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The Gibraltar subduction: A decade of new geophysical data

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The Gibraltar arc, spans a complex portion of the Africa–Eurasia plate boundary marked by slow oblique convergence and intermediate and deep focus seismicity. The seemingly contradictory observations of a young extensional marine basin surrounded by an arcuate fold-and-thrust belt, have led to competing geodynamic models (delamination and subduction). Geophysical data acquired in the past decade provide a test for these models and support a narrow east-dipping, subduction zone. Seismic refraction studies indicate oceanic crust below the western Gulf of Cadiz. Tomography of the upper mantle reveals a steep, east-dipping high P-wave velocity body, beneath Gibraltar. The anisotropic mantle fabric from SKS splitting shows arc-parallel “fast directions”, consistent with toroidal flow around a narrow, westward retreating subducting slab. The accompanying WSW advance of the Rif–Betic mountain belt has constructed a thick pile of deformed sediments, an accretionary wedge, characterized by west-vergent thrust anticlines. Bathymetric swath-mapping images an asymmetric embayment at the deformation front where a 2 km high basement ridge has collided. Subduction has slowed significantly since 5 Ma, but deformation of recent sediments and abundant mud volcanoes suggest ongoing activity in the accretionary wedge. Three possible origins for this deformation are discussed; gravitational spreading, overall NW–SE convergence between Africa and Iberia and finally a WSW tectonic push from slow, but ongoing roll-back subduction. In the absence of arc volcanism and shallow dipping thrust type earthquakes, evidence in favor of present-day subduction can only be indirect and remains the object of debate. Continued activity of the subduction offers a possible explanation for great ($M > 8.5$) earthquakes known to affect the area, like the famous 1755 Great Lisbon earthquake. Recent GPS studies show SW motion of stations in N Morocco at velocities of 3–6 mm/yr indicating the presence of an independent block, a “Rif–Betic–Alboran” microplate, situated between Iberia and Africa.

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1. Introduction

Since the Oligocene, the geodynamic evolution of the western Mediterranean region has been characterized by the slow convergence of Africa towards Eurasia (in a N to NW direction) with simultaneous extension and formation of young oceanic basins in a back-arc setting caused by the rapid roll-back of narrow slabs of subducting oceanic lithosphere (Faccenna et al., 2004; Jolivet et al., 2008; Malinverno and Ryan, 1986; Rehault et al., 1985). The West Alboran Sea constitutes one of these young basins, with thin crust, high heat flow and thick Neogene sediments (> 10 km). It is enclosed on three sides by the westernmost Alpine fold-and-thrust belt, the Betic Mountains to the N and NW and the Rif to W, SW and S. These mountain belts and the basin, together form the Gibraltar arc, straddling the modern Africa–Eurasia plate boundary (Fig. 1). The region is marked by a relatively broad band of moderate seismicity, extending about 200 km N to S and with some scattered intermediate depth seismicity located primarily below the West Alboran Sea (Fig. 2). A few deep focus (>600 km depth) events have occurred below S Spain (near Granada), including a M7.1 event in 1954 and a M6.3 event in 2010 (Buform et al., 1991, 2011; Grimison and Chen, 1986; Okal, 2001). Earlier seismological studies performed here showed high P-wave velocity anomaly in the upper mantle, interpreted as a body of cold, dense lithosphere and associated with deep-focus seismicity beneath Granada (southern Spain), but without a clear connection to the scattered intermediate and shallow seismicity (Blanco and Spakman, 1993; Calvert et al., 2000; Seber et al., 1996). The P–T–t paths of high-grade metamorphic rocks from the internal Betics southern Spain and also from the basement below the Alboran Sea

indicated rapid exhumation in the Miocene (Platt and Vissers, 1989). The dense lithospheric body was therefore initially interpreted to be a body of delaminated over-thickened orogenic continental lithosphere (Houseman and Molnar, 1997; Seber et al., 1996) and proposed to be the cause of rapid uplift and subsequent exhumation of overlying crustal rocks, thus offering an explanation for the P–T–t paths observed (Platt and Vissers, 1989; Vissers et al., 1995) (Fig. 3A). High-heat flow and extremely thin crust and lithosphere in the Alboran Sea as well as the negative P-wave velocity anomaly in the upper mantle (indicating hot asthenosphere at shallow upper mantle depths) were also interpreted as supporting this geodynamic evolution (Calvert et al., 2000; Torne et al., 2000).

An alternative geodynamic model was also put forward to explain the majority of these observations involving east-dipping subduction of a narrow corridor of Tethyan oceanic lithosphere. This subduction is proposed to have migrated by the process of “slab roll-back” from a position much further east, thereby causing back-arc extension in the overriding plate in its wake (Gutscher et al., 2002; Lonergan and White, 1997) (Fig. 3B). The latter workers proposed that this narrow subduction zone is still active, albeit at slow rates (≤ 1 cm/yr) on the basis of apparent offsets of sediments at the seafloor imaged by multi-channel seismic profiles.

Despite an absence of instrumentally observed thrust earthquakes, they argued that the fault plane could be locked and might be the source of great earthquakes and tsunamis, like the famous 1755 Lisbon event (Gutscher, 2004; Gutscher et al., 2006a, 2006b, 2009a). It may also have been the source of earlier events poorly described in historical documents or only revealed by paleo-tsunami research methods (Baptista

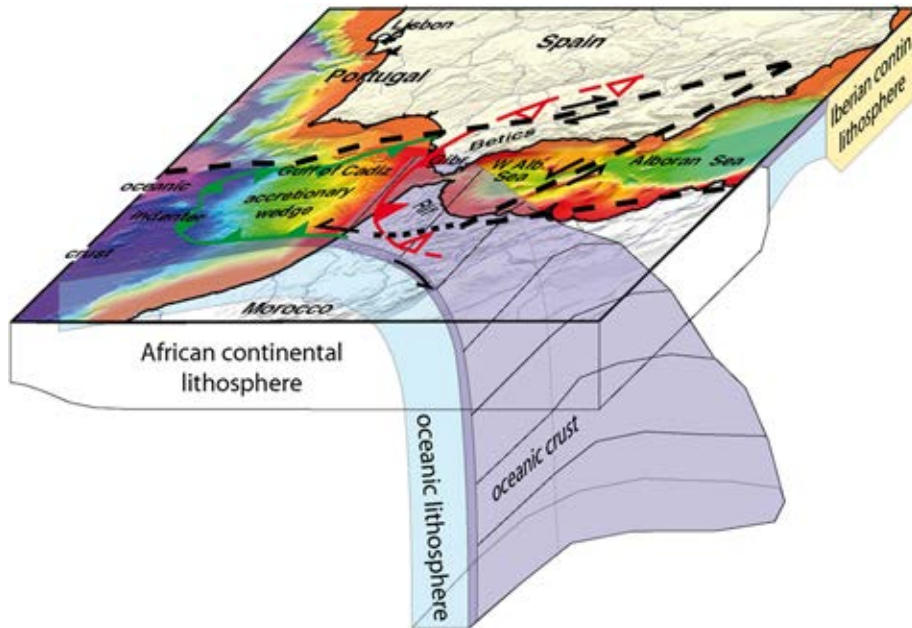


Fig. 1. 3-D block diagram of the lithospheric structure of the Iberia–Maghreb region, with shaded hill relief at the surface. The primary plate and block boundaries, expressed by crustal seismicity and the GPS velocity field are shown as a thick dashed lines, the active Rif–Betic front as filled red teeth and the deformation front of the accretionary wedge by green teeth. The asymmetric shape of the oceanic slab at depth is from tomography.

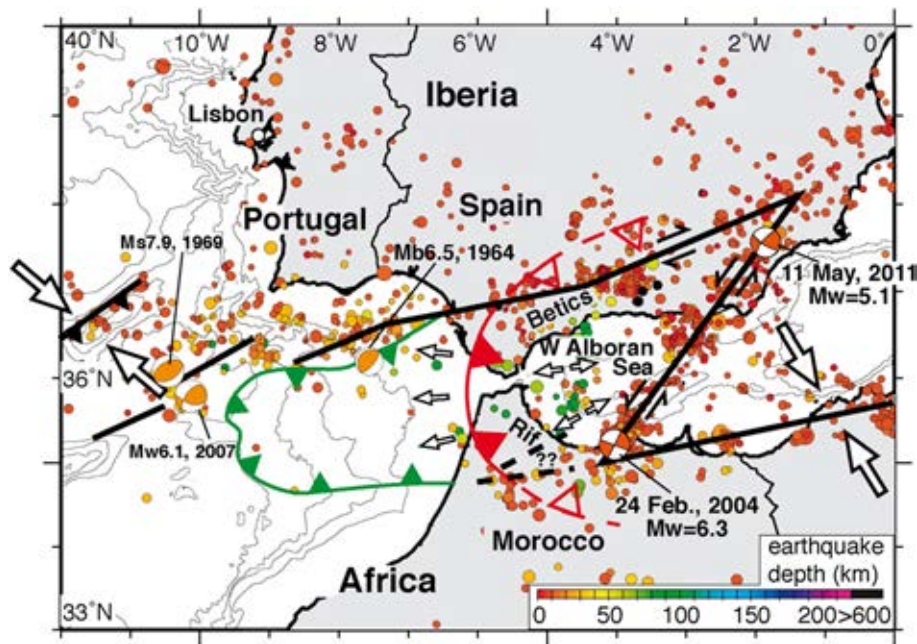


Fig. 2. Seismicity in the S Iberia region (hypocenter depths are scaled by color), with focal mechanisms of large recent earthquakes shown (Stich et al., 2006, 2007). Prominent faults and the relative kinematics between Africa and Iberia and the Rif-Betic-Alboran block are also shown (after Gutscher, 2004).

and Miranda, 2009). The proposed existence of an active, yet locked subduction zone, potentially capable of generating M8–9 megathrust earthquakes has important implications for regional natural hazard assessment. The search for the source of the 1755 event has therefore been the object of intense research activity in this past decade, much of which will be covered below.

The hypothesis of an active* east-dipping subduction zone beneath Gibraltar, first presented in 2002 made several testable predictions;

- the presence of a slab of east dipping oceanic lithosphere:
 - A) at shallow (crustal) depths
 - B) at great (upper mantle) depths
- active dewatering processes in the accretionary wedge (related to internal deformation and compaction)
- active tectonic deformation along the boundaries of the accretionary wedge
- an independent W to SW moving Alboran micro-plate, driven by slab roll-back.

(* – Please note that the term “active subduction” is used in the sense of a roll-back subduction with ongoing activity, and not in the sense of a subduction driven by large-scale horizontal plate motion, like the Pacific Plate for instance).

The first purpose of this paper is to summarize the results of one decade of new geophysical experiments performed in this region, both on shallow crustal and deep lithospheric structure, as well as kinematics, seismological and modeling studies. The second main objective is to consider how these results weigh in on the scientific debate, which was reinvigorated 10 years ago. The predictions listed above will be examined in turn, to see how they fare in the light of this concerted effort across several fields of earth science.

2. Results of recent studies

2.1. Crustal and lithospheric studies

Studies of crustal and lithospheric structure using seismological techniques are the most reliable methods for trying to distinguish between the competing geodynamic models, delamination and subduction. In the past decade thanks to a concerted effort by several

international and European programs, earth scientists have succeeded in collecting an unprecedented amount of high quality geophysical data in the southern Iberia–northern Morocco region.

2.1.1. Shallow lithospheric studies (crustal structure)

The crustal structure of the Gulf of Cadiz until recently was known mostly through numerous multi-channel seismic experiments conducted here since the 1990s and from a few wide-angle seismic experiments (WAS) (Fig. 4).

More specifically, the results of the SISMAR WAS survey (recorded by Ocean Bottom Seismometers – OBS, as well as some land stations) indicated the presence of a fairly typical, 7 km thick oceanic crust (of Jurassic age) in the Seine abyssal plain off the W coast of Morocco between Coral Patch seamount (35°N) and the Mazagan plateau (33.5°N) (Contrucci et al., 2004). This oceanic crust was interpreted to have formed at the Mid-Atlantic ridge spreading center following rifting at 195 Ma, with the onset of seafloor spreading (Sahabi et al., 2004). The presence of Atlantic oceanic crust here is also borne out by a coherent set of seafloor spreading magnetic anomalies (Roesser et al., 2002; Verhoeve et al., 1991, 1996) (Fig. 5). However, in the Gulf of Cadiz, there are no clearly identifiable parallel magnetic anomalies east of 11°W (Rovere et al., 2004), like those commonly observed on oceanic crust. Therefore the nature of the crust here has remained ambiguous.

