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Probabilistic Seismic-Hazard Assessment of the Canary Islands

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Abstract This article presents the first probabilistic seismic hazard assessment of the Canary Islands. The Canary Islands form a volcanic archipelago located on the passive margin of the African plate, 100 km off West Africa. Active volcanism has taken place on the islands in historical times, commonly together with the occurrence of volcanic-related seismic sequences, some of them felt as high as $I_{MSK} = X$. In 1989 a notorious seismic sequence (m_{bLg} 5.2) took place along a submarine fault located between the islands of Gran Canaria and Tenerife, clearly representing the occurrence of tectonic seismicity in the archipelago as well. In this article we review the geology and tectonics of the islands as well as recent paleoseismological findings on south Tenerife. We also revise, complete, and decluster the historical and instrumental seismic catalog of the islands. Seismic-hazard analysis is then performed following the standard Cornell (1968) method, defining three seismogenic sources and selecting an appropriate ground-motion attenuation relationship from Hawaiian data. Two hazard maps of the archipelago have been developed for return periods of 475 and 950 yr, as well as hazard curves for the capital cities. Calculated peak ground acceleration values at Santa Cruz de Tenerife and Las Palmas de Gran Canaria are 0.06 and 0.08*g*, and 0.05 and 0.07*g*, for the 475- and 950-yr return periods, respectively. Finally, we analyze the impact on hazard resulting from uncertainties associated with the seismogenic source model and the ground-motion attenuation relationship.

Introduction

The Canary Islands form an archipelago of seven volcanic islands off the northwest coast of Africa. In recent decades marine geophysical data along with volcanological and geodynamic investigations have allowed the development of new theories and concepts such as volcano flank collapses and giant landslide processes (e.g., Navarro and Coello, 1989; Watts and Masson, 1995). However, few investigations have been carried out so far on seismicity and none on seismic hazard. The Spanish Seismic Code (NCSE-02) is currently the only reference related to seismic hazard in the archipelago. The NCSE-02 provides an updated version of the 1994 seismic-hazard map of Spain (NCSE-94). Both maps were derived in terms of macroseismic intensity, and then converted to a characteristic ground acceleration, which in practice is taken as peak ground acceleration (PGA), related to a 500-yr return period. However, the probabilistic assessment was not performed for the Canary Islands either in the 1994 nor the 2002 version, and a 0.04*g* PGA was arbitrarily adopted for the whole archipelago (Martínez-Solares, pers. comm., 2005).

In fact, conducting a seismic-hazard analysis of the Canarian Archipelago is plagued by important shortcomings. Very few tectonic structures have been described so far and seismic instrumental recording dates only since 1975. Nevertheless, assessing the seismic hazard is currently of prime importance for the near-future development of industrial facilities and urban expansion on the islands.

In this article we first review the geology and tectonics of the archipelago, as well as recent paleoseismological findings. Second, we revise, complete, and decluster the seismic database available. Seismic hazard is then computed following the Cornell (1968) approach considering three seismogenic sources and a ground-motion attenuation relationship derived from Hawaiian data (Munson and Thurber, 1997). Two seismic-hazard maps for the 475- and 950-yr return periods are obtained as well as hazard curves for the two Canarian capital cities. Uncertainties related to the adopted seismogenic source model and the chosen ground-motion model are also analyzed.

Geological and Tectonic Setting

The Canary Islands are located 100 km off the west coast of Africa, opposite Cape Juby, on the border of the African passive margin (Fig. 1). The archipelago is made up of seven main volcanic islands lying on an oceanic Jurassic lithosphere (Uchupi *et al.*, 1976). In the past 500 years several volcanic eruptions have taken place in Tenerife, La

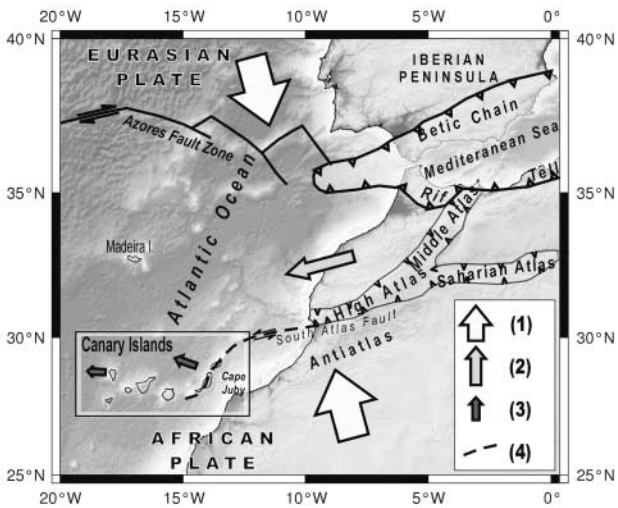

Figure 1. Regional tectonic setting of the Canary Islands. (1) General direction of collision between the Eurasian and the African Plates; (2) escape of North Africa toward the Atlantic Ocean (Gómez *et al*, 1996); (3) extensional direction in the eastern Canary Islands and La Palma (Fernández *et al*, 2002); (4) supposed offshore prolongation of the South Atlas fault (Emery and Uchupi, 1984).

Palma, Lanzarote, and El Hierro. The most recent eruption occurred in 1971 on La Palma (Teneguía volcano).

The eastern islands (Lanzarote and Fuerteventura) form the East Canary Ridge, which runs south-southwest–north-northeast parallel to the continental margin. The oldest volcanic deposits in the archipelago (called basal complex) are located on these islands and date Cretaceous (Bravo, 1964; Fúster and Aguilar, 1965). The oldest subaerial volcanism is also located on these islands and dates 20.6 Ma (Coello *et al.*, 1992). The western islands (Gran Canaria, Tenerife, La Gomera, El Hierro, and La Palma), in contrast to the eastern islands, run east–west and the age of the basal complex decreases to the west, being as young as Pliocene in La Palma and El Hierro.

