Gibraltar subduction zone is invading the Atlantic

João C. Duarte[1], Nicolas Riel[2], Filipe M. Rosas[1], Anton Popov[2], Christian Schuler[2], Boris J.P. Kaus[2]

[1]Instituto Dom Luiz (IDL) and Geology Department, Faculty of Sciences, University of Lisbon, 1749-016 Lisbon, Portugal (jdduarte@fc.ul.pt)
[2]Institut of Geosciences, Johannes Gutenberg-University, 55099 Mainz, Germany

This manuscript has been published in Geology.

https://doi.org/10.1130/G51654.1

Twitter: @JoaoCDuarte

Gibraltar subduction zone is invading the Atlantic

João C. Duarte[1], Nicolas Riel[2], Filipe M. Rosas[1], Anton Popov[2], Christian Schuler[2], Boris J.P. Kaus[2]

[1]Instituto Dom Luiz (IDL) and Geology Department, Faculty of Sciences, University of Lisbon, 1749-016 Lisbon, Portugal (jdduarte@fc.ul.pt)

[2]Institut of Geosciences, Johannes Gutenberg-University, 55099 Mainz, Germany

ABSTRACT

Subduction initiation is a cornerstone of the Wilson cycle. It marks the turning point in an ocean's lifetime, allowing its lithosphere to be recycled into the mantle. However, formation of subduction zones in Atlantic-type oceans is challenging, given it commonly involves the action of an external force, such as the slab pull from a nearby subduction zone, a far-field compression or the impact of a plume. Notwithstanding, the Atlantic already has two subduction zones, the Lesser Antilles and the Scotia arcs. These subduction zones have been forced from the nearby Pacific subduction zones. The Gibraltar Arc is another place where a subduction zone is invading the Atlantic. This corresponds to a direct migration of a subduction zone that developed in the closing Mediterranean basin. Nevertheless, few authors consider the Gibraltar subduction still active because it has significantly slowed down in the last millions of years. Here, we use new gravity-driven geodynamic models that reproduce the evolution of the Western Mediterranean, show how the Gibraltar Arc formed and test if it is still active. The results suggest that the arc will propagate further into the Atlantic after a period of quiescence. The models also show how a subduction zone starting in a closing ocean (Ligurian) can migrate into a new opening ocean (Atlantic) through a narrow oceanic corridor. Subduction invasion is likely a common mechanism of subduction initiation in Atlantic-type oceans and a fundamental process in the recent geological evolution of Earth.

INTRODUCTION

Oceans form, grow and then start to close following the so-called Wilson cycle (Burke and Dewey, 1975). Subduction initiation marks the turning point of the cycle, whereby the ocean's lithosphere starts to be recycled back into the mantle (Dewey, 1969). However, subduction zones have difficulty initiating in the interior of mature Atlantic-type oceans that have formed from the breakup of a supercontinent. This is because the aged oceanic lithosphere is thick and strong, making it resistant to breaking and bending, which are two necessary conditions for the start of subduction in an ocean surrounded by passive margins (McKenzie, 1977; Cloetingh et al., 1982; Mueller and Phillips, 1991; Stern and Gerya, 2018; Lallemand and Arcay, 2021). Notwithstanding, the average age of the seafloor worldwide is only ca. 60 Ma on a planet that is 4540 Ma old, and there is barely any oceanic lithosphere older than 200 Ma (Muller et al., 2008). This suggests that the establishment of subduction zones in Atlantic-type oceans must be a common process in the recent history of the Earth.

The Atlantic Ocean is a unique laboratory for studying subduction initiation. It has two fully developed subduction zones with slabs imaged in the upper mantle and unambiguous volcanic arcs: the Lesser Antilles and Scotia arcs. These two subduction zones have initiated associated with the Eastern Pacific subduction zones. The two arcs formed in the Cretaceous, but their propagation has been limited by transform boundaries to the south and continental promontories to the north. There is a third arc, the Gibraltar Arc, that may just be entering the Atlantic, although its activity is debated (Gutscher et al., 2002, 2012; Zitellini et al., 2009).

The Gibraltar arc formed as a part of the Western Mediterranean subduction zones that developed since the Oligocene (Fig. 1). Its slab can be imaged below the Alboran Sea, while its accretionary wedge is already within the Atlantic (Gutscher et al., 2002). However, the western propagation of the Gibraltar Arc slowed down in the last 5 m.y. (Lonergan and White, 1997; Gutscher et al., 2012), leading authors to conclude that it is becoming inactive (Zitellini et al., 2009). It has also been proposed that the slab is breaking off (Heit et al., 2017). But even though this may be the case below the Betics (Spain) and the Maghrebides (Algeria), there is no clear sign of a surface rebound in the westernmost termination of the Gibraltar Arc, suggesting that the slab here may still be connected to the surface. Moreover, the presence of a 15 km-thick accretionary wedge in the Gulf of Cadiz suggests that the slab is still pulling down a narrow strip of oceanic lithosphere that once linked the Ligurian Ocean to the Atlantic.

Here, we present new results of a geodynamic numerical model that reproduces the formation of the Gibraltar Arc and explores what may be its fate. We test if the slowdown of the Gibraltar subduction zone results from stalling and if it may further propagate into the Atlantic. The models are gravity-driven, and the velocities emerge from buoyancy forces. The model simulates the first-order evolution of the Western Mediterranean for the last 30 m.y. To study the potential propagation of the Gibraltar subduction zone into the Atlantic, the model is run ~40 m.y. into the future.

SUBDUCTION INVASION OF THE ATLANTIC

Muller and Phillips (1991), following previous work by Cloetingh et al. (1982), recognized that due to the strength of the lithosphere subduction zones are unlikely to initiate in Atlantic-type oceans and that they are more likely to propagate from contiguous oceans that already contain subduction zones. These authors used the term “infection” to describe the phenomenon and proposed that the Lesser Antilles and the Scotia arcs are two prime examples. They also proposed that a comparable process could be ongoing in the Gibraltar

Arc. Since then, several works have investigated this region. Royden (1993) proposed the arc was already well inside the Atlantic, while Lonergan and White (1997) and Rosenbaum et al. (2002) concluded the arc had become stalled between Africa and Iberia. The same year, Gutscher et al. (2002) presented evidence the Gibraltar subduction zone was still active, although Gutscher et al. (2012) recognized its activity had decreased over the last 5 m.y. Duarte et al. (2013), proposed two scenarios for the evolution of Gibraltar Arc. In one scenario, the arc stalls and a new subduction zone initiates to the West. In the other scenario, the Gibraltar Arc invades the Atlantic.

GEODYNAMIC MODEL OF THE WESTERN MEDITERRANEAN AND THE GIBRALTAR ARC

To test whether the Gibraltar Arc is stalled or still propagating west, we have set up a simplified geodynamic numerical model of the Western Mediterranean using the code LaMEM (Kaus et al., 2016). It starts at ~30 Ma with a northwest-dipping slab overridden by a set of continental blocks similar to the reconstruction of Rosenbaum et al. (2002) (Figs. 1, 2A; and Fig. S1 in the Supplementary Material). This configuration coincides with the period of continental collision between Africa, Adria and Eurasia, which led to the deceleration of the convergence. Because subduction could no longer be accommodated by the northward movement of Africa, subduction had to be accommodated by slab rollback. Here we describe the results of the reference model.

