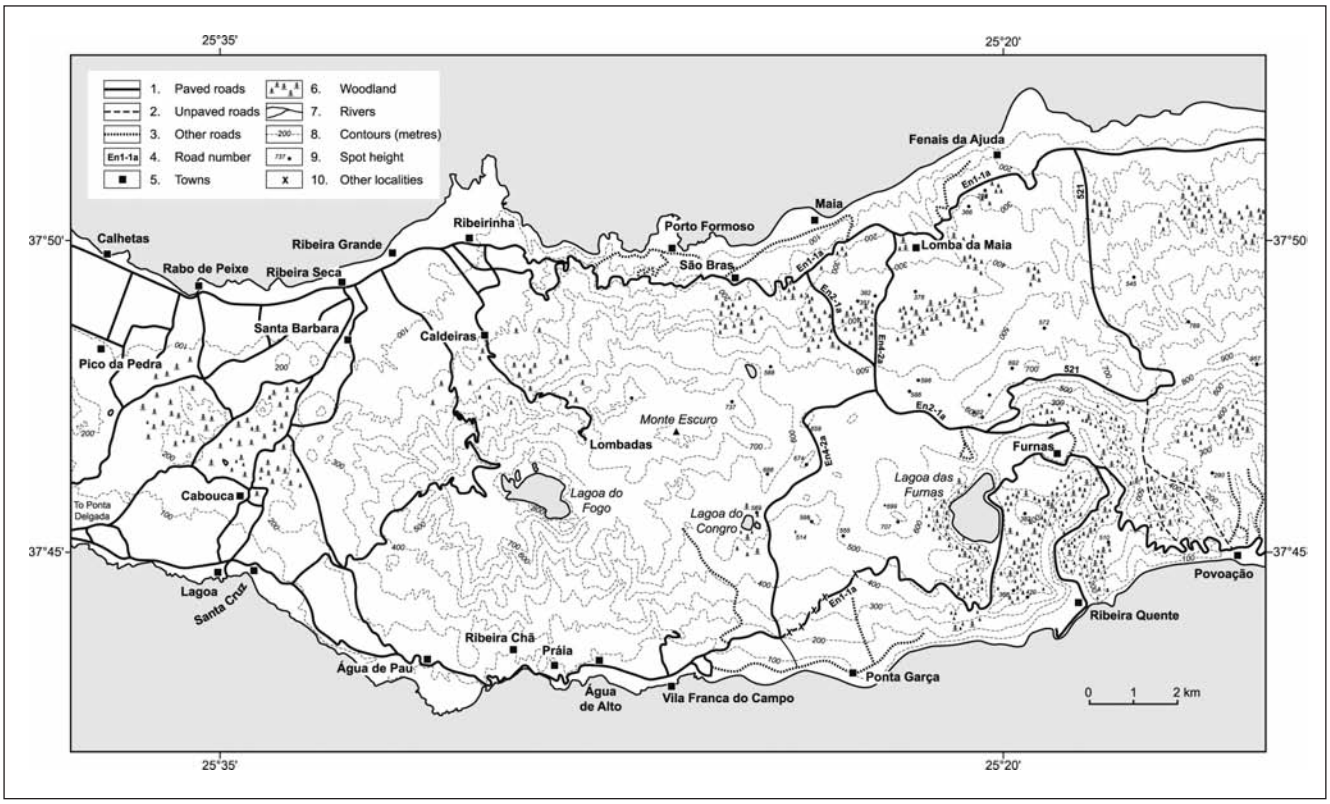

Fig. 6 – **Fogo volcano: roads and drainage (adapted from Wallenstein *et al*., 2005).** 1: paved roads; 2: unpaved roads; 3: other roads; 4: road number; 5: towns; 6: woodland; 7: rivers; 8: contours (metres); 9: spot height (metres); 10: other localities.

