# HAZARD IN THE GULF OF CADIZ: REVIEW OF THE LARGE SEISMOGENIC STRUCTURES

## *Peligrosidad en el Golfo de Cádiz: Revisión de las principales estructuras sismogénicas.*

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***Abstract**: The Gulf of Cadiz is located at the SW Iberian Margin and hosts the African-Eurasian plate boundary. This is one of the most seismogenic areas in Western Europe, where historical and instrumental earthquakes occurred, ranging from $M_w$ 6 to 8.5, and some of them triggered destructive tsunamis. The ICM-CSIC team keeps investigating the Gulf of Cadiz area since more than 15 years, carrying out multiscale bathymetric, high-resolution to deep seismic and sampling surveys. The active structures in the Gulf of Cadiz can be classified in two main families: The WNW-ESE dextral strike-slip faults and the NE-SW thrusts faults. The orientation of these faults is compatible with the current plate convergence in the region. The largest active strike-slip faults are: - the Lineament South and the Lineament North that may generate earthquakes up to $M_w$ 8; while the active NE-SW thrust faults, the Marquês de Pombal, the Horseshoe and the Coral Patch Ridge faults can individually generate earthquakes up to $M_w$7.8.*

***Key words**: Gulf of Cadiz, strike-slip faults, reverse faults, earthquakes tsunamis*

## Introduction

The Gulf of Cadiz is located in the southwestern margin of Iberia, along the NW-SW convergence between African – Eurasian plate boundary (3.8-5.6 mm/yr) (Nocquet and Calais, 2004). According to Zitellini et al., (2009) the current plate boundary is hosted along the transcurrent LS (Lineament South) (Figure 1) fault. The SW Iberian margin is a region of moderate seismic activity ($M_w$~5.5) characterized by shallow to deep (up to 60 km depth) earthquakes. Nevertheless, the Gulf of Cadiz is also the source of the largest and most destructive earthquakes that affected Western Europe and was accompanied by devastating tsunamis.

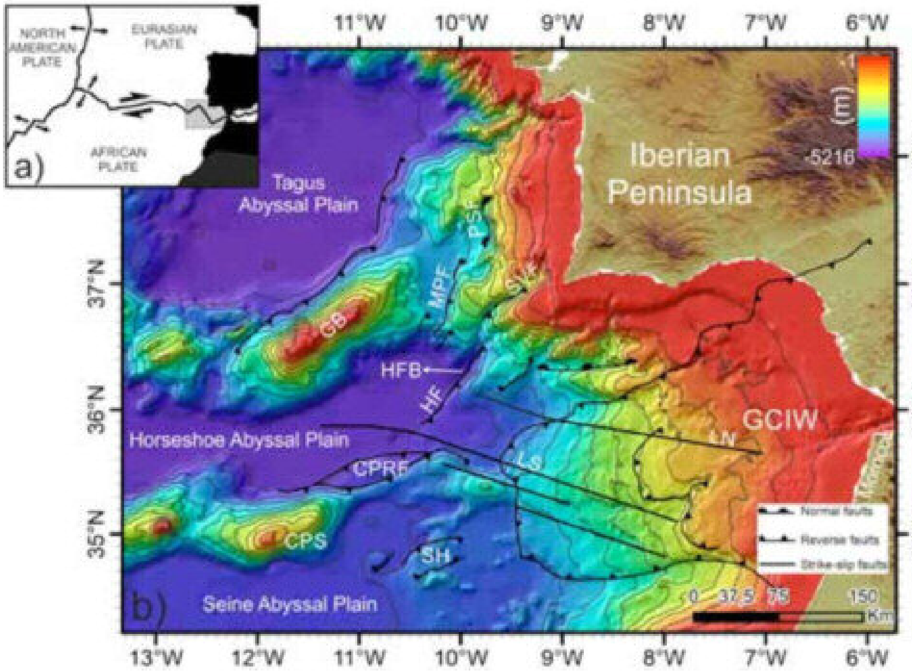


*Figure 1: A) Plate tectonic setting of the SW Iberian margin at the boundary between the Eurasian and African Plates. The grey rectangle corresponds to the area depicted in b B) Regional bathymetric map of the SW Iberian margin with the main tectonic structures (Gràcia et al., 2010) located. CPRSF: Coral Patch Ridge Faults; CPS: Coral Patch Seamount; GCIW: Gulf of Cadiz Imbricated Wedge; GB: Gorringe Bank; HF: Horseshoe Fault; HFB: Horseshoe fault basin; LN: Lineament North; LS: Lineament South; MPF: Marquês de Pombal Fault; PSF: Pereira de Sousa Fault; SVF: São Vicente Fault; SH: Seine Hills Faults.*

