Are subduction zones invading the Atlantic? Evidence from the southwest Iberia margin

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ABSTRACT

Subduction initiation at passive margins plays a central role in the plate tectonics theory. However, the process by which a passive margin becomes active is not well understood. In this paper we use the southwest Iberia margin (SIM) in the Atlantic Ocean to study the process of passive margin reactivation. Currently there are two tectonic mechanisms operating in the SIM: migration of the Gibraltar Arc and Africa-Eurasia convergence. Based on a new tectonic map, we propose that a new subduction zone is forming at the SIM as a result of both propagation of compressive stresses from the Gibraltar Arc and stresses related to the large-scale Africa-Eurasia convergence. The Gibraltar Arc and the SIM appear to be connected and have the potential to develop into a new eastern Atlantic subduction system. Our work suggests that the formation of new subduction zones in Atlantic-type oceans may not require the spontaneous foundering of its passive margins. Instead, subduction can be seen as an invasive process that propagates from ocean to ocean.

INTRODUCTION

The Wilson Cycle, a paradigmatic concept in plate tectonic theory, describes the evolution of an Atlantic-type ocean in three phases: (1) opening and spreading; (2) spontaneous foundering of the passive margins and development of new subduction zones; and (3) consumption and closure. The key process by which a passive margin becomes active is still controversial and unknown (Nikolaeva et al., 2010; Stern, 2004; Gurnis et al., 2004). It is unclear how a new subduction system might form in isolation from a previously existing one. Also, despite the abundance of both passive and active continental margins on Earth, no cases of spontaneous transition between these two types of margins have been identified (Nikolaeva et al., 2010). All cases of incipient subduction seem to be associated with existent convergent settings such as backarc basins, e.g., in the northern margin of Algeria (Kherroubi et al., 2009), or by the conversion of oceanic transform faults and/or fracture zones (Mueller and Phillips, 1991). The search for an incipient subduction zone at an Atlantic-type margin has long been one of the major challenges in plate tectonics. Identification could provide crucial data to constrain conceptual and geodynamic models of subduction initiation, which would improve our knowledge of the forces driving and resisting plate tectonics (Gurnis et al., 2004).

