HISTORICAL SEISMOLOGIST

Maximum Observed Intensity Map for the Azores Archipelago (Portugal) from 1522 to 2012 Seismic Catalog

by João Fontiela, Mourad Bezzeghoud, Philippe Rosset, and Francisco Cota Rodrigues

ABSTRACT

The Azores archipelago is a seismically active region composed of nine islands and located at the triple junction of the American, Nubian, and Eurasian plates. Since its settlement in the fifteenth century, 33 earthquakes with intensity higher than VII have been reported. This article shows areas that experienced strong ground shaking using maximum observed intensity (MOI) mapping. For this purpose, 323 records from 167 earthquakes in the period 1522–2012 have been compiled, and MOI values are interpolated on a regular grid of points using the kriging method. The comparison of observed and calculated MOI for four damaging and deadly earthquakes indicates a good calibration of the procedure relative to the available dataset. For the islands of the central group, which comprises Terceira, Graciosa, São Jorge, Pico, and Faial, the highest calculated intensities (XI) are located in the eastern part of São Jorge Island. Intensities (X) are observed on Faial along a northwest–southeast stripe. For Graciosa, Terceira, and Pico, the estimated maximum intensities are IX, VIII, and VII, respectively. For the eastern group of islands, the highest intensities (X) are located in the southeastern part of São Miguel Island, and on Santa Maria Island the maximum intensity of VI is observed in its eastern part. Finally, Flores and Corvo Islands, located on the American plate, have a very low seismicity.

Electronic Supplement: List of the earthquakes that were used to draw the maximum observed intensity (MOI) map for the Azores archipelago.

INTRODUCTION

Among the multiple methods to assess seismic hazard (i.e., Panza *et al.*, 2014; Parvez and Rosset, 2014; Stirling, 2014), a maximum observed intensity (MOI) map gives the areas that in the past were affected by strong ground shaking. An MOI map can be rapidly computed using macroseismic observations of past earthquakes. This method is useful in regions where information about large historical earthquakes exists and when instrumental seismic data are limited (Ayadi and Bezzeghoud, 2015). Such zonation maps have been produced for Algeria, Portugal, Greece, Italy, and Europe (Ayadi and Bezzeghoud, 2015; Ferrão *et al.*, 2016; Galanopoulos and Delibasis, 1972; Boschi *et al.*, 1995; and Kárnik *et al.*, 1980, respectively). However, the applicability of this method to knowledge of seismic hazard is conditioned by the stationarity of the events, the locations of the events, and the tectonic regime of the area being mapped.

The macroseismic data available in the Azores are often limited to the maximum intensity averaged across a settlement, sometimes by an average across a larger administrative unit, and in the worst case at the scale of an island. Generally, this does not allow an estimation of the influence of site conditions on the intensity reports. Nevertheless, the elaboration of discrete MOI mapping using nondiscrete macroseismic reports for distant islands is possible using the kriging method (Krige, 1951; Matheron, 1965). Indeed, this is an interpolation procedure that estimates values for locations without data using neighboring sites where data exist. However, kriging requires a variogram to give the degree of spatial correlation between neighboring sites. With this information, kriging can interpolate sites without bias, minimize the error, and assess the uncertainty of the result (Davis, 2002). The application of the kriging method in isoseismal mapping was tested and validated by several authors (e.g., Gasparini *et al.*, 2003; De Rubeis *et al.*, 2005; Schenková *et al.*, 2007; or Linkimer, 2008).

Considering the lack of instrumental data and the gaps between each island, MOI mapping remains a good means to map out the areas that in the past experienced the effects of strong earthquakes in the Azores archipelago. In this study, first the kriging procedure is calibrated using four single events, and then the MOI zonation maps are calculated and drawn based on the calibration procedure.

