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The Lower Tagus Valley (Portugal) earthquakes: Lisbon 26 January 1531 and Benavente 23 April 1909

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Abstract. The Lower Tagus Valley (LTV) has been the source of several local earthquakes that affected the region of Lisbon, in the central part of Portugal. In spite of absence of strong earthquakes during the last 100 years, past events have produced large damage in this area. We present the state of the art concerning the last two major earthquakes, which occurred in 1531 and 1909. The effects of both events are described, based on coeval reports already interpreted by several authors. The source parameters determined by different authors are also presented. The characterization of the seismogenic potential of the LTV is very important to better estimate the seismic hazard and risk of the region of Lisbon and Tagus Valley.
Keywords: Lower Tagus Valley; 1531 Lisbon earthquake; 1909 Benavente earthquake; historical earthquakes.

[es] Los terremotos del Bajo Valle del Tajo (Portugal): Lisboa 26 de Enero de 1531 y Benavente 23 de Abril de 1909

Resumen. El Bajo Valle del Tajo (LTV) ha sido la fuente de varios terremotos que afectaron la región de Lisboa, en el Centro de Portugal. Aunque no han ocurrido terremotos fuertes en los últimos 100 años, eventos anteriores produjeron grandes destrozos en la zona. Presentamos el Estado del Arte sobre los dos últimos grandes terremotos, ocurridos en 1531 y 1909. Se describen los efectos de ambos terremotos a partir de informaciones coevas interpretadas por diferentes autores. Asimismo, se presentan los parámetros de la fuente determinados por diferentes autores. La caracterización del potencial sismogenético del LTV es muy importante para una mejor evaluación de la peligrosidad y el riesgo sísmico en la región de Lisboa y el Valle del Tajo.
Palabras clave: Bajo Valle del Tajo; Terremoto de Lisboa de 1531; Terremoto de Benavente; Terremotos históricos.

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1. Introduction

The Lower Tagus Valley (LTV) region is located in the central part of Portugal mainland, bordering the Atlantic Ocean. It belongs to the administrative region of Lisbon and Tagus Valley (CCDR-LVT), which comprises the Lisbon Metropolitan Area, the Tagus Lezíria, the Middle Tagus and the West Zone (Figure 1). The LTV includes the southern sub-regions (the Lisbon Metropolitan Area and the Tagus Lezíria).

The LTV can be characterized as a major regional geomorphic feature consisting of a NNE-SSW wide valley where the Tagus River runs before it reaches the Atlantic Ocean, near Lisbon. Its marked linear trend, evident in maps and satellite imagery, has long been interpreted as resulting from a geological structural control, namely the presence of a fault zone located along the valley, commonly referred to as the "Lower Tagus Valley Fault". As we will detail below, the occurrence of a significant seismic activity along the valley corroborates the presence of active, seismogenic faults in the area, although evidencing a relatively more complex pattern.

The seismic history of Portugal is dominated by the occurrence of the 1st November 1755 high magnitude earthquake, which produced large damage in Lisbon. This earthquake was originated offshore, SW of Portugal mainland, strongly affecting many regions and towns of Portugal, Spain and Morocco. However, Lisbon has also been affected by some intraplate earthquakes originated in the LTV.

Reliable references to past earthquakes that affected the Portuguese territory date back to the 14th century, but the first event described in detail was the one originated in the LTV on 26 January 1531. A moment magnitude (Mw) larger than 6.0 was assigned to it by several authors (Vilanova and Fonseca 2007, Baptista et al. 2014).

Four centuries later occurred another strong earthquake in the LTV on 23 April 1909 (Mw = 6.0, estimated by Stich et al. 2005). It produced large damage in several small villages located in the eastern bank of the Tagus River, as Samora Correia, Benavente and Santo Estevão (Figure 1). Benavente, located ca. 30 km NE of Lisbon, was in the middle of the epicentral area and therefore this earthquake is often referred to as the "1909 Benavente earthquake".

This event was the largest earthquake that occurred onshore the Iberian Peninsula during the XX century. Several authors early recognized its relevance, as it is evident from the several studies that were immediately devoted to it (Calderón 1909, Comas Solà 1909, Cabral 1909, Messerschmitt 1909, Bensaude 1909, Navarro Neumann 1910, Diniz 1910, Choffat and Bensaude 1912). These studies dealt mainly with the macroseismic field although, even at such early times of instrumental seismology, some of the studies used already seismographic records (Comas Solá 1909, Messerschmitt 1909, Inglada 1909, Navarro Neumann 1910).

In Portugal, the occurrence of the 1909 Benavente earthquake contributed to the development and installation of the national seismological network (Miranda 1932, Mendes-Victor 2003). At that time, only one seismographic station existed in Portugal mainland, at the Observatory of Coimbra University (COI), and one in the Azores islands (Ponta Delgada - PDA). Both stations recorded the earthquake but unfortunately the seismograms were lost. In 1910, a Mainka seismograph was installed in the Observatory of Lisbon University, followed by the installation of Agamennone seismoscopes in three meteorological stations in Portugal mainland (Penhas Douradas, Évora and Lagos) and one in Madeira Island (Funchal) (Mendes-Victor 2003). This is why many authors state that the instrumental seismicity in Portugal began in 1910.

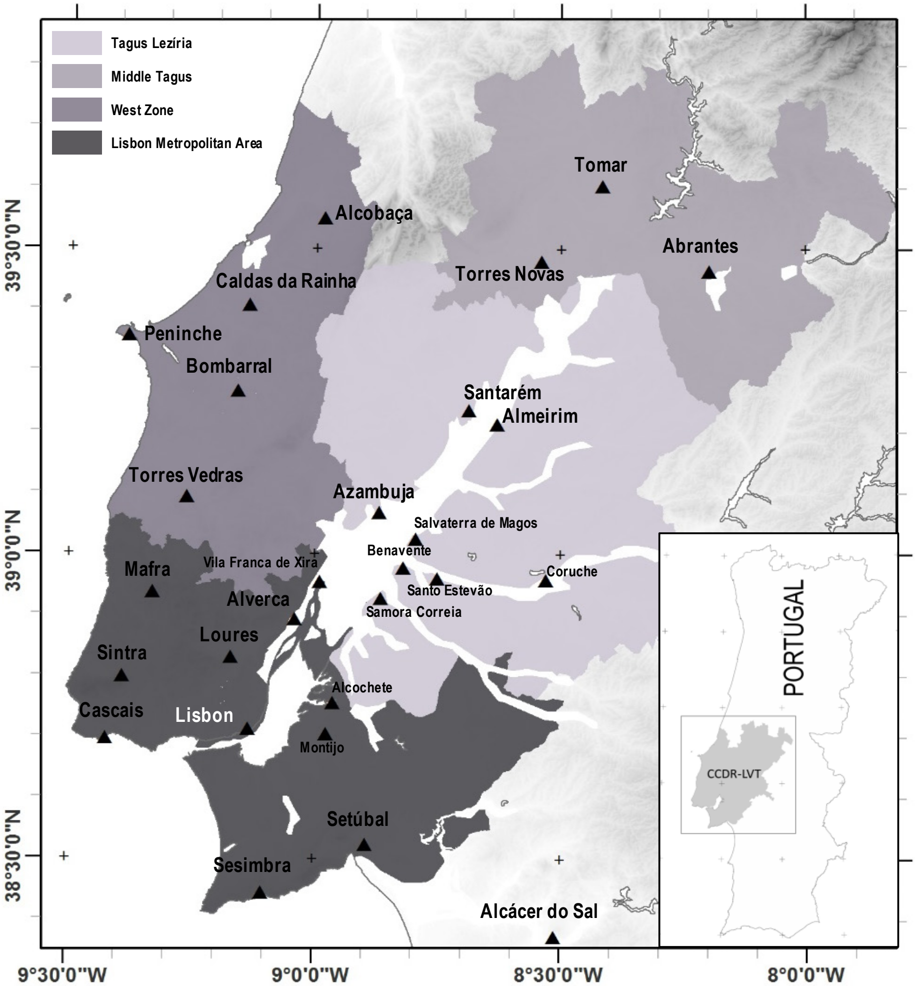


Figure 1. The administrative region of Lisbon and Tagus Valley (CCDR-LVT) located in the central part of Portugal. It comprises four sub-regions: the Middle Tagus, the West Zone rises, the Tagus Lezíria and the Lisbon Metropolitan Area. The LTV includes these two last sub-regions.

At the time of its occurrence, the most affected area was a rural zone with few inhabitants (about 6,300 people). Today this region still comprises an important rural area but the local villages have grown and the population presently reaches ca. 28,300 inhabitants. A considerable number of infrastructures with relevant importance to the country are presently located in the former epicentral area. Due to the concentration of the population, lifelines, critical infrastructures and the proximity to Lisbon, the scenario of occurrence of an earthquake similar to the 1909 event represents a high risk for the whole Lisbon Metropolitan Area (Figure 1), where more than one quarter of the Portuguese population lives (almost 3 million people, according to the last census of 2011).

During these last 100 years the seismic activity of the LTV has been low with about one felt earthquake per year. Since 1970 more than 700 earthquakes were recorded, from which 41 were felt, but only four exceed magnitude 4.0 and 30 had magnitudes between 3.0 and 3.9 (Martins and Mendes-Victor 2001, Carrilho et al. 2004, Custódio et al. 2015, IGN 2017). It is for this reason that even today the 1909 earthquake remains very significant, evidencing the seismic activity in the LTV and contributing in a very important way for the regional seismic hazard and risk assessment (Fonseca and Vilanova 2010). Recently, several studies have been performed to better understand its source mechanism, as well as the seismic attenuation processes in the western part of the Iberian Peninsula (Stich et al. 2005, Cabral et al. 2011, Teves-Costa and Batlló 2011).

In this work we will describe the present knowledge on the above referred two main LTV earthquakes, based on the up to date information collected from published papers of various authors.

2. Seismotectonic setting

The Lower Tagus valley (LTV) is sited in the Lower Tagus Cenozoic Basin (LTB; central-western mainland Portugal) which consists of a NE-SW elongated tectonic sink that developed as a complex left-lateral strike-slip basin in the Paleogene, acted by an approximately N-S compression. It later evolved to a transpressive foredeep basin during the Miocene, under a NNW-SSE to NW-SE compression that caused tectonic inversion of the extensional Mesozoic Lusitanian Basin (LB) located to the W (Fonseca 1989, Ribeiro et al. 1990, Cabral 1995, Rasmussen et al. 1998, Cabral et al. 2003, Carvalho 2003, Carvalho et al. 2016) (Figure 2).