The study of Gràcia et al., 2010 on the basis of the turbidite paleoseismology found that the regional recurrence interval for the Great earthquakes (Mw 8) is about 1800 yr.

In this work we aim to review and compile the main active structures in the Gulf of Cadiz that have been recognized, during the successive geological and geophysical surveys carried out in the area by the ICM-CSIC team since the mid-90s (Figure 2). This information will be completed during the forthcoming geological and geophysical marine survey on May of 2018 and May of 2019, in the frame of the INSIGHT project.

Fault investigations focus on the active structures located at the external part of the Gulf of Cadiz, which corresponds to two main families : (1) large WNW-ESE trending dextral strike-slip faults, such as the Lineaments North (LN) and South (LS) (e.g. Terrinha et al., 2009; Zitellini et al., 2009; Bartolome et al., 2012; Martínez-Loriente et al., 2013) and (2) NE-SW trending thrusts, such as the Marquês de Pombal (MPF), São Vicente (SVF), Horseshoe (HF), North and South Coral Patch (NCPF and SCPF) and Gorringe Bank (GBF) faults (e.g. Gràcia et al., 2003a; Terrinha et al., 2003; Zitellini et al., 2004; Martínez-Loriente et al., 2014, 2018) (Figure 1).

**The strike-slip faults**

The dextral strike-slip faults have a WNW-ESE trend and connect the Gorringe Bank in the North with the Moroccan shelf (Zitellini et al., 2009). Martínez-Loriente et al. (2014) proposed the LS and LN as a boundary between different geological domains of the basement at the Africa-Eurasia plate boundary, and Zitellini et al., (2009) proposed the LS as the current plate boundary, between Nubia and Eurasia. The topographic expression of the lineaments is a set of continuous crest and troughs with a width of hundreds of meters over the seafloor (Figure 3).

The LS (Figure 3) extends from the Horseshoe Abyssal Plain to the Gulf of Cadiz Imbricated Wedge along 150 km. The deformation associated to LS spands 2-3 km at the seafloor across strike, cutting the seismostratigraphic sequences including the Quaternary unit up to the seafloor (Terrinha et al., 2009). Ultra-high resolution (UHR) parametric profiles along the LS, (figure 3) display positive and negative flower-like structures (Bartolome et al., 2012).

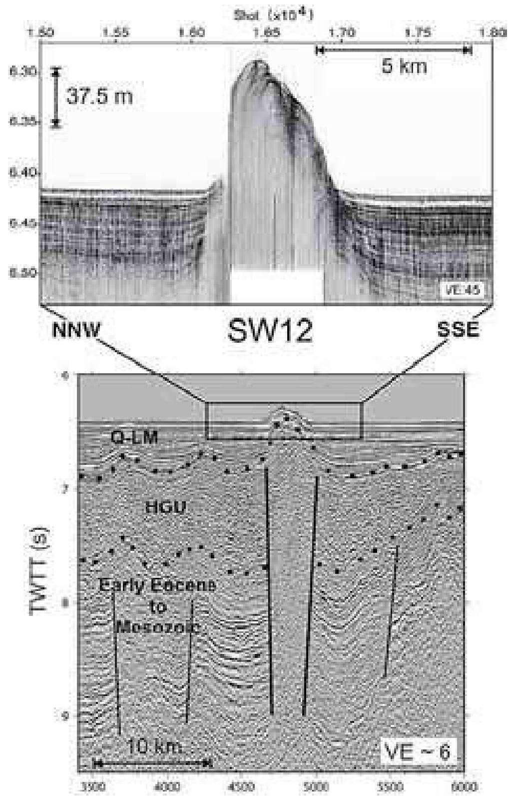


*Figure 3: Interpretation of the multichannel seismic reflection profile of the line SW12 across the Lineament South. CMP: common mid-point; HGU: Horseshoe Gravitational Unit; Q-LM: Late Miocene-Quaternary; TWTT: two-way traveltime. Modified from Bartolome et al., (2012).*