North from the Seine abyssal plain, the first WAS study used sonobuoy recordings of airgun shots in the Horseshoe abyssal plain (Purdy, 1975). Forward modeling of these data indicated oceanic like velocities at crustal depths and anomalously low-velocities at deeper levels. Additionally, forward modeling of airgun shots recorded along the onshore continuation of the IAM-3 profile, also indicated significant crustal thinning offshore of the SW tip of Iberia (Gonzalez et al., 1996), but the unreversed nature of the profiles (recorded only by land stations) did not provide sufficient constraints on velocities or velocity gradients, and therefore could not reveal the exact nature of the crust. The first OBS work in the Gulf of Cadiz, indicated a thin crust (7–9 km thick) below 3–5 km of low-velocity sediments (Fig. 6). In the SW to central Gulf of Cadiz, this crust showed a sub-horizontal to slightly east-dipping (1–2°) geometry with a rapid E-ward increase in the overlying sedimentary thickness (Gutscher et al., 2002). However, the number

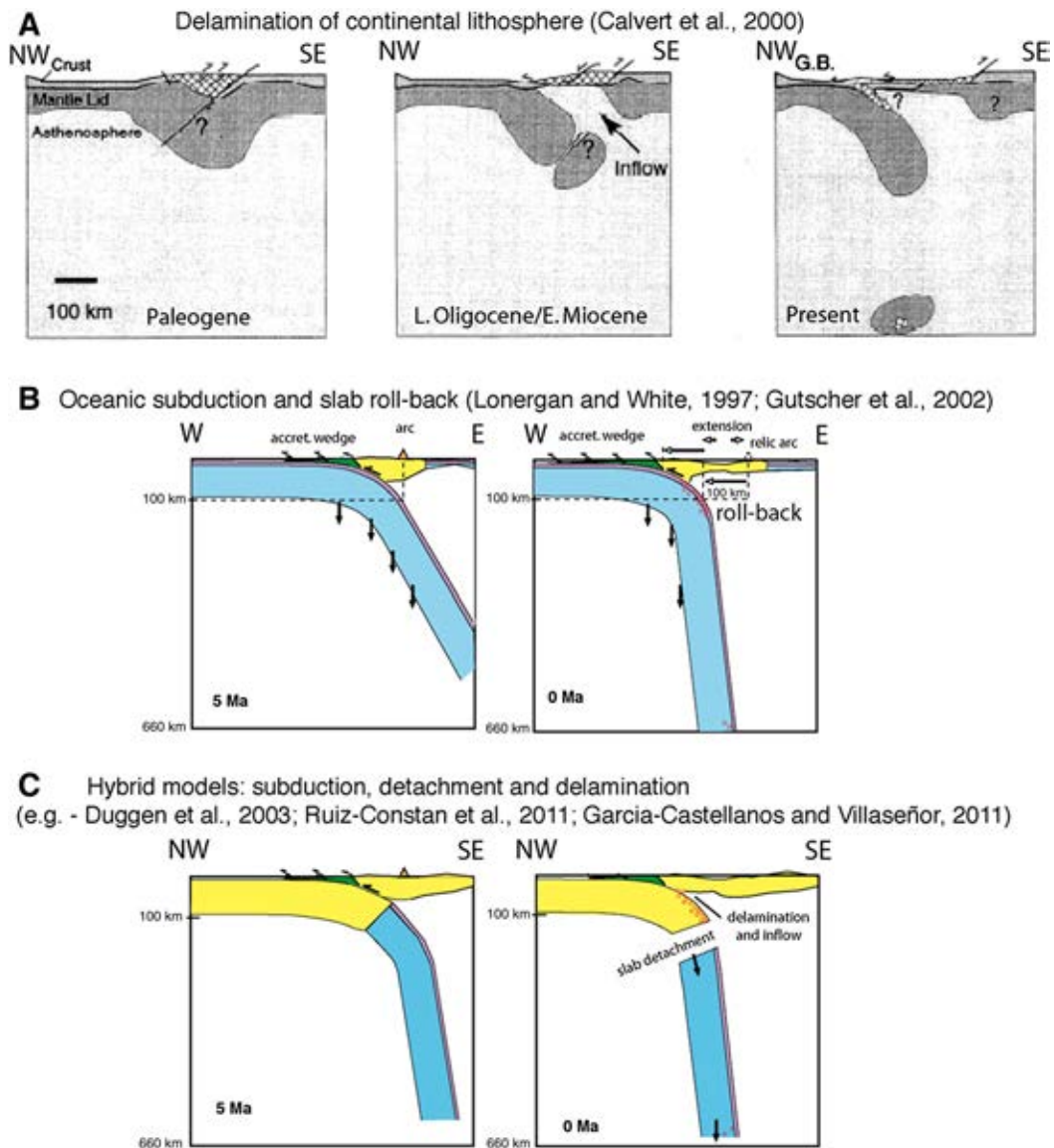


Fig. 3. Three evolutionary models in cross-section for the Gibraltar-Alboran region. A: The delamination of continental lithosphere model (Calvert et al., 2000) also integrating the collision and exhumation of high P-T rocks (Platt and Visser, 1989). There is no oceanic lithosphere involved. G.B. indicates the Guadalquivir Basin in the foreland of SW Spain to the NW of the Betic front. B: The “slab roll-back model” featuring east-dipping subduction of oceanic lithosphere. There is a continuous slab of Tethyan oceanic lithosphere from the Atlantic all the way down to the 660 km discontinuity. Considering the position of the relic arc and the 100 km slab depth contour, the slab hinge has retreated about 100 km to the west. The Gibraltar-Alboran block overriding the subducting slab is continental in nature and highly stretched in the West Alboran Sea. At the eastern limit of the section, the young oceanic lithosphere in the East Alboran Sea likely formed during an earlier episode of back-arc spreading (Booth-Rea et al., 2007). C: A hybrid model displaying oceanic subduction until 5 Ma, followed by slab detachment and some residual continental subduction/collision as well as local delamination. It follows mostly a recent seismotectonic study (Ruiz-Constan et al., 2011). For panels B and C, yellow represents continental lithosphere (crust and mantle lithosphere), light blue oceanic lithosphere and light violet oceanic crust. The deformed sediments of the accretionary wedge are shown in dark green. Small red circles are intermediate and deep focus earthquakes.

and quality of OBS (Ocean Bottom Seismometer) recordings (only three instruments yielded PmP upper mantle arrivals) could not provide sufficient constraints on the crustal type.

Finally, the Nearest-P2 WAS profile, acquired in 2009, with 15 OBS instruments at a <15 km spacing, as well as several land stations (Figs. 7 and 8), allowed workers to define the crustal structure offshore SW Portugal and in the central Gulf of Cadiz (Sallares et al., 2011). These latest results image a 30 km thick Variscan age continental crust beneath the Algarve coast, which thins abruptly towards the south, over a horizontal distance of 50 km, down to a thickness <10 km. Starting 100 km south of the Algarve coast of S Portugal and extending beneath the central Gulf of Cadiz and the toe of the accretionary wedge, these latest findings document a 7 km thick crust, with uniform thickness and a well-developed crust-mantle boundary, as well as seismic velocities and

velocity gradients typical of oceanic crust (Sallares et al., 2011) (Fig. 8). As the southern portion of the Nearest profile P2, is about 40 km from the western extremity of the WSW-ENE trending SISMAR profile SIS-16, this strongly suggests that the gently E-dipping 7–9 km thick crust on the SISMAR profile is also oceanic in nature.

This relatively limited corridor of oceanic crust (probably no more than 150 km in N-S extent) would appear to have formed not at the Mid-Atlantic Ridge spreading center, but rather along the Africa-Eurasia plate boundary during an episode of oblique seafloor spreading and thus belong to the western extremity of a Tethyan oceanic domain (Frizon de Lamotte et al., 2011; Sallares et al., 2011; Schettino and Turco, 2011; Stampfli and Borel, 2002; Stampfli et al., 2002) (Fig. 9). A relevant modern day analog is the oceanic crust formed at the Azores triple junction between the Eurasia and African plates.

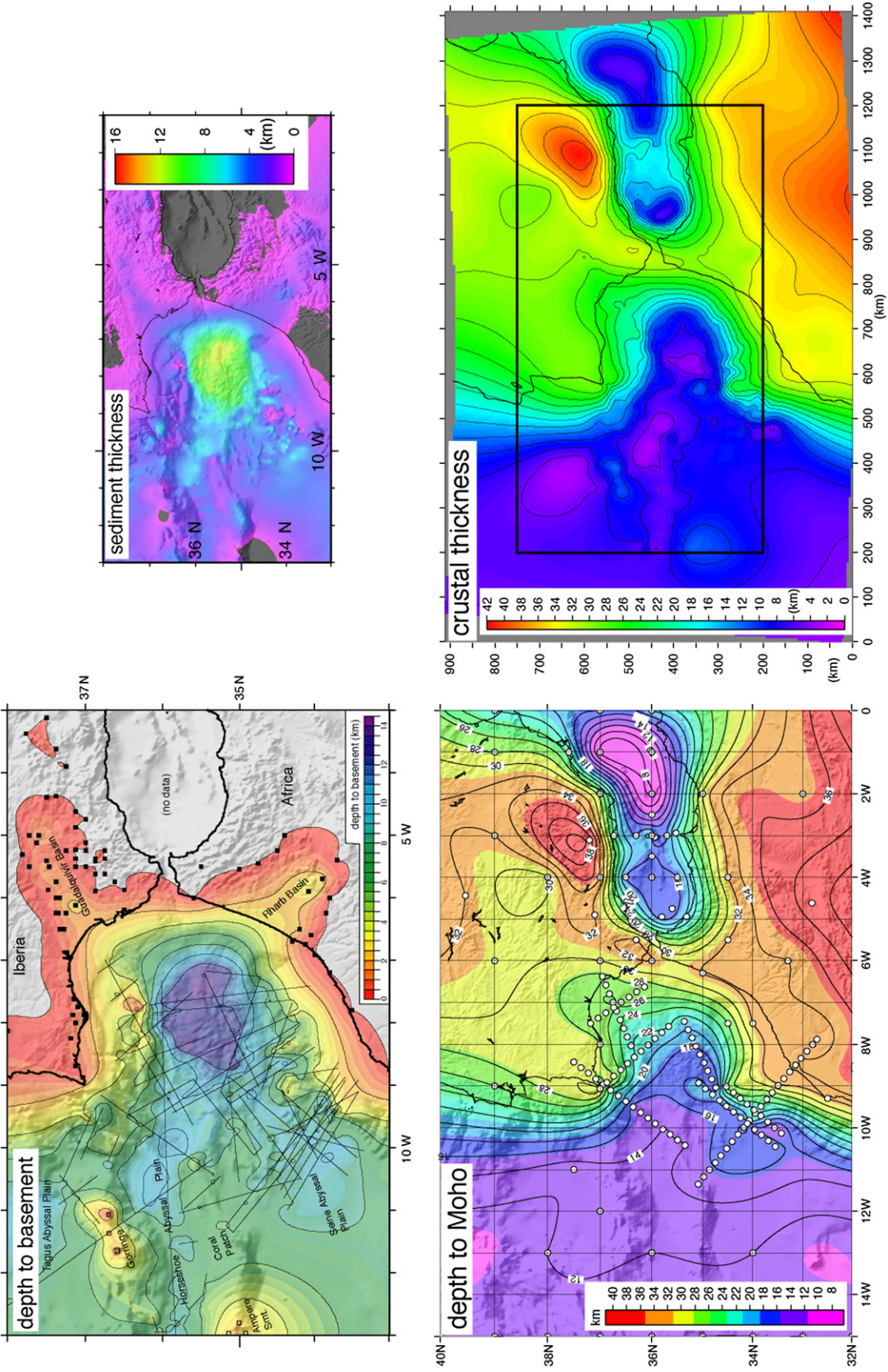


Fig. 4. Maps of crustal structure in the S Iberia region from a compilation of published multi-channel seismic profiles (see lines upper left) (Thiebot and Gutscher, 2006) and wide-angle data available up to 2008 (circles lower left) (Gutscher et al., 2009a). Upper left: depth to basement map. Lower left: depth to Moho map. Upper right: sediment thickness map (only W of Gibraltar). Lower right: crustal thickness map (with rectangle showing the region which is fairly well constrained, from 13°W to 2°W longitude).

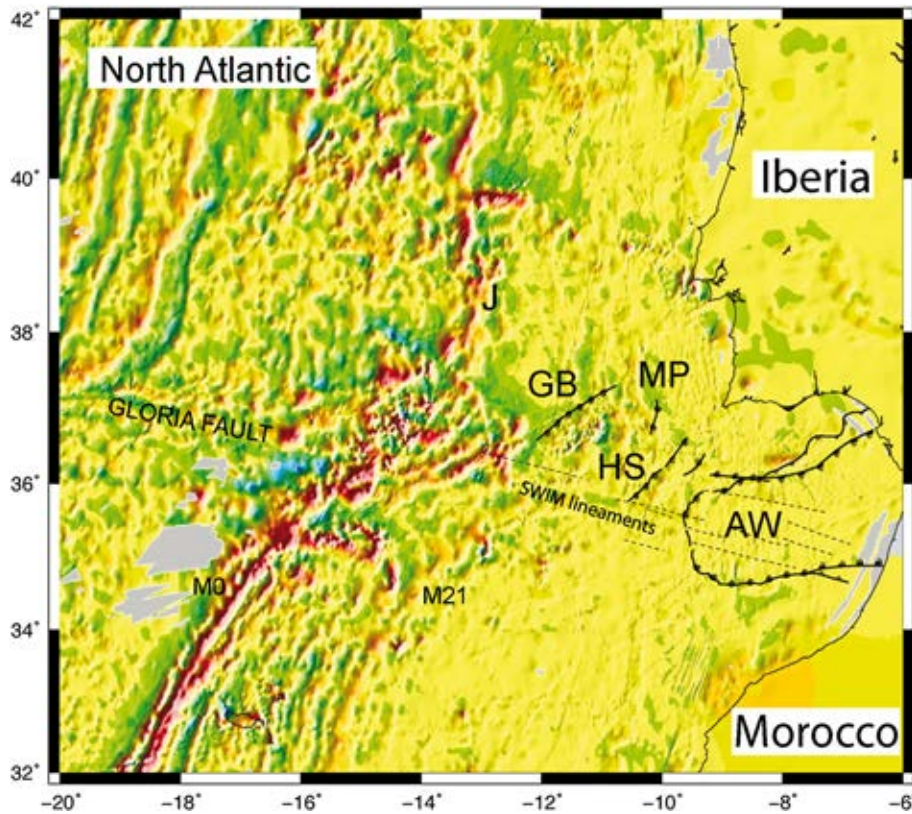


Fig. 5. Magnetic anomalies map of the NE Atlantic/SW Iberia region (Luis and Miranda, 2008) with Atlantic sea-floor spreading anomalies (M0 – Aptian 109 Ma, and M21 – Upper Oxfordian 142 Ma). No coherent sea-floor spreading anomalies are visible east of 12°W.