The LTB comprises up to ca. 2000 m of Tertiary sediments consisting of alluvial fan deposits of Eocene-Oligocene age 200-400 m thick, overlain by Miocene fluvial and shallow marine sediments showing a variable width that surpasses 1000 m in depocenters. Fluvial sands and gravels of fini-Zanclean to Piazencian age, generally less than 100 m thick, unconformably overlie the Miocene deposits (Cabral et al. 2003, Carvalho 2003, Carvalho et al. 2016, Cunha et al. 2009, Pais et al. 2012, Rasmussen et al. 1998). The culminating surface of the Pliocene sedimentation is still preserved as a plateau in some areas of the LTB, reaching an altitude of ca. 190 m in the NE region of the basin and decreasing in height towards the SW. The regional uplifting that occurred since the Lower Pleistocene lead to entrenchment of the present fluvial network and the generation of a staircase of fluvial terraces (Martins 1999, Martins et al. 2009; 2010, Cunha et al. 2016). Along the present alluvial plain of the Tagus River occurs a thick (up to 70 m) Upper Pleistocene to Holocene alluvial cover.

Surface geology, borehole and geophysical data (seismic reflection, magnetic and gravimetric data) indicate a complex structure characterized by a segmented fault system dominated by several longitudinal, approximately N-S to NE-SW stepped faults evidencing vertical offsets affecting Cenozoic sediments (mostly high angle reverse, though probably working as oblique left-lateral reverse). These are linked by WNW-ESE to NW-SE faults also accommodating significant vertical offsets, which together constrain a few Neogene depocentres and structural highs in the basin. (Fonseca 1989, Rasmussen et al. 1998, Cabral et al. 2003, Carvalho 2003, Carvalho et al. 2016).

As referred, the LTV has been the site of M 6-7 earthquakes that caused severe damage and many casualties having thus been the subject of several studies focusing on the regional neotectonics and earthquake activity. In spite of their buried, hidden character, several active faults were identified, as exemplified below.

The Vila Franca de Xira fault consists of a NNE-SSW to N-S trending complex fault zone located along the southwestern border of the LTB, near Lisbon, with an overall length of up to ca. 50 km (Figure 2). It was generated in the Mesozoic as a normal fault zone of the LB (e.g., Rasmussen et al. 1998, Kullberg 2000, Carvalho et al.2005), and was later tectonically inverted, moving with oblique reverse-left lateral slip since the Neogene (Ribeiro et al. 1990, Cabral et al. 2003, Carvalho et al. 2006; 2008; 2011). It outcrops north of Lisbon as a steep east-verging reverse fault placing Jurassic rocks of the LB, at the west, over Miocene deposits of Tortonian age, at the east. Direct evidence of faulted Pliocene to Quaternary sediments has not been detected so far, though the fault presents a prominent scarp apparently displacing in about 100 m a regional erosion surface ca. 1 Ma old. This offset corresponds to a vertical slip rate of approximately 0.1 mm/yr in that time interval (Cabral 1995). This fault is considered the best candidate for having generated the 1531 Lisbon earthquake, felt with intensity IX in Vila Franca de Xira and with an estimated Mw close to 6.6 (Baptista et al. 2014).

The Azambuja fault is another NNE-SSW trending structure located in the LTV (Figure 2) exhibiting geomorphic and structural evidence of Pliocene to Quaternary activity (Cabral 1995, Cabral et al. 2003; 2004). This fault is evident in seismic reflection lines, showing steep thrust geometry downthrowing to the east the Cenozoic sediments of the LTB. It has a clear morphological signature, presenting an east facing, 15 km long scarp that results from the offset of a Lower Pleistocene erosion surface. The scarp increases height from north to south reaching ca. 80 m near the village of Azambuja, where it is interrupted by the present Tagus riverbank. The fault continues southwards hidden under the recent alluvium of the Tagus River, probably extending for at least further 15 km where it was detected affecting Tertiary horizons in a seismic section, thus totalizing an overall length of over 30 km (Cabral et al. 2004; 2011). Geological and morphotectonic studies indicate Quaternary slip on the fault in the range of 0.05-0.06 mm/yr (Cabral et al. 2004). The southern, hidden sector of the Azambuja fault extends to the meizoseismal area of the 1909 earthquake, making this fault a likely source for the seismic event (Cabral et al. 2011).

The Pinhal Novo-Alcochete Fault (PNAF) is a NNW-SSE structure located in the southern area of the LTV, east of Lisbon (Figure 2), barely expressed at the surface geology, as it is buried under a thick Cenozoic sedimentary cover. Although being a blind structure, the PNAF has been recognized for quite a long time by subsurface information, mostly seismic reflection and borehole data for oil exploration. The available data evidence the occurrence of a wall of Lower Jurassic evaporites intruding the fault zone (e.g., Walker 1983, Ribeiro et al. 1990), which shows a branched geometry, extending over a deformation zone up to 1.5 km wide (Cabral et al. 2003, Moniz 2010, Moniz and Cabral 2014). It was generated as an extensional structure at the eastern border of the Mesozoic LB in this sector, and was later reactivated with left-lateral strike-slip motion in the Miocene (Ribeiro et al. 1990). The subsurface data show that the basal unconformity of the Pliocene sediments is folded and downthrown to the east, indicating late Neogene to Quaternary tectonic activity under the current stress field. Plio-Quaternary activity is further supported by geomorphic evidence, namely the presence of an uplifted ridge and asymmetrical drainage network (Moniz 2010, Moniz and Cabral 2014).

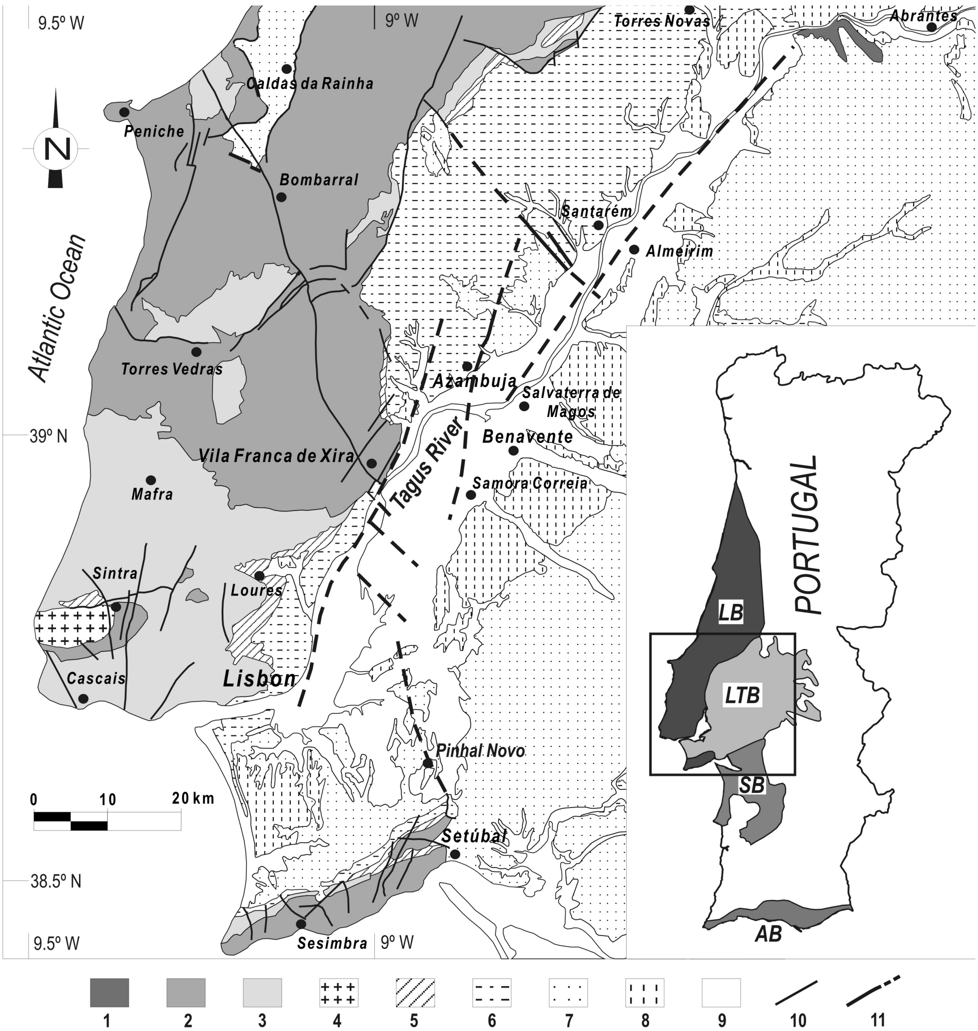


Figure 2. Geological Map of the Lower Tagus Valley region, adapted from Carta Geológica de Portugal, 1:500,000 scale (Oliveira et al. 1992). 1, Paleozoic basement; 2 and 3, Jurassic and Cretaceous sediments of the Lusitanian Basin; 4, Sintra Late-Cretaceous intrusive massif; 5, 6 and 7, Paleogene, Miocene and Pliocene sediments of the Lower Tagus Basin; 8 and 9, Pleistocene and Holocene fluvial sediments of the Tagus river; 10, mapped fault according to Oliveira et al. (1992); 11, active fault (certain and probable location); AB, Algarve Basin; LB, Lusitanian Basin; LTB, Lower Tagus Cenozoic Basin; SB, Sado Cenozoic Basin.

Search for surface faulting evidence and paleoseismic data has been performed by several teams on the Lower Tagus fault system, though the results are still scarce and controversial (Fonseca et al. 2000, Vilanova 2003, Vilanova and Fonseca 2004, Cabral and Marques 2001, Cabral et al. 2011, Besana-Ostman et al. 2012, Canora et al. 2015). Based on detailed geomorphic studies, Besana-Ostman et al. (2012) argue to have recognized a major active structure extending NNE-SSW for 85 km along the western bank of the Tagus River, which they call the "Lower Tagus Valley fault zone". Canora et al. (2015) have performed geomorphological, paleoseismological and seismic reflection studies on a proposed structure at the eastern side of the Tagus valley, which they name "eastern strand of the Lower Tagus Valley Fault Zone", claiming left-lateral strike-slip fault activity with a minimum slip rate of 0.14-0.24 mm/yr. Based on geomorphic and paleoseismic evidence they infer at least six surface rupture events in the past 10 ka, at least two having occurred after 1175 ± 95 cal yr BP.

