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The quest for the Africa–Eurasia plate boundary west of the Strait of Gibraltar

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ABSTRACT

The missing link in the plate boundary between Eurasia and Africa in the central Atlantic is presented and discussed. A set of almost linear and sub parallel dextral strike–slip faults, the SWIM[1] Faults, that form a narrow band of deformation over a length of 600 km coincident with a small circle centred on the pole of rotation of Africa with respect to Eurasia, was mapped using a new swath bathymetry compilation available in the area offshore SW Portugal. These faults connect the Gloria Fault to the Rif–Tell Fault Zone, two segments of the plate boundary between Africa and Eurasia. The SWIM faults cut across the Gulf of Cadiz, in the Atlantic Ocean, where the 1755 Great Lisbon earthquake, M~8.5–8.7, and tsunami were generated, providing a new insight on its source location.

1. Introduction

The present-day plate boundary between Northwest Africa and Southwest Eurasia (Fig. 1) has been a matter of debate since the early plate tectonic reconstructions of McKenzie (1970) and Dewey et al. (1973). The solution to this puzzle has important implications in terms of both plate tectonic theory and in the understanding of earthquake and tsunami hazards. Firstly, it connects the west Alpine orogen termination, the Betic–Rif orogenic arc, to the oceanic plate boundary, the Gloria Fault. Secondly, this was the source area of the 1755 Great Lisbon earthquake, with estimated M=8.5 to 8.7 (Martinez-Solares and López Arroyo, 2004) and maximum MMI=XI, which caused the largest tsunami ever experienced in Western Europe. The population of Europe was shocked to learn that the capital of one of the most powerful maritime empires of the eighteenth century could be destroyed within a few minutes. The ground shaking was felt as far as in Finland and it generated tsunami waves that reached the southern Brazil, the Caribbean and Scotland, and seches in the Scottish and central Europe lakes. The most fantastic hypotheses were suggested by contemporaneous writers to explain the phenomena. For example, the German Philosopher Immanuel Kant wrote, in 1756, about huge explosions of inflammable gases inside a coalescing series of subterranean caves underneath the Alpine chain and their continuation offshore, while religious leaders preferred simply the punishment of God or action of the devil. Since then, determining of the source location of this event has challenged a number of authors leading to the conclusion that the great earthquake occurred at sea, somewhere offshore SW Iberia, but without reaching a definitive agreement on its precise location (e.g. Baptista et al., 1998; Buforn et al., 1998).

The empirical relationships proposed by Wells and Coppersmith (1994) for reverse faults indicate that for such an huge enormous release of elastic energy, the rupture area has to be approximately 27,000 km^2 and that the fault length should be approximately 370 km.

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[1] SWIM is the acronym of the ESF EuroMargins project “Earthquake and Tsunami hazards of active faults at the **S**outh **W**est **I**berian **M**argin: deep structure, high-resolution imaging and paleoseismic signature”.

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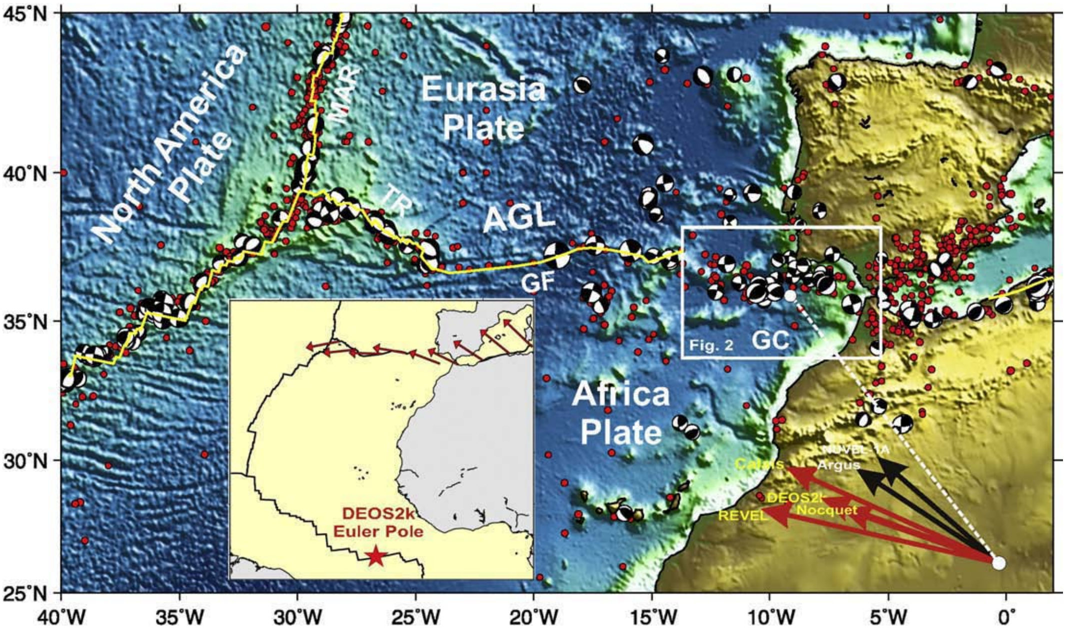

Fig. 1. Shaded bathymetry map of Iberia, northwest Africa and Central Atlantic (Smith and Sandwell, 1997) with the main elements of plate boundaries superimposed: AGL: Azores–Gibraltar Line; GC: Gulf of Cadiz; GF: Gloria Fault; MAR: Mid-Atlantic Ridge; TR: Terceira Ridge. Solid yellow line: plate boundaries from Bird (2003). Box for Fig. 2: location of the study area. Small red circles: epicenters, from ISC, $M>4$, 1964 to present, http://www.ISC.ac.uk. Focal mechanisms from CMT catalogue for whole area, http://www.seismology.harvard.edu; between 20° W–5° W data completed from various sources. Arrows at right bottom corner show the relative movement of Africa with respect to Eurasia at the centre of the Gulf of Cadiz, according to different authors. Black arrows deduced from geological indicators (Argus et al., 1989; DeMets et al., 1994) and red arrows from GPS (Sella et al., 2002; Fernandes et al., 2003; Calais et al., 2003; Nocquet and Calais, 2004). Inset: location of the Euler pole and the relative movement of Nubia with respect to Eurasia after Fernandes et al. (2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Recent work by Stich et al. (2007), scaling the source characteristics of the 2007 Horseshoe earthquake (Mw 6.0) to the size of the 1755 Lisbon event, also suggested fault lengths of 230–315 km. Earthquakes of this magnitude only occur associated with plate boundaries, either at subduction zones, intra-continental orogenic sutures or conservative plate boundaries, such as the San Andreas Fault. In the case of the Lisbon Earthquake the closest plate boundary is located at the western part of the Eurasian–African Plates (Fig. 1). This boundary extends along a west to east direction, from the Azores islands through the Gulf of Cadiz into the western Mediterranean across the Gibraltar orogenic arc. The pole of rotation of Africa with respect to Eurasia is located in the Atlantic near the Equator and at a longitude ~20°W[2], due south of the mid-point between the Azores and the Gulf of Cadiz (inset in Fig. 1). For this reason, the central part of the Azores–Gibraltar plate boundary is a transform fault, the Gloria Fault (Fig. 1). West of the Gloria Fault, the Terceira Ridge is an oceanic trans-tensional plate boundary where oceanic-crust accretion occurs at present. East of the Gloria fault, and already in the Gulf of Cadiz, the plate boundary is not well established because deformation is distributed over a broad elongated area about 200 km wide. Further East, to the east of the Straits of Gibraltar, the Nubia–Iberia plate boundary is defined by a right-lateral transpressive shear zone, the Rif–Tell fault zone (Morel and Meghraoui, 1996).