2.1.2. Deep lithospheric and upper mantle studies

Early tomographic models in the region showed a high P-wave velocity anomaly at depth corresponding to the region of deep-focus seismicity in southern Spain (Blanco and Spakman, 1993). The first evidence of a possible east-dipping slab of oceanic lithosphere was provided by the global tomographic model of Bijwaard and Spakman, displayed as E–W cross-sections (Gutscher et al., 2002) and also in the TransMed Atlas (Spakman and Wortel, 2004), where a steep E dipping high P-wave velocity anomaly was observed. Opponents of

the subduction model argued this anomaly could be delaminated lower continental lithosphere (Calvert et al., 2000; Platt and Houseman, 2003) (Fig. 3A).

Since then, the results of the international seismological project “Topo-Iberia” offer new insights on the deep geodynamic processes that have shaped the Rif–Betic–Alboran region. A study of the dispersion of teleseismic body-waves traveling through the dense lithospheric body in the upper mantle concludes that it must contain a fairly thin (~10 km) low-velocity wave-guide, interpreted to be oceanic crust of

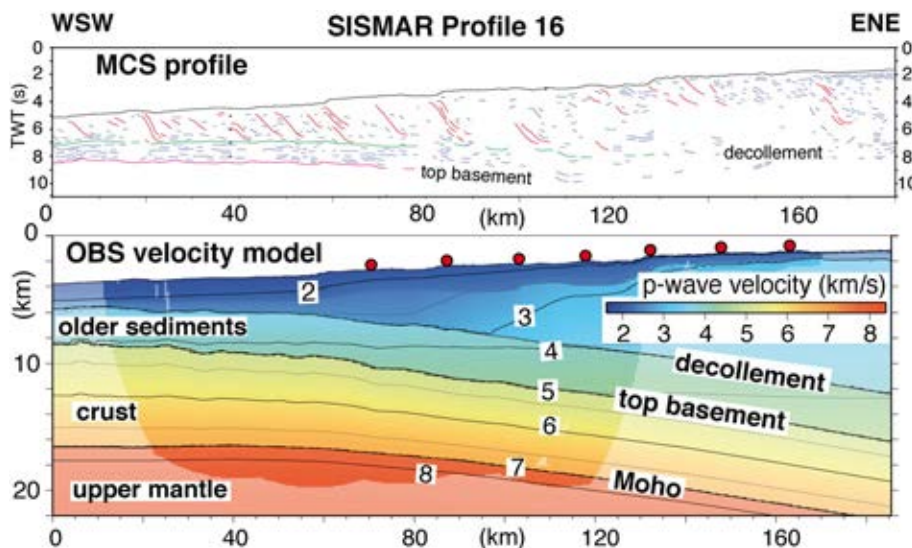


Fig. 6. (top) Line-drawing of MCS profile SIS-16, showing undeformed sediments beneath an eastward thickening, west-vergent thrust wedge, (bottom) P-wave velocity model from forward modeling of wide-angle refraction data recorded by 7 OBS (red circles) (Gutscher et al., 2002). The 7–9 km thick crust dips gently to the east (for location see Fig. 7).

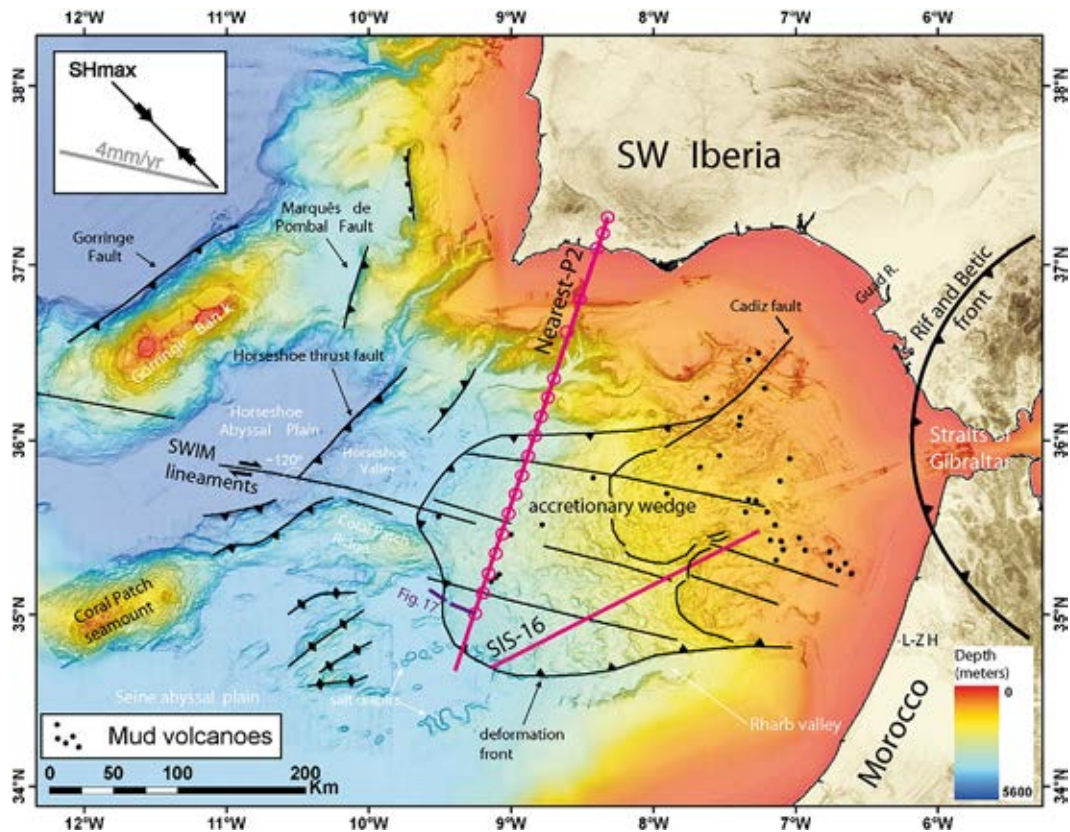


Fig. 7. Location map of the Gulf of Cadiz, showing topography on land (SRTM data) and swath-mapping bathymetry (Gutscher et al., 2009a, 2009b; Zitellini et al., 2009) at sea. Overlain are the active faults identified on the basis of morphology and seismic profiles (Duarte et al., 2011). Colored lines show location of seismic profiles discussed here.

a descending slab (Bokelmann and Maufroy, 2007; Bokelmann et al., 2011). The dispersion pattern is only observed for teleseismic waves rising from the east beneath the station Ceuta (in the straits of Gibraltar) and is not observed for a control station in the Variscan continental domain of western Iberia (Manteigas in north-central Portugal). This observation of a low-velocity wave-guide in a steep E-dipping high P-wave velocity body, confirms one of the first predictions of the subduction model and cannot be readily explained by the delamination model.

Shear-wave splitting of SKS phases indicates significant anisotropy (0.5–1.3 s) with fast directions in the upper mantle aligned parallel to the Rif–Betic arc, swinging from N–S just west of Gibraltar, to E–W in southern Iberia, just north of the Betics (Buontempo et al., 2008; Diaz et al., 2010) (Fig. 10). This C-shaped pattern is consistent with toroidal flow around the slab as it retreats to the west. The delamination hypothesis, predicting radial inward flow and fast directions, is contradicted by the observations (Bokelmann et al., 2011; Diaz et al., 2010). The upper mantle fabric surrounding the Gibraltar arc is nearly the

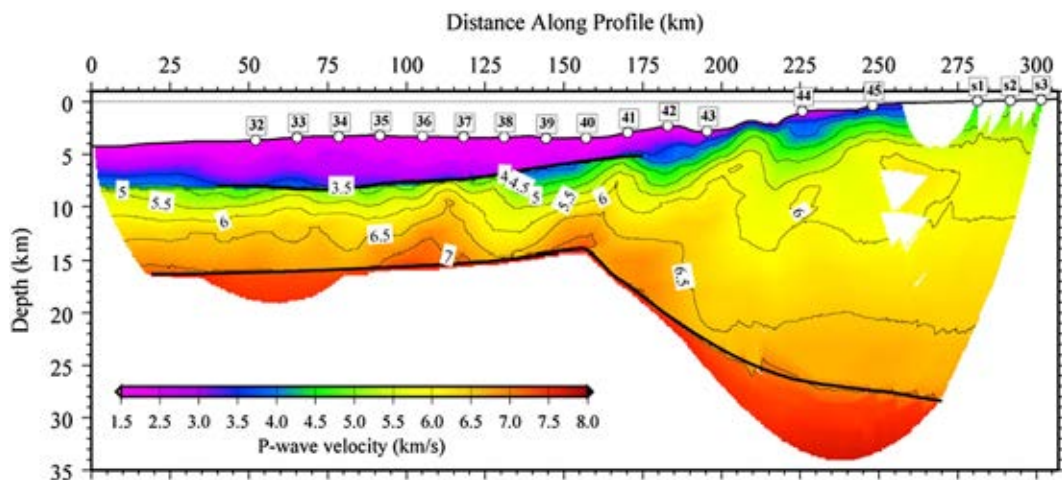


Fig. 8. P-wave velocity model from inversion of seismic refraction profile Nearest-P2 (for location see Fig. 5). Data were recorded by 14 OBS and 3 land stations (Sallares et al., 2011). The model reveals a 7 km thick oceanic crust underlying the low-velocity sediments of the "lens-shaped" accretionary wedge. The 25–30 km thick Variscan continental crust to the north (at right), thins abruptly to <15 km over a horizontal distance of about 50 km.

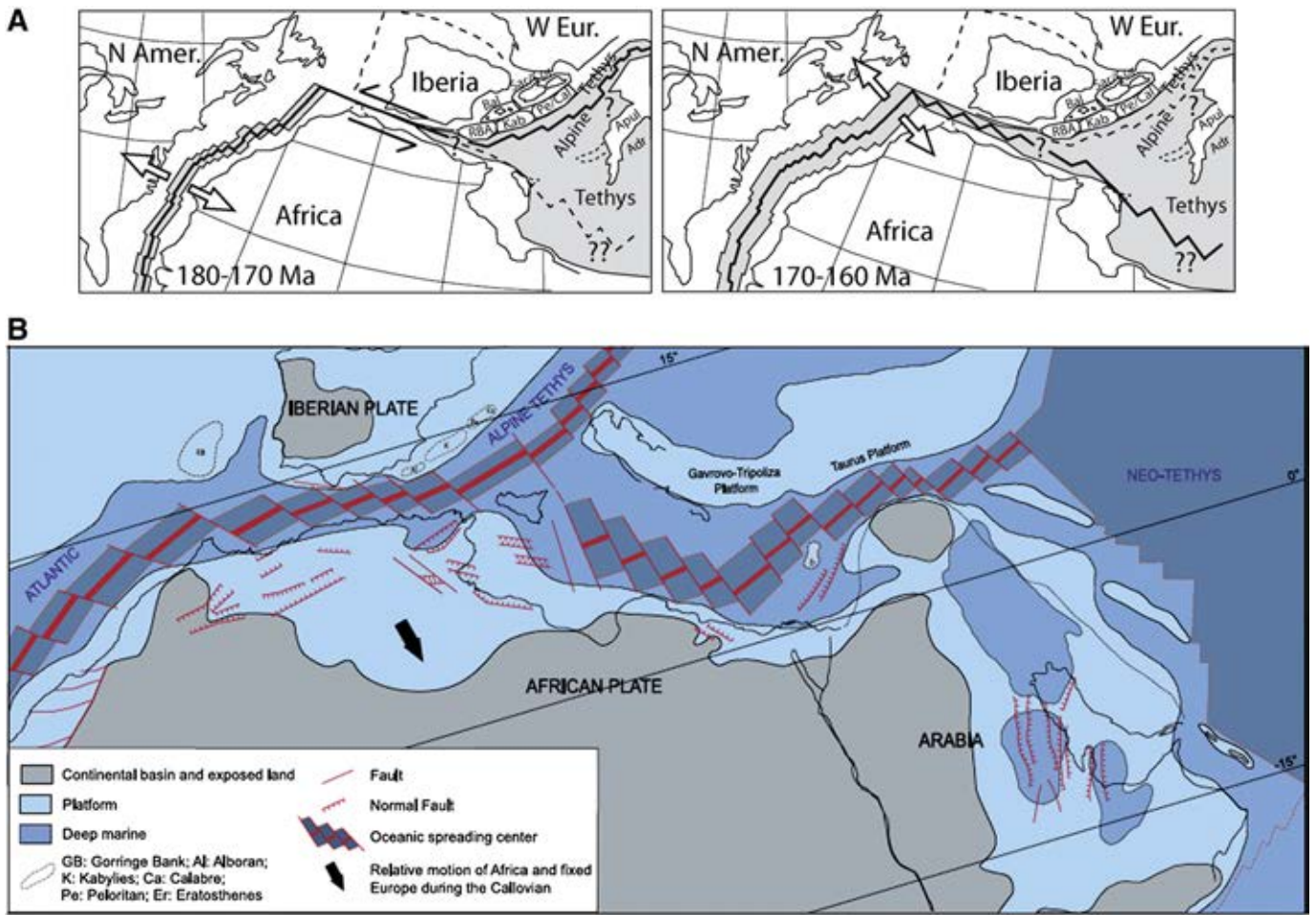


Fig. 9. Paleogeographic reconstructions of the Atlantic-Tethyan oceanic realms in the Jurassic. (top) Schematic reconstruction showing two-stage rifting opening showing first pure strike-slip motion between the NW corner of Africa and the southern Grand Banks margin (transform margin), followed by a shift in plate motions leading to oblique and highly segmented seafloor spreading along the N margin of Africa (southwestern Tethyan margin) (modified after Bill et al., 2001; Sallares et al., 2011) (bottom) Detailed reconstruction showing segmentation of the western Tethyan oceanic lithosphere formed at an oblique spreading center (Frizon de Lamotte et al., 2011).

mirror image of the arc-parallel fast-directions observed in the upper mantle surrounding the Apennine and Calabrian arc of southern Italy where roll-back subduction occurs (Baccheschi et al., 2007). Thus, these two new types of seismological data are best explained by the presence of subducted oceanic lithosphere and an upper mantle fabric entirely consistent with the roll-back subduction model.

