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Absolute plate motions and regional subduction evolution

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Key Points:

- Absolute plate motions are critical for modeling natural subduction systems
- Development of slab rollback depends on plate-slab-mantle coupling
- 3-D subduction modeling may provide new constraints on absolute plate motions

Supporting Information:

- Readme
- Supplementary_movie_1
- Supplementary_movie_2
- Supplementary_movie_3

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Abstract We investigate the influence of absolute plate motion on regional 3-D evolution of subduction using numerical thermomechanical modeling. Building on our previous work, we explore the potential impact of four different absolute plate motion frames on subduction evolution in the western Mediterranean region during the last 35 My. One frame is data-based and derived from the global moving hotspot reference frame (GMHRF) of Doubrovine et al. (2012) and three are invented frames: a motion frame in which the African plate motion is twice that in the GMHRF, and two frames in which either the African plate or the Iberian continent is assumed fixed to the mantle. The relative Africa-Iberia convergence is the same in all frames. All motion frames result in distinctly different 3-D subduction evolution showing a critical dependence of slab morphology evolution on absolute plate motion. We attribute this to slab dragging through the mantle forced by the absolute motion of the subducting plate, which causes additional viscous resistance affecting subduction evolution. We observed a strong correlation between increase in northward Africa motion and decrease in the speed of westward slab rollback along the African margin. We relate this to increased mantle resistance against slab dragging providing new insight into propagation and dynamics of subduction transform edge propagator (STEP) faults. Our results demonstrate a large sensitivity of 3-D slab evolution to the absolute motion of the subducting plate, which inversely suggests that detailed modeling of natural subduction may provide novel constraints on absolute plate motions.

1. Introduction

The influence of global plate tectonics on the local style of subduction evolution may be prominent but is unexplored in subduction modeling [*Billen*, 2008; *Gerya*, 2010]. In recent studies [e.g., *Heuret et al*., 2007; *OzBench et al*., 2008; *Funiciello et al*., 2008; *Stegman et al*., 2010; *Schellart and Moresi*, 2013], the motions of subducting and overriding plates were investigated in more generic approaches using geometrically and rheologically simplified 2-D, or 3-D models implementing rectangular plate domains, straight trenches, and trench perpendicular convergence. Many of these studies implemented a constant or linear rheology [e.g., *Funiciello et al*., 2008; *Capitanio et al*., 2010; *Schellart and Moresi*, 2013], and/or did not include the overriding plate [e.g., *Funiciello et al*., 2008; *Stegman et al*., 2010; *OzBench et al*., 2008]. The motions of the subducting and overriding plates were either restricted to trench-perpendicular direction [*Heuret et al*. 2007; *Stegman et al*., 2010; *Duretz et al*., 2011; *Schellart and Moresi*, 2013] or were left free in trench-perpendicular direction while subduction dynamics are driving plate motion [*Funiciello et al*., 2008; *Schellart and Moresi*, 2013; *Capitanio et al*., 2010; *Garel et al*. 2014; *Magni et al*., 2014]. It is generally observed that the motion of subducting and overriding plates and the viscous coupling between slab and mantle plays an important role in the evolution of regional subduction dynamics. By prescribing only stress boundary conditions on the subducting and overriding plates a strong influence of far-field forcing on regional slab evolution is also observed [*Leng and Gurnis*, 2011; *Chertova et al*., 2012]. Depending on the far-field forces imposed this led to either slab rollback, stationary subduction, or subduction with an advancing trench relative to the mantle, all for the same initial configuration of the subducting lithosphere and overriding plate.

Because of the simplified plate geometries used in 3-D or the restriction to 2-D subduction modeling, the application of these studies to understanding natural subduction evolution mostly concerns the central parts of laterally extensive and relatively straight subduction zones. Natural subduction, however, usually involves oblique plate convergence along curved plate boundaries. Recent investigations have highlighted that along-trench lithosphere heterogeneity has an important effect on subduction evolution [*Duretz et al*., 2014; *Magni et al*., 2014; *Chertova et al*., 2014]. In addition, the regional motion of the two plates involved in a subduction process is also coupled to the global interaction between tectonic plates and underlying mantle [e.g., *Warners-Ruckstuhl et al*., 2012].

Here, we make a next step contributing to the understanding of the interaction between regional subduction evolution and global plate tectonics by incorporating such first-order complexities. In particular, we investigate the effect of different plate motions on subduction evolution for which we use the natural geodynamic setting of western Mediterranean subduction of the last 35 My [*Chertova et al*., 2014]. This comprises oblique plate-convergence of the African (Nubia) and Eurasian (Iberian) plates involving strongly curved plate boundaries with laterally varying rheology. Within this oblique convergent setting, the subduction trench rotated by $>180^\circ$ from plate-boundary parallel, to plate-boundary perpendicular, to again plate boundary parallel leading to the present-day Rif-Gibraltar-Betic slab [*Rosenbaum et al*., 2002; *Spakman and Wortel*, 2004; *van Hinsbergen et al*., 2014; *Chertova et al*., 2014].

In *Chertova et al*. [2014], hereafter called Chert14, we modeled various subduction evolution scenarios for the region with a focus on optimizing the rheology of slab and mantle while the oblique plate convergent setting of subduction was the same in all experiments. Here, we adopt the preferred subduction scenario from Chert14 and focus on varying the absolute motions of the two major plates involved to investigate their effect on subduction evolution.

Absolute plate motions are the ideal kinematic boundary conditions for incorporating far-field forcing into regional modeling of *natural* subduction. These are the motions of lithosphere plates relative to the underlying mantle as defined in a mantle reference frame [e.g., *Torsvik et al*., 2008; *Van der Meer et al*., 2010; *Doubrovine et al*., 2012]. Absolute plate motions result from all forcing of plate motion and are therefore consistent with the far-field forcing of global plate tectonics and global plate-mantle interaction, and are as well consistent with the regional forcing of subduction, e.g., slab buoyancy and local slab-mantle coupling. So far, absolute plate motion models are determined from a global collection of data and assumptions that unavoidably lead to uncertainty in their estimation [e.g., *Doubrovine et al*., 2012]. At best an estimate of the local plate motion can be obtained that results from the global interaction of plates and underlying mantle, i.e., representing far-field forcing.

In Chert14, the influence of far field forcing was represented by means of kinematic side-boundary conditions for continental northern Africa and Iberia, determined from the global moving hot spot reference frame (GMHRF) of *Doubrovine et al*. [2012]. Here, we examine the effect of using three other absolute plate motion frames on the subduction evolution in the western Mediterranean region from 35 Ma until present. We use the relative motions between Iberia and Africa as detailed in *van Hinsbergen et al*. [2014] to implicitly define the following frames that implements (1) the motion of African plate defined by the GMHRF used for our reference model; (2) the African plate fixed to the deep mantle; (3) the Iberian continent fixed to the deep mantle; and (4) the motion of the African plate taken two-times that of the GMHRF. Apart from the reference motion frame determined from *Doubrovine et al*. [2012], the three other are invented frames. The second and third motion frames were inspired by the observation that so far all tectonic and numerical studies of the regional tectonic evolution utilize a relative plate motion frame defined either relative to the African plate or to European plate [e.g., *Rosenbaum et al*., 2002; *Handy et al*., 2010; *Jimenez-Munt and Negredo* 2003; *Perouse et al*., 2011; *Cunha et al*., 2012]. The fourth motion frame we use is motivated by the fact that large uncertainty exists in estimated absolute plate motions [*Doubrovine et al*., 2012].

