ACTIVE FAULTING IN THE MESOZOIC OCEANIC LITHOSPHERE OFFSHORE THE SW IBERIAN MARGIN. SIGNIFICANCE FOR EARTHQUAKE AND TSUNAMI HAZARD

Fallas activas en la litosfera oceánica mesozoica offshore del Margen SO Ibérico. Significado para el riesgo de terremotos y tsunamis

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***Abstract**: Newly acquired high-resolution multichannel seismic profiles together with bathymetric and subbottom profiler data from the external part of the Gulf of Cadiz (Iberia-Africa plate boundary) reveal active deformation involving old (Mesozoic) oceanic lithosphere. This area is located 180 km offshore the SW Iberian Margin and embraces the prominent NE-SW trending Coral Patch Ridge, and part of the surrounding deep Horseshoe and Seine abyssal plains. E-W trending dextral strike-slip faults showing surface deformation of flower-like structures predominate in the Horseshoe Abyssal Plain, whereas NE-SW trending compressive structures prevail in the Coral Patch Ridge and Seine Hills. Although the Coral Patch Ridge region is characterized by subdued seismic activity, the area is not free from seismic hazard. Most of the newly mapped faults correspond to active blind thrusts and strike-slip faults that are able to generate large magnitude earthquakes (Mw 7.2–8.4). This may represent a significant earthquake and tsunami hazard that has been overlooked so far*

***Key words**: multichannel seismics; blind thrusts; strike-slip faults; Iberia- Africa boundary.*

INTRODUCTION

Active deformation involving old oceanic lithosphere offshore the southwest Iberian margin is driven mainly by the NW–SE convergence (3.8-5.6 mm/year) between the African and Eurasian plates (e.g., Nocquet and Calais, 2004). Convergence is accommodated over a wide active deformation zone suggesting distributed deformation among a number of tectonic structures (Fig. 1). Earthquake mechanisms reveal reverse to strike-slip faulting solutions in the external Gulf of Cadiz (e.g., Buforn et al., 2004; Stich et al., 2005, 2007). This area, which is interpreted to be underlain by Jurassic-Cretaceous age oceanic lithosphere on the basis of refraction and wide-angle reflection seismics (WAS), magnetic data, and kinematic reconstructions (e.g., Ryan et al., 1973; Purdy, 1975; Gràcia et al., 2003a, 2003b; Contrucci et al., 2004; Rovere et al., 2004; Sallarès et al., 2011, 2013; Martínez-Loriente et al., 2014), is characterized by intense seismic activity of moderate magnitude. However, large historical and instrumental earthquakes have been nucleated here, such as the 1755 Lisbon Earthquake (M_w 8.5) and the 1969 Horseshoe Earthquake (M_w 8.0) (Fig. 1). In SW Iberia, seismic hazard assessment is mainly based on instrumental and historical earthquake catalogs that actually represent very short periods, especially when considering high-magnitude earthquakes with long recurrence intervals (> 2000 years) (Gràcia et al., 2010).

During the last two decades, numerous geological and geophysical surveys have been carried out in the region seeking faults that may be potential sources of large magnitude earthquakes. The present work focuses on the area of the external part of the Gulf of Cadiz located south of the SWIM Fault Zone (SFZ), a 600 km long dextral strike-slip deformation zone connecting the Gorringe Bank with the Moroccan shelf (Zitellini et al., 2009) (Fig. 1). The tectonic structures of this area have been considered as inactive mainly due to (1) the lack of instrumental seismicity associated with them (Zitellini et al., 2009), and (2) the low resolution of pre-existing multichannel seismic (MCS) profiles, where deformation of Quaternary units could not be recognized (e.g., Sartori et al., 1994; Tortella et al., 1997). We present our main outcomes focusing into two aspects: a) the characterization of the pattern and timing of the deformation of the tectonic structures located in the Coral Patch Ridge region and neighboring Horseshoe and Seine abyssal plains, and b) the evaluation of the seismic potential of the most relevant active structures on the basis of their fault parameters (i.e., geometry, kinematics, maximum magnitude). Our findings demonstrate that the newly mapped structures represent a significant earthquake and tsunami hazard for the South Iberian and North African coasts that has not been accounted for to date.

