CHARACTERIZING ACTIVE FAULTS AND ASSOCIATED MASS TRANSPORT DEPOSITS IN THE SOUTH IBERIAN MARGIN (ALBORAN SEA AND GULF OF CADIZ): ON-FAULT AND OFF-FAULT PALEOSEISMIC EVIDENCE

Caracterización de fallas activas y deslizamientos asociados en el Margen Sur de Iberia (Mar de Alboran y Golfo de Cadiz): Evidencias paleosísmicas

E. Gràcia (1), R. Bartolomé (1), C. Lo Iacono (1), X. Moreno (1,2), S. Martínez-Loriente (1), H. Perea (3), E. Masana (2), R. Pallàs (2), S. Diez (1), J. Dañobeitia (1), P. Terrinha (4) and N. Zitellini (5)

(1) Unitat de Tecnologia Marina - CSIC, CMIMA, Pg. Marítim de la Barceloneta, 37-49, 08003 Barcelona, Spain
egracia@cmima.csic.es
(2) RISKNAT, Dpt. Geodinàmica i Geofísica, Universitat de Barcelona, Martí i Franquès s/n, 08028 Barcelona, Spain
(3) Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Campo Grande, 1746-016 Lisboa, Portugal
(4) LNEG- Laboratorio Nacional de Geologia e Energia, Unidade de Geologia Marinha, Aptd 7586, 2720-866 Amadora, Portugal
(5) Istituto di Scienze Marine, (ISMAR) - CNR, Bologna, Italy

***Abstract**: During the last years we have carried out successive high-resolution marine geological and geophysical surveys to investigate the seismic potential of the slow-moving seismogenic faults from the South Iberian Margin. Based on multiscale acoustic mapping, sub-seafloor seismic imaging and dating methods we have characterized submarine fault systems with unprecedented resolution. We present primary paleoseismic evidence obtained by direct investigations of selected faults from the Mediterranean Sea (i.e. Carboneras Fault, Bajo Segura Fault, Adra Fault) and the external part of the Gulf of Cadiz (i.e. Marques de Pombal Fault, Horseshoe Fault, Coral Patch Ridge Fault and SWIM lineaments). The obtained fault seismic parameters suggest that these faults are active and capable of generating large magnitude (Mw > 6) seismic events, representing an earthquake and tsunami hazard for the surrounding coastal areas. Secondary paleoseismic evidence in the SW Iberian Margin (based on landslides and turbidite deposits) yields a regional recurrence rate of large magnitude earthquakes of 1800 – 2000 years.*

***Key words**: Active faulting, submarine paleoseismology, recurrence interval, earthquakes and tsunamis.*

INTRODUCTION

Crustal deformation in the south Iberian margin, which includes the offshore Atlantic and Mediterranean regions, is driven mainly by the NW–SE convergence (4-5 mm/year) between the African and Eurasian plates (e.g. Argus et al., 1989). Convergence is accommodated over a wide active deformation zone suggesting distributed deformation among a number of tectonic structures. Earthquake mechanisms reveal that reverse to strike-slip faulting style dominates along the eastern Alboran Sea and external Gulf of Cadiz (e.g. Buforn et al., 2004; Stich et al., 2003, 2005), as corroborated by marine geological and geophysical data (e.g. Comas et al., 1999; Gràcia et al., 2003a,b, 2006; Terrinha et al., 2003, 2009; Zitellini et al., 2004, 2009). Regional seismicity is characterized by shallow to deep earthquakes of low to moderate magnitude (Mw < 5.5) (Buforn et al., 2004; Stich et al., 2003, 2005). However, large and destructive earthquakes (Mw ≥ 8.0 and MSK Intensity X-XI) such as the 1755 Lisbon Earthquake, have also occurred in the region (e.g. Martínez Solares and López Arroyo, 2004), and may represent a significant earthquake and tsunami hazard along the Iberian Peninsula and North African coasts. In south Iberia, assessment of seismic hazard is largely based on the relatively short period of instrumental and historical earthquake catalogues. This may not be sufficient to assess seismic hazard models in the Iberian Peninsula, especially when considering high-magnitude earthquakes with long recurrence intervals (> 10^3 years) (e.g. Masana et al., 2004; Gràcia et al., 2010).