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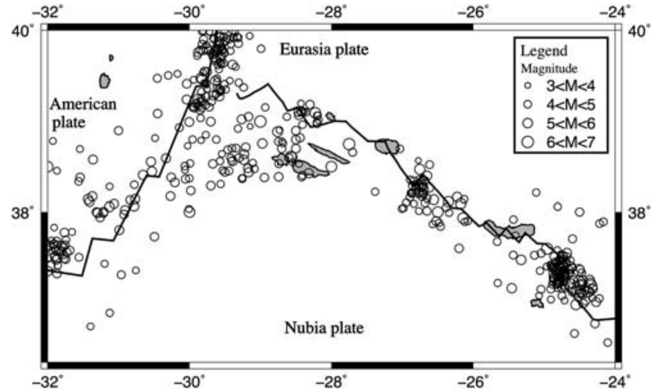
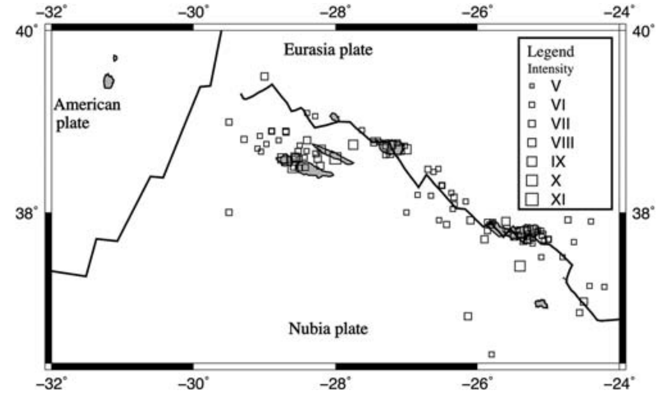


▲ **Figure 1.** Instrumental seismicity (M_b) in the Azores between 1926 and 2015.



▲ **Figure 2.** Earthquake catalog used to calculate the maximum observed intensity (MOI).

SEISMICITY

The Azores archipelago is located at the triple junction of the American, Nubia, and Eurasian plates (Fig. 1). Flores and Corvo Islands are on the American plate, whereas the other seven islands are at the boundary of the Nubian and Eurasian plates. The latter islands are divided into two groups: (1) a central group formed by Terceira, Graciosa, São Jorge, Faial, and Pico Islands and (2) an eastern group including São Miguel and Santa Maria Islands. Earthquakes recorded in the Azores between 1926 and 2015 (M_b 3 in Fig. 1) are located in two major segments first identified by Machado (1959). One segment, oriented from northwest to southeast, follows Graciosa, Terceira, and São Miguel Islands to the west transition of the Gloria fault. A second segment crosses Faial and Pico Islands.

Nunes *et al.* (2001) inventoried 33 destructive earthquakes that caused more than 6200 fatalities. The deadliest events occurred in 1522 at São Miguel Island (around 5000 deaths, maximum modified Mercalli intensity [MMI] $I_{max} = X$), in 1757 at the São Jorge Islands (1046 deaths, $I_{max} = XI$), in 1614 at Terceira Island (more than 200 deaths, $I_{max} = IX$), and also at Terceira Island in 1980 (61 deaths, $I_{max} = IX$).

On Graciosa Island, the strongest events with MMI IX occurred on 13 July 1730 and 21 January 1837 (Nunes *et al.*, 2001). More recently, on 1 January 1980 an M_w 6.8 earthquake with MMI IX occurred between Graciosa, São Jorge, and Terceira Islands and caused extensive damage in Angra do Heroísmo (a city on, Terceira Island) as well as on Graciosa Island and São Jorge Island.

On São Miguel Island, the seismicity is mainly associated with the Sete Cidades, Fogo, and Furnas volcanoes. Fontiela *et al.* (2014) also mentioned seismogenic zones in the southeastern part of the island which caused heavy damage in the village of Povoação in 1881 (MMI VII), 1932 (MMI VII), 1937 (MMI VII), and 1952, when two earthquakes occurred on the same day, each with MMI VII.

