A Phenomenological Reconstruction of the Mw9 November 1st 1755 Earthquake Source

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1 Introduction

The 1755 'Great Lisbon' earthquake is one of the two or three most studied earthquakes in history. However, unlike other iconic earthquakes, such as Tokyo in 1923 or San Francisco in 1906, there is still no consensus as to the location and extent of the originating fault rupture.

This review sets out to synthesize all the different contemporary information sources on the event itself and then to build from these the outline of what can be understood about the structure of the source. This synthesis of information is complicated because the reports on the 1755 earthquake are heavily biased towards the north of the affected region even though the areas of significant (MSK VIII and higher) damage are comparable north and south of the Gulf of Cadiz.

Large earthquakes defy simple scaling relations for determining their magnitude (Frankel 1994). Based on felt area radii, Johnston (1996) extrapolated a moment magnitude Mw of 8.7 +/– 0.39, while Abe (1979) estimated a magnitude based on the logarithm of farfield tsunami heights to arrive at a Tsunami Magnitude Mt = Mw of 8.75 or greater. In order to match the ratio between the heights of the 1755 and 1969 tsunamis at local ports Baptista et al. (1998a) required an energy release about 40 times greater than that of 1969 (Mw7.9), implying a 1755 magnitude between 8.9 and 9.4. As discussed in this chapter, a magnitude of at least 9.0 is indicated from the energy radiated into the farfield at long periods, which was stronger than in other recent magnitude 9+ earthquakes.

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2 Summary of Proposed Sources

A number of tectonic structures have been proposed as the source (or a component of the source) of the Nov 1st 1755 earthquake (see Fig. 1).

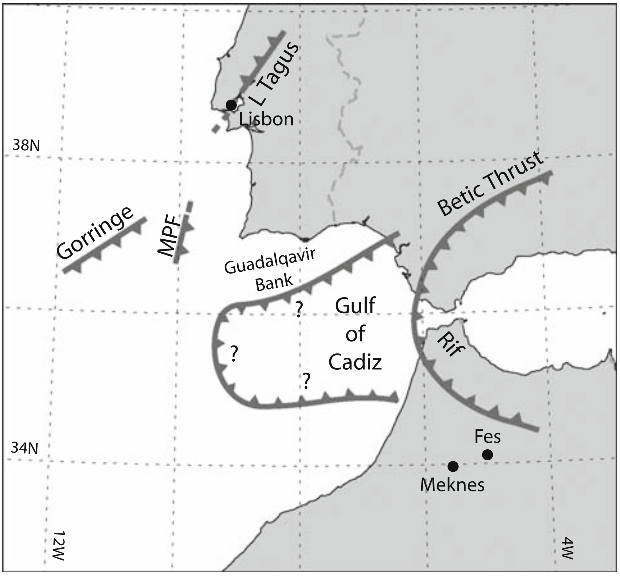

Fig. 1 Principal tectonic structures identified around SW Iberian continental margin. Note that the Gulf of Cadiz overthrust structure proposed by Gutscher et al. (2002) still remains controversial

2.1 Gorringe Bank

The Gorringe Bank is a northeastern trending asymmetric ridge of oceanic lithosphere approximately 180 km long and 60–70 km wide, that rises to within 25 m of sea level. The reasons and timing for the uplift are not resolved, but most authors conclude that the ridge has been uplifted by two bounding reverse faults implying very high levels of horizontal compression (Sartori et al. 1994), with an estimated 50 km of crustal shortening since the mid-Miocene (Hayward et al. 1999).

Through the 1990s, the source of the 1755 earthquake was widely considered to be a bounding fault to the Gorringe Bank; as for example by Johnston (1996) who proposed 12 m of displacement on a 200 km long reverse fault extending down to a depth of 50 km. There were two principal arguments in support of this source: (a) that the ridge was by far the most prominent feature with a presumed tectonic origin in the area to the southwest of Portugal; and (b) the occurrence of the Feb 28th 1969 Ms7.9 earthquake was taken to indicate activity at the ridge. However the 1969 earthquake was located to the southwest of Gorringe Bank beneath the Horseshoe Abyssal Plain, on a fault without pronounced pre-existing topography, although the focal mechanism showed reverse displacement with a minor strike-slip component on a N35W striking fault plane with dip angle of 52 degrees (Fukao 1973) similar to the orientation of the Gorringe Bank. The well studied macroseismic field from the 1969 earthquake was also considered to have some similarities with the intensity field from the 1755 earthquake although typically two intensity grades lower However Baptista et al. (1998b) explored a potential 120 km long reverse fault source for the 1755 earthquake on the Gorringe Bank and found from tsunami arrival times that this location was too far to the west.

2.2 *Marques de Pombal Fault (MPF)*

The acquisition of multichannel seismic reflection profiles from the offshore continental margin of SW Iberia has made it possible to identify and map active tectonic structures cutting through the Quaternary sedimentary section and intersecting the sea floor. Inevitably only significant vertical displacement is easy to see in these sections. The 100 km long N-S trending Marques de Pombal thrust, located 100 km offshore SW of Cape St Vincent, midway between the Gorringe Bank and the coast was first identified as an important neotectonic structure by Zitellini et al. (1999 and 2001) in a multi-channel seismic reflection survey. The structure is located along the 1755 tsunami source zone, proposed by Baptista et al. (1998b) from tsunami travel times.

2.3 *Guadalqavir Bank – Northern Gulf of Cadiz Reverse Fault*

Offshore to the south of the Algarve coast in the northern Gulf of Cadiz another active compressional N75E reverse fault structure was identified in seismic reflection profiles at the northern edge of the accretionary wedge (Jimenez-Munt et al. 2001; Negredo et al. 2002). This fault was considered a potential source of the M6.5 1964 earthquake (Udias and Arroyo 1970) and has an orientation similar to that of the N55E fault identified to be the source of the 1969 earthquake. Baptista et al. (2003) proposed that the 1755 earthquake source was a compound of the two separate fault sources of the Marques de Pombal thrust and the Guadalqavir Bank fault. However what is observed on seismic reflection profiles intersecting the sea floor is likely to be a short section of high angle reverse stepover structure of fault systems that also have a less easily detectable low angle or strike-slip configuration.

2.4 *Gulf of Cadiz Subduction Zone Overthrust*

The existence of a 180 km N-S shallow easterly dipping overthrust fault system below the Gulf of Cadiz was first proposed by Gutscher et al. (2002), forming the top of a proposed subduction zone overthrust system passing to the east under the Straits of Gibraltar. Thiebot and Gutscher (2006) considered evidence from seismic reflection profiles in the western Gulf of Cadiz basin, suggested ramp faults cutting through to the sea floor. The existence of active compressional tectonics in the region, characteristic of a subduction zone forearc setting is revealed by the population of mud volcanoes in the eastern Gulf of Cadiz sea floor, indicative of the active dewatering (Gardner 2001; Pinheiro et al. 2003; Somoza et al. 2003; Rooij et al. 2005). The majority of the 30 volcanoes so far identified are located along a front extending to the SSE from close to Faro on the Algarve Coast of Portugal as far south as the continental margin of Morocco. While the proposal that there is a deep subduction zone beneath the Gibraltar arc remains controversial, (see Platt and Houseman 2006), the existence of a shallow easterly dipping overthrust fault system beneath the Gulf of Cadiz, fits a number of features of the 1755 earthquake source.

