



Tsunamis Along the Azores Gibraltar Plate Boundary

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Abstract—The Eurasia–Nubia plate boundary between the Azores and the Strait of Gibraltar has been the place of large tsunamigenic earthquakes. The tectonic regime is extensional in the Azores, transcurrent along the Gloria Fault, and compressional in the Strait of Gibraltar. Here, the plate boundary is not clearly defined. The knowledge of past events that occurred in the area constitutes an essential contribution to the evaluations of seismic and tsunami hazard in the North-East Atlantic. In this study, we present an overview of the six major events in the area and show the use of tsunami data to add some constraints on their source. The historical events occurred in the eighteenth-century between 1722 and 1761, while the twentieth-century events occurred between 1941 and 1975. We speculate that major tsunamigenic earthquakes that occur in the Iberia-Maghreb area take place at the boundaries of a lithospheric block approximately defined by the location the six events summarized here, which role and dynamics are not yet understood.

Key words: Tsunamis, Atlantic, Eurasia–Nubia plate boundary.

1. Introduction

The western segment of the Eurasia–Nubia Plate Boundary between the Azores archipelago and the Strait of Gibraltar has been the place of several large tsunamigenic earthquakes.

The tectonic regimes change from an extensional one in the Azores to a compressional one, towards the Strait of Gibraltar. Between 24°W and 20°W, the plate boundary follows a morphological feature, firstly identified by Laughton et al. (1972), called the Gloria Fault (see Fig. 1). This feature is an almost linear structure characterized by right-lateral strike-

slip motion (Buforn et al. 1988, 2004; Argus et al. 1989). Between 20°W and 18°W, it changes strike, from N84E to N71E (Baptista et al. 2016). Large earthquakes related with this plate boundary also occur away from the Gloria Fault (Baptista et al. 2017), suggesting a second source zone 200 km south of Gloria, striking almost East–West (Lynnes and Ruff 1985; Buforn et al. 1988). Buforn et al. (1988) interpreted it as the development of a tectonic micro-block or the re-activation of a previous transform domain (Kaabouben et al. 2008).

The Gloria area has been the origin of several instrumental earthquakes of magnitude higher than 7, followed by small or moderate tsunamis: the 25 November 1941 (Gutenberg and Richter 1949; Udias et al. 1976; Baptista et al. 2016) and the 26 May 1975 (Lynnes and Ruff 1985; Buforn et al. 1988) (see Fig. 1).

To the East of the Gloria Fault, the seismicity is distributed over a large area, making difficult the identification of the plate boundary. Here, the present-day tectonic regime is dominated by the convergence between Africa and Eurasia at ~ 4 mm/year (Argus and Gordon 1991; DeMets et al. 1994) and the westward migration of the Cadiz Subduction slab ~ 2 mm/year (Gutscher et al. 2002; Duarte et al. 2013). This area, called the South West Iberian Margin (SWIM) hosts a set of linear and sub-parallel dextral strike-slip faults Zitellini et al. (2009) forming a deformation zone (Miranda et al. 2015). Zitellini et al. (2009) showed that the seismic strain is accommodated by the active morpho-tectonic features and faults already mapped by (Zitellini et al. 2001, 2004; Gracia et al. 2003; Terrinha et al. 2009). This area hosts the sources of the major tsunamigenic earthquakes of the 1 November 1755 (Johnston 1996; Baptista et al. 1998b; Zitellini et al. 2001; Gutscher et al. 2002) and the 31 March 1761 (Baptista et al.

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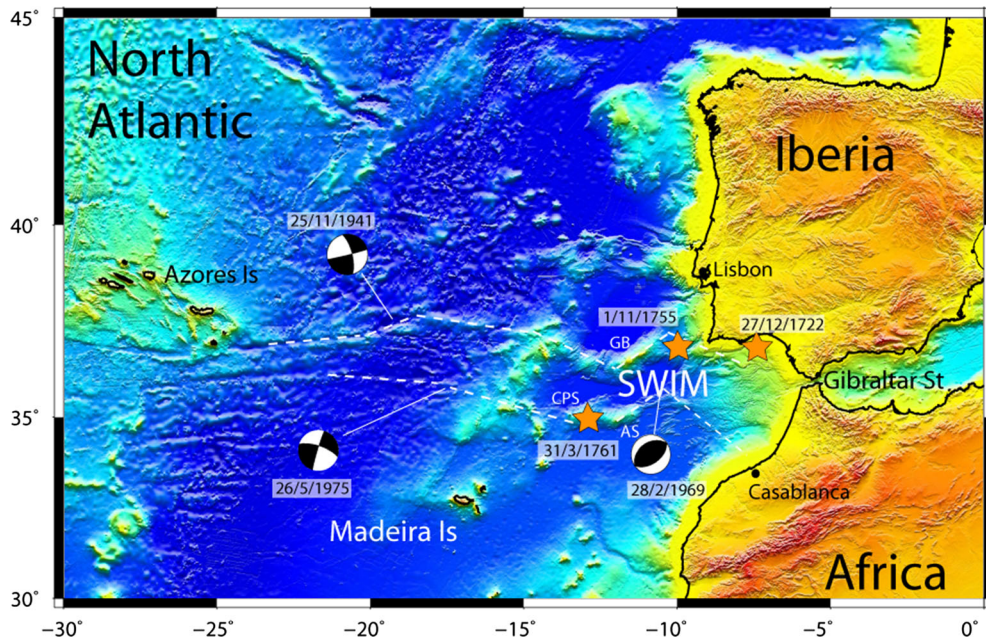


Figure 1

Overview of the study area. Beach balls represent the focal mechanisms of the instrumental events—1941, 1969 and 1975; orange stars represent the presumed epicentres of the historical events 1722, 1755 and 1761. White dashed lines follow main geological lineaments. *GS* Gibraltar Strait, *CP* Coral Patch Seamount, *GB* Gorringe Bank

2006; Wronna et al. (2019). The largest instrumental tsunamigenic earthquake occurred on 28 February 1969 with a magnitude of M_s 8.0, see Fig. 1 for location.

The earthquake and tsunami compilations for the North-East Atlantic area between the Mid Atlantic Ridge in the Azores and the Strait of Gibraltar include reports on the events along this segment of the Eurasia–Nubia Plate Boundary (Baptista and Miranda 2009). According to the Portuguese tsunami catalogue, the oldest historical events occurred in 60 BC and 382 AD, however, paleo-tsunami evidences were found back to 7000 BP (Baptista and Miranda 2009); these events are out of the scope of this study.