To investigate the seismic potential of the slow-moving seismogenic faults of the south Iberian Margin we have carried out several marine geophysical surveys in the Alboran Sea and Gulf of Cadiz in the frame of National (IMPULS and EVENT) and European projects (ESF EuroMargins SWIM and EU FP-VI NEAREST). We present our main outcomes focusing into two aspects: a) the characterization of active and seismogenic submarine faults of the southern Iberian Margin aiming to find their paleoseismic parameters, and b) the identification and age of landslides and turbidite deposits as secondary paleoseismic evidence to obtain the recurrence rate of large magnitude (Mw > 6) earthquakes occurred in the area.

DATA AND METHODS

State of the art methodologies integrate the most advanced tools in marine geosciences covering different scales of resolution. Acoustic mapping techniques, such as swath-bathymetry and sidescan sonar data, allow identifying the geomorphic evidence of active faults, such as seafloor ruptures, folds, fault scarps and fault traces. Sub-seafloor seismic imaging methods, ranging from high-resolution sub-bottom profiler (uppermost tens of meters of penetration) to multichannel seismic data (several km of penetration) allow to detect the stratigraphic evidence of past seismic activity, such as displaced seismic horizons, folded and faulted reflectors, zones of shearing and discontinuities. Pre-stack depth migration of MCS profiles yield a corrected geometry of seismic reflectors, and thus, may help to calculate fault seismic parameters (i.e. length, segmentation, fault dip, slip rate, maximum magnitude earthquake, elapsed time since last event). Sediment sampling methods and subsequent analyses (texture, sediment composition, physical properties and accurate chronology) allow identifying, characterizing and dating coeval submarine mass transport deposits triggered during seismic events, essential to calculate recurrence interval of large magnitude earthquakes.

PRIMARY PALEOSEISMIC EVIDENCE IN THE ALBORAN SEA: ACTIVE FAULTING

In the Alboran Sea, we mainly focused into the marine terminations of the Eastern Betic Shear Zone (EBSZ), and its link with the structures onshore. They correspond to the Bajo Segura Fault to the north and the Carboneras Fault to the south (Fig. 1). The Bajo Segura Fault offshore was explored during the EVENT-SHELF cruise on board the RV Garcia del Cid in 2008. The analysis of the Sparker seismic data reveals a thick Quaternary sedimentary sequence affected by folding and reverse faulting reaching up to the seafloor (Perea et al., 2009), suggested as a potential source of the historical the 1829 Torrevieja earthquake. A precise dating of the Quaternary sequences is needed in order to quantify the vertical slip rates of the imaged faults.

The Carboneras Fault offshore (100 km long) was first mapped using swath-bathymetry, sidescan sonar TOBI and parametric echosounder during the HITS-2001 cruise (Fig. 1). We imaged seafloor ruptures, deflected channels, pressure ridges, water gaps and push-ups, typically found on active transpressional fault systems. The observed segmentation allowed us to know that the fault is capable of generating up to Mw 7.4 earthquakes (Gràcia et al., 2006). During the subsequent IMPULS-2006 survey, we obtained a dense grid of high-resolution multichannel seismic (MCS) data which allowed us to characterize the along-fault geometry between the 3 segments (north, central and south) and intersection zones. MCS profiles show a vertical displacement of 0.1-0.15 s TWTT at the horizon corresponding to the base of Quaternary, suggesting dip-slip rates of 0.05-0.06 mm/a for the North segment (Moreno et al., 2008). Precise dating of the Quaternary faulted seismic reflectors identified in the MCS and TOPAS data was a challenge, as there were no wells or very long cores (> 20 m) near the fault zone. A first approach was based on radiocarbon dating of gravity cores (3-5 m long) located off-fault, which allowed us to obtain an age model for the Holocene and Last Glacial–Interglacial Transition period. Extrapolating the resulting sedimentation rate, we obtained a rough estimation of the age of the underlying Pleistocene sequences. The second approach was based on seismostratigraphy, as high amplitude reflectors can be correlated with glacial-inter glacial periods. This helped in setting a timeframe for the measured offsets and establishing maximum dip-slip rates of 0.10-0.16 mm/a for the last 128 ka (Moreno et al., 2008). Based on left-laterally offset gullies, a strike-slip rate of 1.3 mm/a was obtained since the base of Quaternary. No information of individual events could be determined from the marine data.