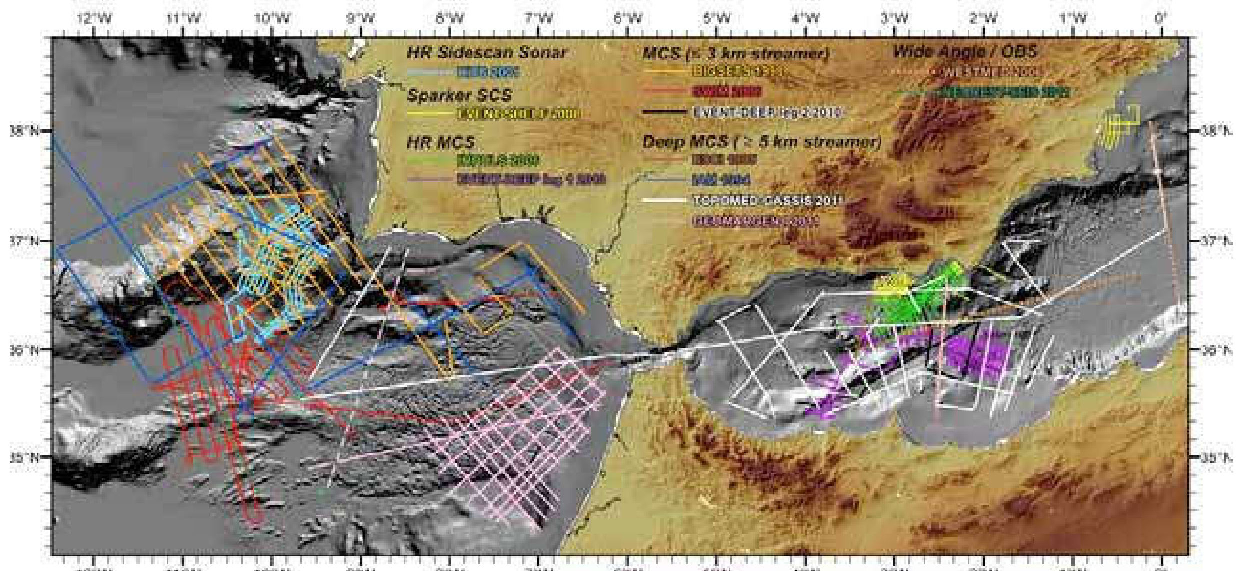


*Figure 2: Compilation of geological and geophysical surveys carried out by the ICM-CSIC team.*

The LN (Figure 1) is also evident in the northern part of Gulf of Cadiz imbricated wedge. It is 130 km long and deformation is distributed within a 4,8 km wide zone (Bartolome et al., 2012). In some UHR parametric profiles a positive flower-like structure, can be observed. According to Bartolome et al., (2012) moderate magnitude earthquakes ($M_w$= 3-5) have occurred associated with the lineaments at shallow to intermediate depths (8-55 km). The same authors evaluate the seismic potential of LS and LN and estimate potential maximum magnitudes of $M_w$=8.3 for the LS and $M_w$=8.1 for the LN.

**Thrusts Faults**

The active thrusts of the Gulf of Cadiz are mainly NE-SW oriented (Figure 1). The thrusts are active since the onset of convergence between SW-Iberia and Africa in the Neogene (Gràcia et al., 2003b). The main thrusts in the Gulf of Cadiz are:

a) The Marquês de Pombal fault (MPF) is a 55 km long west-verging monocline thrusts (Terrinha et al., 2003). The hanging-wall of the MPF shows an irregular upper surface due to the abundant slumps and landslides (Vizcaino et al., 2006) that may reach more than 20 km of runout (Gràcia et al., 2003a). The morphological expression of the thrust is related to the tectonic evolution of the fault since the Middle Miocene. The faulting and some folds affect the whole sedimentary sequence, including the Quaternary, which indicates present-day tectonic activity. The MPF has been proposed as source structure of the 1755 Lisbon earthquake (Zitellini et al., 2001).

