The Alpine Orogeny in the West and Southwest Iberia Margins

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Abstract

The Alpine orogeny is well recorded onshore and offshore by tectonic inversion of the Mesozoic rift basins. Large scale linear seamounts (more than 250 km long and with up to 5 km of uplift) involving oceanic and continental lithosphere were carried on top of thrusts, such as the Gorringe seamount and the Estremadura Spur in the SouthWest and West Iberia Margin, respectively. The SouthWest Iberia Margin also recorded the westward migration of the Gibraltar Oceanic slab as the westwards propagation of the Neo-Tethys subduction. Rotation of the tectonic compression from NW-SE to WNW-ESE in

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C. Quesada and J. T. Oliveira (eds.), *The Geology of Iberia: A Geodynamic Approach*, Regional Geology Reviews, https://doi.org/10.1007/978-3-030-11295-0_11

Pliocene times caused the development of large scale dextral wrench faults as the present day Africa-Iberia plate boundary. Neotectonics of this plate boundary caused large to mega-scale destructive earthquakes and tsunamis.

11.1 Introduction

The West Iberia Margin (WIM) comprises the part of Iberia that was stretched parallel to the main Atlantic continental rifting and experienced oceanic drifting that generated the oceanic magnetic anomalies roughly parallel to the Mid Atlantic Ridge. The study area comprises the West Iberia onshore-offshore rift basins across the Iberia and Tagus abyssal plains to the Madeira-Tore Rise north of the Azores-Gibraltar Fracture Zone (Fig. 11.1).

The Southwest Iberia Margin (SWIM) lies to the West of the Gibraltar Arc comprising the rifted continental margin (the Algarve Basin), the oceanic lithosphere associated with the westernmost Tethys Ocean (Neo-Tethys or Ligurian Tethys), the accreted terranes associated with the closure and subduction of its oceanic lithosphere, the Horseshoe Abyssal Plain and the Gorringe-Josephine Ridge. The SWIM lies near the Eurasia-Africa plate boundary since Early to Middle Jurassic times that has experienced a long lasting history of different kinematics, such as transtensional during Jurassic until Late Cretaceous times, frontal collision in the Paleogene to Early-Mid Miocene times and dextral transpression from approximately Late Miocene through Present (e.g. Srivastava et al. 1990; Schettino and Turco 2009, 2011).

The Alpine Orogeny in the WIM and SWIM affected mainly the rifted areas of the margins essentially through tectonic inversion of the rift Lusitanian and Algarve Basins that are well exposed onshore and of their lateral equivalents in the near offshore. Most of the inversion tectonic structures resulted from inversion or shortcut of extensional faults. Metamorphism has not been recognized in the inverted basins of the WIM and SWIM. Salt décollements played an important role and in the Algarve Basin, at least one allochthonous salt detachment has been recognized and mapped (Matias et al. 2011; Ramos et al. 2017c).

In this paper the term "tectonic inversion" applies to shortening of the Mesozoic rift basins that resulted from the approximate frontal collision of Iberia with Africa or Eurasia mostly during Late Cretaceous to Late Miocene times contemporaneously with mountain building of the Alpine chains in Iberia. In the deep offshore large scale contractional structures near the plate boundary have been described, the nature of which is varied, such as the Gorringe Bank thrust and the Accretionary Wedge of the Gulf of Cádiz that are associated with the Neogene through Present day Eurasia-Africa plate boundary kinematics (e.g. Srivastava et al. 1990). The Estremadura Spur pop-up extends from the

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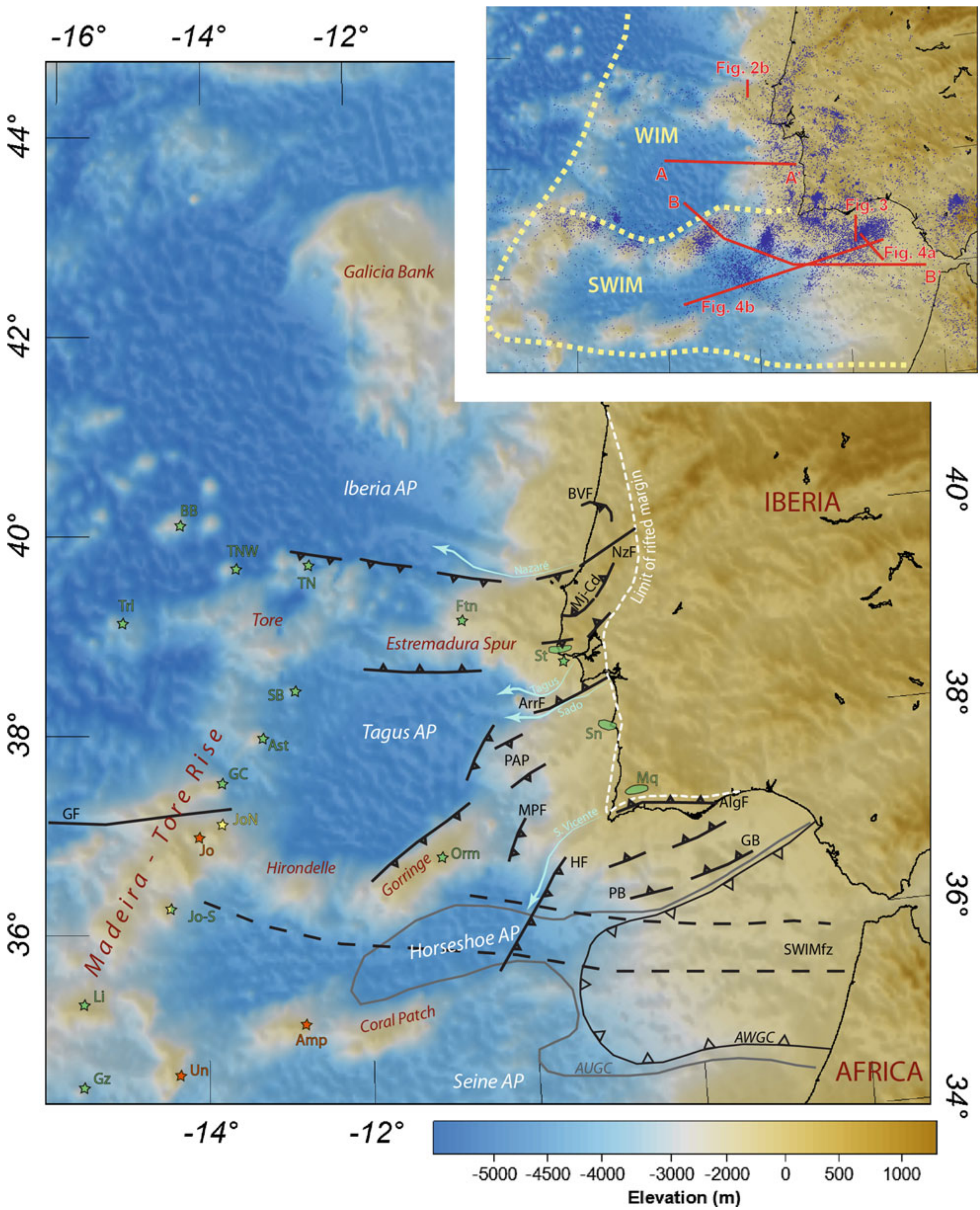

Fig. 11.1 The WIM and SWIM Alpine Orogeny domains, tectonic and magmatic structures and seismicity. AlgF: Algibre fault; ArrF: Arrábida fault; AUGC: allochthonous unit of the Gulf of Cádiz; AWGC: accretionary wedge of the Gulf of Cádiz; BVF: Serra da Boa Viagem fault; GF: Gloria fault; HF: Horseshoe fault; Mj-Cd: Montejunto—Candeeiros system; MPF: Marquês de Pombal fault; NzF: Nazaré fault; PAP: Príncipes de Avis plateau; SWIM fz: Southwest Iberia Margin fault zone. Blue arrows: offshore canyons. Inset: SWIM and WIM boundaries, seismicity; red lines: location of profiles in Fig. 11.7. Ages for West Iberia magmatism: Cretaceous (green), Miocene-Paleogene (orange) or Quaternary (yellow) (Schärer et al. 2000; Geldmacher et al. 2006; Merle et al. 2006, 2009; Miranda et al. 2009; Grange et al. 2010). Onshore magmatic complexes: Mq: Monchique; Sn: Sines; St: Sintra. Offshore dated magmatism: Amp: Ampere; Ast: Ashton; BB: Bikini Bottom; Ftn: Fontanelas seamount; GC: Gago Coutinho; Gz: Godzilla; Jo: Josephine; JoN: Josephine North; Jo-S: Jo-Sister; Li: Lion; Orm: Ormonde; SB: Sponge Bob; Trl: Torillon; TN: Tore North; TNW: Tore NW; Un: Unicorn

continental shelf to the ocean-continent transition, off the Lusitanian Basin as the lateral continuation of the onshore tectonic inversion (Fig. 11.1).

From Pliocene to Present times the tectonic regime in the WIM and SWIM changed. The mountain building and shortening decelerated and wrench tectonics led to the formation of 600 km long lineaments interpreted as dextral strike-slip faults materializing the wrench part of the plate boundary. Also, westwards directed thrusts, uplift of the SW coast of Portugal and the southwards directed thrusting off the Guadalquivir Bank occurred in this time interval (Zitellini et al. 1999, 2004; Gràcia et al. 2003a; Terrinha et al. 2003; Ramos et al. 2016, 2017c). Last but not least, the recorded intermediate frequency and magnitude earthquakes together with the occurrence of large magnitude events of M7.9 (the Horseshoe earthquake in 1969, Fukao 1973) and estimated M $\sim$ 8.5–8.9 (1755 Lisbon earthquake, Johnston 1996) are a strong indication of important compressional active tectonics. This tectonic regime is known as the "tectonic reactivation of the Margin".

The counter-clockwise rotation of the movement of Africa with respect to Iberia from Late Miocene times (e.g. Dewey et al. 1989; Fernandes et al. 2007) and the end of subduction of the Neo-Tethys east of the Gibraltar Strait (e.g. Rosenbaum et al. 2002; Vergés and Fernández 2012) are probably two of the main causes for the changes in the tectonic regime.

Intrusive and volcanic complexes associated to the Upper Cretaceous Alkaline Magmatism (UCAM) occur from the onshore WIM to the Madeira-Tore Rise (MTR). The ages of the onshore complexes vary from approximately 94 to 69 Ma. Along the MTR various bodies were sampled and ages vary from approximately 100 Ma to 80 Ma. Although the tectonic control of the emplacement and origin of the UCAM is still under study and discussion, it is clear that its occurrence marks the end of the Mesozoic rifting and post-rift basins in the WIM and SWIM, i.e. suggesting that magmatism is associated to the inversion tectonics.

11.2 The Upper Cretaceous Alkaline Magmatism (UCAM)

Mata J

The WIM and SWIM were the locus of significant magmatic activity during the Upper Cretaceous. Both onshore and offshore magmatism was alkaline, being clearly distinct from the 202–198 Ma and the 148–140 Ma magmatic cycles that occurred during the previous stages of the West Iberia evolution (see Mata et al. 2015 for a review). The first cycle was tholeiitic and characterized by negative εNd_i but somewhat radiogenic initial Sr isotope ratios (>0.7050) (e.g. Martins et al. 2008; Callegaro et al. 2014); the second cycle was mildly alkaline with εNd_i ranging from +1.6 to +4.2 and initial Sr isotope ratios close to the $CHUR_{145}$ (Grange et al. 2008; Mata et al. 2015). In turn, the Upper Cretaceous magmatism was clearly alkaline and characterized by $\varepsilon Nd_i > 5$ and initial Sr isotope ratios indicating a time-integrated evolution of the mantle source characterized by Rb/Sr ratios clearly lower than the CHUR (e.g. Miranda et al. 2009; Grange et al. 2010).

The onshore UCAM includes the 3 subvolcanic complexes of Sintra, Sines and Monchique, as well as the Lisbon Volcanic Complex, the Mafra radial complex and hypabyssal/volcanic rocks cropping out in the Algarve Basin (SWIM) (Fig. 11.1). This onshore magmatism ranges in age from approximately 94 to 69 Ma (see Miranda et al. 2009; Grange et al. 2010), yet doubts still subsist owing to the lack of a more robust data base. For example, an age close to 72 Ma based on a K-Ar determination by Ferreira and Macedo (1979) was attributed to the Lisbon Volcanic Complex. However, the position of the paleomagnetic pole determined on rocks of this complex suggests an older age (Neres et al. 2012). The offshore UCAM extends to the Madeira-Tore Rise (MTR), along which various Upper Cretaceous bodies were sampled with ages varying from 104.4 $\pm$ 1.4 and ca. 68 Ma (Merle et al. 2006, 2009; Neres et al. 2014).

Considering the three subvolcanic massifs there is an age migration from north (Sintra: 83–80 Ma) to south (Monchique: 70–69 Ma), which was interpreted by Grange et al. (2010) as resulting from the motion of Iberia above a sub-lithospheric mantle plume. Interestingly, these authors also noticed a N to S trend of geochemical variation manifested, for example, by an increasing alkalinity, $(^{206}Pb/^{204}Pb)_i$ and εHf_i, but a decrease in $(^{87}Sr/^{86}Sr)$ from Sintra to Monchique, through Sines. Such variation depicts different degrees of plume-lithosphere interaction.