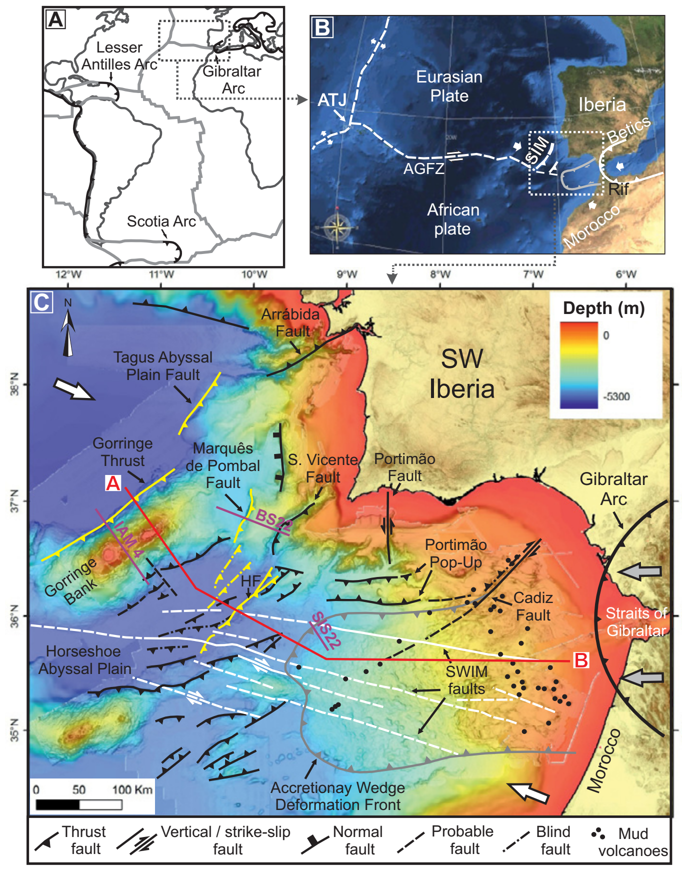

Figure 1. A : Simplified tectonic map of Atlantic Ocean with location of Atlantic arcs (modified from Schellart and Lister, 2004). B: Location of study area (dashed rectangle). ATJ—Azores triple junction; AGFZ—Azores-Gibraltar fracture zone. C: Tectonic map of southwest Iberia margin (SIM). Gray arrows show Gibraltar Arc westward movement (3–6 mm yr^{-1}); white arrows show Africa-Eurasia WNW-ESE convergence (~4 mm yr^{-1}). Segment A–B and seismic profiles IAM4, BS22, and SIS22, in red and purple, are shown in Figure 2. HF—Horseshoe fault.

The margins of the Atlantic Ocean are generally described as type examples of passive margins. However, there are three subduction zones in the Atlantic: the Scotia Arc, the Lesser Antilles Arc, and the Gibraltar Arc (Fig. 1A). The Gibraltar Arc is located at the western end of the Mediterranean collision belt, where a retreating convergent plate boundary is propagating into the Atlantic (Fig. 1). This subduction zone developed during the Neogene due to the rapid rollback of an east-dipping oceanic slab, now located underneath the Gibraltar Arc (see the tomographic sections in Fig. DR4 in the GSA Data Repository[1]; Gutscher et al., 2002). Although instrumental thrust earthquakes and recent arc volcanism are absent, multiple lines of evidence, including folding and faulting of young sediments along the accretionary wedge deformation front and the motion of an independent tectonic block (Alboran block) at velocities distinct

[1]GSA Data Repository item 2013235, Figure DR1 (high-resolution bathymetry and multichannel seismic data), Figure DR2 (seismic profile of the Marquês de Pombal fault), Figure DR3 (seismic profiles of the accretionay wedge), Figure DR4 (tomographic section and calculation of the slab-pull force), Figure DR5 (GPS displacement vectors), Table DR1 (high-resolution bathymetry data sources), and Table DR2 (seismic data sources and specifications), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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from and more rapid than the Africa-Eurasia convergence, suggest continued Gibraltar subduction activity (Fig. DR5). Nonetheless, the activity of the Gibraltar subduction is still disputed (see discussion in Gutscher et al., 2012). The westward migration of the Gibraltar Arc, in addition to the oblique convergence between Africa and Eurasia (Figs. 1B and 1C), induces compressive stresses in the southwest Iberia margin (SIM), making this region a potential locus for subduction initiation. Anomalous high-magnitude seismicity, such as the M >8.5 Lisbon earthquake of A.D. 1755 and the M ~8 earthquake on 28 February 1969, complies with such a scenario (Gutscher et al., 2002; Ribeiro et al., 1996).

Several pioneering works addressed the potential development of a subduction system in the SIM (e.g., Mueller and Phillips, 1991; Royden, 1993; Ribeiro et al., 1996; Faccenna et al., 1999); however, they lacked the necessary structural constraints (bathymetric and seismic data) to construct a detailed tectonic map. In this paper we use a new tectonic map to reevaluate the problem of subduction initiation at the SIM (Fig. 1C). In addition, we propose testable hypotheses for the geodynamic evolution of this area. Our work supports the idea that preexisting convergent plate boundaries may have a fundamental role in the reactivation of passive margins in an Atlantic-type ocean.

