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ORIGINAL ARTICLE

The source of the 1722 Algarve earthquake: evidence from MCS and Tsunami data

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Abstract The 27 December 1722 Algarve earthquake destroyed a large area in southern Portugal generating a local tsunami that inundated the shallow areas of Tavira. It is unclear whether its source was located onshore or offshore and, in any case, what was the tectonic source responsible for the event. We analyze available historical information concerning macroseismicity and the tsunami to discuss the most probable location of the source. We also review available seismotectonic knowledge of the offshore region close to the probable epicenter, selecting a set of four candidate sources. We simulate tsunamis produced by these candidate sources assuming that the sea bottom displacement is caused by a compressive dislocation over a rectangular fault, as given by the half-space homogeneous elastic approach, and we use numerical modeling to study wave propagation and run-up. We conclude that the 27 December 1722 Tavira earthquake and tsunami was probably generated offshore, close to 37°01′N, 7°49′W.

Keywords Tsunamis · Historical seismicity · Modelling

1 Introduction

The Algarve coast, the southern limit of the Portuguese continental territory, is located close to the western sector of the Nubia–Eurasia interplate domain, a complex transpressional domain, where a significant number of tsunami events have been generated. Some of these were large enough to dramatically affect the Algarve costal landscape and left sedimentary signatures that can be identified today (Luque et al. 2001).

In historic times, the first event known that affected the Algarve took place ca. 382 DC. It is described by roman writers like Amiano Marcellino (in Brito 1597) who describe huge morphological changes close to St. Vicent Cape (see Fig. 1 for location), with the disappearing of an existing (Eriteia) island and the formation of a few islets. More recently, the best known events are the tsunamis of 27 December 1722

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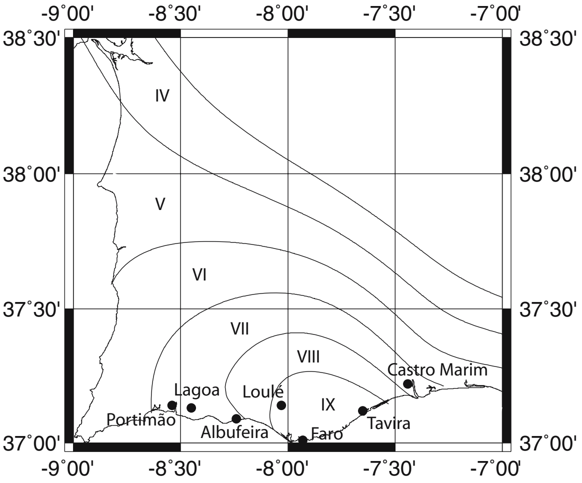

Fig. 1 Isoseismal map of the 27th December 1722 earthquake. MM intensities are listed in Table 2. *SVC* St. Vicent Cape

and 1 November 1755, which caused significant flooding in Algarve and a large amount of destruction. In the short instrumental period, after the installation of Lagos tide gauge in 1881 (see location in Fig. 2), only small amplitude tsunamis, like those generated by the 28 February 1969 and the 26 May 1975 earthquakes, have been recorded.

In previous papers, we studied some of these events: e.g., the 1755 "Lisbon" earthquake and tsunami (Baptista et al. 1998a,b, 2003; Gutscher et al. 2006), the 1761 event (Baptista et al. 2006), the 1969 Horseshoe earthquake (Gjevic et al. 1997), and the 1975 event (Rabinovich et al. 1998). The 1755 tsunami crossed the North Atlantic and was detected in northern and Central America (Baptista et al. 1998a; Baptista et al. 2003); the 1761 was observed in the UK and Ireland (Baptista et al. 2006); the 1969 and 1975 events were recorded in the Azores and the Canary Islands (Spain). Other moderate or strong magnitude events were generated within the Gulf of Cadiz but did not generate tsunamis, as it is the case of the 15 March 1964 earthquake. The recent 14 August 1978 earthquake generated a small tsunami recorded in Cadiz tide station, with 0.12-m amplitude (Campos 1992; Tel et al. 2004). All these events affected the area regionally; most of them crossed the North Atlantic and were detected in northern and Central America. In this paper, we will focus on the 27 December 1722 event, considered to have generated a local tsunami that affected only the coast of Algarve, but which impact was very large as the combined effect of the earthquake and tsunami devastated areas of Loulé, Tavira, and Faro (see Figs. 1 and 2 for locations). The earthquake itself was felt as far as Lisbon or Seville.