The seismicity of the second segment is concentrated in the region of Faial Island, mainly on the western part, and on Pico Island. Faial Island was struck by an earthquake on 31 August 1926 with MMI X and on 9 July 1998 by an M_w 6.0 earthquake (Borges *et al.*, 2007) with maximum intensity of VIII. An earthquake of M_b 5.0 (I_{max} VIII) struck Pico Island on 23 November 1973. São Jorge island, which is located between the first and the second segment described above, was struck by a major earthquake with MMI XI on 9 July 1757. Nowadays, the seismicity on this island is very low, as depicted in Figure 2. Table 1 presents an overview of the historical and recent seismicity with intensity equal to or greater than VIII on the islands as well as the reported damage and death tolls caused by earthquakes.

Volcanic activity is an important source of earthquakes in the archipelago. França *et al.* (2003) state that since the fifteenth century, 26 volcanic eruptions have occurred, with 12 of them being subaerial (5 at São Miguel, 3 at Pico, 2 at São Jorge, and 1 each at Terceira and Faial). Among the submarine eruptions, some were located close to the islands. Seismic tremor occurring before the eruptions, as a precursory signal due to magma ascent, and during the volcanic eruptions threatened local population and affected building strength due to continuous shaking. For example, the Capelinhos eruption on Faial Island in 1957–1958 generated hundreds of felt earthquakes, the strongest one with intensity IX. In 1964, the onshore eruption on São Jorge Island also induced earthquakes with a maximum reported intensity of VIII.

DATA AND METHOD

Macroseismic Dataset

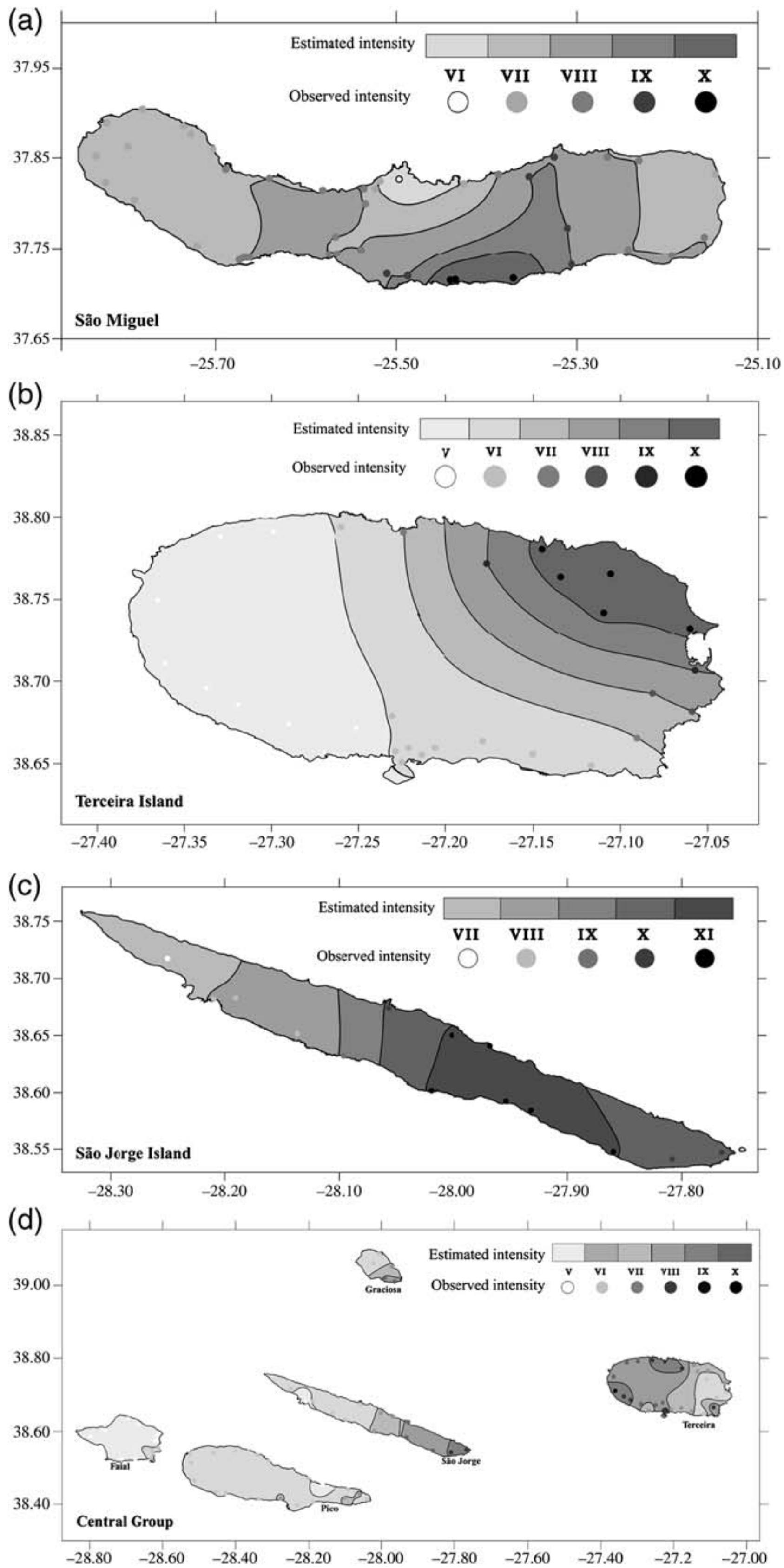
The dataset analyzed in this study includes all records with maximum intensity (I_{max}) equal to or greater than V in the catalogs provided by the Catálogo Sísmico da Região dos Açores (CSRA) (Nunes *et al.*, 2004), the Instituto Meteorologia (1999, 2000, 2002, 2003), and other sources (Machado, 1949, 1966; Madeira, 1998; Nunes *et al.*, 2001; Silveira, 2002; Silva, 2005). In total, 323 records from 167 earthquakes for the period 1522–2012 were selected to be used in the kriging (Fig. 2). Fourteen historical events with intensities greater than or equal to VII that occurred between 1522 and 1912 (Nunes *et al.*, 2001) were added to this catalog to increase the dataset