The segmentation fault pattern that has been recognised so far in the LTV, and the common fault-magnitude scaling laws, point to a generation potential of $M \approx 7$ maximum local earthquakes, which is slightly higher than the magnitude of the events that have been reported to the present.

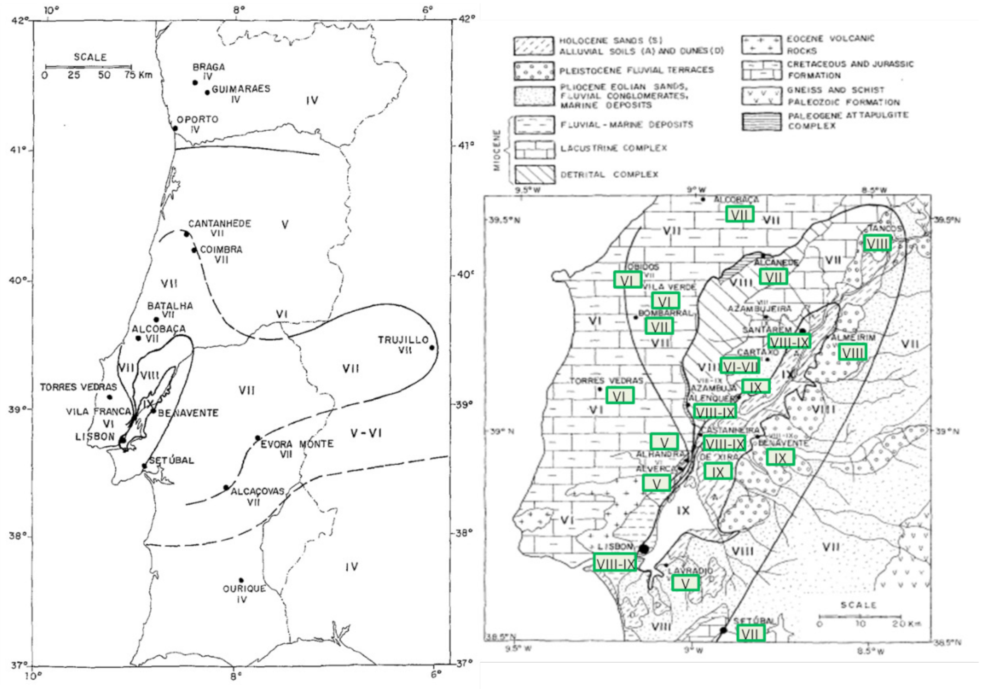
3. The Lower Tagus Valley Earthquakes

3.1. The 26 January 1531 Lisbon earthquake

The seismic activity of the Lower Tagus Valley is characterized by several small and medium size earthquakes, and by some strong earthquakes that occurred in historical times. In particular, the town of Lisbon has been struck by several moderate to large earthquakes (for instance in 1344, 1356, 1531, 1755, 1909), of which those occurred in 1344, 1531 and 1909 were generated in the LTV region (Moreira 1984; 1991a). Although only in the middle of the 14th century it is possible to find reliable references to past earthquakes that affected Portugal, several authors (Moreira de Mendonça 1758; Galbis Rodriguez 1932; Moreira 1991a; Martínez Solares and Mezcua 2002) reported that the earthquake that occurred in 1344 must have had its epicentre in the LTV. It produced important damages in the town of Lisbon (e.g., the main chapel of the Cathedral collapsed) and many people died (Moreira 1991a). The inferred maximum Modified Mercalli (MM) intensity was VII-VIII (Oliveira 1986) and magnitudes assigned to it range from Mb 6.0 (Martins and Mendes-Victor 1990; 2001) to Mw 6.7 (Vilanova and Fonseca 2007). However, this is a controversial event because there are not contemporary references (the existing references date from the XVI century onwards).

Among historical earthquakes, the first described in detail was the one that occurred on January 26, 1531. It was preceded by several shocks since the beginning of the month. Its epicentre was probably located between Vila Franca de Xira and Azambuja, and the maximum assigned intensity (MM) was IX-X (Moreira 1984). In Lisbon intensities of VIII and IX were reported. About 25% of the houses were damaged, 10% suffered total collapse and 2% of the population was killed (Henriques et al. 1988). Vogt (1985) and Justo and Salwa (1998) pointed to a total of 1000 casualties. Liquefaction phenomena, as well as large destruction, was reported in the LTV region (for instance, in Vila Franca de Xira, Azambuja, Santarém and Almeirim), causing many victims as far as Tomar, in the northern part of the LTV (Moreira 1991a). Movements in the Tagus waters were also reported, indicating that boats that were about 90 m from the shore stayed dry or touched with the keel in the river bed. Baptista et al. (2014) consider the occurrence of a tsunami. The earthquake was also strongly felt in the southern Tagus margin (for instance, in Setúbal and Alcácer do Sal), where it was mentioned that water came out abundantly from cracks opened in the soil. This earthquake was followed by several aftershocks that were felt in the entire region during the following months.

Magnitude Mb 7.1 (Martins and Mendes-Victor 2001), Mw 6.9 (Vilanova and Fonseca 2007) or Mw 6.0-6.6 (Baptista et al. 2014) is assigned to it. Moreira (1991a) presented an isoseismal map for the Lower Tagus Valley region and Justo and Salwa (1998) presented a general isoseismal map for Portugal and adjacent Spanish region as far as Trujillo, suggesting a very low seismic attenuation in the eastern direction. (Figure 3a). Based on the large water agitation described in the Tagus estuary, the effects produced in small boats anchored in the upper estuary and on the river banks, as well as the damage reported in several riverside localities, Baptista et al. (2014) modeled a probably generated tsunami assuming that the Vila Franca de Xira Fault was the tectonic source of this earthquake. Accordingly, the coseismic uplift produced in the northwestern margin of the river affected the Tagus inner estuary, generating the tsunami. Baptista et al. (2014) also made a critical revision of the macroseismic data, assigning new intensity data points (Figure 3b). Based on this new macroseismic data they calculated an epicenter at 39.00° N, 8.89°W and a magnitude Mw 6.06±0.31. The tsunami modeling in the Tagus estuary demands a magnitude Mw 6.6 which is higher but closer to previous estimations.



(a) **(b)**

Figure 3. Isoseismal maps for the 1531 earthquake: (a) far field (from Justo and Salwa, 1998); (b) near filed isoseismals from Justo and Salwa (1998) with the intensities assigned by Baptista et al. (2014) superimposed (in green). [The color version of this figure is available only in the electronic edition.]

3.2. The 23 April 1909 Benavente

On April 23, 1909, at 5:40 p.m. (GMT), a strong earthquake with epicentre close to the town of Benavente was felt in the whole LTV region. This earthquake produced 46 fatalities and 75 people were injured.

In the epicentral area, the small towns of Benavente, Samora Correia and Santo Estevão suffered severe damage. About 80% of the houses were uninhabitable due to collapse or severe damage and Choffat and Bensaude (1912) assigned intensity X to these locations. Also, in other small towns scattered in this region, many buildings and houses collapsed or suffered severe damage.

Choffat and Bensaude (1912) published a detailed report, which presents a large amount of information about the effects of this earthquake in the whole country, including maps and photographs. This exhaustive report is the primary source of information on the 1909 Benavente earthquake. The work describes the damage and effects caused by the earthquake mainly in Portugal. These descriptions are more detailed for the zones near the epicentre and become more generic for the less affected zones. Below is the damage description for the main affected zones, taken from this report.

In Benavente, a town with 3,557 inhabitants (at that time), 40% of the buildings collapsed or had to be demolished, and another 40% required major repairs; only 1 building suffered no damage. This was the village where there were more victims (30 dead and 35 injured). In Santo Estevão, with 832 inhabitants, only 11 houses remained habitable after minor repairs. In Samora Correia (2,084 inhabitants) most houses (mainly built of mud and stone) collapsed and even good masonry constructions suffered major damage. The church did not collapse but was severely fissured. In Salvaterra de Magos (4,663 inhabitants) most houses stood up but they had to be demolished later due to their severe damage (some of them collapsed some days after during a wind storm). Only 6 buildings, built of good masonry, remained habitable (Choffat and Bensaude 1912).

In the Tagus Lezíria sub-region (see Figure 1), corresponding to an alluvial plain, only isolated houses belonging to the guards of the Company of the Lezírias existed. In the northern part these houses were destroyed, suffering less in the southern part. Most important damage was observed in Alverca, Alhandra and Vila Franca de Xira on the buildings and houses built in the Tagus margin. In the alluvial plain numerous cracks were observed, often accompanied by water and sand ejections. This also occurred during the strongest aftershocks in May 4 and August 2 (Choffat and Bensaude 1912). The ejections of sand and water during the earthquake were the phenomena that most impressed the population. The sand seemed black when ejected (it was wet), but after dried it turned white, contrasting with the dark soil, especially in the freshly drawn lands, where the seeds had not yet germinated. These cracks could be distinguished at a great distance by the white marks that they formed (Figure 4).