After the model starts, at 30 Ma (0 Myr model time), the subduction trench retreats as a consequence of slab rollback (Fig. 2A; see File S1). The overriding continental blocks follow the trench, which propagates radially to the south (Fig. 2B). During the first stages of slab sinking, the trench retreat accelerates to a velocity of ~11 cm/yr (Fig. 3). At ~8 m.y., the slab reaches the 660 km discontinuity and the trench retreat decelerates. At ~13 m.y., the central segment of the trench arrives in North Africa, the Kabylies (present-day Algeria) collide with Africa and the slab breaks off (Fig. 2C). At this point, there is still an E-W oceanic corridor that continues to subduct as the slab rolls back to the west. The Betic and the Rif (present-day Morocco) blocks follow, with the Betics rotating 180° degrees. The subduction continues decelerating as the oceanic lithosphere between Africa and Iberia narrows. At ~20 m.y., the Betics and the Rif accrete to Iberia and Africa, respectively (Fig. 2D). After this point, the slab squeezes into the Atlantic. This coincides with an increase in the trench retreat velocity (Fig. 3), caused by the detachment of the slab from the Betic and the Rif blocks. At 30 m.y., the Gibraltar Arc is formed with the trench positioned in the Atlantic (Fig. 2E), mimicking the present-day configuration.

A notable observation is the abrupt deceleration of the trench retreat once it enters the Atlantic (Fig. 3). This may be explained by the fact that the narrow Gibraltar slab must pull the wider Atlantic lithosphere down. The slab is also pinched at depth causing the slab pull from the plate laying at the 660 km discontinuity to be less effective (Fig. 4). At this point, the Gibraltar subduction zone seems doomed to fail. To test whether the subduction zone is likely to fail, we have let the model run into the future.

From present-day, the trench retreat velocity continues to decelerate for another 20 m.y., when it almost stops (Fig. 3). Strikingly, after this point, the trench retreat velocity slowly speeds up, and the subduction zone widens and propagates oceanward (Fig. 2F).

IS THE GIBRALTAR SUBDUCTION ZONE INVADING THE ATLANTIC?

Our model reproduces several first-order features of the natural prototype. While the initial conditions are simple, the timings replicate the reconstructions of Rosenbaum et al. (2002) and Lonergan and White (1997). The model also reproduces second-order features such as the 180° degrees clockwise rotation of the Betic block, which results from a change of the slab rollback direction from southeast- to west-directed. Such rotation is hard to envisage dynamically and may explain why some authors have proposed that the slab came from the south (Fernàndez et al, 2019; Peral et al., 2022; see also Chertova et al., 2014). The model also reproduces a Trans-Alboran shear zone, separating the Betic and Rif blocks with a dextral sense of shearing (Figs. 2D-F), and explains why the Alboran region is made of stretched continental crust. The driving westward slab pull force is resisted by the collision of the Betic/Rif blocks, causing them to stretch (Figs 2E). Also striking is the sliver of ophiolites that forms along the Betic suture (Fig. 4A).

The model also replicates several geophysical observations. Namely, the slab imaged with tomography (Spakman and Wortel, 2004) (Fig. S2), the toroidal flow around the slab edges inferred from SKS splitting (Diaz et al., 2010; see also Lo Bue et al., 2022) (Fig. S3), and the fast westward velocity of the Gibraltar Arc observed with a global navigation satellite system (GNSS) (Billi et al., 2023) (Fig. S4).

Another key result is the deceleration of the Gibraltar subduction zone over the last 5 m.y. (Rosenbaum et al., 2002; Lonergan and White, 1997). This abrupt deceleration led most authors to conclude that the subduction zone was shutting down and the slab was breaking off. However, the observations do not show a significant surface rebound in the forearc region (Civiero et al., 2020), as one would expect from a break-off. In fact, what we can observe is that parts of the arc are still being pulled down. Plus, a 15-km-thick accretionary wedge with signs of tectonic activity is observed to the West. Two other arguments often used to disregard the activity of the subduction zone are the lack of seismicity and the lack of recent back-arc volcanism. However, this tectonic silence is an expected outcome of a period of subduction quiescence. If the movement along the subduction interface is small, the accumulation of the seismic strain will be slow and may take hundreds of years to accumulate. This agrees with the long recurrence period estimated for big earthquakes in the region (Gràcia et al., 2010). The sudden slowdown of a rolling back subduction zone also causes the slab to steepen (Figs. 2E, 3, 4 and S2), and a slow sinking vertical slab may not be able to source a volcanic arc. Instead of the fluids being released into the asthenospheric mantle below a potential volcanic arc, they may ascend throughout the subduction interface and feed mud volcanism, which is observed in the forearc of Gibraltar (Medialdea et al., 2009). Forearc mud-volcanism is also present in the Mariana forearc (Fryer et al., 2020), which also has a rather steep slab.

Why is the slab not breaking off? For a slab to break off the slab pull force must exceed its strength. However, in our models, we see that the upper part of the slab achieves an inverted triangular shape, thinning with depth (Fig. 4). Also, the fact that there was a long and narrow oceanic corridor, led the big Ligurian slab to rest on the 660 km discontinuity, no longer pulling the segment attached to the surface down. This implies that there is not enough pull force to break the slab. The slowdown may also cause the deeper parts of the slab to thermally equilibrate, weaken and lose (thermal) negative buoyancy. Notwithstanding, the pull seems to be just enough to slowly continue to bend the Atlantic oceanic plate. This eventually causes the subduction zone to re-accelerate and propagate into the Atlantic. Another factor is that the slab may be too strong to break. Note that this is one of the oldest oceanic lithosphere on Earth, of Jurassic age, possibly with a thickness of ~120 km (Molina-Aguilera et al., 2019). In the sensitivity tests (see Table S2), the only situation in which we obtained a slab break-off was with significantly stronger passive margins, which prevented the efficient propagation of subduction-transform edge propagator faults when the slab reached the Atlantic domain.

What about the future? Our reference model shows the Gibraltar trench will likely migrate further into the Atlantic. The upper part of the slab has already crossed the Strait of Gibraltar, and the current slowdown may result from a temporary loss of the slab-pull force and the need for the bigger Atlantic oceanic plate to bend. We have run additional models (see Supplementary Material), with a wider and a narrower corridor connecting the Ligurian and the Atlantic oceans. In the case of a wider corridor, subduction propagation is faster, while in the case of a narrow oceanic corridor, subduction propagation is slowed down, although still manages to invade the Atlantic. We have also run sensitivity tests to the reference model exploring plate, mantle and passive margin strength. They show that rollback is facilitated by a weak mantle and weak passive margins (see Table S2). Another factor that contributed to the fast westward retreat of the Gibraltar slab was the break-off along the Kabylies. In nature, there are slab segments still hanging below the Apennines and the Calabrian Arc in the east, but they are not considered in our work (see Lo Bue et al., 2022).

Our models are also sensitive to the initial configuration of the continental blocks, although it does not change the overall subduction dynamics. Small changes can cause the blocks to collide in different locations, even though their outward radial dispersion is always consistent. Notwithstanding, because we do not prescribe any kinematic constraint to these blocks, the almost perfect match between the path of the blocks in nature and in our simulation is an independent test of the robustness of the model.

Another simplification is that we do not impose a velocity on Africa, although we would argue that this velocity has been small (millimeters per year) in the last millions of years. The collision of Adria with Eurasia slowed down convergence, forcing the trench to retreat at a velocity one order of magnitude higher than that of the large-scale convergence. We, therefore, argue that this simplification does not affect the first-order dynamics of the system. Nevertheless, in our model, Africa moves slightly to the North as the result of the pull of the north-dipping slab. An additional push from Africa would likely favor subduction propagation. Furthermore, the narrowing corridor in the reference model somewhat accounts for the effect of a slowly approaching Africa.

FINAL REMARKS AND IMPLICATIONS

Our new geodynamic model reproduces the evolution of the Western Mediterranean and the formation of the Gibraltar Arc. The model also suggests that the Gibraltar subduction zone is active and that a period of quiescence is expected before it becomes fully sustained and contributes to the renewal of the Atlantic Ocean floor.