2. Model Description

In Chert14, we investigated subduction evolution of the western Mediterranean region since ~ 35 Ma by varying initial conditions, initial subduction configurations, and by varying rheological settings of diffusion, dislocation creep, and yield stress of the lithosphere and the continental margins, and of the slab and ambient mantle. Here, we adopt the particular initial conditions and the rheological settings that were determined for the subduction evolution that successfully predicts first-order features of present-day slab morphology in the upper mantle. This model is used here as the reference subduction model and is introduced in section 2.3. In sections 2.1 and 2.2, we will first briefly review our 3-D modeling approach and the initial model set up and conditions. We refer to Chert14 for the analysis that has led to determining these model conditions and features. Here, we experiment with varying the kinematic boundary conditions for the African and Iberian lithosphere, which are described in detail in section 2.2.

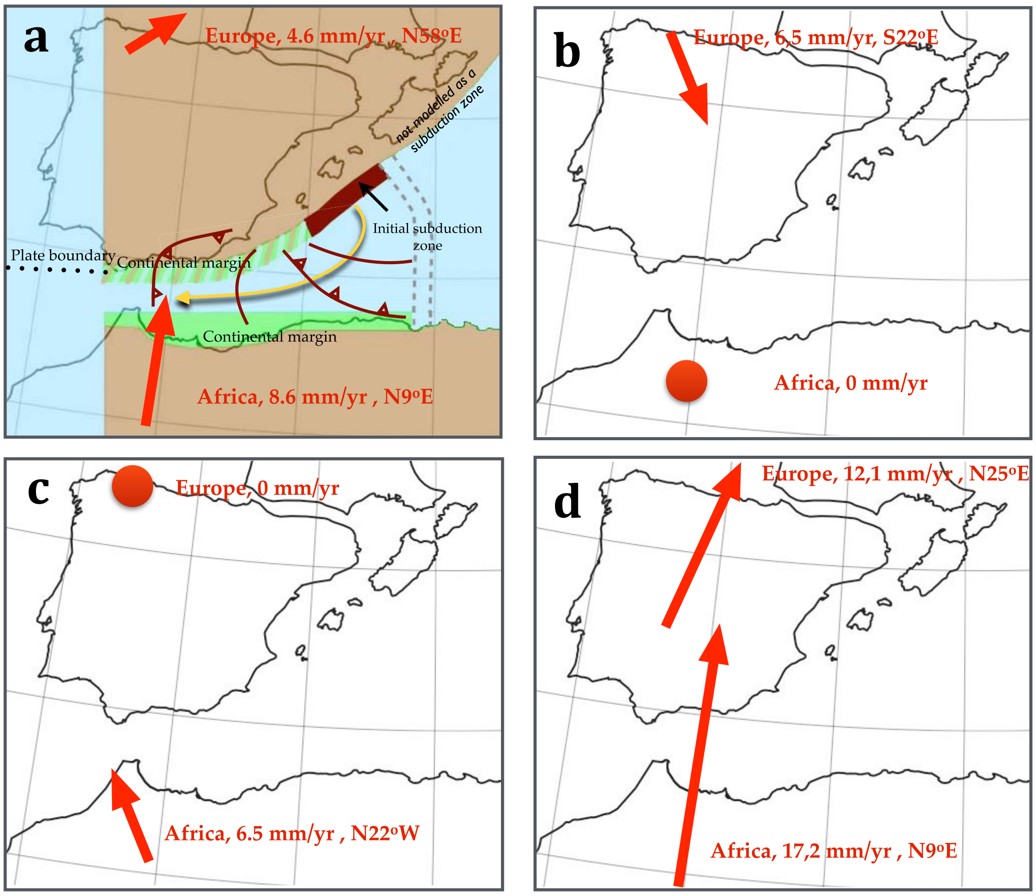

Figure 1. (a) Initial subdivision of the model domain in continental lithosphere (brown), oceanic lithosphere (blue), and continental margins (green and green-dashed). The thick dark red line indicates the initial subduction zone (see text for details) Trench positions through time are depicted with barbed lines while the yellow arrow indicates the direction of the slab rollback. The four plots show the absolute plate motion vectors (red arrows) for Africa and Iberia for four models (a) 35My-average based on *Doubrovine et al.* [2012]; (b) Iberia fixed to the mantle; (c) Africa fixed (dot) to the mantle; (d) 2 times faster Africa motion than in A while the absolute motion of Iberia is constrained by the relative motion between the two plates as in model Figure 1b.

2.1. Initial Numerical Setup

We perform our experiments in 3-D space using the finite element package SEPRAN. The equations of mass, momentum and energy conservation and the transport equation for advection of nondiffusive material properties are solved in the extended Boussinesq approximation [*Christensen and Yuen*, 1984; *van Hunen*, 2001; Chert14]. Our models include two major phase transitions at 410 km and at 660 km in the unperturbed mantle [*Cizkova et al.*, 2007; *Chertova et al.*, 2012; *Garel et al.*, 2014]. For the detailed description of these equations, we refer to *Christensen and Yuen* [1984]. We use the same 3-D model setup as in Chert14, illustrated here in Figure 1a. The size of the modeling domain is 1650 × 1300 × 1000 km. On the vertical sides, we use open boundary conditions, which have much less influence on the flow in the modeling domain than the more common free-slip boundary conditions [*Chertova et al.*, 2012, Chert14]. For the top boundary, we use free-slip conditions and no-slip for the bottom boundary. To allow slab decoupling from the top surface and from the overriding plate, a crustal layer with a viscosity of 9×10^{19} Pa s and with a thickness of 30 km is initially placed on the top of the subducted slab. We implement kinematic boundary conditions for the top 150 km of the southern and northern side boundaries. These boundary conditions are used to prescribe various absolute motions of the African (Nubian) and Eurasian (Iberian) plates in our experiments (section 2.2).

Composite rheology is implemented in our models, which combines temperature-dependent and pressure-dependent diffusion creep and dislocation creep, with a third term limiting the viscosity by prescribing the maximum yield stress. Used parameters for diffusion, dislocation creep, and for yield stress values used here were determined in our previous work [Chert14]. Lagrangian particles are used for implementing the maximum yield stress separately for the oceanic and continental lithosphere, and for the continental margins. These particles are also used to define the weak crustal layer on the top of the subducted plate.

2.2. Initial Model Configuration and Kinematic Boundary Conditions

We briefly summarize the initial continent-ocean configuration corresponding to the paleogeography at ~35 Ma and the particular constraints on rheology. These were determined from an analysis of many subduction models in which the rheological strength of lithosphere, margins, and mantle were tuning parameters in modeling subduction evolution of the region [Chert14]. Figure 1a shows the configuration of five different lithosphere domains: two continental domains, Africa and Iberia, shown in brown, a continuous domain of oceanic lithosphere shown in blue, and two narrow zones corresponding to the continental margins. A yield strength of 800 MPa is used for the oceanic and continental lithosphere. A weak African margin is implemented with a yield strength of 100 MPa, while the European margin is as strong as the oceanic subducted lithosphere (800 MPa). The European margin was gradually thickened from 0 to 30 km from Gibraltar to western Baleares. This results in a lowered geotherm and consequently in a stronger margin rheology through the temperature control on rheology.

