Seismotectonics and Seismic Hazard of the Canary Islands

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ABSTRACT

Seismic hazard in the Canary Islands has been analysed by probabilistic and deterministic methods. Three seismogenic zones have been defined considering seismicity, tectonics, and geophysical data. The seismic catalogue of the Canary Islands, as well as tectonic and paleosismological data has been revised to estimate earthquake recurrence vs. magnitude relationships in each of the seismogenic zones. A peak ground acceleration (PGA) attenuation relationship derived from Hawaiian data on rock sites was used in the hazard calculations, as no such relationships are available for the Canary Islands.

The probabilistic seismic hazard maps presented in this work highlight the east coast of Tenerife as the onshore area with highest seismic hazard in the archipelago. This result is due to the existence offshore east of Tenerife of a seismogenic source capable of generating moderate-to-large magnitude (M>6.0) tectonic earthquakes. The calculated PGA value for 475-years return period is 0.06g for the eastern half of Tenerife and 0.05g for the rest of the Canary Islands. These values are 50% and 25% larger than those stated in the Spanish Seismic Code [NCSR-02], respectively.

The values of ground acceleration estimated by deterministic method for the cities of Santa Cruz de Tenerife and Las Palmas de Gran Canaria are 0.20 and 0.12 g, respectively. These values are noticeable larger than those calculated by probabilistic methods, even for the 950-years returns period values (0.09 and 0,07g, respectively). The results obtained from both methodologies, as well as their application in seismic design, are discussed.

INTRODUCTION

The volcanic archipelago of the Canary Islands is located 100 km off the west coast of Africa, opposite Cape Juby (**Fig. 1**). The volcano-seismic activity of the islands is known since historical times. Nevertheless, before the start of seismic instrumental recording on the islands only chronicles of earthquakes related to volcanic eruptions were known. Recent geophysical and paleoseismological observations have also clearly demonstrated the occurrence of tectonic earthquakes as well [i.e.: Mezcua et al., 1992; González de Vallejo et al., 2003].

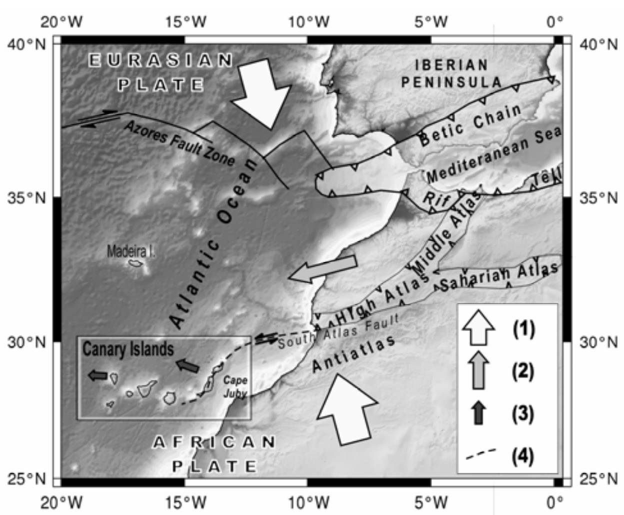

Figure 1. Regional tectonic frame of the Canary Islands. (1): General direction of collision between the Eurasian and the African Plates. (2): Escape of North Africa toward the Atlantic Ocean (Gómez *et al*, 1996). (3): Extensional direction in the eastern Canary Islands and La Palma (Fernández *et al*, 2002). (4): Supposed offshore prolongation of the South Atlas Fault (Emery & Uchupi, 1984).

The only reference related to seismic hazard in the archipelago is the current Spanish Seismic Code [NCSR-02]. The code states a ground acceleration level of 0.04g on all the islands for a 500-years return period.

In this paper we summarized the first results from an ongoing research project on the seismotectonics and seismic hazard of the Canary Islands [González de Vallejo et al., 2005].