Despite this, it has to be emphasized that the geochemical characteristics of the UCAM clearly imply a lower lithospheric contribution than the two above mentioned earlier Mesozoic magmatic cycles, allowing considering a secular decrease of the lithosphere role in magma composition, a tendency accompanied by an increasing depth of magma generation (Mata et al. 2015). These differences reflect the origin of the UCAM from a mantle plume as opposed to the inception of the two previous magmatic cycles in response to the adiabatic decompression induced by two important rifting events well marked in the sedimentary sequence.

11.3 The West Iberia Margin (WIM) Inversion Tectonics

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Inversion tectonics in the West Iberia Margin (WIM) is recorded onshore in the Lusitanian Basin by several compressional structures, and offshore along the Estremadura Spur and Príncipes de Avis submarine mountains (Fig. 11.1). With the natural exception of the continental shelf that has been subjected to intensive and recurrent marine erosion associated to the Quaternary sea level oscillations, the tectonic inversion structures originated vigorous mountainous reliefs from the onshore to the deep abyssal plains. The deep submarine mountains rise more than 2 km above the regional depth (with a maximum for the Gorringe Bank of approximately 5 km above the Tagus Abyssal Plain) and display fairly continuous sedimentary successions up to Present. Onshore, mountains barely exceed 0.6 km in height due to the strong subaerial erosion and are usually characterized by exposures of Jurassic rocks in the core of thrust-related anticlines.

The compressional events that affected the WIM during the Alpine Orogeny are associated with the convergence initially accommodated along the northern and southern boundaries of Iberia that led to the formation of the Pyrenees and the Betics with tectonic peaks in Eocene and Miocene times, respectively. However, the concentration of tectonic shortening that resulted from these two orogenic events in the Lusitanian Basin is neither homogeneously distributed nor directional. As a matter of fact, the Miocene tectonic inversion (Betic phase) is widespread across the Lusitanian Basin and the Paleogene deformation (Pyrenean phase) concentrates in the Lisbon-Sintra region mainly (Fig. 11.2a).

In the Lisbon area, the Miocene unconformity cuts through folded Paleogene continental sediments, Cretaceous sediments and the Lisbon Volcanic Complex of Cretaceous age. The exhumation of the Sintra Igneous Complex of Late Cretaceous age was accommodated by overthrusting to the north over the Upper Jurassic and Lower Cretaceous succession. The exhumation was dated using fission track analyses in apatite that yielded a thermal exhumation age of ~55 Ma, i.e. Eocene times (Stapel et al. 1996; Terrinha et al. 2018).

The overlap of ages of volcanic edifices along the Madeira-Tore Rise (MTR) (~100–80 Ma, Geldmacher et al. 2006; Merle et al. 2006, 2009) and of the Foz da Fonte and Sintra intrusives (94 ± 2 Ma and ~80 Ma, respectively, Miranda et al. 2009) together with the geophysical evidence of a trail of intrusions along the Estremadura Spur suggest the existence of a magmatic linkage between the MTR and the Lusitanian Basin (Neres et al. 2014). The concentration of intrusions and volcanism in the Sintra-Lisbon area has certainly caused a positive thermal anomaly favouring concentration of the Pyrenean compressive tectonics. The lack of clasts and blocks from the Miocene formations in the deposits associated with the thrusting is in agreement with Paleogene or even Late Cretaceous age of this tectonic event.

The Late Cretaceous was a key period in the kinematic history of the Iberian plate: during these times Iberia drifted southwards with respect to Eurasia, opening the oceanic floored Bay of Biscay, in a motion that is commonly known as the rotation of Iberia. This kinematic event is well registered in the Bay of Biscay magnetic anomalies, as well as in the paleomagnetic record of Iberia. This was presented by Van der Voo (1969) as one of the first links between paleomagnetism and plate tectonics. However, intense debate still subsists about the reconstruction of the opening of the Bay of Biscay and that of the Atlantic off West Iberia, with important implications to the subsequent tectonic evolution of the Iberian plate in particular of the Pyrenean domain (see Barnett-Moore et al. 2017 and references therein). The timing for the onset of rotation is not consensual as it occurred during the Cretaceous Normal Superchron (125–84 Ma). However, the end of the rotation is well constrained at 80 Ma (age of C33r anomaly, which matches the ridge abortion age in the Bay of Biscay). This age coincidence between the Iberia rotation with respect to Eurasia and the main phase of onshore and offshore magmatism, in particular in the Lisbon region, suggests a link between the Late Cretaceous magmatism, the rotation of Iberia and the early stages of tectonic inversion of West and Southwest Iberia.

The main compression direction during Miocene times was NW-SE oriented, in agreement with the trajectory of Africa with respect to Iberia and kinematics of the faults. The E-W to NE-SW trending faults were reactivated as reverse faults and the N-S to NNE-SSW faults were reactivated as sinistral transpressive faults (Fig. 11.1). The comparison of the structural maps of the basement, extensional structures and tectonic inversion structures, including the outcropping salt walls in the Lusitanian Basin, shows that the onshore and nearshore inversion structures resulted mostly from reactivation of extensional structures and most of the basement extension was not recovered during tectonic inversion (Ribeiro et al. 1990, 1996; Kullberg 2000; Kullberg et al. 2000, 2013).

The Miocene compressional event was firstly described by Choffat (1908) in his early works on the Arrábida fold and thrust belt, the most elegant example of the compressive Alpine Orogeny in the Portuguese territory. Onshore, it forms a 35 km long belt of an imbrication of three retrogressive southwards directed low angle thrusts, the southernmost and northernmost of which have been dated at 17.5–16.5 Ma and 9–7 Ma, respectively (Kullberg et al. 2013 and references therein). The Arrábida thrust belt extends into the offshore forming altogether an approximately 95 km long thrust belt (Fig. 11.1) at the southern edge of the Estremadura Spur.

The Montejunto and Boa Viagem mountains are hanging-wall anticlines developed on top of thrust ramps, while the Candeeiros mountains resulted from transpressive tectonics along ~N-S striking inverted extensional faults (Fig. 11.1).

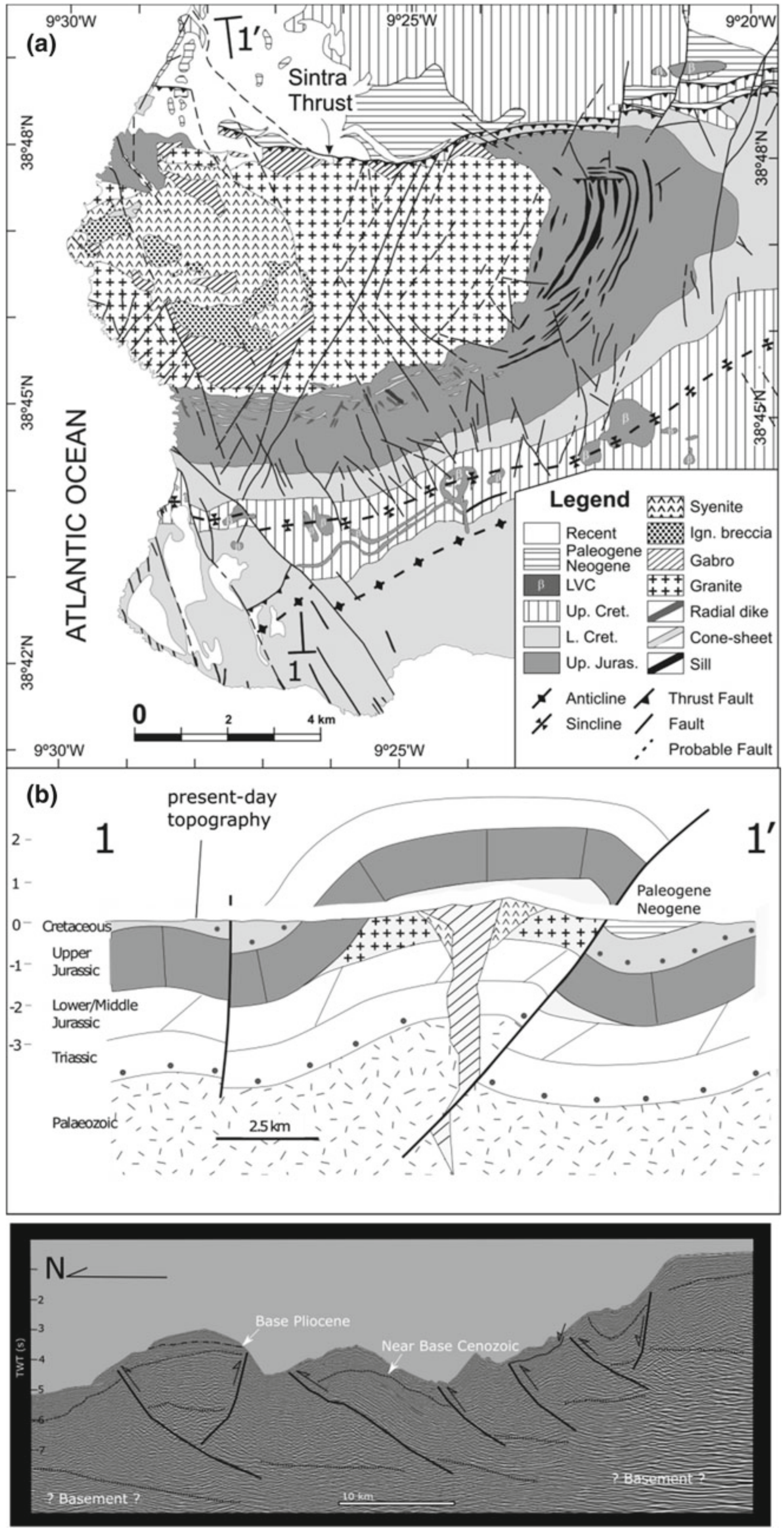

Fig. 11.2 Alpine thrusts in the Lusitanian Basin, above: Sintra thrust (**a**: map; **b**: cross section; from Terrinha et al. 2018). Below: multichannel seismic profile across the offshore prolongation of the Nazaré Fault (courtesy of ENMC, for location see inset in Fig. 11.1). Both structures are interpreted as basement involving thrusts. The Sintra thrust uplifted the Sintra Igneous Complex, whose exhumation occurred in Paleogene times (see text). The Nazaré Fault is a complex fracture zone that acted as a transfer fault during the Mesozoic rifting and was reactivated during the Alpine compression

Inspection of the bathymetry of the Estremadura Spur shows a continuous sequence of folds connecting the Tore seamount to the onshore. Seismic reflection profiles across the Estremadura Spur attest for a pop-up compressional structure with two main thrusts with opposite transport directions (Neves et al. 2009). The W-E trending northern boundary of the Estremadura Spur rotates towards NE-SW, i.e. perpendicular to the main Miocene tectonic compression, thus reactivating as a compressive structure the Nazaré Fault, the main transfer fault during the Mesozoic rifting in the Lusitanian Basin (Stapel et al. 1996; Rasmunssen et al. 1998; Kullberg et al. 2013) (Fig. 11.2b).

On the other hand, the W-E trending southern boundary of the Estremadura Spur rotates towards NW-SE, i.e. to a trend approximately parallel to the Miocene compression vector, favouring transpressional tectonics (Figs. 11.1 and 11.2b). Accordingly, the shortening in the southern boundary of the Estremadura Spur is transferred to the submarine part of the Arrábida thrust belt.

The Príncipes de Avis Mountains form a trapezoidal plateau on the continental slope. The joint interpretation of seismic reflection profiles (Zitellini et al. 2004) and swath bathymetry (Zitellini et al. 2009) allows identification of SW-NE trending crests associated to NW-wards directed thrusts and backthrusts (Terrinha et al. 2003; Cunha et al. 2010; Zitellini et al. 2004), mostly formed during Miocene times.

11.4 The Southwest Iberia Margin (SWIM) Inversion Tectonics

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The SWIM can be subdivided into two domains according to the structural style and geological evolution during the Alpine orogeny (Fig. 11.1): (i) the onshore-offshore Algarve Basin and its western prolongation across the Gorringe Bank to the Josephine-Hirondelle Ridge consisting of autochthonous and parautochthonous terrains of an inverted continental rifted margin, and (ii) the Gulf of Cádiz allochthonous units that include the so-called Allochthonous Unit of the Gulf of Cádiz (AUGC), and the Accretionary Wedge of the Gulf of Cádiz (AWGC) (e.g. Torelli et al. 1997; Medialdea et al. 2004; Gutscher et al. 2002; Iribarren et al. 2009; Terrinha et al. 2009).