The westward variation of the age of the volcanism is one of the main observations in support of a hotspot model to explain the origin of the archipelago (e.g., Morgan, 1971; Burke and Wilson, 1972; Morgan, 1983) following the success of the model in explaining the Hawaiian volcanism (Wilson, 1963). However, several works have pointed out the difficulties of the hotspot model in explaining the tectonic features of the archipelago and alternative theories have been proposed invoking the interaction of magmatism with tectonic stress fields in relation to the Atlas Range tectonic frame (i.e., Anguita and Hernán, 1975; Hoernle and Schmincke, 1993; Anguita and Hernán, 2000).

Anguita and Hernán (2000) proposed a unifying evolution model that considers stages of active volcanism during periods of extensional tectonics and stages of block uplifting in association to shear faulting under a transpressive regime. This geodynamic environment has been related to the convergence between African and Eurasian plates in the frame of an escape-tectonics model (Fernández *et al.*, 2002) (Fig. 1). The archipelago and the African continent would be tectonically connected by the offshore extension of the South Atlas fault zone (Emery and Uchupi, 1984). However, the sedimentary apron off northwestern Africa does not show the presence of such a structure (Anguita and Hernán, 2000). The origin and evolution of the Canarian Archipelago is still controversial.

Very few tectonovolcanic structures have been described yet in the Canarian Archipelago (Fig. 2). One of the first structures described were mercedes star-shaped triple junctions located in relation to the main volcanic centers on Tenerife and El Hierro (Navarro, 1974). Seismic exploration and, recently, marine geophysics have revealed the different crustal structure of the eastern islands to the western islands (Banda *et al.*, 1981; Carbó *et al.*, 2003). The eastern islands lie on a crust 15 km thick and form a very conspicuous north-northeast–south-southwest structure, the so-called East Canary Ridge. In contrast, the crust in the western islands is 11 km thick and structures show a general north–south trend.

Gran Canaria-Tenerife Submarine Fault

The most important tectonic feature of the archipelago is located between the islands of Tenerife and Gran Canaria (Fig. 2). In this area, a northeast–southwest-trending fault was first described by Bosshard and McFarlane (1970), and later, Mezcua *et al.* (1990, 1992), pointing it out as the source of the largest instrumented earthquake recorded in the archipelago, the seismic event of 9 May 1989 (m_{bLg} 5.2). A series of liquefaction-related structures (e.g., clastic dikes, tubular vents) have been recently identified in Holocene sand deposits in southern Tenerife (González de Vallejo *et al.*, 2003). These authors estimated a magnitude of M_w 6.8 for the causative paleoearthquake, and pointed out the Gran Canaria-Tenerife submarine fault as the most likely causative source.

Seismic Catalog

The seismic database used in this study has been provided by the Instituto Geográfico Nacional (IGN), the Spanish governmental institution in charge of the maintenance and operation of the National Seismic Network. This database has been completed with the addition of four events registered by the International Seismological Centre between 1964 and 1975 (ISC, 2001), and with the paleoseismic event of the south coast of Tenerife.

The seismic catalog of the Canary Islands can be divided into two main periods: preinstrumental or historical, and instrumental. However, the paleoseismological data available permit extending back several thousand years the seismic record in the Gran Canaria-Tenerife area.

