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Reanalysis of the 1761 transatlantic tsunami

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Abstract. The tsunami catalogues of the Atlantic include two transatlantic tsunamis in the 18th century the extensively studied 1st November 1755, and 31st March 1761. The latest event struck Portugal, Spain, and Morocco around noontime. Several sources report a tsunami following the earthquake as far as Cornwall (United Kingdom), Cork (Ireland) and Barbados

- 10 (Caribbean). An earlier analysis of macroseismic information and its compatibility with tsunami travel time information located the epicentre circa 34.5°N 13°W close to the Ampere Seamount at the eastern end of the Gloria Fault (North East Atlantic). The estimated magnitude of the earthquake is 8.5. In this study, we propose a tectonic source for the 31st March 1761 earthquake compatible with the tsunami observations in the Atlantic. We revisit the tsunami observations, reevaluate tsunami travel time data, and include a report from Cadiz not used before. The global plate kinematic model NUVEL 1A
- 15 computes a convergence rate of 3.8 mm/y in the area of the presumed epicentre. We propose a source mechanism for the parent earthquake compatible with the geodynamic constraints in the region capable of reproducing most of the tsunami observations. The results of our study support the hypothesis that the 1761 event took place in the area of Coral Patch and Ampere seamounts, SW of the 1st November 1755, mega-earthquake source. Finally, this study shows the need to include the 1761 event in all seismic and tsunami hazard assessments in the Atlantic Ocean.

20 1. Introduction

The coast along the southwest Iberian margin is prone to earthquakes and tsunamis. The earthquake and tsunami catalogs for the Iberian Peninsula and Morocco report three tsunamigenic earthquakes in the 18th century: 1722, 1755 and 1761 (Mezcua and Solares, 1983; Oliveira, 1986; Baptista and Miranda, 2009). While the 1722 event is believed to be a local event (Baptista et al., 2007), the 1st November 1755 and the 31st March 1761 earthquakes generated transatlantic tsunamis (Baptista et al.,

- 25 1998; Baptista et al., 2003; Baptista et al., 2006; Barkan et al., 2009). The source of the 1755 event has been extensively studied in recent years e.g. Baptista et al. (1998), Zitellini et al. (2001), Gutscher et al. (2006) and Barkan et al. (2009). On the contrary, the tectonic source of 31st March 1761 remains poorly understood. The seismic catalogs present different earthquake locations: 10.00 W, 37.00 N (Mezcua and Solares, 1983) or 10.50 W, 36.00 N (Oliveira, 1986). Baptista et al. (2006), used macroseismic intensity data and tsunami travel time observations to locate the source circa 13.00 W, 34.50 N and
- 30 estimated the magnitude in 8.5.





The source location obtained by Baptista et al. (2006) places the 1761 event southwest of the South West Iberian Margin (SWIM) in the outer part of the Gulf of Cadiz (Fig. 1). The SWIM is dominated by large NE-SW trending structures limiting the Horseshoe Abyssal Plain (HAP). The large NE-SW striking structures are the Coral Patch fault (CPF), the Gorringe Bank fault (GBF), the Horseshoe fault (HSF) and the Marques Pombal fault (MPF). To the south, the (HAP) is limited by the igneous Ampere and Coral Patch seamounts. The present day tectonic regime is constrained by NW-SE plate convergence between

5 Ampere and Coral Patch seamounts. The present day tectonic regime is constrained by NW-SE plate convergence between Africa and Eurasia at ~4 mm/yr (Argus et al., 1989; DeMets et al., 1994) and westward migration of the Cadiz Subduction slab ~2 mm/yr (Gutscher et al., 2012; Duarte et al., 2013).



Figure 1. Source location by Baptista et al. (2006) and the tsunami observation points of the tsunami in 1761. The main features of the Azores Gibraltar fracture zone are the Azores Triple Junction (ATJ), the Gloria Fault (GF) and the Southwest Iberian Margin (SWIM).

In this study, we revisit the source of the 1761 transatlantic tsunami. We re-evaluate the tsunami source using plate kinematic constraints, tsunami travel time data and eyewitness reports. We use the geodynamical constraint to propose an earthquake scenario and compute the initial sea surface displacement. This displacement is used to initiate the tsunami propagation model.

15 The results of the numerical simulations are checked against the historical observations. Finally, we use Cadiz and Lisbon observations in 1755 and 1761 to compare the size of the events.