GEOLOGIC AND SEISMOTECTONIC SETTING

The Canarian Archipelago is made up of seven main volcanic islands, and several islets and seamounts, which form a wide band with a general east-west trend (Fig. 1). The oldest volcanic deposits (basal complex) are located on the eastern islands and date Cretaceous [Bravo, 1964; Fúster and Aguilar, 1965]. The age of the basal complex decreases to the west in the western islands, as young as Pliocene in La Palma and El Hierro. The oldest subaerial volcanism is also located on the eastern islands and dates 20.6 Ma [Coello et al., 1992]. 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 [Morgan, 1971; Burke and Wilson, 1972; Morgan, 1983; among others] following the success of the model in explaining the Hawaiian volcanism [Wilson, 1963]. However, several works have pointed out the difficulties of the hot spot 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 with 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 NW Africa does not show the presence of such a structure [Anguita and Hernán, 2000]. The origin and evolution of the Canarian Archipelago is under controversial discussion.

Nevertheless, some tectonovolcanic structures have been already described on land as well as on the ocean floor.

[Navarro, 1974; Carbó et al., 2003] (**Fig. 2**). The main tectonic feature of the archipelago is located between the islands of Tenerife and Gran Canaria. In this area, a NE-SW trending fault was first described by Bosshard and McFarlane (1970). Later, Mezcua et al. (1992) pointed it out as the source of the seismic event of May 9, 1989 ($m_{b(Lg)}$=5.2), the largest instrumented earthquake recorded in the archipelago (**Figs. 3**). These authors, based on the distribution of the aftershocks and the focal mechanism of the main event, described this fault as a left-lateral strike-slip fault with reverse component of motion.

