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Estimating building exposure and impact to volcanic hazards in Icod de los Vinos, Tenerife (Canary Islands)

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ABSTRACT

Principal and subsidiary building structure characteristics and their distribution have been inventoried in Icod, Tenerife (Canary Islands) and used to evaluate the vulnerability of individual buildings to three volcanic hazards: tephra fallout, volcanogenic earthquakes and pyroclastic flows. The procedures described in this paper represent a methodological framework for a comprehensive survey of all the buildings at risk in the area around the Teide volcano in Tenerife. Such a methodology would need to be implemented for the completion of a comprehensive risk assessment for the populations under threat of explosive eruptions in this area. The information presented in the paper is a sample of the necessary data required for the impact estimation and risk assessment exercises that would need to be carried out by emergency managers, local authorities and those responsible for recovery and repair in the event of a volcanic eruption. The data shows there are micro variations in building stock characteristics that would influence the likely impact of an eruption in the area. As an example of the use of this methodology for vulnerability assessment, we have applied a deterministic simulation model of a volcanic eruption from Teide volcano and its associated ash fallout which, when combined with the vulnerability data collected, allows us to obtain the vulnerability map of the studied area. This map is obtained by performing spatial analysis with a Geographical Information System (GIS). This vulnerability analysis is included in the framework of an automatic information system specifically developed for hazard assessment and risk management on Tenerife, but which can be also applied to other volcanic areas. The work presented is part of the EU-funded EXPLORIS project (Explosive Eruption Risk and Decision Support for EU Populations Threatened by Volcanoes, EVR1-2001-00047).

1. Introduction

Due to the rare occurrence of cataclysmic eruptions globally, which is about once every 10 years, the effects of volcanic eruptions are not in the public awareness as consistently as those of other natural phenomena such as earthquakes, tsunamis or hurricanes. This, however, in no way reduces the importance of efforts made to predict, prevent and prepare for the disasters that ensue, which involve large-scale economic and humanitarian losses. Evidence from the historical record shows how absolute and terminal such events can be. However, more research needs to be carried out to assess how a modern city would stand up to the rigours of an explosive eruption. Whether buildings or their occupants could, in some cases, survive the onslaught of earthquakes, ash fall and pyroclastic density currents remains to be determined and is the focus of the research presented here. Such issues concern thousands of European citizens who live under the shadow of an active volcano, each of which has the potential to cause a humanitarian disaster within a matter of days.

The EXPLORIS project was set up by 14 universities and funded by the European Commission in order to investigate the impact of explosive eruptions at a number of specific sites. This paper presents the results of methods implemented to estimate building exposure by quantifying the locations and typologies of building stock around one of the volcanoes in the study: Teide in Tenerife (Fig. 1). The aim of this part of the project was to collect enough information to estimate how many people and buildings are at risk and how they are distributed in micro zones around the slopes of the volcano. The study is set up as a prototype study on the basis of which a complete survey of the total area at risk could be carried out. For each micro zone, qualitative information has been gathered on the construction characteristics of the building stock present. The information gathered indicates the vulnerability of such buildings to various volcanic phenomena and consequently estimates the exposure of their inhabitants to the impact of an eruption through its component hazards. Such estimates have been performed using an automated information system that

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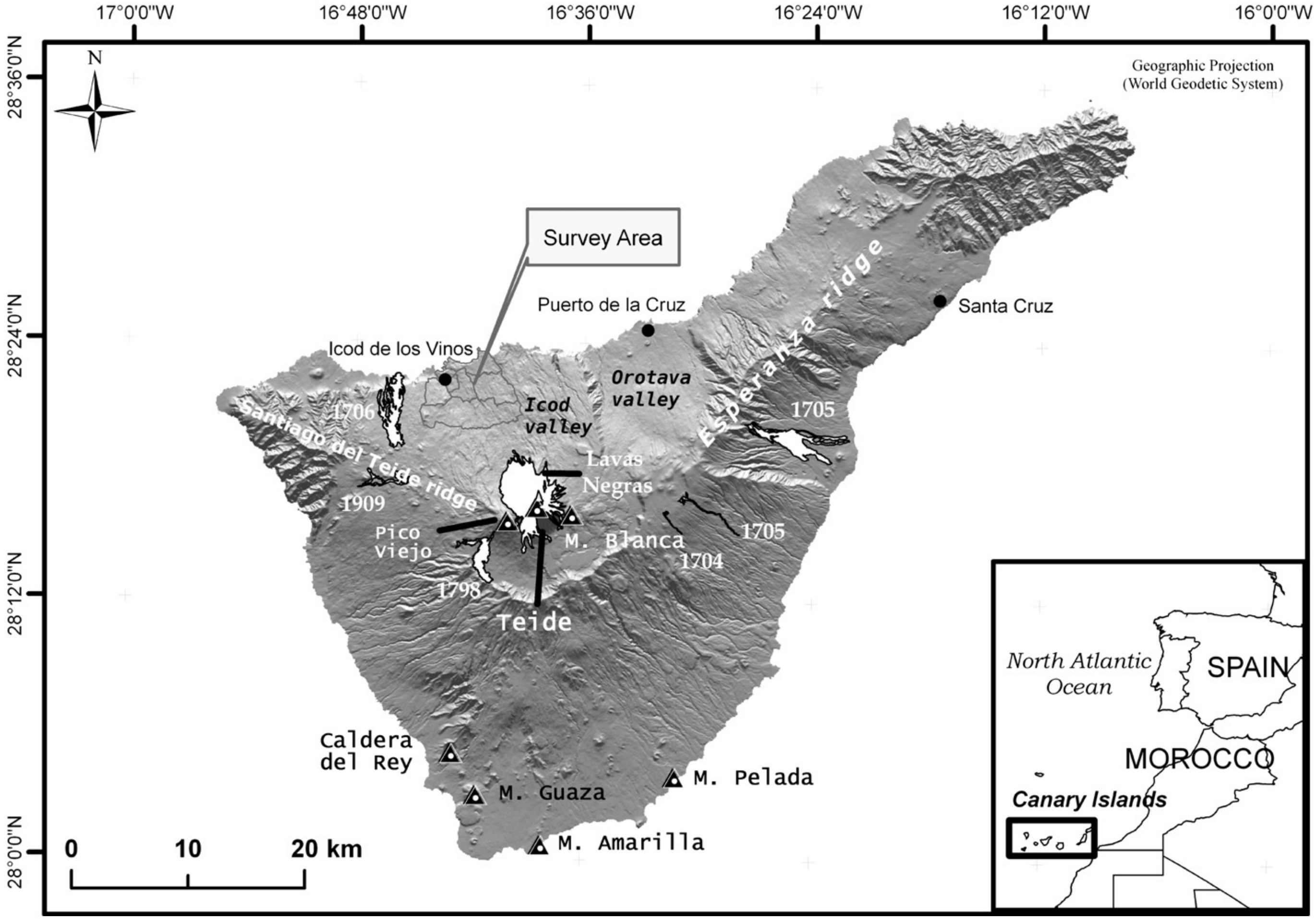