Fig. 6 – ***Le volcan Fogo : routes et drainage (modifié d'après Wallenstein* et al., *2005).*** *1 : routes asphaltées ; 2 : routes sans revêtement ; 3 : pistes ; 4 : numéro de la route ; 5 : villes ; 6 : forêt ; 7 : rivières ; 8 : courbes de niveau (mètres) ; 9 : altitude du lieu (mètres) ; 10 : autres localités.*

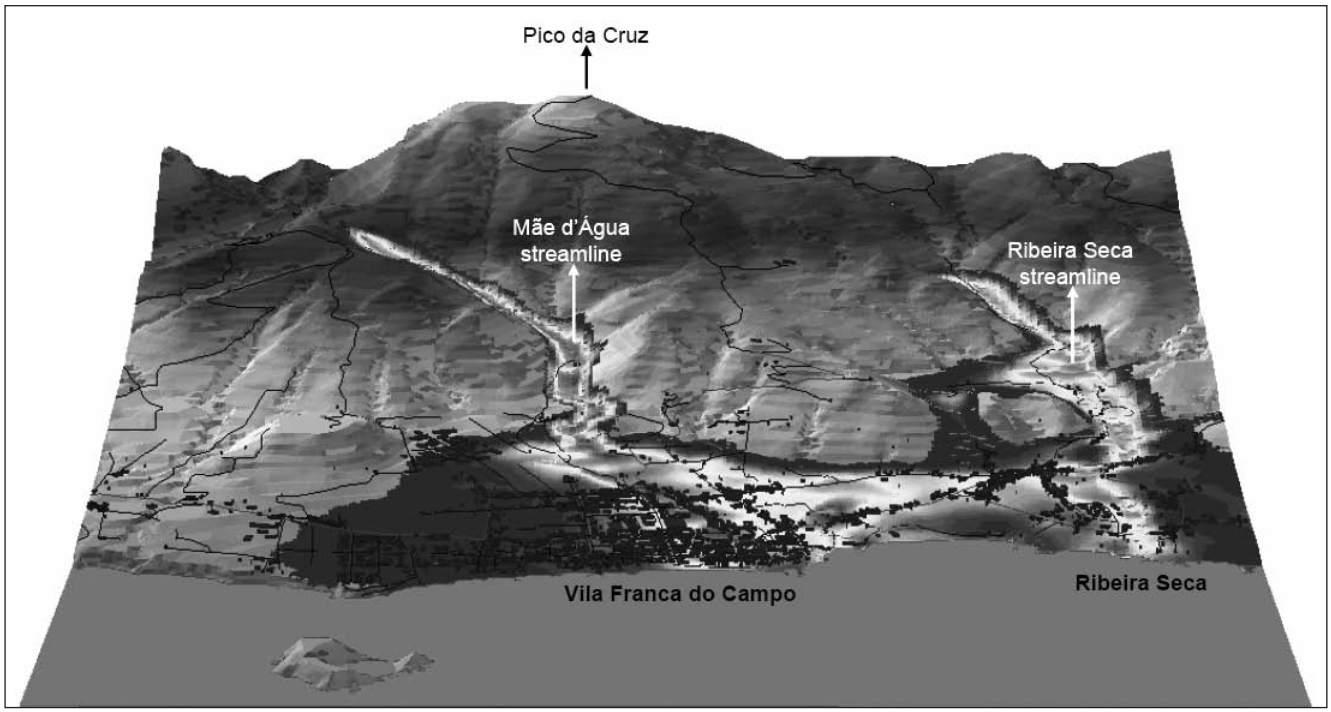

Fig. 7 – **The estimated area that was flooded during 1522.** The area is obtained by the application of a probability model developed by Feltpeto et al. (1996) for gravity flows which is superimposed over a three dimensional view of the Vila France do Campo area (adapted from Marques, 2004). Looking north.

