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PAPER

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Mantle resistance against Gibraltar slab dragging as a key cause of the Messinian Salinity Crisis

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Abstract

The Messinian Salinity Crisis (5.97–5.33 Ma) was caused by the closure of the Atlantic-Mediterranean gateways that cut through the Gibraltar orogenic system. The geodynamic drivers underlying gateway closure and re-opening are still debated. Here, we interrogate the gateway successions to find the imprints of surface deformation, infer the timing and nature of associated geodynamic drivers, and test such inferences against numerical simulations of slab dynamics. We find that since the latest Miocene, a tectonic framework was established in the gateway region dominated simultaneously by (a) relative plate convergence, (b) slab tearing under the eastern Betic Cordillera and (c) mantle resistance against north-northeastward dragging of the Gibraltar slab by the African plate's absolute motion. We propose that mantle-resisted slab dragging and slab tearing operated in concert closing the gateways that caused the Messinian Salinity Crisis, whereas sinking of heavy oceanic lithosphere located between buoyant continental plates re-opened the Strait of Gibraltar at 5.33 Ma.

1 | INTRODUCTION

An important phase of paleogeographic re-organization occurred between 8–6 million years ago (Ma), when the Atlantic-Mediterranean portal changed its configuration from a foreland-basin system of gateways (the Betic and Rifian corridors; Figure 1) to a single channel (the proto-Strait of Gibraltar; Krijgsman et al., 2018). First-order consequences of this re-organization were marked changes in fauna, sedimentation and hydrology of the Mediterranean Sea, which witnessed first an increase in stress-tolerant benthic foraminifera and the occurrence of sapropels interbedded with marlstone between 8–6 Ma (Flecker et al., 2015; Kouwenhoven, Hilgen, & Zwaan, 2003), and later the deposition of giant evaporite beds during the peak of the Messinian Salinity Crisis (Roveri et al., 2014).

Since eustatic sea-level changes are estimated at only 10–20 m during the latest Miocene (Miller, Mountain, Wright, & Browning, 2011), the causes of final closure of the Betic, Rifian and proto-Gibraltar gateways (Krijgsman et al., 2018), as well as the opening of the Strait of Gibraltar that ended the Messinian Salinity Crisis, are commonly sought in tectonic processes (Duggen, Hoernle, Bogaard, Rüpke, & Phipps Morgan, 2003; Jolivet, Augier, Robin, Suc, & Rouchy, 2006). Tectonic processes in the gateway region are associated with the formation of the Gibraltar orogenic system (Figure 1) that occurred during both relatively slow Africa-Iberia convergence (Jolivet et al., 2006; Platt et al., 2003) and, up to the late Miocene, relatively rapid westward retreat of the east-dipping Gibraltar slab (Duggen et al., 2003; Lonergan & White, 1997).

Several processes have been proposed to explain gateway closure, such as slab dynamics involving mantle delamination, slab break-off and dynamic topographic rebound (Duggen et al., 2003; Garcia-Castellanos & Villasenor, 2011), rejuvenation of plate convergence and associated crustal deformation affecting the Atlantic-Mediterranean connectivity (Jolivet et al., 2006), or isostatic responses to salt loads (Govers, Meijer, & Krijgsman, 2009). Rollback and slab steepening may have ended the Messinian Salinity Crisis by the opening, or deepening, of the Strait of Gibraltar (Garcia-Castellanos & Villasenor, 2011; Govers, 2009). Linking these models to recent field evidence from the gateway basins (Capella et al., 2017; Flecker et al., 2015) may help identifying which of these processes, or others, opened and closed the gateways at different times.

Here, we address available field evidence of crustal deformation in the upper Miocene-Pliocene sedimentary archive of the Gibraltar orogenic system. We compare the geological reconstruction of the tectonic framework of the past with that of the present-day as reflected in GPS motions and active structures. Then, we test it against predictions obtained from numerical simulation of the Gibraltar subduction (Spakman, Chertova, Berg, & Hinsbergen, 2018) to propose a combination of geodynamic processes that explains the closure and re-opening of gateways at different locations in the Gibraltar arc causing the Messinian Salinity Crisis and its resolution.

2 | THE GIBRALTAR SLAB AND THE GIBRALTAR OROGENIC SYSTEM

The Gibraltar slab did not originate in the area of the Strait of Gibraltar but more than 500 km to the east-northeast, at a subduction zone situated below the Baleares Islands block (Figure 1a) that accommodated Africa-Iberia convergence since Cretaceous-Palaeocene time (Booth-Rea, Ranero, Grevemeyer, & Martínez-Martínez, 2007; Chertova, Spakman, Geenen, Berg, & Hinsbergen, 2014a; Van Hinsbergen, Vissers, & Spakman, 2014; van Hinsbergen et al., 2019; Rosenbaum, Lister, & Duboz, 2002; Spakman & Wortel, 2004).

