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The tectonic source of the 1755 Lisbon earthquake and tsunami

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Abstract
The SW continental margin of Iberia is affected by several tectonic structures of Cenozoic to Recent age, generated by the dynamics of the Iberia-Africa plate margin. This activity is testified by diffuse seismicity along the eastern portion of the Azores-Gibraltar line. The most important active structure, detected during a reflection seismic survey in 1992, is a thrust-fault, some 50 km long and with dip-slip throw of more than 1 km, located offshore Cabo de S. Vincente. A relocation of historical earthquakes in the area shows that this structure lies very close to the epicentre of the catastrophic 1755 Lisbon earthquake and that it should be the generator of the event. This submarine structure can now be studied for modelization of tsunamis and consequent risk mitigation.

Key words *SW Iberia continental margin – seismicity – tsunami – tectonic structures*

1. Introduction

Along the Atlantic side of SW Iberia seismicity is frequent and strong as testified by the occurrence of many historical tsunami events affecting the Western Iberian coasts, such as the 60-63 B.C. event which destroyed Cadiz, and the A.D. 1531, 1722, and 1755 earthquakes (Simoes *et al.*, 1992). The latter event, known as the 1755 Lisbon earthquake, was the largest and generated anomalous sea waves that struck the coasts of Portugal, Spain and Morocco and were observed all over the North Atlantic. It caused some 10 000 casualties, about 1000 of which attributed exclusively to the tsunami (Simoes *et al.*, 1992; Baptista *et al.*, 1998a).

The seismicity of the SW Iberian margin derives from the tectonic activity along the boundary separating the African and Eurasian plates. This boundary, also called the Azores-Gibraltar Line (AGL), trends roughly E-W connecting the Azores Triple Junction to the Gibraltar Strait (fig. 1). Along this line, the present plate motion is divergent east of the Azores (Tercieira Ridge), transform in the middle segment (Gloria fault), and convergent east of the Tore-Madeira Ridge to the Gulf of Cadiz and the Gibraltar Strait (Grimison and Chen, 1986; Argus *et al.*, 1989). In the latter area, analysis of the focal mechanism shows NNW-SSE trending compressional stresses (fig. 1), with geographically scattered hypocentres, spanning in depth from shallow to some 100 km (Fukao, 1973;

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Grimison and Chen, 1986; Burfon *et al.*, 1988; Argus *et al.*, 1989).

From a tectonic point of view, the area is characterized by a number of compressional structures, affecting both the continental margin and the oceanic crust (Mauffret *et al.*, 1989; Sartori *et al.*, 1994; Torelli *et al.*, 1997; Tortella *et al.*, 1997).

These structures have formed since Cenozoic times (Olivet *et al.*, 1984) when convergent motion started, producing an inversion of previous extensional features and important uplifts in a wide sector (Sartori *et al.*, 1994). A few of these structures appear still active, generating ruptures up to the seafloor.

In this paper we describe the features of one of the most impressive among them, discussing its possible role as the source area for the above reported 1755 Lisbon earthquake.

2. Materials and methods

A regional multi-channel seismic reflection survey (MCS) was performed in 1992 by the R/V OGS EXPLORA with funding from the Italian National Research Council (Cruise AR92) to investigate the stratigraphic and tectonic features of the eastern end of the Azores-Gibraltar line. At sea we used a 32 airgun array energy source with a total capacity of 80 L. A 120 channels, 3 km long receiving streamer was used for recording down to 13 or 14 s TWT. Details of the onshore processing of the data are reported in Sartori *et al.* (1994). The MCS lines were acquired across the area characterized by compressive natural seismicity, spanning from the Tore-Madeira Ridge to the Gulf of Cadiz and the Gibraltar Strait (figs. 1 and 2). They were shot with direction roughly

