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Volcanic hazard vulnerability on São Miguel Island, Azores

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Abstract

In recent years much progress has been made in researching a wide variety of extreme events on São Miguel. In addition there are a number of volcano-related risks which impact upon the people of São Miguel. Some of these may occur both before and during volcanic emergencies (e.g. earthquakes), whilst others render São Miguel dangerous even when its volcanoes are not erupting (e.g. flooding, landslides, tsunamis and health impacts, especially the effects of CO_2 seepage into dwellings). In this chapter we first define what vulnerability means to the people of São Miguel, and

relate this to the cultural and economic characteristics of the island. The following aspects of vulnerability are discussed: a. physical (i.e. housing, settlement and the characteristics of evacuation routes and plans); b. demographic and economic;

c. social and cultural and perceptual (i.e. do people have an accurate cognition of risk). Particular areas of concern relate to housing; the identification of isolated dwellings which would be difficult to evacuate; the vulnerability/resilience of evacuation routes following recent infrastructure improvements; characteristics of the island's transient population; management of livestock under emergency conditions; local leadership roles and educational outreach.

Volcanic hazard may be defined as the probabilities of occurrence of eruptions and volcano-related phenomena. Risk is the interaction between the probability of an extreme physical event and its impact on a vulnerable human population (Susman et al. 1983, p. 264, see also Bankoff 2001, p. 24-27; Wisner *et al.* 2004, p. 3-16). In recent years considerable progress has been made in researching a wide variety of extreme events on São Miguel. Particular attention has been paid to reconstructing past eruptions, drawing up future eruption scenarios and assessing the probable effects of such eruptions on people living on the island. These are discussed on other chapter in this volume (Ferreira *et al*. 2014; Gaspar *et al*. 2014 - Eruptive frequency and volcanic hazard zonation; Gaspar *et al*. - Earthquakes and volcanic eruptions in the Azores region; Queiroz *et al*. 2014; Wallenstein et al. 2014). Future eruption scenarios for the three active central volcanoes of São Miguel (i.e. Sete Cidades, Fogo and Furnas - Fig. 1) are summarised in Table 1 and, in addition to the direct effects of future volcanic eruptions, there are a number of volcano-related risks which impact upon the people of São Miguel. Some of these, such as earthquakes generated by magma movement (Silveira *et al*. 2003; Wallenstein *et al*. 2005, 2007; Gomes *et al*. 2006), may occur both before and during volcanic emergencies, whilst others render São Miguel dangerous even when its volcanoes are not erupting (Malheiro 2006; Wallenstein *et al.* 2007). Such phenomena have been studied by a number of authors and include:

a. climatic and geomorphological hazards, particularly flooding and landslides, triggered by both rainfall and seismic activity (Louvat & Alleger 1998; Chester *et al.* 1999; Duncan *et al*. 1999; Valadão *et al.* 2002; Gomes *et al*. 2005; Marques *et al.* 2005, 2006, 2007, 2008; Wallenstein *et al*. 2005, 2007);

b. the exposure of coastal areas to tsunamis generated by either near or distant earthquakes and/or collapses into the Atlantic ocean from its many islands (Andrade *et al.* 2006); and

c. the health impacts on the population, especially the effects of CO_2 seepage into dwellings (Baxter *et al*. 1999, 2005; Hansell *et al*. 2006; Viveiros *et al.* 2009, 2010).

CO_2 acts as a carrier for radon and Baxter (2005, p. 280-282) argues that smokers are particularly at risk of developing lung cancer.

Human vulnerability has also been studied and research has concentrated not only on detailing the threats faced by the population of São Miguel, but also on how people would cope in the event of a future eruption or volcano-related emergency. *Vulnerability*, or the susceptibility to damage, is defined as "the characteristics of a person or group ….. that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard... . It involves a combination of factors that determine the degree to which someone's life, livelihood, property and other assets are put at risk" (Wisner *et al*. 2004 p.11). Whereas hazard assessment focuses on the physical processes that produce extreme and potentially damaging occurrences, *vulnerability* analysis concerns the ways in which these - often in combination with pre-existing social and economic circumstances - produce unsafe conditions for groups within a population. Traditionally hazard analysis has stressed the physical processes that produce disasters, but more recently a number of authors have emphasised that hazards may act as ‘triggers’ that bring to the surface more deep-seated economic, political and cultural issues that are already present within a society (Hewitt 1997; Pelling 2001), a disaster being viewed as a "highlighter or amplifier of daily hardship and everyday emergencies rather than as an extreme and rare phenonema" (Gaillard & Texier 2008, p. 347). In order to reduce disaster susceptibility and increase what is termed, *resilience* or *capacity*, these deep-rooted causes of vulnerability have also to be addressed (Degg & Homan 2005; Gaillard 2007).

Over the past decades several scholars have devised typologies, whereby the characteristics that produce human vulnerability in different societies may be classified (e.g. Alexander 1997; Zaman, 1999; Degg and Homan, 2005). We propose a similar scheme that is tailored to the situation in the Azores and which we will use to study human vulnerability on São Miguel (Table 2).

Physical vulnerability

On São Miguel physical vulnerability is expressed in its housing stock; the distribution of its population and settlement and the characteristics of its evacuation plans.

Housing

The housing stock of São Miguel is highly vulnerable to losses in the event of seismic events and tephra-fall. During historic times the island has been affected by ten major earthquakes (1522, 1638, 1713, 1810, 1811, 1848, 1852, 1932, 1935 and 1952), together with several episodes of seismic swarms associated with volcanic activity. In a study of the *freguesias* (i.e. parishes) within the *concelho* (i.e. county or municipality) of Ponta Delgada, that lie either on the flanks of Sete Cidades volcano or within its caldera (Fig. 2), Gomes *et al.* (2006) have classified housing according to its vulnerability using a scheme developed in connection with the European Macroseismic Scale 1998 (Grünthal 1998). In this classification the buildings most at risk from earthquakes (Classes A and B) are constructed from *rubble-stone* and *simple-stone*. *Rubble-stone* is defined as traditional construction "in which undressed stones are used as the basic building material, usually with poor quality mortar, leading to buildings which are heavy and have little resistance to lateral stress. Floors are typically of wood, and provide no horizontal stiffening. *Simple-stone* differs from *rubble-stone* construction "in that the building stones have undergone some dressing prior to use. These hewn stones are arranged in the construction of the building according to some techniques to improve the strength of the structure, e.g. using larger stones to tie in the walls at the corners. In the normal case, such buildings are treated as vulnerability class B, and only as class A when in poor condition or put together with particularly poor workmanship" (Grünthall 1998, p. 34-5).

Before the 1970s most dwellings were up to two storeys in height and of *rubble-stone* construction, though some have subsequently been improved by the addition of reinforced slabs and columns. From the 1970s buildings have usually been constructed using reinforced concrete frames and/or un-reinforced concrete blocks. Official data show that in Povoação and Lagoa *concelhos*, 41% of houses were built before 1971 and *ca*.40% in Ponta Delgada *concelho* (INEP 2002, p.18). In their field area Gomes *et al.* (2006) concluded that some 76% and 17% of houses belonged, respectively, to vulnerability Classes A and B. On Faial some 508 rubble-stone buildings were damaged and 273 destroyed in the two-day volcano-tectonic swarm in May 1958 which was associated with the Capelinhos volcanic eruption (Coutinho *et al*. 2008, 2010), while on July 9 1998 an earthquake, with an epicentre located off the coast of the island and having a Mercalli Magnitude of 5-6, killed 8 people, injured 150, rendered 1,500 people homeless and damaged many buildings (Coutinho *et al*. 2008). Using the *European Macroseismic Scale (EMS)*, Gomes *et al.* (2006) demonstrate that the maximum historic intensity reached on Sete Cidades volcano on São Miguel was IX and that this took place during the seismic crisis associated with the offshore volcanic eruptions of 1713 and 1811. Traditional housing is so vulnerable that an earthquake with an *EMS* intensity of IX would cause between 57% and 77% of dwellings in Sete Cidades *area* (Fig. 2) to be either destroyed or badly damaged, representing between 2,480 and 3,350 homes.