Fig. 1. Location map of Tenerife and the studied area.

combines the data gathered into a geospatial database and performs estimates given different vulnerability formulas and simulated hazard intensity levels.

In this paper, first we situate the survey area in the European context and history of the Teide volcano that threatens the inhabitants of the island. Then, we discuss the hazards for which the information has been obtained and the types of data collected and the methods used for the collection, organisation and analysis of the data. We apply a deterministic simulation model of an explosive eruption from Teide volcano and its associated ash fallout on the results of this analysis in order to illustrate the use of this methodology for vulnerability assessment.

2. Background

2.1. Tenerife

The geological evolution of Tenerife (see Martí et al., 2008) involves the construction of two main volcanic complexes: a basaltic shield (>12 Ma to present) that is mostly submerged but forms about 90% of the island, continuing at present its subaerial construction through two rift zones (Santiago del Teide and Dorsal rifts); and, the Central Complex (>3.5 Ma to present), which comprises the Las Cañadas edifice (>3.5 Ma–0.18 Ma), a composite volcano characterised by abundant explosive eruptions of highly evolved phonolitic magmas, and the active Teide–Pico Viejo stratovolcanoes (0.18 ka to present) that evolved from basaltic to phonolitic and which have mostly undergone effusive activity (Ablay and Marti, 2000). Along the whole history of Tenerife the ascent of mantle-derived basaltic magmas has been controlled by two main tectonic lineations trending NW–SE and NE–SW, which are still active at present controlling the eruption of basaltic magmas outside the central complex and continuing the construction of the basaltic shield. The Cañadas caldera, in which the Teide–Pico Viejo stratovolcanoes stand, truncated the Cañadas edifice and has formed from several vertical collapses of the volcanic edifice following explosive emptying of high-level magma chamber in addition to the occasional lateral collapse of the volcano flanks (Marti et al., 1997; Marti and Gundmundson, 2000).

Explosive activity on Tenerife is mostly associated with the eruption of phonolitic magmas, but it is also represented by strombolian and violent strombolian phases during basaltic eruptions and a small number of phreatomagmatic basaltic explosions in littoral cones and at the central complex. Phonolitic volcanism has been restricted to the central complex, the Cañadas edifice and currently at the Teide–Pico Viejo stratovolcanoes, with only two existing phonolitic manifestations (Montaña Guaza and Caldera del Rey) outside the central area, on the lower south-western flank of Tenerife.

Explosive phonolitic activity, characterised by repose intervals between 5 and 30 ka, and by large volume plinian and ignimbritic eruptions, occasionally associated with caldera forming episodes, has dominated the construction of the Cañadas edifice. Phonolitic activity in the active Teide–Pico Viejo stratovolcanoes, which started to grow up at the interior of the Cañadas caldera at about 180 ka ago, only began around <35 ka ago, mostly generating lava flow and domes,

Table 1
Historic well documented eruptions on the Island of Tenerife (modified from Araña et al., 2000)

1704–1705	Siete Fuentes, Fasnia and Arafo volcanoes. Candelaria village was evacuated. The three eruptions lasted 5, 9 and 22 days respectively.
1706	Montaña Negra volcano destruction of the town of Garachico and its port and harbour, until then the main port of the island. Eruption lasted 10 days.
1798	Chahorra volcano, Narices del Teide. Eruption lasted 3 months.
1909	Chinyero volcano. Eruption lasted 10 days.

some of them associated with minor explosive phases, and the subplinian eruption of Montaña Blanca (2020 BP) at the eastern flank of Teide. Phonolitic activity in Teide–Pico Viejo has occurred from the central vents and also from the flanks of the two twin stratavolcanoes, with repose intervals between 250 and 1000 years, with the last eruption (Lavas Negras) dated in 1240±60 BP. Flank eruptions are mostly characterised by the emplacement of exogenous domes and associated lava flows.

Recent basaltic eruptions have nearly always occurred along the NE–SW and NW–SE rift zones and the southern sector of Tenerife with recurrence time range around 100–200 years during the last millennium, being rare at the interior of the caldera due to the shadow effect imposed by the presence of shallow phonolitic reservoirs. However, some significant basaltic eruptions also exist at the interior of the caldera (Narices del Teide in 1798), along the caldera floor or also on the flanks or earlier central vents of the Teide–Pico Viejo complex. All basaltic eruptions have developed explosive strombolian phases leading to the construction of cinder and scoria cones and occasionally producing intense lava fountains and violent explosions with the formation of short eruption columns. Violent basaltic phreatomagmatic eruptions are not rare along the coast, with the formation of maars and tuff rings (Montaña Pelada, Montaña Amarilla, etc.), or even associated with the Teide–Pico Viejo complex, where they have generated high energy pyroclastic surges (Pico Viejo crater, and Teide old crater) (Ablay and Marti, 2000).