In late Oligocene time, the slab reached sufficient length to initiate rollback (Chertova, Spakman, Geenen, et al., 2014a); slab rollback opened the oceanic Algerian Basin (Figure 1a) at high rates (up to ~90 mm/year) in middle to late Miocene time, until the slab arrived in the Gibraltar region in the late Tortonian (~8 Ma) (Do Couto et al., 2016; van Hinsbergen et al., 2014). During this process, a large fragment of crust in the upper plate separated from Eurasia and formed the Alborán domain, presently a highly extended fold-thrust belt that formed during earlier stages of subduction (Booth-Rea et al., 2007; Lonergan & White, 1997). Throughout the Miocene, the Alborán domain was thrust over the African and Iberian margins (Platt et al., 2003) forming the Rif Belt in Morocco and the Betic Cordillera in Spain (Vergés & Fernàndez, 2012) (Figure 1b).

The palaeogeographic re-organization brought about by the over-thrusting of the Alborán domain fundamentally changed the role of the Mediterranean in oceanic circulation that switched from being an oceanic corridor to a landlocked basin controlled by regional climate and connectivity at the sill (Capella et al., 2019). Importantly, the docking of the Alborán domain around 8 Ma, coincided with cessation, or strong deceleration, of the Gibraltar slab rollback with no unequivocal evidence for continuing subduction up to present-day (Gutscher et al., 2012). Only small-magnitude, distributed shortening and locally also extension and strike-slip deformation occurred under the slow (<5 mm/year), NW-SE relative plate convergence between Africa-Iberia. This regime is proposed to dominate the tectonics of the region since the late Miocene (Jolivet et al., 2006; Pedrera et al., 2011). The docking of the Alborán domain along the Gibraltar arc set the stage for the Messinian Salinity Crisis of which the final onset (5.97 Ma), however, was initiated as much as 2 Myr later.

3 | GEODYNAMIC CONTROL ON THE EVOLUTION OF THE ATLANTIC-MEDITERRANEAN GATEWAYS INFERRED FROM THE LATE MIOCENE SEDIMENTARY RECORD

Mantle tomography and other seismological investigations provide a clear 3D image of the present-day geometry of the Gibraltar slab showing its lateral continuity with the surface plates, as well as where it is detached and may have delaminated the continental lithospheric mantle (Bezada et al., 2013; Chertova, Spakman, Geenen, et al., 2014a; Gutscher et al., 2002; Heit et al., 2017; Levander et al., 2014; Mancilla et al., 2015; Piromallo & Morelli, 2003; Spakman & Wortel, 2004; Villaseñor et al., 2015). The dynamic evolution towards this present-day snapshot requires geological observations of which first-order regional trends can be tested against predictions from numerical modelling of subduction evolution in the overall convergent plate setting (Chertova, Spakman, Geenen, et al., 2014a; Spakman et al., 2018). Following, we summarize the geological observations on the tectonic evolution of the Betic, Gibraltar and Rifian gateways with emphasis on the key interval between 8 and 5 Ma.

3.1 | Betics

Rapid slab rollback transporting the Alboran domain westward between the slowly converging African and Iberian plates caused thrusting in the Betic and Flysch units from the early Miocene onwards, concurrent with the formation of onshore extensional basins and exhumation of part of the Internal Betics. This overall shortening lasted until the end of the Miocene and migrated towards the orogenic front in the Guadalquivir Basin. Here, we focus on the phases of deformation recorded in the eastern, central and western Betics (Figure 1) at the end of the Miocene, at a phase corresponding to the deceleration of slab retreat.

In the basins of the eastern Betics (Figure 1b), structures that formed during middle to late Miocene NE-SW extension (Booth-Rea, Azañón, & García-Dueñas, 2004; Vissers, 2012) were locally inverted by small-scale N-S to NW-SE shortening from the late Miocene onwards (Giaconia et al., 2014; Meijninger & Vissers, 2007).