Related structures, such as the NNW-SSE trending, closely spaced and short subvertical faults located to the west of the Carboneras Fault, referred here as Adra FZ (Fig. 1), have also been imaged and investigated using acoustic and multi-scale seismic data (TOPAS, Sparker and high-resolution MCS). One of these structures, trending NW-SE, is very likely to be the source of the 1910 Adra Earthquake of estimated Mw 6.0 (Stich et al., 2005).

Two relevant fault systems have recently been explored using high-resolution and deep penetration multichannel seismic reflection methods during the EVENT-DEEP cruise (May-June, 2010) on board the R/V Sarmiento de Gamboa. We focused on the 250 km long WNW-ESE trending dextral strike-slip Yussuf Fault and the 150 km long NNE-SSW trending fault to the SW of the Alboran Ridge, referred as Al-Hoceima Fault (Fig. 1). The main objective was to image and characterize their geomorphology and detailed structure to investigate how they accommodate the present-day strain regime, as they may be sources of large events such as the 1994 Al Hoceima Mw 6.0 earthquake. The closely spaced high-resolution seismic profiles together with the chronological control from ODP Leg 161 sites may yield the seismic parameters of these faults.

PRIMARY AND SECONDARY PALEOSEISMIC EVIDENCE IN THE GULF OF CADIZ: ACTIVE FAULTS, LANDSLIDES AND TURBIDITES

In the SW Iberian Margin, direct fault investigations mainly focused on the active structures located at the external part of the Gulf of Cadiz, source of the largest earthquakes and tsunamis that affected Western Europe since historical times. Recent surface ruptures have been recognized in this area, which correspond to the active NE-SW trending west-verging folds and thrusts of the Marques de Pombal Fault, Sao Vicente Canyon Fault, Horseshoe Fault and Coral Patch Ridge Fault (Zitellini et al., 2004; Gràcia et al., 2003a; Terrinha et al., 2003). In addition, long WNW-ESE strike-slip faults referred as SWIM Lineations have recently been identified (e.g. Zitellini et al., 2009; Terrinha et al., 2009) (Fig. 1).

The Marques de Pombal Fault is a 50 km long west verging monocline thrust cutting through the Plio-Quaternary units (Fig. 1). Deformation is accommodated by a blind thrust to the south and a fold to the North. This fault, together with the Horseshoe Fault has been suggested as a potential source of the 1755 Lisbon earthquake (e.g. Gràcia et al., 2003a; Zitellini et al., 2004). The Horseshoe Fault is an 80-90 km west-verging thrust limited to the north by the NNE-SSW Sao Vicente Canyon Fault and to the south by the ENE-WSW trending Coral Patch Ridge Fault (Fig. 1). MCS data evidence that it is an active structure, as the fault reaches up to the surface cutting through the Plio-Quaternary units (Gràcia et al., 2003a). Pre-stack depth migrated profiles show that the Horseshoe Fault has uplifted the Upper Miocene Horseshoe Gravitational Unit more than 750 m, yielding a maximum vertical slip rate of 0.125 mm/yr. The fault is also the source of intermediate to large magnitude earthquakes, such as the 2007 Horseshoe event (Mw 6.0) (Stich et al., 2007).