2.5 Lower Tagus Valley Fault

A Lower Tagus Valley LTV fault zone was trenched and found to present geological evidence of recent displacement by Fonseca et al. (2000), who estimated 0.5–0.7 mm/yr displacement over the past 1500 years (Vilanova et al. 2003; Vilanova and Fonseca 2004). Based on the degree to which high intensity ground shaking in 1755 occurred in the vicinity of the fault, as well as contemporary reports suggesting localized deformation and tsunami generation, Vilanova and Fonseca (2004) propose that the LTV fault was involved as an element of the 1755 earthquake source.

3 Phenomenological Evidence on the 1755 Earthquake Source

While all the potential fault sources that have been proposed can explain some of the data on the 1755 earthquake, no proposal has been capable of explaining the totality of observations. This paper explores nine separate lines of phenomenological evidence that can be retrieved from contemporary accounts concerning:

1. Event duration and source complexity
2. Levels of ground shaking as reflecting distance to the rupture
3. Farfield long period effects reflecting the generation and transmission of long period ground shaking
4. Evidence for coseismic deformation
5. Nearfield tsunami amplitudes and travel times
6. Farfield tsunami polarization and amplitudes
7. Triggered seismicity and the implications on coseismic far-field stress changes

All the different classes of phenomenological evidence have then been synthesized to constrain what can be projected as to the size and configuration of the fault rupture source.

3.1 Duration and Complexity – Ground Motion

At any location the maximum duration of strong ground motion will be sensitive to the disposition of the fault in relation to the observer as well as how the rupture propagates. Consider an idealised 300 km ‘line’ fault with realistic terrestrial physics – a rupture velocity of 3 km/sec, radiating the strongest modes of surface wave vibration at a group velocity of 4 km/sec for the lower frequencies, reducing to 3 km/sec for the higher frequencies. Meanwhile the fastest P waves travel at 6 km/sec. What is the maximum duration of the earthquake at different observation points – assuming the observer detects the full sequence of vibrations?

For an observer at the epicentre immediately above the start of line rupture, the final vibrations will be radiated from the other end of the fault 100 seconds after the start of rupture (and after vibrations have first been felt) and the slowest surface waves will then take 100 seconds to arrive, implying a duration of 200 seconds. For an observer at the opposite end of the fault – the first P wave vibrations will be felt after 50 seconds, and the rupture will itself arrive at 100 seconds implying a duration of 50 seconds of strong shaking. At the midpoint of the fault the duration will be 125 seconds. In either direction beyond the line of the fault, the duration of the full suite of vibrations will extend by the difference in velocity between the fastest P waves and the slowest surface wave group velocity, of one minute per 360 km, and slightly less than this for directions orthogonal to the fault.

Real faults have a 2D surface, can undergo bilateral as well as unilateral rupture, the initial P waves may not be felt at significant distances while vibrations may not be perceived radiated from far sections of the fault. For example while the Mw 9.2 1964 Alaska earthquake, involved 800 km of fault rupture starting at Valdez and ending beneath Kodiak Island 300 seconds later, an observant geologist at Valdez only felt vibrations for 210 seconds implying that vibrations radiated from further than about 300 km down the fault rupture were too weak to be observed. In the Indian Ocean earthquake of Dec 26th 2004 the fault rupture extended for 1200 km and had a duration of 8 minutes, but the fault continued too far from any observer for the whole wavetrain of vibrations to be felt, at a single location.

In terms of the reported durations from the Nov 1st 1755 earthquake (see Fig. 2). At Cadiz and Lisbon the duration of ground shaking was reported as 6 minutes (Gentlemen’s Magazine, Feb 1756). At Tangier and Tetuan in Morocco the duration was 7-8 minutes, and involved three violent shocks. At Oporto about 300 km to the north of Lisbon it lasted 7 minutes and 600 km to the northeast at Madrid it was reported as 8 minutes, suggesting that the wave

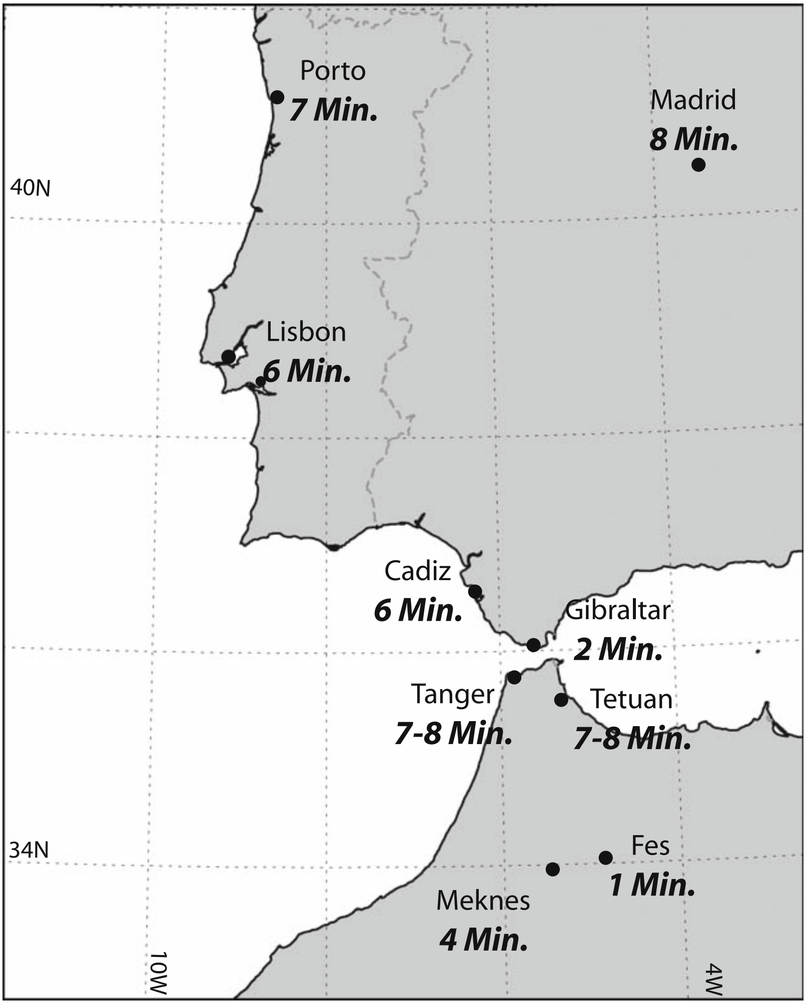

Fig. 2 Reported durations of the Nov 1st 1755 (09.30) mainshock

train was extending much as would be predicted and also that the full sequence of ground motions continued to be strong enough to be observed. However further to the southeast the amplitude of ground motion passed below detectability for some part of the wave train.

Not knowing the point of the beginning or end of the fault rupture, or how far the fault was located from each of these locations, if the 6 minute duration at Lisbon and Cadiz was within 300 km of the actual fault rupture then if there was a single episode of fault rupture without interruption this must have had a minimum duration of 150 seconds (i.e. half of 5 minutes). Given that the observations at two distinct azimuths from the fault in Cadiz and Lisbon were the same, and that the rupture was almost certainly less than 300 km from Lisbon implies a longer rupture duration, of 200 seconds or longer. At standard rupture velocities of 3 km/sec (the 2004 Indian Ocean earthquake had an average rupture velocity of 2.8 km/s while the 1964 Alaska ruptured at an average speed of 3.5 km/sec: Christensen and Beck 1994). 150 seconds therefore gives a minimum 450 km long fault, while 200 seconds implies at least 600 km.