Local tsunamis are important for the assessment of geophysical risks because they can generate a large number of casualties and a significant damage in a particular area of the coast. In some cases, they have larger effects than those generated by larger events but far from the most vulnerable areas. It is believed that the source of the 1722 earthquake is different from those of the 1755 and 1969 earthquakes, but despite the studies already made (e.g. Mezcua 1982), no consensus has been yet obtained concerning the location and characteristics of the earthquake source and the local tsunami.

As we will see, the macroseismic field is constrained only by a small number of descriptions in a few locations close to the coast and cannot univocally define the source area. In similar situations, hydrodynamic modeling has been used to test among a set of candidate sources, which are the most probable from the point of view of tsunami observations (e.g., Tinti et al. 2001). The aim of this work is to compile all available geophysical data for the 27 December 1722 earthquake and tsunami and to use hydrodynamic modeling methods to evaluate among a set of fault candidates, which is the most probable source of the Tavira earthquake and tsunami.

All candidate fault parameters were deduced from systematic seismo-stratigraphic analysis of a large set of multichannel seismic (MCS) reflection profiles covering the Algarve Basin (Lopes 2002; Lopes and Cunha 2007; Lopes et al. 2006). These profiles were made available in digital form and interpreted with the help of five oil exploration wells, as deep as 3 km, where additional logs and units descriptions are available.

Because of the lack of instrumental geophysical data, we had to fix a scenario for modeling proposals. To do so, the strike and size of each candidate source was deduced from the morphostructural map, dip and rake were fixed with reasonable guesses according to each tectonic style, and an average slip of 2 m was considered for all cases. Wave propagation and run-up was computed using Mader (1998, 2004) SWAN model.