2.2. Teide

Tenerife consists of a complex of overlapping Miocene-to-Quaternary stratovolcanoes that have remained active into historical time. Teide, the volcano in question for the purposes of this study, is situated inside the Cañadas caldera, a 9 by 16 km volcanic depression at an altitude around 2000 m, formed after a long period of explosive volcanism. Teide, the volcano that dominates the centre of the island has an altitude at its summit of 3718 m, the highest point in Spain and indeed the Atlantic ocean. Its height from the surrounding seabed is >7000 m. It is the world's third largest volcano after Mauna Loa and Mauna Kea in Hawaii. Currently dormant, it last erupted in 1798 (see Table 1) with the mafic eruption of Narices del Teide, at the western flank of the twin volcano Pico Viejo. Teide has been very active during the last 5000 years with at least eight phonolitic eruptions from its central vents and flanks, including the subplinian eruption of Montaña Blanca at about 2000 years ago (Ablay et al., 1995; Carracedo et al., 2003, 2007). The history of eruptive activity in the area includes both effusive and explosive eruption typologies.

2.3. Icod de los Vinos

The Icod de los Vinos valley (Fig. 1) and the neighbouring Orotava valley are both products of previous eruptions, both as a result of

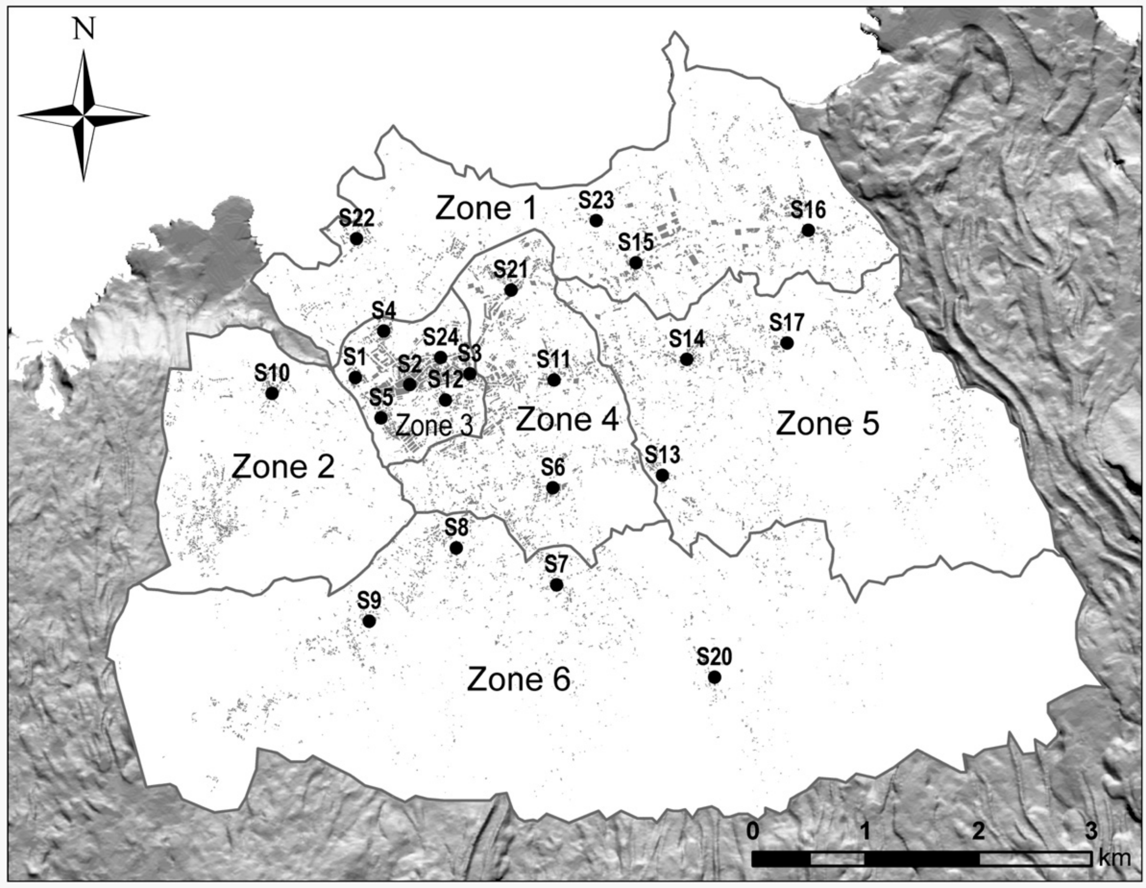

Fig. 2. Location of Survey Zones in Icod de los Vinos, each zone containing a few survey locations, where building category data were collected (labelled S1, S2, … S24). Grey small polygons correspond to residential buildings.

landslide and edifice collapse and as a result of lava deposition (Marti et al., 1997; Hurlimann et al., 2004). Such areas can be therefore considered potential sites of hazardous volcanic phenomena as a result of lava flow volcanism but even considerably more if explosive eruptions from Teide occur, a possibility that should not be ruled out if we take into account the existence of the Montaña Blanca eruption and the petrology of the Teide phonolites (Ablay and Marti, 2000).

2.4. Population background

Tenerife is the largest of the seven Canary Islands situated in the Atlantic Ocean off the coast of Africa (Fig. 1). As part of the group, it forms a Spanish semi-autonomous region, Santa Cruz de Tenerife being the administrative capital. It has an area of 2034 km^2 and a population of 778,071 (2003 census), with a population density of 382.53 people per km^2. The focus of tourism is to the south and west of the island, with significant development however along all the coastal areas. The resident population more than doubles when tourist populations are taken into account.

The town of Icod de los Vinos was founded six years after Tenerife was first colonised by the Spanish, in 1501. The municipality of the same name, that encompasses the town and its hinterlands, consists of a fertile valley extending from the slopes of Teide to the sea. It contains 10 km of coastline and has an average altitude of 235 m. In 2003, it had a population of 22,950, with an average population density of 239.4 people per km^2, a figure which is significantly lower than the average for the island as a whole. This relatively low density reflects the predominantly agricultural use of the land in this area (bananas and wine are the two most important crops). There has also been a tourist presence in the valley since the 1890s due to its vicinity to the neighbouring town, Puerto de la Cruz. It remains, however, relatively untouched by the scale of tourism seen in other parts of the island.