ACTIVE FAULTING IN THE CORAL PATCH RIDGE REGION. SEISMIC HAZARD ASSESSMENT

The combined interpretation of high-resolution SWIM 2006 MCS reflection profiles together with swath-bathymetry, subbottom profiles and sediment cores yield new insights into the tectonic architecture and crustal structure of the external part of the Gulf of Cadiz.

In the Horseshoe Abyssal Plain (HAP) two main families of subvertical faults are observed on the basis of their activity: (a) those affecting the Mesozoic up to Lower Eocene sediments (units V-II); and (b) those that deform all the sedimentary sequence from the basement to the seafloor (units

V-I) (Fig. 2a). In the former case, we refer to tectonic structures of little entity that generate folds, discontinuities and small vertical displacements within the Mesozoic Units, although few of the structures deform the sediments up to the top of Unit II (Fig. 2a). The later family is characterized by subvertical faults that cut, fold and displace the whole sedimentary sequence up to the seafloor, generating small (<16 km long, <160 m high), elongated hills observed in the HAP. Most of these structures show flower-like geometries characteristic of strike-slip faults. However, as some of them show a dip-slip component, transpressive behavior can also be proposed producing significant vertical displacement (i.e., 600 m at the top of Unit IV) (Fig. 2a). The most prominent of these active faults corresponds to the LS, a WNW-ENE trending dextral strike-slip fault that extends for 180 km across the HAP and part of the GCIW (Fig. 1) (e.g., Zitellini et al., 2009; Bartolome et al., 2012; Martínez-Loriente et al., 2013). The LS corresponds to a 2–4 km wide fault zone with transparent seismic facies that is bounded by subvertical faults that cut across the entire sedimentary sequence from at least 11 km deep up to the seafloor. The LS produces approximately 500 m of vertical displacement of the top of Unit IV and 200 m of the top of Unit II (Fig. 2a).

The Coral Patch Ridge (CPR) is formed by two main NW-verging anticline thrust faults: the 65 km long North Coral Patch Ridge fault (NCP) and the 83 km long South Coral Patch Ridge fault (SCP) (Figs. 1 and 2b). These thrusts are characterized by backlimbs that dip less than the fault-ramp and forelimbs that are quite narrow in relation to their long backlimbs, suggesting that they were generated by shear fault-bend folding (Suppe et al., 2004). The seismic images show the ramps of the fault-bend folding thrusts, whereas the lower flats are probably located below the window of acquisition. The SCP thrust fault has a NW-ward sense of displacement, folding and uplifting the southeastern hanging-wall fault block, and cutting through the whole stratigraphic sequence up to the seafloor (Fig. 2b). Both thrusts show higher fault dips within the first km below the seafloor (average 40º), decreasing within the basement (average 25º) (Fig. 2b). A secondary active thrust south of the SCP fault is also observed with little vertical displacement. This thrust would propagate from a shallow depth detachment layer located at the uppermost part of the oceanic crust (Martínez-Loriente et al., 2013).

