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Anatomy and tectonic significance of WNW-ESE and NE-SW lineaments at a transpressive plate boundary (Nubia-Iberia)

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Abstract: Recent mapping of the Gulf of Cadiz seafloor permitted to identify major tectonic lineaments: the SWIM lineaments (Zitellini *et al.*, 2009) and Cadiz lineament, striking WNW-ESE and NE-SW, respectively. Multibeam swath bathymetry and interpretation of multi-channel seismic data indicate that these features can be interpreted to correspond to the seafloor morphological expression of active dextral strike-slip faults. Based on the interpreted data and recently published GPS plate kinematic velocity vectors of Nubia with respect to Iberia and the Alboran block (e.g. Fernandes *et al.*; 2003 Stich *et al.*, 2006) we propose that the SWIM Faults are related to the general NW-SE convergence of Nubia with respect to Iberia, and the Cadiz fault is related to the westward movement of the Gibraltar orogenic arc.

Keywords: Gulf of Cadiz, seafloor mapping, SWIM lineaments, Cadiz lineament, active tectonics, Alboran block, Gibraltar orogenic arc.

The Gulf of Cadiz is located in a complex tectonic area, encompassing the controversial SW Eurasia-NW Africa plate boundary (see figure 1). Some authors believe that this is a diffuse plate boundary (Sartori *et al.*, 1994; Medialdea *et al.*, 2004), other describe an active subduction with roll-back of a subducted slab (Gutscher *et al.*, 2002), while others postulate a prolongation of a transpressive deformation belt from the Rif-Tell (Morel and Meghraouie, 1996; Zitellini *et al.*, 2009). This region experiences a general NW-SE to WNW-ESE convergence between Nubia and Eurasia at a rate of 5-6 mm a^{-1} (Calais *et al.*, 2003). Stich *et al.* (2006) proposed that the SW Iberian Margin is also accommodating a 3.5 mm a^{-1} of westward motion of the Gibraltar arc relative to intraplate Iberia. Seismicity is distributed over a more than 400 km wide zone between the Gibraltar arc and the Horseshoe fault (Fig. 1) and earthquakes are characterized by magnitudes usually smaller than 5.5. In the western part of the Gulf of Cadiz, in the area that encompasses the Horseshoe fault until the eastern part of the Gloria fault, seismicity is distributed over a narrower area and instrumental seismicity is higher, with recent events of M=6