An estimated 80% of buildings on Furnas volcano are constructed from rubble-stone and, in a survey that also covered part of Fogo volcano, Pomonis *et al.* (1999) identified an additional feature of physical vulnerability. Even a small eruption would produce extensive tephra deposition and could affect towns and villages downwind of eruption sites especially if hydromagmatism featured in such an event (Table 1). Higher magnitude eruptions would cause more extensive damage. In the villages examined by Pomonis and his colleagues (i.e. Furnas, Ribeira Quente, Povoação and Ponta Garça - see Fig. 2), they found that *ca*. 18% of buildings had roofs that were in poor condition and, hence, highly vulnerable to collapse. More recently important research has been published on strengthening traditional Portuguese buildings generally (Oliveira 2003; Murphy-Corella 2009, see also Spence 2007, page 187, Table 7) and Azorean housing in particular (Costa 2002). Costa and Arede (2006) point out that resilience could be greatly improved by relatively simple measures including, *inter alia*: reinforcing walls and roofs by connecting structural elements together so as to improve rigidity; and ensuring that roofs are not only in good condition but also firmly connected to walls.

Distribution of population and settlement

In 2001, the date of the most recently published census, the resident population of São Miguel was recorded as 131,530 (INEP 2002) and by early 2011 had risen to an estimated 134,000 (INEP 2011b). The most recent census was held in March 2011. At the time of writing no results are available. The *Serviço Regional de Estatística dos Açores*, provide estimates of the population resident in each *concelho*, for various years since 2001, the latest data being for December 2008 (SREA 2011).

About 9% of the population lives in the *Sete Cidades area*, 43% in the *Fogo area* and 19%

in the *Furnas area*, some 71% of the total (Fig. 2). The overall distribution shows two general characteristics:-

i. The interior of São Miguel is mountainous and population is concentrated near to the coast, with Sete Cidades, Covoada, Arrifes, Fajã de Cima, Fajã de Baixo, Pico da Pedra (Ribeira Grande *concelho*), Cabouco, Santa Bárbara (Ribeira Grande *concelho*), Furnas and Nossa Senhora dos Remédios, being the only inland settlements of importance, though it shoud be noted that Covoada, , Fajã de Cima and Fajã de Baixo are suburbs of Ponta Delgada (Fig. 2).

ii. A marked population focus around Ponta Delgada, the island's capital and principal settlement, which contains 15% of the island's inhabitants in the four *freguesias* which comprise the capital in official statistics, double this figure if adjacent commuter settlements are included and some 48% if the whole *concelho* is taken into account (INEP 2002; SREA 2008).

In one respect the overall distribution of settlement is highly fortuitous because much of the land in the three volcanic *areas* is rural and many *freguesias* show low population densities; figures of less than 100 people per km^2, for example, are commonplace in the northeast and east of Furnas and Fogo *areas*. In the Sete Cidades *area* (Fig. 2) figures are only slightly higher and range from *ca.*72 to *ca.*171 people per km^2. Although in many volcanic regions low population densities represent a major impediment to successful evacuation, since it is may be difficult to locate people, in the case of São Miguel this is not a serious problem because population is highly concentrated within the principal settlement (*povoação sede de freguesia*) of each parish. Study of detailed maps (1: 25,000 scale) and aerial photographs, together with information collected in the field, shows some isolated farms and houses that would require special attention in the event of a planned evacuation. Another issue concerns people who live in settlements with poor communications, a factor that is reviewed in section 2.3.

Eruptions on São Miguel are rare (Table 1), yet certain villages are at considerable risk of being damaged each year by volcano-related events. As a result of its volcanic character the island has considerable relief amplitude and plentiful, often intense, rainfall has produced a high drainage density. Storms are particularly prevalent between September and April and in April 1996 slope failure occurred on the inner slopes of Furnas caldera and a landslide reached the western margin of Furnas village. On October 31 1997 and following a long period of heavy rainfall, around 1000 small landslides occurred in Povoação *concelho* and two of these were responsible for 29 fatalities, 114 residents being left homeless mainly in the village of Ribeira Quente (Fig. 2 - Gaspar *et al.* 1997; Cole *et al.* 1999; Wallenstein *et al*. 2005; Marques *et al*. 2008). Ribeira Quente was cut off from the rest of the island for more than 12 hours and total economic losses were estimated at more than €20 million (Cunha 2003). Research in Povoação *concelho* by Marques et al. (2008, p. 486), involved historical records of rainfall intensity (mm/day) being plotted against rainfall duration (D days) and showed that intensity increases exponentially as duration decreases, according to the regression equation $I = 144.06\ D^{-0.5551}$. As Figure 3 shows, the regression curve may be used to define thresholds above which landslides may occur. Historical data indicate that landslides are related to both: short duration (1-3 days) precipitation events, with high mean intensities of 78 - 144 mm/day; and longer (1-5 month) rainfall episodes, with lower mean intensities of between 9 and 22 mm/days. On São Miguel rainfall regimes with these characteristics are common between October and March and landslides occur in São Miguel during most winters. Mean rainfall of 911 mm at Ponta Delgada is enhanced by topographic effects (Moreira 1987), rising to 1992 mm at Furnas (height 290 m), being characterised by both high inter-annual and inter-seasonal variations. In Povoação *concelho* some 85% of historic landslides have occurred between October and March and, between 1918 and 2002, some 40 instances of landslides were recorded with only 1/4 being classified as 'minor' (Marques *et al*. 2008, p. 484).

Landslides may also be triggered by seismic activity. For example more than 46,000 earthquakes occurred in the Fogo area between May and December 2005, some 180 being felt by residents in near to the epicentre. The strongest shocks occurred on September 20 and 21 and had magnitudes (M_L) 4.1 and 4.3, respectively, and caused extensive slope failure in the central part of the island. During this episode more than 250 landslides were triggered (Marques *et al*. 2007).

Evacuation plans

Most settlements on São Miguel are linked by roads located near to the coast (Fig. 4), but this does not apply either to the, albeit few, inland settlements or other villages that are linked to coastal routes by highly vulnerable subsidiary roads. Furnas and Sete Cidades villages are, for instance, located within active calderas and would require early evacuation if an eruption were threatened, whereas an isolated coastal settlement – such as Ribeira Quente (Fig. 2 and Table 3) - is particularly at risk. The road linking the village to the island's network utilizes the valley of the Ribeira Amarela, which drains Furnas crater lake before passing through Furnas village and reaching Ribeira Quente by means of a very steep-sided and narrow valley. Any flooding, produced by draining of the crater lake and/or temporary damming of the valley, would destroy the road, making early evacuation essential if major loss of life were to be avoided (Chester *et al*. 1995). Similar comments apply to the small village of Praia, located 1 km to the west of Água de Alto (Fig. 2), where the draining of the Lagoa do Fogo through the south flowing Ribeira da Praia would produce similar widespread destruction.

In research carried out on Furnas volcano (Chester *et al.* 1995; 1999; Duncan *et al.* 1999), detailed studies were made of roads that could be used should an evacuation of the *area* be required, later this approach was extended to Fogo (Wallenstein 1999; Wallenstein *et al.* 2005, 2007; Table 3 and Fig. 4) and these studies highlighted three further areas of human vulnerability many of which also apply to Sete Cidades.

First many roads that could be used as evacuation routes are highly exposed to landslides and debris flows. At their most extreme these phenomena could destroy whole stretches of road, while less serious events would seriously restrict capacity. On Fogo there are particular problems with the northern and southern coast roads (EN1-1[a]) and at certain points on EN2-1[a], which links Furnas village to the north coast (Fig. 4). A second feature of vulnerability concerns masonry bridges that are present on many roads, together with the occurrence of rubble-stone buildings in virtually every town, both of which are highly susceptible to earthquake damage. Such damage would block roads and seriously impede evacuation. A third issue is strategic. Fogo is located in the centre of São Miguel (Fig. 1) and both the northern and southern coastal routes would be cut by even a small eruption, a landslide, an episode of heavy rainfall or an earthquake, so isolating the population living in much of the *Fogo area* (in excess of 45,000 people), together with those to the east in the *concelhos* of Povoação and Nordeste (*ca*.10, 000 people). In order to avoid this eventuality, evacuation would have to begin before the main phase of eruption. As will be discussed later when social/cultural and perceptual/informational vulnerability are reviewed, persuading people to evacuate before there are any clear signs of eruption would be problematic. Similar problems may also be encountered in trying to encourage people to leave Sete Cidades and Furnas villages, because both settlements would be devastated by even small scale intra-caldera eruptions and roads linking these settlements to the main coastal roads could easily be damaged and rendered unusable. In the *Furnas* and *Sete Cidades areas*, any disruption of the northern and southern coastal roads would isolated many communities. On Sete Cidades, the *freguesias* of Bretanha, Mosteiros and Ginetes are particularly vulnerable and involve a possible *ca*. 4000 people, whereas in the *Furnas area* and to its east affected *freguesias* could include Salga, Achadinha, Achada, Santana, Nordestinho, Lomba da Fazenda, Nordeste, Água Retorta, Faial da Terra, Nossa Senhora dos Remédios and Povoação and *ca.* 9, 600 people would be affected (Figs. 2 and 4).

