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Pre-stack depth migration seismic imaging of the Coral Patch Ridge and adjacent Horseshoe and Seine Abyssal Plains (Gulf of Cadiz): tectonic implications

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Abstract: Recently acquired multichannel seismic (MCS) profiles during rhe SWIM-2006 cruise allow us to characterize the shallow and deep geomecry and timing of deformation of che suuctures comprising che Coral Parch Ridge and adjacent Horseshoe and Seine Abyssal Plains (SAP), ar rhe westernmost Gulf of Cadiz. T his region is where rhe epicentres of che largest instrumental earrhquakes occurred, such as che one on 28th February 1969 (Mw 8.0). We present a detailed seismo-stratigraphic and tectonic interpretation of two SWIM-2006 MCS profiles that we have pre-stack deprh migrated in order to correct rhe reflectors geometry. Based on drilled wells, we have distinguished six seismo-stratigraphical units (from Triassic to Plio-Quaternary). We have also characterized rhe 300 km long WNW-ESE linearnents, corresponding to an active dexrral strike-slip fault, and rhe geometry of the Coral Patch Ridge. Finally, presem-day active faulting has been observed at the Horseshoe Abyssal Plain and SAP, mainly corresponding to subverrical faults cutting che whole sedimentary sequences up to the surface, sorne of rhem associated with earthquake swarms.

Keywords: Gulf of Cadiz, multichannel seismics, seismo-stratigraphy, srrike-slip fault, rhrust fault, seismiciry.

The scudy area is located in che SW Iberian Margin, in che westernmost pare of che Gulf of Cadiz. This region hosts che presenc-day convergenc boundary becween Eurasian and African places (4.5-5.5 mm a-^{1}) (Grimison and Chen, 1986; Argus ***etal.,*** 1989) and is characterized by moderare to intense magnitude seismic activity (Buforn ***et al.,*** 1995; Baptista ***et al.,*** 19986; Stich ***etal.,*** 2005). T he Gulf of Cadiz is also che source of che largest seismic events in Western Europe, such as che 1st November 1755 Lisbon Earchquake (Mw 8.5) Qohnston, 1996) and che 28th February 1969 one (Mw 8.0) (Fukao, 1973). Recent estimations of depth and seismic moment tensors (Mw 3.8 to 5.3) for che earchquakes chac have occurred in che area show reverse and scrike-slip faulting solucions at a depth ranging becween 6 and 60 km (Stich ***etal.,*** 2007).

Numerous marine geophysical cruises have been carried out in che region during che last fifteen years (Sarcori ***etal.,*** 1994; Banda ***etal.,*** 1995; Gutscher ***et al.,*** 2002; Gracia ***et al.,*** 2003a, b; Terrinha ***et al.,*** 2003; Zicellini *et al.,* 2004); however, there are still sorne key questions to be solved. For example, what is che nature of che crust and where is che oceanic-continental crust transition located, where is che position of che boundary between che African-Eurasian places from che Gorringe to che Straits of Gibraltar, which are che tectonic sources responsible of che largest earthquakes and tsunamis chat have occurred in che area, or what is che real depth-geometry of che active structures idencified in che region.

To answer sorne of these questions we have made a pre-stack depth migration of nine of che sixteen multi-channel seismic profiles acquired during che SWIM-06 marine geophysical cruise. The new seismic images obtained allow us to characterize che real deep and shallow geometry of che active faults and to quantify che deformacion rate and faulc parameters. The present scudy is based on a selection of two profiles (SWl 3 and SWl 6) and focuses on: a) a seismostratigraphic analysis and calibration from che DSDP site 135, b) che characterization of che upper and lower boundaries of che Horseshoe Gravitational Unir, and c) che obtention of che real geometry of prominent structures, such as che Coral Patch Ridge Fault, che scrike-slip SWIM lineaments, and other active faults.