Icod de los Vinos has seen three significant phases of development in its existence. The first wave of building from its inception in the 1500s to before the Second World War, saw a relatively consistent use of construction, materials and techniques. From the 1930s modern building techniques were introduced. The third phase saw development in the area increase significantly with the declining cost of air travel in the 80s. Construction in this period was and is predominantly of reinforced concrete.

3. The hazards

The focus of the EXPLORIS project was to research the impact and risk of EU populations for explosive eruptions. As a result, the hazards considered when gathering building stock data were earthquakes, pyroclastic density currents (including pyroclastic flows and surges) and tephra fall.

Each of these hazards affects the building stock in a different way. Tephra fall damage mainly affects human survivability through the loading of ash and other volcanic material on roofs, which in critical cases may cause roof collapse that may be responsible for death and injury through both trauma and exposure to subsequent phenomena such as pyroclastic flows (see below), see Spence et al. (2005b).

Table 2
Classes of construction material for the vertical load-bearing frame and their identifiers (from Spence et al., 2005a)

Field name	Type	Other descriptive notes
CF	Reinforced concrete, in filled frame	
MB	Masonry, block/squared/cut stone	Unreinforced
MR	Masonry, rubble	
TI	Timber	With lightweight cladding

Table 3
Classes of building height and their identifiers (from Spence et al., 2005b)

Field name	Number of storeys	Other descriptive notes
S	1 (single-storey)	Attics are considered as an extension of the storey below them, not as an extra storey.
L	2 (low-rise)	
M	3,4,5 (medium-rise)	
H	6+ (high-rise)	

Pyroclastic density current damage may affect human survivability through building failure in a number of ways. These are lateral pressure on external walls that may eventually cause window failure and total building collapse; high temperatures and infiltration of ash into the building envelope that affect humans directly or that may cause ignition of fires in and around the building, (Spence et al., 2004). Such building failures can lead to casualties from asphyxiation, poisoning, burns and other related heat traumas. (Baxter et al., 2005).

Volcanogenic earthquakes act on buildings in much the same way as tectonic earthquakes, by exerting complex shaking forces on buildings that can lead to building damage or total collapse (Coburn and Spence, 2002). Such impacts may lead to death and injury of victims through trauma. Volcanogenic earthquakes rarely result in ground shaking intensities in inhabited areas sufficiently high to be critical for human safety (Zobin, 2001). However, they more commonly predispose vulnerability to other phenomena that occur later in the eruption event sequence (Zuccaro et al., 2008).

4. Building stock survey methodology

Knowledge about the eruptive history of the island and of Teide allowed us to select a suitable location for the building stock surveys to be carried out, where the possibility of volcanic hazards threaten resident populations. Information about the building typologies in the area is vital to mitigating the effects of such hazards in the event of an explosive eruption. Icod de los Vinos was chosen as the sample survey area as it is one of the likely areas to be affected by hazardous volcanic phenomena.

A team of academics, students and professionals from Cambridge University and CSIC carried out the survey in Icod in September 2004. Support was given from the local administration of the municipality, who provided up to date GIS data of the area. Survey forms were designed and disseminated to teams of 2 for data collection at survey areas distributed around the town and its neighbouring villages (see Fig. 2).

The data collected on the forms are presented in the following tables. Table 2 presents the classification of vertical structural typologies into 7 European types for which 4 were present in the Icod de los Vinos area. These were: concrete frame buildings, squared masonry buildings, rubble masonry buildings and timber frame buildings. The vertical structural typology was considered key in the assessment of building vulnerability as it is a good indicator of how the building will respond to the forces and temperatures produced by the three hazards considered. Both earthquakes and pyroclastic density currents subject built structures to lateral forces, which are resisted differently by different types of building construction. Table 3 presents the building height classification used for the survey. Building height contributes significantly to a building's vulnerability to earthquakes as well as to the effect of pyroclastic density currents

Table 4
Age classes and their identifiers (from Spence et al., 2005b)

Field name	Tenerife age band
O (old)	Pre 1930
M (modern)	1930–1980
R (recent)	Post–1980

Table 5
Roof classes, their resistances, and the equivalent roof structures found in the Icod de los Vinos survey

Roof class	Description	Roof structure classes found in Icod de los Vinos survey	Typical design load range	Mean collapse load
WE (weak)	Sheet roofs, old or in poor condition. Tiled roof, old or in poor condition. Masonry vaulted roof.	Old pitched tile or sheet metal	Pre-design code, or no design code.	2.0 kPa
MW (medium weak)	Sheet roof on timber; average quality; average or good quality tiled roof on timber rafters or trusses. Steel or precast rc joists and flat terrace roof.	Modern pitched tile or sheet metal, old flat or pitched concrete	1–2 kPa	3.0 kPa
MS (medium strong)	Flat rc roof not all above characteristics; sloping rc roof. Sheet roof on timber rafters or trusses, good quality and condition, designed for cyclone areas.	Recent pitched tile or sheet roofs, modern flat or pitched concrete	2–3 kPa	4.5 kPa
ST (strong)	Flat rc roof designed for access; recent, good quality construction, younger than 20 years.	Recent flat or pitched concrete	>3 kPa	7.0 kPa

and surges. It is not however the only criterion to determine vulnerability. State-of-the-art methods use acceleration spectral response analysis of the ground and of the building structure for each site. However, this paper presents a methodology to survey every building in the area quickly and cheaply. It is therefore not feasible to do an analysis for each building in the region. Future work could however incorporate sample data of this type with the data collected in this paper.