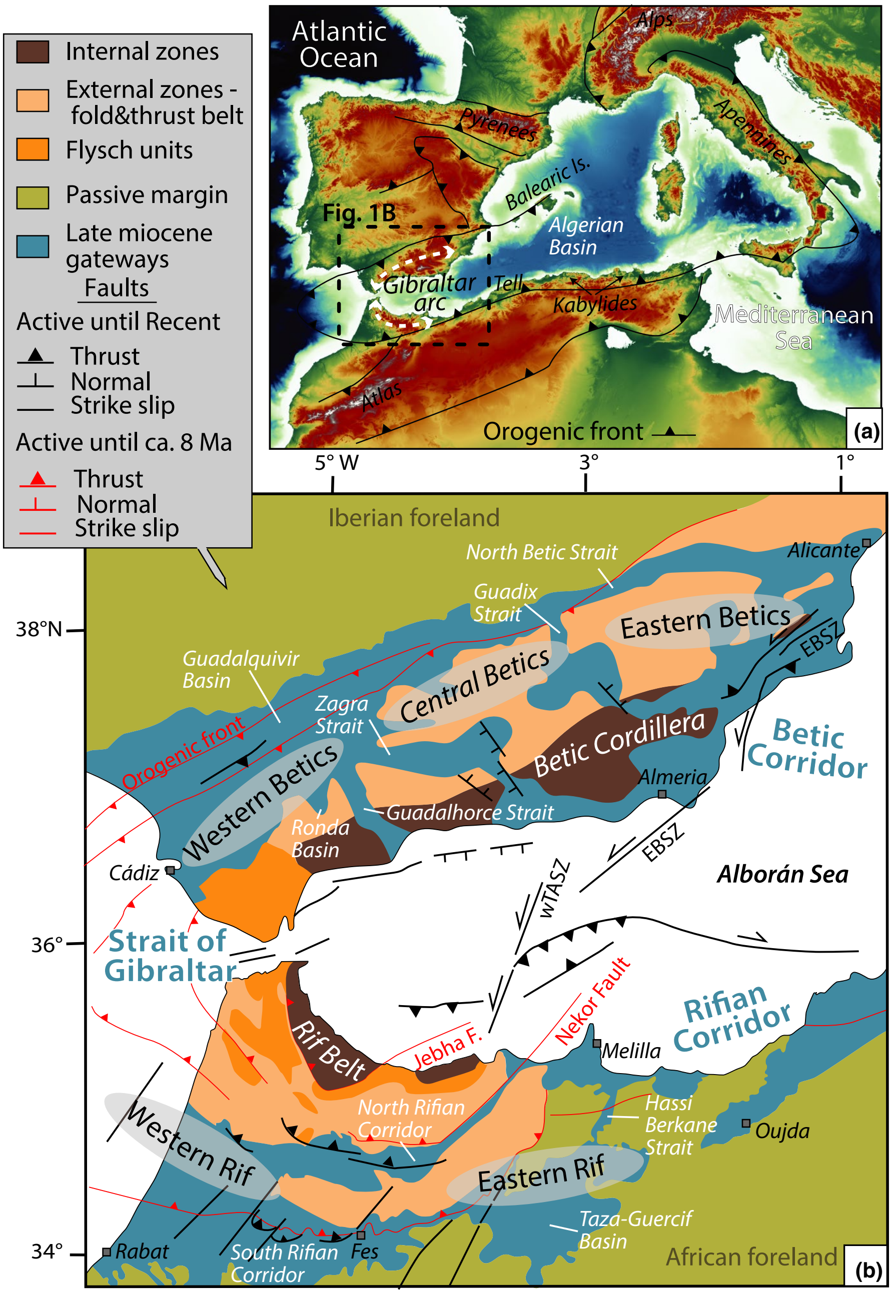


FIGURE 1 (a) Overview of orogenic boundaries in the Western Mediterranean. (b) Paleogeography of the late Miocene Atlantic-Mediterranean gateways, with main tectonic elements, faults, and domains of the Gibraltar orogen. Modified after (Flecker et al., 2015). Shaded areas depict the subdivision adopted to characterize the kinematic evolution. EBSZ: Eastern Betics Shear Zone; wTASZ, west Trans Alborán Shear Zone [Colour figure can be viewed at wileyonlinelibrary.com]

In the central Betics, a NE-SW to NW-SE extension was recorded from late Miocene onwards, contemporaneously with vertical uplift, while the record was less affected by shortening (Galindo-Zaldívar et al., 2003; Reicherter & Peters, 2005; Rodríguez-Fernández & Sanz de Galdeano, 2006). In the western Betics, NW-SE directed shortening is recorded in intramontane basins (Jiménez-Bonilla, Expósito, Balanyá, Díaz-Azpiroz, & Barcos, 2015) and along the coast of the Gulf of Cadiz. In contrast with the western Betics, the N-S to NW-SE shortening of the eastern Betics was coeval with considerable uplift (Janowski et al., 2017) and with the formation of late Miocene extensional basins, regionally controlled by large fault systems, such as the SW-NE striking Alhama de Murcia fault that acted as normal fault in the late Miocene and changed into a transpressive fault as part of the Eastern Betics Shear Zone during the latest Miocene—early Pliocene (Meijninger & Vissers, 2006, 2007). The NW-SE to NNW-SSE shortening remains active today in the west (Ruiz-Constán et al., 2009) as well as in the east where it leads to distributed deformation superposed on SW-NE aligned crustal motions that are accommodated by the left-lateral transpressive Eastern Betic Shear Zone (Borque et al., 2019). The late Miocene to Present shortening regime is aligned with the relative convergence direction between Africa and Iberia (e.g. Jolivet et al., 2006), but contributions to shortening from subduction dynamics, particularly after slab rollback has come to a near halt, cannot be excluded.

The ~SW-NE extension of the central Betics (Figure 1b), which is still ongoing today (Mancilla et al., 2015; Palano, González, & Fernández, 2015), occurred while the region was uplifted above sea-level from the late Tortonian onwards (Corbí et al., 2012;

Rodríguez-Fernández & Sanz de Galdeano, 2006). Convergence-induced shortening created only localized antiforms that disconnected peripheral basins from the main gateways, such as the Ronda Basin in the western Betics (Jiménez-Bonilla et al., 2015).