Efforts to find a discrete plate boundary in the Gulf of Cadiz, connecting the Gloria Fault and the Rif–Tell fault zone have failed despite the use of different approaches, such as plate kinematic reconstructions (e.g. McKenzie, 1970; Srivastava et al., 1990), gravity data (Purdy, 1975), and, more recently, multi-channel seismic reflection (Sartori et al., 1994) coupled with tomography (Gutscher et al., 2002) and plate kinematic data derived from GPS measurements (Fernandes et al., 2007).

The goal of this paper is to describe and discuss a newly found set of almost linear and sub parallel, WNW–ESE trending vertical faults, the SWIM Faults, that form a narrow band of deformation over a length of 600 km connecting the Gloria Fault to the Rif–Tell plate boundary. These provide new constraints on the plate boundary configuration in this region (Figs. 2, 3 and Plate I).

2. The Gulf of Cadiz: geological setting

The last 200 Ma of the geological history of the Gulf of Cadiz is intimately related to plate tectonic interaction between Southern Eurasia and North Africa, when these two plates started to move apart from North America. Palinspastic reconstructions of the Atlantic have shown that (e.g. Srivastava et al., 1990) the continental margins of South Iberia and Northwest Africa formed during the Jurassic continental break-up between North America and Africa while the western continental margin of Iberia resulted from separation of Iberia with respect to North America in Cretaceous times. As a consequence, the Tagus, Horseshoe and Seine Abyssal Plains are underlain by oceanic crust of Late Jurassic–Early Cretaceous age. From approximately Chron M0 to Chron 34 (118–84 Ma) (Gradstein et al., 2004) Iberia moved independently from Eurasia and Africa, after which Iberia became welded to Africa. At Chron 13 (35 Ma) the plate boundary between Iberia and Africa again became active. However, the present day plate tectonic arrangement was reached only at Chron 6 (20 Ma). In the Gibraltar Arc domain, the westwards directed thrusting of the Betic–Rif orogenic arc (Dewey et al., 1989; Maldonado et al., 1999) was coeval with subsidence, extension and crustal thinning in the Western Alboran Sea during Oligocene through Miocene times. In the Gulf of Cadiz this thrusting produced a complex of imbricated thrusts detaching from a decollement surface located at the top of the Cretaceous sedimentary units (Gutscher et al., 2002). This resembles a subduction accretionary complex (Gutscher et al., 2002), clearly defined by the seafloor morphology (Figs. 3 and 7). The

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[2] Current GPS measurements suggest the African plate has split into two blocks, which are identified as the larger Nubia plate and the smaller Somalia plate. The GPS measurements mentioned in the text refer to the Nubia sub-plate.

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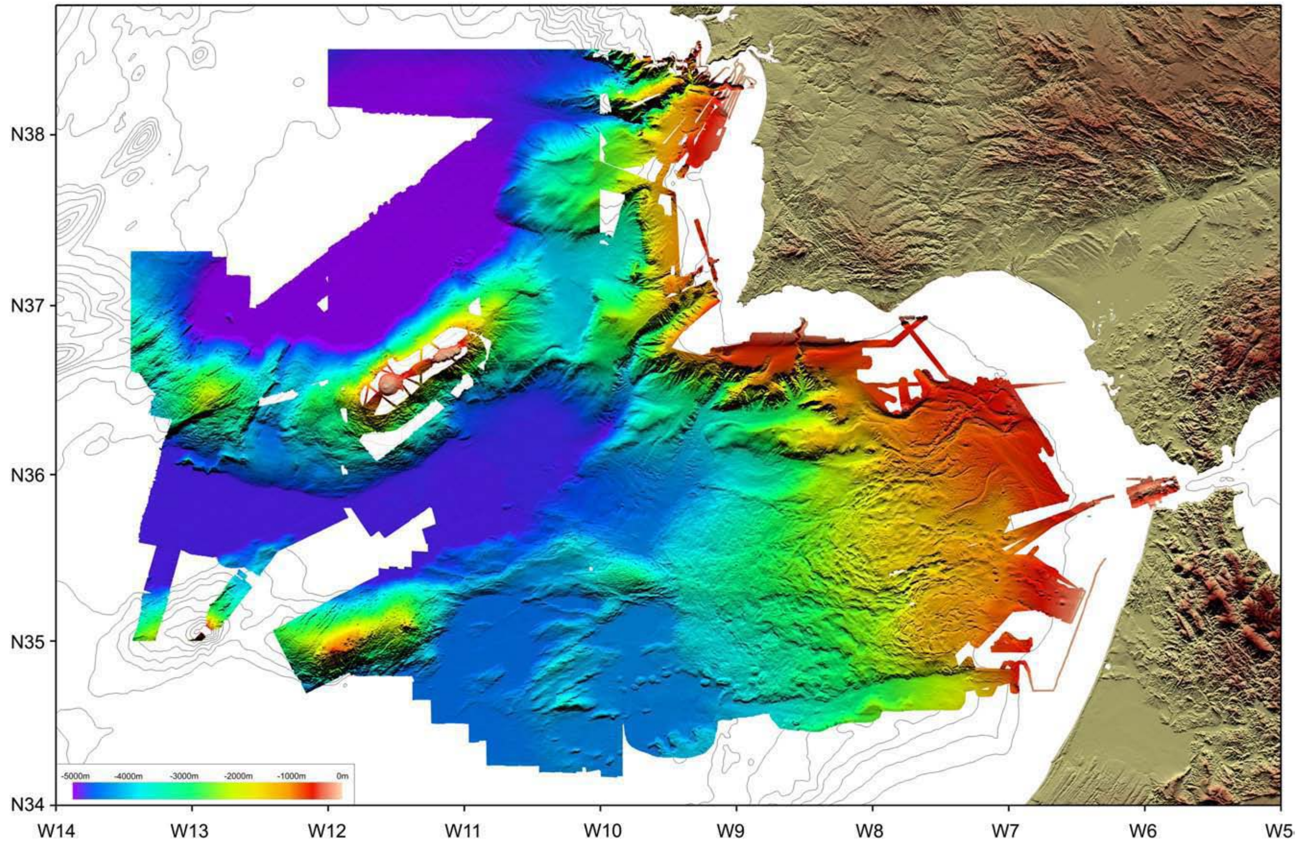

Fig. 2. The SWIM multibeam compilation. Swath bathymetry map compiled on behalf the SWIM collaborative research agreement; see Plate 1 for complete list of contributors. Color scale in meters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

accretionary wedge is covered by a sedimentary pile of variable thickness, ranging from 0.2 km to 2 km of Late Miocene to Plio–Quaternary age (Fig. 7). This cover is pierced by mud volcanoes, salt diapirs and fluid escape features showing evidences of both strike–slip and compressional deformation (Pinheiro et al., 2003; Somoza et al., 2003; Rosas et al., in press; Gutscher et al., in press). Groundtruthing of the active mud volcanoes has shown the presence of hydrocarbons of thermogenic origin (Stadnitskaia et al., 2006) and fluids derived from clay mineral dehydration, indicating active processes of fluid migration from depths up to 5 km below the seafloor (Hensen et al., 2007).