SUBDUCTION INITIATION IN THE ATLANTIC

Assuming that various Wilson Cycles occurred since the onset of plate tectonics, the almost absence of oceanic lithosphere older than 200 Ma suggests that new subduction systems are likely to initiate repeatedly close to passive margins, where there is older oceanic lithosphere (Goren et al., 2008). It is traditionally assumed that spontaneous subduction initiation occurs when the cold, gravitationally unstable, oceanic lithosphere collapses into the asthenosphere, as a consequence of aging and thermal contraction. However, several works showed that the strength of the oceanic lithosphere also increases with its age, and it consequently does not make it more susceptible to spontaneous collapse (Mueller and Phillips, 1991; Cloetingh et al., 1989). This conclusion is supported by the existence of 170 Ma old oceanic lithosphere adjacent to the northwest Africa and the northeast America passive margins. Furthermore, the geological record does not seem to reveal examples of an Atlantic-type margin evolving spontaneously into an Andean-type margin (Mueller and Phillips, 1991; Cloetingh et al., 1989). One way to overcome this contradiction is to consider that the initiation of subduction at passive margins requires the action of an external tectonic force transmitted from a nearby subduction zone or collisional belt (Mueller and Phillips, 1991; Cloetingh et al., 1989).

The Atlantic is almost entirely bounded by passive margins. However, there are at least two regions where Atlantic oceanic lithosphere is being consumed in subduction zones: in the Scotia and Lesser Antilles Arcs (Fig. 1A). These arcs correspond to cases where subduction initiation was induced by the proximity of another subduction system (the eastern Pacific subduction zones), possibly due to stress transmission across narrow continental landmasses that once existed between the Pacific and the Atlantic Oceans (Mueller and Phillips, 1991; Goren et al., 2008). In this context, Mueller and Phillips (1991) considered that subduction zones may be introduced into pristine oceans (i.e., oceans without subduction zones) in a way that might be viewed as a process in which an ocean with subduction zones comes into contact with and invades the pristine oceanic basin.

It is conspicuous that both the Scotia and Lesser Antilles Arcs are propagating along fracture zones that connect the arcs to the Mid-Atlantic Ridge (Fig. 1A). A third plate limit of this type in the Atlantic is the Azores-Gibraltar fracture zone (Figs. 1A and 1B), which extends from the Azores triple junction to the foreland of the Gibraltar Arc. This area was proposed to be a third place where an initial stage of this invasion process could be occurring (Mueller and Phillips, 1991; Royden, 1993). In the Scotia and the Lesser Antilles Arcs, the trenches do not seem to have propagated laterally along the adjacent passive margins (Fig. 1A); on the contrary, in the foreland of the Gibraltar Arc the compressive deformation propagated northward by ~300 km along the SIM (northeast-southwest thrusts in Fig. 1C).

SIM

The new tectonic map of the SIM (Fig. 1C) was constructed through the analysis of stratigraphically calibrated seismic reflection profiles (compiled from 6 surveys comprising ~20,700 km of seismic sections) using the commercial software Landmark OpenWorks (http://www.halliburton.com/ps/default.aspx?pageid=852), coupled with the analysis of 180,000 km^2 of high-resolution bathymetry (compiled from 19 surveys), which together provided morphotectonic information at the scale of the entire study area (Fig. DR1 and Tables DR1 and DR2). Three active tectonic systems can be recognized in this map: (1) the accretionary wedge (in gray); (2) a group of northeast-southwest–striking thrusts (in yellow); and (3) WNW-ESE–striking dextral strike-slip faults (SWIM fault system; in white).

Accretionary Wedge

The accretionary wedge marks the propagation of the Mediterranean Alpine collision belt into the Atlantic. It is defined by a west-dipping U-shaped seafloor morphology (Fig. 1C). Structurally, it consists of an eastward-thickening pile of westward-thrusted sediments (Fig. 2; Fig. DR3). The east-dipping thrusts root in a décollement layer and occasionally breach throughout the seafloor, exhibiting a geometry compatible with ongoing subduction beneath the Gibraltar Arc (Gutscher et al., 2002, 2012). The existence of this subduction zone is supported by seismic tomography (see Fig. DR4), and it is a remnant of the subduction system that consumed the western Mediterranean Tethyan Ocean during the Cenozoic (Fig. 3A; Lonergan and White, 1997). Gutscher et al. (2002, 2012) proposed that the subduction is active and retreating westward along an east-west–trending corridor of oceanic lithosphere.