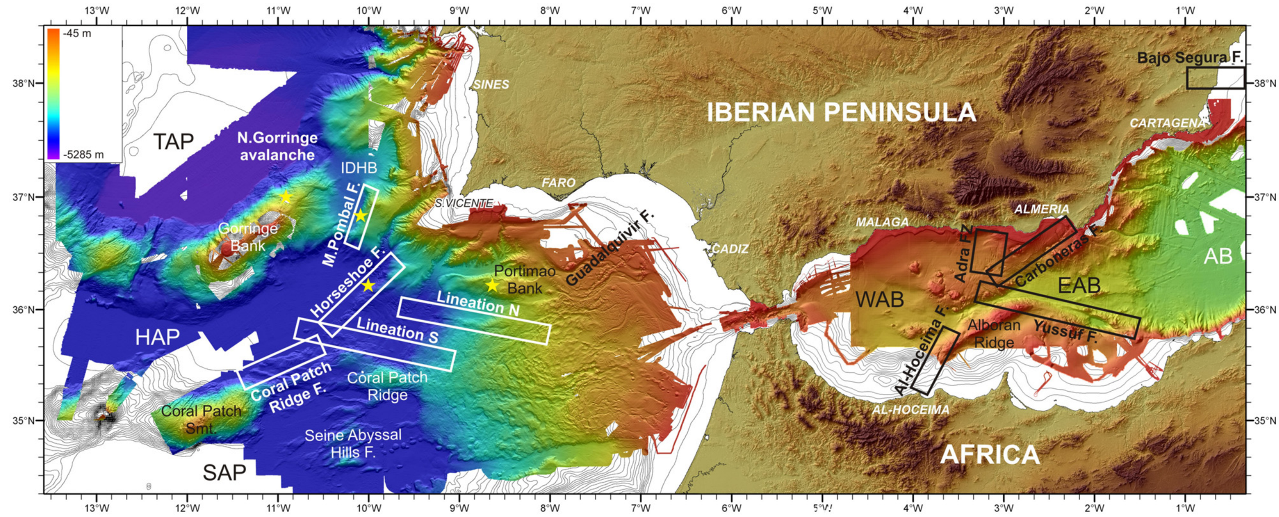

Figure 1. Topographic and bathymetric map of the South Iberian and North African margins, which include the Alboran Sea and Gulf of Cadiz. In the Alboran Sea (bathymetric map modified from MEDIMAP et al., 2008), the studied fault systems are depicted by a black outlined box. WAB: Western Alboran Basin; EAB: Eastern Alboran Basin; AB: Algerian Basin. In the Gulf of Cadiz (bathymetric map modified from Zitellini et al., 2009), the studied fault systems are marked by white outlined boxes. Yellow stars depict large landslides. TAP: Tagus Abyssal Plain; IDHB: Infante Don Henrique Basin; HAP: Horseshoe Abyssal Plain; SAP: Seine Abyssal Plain.

The Coral Patch Ridge Fault is an active 60 km long low-angle blind thrust verging to the NW. The fault separates the Horseshoe Abyssal Plain from the Seine Abyssal Plain, generating a cumulated relief of 700 m high (Fig. 1). Lithostratigraphy defined by DSDP Site 135 allowed us to distinguish six seismostratigraphic units related to pre-rift, syn-extensional and syn-compressional phases (Martinez-Loriente et al., 2009). To the south, the Seine Abyssal Hills Faults are a succession of highs and depressions, corresponding to conjugated ENE-WSW trending folds and thrusts verging to the NW and SE. Although this area is characterized by a subdued seismic activity, TOPAS and MCS data reveal that these thrusts are active and may be able to generate earthquakes up to magnitude Mw 7.

Large WNW-ESE trending lineaments, referred as SWIM Lineations, extend hundreds of km from the Horseshoe Abyssal Plain to the inner part of the Gulf of Cadiz (Terrinha et al., 2009; Zitellini et al., 2009) (Fig. 1). Recently acquired MCS data evidence that these structures correspond to large strike-slip faults, with a 3 to 6 km wide deformation zone and reaching up to 10 km deep (Bartolomé et al., 2009). TOPAS images reveal surface ruptures and morphologies of positive and negative flower structures. Moment tensor inversion of Mw < 6.0 earthquakes occurred along the Lineation S (Stich et al., 2005), show right-lateral strike-slip fault solutions, consistent with the geometry identified in the seismic data.

In the Gulf of Cadiz we have also used landslides and turbidites as secondary paleoseismic evidence. An overview of the Quaternary mass movements in the Gulf of Cadiz allowed us to identify retrogressive slope failures, headscarps, mass slides and gravity flows (Fig. 1). Over-steepened slopes and earthquake activity are the most likely triggering mechanisms of the observed mass transport deposits. Several slides are associated with active faults and may yield information of the fault past activity. TOBI sidescan sonar and TOPAS data across the Marques de Pombal Fault reveal a large (260 km^2) translational landslide and debris flow. The most recent slide, with age of about 230 yr BP, may have been triggered by the 1755 Lisbon earthquake. By dating the previous slide deposits a recurrence period of 2000 yr was obtained (Vizcaino et al., 2006), suggesting a cyclic activity of the Marques de Pombal Fault. Mass failures may also contribute to tsunami generation in the SW Iberian Margin. The north Gorringe rock and debris avalanche, with an estimated volume of 70-80 km^3, may represent a potential threat for the coastal areas, as suggested by numerical tsunami modeling. Results show that the Portuguese coast would be hit by 10 m high tsunami waves in around 30 minutes, and the Spanish and African coasts in about 60 minutes.