*Fig. 7 – **Estimation de la surface de la région inondée en 1522.** Cette surface est calculée en utilisant un modèle de probabilité (Feltpeto et al., 1996), surimposé à une vue 3D du secteur de Vila France do Campo (modifié d'après Marques, 2004). Vue vers le nord.*

The situation on Fogo is very similar to that described for Povoação *concelho* and for the Azores more generally (Malheiro, 2006). Fogo is an immature, potentially unstable landform with a significant proportion of pyroclastic materials within its volcanic succession. These pyroclastic deposits are notable for their very low resistant parameters of cohesion and friction angles and high values for permeability, which favour the ready circulation of ground water. In common with Furnas, Fogo's climate is characterized by heavy rainfall (mean value of 1,255 $l.m^{-2}$ at 65 m rising to 3,830 $l.m^{-2}$ at 947 m) and storms, particularly between the months of September and April (Wallenstein *et al*., 2005). On Fogo steep slopes, developed on these incoherent materials, are heavily dissected and landslides have been a frequent indirect volcanic hazard, the high density of mapped landslip scars bearing witness to a long history of landslip activity (Valadão *et al.,* 2002). Recent examples include a landslide that destroyed a mineral water plant in the Lombadas valley, just northeast of the summit (fig. 6), and the landslides and flash floods that occurred on the southern flank of Fogo in October 1998 during the passage of tropical storm *Jeanne*.

The most violent example of an earthquake triggering a landslide took place on October 22, 1522. This was the largest such event to have affected the island since it was settled and several landslides were triggered. The most hazardous and spectacular of these was a cataclysmic landslide that was initiated from an altitude of 450 m on the southern flank of Fogo. This event generated a debris flow, which buried and completely destroyed the town of Vila Franca do Campo. About 5,000 people lost their lives and an area of ~4.5 km^2 was covered by several millions of cubic metres of debris (fig. 7). The stratigraphic position of the 1522 debris flow deposits are well constrained. In many outcrops in the Vila Franca do Campo area, the sediments directly overly deposits of the Fogo A formation and in some places it is possible to observe the Furnas AD 1630 sub-plinian eruption products resting on top. With thicknesses ranging from a few centimetres to over 2.5 m, deposits from the 1522 debris flows either show a sheet-like morphology or occur as fills within contemporary stream channels. Within stream channels, deposits rest directly on surfaces that were formed by the abrasive erosion of the flow. Four distinct flow units have been identified and interpretation of these has allowed a model of emplacement to be proposed (fig. 7), so allowing the construction of scenarios of future debris flows on Fogo Volcano. A small tsunami was produced by the flow of debris into the Atlantic and destroyed two boats anchored near Vila Franca islet, some 2 km offshore (Fructuoso, 1522-1591†). After the Lisbon earthquake of 1755, which killed around 30,000 people (Oliveira, 1986; Chester, 2001), this event represents the largest natural catastrophe to have affected Portugal. More recently and despite their moderate magnitude, the 2005 Fogo-Congro seismic swarms were also responsible for extensive slope failure in the Fogo District, triggering hundreds of slope failures; these being mostly debris flows and shallow soil slips that evolved downslope into debris flows (see fig. 8 and Marques *et al*., 2006).

Fig. 8 – **View of the Ribeira Grande watershed on the northern flank of Fogo showing extensive landslide scars from the summer 2005 seismic activity.** Length of valley about 1 km.

*Fig. 8 – **Vue du basin versant de Ribeira Grande sur le flanc nord du volcan Fogo, montrant de nombreuses et grandes cicatrices de glissements de terrain déclenchés par l'activité sismique de l'été 2005.** La longueur de la vallée est d'environ 1 kilomètre.*

Some rural roads were temporarily closed and temporary dams were formed in the Ribeira Grande watershed (Marques *et al*., 2006).