The divide between these domains is not a single geological structure. To the south of Portugal the divide is the southern boundary of the Algarve Basin, the Guadalquivir Bank and its lateral morphologic prolongation, the Portimão Bank. The Guadalquivir Bank consists of a basement high initially formed as an extensional horst during Mesozoic rifting (Terrinha 1998; Gràcia et al. 2003a). However, it has been reactivated and transported by a south-directed intra-crustal blind thrust as strongly suggested by the northward tilted package of Pliocene-Quaternary sediments observed in the seismic reflection profiles across the northern

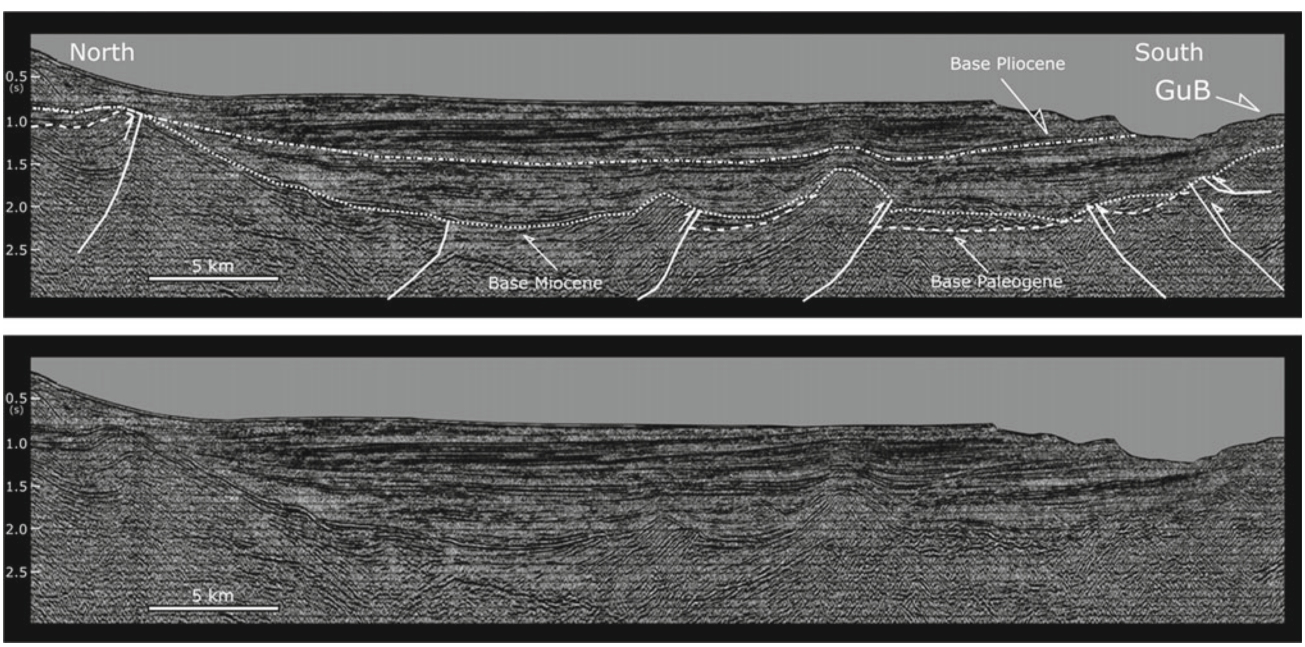

Fig. 11.3 North-South multichannel seismic profile off the Algarve coast, south Portugal, showing a series of southwards directed thin-skinned thrusts and northwards direct basement involving back-thrusts near the Guadalquivir Bank (GuB). For location see inset in Fig. 11.1

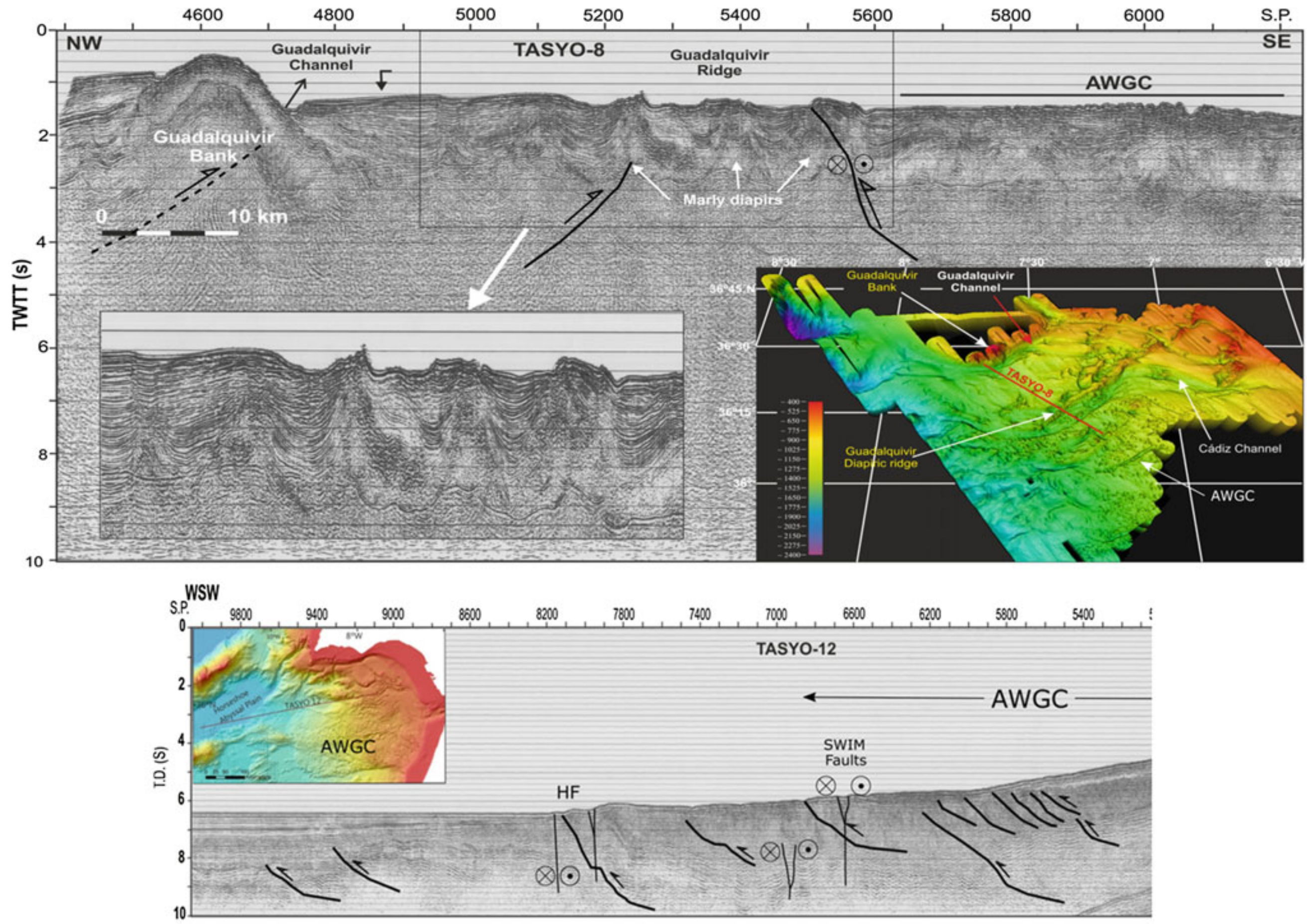

Fig. 11.4 Multichannel seismic profiles in the Gulf of Cádiz (TASYO 8 and 12), adapted from Medialdea et al. (2004). **a** Profile Tasyo 8 cuts approximately perpendicularly to the Algarve Basin, Guadalquivir Diapiric Ridge and Gulf of Cádiz tectonic domains. Note also the tilted Quaternary units on the northern flank of the Guadalquivir Bank and southwards directed interpreted thrust (from Ramos et al. 2017). **b** Profile Tasyo 12 along dip section of the Gulf of Cádiz, showing main faults within the AWGC, the HF and SWIM faults. For detailed stratigraphic interpretation see Medialdea et al. (2004)

flank of this basement high (Ramos et al. 2017a, Figs. 11.3 and 11.4). Blind north-directed back-thrusts have also been reported in this tilted sedimentary package, adding further evidences for the contractional reactivation of the Guadalquivir Bank. At Present the Guadalquivir Bank sits on top of an elongated seismicity cluster, probably reactivating the deep crustal part of the south-directed thrust (Palano et al. 2015; Custódio et al. 2015) (Figs. 11.1, 11.3 and 11.4a).

To the north of the Guadalquivir Bank the crust was mildly thinned during the Mesozoic rifting (proximal domain) with present day thicknesses of approximately 30 km, near the Triassic-Paleozoic basin boundary, to ~20 km just north of the Guadalquivir Bank (Sallarès et al. 2011). The Guadalquivir and Portimão Banks sit on top of an ENE-WSW oriented uplifted elongate area, the necking domain with crustal thicknesses from 15 to 20 km that separates the proximal domain from the highly extended domain with extremely rotated blocks that marks the transition to the oceanic crust. These basement uplifts are thus located in the former necking domain (Ramos et al. 2017a), which was intruded by a post-rift ENE-WSW elongated, 80 × 20 km magmatic intrusion of possible Cretaceous age (Neres et al. 2018). South of the continent-ocean transition the basement below the Mesozoic sediments appears to be constituted by at least three geological domains of different origin and compositional affinity. The Seine Abyssal Plain (SAP) and the Gulf of Cádiz (GC) domains, which compose the internal Gulf of Cádiz, are floored by Atlantic-type oceanic crust. The SAP appears to be generated during the first stages of slow seafloor spreading in the NE Central Atlantic in the Early Jurassic. The GC domain originated in the Alpine-Tethys spreading system between Iberia and Africa, coeval to the formation of the SAP and ended just after the North Atlantic continental breakup (Late Jurassic). On the other hand, the Gorringe Bank (GB) domain is mostly made of mantle rocks. It was generated by mantle exhumation during the first stages of North Atlantic opening. This domain is likely part of the Zone of Exhumed Continental margin (ZECM) that has been identified to constitute the ocean-continent transition along most of the SWIM (Sallarès et al. 2011, 2013; Martinez-Loriente et al. 2014).

11.4.1 The Algarve Basin, Gorringe Bank and Josephine-Hirondelle Ridge

11.4.1.1 Geometry and Kinematics

To the north of the Guadalquivir Bank the geometry of the tectonic inversion of the Algarve Basin has two different styles, (i) thick-skinned thrusting along the northern basin margin, where the Triassic-Hettangian evaporite layer is negligible to absent, and (ii) the area to the south of the Algibre Fault where the Hettangian salt has decoupled the contractional structures in the cover from the basement-involved thrusts underneath. A sub-domain within the latter, in the central part of the offshore Algarve Basin, where an allochthonous salt sheet occurs (the Esperança Salt Nappe) adds further complexity to the thin skinned tectonics in the central part of the offshore Algarve Basin (Fig. 11.1; Matias et al. 2011; Ramos et al. 2016; 2017a, b, c).

The Algarve Basin is bounded to the north by a mountainous relief of Paleozoic basement that overthrusts the basin to the south in some places. However, most of the Alpine deformation was accommodated within the basin where most of the southwards directed extensional faults were inverted. The Triassic-Hettangian salt acted as a décollement horizon both during the extensional deformation and the subsequent Alpine shortening. Contractional deformation during tectonic inversion of the basin was localized in the former developed salt structures that were reactivated and squeezed as evidenced by the geometries imaged in the seismic lines. Depth converted seismic profiles allowed for producing true vertical thickness maps, based on which a new tectonic inversion model was proposed, in which southwards directed basement involved blind thrusts controlled vertical basin uplift and localization of the Paleogene and Neogene depocentres forming an imbricate system of four major thrust (Ramos et al. 2016, 2017a) (Figs. 11.1 and 11.3).

11.4.1.2 Polyphase Tectonic Inversion

Two types of tectonic inversion events have been reported in the Algarve Basin, i) transient events that occurred between rifting phases, and ii) final tectonic inversion.

The transient tectonic inversion episodes are mainly reported from inspection of onshore outcrops and mapping. Well documented shortening structures occur in the lower Pliensbachian, upper Callovian and Uppermost Jurassic as typical fold and thrust structures are truncated by well dated erosion unconformities. The upper Callovian and Uppermost Jurassic events are associated with two of the main stratigraphic hiatuses in the Algarve Basin, the Mid Jurassic-Upper Jurassic and Upper Jurassic-Lower Cretaceous hiatuses of widespread erosion across the Basin. The sedimentary facies and ammonite record across these unconformities show an abrupt change from deep water to shallow water depositional environments. Extensional tectonics occurred before and after the shortening structures. These transient inversion events accounted for interruption of the Tethyan-Boreal (proto-Atlantic) oceans marine pathways between Africa and Western Eurasia with consequent ecological changes recorded by the marine fauna of ammonites (Terrinha et al. 2002).

The "final tectonic inversion" term is applied to the shortening events that post-date the last rifting phase, contemporaneous with the onshore mountain building of the Pyrenees and Betic orogens. Onshore, the Lower Miocene succession (Burdigalian in age) is shallowly dipping and lies unconformable on top of Mesozoic rocks deformed by thrusts and related folds. The lack of post-Cenomanian through Paleogene sediments does not allow the precise dating of tectonic events during this long time interval. However, a suite of ductile to brittle thrusts, folded basic dykes (dated as 72 Ma old), subsequently fractured within the Loulé salt diapir, indicate progressive exhumation of the basin during this long time interval (Terrinha et al. 1990; Davison et al. 2016).