Finally, to investigate the recurrence rate of great magnitude (Mw> 8) Holocene events, such as the 1755 Lisbon earthquake, we tested the “turbidite paleoseismology” model in the SW Iberian margin. Sediment cores collected in the Tagus Abyssal Plain, Infante Don Henrique Basin, Horseshoe and Seine Abyssal Plains reveal that deep-sea basins preserve a record of episodic deposition of turbidites (Fig. 1). In the SW Iberian Margin, excluding specific climatic events, earthquakes are the most likely triggering mechanism for synchronous, widely-spaced distributed turbidites during the Holocene, when the sea level was relatively stable. Age correlation together with textural, physical properties and geochemical signatures of turbidite deposits reveals a total of 7 widespread turbidite events for the Holocene. Precise dating of the most recent turbidite event based on ^{210}Pb and ^{137}Cs geochronology provides an age of AD 1971 ± 3 (Garcia Orellana et al., 2006). This age corresponds to a high-magnitude instrumental earthquake in the region: the 1969 Horseshoe earthquake (Mw 8.0). Calibrated ^{14}C ages of subsequent widespread turbidite events correlate with the dates of important historical earthquakes and paleotsunami deposits in the Gulf of Cadiz area, such as AD 1755 and 218 BC, respectively. Taking into account older synchronous events, from 4960-5510 yr BP to 8715-9015 yr BP, a great earthquake recurrence interval of about 1800 years is obtained for the Holocene (Gràcia et al., 2010).

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References

Argus, D.F., Gordon, R.G., DeMets, C. & Stein S. (1989). Closure of the Africa- Eurasia-North America plate motion circuit and tectonics of the Gloria fault. . *J. Geophys. Res.,* 94: 5585-5602.

Bartolomé, R., Gràcia, E., Stich, D., Martínez–Loriente, S., Klaeschen, D., Masana, E., Diez, S., Lo Iacono, C., Moreno, X., Zitellini, N., Mànuel, A. & Dañobeitia, J.J. (2009). Seismic evidence of active strike-slip faulting in the external Gulf of Cadiz (SW Iberian Margin). *EOS Trans AGU*, Fall meeting Suppl., San Francisco (USA), 14-18 Dec. 2009.

Buforn, E., Bezzeghoud, M., Udías, A. & Pro, C. (2004). Seismic sources on the Iberia-African Plate boundary and their Tectonic Implications. *Pure Appl. Geophys*., 161, 623-646.

Comas, M.C., Platt, J.P., Soto, J.I. & Watts, A.B. (1999). The origin and tectonic history of the Alboran Basin: insights from leg 161 results. In: R. Zahn, M.C. Comas, A. Klaus (Eds.), *Proc. ODP, Sci. Res.*, vol. 161, Ocean Drilling Program, College Station TX, pp. 555– 580.

Garcia-Orellana, J., Gràcia, E., Vizcaino, A., Masqué, P., Olid, C., Martínez Ruiz, F., Piñero, E., Sanchez-Cabeza, J.A & Dañobeitia, J.J. (2006). Identifying instrumental and historical earthquake records in the SW Iberian Margin using 210Pb turbidite chronology. *Geophys. Res. Lett.,* 33 (24), L24601, doi: 10.1029/2006GL028417.

Gràcia, E., Dañobeitia, J.J., Vergés, J. & PARSIFAL Team (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.J., Vergés, J., Bartolomé, R. & Córdoba, D. (2003b). Crustal architecture and tectonic evolution of the Gulf of Cadiz (SW Iberian Margin) at the convergence of the Eurasian and African Plates. *Tectonics*, 22(4), 1033-1058.

Gràcia, E., Pallàs, R., Soto, J.I., Comas, M., Moreno, X., Masana, E., Santanach, P., Diez, S., García, M. & Dañobeitia, J.J. (2006). Active faulting offshore SE Spain (Alboran Sea): Implications for earthquake hazard assessment in the Southern Iberian Margin. *Earth Planet. Sci. Lett.,* 241 (3-4), 734-749.

Gràcia, E., Vizcaino, A., Escutia, C., Asioli, A., Rodés, A., Pallàs, R., Garcia-Orellana, J., Lebreiro, S. & Goldfinger, C. (2010). Holocene earthquake record offshore Portugal (SW Iberia): Testing turbidite paleoseismology in a slow-convergence margin. Quaternary Science Reviews, 29, 1156–1172.