Our model also reproduces a direct propagation of a subduction zone from a closing ocean (the Ligurian), through a narrow oceanic corridor into a pristine Atlantic-type ocean (the Atlantic).

This type of invasion differs from the other Atlantic cases - Scotia and Lesser Antilles - where subduction was transmitted from an open ocean (the Pacific) across narrow land bridges involving the formation of two new subduction zones in the Atlantic (Riel et al., 2023; Schellart et al., 2023). This implies that subduction invasion should be regarded as a class of subduction initiation mechanisms that may involve different processes, all leading to the introduction of subduction zones in Atlantic-type oceans (see also Waldron et al., 2014).

Given the three known cases in the Atlantic, and new recent geodynamic models showing how they have dynamically evolved, we conjecture that subduction invasion is a common mechanism of subduction initiation in Atlantic-type oceans with a fundamental role in the recent evolution of the Earth.

ACKNOWLEDGMENTS

This work was funded by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC) – UIDB/50019/2020 (https://doi.org/10.54499/UIDB/50019/2020), UIDP/50019/2020 (https://doi.org/10.54499/UIDP/50019/2020) and LA/P/0068/2020 (https://doi.org/10.54499/LA/P/0068/2020). This study was also supported by the European Research Council (ERC) through the MAGMA project, ERC Consolidator Grant #771143. Simulations were conducted using the supercomputer Mogon II of the Johannes Gutenberg University Mainz (hpc.uni-mainz.de). We appreciate the reviews by Taras Gerya, Manuele Faccenda and an anonymous reviewer.

REFERENCES CITED

Billi, A., Cuffaro, M., Orecchio, B., Palano, M., Presti, D., and Totaro, C., 2023, Retracing the Africa–Eurasia nascent convergent boundary in the Western Mediterranean based on earthquake and GNSS data: Earth Planet. Sci. Lett., v. 601, 117906, doi:10.1016/j.epsl.2022.117906

Burke, K. & Dewey, J.F., 1975, The Wilson Cycle: In: Geological Society of America, Northeastern Section, 10th Annual Meeting, Syracuse, NY, Abstracts with Programs, Boulder, CO, 48.

Civiero, C., Custódio, S., Duarte, J.C., Mendes, V.B., Faccenna, C., 2020, Dynamics of the Gibraltar Arc System: A complex interaction between plate convergence, slab pull and mantle flow: Journal of Geophysical Research: Solid Earth, e2019JB018873, doi: 10.1029/2019JB018873

Chertova, M. V., W. Spakman, T. Geenen, A. P. van den Berg, and D. J. J. van Hinsbergen 2014, Underpinning tectonic reconstructions of the western Mediterranean region with dynamic slab evolution from 3-D numerical modeling, J. Geophys. Res. Solid Earth, 119, doi:10.1002/2014JB011150.

Cloetingh, S.A.P.L., Wortel, M.J.R., Vlaar, N.J., 1982, Evolution of passive continental margins and initiation of subduction zones: Nature, v. 297, p. 139–142, doi: 10.1038/297139a0

Dewey, J.F., 1969, Continental margins; a model for conversion of Atlantic type to Andean type, Earth and Planetary Science Letters, v. 6, 1p. 89–197, doi: 10.1016/0012-821X(69)90089-2

Diaz, J., Gallart, J., Villasenor, A., Mancilla, F., Pazos, A., Cordoba, D., Pulgar, J.A., Ibarra, P., Harnafi, M., 2010, Mantle dynamics beneath the Gibraltar Arc (western Mediterranean) from shear-wave splitting measurements on a dense seismic array: Geophysical Research Letters, v. 37, L18304, doi: 10.1029/2010GL044201.

Duarte, J.C., Rosas, F.M., Terrinha, P., Schellart, W.P., Boutelier, D., Gutscher, M.-A., and Ribeiro, A., 2013, Are subduction zones invading the Atlantic? Evidence from the southwest Iberia margin: Geology, v. 41, p. 839–842, doi: 10.1130/G34100.1.

Fernàndez, M, Torne, M., Vergés, J., Casciello, E., & Macchiavelli, C., 2019, Evidence of Segmentation in the Iberia–Africa Plate Boundary: A Jurassic Heritage?: Geosciences, v. 9, p. 343. doi: 10.3390/geosciences9080343

Fryer Pet al. 2020 Mariana serpentinite mud volcanism exhumes subducted seamount materials: implications for the origin of life. Phil. Trans. R. Soc. A, v. 378, 20180425, doi: 10.1098/rsta.2018.0425

Gràcia, E., Vizcaino, A., Escutia, C., Asioli, A., Rodés, A., Pallàs, R., Garcia-Orellana, J., Lebreiro, S., Goldfinger, C., 2010, Holocene earthquake record offshore Portugal (SW Iberia): testing turbidite paleoseismology in a slow-convergence margin: Quaternary Science Reviews, v. 29, p. 1156-1172, doi: 10.1016/j.quascirev.2010.01.010.

Gutscher, M.-A., Malod, J., Rehault, J.-P., Contrucci, I., Klingelhoefer, F., Spakman, W., and Mendes-Victor, L., 2002, Evidence for active subduction beneath Gibraltar: Geology, v. 30, no. 12, p. 1071–1074, doi:10.1130/0091-7613(2002)030<1071:EFASBG>2.0.CO;2.

Gutscher, M.A., Dominguez, S., Westbrook, G.K., Le Roy, P., Rosas, F., Duarte, J.C., Terrinha, P., Miranda, J.M., Graindorge, D., Gailler, A., Sallares, V., and Bartolome, R., 2012, The Gibraltar subduction: A decade of new geophysical data: Tectonophysics, v. 574, p. 72–91, doi:10.1016/j.tecto.2012.08.038.

Heit, B., Mancilla, F.D., Yuan, X., Morales, J., Stich, D.S., Martín, R., & Molina-Aguilera, A., 2017, Tearing of the mantle lithosphere along the intermediate-depth seismicity zone beneath the Gibraltar Arc: The onset of lithospheric delamination: Geophysical Research Letters, v. 44, p. 4027 – 4035, doi:10.1002/2017GL073358

Kaus, B.J.P., Popov, A.A., Baumann, T.S., Pusok, A.E., Bauville, A., Fernandez, N., Collignon, M., 2016, Forward and inverse modelling of lithospheric deformation on geological timescales. In Proceedings of NIC symposium, v. 48 (John von Neumann Institute for Computing (NIC), NIC Series, 2016).

Lallemand, S., and Arcay, D., 2021, Subduction initiation from the earliest stages to self-sustained subduction: Insights from the analysis of 70 Cenozoic sites: Earth-Science Reviews, v. 221, 103779, doi:10.1016/j.earscirev.2021.103779

Lo Bue, R., Rappisi, F., Vanderbeek, B.P., and Faccenda, M., 2022, Tomographic Image Interpretation and Central-Western Mediterranean-Like Upper Mantle Dynamics From Coupled Seismological and Geodynamic Modeling Approach: Front. Earth Sci. 10:884100, doi: 10.3389/feart.2022.884100

Lonergan, L., and White, N., 1997, Origin of the Betic-Rif mountain belt: Tectonics, v. 16, p. 504–522, doi:10.1029/96TC03937.

McKenzie, D.P., 1977, The initiation of trenches: A finite amplitude instability, in Talwani, M., and Pitman W.C., III, eds., Island Arcs, Deep Sea Trenches and Back-Arc Basins: Maurice Ewing Series, American Geophysical Union, v. 1, p. 57–61.