Announced in 2002 (Anon 2002), in 2007 work began on a new programme of high speed roads on São Miguel (Fig. 4). Put Known by the acronym SCUTS (*Estradas sem custos para utilizador*, or roads without charge to the user), this programme involves private finance of 325 million Euros and is be funded from general taxation over a 30 year period. The new roads were all fully open by the end of 2011. Although promoted primarily for reasons of economic development, especially of the eastern extremities of the island, the impacts on Civil Protection and evacuation planning in the *Fogo* and *Furnas areas* are likely to be both profound and in some respects uncertain. As Figure 4 shows, the new roads do not impact upon the *Sete Cidades area*.

The principal positive impact on the vulnerability of the *Fogo* and *Furnas areas* is that the towns of Água de Pau, Água de Alto, Vila Franca do Campo, are now bypassed as was Ribeira Grande a few years earlier. With regards to the latter, this has removed a major 'bottle neck' which could have inhibited evacuation, while the stream flowing through the town - the dangers of which are discussed in Table 3 - has been more effectively bridged. The Ribeira Grande to São Brás and the São Brás to Lomba da Fazenda roads on the north of the island, and the Lagoa to Vila Franca do Campo road in the south only opened towards the close of the construction period and it is only with time that major changes in the balance between vulnerability and resilience of communities in the event of an eruption and a planned evacuation will be able to be assessed. On the one hand the new roads are, not only of a higher standard and much faster - travel times from Ribeira Grande to Nordeste being cut by some 45 minutes - but they are also constructed further inland, at a greater height and, consequently bridge many rivers and streams in a far more satisfactory manner than was the case hitherto using existing roads (Fig. 5). Indeed severe flooding, landsliding and even laharic activity could be accommodated without severely damaging these new bridges. On the other hand the new roads, that from São Brás to Nordeste (Fig. 5), do not replace but rather supplement existing routes with their many vulnerable sites (Table 3). New features of vulnerability could be created and may include:-

a. Poor weather, particularly fog, higher rainfall and strong winds at high altitudes particularly in winter.

b. The new routes are closer to the Furnas and Fogo calderas and during eruption could carry a higher ash loading than may be the case with existing roads.

c. The vulnerability of access points from the existing road system to the new roads is not clear. In time a new road survey will be required and revised evacuation plans will have to be published.

Demographic and economic vulnerability

Demographic vulnerability

Over the past fifty years the principal demographic characteristics of São Miguel have been out-migration to mainland Portugal and abroad, together with internal migration and commuting to the principal settlements of the island, particularly Ponta Delgada (Trindade 1976; Williams 1982; Silva 1988/9; Fortuna 1988; Rocha 1988/9, 1990). In recent years out-migration has been less significant and the island's population increased by *ca*.4% between 1991 and 2001 (INEP 2002) and *ca.* 2% between 2001 and 2011, showing an annual rate of natural increase of 0.33% in 2009 compared to an average for the Azores of 0.24% (SREA 2007, 2010, 2011b). Long-term features of out-migration and an historic lack of full employment are still present within the island's demographic profile while internal migration and commuting continue apace. In recent years employment opportunities in the Azores have been better than in Portugal as a whole. Data for 2009 show 9.5 % unemployment in Portugal and 6.7% in the islands (SREA 2010b). For the third quarter of 2011 figures were 12.4% for Portugal and 11.6% for the Azores (SREA 2010d). This means that in the late 1990s (Chester *et al.* 1999) *dependency ratios* (i.e. % of the population under 15, plus % over 65) across the *Furnas area* ranged from 38-46%, and the proportion of the population classified as economically active was never greater that 36% in any *freguesia*. In addition many older people were illiterate and rates exceeding 15% of the population occurred in 11 of the 15 *freguesias* that comprise the *Furnas area*. As mentioned in the introduction, the study of natural hazards often highlights deep-seated issues that normally lie dormant within a society. It was concluded by Chester *et al.* (1995) that, as a result of these long-standing demographic characteristics, a high proportion of the population would require assistance, especially in following instructions should an eruption-related emergency be declared. More recent data show that high dependency, low levels of economic activity and poor educational attainment remain features of the island's demography. For instance in 2001 *dependency ratios* for the *concelhos* that comprise São Miguel ranged from 33% in Ponta Delgada to 43% in Ribeira Grande, the economically active population varied from 36% in Povoação to 44% in Ponta Delgada, while illiteracy was still 16% in Vila Franca do Campo and 7% in Ponta Delgada (INEP 2002).

One feature of the population statistics for the Azores is that data at the most detailed level of sub-division (i.e. the *freguesia*) and which are so important in assessing demographic vulnerability are derived from the census, the latest figures available being from 2001. Figures from the 2011 census have not yet been published (SREA 2011b). Although the Regional Statistical Service (*Serviço Regional de Estatística dos Açores*) has a policy of updating some sets of data and estimating others between censuses (see SREA 2006b, 2007, 2010, 2011a, 2011b), statistics are only available for *concelhos* and in some cases for whole of São Miguel. Another feature of demographic vulnerability, which is not captured by official statistics, is the transient nature of much of São Miguel's population. A census can only give a snapshot of population on a specific date, traditionally in Portugal in March or April in the first year of the decade and, as field surveys have shown in rural areas especially, many houses are often only occupied at weekends and/or in summer. The number of people who would have to be evacuated on, say, a Saturday in August would be far greater than on a weekday in January. Tourist numbers also vary over the year and recently the number arriving in São Miguel has shown a rapid increase. The numbers of nights spent on the island by tourists more than tripled between 1993 and 2003 and reached a figure of over 700,000 in 2010 of whom *ca.*40% were ordinarily resident of other areas of Portugal, with some 39% visiting in July, August and September (SREA 2005a, 2005b, 2007, 2010, 2011c). In 2009 just over 5,200 people could be accommodated in hotels and other lodgings on any given night suggesting a total annual capacity of *ca*. nearly 2 million rooms, assuming each visitor only stayed one night. The average stay was, however, 3.5 nights and average occupancy only 37.5%, implying that there are many visitors to the island who are effectively 'lost' from the official record (SREA 2010a). From a hazards management perspective it is important to know:

a. where the excess population is accommodated; and

b. how many visitors are true tourists and, conversely, how many are expatriates returning to family homes that are either vacant or under-occupied for most of the year.

If civil protection and evacuation planning are to be effective, then a detailed study of this transient population is required.

Economic vulnerability

Some hazards, such as landslides, flooding and even low intensity seismic activity, will have economic impacts that are spatially limited to a small number of *freguesias*. It is widely recognised, however, that if any of the future eruption scenarios listed in Table 1 were to occur then the effects on the economy of São Miguel would be severe, necessitating the closure of many enterprises and a period of widespread unemployment. Outside assistance from the Portuguese government and/or the European Union would be required. There is one major change, nevertheless, that has occurred in the economy of São Miguel in recent decades which has produced an important new area of vulnerability.

In the late 1970s agriculture and fishing accounted for nearly 40% of total employment, but by 2009 this had fallen to just under 13% (SREA 2010b). Over the past few decades the major economic changes have been declines in both subsistence agriculture and the production of export crops and a rapid increase in cattle rearing. In 1980 there were just over 36,000 cattle in the whole of São Miguel (Langworthy 1987), whereas in the 1999 agricultural census this figure had risen to over 108,000 around 45% of the total for the Azores (INEP 2001). Although cattle numbers have declined slightly in the Azores in recent years, assuming a similar proportion to 1999, this still implies that just over 110,000 cattle were reared on São Miguel in 2009 (SREA 2010b). All three volcanic *areas* have large numbers of cattle, mostly located above heights of 300 m in summer and at lower altitudes in winter, and with some *freguesias* providing a home for more cattle then people. Such large numbers of livestock have major implications for contingency planning. In a volcanic emergency, animals - both living and dead - could block many of the roads that would have to be used for evacuation, and this is an issue that needs to be addressed by Civil Defence planners.

Social and cultural vulnerability

In studies of hazard exposure on Furnas and Fogo volcanoes (Chester *et al*. 1995, 1999, 2002; Wallenstein *et al*. 2005), aspects of social and cultural vulnerability are highlighted which apply with equal measure, not only to the Sete Cidades, but also more generally to São Miguel as a whole. Through processes of mobility, especially as a result of more comprehensive programmes of education that have been put in place since the 1974 revolution and inter-marriage, social stratification is not so prominent a feature of island life as it was a few decades ago, but is still recognisable. According to pioneer sociological research carried out in the 1980s by Francis Chapin (Chapin 1989), the people of São Miguel usually belong to one of five social groups (Table 4), but since Chapin carried out his research several changes have occurred and Table 4 has been up-dated to reflect more recent conditions.