2. Geodynamical context

The western segment of the plate boundary between Africa and Eurasia in the NE Atlantic Ocean extends from the Azores Triple Junction (ATJ) to Gibraltar. The main features of the Azores Gibraltar fracture zone are the ATJ; the Gloria Fault (GF) and the SWIM (Fig. 1). At the ATJ, the plate boundary is defined by active interplate deformation (Fernandes et al., 2006).

- 5 The GF is a large W-E striking transverse fault with scarce seismicity (Laughton and Whitmarsh, 1974) with a strong magnitude event on 25th November 1941 (Gutenberg and Richter, 1949; Moreira, 1984; Baptista et al., 2016). The Gloria fault defines a sharp boundary between Eurasia and Africa (Laughton and Whitmarsh, 1974). Further East, towards the Gulf of Cadiz, in the SWIM area the plate boundary is not clearly defined (Zitellini et al., 2009). Large scale dynamics are imposed by convergence between Africa and Eurasia and by the westward propagation of the Gibraltar arc. Most recent studies agree
- 10 that the source of the 1755 Lisbon earthquake with a magnitude of about 8.5±0.3 is in the SWIM (Johnston, 1996; Baptista et al., 1998; Zitellini et al., 1999; Gutscher et al., 2002; Solares and Arroyo, 2004; Ribeiro et al., 2006). Identified faults in the SWIM include large NE-SW trending thrust faults namely the Horseshoe Fault (HSF), the Marquês de Pombal fault (MPF), the Gorringe bank fault (GBF) and the Coral Patch fault (CPF) (Fig. 1). The GBF and the CPF bound the Horseshoe Abyssal Plain (HAP) and the aseismic SWIM-Lineaments WNW-ESE trending dextral strike-slip faults (Zitellini et al., 2009). The
- 15 NE-SW striking thrusts are deep rooted faults accompanied with morphological seafloor signatures. Moderate and small magnitude events (M<5) characterize the seismicity of the area. These faults lie between the Gorringe Bank and the Strait of Gibraltar (Custódio et al., 2015). South of the HAP the Coral Patch ridge shows surface deformation, with a predominating flower structure geometry (Rosas et al., 2009; Terrinha et al., 2009; Martínez-Loriente et al., 2013).</p>
- Considering the earlier mentioned faults, the CPF is closest to the area suggest by Baptista et al. (2006). Also, this area southwest of the SWIM, is in a slow deforming compressive regime dictated by the major tectonic driving forces (Eurasia Africa convergence and Gibraltar arc westward propagation). The IGN seismic catalogs list a 6.2 magnitude around the Coral Patch on 11th of July 1915.

We used the global kinematic plate model Nuvel-1A. This model is a recalibrated version of the precursor model Nuvel-1 that implements rigid plates and data from plate boundaries such as spreading rates, transform fault azimuths, and earthquake slip

25 vectors (DeMets et al., 1990). The NUVEL 1A model (DeMets et al., 1994; 1999) predicts a convergence rate of 3.8 mm per year in the zone close to the source area determined by Baptista et al. (2006) for the 1761 tsunami (Fig. 2).







Figure 2. Source locations and back ray tracing contours (black lines) for TTT of 7 - 7.5 hours to Barbados. The orange limited area defines the results obtained using macroseismic analysis combined with backward ray tracing but discarding the TTT for Barbados by Baptista et al. (2006).

5 Consequently, we placed a hypothetical fault as an extension of the CPF closest to the area presented by Baptista et al. (2006). We computed the convergence rate and plot the tangent velocity vector along the Euler circle using Mirone suite (Luis 2007) at the hypothetical fault (Fig. 3). For this hypothetical fault, we test different earthquake fault parameters and compute the coseismic deformation using the Mansinha and Smiley equations (Mansinha and Smiley, 1971). We assume that the initial sea surface elevation mimics the sea bottom deformation and we use it to initiate the tsunami propagation model. We check the results against the historical observations.

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Figure 3. Circle around the Euler pole at the proposed hypothetical fault location. The model Nuvel 1A (DeMets et al., 1994, 1999) computes a 3.8 mm y⁻¹ convergence. We plot the tangent velocity vector at the proposed fault. The black lines depict the backward ray tracing contours in hours, for TTT of 7-7.5 hours to Barbados.

5 3. Reassessment of historical data on the 1761 tsunami

The study by Baptista et al. (2006) presents most of the tsunami information used herein. In this study, we re-assess the information on tsunami observations and analyze the report from Cadiz (Journal Historique, 1773, in Baptista and Miranda, 2009). Below we present a synthesis of the tsunami observations and our reappraisal of the Cadiz and Barbados reports. Table 1 presents a summary of the tsunami observations for the points presented in Fig. 1.