Table 1
Historical Earthquake in Azores with Intensity ≥VIII (See Sources at the Seismicity Section)

Date (yyyy/mm/dd)	Location/Island Most Affected	I_{max}	Magnitude	Observations
1522/10/22*	Vila Franca/São Miguel	X		Inland epicenter. Death toll: 4000–5000.The earthquake triggered a landslide that buried Vila Franca do Campo located on the south coast of São Miguel island.
1547/05/17	North zone/Terceira	VII/VIII		Several earthquakes struck the island causing minor damage. More than three deaths.
1591/07/26	Vila Franca/São Miguel	VIII/IX		Destructive earthquake that destroyed Vila Franca do Campo.
1614/05/24*	Praia da Vitória/ Terceira	IX		The earthquake was inland and caused heavy damage at Vila da Praia and neighboring settlements. More than 1600 houses collapsed. Death toll: >200.
1713/12/08	Ginetes/São Miguel	VIII		Heavy damage in the southwest settlements of São Miguel Island. No casualties reported.
1730/06/13	Luz/Graciosa	VIII/IX?		Heavy damage at the settlement of Luz.
1757/07/09*	Calheta/São Jorge	XI	M 7.4	Severe damage on São Jorge Island. Reported damage on neighboring islands. Death toll: 1046.
1800/06/24	Praia da Vitória/ Terceira	VII/VIII		Heavy damage on the eastern part of Terceira Island.
1801/01/26	São Sebastião/ Terceira	VIII		High damage on the southeastern part of Terceira Island, especially at Vila da Praia, and heavy damage at São Sebastião. Two people died.
1837/01/21	Guadalupe and Santa Cruz/Graciosa	IX?		Heavy damage at some settlements on Graciosa Island. Death toll: 3.
1841/06/15	Praia da Vitória/ Terceira	IX		Severe damage on Vila da Praia. No casualties reported.
1852/04/16	Ribeira Grande/São Miguel	VIII		Heavy damage to most of the settlements on São Miguel. Death toll: 9–12. Several tens injured.
1912/11/06	Praia da Vitória/ Terceira	VII/VIII		Light damage reported at Vila da Praia and neighboring settlements.
1926/08/31	Horta/Faial	X	M_b 5.3–5.9	Heavy damage reported at Horta and in neighboring settlements. More than 200 injuries and 9 fatalities.
1946/12/27	Serreta/Terceira	VII/VIII		Light damage reported at the settlements on the northwest and north parts of Terceira Island. No casualties reported.
1952/06/26	Ribeira Quente/São Miguel	VIII		Heavy damage in some areas of the settlements on the south and southeast part of São Miguel. No casualties reported.
1958/05/13	Praia do Norte and Ribeira Funda/Faial	VIII/IX		The event occurred during the Capelinhos eruption and caused heavy damage at the northwestern settlements of Faial Island.
1964/02/21	Rosais/São Jorge	VIII	M_b 5.5	The event occurred during the onshore eruption of Rosais on São Jorge Island. Heavy damage on the western side of the island.
1973/11/23	Bandeiras/Pico	VII/VIII	M_b 5.0	Heavy damage at the settlements on the northern part of the island. No casualties reported.
1980/01/01*	Doze Ribeiras[a]/ Terceira	VIII/IX	M_w 6.8	Heavy damage at several settlements of Terceira and São Jorge Islands and on Graciosa Island. Death toll: 61.
1998/07/09	Ribeirinha/Faial	VIII/IX	M_w 6.0	Heavy destruction at several settlements of Faial and Pico. Death toll: 8.

*Events select to calibrate kriging technique.

time span. Clustered earthquakes associated with volcanic eruptions (1957–1958 and 1964), as well as aftershocks that lasted several months after the mainshock, were removed because our interest is on the mainshock to map the maximum intensity by the kriging technique. The dataset is expressed in terms of the MMI scale of 1956 (MMI-56; Gutenberg and Richter, 1956), rounded to the next integer. It is listed in Ⓔ Table S1 (available in the electronic supplement to this article).