The initial temperature distribution for the 100 My oceanic lithosphere is computed from the equation of a cooling of semi-infinite half space [*Turcotte and Schubert*, 2002]. For the continental lithosphere, we use a constant temperature gradient of 10 K/km to a depth of 150 km and for the sublithospheric mantle a constant temperature gradient of 0.3 K/km is taken similar to other studies [e.g., *Ghazian and Buiter*, 2013]. The different geotherms in the oceanic and continental lithosphere (being cooler and thicker) lead to a more negatively buoyant continental lithosphere but also to a stronger rheology for the continental lithosphere.

The double-dashed line in Figure 1a indicates a weak lithosphere-decoupling zone which separates the future Rif-Gibraltar-Betic slab in the west from the subduction that developed to the east of this zone [*Spakman and Wortel*, 2004; Chert14]. This zone was given a width of 70 km and was made rheological weak by filling it with young (20 Ma) oceanic lithosphere. The initial subduction zone at ~35 Ma is shown in dark red in Figure 1a and is located SE from the Baleares. The initial length of the slab is ~200 km measured from the surface with a dip of ~40°. A maximum strength of 300 MPa was prescribed for the oceanic lithosphere in the Atlantic region to accommodate the relative NW-SE convergence between the African and Eurasian plates. In the numerical models, this effectively results in focusing plate boundary deformation to a ~150 km wide zone that occurs to the west of Gibraltar.

Figures 1a–1d depict the applied kinematic boundary conditions for the four different absolute plate motion models used in our experiments. Figure 1a shows the average absolute plate motions for the last ~35 Ma as used in Chert14, based on the GMHRF of *Doubrovine et al*. [2012] with Africa moving N9°E with 8.6 mm/yr and Europe moving N58°E with 4.6 mm/yr. The two plate motion vectors are consistent with the average relative motion between Iberia and Africa using the intra-African and intra-Iberian deformation-corrected plate circuit as detailed in *van Hinsbergen et al*. [2014]. The second absolute plate motion frame fixes the African plate to the mantle and thus requires the Iberian continent to move in the direction S22°E at a speed of with 6.5 mm/yr (Figure 1b). The third absolute plate motion frame with Iberia fixed to the mantle requires Africa moving in N22°W direction at 6.5 mm/yr (Figure 1c). Finally, we defined a two-times-faster velocity for Africa than predicted by the average values of the GMHRF, i.e., 17.2 mm/yr in N9°E, and an absolute Iberian motion of 12.1 mm/yr to N25°E to keep the relative Africa-Iberia velocity the same as in the other models (Figure 1d).

The last three frames are not intended to simulate real absolute plate motions but rather define variants of absolute plate motion frames that incorporate *the same* relative Africa-Iberia convergent motion vector averaged over the last 35 My. Therefore, modeled slab evolution is sensitive to changes in the global plate motion frame rather than to changes in the local relative plate motion. Note that the difference between any two of the motion models can be described by just one uniform Euler rotation defining a different interaction between the evolving subduction system and the ambient mantle.

2.3. Reference Subduction Model

The initial and boundary conditions (Figure 1a; section 2.2) constrain a subduction evolution model of the Rif-Gibraltar-Betic slab starting at 35 Ma, which is shown in Figure 2 and in supporting information S1 as a

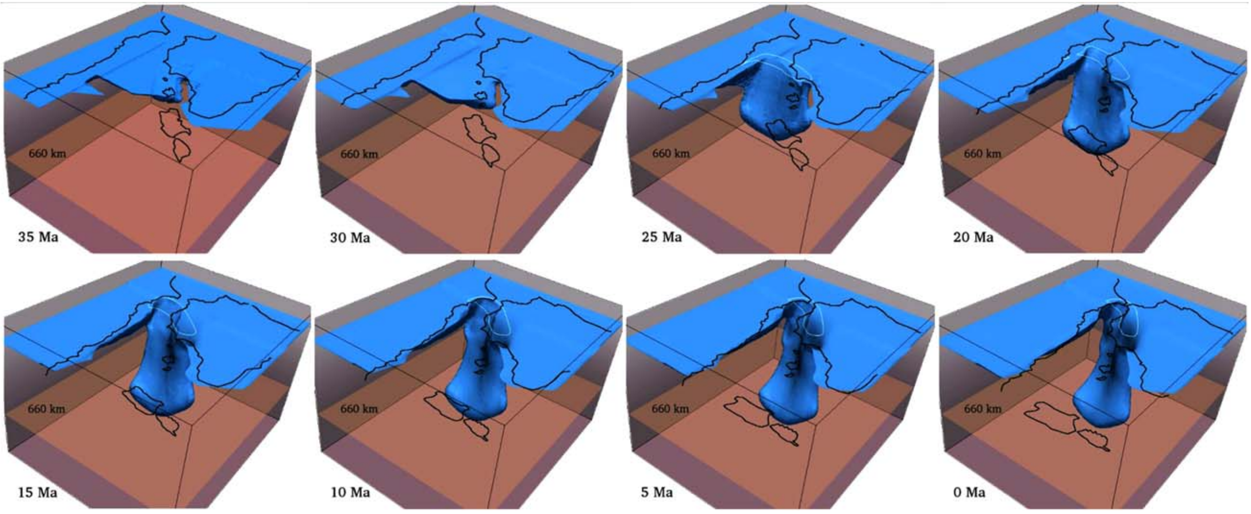

Figure 2. Evolution of the reference model in 5 My steps and viewed from the northeast. The 1400 K isotherm is shown. Blue contour shows the surface projection of the slab outline at a depth 200 km. The reference model is model S1.3-2 of Chert14.

3-D movie. This will be our reference subduction model, which is called model S1.3-2 in Chert14 and successfully predicts the tomographically observed slab morphology [*Spakman and Wortel*, 2004; *Bezada et al*., 2013; Chert14]. The initial configuration of Figure 1a corresponds to the paleogeographic situation at ∼35 Ma in which initial subduction is confined to the Baleares margin [e.g., *Lonergan and White*, 1997; *Rosenbaum et al*., 2002; *Spakman and Wortel*, 2004; *van Hinsbergen et al*., 2014]. The initial slab buoyancy is small and during the first 5 My subduction develops slowly at the Baleares trench, which is stationary relative to Iberia, leading to a slab length increase of only ∼30 km. From ∼30 Ma onward, the trench rotates to a southwestward direction and fast rollback develops over the next 5 My. When the trench reaches the African margin, its western portion has rotated into a ∼N-S strike. This western segment subsequently rolls back westward, accommodated by lithosphere tearing along the African margin. After 23–25 My, the slab reaches the Gibraltar region and only slow trench retreat in northwestward direction is observed until the present. In the predicted present-day slab morphology, the slab edge is located under the Rif (Northern Morocco), extends northward to Iberia and curves to the NE under the south Iberian Betic range towards the Baleares. The deeper part of the slab is located under the Alboran Sea and southern Iberia. These are the first-order features that are in a good agreement with imaged slab morphology.