Flash Floods

Flash floods are normally associated with specific geomorphological factors and are triggered by heavy rainfall. On São Miguel catchments are small and this, combined with steep profiles, means that river regimes are characterised by rapid discharge immediately following major rainfall events. As has been recognised for some time (Chester *et al*., 1999), natural dams produced by sediment and vegetation heighten the danger of flash flooding, and in December 1998 such an event swept through the village of Praia on the lower southern flank of the volcano (fig. 6). Praia is located at the foot of the valley whose catchment extends to just below the southern margin of the Fogo caldera lake. Here the lip of the Fogo Lake is only a few metres high, and even a relatively small landslide from either the steep western or eastern walls could cause a surge of water that would breach the lip and send a catastrophic flood down the Praia valley. Recent building development has occurred on a delta of debris flow deposits, which were emplaced at the mouth of the Praia valley during the 1563 eruption (Wallenstein *et al*., 1998; Wallenstein, 1999). This is a hazardous location and emphasises the need for risk assessment in plan-

Major landslide and flash flood risks
South Flank: Lagoa, Água de Pau, Ribeira Chã, Agua d'Alto, Vila Franca do Campo and Ribeira das Taínhas. Around 22,000 people (~39% of the population of the Fogo District) live in this area, which is located within a radius of 8 km of the centre of the Lagoa do Fogo. People are highly exposed to landslides and floods. The risks include: a. River valleys that drain the summit region (fig. 6), would be flooded if the walls of the Lagoa do Fogo were to be breached. Landslides would choke valleys with sediment and up-rooted trees would create temporary dams, so exacerbating flooding dangers. b. Flood risk was noted in all the valleys that reach the southern coast and is particularly acute at Praia (see main text). Many places were noted along the southern coastal road (i.e. En11a - fig. 6) where, given a combination of circumstances, the route would be blocked. Blocking of this less than secure southern route would severely hamper communications over much of São Miguel.
North Flank: Santa Bárbara, Ribeira Seca, Ribeira Grande, Ribeirinha, Porto Formoso and Maia). Over 15,000 people (~27% of the total for the Fogo District) live in these settlements on the north flank. Towns and villages are not as close to the summit as those on the south flanks and have far better road access to the west and to the island's capital, Ponta Delgada (i.e. roads En 1 1a and En 3 1a). Specific concerns are raised by: a. The main road (En1 1a) passes close to the town of Ribeira Grande and the stream with the same name and has a large catchment reaching almost to the caldera rim. Flash floods are a major risk. b. There are many examples where roads and villages could be affected by landslides. c. The hazard posed by flash flooding was noted in several north flowing river valleys. d. Many bridges could not resist the effects of either flash flooding or large landslides.

Table 2 – **Summary of a survey of the exposure of settlements and roads on the northern and southern flanks of Fogo to the effects of landslides and flash floods (population data from INEP, 2002).** This table should be read in conjunction with fig. 6.

*Tableau 2 – **Résumé d'une enquête à propos de l'exposition des constructions et des routes sur les flancs nord et sud du volcan Fogo, face aux effets des glissements et des crues éclair (données démographiques d'après INEP, 2002)**. Ce tableau devrait être comparé à la fig. 6.*

ning. Praia village is an extreme example of a populated area which is at risk from flash flooding and other instances are to be found on the northern and southern lower flanks of Fogo (figs. 4 and 6). A survey was undertaken of the landslide and flood risks for that part of the Fogo District, which is located on the slopes of the volcano (i.e. from the settlements of Santa Barbara to Maia on the northern flank, and from Lagoa to Vila Franca do Campo on the southern flank (see fig. 6). The results are summarized in Table 2. This complements a reconnaissance study of volcanic hazard exposure in the Fogo District and an account of the possible effects of an eruption on the settlements of the Fogo District and its roads has already been published (Wallenstein *et al*., 2005).