The Portuguese tsunami catalogue (Baptista and Miranda 2009) include tsunami or tsunami-like observations following the earthquakes of 27 December 1722, 1 November 1755, and 31 March 1761. The nineteenth century seems to be a quiet period, with no significant events reported. Since the installation of the tide gauge network, three tsunamigenic earthquakes occurred in the twentieth century between the Azores Triple Junction and the

Gulf of Cadiz (see Fig. 1). The first one was the strong strike-slip earthquake of magnitude 8.3 in the Gloria Fault (Baptista et al. 2016) followed by the 28th February 1969 earthquake in the Horseshoe Abyssal plain and the 26 May 1975 earthquake 200 km south of Gloria Fault. This study shows the use of tsunami data to constrain the source of the parent earthquakes with scarce or non-instrumental data available in the western segment of the Eurasia–Nubia plate boundary.

2. Methods

The approach presented here to study tsunami events is based on the compilation of historical and instrumental information on each tsunami to produce datasets of tsunami observations. These datasets include tsunami travel times (TTT), wave heights and run up heights for historical events and tide records for the instrumental ones. The inversion of the tsunami travel times provides information on the source location; The forward simulation of the tsunami using

the shallow water approximation supports the selection of a preferred earthquake mechanism that best fits tsunami data. Finally, the inversion of the tsunami waveforms enables the computation of the initial sea surface displacement.

2.1. Backward Ray Tracing of Tsunami Travel Times

The Backward Ray Tracing (BRT) technique consists on the back projection of tsunami wave fronts from each observation point on the coast towards the source area (Miyabe 1934). Gjevik et al. (1997), Baptista et al. (1998b, 2016) present the inversion technique used for the study of all events presented herein. It consists on the definition of dataset of points of interest (POIs) along the coast corresponding to each observation point or one per tide station. The position of each POI is the node of the bathymetric grid closest to the actual location of the observation point or tide station, at a depth not less than 10 m to avoid strong non-linear effects. The back propagation of the wave from each POI uses the algorithm implemented in the Mirone suite (Luis 2007; <http://w3.ualg.pt/~jluis/mirone/main.html>). The location of the tsunami source is the minimum of the averaged travel time square errors (in the least squares sense). The spatial distribution of the misfit is given by:

$$e^2(x, y) = \frac{\sum_{i=1}^n (t_i^o - t_i^p)^2}{n} \quad (1)$$

where t_i^o and t_i^p are the observed and predicted travel time for each POI and n is the total number of POIs. The minimum of the averaged travel time square errors is always different from zero because of observation errors, instrumental errors and due to the finite dimension of the fault.

2.2. Forward Tsunami Simulation

In forward tsunami simulations of earthquake induced tsunamis the sea bottom deformation caused by the earthquake is computed using Okada (1985) equations; the ocean bottom deformation is then transferred to the free surface assuming that the water is an incompressible fluid. The initial conditions of the numerical simulation are the free surface

displacement and a null velocity field. Non-linear shallow water codes are currently used to simulate tsunami propagation from source to coastal areas and inundation phase (tsunami propagation over dry land). The details on the codes used in the six events presented here can be found in (Gjevik et al. 1997; Baptista et al. 1998b, 2003, 2007, 2016; Kaabouben et al. 2008; Wronna et al. 2015, 2019).

The forward simulation of the tsunami using different initial conditions is used to discriminate among the different earthquake mechanisms the one that fits better the tsunami observations.

2.3. Inversion of Tsunami Waveforms

The problem of tsunami waveform inversion was firstly proposed by Satake (1987) leading to the publication of a number of studies focused on the use of inversion methods to estimate the tsunami source were. These studies can be broadly divided in two categories: with a priori assumptions on the fault model Satake (1987, 1993), Johnson et al. (1996), Hirata et al. (2003), Titov et al. (2005) and without a priori assumptions on the fault model and/or the source mechanism Baba et al. (2005), Satake et al. (2005), Tsushima et al. (2009), Wu and Ho (2011), Yasuda and Mase (2012) and Baptista et al. (2016). The results presented herein on the inversion of the source the 25 November 1941—without a priori constraints—are fully described in Baptista et al. (2016). The initial sea surface elevation over the source area was computed using the waveforms recorded at the tide stations shown in Fig. 4 (black dots) by inversion of the following equation

$$\eta_m(t_t) = \sum_{i=1}^{nl} \sum_{j=1}^{nc} G_{ij}^m(t_t) h_{ij}, \quad (2)$$

where $G_{ij}^m(t_t)$ are the empirical Green's functions computed by the shallow water model for t time steps, $(nl \times nc)$ are the set of unit sources and h_{ij} is the amplitude of the initial water displacement attributed to the ij unit source (see Baptista et al. 2016 for details).

3. The Events

3.1. The 27 December 1722 Event

The 27 December 1722 earthquake occurred offshore the south Portuguese coast in the western sector of the Eurasia–Nubia inter-plate domain (see Fig. 1). After the earthquake, tsunami observations were reported in the south coast of Portugal. Baptista et al. (2007) analyzed the historical information on the earthquake and used seismo-tectonic information of the offshore area to propose an offshore source compatible with the flooding described in the historical observations. To set the parameters of the candidate faults, these authors used seismo-stratigraphic analysis of a set of multichannel seismic (MCS) reflection profiles covering the Algarve Basin (Lopes et al. 2006) to infer the strike and size of each candidate source. Each candidate source was used to initiate the tsunami propagation model. A slip of 2 m was assumed to comply with the magnitude of the earthquake; dip and rake angles were fixed with reasonable guesses according to each tectonic style. The results of tsunami forward modelling suggest a source located in the offshore close to 37°01'N, 7°49'W.

Andrade et al. (2016) suggested for a source located in the riverbed. However, Andrade et al. (2016) do not discuss the tectonic implications of this source neither present hydrodynamic simulations supporting the conclusion. Nevertheless, the fact that this is a historical event with scarce observations there is room for alternative candidate sources always close to the shore.

3.2. The 1st November 1755 Event

The Lisbon earthquake of the 1st November 1755, generated a massive transatlantic tsunami that ravaged the coast of SW Portugal, Spain in the Gulf of Cadiz and the Atlantic coast of Morocco. The tsunami reached as far as the Caribbean Islands and UK.

Several authors investigated the source of the Lisbon earthquake, using either macro-seismic data (Solares et al. 1979; Levret 1991), averaged tsunami amplitudes (Abe 1979) of the 28 February 1969, or

scale comparisons with the 28 February 1969 event (Johnston 1996). Solares and Arroyo (2004) estimated the magnitude in 8.3 ± 0.4 , assuming a source area in the region offshore Iberia close to the epicenter of the 28 February 1969 earthquake (Fukao 1973).