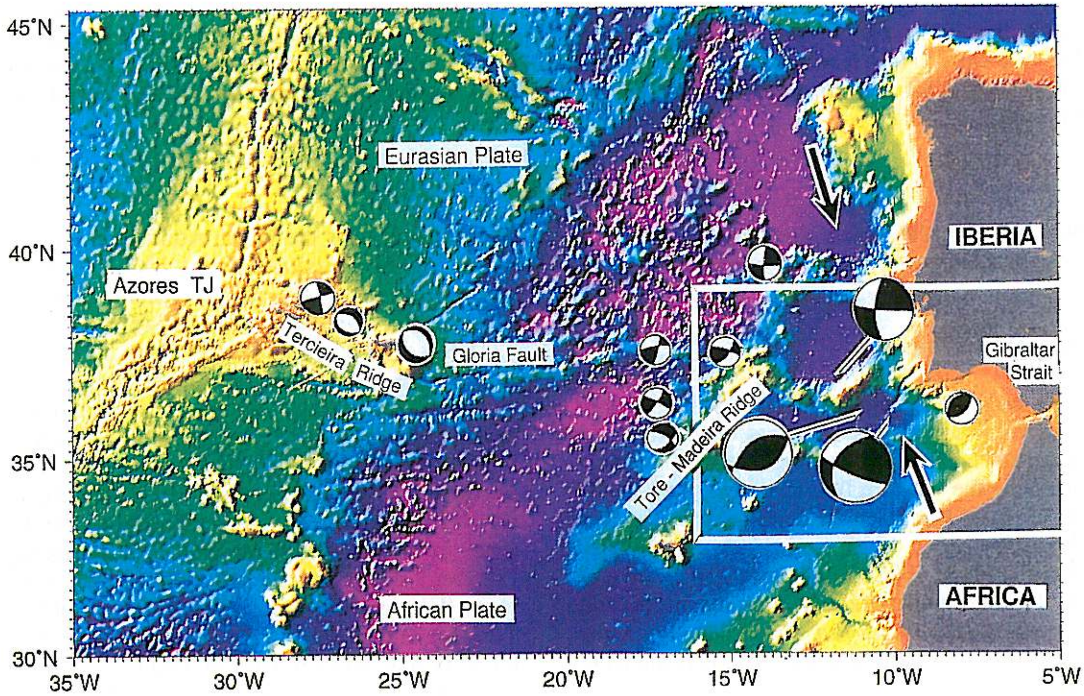

Fig. 1. Colour shaded relief of the bathymetry of Central Eastern Atlantic (data from Smith and Sandwell, 1997) showing the main elements of the Azores Gibraltar Line (AGL) as reported in the text. Solid arrows, displaying the regional stress field of the eastern AGL, and selected focal mechanisms are shown (after Grimison and Chen, 1986). The box (Eastern AGL) outlines the area depicted in fig. 2.