At present, to the east of ~4°W (Figure 2), the slab below the central-eastern Betics is detached from Iberian lithosphere (Mancilla et al., 2015) and the detached portion of the slab curves into a near E-W orientation below the central-eastern Betic Cordillera (Bezada et al., 2013; Spakman & Wortel, 2004; Villaseñor et al., 2015). The surface rebound following slab detachment (Duretz, Gerya, & May, 2011; Wortel & Spakman, 2000) has been invoked to explain the uplift of the central and eastern Betics (Duggen et al., 2003; Garcia-Castellanos & Villasenor, 2011; Spakman & Wortel, 2004), with slab detachment starting under the easternmost Betics in the late Miocene and subsequently progressing towards the west-southwest. We note that slab detachment under the eastern-central Betics defines the youngest stage of slab rupture in the region. Since the early Miocene, slab detachment and vertical lithosphere tearing created STEPS (Govers and Wortel, 2005) that were active along the North African margin and facilitated the rotation of SW-S-directed rollback from the Balearic margin towards North Africa to W- and NW-directed rollback (Booth-Rea et al., 2007; Chertova, Spakman, Geenen, et al., 2014a; van Hinsbergen et al., 2014; Spakman et al., 2018; Spakman & Wortel, 2004).

3.2 | Gibraltar

In the area of the Strait of Gibraltar, an accretionary prism consisting of deep-marine clastic deposits known as the Flysch units (Figure 1b) became a threshold to marine connectivity since early-middle Miocene times. These deposits were detached from their basement during the phase of westward rollback to form an imbricated mountain front (Crespo-Blanc & Campos, 2001; Luján, Crespo-Blanc, & Comas, 2011).

The modern Strait of Gibraltar straddles the Flysch accretionary prism, but the dynamic causes of the renewed Mediterranean-Atlantic connection at the end of the Messinian remain unexplained (Garcia-Castellanos & Villasenor, 2011; Loget & Van Den Driessche, 2006). Govers (2009) suggested that it may have occurred because of westward rollback and steepening of the slab, driving regional subsidence without major crustal extension. Although headward river erosion is generally the preferred scenario (Loget & Van Den Driessche, 2006), later works (Luján et al., 2011) showed that strike-slip fault systems and high-angle normal faults are present both onshore and offshore in the area of the Strait of Gibraltar. These faults cross-cut the Flysch imbricates and control the orientation and bathymetry of depocentres, thus suggesting a likely tectonic origin of the modern strait (Luján et al., 2011). Recent (up to Holocene) deformational events are mostly related to E- to ENE-orientated strike-slip faults (Luján et al., 2011). The Camarinal Sill—which remains the most plausible late Messinian gateway (Krijgsman et al., 2018)—is bounded by N-S- to NNW-SSE-orientated scarps, which could be faults inherited from the Flysch imbricates that reactivated with a normal component (Luján et al., 2011).

3.3 | Rif

In the external Rif, Miocene basin evolution was controlled by thin-skinned thrusting associated with the westward drift of the Alborán domain which locally created W- to SW-ward transport kinematics (Platt et al., 2003), and SW-ward migration of the foredeep (Capella et al., 2018, 2017; Chalouan et al., 2008) (Figure 1). By the late Miocene, the Rifian Corridor developed as a system of interconnected basins on top of thrust-sheets and a partly submerged foreland, as either piggy-back or foredeep depocentres, with the marginal marine incursions dating ~8 Ma (Capella et al., 2018; Roldán et al., 2014). Between 8 Ma and the latest Tortonian (~7.25 Ma), a marked switch occurred from basin subsidence to thick-skinned contraction resulting in fault kinematics orientated N-S to NE-SW. Field and seismic evidence suggested that thrusting inverted Mesozoic normal faults in the African margin (Capella et al., 2017; Sani, Ventisette, Montanari, Bendkik, & Chenakeb, 2007). The latest Miocene contraction is orientated on average NNE-SSW which is consistent with recent GPS motions for the western Rif (Koulali et al., 2011; Palano et al., 2015).

To the east of the Nekor fault, E-W to ENE-WSW extension was recorded since the late Miocene (Galindo-Zaldívar et al., 2015). Further south, the Taza-Guercif Basin (Figure 1b) experienced basin uplift and regression already during the early Messinian (Capella et al., 2018; Gomez, Barazangi, & Demnati, 2000). Some NW-SE orientated shortening is recorded in the sediments (Bernini, Boccaletti, Moratti, & Papani, 2000), but caused only minor vertical offsets; the majority of thrust faults is buried and did not break through the upper Miocene sequences (Gomez et al., 2000), suggesting only moderate crustal deformation since ~8 Ma compared to the Rif west of the Nekor fault.