To the west of the Betic–Rif orogenic arc, from the Gulf of Cadiz to longitude 15°W (see Fig. 1), major compressive structures formed between the Late Cretaceous and present (Sartori et al., 1994). The submarine mountains that border these abyssal plains, such as Gorringe Bank, Coral Patch Seamounts and Ridge, and the series of elongated hills in the northern Seine Abyssal Plain, formed by the NW–SE trending compression during the latest stages of the Iberia–Nubia convergence, from Late Cretaceous through Miocene–Late Pliocene times (Plate II in Supplementary Material). At the present day, an important part of the instrumental seismicity occurs beneath the Horseshoe Abyssal Plain whilst the Tagus and the Seine Abyssal Plains are almost aseismic (Fig. 1). In fact, multi-channel seismic reflection data show that the major thrusts are sealed by the Late Miocene–Early Pliocene and Middle Miocene sedimentary sequences in the Seine and Tagus Abyssal Plains, respectively (see Plate II in Supplementary Material). Further east, along the SW Iberian Margin, there are numerous active thrust faults, all associated with instrumental seismicity, including the Horseshoe Fault, the Marquês de Pombal Fault and the Portimão–Guadalquivir Bank Fault (Fig. 3) (Zitellini et al., 2001; Gracia et al., 2003a,b; Zitellini et al., 2004).

3. The new findings

A high-resolution multibeam bathymetric compilation of the Gulf of Cadiz was produced under the ESF EuroMargins SWIM project “Earthquake and Tsunami hazards of active faults at the South West Iberian Margin: deep structure, high-resolution imaging and paleoseismic signature” (Fig. 2, Plate I and zipped ascii file[3]in Supplementary Material). It results from the compilation of 19 surveys totalling over 200 days of ship time, all performed between 2000 and 2006 by teams belonging to 14 research institutions from 7 European countries.

The new map provides detailed morpho-tectonic information at the scale of the whole study area and, particularly when viewed in conjunction with existing seismic reflection profiles, provides new answers to old questions: which structures take up present day tectonic deformation? Where is the Africa–Eurasia plate boundary, West of Gibraltar, located?

The SWIM bathymetry revealed the existence of a series of subparallel WNW–ESE trending lineaments, which we refer to as the SWIM lineaments (Figs. 3, 4). They extend from the Hirondelle Seamount to the Moroccan continental shelf, crossing over the Horseshoe Abyssal Plain and Gulf of Cadiz accretionary wedge. These lineaments are made up of a series of narrow ridges and valleys corresponding to fold crests and fault traces in the Holocene sediments (Figs. 2, 4) and they are punctuated by several active mud volcanoes along with these. Inspection of MCS profiles showed that the SWIM lineaments are faults (the SWIM faults) that affect the seafloor. They are deeply rooted into steep faults that cut through the

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[3] Zipped xyz ascii file containing the SWIM digital map at 250 m grid-cell resolution. See the legend in (Reference) Plate I to quote the data set.

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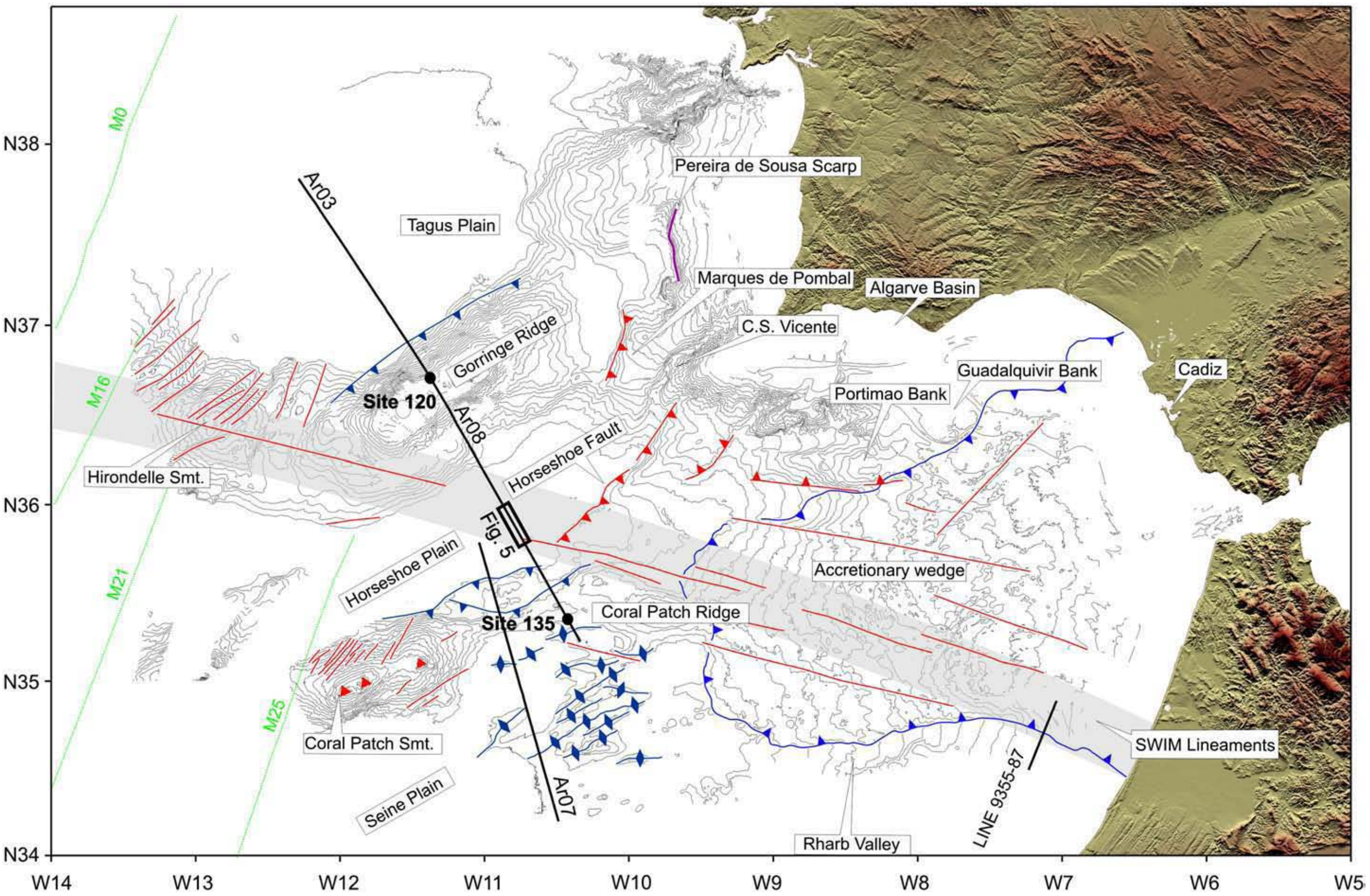

Fig. 3. Tectonic map derived from the swath bathymetry map presented in Fig. 2 with feature names and structural interpretation. Black thick lines: location of multi-channel seismic lines shown in Supplementary Material; gray stripe: 40 km wide, centered at the small circle relative to Euler pole of rotation of Africa with respect to Eurasia inferred by Fernandes et al. (2003); red line with triangle: active reverse fault; purple line with triangle: external limit of the accretionary wedge; blue line with triangle: inactive reverse fault; blue lines with rhombus: axis of inactive anticline; short, close-spaced red line: lineament related to accretion of oceanic crust; violet line: Cretaceous normal fault; long, WNW–ESE oriented, red lines: SWIM Lineaments; red triangle: volcanic edifice; green dotted line: oceanic magnetic lineation with chrons alongside. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Upper-Miocene gravitational unit of the Horseshoe Abyssal Plain and underlying Mesozoic sediments (Plate II in Supplementary Material). The angular relationship between en-echelon fold axes of surface sediments and the SWIM faults indicate a dextral strike–slip movement (Rosas et al., in press) that is compatible with the steepness and flower-structure style of these faults when observed on seismic profiles (Plate II in Supplementary Material and Fig. 5). Cross-cutting criteria show that the SWIM faults offset the Horseshoe Fault, which is one of the three most seismically active faults in the area (Fig. 3). The northern limit of the SWIM Faults zone is located along the seismogenic Portimão Bank Fault, a southward directed Paleogene–Miocene thrust, presently taking up dextral strike–slip and thrust deformation. Analogue modelling and strain analysis of the geometrical pattern of seafloor en echelon folding suggests that the SWIM strike–slip faults may be only 2 Ma old (Rosas et al., in press). This is in agreement with the fact that the SWIM faults post-date the NE–SW thrusts, such as the Horseshoe Fault. In addition to this, the SWIM faults cross-cut the accretionary wedge (Fig. 4) which, in turn, is sealed, in the offshore Guadalquivir and Rharb foreland Basins, by a thick sedimentary cover of Early Pliocene through Holocene age (Fig. 7).