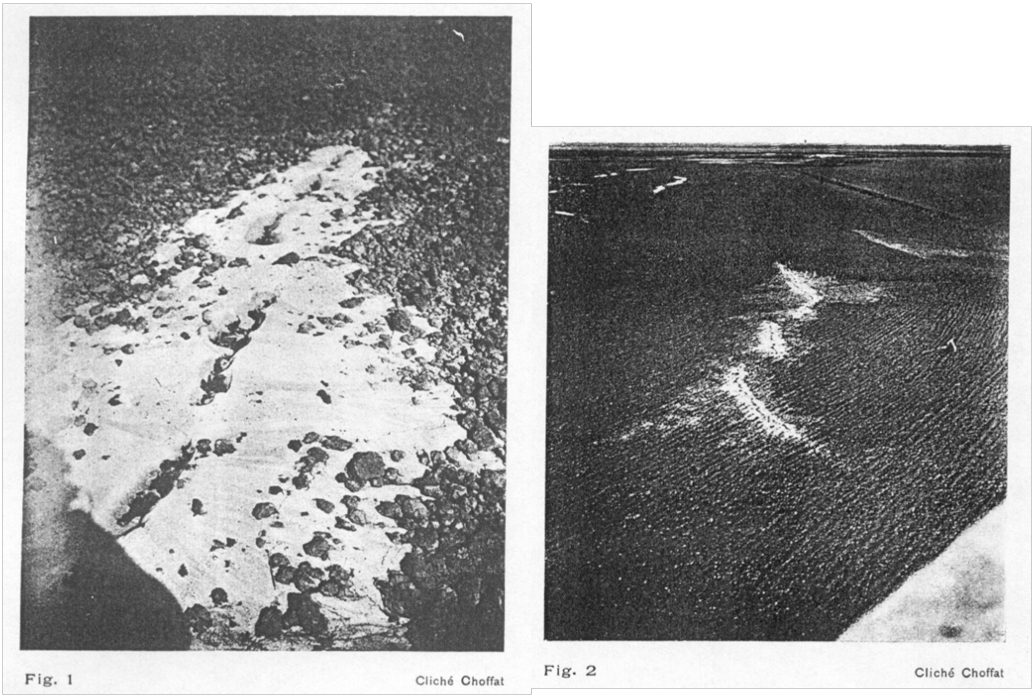


Figure 4. Photos of cracks and sand ejections generated in the Tagus alluvial plain (from Choffat and Bensaude 1912).

In Lisbon, Choffat and Bensaude (1912) estimated intensities between III and VII. Most damage consisted of fall or partial collapse of chimneys, cracks on façades, stucco fall, tilt of old houses, cracked walls and fall of two florets on the façade of a building. The damage was not homogeneously distributed along the town: the eastern part suffered more damage than the central and western parts of the town.

For each locality, Choffat and Bensaude (1912) assigned an intensity based on the Mercalli—Cancani intensity scale (Cancani 1904, Davison 1933), but with a small personal adaptation to take into consideration the specific characteristics of the Portuguese building constructions (Bensaude 1909). From Spain, they took the works of Calderón (1909) and Navarro Neumann (1910) as reference, although they have consulted additional sources. Fonseca and Vilanova (2010) reproduced their map for the entire affected area (in Portugal and Spain). In Figure 5 their isoseismal map for the meizoseismal zone is shown.

Later, especially for the compilation of macroseismic data, several authors presented other isoseismal maps for this earthquake: (i) Mezcua (1982) published a map that covers the whole Iberian Peninsula, which is mainly based on the original map of Choffat and Bensaude (1912) with slight modifications; (ii) Senos et al. (1994) presented a map for Portugal and Moreira (1991a) published a partial map focusing the epicentral area.

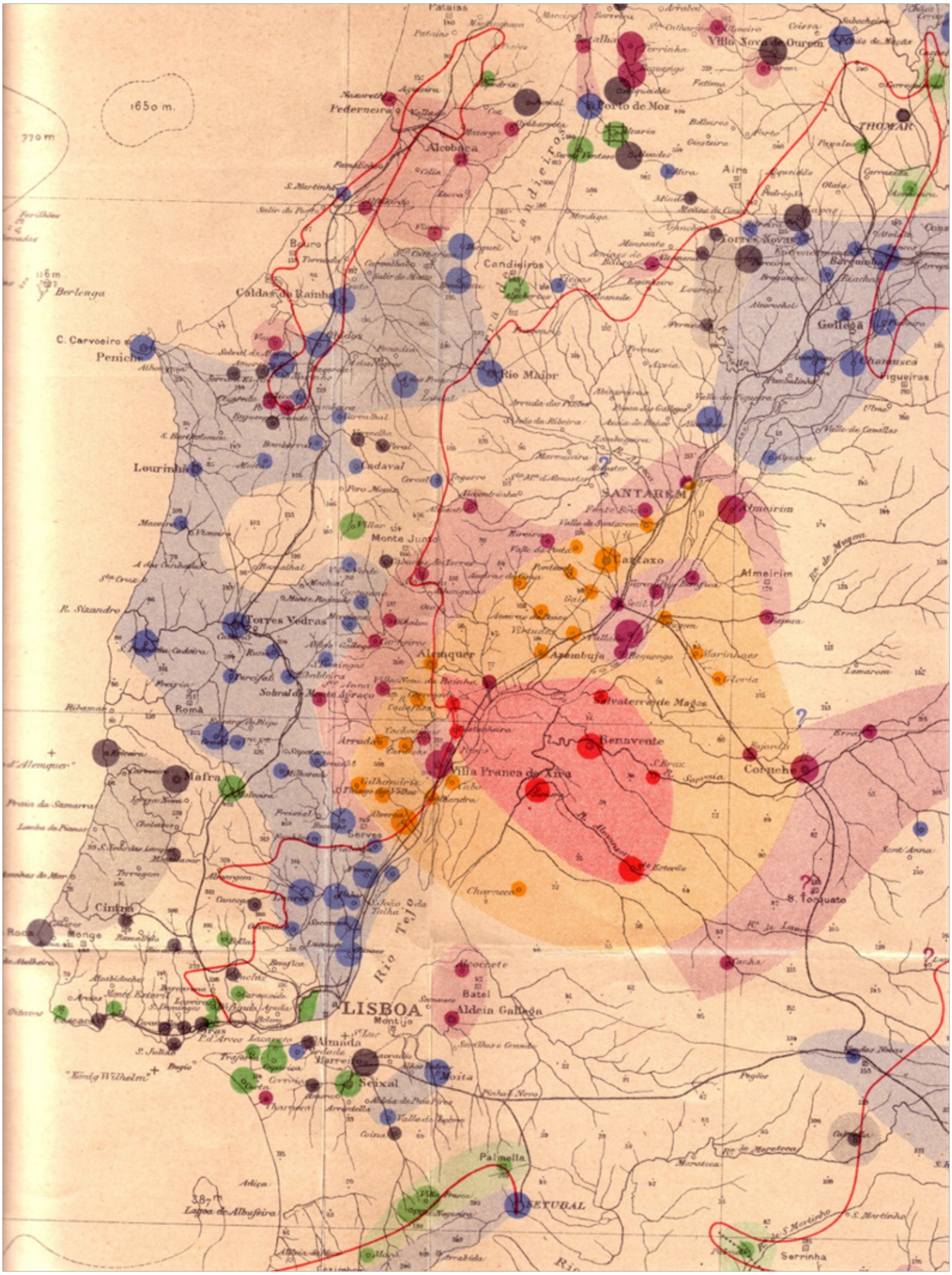


Figure 5. Isoseismal map for the epicentral area of the 23 April 1909 earthquake presented in Choffat and Bensaude (1912) report. [The color version of this figure is available only in the electronic edition.]

The intensity distribution in the near-field is well constrained due to the large amount of intensity data points; however, in the macroseismic far field, the isoseismal curves present a strange pattern, that can be due to the small amount of intensity data points in Spain. Teves-Costa and Batlló (2011) presented an extensive review of the macroseismic field, adding several intensity data points in Spain, and they discussed the intensity distribution in the far field with the seismic attenuation in the Iberian Peninsula. The isoseimal map produced by these authors, for the whole Iberian Peninsula, is presented in Figure 6. In spite of the large increase of macroseismic information in Spain, the isoseismal curves still present an abnormal seismic attenuation. However, this pattern is not very different from the one presented in Justo and Salwa (1998) for the 1531 earthquake (see Figure 3a). Several authors associated this pattern with particularly low seismic attenuation and complex seismic propagation processes observed in the central part of the Iberian Peninsula (Choffat and Bensaude 2012, Justo and Salwa 1998, Martínez Solares and Mezcua 2002, Teves-Costa and Batlló 2011). The existence of local site effects, in particular for the larger towns, cannot be discarded: if they are not clearly identified they can significantly modify the isoseismal pattern. Also, regional geology dependent effects seem to be present.

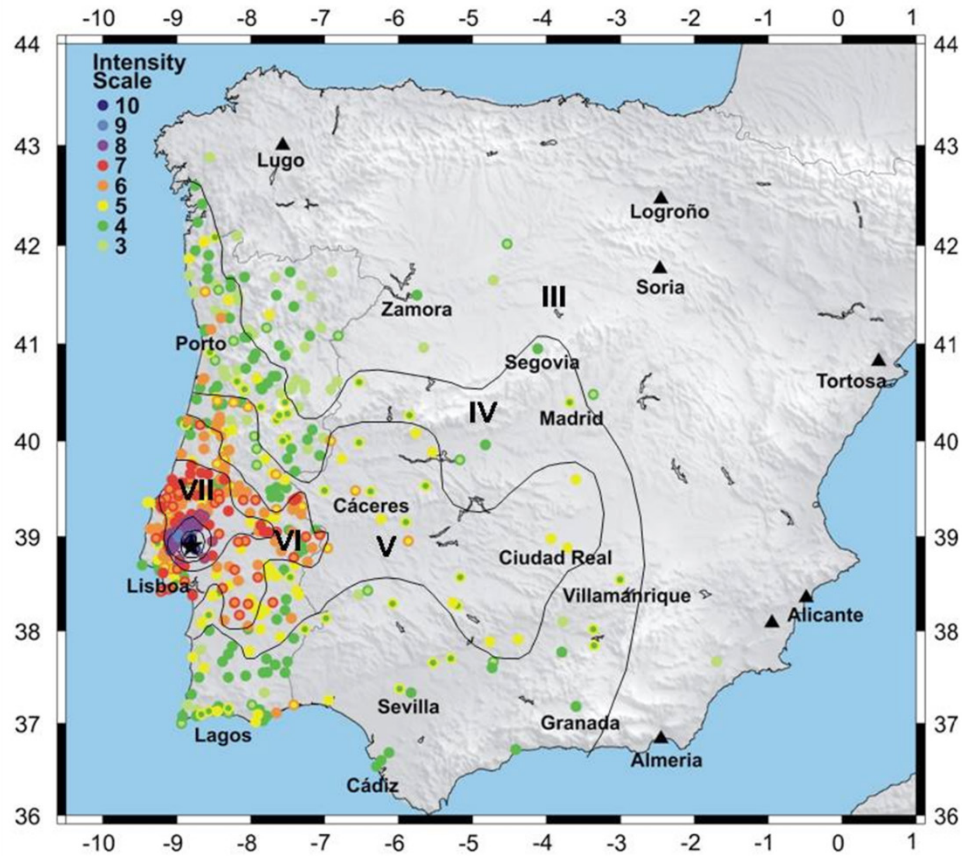


Figure 6. Isoseismal map of the 23 April 1909 earthquake (from Teves-Costa and Batlló 2011). [The color version of this figure is available only in the electronic edition.]