2.2. Active dewatering processes in the accretionary wedge

Until 2002, one single article had been published concerning two mud volcanoes (Yuma and Ginsburg) in the Gulf of Cadiz (Gardner, 2001), but much work was already in progress. Today, a total of 51 active mud volcanoes have been identified and sampled in the Gulf of Cadiz at depths ranging from 250 m to 3900 m (Medialdea et al., 2009; Pinheiro et al., 2003; Somoza et al., 2003). All of these mud volcanoes are located within the boundaries of the accretionary wedge (Figs. 7 and 15) and offer testimony to the active internal deformation, compressional and dewatering processes occurring here. There seems to be an intimate relationship between faults within the accretionary wedge (typically thrust faults) and the presence of mud volcanoes (Medialdea et al., 2009). Furthermore, numerous mud volcanoes are aligned the long WNW-ESE trending “SWIM” lineaments (Zitellini et al., 2009) suggesting deep rooted fluids (from the crust and even upper mantle) may be involved in these structures, a connection also suggested by certain geochemical signatures from the methane in mud volcano fluids sampled in the Gulf of Cadiz (Hensen et al.,

2007). It can be argued that the occurrence of mud volcanoes is not restricted exclusively to subduction zones. Indeed, they also exist on passive margins or even in back-arc settings (Kopf, 2002). However, such a large concentration (over 50 documented examples) over a relatively small area has so far only ever been observed in other subduction zones where very thick sedimentary sections are being actively accreted, like the Barbados Ridge (Lesser Antilles subduction) or Mediterranean Ridge (Hellenic subduction) (Kopf, 2002).

2.3. Active deformation in the Gulf of Cadiz

Since the Gulf of Cadiz encompasses the Iberia-Africa plate boundary (whose kinematics will be described in more detail further below), there are at least two possible origins of active deformation in this region; the faults directly associated with the Iberia-Africa plate boundary, and possible deformation related to the E dipping subduction zone, if it is still active. Therefore, identifying and establishing the chronology of deformation recorded within the Miocene, Pliocene and Quaternary strata in the entire Gulf of Cadiz region should provide a reliable indicator of which of these processes is still active and in which sectors. The different types of marine geophysical data and the evidence they provide will be examined in turn along with the results of pertinent modeling studies (both analog and numerical). Finally, the results of geodetic studies will all be considered as well.

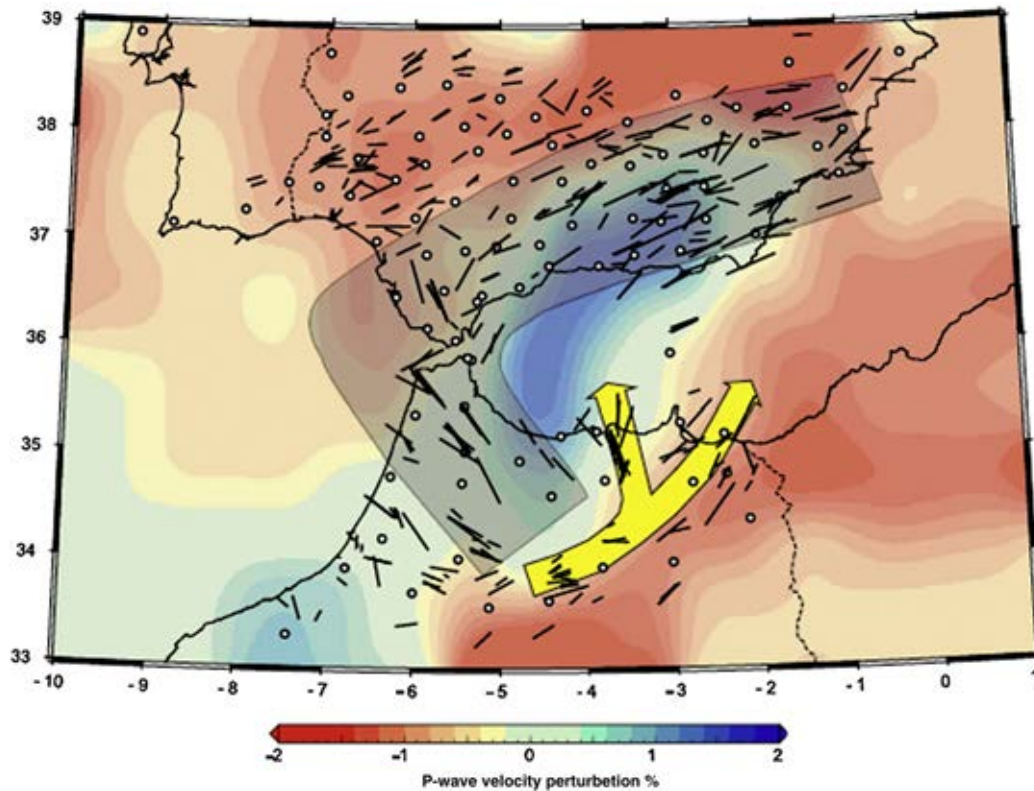


Fig. 10. Upper mantle anisotropy from SKS splitting, fast directions shown (bars represent 0.5–1.3 s time shift), displayed on the regional 200 km horizontal tomographic slice (Diaz et al., 2010).

2.3.1. Seismic reflection profiles

The presence of a thick wedge of sediments in the Gulf of Cadiz, with a chaotic internal structure was observed in seismic profiles in the 1990s and interpreted to be the result of giant scale gravitational sliding (Sartori et al., 1994; Torelli et al., 1997). These deposits, which thinned and tapered below the Horseshoe abyssal plain, were described as an olistostrome and ascribed a Miocene/Tortonian age. This interpretation also strongly influenced later workers to consider that the main phase of tectonic activity and the construction of this chaotic mélange were limited to the Miocene (Iribarren et al., 2007; Zitellini et al., 2009).

Multi-channel seismic reflection data from the Gulf of Cadiz image an eastward thickening wedge of deformed sediments, overlying an eastward dipping layer of undeformed sediments 2–3 km thick, directly above the basement (Gutscher et al., 2002, 2009a, 2009b; Iribarren et al., 2007; Thiebot and Gutscher, 2006) (Fig. 6). This geometry is characteristic for accretionary wedges and requires a W-directed tectonic push (Davis et al., 1983). The overall WSW transport direction is expressed by W, NW and SW vergent thrust anticlines observed in the seismic profiles (Gutscher et al., 2009a; Thiebot and Gutscher, 2006). While most workers now concur that this thick pile of deformed sediments was formed by westward vergent imbricate thrusting, some believe that this phase of tectonic activity ended in the Miocene and that the accretionary wedge is now inactive (Iribarren et al., 2007; Zitellini et al., 2009). This will be discussed in greater detail below.

2.3.2. Bathymetry

Recently published multi-beam bathymetric data from the SW Iberia region highlight the rugous surface and the sharp U-shaped boundaries of this accretionary complex (Gutscher et al., 2009b) (Fig. 1). The wedge exhibits a general tongue-shape and has a WSW–ENE oriented symmetry axis. Because it occupies the deep oceanic domain between SW Iberia and NW Morocco and is somewhat similar in shape to the toe of a valley glacier, most workers initially proposed it was formed through a long-term or catastrophic process of gravitational sliding (Maestro et

al., 2003; Torelli et al., 1997). The upper portions of the accretionary wedge do indeed show certain characteristic features of gradual down-slope transport, like transtensional valleys, typical of rafting tectonics and steep rounded escarpments at the front of two large lobate sectors of the accretionary wedge (Gutscher et al., 2009b). However, the external portion of the accretionary wedge is characterized by a nearly constant and extremely shallow surface slope (of 1° on average) as well as tightly spaced gently undulating parallel anticlinal ridges in the lowermost portion, near the deformation front. These characteristics are common features of a critical Mohr–Coulomb wedge, constructed above an extremely weak basal decollement (Davis et al., 1983; Gutscher et al., 1998; Lallemand et al., 1994). In order to better understand the mechanics driving the deformation observed in the morpho-bathymetry some workers performed analog modeling studies, which will be described further below.

The morpho-bathymetry of the accretionary wedge alone is not conclusive in determining the age of the most recent deformation, nor the physical mechanisms driving it, so several surveys conducted high-resolution seismic profiling of the deformation front and its lateral boundaries. The results of this work indicate ongoing compressional deformation and transpressional deformation (Crutchley et al., 2011; Gutscher et al., 2009a, 2009b; Maad et al., 2010), with likely prolongations onshore in SW Spain at the Guadalquivir River and in NW Morocco, the Lalla-Zahra hills (labeled L–Z H in Fig. 7). The origin of this deformation will be discussed in greater detail below (in the Discussion section).

The deep seafloor offshore SW Iberia is characterized by a domain of primarily NE–SW trending morphologic ridges (Gorringe Bank, Coral Patch seamount) and fault controlled escarpments (Horseshoe and Marques de Pombal faults) (Fig. 7). Several of these structures are associated with moderate crustal and upper mantle seismicity and have also been proposed as the possible origin of the great historical Lisbon earthquake and tsunami (Baptista et al., 2003; Gràcia et al., 2003a; Johnston, 1996; Stich et al., 2007; Terrinha et al., 2003, 2009; Zitellini et al., 2001).

On the basis of bathymetric mapping offshore SW Portugal, several long (> 100 km) ESE–WNW striking lineaments were identified and observed to correlate with subvertical faults imaged in multi-channel seismic reflection profiles (Rosas et al., 2009; Terrinha et al., 2009). These form part of a network of parallel structures, known collectively as the “SWIM” lineaments (Fig. 7). They affect the Horseshoe and Seine abyssal plains, partially bound several basement highs (like the Coral Patch Ridge) and cut into the accretionary wedge as well, and were therefore proposed to be a nascent plate boundary, with large-scale dextral shear (Zitellini et al., 2009).

2.3.3. Analog modeling

In recent years several analog modeling studies have addressed the topic of the relative motion, degree of activity and interplay between the tectonic structures along the complex Africa–Eurasia plate boundary in the Gulf of Cadiz. One of the SWIM lineaments was shown to correspond to a basement fault, rooted into more consolidated Mesozoic strata, and overlain by a soft cover of Pliocene–Quaternary sediments which showed signs of recent deformation in the form of en-echelon folds aligned above the fault trace (Rosas et al., 2009; Terrinha et al., 2009). The structural and mechanical relationship between basement faulting and the en-echelon folding of the overlying sedimentary cover were investigated by analog modeling (Rosas et al., 2009). These workers concluded that the observed en-echelon folds could be well reproduced by the equivalent of 7 km of dextral shear along the lineament, which given the current 4 mm/yr plate motion (Argus et al., 1989; Calais et al., 2003) could have occurred over a period of 1.8 Ma (Rosas et al., 2009).

The interaction between one of the major strike–slip SWIM faults and the Horseshoe thrust fault was also investigated through analog modeling with the purpose of understanding the morpho-tectonic

pattern and recently recognized seismicity distribution (Geissler et al., 2010) observed at the intersection (corner zone) between these two tectonic structures (Rosas et al., 2012). Results show that in this corner zone, the wrench–thrust tectonic interference pattern is expressed by the formation of steep oblique (dextral reverse) faults in the zone of intersection, consistent with present day activity of both the SWIM dextral wrenching and the NW vergent Horseshoe thrust. Nonetheless, a direct relationship between these upper crustal corner faults, imaged at a maximum depth of 6–10 km, and the deep earthquakes in the upper mantle (40–60 km depth) (Geissler et al., 2010) is difficult to envisage. Any potential connection would necessarily involve stress transfer across rheologically different portions of the lithosphere (Rosas et al., 2012).

Two analog modeling studies focused on the deformation of the accretionary wedge. The first study addressed the overall kinematics related to the construction of the accretionary wedge and the interaction with a ESE–WNW trending basement high (Coral Patch Ridge) indenting the wedge in its central frontal area. The resulting asymmetric indentation pattern is expressed by a shallower surface slope of the northern toe of the wedge and a deformation front which has advanced further, with respect to the wedge directly south of the indenter, which is steeper and features an embayment (Fig. 11). This geometry is consistent with a WSW directed transport of the accretionary wedge, and is successfully reproduced by analog modeling (Gutscher et al., 2009a).