4 | TOWARDS A UNIFYING SCENARIO FOR GEODYNAMIC FORCING ON THE GATEWAYS

These available geological observations constrain the particular tectonic framework that was established at ca. 8 Ma, following the earlier emplacement of the Alborán domain onto the Iberian and African margins. This framework consisted of (a) NW-SE directed contraction in the eastern Rif and western Betics; (b) N-S to NE-SW directed contraction exclusively in the Western Rif; (c) NE-SW extension, recorded in the central-eastern Betics. These late Miocene and younger patterns of deformation also agree well with the present-day strain-rate field as determined from GPS measurements (Spakman et al., 2018), suggesting that the style, and hence likely

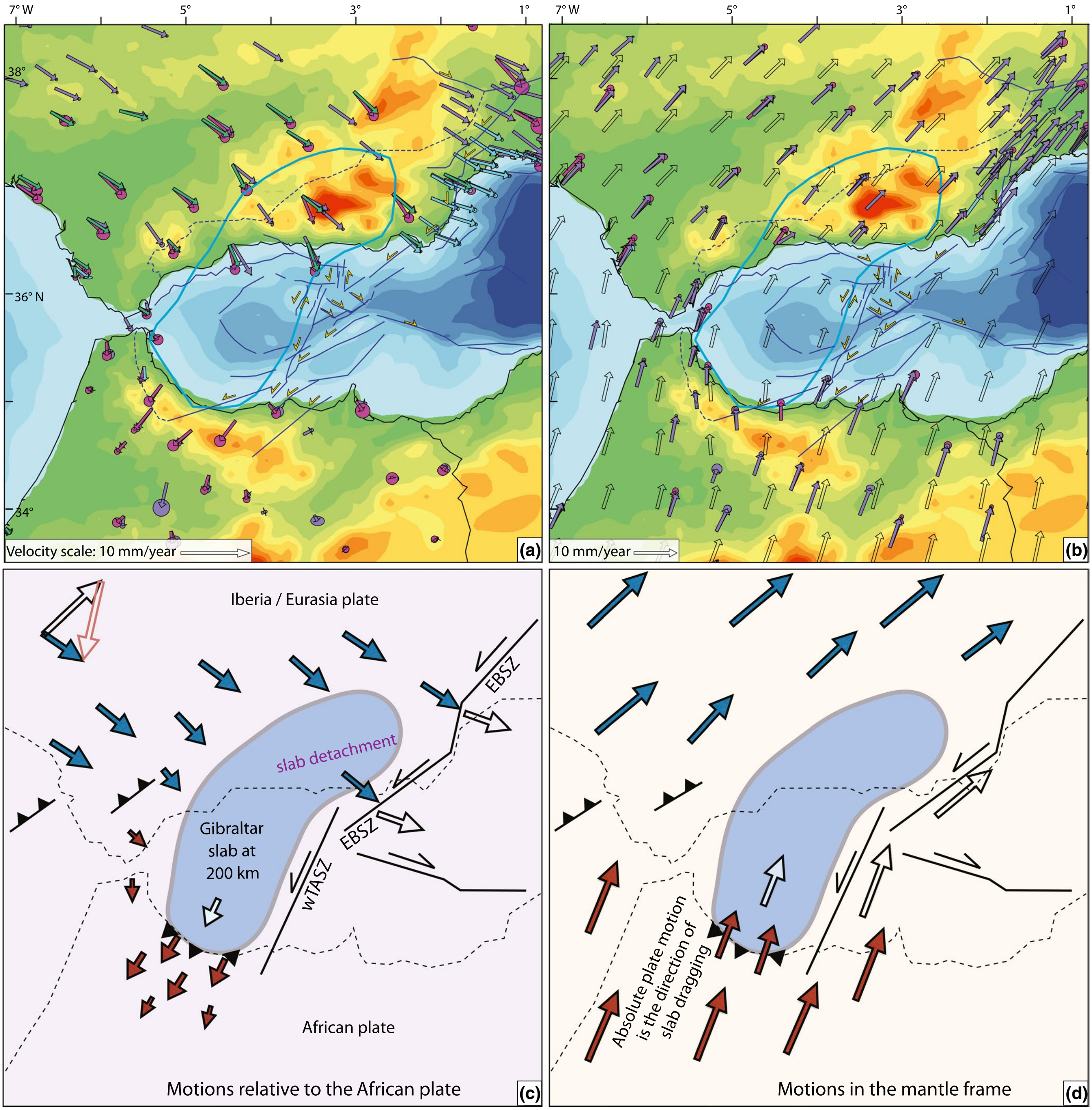


FIGURE 2 Crustal motions with respect to the African plate (left) and in an absolute plate motion frame (right). (a) GPS motion vectors in an African-fixed frame modified from (Spakman et al., 2018) showing relative plate convergence (Iberia relative to Africa) and SSW directed shortening of Moroccan Rif. Vector colours: purple (Palano et al., 2015), green (Mancilla et al., 2013), light blue (Echeverria et al., 2013), magenta (Koulali et al., 2011). The light blue contour shows the outline of the tomographically imaged slab at a depth of 200 km which is in part detached (from ~4°W to the east). Dark blue lines indicate important tectonic lineaments and faults, predominantly the Trans Alborán Shear zone (TASZ) and the Eastern Betics Shear Zone (EBSZ) and with the sense of motion indicated by yellow half-arrows. (b) GPS vectors plotted in the absolute plate motion (mantle frame) of the Africa plate of the past 10 Myr (Doubrovine, Steinberger, & Torsvik, 2012). Transparent vectors depict crustal flow field predicted from an analysis of the GPS motion field (Spakman et al., 2018). (c and d) Are cartoon simplifications of (a and b), respectively, focussing on the motion of the slab (white vectors) with respect to crustal motions (red and blue vectors). (c) Shows how the mantle resistance against NNE-directed slab dragging (red vectors) leads to SSW indentation of the Moroccan Rif (black triangles) when viewed from the Africa-fixed relative plate motion frame. The transparent arrow in the slab shows slab motion towards the Rif; other transparent vectors show predicted crustal motion. The three arrows in the upper left corner show the relative motion (blue vector) as the difference between the two absolute plate motions. (d) Shows motion in the mantle frame, i.e. motions relative to the deep mantle. Notice the general alignment of the major fault systems, wTASZ, EBSZ, and of the crustal flow field, with the Africa- and Iberia absolute plate motion [Colour figure can be viewed at wileyonlinelibrary.com]

drivers of crustal deformation since the late Miocene have not significantly changed (Pedrera et al., 2011).

3-D numerical subduction modelling (Spakman et al., 2018) shows that after rollback strongly decelerated in the late Miocene, the subducted slab has been dragged laterally through the mantle by the ~NNE-directed absolute motion of the African plate, i.e. almost parallel to the Gibraltar trench (Figure 2). The mantle surrounding the Gibraltar slab resists this lateral slab transport, which leads to a relative motion between the slab and the advancing African lithosphere causing a SSW-directed indentation of the Moroccan Rif (Figure 2a) or, when viewed in the mantle frame, collision of the African plate with the slab (Figure 2b). This occurs at the transition from slab to African continental lithosphere, which is situated below the internal Rif.