Baptista et al. (1998a, b) presented the first comprehensive analysis of the tsunami observations of this event and used tsunami backward ray tracing techniques to locate the source area between the Gorringe Bank and the southwestern end of the Portuguese coast (see Fig. 2). These authors used a non-linear shallow water code by Mader (1988) to test these sources; the first one corresponds to a source parallel to the Gorringe Bank. The other sources are located in the South West Iberian Margin (SWIM) similar to the elongated shape presented in Fig. 2. All sources were compatible with a magnitude 8.3 parent earthquake. The results show that a source elongated along the SWIM with an azimuth compatible with the results of the backward ray tracing presented in Fig. 2 produce tsunami wave heights and travel times consistent with the observations (Baptista et al. 1998b). Finally, these authors excluded a source compatible with the Gorringe Bank fault because it produces late travel times to the Iberian coast and small tsunami amplitudes. The results presented by Omira et al. (2009) favor this conclusion as the tsunami radiation pattern of a source on the Gorringe Bank shows that most energy is radiated towards NE and Morocco with a minor impact along the Gulf of Cadiz.

The search for the tectonic source of this event was the goal of bathymetric and multi-channel seismic campaigns conducted by Zitellini et al. (1999, 2001), Gutscher et al. (2002) and Gracia et al. (2003). Zitellini et al. (2001) identified several compressive structures located in the SWIM among which the named Marques de Pombal fault (MPf), 100 km offshore southwest of Saint Vicente cape (see Fig. 3). The MPf was interpreted as a possible source of the 1755 earthquake and tsunami. However, hydrodynamic modeling using the MPf with an average slip of 20 m produces wave heights incompatible with the observations along Iberia, Morocco and Madeira archipelago. Moreover, the corresponding seismic moment seems too small to justify the

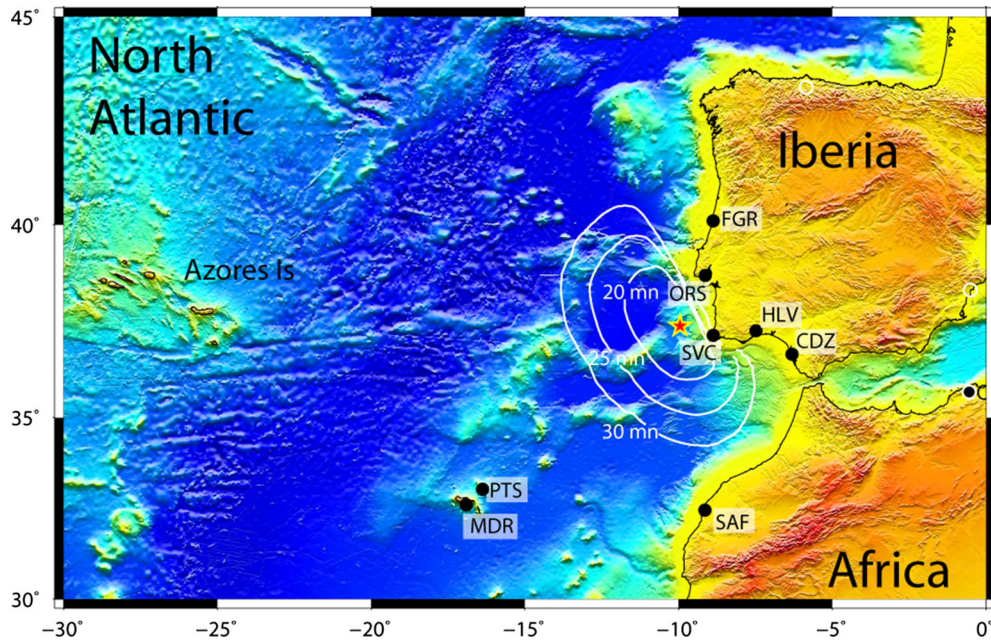


Figure 2

Backward Ray Tracing for the 1755 event. The star coincides with the minimum error of the backward ray tracing simulation. Observation points of the 1755 event used for backward ray tracing simulation. *FGR* Figueira, *ORS* Oeiras, *SVC* Saint Vincent Cape, *HLV* Huelva, *CDZ* Cadiz, *PTS* Porto Santo, *MDR* Madeira, *SAF* Safi (see Baptista et al. 1998b for details)

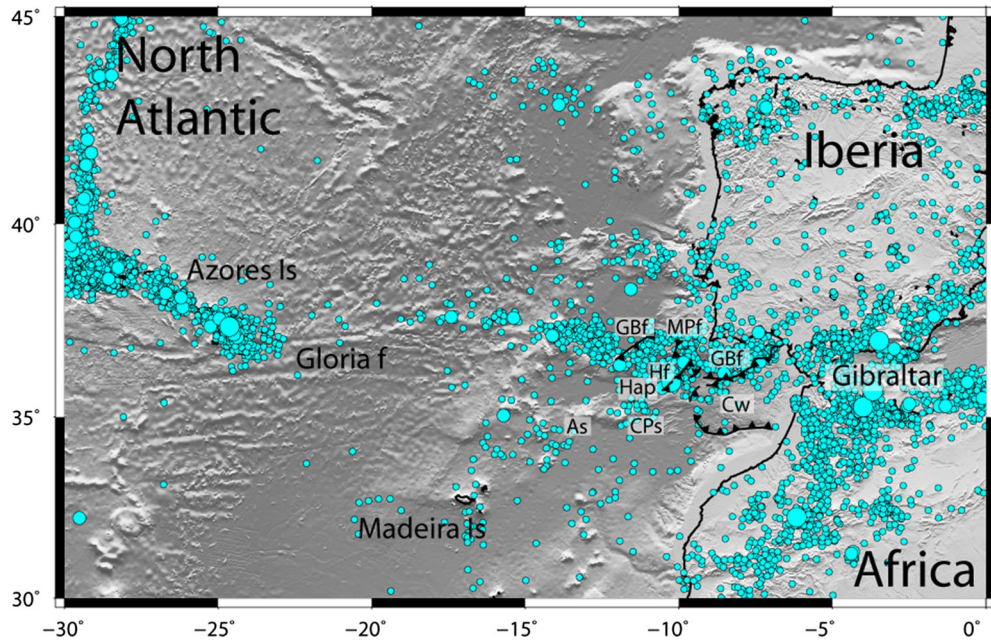


Figure 3

Seismicity of the period 1987–2017 (earthquake magnitudes greater than 3) of the South West Iberia (International Seismological Centre Bulletin) and active structures identified in marine surveys; *GBf* Gorringe Bank, *MPf* Marquês de Pombal fault, *Hf* Horseshoe fault, *GBf* Guadalquivir Bank fault, *Cw* Cadiz Wedge, *As* Ampere seamount, *CPs* Coral Patch seamount, *Hap* Horseshoe abyssal Plain

observed macro-seismic field. To solve this problem Baptista et al. (2003) proposed a composite source of Marquês de Pombal and Guadalquivir faults for the source of this event. Figure 3 shows the location of these active structures.