4. Source parameters of the 1909 earthquake

4.1. Instrumental seismic records collection

When the Benavente earthquake occurred, in 1909, seismology was still in its early times. However, the earthquake was recorded all over Europe and also in some seismic observatories located in other continents (Figure 7). The exchange of information was fast and, in a few months, Navarro Neumann (1910) was able to collect information from 51 stations. In recent times, Dineva et al. (2002) collected as much original material as possible (station bulletins, telegrams, etc.). From this search, arrival times from 54 seismic observatories located across de globe were assembled.

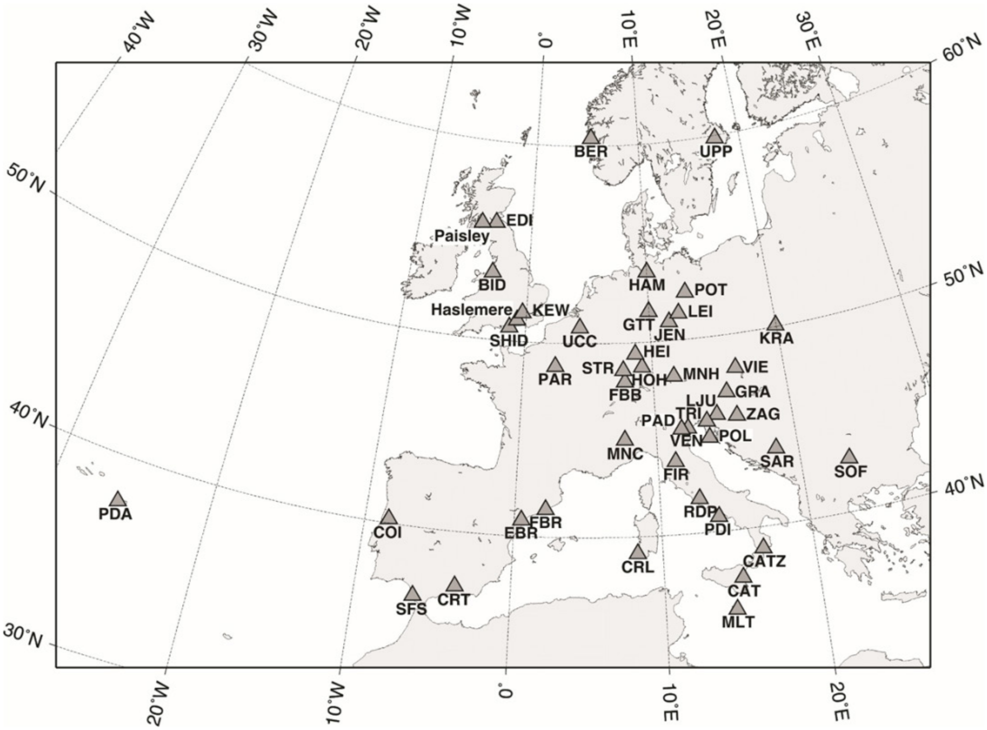
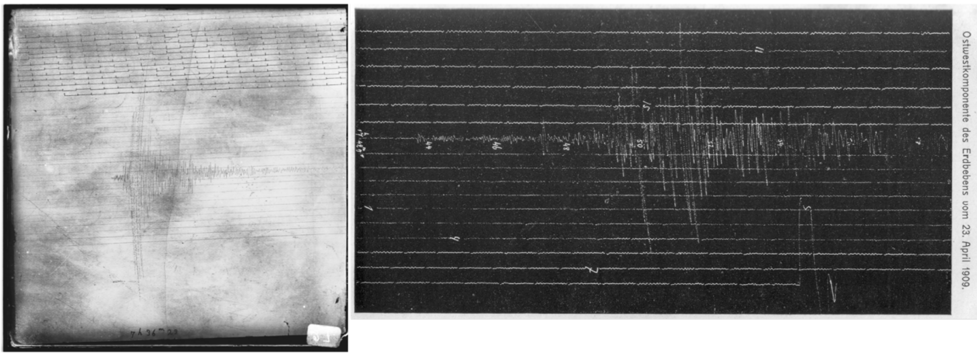


Figure 7. Location of the European seismic stations that recorded the 23 April 1909 earthquake. Besides these, other stations in Asia, Africa, North and South America recorded this event.

A throughout search for original records of the event showed that many of them were lost or were destroyed. Nowadays, combined efforts of Teves-Costa et al. (1999, 2005), Dineva et al. (2002) and Stich et al. (2005) to locate records of the Benavente earthquake allowed to recover 31 potentially useful seismograms of this event (Table 1). Data sources include original smoked paper recordings and photographic contacts as well as photocopies or reproductions of seismograms in journals. The latter ones are frequently of lower quality than original recordings, and in such cases it may be more difficult to identify seismogram components, polarity and start time. Figure 8 shows two seismograms of the event. The first one (Figure 8a) corresponds to the Omori instrument at the Cartuja (CRT) observatory. The original was lost and the one presented was obtained from a photographic contact. The second one (Figure 8b) is a component of the Wiechert record obtained at Munich (MNH). The shown record was published in a contemporary journal but, in this case, the original is also preserved. Similar seismograms were used to estimate the location and magnitude of the earthquake (for instance, Antunes 1956, Moreira 1991a). Stich et al. (2005) used seismograms that were originally recorded on smoked paper to calculate the moment tensor for this event. The records were digitized, corrected for stylus finite length curvature effect and interpolated, following the procedures described in Dineva et al. (2002), before being used in the computation.

Table 1. Seismic stations and recording instruments from which useful seismograms were recovered and used in the instrumental studies

STATION	CODE	SEISMOGRAPH TYPE	Nb. RECORDS
Cartuja (Spain)	CTR	Mod. Omori; Wiechert; Bifilar	3
DeBilt (Netherlands)	DNB	Bosch-Omori	1
Ebro (Spain)	EBR	Grablovitz	2
Fabra (Spain)	FBR	Cancani	2
Gottingen (Germany)	GTT	Wiechert	3
Hamburg (Germany)	HAM	Wiechert; Hecker	4
Hohenheim (Germany)	HOH	Bosh-Omori; Trif. Schmith	3
Jena (Germany)	JEN	Wiechert	2
Leipzig (Germany)	LEI	Wiechert	2
Munich (Germany)	MNH	Wiechert	2
Porto d'Ischia (Italy)	PDI	Grablovitz	2
Rocca di Papa (Italy)	RDP	Agamennone	2
Strasbourg (France)	STR	Wiechert	1
Uppsala (Sweden)	UPP	Wiechert	2



(a) **(b)**

Figure 8. Reproduction of two preserved seismograms of the 23 April 1909 earthquake: (a) from Cartuja observatory (CRT), in Spain; (b) from Munich seismic station (MNH), in Germany.

4.2. Location, magnitude and focal mechanism

When the 1909 earthquake occurred, and following the practice at that time, location was given as the name of the nearest town to the earthquake Imax zone, which is Benavente. Anyway, the report of the British Association for the Advancement of Sciences (BAAS 1912) already includes a geographical location (39ºN, 9ºW) and classifies it as “destructive”. It is necessary to wait for the work of Antunes (1956) to find epicentral coordinates calculated from the instrumental arrival times (38º56’N, 08º44’W). Munuera (1963) in his Iberian catalogue proposes the coordinates 37.8ºN, 8.9ºW (significantly misallocated). It is not clear if these last coordinates were calculated using instrumental data and graphical methods or relayed on the macroseismic information. The coordinates of Antunes (1956) were used in several catalogues (Kárník 1969: -38.9ºN, 8.8ºW; Mezcua and Martínez Solares 1983: -38.95ºN, 8.8ºW; Oliveira 1986, Martins and Mendes-Victor 1990; 2001).

Cabral et al. (2013) calculated again the epicentral coordinates based on the instrumental arrival times already collected and consigned in Dineva et al. (2002), and using the program Hypocenter (Lienert 1994) under the SEISAN package (Ottemöller et al. 2011). The solution presenting the smallest error locates the earthquake at 38.72ºN, 9.11ºW, near Lisbon, but, as shown in Figure 9, where the error ellipse is plotted, the accuracy of the calculated epicenter is not best than 50 km in any direction, resulting in a useless solution. A similar result was found by Dineva et al. (2002) and Teves-Costa et al. (2005). The main causes of such a large error lie in the low accuracy of the station clocks at that time (time was kept independently at each station only with nocturnal astronomical observations and absolute time errors larger than 10 s were not exception), the poor timing resolution of some seismograms (at Coimbra-COI, the nearest station, the paper speed was 1 mm/min, that is, 0.1 mm of record equals to 6 s), and misinterpretation of phases, though several evident errors were removed (Cabral et al. 2013).

In the last decades, several algorithms allowing to locate earthquakes using intensity data points have been devised. For the 1909 event, macroseismic location and magnitude were determined using the BOXER 3.3 program (Gasperini et al. 1999). Intensity data points published in Teves-Costa and Batlló (2011), and an intensity attenuation law for the Iberian Peninsula (Stucchi et al. 2010), were used. The calculated epicenter is located at 38.98ºN, 8.86ºW, near Benavente (see Figure 9). This location, showing a small error (±9 km), is not surprising because BOXER takes as epicenter the baricenter of the highest intensity degrees, previously known as distributed around Benavente. As discussed below, the used algorithm gives a moment magnitude of 6.0 ± 0.2 (Cabral et al. 2013).

Together with the coordinates, several authors also estimated the origin time (Antunes 1956, Dineva et al. 2002, Teves-Costa et al. 2005). According to the seismic bulletin of Coimbra (the station closer to the epicenter), P wave arrival was detected at 17h 40m 12s (Dineva et al. 2002). In spite of the large errors (≥ 8 s) the mean origin time estimated by the different authors is very similar and close to 17 h 39 m 39 s.