Structural mapping using marine multichannel reflection seismic profiles allowed production of maps showing contractional structures and unconformities of Late Cretaceous, Paleogene and Early Miocene ages widespread across the basin, clearly showing the poly-phase character of the collision of Iberia with the Eurasia and Africa counterparts (Terrinha 1998; Lopes et al. 2006; Ramos et al. 2017a). The lack of Upper Cretaceous to Lower Neogene sedimentary record (Cenomanian to Burdigalian) onshore and the development of a depocentre of Upper Miocene through Quaternary sediments in the central offshore Algarve Basin support a model of crustal shortening related to south-directed thrusting followed by mountain collapse (Fig. 11.3). This change of kinematics and localization of the tectonic deformation, usually known as the tectonic reactivation of the SWIM and WIM, started in the Late Miocene-Early Pliocene, coincident with the opening of the Strait of Gibraltar, the onset of the Mediterranean Outflow Water, important climate change and dramatic change from carbonate to siliciclastic sedimentation in the continental shelf of the SWIM and WIM.

In the deep offshore, the Gorringe Bank rises 5 km above the Tagus Abyssal Plain by means of a large scale fold and lithospheric scale thrust with an estimated northwestwards directed movement of about 20 km (Galindo-Zaldívar et al. 2003; Jiménez-Munt et al. 2010; Sallarès et al. 2013) in a short period of time (from the Early to the Middle Miocene; Tortella et al. 1997; Jiménez-Munt et al. 2010).

The ~70 km long Marquês de Pombal N-S striking and easterly dipping fault was interpreted as a Mesozoic extensional fault inverted in Miocene times (Zitellini et al. 1999; Gràcia et al. 2003a; Terrinha et al. 2003). However, Roque (2007) and Pereira and Alves (2013) showed that this reverse fault and contractional deformation in between the Gorringe Bank and the mainland started as early as in Eocene times. This Early Cenozoic uplift generated important localized erosional unconformities and submarine valleys as early precursors of the São Vicente canyon that developed mainly in Pliocene-Quaternary times when the main displacement on the Marquês de Pombal thrust occurred (Roque 2007; Valadares 2012).

The westward prolongation of the Gorringe Bank to the Madeira-Tore Rise forms a prominent ridge, the Hirondelle-Josephine seamounts (see Fig. 11.1 for location), also associated with the Alpine orogeny and still active in the Present (e.g. Hayward et al. 1999; Omira et al. 2016).

11.4.2 The Gulf of Cádiz

The area generally known as the Gulf of Cádiz encompasses the region between SW Iberia and NW Africa across which the present day and paleo plate boundaries cut across. The following tectonic-stratigraphic units and faults stand out as the main structures: the Accretionary Wedge of the Gulf of Cádiz (AWGC), the Allochthonous Unit of the Gulf of Cádiz (AUGC) (e.g. Torelli et al. 1997; Medialdea et al. 2004; Gutscher et al. 2002; Gràcia et al. 2003b; Iribarren et al. 2009), the Horseshoe Fault (HF) (Zitellini et al. 2004; Martínez-Loriente et al. 2018), the SWIM Fault system (Terrinha et al. 2009; Zitellini et al. 2009; Bartolomé et al. 2012) and the Coral Patch Ridge Fault system (CPRFS) (Martínez-Loriente et al. 2011, 2013) (Figs. 11.1 and 11.4).

In the early scientific literature the AWGC and the AUGC were merged into one single unit possibly due to lack of data and the similar seismic chaotic signal. However, due to the large amount of academic and industry seismic reflection, seismic refraction and swath bathymetry data acquired since the 90ies, the views on the geodynamics of the Eurasia-Africa plate boundary evolved substantially. The AWGC formed in the footwall of the Gibraltar Arc westward-directed frontal thrust over the oceanic slab of the remnant of the Tethys Ocean. A widespread unconformity of Pliocene age covering the AWGC suggests that most of the thrust stacking occurred before Pliocene times, probably during the Paleogene-Miocene when the Alborán oceanic crust was being consumed under the western Tethys subduction zone (Gutscher et al. 2002).

The AUGC is a body with a seismic chaotic facies that is located in front of the AWGC and covers most of the Horseshoe Abyssal Plain. This body is believed to be a large olistostrome fed from the pre-Miocene tectonic highs that resulted from early Alpine orogenic events, such as early uplift and thrusting of the Gorringe Bank, the Algarve Basin and the Coral Patch Ridge seamounts (e.g. Torelli et al. 1997; Medialdea et al. 2004; Iribarren et al. 2009).

11.5 Tectonic Reactivation of the SWIM and WIM

Terrinha P, Gràcia E, Hensen Ch, Gutscher MA, Matias L, Pinheiro L, Somoza L, Medialdea T, Sallarès V, Bartolomé R, Martínez-Loriente S, Magalhães V, Rosas F, Duarte J, Neres M, Silva S, Roque C, Neves C, Ribeiro A, Zitellini N

The 1755 Lisbon earthquake destroyed Lisbon (intensity X-XI MSK), was felt as far as in Finland and was accompanied by a tsunami that devastated the SW Iberian and NW African coasts (Baptista et al. 1998; Baptista and Miranda 2009). The existence of large magnitude earthquakes: (Mw > 8.5), estimated magnitude of the 1755 Lisbon earthquake (Johnston, 1996), and M7.9 of the Horseshoe earthquake in 1969 (Fukao 1973) together with moderate frequency and magnitude seismicity in the offshore and onshore of the SWIM, attest for the existence of important compressive tectonics along the SWIM, near the Eurasia-Africa plate boundary.

The recognition of the uplift of the Pliocene marine unconformity to approximately 120 m and of Quaternary marine erosion surfaces to ~55 m above sea level are independent onshore indicators of vigorous neotectonics (Feio 1951). Based on these evidences and on recognition of reverse and strike-slip faulting of Quaternary age in the onshore, Ribeiro and Cabral (1987) and Ribeiro et al. (1996) speculated for the first time on the possibility of the compressive reactivation of the Atlantic passive margin of Iberia and nucleation of a subduction zone, a subject that was re-visited by various authors using state-of-the art data sets of swath bathymetry and reflection seismics (e.g. Terrinha et al. 2009 and Duarte et al. 2013).

In the 90ies various projects sponsored the mapping of the SWIM seafloor searching for seismogenic and tsunamigenic tectonic sources. The first comprehensive bathymetric map of the SWIM was published by Zitellini et al. (2009). From 1999 to Present, a large wealth of geophysical and geological data dedicated to the understanding of tectonic sources were acquired, most of which were summarised by Gutscher et al. (2012). The geophysical data comprehend mostly seismic reflection and refraction data, ocean bottom seismometers (OBS) recording of seismicity, side-scan sonar and swath bathymetry surveys. Geological data comprehend various types of seafloor sampling including high resolution coring for dating fault movement events (e.g. Gràcia et al. 2010). The exploration data have been complemented by continuous collection of onshore geodetical data. Analogue and numerical modelling allowed for understanding fault interaction mechanisms and to recognize that strike-slip and thrust faults not only allow for deformation partitioning but may also be means of propagating large ruptures caused by large earthquakes (Rosas et al. 2016).

Analog modelling replicated cross cut intersection patterns on the surface of the AWGC suggesting that both westwards directed thrusting and dextral W-E strike-slip faulting are active at Present (Duarte et al. 2011; Rosas et al. 2012). This implies that the oblique collision of Eurasia and Africa is active as well as the subduction process, which is in agreement with the very deep earthquakes, $\sim$600 km of depth under the Granada region in southern Spain, although a Benioff surface of seismicity is not observed (Gutscher et al. 2002, 2012; Zitellini et al. 2009).

Numerical neotectonic modelling of the region comprising the plate boundary and intraplate regions of Iberia and North Africa allowed estimating the fault slip and deformation rates, as implied by geodynamic constraints. This modelling also supports that a driving mechanism additional to the lithospheric Africa-Eurasia collision forces must be active in the Alborán domain in order to best fit the present day geodetic, stress and seismicity patterns. This sublithospheric mantle mechanism, induced by dynamic processes of the subducted Gibraltar slab, has its main effect in the westwards movement of an independent Alborán domain, constraining the propagation of stress and strain to the Gulf of Cádiz domain, in particular controlling the kinematics of the Gibraltar related AWGC (Neres et al. 2016).

The reactivation of the SWIM is also testified by the seismic activity (Fig. 11.5). Micro-seismicity studies, based on ocean bottom seismometers temporary networks, showed that hypocenters are mostly in the upper lithospheric mantle and cluster in three areas: Gorringe Bank, São Vicente Canyon and along a roughly NW-SE lineament in the Horseshoe Abyssal Plain (Geissler et al. 2010; Silva et al. 2017; Grevemeyer et al. 2016, 2017). These areas are coincident with known fault interference zones that may be replicated at upper mantle depth, as evidenced by the micro-seismicity focal mechanism solutions (Silva et al. 2017). Additionally, these clusters of seismicity are also coincident with the boundaries between different lithospheric domains. The proposed Horseshoe Abyssal plain Thrust (HAT) that separates serpentinized mantle from oceanic crust is a blind fault that can accommodate part of the deep seismicity (Martínez-Loriente et al. 2014). Both geological settings (fault interference zones and rheological boundaries) can promote stress and strain localization (Rosas et al. 2012; Martínez-Loriente et al. 2014).

Micro-seismicity and ML $\approx$6 events (e.g. the December 17th, 2009 earthquake in the São Vicente cluster) are located deeper than active crustal faults suggesting that these faults are either locked or moving aseismically. Silva et al. (2017) suggested, based on analysis of OBS data, that the existence of a serpentinized mantle layer in the area (down to $\approx$20 km in depth, e.g., Sallarès et al. 2011, 2013) induces a tectonic decoupling between the crust and the lithospheric upper mantle, inhibiting micro-seismicity above the serpentinized mantle layer. Seismic ruptures may instead propagate up to crustal active thrust faults across the serpentinized mantle layer only during very high-magnitude events.

One of the latest result that came out from the joint analysis from exploration seismic reflection, swath bathymetry data and numerical modelling is that earthquake triggered submarine landslides are capable of generating large tsunamis in the SWIM (e.g. Lo Iacono et al. 2012; Omira et al. 2016 for the Gorringe Bank and Hirondelle seamount Quaternary landslides, respectively). These landslides are associated both with the important seismicity and the vigorous reliefs of the SWIM. As a matter of fact, the SWIM shows a wide variety of morpho-tectonic domains from which stand out very high submarine mountains rising up to 5 km above the abyssal seafloor (Figs. 11.1 and 11.6, Valadares 2012). These mountainous reliefs result from Quaternary reactivation of thrusts formed during the Alpine Orogeny: the Gorringe Bank, the Coral Patch Ridge, the Marquês de Pombal plateau, the Horseshoe Fault anticline, the Guadalquivir Bank, the AWGC and the Príncipe de Avis Mountains (for seismic profiles see Zitellini et al. 1999, 2004; Gràcia et al. 2003a; Terrinha et al. 2003; Martínez-Loriente et al. 2011, 2013, 2018; Gutscher et al. 2012).

The swath bathymetry compilation revealed a combined action between different shaping processes in order to generate the wide variety of the seafloor morphologic features identified (Fig. 11.6). In a broad scale, the SW Iberian margin incorporates part of three abyssal plains (Tagus, Horseshoe and Seine abyssal plains) separated by two submarine linear mountains, the Gorringe-Hirondelle and the Coral Patch ridges that resulted from Alpine compression. At the center of the Gulf of Cádiz a major arcuate horseshoe shaped and wrinkled seafloor domain is present (the AWGC). The drainage arrangement and submarine sediment transport that accommodates the source to sink sediment transport is processed by three major systems: (i) the Mediterranean Outflow Water (MOW) contourite system that starts on the approaches of the Strait of Gibraltar and extends on the East and North sectors of the Gulf of Cádiz; (ii) the submarine canyons that cut across the continental slope, and (iii) a system of several E-W trending submarine