These lengths could be overestimated if rupture was interrupted between fault segments. Reports from Lisbon often stress that there were three distinct phases of shaking, with a weaker phase of long period motion for the first minute, followed by stronger vibrations that led to significant building damage. However this is similar to the reports from Valdez in 1964 in which a phase of weaker motions gave way to much stronger ground shaking, simply as a function of the amplitude of the different wave trains and the location of specific areas of strong energy radiation along the fault. As discussed below, the nature of the long period seiching in the 1755 earthquake demonstrates that the wave train had become coherent and continuous in the far field, implying that there was in fact a single episode of fault rupture.

3.2 The Macroseismic Field – and What it Reveals About Proximity to the Fault Rupture

There is general agreement that the fault rupture associated with the 1755 earthquake was predominantly located offshore. Observations from ships indicated the strongest impulse (from water-transmitted T waves) in a region extending from latitude 38.30 N down to 36.24 N and between 7 and 12 W (Rudolph 1887).

Detailed reports of the onland affects of the 1755 earthquake were collected across Spain and Portugal soon after the earthquake, from which macroseismic intensities have been interpreted and mapped (Martinez Solares et al. 1979; Moreira 1983). However no comparable survey was performed in Morocco and the observations in that country have never received the same scrutiny. (Intensity maps often misleadingly incorporate the high intensities of another damaging earthquake that occurred in northern Morocco later in November 1755.)

At the time of the earthquake Morocco was split into two caliphates: ‘Fez’ to the north and ‘Morocco’ to the south (with its capital at Marrakech), separated by the Oun Er-Rbia River. A small number of detailed accounts of the earthquake have survived (see Aboulqasem ben Ahmed Ezziani (1886), Cigar N. (1981), Gazette de Cologne, Jan 11th 1756. Gentlemens Magazine (Jan 1756), Gentil L. and Pereira de Sousa F.-L, (1913), Rolland F.A. (1923), Taher 1979 as well as Manuscript letters from Franciscan Missionaries in Morocco back to Madrid). From these accounts it is notable that there is an increase in the severity of the earthquake in passing to the southwest. In the north where a strong E-W shaking was reported accompanied with ‘a noise like millstones’, descriptions are consistent with a general MSK intensity of VII: at Tangiers ‘a great pile of ancient buildings near the gate of the town tumbled down, but damage throughout the town was otherwise fairly limited', while at Fez – 'Buildings were injured but only 2 or 3 people were killed. Bricks fell out of walls.' However along the coast to the southeast, at Sale – 'it did vast damages – numbers of house having tumbled down' while inland at Morocco (Marrakech): 'The majority of the houses and public buildings of the town were totally flattened, and a great multitude of the inhabitants were buried in the rubble'. At Safi and St Croix (Agadir) on the southwest coast 'many houses and other buildings were destroyed, which buried a large number of people'. All of these accounts are consistent with intensities VIII-IX – see compiled map for the whole macroseismic field Fig. 3. There were major landslides in the mountains of

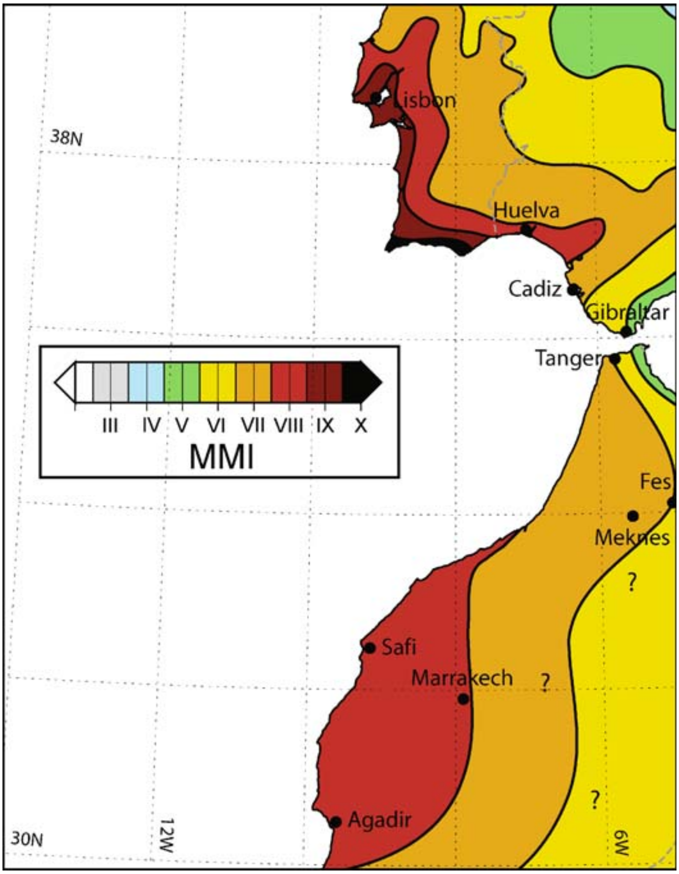

Fig. 3 Macroseismic MSK intensities of the Nov 1st 1755 mainshock. Compiled isoseismic map from Grandin et al. (submitted 2007), modified for Morocco. Data provided by Pereira de Sousa (1919) and Moreira (1984) for Portugal and Martinez-Solares (1979) for Spain. The MSK intensities for Morocco are determined from several accounts and differ from Levret (1991) (see text)

southern Morocco: at 8 leagues from Marrakech one report mentions up to 10,000 soldiers killed by a combination of building collapse and rock falls.

Strong ground motion is a good indicator of proximity to the fault rupture. In recent major 'comparable' (M8 onland shallow thrust fault earthquakes), such as the 'Great Kwanto' Tokyo M8.2 earthquake of Sept 1st 1923 and the M7.9 Gujarat earthquake of Jan 26th 2001, the highest earthquake intensities (in particular MSK IX and X, reflecting general destruction) were only found overlying the fault rupture. The region with the highest levels of damage in the 1755 earthquake was the western Algarve coast as far to the east as Tavira, where MSK intensity levels are consistently assessed as X, reflecting the fact that almost all buildings were leveled by the earthquake. By comparison with Gujarat in 2001 or southern Tokyo Bay in 1923 the western end of the Algarve must have overlain (or been located in close proximity to) a section of the 1755 fault rupture. Southern Morocco is also clearly closer to the fault rupture than northern and northeastern Morocco, implying that the fault rupture extended far to the south, even as far as the coastline of Morocco at 32–33 N? The levels of damage and the reports of intense high frequency vibration in the City of Lisbon also imply that there was nearby fault rupture (as proposed by Vilanova and Fonseca 2004).

3.3 Farfield Long Period Affects

The most extraordinary feature of the 1755 earthquake remains the range and intensity of farfield long period effects (see spatial extent on Fig. 7). Such effects were completely new to the experience of Europeans and to scientific observation, and 250 years later still remain the most widespread and varied examples of earthquake seiching known from any earthquake. At distances of a few hundred kilometers from the earthquake source, long period strong motion could be damaging: as at Malaga where the tops of some high buildings fell. At distances greater than 1000 km there were many observations of chandeliers hung from cathedral roofs oscillating, as in Milan and Amsterdam. Across a broad area of the coastal plain of northern Germany, on this Sunday morning, 'branches' hanging from the roofs of churches were seen to vibrate: as at Emshorn, Bramstadt, Willster, Kellinghusen and Melidorf. At Glucksdorf, three large branches, each weighing a ton, were set into slow oscallation from East to West for the Space of an Hour.