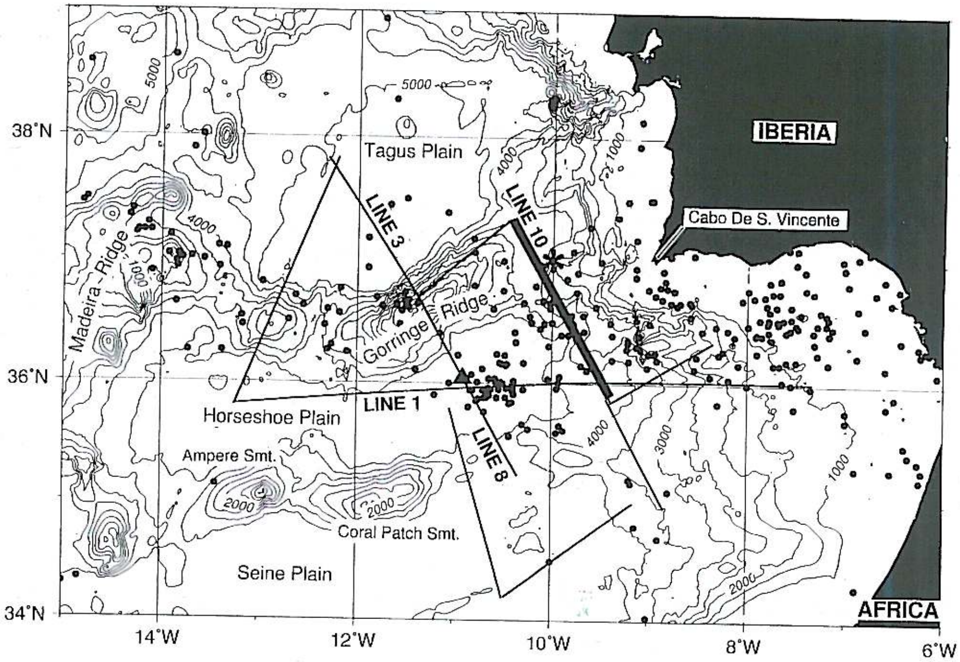

Fig. 2. Simplified bathymetric map of the Eastern Azores Gibraltar line showing the location of AR92 seismic lines. The heavy line shows the location of the profile reported in fig. 3. Solid circles indicate instrumental earthquake epicentres in the area. The star indicates the position of the 1755 A.D. event (from Udias *et al.*, 1976), the triangle the location of 02/28/1969 earthquakes (from Martinez Solares *et al.*, 1979).

parallel and normal to the present NNW-SSE trending slip vectors, from the Tagus plain to the Seine plain in latitude, and from the Gulf of Cadiz to the Horseshoe plain in longitude, encompassing the entire deformation area present at sea, as far as they reached undeformed crust. Tracks of the lines are reported in fig. 2 together with the geographic locations discussed throughout the text. The results of several lines have already been reported in Sartori *et al.* (1994) and in Torelli *et al.* (1997). Here we report essentially the analysis of line AR10, shot across the SW Iberian continental margin.

3. Results

On Line AR92-10 (fig. 3) an impressive thrust structure is observed (SP 1200-2000); associated with evidence of an ongoing tectonic deformation (SP 2400-3000) with intense folding, interruption of stratigraphic units and uplift of the seafloor. The deformed area encompasses the whole line (about 200 km in length) and the thrust structure alone can be followed for more than 50 km. It is worth stressing that structures with a similar significant and active displacement of the seabottom have not been observed on other lines, reported by Sartori *et al.* (1994) and Torelli *et al.* (1997), even in the areas with the highest concentration of instrumentally recorded seafloor seismicity (*e.g.*, line 1 in fig. 2).

In fig. 3 we can distinguish from bottom to top: the acoustic basement (unit «e») made up by continental crust thinned during the Eurasia-North America Mesozoic rifting; a pre-compressional sedimentary sequence (units «d» and «c»), small, gravitationally discharged, olistostromes (unit «b», SP 2000-2500), and a