As far as planning for a hazard-based emergency is concerned, two points emerge. First, the social structure shown in Table 4 has important implications for the management of any emergency. Within rural villages *proprietários* and members of the *established educated* groups (especially government officials, local doctors and school teachers) already possess established leadership roles within their communities. It is upon these two groups, plus local political leaders who are also usually drawn from these cohorts, that civil defence planners would have to rely in the event of a volcano-related crisis. A second issue concerns the high concentrations of *trabalhadores* found within rural areas of which the three volcanic *areas* are typical. Illiteracy although falling as older people die is an issue, but more important is strong attachments to land, community and livestock which could mean that orders to evacuate would at best ignored and at worst resisted. This feature, which is perceptual as well as social and cultural, is more fully discussed below and re-enforces an issue already aired regarding the problems caused by the presence of large populations of livestock, particularly cattle.

Perceptual and informational vulnerability

An individual's susceptibility to risk depends on many factors. Location of a person's home and the characteristics of his or her livelihood, activities and resources have already been discussed. Susceptibility is also determined by a person's ability for self-protection (Cannon 1994) and their physiological resilience, which itself may depend on factors such as age, psychological make-up and the accuracy with which a person may perceive the threat of being affected by a natural calamity (Dibben & Chester 1999). In order to investigate these factors in the context of Furnas volcano, an in-depth interview-based study of 50 respondents within the village of Furnas was carried out by one of us (Dibben 1999). In addition interviews were conducted with the Civil Defence authorities, local government officials and people affected by previous earthquakes. Five themes were covered by the interviews:

1. length of residence and reasons for moving to the village;

2. the respondent's attitude to the social and physical character of the village;

3. perceptions of volcanic and others hazards;

4. disaster preparation and

5. attitudes to measures for the mitigation of risks.

As far as vulnerability between eruptions is concerned and despite the fact that a number of people (e.g. civil defence workers and medical staff) in Furnas village knew of the risk of CO_2 seepage into buildings, not one interviewee at that time realised that gases posed a hazard to health. This suggests that at the time of the survey comprehensive information on civil protection had not been diffused throughout the village. There is a significant lung cancer risk to those who live in CO_2 exposed buildings, or whose employment involves working in hollows or cellars and this is a serious omission.

Responses to the interviews illustrated further aspects of vulnerability. Of the residents surveyed by Dibben (1999), none had prepared themselves for a future eruption, either mentally or physically, even though they generally knew that the volcano was active. Indeed Dibben & Chester (1999, p.10) record that respondents were shocked by the question, adding that either they did not know what they would do, or else they would simply run away. Even more worrying was that many people felt they would have no warning and did not know to whom to turn for advice, often citing television or scientists from the University of the Açores as their only sources of information. Some interviewees even thought that the presence of fumaroles in the village meant that eruptions were less likely and that earthquakes would be weaker. At a deeper psychological level, 28% of respondents believed they had little control over future events, some being very fatalistic and others placing their fate in the hands of God. Responses to the questions asked in the interviews, however, did not reveal any evidence of economic or social marginalisation (Susman *et al.* 1983), with all socio/economic groups being equally ill-informed. Surprisingly since felt earthquakes on São Miguel occur frequently, interviewees had little idea about how to respond to seismic events.

Behaviours amongst the respondents ranged from 'staying in bed' to 'curling up in a corner'; with not one interviewee indicating that he or she had tried to remove him or herself from their home and/or village.

Attachment to place, mentioned when economic, social and cultural vulnerabilities were being discussed, comes out very strongly in the interviews. Attachment often reflects stable long-term bonds between, people their homes and communities (Rivlin 1987; Dibben and Chester 1999), with a majority of respondents being very positive about their home village, but showing some negativity towards outsiders. Accepting two mutually incompatible explanations, or holding one view but acting in opposition to it is often termed *parallel practice* (Coutinho *et al*. 2010) and at Furnas people recognised that the village was both a fine place to live and a potentially very dangerous one. It should be noted that *parallel practice* is sometimes termed *cognitive dissonance* in hazard studies. However in psychology where the term was first used it has a more restrictive definition (Carroll 1990, p. 123-4) and, hence, the term *parallel practice* is used in the present paper.

The Furnas attitude survey was carried out more than a decade ago and ideally needs, not only to be repeated, but also undertaken in other villages representative of the situation of the Fogo and Sete Cidades *areas*. The present authors see no reason to believe, however, that its findings are atypical of the attitudes of rural dwellers in other areas of São Miguel. Providing clear leadership, reliable information and instilling confidence amongst the people living on the three volcanoes is clearly an educational and policy priority. In recent years an important start has been made. For instance: the *Centro de Vulcanologia e Avaliação de Riscos Geológicos (CVARG*) and its seismic network in particular is viewed by hundred of school children every year in pre-arranged visits; information provided by the Civil Protection Authorities (*Serviço Regional de Protecção Civil e Bombeiros dos Açores - SRPCBA*) for *concelhos* and *freguesias* has been greatly improved; and the *CVARG* has enhanced its capacity to provide dynamic hazard scenarios and scientific support for the *SRPCBA.*

Conclusion: Moving Forward

The 1990s were designated by the United Nations the *International Decade for Natural Disaster Reduction (IDNDR), being* superseded from the end of the millennium by the *International Strategy for Disaster Reduction (ISDR)*. In recent years research carried out under the influence of these initiatives has increasingly stressed the uniqueness of human vulnerability in volcanic regions and the need to construct plans for hazard reduction, which are more fully aware of the complexities of local society and culture (United Nations 1999, 2002, 2005). As argued elsewhere (Chester 2005, p.427-428), an approach to hazard reduction has developed that draws heavily on the methodology used in *Environmental Impact Analysis (EIA)* (Fig. 6)*,* *EIA* being developed from the 1960s to evaluate the impact of large, potentially environmentally damaging, projects. In terms of their impacts on society, volcanoes are similar to such projects and there are close parallels between the methodology used in *EIA* and approaches currently being developed to study volcanoes, society and culture in many volcanic regions including the Azores. As in *EIA*, so in recent more 'incultured' approaches to hazard assessment, the large number of social and physical factors which need to be studied may be expressed as *checklists*, whilst the *overlay* approach may be used to compare spatial (i.e. geo-referenced) data.

On São Miguel a start has been made in introducing such an approach with the development of AZORIS by CVARG, a spatial data-base for risk analysis which has the aim of improving land-use planning and emergency responses to hazardous events (Gaspar *et al.*, 2004). Using a *Geographical Information System (GIS),* AZORIS, an acronym for AZOes RISk, employs nine geo-referenced sets of data which range, on the one hand, from those concerned with volcanological and geophysical factors producing hazard exposure, to geographical and socio-economic aspects of risk and vulnerability on the other. In 2004 the data sets used in

AZORIS comprised information on the following factors: geographical and socio-economic; civil protection; geological and geomorphological; landslides; volcanological; seismological; geodetic; fluid geochemistry and meteorological.

Whilst recognizing that some important sets of data cannot be expressed in geo-referenced formats, AZORIS provides a facility for such documents to be viewed alongside spatial data so maximizing the advantages of *checklist* and *overlay* methodologies. Research on improving the database is ongoing and information acquired by geophysical field monitoring is, for instance, routinely transmitted to CVARG and CIVISA (*Centro de Informação de Vigilância Sismovulcânica dos Açores* or Centre for Information and Seismovolcanic Surveillance of the Azores) for storage in AZORIS (Gaspar *et al*. 2011). Once published and analysed, relevant information from the 2011 census will be entered.

Another example is exemplified by a recent study of seismic risk and vulnerability at the village scale (Martins et al., 2012). Detailed data on geo-referenced features of the demography, socio-economic conditions and the building characteristics of Vila Franco do Campo (Fig. 1) were first weighted and then modelled by means of a quantitative multi-criteria analysis (MCA). Results show how the historic core of the village is particularly at risk because of strong spatial correlation between seismically 'unfit' buildings buildings and vulnerable economically and socially disadvantaged people. This approach could be applied to other settlements in São Miguel.