Conclusion

This paper demonstrates that indirect volcanic hazards are an ever present threat to people living on the flanks of the volcano and its immediate environs. Recurrence intervals of extreme natural events are probabilistic and people living on and in the vicinity of Fogo have been extremely fortunate to have not been more adversely affected by indirect hazards. The 1522 landslides, debris flow and tsunami caused the deaths of 5,000 people, but today more than 11,000 people live in the *concelho* of Vila Franco do Campo and would be at risk. Interactions between the volcanic edifice and seismicity, hydrothermal/gas activity, landslides and flash floods all create major hazards and there is a need for a far more detailed and comprehensive study so that appropriate planning and response procedures may be developed. It is pleasing to note that in November 2005, on the final day of the field programme for this paper, a major civil defence exercise was being conducted in Vila Franca do Campo and during 2006 two similar exercises were conducted in the Fogo district. They were focused on the deployment of civil and military teams in response to hypothetical scenarios of devastating earthquakes.

Acknowledgements

The authors wish to thank Mrs S. Mather for expertly drafting the figures and Dr F. Marret for translations into French. Most of the fieldwork was supported by the Centro de Vulcanologia e Avaliação de Riscos Geológicos da Universidade dos Açores. We would like to thank Dr K. Nemeth, Professor J.-C. Thouret and the other reviewers whose helpful comments have greatly improved this paper.

References

Andrade C., Borges P., Freitas M.C. (2006) – Historical tsunami in the Azores Archipelago (Portugal). *Journal of Volcanology and Geothermal Research* 156, 172-185.

Baxter P.J., Baubron J.-C., Coutinho R. (1999) – Health hazards and disaster potential of ground gas emissions at Furnas Volcano, São Miguel, Azores. *Journal of Volcanology and Geothermal Research* 92, 95-106.

Blong R.J. (1984) – *Volcanic Hazards. A Sourcebook on the Effects of Eruptions*. Academic Press, Sydney, 424 p.

Bonagura M., Damiano N., Saccorotti G., Ventura G., Vilardo G., Wallenstein N. (2004) – Fault geometries from the space distribution of earthquakes at São Miguel Island (Azores): inferences on the active deformation. *Geophysical Research Abstracts* 6, 07635. European Geosciences Union, Vienna.

Booth B., Walker G.P.L., Croasdale R. (1978) – A quantitative study of five thousand years of volcanism on São Miguel Azores. *Philosophical Transactions of the Royal Society of London*, Series A 228, 271-319.

Calvari S., Tanner L.H., Gropelli G., Norini G. (2004) – Valle del Bove, eartern flank of Etna volcano: A comprehensive model for the opening of the depression and implications for future hazards. *In* Bonnacorso A., Calvari S., Coltelli M., Del Negro C., Falsaperla S. (Eds.), *Mt. Etna: Volcano Laboratory*. Geophysical Monograph Series 143, American Geophysical Union, 65-75.

Chester D.K. (2001) – The 1755 Lisbon earthquake. *Progress in Physical Geography* 25, 363-383.

Chester D.K., Duncan A.M., Guest J.E., Kilburn C.R.J. (1985) – *Mount Etna, anatomy of a volcano*. Chapman and Hall, London, 389 p.

Chester D.K., Dibben C., Coutinho R., Duncan A.M., Cole P.D., Guest J.E., Baxter P.J. (1999) – Human adjustments and social vulnerability to volcanic hazards of Furnas Volcano, São Miguel, Azores. *In* Firth C.R., McGuire W.J. (Eds.), *Volcanoes in the Quaternary*. Geological Society, London, Special Publications, 161, 189-207.

Cunha A. (2003) – The October 1997 landslides in São Miguel Island, Azores. *In* Javier H. (Ed.), *Lessons learnt from landslide disasters in Europe*. European Commission Joint Research Centre, ISPRA, Doc 20558EN, 92 p.

Delmelle P., Bernard A. (2000) – Volcanic lakes. *In* Sigurdsson H. (Ed.), *Encyclopedia of Volcanoes*. Academic Press, San Diego, 877-895.

Felpeto A., Garcia A., Ortiz R. (1996) – Mapas de riesgo. Modelizácion. *In* Ortiz, R. (Ed.), *Riesgo volcánico*. Série Casa de los Volcánes 5, Servicio de Publicationes Cabildo de Lanzarote, Canarias, 67-98.