Across Holland and northern Germany, many rivers and canals were sent into pronounced oscillation (see accounts in the London Evening Post, Dec 6–9th 1755). The River Eidar which separates the old Town of Rendsburgh from the new – rose to a great height. The water of the Staehr was very much agitated at Itzehoe, as was the water that surrounds the Garrison at Fort Steinbourg, while the Schwinge and the Ost and were greatly agitated at Cuxhaven. In southern Britain observations came from ponds and lakes: as at Pibley Pond in the county of Derby, English Midlands: where in a 30 acre body of water: the water rose two feet (0.6 m) and continued flowing backwards and forwards for 2 hours. Smaller ponds in the neighbourhood of Bury St Edmunds, in Suffolk continued oscillating for 8 or 10 minutes, while in a pond at Dunstal in a different mode of resonance ‘the water rose successively for several Minutes in the form of a Pyramid, and fell down like a Water spout’ (London Evening News Dec 6th–9th 1755). Further to the north many lakes and fjords were sent into motion in northern Britain and Scandinavia (Kvale 1955). At Loch Lomond in west Scotland water levels rose and fell 0.8 m with a period of 10 minutes, with the principal phase lasting for 45 minutes. Similar behaviour was seen at Loch Long and Loch Katrine, and the rise in the waters at Loch Ness was ‘so violent as to threaten destruction to some houses built on the sides of it’ (Scots Magazine 1755). The area of seiching extended south through Switzerland and canals were sent into prominent oscillation around Milan.

The best modern scientific studies of far-field long period affects were made following the 1964 Alaska earthquake (McGarr and Vorhis 1968) where seiching was measured widely from water gauges but observed less often – as along the Gulf coast of Texas and Lousiana where it affected small enclosed lakes, bayous and coastal navigation canals, with a predominant resonant period of 10–15 second. Widespread seiching was also observed from the 2004 Indian Ocean earthquake (Amateur Seismic Centre 2005) in ponds and tanks in Assam, Jharkand, Maharastra, Manipur, Orissa and West Bengal as well as in northern Thailand and eastern Nepal. However in comparison with the observations made in 1964 or 2004, the 1755 earthquake showed a stronger signature in terms of the ubiquity of observations across a very wide range of resonant periods, implying a greater amplitude and spectrum of long period energy, within a coherent low frequency wave train. This implies a single phase of rupture on a very large seismic source.

3.4 Coseismic Deformation

With a source predominantly located offshore it is not surprising to find few accounts suggesting coseismic deformation (Fig. 4). However Mr Stoqueler the Hamburg Consul at Lisbon was walking outside at Colares at the westernmost point of land near the Rock of Lisbon (Cabo da Roca) when the earthquake hit and recounted that: ‘it is there apparent that (the sea) does not reach its usual bounds for you walk almost dry to places where before you could not wade’. (Gentlemens Magazine, March 1756), reflecting an estiumated 0.3–0.4 m of uplift. That there was preseismic and coseismic strain close to this location is suggested by the observation that a fountain at nearby Sintra that was greatly decreased in the afternoon of the 31st, in the morning of the 1st it ran very muddy, and after the earthquake it returned to its usual state, both in quantity

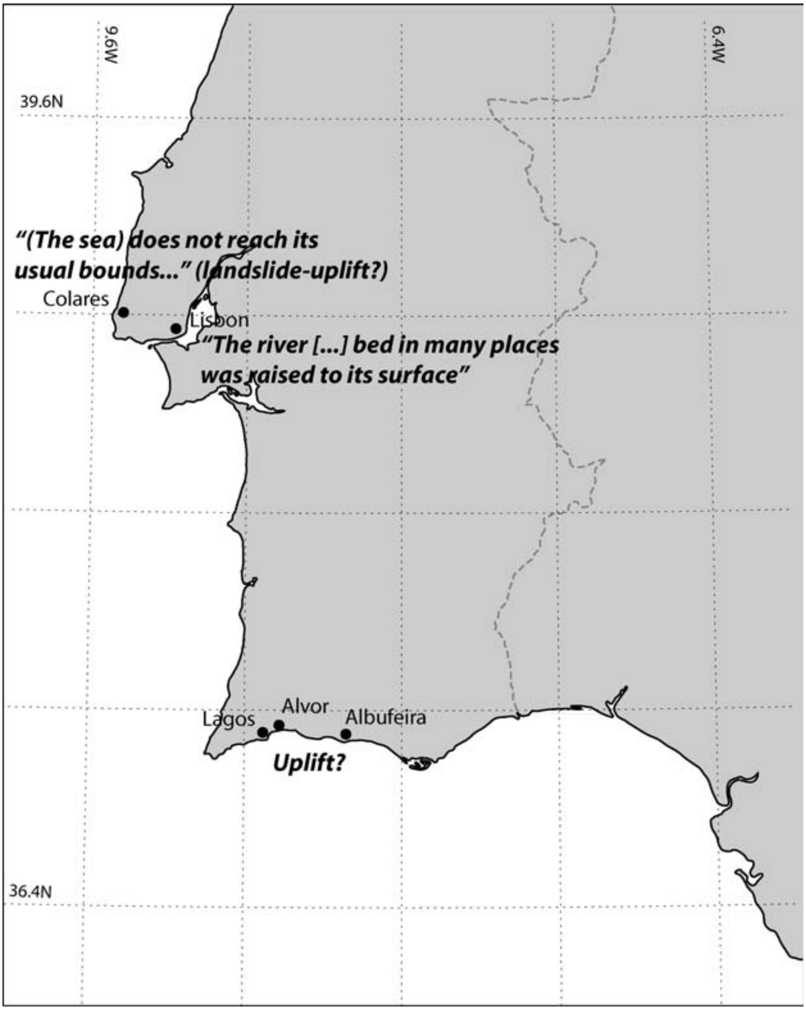

Fig. 4 Reports indicating potential coseismic deformation from the Nov 1st 1755 earthquake

and clearness. Another report suggestive of coseismic deformation came from Lisbon itself where it was said that 'the river which forms a great Bay opposite the town, was equally disturbed: its bed in many places was raised to its surface'.

Along the coast of the western Algarve there were pronounced geomorphological changes, which could imply some coseismic uplift, although it has not been possible to separate out the profound affects of sediment movements associated with the tsunami. After the earthquake and tsunami the harbour at Faro was so choked that the seat of administration was moved to Tavira, while at the harbour of Alvor only small craft could be handled where formerly boats of 45 tons had docked (Chester 2001).

3.5 The Local Tsunami

The 1755 tsunami was particularly destructive along the western Algarve coast where accounts are comparable to the experience of Banda Aceh on Dec 26th 2004. Water levels reached 15 m and more above sea level, as at Alvor where the water flowed 500 m inland and rose to the level of the village. In Nova de Portimao water reached 2.6 m high inside the church, while at Lagos the sea rose 10 m high and invaded the land more than 800 m (Sousa and Pereira). In Albufeira 16% of the population of the village was killed by the tsunami while in Armacao de Pera only one building remained standing. At Cadiz the tsunami reached an estimated 15 m above sea level overwhelming the causeway connecting the town with the shore.

The tsunami was also very destructive along the Coast of Morocco, in Tangier it flowed into the heart of the city, rising 50 feet (15 m) perpendicular, 'leaving behind it a vast quantity of fish and sand'. At Sale the sea flowed into the heart of the city and drowned several inhabitants, overwhelming all those who went outside the walls of the town and causing many deaths. In Algazait – several walls fell down and a great Part of the Town was overflowed. A caravan traveling towards Marrakech along the beach was overwhelmed, killing the animals and large numbers of people.