The second study addressed the question of the relative timing of deformation of the toe of the accretionary wedge and the N120E oriented SWIM lineaments through a series of three experiments (Duarte et al., 2011). The first featured an accretionary wedge growing and overriding an inactive, oblique basement fault. Surprisingly, an oblique structure emerged, cutting across the thin portion (toe)

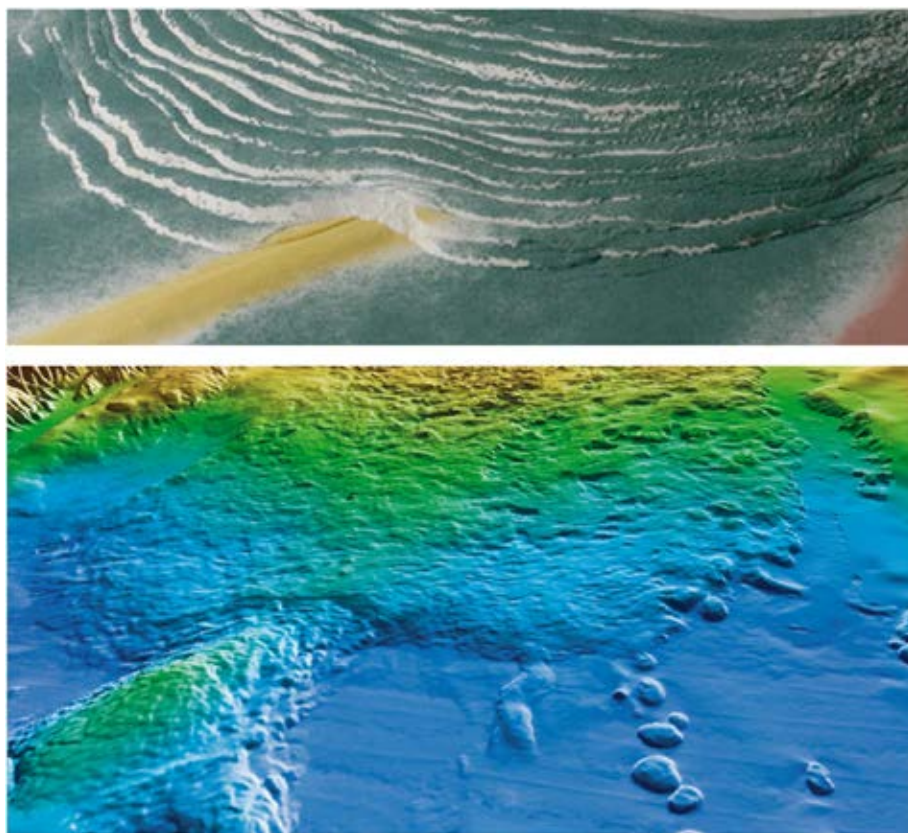


Fig. 11. Analog modeling applied to the kinematics of the accretionary wedge (Gutscher et al., 2009a). (top) close-up view of the final stage of an experiment featuring regular accretion against an arcuate backstop followed by collision with an oblique rigid indenter (bottom) 3-D view (looking ENE) of the bathymetry of the toe of the accretionary wedge and the ESE–WNW oriented Coral Patch ridge basement high.

of the accretionary wedge, but it was not expressed in the foreland, (since no motion occurred across the lineament). The second experiment featured first a phase of wedge growth, followed by dextral motion along the basement fault (Fig. 12) producing a marked dextral offset of the deformation front as well as strong deformation at the surface of the wedge. However, no dextral offset is observed in the natural example (Fig. 7 and Fig. 11 bottom). The third experiment tested simultaneous wedge growth and strike-slip motion. This experiment was most successful in reproducing the general features observed in the morpho-bathymetry from the Gulf of Cadiz, an expression of the lineaments in the foreland, but with no visible dextral offset of the wedge front. The second experiment of Duarte et al. (2011) challenges the interpretation favored by Zitellini et al. (2009), that the accretionary wedge has become inactive, and that significant dextral displacement has occurred since along a new plate boundary.

The interpretation favored by the modelers is that the SWIM faults have absorbed some minor dextral shear, through the reactivation of Tethyan sea-floor spreading fabric, most likely a series of fracture zones forming an ancient Tethyan plate boundary (Duarte et al., 2011) (Fig. 9). This is also consistent with the observation on the Nearest WAS profile P2 that the northern SWIM lineament affects the entire oceanic crust into the upper mantle, in agreement with an origin as either fracture zone or oceanic spreading fabric (Sallares et al., 2011). Lastly, this provides a simple explanation why the SWIM lineaments are not expressed on-land in NW Morocco, since they are on the downgoing (oceanic) plate and do not form a continuous plate boundary connecting the SW Rif fold-and-thrust belt to the Gorringe-Gloria fault region over a 600 km distance.

2.3.4. Numerical modeling of regional kinematics and regional stress field

Several studies have attempted to address the kinematics of the western portion of the Africa-Eurasia plate boundary through numerical modeling using thin spherical shell type plates (Jiménez-Munt and Negredo, 2003; Jiménez-Munt et al., 2001; Negredo et al., 2002). The earlier approaches considered the two large plates and either a small number of continuous and idealized large-scale faults (Jiménez-Munt and Negredo, 2003; Jiménez-Munt et al., 2001) or alternatively a large number of shorter discrete, pre-defined fault segments (Negredo et al., 2002), in both cases following as closely as possible structures mapped on land and offshore. These early studies compared the stress and strain fields obtained from the numerical modeling to regional observations of stress (earthquake focal mechanisms) and deformation

(e.g. mapped thrust-faults or normal faults for instance). They concluded that in the Gulf of Cadiz-Alboran Sea region, plate motion and deformation was not limited to a single, narrow, discrete plate boundary, and that significant amounts of deformation were accommodated in southern Spain, in northern Morocco and in offshore regions as well (Jiménez-Munt and Negredo, 2003; Jiménez-Munt et al., 2001; Negredo et al., 2002). These earlier studies, however, were limited by two factors, the knowledge of tectonic structures offshore was incomplete, since there were almost no morpho-bathymetric data available at the time, and secondly there were no geodetic studies providing a detailed description of the modern day strain field.

More recently, the same type of thin sheet numerical model was performed, integrating mapped faults, the rheological properties of the lithosphere, and comparing the results to GPS kinematic observations as well as stress indicators produced from earthquake focal mechanisms and borehole breakouts across a broad region encompassing Iberia, its Atlantic continental margin and parts of the Algeria-Morocco Atlas (Cunha et al., 2012). This model considered only the oblique motion between Nubia and Iberia, but did not take into account the subducted oceanic slab beneath Gibraltar nor the deformation in the accretionary wedge of the Gulf of Cadiz. In our study area of interest (the Gibraltar-Cadiz region) for their favored fault model, the modeling provided a relatively good fit between the observed and predicted seismic strain pattern based and the GPS velocities in the Gibraltar-Rif region. It succeeded in predicting a general westward motion within the Rif-Betic-Alboran region, but at speeds lower than the overall WNW motion of Africa (in an Iberia fixed reference frame) (Cunha et al., 2012). A further limitation of this model is that it did not provide a good fit with respect to the observed maximum horizontal stresses. The model also does not take into account, nor explain, the intermediate and deep focus seismicity in the Alboran Sea. The general implications of this work is that the shallow seismicity (10–60 km depth) associated with the main mapped faults (roughly E-W oriented dextral strike-slip faults and NE-SW northwards directed thrusts) is primarily controlled by the oblique plate movement of Nubia with respect to Iberia and that the subducted slab (which was not modeled) may be detached from its root or locked without significant seismicity in the last century of observations. Finally, these workers conclude that the WNW-ESE trending “SWIM” lineaments, proposed to be a nascent plate boundary with significant dextral strike-slip motion (Zitellini et al., 2009) “should not be regarded as mature lithospheric-scale features marking the present day plate boundary between Nubia and Eurasia” (Cunha et al., 2012).

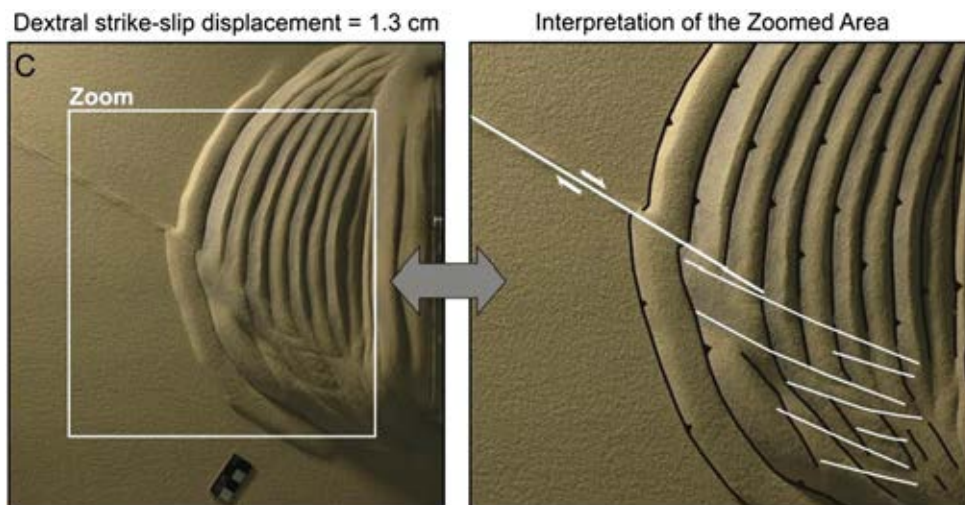


Fig. 12. Analog modeling applied to the interaction of the SWIM lineaments with the accretionary wedge (Duarte et al., 2011). (left) Final stage of an experiment which featured construction of an accretionary wedge against a rigid linear backstop, followed by 1.3 cm of dextral strike-slip motion along a N60W oriented basement fault (right) close-up view and interpretation of the final stage. If significant dextral motion post-dates the phase of wedge construction, then the deformation front must be offset. However, the morpho-bathymetry of the wedge shows no dextral offsets.

2.4. Geodetic studies and an independent Alboran micro-plate

Geodetic studies of the kinematics in this region are rendered difficult because relative motions are very slow, typically 1–5 mm/yr. Furthermore, it proved difficult to integrate and combine data from the handful of permanent stations across three different countries (Portugal, Spain and Morocco) with the networks of temporary stations established, usually in Morocco. Thus, the earliest studies typically featured relatively large error ellipses and often arrived at contradictory interpretations (Fadil et al., 2006; Fernandes et al., 2007; Stich et al., 2006; Tahayt et al., 2008). Thanks to coordinated efforts by several international groups, geodetic studies have improved significantly, with the inclusion of 65 permanent and 31 temporary stations and observation periods spanning 10 years in many cases (Koulali et al., 2011). This most complete displacement field strongly suggests the presence of an independent “Rif–Betic–West Alboran” microplate, situated between Iberia and Africa, moving towards the W at 3–6 mm/yr with respect to Iberia and moving to the SW at 2–3 mm/yr with respect to Nubia (Koulali et al., 2011) (Fig. 13). This is the overall type of block motion predicted by an active subduction and roll-back geodynamic model. However, the exact location of the block boundaries offshore is not constrained by the GPS stations. In particular, the ENE–SWS trending boundary crossing the entire Gulf of Cadiz is hypothetical and does not correspond to any known, seismically active structure. Calculations performed by these authors of the relative displacements along the boundaries of the proposed Alboran–Cadiz micro-plate indicate 3–4 mm/yr of dextral motion along a fault zone extending from the N Gulf of Cadiz and across Spain (the ENE–WSW trending Cadiz–Alicante fault zone), the same amount (3–4 mm/yr) of sinistral shear across the Alboran Sea along the NE–SW striking trans-Alboran shear zone, and only minor amounts of residual motion (1 mm/yr) along the WNW–ESE hypothetical fault in

the Gulf of Cadiz. It is especially interesting to note that the predicted sense of motion is actually sinistral (Koulali et al., 2011) which contradicts the dextral sense of motion predicted by Zitellini et al. (2009) for the SWIM lineaments in roughly the same location.

Suggestions that the SW motion of this microplate might be due to lateral expulsion of the Alboran block (caught between the Iberia and NW African plates) are challenged by two observations. First, the stations nearest the Strait of Gibraltar show the fastest W motion, which decreases progressively towards the E, towards Almeria (Fig. 13). This suggests that the main engine of motion is located to the W. Secondly, the W motion of some stations near Gibraltar (in an Iberia reference frame) is more rapid (reaching as much as 6 mm/yr), than the NW movement of Africa stations. This casts further doubt on the possibility that the origin of this more rapid W motion could be the more slowly NW moving African plate. The current set of GPS observations is not sufficiently dense, nor the error margins sufficiently small to discriminate between a model, where the independent block has sharp distinct boundaries, or on the other hand is bounded by a broadly deforming zone, with a gradual transition into the adjacent Iberian or African displacement fields (Fig. 13).

3. Discussion

Two of the main questions regarding the tectonic evolution of the SW Iberia region and its modern day kinematics were: Did lithospheric delamination of continental lithosphere or east-dipping subduction of oceanic lithosphere shape the Cadiz–Gibraltar region? And if subduction did occur, is it still active today?