Gutscher et al. (2002) using seismic and tomography images of the crustal structure of the Gulf of Cadiz suggested the presence of an east dipping slab of cold, oceanic lithosphere beneath the Gibraltar–Cadiz wedge (see Fig. 3). The dimensions of this tectonic feature (app. 200×200 km) are compatible with an 8.8 magnitude earthquake with a co-seismic displacement of 20 m. However, the tsunami propagation from this source produces late arrivals and small wave heights along the Portuguese west coast and Safi in Morocco (Gutscher et al. 2006).

Gracia et al. (2003) and Zitellini et al. (2004) identified the Horseshoe Fault (see Fig. 4) that strikes perpendicular to the present-day relative movement

between Nubia and Eurasia as a possible source for this earthquake. Omira et al. (2011) investigated the tsunamigenic potential of the Horseshoe and Marques de Pombal faults and discuss the impact along the Gulf of Cadiz and Morocco. However, none of the tsunamis caused by the rupture of these single structures reproduces the set of observations in the area.

Santos et al. (2009) using wave ray analysis relocate the source on the Gorringe bank but the hydrodynamic modelling results are incompatible with the observations producing large wave heights north of Lisbon and small wave heights along the south Portuguese coast and south Spain.

Barkan et al. (2009) proposed a NW–SE trending fault in the Horseshoe Plain almost perpendicular to previously suggested NE–SW trending faults; the only known tectonic structure with a NW–SE orientation in this area is a paleo plate boundary.

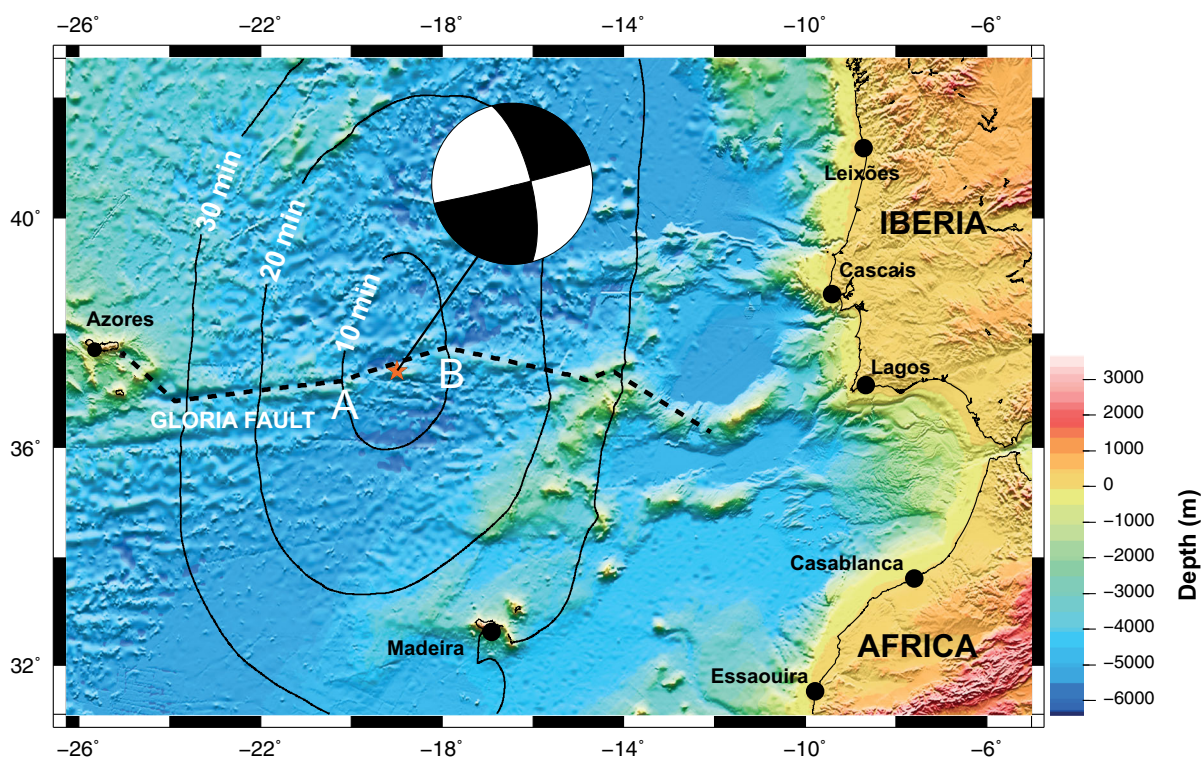


Figure 4

Backward Ray Tracing for the 1941 event. The star coincides with the minimum error of the backward ray tracing simulation. Black dots show the locations of the tide stations used for backward ray tracing simulation and beach ball shows the focal mechanism (see Baptista et al. 2016 for details)

3.3. The 31.03.1761 Event

The 31st March 1761 earthquake and tsunami occurred just 6 years after the Lisbon event in 1755 at 12:05 a.m. Lisbon time. Mezcua and Solares (1983) located the epicenter location was given at 37.00°N, 10.00 W whereas Oliveira (1986) put it at 36.0°N 10.50°W.

The first comprehensive compilation of the earthquake and tsunami is the study by Borlase (1762) in the Philosophical Transactions of the Royal Society of London. These data was recompiled and published by Perrey (1847) and Mallet (1852), Moreira (1984) and De La Torre (1997). Baptista et al. (2006) presented an extensive analysis of macro-seismic data, tsunami data and seaquake observations. The authors used macro-seismic intensity data and epicentral intensity of IX to obtain a new isoseismal map that suggests a source location South West of the Iberian Margin. The use of tsunami travel times in the backward ray tracing simulations lead to a source area compatible with the isoseismal map. Within the limitations of historical data the authors conclude for an earthquake that occurred at 12:01 a.m. on the 31 March 1761 (Lisbon time) with an epicenter located around 34.5°N, 13°W (see Fig. 1). Wronna et al. (2019) proposed a source of 200 km long by 50 km compatible with the geodynamic constraints imposed by Nuvel 1A (DeMets et al. 1994) with a velocity convergence of 3.8 mm/year in the area. The rupture mechanism would be a thrust fault located southwest of the source of the 1755 event close to the Coral Patch seamount (see Fig. 1). These authors proposed a compressive source in this area compatible with the Plate kinematics that reproduces quite well both the near field and the far field tsunami observations.

3.4. The 25 November 1941 Event

The 25 November 1941 earthquake occurred at 18:03:54 UTC. After the earthquake a tsunami was recorded in the tide stations of the North East Atlantic with a maximum amplitude of 40 cm peak to throw in Azores and Madeira islands (Baptista et al. 2016), see Fig. 4 for location of the tide stations, epicenter, and focal mechanism.