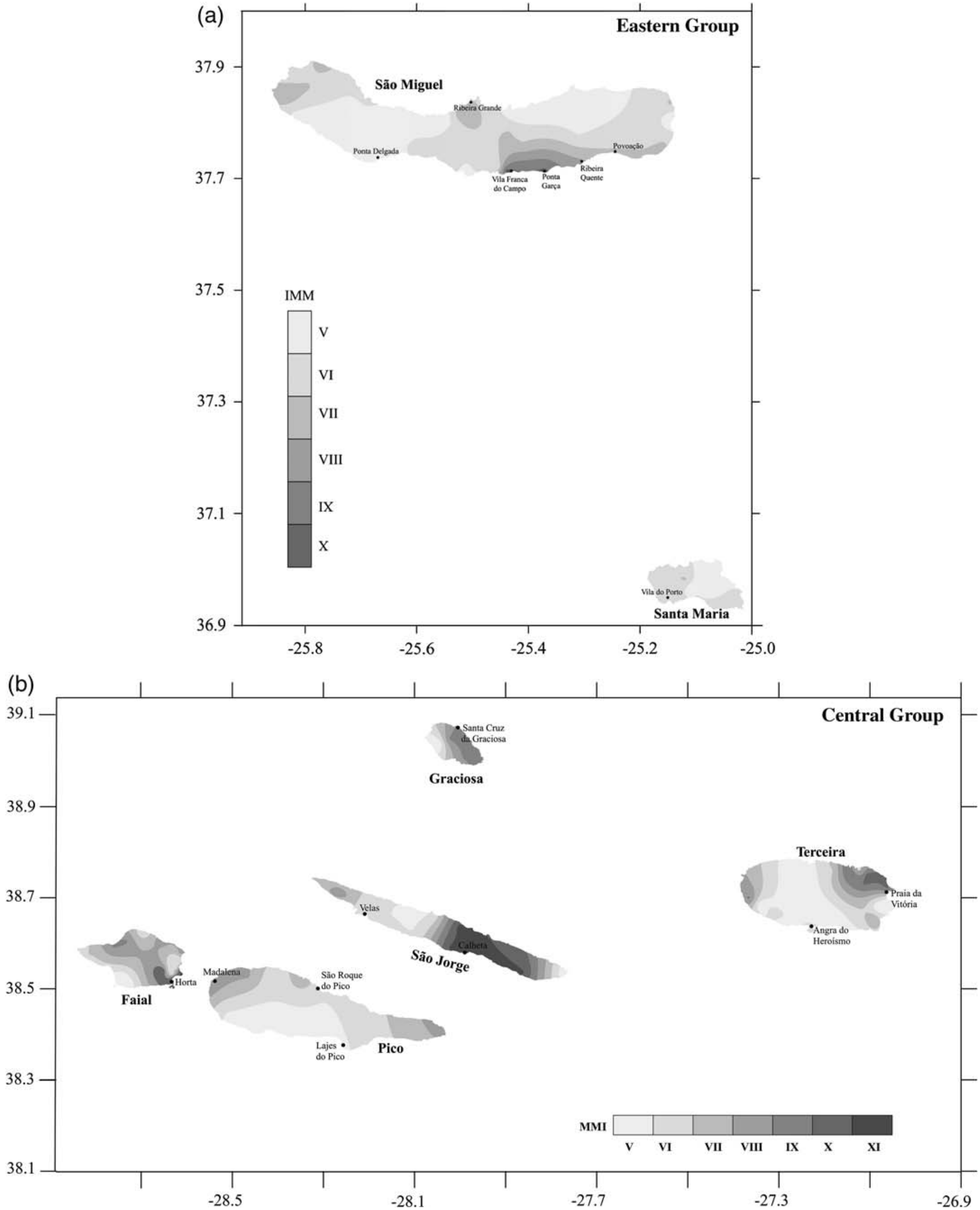
▲ **Figure 3.** Isoseismal maps interpolated by kriging for the (a) 1522, (b) 1614, (c) 1757, and (d) 1980 earthquakes.

Kriging Technique

The kriging method (Krige, 1951; Matheron, 1965) is a well-known method to interpolate spatial data. It uses an interpolation function based on a variogram model derived from the data. The variogram expresses the spatial variation, the error estimation, the confidence interval, and the degree of spatial autocorrelation of the dataset. This interpolation method is appropriate for drawing regional trends and local anomalies without bias because the expected values of the estimates and of the observed values at the same locations are equivalent. Among the numerous types of kriging methods, the ordinary kriging (OK) is the best for drawing isoseismal maps (De Rubeis *et al.*, 2005). It requires a dataset of measurements and their geographic coordinates. One assumes stationarity of the spatial data and an average regionalized variable, that is, the variable is distributed in space. The OK is based on the assumption that the random process is essentially stationary with constant mean, and the variance depends on the distance and direction between places (Oliver and Webster, 2015).

MAXIMUM OBSERVED INTENSITY MAPPING

Before we produced MOI maps we needed to verify if kriging is suitable to draw isoseismal maps with large and small macroseismic datasets and with different spatial extents. The calibration is a process introduced to check if the results are accurate. It consists of using some earthquakes that were studied in detail by other authors (Machado, 1949, 1966; Madeira, 1998; Nunes *et al.*, 2001; Silveira, 2002; Silva, 2005) to verify if kriging is able to replicate macroseismic maps of those earthquakes. To avoid drawing macroseismic or MOI maps under different conditions, we prefer to use the same kriging parameters as stated by Schenková *et al.* (2007). To calibrate our kriging method, we selected four earthquakes based on their large I_{max} values, death tolls, and spatial extents of the observed data. We selected the 1522, 1614, 1757, and 1980 events (summarized in Table 1). The observed data of the 1522, 1614, and 1757 earthquakes come from a single island, whereas the data of the 1980 earthquake come from five islands. During calibration, the OK interpolation method was applied individually to the data from each one of the four selected earthquakes (see Ⓔ Table S1) to produce isoseismal maps (as shown in Fig. 3a–d). The calibration