Numerical predictions of SKS-splitting resulting from upper mantle anisotropy developed by accumulating mantle shear during 35 Myr of subduction evolution (Chertova, Spakman, & Faccenda, 2017) show that observed SKS-splitting (e.g. Diaz et al., 2015, 2010) can be explained by a combination of local slab-induced mantle flow (anisotropy signature inherited from rollback until ~8 Ma) and long-term externally excited cm/year-scale mantle flow, which overprints effects of slab dragging (~6 mm/year). Hence, observations of SKS-splitting are consistent with the modelled subduction evolution (Chertova, Spakman, Geenen, et al., 2014a; Chertova, Spakman, & Steinberger, 2018; Spakman et al., 2018) including the impact of external mantle flow (Chertova et al., 2018). Furthermore, the numerical-model prediction of mantle-resisted slab dragging is robust with respect to variations in slab-mantle rheology (Chertova, Spakman, Berg, & Hinsbergen, 2014b; Spakman et al., 2018). Predictions derived for crustal behaviour concern first-order features of regional style of deformation. This assumes that the first-order regional crustal deformation is driven by the regional interaction of the lithospheric-mantle of the continental plates, continental margins, and of the Gibraltar slab, as modelled. In concert with the relative NW-SE relative plate convergence, mantle-resisted slab dragging predicts a regional style of surface deformation that explains the SW-directed deformation and motion of the Rif, nearly orogen-parallel extension of the central-eastern Betics above a progressively tearing slab, and the occurrence of, and sense of motion on the Trans-Alborán and eastern-Betics shear zones, as can still be inferred at present from GPS motions (Figure 2) (Spakman et al., 2018).

4.1 | Slab-dragging and slab tearing causing the Messinian Salinity Crisis

The indentation of the Rif by mantle-resisted slab dragging together with central-eastern Betics slab detachment (Figure 3) can be combined into a geodynamic model that explains gateway closure and re-opening. The first essential step preconditioning the Gibraltar region for the isolation of the Mediterranean was the early to late Miocene westward slab roll-back during which the Alborán domain was thrust on top of the African continental margin to the south and Iberian margin to the north, with the formation of the Flysch prism in the middle (Figure 1b). The latter closed the deep, oceanic corridor that had formed between Iberia and Northwest Africa during the Jurassic break-up of Pangea (Vissers, Hinsbergen, Meijer, & Piccardo, 2013). Flexure related to the emplacement of the Alborán domain onto the continental margins led to foreland basin subsidence in the Iberian and African margins which formed the Betic and Rifian Corridors (Figure 1b). Although these still allowed Atlantic-Mediterranean water exchange, it was this tectonic event that led to the first restriction of the Mediterranean Sea, documented in sedimentological, geochemical and faunal records (Capella et al., 2019; Flecker et al., 2015).