- After 10 years of geophysical investigations, it is now demonstrated that the crust in the Gulf of Cadiz is oceanic in nature, dips to the east and appears to be connected to a slab of oceanic lithosphere imaged

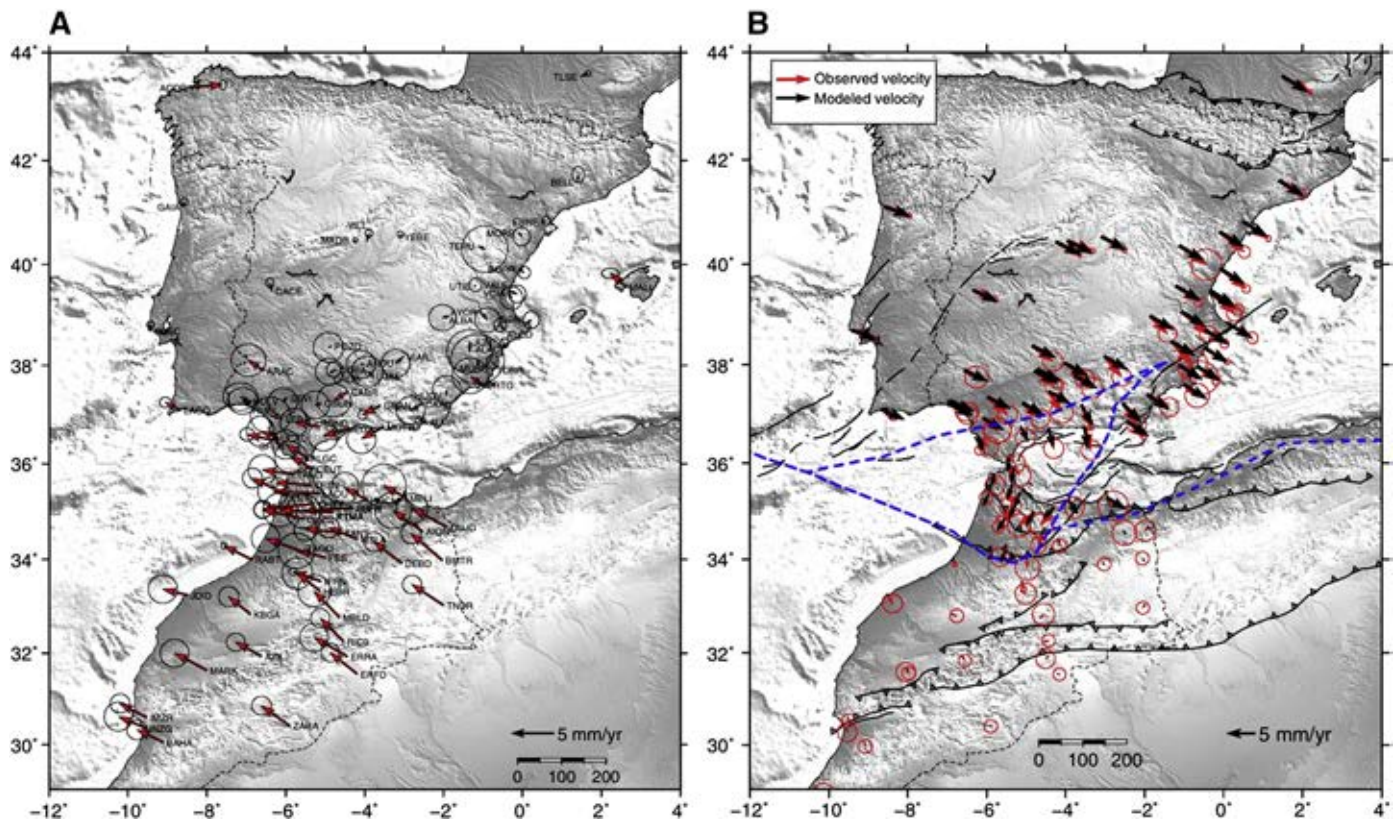


Fig. 13. GPS displacement vectors from 10 years of observation of fixed and field stations (Koulali et al., 2011) (left) Iberia (Eurasia) fixed reference frame, (right) Africa (Nubia) fixed reference frame, with plate/block boundaries proposed by the workers shown as blue dashed line.

deep below Gibraltar and the West Alboran Sea. Moreover, the upper mantle fabric (arc parallel fast directions) is consistent with toroidal flow around a narrow retreating slab. These observations strongly support the subduction model, while systematically contradicting the delamination model which does not predict oceanic slabs in the mantle.

- Furthermore, the distribution of Calc-alkaline magmatism in S Spain, the Alboran Sea and NE Morocco during the period 15 Ma to 5 Ma, discussed in detail in several publications (Duggen et al., 2003, 2004, 2005; Maury et al., 2000) also lends strong independent support for oceanic subduction beneath the W Alboran domain during this time span. This type of magmatism and the characteristic rare-earth signatures are diagnostic of water induced melting in the peridotite mantle wedge. It requires water to have been transported by the subducted slab and sediments down to great depths beneath the arc. Delamination of the lower portion of continental lithosphere does not carry water down to these (80–120 km) depths and thus cannot account for this type of magmatism.

The combined weight of all of these studies suggests that oceanic subduction was the primary geodynamic process, which has acted here since the Oligocene. “Delamination only” models (e.g. — Fig. 3A, excluding subduction of oceanic lithosphere) are incompatible with the currently observed regional crustal and lithospheric structure as well as with the distribution of Oligocene to Miocene arc volcanism. More recently, hybrid models have started appearing in the literature, commonly featuring an earlier phase of subduction (typically until Miocene/Messinian times) often followed by slab detachment and in some cases delamination of a portion of the adjacent continental lithosphere (Booth-Rea et al., 2007; Duggen et al., 2003; Fadil et al., 2006; Ruiz-Constan et al., 2011; Ueda et al., 2012; Vernant et al., 2010). Indeed, depending on the exact location and orientation of the cross-sections, the region beneath southern Spain where slab detachment has occurred, as imaged by tomographic studies (Garcia-Castellanos and Villaseñor, 2011; Spakman and Wortel, 2004) is crossed (Figs. 1 and 3C). Here, from the Alboran Sea and crossing the central to western Betics, the schematic cross-section of Fig. 3C seems applicable.

Addressing the second question, “Is subduction still active today?” is more difficult, though the active mud volcanism and geodetic work on the regional kinematics described above provide some clues.

One of the most reliable indicators of active deformation (in the absence of significant instrumentally observed seismicity) is folding and thrusting of young sedimentary strata. Deep penetration multi-channel seismic data successfully image the underthrust sedimentary section and the eastward thickening body of highly deformed sediments with abundant east-dipping reflectors, commonly associated to west-vergent thrust ramps (Gutscher et al., 2002, 2009a, 2009b; Iribarren et al., 2007). These data do not image thrust faults climbing to and cutting the seafloor, nor do they have the resolution to image this type of detail (on a scale of 100–200 m). Therefore, the ongoing activity of the accretionary wedge remains a matter of debate. Several authors argue that thick accumulations of undeformed Pliocene sediments observed to seal and overlie the deformation front of the accretionary wedge in several places (up to 2–3 km in the Rharb Valley for instance) offer conclusive proof that tectonic activity in the wedge has ceased since the Miocene (Iribarren et al., 2007; Zitellini et al., 2009) (Fig. 14).

However, other workers have pointed out that while in certain places (just offshore the Rharb Basin of Morocco and the Guadalquivir Basin of Spain) the Miocene deformation front has indeed been abandoned and sealed by thick undeformed Plio-Quaternary sediments, there is substantial evidence, in the form of published multi-channel seismic reflection profiles that the deformation front has stepped inwards to the Rharb Valley Lalla-Zahra Hills line and to the Cadiz Fault–Guadalquivir River line (Duarte et al., 2011; Gutscher et al., 2009a, 2009b; Maad et al., 2010) (Fig. 15). Indeed, there is a 10 km dextral

offset in the coastline of SW Spain at the mouth of the Guadalquivir River corresponding to this limit. Deformed external Betic allochthons and the first hills of the Betic front are located to the SE of this boundary, while the thick undeformed sediments of the Guadalquivir fore-deep basin are located to the NW. In like manner, the Lalla-Zahra hills in NW Morocco (labeled L–Z H in Fig. 7) form a sharp boundary between uplifted and deformed Miocene and Plio-Quaternary sediments to the north, and thick undeformed Plio-Quaternary and Miocene fore-deep sediments of the Rharb Basin to the south (Gutscher et al., 2009a; Maad et al., 2010). Recent geophysical studies on land show signs of active deformation and south vergent transpressional thrusting along this boundary (Toto et al., 2012). Were it not for the rapidly aggrading and lithified coastal dune system along this portion of the Moroccan coast, the coastline would also make an in-step here (sinistral in this case). There are portions of the Rharb basin below sea-level here, which regularly fill with rain making shallow ponds during the rainy season. (The local Arab name for these shallow and seasonally flooded depressions is Merja.) These two morpho-tectonic boundaries can be traced in high-resolution maps of the relief (Fig. 7 and Supplementary Fig. 19). The southern limit can be traced offshore by high-resolution seismic images from the SE lateral ramp region (in the Rharb submarine valley), which show folding, with associated transpressional faults emerging at the seafloor (Gutscher et al., 2009a; Maad et al., 2010). Other studies have documented superficial raft-tectonics type sinistral fissures nearby in the southern lobe of the accretionary wedge (Crutchley et al., 2011).

High-resolution seismic data from the NW and SW deformation front of the accretionary wedge, show evidence of widespread undulating folding of the Plio-Quaternary sedimentary cover, most commonly as blind-thrusting in the W wedge region, (Gutscher et al., 2009a, 2009b). However, these observations were interpreted otherwise by other authors (Iribarren et al., 2007), who point out that the Plio-Quaternary cover in most places is only gently undulating and that this could be the result of sedimentary drape over a previously active, but now tectonically extinct structure (Fig. 14D). These observations and this debate are illustrated in a schematic figure of the sedimentary relations involved (Fig. 16).

The “sedimentary drape” hypothesis (Fig. 16, left) follows most closely the ideas of Iribarren et al. (2007) and reflects a popular interpretation. Note, that syn-tectonic deformation in sediments will follow an inclined hinge axis (Fig. 16, right), which locally may also be inclined in the other direction for back-thrusts, (but not shown here). One major difference between “draped” sediments and syn-tectonic sediments should be the presence of “cusps” (a sharp, V-shaped geometry) at the sea-floor and in the shallowest strata. Prolonged sediment draping (over a period of up to 5 million years) can be expected to slowly smooth out the effects of originally sharp, underlying fault escarpments (Fig. 16, lower left).

High-resolution seismic images from the W toe region of the accretionary wedge document abundant short wavelength folding of the uppermost strata (Fig. 17). The 3.5 kHz Topas sub-bottom profiler images show primarily asymmetric folds, with a steeper forelimb and shallower back limb, indicating a mainly W vergence. The seafloor slope is dissected into numerous discrete steps by several major scarps, likely the surface expression of thrust faults at depth of unknown age. The seafloor itself and the shallow strata are commonly folded into distinct cusps. Some cusps visible deeper below, become progressively smoothed out towards the surface, suggesting that sediment draping has occurred here over a structure that has become inactive. In other places sharp, fresh cusps are present at the seafloor, implying deformation here is very recent and likely still active (Fig. 17). We therefore see evidence for both draping (of inactive structures) and syn-tectonic sedimentation at the W deformation front of the accretionary wedge.

Some authors accept that the fresh, rugous, morpho-bathymetric expression (Fig. 7 and Fig. 11, bottom) as well as the seismic images

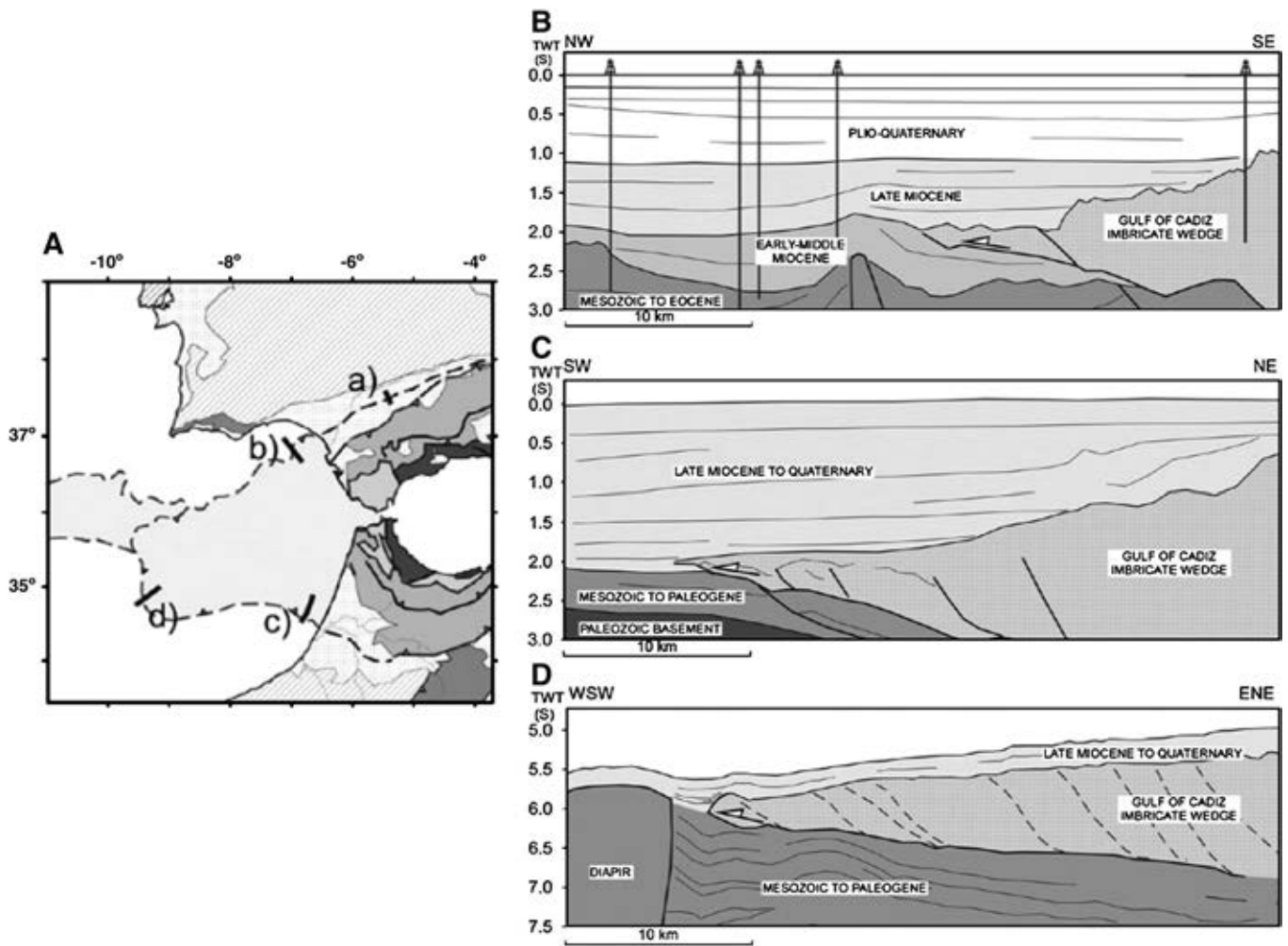


Fig. 14. Location map (left) and line drawings of three seismic reflection profiles (Iribarren et al., 2007), B) offshore Guadalquivir Basin (SW Spanish shelf), C) Rharr Valley (offshore NW Morocco) and D) western deformation front of accretionary wedge. B and C show large thicknesses (2–3 km) of undeformed Plio-Quaternary sediments overlying the Miocene deformation front of the accretionary wedge. These authors consider these observations as conclusive evidence that tectonic activity in the accretionary wedge has ceased since the Miocene. Note also, the undulating Plio-Quaternary sequence in D (discussed further below).