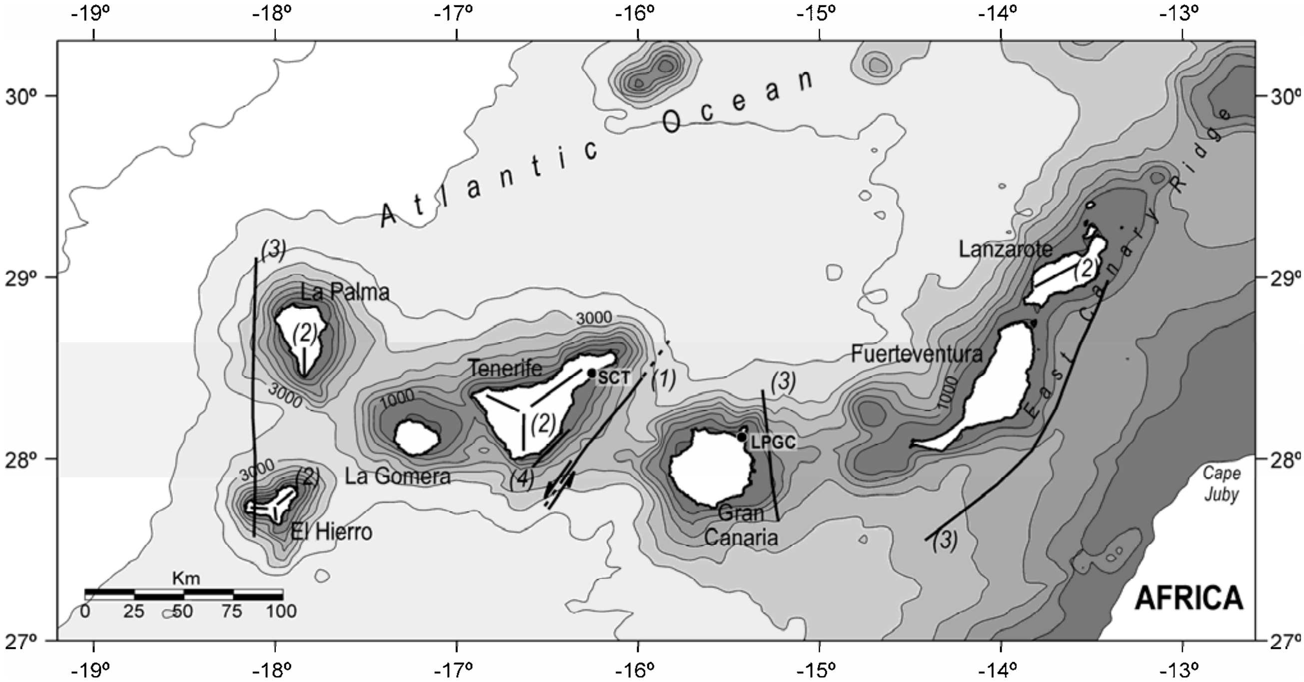

Figure 2. Main tectonovolcanic features and lineations of the Canary Islands, after: (1) Bosshard and McFarlane, 1970; Mezcua *et al*., 1992; (2), Navarro, 1974, (3) Carbó *et al*., 2003, (4) González de Vallejo *et al*, 2003. Isolines show the bathymetry. The capital cities of the archipelago are displayed: Santa Cruz de Tenerife (SCT) and Las Palmas de Gran Canaria (LPGC).

SEISMICITY

The beginning of the historical seismicity in the islands date from the XIV century, 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 on the archipelago took place near Yaiza (Lanzarote) in 1730 (I_{MSK}=X) related to the Lanzarote eruption (1730-1736) of the Timanfaya volcano. 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).

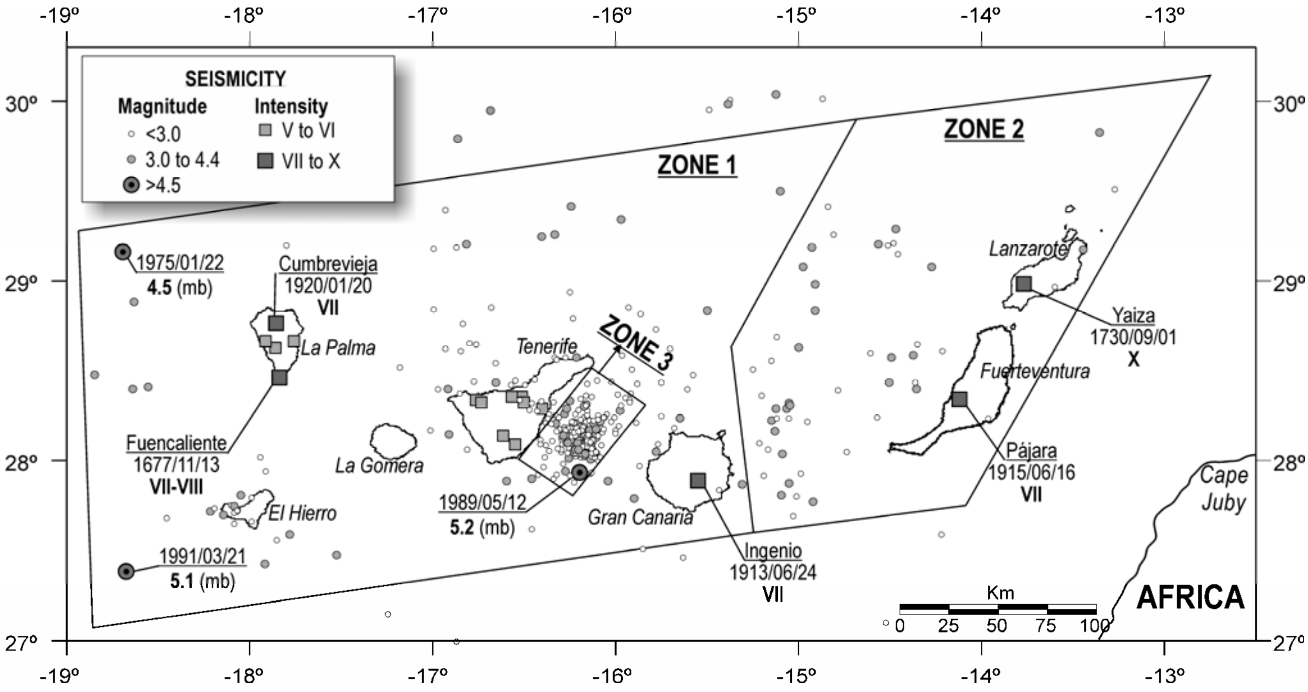

Figure 3. Seismicity of the Canary Islands. Only historical events with intensity greater than V (MSK) are displayed. Main events are labelled (location, date and intensity for the historical, and date and magnitude for the instrumental events from the IGN catalogue). The seismogenic zones considered in the hazard calculations are shown. See text for details.