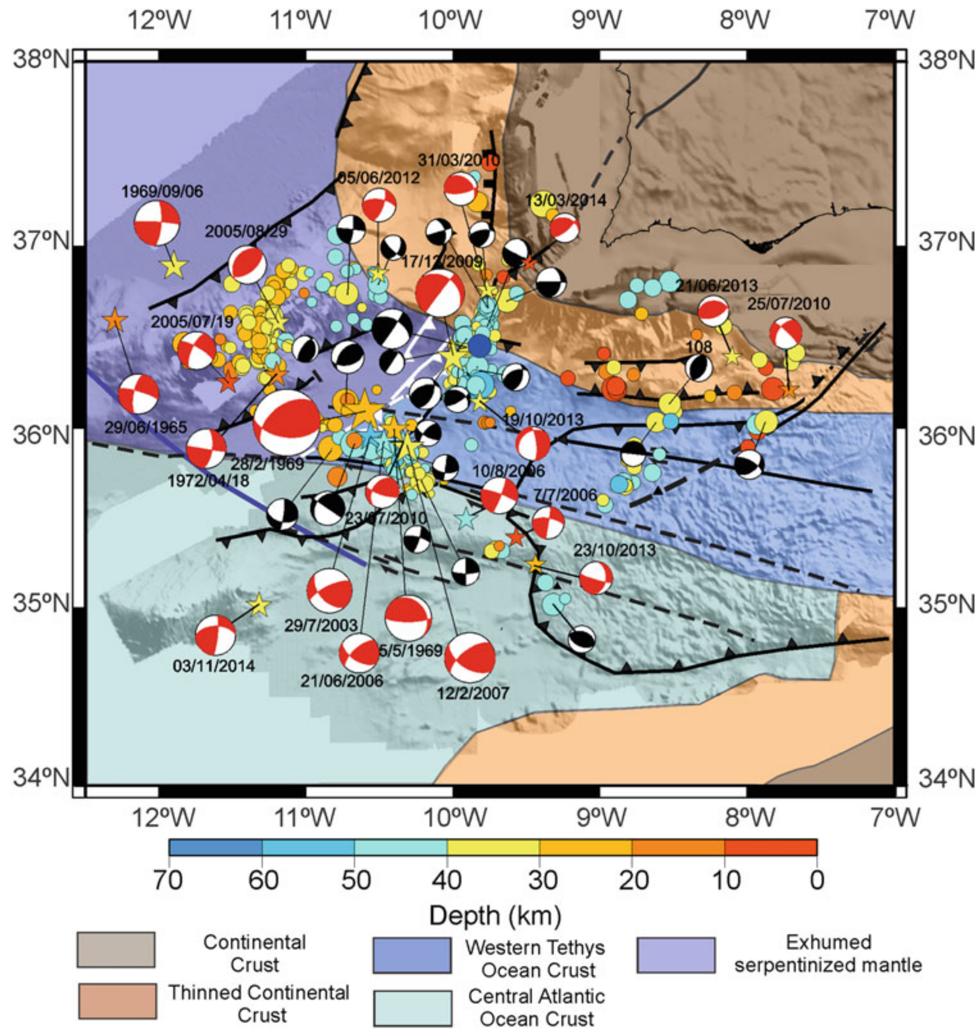

Fig. 11.5 Earthquakes and focal mechanism solutions ($ML \geq 3.0$) recorded in the NEAREST OBS network (max ML = 4.8, circles and black compression quadrants) and the fault plane solution for the highest magnitude earthquakes recorded in the land network (stars and red compression quadrants) (Silva 2017; Silva et al. 2017). Full black lines define active faults, dashed lines are inferred or possible active faults, white lines are blind faults and blue line is the PIAB-Paleo Iberia-Africa plate Boundary (Rovere et al. 2004). Lithospheric domains adapted from Martínez-Loriente et al. (2014)

valleys that connect the surroundings of the Gibraltar Strait and Guadalquivir Basin to the Horseshoe Abyssal Plain (Hernandez-Molina et al. 2003, 2016; Terrinha et al. 2009; Roque et al. 2012). These erosive systems that occur in the western part of the SWIM are in concordance with the Pliocene uplift of the continental SWIM. The tectonic plateaus make up another important geomorphological domain. These have a more or less flat top and are uplifted carried on top of reverse faults (cf. with Figs. 11.1 and 11.6).

A significant amount of structures resulting from vertical escape of fluidized sediments like marl and salt diapirs (Fig. 11.4a) and mud volcanoes, ranging from approximately 0.1 km to more than 10 km in diameter, are tectonically controlled (Medialdea et al. 2009) and crop out mainly in the AWGC but also in the Seine and Horseshoe Abyssal Plains (Fig. 11.6). Mud volcanoes (MV), mud diapirs and diapiric ridges, carbonate mounds and pockmarks have been identified in the Gulf of Cádiz. The, so far, more than 60 mud volcanoes confirmed by coring in the Gulf of Cádiz occur in clusters, are cone-shaped edifices ranging from 100 to 3500 m in diameter, which can tower in places up to 500 m above the seabed (Somoza et al. 2003; Magalhães et al. 2012). Edifices are made up of mud flows containing fluids (water, brine, gas, oil) intercalated with hemipelagic sediments. Most mud volcanoes are presently active with evident indications of fluid and gas seepage (degassing structures, H_2S smell related to sulphate reduction driven by anaerobic oxidation of methane) and have chemosynthetic fauna and precipitation of methane-derived authigenic carbonates (e.g. Díaz-del-Río et al. 2003; Pinheiro et al. 2003; Somoza et al. 2003; Van Rensbergen et al. 2005; Magalhães et al. 2012; León et al. 2012; Hensen et al. 2007; Toyos et al. 2016; Scholz et al. 2009, 2010). The largest number of mud volcanoes is found at shallow to intermediate depths close to the Gibraltar arc deformation front and are thought to result from overpressured sediments associated to westward directed thrusts (Somoza et al. 2003). The most important drivers of sediment overpressuring are the transformation of smectite to illite occurring in thick Miocene terrigeneous sediments (e.g. Scholz et al. 2010) and the presence of

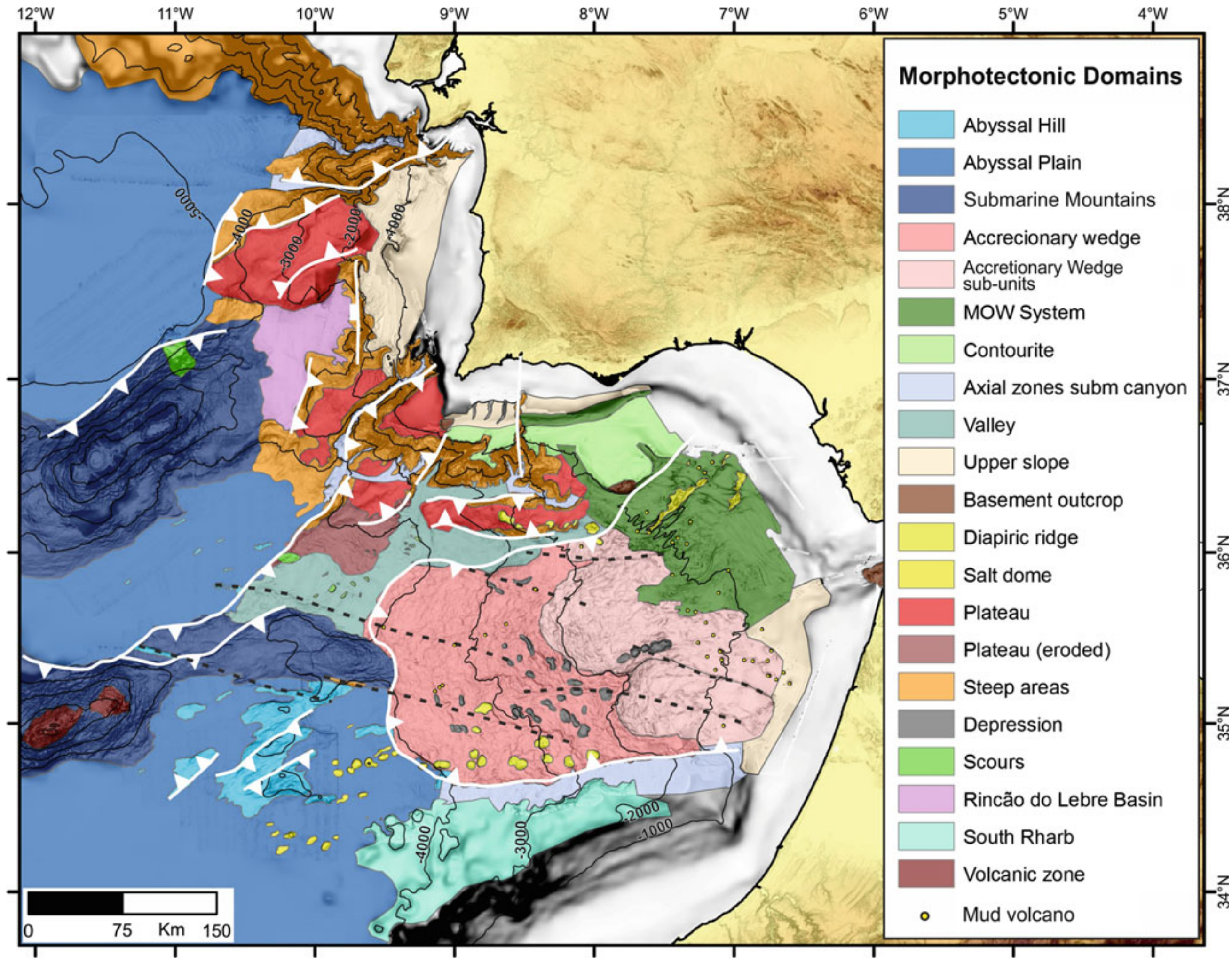

Fig. 11.6 Morphotectonic domains in SW Iberia (modified from Valadares 2012). White lines with triangles, rectangle, no symbol: thrust faults; normal fault, strike-slip fault. Black dotted lines: lineaments corresponding to the SWIM strike-slip faults (see text for description). These lineaments have complex morphologies as they consist of alignments of ridges, troughs, escarpments and in some cases mud volcanoes. This is the result of deformation from basement to seafloor, fluid migration, gravity collapse and sliding and interference of the SWIM faults with the Horseshoe Fault and AWGC (e.g. Terrinha et al. 2009; Zitellini et al. 2009). Thrust faults in the Seine Abyssal Plain (see Fig. 11.1 for location) result from tectonic shortening of previous rift faults (e.g. Valadares 2012; Martínez-Loriente et al. 2013)

thermogenic gas (Nuzzo et al. 2009). In this area, MV fluids are also strongly influenced by the leaching of Upper Triassic evaporites (Haffert et al. 2013).

Further westwards, on the lower slope and the continental rise (≈3000–4500 m water depth), the mud volcanoes are clearly associated with the active ~W-E strike-slip faults (Medialdea et al. 2009) within the Gloria-SWIM plate-boundary system; i.e. the eastern prolongation of the Gloria Fault plate boundary (Scholz et al. 2009; Hensen et al. 2015). A number of mud volcanoes have even been discovered ~90 km west of the deformation front of the accretionary wedge of the Gulf of Cádiz, and thus outside their typical geotectonic environment. Geochemical signatures of MV-fluids in this area indicate that these have at least partially interacted with the oceanic basement, implying the existence of a hydrological connection from the seafloor to the old (Upper Jurassic) oceanic crust along the SWIM strike-slip faults (Hensen et al. 2015).

From this intensive effort on trying to understand the Recent tectonic framework and tectonic sources, the following conclusions can be pointed out: (i) two major plate scale tectonic mechanisms drive deformation in the SWIM, the subduction of a remnant oceanic slab of the westernmost Neo-Tethys Ocean underneath Gibraltar and the dextral transpressive movement along the SWIM Fault system; (ii) various faults and fault systems have been recognized and mapped in the SWIM, from which stand out the AWGC, the Guadalquivir Ridge, the Guadalquivir-Portimão Bank thrust, the Gorringe thrust and Hirondelle-Josephine Ridge, the HF, the SWIM faults and the CPRF; (iii) the tectonic

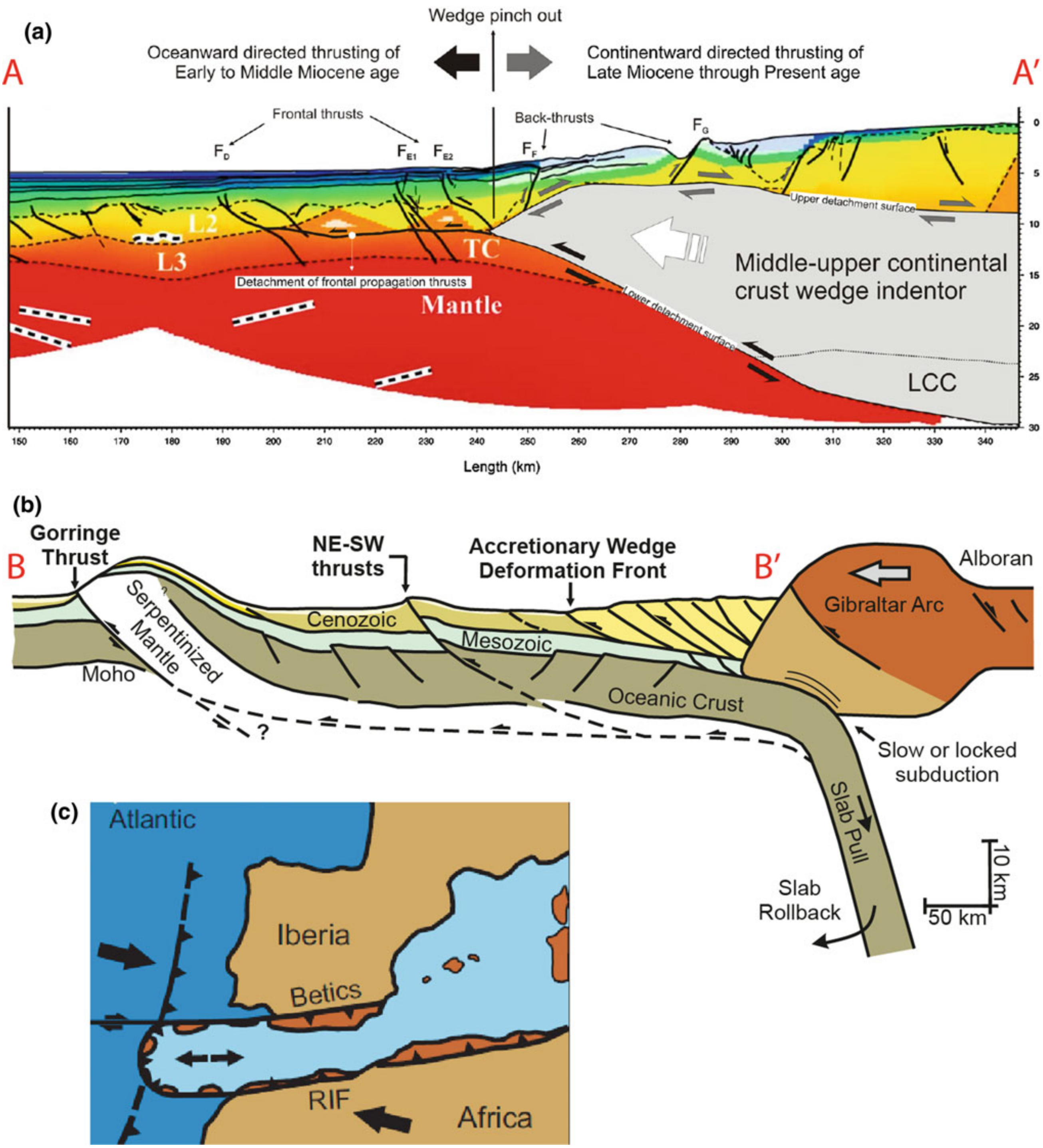

Fig. 11.7 Tectonic driving mechanism off: (a) the WIM and (b) the SWIM. These two speculative deep mechanisms are based on interpretation of images and models obtained from refraction and reflection seismic profiles. In Fig. (**a**) (adapted from Neves et al. 2009) it is suggested that contraction faults off the WIM detach at a décollement formed during the Mesozoic rifting near the Moho in the transitional crust and towards the continent. Fig. (**b**) suggests that roll-back of the Tethyan subducted slab propagates contraction oceanwards towards the inner Atlantic (from Duarte et al. 2013). **c** Speculative model of interaction of SWIM strike-slip faults, thrust faults and slab roll-back enabling subduction propagation along the WIM