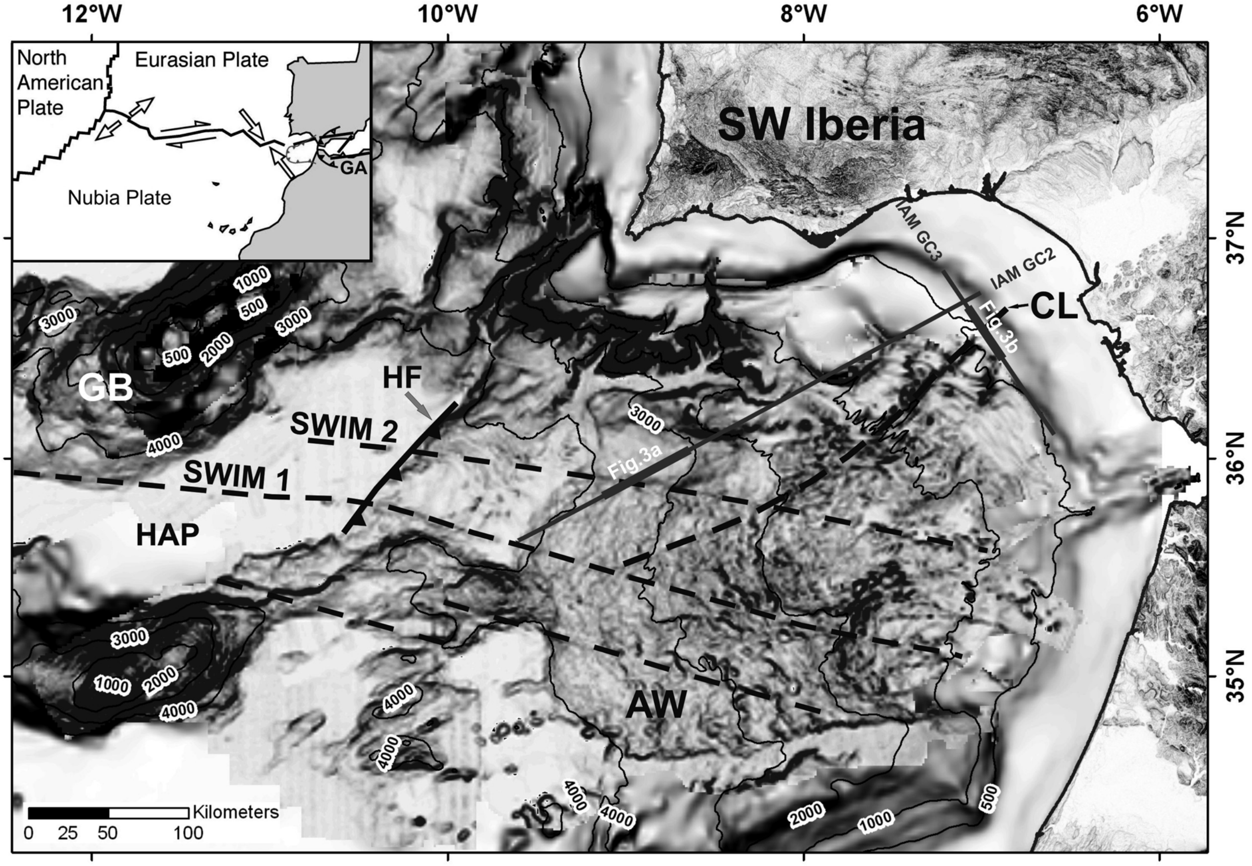

Figure 1. Bathymetric map of the Gulf of Cadiz (low resolution multibeam compilation of the SWIM dataset and GEBCO bathymetry). Topography of onshore area is also shown as shaded relief. Dashed lines represent the main tectonic lineaments studied in this work. The inset shows the tectonic context of the area (adapted from Gutscher *et al.*, 2002). The location of two seismic profiles, IAM GC2 and IAM GC3, are also shown. AW: Accretionary Wedge; CL: Cadiz Lineament; GA: Gibraltar Arc; GB: Gorringe Bank; HF: Horseshoe Fault; HAP: Horseshoe Abyssal Plain.

and the 1969 event of M=7.9 (Fukao, 1973; Stich *et al.*, 2006). Zitellini *et al.* (2004) described a number of active structures scattered along the Gulf of Cadiz and SW Portugal showing that tectonic strain is presently accommodated between 35.5º N and 38º N (approximately 250 km), which suggests a diffuse strain distribution of the plate convergence.

Over the last two decades a large amount of geological and geophysical data have been collected aiming at identifying the main tectonic features present in the Gulf of Cadiz and to clarify how deformation has been accommodated during Alpine to present times (Zitellini *et al.*, 2009). In this work we describe the morphology and structure of WNW-ESE and one NE-SW trending lineaments recently mapped in the Gulf of Cadiz region and discuss their tectonic significance.

This work is extracted from a much larger study based on the analysis and interpretation of 180,000 km^2 of multibeam swath bathymetry and reflectivity (backscatter) data of the Gulf of Cadiz area and more than 20,700 km multi-channel seismic profiles. This dataset was collected throughout several surveys carried out by international teams of several countries and compiled for the ESF Eurocores EuroMargins SWIM project (Earthquake and Tsunami hazards of active faults at the South-West Iberian Margin: deep structure, high-resolution imaging and paleo-seismic signature, REN2002-11234-EMAR, 01-LEC-EMA09 F) (http://www.swim.ul.pt/index_topo.htm) and NEAREST project (Integrated observations from NEAR shore sourcES of Tsunamis: towards an early warning system, GOCE Contract n. 037119) (http://nearest.bo.ismar.cnr.it/).