After the arrest at ~8 Ma of rapid west-ward rollback, NNE-directed slab dragging became the remaining slab motion (Spakman et al., 2018). The indentation of the Moroccan continental margin, generated by the mantle resistance against NNE slab dragging, initiated the event of regional thick-skinned tectonics west of the Nekor fault that closed the Rifian Corridor in the early Messinian, at around 7 Ma (Capella et al., 2018, 2017). This SSW indentation is likely also responsible for the thickened crust contiguous to the slab edge (Gil et al., 2014) as well as the on average NNE-SSW contraction observed in the Rif (Capella et al., 2017; Pedrera et al., 2011) rather than NW-SE orientated Africa-Eurasia convergence, whose direction is compatible only with the minor shortening and folding recorded in the eastern Rif and the western Betics (Bernini et al., 2000; Jiménez-Bonilla et al., 2015) (Figure 1b).

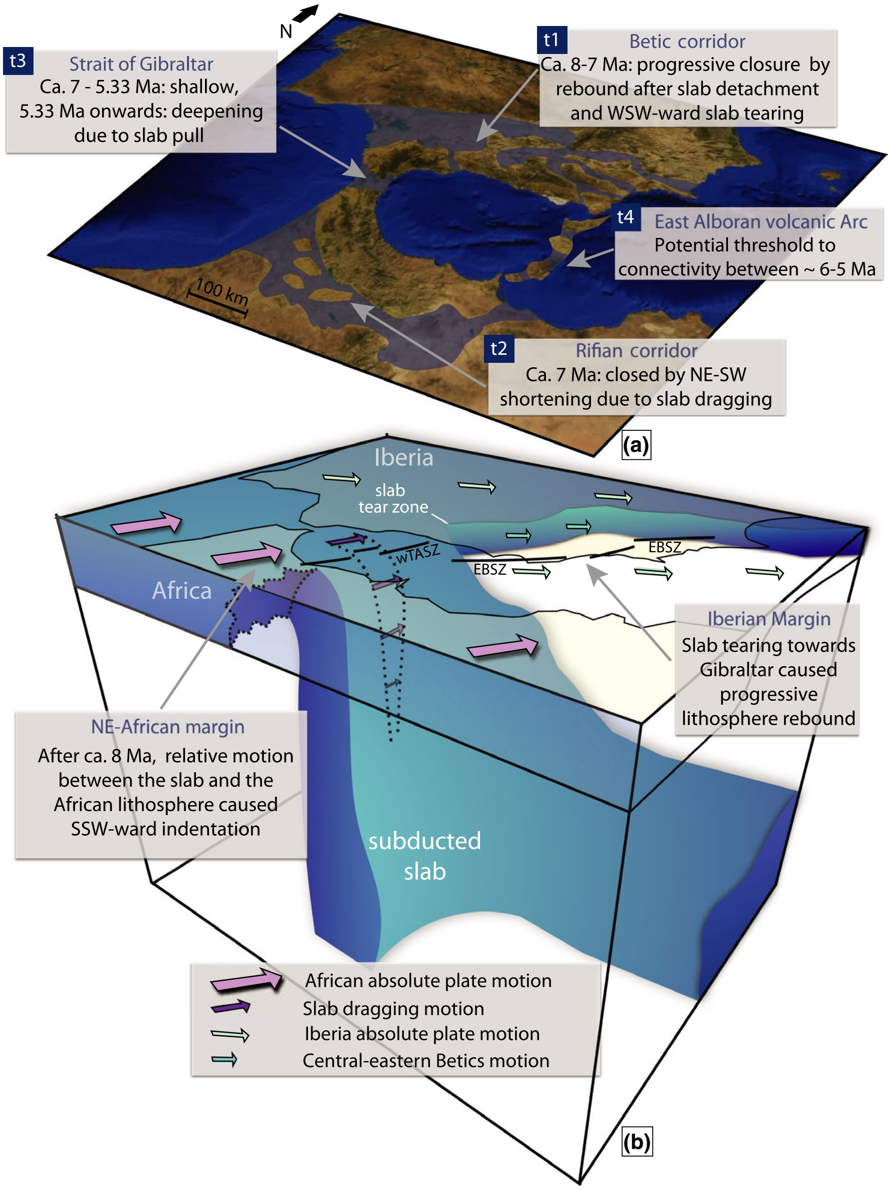
We note that the Rifian gateway closure occurred directly to the south of the slab where it is still continuous with Moroccan lithosphere today, thus requiring a different closure mechanism than the uplift proposed to take place following slab tearing and delamination of lithospheric mantle (Duggen et al., 2003). The latter mechanism fails to explain the NE-SW verging thick-skinned tectonics, crustal thickening, and continuous shortening of the western Rif that started in the late Miocene and is still active today.

