Tectonophysics 717 (2017) 226–241

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Micro-seismicity in the Gulf of Cadiz: Is there a link between micro-seismicity, high magnitude earthquakes and active faults?

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ARTICLE INFO

Article history:
Received 10 December 2016
Received in revised form 25 July 2017
Accepted 28 July 2017
Available online 29 July 2017

Keywords:
Nubia-Eurasia plate boundary
Micro-seismicity
Neotectonics
Aseismic slip
High-magnitude earthquakes
Serpentinization

ABSTRACT

The Gulf of Cadiz seismicity is characterized by persistent low to intermediate magnitude earthquakes, occasionally punctuated by high magnitude events such as the M ~ 8.7 1755 Great Lisbon earthquake and the M = 7.9 event of February 28th, 1969. Micro-seismicity was recorded during 11 months by a temporary network of 25 ocean bottom seismometers (OBSs) in an area of high seismic activity, encompassing the potential source areas of the mentioned large magnitude earthquakes. We combined micro-seismicity analysis with processing and interpretation of deep crustal seismic reflection profiles and available refraction data to investigate the possible tectonic control of the seismicity in the Gulf of Cadiz area. Three controlling mechanisms are explored: i) active tectonic structures, ii) transitions between different lithospheric domains and inherited Mesozoic structures, and iii) fault weakening mechanisms. Our results show that micro-seismicity is mostly located in the upper mantle and is associated with tectonic inversion of extensional rift structures and to the transition between different lithospheric/rheological domains. Even though the crustal structure is well imaged in the seismic profiles and in the bathymetry, crustal faults show low to negligible seismic activity. A possible explanation for this is that the crustal thrusts are thin-skinned structures rooting in relatively shallow sub-horizontal décollements associated with (aseismic) serpentinization levels at the top of the lithospheric mantle. Therefore, co-seismic slip along crustal thrusts may only occur during large magnitude events, while for most of the inter-seismic cycle these thrusts remain locked, or slip aseismically. We further speculate that high magnitude earthquake's ruptures may only nucleate in the lithospheric mantle and then propagate into the crust across the serpentinized layers.

1. Introduction

The Gulf of Cadiz is located at the eastern termination of the Azores-Gibraltar plate boundary between the Nubia and Eurasia plates, and to the west of the Gibraltar arc (Fig. 1A). Here, the plate boundary is known to be diffuse (Sartori et al., 1994; Zitellini et al., 2009) and deformation is partitioned on thrusts and strike-slip faults (e.g. Terrinha et al., 2009; Fig. 1B). The seismicity is characterized by scattered events of low to intermediate magnitude (Fig. 1C and Table 1), and occasional high magnitude earthquakes. An example is the November 1st, 1755 Great Lisbon earthquake that had an estimated magnitude of 8.7 (Johnston, 1996) and produced an ocean-wide tsunami with waves that reached up to 6 m in height in Lisbon and 10–15 m at the Cape São Vicente, in the southern coast of Portugal (Baptista and Miranda, 2009). In the instrumental record, the most significant event was the February 28th, 1969 with a Ms ≈ 7.9 (Fukao, 1973, Fig. 1C and Table 1), which generated a small tsunami recorded in several tide-gauges reaching a maximum amplitude of 0.6 m in Casablanca (Baptista and Miranda, 2009 and references therein).

In the last decades, research projects concerning the investigation of the seismogenic and tsunamigenic sources in the area favored the improvement of the coverage of the high-resolution bathymetry and

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http://dx.doi.org/10.1016/j.tecto.2017.07.026
0040-1951/