The SWIM faults concentrate along a narrow, 40 km wide band (the gray band of Fig. 3, hereafter termed SWIM Fault Zone), corresponding to the trace of a small circle centred on the present-day pole of rotation of the Nubia plate with respect to Iberia (Figs. 1, 3) (Fernandes et al., 2003). The SWIM Fault Zone has a total length of approximately 600 km, located between the eastern and western ends of two well established plate boundaries, the Gloria Fault and the Rif–Tell fault, respectively (Fig. 3). In the Horseshoe Abyssal Plain, the SWIM Fault Zone does not show a continuous superficial expression because the Quaternary sedimentation rate, dominated by turbidity flows, largely exceeds the strike–slip rate of deformation, as depicted on the seismic reflection profile AR08 (Fig. 5). The SWIM Fault Zone forms the southern boundary of the main tectonically and seismically active area of the Gulf of Cadiz (Fig. 6a). To the south of the fault zone, earthquake activity is minor and tectonic shortening negligible, as shown by the existence of a regional unconformity sealing the main thrusts of the Seine Plain (Plate II in Supplementary Material).

4. Discussion and conclusion

Although the papers published in the last 25 yrs failed to reach a consensus on the Africa–Eurasia plate boundary between the Gloria Fault and Strait of Gibraltar, they highlighted some of the main geological processes and structures in this part of the world. Sartori et al. (1994) described this plate boundary as a “diffuse boundary” after describing a 200 km wide belt of shortening between Gorringe Bank and Coral Patch Ridge encompassing the Horseshoe and Seine Abyssal Plains. Gutscher et al. (2002) argued in favour of active subduction beneath the Gibraltar orogenic arc. Moruel and Meghraoui (1996) described the transpressive plate boundary at the Rif–Tell, to the east of Gibraltar. Andeweg and Cloetingh (2001) found evidences of active sinistral shear in the western Alboran region. Cloetingh et al. (2002) demonstrated the occurrence of large-scale Alpine to recent intraplate deformation in Iberia. Stich et al. (2006, 2007) described the

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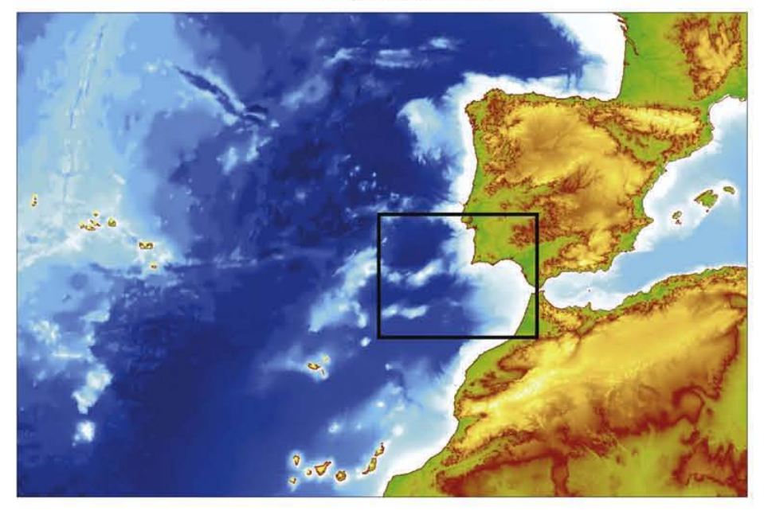
BATHYMETRY OF THE GULF OF CADIZ, NE ATLANTIC OCEAN:

THE SWIM MULTIBEAM COMPILATION

Scale: 1 / 750 000
Mercator Projection (N 36º)
Ellipsoïd WGS84



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Cartographer

Susana Diez, *Unidad de Tecnología Marina - CSIC, CMIMA*, Barcelona (Spain)

The SWIM multibeam bathymetry compilation of the Gulf of Cadiz area and SW Margin of Portugal is the result of collaborative research performed between 2000 and 2006 by teams from 7 European countries and 14 research institutions. The new dataset was acquired with the main objectives of mapping i) the morphotectonic structures of the Gulf of Cadiz that comprehends the SW Eurasia – NW Africa plate boundary that is prone to generate large earthquakes and tsunamis, ii) the sedimentation features that result from the Mediterranean Outflow Water and iii) the mud volcanoes, salt and mud diapirs and other fluid exhalation structures mostly associated with the accretionary wedge of the Gulf of Cadiz.
Institutions and laboratories have provided data files and Digital Terrain Models (DTM) at a 100 m grid spacing in order to produce the SWIM multibeam compilation.

Reference: Bathymetry of the Gulf of Cadiz, North-East Atlantic: The SWIM Multibeam compilation. One map at 1 / 750 000, in N. Zitellini, E. Gràcia, L. Matias, P. Terrinha, M.A. Abreu, G. DeAlteriis, J.P. Henriet, J.J. Dañobeitia, D.G. Masson, T. Mulder, R. Ramella, L. Somoza and S. Diez; *Earth and Planetary Science Letters,* this volume.

Data sources

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   Ifremer (France)
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   Geología Marina, IGME (Spain)
3. **PARSIFAL cruise, 2000, R/V Hespérides, Simrad EM 12S**
   Unidad de Tecnología Marina - CSIC, CMIMA (Spain)
4. **CADISAR-1 cruise, 2001, R/V Le Suroît, Simrad EM 300**
   Département de Géologie et Océanographie, Université Bordeaux (France)
5. **HITS cruise, 2001, R/V Hespérides, Simrad EM12S**
   Unidad de Tecnología Marina - CSIC, CMIMA (Spain)
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7. **GORRINGE cruise, 2003, R/V Urania, Reason Seabat 8101**
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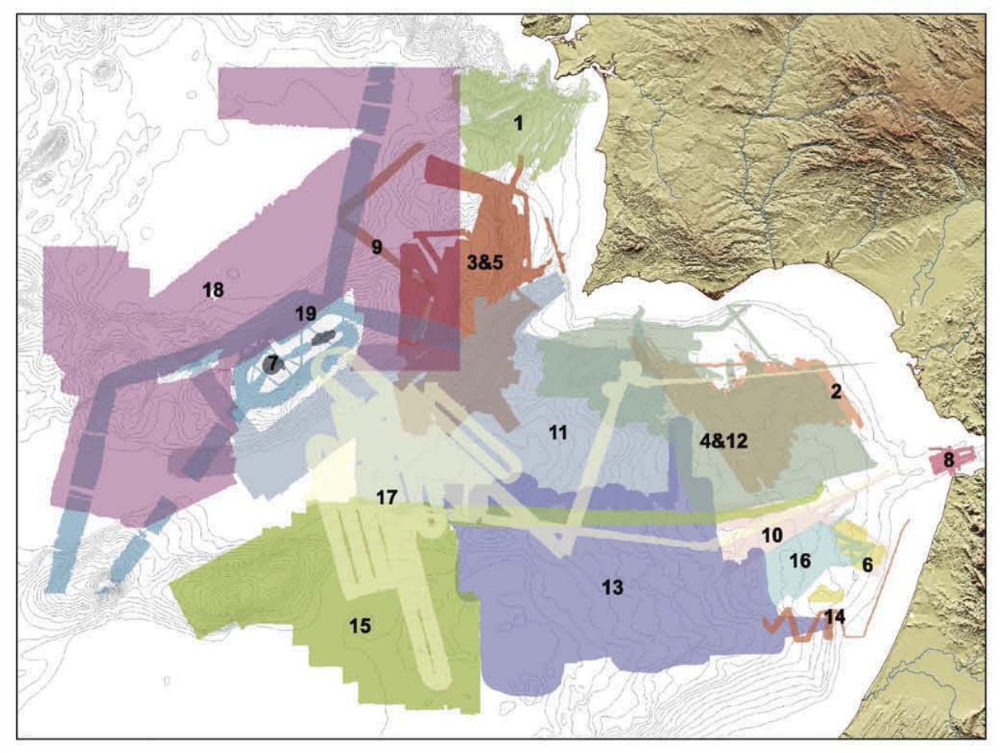
15. **SWIM-2 cruise, 2005, R/V OGS Explora, Reason Seabat 8150**
    Istituto di Scienze Marine, ISMAR (Italy)
16. **HERMES cruise, 2006, R/V Charles Darwin, Simrad EM 12S**
    NOC, Southampton (UK)
17. **SWIM cruise, 2006, R/V Hespérides, Simrad EM 120**
    Unidad de Tecnología Marina - CSIC, CMIMA (Spain)
18. **Digital Terrain Model** from EMEPC (Portugal)
    Data from R/V D. Carlos I, Simrad EM 120
19. Several **R/V L'Atalante and R/V J. Charcot transit data** provided by SISMER database have been integrated:
    TRANSEAGOR cruise, 1978, R/V J. Charcot, Seabeam
    BRESMAD cruise, 1990, R/V L'Atalante, Simrad EM 12D