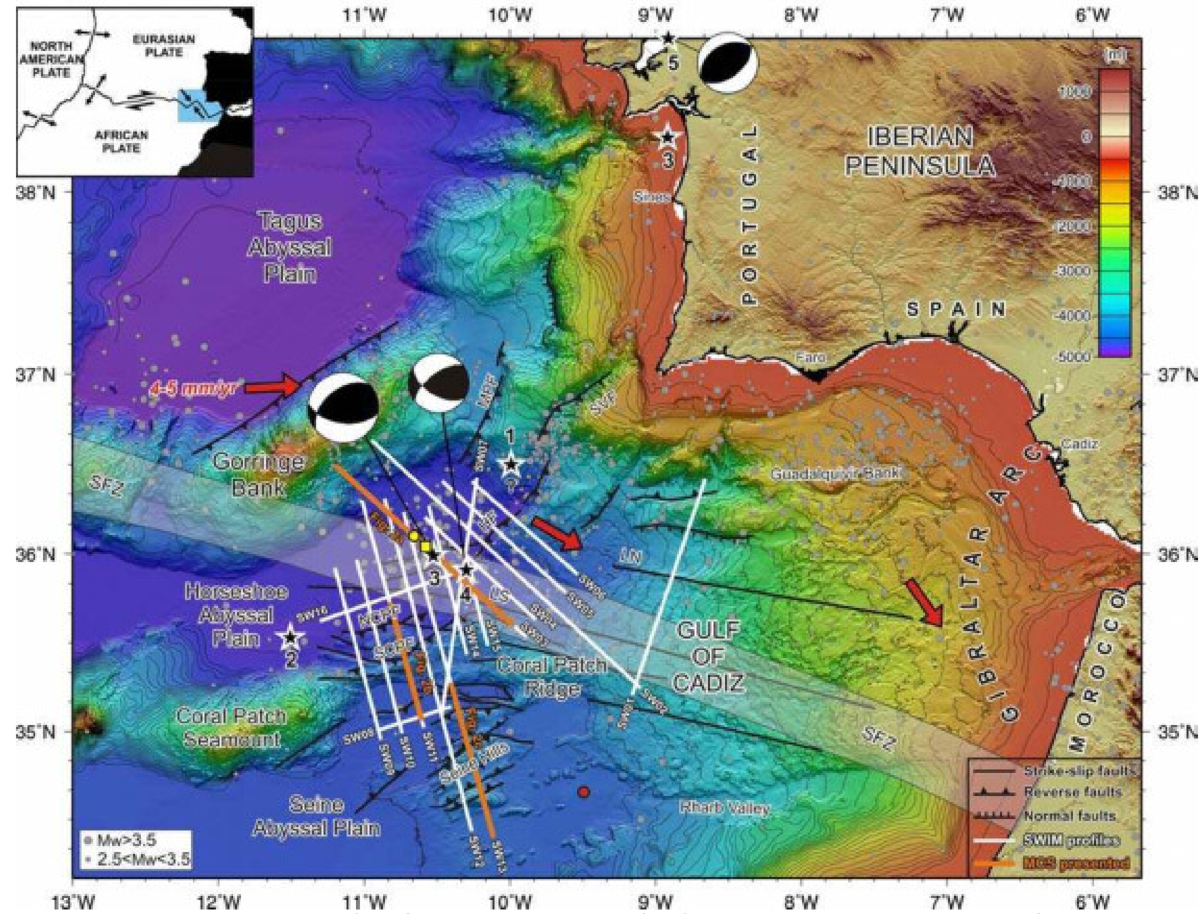

Figure 1. Regional bathymetric map of the SW Iberian margin (modified from Martínez-Loriente et al. (2013)).SWIM 2006 dataset is depicted as white lines, whereas the segments of the MCS profiles shown in Figure 2 are depicted as orange lines. Sediment core MD03-2703 is labeled as yellow circle, MD03-2704 as yellow square, and JC27-20 as red circle. Seismicity from the Instituto Geográfico Nacional catalog for the period between 1965 and 2012 is depicted (I.G.N., 2012). Black stars correspond to: 1: Proposed epicenter location for the Lisbon Earthquake, 1 November 1755, estimated Mw 8.5 (Buforn et al., 2004); 2 Horseshoe Earthquake, 7 November 1915, Mw 6.2 (IGN Catalogue); 3: Horseshoe Earthquake, 28 February 1969, Mw 7.9–8.0 (Fukao, 1973); 4: HF Earthquake, 12 February 2007, Mw 6.0 (Stich et al., 2007). Red arrows show the direction of convergence between the Eurasian and African plates from the NUVEL1 model (Argus et al., 1989). HF: Horseshoe Fault; LN and LS: Lineament North and South; MPF: Marquês de Pombal Fault; NCPF and SCP: North and South Coral Patch Ridge Fault; SVF: São Vicente Canyon Fault; SFZ gray band: SWIM Fault Zone. Inset: Plate tectonic setting of the southwest Iberian margin at the boundary between the Eurasian and African Plates.