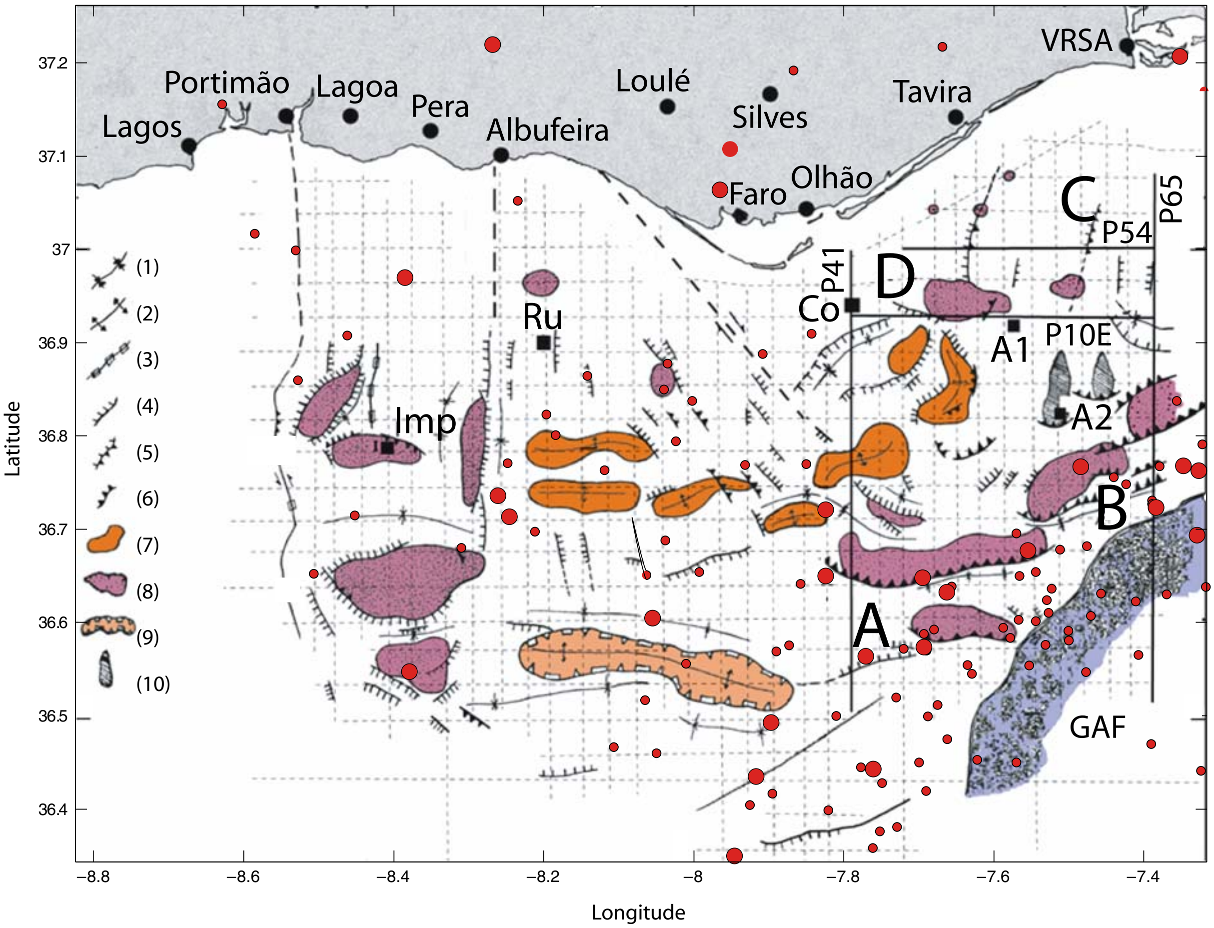

Fig. 2 Synthesis map of the Cenozoic main morpho-structures. *PMFZ* Portimão Fault Zone; *ALFZ* Albufeira Fault Zone; *SMQFZ* São Marcos Quarteira Fault Zone; *GAF* Guadalquivir Allocthonous Front; *1* syncline axis; *2* anticline axis; *3* strike–slip fault; *4* normal fault; *5* reversal normal fault; *6* thrust fault; *7* structural high; *8* evaporitic structure; *9* reversal half-graben; *10* ramp anticline. Potential sources: A to D. In *bold line* is indicated the location of the seismic profile shown in Fig. 4. Also plotted are the grid of multichannel seismic (*MCS*) profiles and five the exploration wells: *Imp* (Imperador1, 1976); *Ru* (Ruivo 1, 1975); *Co* (Corvina 1, 1976); *A1* (Algarve 1, 1982), and *A2* (Algarve 2, 1982). Seismicity obtained from ISC database for the period 1963–2005 includes only magnitude 3–4 (*small circles*) and magnitude above 4 (*large circles*) events

2 The 1722 tsunami and earthquake

According to Mendonça (1758), in the 27th December 1722, an earthquake stroke Tavira at approximately 5–6 P.M. It was felt all over Algarve, from St. Vicent Cape up to the Spanish border. This information is reproduced in most seismic catalogues (e.g. Galbis-Rodriguez 1932; GPSN 1991; Mendes-Victor and Martins 2001).

Available original information is scarce and is reproduced here: in Portimão, the Church of the Jesuits, the main Church, and the Capuchos Convent were destroyed (Mendonça 1758). The newspaper Gazeta de Lisboa (1723) when referring to the effects of the earthquake in the College Church states: "some fissures opened on the vault of the College Church, cracking some stones from the tribunes and doors." Indirect information concerning the need to refit the church main door is also given by a coeval document (ANTT 1719–1759, in Wagner 1993). In Tavira, "it ended with a awful thunder, 27 houses collapsed and the others were damaged" (Mendonça 1758); St Francis Convent was much destroyed (Mendonça 1758). In Faro, several houses felt causing a few casualties, other houses were unroofed, the Cathedral tower was damaged, and the bells wrung (Mendonça 1758). In Albufeira, a part of the castle wall collapsed (Mendonça 1758). In Loulé, the new Capuchos Convent and all the village were destroyed (Mendonça 1758). In Alagoa, the Church and the Carmo Monastery were ruined (Mendonça 1758). In Castro Marim, the Castle and the Warehouses suffered some damage (Mendonça 1758). In Lisbon (ca. 300 km to the north), bells rung in a church situated in Xabregas, at the eastern part of the city (Belém 1750; p. 200). In Seville (AMSev, XVIII, in Moreira et al. 1993), the earthquake was also felt. According to Cherkaoui (personal communication in Moreira et al. 1993), no information exists on Morocco concerning this earthquake.