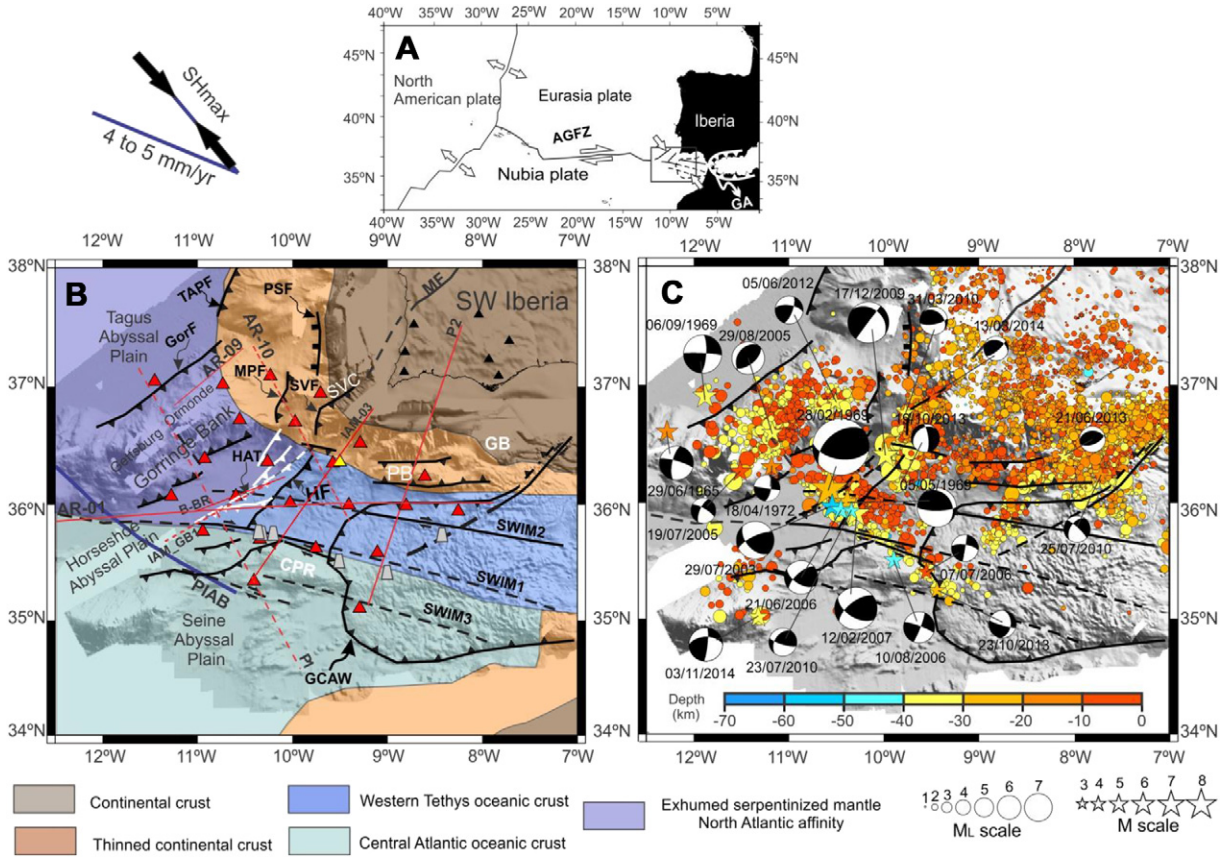

Fig. 1. Gulf of Cadiz setting. A - location of the studied area in the general geodynamic context (AGFZ - Azores Gibraltar Fracture Zone; GA - Gibraltar Arc). In the upper left, average maximum horizontal stress (black arrows, from Ribeiro et al., 1996; Borges et al., 2001; Heidbach et al., 2008 and Palano et al., 2013), and the present day convergence between Eurasia and Nubia (blue line, Fernandes et al., 2003; Stich et al., 2006; Koulali et al., 2011 and Nocquet, 2012). B - the Gulf of Cadiz tectonic setting. The main crustal domains (in colors) are modified from González et al. (1996); Rovere et al. (2004); Sallarès et al. (2011) and Martínez-Loriente et al. (2014). Inferred Late Jurassic–Early Cretaceous plate boundary between Iberia and Africa (PIAB in blue) is defined based on Rovere et al. (2004). Thin red lines show the location of refraction-wide-angle seismic profiles, B-BR from Purdy (1975); P1 from Sallarès et al. (2011) and P2 from Martínez-Loriente et al. (2014), as well as multichannel seismic reflection profiles IAM-03 from González et al. (1996), AR-01 and AR-09 from Rovere et al. (2004), AR-10 from Zitellini et al. (2001) and IAM-GB1 from our work (dashed lines are the profiles shown in this work). The tectonic map is adapted from Duarte et al. (2013) while the mud volcanoes (gray trapezes) were extracted from Hensen et al. (2015). Solid black lines are active faults, white solid lines are blind faults and black dashed lines are probable faults. The NEAREST seismic network is shown with red triangles (each triangle is the location of an OBS) and the yellow triangle is the location of the GEOSTAR (details on the sensors are provided in Section 3.1). The locations of land stations are also depicted with black triangles. The bathymetry is from Zitellini et al. (2009). CPR - Coral Patch Ridge; GB - Guadalquivir Bank; GCAW - Gulf of Cadiz Accretionary Wedge; GorF - Gorringe Fault; HAT - Horseshoe Abyssal Plain Thrust (after Martínez-Loriente et al., 2014); HF - Horseshoe Fault; MF - Messejana Fault; MPF - Marquês de Pombal Fault; PSF - Pereira de Sousa Fault; PB - Portimão Bank; SVC -São Vicente Canyon; SVF - São Vicente Fault; TAPF - Tagus Abyssal Plain Fault. C - instrumental seismicity from 2000 to 2015 is shown with circles (recorded by the Instituto Português do Mar e da Atmosfera seismic network). The higher magnitude instrumental earthquakes that occurred within the NEAREST network area are shown with starts (from Buforn et al., 1988; Stich et al., 2005, 2010 and Custódio et al., 2016). The main tectonic structures are also shown.