Northeast-Southwest Thrust System

The northeast-southwest–striking thrust system comprises the Horseshoe, Marquês de Pombal, and Tagus Abyssal Plain faults and the Gorringe thrust, and extends for ~300 km along the SIM (see Figs. 1C and 2; Fig. DR2). The thrust-related morphologies have prominent escarpments reaching 5000 m in height and root deep into the basement, possibly

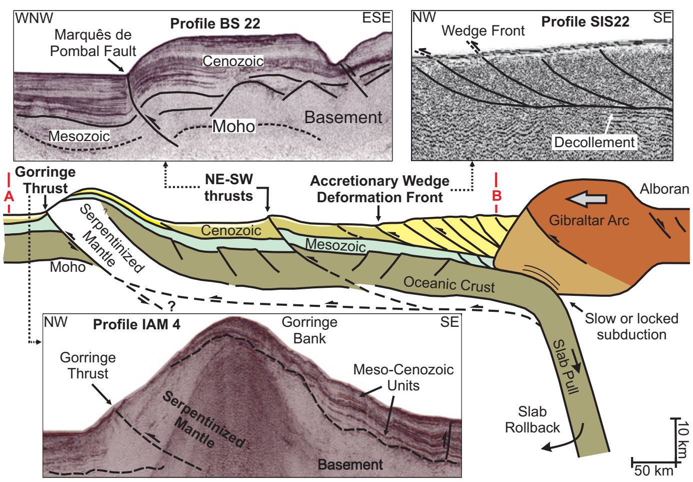

Figure 2. Schematic crustal section across Gibraltar Arc–southwest Iberia margin (SIM) region. Approximate direction and position of segment A–B are shown in Figure 1C. Three representative seismic sections (clockwise: BS22, SIS22, and IAM4) are also depicted. Refer to Figure 1C for vertical and horizontal scales. Note that it is not clear if Gorringe roots in intralithospheric décollement, or if it cuts through lithosphere.