Baptista et al. (1998b) employed all the available accounts of elapsed time of the nearfield tsunami (relative to the earthquake shaking) along with reported tsunami heights (see Fig. 5), to determine what these revealed about the configuration of the tsunami source. This study provides some important constraints on the fault source. In order to explain the 45 minute arrival time of the tsunami to Figuera (40.14 N) to the north of Lisbon, the seismic source had to extend as far north as the latitude of Lisbon. The best fit in terms of tsunami arrival times was found to be a 300 km long NNW-SSE source located midway between the coast of southwest Portugal and the Gorringe Bank, and running as far south as the Guadalquivir Fault.

However even this source does not extend far enough to the south to explain the observed 30 minute travel time of the tsunami at Safi on the southwest coast of Morocco, (the modeled source predicted arrival times of 70 and 85 minutes – a greater mismatch than for any other observation point). This implies that the deformation must have extended significantly further to the south than proposed by Baptista et al. (1998b).

Also all contemporary accounts highlight the fact that tsunami heights were much greater on the Algarve coast than on the westerly facing coast to the north of Cape St Vincent (Pereira de Sousa 1911), suggesting that there was greater sea floor displacement to the south. In terms of tsunami heights, the modeling of Baptista et al. (1998b) produced reasonable fits with the height data for the northern coastal locations but has problems in generating suitable heights for Cadiz (modeled 5–7 m, observed 15 m) and Madeira (modeled 1.5–2.4 m v

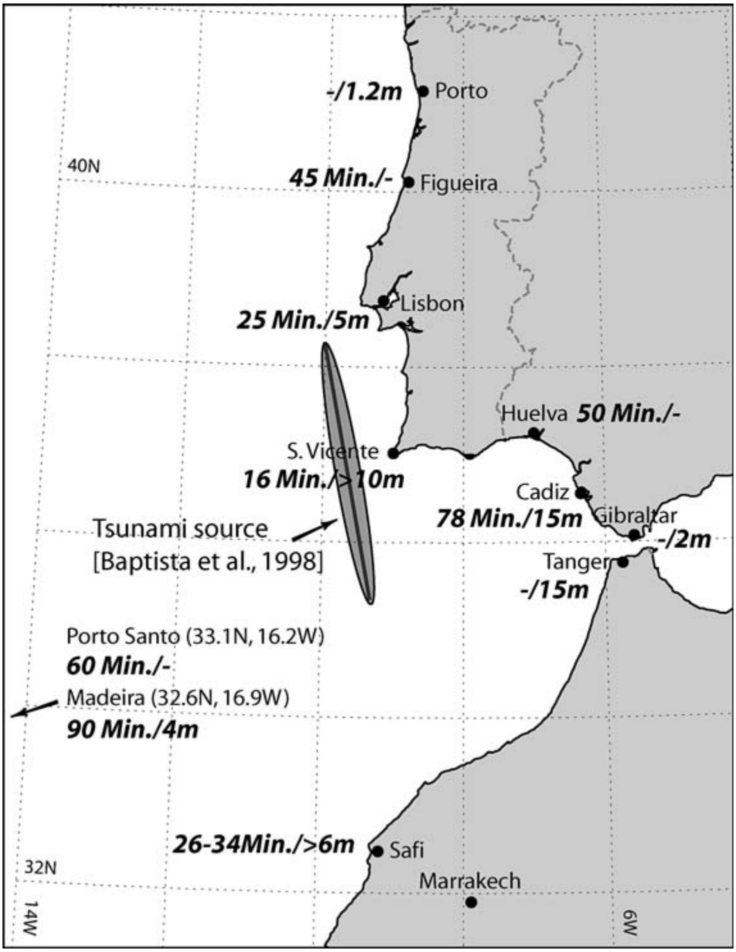

Fig. 5 Tsunami travel times, heights and proposed tsunami source, from Baptista et al. (1998b)

observed 4 m). This suggests again that the actual source must have exhibited higher amounts of seafloor deformation to the south.

There is also a question as to whether there were in fact two separate tsunamis in Lisbon – one generated by local deformation and the second reflecting the arrival of the tsunami from the main earthquake source. According to several eyewitnesses the sea in Lisbon 'rose up first within 10 minutes of the earthquake' (Gentlemens' Magazine, March 1756). At the time of a second great shock, within minutes of the first, a boat captain reported that the river rose at once near twenty feet and in a moment subsided immediately upon this extraordinary concussion.

3.6 The Farfield Tsunami

The occurrence of the 2004 Indian Ocean tsunami has significantly expanded the understanding of farfield tsunami amplitudes and what they reveal about the pattern of coseismic sea floor deformation. A fault extending for hundreds of kilometers creates 'lensing' – in which the long wavelength tsunami propagates coherently in directions orthogonal to the fault, while for directions parallel to the fault there is destructive interference of tsunami waves generated within 2–3 minutes all along the linear zone of seafloor deformation (as the rupture moves at speeds an order of magnitude faster than a deep water tsunami). Therefore the azimuthal variation in farfield tsunami amplitudes of the largest earthquakes should reveal the orientation of the causative fault. For example, the strong tsunami amplitudes observed along an E-W trending band across the Indian Ocean (including Thailand, Sri Lanka and Somalia) on Dec 26th 2004 demonstrate that the causative fault was oriented approximately N-S.

The tsunami from the November 1st earthquake was observed at a number of locations in southern Cornwall, England, occurring at low tide reaching maximum amplitudes of 1–2 m. Given the distance (of around 1500 km), these amplitudes are not very significant and suggest that the tsunami propagation was relatively incoherent to the north.

The timing of the 1755 earthquake and the propagation speeds across the North Atlantic meant that the event had the potential to arrive in daylight at all the colonized ports from Brazil, through the Caribbean and along the east coast of North America. However along all the ports of the East coast of North America such as at New York and Boston, the tsunami went unobserved and therefore presumably had an amplitude less than 0.5 m. In Charleston, South Carolina the rice merchant Henry Laurens, wrote on Jan 12th 1756 in response to a request for information from Gidney Clarke in Barbados, that it was not seen 'here'), The absence of observations along the North American coastline contrasts with what was observed in the islands of the northeast Caribbean (see Gray 1756). On Martinique the tsunami overflowed the low land entering the upper rooms of houses and also retreated a mile. On the island of Saba it flowed twenty one feet (6.5 m). At St Martin's 'a sloop that rode at anchor in fifteen feet of water was laid dry on her broadside' (>5 m). On Antigua the water rose twelve feet perpendicular (3.5 m). The tsunami heights were lower further to the south at Barbados where the amplitude was measured as five feet (1.5 m) – and where the 'water ran over the wharfs into the houses'.

The explanation as to why a tsunami arrived at heights of up to 6 m in the Lesser Antilles while remaining undetected for similar distance ranges along the US East Coast is most simply explained by the polarization of the tsunami amplitudes as a result of the shape of the originating sea floor deformation (see Fig. 6). To maximize the WSW radiation of tsunami wave energy towards the Caribbean the primary orientation of the sea floor deformation off the SW coast of Portugal must have been NNW-SSE.