The above information was used to assess Medvedev–Sponheuer–Karnik (MSK) intensity values, listed in Table 1 together with the coordinates of the locations described above; the corresponding isoseismal map (Fig. 1) is similar to previous descriptions of the macroseismic field (e.g., Mezcua 1982) and shows that damage concentrates along and close to the coast (from Castro Marim to Lagos) with open isoseismals suggesting an epicenter near the shore. The epicenter area of the earthquake is difficult to access based only on the macroseismic intensity distribution. The uncertainty is large enough that its location, onshore or offshore, has been questioned. The epicenter location given by IGN catalogue (Mezcua 1982) or Mendes-Victor and Martins (2001) is 37°10′N, 7°35′ W, onshore, slightly east of Tavira town. Steikhardt (1931; in Moreira 1991), Moreira (1982), and Baptista et al. (1999) considered that the earthquake epicenter should be located offshore because of the probable occurrence of a tsunami.

Mendonça (1758), which is the most valuable reference, describes the earthquake as originated in the sea: "All this earth quake come from the impulse, with which exploded a great amount of fire in the sea, between Faro and Tavira; because many people saw the flames climbing among the waters, roaring as forced by some tempest." He also describes clearly water retrieval: "in the river waters split apart, in such a way that a vessel that was going out the river was left dry for a long time".

Table 1 Macroseismic MSK intensities

	Long	Lat	MSK	Source
Albufeira	−8.24°E	37.09°N	7.5	MM
C. Marim	−7.44°E	37.22°N	7	MM
Faro	−7.93°E	37.01°N	9	MM
Lagoa	−8.45°E	37.13°N	7.5	MM
Loulé	−8.03°E	37.14°N	9	MM
Portimão	−8.54°E	37.14°N	7	MM
Tavira	−7.65°E	37.12°N	9.5	MM
Sevilha	−6.00°E	37.39°N	4	VSM
Lisboa	−9.14°E	38.71°N	4	JB

Sources are flagged as: MM (Mendonça 1758); JB (Belém 1750); VSM (Moreira et al. 1993).

The flooding of Tavira area is well documented and persisted in the collective memory of the population. According to the "Chronica Serafica da Santa Provincia dos Algarves" (Belém 1750, cap. XXII, pp. 200–201), some days after, a thanksgiving procession took place in the town of Tavira, which was repeated every year since, in the same day of 27th December, with the presence of the Senate, the Communities, and a large amount of people "to keep the memory of the great benefit, although the large damage suffered, the entire town could have been entirely submerged" (Belém, 1750, cap. XXII, pp. 200–201).

Solares and Mezcua (2002) attribute M~6.5 to the Tavira earthquake from the analysis of the macroseismic field. In a later section of this work, we will discuss the likelihood of this determination.

3 Candidate source selection

3.1 Morphostructural analysis

The data set for the morpho-structural analysis of the Algarve platform (Lopes 2002; Lopes et al. 2006) comprises a very dense network of 64 Chevron and Challenger MCS reflection profiles, made in 1974 between Portimão and Vila Real de Santo António (36°20′–37°00′ parallels and 7°20′–8°40′ meridians), covering 7,700 km^2 central in the eastern sectors of the Algarve offshore (cf. Fig. 2 for locations). Two sets of seismic lines with perpendicular strikes (E–W and N–S) and with regular (ca. 2 km) spacing almost provide a 3D picture of the main structures. The seismic interpretation was controlled by biostratigraphic data from five wells drilled during the seismic reflection surveys; their locations are also shown in Fig. 2.

The morpho-structural framework of the central and eastern sectors of the Algarve offshore is controlled by major fault structures that determine three main tectonic domains, all bounded to the south by the N70°-trending Guadalquivir Bank (Fig. 2). This mosaic fault-controlled basinal area comprises, from W to E, three different domains.

The Western Central Domain is a narrow (25 km-wide) N–S-trending domain, about 1,500 km^2, limited to the west by the N–S striking Portimão–Monchique Fault Zone (PMFZ) and to the east by the Albufeira Fault Zone (ALFZ), which is an anastomosing fault zone, striking approximately N–S and coincident to the Albufeira meridian.

The Eastern-central Domain is a triangle-shaped area (1300 km^2) bounded to the west by the ALFZ and to the east by the N140° striking St. Marcos–Quarteira Fault Zone (SMQF).