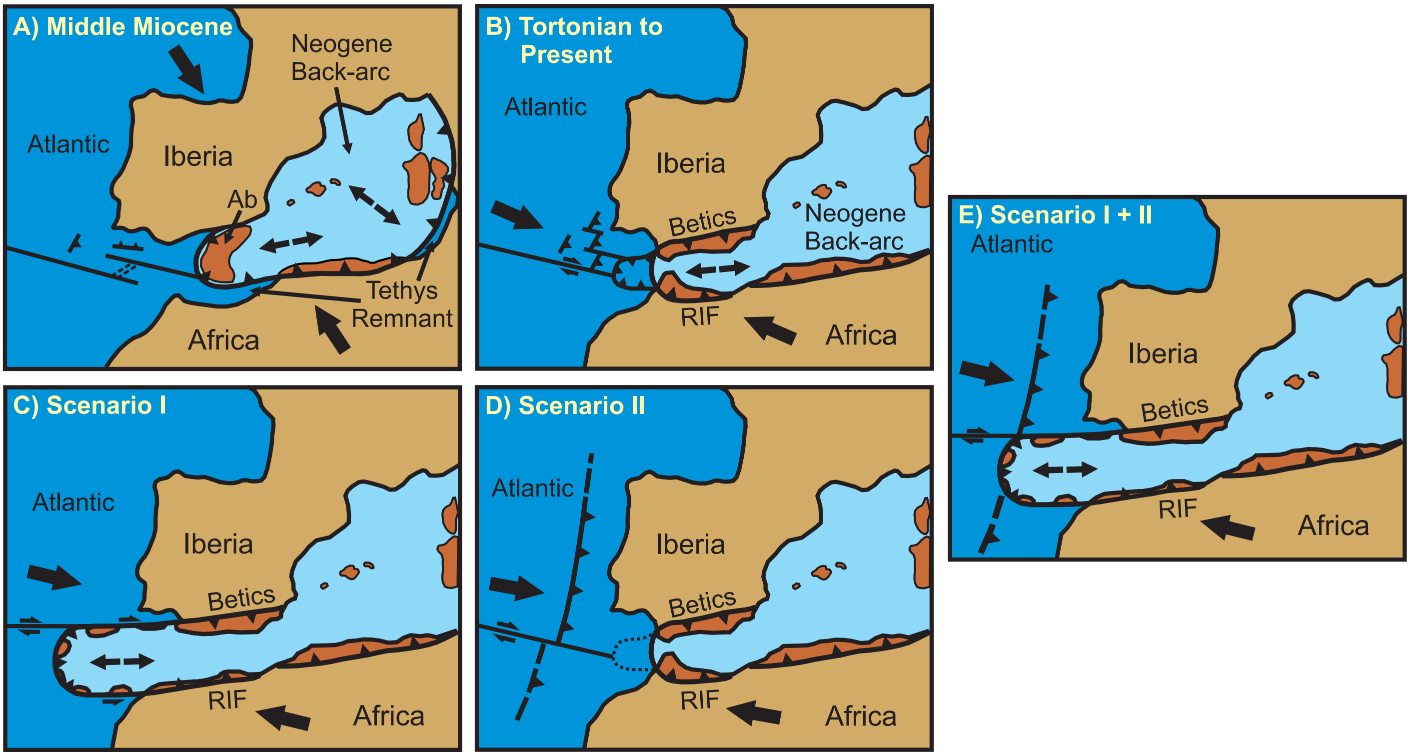

Figure 3. A, B: Reconstruction of tectonic evolution of southwest Iberia margin (SIM) and western Mediterranean region since Miocene (adapted from Rosenbaum et al., 2002). Ab—Alboran block. C, D: Hypothetical evolution scenarios. I: Gibraltar subduction migrates into Atlantic domain. II: New subduction system forms in SIM while Gibraltar subduction zone becomes inactive. E: Combined scenario I + II: Gibraltar subduction migrates westward and propagates northward along SIM.

cutting into the mantle (Fig. 2). The northwest-directed thrusting kinematics are given by the short limb–long limb thrust-related folding geometry affecting the sedimentary cover. The total amount of WNW-ESE crustal shortening across Gorringe Bank region is ~50 km (Hayward et al., 1999). This thrust system results from deformation migration from the Gibraltar wedge along the SIM, concomitant with the rotation of the convergence direction between Africa and Eurasia since the Miocene (Terrinha et al., 2009; Figs. 3A and 3B). These structures are the expression of a new compressive deformation front forming away from the Gibraltar Arc and along the SIM, and appear to correspond to the onset of the margin inversion and nucleation of a new subduction zone (Terrinha et al., 2009; Ribeiro et al., 1996). Moreover, the Gorringe Bank consists mostly of highly serpentinized mantle peridotites and gabbros (Hayward et al., 1999), which in addition to induced compression, provide an efficient weakening mechanism that facilitates lithospheric rupture (Cloetingh et al., 1989; Masson et al., 1994).

SWIM Fault System

The SWIM fault system is a group of WNW-ESE–striking subvertical structures, interpreted as dextral strike-slip faults (Fig. 1C; Terrinha et al., 2009). These west-northwest–east-southeast structures correspond to the dextral reactivation of basement rift-related Mesozoic faults (Figs. 3A and 3B; Duarte et al., 2011) and are likely acting as transfer zones connecting the two compressive tectonic systems, i.e., the Gibraltar Arc and the northeast-southwest thrusts.

TECTONIC EVOLUTION OF THE SIM: SUBDUCTION PROPAGATION OR INDUCED INITIATION?

The structures mapped in the SIM are compatible with the existence of two tectonic driving mechanisms: the westward movement of the Gibraltar Arc, and the west-northwest–east-southeast convergence between Africa and Eurasia (gray and white arrows in Fig. 1C, respectively). This interpretation is supported by GPS data that show an ~4 mm yr^{-1} WNW-ESE convergence between Africa and Eurasia, and 3–6 mm yr^{-1} of westward movement of the Gibraltar Arc in relation to Eurasia (see GPS vectors in Fig. DR5; Koulali et al., 2011). It is difficult to quantify the exact contribution of each of the two mechanisms that best comply with the evolving tectonic framework of the SIM. Nevertheless, it is possible to speculate on general evolution scenarios.