Medialdea, T., Somoza, L., Pinheiro, L.M., Fernández-Puga, M.C.., Vázquez, J.T., León, R., Ivanov, M.K., Magalhaes, V., Díaz-del-Río, V., Vegas, R., Tectonics and mud volcano development in the Gulf of Cádiz: Marine Geology, v. 261, p. 48-63, doi: 10.1016/j.margeo.2008.10.007

Molina-Aguilera, A., Mancilla, F.L., Morales, J., Stich, D., Yuan, X., Heit, D., 2019, Connection between the Jurassic oceanic lithosphere of the Gulf of Cádiz and the Alboran slab imaged by Sp receiver functions: Geology, v. 47, p. 227–230, doi: 10.1130/G45654.1

Mueller, S., and Phillips, R.J., 1991, On the initiation of subduction: Journal of Geophysical Research, v. 96, p. 651–665, doi:10.1029/90JB02237.

Müller, R.D., Sdrolias, M., Gaina, C., Roest, W.R., 2008, Age, spreading rates, and spreading asymmetry of the world's ocean crust: Geochemistry, Geophysics, Geosystems, v. 9, Q04006, doi: 10.1029/2007GC001743

Peral, M., Fernàndez, M., Vergés, J., Zlotnik, S., Jiménez-Munt, I., 2022, Numerical modelling of opposing subduction in the Western Mediterranean: Tectonophysics, v. 830, 229309, doi: 10.1016/j.tecto.2022.229309

Riel, N., Duarte, J.C., Almeida, Kaus, B., Rosas, F., Rojas-Agramonte, Y., Popov, A., 2023, Subduction initiation triggered the Caribbean large igneous province: Nature Communications, v. 14, 786, doi: 10.1038/s41467-023-36419-x

Rosenbaum, G., Lister, G.S., and Duboz, C., 2002, Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene, *in* Rosenbaum, G., and Lister, G.S., eds., Reconstruction of the Evolution of the Alpine-Himalayan Orogen: Journal of the Virtual Explorer, v. 8, p. 107–126.

Royden, L.H., 1993, Evolution of retreating subduction boundaries formed during continental collision: Tectonics, v. 12, p. 629–638, doi:10.1029/92TC02641.

Schellart, W.P., Strak, V., Beniest, A., Duarte, J.C., Rosas, F.M., 2023, Subduction invasion polarity switch from the Pacific to the Atlantic Ocean: A new geodynamic model of subduction initiation based on the Scotia Sea region: Earth-Science Reviews, v. 236 104277, doi: 10.1016/j.earscirev.2022.104277.

Spakman W., Wortel M.J.R., 2004, A tomographic view on western Mediterranean geodynamics, in Cavazza W, Roure F., Spakman W., Stampfli G.M., Ziegler P. (Eds.), The TRANSMED Atlas-The Mediterranean region from crust to mantle, Springer V., Berlin, Heidelberg, p. 31–52.

Stern, R.J., Gerya, T., 2018, Subduction initiation in nature and models: A review: Tectonophysics, v. 746, p. 173-198, doi: 10.1016/j.tecto.2017.10.014.

Waldron, J.W.F., Schofield, D.I., Murphy, J.B., Thomas, C.W., 2014, How was the Iapetus Ocean infected with subduction?: Geology, v. 42, p. 1095–1098. doi: 10.1130/G36194.1

Zitellini, N., Gràcia, E., Matias, L., Terrinha, P., Abreu, M., DeAlteriis, G., Henriet, J., Dañobeitia, J., Masson, D., & Mulder, T., 2009, The quest for the Africa–Eurasia plate boundary west of the Strait of Gibraltar: Earth and Planetary Science Letters, v. 280, p. 13– 50, doi: 10.1016/j.epsl.2008.12.005

FIGURE CAPTIONS

Figure 1 – Evolution of the Western Mediterranean (Rosenbaum et al., 2002). Coloured contoured lines represent the evolution of the Western Mediterranean trench position from 30 Ma to present-day. Red-outlined polygons show the initial position of the continental blocks. The white barbed lines mark the present-day position of the trenches, collision and suture zones. Bt – Betics; Rf – Rif; Kb – Kabylies; Sd – Sardinia; Cb – Calabria; Cs – Corsica.

Figure 2 – Evolution of the reference model since the Oligocene at ca. 30 Ma (0 m.y. in modeling time). Trench is marked in black. Pink— continental lithosphere; purple—Ligurian oceanic lithosphere; gray—Atlantic oceanic lithosphere. Black contours mark elevation above the seafloor (in intervals of 1 km). Red contours mark iso-depth (in intervals of 200 km).

Figure 3 – Modeled velocity evolution of the retreat of Gibraltar trench. 30 m.y. approximately corresponds to the present day. Yellowish area marks the life span of the Ligurian Ocean subduction zone and the blue area the span of an Atlantic subduction zone.

Figure. 4 – Perspective views of the modeled Gibraltar arc region at 30 m.y., corresponding to present day. (A) Bird’s eye view from southeast. (B) Mantle view from southeast. Red lines are depth isocurves at 200 km intervals.