b) The Horseshoe fault (HF) is an NE-SW trending, 110 km-long anticline thrust (Figures 1, 4). It runs from the Coral Patch Ridge to the mouth of the São Vicente Canyon. It is an east-dipping thrust (Gràcia et al., 2003a) that reaches the seafloor with associated present-day seismicity (Silva et al., 2017). This thrust affects all the sedimentary sequence and roots in the Jurassic basement (Figure 4). The hanging-wall block of the north segment of the HF corresponds to the SE flank of the São Vicente Canyon, while the footwall block forms the Horseshoe fault basin in the Horseshoe Abyssal Plain.

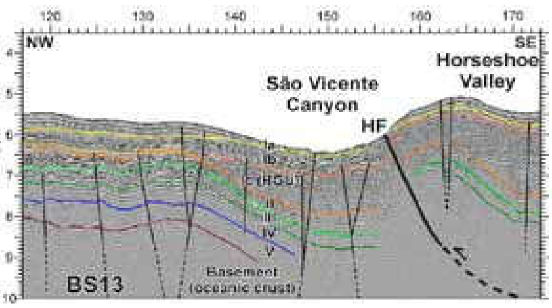


*Figure 4: Interpreted of section of the time migrated profile BS13 across the south termination of The São Vicente canyon, which is faulted by the Horseshoe Fault (HF). Ia: Plio-Quaternary; Ib: Middle Miocene-Pliocene; Id: Upper Oligocene-Middle Miocene; HGU: Horseshoe Gravitational Unit; II: Upper Cretaceous-Early Eocene; III: Cretaceous; IV: Lower Cretaceous; V: Upper Jurassic; TWTT: two-way traveltime. Modified from Martínez-Loriente et al., 2018.*

c) The CPR is a 160 km long ridge with a rhomboidal shape that separates the HAP from the Seine Abyssal Plain (SAP). The North Coral-Patch Ridge (NCPF) and the South Coral-Patch Ridge (SCPF) faults. The NCPF (Figure 1) is 65 km long and the SCPF is 83 km-long. The seismic profiles analyzed by Martínez-Loriente et al., (2013) show that these structures cut, fold and show growth-strata configuration in the most recent sedimentary units of Holocene age, indicating that they are active and may able to generated earthquakes up to magnitude $M_w$ 7 (Martínez-Loriente et al., 2013).

d) The Gorringe Bank ridge (GB) is a compressive structure raised by a large-scale thrust of the northwestern segment of the HAP that overthrusts the TAP (Sallarès et al.,2013). Nowadays, the GB is a source of low-magnitude seismicity and Plio-quaternary sediments show a slight deformation associated to the main thrust. The micro-seismicity of GB is located at depths between 20 and 40 km (Silva et al.,2017).

**Conclusions**

The ICM-CSIC team keeps investigating the Gulf of Cadiz area for more than 15 years. These surveys allowed to recognize the main tectonic structures in the region. The main active structures in the Gulf of Cadiz are two families: the NE-SW trending thrusts and the WNW-ESE strike-slip faults. The orientation of these faults is compatible with the current plate convergence in the region. The thrusts consist of NE-SW trending reverse faults with NW or SE-vergence that vary in length from 55 to 110 km. The main thrusts can generate moderated ($M_w$>6) to large ($M_w$>8) earthquakes. The LS and LN strike–slip faults are respectively 150 km-long and the 130- km long, which have generated instrumental earthquakes of moderated magnitude and can generated large earthquakes up to Mw=8. These structures may pose significant seismic and tsunami hazard for the Portuguese, Spanish and North African coasts.

**References**

Bartolome, R., Gràcia, E., Stich, D., Martínez-Loriente, S., Klaeschen, D., Mancilla, F., et al. (2012). Evidence for active strike-slip faulting along the Eurasia-Africa convergence zone: Implications for seismic hazard in the southwest Iberian margin. *Geology,* 40(6), 495-498.