The SWIM lineaments

Morphology

The SWIM lineaments are linear features that strike approximately WNW-ESE and extend from the easternmost part of the Gulf of Cadiz accretionary wedge until the Horseshoe abyssal plain, south of the Gorringe submarine mountain (Fig. 1). They cut across various morphological domains, contain various active mud volcanoes along their path and offset the NE-SW Horseshoe fault scarp (Fig.2), an active reverse fault (Gràcia *et al.*, 2003; Zitellini *et al.*, 2004). These linear features correspond to the alignment of elongated crests and troughs on the sea floor with wavelengths of the order of tens of kilometers. According to Zitellini *et al.* (2009), the longest of the SWIM lineaments, SWIM 1, exceeds 600 km, and it can be followed from the Gorringe bank southern flank to the Morocco shelf and corresponds to a strike-slip fault. In some segments of this lineament it is possible to identify E-W-striking undulations with maximum lengths of about 8 km (Fig. 2). These features show an en echelon pattern that corresponds to oriented folds of the recent sedimentary cover, allowing us to establish a dextral strike-slip movement. The width of each individual SWIM lineament is only of a few hundreds of meters.

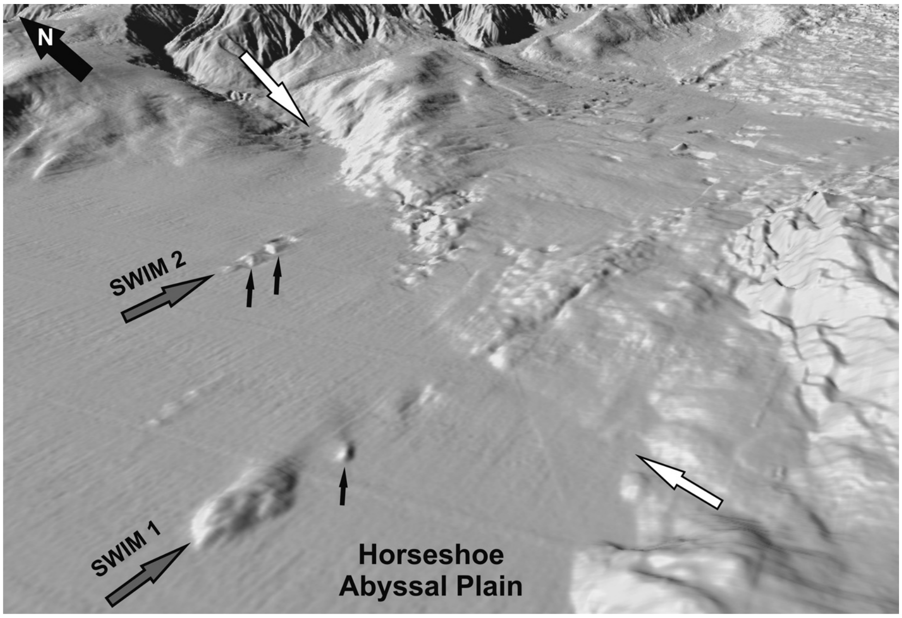

Figure 2. Shaded relief 3D image of the Horseshoe Abyssal Plain and continental rise to the east; view from SW, showing the SWIM tectonic lineaments 1 and 2, indicated by grey arrows; MATESPRO bathymetric data Terrinha *et al.* (2009) and Rosas *et al.* (2009). The small black arrows show seafloor deformation corresponding to NE-SW-oriented en echelon folds. The white arrows indicate the slope break that corresponds to the morphological expression of the Horseshoe Fault.