The northeastern Seine Abyssal Plain (SAP) region is also characterized by two types of faults: (1) WNW-ESE trending strike-slip faults; and (2) NE-SW trending reverse faults. The strike-slip faults are mainly located north of the Seine Hills. In the MCS profiles, they are imaged as subvertical faults developing positive flower-like structures and showing seafloor ruptures (Fig. 2c). The later family are referred to as the Seine Hills (SH), which is a succession of ridges (SH2 to SH6) that correspond to NE-SW trending thrust-folds with NW and SE vergences (Fig. 2c). These thrusts may have developed by fault-bend folding (e.g., SH2 and SH3) (Suppe, 2004) or by fault-propagate folding (e.g., SH5) (e.g., Allmendinger, 1998). At the tip of the upper flats of these thrusts, structural wedges (or triangle zones) (Medwedeff, 1989) were developed, having generated associated back-thrusts and kink folds that accommodate the shallow deformation near the seafloor (Fig. 2c). In the case of the fault-propagation folds (e.g., SH5), the MCS images show asymmetric folding with narrow and steep forelimbs in contrast to their corresponding backlimbs. The SH4 and SH5 are structured as a "classic" trishear fault-propagation fold formed by distributed shear within a triangular zone that expands outward from a fault tip (Erslev, 1991). In the case of the SH6, a trishear fault-propagation fold developed at its tip on the NW side, and shows a wedge structure at depth. Furthermore, the SH6 may involve a basement normal fault (i.e., oceanic crust) reactivated as reverse (Fig. 2c). In general, the SH faults deform all the units from the oceanic crust to the uppermost Quaternary sediments by faulting, blind faulting or folding, and originate >450 m high, ~50 km long reliefs as observed on the bathymetric map (Fig. 1). Although the Seine Hills are mainly blind thrusts, the growth-strata configuration of the youngest sediments confirms the present-day activity of these faults (Fig. 2c) (Martínez-Loriente et al., 2013).

Between the major SH thrusts, secondary blind thrusts showing kink-folds and asymmetric folds are also imaged and likely root in a common shallow detachment level that continues toward the CPR area (Fig. 2b and 2c). The SH1 is a 38 km long isolated hill located west of the SH2-SH6 succession (Fig. 1). According to its morphological expression and internal geometry, we distinguish two main segments corresponding, from west to east, to an 18 km long, W-E trending transpressive fault, and a 20 km long, NE-SW trending reverse fault (Fig. 2b). The strike-slip segment is characterized by subvertical faults defining a positive flower structure, whereas the thrust segment shows a fault with lower dip (45º), which flattens (20º) at the basement (Fig. 2b). Both SH1 segments fault and fold the sedimentary sequence from the basement up to the seafloor (Fig. 2b) (Martínez-Loriente et al., 2013).

As for the earthquake and tsunami hazard assessment, the strike-slip faults are seismogenic and have the potential to generate up to Mw 8.4 earthquakes (i.e. LS), following the relationship between the seismic moment and the moment magnitude as $M_w=2/3\cdot\log_{10}(M_0)-6.0$ (Kanamori, 1977). Regarding the thrusts located south of the SFZ, despite the low seismic activity recorded in the area, our data suggests that they are active and potential sources of Mw 7.6 earthquakes (i.e. SCPF) and associated tsunamis (Martínez-Loriente et al., 2013). Seismic and tsunami hazard in the South Iberian and North African coasts would significantly increase if offshore active structures such as those identified in the Coral Patch Ridge region were considered.