The vulnerability of buildings on São Miguel to seismic activity and volcanic ash fall is now known in some detail. In order to mark the 200th anniversary of the Lisbon earthquake a symposium was held in 1955 and found that Portuguese buildings were highly vulnerable to earthquake losses and that a more comprehensive building code was urgently needed (Ordem dos Engenheiros, 1955). A code was published in 1958, the impact of which was generally viewed to have been ineffective (Azevedo et. al. 2009, p.561-562) and a new code was introduced in 1983 (RSA 1983). Only time and another earthquake will allow the effectiveness of the 1983 code to be tested. As argued above, in the Azores the principal cause for concern is not relatively newly constructed structures, but houses and other heritage buildings which were erected before there were effective codes.

Other aspects of vulnerability require further research so that emergency planning may be improved and the AZORIS methodology made more comprehensive. In particular these areas relate to: identifying isolated housing; the more detailed investigation of the degree to which evacuation routes would be robust in the event of an eruption; the annual variability in the island's transient population and its location at different times of the year; the location of São Miguel's livestock; issues of local leadership; devising policies of educational outreach to the community so that risk perception more accurately reflects the actual risk.

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Figures caption

Figure 1. Map showing the location of the Azores and the island of São Miguel.

Figure 2 The limits of the Sete Cidades, Fogo and Furnas *Areas*. The figures also show population numbers for each *freguesia*. *Areas* comprise those locales likely to be affected by the most probable future volcanic eruptions/volcano-related events occurring at the three volcanoes. The three maps are based on: Gomes *et al.*, 2006 - Sete Cidades; Wallenstein *et al.*, 2005 – Fogo and Chester *et al.,* 1999 - Furnas. It should be noted that in July 2002 Bretanha *freguesia* was sub-divided into two new parishes: Ajuda da Bratanha and Pilar da Bretanha. Because most statistical data relate to the pre-2002 boundaries, the sub-division is not recognised in this figure. The population total for Ponta Delgada includes the four *freguesias* (i.e. Matriz, São José, São Pedro and Santa Clara) which are recognised in official statistics (INEP 2002), together with adjacent commuter settlements.

Figure 3 Regression line of rainfall intensity (mm/day) and event duration (days) for Povoação *concelho,* 1918-2002. The line defines thresholds between land stability and instability. The inset maps shows the same plot using a log-log scale. Triangles are used to denote disastrous landslides, squares severe landslides and circles minor landslides (Based on Marques et al. 2008, p. 491, figure 11, and used with the permission of the author).

Figure 4 The principal roads of São Miguel: A. Before the improvements carried out under the

SCUTS Programme 2007-12; and B. Roads constructed under the SCUTS Programme.

Figure 5 Photograph of high level bridge on the new road between São Brás to Lomba da Fazenda (Photograph Nicolau Wallenstein).

Figure 6. An evolving framework for the study of volcanoes and human vulnerability. Parallels with *Environmental Impact Assessment (EIA)* should be noted. Modified from Chester 2005, . 428, fig. 14.8.

Table 1. *Scenarios of future eruption. Based on: Moore, 1990; Cole et al., 1999, 2008; Guest et al., 1999; Queiroz et al., 2008 and Wallenstein et al., 2005, 2009*.

Sete Cidades	Fogo	Furnas
At least three major caldera forming events have occurred in the last c. 36,000 years. Around 5,000 ago, intra-caldera volcanic activity changed from magmatic to predominantly hydromagmatic. At least 17 intra-caldera eruptions are recognised. Offshore vents have also erupted in 1638, 1682, 1713, 1811 and 1880.	Trachytic plinian and sub-plinian explosive eruptions have occurred on Fogo, together with less violent basaltic events. The most recent event occurred in 1536, was sub-plinian and comprised pronounced seismic activity, deposition of extensive ash-fall (partially generated hydromagmatically) and the production of debris flows.	The most recent eruption took place in 1630. Damaging pre-cursory earthquakes caused considerable damage to settlements, and this was followed by explosive sub-plinian activity that produced widespread air-fall, pyroclastic flows/surges, floods and landslides. The intra-caldera area was devastated, as were several valleys draining the volcano.
In terms of hazard, a future intra-caldera event will probably have a hydromagmatic element and	A plinian event is considered the most extreme future scenario, the most likely being	A 1630 type event is considered to be the most likely future eruption scenario.

affect both the caldera and volcano's flanks.	a sub-plinian event such that which occurred as 1536.

Table 2. *Typology of human vulnerability to volcano and volcano-related hazards on São Miguel (based on: Alexander, 1997; Zaman, 1999; Degg and Homan, 2005).*

Type of Vulnerability	Characteristics on São Miguel
Physical	Housing quality, population distribution/ settlement and the characteristics of evacuation plans
Demographic and economic	Detailed demographic characteristics of the population at risk: their economic status; demographic structure and dependent cohorts within the population. Implication for emergency planning and leadership.
Social and cultural	The social structure and cultural *milieu* of the people at risk
Perceptual and informational	Accurate and inaccurate perceptions of risk. The lack of accurate information

Table 3. *Site characteristics of the principal settlements of the Fogo Area, and issues raised by the survey of roads (after Wallenstein et al., 2005 and updated by data collected in the field). Areas are defined by freguesia (see Fig. 2) and population data are taken from the 2001 census (INEP 2002), updated where possible by the estimates provided by Serviço Regional de Estatístíca dos Açores (SREA 2011a).*

Major Constraints by Area
Area 1. South Flank (Lagoa, Água de Pau, Ribeira Chã, Água de Alto, Vila Franca do Campo and Ribeira das Taínhas). Nearly 22,000 people (~39% of the population of the *Fogo Areas*) live immediately to the south of the volcano within an 8km radius of the centre of the Lagoa do Fogo. Parts of the villages of Água de Pau and Ribeira Chã are less than 5km distant. People in this sector are highly vulnerable, not only because of their proximity to the summit, but also because the main coast road (route En 1-1a) would be blocked by tephra fall in even a small eruption. Further constraints include:- a. River valleys that drain the summit region, would be flooded if the walls of the Lagoa do Fogo were breached. Valleys would also be routes for *lahars* and *pyroclastic flows.* b. Landslides would choke valleys with sediment and up-rooted trees would create temporary dams, so exacerbating the risk of flooding. It is because of the dangers faced by people living in this sector and the fact that communications are far from secure, that pre-eruption evacuation is essential. Early evacuation of Ribeira das Taínhas and Ribeira Chã *freguesias* is particularly important

because some of their population can only be reached by minor roads.

Area 2. North Flank (Ribeira Seca, Ribeira Grande, Ribeirinha, Porto Formoso, São Brás and Maia) and Inland (Santa Bárbara), Over 15,000 people (~27% of the *Fogo Area*) live in these *freguesia.* Although not so close to the summit as the towns to the south and possessing much better road access to Ponta Delgada and the west (roads En 1-1[a] and En 3-1[a]), a sub-plinian or even a basaltic eruption would cause major difficulties. Specific concerns include:-

a. The main road passes near to Ribeira Grande and the stream with the same name has a large catchment reaching almost to the caldera rim. In an eruption it would be filled with volcanic products.

b. The settlement of Caldeiras da Ribeira Grande (Fig. 2), just over 3km from the caldera, is an isolated and highly exposed settlement.

Early evacuation of this area of the north coast is essential.

Area 3. North Coast (Calhetas and Rabo de Peixe) and Inland (Pico da Pedra) These settlements would only be affected by tephra, if winds were from the east and/or if an eruption was sub-plinian. Good road links to the west of the island and to Ponta Delgada, suggest that evacuation would be relatively straightforward.

Area 4. North coast (Lomba da Maia, Fenais da Ajuda and Lomba da São Pedro). These villages would only be affected if winds were from the west and/or a sub-plinian event occurred. A major issue is that, if the roads in areas 1 and 2 were closed, then the population in this area would be isolated from Ponta Delgada and the west of the island.

Area 5. South Coast (Ponta Garça and Ribeira Quente) and Inland (Furnas) If Lagoa das Furnas would be affected by an eruption of Fogo, then evacuation would involve removing people quickly from the caldera region. There are major flood risks on the road running by the side of the Lagoa das Furnas (i.e. En 1-1[a]). The best overall route for evacuation is the EN2-1[a], which runs to the west and north west of Furnas.

Ribeira Quente is a very dangerous settlement. Not only would floodwaters be concentrated within the valley leading to the village but, the road also has several major constraints on its use during an eruption. These include hazards from: falling trees; landslides; flooding and roadway instability. It is likely that once an eruption started this route would be unusable as was case during the 1997 landslides.

Ponta Garça is located some distance to the south of the main southern road (En1-1a) and early evacuation would be called for.