Gràcia, E., Dañobieitia, J., Vergés, J., & Team, P. (2003a). Mapping active faults offshore Portugal (36ºN-38ºN): Implications for seismic hazard assessment along the southwest Iberian margin. *Geology,* 31(1), 83-86.

Gràcia, E., Dañobeitia, J., Vergés, J., & Bartolome, R. (2003b). Crustal architecture and tectonic evolution of the Gulf of Cadiz. *Tectonics,* 22, 1033.

Gràcia, E., Vizcaino, A., Escutia, C., Asioli, A., Rodés, A., Pallàs, R., et al. (2010). Holocene earthquake record offshore Portugal (SW Iberia): testing turbidite. *Quaternary Science Reviews,* 29, 1156-1172.

Martínez-Loriente, S., Gràcia, E., Bartolome, R., Sallarès, V., Connors, C., Perea, H., et al. (2013). Active deformation in old oceanic litosphere and significance for earthquake hazard: Seismic imaging of the Coral Patch Ridge area and neighboring abyssal plains (SW Iberian Margin). *Geochemistry, Geophysics, Geosystems,* 14(7), 2206-2231.

Martínez-Loriente, S., Sallarès, V., Gràcia, E., Bartolome, R., Dañobeitia, J., & Zitellini, N. (2014). Seismic and gravity constraints on the nature. *Journal of Geophysical Research: Solid Earth,* 119, 127-149.

Martínez-Loriente, S., Gràcia, E., Bartolome, R., Perea, H., Klaeschen, D., Dañobeita, J., y otros. (2018). Morphostructure, tectono-sedimentary evolution and seismic potential of the Horseshoe Fault, SW Iberian Margin. *Basin Research*, 30, 1-19.

Nocquet, J.-M., & Calais, E. (2004). Geodetic Measurements of Crustal Deformation in the Western Mediterranean and Europe. *Pure and Applied Geophysics,* 161, 661-681.

Sallarès, V., Martínez-Loriente, S., Prada, M., Gràcia, C., Ranero, C., Gutscher, M., et al. (2013). Seismic evidence of exhumed mantle rock basement at the Gorringe Bank. *Earth and Planetary Science Letters,* 365, 120-131.

Silva, S., Terrinha, P., Matias, L., Duarte, J., Roque, C., Ranero, C., y otros. (2017). Micro-seismicity in the Gulf of Cadiz: Is there a link between micro-seismicity, high magnitude earthquakes and active faults? *Tectonophysics,* 717, 226-241.

Terrinha, P., Pinheiro, L., Henriet, J., Matias, L., Ivanov, M., Monteiro, J., y otros. (2003). Tsunamigenic-seismogenic structures, neotectonics, sedimentary processes and slope instability on the southwest Portuguese Margin. *Marine Geology,* 3266, 1-19.

Terrinha, P., Matia, L., Vicente, J., Duarte, J., Pinhero, L., Lourenço, N., et al. (2009). Morphotectonics and strain partitioning at the Iberia-Africa plate boundary from multibeam and seismic reflection data. *Marine Geology,* 267, 165-174.

Vizcaino, A., Gràcia, E., Pallàs, R., Garcia-Orellana, J., Escutia, C., Casas, D., et al. (2006). Sedimentology, physical properties and age of mass transports deposits associated with the Marquês de Pombal Fault, Southwest Portuguese Margin. *Norwegian Journal of Geology,* 86, 177-186.

Zitellini, N., Mendes, L., Cordoba, D., Dañobeitia, R., Nicolich, R., Pellis, G., et al. (2001). Source of 1755 Lisbon Earthquake and Tsunami Investigated. *Eos,* 82(26), 285-296.

Zitellini, N., Rovere, M., Terrinha, P., Chierici, F., Matias, L., & Team., B. (2004). Neogene Through Quaternary Tectonic Reactivation of SW Iberian Passive Margin. *Pure and Applied Geophysics,* 161, 565-587.

Zitellini, N., Gràcia, E., Matias, L., Terrinha, P., Abreu, M., DeAlteriis, G., et al. (2009). The quest for the Africa-Eurasia plate boundary west of the Strait of Gibraltar. *Earth and Planetary Science Letters,* 280, 13-50.