Data and methods

The SWIM-2006 cruise took place at che externa! pare of che Gulf of Cadiz from 31st May to che 14th June 2006 onboard che Spanish R/V Hesperides (P. l. E. Gracia). We acquired sixteen high-resolucion MCS

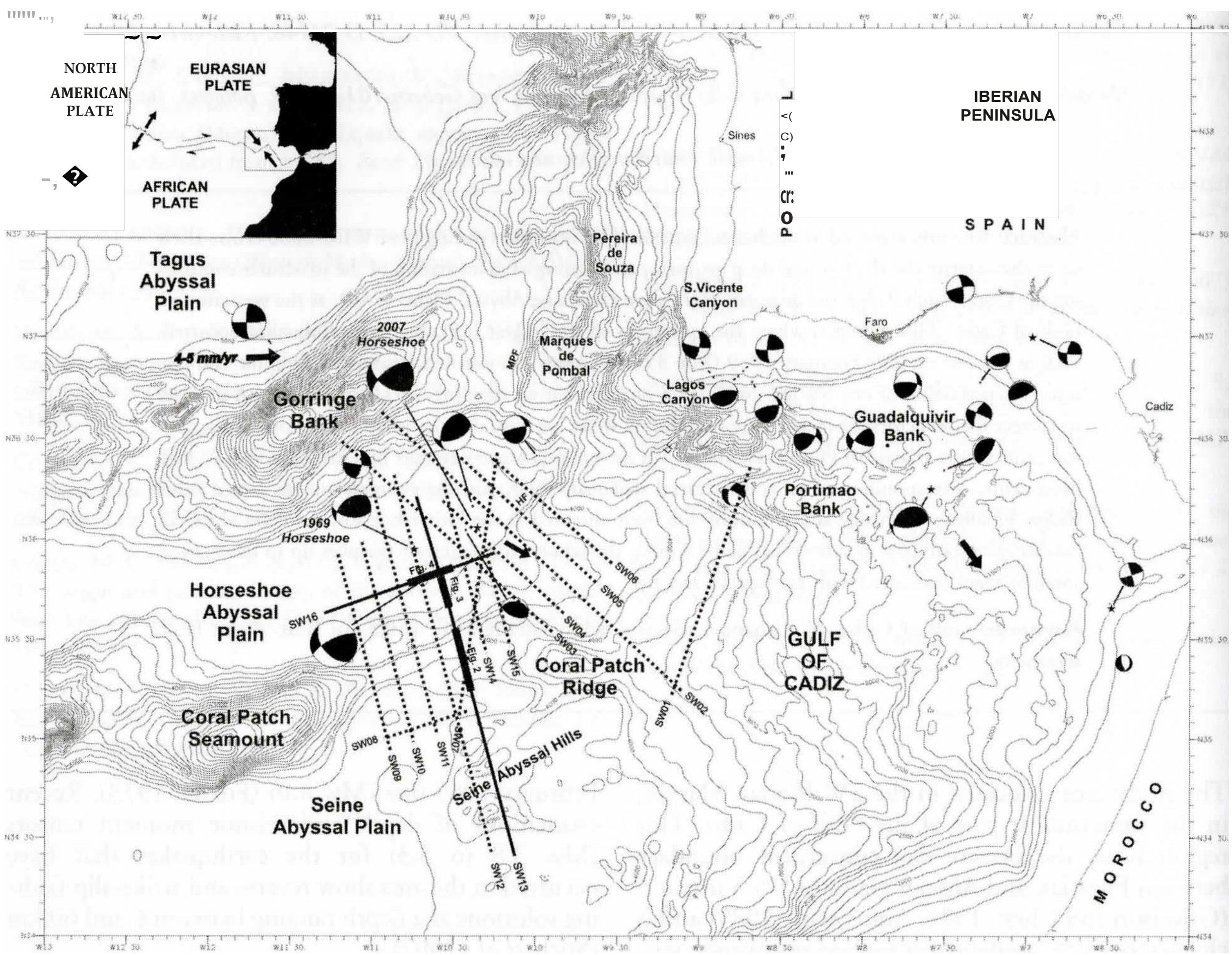

Figure l. Bachymecric map of che Gulf of Cadiz wich che locacion of che MCS profiles acquired during che SWIM-2006 cruise (che posicion of che SW13 and SW16 profiles are indicaced in black) and che locacion of che figures 2, 3, and 4. Place convergence is shown by black arrows. Fault plane solutions are from Buforrn *et al.* (1995) and Scich *et al.* (2005, 2007). Insec: tectonic setting of che SW Iberian Margin at che boundary between che Eurasian and African Places.

profiles (SW01 to SWl6) together wich Simrad EM120 swach-bachymetry and backscatter, TOPAS sub-bottom profiles, magnetics and gravity data (Fig. 1), cocalling more than 2700 km of marine geophysical daca.