Martínez Solares, J.M. & López Arroyo, A. (2004). The Great historical 1755 earthquake: Effects and damage in Spain. *J. Seism*., 8, 275-294.

Masana, E., Martínez-Díaz, J.J., Hernández-Enrile, J.L. & Santanach. P. (2004). The Alhama de Murcia fault (SE Spain), a seismogenic fault in a diffuse plate boundary: Seismotectonic implications for the Ibero–Magrebian region. *J. Geophys. Res.,* 109, 1–17.

Martínez-Loriente, S.,Gràcia, E., Bartolomé, R., Sallarès, V. & Terrinha, P. (2009). Active tectonics at the external part of the Gulf of Cadiz based on depth and time migrated MCS profiles. 6º Simposio sobre el Margen Ibérico Atlántico, Oviedo (Spain).

MEDIMAP Group, Loubrieu, B. & Mascle J. (2008). *Morpho-bathymetry of the Mediterranean Sea*. CIESM edition.

Moreno, X., Masana, E., Gràcia, E., Bartolomé, R. & Piqué-Serra, O., (2008). Estudio paleosismológico de la Falla de Carboneras: Evidencias tierra-mar de actividad tectónica reciente. *GeoTemas*, v. 10, p. 1035-1038.

Perea, H., Gràcia, E., Bartolomé, R., Lo Iacono, C., Masana, E. & EVENT-SHELF Team (2009). Structure and potential seismogenic and tsunamigenic sources of the offshore Bajo Segura Fault zone, SE Iberian Peninsula (Mediterranean Sea). *European Geosciences Union*, Vienna (Austria), 19-24 April.

Stich, D., Ammon, C.J. & Morales, J. (2003). Moment tensor solutions for small and moderate earthquakes in the Ibero-Maghreb region. *J. Geophys. Res.,* 108. B3, 2148-2168.

Stich, D., Mancilla, F. & Morales, J. (2005). Crust mantle coupling in the Gulf of Cadiz (SW Iberia). *Geophys. Res. Lett.*, 32, L13306.

Stich, D., Mancilla, F., Pondrelli, S. & Morales, J. (2007). Source analysis of the February 12th, Mw 6.0 Horseshoe earthquake: Implications for the 1755 Lisbon earthquake. *Geophys. Res. Lett.*, 34, L12308.

Terrinha, P., Pinheiro, L.M., Henriet, J.P., Matias, L., Ivanov, M.K., Monteiro, J.H., Akhmetzhanov, A., Volkonskaya, A., Cunha, T., Shaskin, P. & Rovere, M. (2003). Tsunamigenic-seismogenic structures, neotectonics, sedimentary processes and slope instability on the southwest Portuguese Margin. *Mar. Geol.,* 195; 1-4, 55-73.

Terrinha, P., Matias, L., Vicente, J., Duarte, J., Luiss, J., Pinheiro, L., Lourenço, N., Diez, S., Rosas, F., Magalhaes, V., Valadares, V., Zitellini, N., Roque, C., Mendes Victor, L. & MATESPRO Team (2009). Morphotectonics and strain partitioning at the Iberia–Africa plate boundary from multibeam and seismic reflection data. *Mar. Geol.,* 267, 156–174.

Vizcaino, A., Gràcia, E., Pallàs, R., Garcia-Orellana, J., Escutia, C., Casas, D., Willmott, V., Diez, S. & Dañobeitia, J.J. (2006). Sedimentology, physical properties and ages of mass-transport deposits associated to the Marquês de Pombal Fault, Southwest Portuguese Margin. *Norw. J. Geol.,* 86, 173-182.

Zitellini, N., Rovere, M., Terrinha, P., Chierici, F., Matias, L. & BIGSETS TEAM (2004). Neogene through Quaternary tectonic reactivation of SW Iberian passive margin. *Pure Appl. Geophys*., 161, 565-587.

Zitellini, N., Gràcia, E., Matias, L., Terrinha, P., Abreu, M.A., De Alteriis, G., Henriet, J.P., Dañobeitia, J.J., Masson, D.G., Mulder, T., Ramella, R., Somoza, L. & Diez, S. (2009). The Quest for the Africa-Eurasia plate boundary west of the Strait of Gibraltar. *Earth Planet. Sci. Lett.,* 280, 13-50.