Figure 1

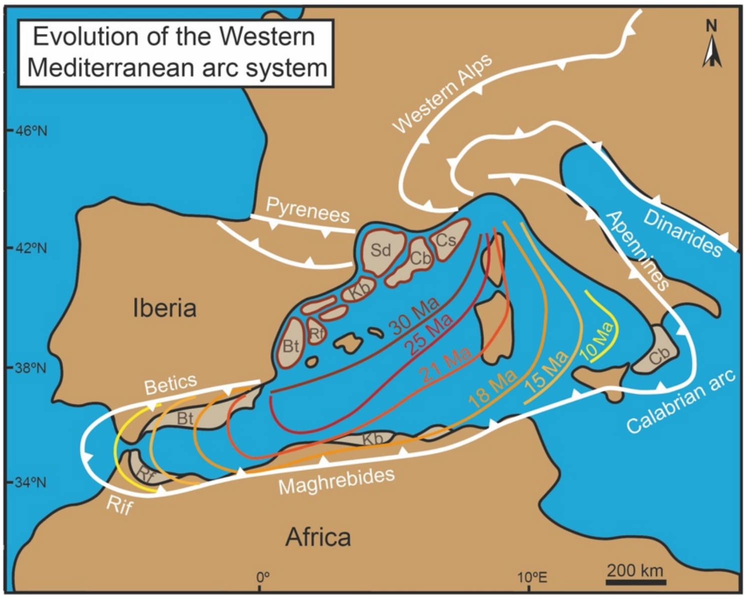


Figure 2

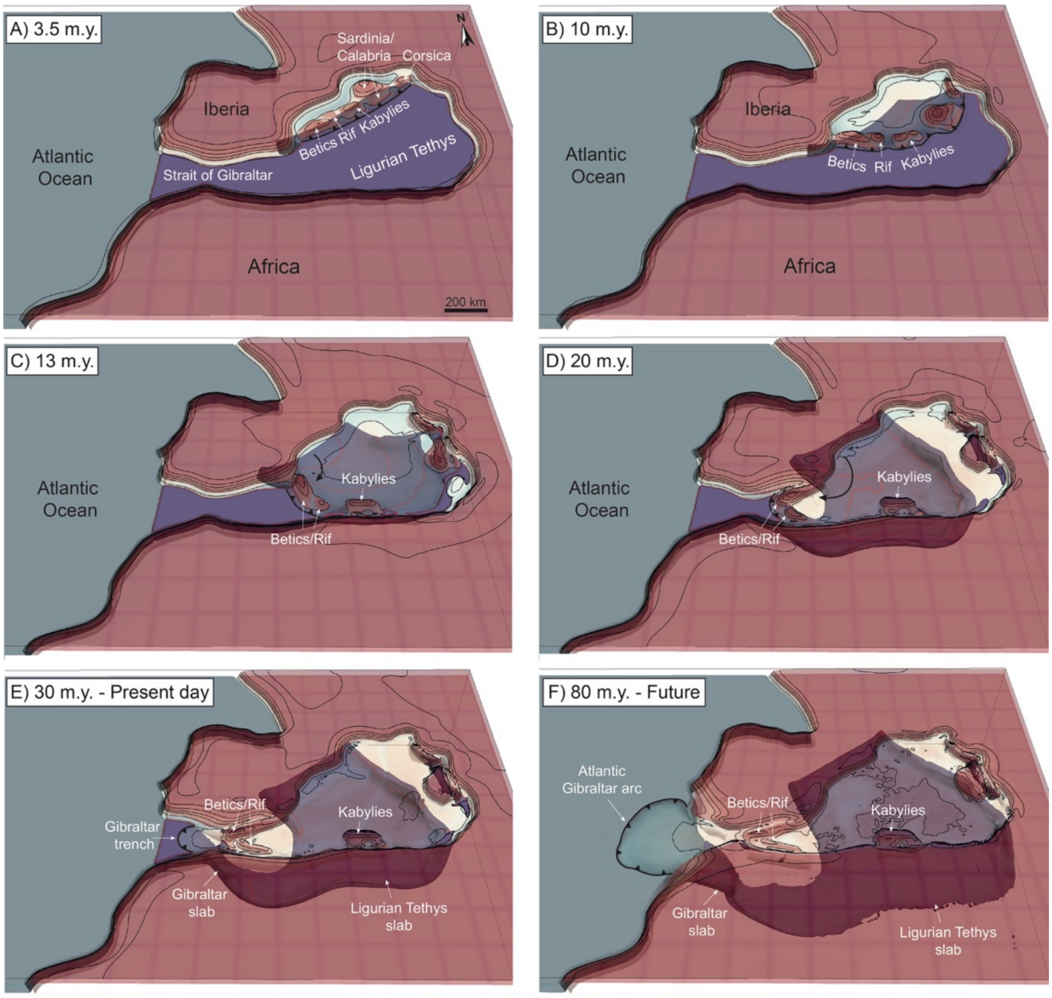


Figure 3

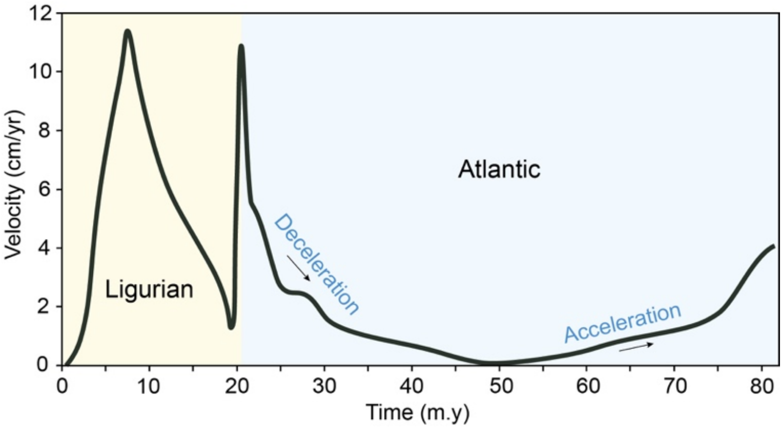
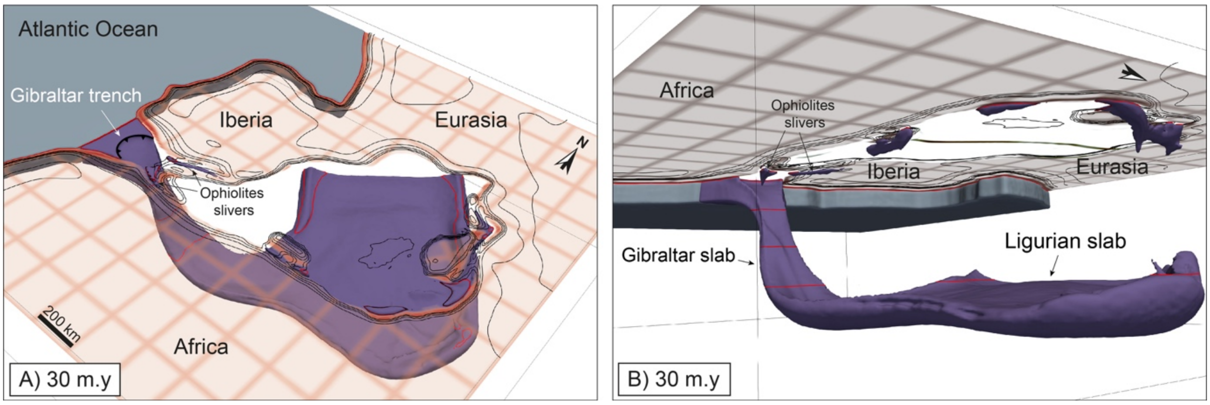


Figure 4



Supplementary Material

Gibraltar subduction zone is invading the Atlantic

João C. Duarte, Nicolas Riel, Filipe M. Rosas, Anton Popov, Christian Schuler, Boris J.P. Kaus

S1. Modelling approach

S1.1. Formulation

We performed the 3-D geodynamic simulations using LaMEM (Kaus et al., 2016; https://github.com/UniMainzGeo/LaMEM). LaMEM is a finite difference staggered grid discretization code that uses particle-in-cell methods to solve the energy, momentum and mass conservation equations.

The rheologies of the rocks are assumed to be visco-elasto-plastic and the total deviatoric strain rate is given by:

$$\dot{\epsilon}_{ij} = \dot{\epsilon}_{ij}^{vis} + \dot{\epsilon}_{ij}^{el} + \dot{\epsilon}_{ij}^{pl} = \frac{1}{2\eta_{eff}}\tau_{ij} + \frac{1}{2G}\frac{\partial \tau_{ij}}{\partial t} + \dot{\lambda}\frac{\partial Q}{\partial \sigma_{ij}} \qquad (1)$$

where $\dot{\epsilon}_{ij}^{vis}, \dot{\epsilon}_{ij}^{el}, \dot{\epsilon}_{ij}^{pl}$ are the viscous, elastic and plastic strain rates, respectively. η_{eff} is the effective viscosity, G the elastic shear modulus, τ_{ij} the deviatoric stress tensor, t the time, $\dot{\lambda}$ is the plastic multiplier, Q the plastic flow potential and $\sigma_{ij} = -P + \tau_{ij}$ the total stress.

The effective viscosity η_{eff} is given by:

$$\eta_{eff} = \frac{1}{2} A^{-\frac{1}{n}} exp\left(\frac{E+PV}{nRT}\right) \dot{\epsilon}_{II}^{\frac{1}{n}-1} \qquad (2)$$

where A is the exponential prefactor, n the stress exponent of the dislocation creep, $\dot{\epsilon}_{II}$ is the second invariant of the viscous strain rate tensor, E, V are the activation energy and volume, respectively, P is the pressure, R is the gas constant and T is the temperature. Plasticity is modelled using the Drucker-Prager yield criterion given by:

$$\tau_Y = sin(\phi)P + cos(\phi)C \tag{3}$$

where τ_Y is the yield stress, ϕ the friction angle and C the cohesion. Strain softening is taken into account by linearly reducing both the friction angle and the cohesion of the material by a factor of 100 between 10 to 60% of accumulated strain. Minimum cohesion is set to 0.01 MPa and maximum yielding stress to 900 MPa.

For more detailed information about the LaMEM code, see Kaus et al. (2016).

S1.2. Model description

The modelled region is a 3-D box of dimensions 3600 × 2400 × 710 km with a resolution of 320 × 224 × 96 cells. It comprises a 50 km thick air layer, and plates (oceanic and continental) are embedded in a 660 km deep upper mantle. The boundary conditions are free slip on all sides and free surface with an open boundary on top.