The first seismic network in the region started operating in 1975. It was composed by three stations located on Tenerife, La Palma and El Hierro [Mezcua et al., 1990]. During the 80's 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 catalogue is mainly composed of low magnitude events (M<5.0) distributed preferentially around Gran Canaria and Tenerife, particularly between the two islands (Figs. 3). The largest earthquakes were recorded in 1989 and 1991. The former ($m_{b(Lg)}$=5.2) was located between both islands and gave rise to a number of aftershocks. The later ($m_{b(Lg)}$=5.1) was located 60 km southwest of La Palma and no aftershocks were recorded, probably due to the long distance to the seismic network.

Most of the seismicity in the Canary Islands has a volcanic origin. 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 single fault [Mezcua et al., 1992] points out the likely occurrence of large tectonic earthquakes (**M**>6.0) as well [González de Vallejo et al., 2003]. The origin of this tectonic seismicity is thought to be related to the African and Eurasian plates collision, which have been active from 23 Ma ago until Present (Fig. 1).

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

PSHA has been performed following the so-called "Poissonian Zoned Method" [Cornell, 1968; McGuire, 1995]. Three seismogenic zones have been defined on the Canarian Archipelago according to the main regional tectonic features and the distribution of seismicity (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; while Zone 3 is restricted to the future occurrence of moderate-to-large tectonic earthquakes (**M**>6.0) inside Zone 1. The seismic parameters estimated for each zone are shown in Table 1. Beta (β) and the mean annual rate (λm_O) were calculated after removing aftershock events from the database and carefully evaluation of the completeness of the catalogue. Maximum magnitude in Zones 1 and 2 was assessed accounting for the maximum recorded event in each zone. It is important to notice that Zone 3 accounts for the occurrence of moderate-to-large tectonic earthquakes inside Zone 1. Hence, minimum magnitude (m_0) in this zone was set at 6.0, while maximum magnitude was assessed from seismological, geological and paleoseismological data. Several different models regarding the size of zone 3 and the uncertainty of the seismic parameters were also taken into account to study their influence of the hazards results.

TABLE 1. Calculated Seismic parameters in each of the seismogenic zones considered in the hazard calculations.

Sources	beta (β)	Mean annual exceedance rate of m_0 (λ_{m_0})	Lower bound magnitude (m_0)	Upper bound magnitude (m_1)
Zone 1	2.5871	0.1676	4.0	6.0
Zone 2	2.2183	0.0865	4.0	6.0
Zone 3	2.5871	0.00095	6.0	6.8

GROUND MOTION ATTENUATION RELATIONSHIP

There is no ground motion prediction equation specifically developed for the Canary Islands nor is there an accelerometer network in operation. The only attenuation equation derived on a similar volcanic archipelago to date is the equation obtained by Munson and Thurber (1997) from Hawaiian strong motion data [Douglas, 2003]. Hence, this equation was used in the hazard calculations. However, the European attenuation relationship of Ambraseys et al. (1996) was also considered for comparison purposes.

SEISMIC HAZARD MAPS AND CURVES

Seismic hazard computation was performed using the program CRISIS, developed at the Instituto de Ingeniería of the UNAM (México) [Ordaz et al., 1999]. **Figure 4** shows the seismic hazard curve for the cities of Santa Cruz de Tenerife (SCT) and Las Palmas de Gran Canaria (LPGC) in terms of PGA *vs.* return period. **Figures 5a** and **5b** shows the resulting seismic hazard maps in terms of PGA levels related to 475 and 950-years return periods, respectively. On the first map all the islands are approximately in the 0.05g level except the eastern and southeastern part of Tenerife, where the 0.06g level is attained. On the 950-years return period map the westernmost islands (El Hierro, La Palma y La Gomera), as well as the easternmost coast of Lanzarote and Fuerteventura, show the lowest PGA level (0.06g). The rest of islands are within the 0.07g level, apart from the east half of Tenerife where PGAs of 0.08 and 0.09g are reached, and a small area on the westernmost coast of Gran Canaria (0.08g). It is clear from the maps that Zone 3 controls the distribution of the highest acceleration levels.