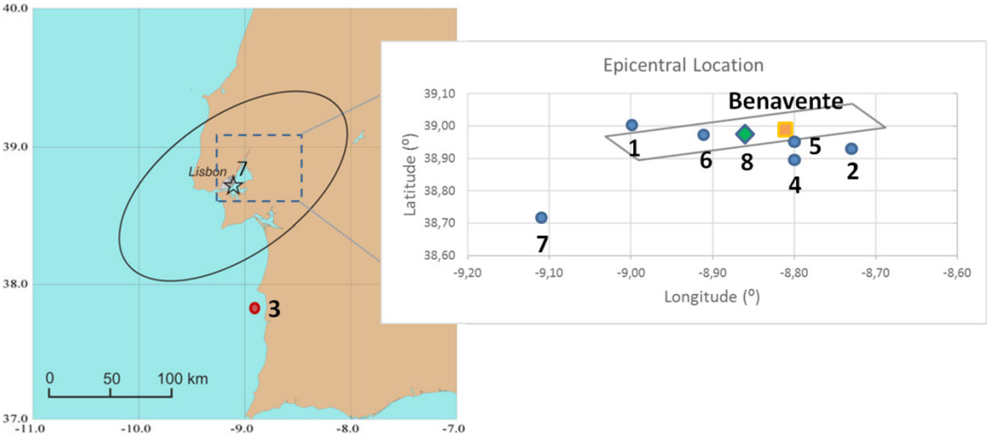


Figure 9. Epicentral coordinates of the 23 April 1909 earthquake presented in different catalogues and estimated by various authors: 1 - BAAS (1912); 2 - Antunes (1956); 3 - Munuera (1963); 4 - Kárník (1969); 5 - Mezcua and Martínez Solares (1983); 6 - Teves-Costa et al. (2005); 7 - Cabral et al. (2013) using Hipocenter program; 8 - Cabral et al. (2013) using BOXER program (point 8 is the central part of the rectangle, also represented in grey, determined by this program). The square indicates the location of Benavente. [The color version of this figure is available only in the electronic edition.]

For some reason, Gutenberg and Richter (1954) did not assign a magnitude to the Benavente earthquake although it could be estimated through the BAAS (1912) (instead, they calculated a magnitude for the 1910 Adra earthquake, occurred just one year after, offshore the SSE Iberian coast and with a similar size). Possibly they did not collect enough data for the location and/or magnitude determination of the 1909 event.

Thus, the first magnitude estimate for this event was provided by Antunes (1956) with M = 7 1/3 obtained from Imax. Munuera (1963) obtained M = 6.6 with the same methodology but using a different equation. Later Ferreira (unpublished manuscript, cited in Kárník 1969, and in Moreira 1991a) used Imax to obtain M = 7.1.

Kárník (1969) made the first calculation using instrumental records. From amplitudes read in bulletins of 13 stations he calculated Ms = 6.6. Moreira (1991a) using a duration formula and just the seismogram from Hohenheim (seismic station located in Stuttgart) calculated M = 6.7.

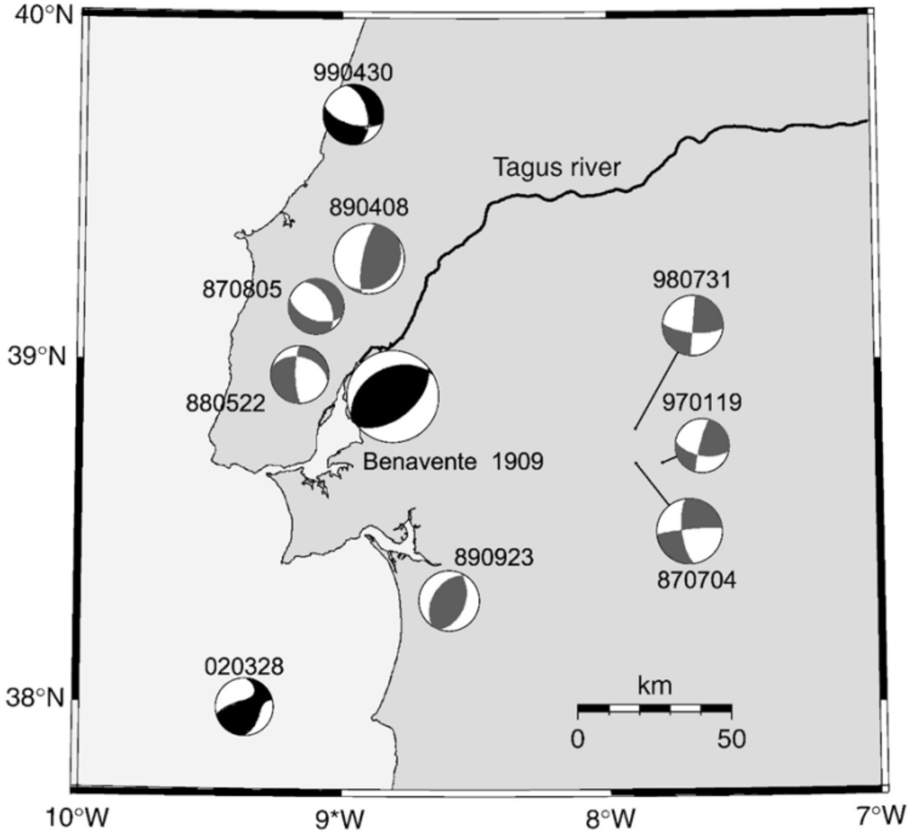


Figure 10. Focal mechanism of the 23 April 1909 earthquake (larger symbol) determined by Stich et al. (2005). The other mechanisms were determined by Moreira (1991b), Borges et al. (2001), Ribeiro et al. (1996) and Stich et al. (2003) (from Stich et al. 2005).

Martins and Mendes-Victor (1990) consigned, in their catalogue, a magnitude 7.6 for this event. As Teves Costa et al. (1999) pointed out, this large value may be due to the use of the Gutenberg and Richter (1954) formula or simply due to a mismatch when transcribing the magnitude of Moreira (1991a).

Dineva et al. (2002) obtained Ms = 6.3 ±0.25 using the maximum amplitude of 19 Milne seismic stations and Teves-Costa et al. (2005) obtained Ms = 6.35 ±0.32 using 15 phases recorded by Wiechert seismographs from 8 seismic stations.

The most recent estimations calculated Mw from the spectra of body waves of the digitized seismograms. Teves Costa et al. (1999) obtained 6.0 using just two stations. Later, Dineva et al. (2002) obtained Mw = 6.2 ±0.2 using a more complete set of seismograms and Teves-Costa et al. (2005) obtained Mw = 6.13 ±0.05 using 31 seismograms from 14 seismic stations (Table 1). Finally, Stich et al. (2005) performed a full wave inversion and obtained Mw = 6.0 ± 0.1, with best fit for h = 10 km.

The most likely moment tensor solution computed by Stich et al. (2005) indicates reverse faulting with nodal planes trending ENE-WSW (strike/dip/rake of N51ºE/52º/83º and N242ºE/38º/99º) (Figure 10). These nodal planes do not match any known outcropping active structure in the area suggesting that the event could have been produced by a blind thrust beneath the Cenozoic sedimentary fill (Cabral 1995, Stich et al. 2005, Cabral et al., 2013). However, this focal mechanism is similar to others obtained for this region (Borges et al. 2001), and it is consistent with the stress field inferred for this area (Ribeiro et al. 1996, Stich et al. 2003, Cabral et al. 2003; 2004).

The main 1909 shock was followed by many aftershocks. The list of aftershocks differs from one catalogue to another. We performed a review using two contemporary sources, the Choffat and Bensaude (1912) report and the official list of felt events published daily in the "*Diário do Governo*". All together we count up to 183 aftershocks. Only the largest one, occurred on August 2nd, was instrumentally recorded. The poor determination of a large number of these events prevents further studies.

5. Conclusions

The seismic activity in the LTV has been low and diffuse since the 1909 event. Current seismicity monitored by the National seismic network, as well as the source parameters estimated for the 1909 earthquake, indicate that the seismogenic sources extend through the upper crust (focal depths below 5 km) and thus comprise faults in the Paleozoic basement, located beneath the Mesozoic rocks of the Lusitanian Basin and the overlaying Cenozoic sedimentary cover that outcrops in the area (Cabral et al. 2013). These hidden faults have contributed, and are a major constraint for the seismic hazard of the region, as well for its seismic risk, and they may be particularly hazardous because they are absent or poorly perceptible at the surface, catching the population unaware of their presence and seismogenic activity. An example of the impact that such hidden active faults may produce is the large 1994, Mw 6.7 Northridge (California, USA) earthquake, which was generated by a blind thrust fault causing great damage and economic losses (Jones et al. 1994).

Study of past earthquakes, as the 1531 and 1909 earthquakes, can help us to characterize the seismogenic potential of the LTV and to better estimate the seismic hazard of Lisbon and Tagus Valley region. According to the studies performed until now, the LTV can produce an earthquake with magnitude Mw 6.0 or larger. However, some authors argue that the LTV seismic zone extends to the southern part of the Lisbon Metropolitan Area and that the earthquake of 11 November 1858, with epicenter offshore and close to the town of Setúbal, was also produced in this seismogenic zone (estimated magnitude Mw 7.1, Vilanova and Fonseca 2007). In spite of a probable overestimation of its magnitude (Stucchi et al. 2013 present Mw 6.8±0.6) this event thus also contributes to the regional seismic hazard.

Taking into consideration the concentration of lifelines and critical infrastructures as well as the number of people living and working in this region (particularly in the Lisbon Metropolitan Area) we can consider that this region presents the higher seismic risk in Portugal mainland. It is why it is necessary to emphasize the historical earthquakes, and not let them fall into oblivion, in order to draw attention for the implementation of mitigation measures to decrease the regional seismic risk.

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7. References

Antunes, M.T.A. (1956). Aspectos geofísicos do terramoto de Benavente de 23 de Abril de 1909. *Revista da Faculdade de Ciências de Lisboa* VI, fasc. 1º, 5-28. [in Portuguese]

Baas (1912). Seismological Investigations - Seventeenth Report of the Committee. In: *Report of the Eighty-second Meeting of the British Association for the Advancement of Sciences*, Dundee, London, John Murray, 69-103.