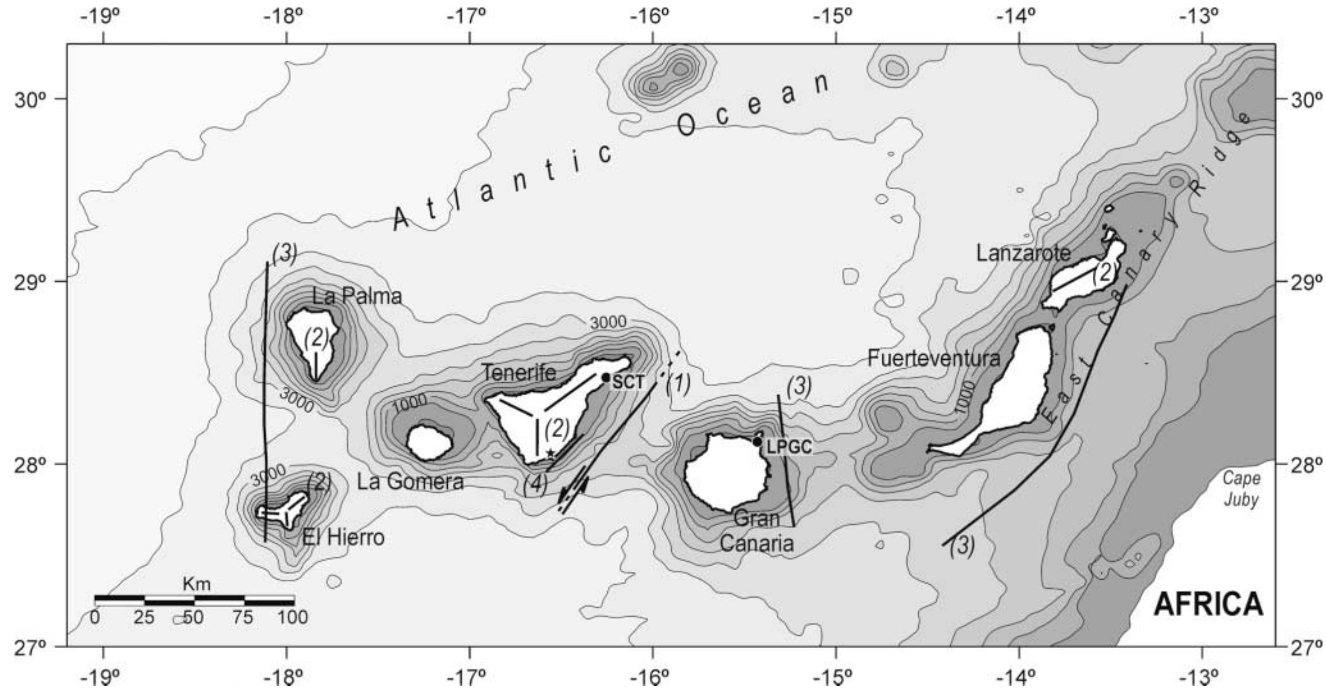

Figure 2. Main tectonovolcanic features and lineations of the Canary Islands. Numbers refer to the main works describing the structures shown in the figure: (1) Bosshard and McFarlane, 1970; Mezcua *et al.*, 1992; (2) Navarro, 1974; (3) Carbó *et al.*, 2003; (4) González de Vallejo *et al*, 2003. Isolines show the bathymetry. The capital cities of the archipelago are displayed: Santa Cruz de Tenerife (SCT) and Las Palmas de Gran Canaria (LPGC). The star marks the location of the paleoliquefaction features described by González de Vallejo *et al.* (2003).

Historical Period

The beginning of the historical period in the islands dates from the fourteenth century. Since then, a noticeable number of earthquakes have been registered, mainly related to volcanic eruptions (Fig. 3). The first great seismic event was registered on La Palma in 1677 (I_{MSK} = VII–VIII). However, the most intense earthquake in the archipelago took place near Yaiza (Lanzarote) in 1730 (I_{MSK} = X) related to the Lanzarote eruption (1730–1736) of the Timanfaya volcano. The so-called Yaiza earthquake took place on 1 September 1730 reaching an Medvedev–Sponheuer–Karnik (MSK) intensity of X, according to the Spanish Seismic Catalogue (Mezcua and Martínez Solares, 1983). The eruption caused large destruction in an area limited to its surroundings, and no particular destruction or casualties were attributed to the ground shaking. An I_{MSK} = X event should have caused destruction in a wider area, which is not described by the historical documents (Lorenzo-Curbelo, 1731; Real Audiencia de Canarias, 1736). Therefore, the intensity assigned to the Yaiza earthquake is very likely to be overestimated.

Other noticeable earthquakes were registered in 1920 and 1949 in Cumbre Vieja (La Palma) (I_{MSK} = VII), in Ingenio (Gran Canaria) in 1913 (I_{MSK} = VII), and in Fuerteventura in 1915 and 1917 (both I_{MSK} = VII). Many other events with intensity VI and V have been registered in the archipelago.

Instrumental Period

The first seismic network in the region started operating in 1975. It was composed of three stations located on Tenerife, La Palma, and El Hierro (Mezcua *et al.*, 1990). During the 1980s, the network was extended to other islands and, since 1990, most of the stations have been updated by digital recording broadband instruments (IGN, 2004).

The instrumental catalog is mostly composed of small events distributed preferentially around Gran Canaria and Tenerife, in particular, between the two islands (Fig. 3). Before 1997, the magnitude scale of most of the earthquakes was related to the duration of the signal (m_D). Since the end of 1997, the magnitude of most of the events has been calculated according to the amplitude of the *Lg* wave (m_{bLg}) and in a few to the m_b scale (IGN, 2004).

The largest instrumental earthquakes in the archipelago were recorded on 22 January 1991 and 9 May 1989. The 1991 event (m_{bLg} 5.1) was located 60 km southwest of La Palma and no aftershocks were recorded, probably because of the long distance to the seismic network. In contrast, the 1989 event (m_{bLg} 5.2) was located between Gran Canaria