The initial plate's configuration investigated in this study are shown in Fig. 1S and consists of North Africa and Europe continental plates, and western Mediterranean and Atlantic oceanic plates (Rosenbaum et al., 2002).

The temperature is set to be 20 °C at the top of the model and within the air layer, and 1500°C at the bottom boundary. In order to keep the air layer at 20°C the conductivity in the air is artificially increased to κ= 100.0 W m^{-1} K^{-1} and the heat capacity is set to C_p= 1×10^{6} J K^{-}

[1]. Initial temperature profiles within the plates are prescribed according to the half-space cooling model (Turcotte & Schubert, 2002). For continental plates, the thickness of the boundary layer is chosen to be 135 km and the half-space cooling age is 120 Ma.

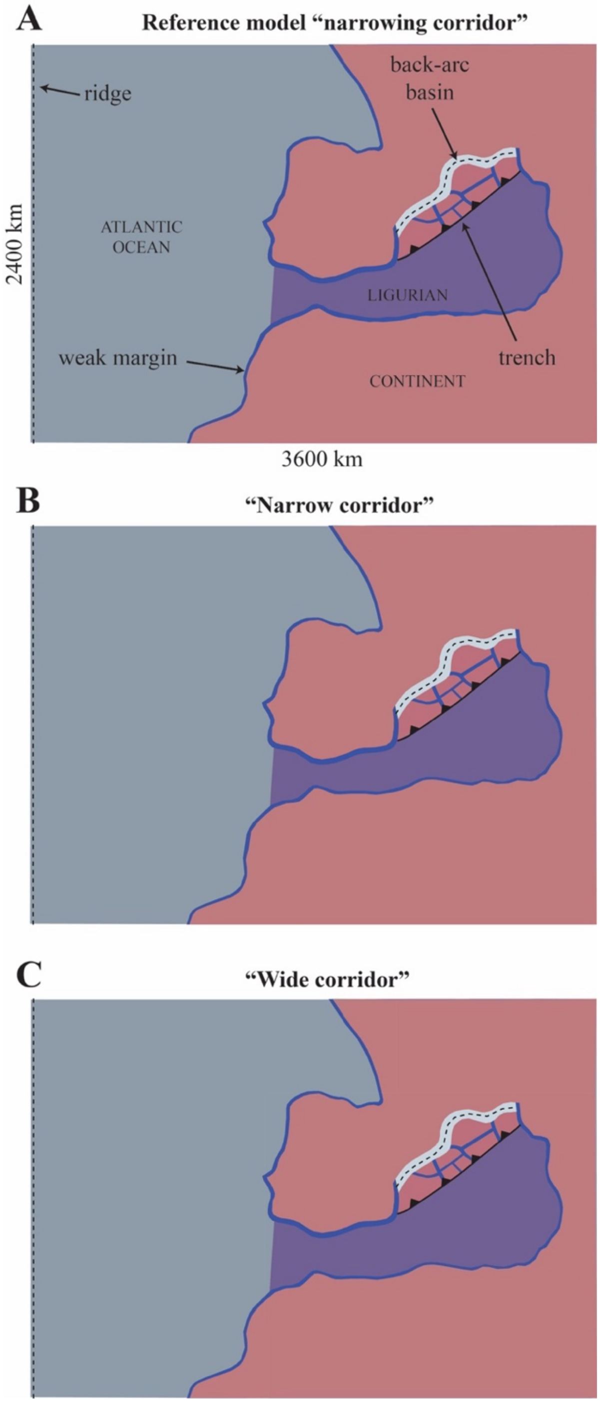


Figure 1S. Model setup. Model A is the Reference Model shown in the main manuscript. Models B and C test the impact of the width of the corridor between the Ligurian Sea and the Atlantic Ocean.

For the Mediterranean lithosphere the boundary layer thickness is set to be 95 km and the cooling age is 90 Ma. For the Atlantic plate the thermal profile is set according to the half-space cooling model with a 95 km thick boundary layer and the cooling age is initialized as a function of the distance to the MOR, using a spreading rate of 0.5 cm yr^{-1}. In the upper mantle, the initial temperature gradient is set to be 0.3 K km^{-1}. Continental and oceanic crust thicknesses are 35 km and 15 km, respectively. Material properties used in this study are given in Table S1.

Subduction is pre-established along the south-western European margin by a pre-subducted 300 km deep slab segment. The initial buoyancy contrast between this pre-subducted slab and the surrounding sub-continental mantle allows for self-sustained gravity-driven subduction roll-back. No internal constraints such as velocity or stress boundary conditions are imposed on any of the plates. Subsequent geodynamic evolution is solely driven by the buoyancy contrast between the downgoing plate and the surrounding mantle. In order to continuously have a weak subduction interface, the maximum strength of the oceanic crust is capped by setting up the plastic cohesion to low value C= 5 MPa (Table S1).

Unit	**ρ (kg m^{-3})**	**Rheology**	**A (Pa^{-n} s^{-1})**	**E (J mol^{-1})**	**n**	**V (m^{-3} mol^{-1})**	**ϕ (°)**	**C (MPa)**
Upper Mantle	3300	Dry olivine[1]	1.1×10^{5}	530×10^{3}	3.5	12.5×10^{-6}	10	30
Oceanic crust	3300	Diabase[2]	8	485×10^{3}	4.7	0	0	5
Continental crust	2800	Quartzite[3]	6.7×10^{-6}	156×10^{3}	2.4	0	10	30

Table S1. Material parameters used in this study. Additional parameters constant across all materials are the elastic shear modulus G= 5×10^{10} Pa, the thermal expansivity α= 3×10^{-5} K^{-1}, the heat capacity C_p= 1050 JK^{-1}, and the thermal conductivity κ = 3.0 Wm^{-1}K^{-1}. The minimum and maximum viscosities are capped to 1×10^{19} and 1×10^{23} Pa s^{1}, respectively. 1: Hirth & Kohlstedt (2003). 2: Mackwell et al. (1998). 3: Ranalli (1995).

A total of ~30 3D geodynamic simulations have been conducted using the supercomputer Mogon II at the Johannes Gutenberg University Mainz (hpc.uni-mainz.de), using 128 cores and a walltime of 28h. A large fraction of these simulations has been conducted to fit as best as possible the real geodynamic time by varying the mantle activation volume, but also to fit the migration and emplacement of the supra subduction blocks (Corsica, Sardinia, Kabylies, Rif and Betic) by varying the starting position of the weak zones separating the blocks (Fig. S1). We present the results of three reference simulations (see supplementary videos) where the starting geometry of the Gibraltar corridor is varied (Fig. S1).

S2. Sensitivity tests to the Reference Model

We have run sensitivity tests to our Reference Model in which we varied the strength of the plates, the strength of the passive margins and the mantle activation volume (see Table S2 and supplementary videos).