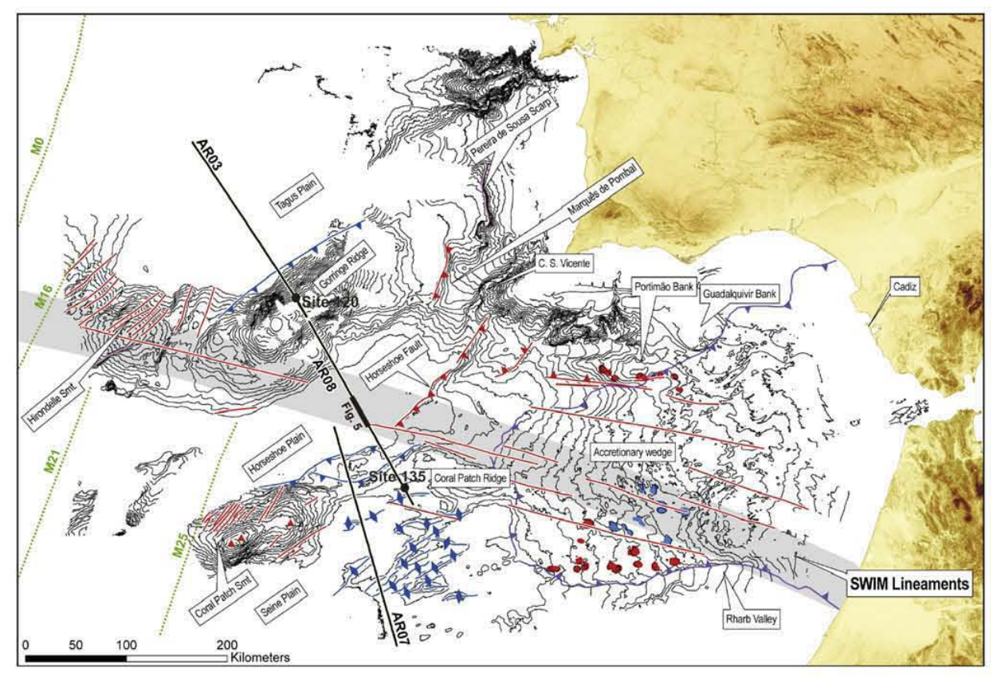
The Gulf of Cadiz and the Southwest Portuguese Margin

The Gulf of Cadiz is an assymetric geographical feature that encompasses the SW Eurasia – NW Africa plate boundary. It is bound to the east by the Betic-Rif orogenic Arc and its respective foreland basins and in the north by the tectonically inverted rifted margin of South Portugal.

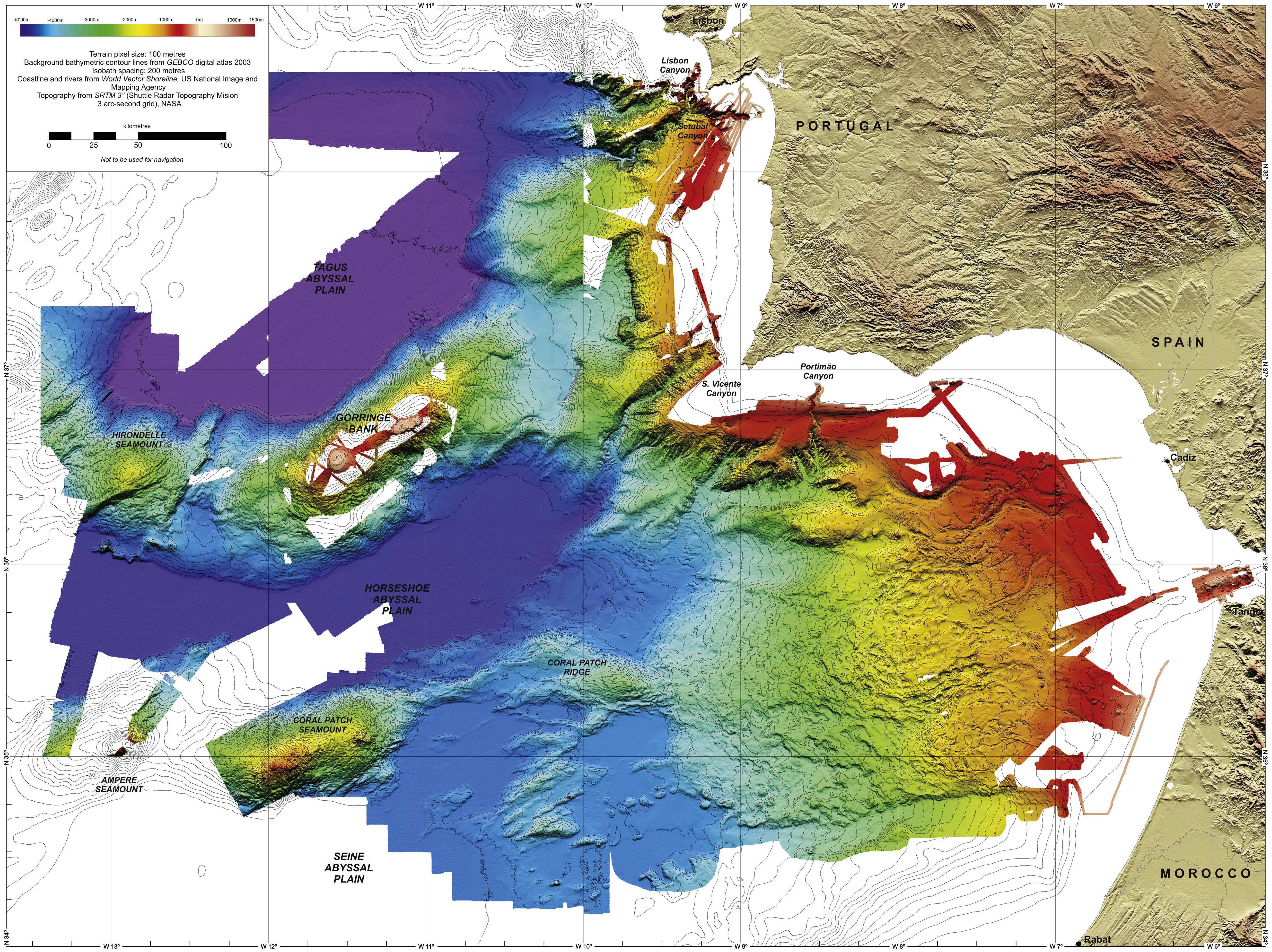
The main submarine morphological features are: i) the Gulf of Cadiz accretionary wedge, ii) the Rharb valley that bounds the accretionary wedge to the south, iii) the valleys and contourite drifts that result from the dynamics of the Mediterranean Outflow Water, iv) the deeply incised South Portuguese Margin by the S. Vincente Canyon, Portimão Canyon and Lagos Canyon, v) the Setúbal Canyon on the West Portuguese Margin, vi) the continental slope escarpments of the Marquês de Pombal Fault, Horseshoe Fault, Portimão-Guadalquivir Fault and the Pereira de Sousa Fault, vii) the Horseshoe Abyssal Plain, viii) the Seine Abyssal Plain and respective abyssal hills, ix) the Gorringe Ridge, x) the Coral Patch Ridge and xi) the SWIM Lineaments whose total extent was revealed by the SWIM bathymetry compilation and are believed to constitute part of the SW Iberia – NW Africa plate boundary.