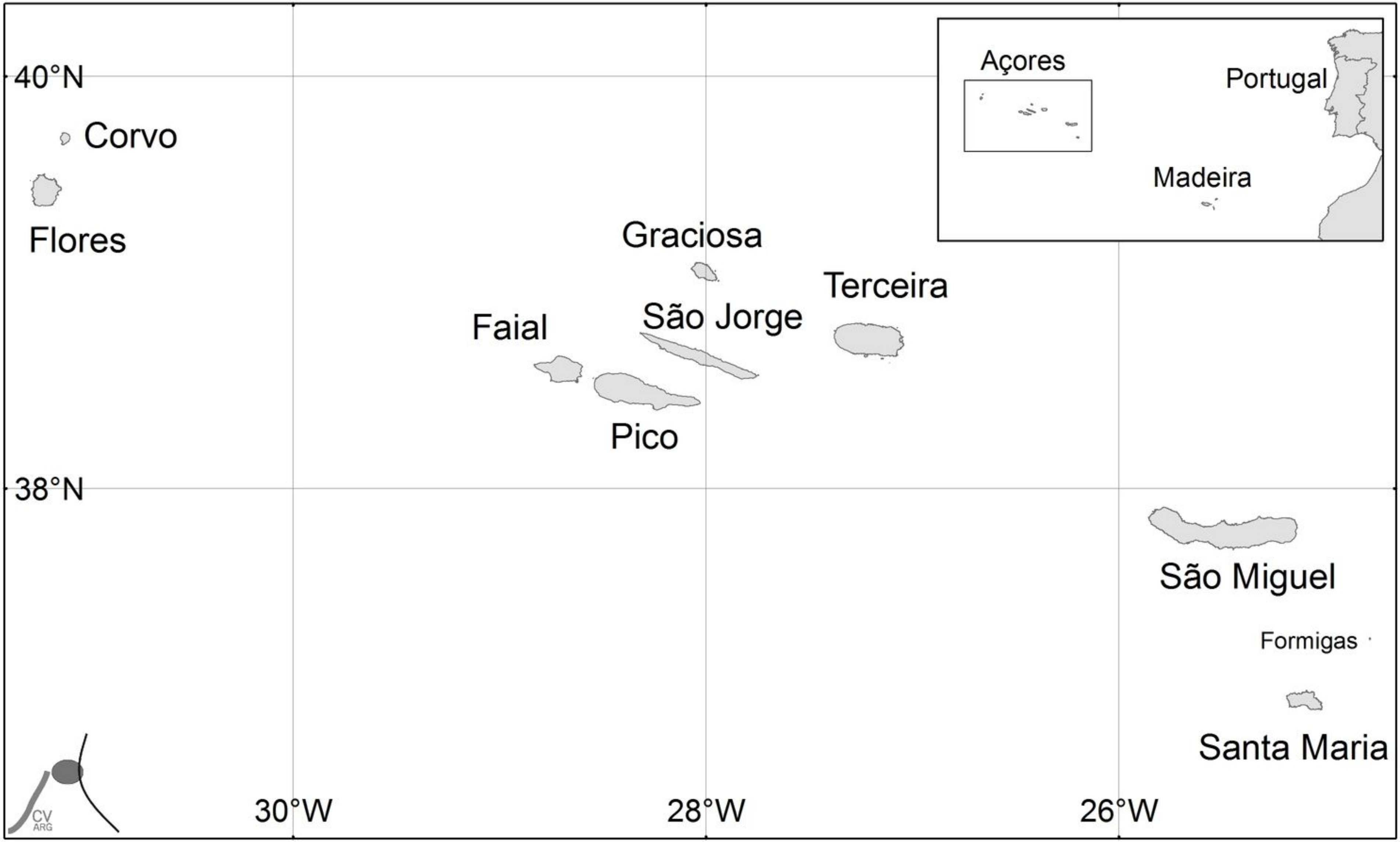
Table 4. *The principal social groupings on São Miguel. Based on Chapin (1989) and updated using the references cited.*

SOCIAL GROUPS	CHARACTERISTICS
Trabalhadores (workers)	In 2009, *ca*.13% of the population is employed in the *primary* economic sector (i.e. agriculture, fishing and extraction) and *ca.*24% in the *secondary* (i.e. manufacturing, energy and construction) sector (SREA 2010b). Many of these were manual workers. Since 1950 many emigrants have been drawn from this group. *Trabalhadores* work for themselves on small holdings (either family owned or rented) and as labourers for others. Mostly they live in towns and villages, commuting to work. In rural areas - like the *Furnas, Fogo and Sete Cidades areas* - *trabalhadores* are predominantly agricultural labourers - raising crops, keeping cattle, and fishing. Illiteracy is common (16% in Vila Franca do Campo and 7% in Ponta Delgada *concelhos* INEP 2002), but has declined during the past decade as older people die.
Proprietários (proprietors)	*Proprietários* own property and do not work for others. In rural areas, such as those that comprise the three volcanic *areas, proprietários* are small-scale village entrepreneurs (e.g. shop keepers, bar owners) and own their own farms. Most members of this group have at least a primary education, but a minority of older people are illiterate. Many

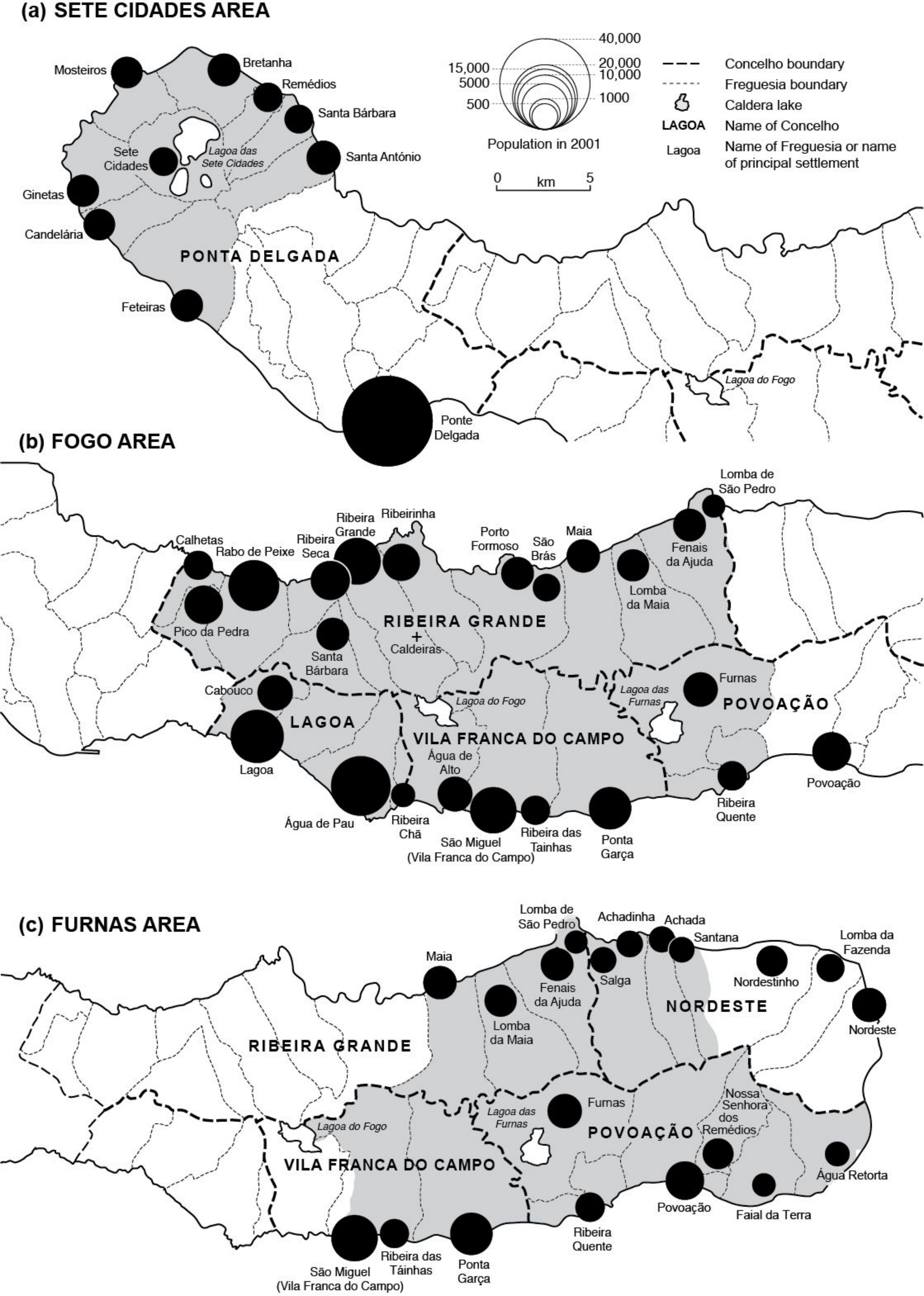
	local leaders are drawn from this group. Often younger *proprietários* have left home, gained higher qualifications and live outside the community, or even abroad. There are often known as educated *proprietary*. *Proprietários* have contacts with many social spheres, both external and internal.
Established educated	The educated 'middle class'. With the exception of doctors and local government officials, few members of this group live in rural areas, but some own summer homes. Heavily concentrated in the Ponta Delgada *area* and surrounding villages from which they commute, relatively few families reside in rural areas like the such as those on the flanks of the three active volcanoes. A numerically small sub-group is the *Nobreza* (nobility), whose ancestors colonised the island and still own much land.
New entrepreneurs	Heavily concentrated in the Ponta Delgada and relatively few families reside in the three 'volcanic' *areas.*