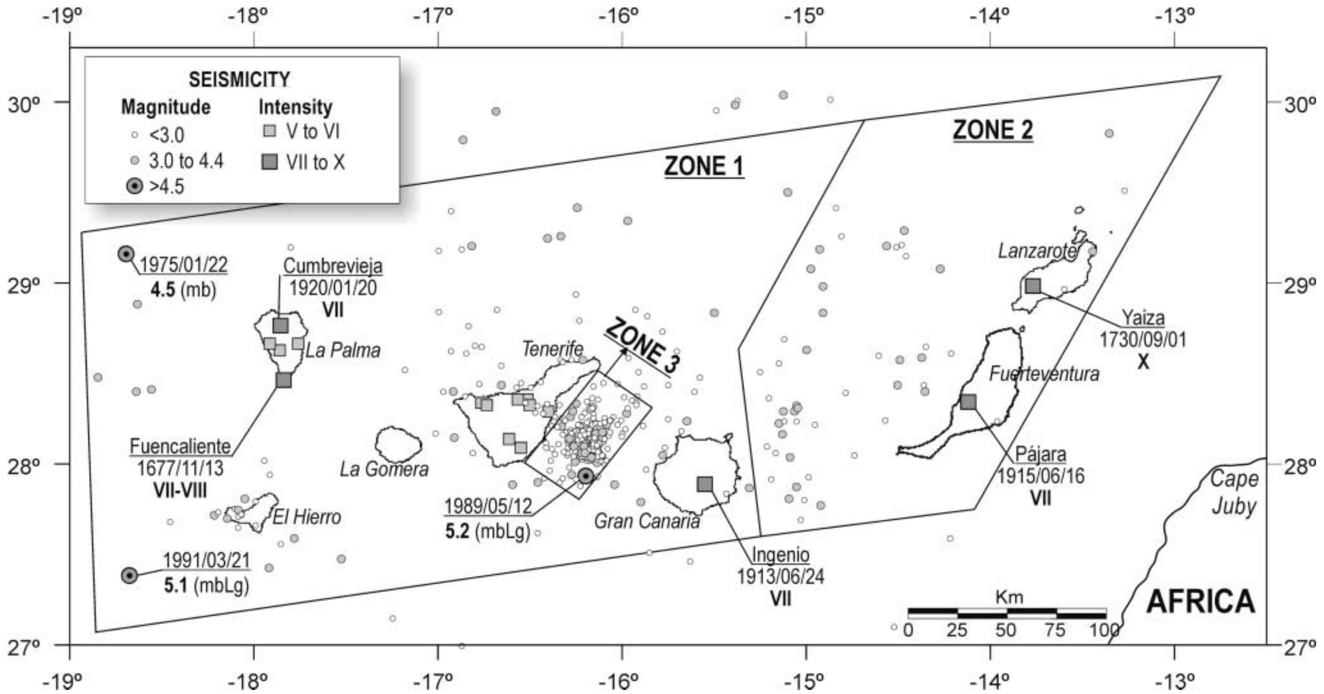

Figure 3. Seismicity of the Canary Islands. Only historical events with intensity greater than V (MSK) are displayed. Only main events are labeled: name of the town, date and intensity for the historical events, and date and magnitude for the instrumental records. The seismogenic zones considered in the hazard calculations are shown. See text for details.

and Tenerife, permitting the record of a noticeable number of aftershocks (Fig. 4). The hypocenter of the mainshock was located by Dziewonski *et al.* (1990) at a depth of 15 km, whereas the IGN located it at a depth of 36 km, with an uncertainty in the focal depth of ± 12 km.

As mentioned previously, the fault located between Gran Canaria and Tenerife was pointed out as the source of the 1989 event (Mezcua *et al.*, 1990, 1992). The focal mechanism of the mainshock shows strike-slip movement with two nodal planes oriented north-northeast–south-southwest and northwest–southeast (Fig. 4). The former agrees very well with the strike of the submarine fault and aftershock distribution. The length of the fault was estimated as 30 km.

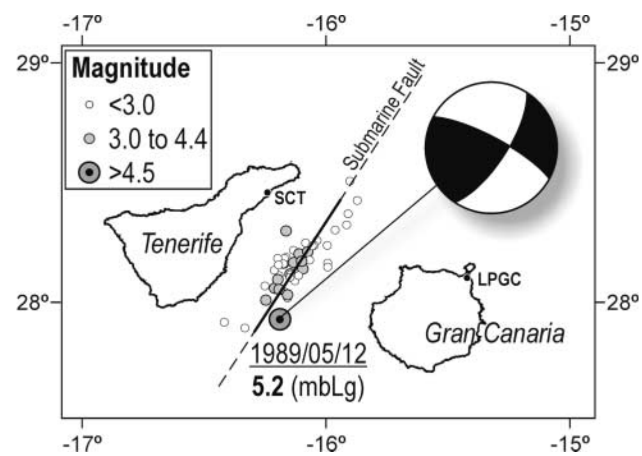

Figure 4. Epicenter of the 1989 earthquake and aftershock distribution. The focal mechanism of the main event is shown (Mezcua *et al.*, 1992). See text for discussion.

Paleoseismological Data

Several paleoliquefaction features related to seismic shaking have been found in Holocene sands on the south coast of Tenerife (González de Vallejo *et al.*, 2003). These authors performed a liquefaction backanalysis, estimating the magnitude of the causative earthquake at M_w 6.8. To date, the Gran Canaria-Tenerife fault is the only known tectonic structure capable of generating such a magnitude in the archipelago. Furthermore, absolute dating of the Holocene sand formation permitted them to infer the occurrence of such an event between 3500 and 10,000 years ago (González de Vallejo *et al.*, 2003).

Seismogenic Sources

The occurrence of seismicity in the Canary Islands is thought to be mainly due to volcanic processes. Monge (1981) found clear relationships between several historical volcanic eruptions and local increases of seismic activity. Nevertheless, the occurrence of the 1989 series and its distinct relation to a 30-km-length fault points out the likely occurrence of large (M_w >6.0) tectonic earthquakes between Gran Canaria and Tenerife. The origin of this tectonic seismicity is thought to be related to the collision of African and Eurasian plates, which have been active from 23 Ma until present (Dewey *et al.*, 1989; McClusky *et al.*, 2003) (Fig. 1).

Based on the main regional tectonic features and the distribution of seismicity, three seismogenic zones have been defined to be used in the hazard calculations: zones 1, 2, and 3 (Fig. 3). The area consisting of zones 1 and 2 accounts for the occurrence of low-to-moderate magnitude events, independent of their tectonic or volcanic origin. The boundaries of the zones have been drawn coinciding with the decrease in seismicity that occurs either toward the open Atlantic Ocean or toward the African continent, respectively (Fig. 3). The northern and southern limits of these zones also follow the offshore extension of the Atlas structure (Figs. 1 and 2). The boundary between both zones represents the abrupt change in crustal thickness that takes place moving away from the eastern islands toward the western islands. The orientation of this boundary coincides approximately with the apparent north-northwest–south-southeast orientation displayed by the East Canary Ridge (Fig. 2).