3. Testing Different Absolute Plate Motion Frames for Modeling 3-D Slab Evolution of the Western Mediterranean Region

In all modeling experiments, the initial configuration and rheological settings described above are maintained, while we impose three different kinematic boundary conditions (Figures 1b–1d) on the top 150 km of the southern and northern sidewalls. As a result, the only differences between the model experiments are the imposed absolute plate velocities of Africa and Iberia, dragging the subduction system differently through the mantle, while the relative plate motion remains the same.

3.1. Africa Fixed to the Mantle and Iberia Moving SSE

The absolute plate motion constraints for this model are given in Figure 1b. Figure 3 shows the evolution of Africa-fixed model (green) in comparison with the reference model (blue). Here we portray a top view, which better reveals the differences between these two models and shows the effect of an Africa-fixed frame on slab evolution. To make this comparison, the position of the slab for the Africa-fixed model in Figure 3 is shifted by lining up the African coastline with that of the reference model (in which the African plate is moving north; Figure 1a). Similar model shifts are done for the Iberia-fixed (Figure 4) and two-times faster Africa models (Figure 5). A movie illustrating slab evolution in which Africa is fixed, as in the numerical model, using a viewpoint in the NE is presented in supporting information S2. Differences between models start to develop after the trench reaches the African margin and westward lithosphere tearing develops.

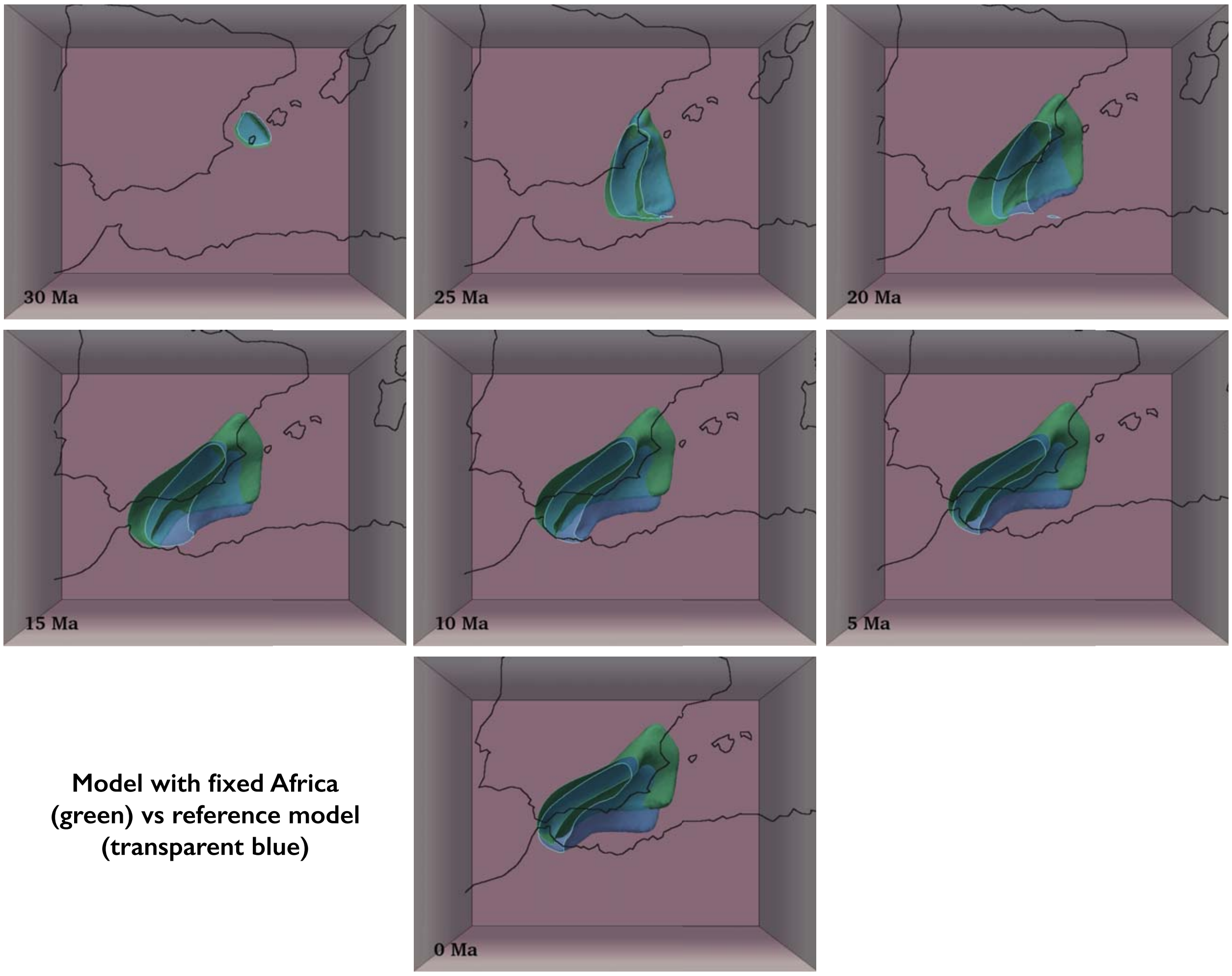

Figure 3. Slab evolution in the reference model (blue) and model in the Africa-fixed model (green). The slab contour is shown from the depth of 200 km downward indicated with blue and green line contours, partly looking inside the (hollow) slab contour. The bottom of the slabs reaches 660 km. The initial 35 Ma slab morphology is skipped, as then the slab is shallower than 200 km. The coastlines are shown in absolute plate motion frame of the reference model (Figure 1a). The slab of the Africa-fixed model has been shifted such that the Africa coastline in both models coincides. The supporting information movie S2 shows the 3-D evolution in which the African plate is fixed to the mantle (as in the numerical model).

Tearing propagates faster than in the reference model. The slab reaches the Gibraltar Strait already at ~16 Ma, which is ~6 My earlier than for the reference slab. Next, the slab starts to rotate clockwise and shows slight rollback toward the south Iberian margin without further westward retreat and without further lithosphere tearing. At shallow levels, the present-day morphology of the slab is comparable to that of the reference slab, although it is located more to the north in the Rif-Gibraltar region (Figure 3). Deeper in the upper mantle the slab starts to differ more and is located farther to the north. This results from slab being overridden by the Iberian continent in a SSE direction during the slab stalling phase since ~16 Ma (supporting information Movie S2). This is also the cause of a slightly more rotated trench and slab. Although differences in the final slab morphology between this model and the reference model are relatively small, the temporal development of the subduction process, which may link to a particular geological/tectonic surface response, is significantly different for these two models.