Table 4 presents the building age classification used for the survey. The use of building age as a classification is another indicator that allows an assessment of vulnerability for all three hazards and enables the impact studies to estimate the likely strength of the component parts of the building such as walls and windows. The age classification was divided into 3 periods of different size: pre-1930, 1930–1980 and post-1980. The watershed dates for these age classes were chosen to reflect the different phases of development that the island was subject to and the changes that occurred to the construction techniques around these dates.

The resistance of roofs to the vertical loading of tephra depends on the roof construction and the age of the building. Table 5 shows the broad classification of different classes of European roofs defined for the EXPLORIS project, and the classification adopted for the types of roof structure found in the Icod de los Vinos survey. The vulnerability of each building class to the other two principal hazards, earthquake and pyroclastic flow, was determined using the composite building classification and the vulnerability methodology described in Spence et al. (2005b).

Table 6
Subsidiary building characteristics collected from the survey forms (adapted from Spence et al., 2005b)

Data collected	Sample categories	Reasons for collection
Opening sizes	Small, medium, large	For PDC vulnerability
Type of shutters	Solid, louvered or roller	For PDCt vulnerability
Types of window frames	Metal or timber	For PDC vulnerability
Air conditioning	Present or not	For PF infiltration vulnerability
Condition of openings	Good or poor	For PDC vulnerability
Roof type	Timber, concrete, coverings	For tephra vulnerability
Distance between buildings	<6 m, 6–10 m, >10 m	For fire hazard estimation
Combustible materials	Present or not	For fire hazard estimation
Building use	Residential or mixed	For population estimation

Table 7
Distribution of building structure class by zone

Count of buildings	Structure				
Zone	CF	MB	MR	TI	Total
1	49	6	20		75
2	15	4		1	20
3	68	6	65		139
4	27	13	20		60
5	12	7	1		20
6	40	23	16	1	80
Total	211	59	122	2	394

Finally Table 6 presents the subsidiary building characteristics on which data was collected through the survey forms. These characteristics provide useful information on the potential impact of a volcanic eruption in terms of tephra, pyroclastic density currents and fire in particular. Of particular interest has been the information about window opening sizes, which has been used in other studies (Spence et al. 2004) to estimate the vulnerability of the inhabitants of buildings to pyroclastic density currents.

The case study area was divided into zones (Fig. 2) in order to differentiate distance from the source of the hazard and built morphology. Hence Zone 6 was characterised as the rural zone that was closest to Teide. Zones 2 and 5 were also rural zones, of similar building density and morphology to Zone 6, but both further away from Teide and near the main transport infrastructure (the main ring road that circles the island). Zone 1 was characterized as the coastal zone with similar if slightly higher density to Zones 2, 5 and 6. Zones 3 and 4 are both urban zones, Zone 3 encompassing both the historic and the commercial centre of Icod de los Vinos, whereas Zone 4 represents the more recent suburban spread of the city. The sites selected for data collection within each zone were then chosen to represent the different types of building construction present within each zone and therefore spread over the entire area in order to pick up the full variety of settlement types and ages. Choosing specific survey locations rather than using a random selection method also made data collection easier to coordinate for a large team (4 teams of 2). Fig. 2 also shows the sites of the survey locations selected within the zones, labelled S1, S2, … S24.

5. Results of building stock survey and discussion

Results from the building stock inventory show the diversity of construction typologies present in the Icod de los Vinos area. Out of 394 buildings surveyed, 54% of them had a concrete frame, 31% of them were constructed out of rubble masonry, 15% were constructed out of squared masonry and 0.5% were built in timber (see Table 7). When considered zone by zone, the proportions of vertical structural typologies changes slightly according to the zones. Zones 2 and 6 are the only zones to contain any timber constructions. Zones 2, 6 and 5, the hinterland zones, have relatively fewer rubble masonry structures,

Table 8
Distribution of building height by zone

Count of class	Height				
Zone	H	L	M	S	Total
1	2	41	1	31	75
2		18	1	1	20
3	6	80	15	38	139
4	1	32	4	23	60
5		7		13	20
6		43		37	80
Total	9	221	21	143	394

Table 9
Distribution of building age by zone

Count of class	Age			
Zone	M	O	*R*	Total
1	26	3	46	75
2	4		16	20
3	59	37	43	139
4	27	1	32	60
5	9		11	20
6	25	14	41	80
Total	150	55	189	394

whereas Zone 3, the historic centre of Icod de los Vinos, has a higher proportion of rubble masonry buildings than average for the area.

When considering the height of the buildings, 36% were single-storey buildings, 56% of the buildings were 2 or 3 stories in height, 5% had 4 or 5 stories and 2% had 6 stories or more. Few zones contained any buildings of 6 stories or more, the exception being Zones 1, 3 and 4. These represent the central, urban/suburban and coastal zones respectively. The centre of Icod de los Vinos town (Zones 3 and 4) contains high-rise apartment and office buildings and the coastal Zone (Zone 1) contains a few high-rise hotels and apartment blocks. The majority of the buildings though, even in these relatively high land-value areas, are less than 3 stories in height (see Table 8).

The distribution of building age in the buildings of Icod de los Vinos is as follows: 48% of the buildings are of recent construction (estimated to have been built after 1980), 38% of buildings are of medium age (1930 and 1980) and 14% of the buildings are categorised as old, before 1930, (see Table 9). The percentage of old buildings was zero or negligible in Zones 2, 4 and 5, very low in Zone 1 and higher than average in Zone 3, which is the zone that represents the historic centre of Icod de los Vinos. Surprisingly, Zone 6 also had a significant number of old buildings, these may have been as a result of old farm villages and settlements that have survived amidst the cultivated and fertile land in the area.