Seismic acquisition was performed using a lÓ m array of 8 airguns at 6 m depth producing 1050 c.i. We used an analogical Teledyne streamer wich 2.4 km of active section, formed by 96 channels (25 m separation) and cowed at 7 m depth. We recorded che MCS data in SEGD 48058 rev-1 formats at a sampling rate of 2 ms. The record length was 11 s twtt (two-way cravel time) wich a shot distance of 37.5 m, wich che exception of profile SW01, located in a shallower area, where we obtained a record length of 9 s twtt wich a shot interval of 25 m.

Standard MCS processing was accomplished using PROMAX software, including data resampled from 2 ro 4 ms, channel and shot editing, top mutes picked in che shot gacher domain, true amplicude recovery, Fx-decon, ensemble predictive deconvolution and geometry CDP gather. A velocity model for Kirchoff depth migration was performed in 9 MCS profiles (SW0l to SW07, SW13 and SW16) using che SIRIUS software from IFM-GEOMAR (Kiel, Germany) by a depth-focussing error analysis of che MCS data. In che present work we focus on two perpendicular MCS sections: profile SW13, trending NNW-SSE and 206 km long, and profile SW16, trending WSW-ENE and 103 km long (Fig. 1). The first profile cuts across che Horseshoe Abyssal Plain, Coral Patch Ridge and Seine Abyssal Plain, while che second one cuts along che Horseshoe Abyssal Plain, obliquely to che SWIM Lineament Souch.

Results

Based on che lichostratigraphic units defined in che 689 m deep well DSDP 135 (Hayes *et al.,* 1972) and calibrated wich che depch-migrated seismic profile SW13, which runs exactly on top ofchis site, we have distinguished six seismo-stracigraphical units in che studied area (Fig. 2): 1) Plio-Quaternary to Miocene Unir (hemipelagites, countourites and turbidite layers), including che Horseshoe Gravitational Unir (Medialdea *et al.,* 2004; Iribarren *et al.,* 2007); 2) Early Eocene-Maestrichtian Unir composed of olive grey to brown silty mudscones, sand layers and brown clays; 3) Cretaceous Unir formed by black and green shales with limestone and chert layers; 4) Early Aptian Unir composed of marls and limestones; 5) Upper Jurassic Unir formed by limescones; and 6) Triassic to Jurassic acoustic basement composed of evaporices and carbonates.

The normal incerseccion between profiles SW13 and SW16, allows us to obcain a complete perspective of che scructures distinguished in che area. For example,