strain is partitioned on thrust and strike-slip faults in the SWIM and its NW Africa counterpart; (iv) micro-seismicity seems to cluster on fault intersections which can be an evidence for seismic strain propagation along interacting large faults, such as the SWIM and HF; (v) convection of seawater from the surface to the basement along the SWIM faults can be a mechanism for further weakening of the oceanic crust that can have consequences on the propagation of the Gibraltar Arc and generation of subduction within this part of the Atlantic; (vi) active faults in the SWIM have the necessary size to generate large to mega-magnitude earthquakes and trigger large landslides, both of which constitute a seismic and tsunami hazard not only for the coasts of the SWIM, WIM and northwest Morocco but also for coasts across the Atlantic.

Recent tectonic deformation in the WIM is also attested using different data, such as, (i) seismic reflection profiles, (ii) geomorphological data, (iii) instrumental seismicity. The Nazaré canyon runs across the deformation belt on the northern boundary of the Estremadura Spur. Both seismo-stratigraphic and instrumental seismicity data are in agreement with recent tectonic deformation and uplift of this region (Figs. 11.1 and 11.2b). A field of pockmarks between 200 and 500 m bsl hosted in Pliocene-Quaternary sediments in the central part of the Estremadura Spur is related with recent deformation as the driving mechanism for fluid expulsion (Duarte et al. 2017).

On the southern part of the Estremadura Spur, the Setúbal and Cascais canyon systems have been very active channels for mass transport processes from the inner shelf to the Tagus Abyssal Plain in the Holocene and it has been suggested that these processes could have been triggered by local earthquakes (Masson et al. 2011; Abrantes et al. 2008; Terrinha et al. 2015). Further north, off Viana de Castelo (lat. 42°N), N-S trending reverse fault scarps of Quaternary age were reported using shallow seismics and video images captured by Remote Operated Vehicles (Rodrigues 2011).

South of the Estremadura Spur on the eastern flank of the Tagus Abyssal Plain, Quaternary tectonic deformation of hemipelagic-sediments and contourites was reported by Neves et al. (2007). Interpretation of seismic refraction data, numerical modelling and deformed MOW deposits of Pliocene-Quaternary age suggests that deformation is driven by impingement of an indentor of a mid-crustal domain inverting a detachment fault formed during the Mesozoic rifting (Fig. 11.7a). Thrusting of the Principes de Avis plateau over the Tagus Abyssal Plain and uplift of the inner continental slope with widespread mass transport processes has been documented (Terrinha et al. 2003; Cunha et al. 2010; Teixeira et al. 2017).

The interaction of the approximately W-E trending SWIM strike-slip faults with the NE-SW striking thrust faults, mantle serpentinization and oceanic slab roll-back has led researchers to speculate on the possibility of initiation of subduction off the WIM (e.g. Ribeiro et al. 1996; Duarte et al. 2013). Two tectonic processes are schematically shown in Fig. 11.7a, b, as speculative driving deformation mechanisms for contraction deformation in the SWIM and WIM (adapted from Neves et al. 2009 and Duarte et al. 2013, respectively). The speculative scenario of subduction propagation in a near geologic future is shown in Fig. 11.7c (adapted from Duarte et al. 2013).

References

Abrantes F, Alt-Epping U, Lebreiro S, Voelker A, Schneider R (2008) Sedimentological record of tsunamis on shallow-shelf areas: The case of the 1969 AD and 1755 AD tsunamis on the Portuguese Shelf off Lisbon. Marine Geology 249(3-4): 283–293. https://doi.org/10.1016/j.margeo.2007.12.004

Baptista MA, Miranda JM (2009) Revision of the Portuguese catalog of tsunamis. NATURAL HAZARDS AND EARTH SYSTEM SCIENCES Volume: 9 Issue: 1 Pages: 25–42. (published online: http://www.nat-hazards-earth-syst-sci.net/9/25/2009/nhess-9-25-2009.pdf)

Baptista MA, Miranda P, Mendes-Victor LM (1998) Constraints on the source of the 1755 Lisbon tsunami inferred from numerical modelling of historical data. Journal Geodynamics 25(2), 159–174. https://doi.org/10.1016/S0264-3707(97)00020-3

Barnett-Moore N, Font E, Neres M (2017) A reply to the comment on "Assessing discrepancies between previous plate kinematic models of Mesozoic Iberia and their constraints" by Barnett-Moore et al. Tectonics, 36:3286–3297. https://doi.org/10.1002/2017TC004760

Bartolomé R, Gràcia E, Stich D et al. (2012) Evidence for active strike-slip faulting along the Eurasia-Africa convergence zone: Implications for seismic hazard in the SW Iberian Margin. Geology 40(6): 495–498. https://doi.org/10.1130/G33107.1

Callegaro S, Rapaille C, Marzoli A, Bertrand H, Chiaradia M, Reinsberg L, Bellieni G, Martins L, Madeira J, Mata J, Youbi N, De Min A, Azevedo MR, Bensalah MK (2014) Enriched mantle source for the Central Atlantic magmatic province: new supporting evidence from southwest Europe. Lithos 188: 15–32. https://doi.org/10.1016/j.lithos.2013.10.021

Choffat P (1908) Essai sur la Tectonique de la Chaîne de l'Arrábida. Comm. Serv. Géol. Portugal, Lisboa, 89 p.

Cunha TA, Watts AB, Pinheiro LM, Myklebust R (2010) Seismic and gravity anomaly evidence of large-scale compressional deformation off SW Portugal. Earth planet Sci Lett 293: 171–179. https://doi.org/10.1016/j.epsl.2010.01.047

Custódio S, Dias NA, Carrilho F, Góngora E, Rio I, Marreiros C, Morais I, Alves P, Matias L (2015) Earthquakes in western Iberia: improving the understanding of lithospheric deformation in a slowly deforming region. Geophysical Journal International 203(1): 127–145, https://doi.org/10.1093/gji/ggv285.

Davison I, Barreto P, Andrade AJM (2016) Loulé: the anatomy of a squeezed diapir, Algarve Basin, southern Portugal. Journal of the Geological Society 174 (1): 41–55. https://doi.org/10.1144/jgs2016-035

Dewey JF, Helman ML, Turco E, Hutton DHW, Knot SD (1989) Kinematics of the western Mediterranean. In: Coward MP, Dietrich D, Park RG (Eds.) Alpine Tectonics, Geol Soc (London) Spec Publ 45: 265–283.

Díaz-del-Río V, Somoza L, Martínez-Frias J, Mata MP, Delgado A, Hernández-Molina FJ, Lunar R, Martín-Rubí JA, Maestro A, Fernández-Puga MC, León R, Llave E, Medialdea T, Vázquez JT (2003) Vast fields of hydrocarbon-derived carbonate chimneys related to the accretionary wedge/olistostrome of the Gulf of Cádiz. Marine Geology 195(1–4): 177–200. https://doi.org/10.1016/S0025-3227(02)00687-4

Duarte JC, Rosas FM, Terrinha P, Gutscher MA, Malavieille J, Silva S, Matias L (2011) Thrust-wrench interference tectonics in the Gulf of Cadiz (Africa-Iberia plate boundary): Insights from (sand-box) analog models. Marine Geology 289(1–4):135–149. https://doi.org/10.1016/j.margeo.2011.09.014

Duarte JC, Rosas FM, Terrinha P, Schellart WP, Boutelier D, Gutscher MA, Ribeiro A (2013) Are subduction zones invading the Atlantic? Evidence from the SW Iberia margin. Geology 41: 839–842. https://doi.org/10.1130/G34100.1

Duarte D, Magalhães VH, Terrinha P, Ribeiro C, Madureira P, Pinheiro LM, Benazzouz O, Kim J-H, Duarte H. (2017) Identification and characterization of fluid escape structures (pockmarks) in the Estremadura Spur, West Iberian Margin. Marine and Petroleum Geology, 82: 414–423 http://doi.org/10.1016/j.marpetgeo.2017.02.026

Feio M (1951) A Evolução do Relevo do Baixo Alentejo a Algarve, pp. 303–477, Com Serv Geol Portugal t.XXXII, 2a parte, Lisboa.

Fernandes RMS, Miranda J, Meijninger BML et al. (2007) Surface velocity field of the Ibero–Maghrebian segment of Eurasia–Nubia plate boundary. Geophys J Int 169 (1): 315–324. https://doi.org/10.1111/j.1365-246X.2006.03252.x

Ferreira MRP, Macedo CR (1979) K-Ar Ages of the Permian-Mesozoic basaltic activity in Portugal. Eur Col Geochron Cosmochron Isotope Geol 6: 26–27.

Fukao Y (1973) Thrust faulting at a lithospheric plate boundary the Portugal earthquake of 1969. Earth and Planetary Science Letters, 18(2): 205–216. https://doi.org/10.1016/0012-821X(73)90058-7

Galindo-Zaldívar J, Maldonado A, Schreider AA (2003) Gorringe Ridge gravity and magnetic anomalies are compatible with thrusting at crustal scale. Geophys J Int 153(1): 586–594. https://doi.org/10.1046/j.1365-246X.2003.01922.x

Geissler WH, Matias L, Stich D, et al. (2010) Focal mechanisms for sub–crustal earthquakes in the Gulf of Cadiz from a dense OBS deployment. Geophys Res Lett 37: L18309, https://doi.org/10.1029/2010gl044289.

Geldmacher J, Hoernle K, Kluegel A, Boogaard P van den, Wombacher F, Berning B (2006) Origin and geochemical evolution of the Madeira-Tore Rise (eastern North Atlantic). J Geophys Res-Solid Earth 111:B09206, https://doi.org/10.1029/2005jb003931

Gràcia E, Dañobeitia JJ, Vergés J, Bartolomé R (2003a) 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): 1033–1057. https://doi.org/10.1029/2001TC901045

Gràcia E, Danobeitia JJ, Vergés J, Córdoba D, PARSIFAL Team (2003b) Mapping active faults offshore Portugal (36°N–38°N): implications seismic hazard assessment along the southwest Iberian margin. Geology 31 (1): 83–86. https://doi.org/10.1130/0091-7613(2003)031<0083:MAFOPN>2.0.CO;2

Gràcia E, Vizcaino A, Escutia C, Asioli A, Rodés A, Pallàs R, García Orellana J, Lebreiro S, Goldfinger C (2010) Holocene earthquake record offshore Portugal (SW Iberia): Testing turbidite paleoseismology in a slow-convergence margin. Quat Sci Rev 29(9–10): 1156–1172. https://doi.org/10.1016/j.quascirev.2010.01.010

Grange M, Scharer U, Comen, G, Girardeau J (2008) First alkaline magmatism during Iberia–Newfoundland rifting. Terra Nova 20(6): 494–503. https://doi.org/10.1111/j.1365-3121.2008.00847.x

Grange M, Scharer U, Merle R, Girardeau J, Comen G (2010) Plume-Lithosphere interaction during migration of Cretaceous alkaline magmatism in SW Portugal: evidence from U–Pb ages and Pb–Sr–Hf isotopes. Journal of Petrology 51(5): 1143–1170. https://doi.org/10.1093/petrology/egq018

Grevemeyer I, Matias L, Silva S (2016) Mantle earthquakes beneath the South Iberia continental margin and Gulf of Cadiz – constraints from an onshore-offshore seismological network. Journal of Geodynamics 99: 39–50, https://dx.doi.org/10.1016/j.jog.2016.06.001.