The Present sub-aerial and submarine geographical configuration of the Gulf of Cadiz results mostly from two plate driving mechanisms, firstly, the subduction slab roll-back that led to the formation of the Betic-Rif Arc, its associated foreland basins and accretionary wedge, and secondly, the oblique collision of Iberia and Africa that led to the formation of the dextral strike-slip SWIM Faults, tectonic inversion of the South Portuguese rifted Margin, thrusting and uplift of the submarine reliefs and submarine canyons.

The WNW-ESE 600 km long SWIM lineaments are believed to constitute part of a recently formed plate boundary, i.e. post-Late Miocene, which is associated with the important decrease or cease of activity of the slab roll-back and increase of deformation by impingement of NW Africa against SW Eurasia.



BATHYMETRY OF THE GULF OF CADIZ, NORTH-EAST ATLANTIC: THE SWIM MULTIBEAM COMPILATION



Terrain pixel size: 100 metres
Background bathymetric contour lines from *GEBCO* digital atlas 2003
Isobath spacing: 200 metres
Coastline and rivers from *World Vector Shoreline,* US National Image and Mapping Agency
Topography from *SRTM 3"* (Shuttle Radar Topography Mision 3 arc-second grid), NASA

Not to be used for navigation

ISMAR: Istituto di Scienze Marine
Consiglio Nazionale delle Ricerche
http://www.bo.ismar.cnr.it

UTM: Unidad de Tecnología Marina
Consejo Superior de Investigaciones Científicas
http://utm.csic.es

IUEM: Institut Universitaire Européen de la Mer
Université de Bretagne Occidentale
http://www.univ-brest.fr/IUEM

Universidade de Lisboa
http://www.ul.pt

NOC: National Oceanography Centre
http://www.noc.soton.ac.uk

Université de Bordeaux
http://www.u-bordeaux1.fr

INETI: *Instituto Nacional de Engenharia, Tecnologia e Inovação*
http://www.ineti.pt

IGME: Instituto Geológico y Minero de España
http://www.igme.es

IAMC: Istituto Ambiente Marino Costiero
Consiglio Nazionale delle Ricerche
http://www.cnr.it

Universiteit Gent
http://www.ugent.be

OGS: Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
www.ogs.trieste.it

EMEPC: Estrutura de Missão para a Extensão da Plataforma Continental
www.emepc.gov.pt

Universität Bremen
http://www.uni-bremen.de

Département Géosciences Marines
http://www.ifremer.fr

Plate I. Bathymetry of the Gulf of Cadiz, North-East Atlantic: The SWIM Multibeam Compilation. Bathymetry map, as in Fig. 2 of the paper, designed to be printable at A0 format with a resolution that will allow the recognition and detection of the features discussed in the text.

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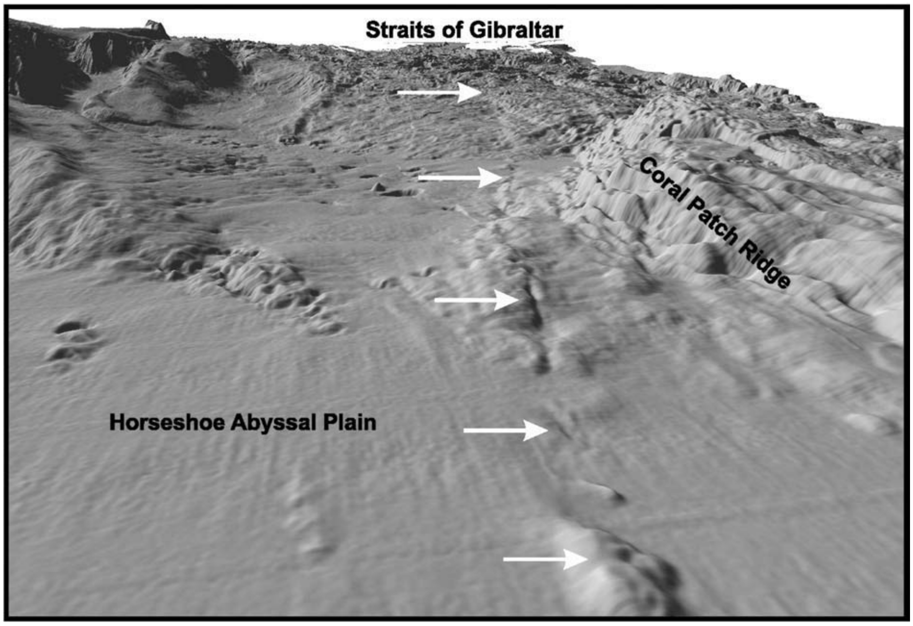

Fig. 4. Shaded relief swath bathymetry image showing an example of one of the SWIM Lineaments running from the Horseshoe Abyssal Plain through the accretionary wedge. The view is from Horseshoe Abyssal Plain from the WNW and 45° elevation. The figure clearly shows the positive and negative features and scarps arranged along the SWIM Lineament.

geodetic westwards motion of the Alboran–Betic–Gibraltar domain. Zitellini et al. (2004) summarized the active thrust structures in the Gulf of Cadiz showing that they coincide with the main clusters of seismicity.

These works, together with the information presented here, implied the existence of two plate driving mechanisms in the Gulf of Cadiz: a) subduction associated with the westward emplacement of the Gibraltar Arc and formation of the Gulf of Cadiz accretionary wedge and; b) oblique lithosphere collision between Iberia and Nubia that caused thrusting in the Horseshoe Abyssal Plain and SW Portuguese Margin and dextral wrenching along the SWIM Fault Zone.

The present day instrumental seismicity, seismic reflection, coring and swath-bathymetry show that the thrust and wrench tectonics in the Central and Northern sectors of the Gulf of Cadiz are active. However, the accretionary wedge has no seismicity and is sealed by an almost undeformed package of sediments deposited since the Early Pliocene, suggesting that subduction is not active at present or it is dying out as demonstrated by MCS line 9535-87 (Fig. 7). On top of this, we observe that deformation shifted northwards, towards Iberia, after the Late Miocene. Only minor deformation is observed south of the SWIM Fault Zone. In the Seine Abyssal Plain the last major shortening event is sealed by a regional unconformity of Late Miocene(?) age (Plate II in Supplementary Material, and Fig. 3). The dextral strike–slip SWIM Fault Zone, first introduced in this work, not only cuts across the accretionary wedge (Fig. 4) but it constitutes the southern boundary of the three seismogenic structures between the Gloria Fault and the Moroccan shelf: the Horseshoe Fault, the Gorringe thrust and the Guadalquivir–Portimão Bank Fault (Fig. 3). These observations favour the existence of only one plate driving mechanism at present, the oblique collision between Nubia and Iberia.