Structure

The interpretation of a segment of a profile across SWIM 2 lineament (Fig. 3a) shows that it corresponds to a fault that cuts through Mesozoic sediments (Unit A) (Tortella *et al.*, 1997). This fault formed during the Mesozoic rifting as a normal fault. This assumption is corroborated by the presence of a syn-rift growth wedge (Unit B). The SWIM 2 fault was later reactivated with a southwards reverse movement because the wedge (Unit B) is over-thrusted towards the SW. This reactivation probably occurred during Paleogene to Miocene times (Rosas *et al.*, *in press*; Terrinha *et al.*, 2009). This movement seems to be coeval with the installation of the Accretionary wedge (Unit D) since it clearly tapers towards the eastern part of the profile. The SWIM fault also deforms and folds the Plio-Quaternary unit (Unit E) and cuts through the seafloor.

The Cadiz lineament

Morphology

The morphology of the Cadiz lineament is more complex than that of the SWIM 2 lineament. It is relatively diffuse and occupies a broader area, with widths varying from several hundreds of meters to a few kilometers. It strikes approximately NE-SW and extends for about 200 km from the northeastern Gulf of Cadiz continental shelf to the westernmost part of the accretionary wedge (Fig.1). The lineament is slightly curved towards the west at the south-western part where it meets the SWIM 1 fault (Fig. 1). It is materialized on the seafloor by the alignment of several different features such as crests, scarps, channels and diapiric ridges (Somoza *et al.*, 2003). The Cadiz lineament is more prominent in its northeastern segment, where it is adjacent to the Guadalquivir bank (a basement high with active seismicity) and it loses morphological expression progressively towards

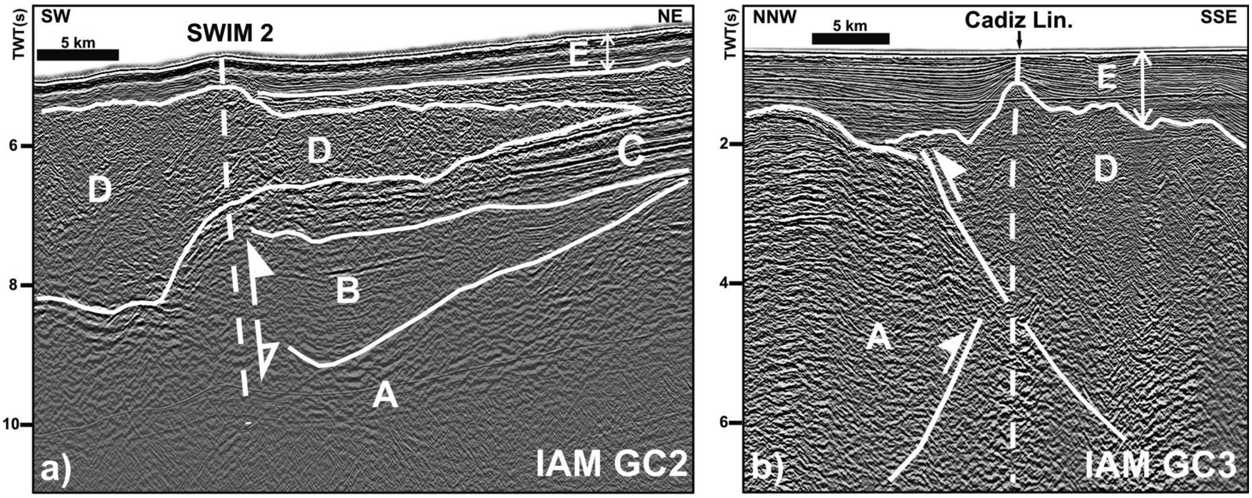

Figure 3. (a) Multi-channel seismic reflection profiles IAM GC2, and (b) IAM GC3. The white dashed lines mark the fault zones corresponding to the lineaments (SWIM 2 on the left and the Cadiz Lineament on the right). The profile a) shows two previous vertical movements of the SWIM fault (white arrows). On profile b) the following features are pointed out, reverse fault of the Guadalquivir basement to the SSE; and a thin-skinned fault of accommodating the over-thrusting movement of the Accretionary wedge over the Guadalquivir basement. A: Basement; B: Sin-rift wedge (Mesozoic age); C: Post-rift unit; D: Accretionary Wedge unit (Miocene age); E: Cover unit (Plio-Quaternary age).

the SW, where it intercepts the SWIM 2 lineament and is almost untraceable in the surroundings of the SWIM 1 lineament.