Finally, zone 3 has been defined to outline a specific area inside zone 1, between Gran Canaria and Tenerife, where moderate-to-large (M_w >6.0) tectonic earthquakes are likely to occur due to the presence of the fault responsible for the 1989 sequence, and in accordance with the size of estimated earthquake magnitudes (M_w 6.8) from paleoliquefaction analysis on the south Tenerife coast.

Estimation of Seismic Parameters

Processing of the Earthquake Catalog

To obtain a declustered and homogeneous database first we processed the seismic database. The declustering process consisted of removing earthquake swarms related to volcanic processes as well as aftershock series of tectonic origin from the earthquake database. This would satisfy the Poisson assumption of the model prior to carrying out the regression analysis to estimate earthquake recurrence relations in each of the zones. First, we removed foreshocks and aftershocks that occurred within an interval of 3 days and at a distance less than 5 km. The declustering process was performed using the SeriesBuster computer program (Álvarez-Gómez *et al.*, 2005), and resulted in the removal of 7% of the earthquakes, almost all of them related to the 1989 aftershock sequence, with magnitudes between 1.1 and 3.1.

Second, we aimed to convert all the magnitudes to a common moment magnitude scale (M_w) in the declustered seismic database. The main problem of this procedure is that there are no local conversion equations available for the different magnitude scales represented in the earthquake database (e.g., m_D, m_b, m_{bLg}). We decided to assume compatibility with the moment magnitude scale. This decision was twofold: (1) magnitudes contained in our database (m_D, m_b, m_{bLg}) are all smaller than 5.4, and (2) the vast majority of our records are to the m_{bLg} scale. For such small earthquakes the IGN m_{bLg} scale shows very small differences to M_w (Rueda and Mezcua, 2002).

Temporal Completeness of the Seismic Record

Analyzing the temporal completeness of our database is of prime importance for estimating earthquake recurrence parameters in each seismogenic zone (Table 1). The starting years of completeness for M_w 2.0–4.0 were estimated considering the consecutive extensions and improvements of the Seismic Network of the Canary Islands. Starting years for the M_w 4.1–5.0 range were estimated from the date of the first events recorded in the ISC catalog. To estimate the temporal completeness of M_w 5.0 and above, necessary to calculate the mean annual rate of occurrence of the M_w 5.1 and 5.2 events in zone 1, it was necessary to consider the historical seismicity record. The historical record in zone 1 started with the occurrence of the 1677 event (I_{MSK} = VII–VII) and it is not until 1852 that the next earthquake with an assigned intensity is known (I_{MSK} = III–IV). Since that year intensities have been reported on a regular basis. Hence, 1850 can be used as a minimum starting year of completeness if it is assumed that the occurrence of a M_w 5.1–5.2 earthquake before this year would have been felt with a higher intensity than IV. Although this procedure is flawed by significant uncertainties, we believe it provides a reasonable estimation accounting for the regional character of this seismic-hazard assessment and the deficiencies of the available data.

Seismic Parameters for Hazard Calculations

In this article seismic hazard is calculated following the well-known method of Cornell (1968). This method assumes that earthquake occurrence follows a Poisson process and is distributed uniformly within several specific areas delimited by the analyst (source zones). In each of these zones, earthquake magnitudes fit an exponential distribution, so the mean annual exceedance rate of magnitude m (λ_m) is given by (Cornell and Vanmarcke, 1969):

$$\lambda_m = \lambda_{m_0} \frac{\exp(-\beta m) - \exp(-\beta m_1)}{\exp(-\beta m_0) - \exp(-\beta m_1)}, \quad m_0 \leq m \leq m_1 \qquad (1)$$

where λ_{m_0} is the mean annual exceedance rate of magnitudes above m_0, and m_1 and m_0 are the upper and lower bounds of the distribution, respectively, and beta (β) is the exponential parameter of the distribution. The λ_{m_0} parameter is given by

$$\lambda_{m_0} = \exp(\alpha - \beta m_0) \qquad (2)$$

where $\alpha = a\ \mathrm{Ln}(10)$ and $\beta = b\ \mathrm{Ln}(10)$, and a and b are the Gutenberg–Richter parameters. The Gutenberg–Richter parameters estimated in each zone after regression analysis are shown in Table 2. Zones 1 and 2 show a very different b-value, which could be related to distinctive seismogenic characteristics. Nevertheless, this observation has to be taken with caution because of significant statistical uncertainty affecting zone 2 parameters (Fig. 5). Zone 3 represents a specific area inside zone 1 where earthquake occurrence is extended to larger magnitudes ($M_w \geq 6.0$) due to the presence of the Gran Canaria-Tenerife submarine fault. Hence, the maximum earthquake potential of zone 3 has been assessed based on the surface length of the Gran Canaria-Tenerife fault and paleoliquefaction evidence on the south coast of Tenerife. Making use of the surface rupture length versus moment magnitude relationship of Wells and Coppersmith (1994) and considering the 30-km length of the fault, an expected M_w 6.8 ± 0.28 event can be derived, which is very similar to the M_w 6.8 estimated on the paleoliquefaction study of González de Vallejo *et al.* (2003). These authors estimated that such a seismic event occurred between 3500 and 10,000 years ago, which is consistent with the mean recurrence period derived from extrapolating instrumental data to the large magnitude range (see Table 2).