10 The Journal des Matiéres du Temps (Journal Historique, 1773), describes the occurrence of an earthquake on April 1773 and compares it with the 31st March 1761 event. The document states that in April 1773, following an earthquake felt in Cadiz, it was feared that it could have triggered a tsunami. The governor of the city ordered the closing of the town gates to prevent people fleeing to the causeway which was inundated in 1755. The report concludes that no tsunami was observed in 1773. However, the text of the report suggests a withdraw of the sea after the 31st March 1761 earthquake in the city.





For Barbados, we reevaluated the Tsunami Travel Time (TTT). Baptista et al. (2006) concluded for the unreliability of this observation and did not use it the simulations to locate the source. In this study, we used 3.5 hours solar time difference between Lisbon and Barbados. The letter by Mason (1761) notes the extraordinary movement of the sea, ebbing and flowing in an eight minutes interval, and the duration of the oscillations for three hours. The summary by Borlase (1762) notes an extraordinary

- 5 withdraw of the water about 4 pm local time coming back to shore to a height of near four feet. Using 4 pm local time for the arrival of the tsunami and the 3.5 h solar time difference between Lisbon and Barbados, we conclude a TTT of 7-7.5 h. We use backward ray tracing for Barbados and find that the 7 h contour falls within the area presented by Batista et al. (2006) close to their suggested location (Fig. 1 and 2) at 34.50 N 13.00 W. Mason (1761) wrote that the tide ebbed and flowed between eighteen inches and two feet. Zahibo and Pelinovski (2001) state 1.2 m wave height in Barbados and refer to (NOAA/NESDIS)
- 10 data). The NGDC/WDS database now gives 1.2 m runup at Barbados referring to Davidson (1936). A letter dated from Lisbon, 2nd April 1761 published by the Philosophical Transactions (Unknown, 1761) describes an anomaly flowing and ebbing of the sea of about 8 feet every six minutes. It also reports that the unusual fluctuation started about 1 hour and 15 minutes after the earthquake and lasted until night. Another letter dated, 3rd April 1761 reports a great agitation of the sea during the time of the earthquake and that some hours after the shock the waters ebbed and flows several feet
- 15 perpendicularly every six minutes (Molloy, 1761). In a summary by Borlase (1762) summary describes that the earthquake lasted between five and seven minutes and that the waters ebbed and flowed three or four feet in a short time lasting the entire afternoon.

A letter from Kinsale reproduced in the Annual Register (1761) and published by the London Chronicle on 11th April 1761 states that at six p.m. at low water, the tide rose quickly about two feet higher than it was and it ebbed again about four minutes

20 later. The movement of the fluxes repeated several times but with decreasing intensity after the in and out flux. Borlase (1762) confirms these tsunami observations.

In Dungarvan, the same report states that the sea ebbed and flowed five times between 4 and 9 o'clock in the afternoon. Borlase (1762) includes observations of the sea in Mount's Bay and other points in the bay like Penzance, Newlyn and Mousehole. It reports the arrival of the waves at around five o'clock in the afternoon about one and a half hour before full ebb.

- 25 According to the report, the first wave was the biggest, reaching a height that is common for one and a half hours high-water and that the sea advanced and recessed five times within an hour. At Penzance pier the water rose about six feet and at Newlyn approximately one mile west the waters reached nearly the same height. About three miles east at St. Michel's mount pier the rose and retreated about four feet. At Mousehole pier about 3 miles southwest of Penzance the observations state large agitation of the sea. At Scilly Islands the report states that the sea rose four feet and that the agitation lasted about 2 hours, longer than
- 30 it did in Mount's-bay.

Additionally, there are some observations of unusual fluxes of the water inside river estuaries.

Finally, we consider the qualitative descriptions at Madeira, and Terceira island in the Azores Islands, and Cadiz. Table 1 presents a summary of all historical data relevant to the tsunami simulation.



Table 1. Summary of the available data of the 1761 tsunami at the time.