In this tectonic framework the SWIM Fault Zone is interpreted as a precursor to the formation of a new transcurrent plate boundary controlling the present-day plate interaction between Iberia and Africa. Seismic strain (Fig. 6a) is accommodated by structures located

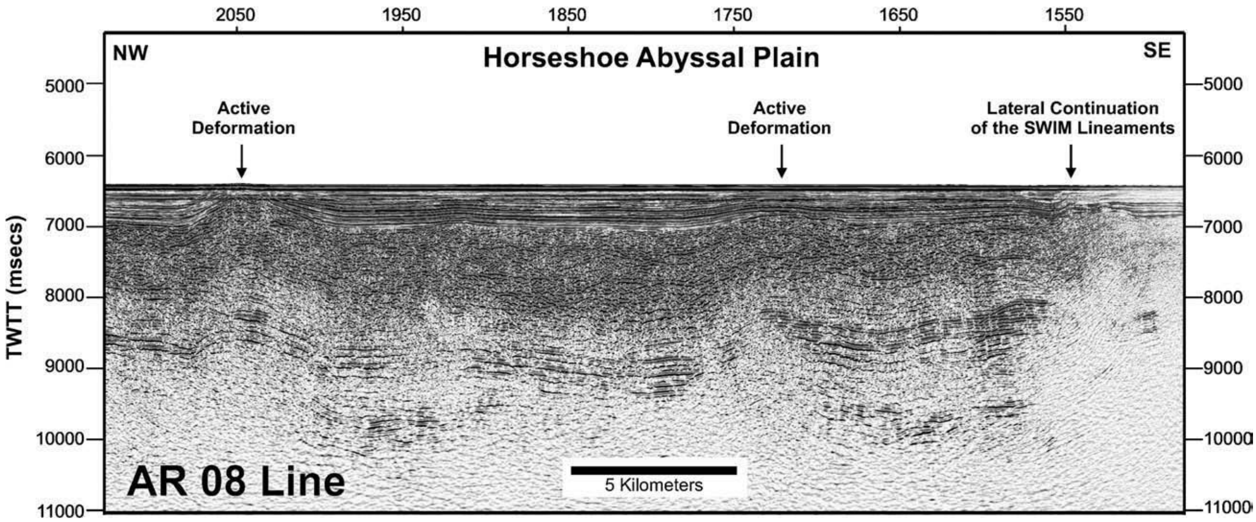

Fig. 5. Multi-channel seismic line crossing SWIM Lineament shown in Fig. 4. Blow-up of multi-channel seismic line AR08; location is in Fig. 3, the full seismic line and its interpretation is shown in the Supplementary Material. This portion of AR08 crosses the SWIM Lineament in the Horseshoe Abyssal Plain. Despite the fact that there is no morphological expression of the lineament this profile shows that the active deformation in the present continues also in the flat part of the Horseshoe Abyssal Plain.

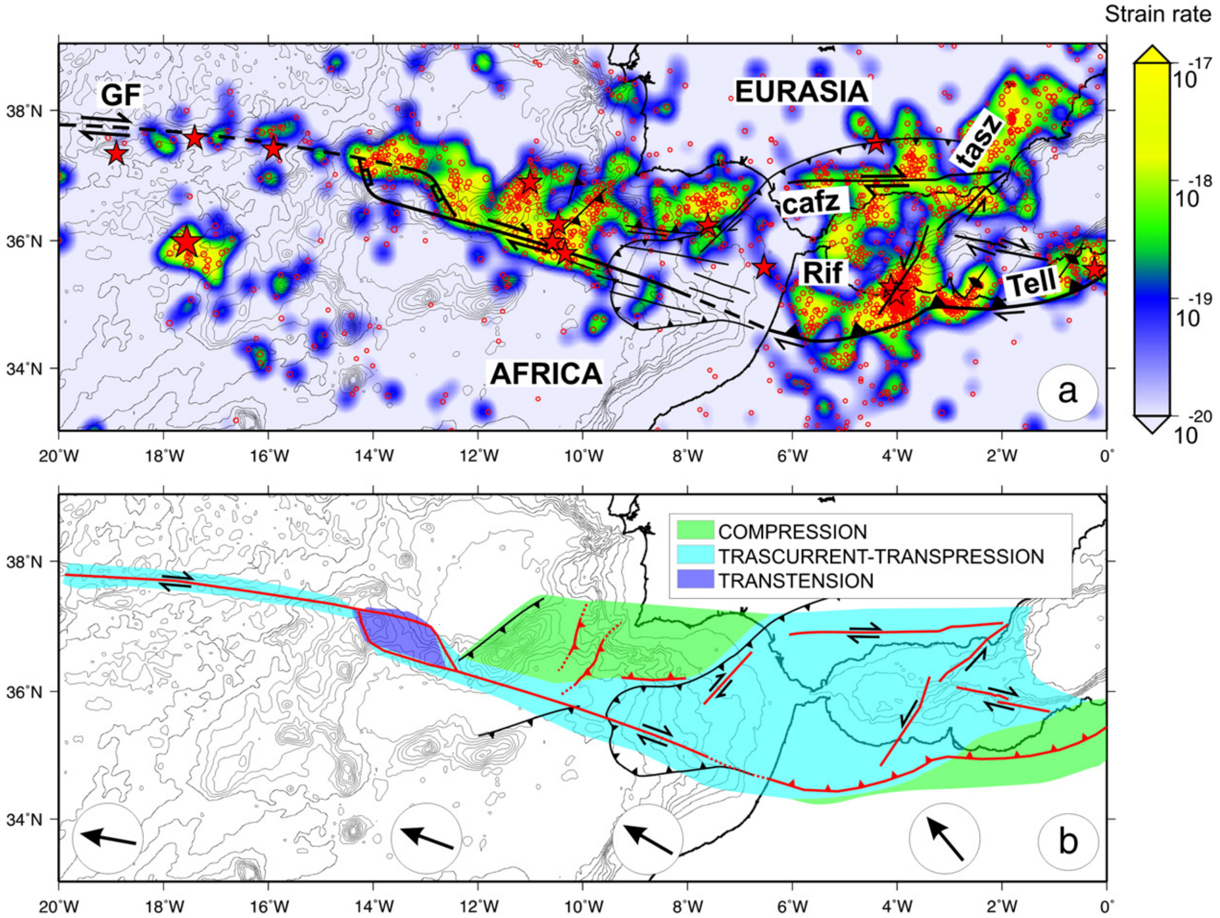

Fig. 6. Conceptual model of the present Africa–Europe Plate Boundary. 6a: proposed SW Eurasia–NW Africa plate boundary, as a small circle centered in Euler pole DEOS2k (Fernandes et al., 2003) coincident with the SWIM Fault Zone; solid: where it is accompanied by instrumental seismicity; dashed: where it lacks seismicity and is in the process of propagation to connect with the Rif–Tell plate boundary, also in black the main faults present in the area (see text for discussion); Colour contours: seismic strain rate computed from all events, open circles, $3<M<5.5$. Star: events $M>5.5$ since 1964. Bathymetry from Smith and Sandwell (1997). Solid thin black lines: SWIM Lineaments; tasz:Trans-Alboran Shear Zone that include the Jebba–N'Kor and Carboneras faults; cafz: Corredor de las Alpujarras Fault Zone (modified after Mauffret et al., 2007). 6b: simplified tectonic sketch of the area; red line: main active faults, black line: inactive faults, arrows: relative motion of Africa with respect to Eurasia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

north of the SWIM Fault Zone and maximum values coincide with the active morpho-tectonic features and faults shown in Fig. 3. Most of the seismic strain in the northern part of the Gulf of Cadiz is concentrated on the Guadalquivir–Portimao Bank. It is bound by an oblique-slip ESE trending thrust fault that marks the contact between the inverted rifted continental South Iberia margin and the accretionary wedge, underlain by thinned continental crust (Gonzalez et al., 1996).