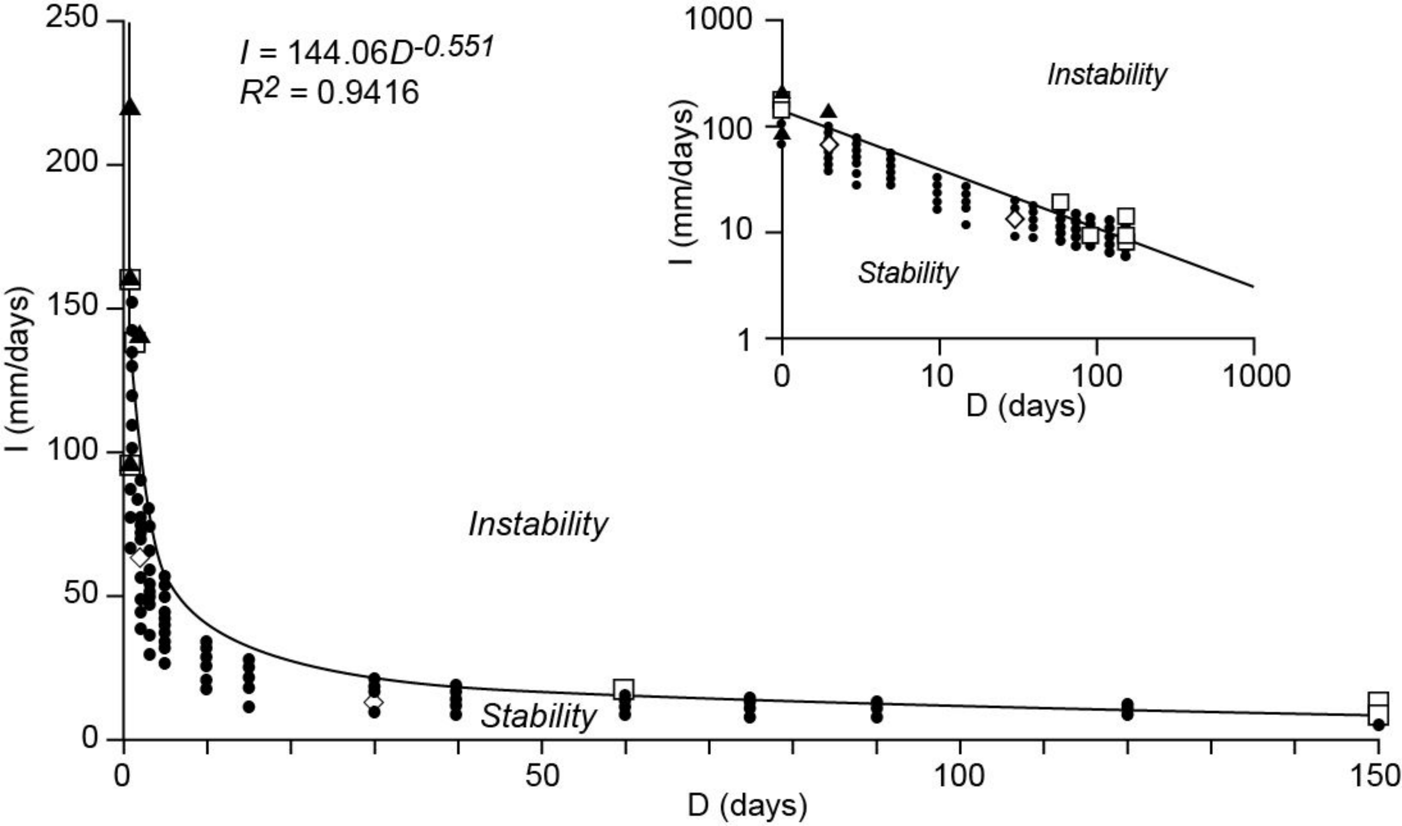
Fig. 6

	Technique	Features	Comments on and examples of applications in volcanic regions
Increasing complexity ↓	Checklist	Lists all the factors - physical, economic, cultural and societal - which need to be considered. Cause/effect relationships are implied but not specified in detail.	The US Geological Survey's programme, Living with Volcanoes (Wright and Pierson 1992: 6) and many initiatives in other countries involve, either implicitly or explicitly, a checklist approach. It is the evolving norm of the IDNDR/ISDR
	Overlays	Traditionally this has relied on overlay maps showing physical, social, historical aspects of the region. Today Geographical Information Systems (GIS) are increasingly being used.	There is much scope for this approach to be used in volcanic regions, because many of the variables are spatial and capable of being either mapped or incorporated into a GIS. The impact of satellite-based systems, significant at present, is likely to be much more prominent in the future (Wadge 1994). GIS based studies have been used in the Azores (see text)
	Matrices	Matrices are used to identify first-order cause/effect relationships.	At the present time variables are not sufficiently well specified to enable matrices and network based studies to be carried out. There may be much scope in the future.
	Networks	Used to identify 'chains' of complex interactions. Ideally this approach requires mathematical modelling.	