Structure

A segment of IAM GC3 seismic profile (Fig. 3b) across the Cadiz lineament shows that it seats on top of a fault zone. This fault is parallel to the deep blind thrust of the Guadalquivir bank towards the SE, as interpreted in figure 3 (Unit A). This movement is corroborated by the gentle folding of the reflectors of Unit A. It is also possible to observe a thin-skinned fault accommodating the over-thrusting of the accretionary wedge described by Gutscher *et al.* (2002) towards NE over the Guadalquivir basement (Unit D). This unit corresponds to imbrications of NNW-verging thrusts, as shown by the planar fabric of the acoustic facies. Near the surface the more continuous cover sediments are clearly folded; however, they do not show evidences of major vertical displacement (Unit E).

Discussion

Based on bathymetric and structural observations we interpret the SWIM lineaments as the morphological expression of dextral WNW-ESE trending strike-slip faults rooted in the Mesozoic rift basin. This interpretation is derived from both observed coherent en echelon folding pattern on the seafloor associated with the faults and the minor vertical displacement of the post-Miocene cover. This assumption is in agreement with recent work by Zitellini *et al.* (2009) and Terrinha *et al.* (2009) that describes in detail the kinematic indicators and the age of these faults. Rosas *et al.* (2009), using analogue models and the en echelon folds has markers for a quantitative strain analysis, suggested that the SWIM lineaments initiated their strike-slip movement 1.8 Ma ago, at least. This interpretation is also in agreement with the general NW-SE to WNW-ESE convergence between Africa and Eurasia at a rate of 5-6 mm a^{-1} and the fact that the SWIM faults offset the Late Miocene movement of the Horseshoe Fault. In this way, the SWIM lineaments can be accommodating a strike-slip component of this convergence, while the main shortening is being accommodated in the northwestwards directed thrusts of the SW Iberian Margin, for example the Horseshoe fault.

The Cadiz lineament has a strong morphological expression, mainly in its northeastern part where salt diapirs have extruded (Somoza *et al.*, 2003). However, no kinematic indicators could clearly be detected in our analysis. It corresponds to an almost vertical fault that deforms the sedimentary cover with no major vertical displacement. Based on recent data published by Stich *et al.* (2006), that reported a 3.5 mm a^{-1} of westward motion of the Gibraltar arc relative to intra-plate Iberia, we propose that the Cadiz lineament is a major dextral strike-slip fault zone that is accommodating this relative motion in the Gulf of Cadiz area. The lack of good strike-slip kinematic indicators in this part of the study area is probably due to the higher rate of recent sedimentation associated with the proximal parts of the Mediterranean Outflow Water and discharge of the Guadalquivir river as well as the extrusion of fluidized material along diapiric ridges (Somoza *et al.* 2003), as well as to the pure shortening at the front of the Guadalquivir bank thrust, as argued in this work.

Conclusions

In this work we studied various major tectonic lineaments localized in the Gulf of Cadiz area. We showed that they correspond to major transpressive dextral strike-slip faults with two different orientations: the WNW-ESE SWIM faults and the NE-SW Cadiz fault. Both faults are active and are probably related with two different driving mechanisms. The SWIM faults are related to the general WNW-ESE convergence between Nubia and Eurasia and the Cadiz fault is related to the westward expulsion of the Gibraltar Arc relative to Iberia, possibly associated with the convergence between the two lithospheric plates.

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