The Eastern Domain is an irregular-shaped area (1,800 km^2), tectonically more complex than the others, that corresponds to a structural depression dominated by compressive structures and also by the Guadalquivir Allocthonous front (Grácia et al. 2003), located in the southeastern extremity of the study area. This 50-km-wide front is configured into a wedge-shaped geometry, thinning northwards and westwards.

3.2 Sources selection criteria

The sources selection for the 1722 earthquake and tsunami was based on the morpho-structural interpretation, with the recognition of structures located closed to the presumed source as given by the macroseismic field, which show evidences of neotectonic activity, evaluated on the relevant 2D seismic profiles. We selected a set of four candidate sources, which we note from A to D (see Fig. 3), described below:

> Source A: a 26 km long E–W trending arcuate thrust front, verging to the south, located north of the Guadalquivir Bank, between −7.53°E, 36.68°N and −7.82°E, 36.63°N (Fig. 3a). This thrust front shows a shallower geometry with thin and flat-lying Hettangian salt slices at depth, overlain by an imbricate thrust wedge, directed to the south and involving Mesozoic sequences. The Cenozoic is cut by the thrust faults at a depth of 500–1,800 m below the bottom of the sea. In spite that its main activity seems to occur during the Upper Tortonian–Messinian (8.0–5.5 Ma), there is evidence for neotectonic activity: some associated salt structures are pushing upwards through the Lower Pleistocene (1.9 Ma), giving rise to the flexuration of the Plio-Pleistocene at a depth of 50–150 m below sea bottom.
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> Source B: a 16-km wide N60° trending zone of imbricate thrust faults verging to the south, located in the southeast end of the eastern domain, between −7.53°E, 36.69°N and −7.38°E, 36.76°N (Fig. 3b). The bottom of the thrust wedges probably involves Hettangian salt slices and the basement at depth. The overlying sedimentary thrust wedge affects strata up to Upper Tortonian–Messinian (8.0–5.5 Ma) at about 3-km depth. In some cases, thrust wedges are associated with salt diapirs that push upward through the Lower Pleistocene (1.9 Ma), showing neotectonic activity. The Plio-Pleistocene flexuration occurs at a depth of 50–150 m below the sea bottom.
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> Source C: Two sets of 15-km long N18°-trending reverse faults, verging to the WNW, located south-southeast of Tavira, between −7.46°E, 37.06°N and −7.52°E, 36.93°N, very close to the inferred epicenter area (Fig. 3c). They have resulted from the inversion of previous extensional structures. They show neotectonic activity inferred by Pleistocene disturbance at a depth of 80–200 m below sea bottom.
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> Source D: A - km long N138°-trending subvertical fault located between −7.690°E, 36.944°N and −7.660°E, 36.917°N (Fig. 3d). It forms the SW border of an E–W salt structure. The post-Miocene fault reactivation is mainly related to the halokinesis. A recent movement seems to have caused about 40 m of local subsidence of the sea bottom.

4 Tsunami modeling

4.1 Nonlinear shallow water model

The elastic deformation of the seafloor was computed with the half-space homogeneous elastic approach for a planar rectangular source (Mansinha and Smylie 1971). Fault parameters are listed in Table 2, where the length and strike of the sources were directly deduced from the MCS data, the width to length ratio was taken as 0.6, and the depth to the top of all fault planes was fixed as 0.1 km.

In what concerns the dip and rake of the candidate sources, whenever the source is interpreted as a thrust (sources A and B), we fixed an average value of 30° for the dip and 90° for the rake angles. We affected a dip of 50° and a rake of 90° to source C because it is