Grevemeyer I, Lange D, Villinger H, Custódio S, Matias L (2017) Seismotectonics of the Horseshoe Abyssal Plain and Gorringe Bank, eastern Atlantic Ocean: Constraints from ocean bottom seismometer data. J Geophys Res-Solid Earth 122: 63–78, https://doi.org/10.1002/2016jb013586.

Gutscher MA, Dominguez S, Westbrook GK, Le Roy P, et al. (2012) The Gibraltar subduction: A decade of new geophysical data, Tectonophysics, 574–575: 72–91. https://doi.org/10.1016/j.tecto.2012.08.038

Gutscher MA, Malod J, Rehault JP, Contrucci I, Klingelhoefer F, Mendes-Victor L, Spakman W (2002) Evidence for active subduction beneath Gibraltar. Geology 30(12): 1071–1074. https://doi.org/10.1130/0091-7613(2002)030<1071:EFASBG>2.0.CO;2

Haffert L, Haeckel M, Liebetrau V et al. (2013) Fluid evolution and authigenic mineral paragenesis related to salt diapirism - The Mercator mud volcano in the Gulf of Cadiz. Geochimica et Cosmochimica Acta 106: 261–286, https://dx.doi.org/10.1016/j.gca.2012.12.016.

Hensen C, Scholz F, Nuzzo M, Valadares V, Gràcia E, Terrinha P, Liebetrau V, Kaul N, Silva S, Martínez-Loriente S, Bartolomé R, Piñero E, Magalhães VH, Schmidt M, Weise SM, Cunha M, Hilario A, Perea H, Rovelli L, Lackschewitz K (2015) Strike-slip faults mediate the rise of crustal-derived fluids and mud volcanism in the deep sea. Geology 43(4): 339–342. https://doi.org/10.1130/G36359.1

Hayward N, Watts AB, Westbrook GK, Collier JS (1999) A seismic reflection and GLORIA study of compressional deformation in the Gorringe Bank region, eastern North Atlantic. Geophysical Journ. Int., 138(3): 831–850. https://doi.org/10.1046/j.1365-246x.1999.00912.x

Hensen C, Nuzzo M, Hornibrook E, Pinheiro LM, Bock B, Magalhães V, Bruckmann W (2007) Sources of mud volcano fluids in the Gulf of Cadiz: indications for hydrothermal imprint. Geochim. Cosmochimica Acta, 71, 1232–1248.

Hernández-Molina J, Llave E, Somoza L, Fernández-Puga MC, Maestro A, León R, Medialdea T, Barnolas A, García M, del Rio VD, Fernández-Salas LM, Vázquez JT, Lobo F, Dias JMA, Rodero J, Gardner J (2003) Looking for clues to paleoceanographic imprints: a diagnosis of the Gulf of Cadiz contourite depositional systems. Geology 31 (1): 19–22. https://doi.org/10.1130/0091-7613(2003)031<0019:LFCTPI>2.0.CO;2

Hernández-Molina FJ, Sierro FJ, Llave E, Roque C, Stow DAV, Williams T, Lofi J, Van der Schee M, Arnáiz A, Ledesma S, Rosales C, Rodríguez-Tovar FJ, Pardo-Igúzquiza E, Brackenridge RE (2016) Evolution of the Gulf of Cadiz margin and southwest Portugal contourite depositional system: Tectonic, sedimentary and paleoceanographic implications from IODP Expedition 339. Marine Geology 377: 7–39. https://doi.org/10.1016/j.margeo.2015.09.013

Iribarren L, Vergés J, Fernàndez M (2009) Sediment supply from the Betic – Rif orogeny to basins through Neogene. Tectonophysics 475: 68–84. https://doi.org/10.1016/j.tecto.2008.11.029

Jiménez-Munt I, Fernàndez M, Vergés J, Afonso JC, García-Castellanos D, Fullea J (2010) Lithospheric structure of the Gorringe Bank: insights into its origin and tectonic evolution. Tectonics 29: 1–16. http://dx.doi.org/10.1029/2009TC002458.

Johnston A (1996) Seismic moment assessment of earthquakes in stable continental regions — III New Madrid 1811–1812, Charleston 1886 and Lisbon 1755. Geophys. J. Int. 126(2): 314–344. https://doi.org/10.1111/j.1365-246X.1996.tb05294.x

Kullberg JC (2000) Evolução tectónica mesozoica da Bacia Lusitaniana. PhD Thesis (unpublished), Univ Nova Lisboa, 361 p. online version: https://run.unl.pt/handle/10362/1465

Kullberg JC, Rocha RB, Soares AF, et al. (2013) A Bacia Lusitaniana: Estratigrafia, Paleogeografia e Tectónica. In: R. Dias, A. Araújo, P. Terrinha & J. C. Kullberg, Geologia de Portugal no contexto da Ibéria, Escolar Editora. 195–347.

Kullberg MC, Kullberg JC, Terrinha P (2000) Tectónica da Cadeia da Arrábida. In: "Tectónica das regiões de Sintra e Arrábida", Memórias Geociências, Museu Nac. Hist. Nat. Univ. Lisboa, 2, 35–84.

León R, Somoza L, Medialdea T, Vázquez JT, González FJ, López-González N, Casas D, Mata MP, Fernández-Puga MC, Giménez-Moreno CJ, Díaz-del-Río V (2012) New discoveries of mud volcanoes on the Moroccan Atlantic continental margin (Gulf of Cádiz): morpho-structural characterization. Geo-Mar Lett 32:473–488. https://doi.org/10.1007/s00367-012-0275-1

Lo Iacono C, Gràcia E, Zaniboni F et al. (2012) Large, deepwater slope failures: Implications for landslide-generated tsunamis. Geology 40 (10): 931–934. https://doi.org/10.1130/g33446.1

Lopes FC, Cunha PP, Le Gall B (2006) Cenozoic seismic stratigraphy and tectonic evolution of the Algarve margin (offshore Portugal, southwestern Iberian Peninsula). Marine Geology 231(1–4): 1–36. https://doi.org/10.1016/j.margeo.2006.05.007

Magalhães VH, Pinheiro LM, Ivanov MK et al. (2012) Formation processes of methane-derived authigenic carbonates from the Gulf of Cadiz. Sedimentary Geology 243–244:155–168. https://doi.org/10.1016/j.sedgeo.2011.10.013

Martínez-Loriente S, Sallarès V, Gailler A, Bartolomé R, Gràcia E, Gutscher MA, Diaz J (2011) Crustal nature and seismic structure of the geological provinces offshore the SW Iberia: Highlights of the NEAREST-SEIS wide-angle seismic survey, Abstract T43E-2409, AGU 2011 Fall Meeting, San Francisco.

Martínez-Loriente S, Gràcia E, Bartolomé R et al. (2013) Active deformation in old oceanic lithosphere and significance for earthquake hazard: Seismic imaging of the Coral Patch Ridge area and neighboring abyssal plains (SW Iberian Margin). Geochem Geophys Geosyst 14: 2206–2231, https://doi.org/10.1002/ggge.20173.

Martínez-Loriente S, Gràcia E, Bartolome R et al. (2018) Morphostructure, tectono-sedimentary evolution and seismic potential of the Horseshoe Fault, SW Iberian Margin. Basin Res 30 (Suppl. 1): 382–400. https://doi.org/10.1111/bre.12225.

Martínez-Loriente S, Sallarès V, Gràcia E, Bartolomé R, Dañobeitia JJ, Zitellini N (2014) Seismic and gravity constraints on the nature of the basement in the Africa-Eurasia plate boundary: New insights for the geodynamic evolution of the SW Iberian margin. J Geophys Res-Solid Earth 119: 127–149, https://doi.org/10.1002/2013jb010476.

Martins LT, Madeira J, Youbi N, Munhá J, Mata J, Kerrich R (2008) Rift-related magmatism of the Central Atlantic magmatic province in Algarve, Southern Portugal. Lithos 101: 102–124.

Masson DG, Arzola RG, Wynn RB, Hunt JE, Weaver PP (2011) Seismic triggering of landslides and turbidity currents offshore Portugal. Geochemistry, Geophysics, Geosystems, 12(12): 1–19. https://doi.org/10.1029/2011GC003839

Mata J, Alves CF, Martins L, Miranda R, Madeira J, Pimentel N, Martins S, Azevedo MR, Youbi N, De Min A, Almeida IM, Bensalah MK, Terrinha P (2015) 40Ar/39Ar ages and petrogenesis of the West Iberian Margin onshore magmatism at the Jurassic-Cretaceous transition: geodynamic implications and assessment of open-system processes involving saline materials. Lithos 236–237: 156–172. https://doi.org/10.1016/j.lithos.2015.09.001

Matias H, Kress P, Terrinha P, Mohriak W, Menezes PTL, Matias L, Santos F, Sandnes F (2011) Salt tectonics in the western Gulf of Cadiz, southwest Iberia. Am. Assoc. Pet. Geol. Bull. 95(10): 1667–1698. https://doi.org/10.1306/01271110032

Medialdea T, Vegas R, Somoza L, Vázquez JT, Maldonado A, Díaz-del Río V, Maestro A, Córdoba D, Fernández-Puga MC (2004) Structure and evolution of the "Olistostrome" complex of the Gibraltar Arc in the Gulf of Cádiz (eastern Central Atlantic): evidence from two long seismic cross-sections. Marine Geology 209 (1–4): 173–198. https://doi.org/10.1016/j.margeo.2004.05.029

Medialdea T, Somoza L, Pinheiro LM, Fernández-Puga MC, Vázquez JT, León R, Ivanov MK, Magalhães V, Díaz del Río V, Vegas R (2009) Tectonics and mud volcano development in the Gulf of Cádiz. Marine Geology 261(1–4): 48–63. https://doi.org/10.1016/j.margeo.2008.10.007

Merle R, Schärer U, Cornen G, Girardeau J (2006) Cretaceous seamounts along the continent-ocean transition of the Iberian Margin: U–Pb ages and Pb–Sr–Hf isotopes. Geochimica et Cosmochimica Acta 70(19): 4950–4976. https://doi.org/10.1016/j.gca.2006.07.004

Merle R, Jourdan F, Marzoli A, Renne PR, Grange M, Girardeau J (2009) Evidence of multi-phase Cretaceous to Quaternary alkaline magmatism on Tore–Madeira Rise and neighbouring seamounts from 40Ar/39Ar ages. Journal of the Geological Society 166: 879–894. https://doi.org/10.1144/0016-76492008-060

Miranda R, Valadares V, Terrinha P, Mata J, Azevedo MR, Gaspar M, Kullberg JC, Ribeiro C (2009) Age constraints on the Late Cretaceous alkaline magmatism on the West Iberian Margin. Cretaceous Research 30(3): 575–586. https://doi.org/10.1016/j.cretres.2008.11.002.

Neres M, Font E, Miranda J, Camps P, Terrinha P, Mirão J (2012) Reconciling Cretaceous paleomagnetic and marine magnetic data for Iberia: New Iberian paleomagnetic poles. Journal of Geophysical Research, Solid Earth 117:B06102. https://doi.org/10.1029/2011jb009067

Neres M, Bouchez JL, Terrinha P, Font E, Moreira M, Miranda R, Launeau P, Carvalho C (2014) Magnetic fabric in a Cretaceous sill (Foz da Fonte, Portugal): flow model and implications for regional magmatism. Geophysical Journal International 199(1): 78–101. https://doi.org/10.1093/gji/ggu250.

Neres M, Carafa MMC, Fernandes R, Matias L, Duarte JC, Barba S, Terrinha P (2016) Lithospheric deformation in the Africa–Iberia Plate Boundary: improved neotectonic modeling testing a basal-driven Alboran plate. Journal of Geophysical Research - Solid Earth 121: 6566–6596, https://doi.org/10.1002/2016jb013012.

Neres M, Terrinha P, Custódio S, Silva SM, Luís J, Miranda JM (2018) Geophysical evidence for a magmatic intrusion in the ocean-continent transition of the SW Iberia margin. Tectonophysics 744: 118–133. https://doi.org/10.1016/j.tecto.2018.06.014

Neves MC, Terrinha P, Afilhado A, Moulin M, Matias L, Rosas F (2009) Response of a multi-domain continental margin to compression: Study from seismic reflection–refraction and numerical modelling in the Tagus Abyssal Plain. Tectonophysics 468: 113–130. https://doi.org/10.1016/j.tecto.2008.05.008.

Nuzzo M, Hornibrook E, Gill F, et al. (2009) Origin of light volatile hydrocarbon gases in mud volcano fluids, Gulf of Cadiz - Evidence for multiple sources and transport mechanisms in active sedimentary wedges. Chemical Geology, 266(3–4): 359–372. https://doi.org/10.1016/j.chemgeo.2009.06.023

Omira R, Ramalho I, Terrinha P, Baptista M, Batista L, Zitellini N (2016) Deep-water seamounts, a potential source of tsunami generated by landslides? The Hirondelle Seamount, NE Atlantic. Marine Geology 379: 267–280. http://dx.doi.org/10.1016/j.margeo.2016.06.010.