Macro-seismic analysis shows largest seismic intensities in the islands of Madeira, Azores and western Portugal VI (MSK). Debrach (1946), Di Filippo (1949) and Moreira (1968) published compilations of macro-seismic data for Morocco, Spain and Portugal respectively.

The epicenter locations given by Antunes (1944) and Gutenberg and Richter (1949) were -18.9°E , 38.7°N and -18.5°E , 37.50°N respectively. The study by Baptista et al. (2016) presents a new epicenter location using the phases of the International Seismological Centre Bulletin and readings of nearby stations in Morocco and Spain at -19.038°E , 37.405°N , and moment magnitude of 8.3. The new epicentre lies west of the epicentre presented by Gutenberg and Richter (1949). Nevertheless, both determinations put the epicentre on the segment AB of the Gloria fault (see Fig. 4).

Baptista et al. (2016) present a comprehensive analysis of the data. The set of tsunami data include records from eight stations available in UK, Azores and Madeira islands, Morocco and three stations in mainland Portugal. The results of the backward ray-tracing simulation locate the source at -19.00°E , 37.35°N quite close to the epicentre location suggesting that the earthquake's co-seismic deformation induced the tsunami. Baptista et al. (2016) invert the tsunami waveforms without a priori constraints on the focal mechanism using the method proposed by Miranda et al. (2014). The inversion of the tsunami waveforms suggest that the earthquake ruptured approximately 160 km of the plate boundary between 20.249°W and 18.630°W . The inverse problem solution was compatible with the majority of tsunami observations. However, the record in Essaouira (Morocco) (see Fig. 4) could not be explained by an earthquake-induced tsunami. The fact that Debrach (1946) and Rothé (1951) report damages to the submarine cables Brest–Casablanca and Brest–Dakar after the earthquake led Baptista et al. (2016) to speculate that a secondary landslide source caused by the earthquake may explain this observation. The lack of information on the exact location of the submarine cables offshore Morocco and on the location of the rupture prevented the authors to model the landslide.

3.5. The 28 February 1969 Event

On the 28 February 1969, at 2:40 a.m. the strongest earthquake since the 1755 event stroke Portugal, Spain and Morocco. The studies on the earthquake by Udias and Arroyo (1972), Mckenzie (1972), Fukao (1973), Buforn et al. (1988), Grimison (1988) conclude for a thrust mechanism with a small left lateral component.

The tsunami that followed the earthquake reached the first tide stations in the Portuguese coast less than 40 min after the shock (Baptista et al. 1992) being recorded in Spain and Morocco.

Gjevik et al. (1997) computed the location of the tsunami source using tsunami data. The source area, in the Horseshoe Abyssal Plain, encompasses the epicenter of the earthquake but requires the exclusion of some of the tsunami travel times.

The studies on the numerical simulation of the tsunami by Heinrich et al. (1994), Guesmia et al. (1996), Guesmia et al. (1998), Miranda et al. (1996) and Gjevik et al. (1997) used the fault mechanism proposed by Fukao (1973) consisting on thrust with a small strike slip component, N55°E parallel to the Gorringe Bank (see Fig. 3); the fault dimensions being 80 km × 50 km, the dip angle of 52°, average slip on the fault of 3.85 m corresponding to a seismic moment of 6.0×10^{10} Nm and a magnitude of 7.9. These studies could reproduce some of the tsunami observations. However, none of these single source models explain the early arrival with a large downward movement observed in the tide record of Casablanca (Morocco), and some authors suggest the occurrence of a landslide (Gjevik et al. 1997; Pires and Miranda 2001).

3.6. The 26 May 1975 Event

The 26 May 1975, $M_s = 7.9$ earthquake occurred in the North East Atlantic 200 km south of the Gloria Fault (see Fig. 1) at 17.5°W, 35.9°N. Studies on the focal mechanism by Lynnes and Ruff (1985) “first-motion” solution and Buforn et al. (1988) concluded for a dextral strike-slip event with no significant dip-slip component, compatible with the relative motion between Eurasia and Nubia plates but 200 km south

of the presumed plate boundary. The tsunami was recorded in Portugal and Spain.

Baptista et al. (1992) presents the spectral analysis of the tsunami records of this event. Later, Kaabouben et al. (2008) inverted tsunami travel times to locate the source. These authors selected three candidate sources given by Lynnes and Ruff (1985) “first-motion” solution, Lynnes and Ruff (1985) “Rayleigh Waves” solution and the focal mechanism proposed by Hadley and Kanamori (1975) and propagated the tsunami. The inversion of TTT confirms the epicentre location of 26 May 1975 earthquake close to the Tydeman Fracture Zone almost parallel to the Gloria Fault (see Fig. 1). The shallow water simulations presented by Kaabouben et al. (2008) using Lynnes and Ruff (1985) fault parameters to compute the initial sea surface displacement reproduce well most of the tsunami waveforms of the tide stations in the North East Atlantic (see Kaabouben et al. 2008 for details).

4. Results and Discussion

The results summarized here show how tsunami research contributed to the knowledge of the geological processes along the Azores–Gibraltar segment of the Eurasia–Nubia Africa plate boundary. The information retrieved from historical reports include tsunami travel times, wave heights, first wave polarity and time intervals between primary waves. The inversion of tsunami travel times allows for the computation of an area that includes the tsunami source and the earthquake epicentre for earthquake-induced tsunamis. Inversion of tsunami waveforms provides results on the initial sea surface displacement giving information on the sea bottom deformation caused by the parent earthquake. In spite of the limitations inherent to the use of historical observations and old tide record time series these datasets provide an independent estimate on the location and the extension of the tsunami source and indirectly on the extent of the seismic source.

1. The 27th December 1722 event took place close to the south Portuguese coast and triggered a small tsunami. Hydrodynamic modelling (Baptista et al.

- 2007) can fairly reproduce the historical reports and is compatible with local geology. This is the easternmost tsunami event known to occur in the Azores-Gibraltar segment of the plate boundary.
2. The inversion of tsunami travel times of the 1 November 1755 places the source of this event in the South West Iberian Margin (SWIM), and exclude a source located in the Gorringe Bank thrust (Baptista et al. 1998b). These results fostered new bathymetric and seismic surveys in the area confirming the existence of active tectonic features that may be the source of the 1755 event (see Fig. 3). All those studies locate the epicentre in the offshore of Iberia. The tectonic structures parallel to the SWIM can reproduce most of the observed tsunami travel times; however, the dimensions of the single structures identified up to now are not compatible with an 8.5–8.75 earthquake and do not reproduce far-field observations. The dimensions of the Cadiz Wedge source (Gutscher et al. 2002) can justify an 8.5 earthquake but fail to reproduce the tsunami travel times on the Portuguese west coast and north of it (Gutscher et al. 2006). The proposed source by Barkan et al. (2009) reproduces part of the observations but does not match any of the neotectonic structures identified. The source of this event is still a question of debate, but most of the modelling studies suggest a location close to San Vincent cape with an NNW–SSW strike.
 3. The 31 March 1761 event is less well known than the 1755 event, but the re-evaluation of macroseismic data by De la Torre (1997) together with the Backward Ray Tracing simulations by Baptista et al. (2006) re-locates the source close to Coral Patch seamount. Recently, Wronna et al. (2019) proposed a compressive source in this area compatible with the Plate kinematics that reproduces quite well both the near field and the far field tsunami observations.
 4. The study of the source of the 25 November 1941 using tsunami data confirms its location quite close to the epicentre location suggesting that the earthquake's co-seismic deformation induced the tsunami. The inversion of tsunami waveforms made possible a re-evaluation of the tsunami source that encompasses the earthquake epicentre.