(Fig. 17) showing deformation of Plio-Quaternary strata on top of the wedge are indeed signs of recent deformation, but prefer to invoke other causes for this deformation. Two popular alternative models frequently proposed by opponents of active subduction are: 1) an initial phase of Miocene wedge construction with west vergent thrusting, cessation of subduction and then a prolonged phase of large scale gravitational spreading of the entire accretionary wedge (but without any W directed tectonic push) and 2) an initial phase of Miocene wedge construction with west vergent thrusting, cessation of subduction and finally the inactive accretionary wedge caught between Africa and Iberia and then slightly reactivated in an overall NW–SE compressional setting. These two hypotheses will now be addressed along with the favored active (but slow) subduction model and are illustrated schematically in Fig. 18.

Most authors agree that the accretionary wedge formed rapidly during the Miocene as a result of a WSW directed tectonic push (Gutscher et al., 2002, 2009a, 2009b; Iribarren et al., 2007) (Fig. 18 left side). The ongoing debate hinges on what occurred since the Miocene.

- The uppermost model considers that residual deformation occurs as a result of widespread gravitational spreading throughout the wedge (producing a general outward flow pattern similar to a glacier) (Fig. 18 top right). The most appropriate published references would probably be (Maestro et al., 2003; Torelli et al., 1997).

- The central model considers that any residual deformation is driven by the overall Africa–Iberia convergence (Fig. 18 center right). This model would predict anticlines with generally NE–SW oriented hinge lines and no SW vergent thrusting at the SW deformation front.
- The lowermost model shows a slowing of the WSW directed tectonic push and limited gravity sliding in the two upper lobes (for more detailed discussion see Gutscher et al., 2009b) (Fig. 18 lower right). Note in this model there is still a significant advance of the western portion of the Alboran block to the WSW (on the order of about 100 km, see also Fig. 3B and discussion further below), whereas in the other two models this movement is considered to have ceased.

The widespread gravitational sliding hypothesis encounters two problems. The first is that in order to have gravity sliding down to the W, you require a basal detachment surface that slopes down in this direction. For the frontal (western) portion of the wedge, all the lithological boundaries dip gently to the east, by about 1–2° (Fig. 6) (Gutscher et al., 2002, 2009a, 2009b; Thiebot and Gutscher, 2006). These include: the decollement at the base of the deformed sediments (and above the higher P-wave velocity, undeformed Mesozoic sediments), the top basement, and the Moho. It is mechanically impossible to induce a thick body to gravitationally slide up an inclined slope. Secondly, there are indeed signs of limited gravitational sliding in the uppermost (eastern) portions of the accretionary wedge,

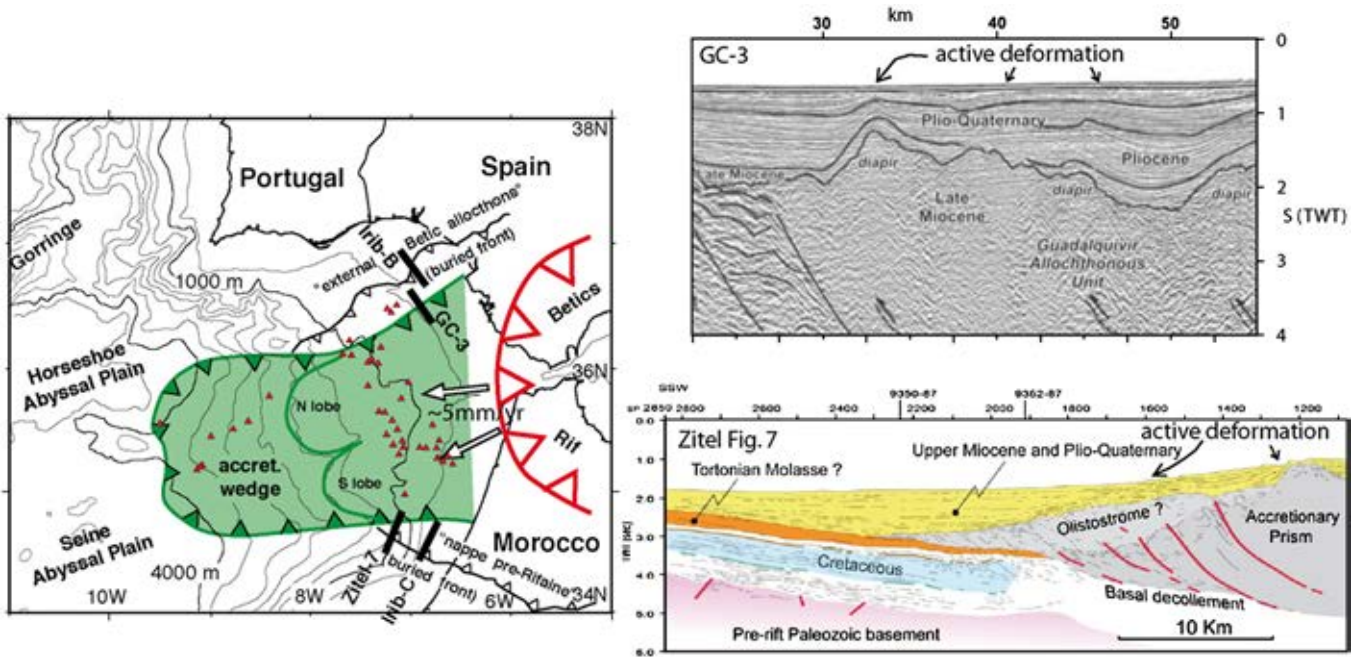


Fig. 15. Location map (left) (after Gutscher et al., 2009b) and two multi-channel seismic reflection profiles line GC-3 (upper right) (Gràcia et al., 2003b) and a Moroccan industry line (lower right) (Zitellini et al., 2009). The words “active deformation” with arrows were added.

affecting the uppermost 1 km of sediments, within two discrete lobes (Fig. 7 and Fig. 18 lower right) (Gutscher et al., 2009b). It produces raft-tectonic type fissures and is bounded by a 10–15° steep, convex,

viscous flow “lip” at its western limit. This is also expressed very clearly in 2-D bathymetric profiles of the surface slope of the accretionary wedge. The lower (western) slope of the accretionary wedge, does not

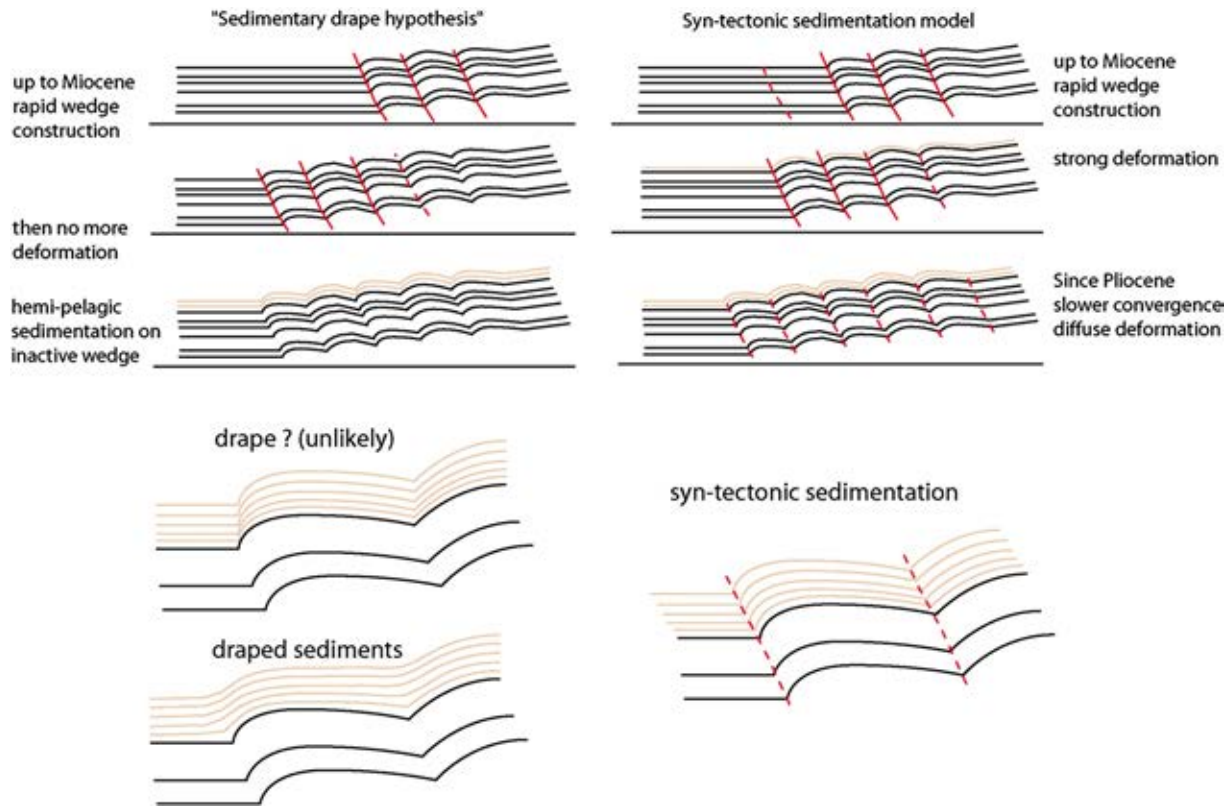


Fig. 16. Idealized cross-sections, schematically indicating geometries and faulting–sedimentary relations, due to different sequences of tectonic events at the toe of the accretionary wedge. The popular “sedimentary drape” hypothesis (left) follows the ideas of Iribarren et al. (2007). Note, that syn-tectonic sedimentation will produce an inclined hinge axis (lower right). A major difference between “draped” sediments and syn-tectonic sediments should be the presence of “cusps” (a sharp, V-shaped geometry) at the sea-floor and shallowest strata. Prolonged sediment draping (>1 million years) can be expected to slowly smooth out the effects of original underlying sharp fault escarpments (see lower left).

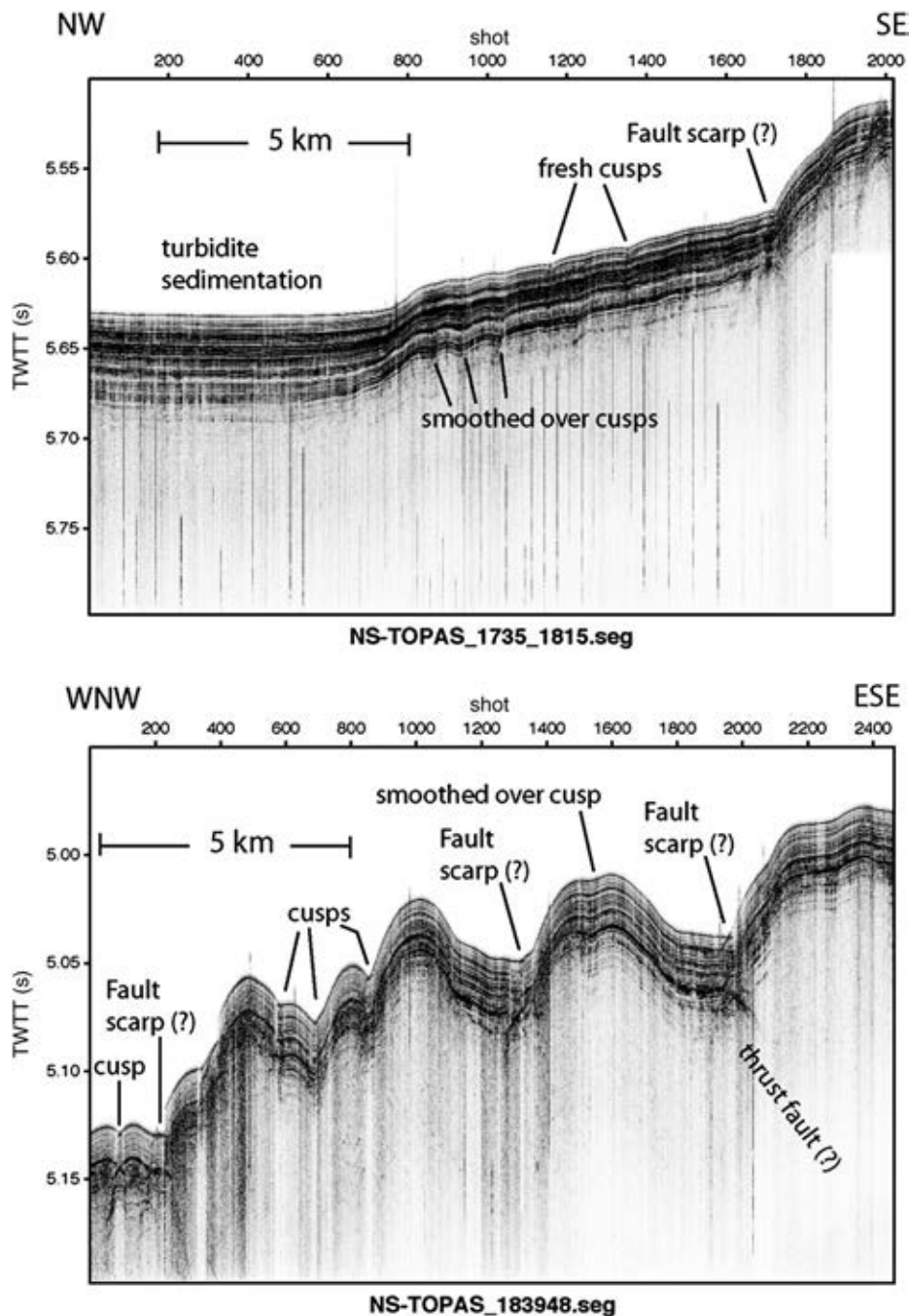


Fig. 17. High-resolution seismic images of the toe of the accretionary wedge, using the Topas system N/O Hesperides Nearest cruise, Nov. 2009, (see Fig. 5 for location). (left) deformation front, showing flat lying turbidite sedimentation in the Seine abyssal plain, successively deformed within the wedge, (right) deformation pattern higher up on the wedge, within the undulating Plio-Quaternary cover. Note the abundant, closely-space anticlinal folds, typically with a steeper forelimb and shallower back limb indicating primarily W vergence. A steep reflection may be an E dipping thrust fault. The location of cusps and potential fault scarps are indicated. Note some sharp cusps observed at depth, are smoothed over towards the surface by the effects of sedimentation and indicate a waning of tectonic activity on the associated structure, while other cusps are sharp and fresh at the surface, indicating they have formed just recently.

show this convex, viscous flow lip, and is characterized instead by a constant 1° surface slope, compatible with a very weak basal friction in a tectonically deforming thrust wedge (Davis et al., 1983; Gutscher et al., 2009b).