Between 7–8 Ma, all the Betic gateways were uplifting (Garcia-Castellanos & Villasenor, 2011; van der Schee et al., 2018). The process underlying this uplift is related to the gradual slab tearing moving towards the west (Mancilla et al., 2015), which also appears in the numerical models of slab evolution (Spakman et al., 2018). Slab tearing under the south Iberian margin decouples the NE-directed Iberian absolute plate motion (Figure 2b) from the westernmost segment of the slab, which is still attached under the western Betics. The NNE directed slab dragging occurs at lower pace than the NE-directed Iberian motion relative to the mantle (Figure 2b,d), which therefore causes a differential motion leading to the SW-NE extension in the eastern-central Betic region (Spakman et al., 2018). At the same time, the dynamic topographic rise causing km-scale uplift occurs as rebound above the detaching slab (Garcia-Castellanos & Villasenor, 2011).

4.2 | Opening of the Strait of Gibraltar

Field evidence suggests that by 7 Ma, the Betic and Rifian gateways were shut and uplifted (Capella et al., 2018; van der Schee et al., 2018). After 7 Ma, an embryonic Strait of Gibraltar took

FIGURE 3 (a) ArcGlobe (ESRI™) topography of the Gibraltar region with projection of the paleogeography of the Mediterranean-Atlantic gateways after (Krijgsman et al., 2018). The three insets illustrate the timing and mechanisms of vertical motion that led to the temporary isolation (~5.33–7 Ma) of the Mediterranean, and refer to the corresponding geodynamic forces. The east Alborán Arc hypothesis suggests that an emergent, volcanic archipelago could have temporarily connected southeastern Iberia with northern Africa (Booth-Rea, Ranero, & Grevemeyer, 2018). (b) Cartoon interpretation of RGB-slab morphology across the upper mantle modified from (Spakman et al., 2018). Vectors illustrate the absolute plate motions for Africa and Iberia as well as slower central-eastern Betics motion (as in Figure 2b,d). N-NNE slab dragging motion is indicated in the slab. The bottom of the cartoon is at the depth of 660 km [Colour figure can be viewed at wileyonlinelibrary.com]



over the connectivity in an area that was either always submerged or barely emergent on top of the Flysch units (Krijgsman et al., 2018). Morphological evidence of ENE- to E-orientated faults at the Camarinal Sill (Luján et al., 2011) suggests that strike–slip structures may have controlled connections at a time of little or no vertical motion.

The infilling of the western Alborán Basin indicates a marked westward depocentre shift between the upper Tortonian and Pliocene units (Do Couto et al., 2016). The timing of this event, the direction of depocentre-shift combined with the location of the slab-hinge below the western Alborán Basin, suggests that subsidence was driven by slab pull (Govers, 2009). The evolution of the Strait of Gibraltar before and during the Messinian Salinity Crisis (Krijgsman et al., 2018) may be a consequence of progressive slab tearing from the eastern to central Betics. Westward lateral migration of the slab tear point under the Betics increases the gravitational load on the slab that is still attached, shifting depocentres (van der Meulen, Meulenkamp, & Wortel, 1998; Wortel & Spakman, 2000). This tear is currently situated within ~100 km of the Strait of Gibraltar (Figure 2) and has therefore been suggested as a potential driver of the re-opening of the Strait at 5.33 Ma (Garcia-Castellanos & Villasenor, 2011). Between 8–7 Ma, however, slab tearing was likely to have little effect on vertical motions of the Strait of Gibraltar because it was confined to the eastern Betics, i.e. 300–400 km to the ENE, and had not propagated much westward yet.

An alternative possibility is that slow vertical sinking of a slab that stopped significant rollback by ~8 Ma acted as the sole driver of the subsidence that gradually opened the Strait of Gibraltar before and after the Messinian Salinity Crisis. The slab dipping steeply below the Strait of Gibraltar comprises cold oceanic lithosphere of Jurassic age (Gutscher et al., 2012) and it is situated between the buoyant continental lithosphere to which it is connected to the north (western Betics) and south (western Rif). It is therefore possible to infer a mechanism by which slow vertical sinking of the slab in between the continents caused sagging since the late Miocene. As the positive buoyancy of the continental lithosphere at either side of the small oceanic Gibraltar corridor acts against slab sinking, vertical velocities on a geological time scale may have been rather small (<<100 m/Myr).

5 | CONCLUSION

We tested the imprints of the tectonic evolution of the late Miocene Atlantic-Mediterranean gateway basins against plausible geodynamic drivers. Structural constraints from the gateway successions show a tectonic framework not dissimilar to that of the present-day, consisting of NNE-SSW contraction in the western Rif, NW-SE shortening in the eastern Rif and western Betics, NE-SW extension in the eastern-central Betics. The closure of the Betic gateway was driven by slab detachment under the eastern Betics and that of the Rifian gateway by SSW-directed indentation of the northern Moroccan margin due to mantle resistance against NNE-directed slab dragging. Early and shallow connections through the Strait of Gibraltar were possibly deepened by slab-pull causing sagging of a stripe of oceanic lithosphere still connected to its continental counterparts to the north and south.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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