Table 2 also shows the lower (m_0) and upper (m_1) magnitude thresholds adopted in zones 1 and 2. Minimum magnitude was set to M_w 4.0 in zones 1 and 2. Standard practice in seismic-hazard assessment usually sets the minimum magnitude to M_w 5.0, which is thought to be the smallest earthquake of engineering interest. Nevertheless, adopting such a value in a low-to-moderate seismic area like the Canary Islands, could lead to underestimating the hazard for relatively high exceedance probabilities (e.g., 10% in 50 yr or 475-yr return period). Besides, seismic events with magnitudes smaller than M_w 5.0 have actually produced significant damage in other parts of Spain (e.g., La Paca, 2005, m_{bLg} 4.7, I_{EMS} = VI; Bullas, 2002, m_{bLg} 5.0, I_{EMS} = V; Mula, 1999, m_{bLg} 4.8, I_{EMS} = VI) (IGN, 2005).

Finally, to assess the maximum magnitude in zones 1 and 2, we adopted a deterministic procedure of increasing the intensity of the maximum historical earthquake (MHE) by half a unit, and transforming it to the moment magnitude scale. MHEs in zones 1 and 2 are I_{MSK} = VIII and I_{MSK} = X, respectively. The former value suggests an average M_w 6.0 with the relationships of IGN (1982) and Benito *et al.* (1999). The latter corresponds to the 1730 Yaiza earthquake (I_{MSK} = X), which earlier was argued to be overestimated. In fact, adopting such intensity would indicate an average

Table 1
Estimated Starting Year of Completeness for Specific Magnitude Ranges

Magnitude Range (M_w)	Starting Year	Temporal Length (years)
5.1–5.2	1850	153
4.1–5.0	1960	43
3.1–4.0	1975	28
2.6–3.0	1980 (zones 1 and 3)	23
	1985 (zone 2)	18
2.0–2.5	1990	13

Temporal length extends from starting year to 2002. See text for explanation.

Table 2
Seismic Parameters of the Seismogenic Zones

Sources	b	a	m_0	λ_{m_0}	m_1	MRP (years)
Zone 1	1.12 (±0.01)	3.72 (±0.05)	4.0	0.1676	6.0	1050 ± 120
Zone 2	0.95 (±0.08)	2.75 (±0.23)	4.0	0.0909	6.0	870 ± 160
Zone 3	1.12 (±0.01)	3.72 (±0.05)	6.0	0.00095	6.8	8350 ± 950

a and b, Gutenberg–Richter parameters with indication of the standard error; m_0 and m_1, lower and upper bounds of magnitude (M_w) distribution; λ_{m_0} mean annual cumulative rate of magnitude $\geq m_0$; MRP, mean recurrence period of m_1 in each of the zones. See text for discussion.

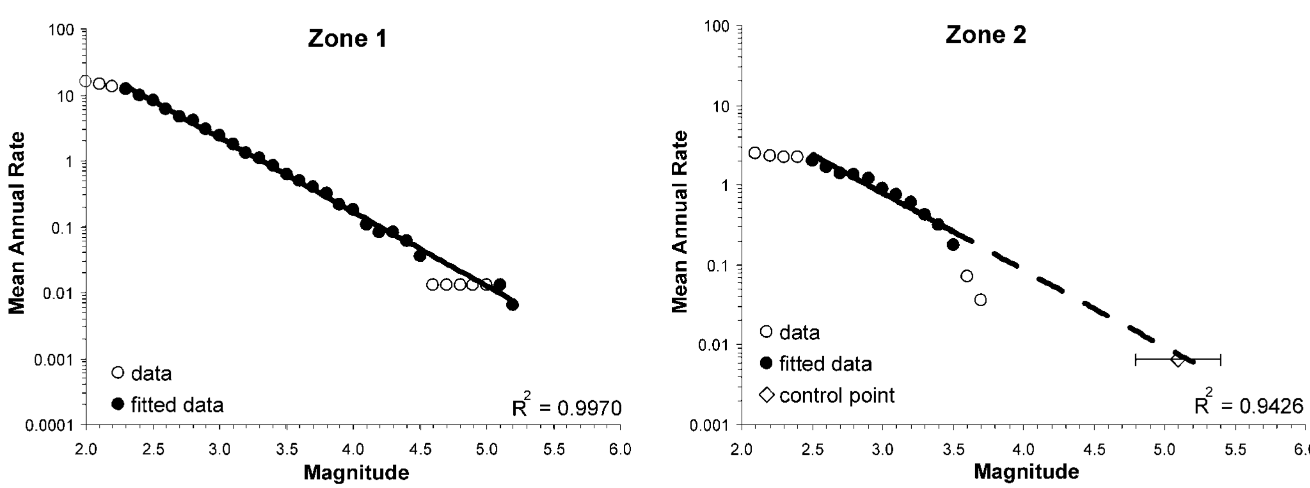

Figure 5. Cumulative earthquake occurrence rates versus magnitude in zones 1 and 2, and exponential fits. See text for details.

M_w 6.8, which is nonrealistic if one considers the maximum size of instrumentally recorded earthquakes related to major eruptions (e.g., Miyake-jima, 1983, M_S 6.2; Oshima, 1986, M_w 6.0 [compare Benoit and McNutt, 1996]). A maximum M_w 6.0 was finally adopted for zone 2.

Ground-Motion Attenuation Relationship

There is no ground-motion relationship specifically developed for the Canary Islands nor is there an accelerometer network in operation. The only attenuation relationship derived for a similar volcanic archipelago to date is the relationship developed by Munson and Thurber (1997) from Hawaiian strong-motion data. Therefore, the Munson and Thurber (1997) equation was selected for the calculations.

Munson and Thurber (1997) obtained a PGA attenuation relationship after a two-stage regression analysis of 52 records from 22 earthquakes. Magnitudes ranged from M_w 4.0 to 7.2 and focal depths from 4 to 14 km. Magnitudes for large events ($M > 6.0$) were measured on the surface wave scale (M_S), and small-to-moderate events by the Richter scale (M_L). The distance parameter is defined as the shortest horizontal distance from the recording site to the surface projection of the fault-rupture area, that is, the Joyner–Boore distance. When this type of distance is not known, epicentral distances are used.