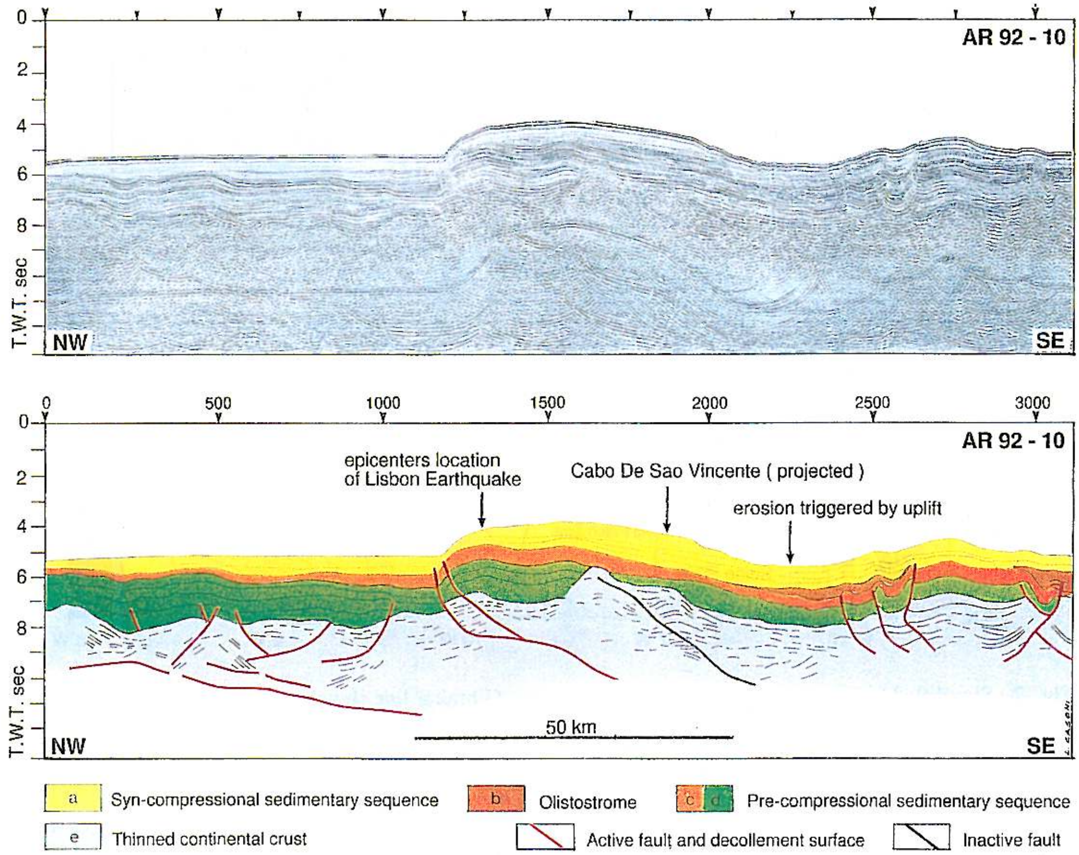

Fig. 3. Seismic line AR92-10 after poststack time migration (for location see fig. 2).

syn-compressional sedimentary sequence (unit «a»).

Northwestward of the major thrust plane (SP 0-1200) the sedimentation has been continuous furnishing the complete record of unit «a» which consists of a syn-tectonic sedimentary body above the sequences «c» and «d». In places (SP 500 and 950), the seafloor morphology is slightly controlled by folding.

Between SP 2000 and 2500 the thrust structure is decoupled by a deep décollement surface, recognizable down to 10 s TWT (about 12-15 km depth), with a dip-slip throw of more than 1100 m (SP 1500) affecting the whole sedimentary cover and the basement. Southeastwards (SP 2400-3500), the décollement surface seems shallower, about 9 s TWT, and is accompanied by folding with minor thrusting. Here the deformation, as inferred from the setting of the sedimentary cover, is still active with displacement of the seafloor (SP 2400).

The large erosional scar present on the hanging-wall of the thrust structure (SP 1900-2300), testifies the switch from a depositional environment, during the pre-compressional time, to the present uplift-related non deposition/erosion along the Cabo de S. Vincente canyon.

The tectonic activity might be very recent or in progress since erosion affects most of the more recent sediments of unit «a» (SP 1900-

2000). The vertical resolution of the seismic line is about 30 m and this does not reveal fresh ruptures or deformation of the most recent sediments in front of the thrust faults (SP 1200) as would be the case had the fault been active in historical times. Yet, considering that the thrust structure is surrounded by present-day active folding we can assert that it is still tectonically active.

4. Discussion

The source location of the 1755 Lisbon earthquake and tsunami has been a debated question. Some authors inferred it was in the vicinity of the Gorringe Ridge (fig. 2). This localization was strengthened by the occurrence of a tsunamigenic earthquake in the area on 02/28/1969 (Martinez Solares *et al.*, 1979, with earlier references). Our lines AR92 3 and 8, recorded across the Gorringe Ridge, do not show evidence of recent major uplift; most of the up-dip movement was confined to before early Pliocene times (see fig. 3a in Sartori *et al.*, 1994).