The Africa-Iberia tectonic push hypothesis implies that since the Miocene any further deformation would be dominated by NW-SE compression. This should have the effect of creating NE-SW trending folds (illustrated schematically in Fig. 18 center, right) and potentially N-S or E-W oriented strike-slip faults. Any such folds would be sub-parallel to the NW deformation front of the accretionary wedge, and

thus impossible to differentiate from the original NW-vergent deformation during the initial phase of wedge construction. However, the new NE-SW trending structural grain predicted by this model for the south-central to SE portion of the wedge is not observed in this region. This model further predicts that the SW deformation front, where original SW vergent folds were present, should not be reactivated in a stress field where Sh_{Max} is NW-SE. This is represented schematically by the two open, white (inactive) thrust teeth (Fig. 18 center, right). So observation of active thrusting here would be a contradiction of this model. It turns out that the high-resolution Topas observations are from this SW

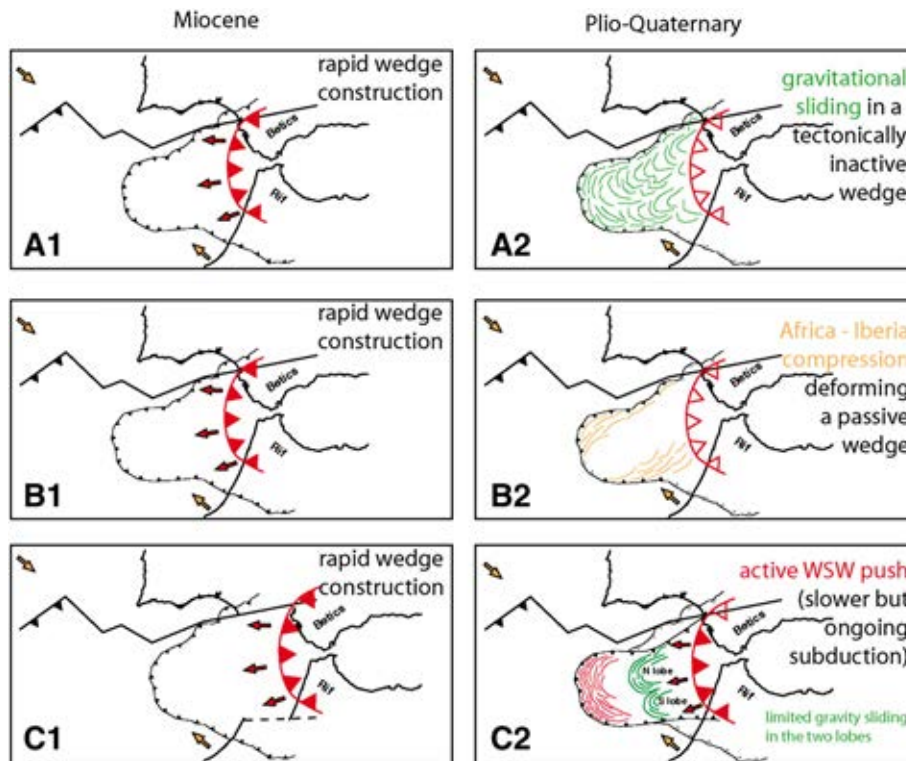


Fig. 18. Schematic map scale deformation pattern in the Cadiz-Gibraltar region showing a two-part evolution of the accretionary wedge, according to three different conceptual models. The general consensus is that rapid growth occurred during the Miocene as a result of a WSW directed tectonic push. Model A (top) considers that residual deformation occurs as a result of widespread gravitational spreading throughout the wedge (producing a general outward flow pattern similar to a glacier). The most appropriate published references would probably be (Maestro et al., 2003; Torelli et al., 1997). Model B (center) considers that any residual deformation is driven by the overall Africa-Iberia convergence. This model would predict anticlines with generally NE-SW oriented hinge lines and no SW vergent thrusting at the SW deformation front. Model C (bottom) shows a slowing of the WSW directed tectonic push and limited gravity sliding in the two upper lobes (for more detailed discussion see Gutscher et al., 2009b). Note in this model there is still a significant advance of the Alboran block to the WSW, whereas in the other two models this movement is considered to have ceased.

to W portion of the deformation front (Fig. 17) and the images show folding and W-vergent thrusting of the shallowest sedimentary strata.

The regional stress field, as expressed by in-situ measurements and shallow, crustal earthquake focal mechanisms, also bears strongly on this debate. If the subducted slab is entirely detached and the subduction has ceased, then ShMax should be oriented NW-SE, specifically aligned with regional Africa-Iberia convergence. Indeed, throughout most of the region this is the case. (Cunha et al., 2012; Fernandez-Ibanez et al., 2007; Pedrera et al., 2011; Stich et al., 2003, 2006). But there is a major perturbation in the stress field in southern Spain, the W Alboran Sea and Rif region, where normal to normal/strike-slip seismicity occurs and where σ_1 is no longer horizontal and oriented NW-SE, but shifts to nearly vertical (Fernandez-Ibanez et al., 2007; Stich et al., 2003, 2006). A generally ENE-WSW extensional stress field in the W Alboran Sea region is also consistent with the GPS displacement field which shows stations in the Rif moving at 5–6 mm/yr to the SW, whereas stations in S Spain are moving only 1–3 mm/yr to the SW, in an Iberia fixed reference frame (Fig. 13, left).

So we are left with a regional kinematic framework with the western Rif-Betic orogenic front moving to the W and SW at 5–6 mm/yr, more rapidly than any other blocks and more rapidly than Africa (which moves at 4 mm/yr to the NW). Behind this block there is an extensional stress field and progressively slower WSW motion. This set of observations is neither consistent with a two-plate model, nor with a two-plate and expulsion/lateral drag on a minor block model. These observations require a second geodynamic engine (in addition to the large-scale NW-SE Africa-Iberia convergence), the roll-back of the subducting slab. The velocity of slab roll-back seems to have slowed since 5 Ma. If we take the position of the relic volcanic arc from 5 Ma and consider that the paleo-slab depth was 100 km (typical for volcanic arcs worldwide)

and compare this to the current 100 km slab depth contour, we obtain a value of about 100 km for the westward motion of the slab hinge (Fig. 3b). This corresponds to a mean roll-back velocity of 2 cm/yr. Modern GPS measurements indicate a WSW motion of the Gibraltar-Alboran block at roughly 6 mm/yr. This movement continues to drive WSW directed compression in the accretionary wedge, expressed as transpression in lateral ramps and as NW-, W- and SW-vergent folding and thrusting in the accretionary wedge, consistent with the recent deformation observed here. Other evidence of post-Miocene tectonic deformation in the Betics include clockwise paleomagnetic rotations of 10–15° observed in Miocene sediments in the Granada region, which is consistent either with subduction or with dextral shear between the Alboran block and Iberia (Mattei et al., 2006). Considering all the evidence presented above, we favor the slow, but ongoing subduction model, characterized by active NW-vergent, W-vergent and SW-vergent thrusting at the toe of the accretionary wedge (Fig. 18, lower right).

4. Conclusions and outlook

While many independent lines of reasoning presented here point to ongoing and slow subduction beneath Gibraltar, a number of enigmas remain to be explained and are frequently evoked when discussing the modern geodynamics in the S Iberia region. Why did arc volcanism cease around 5 Ma? Why are there no thrust-type earthquakes, characteristic of an active subduction zone? And if subduction was active until the Miocene and caused the rapid phase of wedge construction, why did it slow down and produce the episode of wedge draping observed in seismic profiles today, with some minor amounts of active deformation, but a major reduction in strain rate nevertheless?

It seems likely that a major geodynamic change occurred at the end of the Miocene. A good indicator of this is the cessation of arc volcanism, preceded by a change to potassium-rich calc-alkaline volcanism (Duggen et al., 2005). Today in the Calabrian subduction and Eolian arc, there is a similar potassium-rich calc-alkaline geochemical signature. Here too, subduction has slowed and thrust type earthquakes are absent, though signs of deformation have been observed in young marine sediments at the toe of the accretionary wedge (Gallais et al., in press; Gutscher et al., 2006b). The potassium-rich signature may indicate partial melting of slivers of continental crust either at the lateral edges of the narrow subducting slab (Duggen et al., 2005) or in the asthenospheric windows opened by the slab tear (Gvirtzman and Nur, 1999). Finally, the wide-spread alkalic volcanism observed throughout the Alboran Sea region (in S Spain, NE Morocco and NW Algeria) since 5 Ma, probably also marks episodes of slab break-off, detachment and the presence of local asthenospheric windows (Maury et al., 2000). The asymmetric high P-wave velocity anomaly observed under the Betics (Spakman and Wortel, 2004) (Fig. 10) is not attached to the surface and strongly implies that slab detachment occurred here in the past and is probably propagating westward as suggested by more recent studies as well (García-Castellanos and Villaseñor, 2011; Ruiz-Constan et al., 2011) (Figs. 1 and 3C). How much of the slab is still attached today? This question is difficult to answer precisely and some workers have suggested only a very small residual portion of the slab remains attached beneath the Rif (Vernant et al., 2010). Other authors have raised the possibility that the slab is entirely detached and no longer affecting the regional geodynamics (Cunha et al., 2012). While the lines of evidence presented above do not favor this end-member proposition, it does seem likely that slab detachment began around 5 Ma and that as the actively subducting slab narrowed, the poloidal flow required to produce an active volcanic arc diminished, largely replaced by the toroidal flow in the upper mantle (Diaz et al., 2010) (Fig. 9). Today there may only be a short segment of the slab still attached, perhaps less than 150 km in a N-S direction. Indeed only two, well oriented tomographic cross sections, at 35°N and at 36° N successfully image a continuous east-dipping slab (Gutscher et al., 2002; Spakman and Wortel, 2004). The ever-narrowing slab, coupled with the continually approaching Iberia and African plates are both likely contributing factors. Improved tomographic models, with a finer resolution would be necessary to resolve this issue. Improving our understanding of the paleo-geometry of the slab(s) which subducted here during the past 5–10 million years and their ultimate fate (detachment and sinking, twisting, producing lateral tears, still attached and rolling back) and the effects on surface tectonics remains one of the great challenges before fully understanding the geodynamic evolution of the westernmost Mediterranean. But given the currently observed 5–6 mm/yr WSW motion of several GPS stations in the westernmost Rif and Straits of Gibraltar, the subduction related tectonics do not appear to have entirely ceased.

If subduction remains active, then why are there no observed thrust type earthquakes? This has been previously discussed, with comparisons made to well-established locked subduction fault planes in the world, like Nankai or Cascadia or the southern Antilles and raising the question whether one of the most famous historical earthquakes, the Great Lisbon earthquake of 1755 may have originated on this shallow-dipping mega-thrust (Gutscher, 2004; Gutscher et al., 2006a, 2009a). If the subduction fault plane is indeed locked, then the GPS stations closest to the fault plane will actually be underestimating the long-term plate motions, due to elastic loading. But this is not possible to confirm or disprove with existing data. Acquisition of more GPS data and over longer periods of observation remains one of the highest priorities and should help pinpoint the boundaries of the intermediate Alboran block and the exact kinematics of the bounding faults. Further work to identify the potentially active faults related to this system, on land and in the adjacent offshore

regions, will be a major focus of research for the years to come. Finally, additional and sophisticated seismological studies (e.g. – receiver functions and higher resolution tomography) as well as numerical modeling studies could be useful to address the latest hybrid geodynamic schemes involving subduction, slab break-off and delamination. These must try to take into account the complex 3-D geometry and lateral variations in lithosphere type, with the former providing more precise boundaries on their distribution at depth and on the continuity (or detachment) of slabs and the latter testing these different scenarios in light of the recent geodynamic evolution and modern kinematics and tectonics.

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