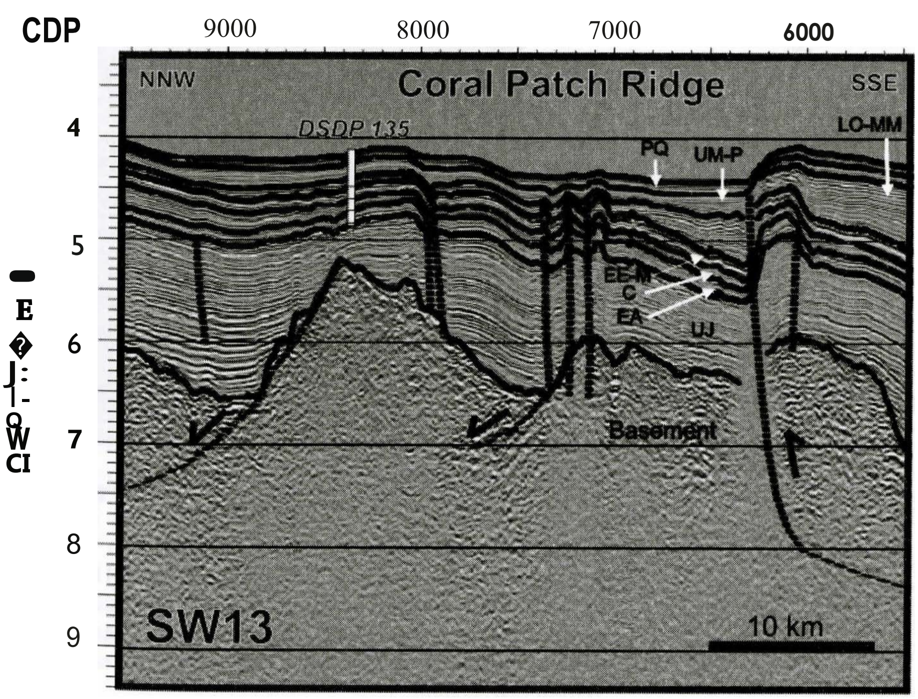

Figure 2. Interpreced seccion of rhe pre-scack depth migraced MCS profile SW13 becween CDP's 5500 and 9500 across che Coral Patch Ridge (1 CDP = 75 m). See location in figure 1. The image shows che location of site DSDP 135 and che seismo-strarigraphic sequence. Unit 1: Late Oligocene to Plio-Quaternary age (LO-PQ) formed by che following sub-units: Late Oligocene to Middle Miocene (LO-MM), Upper Miocene to Pliocene (UM-P), and Plio-Quaternary (PQ); Unit II: Early Eocene to Miocene age (EE-M); Unit III: Cretaceous age (C); Unit IV: Early Aptian age (EA); Unir V: Upper Jurassic age (UJ); and Unit VI: Triassic to Jurassic age, defining rhe acoustic basemenr. Vertical exaggeracion: 5.

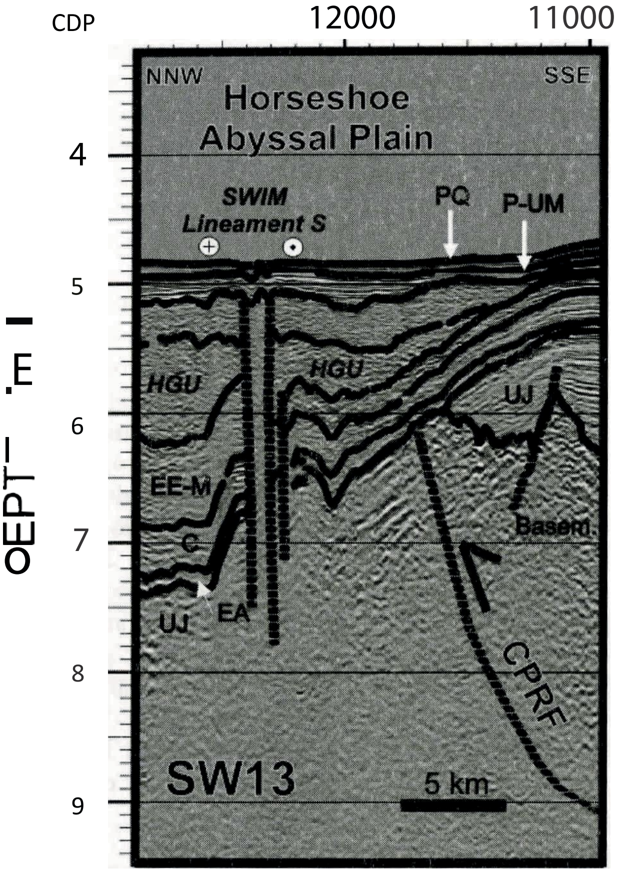

Figure 3. Incerprecedseccionofchepre-scackdepchmigracedpro file SW13 becweenCDP's 11000 and 12800 ac che Horseshoe Abyssal Plain. Seelocacion in figure 1. The image shows che real dip geometry of che Coral Patch Ridge Faulc and che SWIM Lineament Souch. Legend of che seismo-stracigraphicunics 1s included in checapcionof figure 2. Vertical exaggeration:5.

the SWIM Lineament South, corresponding to the bathymetric expression of a WNW-ESE shear zone (Barcolomé *et al,* 2008; Rosas *et al., accepted*), is crossed by both seismic profiles. SWIM Lineament Souch is an active scrike-slip fault displacing che entire sedimentary sequence up to che surface and locally struccured as a flower scructure. This lineament runs across the Horseshoe Abyssal Plain to chewestern pare of che Gulf of Cadiz accretionary wedge, reaching down to a depth of 8 km (Figs. 3 and 4). The Coral Pacch Ridge (CPR), crossed by profile SW13, is com posedof a seriesof posicive reliefs generatedby narrow ly spacedENE-W SW trending folds and thrusts main ly verging to the NW An example of these prominent reverse faulcs is located around CDP 6200 on profile SW13 (Fig. 2), probably reaccivacedfrom the Mesozoic rifting phase, causing the vertical uplift and folding of che sedimentary pile above.We have also identified on the MCS profiles that the Jurassic acousticbasementis scruccured in half-grabens (Fig. 2) and thac che deep geometry of the Coral Pacch Ridge Paule corresponds to a large blind thrust (Fig. 3).