In reducing the uncertainty on the PGA prediction, it is of prime importance to ensure compatibility between the magnitude scale and the type of distance used in the attenuation relationship and the ones actually used in the hazard calculations (compare Bommer *et al.*, 2005). The use of M_L for small-to-moderate earthquakes and M_S for large events in the Munson and Thurber (1997) relationship permits us to reasonably assume compatibility with the M_w (e.g., Sabetta and Pugliese, 1996). On the other hand, we assume the Joyner–Boore distance is compatible with epicentral distance, which is reasonable when seismic sources are modeled as zones and in particular, for small-to-moderate earthquakes. Hence, no transformations were performed on the magnitude and distance parameters of the Munson and Thurber (1997) relationship.

It is standard practice in seismic-hazard assessments to make use of more than one attenuation relationship via a logic tree, as a way to account for the epistemic uncertainty in ground-motion attenuation. In our particular case there is no other attenuation relationship but that of Munson and Thurber (1997) suitable for the volcanic and oceanic conditions of the Canarian Archipelago. However, it is very interesting to compare that relationship with the one of Ambraseys *et al.* (1996), which is one of the most used in Europe (compare García-Mayordomo *et al.*, 2004). Ambraseys *et al.* (1996) predicts higher PGA values for small-to-large magnitudes (M_S 5.0–7.0) and at short distances (<10 km approximately) (Fig. 6). On the other hand, Munson and Thurber (1997) predict higher PGA in the medium distance range (10–100 km), although it attenuates much faster. Munson and Thurber (1997) observed the same effect, but comparing it with the Boore *et al.* (1993) attenuation equation for western America. These significant differences between attenuation models suggest that the distinctive characteristics of active volcanic crust (e.g., fracturation, temperature, and fluids) may produce a damping effect on high-frequency ground motion, in particular, at short distances.

Seismic-Hazard Results

Seismic hazard has been calculated for a grid spacing of 0.1°, as well as for the two capital cities (Las Palmas de Gran Canaria and Santa Cruz de Tenerife). Computation was performed using the program CRISIS (Ordaz *et al.*, 1999). Figure 7 shows the seismic-hazard curve for the capital cities, and Figure 8a and b shows the resulting seismic-hazard maps in terms of PGA levels related to 475- and 950-yr return periods, respectively. PGA are for rock conditions, which are the most common site conditions on the islands. It is clear from both maps that zone 3 controls the distribution of the highest acceleration levels.

Analysis of Main Uncertainties

To analyze the impact of our seismogenic source model on the results, seismic hazard was computed including three alternative models: A, B, and C. In model A, zones 1 and 2 are considered as just one background zone. In model B, zone 3 is not defined and included in the analysis and a M_w 6.8 upper-bound magnitude is assumed for zone 1. Finally, in model C, zone 3 geometry is fitted exclusively to the aftershock distribution of the 1989 event, and earthquake occurrence is limited to a M_w 6.8 earthquake with a mean recurrence period of 3500 yr, that is, a characteristic earth-

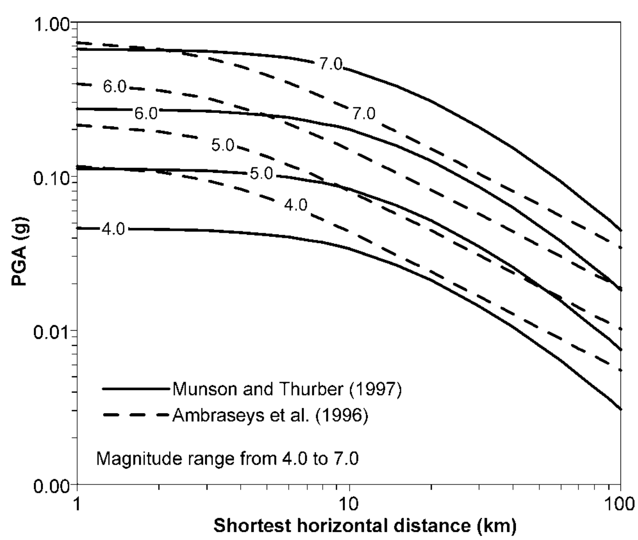

Figure 6. Munson and Thurber (1997) PGA attenuation curves for M_w 4.0 to 7.0 for rock conditions. The Ambraseys *et al.* (1996) curve is also shown for comparison purposes. See text for discussion.

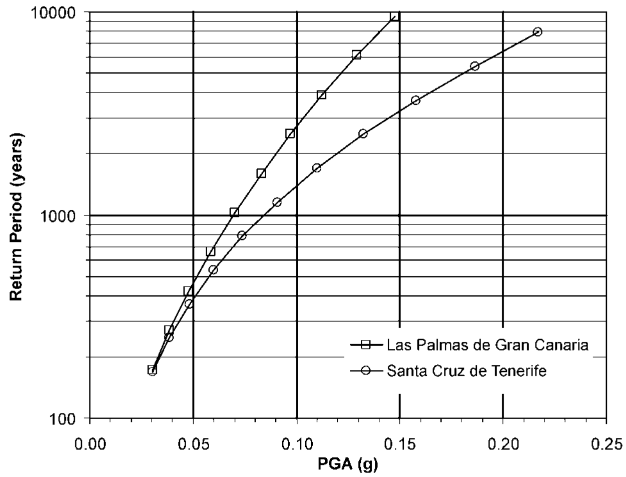

Figure 7. Seismic-hazard curves for the two capital Canarian cities. PGA values are for rock conditions.

quake model is assumed. The recurrence period of 3500 yr represents an upper-bound estimate of the recurrence interval for maximum events consistent with the paleoseismological data. Models A and B resulted in PGA levels 0.01 and 0.02*g* units below the previously presented results for the 475- and 950-yr return periods, respectively. Similarly, model C resulted the same PGA levels as obtained in models A and B.