3.2. Iberia Fixed to the Mantle and Africa Moving NNW

The plate motion constraints for this model are given in Figure 1c. The slab evolution is shown in Figure 4 (green slab) together with the evolution of the reference subduction model. A movie illustrating the evolution of this model with Iberia fixed to the mantle, as in the numerical model, is given in supporting information S3. The initial phase of stationary subduction is similar for both models. During initial southward rollback between 30 and 25 Ma, the slab in the Iberia-fixed model assumes already a slightly more northerly

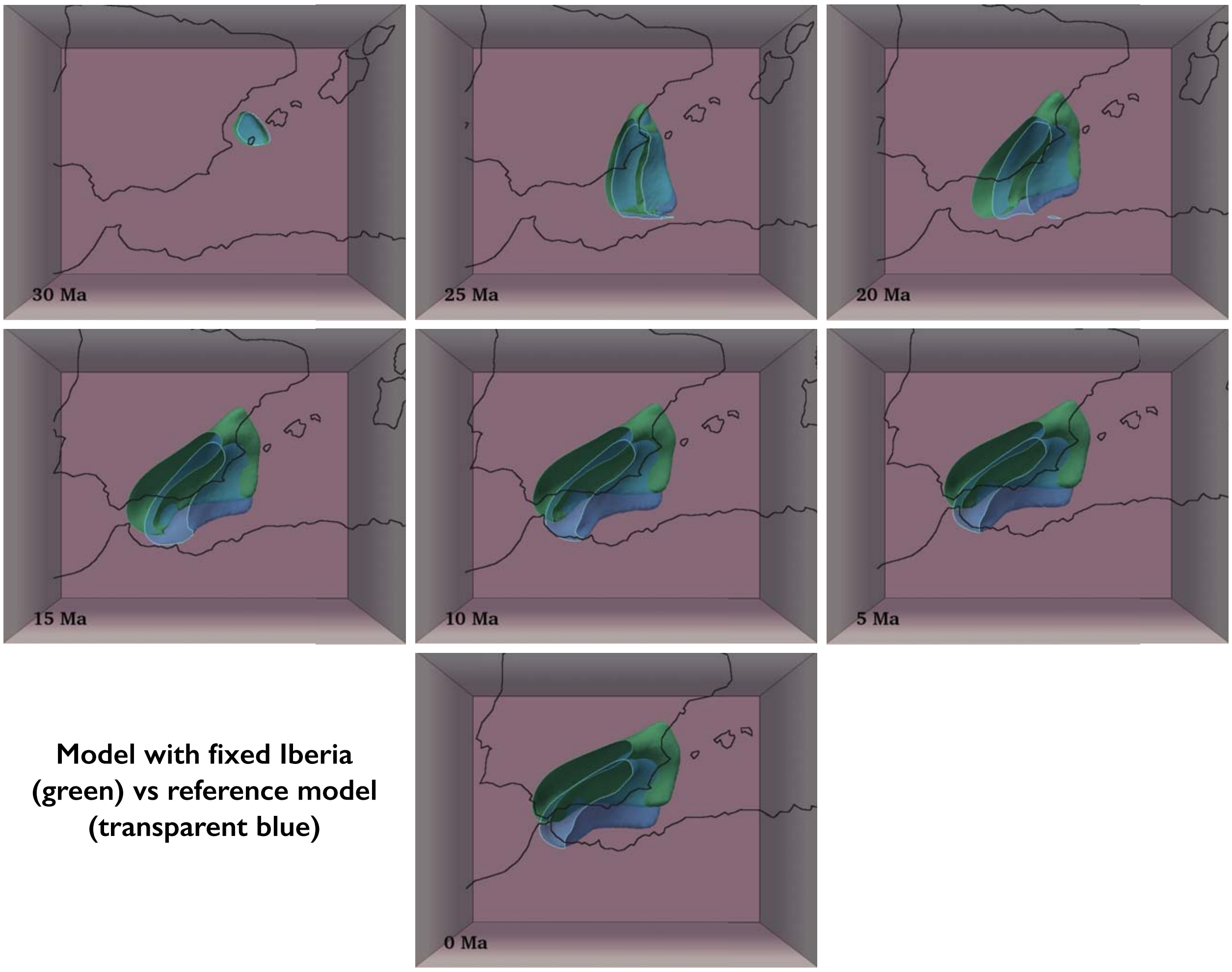

Figure 4. Slab evolution in the reference model (blue) and in the Iberia-fixed model (green). The slab contour is shown from the depth of 200 km downward. The initial, 35 Ma slab morphology is skipped, as the slab is shallower than 200 km. The coastlines are shown in absolute plate motion frame of the reference model (Figure 1a; also see caption of Figure 3). The supporting information movie S3 shows the 3-D slab evolution with Iberia fixed to the mantle (as in the numerical model).

position. After the trench reaches the African margin at ∼25 Ma, lithosphere tearing along the African margin develops slower than in the Africa-fixed model but still faster than in the reference model. At ∼14 Ma, 2 Ma after the Africa-fixed model and 4 My before the reference model, the slab reaches the Gibraltar region while lithosphere tearing under Africa and slab rollback continue. In contrast to both the Africa-fixed model and the reference model, the trench retreats more and more to the northwest under the Iberian plate and eventually also a part of the continental lithospheric mantle becomes involved in subduction as a result of its negative buoyancy and despite its larger strength as compared to the subducting slab. The NW-directed slab retreat is a clear effect of the prescribed kinematic boundary (absolute motion) conditions of the Iberia-fixed frame. During its evolution, the slab is connected to both the African and Iberian plates. In the reference model, the slab is dragged by Africa and Iberia toward N-NE (Figure 1a) while in the Iberia-fixed model the slab is pushed under Iberia by the African plate advancing to the NW (Figure 1c). This African plate push is visible in the supporting information S2 from ∼15 Ma onward.

The final slab morphology of the Iberia-fixed model shows a significant difference with the reference model slab. The slab is located much more to the north at all depths from 100 to 660 km and the trench is rotated more clockwise than for the reference model. Relative to the African coastline, the more northwestern position owing to advancing Africa is accommodated by tearing along the African margin, which also propagates further to the west and to the north, even where no lithosphere weakening was prescribed, as compared to the reference model.