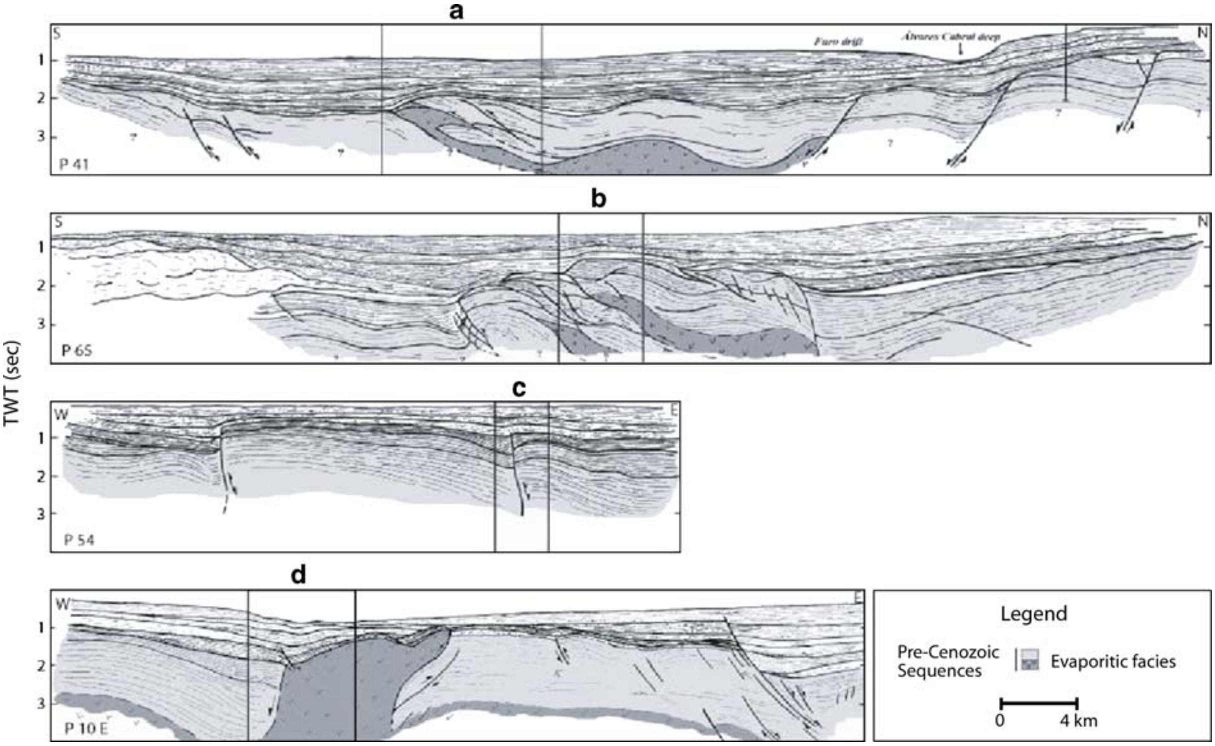


Fig. 3 **a**–**d** Seismostratigraphic interpretation of the four profiles plotted in Fig. 2, crossing the four candidate sources considered here. Two-way travel times in second

interpreted as the inversion of a previous normal fault. In the case of source D, interpreted as probable collapse, we presumed a rake of −90°.

The average slip of candidate sources was set equal to 2 m, which is compatible with the distribution shown by Wells and Coppersmith (1994) for thrusts with moment magnitudes close to 6.5. To account for slip variability within the fault plane, we used the smooth closure condition as described by Freund and Barnett (1976) with a skewness parameter of 0.3. The use of variable slip is closer to what is observed (or indirectly determined by geophysical studies) for slip distribution in real faults.

The tsunami is modeled as a long wave governed by the equations of the shallow water approximation (Mader 1998, 2004). The boundary conditions ensure pure wave reflection on the solid boundary (coastlines) and full wave transmission on the open boundary (open sea). The initial seawater disturbance is assumed to be equal to the coseismic displacement produced by the dislocation at the fault, whereas the initial velocity is assumed to be identically null.

Bathymetric data were obtained from the merge of 1:25,000 digital topographic maps for the onshore areas and the digitization of bathymetric maps for the offshore. The grid step is 0.0025° (ca. 278 m northing and 219 m easting) and the calculations were made in geographical coordinates. Time step for numerical simulations was 0.2 s.

Table 2 Parameters of the four candidate sources used in this study

Source	Length (km)	Width (km)	P1	P2	Strike	Dip	Rake	Slip (m)
A	26	15.6	−7.53°E, 36.68°N	−7.82°E, 36.63°N	76°	30°	90°	2
B	16	9.6	−7.53°E, 36.69°N	−7.38°E, 36.76°N	60°	30°	90°	2
C	15	9.0	−7.46°E, 37.06°N	−7.52°E, 36.93°N	18°	50°	90°	2
D	4	2.4	−7.69°E, 36.94°N	−7.66°E, 36.92°N	138°	90°	−90°	2