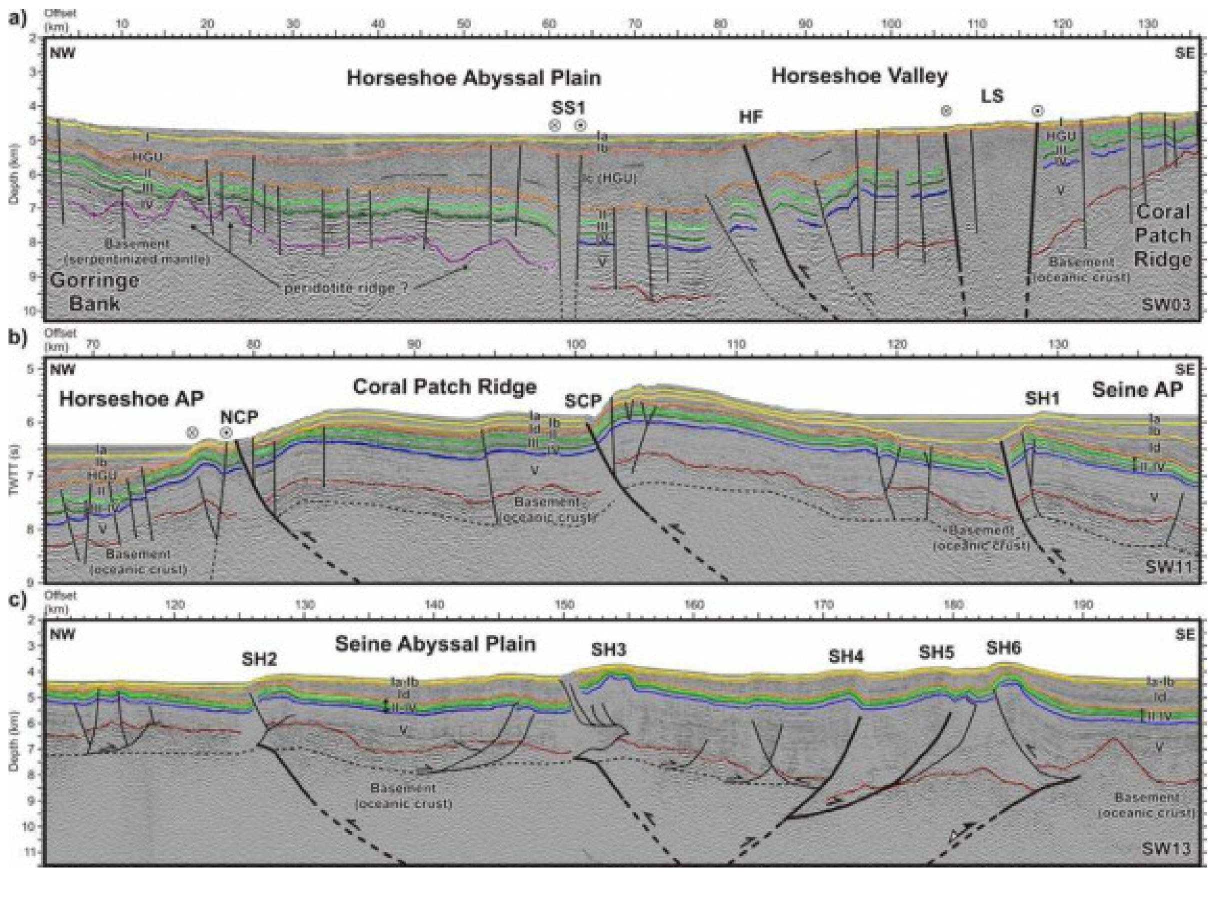

Figure 2. (a) Interpreted prestack depth migrated (PSDM) profile SW03 across the Horseshoe Abyssal Plain from the Gorringe Bank to the Coral Patch Ridge, which intersects the Horseshoe Fault (HF), the Lineament South (LS), and the Strike-slip Fault 1 (SS1). VE=4. (b) Interpreted section of the time migrated profile SW11 crossing the central part of the Coral Patch Ridge, from the Horseshoe to the Seine abyssal plains. The NCP, SCP and SH1 thrusts are imaged. TWTT: Two-way travel time. VE=2 (c) Interpreted section of the PSDM profile SW13 across a set of strike-slip faults in the northern part of the section and across the Seine Hill faults (SH2 to SH6). VE=2. Location of MCS profiles in Figure 1. Nature of the basement is inferred from Sallarès et al. (2013) and Martínez-Loriente et al. (2014). Modified from Martínez-Loriente et al., (2013).

Acknowledgments: The authors acknowledge the support of the Spanish Ministry of Science and Innovation (MICINN) through National Projects EVENT (CGL2006–12861-C02-02) and SHAKE (CGL2011–30005-C02-02); the European Transnational Access SALVADORE program of the EU (RITA-CT-2004–505322), the ESF EuroMargins SWIM project (01- LEG-EMA09F and REN2002–11234E-MAR), the EU program ‘‘Global Change and Ecosystems’’ contract n. 037110 (NEAREST), and the ESF TopoEurope TOPOMED project (CGL2008–03474-E/BTE). We also acknowledge funding from the MICINN through the ‘‘Ramon y Cajal’’ program (R. Bartolome) and from the CSIC through a JAE Pre-Doc fellowship (S. Martínez-Loriente). This work was carried out within the Grups de Recerca de la Generalitat de Catalunya B-CSI (2009 SGR 146).

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