Location	Local	TTT	Information Polarity Period		Duration	Source		
	Time		on Wave					
			height					
			Eluctuation				Unknown (1761);	
Lisbon	13:15	1 h 15 min	of 2.4 m	-	6 min	Lasted until night	Molloy (1761);	
			01 2.4 111				Borlase (1762)	
Cadiz				D			Journal des Matieres	
Caulz	-	-	-	D	-	-	du Temps (1773)	
						Repeated several	Annual Register	
Kinsale	18:00	6 h	0.6 m	U	4 min	times	(1761);	
						times	Borlase (1762)	
Scilly	17:00	5 h	0.6-1.2 m	U	_	More than 2 hours	Borlase (1762)	
Islands								
Mount's	17:00	5 h	1.2-1.8 m	U	12 min	1 hour	Borlase (1762)	
Bay								
Dungarvan	16:00	4 h	-	-	-	5 hours	Borlase (1762)	
						Seemed to stop	Mason (1761);	
			0.45-0.6 m		8 min	after 4 hours but	Annual Register	
						lasted until 6 in	(1761)	
Barbados	16:00	7-8 h				the morning.		
			Fluctuation			Increased again at		
			of 1.2 m		3-6 min	ten for short time	Borlase (1762)	
						then decreased.		
			Fluctuation			Lasted longer in		
Madeira	-	-	of ~ 2 m;		-	the eastern parts	Heberden (1761)	
			higher in the			of the island than	· · · ·	
			East			in the South.		
Azores	-	-	Large	U	Some min.	3 hours	Fearns (1761)	





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4. Tsunami Simulations

4.1 The numerical model

We used the code NSWING (Non-linear Shallow Water model wIth Nested Grids) for numerical tsunami modeling. The code solves linear and non-linear shallow water equations (SWEs) in a Cartesian or spherical reference frame using a system of

5 nested grids and a moving boundary condition to track the shoreline motion based on COMCOT (Cornell Multi-grid Coupled Tsunami Model; Liu et al., 1995; 1998). The code was benchmarked with the analytical tests presented by Synolakis et al. (2008) and tested in Miranda et al. (2014) and Baptista et al. (2016), Wronna et al. (2015) and Omira et al. (2015).

We computed offshore wave heights for points located close to the observations points (Fig. 1) included in the tables 3 and 4. For transatlantic propagation we considered Coriolis effect in the tsunami simulation. All tsunami simulations were checked against historical data.

Additionally, we computed inundation in Cadiz using a PDEM (Paleo digital elevation model) because of the possibility of comparison of the observations of the 1755 and 1761 events. For Cadiz, we reconstructed the PDEM for Cadiz following the methodology presented by Wronna et al. (2017).

To compute inundation, we employed a set of coupled nested grids with a final resolution of 25 m. We applied a refinement

15 factor of 4 for the four nested grids. Consequently, the intermediate grids have a resolution of 100 m and 400 m respectively, and we interpolated the source area bathymetry (GEBCO, 2014) to 1600 m resolution. We run the model for 10 hours propagation time to ensure that the tsunami simulation reached all the observation points.

To initiate the tsunami propagation model, we computed the co-seimic deformation according to the half space elastic theory (Mansinha and Smylie, 1971) implemented in Mirone suite (Luis, 2007). Assuming the water as an incompressible fluid we

20 translate the sea bottom deformation to the initial sea surface deformation and set the velocity field to zero for the time instant t = 0s.

4.2 Testing the hypothesis

We placed the hypothetical fault area with its center at 12.00 W, 35.00 N to the west of the large NE/SW striking compressive structures (Martinez-Loriente et al., 2013) and 85 km northeast of the epicenter suggested by Baptista et al. (2006) (Fig. 3).

- 25 Our tests considered the fact that the historical accounts indicate an earthquake and tsunami less violent than the 1755. To account for this we used the fault dimensions presented in table 2 corresponding to a magnitude 8.4-8.5 earthquake (Baptista et al., 2006), consequently the wave heights in Lisbon and Cadiz must be smaller than those observed in the 1755 tsunami (Baptista et al., 1998). The fault dimensions presented in table 2 are compatible with the scaling laws of Wells and Coppersmith (1994), Manighetti et al. (2007) and Blazer et al. (2010). We approximated the rake angle according to the difference between
- 30 the tangent velocity arrow and the circle around the Euler Pole (Fig. 3).
 To tune the observed period, we tested hypothesis A with a multi segment fault with 4 segments each 50 km and a mean slip of 11 m. However, we could not reproduce most of the observations of the time interval between ebbing and flow of the tide.





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In the 20th century, two strong magnitude earthquakes occurred in the Gloria Fault area. We tested the compatibility of the tsunami observations in 1761 set with the tsunamis produced by the earthquakes of the 25th November 1941 (Baptista et al., 2016) and 26th May 1975 (Kaabouben et al., 2009). These two events produce less than one-meter wave height in the North East Atlantic and barely observed wave in the Caribbean Islands (Baptista et al., 2016; 2017). Moreover, the epicenters of the 25th November 1941 and 26th May 1975 are located outside the area determined by Baptista et al. (2006).