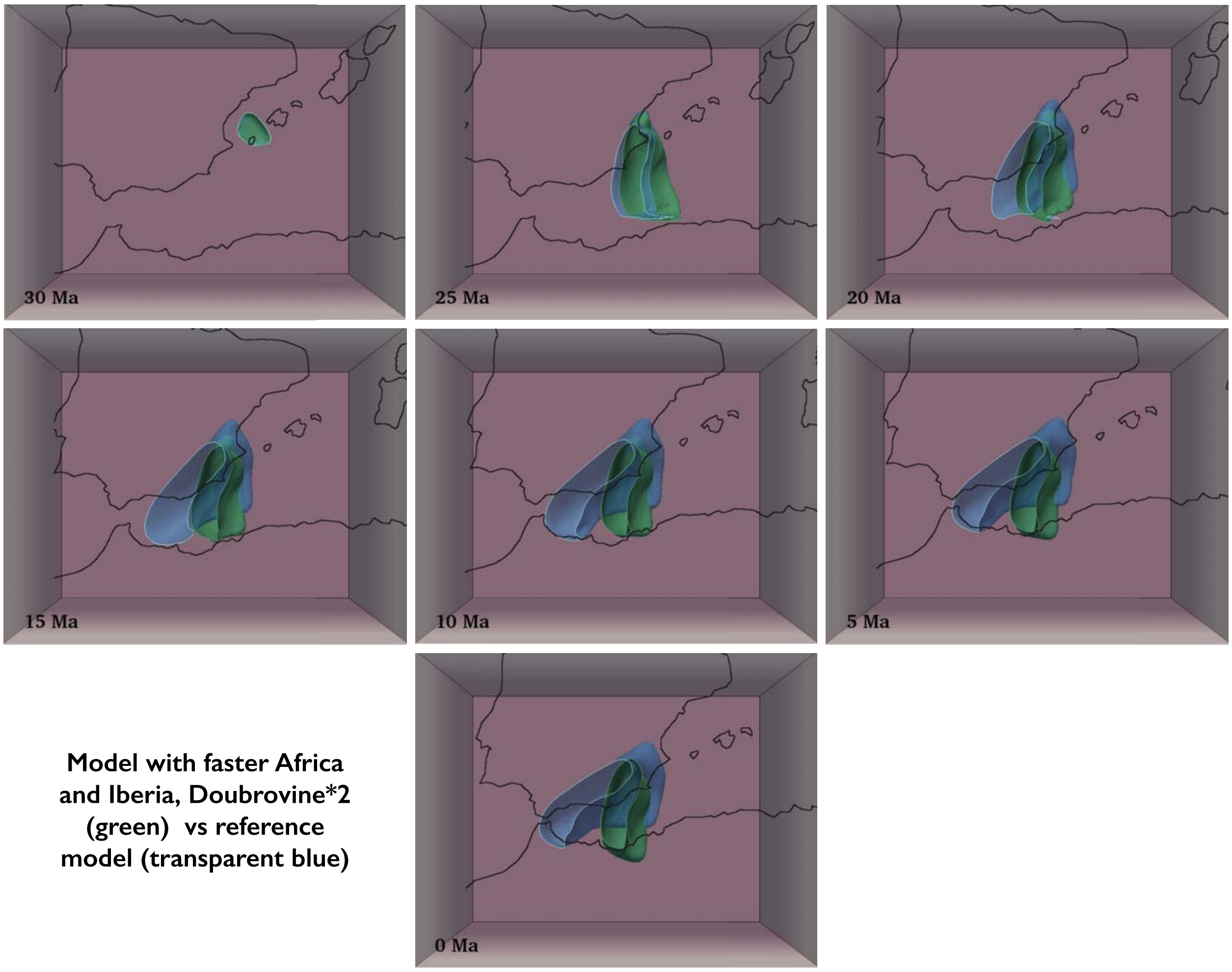

Figure 5. Subduction evolution in the reference model (blue) and in the model with two times faster Africa (green). The slab contour is shown from the depth of 200 km downward. The initial, 35Ma slab morphology is skipped as slab is shallower than 200 km. The coastlines are shown in absolute plate motion frame of the reference model (Figure 1a; also see caption of Figure 3).

3.3. Model With Two-Times Faster Africa Motion

Next, we test the plate motion model as depicted in Figure 1d. The evolution of this model in comparison with the reference model is shown in Figure 5. Until 25 Ma, the subduction process in these models develops similarly. Next, in the reference model fast westward rollback and lithosphere tearing along the African margin develops. However, in the model with larger absolute plate motion velocities, lithosphere tearing develops much slower. Since arrival of the slab at the African margin at 25 Ma only about 100 km of westward margin tearing occurs due to steepening of the slab. As a consequence, slab rollback is very slow. The final slab position is clearly different from the previous models, as the slab stalls with a N-S strike and is in a position far east of Gibraltar stretching from the SE Betics to Africa.

3.4. Trench-Normal Lithosphere Tearing During Trench-Parallel Absolute Plate Motion

The experiments described above demonstrate significant differences in subduction evolution depending on the adopted absolute plate motions. We infer three phases of subduction rollback: (1) the initial phase of slow roll back between 30 and 25 Ma which shows comparable slab behavior in all four models; (2) an intermediate rollback phase which culminates into margin/slab tearing and westward rollback at different speeds along the African margin; and (3) the final phase that starts when the slab has arrived in the Gibraltar region (in three models) and in which the slab is being deformed, rotated, and dragged NW or NE depending on the absolute motion of the two plates to which the slab is still attached.

A most conspicuous observation we can make for phase 2 is that westward slab tearing and slab rollback seems dependent on the northward absolute plate velocity of the African plate. In Figure 6, a comparison

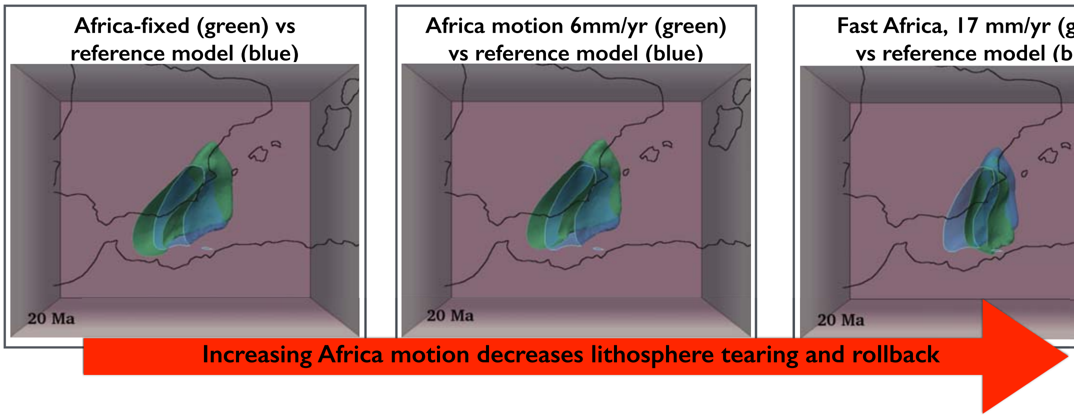

Figure 6. Slab morphology in the four subduction models at 20 and 15 Ma. The reference model is shown in blue in all panels and belongs to a northward Africa motion of 8 mm/yr. The first column shows the Africa-fixed model; the second column the Iberia-fixed model; the third column shows the model with two times faster Africa. The 1400 K isotherm is shown from 200 km downward. The coastlines are shown in absolute plate motion frame of the reference model [Figure 1a; *Doubrovine et al*. 2012].

between the four models is shown for a snapshot at 20 Ma. The models are arranged such that from left to right the absolute motion of Africa is increasing. The Africa-fixed model (left) shows the fastest rollback arriving earliest at the Gibraltar Strait. The rollback of the slab is parallel to the margin and there is no significant north component of rollback i.e., margin/slab rupture occurs in response to shear stresses oriented predominantly vertically and parallel to the margin. The Iberia-fixed model (middle) has a northward component of African motion of ~6 mm/yr in which the tear propagates slower than in the Africa-fixed model. In both models, tearing and rollback are faster than in the reference model, which has a northward African motion of nearly 8.6 mm/yr. In Figure 6 (right), the African plate is moving north at ~17.2 mm/yr and tearing and rollback prove to be strongly inhibited from the moment the trench has rotated perpendicular to the advancing African margin. The differences between these models are primarily caused by the different absolute plate motion frames, as the relative motion between Africa and Iberia is the same in all experiments (Figure 1). The subducting plate is attached to both moving continents and as a result the slab is dragged through the mantle, which is visible in all models (Figures 4–6, 9; supporting information Movies). Slab dragging is governed by absolute plate motion and leads to increase of mantle resistance against slab motion in case of absolute motion increase.