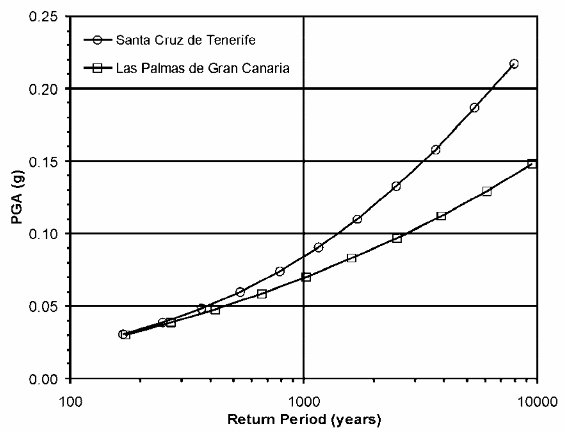

Figure 4. Seismic hazard curves for the two capital Canarian cities. PGA values are for rock conditions.

DETERMINISTIC SEISMIC HAZARD ANALYSIS (DSHA)

A DSHA for the two capital cities, Santa Cruz de Tenerife and Las Palmas de Gran Canaria, has been carried out considering the same seismogenic sources model and ground motion attenuation equation as in the PSHA. Maximum Credible Earthquakes have been selected in accordance with the upper bound magnitudes set for each seismogenic zone. In Santa Cruz de Tenerife the worst case is controlled by the occurrence of magnitude 6.8 MCE of Zone 3, at a minimum distance of 25 km, which draws a mean PGA estimate of 0.21g. On the other hand, either Zone 1 or 2 controls the worst case at Las Palmas de Gran Canaria. A mean PGA of 0.16g can be estimated considering the magnitude 6.0 MCE of these zones.

DISCUSSION AND CONCLUSIONS

The probabilistic seismic hazard maps presented in this work highlight the east coast of Tenerife as the onshore area with highest seismic hazard in the archipelago. This result is due to the existence offshore east of Tenerife of a seismogenic source capable of generating moderate-to-large magnitude (**M**>6.0) tectonic earthquakes. The calculated PGA value for 475-years return period is 0.06g for the eastern and southeastern part of Tenerife and 0.05g for the rest of the Canary Islands. These values are 50% and 25% higher than those stated in the Spanish Seismic Code [NCSR-02], respectively. A PGA on rock attenuation relationship derived from strong ground motion records of Hawaii was used to perform the calculations [Munson and Thurber, 1997]. The use of the European attenuation relationship of Ambraseys et al. (1996) provides results as much as 0.01g higher than those presented above.

Seismic hazard at the capital cities was also assessed following the deterministic methodology. This method provided PGA values of 0.21 and 0.16g for Santa Cruz de Tenerife and Las Palmas de Gran Canaria, respectively. According to the probabilistic seismic hazard curve calculated at both sites (Fig. 4) these acceleration levels would correspond approximately to a 7,000-years and 10,000-years return period, respectively.

A comparison of the hazard results is shown in **Table 2**. Deterministic PGA values are around 3.5 to 2 times larger than the estimated probabilistic PGAs for 475 and 950-years return periods, respectively.

TABLE 2. Comparison among the PGA results obtained from the probabilistic (PSHA) and the deterministic (DSHA) analysis performed at Santa Cruz de Tenerife (SCT) and Las Palmas de Gran Canaria (LPGC) sites.