Table 2. The fault dimensions and parameters used herein to investigate candidate sources of 1761 event. We describe hypotheses (Hyp.) A-MS, A, B, GF 41 and GF 75 by the fault parameters length (L), width (W), strike, dip, rake, slip and depth. Additionally, we present the moment magnitude (Mag.), the assumed shear modulus (µ) and the focal mechanism.

Scenario	L	W	Strike	Dip	Rake	Mean	Depth	Mag.	µ [Pa]	Focal
	[km]	[km]	[°]	[°]	[°]	slip [m]	[km]			mechanism
Hyp. A-MS	4 x 50	50	76	40	135	11	10	8.4	4*10 ¹⁰	
Нур. А	200	50	76	40	135	11	10	8.4	4*10 ¹⁰	
Нур. В	280	50	254.5	70	45	15	10	8.5	4*10 ¹⁰	
Нур. GF 41	250	50	76	88	161	15	1	8.5	4*10 ¹⁰	
Нур. GF 75	250	50	271	88	161	15	1	8.5	4*10 ¹⁰	\bigcirc

5. Results

- 10 We present the results of hypothesis A-MS and B. Hypothesis A-MS has a more significant inverse component compared to B. Figures 4-7, present the maximum wave height and the synthetic tsunami at the virtual tide gauges (VTG) of hypothesis A-MS and B. Tables 3 and 4 summarise these results. The wave height herein represents the maximum positive amplitude above the still water level, which is set to be 0 in the tsunami simulation. We placed VTGs close to all observation sites as presented in Fig. 1. The geographical coordinates and depths their coordinates and depth are given in tables 3 and 4. To compare the
- synthetic wave heights with the observations, we used the Green's Law (Green, 1838) to extrapolate the wave height values 15 for the first and the maximum wave between the depths of the VTG to points located at 5 m depth. For Lisbon and Cadiz, where high-resolution bathymetry is available we computed the tsunami inundation.





5.1 Hypothesis A-MS

Figures 4 and 5, show the distribution of the maximum wave height and the respective synthetic tsunami records for hypothesis A-MS.

- Analysis of Fig. 4 show significant wave heights around the Gorringe Bank with values up to 14 m. The Gorringe Bank is a seamount located 120 km north of our possible fault with the minimum depth of about 70 m. This hypothesis also produces wave height values above 5 m at some points along the coast of Morocco. In the Gulf of Cadiz, maximum wave heights exceed 4 m. Along the southwestern tip of the Iberian Peninsula, the wave heights attain 5 m. In Cadiz, the predicted wave heights are close to 1.8 m. Close to Lisbon wave heights are about 1.6 m when considering the coarse scale model (Fig. 4). In Great Britain, at the Scilly Islands wave heights exceed 1.9 m, and in Mount's Bay, maximum wave heights reach 1.7 m. Along the
- 10 south coast of Ireland in Kinsale and Dungarvan the wave height reaches close to 1 m. In the Atlantic, at the eastern coast of Madeira Island, the wave heights reach 1 m whereas on the southern coast of the Island the wave heights are 0.5 m smaller. At the Azores close to Terceira Island wave heights are slightly higher than 2.5 m along the southern coast of the island. The wave heights in the south of Barbados reach 0.5 m whereas in the north part of the island do not exceed 0.2 m.



15 Figure 4. Maximum wave height distribution (color scale in m) in the Atlantic basin produced by the source of hypothesis A-MS.





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In Lisbon, the VTG shows a first peak 1.4 m with a maximum value close to 1.8 m for the third wave, after two hours and twenty minutes of tsunami propagation. The TTT to Lisbon is 1 hour and 10 minutes and the first wave has a period of 20–25 minutes (table 3 and Fig. 5 (a)). In Cadiz, the synthetic tsunami waveform shows a drawdown 1 hour after the earthquake with a negative amplitude of 0.6 m and a maximum wave height of 2.4 m (table 3 and Fig. 5 (a)).

- The Scilly Islands synthetic tsunami waveform shows a TTT of 4 hours and a first positive and maximum peak of 0.8 m and the wave has a 15-minute period. The results obtained for Mount's Bay are similar to the ones from the Scilly Islands. The maximum wave height is 0.8 m although the first wave height is 0.6 m with 15 minutes period. In Mount's Bay, TTT is 4 hours and 30 minutes. In Kinsale, the tsunami model computes a TTT of 4 hours, and 15 minutes and the maximum wave
- 10 height is about 0.7 m. The period at the VTG is shorter than 15 minutes. In Dungarvan, the tsunami arrives 5 hours after the earthquake. All VTGs in northern Europe recorded the first wave as an upward movement (Fig. 5 (b)).