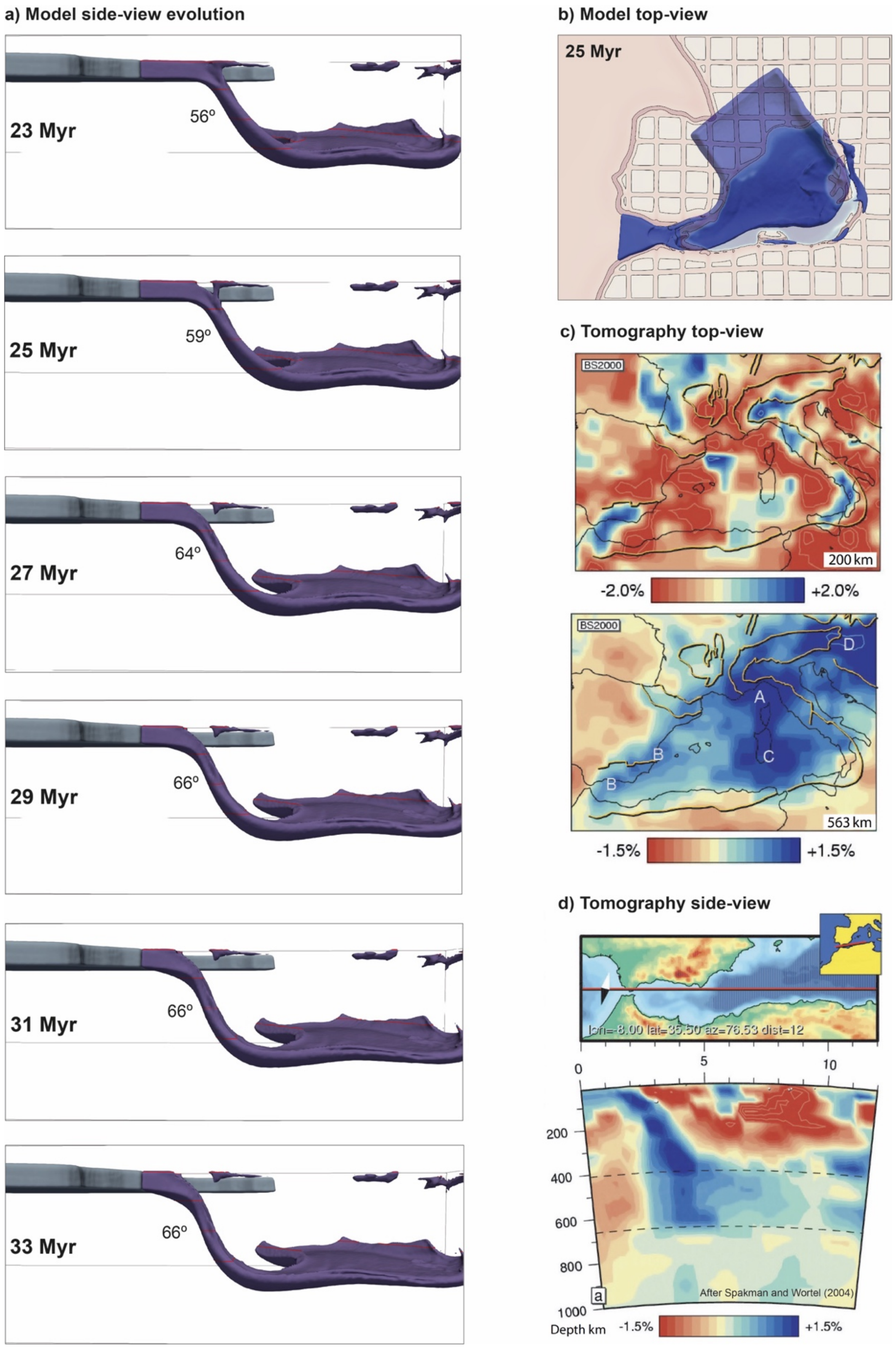
Tested parameters	**Internal frictional angle of all material (°)**	**Internal frictional angle of weak margin (°)**	**Mantle Activation Volume (m^{-3} mol^{-1})**	**Model Results**
Reference model	**10**	**1**	**12.5**	**Reference**
S_Margin	10	2	12.5	Slab stalls in Gibraltar
VS_Margin	10	5	12.5	Slab stalls in the Alboran
S_Plates	20	1	12.5	Slow invasion, no blocks' movement
S_Plates_W_Mantle	20	1	11.5	Extremely fast subduction invasion
S_Plates_S_Margin	20	2	12.5	Extremely slow subduction retreat
S_Plates_S_Margin_W_Mantle	20	2	11.5	Relatively fast subduction invasion
S_Plates_VS_Margin	20	5	12.5	Extremely slow subduction retreat
S_Plates_VS_Margin_W_Mantle	20	5	11.5	Slab breaks off in Gibraltar

Table S2. Where S stands for „strong", VS for „very strong" and W for „weak". A weaker mantle is prescribed by decreasing the activation volume of the peridotite rheology for both diffusion and dislocation creep laws. This is done in order to adjust the modelling time (to be comparable to natural observations). Because the models are solely driven by buoyancy forces, changing the strength of the margin largely decreases the velocity of the rolling-back oceanic plate. In this case, having a less viscous mantle helps counteract the velocity decrease and maintain reasonable geodynamic timescales. Results with different combinations of these parameters are shown as supplementary videos. Note that the Reference model reproduces both the timings and the positions of the blocks obtained from geological observations, which serve as an independent validation of our models (see additional comparisons with nature below).

All videos are available for download here:

https://pubs.geoscienceworld.org/gsa/geology/article-abstract/doi/10.1130/G51654.1/634682/Gibraltar-subduction-zone-is-invading-the-Atlantic

S3. Comparison between the model and tomography from the natural prototype


a) Model side-view evolution

b) Model top-view

c) Tomography top-view

d) Tomography side-view

Figure 2S. A) Model side-view from the south. Note the increase in the slab dip angle. B) Model top-view. C) Tomography horizontal slices at 200 km and 563 km depths. D) Tomography cross-section across Gibraltar.

S4. Comparison between the model mantle flow at 200 km depth and the SKS splitting data