When the three principal building characteristics are combined together to form a building classification, 22 classes were present in the survey out of a possible 48 combinations of principal characteristics. Each building classification represents a unique combination of characteristics that determine its resistance to the three hazards mentioned: Tephra, volcanogenic earthquakes and pyroclastic density currents. The classes (see Table 10) were distributed in varying proportions for each of the zones in the survey area. The effects of such differing classification profiles (see Fig. 3) can then be analysed automatically using spreadsheets and computational codes in order to understand their effects on the impact of a potential volcanic eruption (see Spence et al., 2005b for an example in Guadeloupe). The overall trend that can be gathered from this data is that the outer zones of the Icod de los Vinos area (Zones 1,2,5 and 6) have a greater homogeneity of building classes than the central urban and historic areas of Icod de los Vinos (Zones 3 and 4) that show a wider variety of vertical structural typologies, building heights and ages due to the longer period of time over which building development has taken place in these areas. To some extent, Zone 6 is an exception to this trend, displaying quite a large mix of building classifications. Which areas are more vulnerable to volcanic hazard is yet to be determined.

The information collected on window sizes has shown significant trends that characterise a proportional relationship between small, medium and large windows for the different vertical structural types. This information, summarised in Table 11, can be used to characterize the proportions of window sizes for the building classes present in the area. Such data can eventually be used to assess vulnerability to window failure of the buildings in the area. On the whole, concrete frame structures showed greater consistency in window proportions, with more large windows present in their facades than medium sized windows and likewise more medium sized windows than small ones. Masonry buildings however on the whole showed that the greatest proportion of their windows were medium sized, followed by large and then small windows, yet the differences between the small and large proportions were small.

The results of the survey show that there are significant variations in building class distributions in the zones considered in Icod de los Vinos. These differences reflect the different construction histories of each area as well as the current land uses. Such information is valuable to emergency managers and planners to estimate the exposure to volcanic hazards at a relatively fine-scale resolution. The methods presented would be applicable to a more complete survey of the area at risk for a comprehensive risk assessment.

This study has concentrated on only three possible volcanic hazards, earthquake, tephra fall and pyroclastic density currents. There are obviously other phenomena associated with volcanic eruptions such as lava flows, lahars, basal avalanches, flank collapse, tsunamis. These other phenomena, though essential in the overall aim of risk mitigation, are beyond the scope of this study, although the data collected here may be useful for such purposes.

The study has also concentrated on gathering data for analysis that would estimate the probability of building failure in terms of causing death or injury to their inhabitants rather than for the purposes of economic loss estimation. The aim of the study is to provide tools inventory buildings in order to reduce the risk to human life as opposed to inventorying them for the broader aim of reducing the risk of economic loss. As a result, information gathered and presented here is tailored specifically to these ends.

Aleatoric and epistemic uncertainties in the data collected have not been addressed at this stage. Although it is acknowledged that they

Table 10
Distribution of building classes by zone

	MRLM	MRLO	MRLR	MRMM	MRMO	MRSM	MRSO	MRSR	MBLM	MBLR	MBSM	MBSO	MBSR
Zone 1	8%	0%	0%	0%	0%	16%	3%	0%	0%	0%	3%	1%	4%
Zone 2	0%	0%	0%	0%	0%	0%	0%	0%	15%	0%	5%	0%	0%
Zone 3	6%	14%	0%	1%	1%	13%	12%	0%	2%	0%	2%	0%	0%
Zone 4	17%	0%	2%	0%	0%	13%	2%	0%	2%	5%	10%	0%	5%
Zone 5	5%	0%	0%	0%	0%	0%	0%	0%	0%	5%	30%	0%	0%
Zone 6	1%	6%	0%	0%	0%	1%	9%	3%	4%	5%	9%	3%	9%

	CFHM	CFHR	CFLM	CFLR	CFMM	CFMR	CFSM	CFSR	TILR
Zone 1	1%	1%	4%	43%	1%	0%	1%	13%	0%
Zone 2	0%	0%	0%	70%	0%	5%	0%	0%	5%
Zone 3	2%	2%	12%	22%	3%	6%	1%	0%	0%
Zone 4	0%	2%	3%	25%	0%	7%	0%	8%	0%
Zone 5	0%	0%	0%	25%	0%	0%	10%	25%	0%
Zone 6	0%	0%	9%	28%	0%	0%	8%	6%	1%