The impact on the results from adopting a higher maximum magnitude value in zone 2, which is affected by the uncertainty in assessing the maximum intensity of the Yaiza earthquake, has been also analyzed. To perform this analysis we account for a variation of $+0.5$ and $+1.0$ magnitude units from the adopted maximum magnitude of M_w 6.0. The use of either of these values did not change the overall results previously presented.

Finally, we have also studied the impact on the hazard maps when considering the Ambraseys *et al.* (1996) ground-motion attenuation. The use of this relationship widened the areas within acceleration levels equal to or higher than 0.05 and 0.07*g* for the 475- and 950-yr return periods, respectively.

Conclusions

The results presented in this article show the first probabilistic seismic hazard assessment of the Canary Islands. The east coast of Tenerife has been identified as the onshore

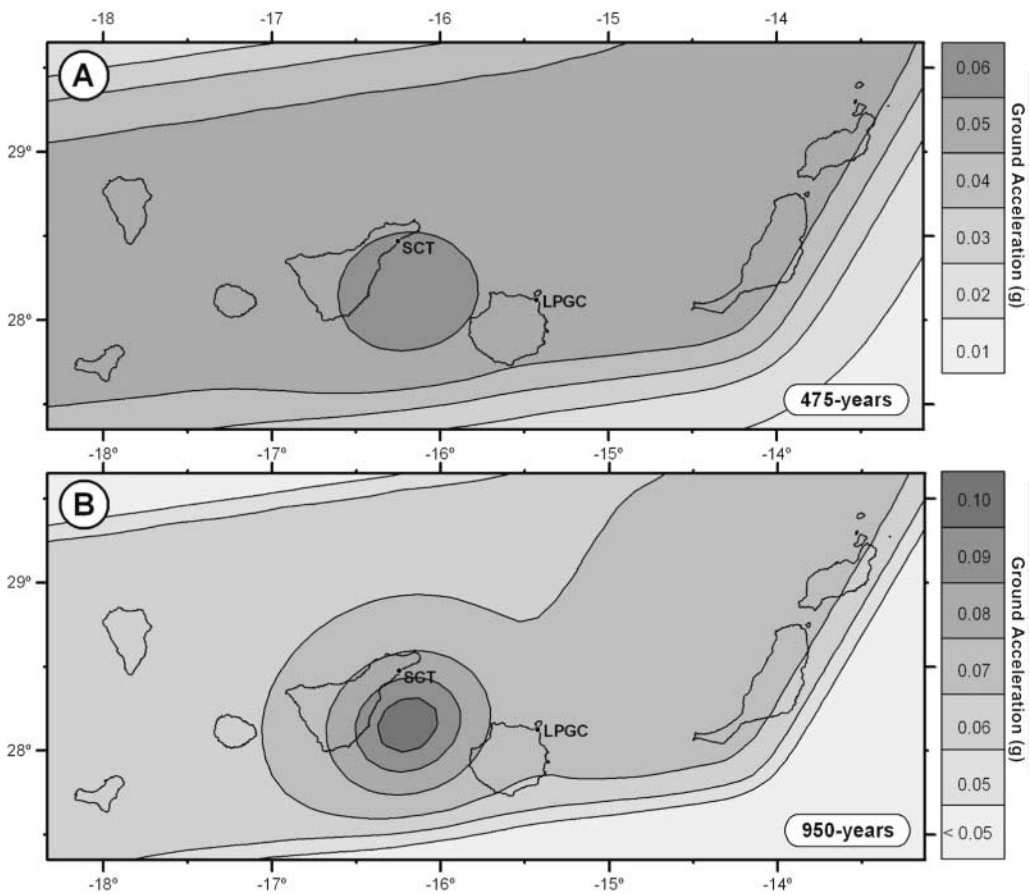

Figure 8. Seismic-hazard maps of the Canary Islands in terms of PGA on rock for the 475- (a) and 950-yr (b) return period. Acceleration values are in *g* units.

area with highest seismic hazard in the archipelago because of the existence offshore east of Tenerife of a seismogenic source capable of generating moderate-to-large magnitude ($M_w > 6.0$) tectonic earthquakes, that is, the Gran Canaria-Tenerife fault.

The eastern and southeastern part of Tenerife show PGA values of 0.06*g* and 0.08 to 0.09*g* for the 475- and 950-yr return periods, respectively. The rest of the Canary Islands show a uniform PGA of 0.05*g* for the 475-yr return period and 0.06 to 0.07*g* for the 950-yr return period. PGA in Santa Cruz de Tenerife and Las Palmas de Gran Canaria are 0.06 and 0.05*g*, respectively for the 475-yr return period, and 0.08 and 0.07*g* for the 950-yr return period, respectively. Our results on Tenerife and the rest of the Canary Islands are 50% and 25% higher than those stated in the Spanish Seismic Code (NCSE-02) for the 475-yr return period, respectively.

The seismic-hazard assessment represents our best estimation possible, considering the limitations of the available data. More research is needed in studying the historical earthquake record, active tectonics, and paleoseismology of the islands. Additionally, the installation of a strong-motion network is of great importance.

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