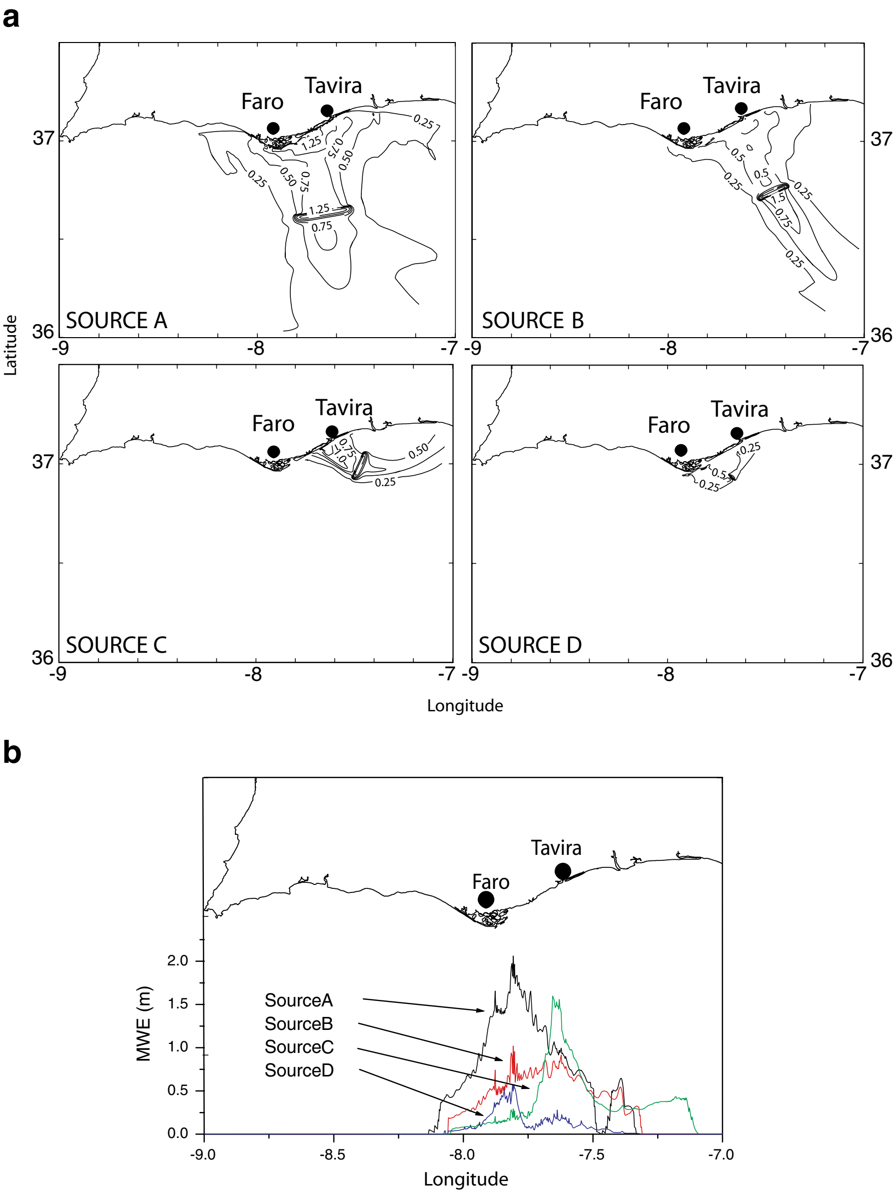
4.2 Numerical simulations

We performed numerical simulations of the tsunamis generated by the candidate faults discussed above. The computation time (1,600 s) is long enough to calculate the main waves in all the most relevant coastal locations along south Portugal.

As we have no direct measures or even quantitative observations of the wave heights, we concentrate on the analysis of maximum water elevation (MWE) distributions, calculated over the entire computation time interval for the study areas, as a direct description of the "radiation pattern" that corresponds to both the source characteristics and propagation along the Algarve shelf. MWE for the different candidate sources are shown in Fig. 4. MWE are computed at the isobath 10 m to allow comparability along the Algarve coast.