The AR92-10 line presented in fig. 3 is a 2D image of the thrust structure and hence it does not precisely establish either the geometry or the extension of the tsunamigenic source. However, a rough and preliminary estimate of the seismic moment $M = mSD$, where $m = 0.7 \times 10^{11}$ Pascal is crustal rigidity, S is the fault area and D is the mean displacement, in the approximation of a rectangular fault plane, gives $M = 1.12 \times 10^{21}$ Nm, for a source extension of 200 km length and 20 km depth and a mean displacement of about 4 m: this estimated value is intermediate between the measured value of the 02/28/1969 earthquake which occurred south of Gorringe Ridge (Fukao, 1973) and the highest value estimated for the 1755 Lisbon earthquake (Martins and Mendes Victor, 1990, see also Gjevik *et al.*, 1997).

Udias *et al.* (1976) hypothesized a source location offshore Cabo de S. Vincente at about 37N-10E, a point close to our line 10. Baptista *et al.* (1998a) compiled a list of almost all the historical parameters of the 1755 Lisbon earthquake and their reliability for a wide range of locations. These parameters include travel time, polarity of the first movement, maximum run-up height, period, number of waves and duration of the sea disturbance. In a further paper, Baptista *et al.* (1998b), using backward ray tracing methods, combined with an «area elimination» criterion, and an independent shallow water simulation, relocated the 1755 Lisbon earthquake source SW of Cabo de S. Vincente, in the vicinity of the previously described thrust structure. The source modelled by Baptista *et al.* (1998b) resulted «*L*-shaped» with estimated extent of about 300 km and a mean depth of the epicentral region of about 2500 m.

Taking into account the possible effects and errors due to bathymetry, the coupling between source and fluid, and the shape and orientation of the source, we can confidently conclude that the discovered thrust structure is the most probable source of the 1755 Lisbon earthquake. To better constrain this conclusion, forward modelling is needed, which will be defined after a 3D reconstruction of the source.

5. Conclusions

One of the most important issues regarding tsunami mitigation and warning is the likelihood of generation of destructive waves after the land recording of a strong earthquake occurring at sea, mainly if in the vicinity of coastal communities, when little time is available for risk assessment and public evacuation. Adams and Furumoto (1970) found a binary relationship between earthquake and tsunami, that unfortunately showed that during a major earthquake at sea... «either a very large tsunami is generated or none at all». About 90% of the world's large, shallow earthquakes occur in the circumpacific belt, with an even higher percentage for intermediate and deep earthquakes. Only a few percent of major earthquake events generate tsunami waves. In the tsunamigenic circumpacific subduction ring, high magnitude seismic events are distributed in a wide belt and their localization is highly variable throughout time. As a consequence, direct measurements of the source motion and of the induced fluid perturbation during the shake are not yet available (Filloux, 1982).

The localization of a possible tsunami source SW of Cabo de S. Vincente, a narrow structure whose features spatially constrain possible future tsunamigenic events, offers a straightforward opportunity for the study of tsunami-generating mechanisms. Therefore, it may be of paramount importance for natural risk assessments along the coasts of Portugal, Southern Spain and Northern Morocco and for the study of key parameters relating source motion and tsunami generation. Ribeiro (1994) estimated a returning period ranging from 300 up to 1500 years for events having a magnitude of about 8.5, comparable to those responsible for the 1755 Lisbon earthquake. Nevertheless, a large number of lower magnitude to instrumental events are likely to occur in the area. Events of magnitude less than 4 cannot currently be revealed by onland based seismographic network in Iberia.

A project funded by the European Commission (BIGSETS) will monitor the submarine thrust structure via the combined use of ocean bottom seismographs, gauge-pressure sensors and land-based tide gauges and seismographs. This will allow the measurement of the source motion, its moment release and the coupling between the source and the fluid during instrumental events.

The combined knowledge of the source structure, shape and extension, its orientation and motion and the induced fluid perturbation will give new insights into the relations between the generated water pressure perturbation and tsunami wave formation (Ward, 1980a,b, 1981, 1982; Comer, 1984).

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