The Horseshoe Gravicational Unir (HGU) of Upper Miocene age and filling most of che Horseshoe Abyssal Plain is crossed by boch profiles. In profile SW13 (Fig. 3), we observe che lateral boundary between chis unir and che CPR, and the resulcing wedge geometry. Profile SW16 extends along che Horseshoe Abyssal Plain and allowed us to identify che upper and lower boundaries of the HGU and its interna! seismic nature, mainly characterized by chaotic facies (Fig. 4). On both profiles we have observedthe deepening of the Mesozoic Units below cheHGU (Fig. 3 and 4).

Discussion and conclusions

The detailed scudy of che MCS profiles allows us to characterizeche deformation sequenceof cheexterna! pare of che Gulf of Cadiz (Fig. 2). We have distin guishedbecweena) pre-rift Triassic and Lower Jurassic

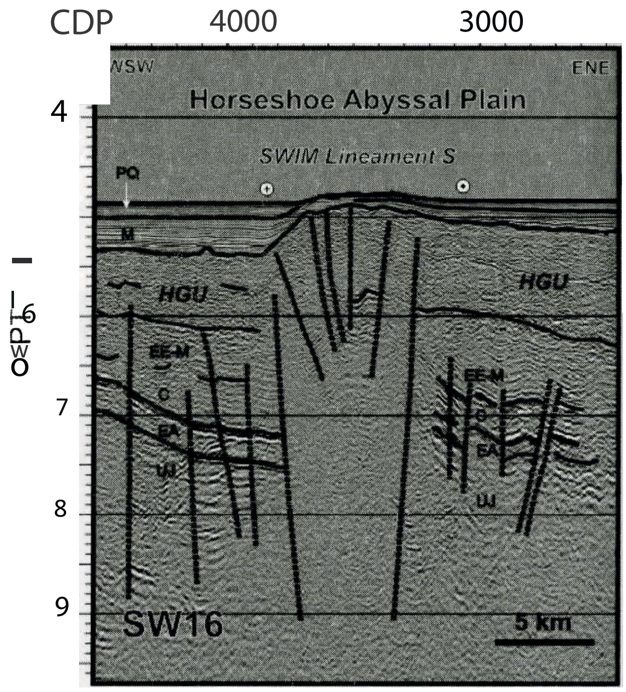

Figure 4. Incerprecedseccionofchepre-stackdepchmigracedpro file SW16 becweenCDP's 2500 and 4500 at che Horseshoe Abyssal Plain. See locacion in figure l. The seccion shows che boundaries of che Horseshoe Gravicacional Unic (HGU), che Mesozoic unics underneach che HGU and che posicive flower scructure geomecryof SWIM Lineament souch. Legend of che seismo-scratigraphicunits is included in che caption of figure 2. Vertical exaggeracion5.

deposics composed of evaporices and carbonates (acouscic basement); 6) syn-rift deposits, made up of Jurassic, E arly Ap[gian, [g retaceousand Early [gocene Maescrichcian Umts, mamly composedof terrigenous edimencs; c) syn-compressional Miocene-Q uacernary deposit[g divid[gd into [g ate Oligoce[g e Mid dle Mio cene, M1ddle M1ocene-Pl10ceneand Pho Quaternary subunics, [gomposed of hemipela[g ites, counrourites and turb1d1telayers, and also compnsmg che Hor seshoe Gravicational Unir (HGU) of Tor ronian age(Torelli *etal.,* 1997), a regional marker infillin g cheHorseshoe Abyssal Plain.

The study of MCS profiles revealspresent-day active faulting at cheHAP and SAP, mainly subvercicalfaulcs curring che whole sedimentary sequenceand chePlio Quacernary unir showing evidence of recent accivicy. The MCS SWIM profiles also allowed us to improve our knowledge of che geometry and extension of che Horseshoe Gravitational Unir, and to characterizeche sedimentary sequence below it. Final ly, we conclude chac pre-stack depch migracion of MCS profiles is highly recommendable in studies where ic is impor tant to know the "real" corrected geomecry of the refleccors, such as decailedneocecconicincerpretacions and calculacionsof faulc seismic parameters, of funda mental importance in arder to assessche seismic haz ard of che souchernIberian Margins.

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