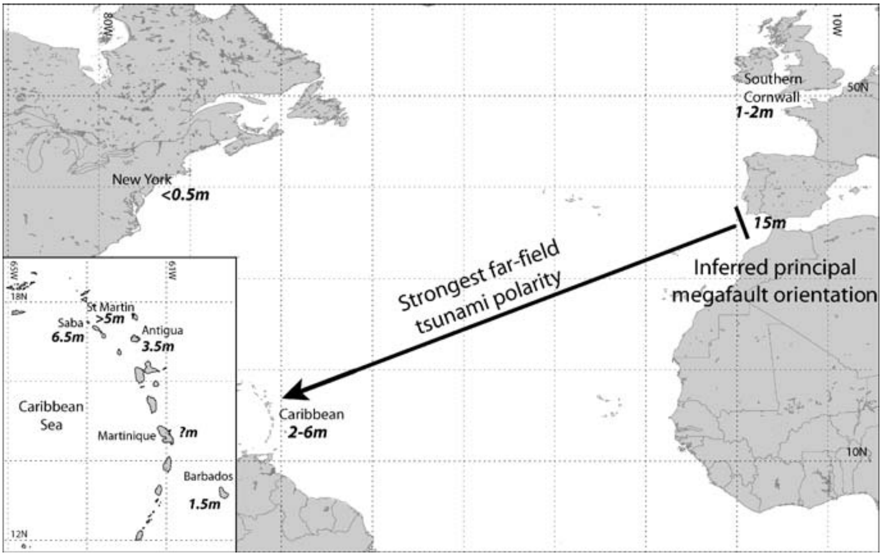

Fig. 6 Farfield tsunami heights reported in the Eastern Caribbean, and implications for tsunami directivity

4 Related Earthquakes

4.1 Preceding Earthquakes

Thirty three years before 1755 on Dec 27th 1722 a major earthquake (assessed as M7+), and accompanied by a local tsunami, caused very high levels of damage along the eastern end of the Algarve coastline – in particular affecting the port of Tavira as well as Loule and Faro, where intensities were mapped as IX (Moreira et al. 1993) . Further to the west, intensities were mapped as VIII. The zone of intense (MMI >VIII) destruction in 1722 lies adjacent to the zone of intense destruction in 1755, suggesting that these two earthquake ruptures might have been contiguous to one another and hence that the 1722 earthquake was preparatory to 1755.

4.2 Aftershocks

In the hours and days following the Nov 1st 1755 earthquake there were many aftershocks, all around the rupture area, so that the list of notable aftershocks at Gibraltar for example, does not overlap with those at Lisbon. There is some suggestion that aftershocks were migrating the rupture north – a major earthquake noted at Lisbon at midday on Nov 1st, was more intense at Oporto 300 km north of Lisbon, where it 'occasioned a good deal of damage, rent several churches from top to bottom and tumbled down one of the turrets of the church of the Congregadoes' (Gentlemens Mag p 562).

One report (London Evening News, Dec 11–13th 1755) suggests (if reliable?) that there may have been a triggered earthquake on Nov 1st close to the northern coast of Algeria, as would explain the account that 'at Algiers, Part of the City is destroyed, and considerable damage done to the Harbour'. Such an earthquake could also explain the observations that the Sea was violently agitated all round the island of Sardinia; that all the Rivers in that Kingdom overtopped their Banks, and drowned great tracts of the Ground, something like an Earthquake; that the damage done by this inundations is very considerable and that 'We have advice that on the first instance the Abundance of Barques, employed in the coral fishery on those Coasts, have been lost.' This could reflect a tsunami from a triggered earthquake off the coast of north Africa (as was observed in the 2003 Zemmouri earthquake off the northern coast of Algeria that caused tsunami damage in the Balearic Islands: Alasset et al. 2006).

4.3 Triggered Mainshocks?

A series of major earthquakes occurred across western Europe, north Africa and Eastern North America in the months and years after 1755. The closer the location in space and time to the Nov 1st earthquake the more that a physical connection can be proposed.

4.3.1 November 18th 1755: Cape St Ann, Massachusetts

The Cape St Ann earthquake situated offshore to the northeast of Boston Massachusetts had a magnitude of M6.2 and is the largest earthquake to have occurred in the New England area since European settlement began in the early 1600́s. Occurring within 17 days of the largest earthquake ever known in the Atlantic Ocean it is tempting to suggest a link, athough the 4000 km spatial separation of these events is too great to be explained within the current generation of earthquake stress transfer models.

4.3.2 November 27th 1755 Meknes, Morocco

On the evening of Nov 27th there was a major earthquake in northern Morocco, reported as 'far stronger' although 'not as long' as the event of Nov 1st. (Some local contemporary accounts are confident that this earthquake was in fact on the night of the 18th/19th). Highest reported intensities were in the city of Meknes where the majority of houses were destroyed, including the palace, many mosques and the tower of the Grand Mosque which was 'demolished right down to its foundation along with the majority of the mosque itself' 10,000 inhabitants of Meknes were counted as dead. The zone of intense MSK IX to X damage extended to Zarhun located 15 km to the north of Meknes, where the Roman site of Volubilis was badly damaged, fissures were noted and a large landslide destroyed the town of Moulay Idriss a few km to the south. The level of destruction was lower at Fez around 50 km to the ENE although there was widespread damage (MSK VII-VIII) and a small number killed. There was however no damage along the coast to the west at either Rabat and Sale. While the full extent of the high intensities in this earthquake is not known, the magnitude is likely to have been in the range M6.5-7. Moratti et al. (2003) propose that this earthquake was located on an E-W, northerly dipping reverse fault outcropping about 15 km to the north of Meknes (i.e. away from the city) but within 5 km north of Fez but this does not reconcile with the relative levels of damage at the two cities, or with the level of destruction at Meknes (which suggests fault rupture in the vicinity of the city) and the question as to the causative fault of this earthquake should probably be left open.

4.3.3 December 9th 1755 Brig in Switzerland

Mw 6.1, one of the major events in history in the Valais region, of southern Switzerland bringing intensities of MMI VIII also caused some minor damage in Milan (Gisler et al. 2004).

4.3.4 February 18th 1756 Aix la Chapelle, Belgium/Germany Border

Magnitude 6.1, (Mw5.8) intensity VIII - the largest earthquake since 1600 in the Lower Rhine Graben region.

4.3.5 December 23rd 1759 Earthquake Kattegat

Largest historical earthquake in the vicinity of Denmark (Ms 5.1-5.6).

4.4 March 31st 1761 Earthquake

The largest of all the earthquakes likely to be linked to Nov 1st 1755 occurred on March 31st 1761 (Borlase 1761). Even though this is the largest earthquake known in Europe since 1755 it is relatively poorly known, in part because in Portugal the Government suppressed accounts fearing that it would lead to ‘consequences of terror and fancy’.

The 1761 earthquake was felt widely onland from southern Ireland in the north (at locations where the Nov 1st 1755 earthquake was not felt), Bordeaux and Barcelona in the east, Morocco in the south and Fayal in the Azores to the west. Onland in Iberia and Madeira intensities were generally V–VI, in Lisbon demolishing some of the remaining 1755 ruins as well as some new buildings ‘to the amount of 20,000 moidores’. There were isolated locations of damage at intensity VII at Evora and Beja inland Portugal, while at Corunna in the northwest corner of Spain the shaking was so strong as to cause landsliding with several properties slipping downhill a few metres. At Madeira the shaking lasted 3 minutes long, and as in 1755 involved E-W motion, leading to rockfalls in the eastern part of the island and damage to some buildings. The earthquake was felt most strongly by vessels between 43 N and 44 N and around 11–14 W also suggesting that the source was situated to the northwest of the Nov 1st 1755 earthquake rupture.

In terms of size measures: the duration of the earthquake was 2 minutes in Morocco, 3 minutes in Madeira, 2.5 minutes at Madrid, 3 minutes at Aranjuez, but 5 minutes in Lisbon suggesting the rupture may have travelled north, starting close to the northern end of the 1755 rupture. The earthquake caused a major tsunami that was detected 1.9 m high in Cornwall, England, flooded quays at Cork, Ireland and arrived 2.4 m high 75 minutes after the shaking at Lisbon. The tsunami was also strong in the Azores and reached 1.2 m in Barbados. At Amsterdam and Maesland Sluis chandeliers swayed and Loch Ness was observed to seiche, rising two feet (0.6 m), indicating once again very significant long period ground motions.