▲ **Figure 4.** Maps of MOI for the (a) eastern and (b) central groups. The islands of the western groups are not represented, due to the low level of seismicity (Fig. 1).

maps replicate well the observed intensities except in some areas of the isoseismal map for the 1522 earthquake, for which the observed intensities are underestimated. From these results, we consider that the OK is calibrated, and it can be used to generate accurate MOI maps.

On the MOI maps, we used all earthquakes of the dataset to produce a single MOI map. The results show an MOI map that is greater than VII for the eastern and the central groups (Fig. 4a and 4b, respectively). For the eastern group (Fig. 4a), Santa Maria Island has the highest I_{max} of VII. On São Miguel Island, the I_{max} estimated on the MOI map is XI. For the islands of the central group (Fig. 5b), São Jorge Island has the highest I_{max} at XI, followed by Terceira and Faial Islands with I_{max} X. On Graciosa Island, I_{max} is IX, and on Pico Island I_{max} is VIII.

The historical seismicity of the Azores is marked by the settlement of the islands in the fifteenth century; consequently, our catalog has a relatively short time period that started in 1522. In comparison, the earthquake catalog for the Portugal mainland has a time span that is more than 200 yrs longer (the first description belongs to the 1309 earthquake) (Ferrão *et al.*, 2016). Considering the time period of the earthquake data, it is likely that from the fifteenth century to the present some or much of the Azores area has not experienced the strongest ground shaking that can take place. Thus, the MOI maps do not represent the highest possible MMI values that can be experienced across the islands. The maps accurately represent the MOI for the time period of the data, but for most places they probably are not the highest intensity that can take place.

FINAL REMARKS

This study provides the first MOI maps for the Azores region based on the seismicity of the last five centuries. Through these maps, we assess past maximum shaking of the largest earthquakes based on the macroseismic observations of past earthquakes. This study reveals that São Miguel is the island of the eastern group that in the past suffered the greatest effects of very destructive earthquakes, especially the central part of the south coast, with maximum intensities ranging between VIII and X. All the islands of the central group experienced very destructive or devastating earthquakes. São Jorge has maximum intensity ranging from VIII to XI; Terceira and Faial have values in the VIII–X range; Graciosa is in the VIII–IX range; and Pico has a maximum intensity of VIII. Because intensity qualitatively describes the ground shaking, the MOI maps are helpful to assess the ground shaking from past seismicity of the Azores. However, they neither describe nor quantify the level of expected future ground shaking, nor allow inference about the seismic hazard; that is, it is not possible to observe that earthquakes repeatedly ruptured on a given part of a fault. In conclusion, the MOI mapping is an approach able to assess maximum intensity of areas that in the past were struck by damaging earthquakes, even if it has a poor instrumental dataset. The good results obtained here confirm that the OK method is able to reproduce the observed macroseismicity, to estimate maximum intensity, and to handle spatial gaps in the data. Thus, the information contained in the MOI maps is a valuable spatial instrument that stakeholders can use to establish their seismic-hazard mitigation plans.

DATA AND RESOURCES

Data are provided by the literature listed in the references in this article and in the Ⓔ electronic supplement, by the Catálogo Sísmico da Região dos Açores (CSRA) (Nunes *et al.*, 2004), and by the Instituto Português do Mar e da Atmosfera (IPMA, Lisbon, Portugal; https://www.ipma.pt, last accessed April 2016).

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