Figure 5. VTG records for hypothesis A-MS at the coordinates of the locations presented in table 3.





In Madeira, hypothesis A-MS produces maximum wave heights of 1.4 m in the eastern part of the island and about 0.7 m, in the southern part; the TTT to the east and southern coast of the island is less than half an hour and about half an hour respectively. In the Azores, close to the island of Terceira, the wave heights reach approximately 1.3 m (Fig. 5 (c)).

5 In Barbados, hypothesis A-MS produces the first wave of about 0.1 m after about 7 hours. Only after 9 hours and 30 minutes, the wave height exceeds 0.4 m. The first wave arrives in Barbados with a leading crest of 0.1 m and a period of about 30 minutes (Fig. 5(d)).

Table 3. Results of the VTGs for hypothesis A

Local	Local		rdinates 8	k depth	TTT	Wave he	eight [m]	Polarity	Period
		Lon. [°]	Lat. [°]	d [m]		First	max.		
Lisbon		-9.136	38.706	3	~ 1 h 10 min	-0.1 m	1.8 m	D	< 30 min
Cadiz		-6.291	36.524	4	~ 1 h	-0.6 m	2.4 m	D	~ 30 min
Scilly Islan	ds	-06.383	49.85	50	~ 4 h	0.8 m	0.8 m	U	~ 15 min
Mount's B	ay	-05.48	50.08	26	~ 4 h 30 min	0.6 m	0.8 m	U	~ 15 min
Kinsale		-08.500	51.653	28	~ 4 h 15 min	0.2 m	0.7 m	U	< 15 min
Dungarvar	L	-07.479	51.949	50	~ 5 h	0.1 m	0.5 m	U	< 15 min
Madaira	East	-16.666	32.750	51	~ 30 min	0.5 m	1.4 m	U	~ 30 min
widuella	South	-16.926	32.619	51	~ 40 min	0.3 m	0.7 m	U	~ 30 min
Azores		-28.017	39.017	53	~ 2 h	0.9 m	1.3 m	U	~ 15 min
Barbados		-59.566	13.033	50	~ 7 h	0.1 m	0.4 m	U	~ 30 min

5.2 Hypothesis B

- 10 Hypothesis B has a steeper dip angle than hypothesis A-MS, resulting in the dominant strike-slip mechanism when compared with hypothesis A-MS. In Fig. 6, we depict the maximum wave height for option B. Figure 6 shows maximum wave heights of 15 m along the coast of Morocco. The wave heights at Gorringe Bank are 12 m slightly smaller than in hypothesis AMS. In the Gulf of Cadiz, the wave heights do not exceed 2 m. These values are lower than those produced by source A-MS. At the southwestern tip of the Iberian Peninsula, maximum wave heights reach up to 5 m. In Cadiz, wave heights reach up to 1.8 m
- 15 (Fig. 6) and 1.4 m close to Lisbon. At the western part of the Scilly Islands the maximum wave height is close to 2.3 m, and in Mount's Bay, the maximum wave height values reach 1.8 m. In Kinsale, the maximum wave height is higher than 1.5 m and close to Dungarvan wave heights exceed 1.4 m. At the Island of Madeira, the eastern part experiences wave heights greater than 2.5 m. At the southern side of the Island wave, heights are smaller compared to the east but still up to 1.3 m (Fig. 6). The maximum wave height of hypothesis B on the eastern side of the island of Terceira exceeds than 5.5 m. At the southern coast
- 20 of Barbados wave heights exceed 0.7 m and at the northern tip of the island the wave height overpass than 0.6 m.

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Figure 6. Maximum wave height distribution (color scale in m) in the Atlantic basin produced by the source of hypothesis B.

Figure 7 presents the corresponding synthetic tsunami waveforms in the VTGs. Table 4 gives a summary of the results. The analysis of the synthetic waveforms shows that a small downward movement of about 0.2 m arrives in Lisbon after 1 hour and

- 5 15 minutes followed by sharp upward movement of 0.9 m. The third wave has a maximum positive amplitude of 2.2 m (Fig. 7 (a)). The maximum wave heights at the Scilly Islands is 0.9 m (Fig. 7 (b)). The first wave is an upward movement of 0.7 m, arriving close to 4 h after the earthquake (TTT). The synthetic tsunami waveform shows 15 minutes period. In Mount's Bay, the first wave arrives at the after 4 hours and 30 minutes with a 15-minute period with 0.6 m. Here, the maximum wave height, 1 m, comes more than 6 hours after the earthquake. In Kinsale, hypothesis B produces a maximum wave height of 1 m with a
- 10 first wave of 0.3 m when extrapolated according to Green's Law. The first wave in the VTG arrives after 4 hours and 15 minutes of tsunami propagation; here, the period is shorter than 15 min (Fig. 7 (b)).