Ferreira T. (2000) – *Caracterização da actividade vulcânica da ilha de S. Miguel (Açores): Vulcanismo basáltico recente e zonas de desgaseificação. Avaliação de riscos*. Tese de doutoramento no ramo de Geologia, especialidade de Vulcanologia. Universidade dos Açores, Departamento de Geociências, 248 p.

Ferreira T., Gaspar J.L., Viveiros F, Marcos M., Faria F., Sousa F. (2005) – Monitoring of fumarole discharge and CO_2 soil degassing in the Azores: contribution to volcanic surveillance and public health risk assessment. *Annals of Geophysics* 48, 787-796.

Fructuoso G. (1522-1591†) – Livro Quarto das Saudades da Terra. 1877, vol. I e II, Ed. Instituto Cultural de Ponta Delgada, Ponta Delgada, unknown number of pages.

Gaspar J.L. (1996) – *Ilha Graciosa (Açores. História vulcanológica e avaliação do hazard*. Tese de doutoramento no ramo de Geologia, especialidade de Vulcanologia. Universidade dos Açores, Departamento de Geociências, 256 p.

Gaspar J.L., Wallenstein N., Coutinho R., Ferreira T., Queiroz G., Pacheco J., Guest J., Tryggvason E., Malheiro A. (1997) – *Considerações sobre a ocorrência dos movimentos de massa registados na madrugada de 31 de Outubro de 1997 na ilha de*

S. Miguel, Açores. Relatório Técnico-Cientifico 14/DGUA/97, Centro de Vulcanologia, 28 p.

Gomes A., Gaspar J.L., Queiroz G. (2006) – Seismic vulnerability of dwellings at Sete Cidades Volcano (S. Miguel Island, Azores). *Natural Hazards and Earth System Sciences* 6, 41-48.

Guest J.E., Cole P.D., Duncan A.M., Chester D.K. (2003) – *Volcanoes of Southern Italy*. Geological Society of London, London, 274 p.

INEP (2002) – *Censos 2001: XIV Recenseamento Gerald a População, IV Recenseamento Geral à Habitação*. Instituto Nacional de Estastística, Lisboa, 87 p.

Larsen M.C., Wieczorek G.F., Eaton L.S., Torres-Sierra H. (2001) – The rainfall-triggered landslide and flash-flood disaster in northern Venezuela, December 1999. *Proceedings of the Seventh Federal Interagency Sedimentation Conference*, Reno, NV, IV, 9-16.

Machado F. (1959) – Submarine pits of the Azores plateau. *Bulletin Volcanologique* 21, 109–116.

Malheiro A. (2006) – Geological hazard in the Azores archipelago: Volcanic terrain instability and human vulnerability. *Journal of Volcanology and Geothermal Research* 156, 158-171.

Marques R. (2004) – *Contribuição para o conhecimento da instabilidade geomorfológica nos Açores:Estudo de movimentos de vertente associados a diferentes mecanismos desencadeantes*. Tese de mestrado em Vulcanologia e Avaliação de Riscos Geológicos. Universidad Dos Açores, Departamento de Geociências, 147 p.

Marques R., Coutinho R., Queiroz G. (2005) – *Considerações sobre a ocorrência dos movimentos de vertente desencadeados pelos sismos de 20 e 21 de Setembro de 2005 no Fogo-Congro (Ilha de São Miguel)*. Caracterização e análise de cenários. Relatório Técnico-Cientifico 27/CVARG/05, Centro de Vulcanologia, 36 p.

Marques R., Coutinho R., Queiroz G. (2006) - Landslides and erosion induced by the 2005 Fogo-Congro seismic crisis (S. Miguel, Azores). *Geophysical Research Abstracts*, Vol. 8, EGU06-A-06925, SRef-ID: 1029-7006. European Geosciences Union.