The location is compatible with a sudden change of strike close to the eastern end of Gloria Fault (Baptista et al. 2016).

5. All studies concerning the 28 February 1969 tsunami locate the source in the Horseshoe Abyssal Plain. However, the thrust mechanisms proposed until now cannot explain the sizeable downward movement observed in Casablanca. Moreover, active and passive seismic research was never conclusive on the identification of a geological source of this earthquake compatible with the seismic (and tsunami) source.
6. Forward modelling and backward ray tracing for the 26 May 1975 tsunami confirm the seismic location of the event, suggesting that the candidate sources Lynnes and Ruff (1985) deduced from seismic data reproduces first arrival, the polarity of the first movement and first peak amplitudes of the tsunami waves.

The six tsunamigenic events generated in the Azores Gibraltar the plate boundary do not follow a single boundary, as early detected by the studies concerning the 1975 event (Bufo et al. 1988). When plotted together on the seafloor bathymetry (see Fig. 1) they provide an approximate picture of a complex lithospheric block (white dashed line in Fig. 1). We can speculate that major seismic and tsunami events take place at the boundaries of this block, which genesis and dynamics are not yet understood.

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REFERENCES

- Abe, K. (1979). Size of great earthquakes of 1837–1974 inferred from tsunami data. *Journal of Geophysical Research: Solid Earth*, 84(B4), 1561–1568.
- Andrade, C., Freitas, M. C., Oliveira, M. A., & Costa, P. J. (2016). *On the sedimentological and historical evidences of seismic-triggered tsunamis on the Algarve Coast of Portugal. Plate Boundaries and Natural Hazards* (pp. 219–238). New York: Wiley.
- Antunes, M. T. (1944). Notas Acerca do Sismo de 25 de Novembro de 1941. In *4th congress of Portuguese association for the advance of sciences*, Porto, 18–24 June, 1942. Tomo III, 2nd Section, pp. 161–172 (in Portuguese).
- Argus, D. F., & Gordon, R. G. (1991). No-net-rotation model of current plate velocities incorporating plate motion model NUVEL-1. *Geophysical Research Letters*, 18(11), 2039–2042.
- Argus, D. F., Gordon, R. G., DeMets, C., & Stein, S. (1989). Closure of the Africa-Eurasia-North America plate motion circuit and tectonics of the Gloria fault. *Journal of Geophysical Research: Solid Earth*, 94(B5), 5585–5602.
- Baba, T., Cummins, R., & Hori, T. (2005). Compound fault rupture during the 2004 off the Kii Peninsula earthquake (M 7.4) inferred from highly resolved coseismic sea-surface deformation. *Earth Planets Space*, 57(3), 167–172.
- Baptista, M. A., Heitor, S., Miranda, J. M., Miranda, P., & Victor, L. M. (1998a). The 1755 Lisbon tsunami; evaluation of the tsunami parameters. *Journal of Geodynamics*, 25(1–2), 143–157.
- Baptista, M. A., & Miranda, J. M. (2009). Revision of the Portuguese catalog of tsunamis. *Natural Hazards and Earth System Sciences*, 9(1), 25–42.
- Baptista, M. A., Miranda, J. M., Batlló, J., Lisboa, F., Luis, J., & Maciá, R. (2016). New study on the 1941 Gloria Fault earthquake and tsunami. *Natural Hazards and Earth System Sciences*, 16(8), 1967–1977.
- Baptista, M. A., Miranda, J. M., Chierici, F., & Zitellini, N. (2003). New study of the 1755 earthquake source based on multi-channel seismic survey data and tsunami modeling. *Natural Hazards and Earth System Sciences*, 3(5), 333–340.
- Baptista, M. A., Miranda, J. M., Lopes, F. C., & Luis, J. F. (2007). The source of the 1722 Algarve earthquake: Evidence from MCS and Tsunami data. *Journal of Seismology*, 11(4), 371–380.
- Baptista, M. A., Miranda, J. M., & Luis, J. F. (2006). In search of the 31 March 1761 earthquake and tsunami source. *Bulletin of the Seismological Society of America*, 96(2), 713–721.
- Baptista, M. A., Miranda, J. M., Matias, L., & Omira, R. (2017). Synthetic tsunami waveform catalogs with kinematic constraints. *Natural Hazards and Earth System Sciences*, 17(7), 1253–1265.
- Baptista, M. A., Miranda, P. E., & Victor, L. M. (1992). Maximum entropy analysis of Portuguese tsunami data; the tsunamis of 28.02.1969 and 26.05.1975. *Science Tsunami Hazards*, 10(1), 9–20.
- Baptista, M. A., Miranda, P. M. A., Miranda, J. M., & Victor, L. M. (1998b). Constrains on the source of the 1755 Lisbon tsunami inferred from numerical modelling of historical data on the source of the 1755 Lisbon tsunami. *Journal of Geodynamics*, 25(1–2), 159–174.
- Barkan, R., Uri, S., & Lin, J. (2009). Far field tsunami simulations of the 1755 Lisbon earthquake: Implications for tsunami hazard to the US East Coast and the Caribbean. *Marine Geology*, 264(1–2), 109–122.
- Borlase, W. (1762). Some account of the extraordinary agitation of the waters in Mount's-bay, and other places, on the 31st of March 1761: In a letter for the Reverend Dr. C Lyttelton. *Philosophical Transactions of the Royal Society*, 52, 418–431.
- Bufo, E., Bezzeghoud, M., Udias, A., & Pro, C. (2004). Seismic sources on the Iberia-African plate boundary and their tectonic implications. *Pure and Applied Geophysics*, 161(3), 623–646.
- Bufo, E., Udias, A., & Colombas, M. A. (1988). Seismicity, source mechanisms and tectonics of the Azores-Gibraltar plate boundary. *Tectonophysics*, 152(1), 89–118.
- De La Torre, F. R. (1997). Revisión del Catálogo Sísmico Ibérico (años 1760 a 1800) Estudio realizado para Instituto Geográfico Nacional, mediante convenio de investigación número 7.070, de 1997, Madrid.
- Debrach, J. (1946). *Raz de marée d'origine sismique enregistrée sur le littoral atlantique du Maroc (in French)*. Annales, Maroc: Service de Physique du Globe et de l'institut scientifique Chérifien.
- DeMets, C., Gordon, R. G., Argus, D. F., & Stein, S. (1994). Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters*, 21(20), 2191–2194.
- Di Filippo, D. (1949). Il terremoto delle Azzore del 25 Nov. 1941. *Annali Geofis*, 2, 400–405.
- Duarte, J. C., Rosas, F. M., Terrinha, P., Schellart, W. P., Boutelier, D., Gutscher, M. A., et al. (2013). Are subduction zones invading the Atlantic? Evidence from the southwest Iberia margin. *Geology*, 41(8), 839–842.
- Fukao, Y. (1973). Thrust faulting at a lithospheric plate boundary the Portugal earthquake of 1969. *Earth and Planetary Science Letters*, 18(2), 205–216.
- Gjevik, B., Pedersen, G., Dybesland, E., Harbitz, C. B., Miranda, P. M. A., Baptista, M. A., et al. (1997). Modeling tsunamis from earthquake sources near Goringe Bank southwest of Portugal. *Journal of Geophysical Research: Oceans*, 102(C13), 27931–27949.
- Gracia, E., Danobeitia, J., Vergés, J., & PARSIFAL Team. (2003). Mapping active faults offshore Portugal (36 N–38 N): Implications for seismic hazard assessment along the southwest Iberian margin. *Geology*, 31(1), 83–86.
- Grimison, N. L. (1988). Source mechanisms of four recent earthquakes along the Azores-Gibraltar plate boundary. *Geophysical Journal International*, 92, 391–401.
- Guesmia, M., Heinrich, P., & Mariotti, C. (1996). Finite element modelling of the 1969 Portuguese tsunami. *Physics and Chemistry of the Earth*, 21(1–2), 1–6. [https://doi.org/10.1016/S0079-1946\(97\)00001-3](https://doi.org/10.1016/S0079-1946(97)00001-3).
- Guesmia, M., Heinrich, P. H., & Mariotti, C. (1998). Numerical simulation of the 1969 Portuguese tsunami by a finite element method. *Natural Hazards*, 17(1), 31–46.
- Gutenberg, B., & Richter, C. F. (1949). *Seismicity of the earth and associated phenomena*. Princeton: Princeton University Press.
- Gutscher, M. A., Baptista, M. A., & Miranda, J. M. (2006). The Gibraltar Arc seismogenic zone (part 2): Constraints on a shallow east dipping fault plane source for the 1755 Lisbon earthquake provided by tsunami modeling and seismic intensity. *Tectonophysics*, 426(1–2), 153–166.
- Gutscher, M. A., Malod, J., Rehault, J. P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., et al. (2002). Evidence for active subduction beneath Gibraltar. *Geology*, 30(12), 1071–1074.