In Madeira, the first and the maximum wave heights are greater in the eastern part of the island compared to the southern part. Maximum wave heights values reach 2.5 m in the east part of Madeira and 2.1 m in the south part of Madeira. In the Azores, the wave height for Terceira island reaches up to 4.2 m (Fig. 7 (c)).







Figure 7. VTG records for hypothesis B at the coordinates of the locations presented in table 4.

Hypothesis B predicts a tsunami travel time of 7 hours to Barbados with a first peak 0.1m and a maximum of 1.1 m after 9 hours and 15 minutes (Fig. 7 (d)). The first wave has a period slightly below 15 minutes. Table 4 gives a summary of the results for hypothesis B.

Local	VTG coordinates & depth		TTT	Wave height [m]		Polarity	Period	
	Lon. [°]	Lat. [°]	d [m]		First	max.		
Lisbon	-9.136	38.706	3	~ 1 h 15 min	-0.2 m	2.2 m	D	> 30 min
Cadiz	-6.291	36.524	4	~ 1 h	-0.4 m	2.6 m	D	~ 30 min
Scilly Islands	-06.383	49.85	50	< 4 h min	0.7 m	0.9 m	U	~ 15 min
Mount's Bay	-05.48	50.08	26	~ 4 h 30 min	0.6 m	1 m	U	~ 15 min

Table 4.	Results	of the	VTGs	for	hypothes	is	B
			1 2 0 0				~

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Kinsale		-08.500	51.653	28	~ 4 h 15 min	0.3 m	1 m	U	< 15 min
Dungarvan		-07.479	51.949	50	~ 5 h	0.1 m	0.7 m	U	< 15 min
Madeira	East	-16.666	32.750	51	~ 30 min	-0.2 m	2.5 m	U	~ 30 min
	South	-16.926	32.619	51	~ 40 min	-0.2 m	2.1 m	U	~ 30 min
Azores		-28.017	39.017	53	~ 1 h 45 min	0.9 m	4.2 m	U	~ 15 min
Barbados		-59.566	13.033	50	~ 7 h	0.1 m	1.1 m	U	~ 30 min
Azores Barbados		-28.017 -59.566	39.017 13.033	53 50	~ 1 h 45 min ~ 7 h	0.9 m 0.1 m	4.2 m 1.1 m	U U	~ 15 min ~ 30 min

6. Discussion and Conclusion

We investigated possible sources of the earthquake and tsunami on the 31st March 1761 earthquake in the Atlantic. We used as a first guess the location proposed by Baptista et al. (2006) and the set of tsunami travel times. After setting the source position, we investigated focal mechanisms for the parent earthquake. We selected hypothesis A-MS, because of its

5 compatibility with the relative movement between Africa and Eurasia predicted by NUVEL 1A. To tune periods, wave heights and TTT we implemented a multi-segment fault in Hypothesis A-MS. Since the location of sources, A-MS and B are the same the set of TTT predicted are similar.

The forward tsunami simulations produce a set of tsunami travel times that reproduce most of the observations within a 15minute error in the near-field and 30-minute error in the far-field. These errors are acceptable considering that the exact location

10 of the historical reports is unknown.

The TTTs predicted by the model reproduce the observations in Lisbon, Mount's Bay and Barbados. The relative position between Mount's Bay and Scilly islands suggest an earlier arrival of the tsunami at the islands for a source located in the Coral Patch area as predicted by the simulation. However, the observation of the Scilly island is compatible with the 30-minute error in the far-field.

- 15 In Kinsale, the TTT predicted by the model is not consistent with the rise of the tide by 6 p.m. However, the observation in Dungarvan, 75 km northeast of Kinsale states that ebbing and flowing of the sea occurred between 4:00 and 9:00 pm. Subsequently, we considered the TTT for Dungarvan to be 4 hours. The tsunami simulations predict a 45-minute delay between Kinsale and Dungarvan, with an earlier arrival at Kinsale. The observations from Ireland and the UK report the tsunami arrival 4 to 6 hours after the earthquake. Our source location is compatible with these observations predicting 4 hours TTT, 4 hours
- 20 15 minutes, 4 hours 30 minutes and 5 hours, for Scilly, Mount's Bay, Kinsale and Dungarvan respectively. Moreover, a source located close to Coral Patch reproduces well the TTT to Barbados (see table 3). Source A produces wave heights compatible with the observations in Lisbon, Kinsale, Scilly and Barbados. In Lisbon, one document (Unknown, 1761) report that the sea level fluctuated eight feet perpendicular, whereas a second one only confirms "a large fluctuation of the sea". To check the reliability of the magnitude of the fluctuation, we estimated the tide condition
- using a table of the moon phases (USNO, 2017). We concluded that in Lisbon the tide was 2.6 m above hydrographic zero (HZ) (in dropping tide conditions) at 1 p.m. on the 31st of March 1761 (table 5). In spring tide conditions, the tide reaches