The source of the 1761 earthquake must lie to the northwest of the 1755 source (Baptista et al. 2006): probably about 300 km offshore (although the latitude remains less resolved). From the tsunami a magnitude of Mw8.5 has been inferred, (Baptista et al. 2006) and allied with the far-field seiching and event duration suggests a source 200–300 km long.

4.5 How do Triggered Earthquakes Constrain the 1755 Nov 1st Earthquake Source?

The probability must be considered that some of the major earthquakes, which occurred across western Europe, north Africa and eastern north America in the months and years after 1755, were not independent to the Nov 1st 1755 earthquake (see Fig. 7). The primary candidates to be linked are (a) the proposed displacement on the Lower Tagus Valley fault as an expansion of the Nov 1st mainshock and (b) the earthquake of Nov 27th in Morocco. It also seems possible that the Dec 9th 1755 and Feb 18th 1756 earthquakes in central Europe may have been advanced as a result of the Nov 1st earthquake. Lastly the M8.5 March 31st 1761 earthquake must be considered closely related to the Nov 1st 1755 fault rupture.

Simple stress transfer models have been created in order to explore alternative source geometries insofar as they would be likely to have triggered these subsequent earthquakes. The stress field due to co-seismic displacement associated with the 1755 Nov 1st earthquake is determined for 4 different source scenarios, the Gorringe Bank, the Marques de Pombal thrust, the Gulf of Cadiz subduction zone overthrust and the proposed tsunami source of Baptista et al.

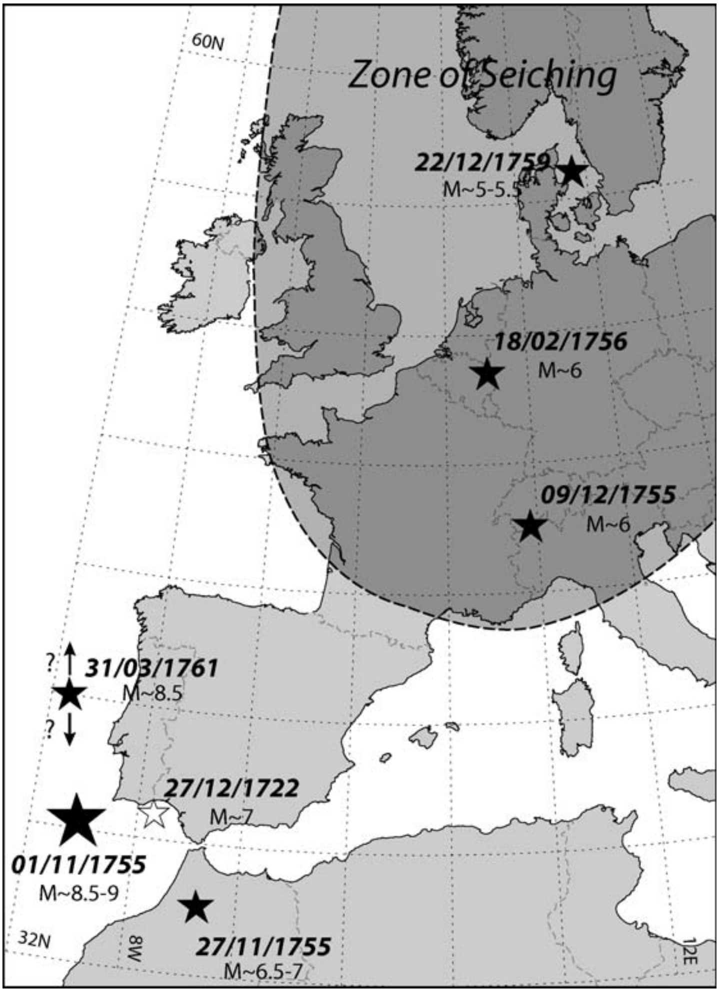

Fig. 7 Principal earthquakes observed before and after the Nov 1st 1755 earthquake, and the principal region affected by seiching of lakes, ponds and canals

(1998b). The source parameters can be found in Table 1 and correspond to a compilation of previous studies, from Johnston (1996) and Baptista et al. (1998a) for the Gorringe Bank, from Zitellini et al. (2001) and Terrinha et al. (2003) for the Marques de Pombal thrust, from Gutscher et al. (2002) for the Gulf of Cadiz overthrust (source simplified, and dip fixed to 25°) and from Baptista et al. (1998b) for the proposed tsunami source.

Figure 8 represents the positive stress changes associated with the 4 different source scenarios. Stress contours of +0.5 bar show the regions where triggering of earthquakes of similar mechanism is more likely to occur. In all cases, the

Table 1 Source parameters used in stress transfer models (apparent coefficient of friction $\mu = 0.4$)

Source	Length (km)	Width (km)	Strike	Dip	Displacement (m)
Gorringe Bank	175	50	55°N	45°	20
Marques de Pombal	150	50	10°N	25°	20
Gulf of Cadiz overthrust	200	200	–10°N	25°	20
Tsunami source	350	150	–10°N	25°	20

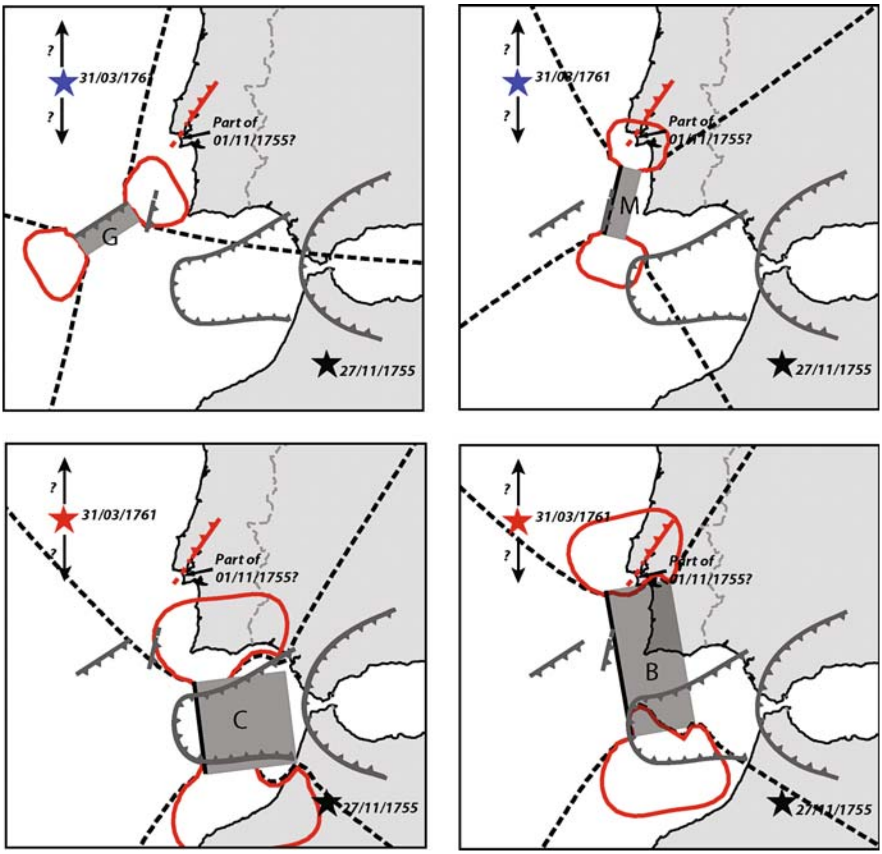

Fig. 8 Alternative fault models of the Nov 1st 1755 mainshock and associated stress changes. Sources G, M, C and B are respectively the Gorringe Bank, the Marques de Pombal fault (extended northward), the Gulf of Cadiz overthrust and Baptista et al. (1998) proposed tsunami source (see model parameters in Table 1). Stress contours are represented in black (+0.5 bar) and in dashed black (0.bar). The Lower Tagus fault as well as the 1761 offshore earthquake are represented in black when possibly triggered, whereas in grey if located in a stress shadow