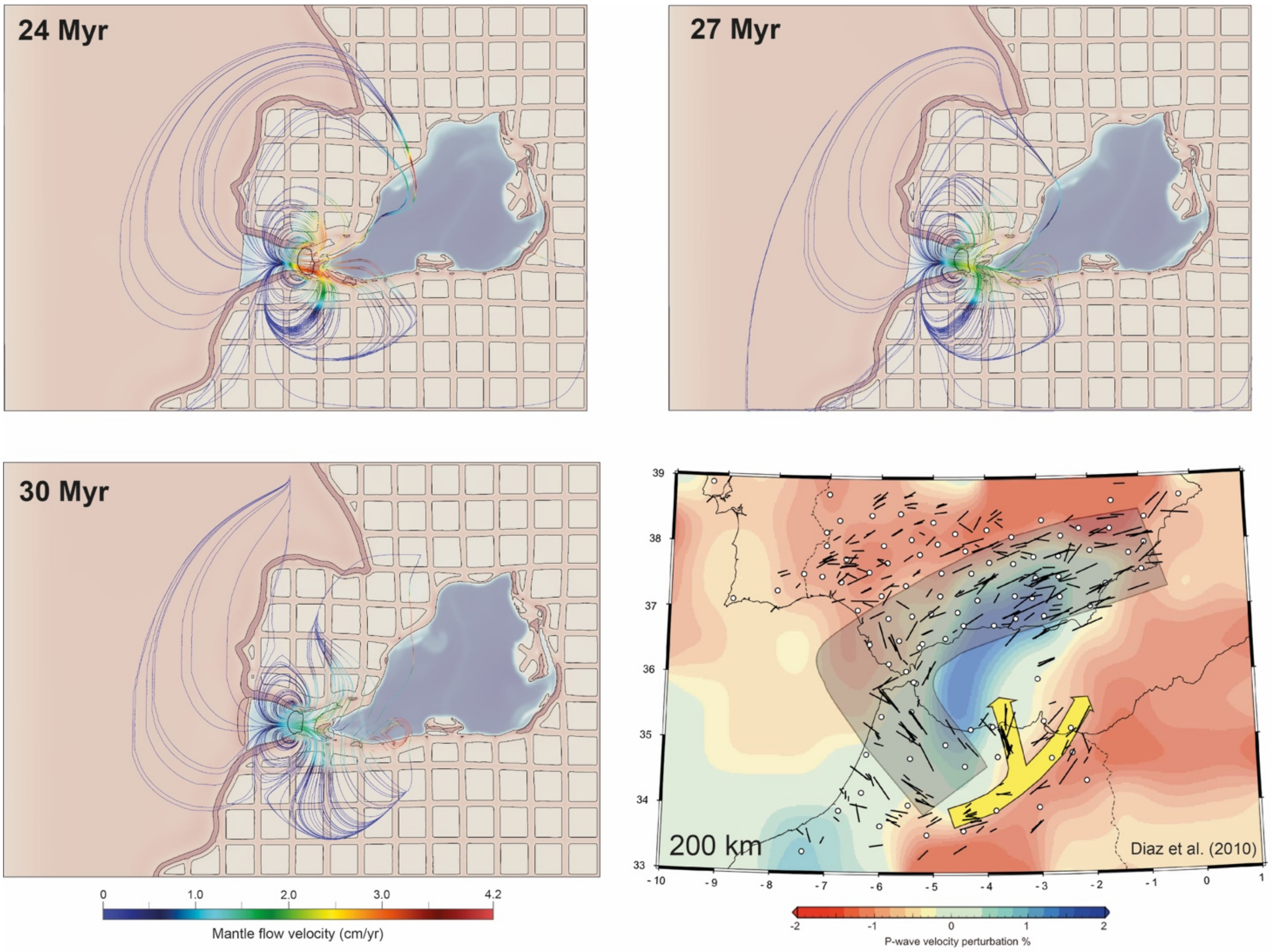
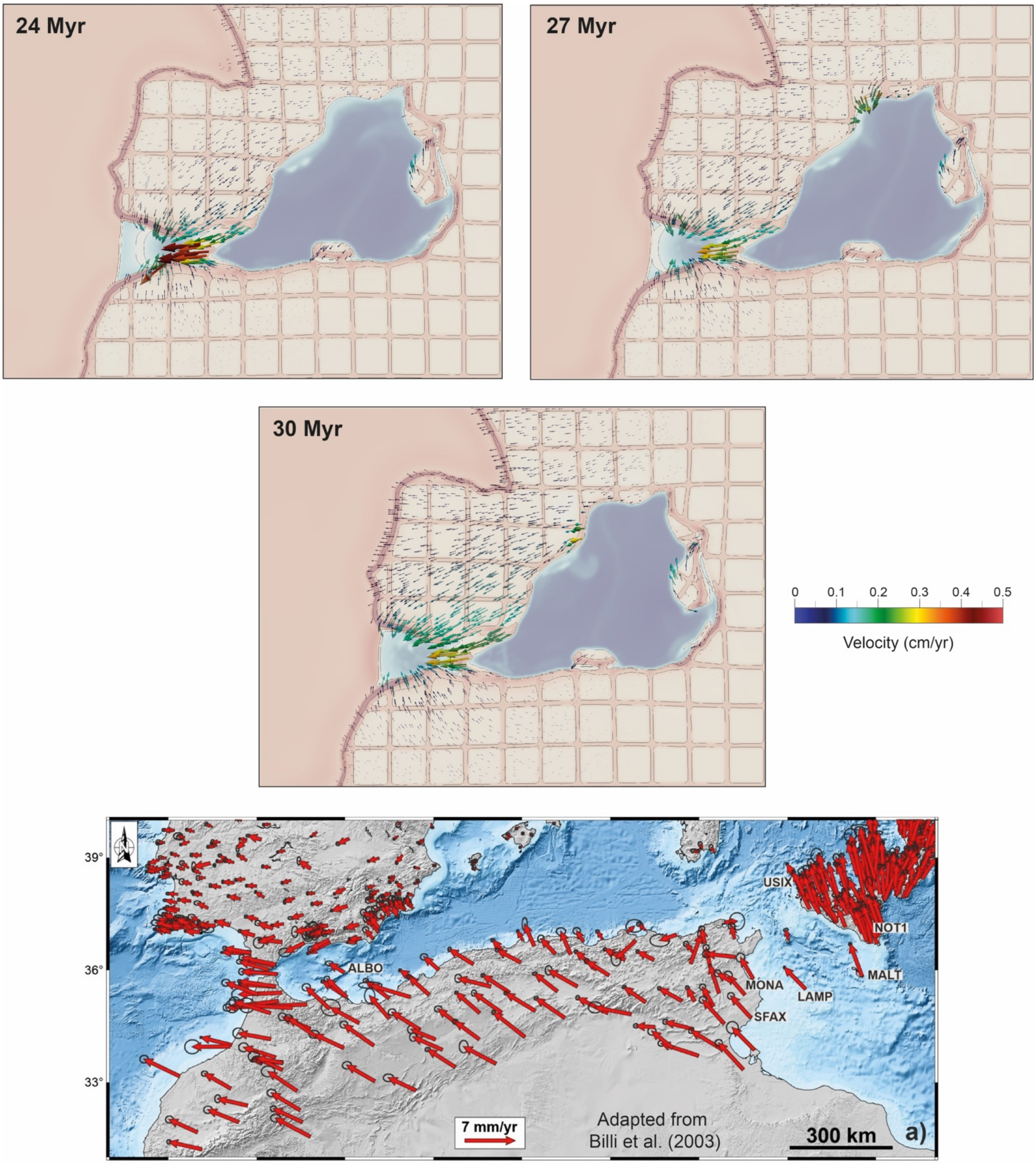


Figure 3S. Model mantle flow velocity at 200 km depth (as indicated by streamlines) and SKS splitting over mantle tomography at a 200 km depth from Diaz et al. (2010). Note the toroidal mantle flow around the slab edges in the model and the natural prototype, relatively stronger in the southern cell.

S5. Comparison between the model surface velocity and GNSS data



Adapted from Billi et al. (2003)

Figure 4S. Model surface velocities in the continental domain and GNSS velocity field data (fixed Eurasia reference frame). Note the abrupt change in direction from NE-SW in Nubia to the E-W in the Gibraltar Region.

References

Billi, A., Cuffaro, M., Orecchio, B., Palano, M., Presti, D., and Totaro, C., 2023, Retracing the Africa–Eurasia nascent convergent boundary in the Western Mediterranean based on earthquake and GNSS data: Earth Planet. Sci. Lett., v. 601, 117906, doi:10.1016/j.epsl.2022.117906

Diaz, J., Gallart, J., Villasenor, A., Mancilla, F., Pazos, A., Cordoba, D., Pulgar, J.A., Ibarra, P., Harnafi, M., 2010, Mantle dynamics beneath the Gibraltar Arc (western Mediterranean) from shear-wave splitting measurements on a dense seismic array: Geophysical Research Letters, v. 37, L18304, doi: 10.1029/2010GL044201.

Hirth, G., & Kohlstedt, D., 2004, Rheology of the upper mantle and the mantle wedge: A view from the experimentalists, In J. Eiler (Ed.), Inside the Subduction Factory, 2004 (pp. 83-105). (Geophysical Monograph Series; Vol. 138). Blackwell Publishing Ltd. https://doi.org/10.1029/138GM06

Kaus, B.J.P., Popov, A.A., Baumann, T.S., Pusok, A.E., Bauville, A., Fernandez, N., Collignon, M., 2016, Forward and inverse modelling of lithospheric deformation on geological timescales: In Proceedings of NIC symposium, v. 48 (John von Neumann Institute for Computing (NIC), NIC Series, 2016).

Mackwell, S.J., Zimmerman, M.E., and Kohlstedt, D.L., 1998, High-temperature deformation of dry diabase with application to tectonics on Venus: J. Geophys. Res., v. 103, p. 975–984.

Spakman W., Wortel M.J.R., 2004: A tomographic view on western Mediterranean geodynamics: in Cavazza W, Roure F., Spakman W., Stampfli G.M., Ziegler P. (Eds.), The TRANSMED Atlas-The Mediterranean region from crust to mantle, Springer V., Berlin, Heidelberg, p. 31–52.