Baptista, M.A., Miranda, J.M., Batlló, J. (2014). The 1531 Lisbon Earthquake: A Tsunami in the Tagus Estuary? *Bull. Seismol. Soc. Am.* 104 (5), 2149-2161.

Bensaude, A. (1909). Le Tremblement de Terre de la Vallée du Tage du 23 Avril 1909 (Note préliminaire). *Bull. Soc. Portug. Sci. Nat.* IV, 89-129. [in French]

Besana-Ostman, G.M., Vilanova, S.P., Nemser, E.S., Flacao-Flor, A., Heleno, S., Ferreira, H., Fonseca, J.D. (2012). Large Holocene Earthquakes in the Lower Tagus Valley Fault Zone, Central Portugal. *Seismological Research Letters* 83:67-76.

Borges, J.F., Fitas, A.J.S., Bezzeghoud, M., Teves-Costa, P. (2001). Seismotectonics of Portugal and its adjacent Atlantic area. *Tectonophysics* 331, 373-387.

Cabral, F.P. (1909). Algumas notas sobre o tremor de terra de 23 de Abril. *Broteria* VIII:182. [in Portuguese]

Cabral, J. (1995). Neotectónica em Portugal Continental. *Memórias do Instituto Geológico e Mineiro* 31, Lisboa, 265 p. [in Portuguese]

Cabral, J., Marques, F. (2001). Paleoseismological studies in Portugal: Holocene thrusting or landslide activity? *EOS Transactions* 82, 351-352.

Cabral, J., Moniz, C., Ribeiro, P., Terrinha, P., Matias, L. (2003). Analysis of seismic reflection data as a tool for the seismotectonic assessment of a low activity intraplate basin - the Lower Tagus Valley (Portugal). *Journal of Seismology* 7, 431-447.

Cabral, J., Ribeiro, P., Figueiredo, P., Pimentel, N., Martins, A. (2004). The Azambuja fault: An active structure located in an intraplate basin with significant seismicity (Lower Tagus Valley, Portugal). *J. Seismol.* 8, 347-362.

Cabral, J., Marques, F., Figueiredo, P., Matias, L. (2011): Active surface faulting or landsliding in the Lower Tagus Valley (Portugal)? A solved controversy concerning the Vila Chã de Ourique site. *J. Seismol.,* 15, 215-234, doi: 10.1007/s10950-010-9221-8.

Cabral, J., Moniz, C., Batlló, J., Figueiredo, P., Carvalho, J., Matias, L., Teves-Costa, P., Dias, R., Simão, N. (2013). The 1909 Benavente (Portugal) earthquake: search for the source. *Nat. Haz.* 69, 1211-1227, doi: 10.1007/s11069-011-0062-8.

Calderón, S. (1909). Nota sobre el terremoto sentido en la península Ibérica el 23 de Abril de 1909. *Bolet Real Soc Esp Hist Nat* IX:219-233. [in Spanish]

Cancani, A. (1904). Sur l'emploi d'une double échelle sismique des intensités, empirique et absolue. In: Rudophl E (ed.) *Proc.* 2ème Conf. *Sismol. Intern.*, 24-28 July 1903, Strasbourg, Beiträge zur Geophysik, Special vol. II, A-10:281-283. [in French]

Canora, C., Vilanova, S.P., Besana-Ostman, G.M., Carvalho, J., Heleno, S., Fonseca, J.D. (2015). The Eastern Lower Tagus Valley Fault Zone in central Portugal: Active faulting in a low-deformation region within a major river environment. *Tectonophysics* 660, 117-131, doi: 10.1016/j.tecto.2015.08.026.

Carrilho, F., Nunes, J.C., Pena, J.A. (2004). Catálogo Sísmico de Portugal Continental e Região Adjacente 1970-2000. In: Senos M.L. (coord). *Instituto de Meteorologia*, Lisbon, Portugal, 227p. [in Portuguese]

Carvalho, J. (2003) Sísmica de alta resolução aplicada à prospecção, *geotecnia e risco sísmico*. PhD Thesis, University of Lisbon, 250 pp. [in Portuguese]

Carvalho, J., Matias, H., Torres, L., Manupella, G., Pereira, R., Mendes-Victor, L. (2005). The Structural and Sedimentary Evolution of the Arruda and Lower Tagus Sub-Basins, Portugal. *Marine and Petroleum Geology* 22, 427-453.

Carvalho, J., Cabral, J., Gonçalves, R., Torres, L., Mendes-Victor, L. (2006). Geophysical methods applied to fault characterization and earthquake potential assessment in the Lower Tagus Valley, Portugal. *Tectonophysics* 418, 277-297, doi: 10.1016/j.tecto.2006.02.010.

Carvalho, J., Rabeh, T., Cabral, J., Carrilho, F., Miranda, J.M. (2008). Geophysical characterization of the Ota—Vila Franca de Xira-Lisbon-Sesimbra fault zone, Portugal. *Geophys. J. Int.*, 174, 567-584, doi: 10.1111/j.1365-246X.2008.03791.x.

Carvalho, J., Rabeh, T., Bielik, M., Szalaiová, E., Torres, L., Silva, M., Carrilho, F., Matias, L., Miranda, J.M. (2011). Geophysical study of the Ota-VF Xira-Lisboa-Sesimbra fault zone and the lower Tagus Cenozoic basin. *J. Geophys. Eng.* 8, 395-411, doi: 10.1088/1742-2132/8/3/001.

Carvalho, J., Pinto, C., Rabeh, T., Dias, R., Torres, L., Borges, J., Torres, R., Duarte, H. (2016). Tectonic Evolution of an Intraplate Basin: the Lower Tagus Cenozoic Basin, Portugal. *Basin Research*, 1-22, doi: 10.1111/bre.12193.

Choffat, P., Bensaude, A. (1912). Estudos sobre o sismo do Ribatejo de 23 de Abril de 1909, *Com. Serv. Geol. Port.*, Lisbon, 146p. [in Portuguese]

Comas Solà, J. (1909). Nota sobre el terremoto olotino del 6 de abril de 1909 y el terremoto peninsular del 29 de abril de 1909: cálculo de la profundidad hipocentral. *Mem Real Acad Cienc y Artes Barcelona* 8:75-84. [in Spanish]

Cunha, P.P., Pais, J., Legoinha, P. (2009). Geologic evolution of the Portugal mainland during the Cenozoic - alluvial and marine sedimentation at a passive continental margin (W Iberia). In: G. Rodríguez, J. Gallastegui, G. Flor Blanco, J. Martín Llaneza, Eds., *6th Symposium on the Atlantic Iberian Margin, MIA09*, Oviedo, Volumen de Actas, Departamento de Geología, Universidad de Oviedo, xi-xx.

Cunha, P.P., Martins, A.A., Buylaert J.-P., Murray, A.S., Raposo, L., Mozzi, P., Stokes, M. (2016) New data on the chronology of the Vale do Forno sedimentary sequence (Lower Tejo River terrace staircase) and its relevance as a fluvial archive of the Middle Pleistocene in western Iberia. *Quaternary Science Reviews*, http://dx.doi.org/10.1016/j.quascirev.2016.11.001.

Custódio, S., Dias, N.A., Carrilho, F., Góngora, E., Rio, I., Marreiros, C., Morais, I., Alves, P., Matias, L. (2015). Earthquakes in western Iberia: improving the understanding of lithospheric deformation in a slowly deforming region. *Geophys. J. Int.* 203, 127-145, doi: 10.1093/gji/ggv285.

Davison C (1933). Scales of Seismic Intensity: Supplementary paper. *Bull. Seism. Soc. Am.* 23:158-166.

Dineva, S., Batlló, J., Mihailov, D., Van Eck, T., (2002). Source parameters of four strong earthquakes in Bulgaria and Portugal at the beginning of the 20th century. *J. Seismol.* 6:99-123.

Diniz J (1910). Contribuição para o Estudo dos Tremores de Terra em Portugal. O abalo sísmico de 23 de Abril de 1909. *Rev. Obras Públ. Minas* 483-484, Lisbon, 81p. [in Portuguese]

Fonseca, J.F.B.D. (1989). *Seismicity and Regional Tectonics of the Estremadura, Southwestern Portugal*. PhD Thesis, Instituto Superior Técnico, Lisbon, 153 pp.

Fonseca, F.B.D., Bosi, V., Vilanova, S.P., Meghraoui, M. (2000). Investigations unveil Holocene thrusting for onshore Portugal. *EOS Transactions*, 81, 412-413.

Fonseca, J.F.B.D., Vilanova, S.P. (2010). The April 1909 Benavente (Portugal) M 6.3 Earthquake. *Seism. Res. Lett.* 81:3 - Historical Seismologist, 4p.

Galbis Rodriguez, J. (1932). *Catálogo sísmico de la zona comprendida entre los meridianos 5°E y 20°W de Greenwich y los paralelos 45°N* y 25°N. Dirección General del Instituto Geográfico, Catastral y de Estadística, Madrid. [in Spanish]

Gasperini, P., Bernardini, F., Valensise, G., Boschi, E. (1999). Defining seismogenic sources from historical earthquake felt reports. *Bull. Seismol. Soc. Am.* 89, 94-110.

Gutenberg, B., Richter, C.F. (1954). *Seismicity of the Earth and Associated Phenomena*. Princeton University Press, 310 pp.

Henriques, M.C.J., Mouzinho, M.T., Natividade, M.F.F. (1988). *O Sismo de 26 de Janeiro de 1531*. Com. Cat. Sísm. Nac., Lisbon, 100p. [in Portuguese]

IGN (2017). *Online seismic catalogue:* http://www.ign.es/web/ign/portal/sis-catalogo-terremotos (last accessed 17 May 2017).

Inglada, V. (1909). Cálculo de la profundidad hipocentral del sismo del Ribatejo (Portugal) de 23 de Abril de 1909. *Proc. Asoc. Esp. Progr. Cienc.*, Oporto, Vol IV:89-107. [in Portuguese]

Jones, L., and other Scientists of the U.S. Geological Survey and the Southern California Earthquake Centre (1994). The magnitude 6.7 Northridge, California, Earthquake of 17 Jan 1994. *Science* 266, 389-397.

Justo, J.L., Salwa, C. (1998). The 1531 Lisbon earthquake. *Bull. Seism. Soc. Am.* 88,319-328.