Palano M, González PJ, Fernández J (2015) The Diffuse Plate boundary of Nubia and Iberia in the Western Mediterranean: Crustal deformation evidence for viscous coupling and fragmented

lithosphere. Earth and Planetary Science Letters 430: 439–447. https://doi.org/10.1016/j.epsl.2015.08.040
Pereira R, Alves TM (2013) Crustal deformation and submarine canyon incision in a Meso-Cenozoic first-order transfer zone (SW Iberia, North Atlantic Ocean). Tectonophysics 601:148–162. https://doi.org/10.1016/j.tecto.2013.05.007
Pinheiro LM, Ivanov MK, Sautkin AP, Akhmanov GG, Magalhães VH, Volkonskaya A, Monteiro H, Somoza L, Gardner J, Hamouni N, Cunha MR (2003) Mud volcanism in the Gulf of Cadiz: results from the TTR-10 cruise. Marine Geology 195(1–4): 131–151. https://doi.org/10.1016/S0025-3227(02)00685-0.
Ramos A, Fernández Ó, Terrinha P, Muñoz JA (2016) Extension and inversion structures in the Tethys–Atlantic linkage zone, Algarve Basin, Portugal. Int J Earth Sci 105(5): 1663–1679, https://doi.org/10.1007/s00531-015-1280-1.
Ramos A, Fernández Ó, Terrinha P, Muñoz JA (2017a) Neogene to recent contraction and basin inversion along the Africa-Iberia boundary in SW Iberia, Tectonics 36: 257–286. https://doi.org/10.1002/2016tc004262.
Ramos A, Fernández Ó, Torné M, Sánchez de la Muela A, Muñoz JA, Terrinha P, Manatschal G, Salas MC (2017b) Crustal structure of the SWIberian passive margin: The westernmost remnant of the Ligurian Tethys? Tectonophysics 705: 42–62. http://dx.doi.org/10.1016/j.tecto.2017.03.012.
Ramos A, Fernández Ó, Terrinha P, Muñoz JA (2017c). Impact of basin structure and evaporite distribution on salt tectonics in the Gulf of Cadiz, Southwest Iberian margin. Marine and Petroleum Geology 88: 961–984. https://doi.org/10.1016/j.marpetgeo.2017.09.028.
Rasmussen ES, Lomholt S, Andersen C, Vejbak OV (1998) Aspects of the structural evolution of the Lusitanian Basin in Portugal and the shelf and slope area offshore Portugal. Tectonophysics 300(1–4): 199–225. https://doi.org/10.1016/s0040-1951(98)00241-8
Ribeiro A, Cabral J (1987) The neotectonic regime of West-Iberia continental margin: a transition from passive to active? Abstracts, EUG IV, Strasbourg, April 13–16, Terra Cognita 7 (2–3): 120.
Ribeiro A, Kullberg MC, Kullberg JC, Manuppella G, Phipps S (1990) A review of Alpine tectonics in Portugal: foreland detachment in basement and cover rocks, Tectonophysics, 184(3–4): 357–366. https://doi.org/10.1016/0040-1951(90)90448-H
Ribeiro A, Cabral J, Baptista R, Matias L (1996) Stress pattern in Portugal mainland and the adjacent Atlantic region, West Iberia. Tectonics 15(3): 641–659. https://doi.org/10.1029/95TC03683
Rodrigues AC (2011) Tectono-estatigrafia da plataforma continental setentroional portuguesa. PhD Thesis (unpublished), Univ. Lisbon, 244p.
Roque C (2007) Tectonostratigrafia do Cenozóico das margens continentais Sul e Sudoeste portuguesas: um modelo de correlação sismostratigráfica. PhD Thesis (unpublished) University of Lisbon, 316 p.
Roque C, Duarte H, Terrinha P, Valadares V, Noiva J, Cachão M, Ferreira J, Legoinha P, Zitellini N (2012) Pliocene and Quaternary depositional model of the Algarve margin contourite drifts (Gulf of Cadiz, SW Iberia): Seismic architecture, tectonic control and paleoceanographic insights. Marine Geology 303–306: 42–62. https://doi.org/10.1016/j.margeo.2011.11.001
Rosas FM, Duarte JC, Neves MC, Terrinha P, Silva S, Matias L (2012) Thrust-wrench interference between major active faults in the Gulf of Cadiz (Africa-Eurasia plate boundary, offshore SW Iberia): Tectonic implications from coupled analog and numerical modeling. Tectonophysics 548–549: 1–21. https://doi.org/10.1016/j.tecto.2012.04.013
Rosas FM, Duarte JC, Terrinha P, Schellart WP (2016) Seismic potential of thrust-wrench tectonic interference between major active faults offshore SW Iberia: a new explanation for the 1755 Great Lisbon Earthquake? In: Duarte JC, Schellart WP (eds), Plate Boundaries and Natural Hazards. AGU Geophysical Monograph 219: 193–218. Published by John Wiley & Sons. ISBN: 978-1-119-05397-2
Rosenbaum G, Lister GS, Duboz C (2002) Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene. In: Rosenbaum G, Lister GS (eds), Reconstruction of the evolution of the Alpine-Himalayan Orogen. Journal of the Virtual Explorer 8: 107–126.
Sallarès V, Gailler A, Gutscher MA et al. (2011) Seismic evidence for the presence of Jurassic oceanic crust in the central Gulf of Cadiz (SW Iberia margin). Earth Planet Sci Lett 311: 112–123. http://dx.doi.org/10.1016/j.epsl.2011.09.003.
Sallarès V, Martínez-Loriente S, Prada M et al. (2013) Seismic evidence of exhumed mantle rock basement at the Gorringe Bank and the adjacent Horseshoe and Tagus abyssal plains (SW Iberia). Earth Planet Sci Lett 365: 120–131. http://dx.doi.org/10.1016/j.epsl.2013.01.021.
Schärer U, Girardeau J, Cornen G, Boillot G (2000) 138–121 Ma asthenospheric magmatism prior to continental break-up in the North Atlantic and geodynamic implications. Earth and Planetary Science Letters, 181(4): 555–572. https://doi.org/10.1016/S0012-821X(00)00220-X
Schettino A, Turco E (2009) Breakup of Pangaea and plate kinematics of the central Atlantic and Atlas regions. Geophys. J. Int. 178(2): 1078–1097. https://doi.org/10.1111/j.1365-246x.2009.04186.x
Schettino A, Turco E (2011) Tectonic history of the western Tethys since the Late Triassic. Geol. Soc. Am. Bull. 123(1–2): 89–105. https://doi.org/10.1130/b30064.1
Scholz F, Hensen C, Reitz A et al. (2009) Isotopic evidence (87Sr/86Sr, δ7Li) for alteration of the oceanic crust at deep-rooted mud volcanoes in the Gulf of Cadiz, NE Atlantic Ocean. Geochimica et Cosmochimica Acta 73: 5444–5459, https://doi.org/10.1016/j.gca.2009.06.004.
Scholz F, Hensen C, Lu Z, Fehn U (2010) Controls on the 129I/I ratio of deep-seated marine interstitial fluids: 'Old' organic versus fissiogenic 129-iodine. Earth and Planetary Science Letters 294: 27–36, https://doi.org/10.1016/j.epsl.2010.02.034.
Silva S (2017) Strain partitioning and the seismicity distribution within a transpressive plate boundary: SW Iberia-NW Nubia. PhD thesis, University of Lisbon, 399 pp.
Silva S, Terrinha P, Matias L, Duarte JC, Roque C, Ranero CR, Geissler WH, Zitellini N (2017) Micro-seismicity in the Gulf of Cadiz: Is there a link between micro-seismicity, high magnitude earthquakes and active faults? Tectonophysics 717: 226–241. https://doi.org/10.1016/j.tecto.2017.07.026
Somoza L, Díaz-del-Río V, León R et al. (2003) Seabed morphology and hydrocarbon seepage in the Gulf of Cádiz mud volcano area: acoustic imagery, multibeam and ultra-high resolution seismic data. Marine Geology 195(1–4): 153–176. https://doi.org/10.1016/S0025-3227(02)00686-2.
Srivastava S, Roest W, Kovacs L, Oakey G, Lévesque S, Verhoef J, Macnab R (1990) Motion of Iberia since the Late Jurassic: Results from detailed aeromagnetic measurements in the Newfoundland Basin. Tectonophysics 184 (3–4): 229–260. https://doi.org/10.1016/0040-1951(90)90442-B
Stapel G, Cloethingh S, Pronk B (1996) Quantitative subsidence analysis of the Mesozioc evolution of the Lusitanian Basin (West Iberian Margin). Tectonophysics 266(1–4):493–507. https://doi.org/10.16951016/s0040-1951(96)00203-x.
Teixeira M, Roque C, Terrinha P, Rodrigues S, Ercilla G, Casas D (2017) Evidence of slope failure in the Sines Contourite Drift area (SW Portuguese Continental Margin) – preliminary results. Geophysical Research Abstracts 19, EGU2017–17335-1,

Terrinha P (1998) Structural Geology and Tectonic Evolution of the Algarve Basin, South Portugal. PhD Thesis. Imperial College, London, 430 p.

Terrinha P, Coward MP, Ribeiro A (1990) Salt tectonics in the Algarve Basin: the Loulé diapir. Comunicações dos Serviços Geológicos de Portugal 76: 33–40.

Terrinha P, Duarte H, Noiva J et al. (2015) The Tagus River delta (off Lisbon, Portugal) as a repository of landslides. Implications on trigger mechanisms, tsunami hazard and neotectonics. Geophysical Research Abstracts 17: EGU2015–5606.

Terrinha P, Ribeiro C, Kullberg JC, Rocha R, Ribeiro A (2002) Compression episodes during rifting and faunal isolation in the Algarve Basins, SW Iberia. Journal of Geology 110(1), 101–113. https://doi.org/10.1086/324206

Terrinha P, Matias L, Vicente J, et al. (2009) Morphotectonics and strain partitioning at the Iberia-Africa plate boundary from multi-beam and seismic reflection data. Marine Geology 267(3–4): 156–174. https://doi.org/10.1016/j.margeo.2009.09.012

Terrinha P, Pinheiro LM, Henriet J-P, Matias L, Ivanov MK, Monteiro JH, Akhmetzhanov A, Volkonskaya A, Cunha T, Shaskin P, Rovere M, the TTR10 Shipboard Scientific Party (2003) Tsunamigenic-seismogenic structures, neotectonics, sedimentary processes and slope instability on the southwest Portuguese Margin. Marine Geology. 3266 1–19. https://doi.org/10.1016/S0025-3227(02)00682-5

Terrinha P, Pueyo EL, Aranguren A, Kullberg JC, Kullberg MC, Casas Sainz A, Azevedo MR (2018) Gravimetric and magnetic fabric study of the Sintra Igneous complex: laccolith-plug emplacement in the Western Iberian passive margin. International Journal of Earth Sciences, 107(5): 1807–1833. https://doi.org/10.1007/s00531-017-1573-7

Torelli L, Sartori R, Zitellini N (1997) The giant chaotic body in the Atlantic Ocean off Gibraltar: new results from a deep seismic reflection survey. Marine and Petroleum Geology 14 (2): 125–134. https://doi.org/10.1016/S0264-8172(96)00060-8

Tortella D, Torné M, Pérez-Estaún A (1997) Geodynamic evolution of the eastern segment of the Azores-Gibraltar zone: the Gorringe Bank and the Gulf of Cadiz region. Mar Geophys Res 19(3): 211–230. https://doi.org/10.1023/A:1004258510797.

Toyos MH, Medialdea T, León R, Somoza L, González FJ, Meléndez N (2016) Evidence of episodic long-lived eruptions in the Yuma, Ginsburg, Jesús Baraza and Tasyo mud volcanoes, Gulf of Cádiz. Geo-Mar Letters 36(3): 187–214, https://doi.org/10.1007/s00367-016-0440-z

Valadares V (2012) The morphotectonics offshore Southwest Iberia and the origin and the evolution of the South Portuguese submarine canyons, PhD thesis, University of Lisbon, 255 p.

Van der Voo R (1969) Paleomagnetic evidence for the rotation of the Iberian Peninsula. Tectonophysics, 7(1): 5–56. https://doi.org/10.1016/0040-1951(69)90063-8

Van Rensbergen P, Depreiter D, Pannemans B et al. (2005) The El Arraiche mud volcano field at the Moroccan Atlantic slope, Gulf of Cadiz. Marine Geology 219: 1–17. https://doi.org/10.1016/j.margeo.2005.04.007

Vergés J, Fernàndez M (2012) Atlantic interaction along the Iberia–Africa plate boundary: The Betic–Riforogenic system. Tectonophysics 579: 144–172. https://doi.org/10.1016/j.tecto.2012.08.032

Zitellini N, Chierici F, Sartori R, Torelli L (1999) The tectonic source of the 1755 Lisbon earthquake and tsunami. Annali di Geofisica 42 (1): 49–55.

Zitellini N, Gracia E, Matias L, Terrinha P (2009) The quest for the Africa-Eurasia plate boundary west of the Strait of Gibraltar. Earth planet Sci Lett, 280(1): 13–50. https://doi.org/10.1016/j.epsl.2008.12.005

Zitellini N, Rovere M, Terrinha P, Chierici F, Matias L, BIGSETS Team (2004) Neogene through Quaternary tectonic reactivation of SW Iberian passive margin. Pure and Applied Geophysics 161: 565–587. https://doi.org/10.1007/s00024-003-2463-4