- Hadley, D. M., & Kanamori, H. (1975). Seismotectonics of the Eastern Azores-Gibraltar Ridge. In *Transactions of American Geophysical Union* (Vol. 56, No. 12, pp. 1028–1028). Washington, DC: American Geophysical Union.
- Heinrich, P., Baptista, M. A., & Miranda, P. (1994). Numerical simulation of the 1969 tsunami along the Portuguese coasts. Preliminary results. *Science of Tsunami Hazards*, 12(1), 3–23.
- Hirata, K., Geist, E., Satake, K., Tanioka, Y., & Yamaki, S. (2003). Slip distribution of the 1952 Tokachi-Oki earthquake (M 8.1) along the Kuril trench deduced from tsunami waveform inversion. *Journal of Geophysical Research: Solid Earth* (1978–2012), 108(B4).
- Johnson, J. M., Satake, K., Holdahl, S. R., & Sauber, J. (1996). The 1964 Prince William Sound earthquake: Joint inversion of tsunami and geodetic data. *Journal of Geophysical Research: Solid Earth* (1978–2012), 101(B1), 523–532.
- Johnston, A. C. (1996). Seismic moment assessment of earthquakes in stable continental regions—III. New Madrid 1811–1812, Charleston 1886 and Lisbon 1755. *Geophysical Journal International*, 126(2), 314–344.
- Kaoubouben, F., Brahim, A. I., Toto, E., Baptista, M. A., Miranda, J. M., Soares, P., et al. (2008). On the focal mechanism of the 26.05.1975 North Atlantic event contribution from tsunami modeling. *Journal of Seismology*, 12(4), 575–583.
- Laughton, A. S., Whitmarsh, R. B., Rusby, J. S. M., Somers, M. L., Revie, J., McCartney, B. S., et al. (1972). A continuous East-West fault on the Azores-Gibraltar Ridge. *Nature*, 237, 217–220. <https://doi.org/10.1038/237217a0>.
- Levret, A. (1991). The effects of the November 1, 1755 “Lisbon” earthquake in Morocco. *Tectonophysics*, 193(1–3), 83–94.
- Lopes, F. C., Cunha, P. P., & Le Gall, B. (2006). Cenozoic seismic stratigraphy and tectonic evolution of the Algarve margin (off-shore Portugal, southwestern Iberian Peninsula). *Marine Geology*, 231(1–4), 1–36.
- Luis, J. F. (2007). Mirone: A multi-purpose tool for exploring grid data. *Computers and Geosciences*, 33(1), 31–41.
- Lynnes, C. S., & Ruff, L. J. (1985). Source process and tectonic implications of the great 1975 North Atlantic earthquake. *Geophysical Journal of the Royal Astronomical Society*, 82, 497–510.
- Mader, C. L. (1988). *Numerical modeling of water waves*. Berkeley: University of California Press.
- Mallet, R. (1852). Report on the facts of earthquake phenomena.
- McKenzie, D. (1972). Active tectonics of the Mediterranean region. *Geophysical Journal International*, 30(2), 109–185.
- Mezcua, J., & Solares, J. M. M. (1983). Sismicidad del área Ibero-mogrebí, I.G.N., No. 203, Madrid. <http://www.ign.es/web/resources/sismologia/publicaciones//SismicidaddelAreaIberoMogrebi.pdf>.
- Miranda, J. M., Baptista, M. A., & Omira, R. (2014). On the use of Green’s summation for tsunami waveform estimation: A case study. *Geophysical Journal International*, 199(1), 459–464.
- Miranda, J. M., Matias, L., Terrinha, P., Zitellini, N., Baptista, M. A., Chierici, F., Embriaco, D., Marinaro, G., Monna, S., & Pignagnoli, L. (2015). Marine seismogenic-tsunami-prone areas: The Gulf of Cadiz. In *Seafloor observatories* (Springer, Berlin, pp. 105–125).
- Miranda, J. M., Miranda, P. M. A., Baptista, M. A., & Victor, L. M. (1996). A comparison of the spectral characteristics of observed and simulated tsunamis. *Physics and Chemistry of the Earth*, 21(1–2), 71–74.
- Miyabe, N. (1934). An Investigation of the Sanriku Tsunami based on mareogram data. *Bulletin of the Earthquake Research Institute, Tokyo University, Suppl. 1*, 112–126.
- Moreira, V. S. (1968). Tsunamis observados em Portugal. Publicacao GEO, 134 (in Portuguese).
- Moreira, V. S. (1984). Sismicidade Histórica de Portugal Continental, Separata da Revista do Instituto Nacional de Meteorologia e Geofísica, Portugal, pp. 1–79.
- Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America*, 75(4), 1135–1154.
- Oliveira, C. S. (1986). A sismicidade Histórica em Portugal Continental e a Revisão do Catálogo sísmico Nacional, Laboratório Nacional de Engenharia Civil, Proc. 36/1177638, 235, Lisboa.
- Omira, R., Baptista, M. A., Matias, L., Miranda, J. M., Catita, C., Carrilho, F., et al. (2009). Design of a sea-level tsunami detection network for the Gulf of Cadiz. *Natural Hazards and Earth System Sciences*, 9(4), 1327–1338.
- Omira, R., Baptista, M. A., & Miranda, J. M. (2011). Evaluating tsunami impact on the Gulf of Cadiz coast (Northeast Atlantic). *Pure and Applied Geophysics*, 168(6–7), 1033–1043.
- Perrey, A. (1847). Sur les tremblements de terre de la Peninsule Ibérique. *Annales des sciences physiques et naturelles, d’agriculture et d’industrie, X. Societé Royale d’agriculture, d’histoire naturelle et des arts utiles*, Lyon.
- Pires, C., & Miranda, P. (2001). Tsunami waveform inversion by adjoint methods. *Journal of Geophysical Research: Oceans*, 106(C9), 19773–19796.
- Rothé, J. P. (1951). The structure of the bed of the Atlantic Ocean. *Eos, Transactions American Geophysical Union*, 32(3), 457–461. <https://doi.org/10.1029/TR032i003p00457>.
- Santos, Â., Koshimura, S., & Imamura, F. (2009). The 1755 Lisbon Tsunami: Tsunami source determination and its validation. *Journal of Disaster Research*, 4(1), 41–52.
- Satake, K. (1987). Inversion of tsunami waveforms for the estimation of a fault heterogeneity: Method and numerical experiments. *Journal of Physics of the Earth*, 35(3), 241–254.
- Satake, K. (1993). Depth distribution of co-seismic slip along the Nankai Trough, Japan, from joint inversion of geodetic and tsunami data. *Journal of Geophysical Research: Solid Earth* (1978–2012), 98(B3), 4553–4565.
- Satake, K., Baba, T., Hirata, K., Iwasaki, S. I., Kato, T., Koshimura, S., et al. (2005). Tsunami source of the 2004 off the Kii Peninsula earthquakes inferred from offshore tsunami and coastal tide gauges. *Earth, Planets and Space*, 57(3), 173–178.
- Solares, J. M., & Arroyo, A. L. (2004). The great historical 1755 earthquake. Effects and damage in Spain. *Journal of Seismology*, 8(2), 275–294.
- Solares, J. M., Arroyo, A. L., & Mezcua, J. (1979). Isoseismal map of the 1755 Lisbon earthquake obtained from Spanish data. *Tectonophysics*, 53(3–4), 301–313.
- Terrinha, P., Matias, L., Vicente, J., Duarte, J., Luis, J., Pinheiro, L., et al. (2009). Morphotectonics and strain partitioning at the Iberia-Africa plate boundary from multibeam and seismic reflection data. *Marine Geology*, 267(3–4), 156–174.
- Titov, V. V., Gonzalez, F. I., Bernard, E. N., Eble, M. C., Mofjeld, H. O., Newman, J. C., & Venturato, A. J. (2005). Real-time tsunami forecasting: Challenges and solutions. In *Developing tsunami-resilient communities* (Springer, Amsterdam, pp. 41–58).