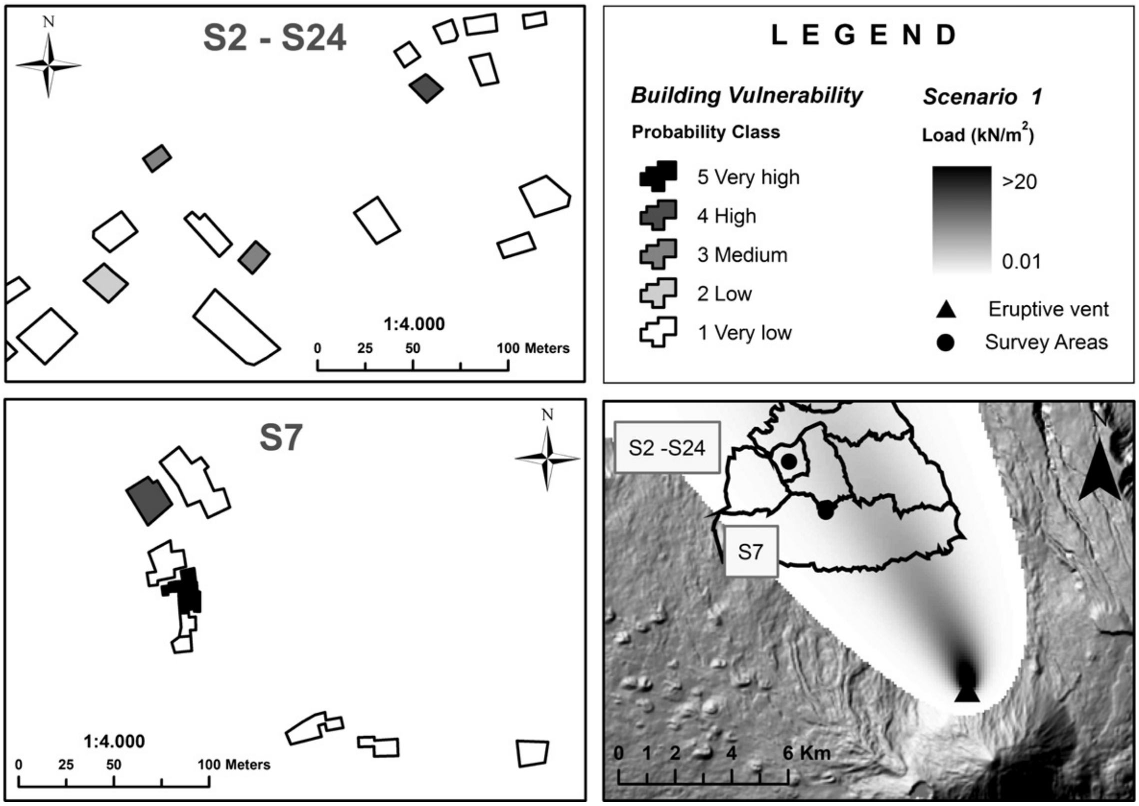

Fig. 3. Left: examples of probability of roof collapse due to tephra load for Scenario 1 (see text for details). Right: numerical simulation of scenario 1.

exist, they are not presented here. These uncertainties arise due to the limitations to the data collection method and to the means of estimating the building characteristics surveyed (expert opinion and guesswork rather than fact). Such uncertainties can be accounted for in a probabilistic risk assessment carried out with the data using methods proposed by Aspinall (2006).

6. Application to a scenario tephra fall event

With the aim of illustrating the application of this kind of inventory to volcanic risk assessment, an example of the generation of detailed maps of probability of roof collapse due to tephra load has been carried out. The contours of the buildings analysed during the fieldwork of September 2004 in Icod de Los Vinos were digitized and georeferenced in a GIS from digital cartography, ortophotos, and fieldwork sheets. All the building information was stored and analysed in a spatial geodatabase. Each of the buildings has as an attribute the code of the classification proposed in this paper (Table 10). Furthermore, each building has been classified in terms of the resistance of their roofs to load, following the classification proposed by Spence et al. (2005a) (Table 5). This paper proposes four categories for roofs (weak, medium weak, medium strong and strong) that correspond to four values of typical roof collapse load (respectively, 2.0, 3.0, 4.5 and 7.0 kPa) and so to four vulnerability curves.

In order to evaluate the potential effect of tephra fallout over Icod de los Vinos area, numerical simulations of tephra dispersal and deposition have been carried out. The eruptive scenario considered is a subplinian eruption of 0.05 km^3 of pumice from an emission centre located on the northern flank of Teide volcano. The model used for the simulation is an advection–diffusion model proposed in Folch and Felpeto (2005), calculating the vertical mass distribution through Suzuki approximation (Suzuki, 1983). Real wind data were used for the simulations, selecting two days where the winds mean directions were S or E, so that the tephra could be deposited over Icod de Los Vinos municipality. Table 12 shows the input parameters used in the two numerical simulations, that are similar to those of the last explosive event that took place in Tenerife: the Montaña Blanca eruption (2020 yBP). The output of the numerical simulations is a map showing the spatial distribution of the tephra load.

A spatial analysis was performed by an intersection of the result of each simulation with the buildings layer, assigning to each building its corresponding load. Therefore, for each building, its expected probability of collapse was calculated given its class, the load estimated by the numerical scenario simulations and the vulnerability functions defined elsewhere (Spence et al., 2005a). Later, the probability of roof collapse obtained by this methodology was reclassified into five categories (with a 20% interval between each

Table 11
Numbers of buildings in each building class and average number of windows per building

Class	CFHM	CFHR	CFLM	CFLR	CFMM	CFMR	CFSM	CFSR	MBLM	MBLR	MBSM
No. of records in class	4	5	29	119	5	14	10	25	10	8	25
Ave. windows per building	53	38	11	9	19	25	5	5	7	9	4
Class	MBSR	MRLM	MRLO	MRLR	MRMM	MRMO	MRSM	MRSO	MRSR	TILR	Total:
No. of records in class	13	27	25	1	1	1	39	26	2	2	394
Ave. windows per building	4	7	8	6	19	34	4	4	5	8	

Table 12
Mean input parameters used for the numerical simulation of tephra fallout

Mean eruption input parameters		Wind data[a]	
Volume of pumice emitted	0.05 km^3	Scenario 1	22/07/2004
Column height	8 km		
Column shape factor A (Folch and Felpeto, 2005)	5 m/s		
Mean grain size	−2 (φ units)	Scenario 2	17/05/2005
Dispersion of grain size	1.5		
Horizontal diffusion coefficient	1500 m^2/s		

[a] Data from deep atmospheric soundings at Güimar Meteorological Station (Tenerife Island).

one). The result is a detailed map that shows the probability of collapse for each building.

The results of the numerical simulation of Scenario 1 and two examples of its corresponding vulnerability map at some of the survey areas are shown in Fig. 3. Those examples indicate that areas containing a great variability on roof types show very different levels of probability of collapse. The results obtained show that, for this specific eruption, buildings with high or very high probability of collapse mostly correspond with MR structure (68%) or MB (27%). In terms of ages, high and very high probabilities are very scarce in recent edifices (30% of O buildings, 17% of M buildings and only 0.6% of R buildings show high or very high probabilities of roof collapse).

Although Scenarios 1 and 2 represent the same eruption and rather similar mean wind directions, the differences in wind speed and changes in direction with height make the distribution of tephra very different for both scenarios (see Figs. 3 and 4). As a consequence, in Scenario 2 the ash loads over the surveyed area are always below 2 kN/m^2, and only rise to values of around 1.2 kN/m^2 in some buildings, in S20. So, the vulnerability for all the buildings is below 20% (class: very low). Fig. 4 is a good example of how the consequences of an eruption can change due to "external" conditions (in this case, wind field). This illustrates the usefulness of this kind of risk analysis, which integrates numerical simulation of scenarios, vulnerability functions and socio-economic data in case of a volcanic emergency.