Lower Tagus Valley fault is likely to have experienced a significant increase of stress. This is consistent with the proposal of Vilanova et al. (2003) that the LTV fault was triggered by the 1755 Nov 1st rupture, within the same episode. The location of the 1761 offshore earthquake is not fully resolved but if we consider the more plausible location represented on Fig. 8, this event could only be triggered by a source oriented NNW-SSE to N-S. A triggering from source C or B might be possible whereas it seems impossible from source G or M (clearly in the stress shadow). The other event that should have been triggered by the 1755 Nov 1st earthquake is the Morocco event of Nov 27th that occurred less than one month later. However, the mechanism of this event proposed by Moratti et al. (2003) is orthogonal to the displacement implied by the majority of the fault sources for the 1755 earthquake, and based on this mechanism it is not easy to see how stress transfer would have triggered the failure. However if the underlying mechanism involved a sinistral displacement along a NE-SW fault, as is typical of Morocco, this would have had the potential to be triggered by E-W stress reduction within the region to the east of the main 1755 fault rupture.

Concerning the Brig, Aix-la-Chapelle and Kattegat earthquakes, they seem too far away from the 1755 Nov 1st source to have experienced a significant stress increase (stress changes < 0.005 bar) and thus they cannot help in constraining the source geometry of the 1755 Nov 1st earthquake.

5 Summary – Constraints on the Nov 1st 1755 Earthquake Source

The purpose of this paper has been to review the full range of phenomenological observations from the 1755 Nov 1st earthquake in order to determine what they reveal about the fault source. Having summarized what can be inferred from each individual set of observations it is possible to explore how these conclusions can be combined into a coherent interpretation.

To summarize these findings.

- The extraordinary energy and spectrum of far-field long-period ground motion implies that there was a single principal episode of fault rupture with a moment magnitude of c. Mw9.
- The duration of the fault rupture implies a fault length of 450–600 km (consistent with the Moment Magnitude).
- The strong polarization in farfield tsunami heights implies that the fault that generated the seafloor deformation had a predominant NNW-SSE orientation.
- The nearfield tsunami travel times and amplitudes are consistent with the proposal that there was a N-S to NNW-SSE oriented zone of strong seafloor deformation located midway between the coast of SW Portugal and Gorringe Bank. This tsunami source corresponds with the location and trend of a prominent high angle reverse fault structure – the Marques de Pombal thrust

showing evidence of geologically recent displacement. However the tsunami source must have been significantly longer than this 100 km mapped fault. While the tsunami source proposed by Baptista et al. (1998b) appears to be consistent with observations of tsunami travel times and tsunami heights along the SW Portugal coast it appears to understate tsunami heights in SW Spain and Madeira and overestimate travel times to Morocco, implying that the tsunami source extended further south into the Gulf of Cadiz and towards the coast of Morocco.

- High levels of destruction (at MSK VIII) both inland and along the coast in southwestern Morocco suggest that this region was within 100–200 km of the causative fault.
- A 600 km fault would need to extend from 38 N (the latitude of Lisbon) down to 32.5 N (close to the coast of Morocco) – see Fig. 9.

As additional and corroborative evidence in support of this proposal:

- Many observers report strong E-W motion – consistent with reverse displacement on a N-S striking fault.

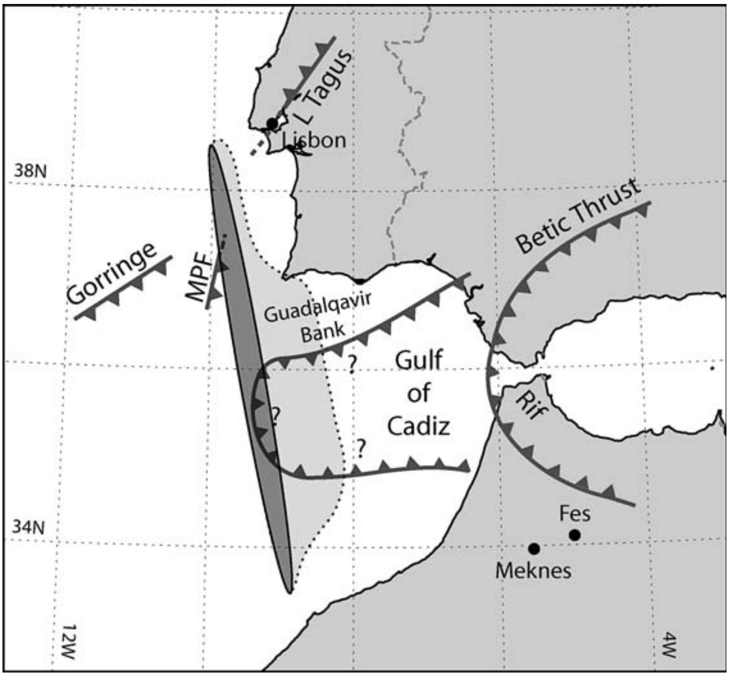

Fig. 9 Proposed zone of seafloor deformation and associated fault rupture in the Nov 1st 1755 mainshock. The dark grey ellipse represents the most likely orientation and extent of the source and the light grey zone represents the possible structure of the fault plane

- Observations from ships report the strongest impulse of water transmitted T waves in the area around the Marques de Pombal thrust. This may be because the fault emerged as a high angle structure on the sea floor in this area. Further south it is expected the fault may be a shallow dipping overthrust structure (dipping at 5–10 degrees towards the east?) in which seafloor deformation was more distributed.
- The pattern of very high intensities in the western Algarve suggests that an element of the fault rupture underlay this area. This could reflect the transition between a relatively steep reverse fault to the north and a shallow dipping overthrust structure to the south, with a much larger downdip extent. Alternatively this could be some kind orthogonal reverse fault structure absorbing the difference between the displacement on the main 1755 fault rupture and the overall NW-SE plate boundary displacement predicted in this region.
- It is likely that displacement on the Lower Tagus Valley fault system was triggered as part of the main rupture sequence.

In terms of the seismotectonic context of the region, the proposed NNW-SSE to N-S fault system appears to lie to the east of a zone of prominent recent seismic activity involving reverse displacement on faults trending NE-SW, including the Ms7.9 1969 earthquake and a more recent Mw6.1 earthquake on Feb 2nd 2007 (Borges et al. 2007). While these focal mechanisms are consistent with the expected plate boundary motions in this region, further to the east, beyond the proposed Nov 1st 1755 source structure, a different tectonic style exists, as around the Gulf of Cadiz and into northern Morocco apparently reflecting decoupling from the expected plate boundary motions. It is presumed that it is the faults along which the Nov 1st 1755 rupture occurred, that provide this decoupling.

Understanding the configuration of the seismotectonics is a pre-requisite for determining the current seismic hazard of this region, as well as helping identify other comparable situations worldwide capable of generating such regionally destructive earthquakes along with their accompanying megatsunamis. From the seismicity of the 20th Century and with the current generation of seismotectonic models for this plate boundary, there would be no suspicion that earthquakes such as the Mw9 Nov 1st 1755 and Mw8.5 March 31st 1761 could be generated in this region.

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