values of 4.3 m above HZ. Adding the 2.4 m reported in Lisbon to the tide condition of 2.6 m we get 5.0 m. We conclude that a 2.4 m rise of the sea would exceed the maximum sea level in spring tide conditions. The eyewitnesses would have noticed this fact, but there are no reports of inundation in Lisbon. The synthetic waveform for Lisbon, with a maximum positive of 1.8 m, presented in Fig, 4 (hypothesis A-MS) is compatible with these considerations.

Table 5. Tide levels at the time of the earthquake and tsunami arrival. 5

	Time	Tide condition	Estimated height relative to Hydrographic Zero				
Earthquake	Noon	Full tide	2.9 m				
Tsunami arrival time	13:15	Dropping tide	2.6 m				

For Cadiz, both hypotheses reproduce the observed drawdown. However, the withdrawal is more significant in source A-MS. The more considerable retreat in Cadiz and the smaller maximum peak in Lisbon favour Hypothesis A-MS.

The wave heights in Mount's Bay are smaller at the VTG compared to the observation but reproduce better the observations at Scilly Islands for both hypotheses. Hypothesis B shows higher wave heights at the VTG at Mount's Bay. The analyses of

Fig. 4 and 6 show the maximum of wave heights over 1.7 m for hypothesis A-MS. For Hypothesis B the maximum heights 10 exceed 1.8 m.

In Kinsale, the observation states about 2 feet wave height and that the first wave was the biggest. Hypothesis A-MS produces a 0.7 m wave that is close to the observation. However, the first wave is not the highest wave. This might be because we placed the VTG in the Atlantic Ocean approximately 7 km away from Kinsale.

- The reports in the Atlantic islands of Madeira and Azores are coherent with the observation of a tsunami event. In Madeira, 15 both models predict bigger waves along the east coast (Fig. 4 and 6). The analysis of the VTGs for Hypothesis A-MS and B show the maximum peak in the VTG in Madeira for Hypothesis A-MS is 1.7m. The report by Heberden (1761) in Madeira states that the water fluctuated between the high and the low water mark which is in the order of 2 m at the time. This fact favours hypothesis A-MS; wave heights predicted by hypothesis B exceed 50 % higher those of Hypothesis A-MS.
- 20 Coeval reports from Barbados report wave heights between 0.45-0.6 m. Hypothesis A-MS produces 0.5 m at the southern part of the island and above 0.4 m at the VTG. Wave heights in hypothesis B overtop these values if applying the Green's law with a wave height up to 1.1 m.

Considering the polarity of the first movement of the tsunami both hypotheses reproduce the observations.

Nevertheless, as expected in the analysis of a historical event, some observations remained unexplained with our hypothesis.

Both simulations compute tsunami wave period in Lisbon and Barbados of about 30 minutes although observations state 25 periods less than 10 minutes for both sites.

Considering the points discussed above the preferred solution is hypothesis A-MS. We base this conclusion on the following arguments.





- The candidate source in hypothesis A-MS is compatible with the geodynamic setting and follows what is considered the area where there are the largest NE/SW compressive structures (Martinez-Loriente et al., 2013).
- It is possible to find a geological source compatible with the source area deduced from TTTs and with macro-seismic intensity data (Baptista et al., 2006).
- 5 The re-evaluated TTT for Barbados is compatible with the source location proposed here. All the other TTTs and wave heights are in better agreement with hypothesis A-MS.
 - Wave heights greater than 14 m produced by hypothesis B would result in a catastrophic scenario which is rather unlikely and nor observed neither or reported.
 - Our solution reproduces the observations in Cadiz
- 10 The tectonic source proposed to reproduce the observations of the 31st March 1761 tsunami is located southwest of the source of the 1st November 1755 event in the South West Iberian Margin.

This study together with the study by Baptista et al. (2006) underlines the need to include the 1761 event in all seismic and tsunami hazard assessments in the Northeast Atlantic Basin.

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