Seismic strain also clusters around the south of Gorringe Bank and the eastern part of the Horseshoe Abyssal Plain. Inspection of seismic reflection profiles and multibeam bathymetry shows that the Gorringe Bank NW-verging frontal thrust has dramatically diminished its activity since Late Miocene times. In contrast, vertical WNW–ESE trending active SWIM faults have developed on its southern flank and in the Horseshoe Abyssal Plain, as shown in Plate II of Supplementary Material. Neotectonic transpressive structures are dominant also in the Betic and Rif–Tell Cordilleras where the Mesozoic and Cenozoic formations are deformed by strike–slip systems, such as the 450 km wide, E–W and ENE–WSW Corredor de las Alpujarras Fault Zone and the Trans-Alboran Shear Zone, which links the southern termination of the Eastern Betic Shear Zone (Carboneras Fault) and the Alboran Ridge with the Jebha Fault in the Moroccan Rif (Fig. 6b). The distribution of these neotectonic structures, seismicity, focal mechanisms and seismic strain show an overall 200 km wide dextral transpression deformation zone associated with oblique plate convergence between the two lithospheric plates. The seismic strain is mainly taken up by thrust-related faults on the SW Iberian margin and by transpressive strike–slip faults in the Betic and Rif. This kinematic model also predicts a transtensional releasing bend at the connection between the Gloria and SWIM faults (Fig. 6b).

The proposed tectonic framework gives a possible explanation for the origin of the 1755 Lisbon earthquake and has implications for large scale earthquake and tsunami hazard analysis since it demonstrates for the first time the existence of a 600 km long active fault zone, most probably a new plate boundary. Since the 28th February 1969 ($M\sim8$) and the 12th February, 2007 ($M\sim6$) (Fukao, 1973; Stich et al., 2007) occurred on the foot-wall of the Horseshoe thrust Fault beneath the Horseshoe Abyssal Plain, the possibility of mechanical connection between the SWIM Faults and the Horseshoe Fault should be seriously envisaged. The western segment of the SWIM Fault and the Horseshoe Fault comprise in total more than 400 km connected fault segments, more than enough to generate an earthquake equivalent to the 1755 Lisbon event.

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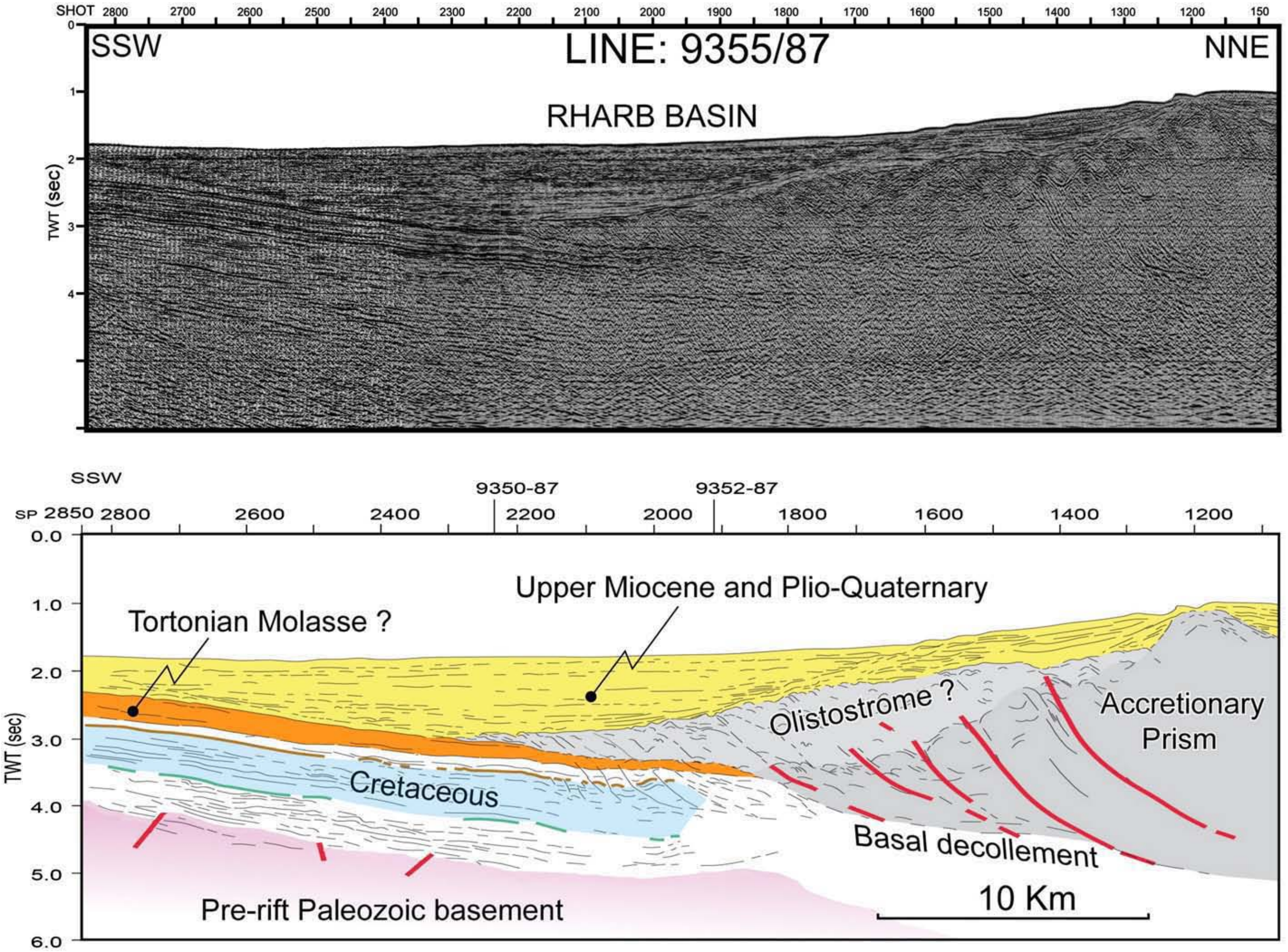

Fig. 7. Multi-channel seismic line ONAREP 9355-87. Mcs Line encompassing the Gulf of Cadiz accretionary wedge at the Rharb Valley, in the Moroccan offshore (modified after Camurri, 2004). Location in Fig. 3.

Nov./Dec. 2003. We thank Marc-Andre Gutscher for the permission to include the swath bathymetric data collected during Delila 2004 and Delsis 2005 Cruises. Dr. Haddou Jabor is gratefully acknowledged for permission to use Multi-channel seismic line ONAREP 9355-87. We acknowledge financial support from the ESF EuroMargins Program, contract n. 01-LEC-EMA09F and from EU Specific Programme “Integrating and Strengthening the European Research Area”, Sub-Priority 1.1.6.3, “Global Change and Ecosystems”, contract n. 037110 (NEAREST); national funding from MEC in Spain (SWIM REN2002-11234MAR, IMPULS, REN 2003-05996MAR and EVENT CGL2006-12861-C02-02 projects), and Portugal (MATESPRO, PDCTM/P/MAR/15264/1999). We thank Vasco Valadares and Filippo D'Oriano for their valuable help on the preparation of figures. ISMAR-BO contribution n.1611.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.12.005.

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