We suggest that the decrease in tearing and rollback speed along the African margin is caused by the combination of resistive viscous flow of mantle material being pushed away by the slab-edge in the north and by increasing lateral slab-mantle shear friction forced by northward African plate-push. These couplings exist in addition to the viscous coupling between slab and mantle related to slab rollback as observed in analogue and numerical experiments based on trench-perpendicular plate motions [e.g., *Funiciello et al*., 2006; *Schellart and Moresi*, 2013; *Capitanio and Replumaz*, 2013].

Figure 7 illustrates the coupling between plates, slab, and mantle in a N-S cross section through the fast moving Africa model, showing in colors the N-component of the velocity field for two plates, mantle and the slab. The largest northward velocities are observed for the African plate. For the Iberian plate, the northward component of plate motion is smallest. For the slab, these values are intermediate and the slab, while sinking, is being pushed by the African plate and experiences viscous resistance from the upper mantle. This can also be seen from the wide area of large northward velocities in the mantle near the slab edge. For this model, indicated by the difference in northward speed, the African plate is overriding the slab, which prevents extension of the continental margin. This keeps the African margin thick and suppresses further lithosphere tearing.

After the slab has rolled back to the African margin and the trench and slab reoriented nearly perpendicular to that margin, the geometry becomes favorable for the development of a STEP fault [*Govers and Wortel*, 2005]. This slab geometry, however, is also almost parallel to absolute Africa motion and thus maximizes lateral mantle shear resistance resulting from slab dragging, increasing N-S compression at the margin.

Although the relative convergence between Iberia and Africa is the same in all experiments, the absolute motion of Iberian lithosphere may also be of influence on the inferred dependence of westward slab rollback on African plate motion. The subducting basin is connected to both continents and Africa-Iberia convergence (Figure 1) may put this margin continuously under compression. To investigate this further, we

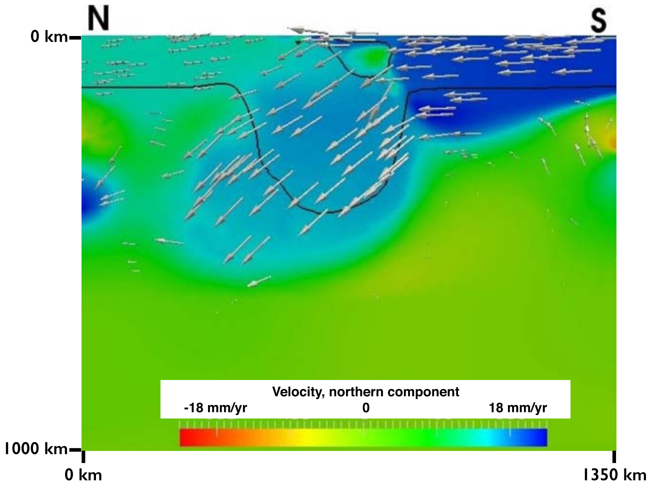

Figure 7. The NS cross section of the model with fast Africa after 15 My of subduction evolution. The northward component of the velocity is shown in colors. Arrows indicate the direction and magnitude of the total velocity field. Black contour shows the 1400°-isotherm.

perform a few additional experiments with a simplified geometry of two westward propagating STEPS in which the northern plate ("Iberia") is now free to move (Figure 8a). The slab has a rectangular shape with a width of 700 km. The initial depth reached by the slab is 200 km and the dip angle is 45°. The southern continental plate ("Africa") is moving in northward direction with a constant velocity. The northern plate also has a rectangular shape and is free to move, as the northern boundary in these experiments is now completely open. Continental plates and the subducting oceanic slab have maximum strength of 800 MPa as in previous experiments. We did not prescribe a weakness zone between the oceanic plate and the northern continent. Instead we assume a thinned continental plate with a thickness of 60 km. Due to the pressure-dependence of the nonlinear rheology, this results in a weaker asthenosphere decreasing shear resistance at the base of the lithosphere. The margin between the southern continent and the oceanic domain has a maximum strength of 100 MPa as in our previous models.

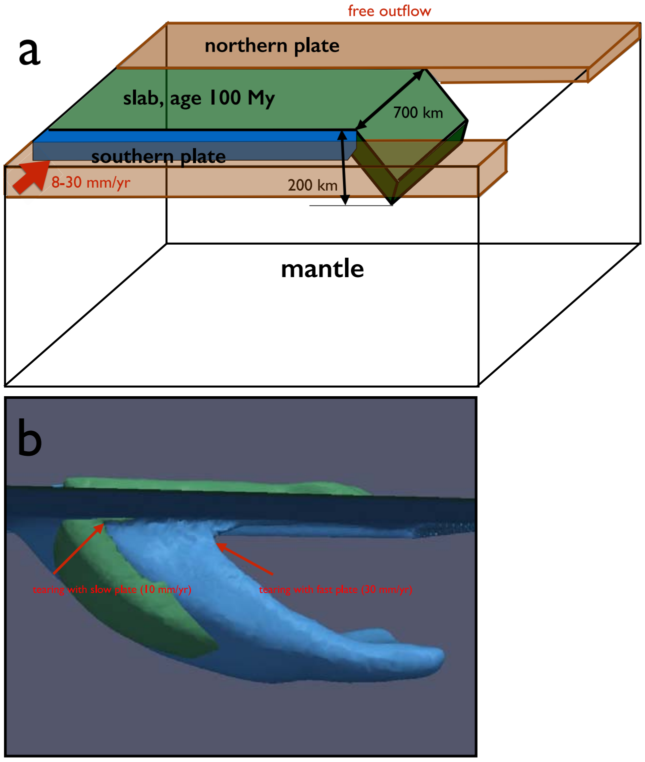

Figure 8. (a) Initial configuration of a subduction model with two STEPS. The slab is shown in green, continental lithosphere is shown in brown. Note the different thickness of the southern and northern continental plates (150 and 60 km, respectively). Red arrow shows the north-directed motion of the southern plate. In blue, the weak continental margin is depicted. Initial slab depth is 200 km and slab dip 45°. (b) The slab shape after 12 My of subduction and STEP evolution for 10 mm/yr (green) and 30 mm/yr (blue) motion of the southern plate.

Models were run under different absolute northward motions for the southern boundary, ranging from 8 to 30 mm/yr. Our experiments show a similar dependence of westward rollback rates and associated lithosphere tearing on increasing absolute plate motion parallel to the slab as was observed in Figure 6. An example is given in Figure 8b. However, now this dependence is observed for a free "Iberian" plate, moving with a slightly lower northward velocity than "Africa." The slowdown of tearing speed can now be *completely* attributed to the increasing northward motion of "Africa."