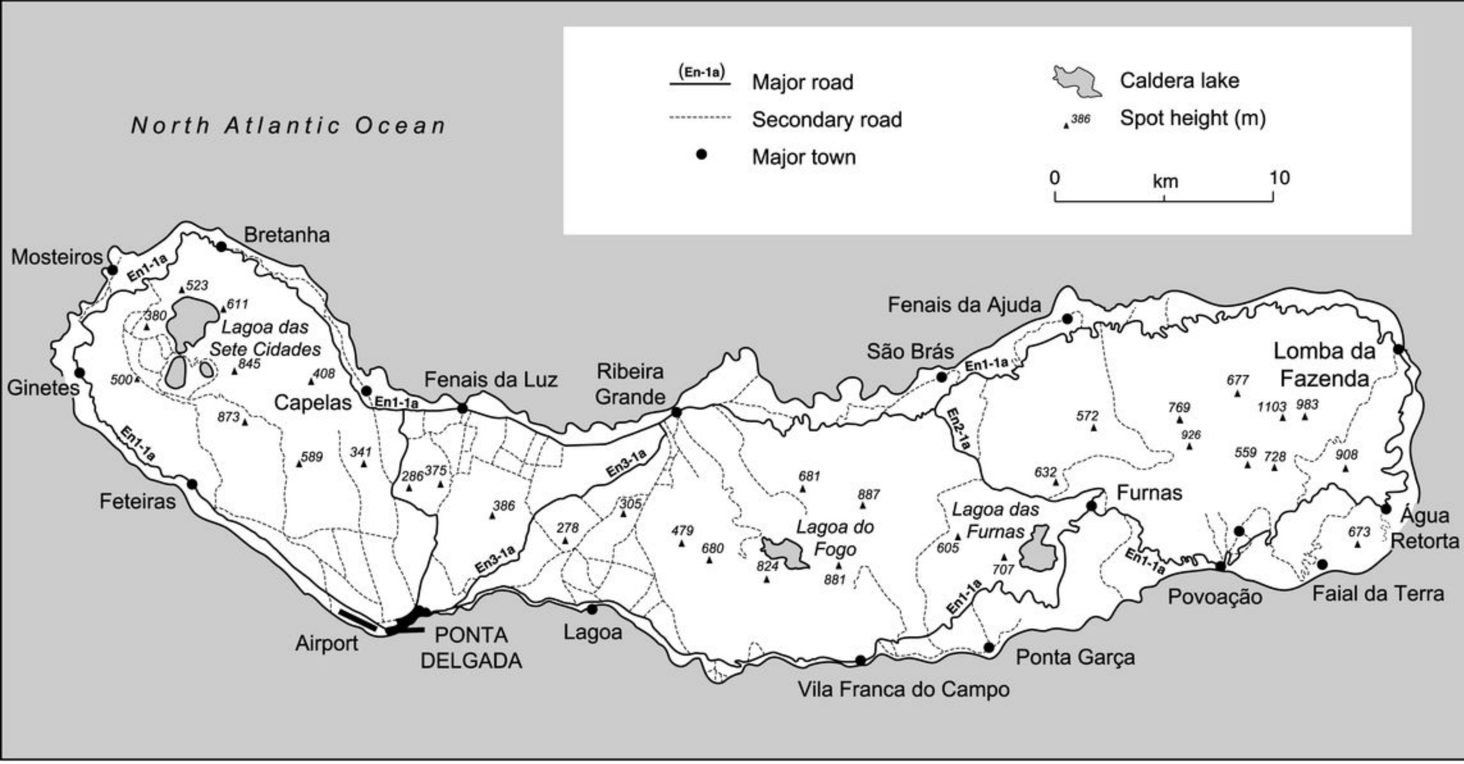


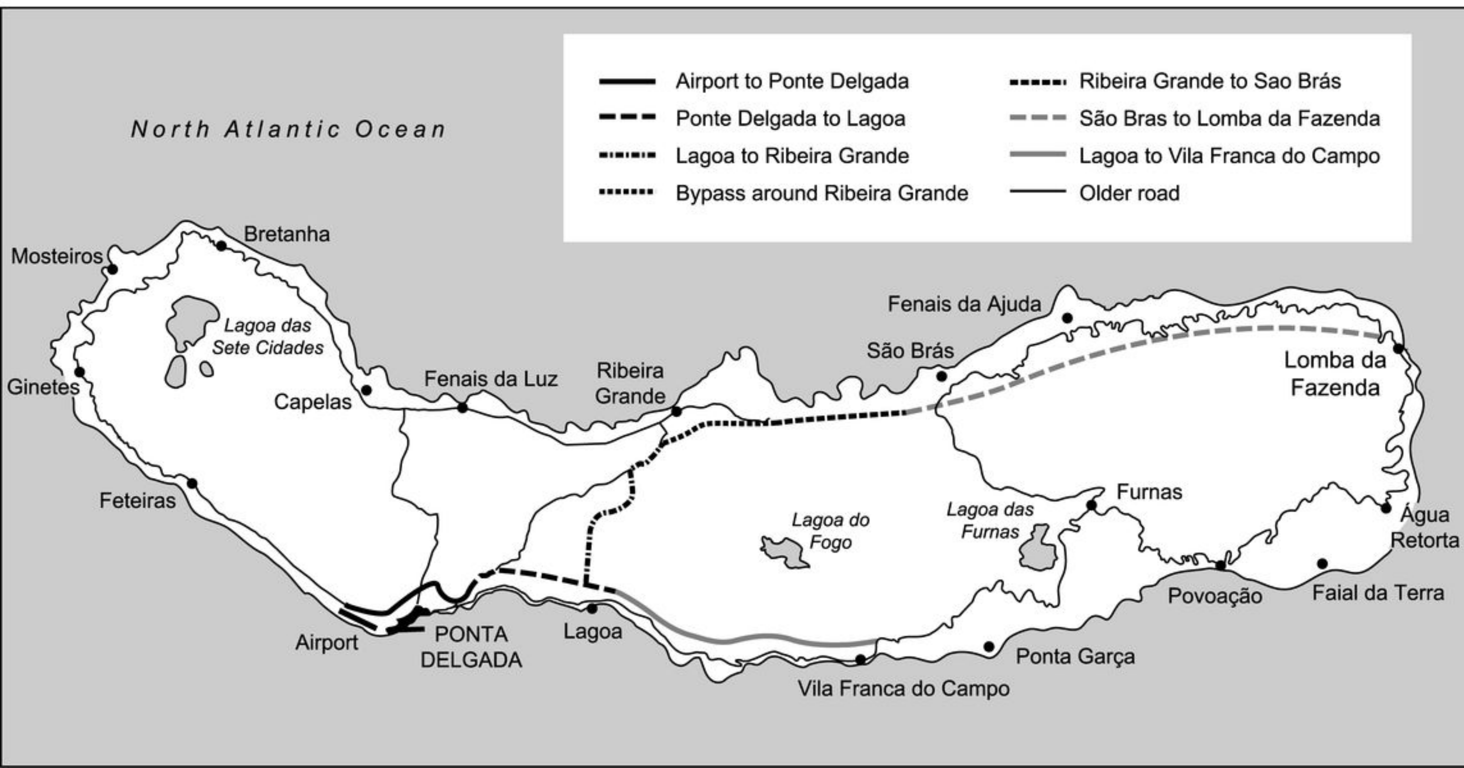
Açores
Portugal
Madeira
40°N
Corvo
Flores
Graciosa
Terceira
São Jorge
Faial
Pico
38°N
São Miguel
Formigas
Santa Maria
30°W
28°W
26°W
CV
ARG


(a) SETE CIDADES AREA
40,000
20,000
15,000
10,000
5000
1000
500
Population in 2001
0
km
5
Concelho boundary
Freguesia boundary
Caldera lake
LAGOA
Name of Concelho
Lagoa
Name of Freguesia or name of principal settlement
Mosteiros
Bretanha
Remédios
Santa Bárbara
Santa António
Sete Cidades
Lagoa das Sete Cidades
Ginetas
Candelária
PONTA DELGADA
Feteiras
Lagoa do Fogo
Ponte Delgada
(b) FOGO AREA
Lomba de São Pedro
Ribeira Grande
Ribeirinha
Calhetas
Rabo de Peixe
Ribeira Seca
Porto Formoso
São Brás
Maia
Fenais da Ajuda
Lomba da Maia
Pico da Pedra
RIBEIRA GRANDE
Caldeiras
Santa Bárbara
Cabouco
Lagoa do Fogo
Lagoa das Furnas
Furnas
POVOAÇÃO
LAGOA
VILA FRANCA DO CAMPO
Lagoa
Água de Alto
Povoação
Água de Pau
Ribeira Chã
São Miguel (Vila Franca do Campo)
Ribeira das Tainhas
Ponta Garça
Ribeira Quente
(c) FURNAS AREA
Lomba de São Pedro
Achadinha
Achada
Santana
Lomba da Fazenda
Maia
Fenais da Ajuda
Salga
Nordestinho
Lomba da Maia
NORDESTE
Nordeste
RIBEIRA GRANDE
Furnas
Lagoa das Furnas
Nossa Senhora dos Remédios
Lagoa do Fogo
POVOAÇÃO
VILA FRANCA DO CAMPO
Água Retorta
Povoação
Faial da Terra
Ribeira Quente
São Miguel (Vila Franca do Campo)
Ribeira das Táinhas
Ponta Garça



$I = 144.06D^{-0.551}$
$R^2 = 0.9416$
I (mm/days)
D (days)
Instability
Stability
250
200
150
100
50
0
0
50
100
150
1000
100
10
1
0
10
100
1000
I (mm/days)
D (days)
Instability
Stability


(En-1a)
Major road
Secondary road
Major town
Caldera lake
386
Spot height (m)
0
km
10
North Atlantic Ocean
Mosteiros
Bretanha
En1-1a
523
611
380
Lagoa das
Sete Cidades
845
408
500
Ginetes
Capelas
En1-1a
Fenais da Luz
Ribeira
Grande
873
En1-1a
589
341
286
375
En3-1a
Feteiras
386
305
278
En3-1a
Airport
PONTA
DELGADA
Lagoa
Fenais da Ajuda
São Brás
En1-1a
En2-1a
Lomba da
Fazenda
677
572
769
1103
983
926
559
728
908
632
Furnas
681
887
Lagoa do
Fogo
479
680
824
881
Lagoa das
Furnas
605
707
En1-1a
En1-1a
Água
Retorta
673
Povoação
Faial da Terra
Ponta Garça
Vila Franca do Campo


Airport to Ponte Delgada
Ponte Delgada to Lagoa
Lagoa to Ribeira Grande
Bypass around Ribeira Grande
Ribeira Grande to Sao Brás
São Bras to Lomba da Fazenda
Lagoa to Vila Franca do Campo
Older road
North Atlantic Ocean
Mosteiros
Bretanha
Lagoa das
Sete Cidades
Ginetes
Capelas
Fenais da Luz
Ribeira
Grande
Fenais da Ajuda
São Brás
Lomba da
Fazenda
Feteiras
Furnas
Lagoa do
Fogo
Lagoa das
Furnas
Água
Retorta
Povoação
Faial da Terra
Airport
PONTA
DELGADA
Lagoa
Ponta Garça
Vila Franca do Campo

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