seismic reflection and refraction data (e.g. see references in Sartori et al., 1994, Banda et al., 1995 and Zitellini et al., 2009). This effort resulted in a remarkable increase of our understanding of the Gulf of Cadiz tectonic structures and their activity. Notwithstanding, there is still a poor correlation between the seismicity and the identified active faults as illustrated in Fig. 1B–C. An example is the uncertainty about the source of the February 28th, 1969 earthquake. Available focal mechanism solutions (FMs) suggest reverse fault kinematics. Some authors favor an E-W striking fault plane (e.g. Buforn et al., 1988), while others suggest a N55^{0}E striking fault plane (e.g. Fukao, 1973), parallel to the strike of the Gorringe Bank thrust (Fig. 1B–C). Moreover, following the empirical laws for fault models in the Gulf of Cadiz lithosphere proposed by Matias et al. (2013), it would be expected that a $M_W = 7.8$ event would produce a rupture area of ≈3410 km^2, with a length of 64 km and a width of 53 km. However, there is no agreement on the specific tectonic structure that may have caused the 1969 event (see Fig. 1B–C).

In the more recent Mw = 6.0 event of February 12th, 2007, moment tensor inversion revealed a thrust kinematics with a small strike-slip component (USGS source). The preferred fault plane orientations are discussed in Stich et al. (2007) and Custódio et al. (2012). Stich et al. (2007) suggested an ENE-WSW fault plane solution, sub-parallel to the Horseshoe Fault (Fig. 1B–C). However, the selected plane is located 20 km to east of the Horseshoe fault and dipping in the opposite direction. On the other hand, Custódio et al. (2012) proposed a WNW-ESE solution, sub-parallel to the SWIM strike-slip faults, dipping 46° to the SW (see Fig. 1B-C. Even though this event had its source near known major active faults, none of these seem to be compatible with the proposed fault plane solutions.

One of the main limitations in finding a cause-effect relationship between seismicity and associated tectonic faults results from: i) the difficulties in mapping seismogenic faults offshore, where observations are limited and based on indirect methods and ii) the sparse geographic and asymmetric distribution of the permanent seismic land stations used to locate the associated earthquakes. This last factor leads to high azimuthal gaps, which result in low accuracy in hypocenter determination.

A key goal of the NEAREST project (Integrated observation from NEAR shore sourcES of Tsunamis: towards an early warning system) was to improve the location of the seismogenic and tsunamigenic sources in the Gulf of Cadiz. The present study is based on the processing