SITE	PSHA		DSHA
	PGA (g)	Return Period (years)	PGA (g)
SCT	0.06	475	0.21
	0.08	950	
LPGC	0.05	475	0.16
	0.07	950	

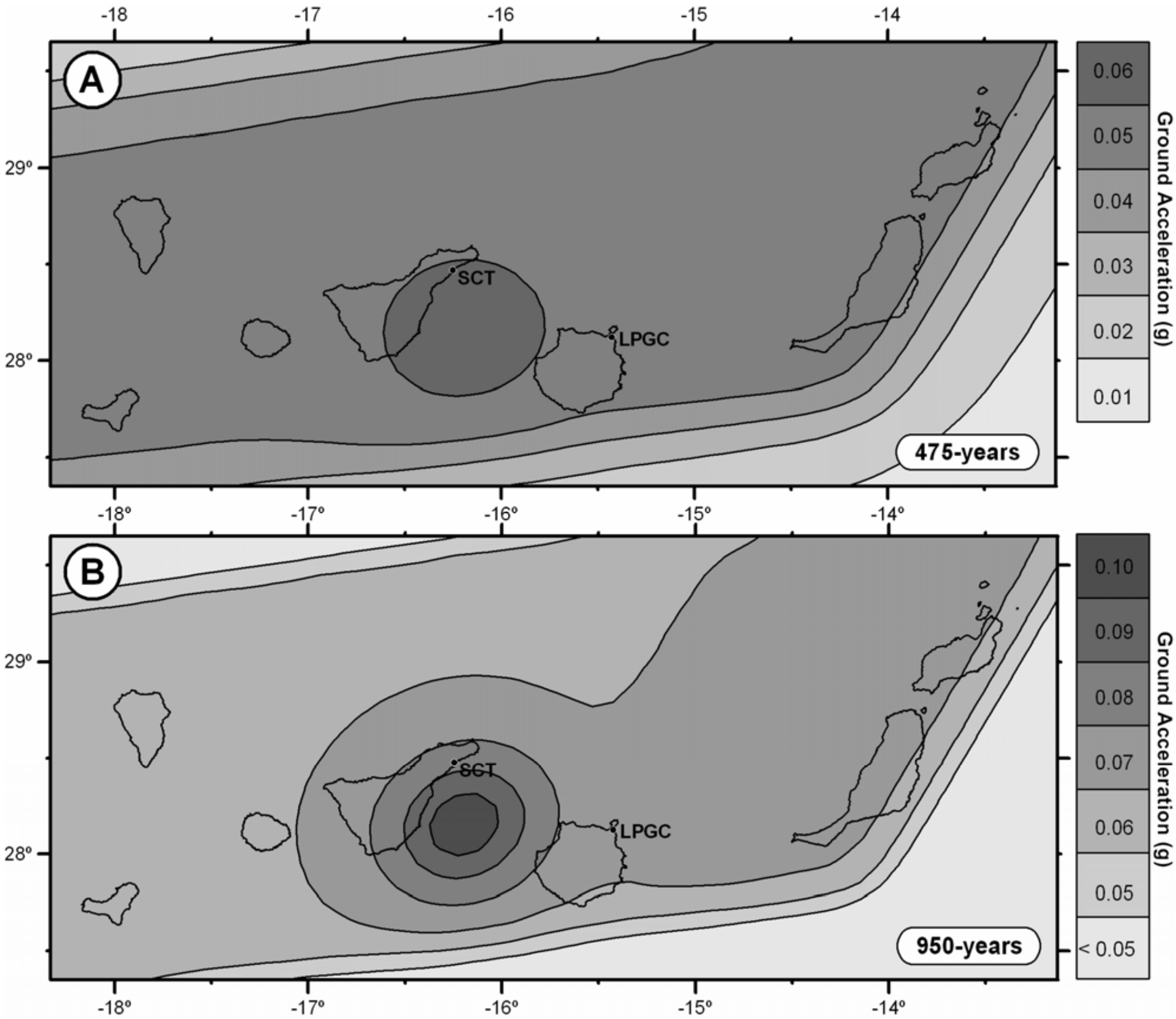

Figure 5. Seismic hazard maps of the Canary Islands in terms of PGA on rock for (A) 475 and (B) 950-years return period. Acceleration values are in g units.

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