This spatial analysis procedure was developed inside a GIS (ArcGis™ 8.2, ESRI©), and is included within the framework of an automatic information system for the assessment of volcanic hazard and risk, specifically developed for Tenerife, but that can also be applied to other volcanic areas (Felpeto et al., 2007).

7. Conclusions

The findings of the data collected in the building stock inventory carried out for the area of Icod de los Vinos, Tenerife, in September 2004 show that building stock classification varies considerably according to different local areas that have been defined by the six zones used. No statistically significant trends were found between physical and morphological characteristics such as building density and building class, however, the differences between the areas are still significant for the determination and estimation of building damage in the event of an explosive volcanic eruption.

Such information could be used to influence mitigation strategies such as evacuation, temporary building reinforcement measures as well as long-term measures such as building codes and regulations and land-use planning directives. For the methods presented here to be effective and reliable in providing information on which to base guidance, a comprehensive survey of all the buildings in the area exposed to volcanic hazard would need to be undertaken.

The effects of a possible eruption critically depend on parameters, such as the location of the emission centre for pyroclastic density

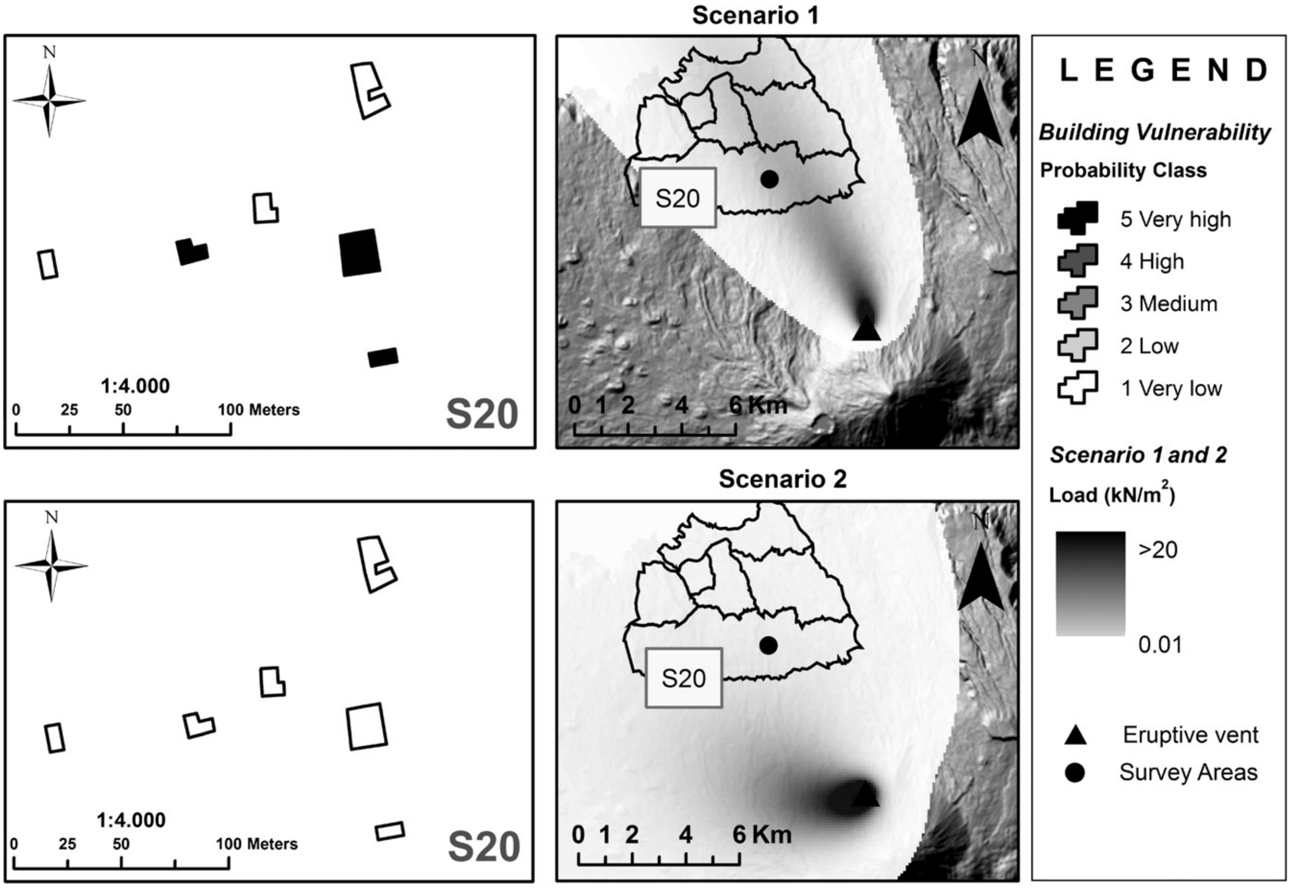

Fig. 4. Left: Comparison of probability of roof collapse maps for Scenarios 1 and 2 at S20 location. Right: numerical simulations of Scenarios 1 and 2 (see text for details).

currents or the particle size for tephra fallout, which can be very difficult to assess before the eruption. Therefore, for this kind of study to become a really useful tool for volcanic emergency management, automation of the analysis procedure is needed in order to provide a quick response. If real time and continuously updated data are included in the procedure, ad hoc vulnerability maps can be generated and updated (e.g. if in the example shown in Section 6, wind fields used in the numerical simulations are short-term wind forecasts, vulnerability maps can be updated daily or with an even higher frequency).

The remit of the EXPLORIS funded study was to only collect information required for modelling casualties and fatalities. Future work in this field could also consider modelling the economic losses under various hazard scenarios. This could easily be done including an assessment of build quality and use category in the survey forms. Taken together they could allow a per square metre construction cost to be assigned, which, when multiplied by the floor area, would give the replacement value of the building, allowing the model to estimate economic losses alongside human casualties and fatalities.

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