Moore R.B. (1990) – Volcanic geology and eruption frequency, São Miguel, Azores. *Bulletin of Volcanology* 52, 602-514.

Oliviera C.S. (1986) – Some quantitative measurements for calibrating historical seismicity. *In Proceedings of the 8th European Conference on Earthquake engineering*. Laboratório Nacional de Engenharia Civil 1, 2.1/71-2.1/78.

Pomonis A., Spence R., Baxter P. (1999) – Risk assessment of residential buildings for an eruption of Furnas Volcano, São Miguel, the Azores. *Journal of Volcanology and Geothermal Research* 92, 107-131.

Queiroz G. (1997) – *Vulcão das Sete Cidades (S. Miguel, Açores). História eruptiva e avaliação dohazard*. Tese de doutoramento no ramo de Geologia, especialidade de Vulcanologia. Universidade dos Açores, Departamento de Geociências, 226 p.

Rodolfo K.S. (2000) – The hazard from lahars and jokülhlaups. *In* Sigurdsson H. (Ed.): *Encyclopedia of Volcanoes*. Academic Press, San Diego, 973-995.

Saccorotti G., Wallenstein N., Ibáñez J., Bonagura M.T., Damiano N., La Rocca M., Quadrio A., Silva R., Zandomeneghi D. (2004) – A seismic field survey at Fogo Furnas volcanoes, São Miguel island, Azores. *Geophysical Research Abstracts*, Vol. 6, 04493. European Geosciences Union.

Scott K., Vallance J.W., Kerle N., Macias J.L., Strauch W., Devoli G. (2005) – Catastrophic precipitation-triggered lahar at Casita volcano, Nicaragua: occurrence, bulking and transformation. *Earth Surface Processes and Landforms* 30, 59-79.

Silva R., Bonagura M., Damiano N., Zandomeneghi D., Saccorotti G., Wallenstein N., Quadrio A., Carmona E. (2004) – Preliminary results of a seismic experiment in Fogo and Furnas volcanoes, São Miguel Island (Azores), Portugal. *Resumos da '4ª Assembleia Luso-Espanhola de Geodesia e Geofísica'*, 343-344.

Silveira D., Gaspar J. L., Ferreira T., Queiroz G. (2003) – Reassessment of the historical seismic activity with major impact on São Miguel Island (Azores). *Natural Hazards and Earth System Sciences* 3, 615-623.

Simkin T., Fiske, R.S. (1983) – *Krakatau 1883: The volcanic eruption and its effects*. Smithsonian Institution Press, Washington D.C., 464 p.

Tilling R.I. (2005) – Volcanic hazards. *In* Marti J. and Ernst G. (Eds.), *Volcanoes and the Environment*. Cambridge University Press, Cambridge, 55-89.

Valadão P., Gaspar J.L., Ferreira T., Queiroz G. (2002) – Landslides density map of S. Miguel Island (Azores archipelago). *Natural Hazards and Earth System Sciences* 2, 51-56.

Wallenstein N. (1999) – *Estudo da história eruptiva recente e do comportamento eruptivo do vulcão do Fogo (S. Miguel, Açores). Avaliação preliminar do hazard*. Tese de doutoramento no ramo de Geologia, especialidade de Vulcanologia. Universidad Dos Açores, Departamento de Geociências, 266 p.

Wallenstein N., Duncan A.M., Almeida H., Pacheco J. (1998) – A erupção de 1563 do Pico do Sapateiro, São Miguel (Açores). *Proceedings of the 1ª Assembleia Luso Espanhola de Geodesia e Geofísica (electronic format)*. Espanha, Almeria. Fevereiro de 1998, 6 p.

Wallenstein N., Chester D.K., Duncan A.M. (2005) – Methodological implications of volcanic hazard evaluation and risk assessment: Fogo Volcano, São Miguel, Azores. *Zeitschrift für Geomorphology* NF, Suppl.Band 140, 129-149.

Article soumis le 21 novembre 2006, accepté le 1er février 2007.