- Tsushima, H., Hino, R., Fujimoto, H., Tanioka, Y., & Imamura, F. (2009). Near-field tsunami forecasting from cabled ocean bottom pressure data. *Journal of Geophysical Research*, *114*, B06309. <https://doi.org/10.1029/2008JB005988>.
- Udias, A., & Arroyo, A. L. (1972). Plate tectonics and the Azores-Gibraltar region. *Nature Physical Science*, *237*(74), 67–69.
- Udias, A., Arroyo, A. L., & Mezcuca, J. (1976). Seismotectonic of the Azores-Alboran region. *Tectonophysics*, *31*(3–4), 259–289.
- Wronna, M., Baptista, M. A., & Miranda, J. M. (2019). Reanalysis of the 1761 transatlantic tsunami. *Natural Hazards and Earth System Sciences*, *19*(2), 337–352.
- Wronna, M., Omira, R., & Baptista, M. A. (2015). Deterministic approach for multiple-source tsunami hazard assessment for Sines, Portugal. *Natural Hazards and Earth System Sciences*, *15*(11), 2557.
- Wu, T. R., & Ho, T. C. (2011). High resolution tsunami inversion for 2010 Chile earthquake. *Natural Hazards and Earth System Science*, *11*(12), 3251–3261.
- Yasuda, T., & Mase, H. (2012). Real-time tsunami prediction by inversion method using offshore observed GPS buoy data: Nankaido. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *139*(3), 221–231.
- Zitellini, N., Chierici, F., Sartori, R., & Torelli, L. (1999). The tectonic source of the 1755 Lisbon Earthquake. *Annali di Geofisica*, *42*(1), 49–55.
- Zitellini, N., Gràcia, E., Matias, L., Terrinha, P., Abreu, M. A., DeAlteriis, G., et al. (2009). The quest for the Africa-Eurasia plate boundary west of the Strait of Gibraltar. *Earth and Planetary Science Letters*, *280*(1–4), 13–50.
- Zitellini, N., Mendes, L. A., Cordoba, D., Danobeitia, J., Nicolich, R., Pellis, G., et al. (2001). Source of 1755 Lisbon earthquake, tsunami investigated. *EOS*, *82*(26), 285–291.
- Zitellini, N., Rovere, M., Terrinha, P., Chierici, F., Matias, L., & Team, B. (2004). Neogene through Quaternary tectonic reactivation of SW Iberian passive margin. *Pure and Applied Geophysics*, *161*(3), 565–587.

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