If we compare the historical descriptions quoted above with the expected MWE distributions, we can conclude that source C is the only one (of the four candidate sources) that can account for the observations. It generates a significant wave directed to the area most affected by the inundation (Tavira) and has

Fig. 4 **a** Maximum water elevation (MWE) along the study area for the four candidate sources; isovalues of MWE are plotted every 0.25 (m. **b** Maximum wave elevation as a function of longitude. The cross-section shown corresponds to a projection of the Algarve coast



no significant effects on other towns along the shore, where no inundation was verified. All the other generate smaller tsunami waves do not focus on Tavira.

5 Magnitude of the 1722 earthquake

The source selection process described above allowed us to select as the most likely location of the earthquake epicenter 37°01′N, 7°49′W. This result can be used to constrain a little further the moment magnitude of the 1722 earthquake if we compare the earthquake magnitude and the source dimensions inferred from seismostratigraphic data. This is presented in Fig. 5, where the Wells and Coppersmith (1994) empirical relationships are plotted against the fault lengths for the four candidate sources. We conclude that the magnitude of the earthquake can be estimated as 6.5, in agreement with the value given Solares and Mescua (2002).

6 Discussion and conclusions

The study of the 1722 earthquake is important for the assessment of the geophysical risks in Southern Iberia. This is because of the fact that large damages can be produced by moderate earthquakes when they are able to trigger very local tsunamis that inundate very shallow areas like Tavira. The fact that coastal areas are being increasingly occupied by tourist resorts amplifies the risk, particularly during the summer.

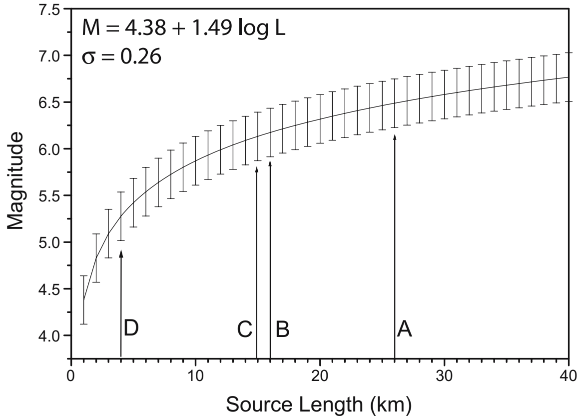


Fig. 5 Empirical relationship between subsurface rupture length and earthquake magnitude, according to Wells and Coppersmith (1994). The four candidate sources lengths deduced from seismostratigraphy are also plotted

The historical information available for the event is rather scarce. Most of the existing compilations are based on the work of Mendonça (1758) and the newspaper "Gazeta de Lisboa". Even the description of the inundation is largely insufficient. Nevertheless, the existing testimonies and the importance of the thanksgiving procession that was kept in Tavira for a long time support the conclusion that the shallow areas close to the village were largely inundated as a consequence of a long period wave generated by the earthquake. This is only compatible with what is expected for a local tsunami event.

From the available data, we cannot discard in definitive the hypothesis of a land-slide triggered by the earthquake as the generator of the 1722 tsunami. However, available bathymetric data close to the shore of Algarve does not allow for the identification of any significant submarine landslide scares.

The selection of the candidate sources is always a complex task because faulting does not happen in a recurrent way on a small number of structures, particularly in slow compressional regimes like the one that characterizes the Iberia–Nubia interplate domain close to Algarve. Nevertheless, the availability of dense MCS data over the whole area gives us a good guess on the candidate structures, either in the sense that they were probably accountable for similar events in the past or in the sense that future local tsunamis can most probably be generated there. The macroseismic field, in spite of the limitation already described, reinforces the conclusion that the 1722 source must be located in the Faro–Tavira close offshore, as is the case of the proposed source.

The proposed source and the thrust mechanism chosen for the modeling would imply a direction of the *P*-axis ca. N72W, close to the lower limit of the distribution obtained by Borges et al. (2001) for the earthquakes of the Gulf of Cadiz, suggesting a nonpure thrust mechanism for the Tavira event. However, available data cannot support further analysis.

Taking into account both the tsunami modeling results and the scarce seismic information available, we estimate that the source of the 1722 Tavira earthquake has a magnitude ca. Mw=6.5 and an epicenter close to 37°01′N, 7°49′W, in the submarine area close to the Algarve coast.

The occurrence of a local tsunami in Tavira area in 1722 has consequences for the tsunami risk evaluation. The elapse time between the trigger of the event and the arrival of the waves to the coastline is very short. This must be taken into consideration in any attempt to design a real tsunami warning system.

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