Gibraltar Arc Propagation

In this scenario, the Gibraltar Arc subduction zone continues to retreat due to slab rollback (Fig. 3C). Eventually, the arc will migrate along the Azores-Gilbratar fracture zone into the open Atlantic, similarly to the Scotia and Lesser Antilles Arcs. However, even though there is evidence of the westward propagation of the Gibraltar Arc, the rate of migration is decreasing (Gutscher et al., 2012). It is possible that such a decrease is being caused by the north-south constriction and narrowing of the oceanic corridor imposed by the Africa-Eurasia convergence that led to collision in the Betics and in the Rif, which may have caused the lateral break-off of the slab. We calculated a slab negative buoyancy force of ~8 × 10^{13} N/m (Fig. DR4), which may be sufficiently high to overcome resisting forces and cause the westward retreat of the arc. However, under this force the narrowing of the oceanic corridor would cause an increase in the rollback rate and a westward acceleration of the Gibraltar arc (Guillaume et al., 2010); the observations show the opposite (Gutscher et al., 2012).

Induced Subduction Initiation at the SIM

In this scenario, the Gibraltar subduction zone will not overcome the resisting forces, the slab breaks off, and the arc migration decreases. If this was the case, a new subduction zone may still develop in the SIM and propagate laterally (Fig. 3D). The loss of the negative buoyancy force (due to break-off) changes force balance, resulting in a rapid increase of horizontal stresses that may propagate along the plate boundary as far as the SIM. Even in the case where slab break-off does not occur, only ~10% of the negative buoyancy of a slab is transmitted to the surface as a slab pull force (Schellart, 2004), i.e., $\sim 8 \times 10^{12}$ N/m, and the force required to promote subduction initiation on a weakened passive margin is one order of magnitude higher ($\sim 7 \times 10^{13}$ N/m; Mueller and Phillips, 1991; Cloetingh et al., 1989). Therefore, an additional force is needed to explain the SIM failure. This force may be provided by the compressive stress field related to the Africa-Eurasia convergence, which is conspicuously subperpendicular to the SIM thrusts (Fig. 1C; GPS vectors in Fig. DR5).

These two scenarios are end members of a spectrum of possibilities, and their combinations are possible. We favor a scenario in which the Gibraltar Arc migrates to the west, and once it reaches the Gorringe Bank region the subduction propagates laterally along the SIM (Fig. 3E). Such propagation would then be facilitated by the existence of serpentinized rocks (Masson et al., 1994) and the northwest-southeast Africa-Eurasia convergence. Moreover, there seem to be some first-order similarities between the natural prototype and numerical models of subduction initiation (Nikolaeva et al., 2010; Gurnis et al., 2004), such as initial flat overthrusting and a frontal topographic bulge (e.g., Gorringe Bank). Further collection of critical observations (e.g., seismic refraction) and the use of self-consistent numerical models should allow us to constrain these scenarios.

CONCLUSIONS

Even though there are uncertainties about the role of the tectonic mechanisms operating in the SIM, it is apparent that a new convergent system is developing in connection with the Mediterranean orogenic belt. Our work suggests that the stresses related to the Gibraltar slab pull are not sufficient to overcome the lithospheric strength in the SIM, and thus the large-scale Africa-Eurasia convergence should also have a fundamental role in the reactivation of the margin. We speculate that the SIM, together with the Scotia and the Lesser Antilles Arcs, may represent the nucleation cells of an Atlantic subduction system that might ultimately lead to its closing. Margin reactivation due to the propagation and/or by stress transfer from a nearby collision zone may be an alternative to the spontaneous subduction initiation model. This process may have a crucial role in plate tectonics, in particular in the closing phase of the Wilson Cycle.

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