Kárník, V. (1969). *Seismicity of the European Area, Part 1*. Reidel, Dordrecht, Netherlands.

Kullberg, J.C.R. (2000). Evolucão Tectónica Mesozóica da Bacia Lusitaniana. PhD Thesis, University of Lisbon, 280 pp. [in Portuguese]

Lienert, B. (1994). *Hypocenter 3.2*, Hawaii Institute of Geophysics & Planetology, Honolulu.

Martínez Solares, J.M., Mezcua, J. (2002). *Catálogo sísmico de la Península Ibérica*. IGN, Madrid, Mon 18, 253p. [in Spanish]

Martins, A.A. (1999). *Caracterização morfotectonica e morfossedimentar da Bacia doBaixo Tejo (Pliocenico e Quaternario)*. PhD Thesis, University of Évora, 500 pp. [in Portuguese]

Martins, A.A., Cunha, P.P., Huot, S., Murray, A.S., Buylaert, J.P. (2009). Geomorphological correlation of the tectonically displaced Tejo River terraces (Gavião-Chamusca area, central Portugal) supported by luminescence dating. *Quaternary International* 199, 75-91, doi:10.1016/j.quaint.2009.01.009.

Martins, A.A., Cunha, P.P., Buylaert, J.-P., Huot, S., Murray, A., Dinis, P., Stokes, M. (2010). K-feldspar IRSL dating of a Pleistocene river terrace sequence of the Lower Tejo River (Portugal, western Iberia). *Quat. Geochronol.* 5, 176-180.

Martins, I., Mendes-Victor, L.A. (1990). Contribuição para o estudo da sismicidade de Portugal Continental. *Instituto Geofísico do Infante D. Luís, Universidade de Lisboa* Publ. 18, 65p. [in Portuguese]

Martins, I., Mendes-Victor, L.A. (2001). Contribuição para o estudo da sismicidade da região oeste da Península Ibérica. *Instituto Geofísico do Infante D. Luís, Universidade de Lisboa* Publ. 25, 67 pp. ISSN 0870-2748. [in Portuguese]

Mendes-Victor, L.A. (2003). *Centennial Seismology Development in Portugal*. In: Lee WHK, Kanamori H, Jennings PC, Kisslinger C (ed): International Handbook of Earthquake and Engineering Seismology - Part B. Chapter 79.44CD, 24pp.

Messerschmitt, J.B. (1909). Registrierungen einiger südeuropäischer Erdbeben auf der Münchener Erdbenstation, Sitzungsberichte der Königblich Bayerischen Akad. Der Wissenschaften, Mathematish - Physikalische Klasse, 16, 1-10. [in German]

Mezcua, J. (1982). *Catalogo general de isosistas de la Península Ibérica*. Instituto Geográfico Nacional, Publ. 202, Madrid. [in Spanish]

Mezcua, J., Martínez Solares, J.M. (1983). *Sismicidad del área Ibero-Mogrebí*. Instituto Geográfico Nacional, Publ. 203, Madrid. [in Spanish]

Miranda, R. (1932). O sismo de Benavente e a tentativa de organização do serviço sismológico em Portugal. *A Terra* 4, 28-31. [in Portuguese]

Moniz, C. (2010). *Contributo para o Conhecimento da Falha de Pinhal-Novo-Alcochete, no Âmbito da Neotectónica do Vale Inferior do Tejo*. MSc Thesis, Faculdade de Ciências da Universidade de Lisboa, 128 pp. [in Portuguese]

Moniz, C., Cabral, J. (2014). The Pinhal Novo-Alcochete fault zone in the seismotectonic framework of the Lower Tagus Valley (Lisbon Region). In: Gómez, J.A.A., González, F.M. (Ed.) Una aproximación multidisciplinar al estudio de las fallas activas, los terremotos y el riesgo sísmico. *Proc. Segunda reunión Ibérica sobre fallas activas y paleosismología*, Lorca (Murcia, España), p. 3-6. URL: http://www.iberfault.org

Moreira, V.S. (1984). Contribuição para o conhecimento da sismicidade historica de Portugal Continental. *Revista do Instituto Nacional de Meteorologia e Geofisica* (special issue), Lisbon, Portugal. [in Portuguese]

Moreira V.S. (1991a). Sismicidade Histórica de Portugal Continental. *Revista do Instituto Nacional de Meteorologia e Geofisica* (2nd revised edition), Lisbon, 79p. [in Portuguese]

Moreira, V.S. (1991b). Historical Seismicity and Seismotectonics of the Area Situated between the Iberian Peninsula, Morocco, Selvagens and Azores Islands. In: Seismicity, Seismotectonics and Seismic Risk of the Ibero-Maghrebian Region. *Instituto Geográfico Nacional*, Monografia num. 8, 213-225, Madrid.

Moreira de Mendonça, J.J. (1758). *História Universal dos Terremotos*. Lisbon. [in Portuguese]

Munuera, J.M. (1963). Datos básicos para el studio de la sismicidad en el area de la Península Ibérica (Seismic Data). *Memorias del Instituto Geográfico y Catastral* XXXII (I), Madrid. [in Spanish]

Navarro Neumann, M.S. (1910). Le tremblement de terre Iberique du 23 Avril 1909. *Ciel et Terre* XV, 41-66. [in French]

Oliveira, C.S. (1986). A Sismicidade Histórica e a Revisão do Catálogo Sísmico. *Proc 36/11/7368, I e D, Estruturas, Relatório 99/86 - NDA*, LNEC, Lisboa. [in Portuguese]

Oliveira, J.T., Pereira, E., Ramalho, M., Antunes, M.T., Monteiro, J.H. (1992) Geological Map of Portugal, scale 1: 500 000. *Instituto Geológico e Mineiro*, Lisboa. [in Portuguese]

Ottemöller, L., Voss, P., Havskov, J. (2011). Seisan v9.0.1, University of Bergen, Norway.

Pais, J., Cunha, P.P., Pereira, D., Legoinha, P., Dias, R., Moura, D., Brum da Silveira, A., Kullberg, J.C., González-Delgado, J.A. (2012). The Paleogene and Neogene of Western Iberia (Portugal). A Cenozoic record in the European Atlantic domain. SpringerBriefs in Earth Sciences, Springer, Series ID: 8897, 1st Edition., 1 vol., 158 pp. doi: 10.1007/978-3-642-22401-0_1.

Rasmussen, E.S., Lomholt, S., Andersen, C., Vejbæk, O.V. (1998). Aspects of the structural evolution of the Lusitanian Basin in Portugal and the shelf and slope area offshore Portugal. *Tectonophysics* 300, 199-225.

Ribeiro, A., Kullberg, M.C., Kullberg, J.C., Manuppella, G., Phipps, S. (1990). A review of Alpine tectonics in Portugal: Foreland detachment in basement and cover rocks. *Tectonophysics* 184, 357-366.

Ribeiro, A., Cabral, J., Baptista, R., Matias, L. (1996). Stress pattern in Portugal mainland and the adjacent Atlantic region,West Iberia. *Tectonics* 15, 641-659.

Senos, L., Ramalhete, D., Taquelim, M.J. (1994). Estudo dos principais sismos que atingiram o território de Portugal Continental. *Instituto de Meteorologia*, Lisbon, Mon 46. [in Portuguese]

Stich, D., Ammon, C.J., Morales, J. (2003). Moment tensor solutions for small and moderate earthquakes in the Ibero-Maghreb region, *J. Geophys. Res.* 108, 2148 (20p.), doi: 10.1029/2002JB002057.

Stich, D., Batlló, J., Macià, R., Teves-Costa, P., Morales, J. (2005). Moment tensor inversion with single-component historical seismograms: The 1909 Benavente (Portugal) and Lambesc (France) earthquakes. *Geophys. J. Int.* 162, 850-858.

Stucchi, M., Rovida, A., Gómez-Capera, A.A., Musson, R., Papaioannou, CH., Batlló, J. (2010). European earthquake catalogue 1000-1963, M>5.8. *NERIES — NA4: a Distributed archive of historical earthquake data (NA4), Deliverable D10*, EC project number 026130, internal report, 30pp. (http://emidius.mi.ingv.it/neries_NA4/deliverables.php)

Stucchi and other researchers of the SHARE project (2013). The SHARE European Earthquake Catalogue (SHEEC) 1000-1899. *J. Seismol.* 17, 523-544, doi: 10.1007/s10950-012-9335-2.

Teves-Costa, P., Borges, J.F., Rio, I., Ribeiro, R., Marreiros, C. (1999). Source Parameters of old Earthquakes: Semi-Automatic Digitization of Analog Records and Seismic Moment Assessment. *Nat. Haz.* 19, 205-220.

Teves-Costa, P., Batlló, J., Rio, I., Macià, R. (2005). O sismo de Benavente de 23 de Abril de 1909 — Estado da arte. *Proc. 4º Simpósio de Meteorologia e Geofísica da APMG*, Sesimbra, 14-17 Fev, 44-49. [in Portuguese].

Teves-Costa, P., Batlló, J. (2011). The 23 April 1909 Benavente earthquake (Portugal): macroseismic field revision. *J. Seismol.* 15 (1), 59-70.

Vilanova, S.P. (2003) Sismicidade e perigosidade sísmica do Vale Inferior do Tejo, Ph.D. Thesis, Instituto Superior Técnico, Lisboa. 259 p. [in Portuguese]

Vilanova, S.P., Fonseca, J.F.B.D. (2004) Seismic hazard impact of the Lower Tagus Valley Fault Zone (SW Iberia). *J. Seismol.* 8, 331-345.

Vilanova, S.P., Fonseca, J.F.B.D. (2007). Probabilistic Seismic-Hazard Assesment for Portugal, *Bull Seism Soc Am* 97, 1702-1717.

Vogt, J. (1985). Revision d'Anciens Seismes Ibero-Maghrebins In: (Levret A., editor) Les Effects du Seisme de Lisbonne du ler Novembre 1755 sur le Territoire Marocain. Esquisse des lntensités Maximales observés Dues aux Grands Seismes Ibero-Maghrebins, Commissariat a l'Energie Atomique, France. [in French]

Walker, D.J. (1983). *Seismic intrepretation for Petrogal concession areas 45, 46, 47/48* - Final report, GPEP, Lisboa [unpublished report]