The maximum speed we have tested is 30mm/yr, which already leads to a strong reduction in tearing rate (Figure 8b). Within the plate-motion range investigated, we do not

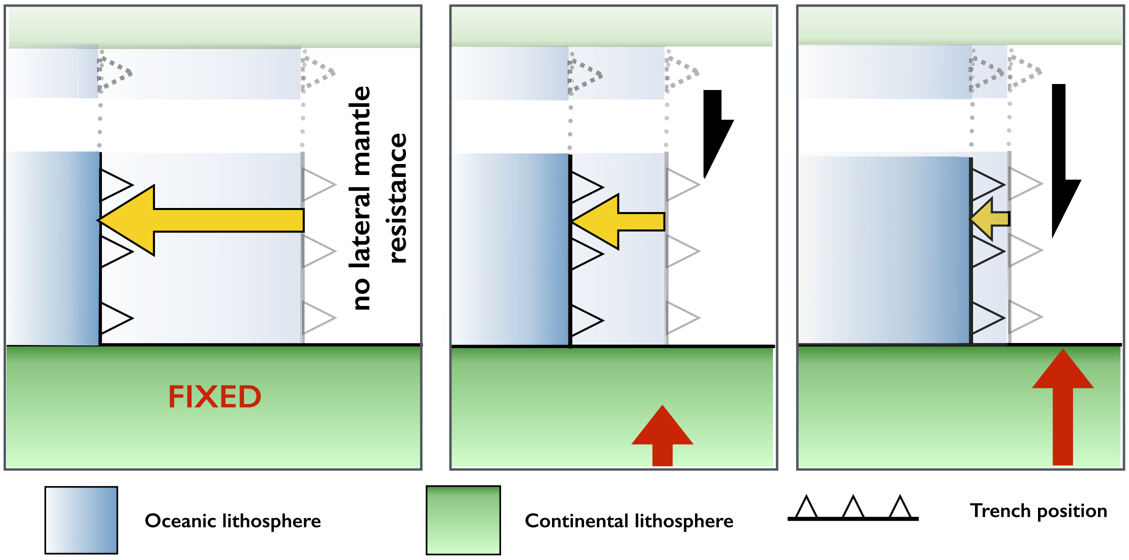

Figure 9. Schematic representation of our results on the dependency of the speed of rollback (yellow vector) and the associated STEP on the absolute motion of the overriding plate (red vector) parallel to the slab. The black vector denotes the overall mantle resistance resulting from slab push by the advancing continent which comprises slab-lateral mantle shear as well as resistance to mantle flow in front of the pushed slab.

observe the stage when tearing and rollback stalls. The northern plate could in all experiments assume a motion similar to the southern plate. We therefore conclude that the relative Iberia-Africa convergence used in our earlier experiments also has a strongly restricting effect on westward STEP propagation along the North African margin. Figure 9 schematically summarizes our findings of the influence of mantle resistance due to forced slab motion perpendicular to the rollback direction on the evolution of a STEP, lithosphere tearing and rollback.

4. Discussion

We can relate the strong differences in subduction evolution directly to the particular regional absolute plate motion frame used in each experiment. In each absolute plate motion frame, the subduction system is dragged differently through the mantle. The resulting resistance defines a particular viscous coupling between slab and mantle that significantly affects subduction evolution and the present-day slab position and morphology. The forced coupling between slab and mantle may prove of wider importance for understanding slab dynamics in relation to tectonic/surface evolution. Although these differences with the reference model in slab position and morphology are relatively small on the scale of the overall slab evolution model, they are systematic. Such differences may impact quite differently when trying to couple the slab's dynamic evolution to the detailed makeup of crust and lithosphere structure, and the tectonic evolution of the Betic-Alboran-Rif region.

A similar setting of rollback at high angles to absolute plate motion exists for the Banda Arc subduction (southeast Asia) where mantle shear resistance against Banda slab motion provides an explanation for the enigmatic strongly folded slab morphology and for the tectonic evolution of the overlying crust [*Spakman and Hall*, 2010]. Another example is the "slab-edge-push" of *Van Benthem et al.* [2014], which is a slab-edge effect of slab motion forced by absolute plate motion.

Here we varied absolute plate motions and adopted those rheological settings that belong to the slab evolution model (the reference model) that provided a good prediction with observed slab morphology. Investigation of trade-offs between faster/slower Africa motion and weaker/stronger rheology of the mantle is necessary for making a closer connection with the particular tectonic evolution of the region and to further constrain absolute plate motions. This is preferably done with models using a more detailed process-based rheology for lithosphere tearing and using a free surface [e.g., *Duretz et al.*, 2011], as well as including the eastern subduction system of the Western Mediterranean region that led to subducted slab under the Apennines and Calabria [*Spakman and Wortel*, 2004; *Faccenna et al.*, 2004; *Rosenbaum et al.*, 2002].

Other STEP settings in a similar geometry with a subduction trench at high angles with an advancing continental plate are the Calabria slab interacting with the African plate in the Central Mediterranean [*Spakman and Wortel*, 2004; *Govers and Wortel*, 2005; *Wortel et al*., 2009], or the Lesser Antilles slab interacting with the South American plate [*VanDecar et al*. 2003; *Govers and Wortel*, 2005; *Van Benthem et al*., 2013; *Boschman et al*., 2014]. For all these STEP settings, the absolute plate motion of the advancing continent, forcing additional slab-mantle resistance, may prove crucial for STEP evolution in determining the dynamics of rollback as well as the dynamic evolution of the plate boundary.

5. Conclusions

We tested the effect of using four different absolute plate motion frames, one data-based and three invented, on the evolution of slab morphology which we investigated in the natural setting of subduction evolution in the western Mediterranean region since ∼35 Ma. We inferred strong absolute plate motion effects on slab morphology, rollback evolution, and present-day slab position. Particularly, we showed that the rate of lithosphere tearing and rollback along a continental margin decreases with the increasing component of absolute velocity oriented normal to the rollback direction, i.e., oriented parallel to the trench. This strongly affects the motion and dynamics of the STEP and the crustal evolution of the deforming plate boundary region, we predict.

We conclude that absolute plate motion of the subducting plate can have large influence on the regional evolution and dynamics of subduction by forcing slab dragging through the mantle that locally results in an additional viscous coupling between the subducting lithosphere and the ambient mantle. As this will also affect the mantle flow field surrounding the evolving slab this opens new research avenues for linking absolute plate motion to observations of seismic anisotropy through 3-D modeling of natural subduction evolution. In general, we conclude that detailed modeling of natural subduction systems may also provide novel constraints on absolute plate motions, such that they can help reducing the uncertainties in the current absolute plate motion models independent of the observations on which such models are based.

Our results demonstrate that regional absolute plate motion, which represents here the far-field global plate-tectonic forcing, is critical for a correct simulation of subduction evolution in natural laboratories. For the western Mediterranean region, we showed that even relatively small changes in absolute plate motions on the order of a few millimetres per year have significant effects on slab morphology evolution due to resistance against slab dragging.

As an outlook, we anticipate that the crustal evolution associated with subduction evolution involving slab drag by absolute plate motions will be distinctly different in different absolute plate motion settings as this may have large influence on the local dynamics of subduction through its coupling with the ambient mantle. Detecting such coupling may also lead to new perspectives on the interpretation of geological observations and may eventually lead to new diagnostics for linking surface deformation to deep processes in convergent plate-boundary regions.

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