

1Mantle flow influence on subduction evolution

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8

9Abstract

10

11The impact of remotely forced mantle flow on regional subduction evolution is largely unexplored.

12Here we investigate this by means of 3D thermo-mechanical numerical modeling using a regional

13modeling domain. We start with simplified models consisting of a 600 km (or 1400 km) wide

14subducting plate surrounded by other plates. Mantle inflow of ~ 3 cm/yr is prescribed during 25

15Myr of slab evolution on a subset of the domain boundaries while the other side boundaries are

16open. Our experiments show that the influence of imposed mantle flow on subduction evolution is

17the least for trench-perpendicular mantle inflow from either the back or front of the slab leading to

1810-50 km changes in slab morphology and trench position while no strong slab dip changes were

19observed, as compared to a reference model with no imposed mantle inflow. In experiments with

20trench-oblique mantle inflow we notice larger effects of slab bending and slab translation of the

21order of 100-200 km. Lastly, we investigate how subduction in the western Mediterranean region is

22influenced by remotely excited mantle flow that is computed by back-advection of a temperature

23and density model scaled from a global seismic tomography model. After 35 Myr of subduction

24evolution we find 10-50 km changes in slab position and slab morphology and a slight change in

25overall slab tilt. Our study shows that remotely forced mantle flow leads to secondary effects on

26 slab evolution as compared to slab buoyancy and plate motion. Still these secondary effects occur
27 on scales, 10-50 km, typical for the large-scale deformation of the overlying crust and thus may still
28 be of large importance for understanding geological evolution.

29

30 **Keywords:** Mantle flow, subduction, Mediterranean, 3-D numerical modeling

31

32 1. Introduction

33 The dynamical and morphological evolution of subducting slabs has for decades been widely
34 investigated by means of 2D and eventually 3D numerical and laboratory modeling. 3D modeling
35 brought focus on the feedback between slab-induced mantle flow and slab evolution with particular
36 attention for the trench-parallel flow and toroidal flow occurring around the edges of a retreating
37 slab [e.g. *Kincaid and Griffiths*, 2003; *Funiciello et al.* 2003, 2004, 2006; *Schellart* 2004; *Piromallo*
38 *et al.* 2006; *Stegman et al.*, 2006; *Schellart et al.*, 2007; *Stegman et al.*, 2010; *Butterworth et al.*,
39 2012; *Capitanio and Faccenda*, 2012; *Jadamec and Billen*, 2012; *Schellart and Moresi*, 2013;
40 *MacDougall et al.*, 2014; *Crameri and Tackley*, 2014; *Sternai et al.* 2014]. These 3D modeling
41 studies have demonstrated the importance of mantle flow that is induced by slab motion, but how
42 remotely forced mantle flow affects slab evolution remains unexplored. By remotely forced, or
43 external, mantle flow we mean flow that is caused by plate motions and subduction elsewhere or is
44 excited by deeper mantle processes such as rising plumes or sinking of detached slab. Slab-induced
45 flow resulting from e.g. slab rollback can be perceived as superposed on, or interacting with this
46 background flow. Until now only a few papers [*Hager et al.*, 1983, *Olbertz et al.*, 1997; *Boutelier et*
47 *al.*, 2008; *Winder and Peacock*, 2001; *Rodriguez-Gonzalez et al.*, 2014; *Ficini et al.* 2017] paid
48 attention to the possible influence of remotely forced mantle flow on subduction evolution. These
49 studies demonstrate a strong influence on slab geometry evolution but due to the 2D nature of the

50 modeling, not allowing for toroidal mantle flow, such inferences are restricted to geodynamic
51 settings in which poloidal flow strongly dominates.

52 Here we investigate the impact of remotely forced mantle flow on subduction evolution with 3D
53 thermo-mechanical numerical modeling using a regional modeling domain by imposing mantle
54 inflow on a subset of the side boundaries. As this topic is unexplored in 3-D our primary purpose is
55 to browse through the model space searching for first-order effects. We monitor the evolution of
56 slab morphology under different external mantle flow conditions both for generic subduction
57 models and for a simulation of natural subduction in the western Mediterranean. For the generic
58 simulations, we use simplified models of subduction evolution comprised of rectangular plates and
59 a straight trench with initial trench-perpendicular plate convergence. This is done to make a link
60 with this often-used model setup in 3-D subduction modeling. We include in our experiments the
61 overriding plate and plates adjacent to the subducting plate, similar to recently used model setups
62 [e.g. *Yamato, 2009; Capitanio et al., 2010; Butterworth, 2012, Meyer and Schellart, 2013; Boutelier*
63 *and Cruden, 2013; Guillaume et al., 2013; Moresi et al., 2014*]. We combine side boundaries with
64 prescribed mantle flow with side boundaries that are open [*Chertova et al., 2012; 2014*] for
65 conservation of mass. Because free-slip boundary conditions are most often used in 3D subduction
66 modeling using a regional model domain, we briefly address the magnitude of the difference
67 between using either boundary condition in the experiments we conduct here. Lastly, we
68 investigate the influence of remotely forced mantle flow in a simulation of the Rif-Gibraltar-Betic
69 subduction evolution since ~35 Ma in the western Mediterranean region. This builds on our earlier
70 work for this subduction system [*Chertova et al., 2014*] in which we used open side boundaries. In
71 these experiments, we impose time-dependent boundary conditions of mantle flow determined from
72 back-advection of the present-day temperature and density structure of the mantle derived from a
73 tomographic model. These experiments also serve to test the robustness of the earlier modeled

74 subduction evolution [Chertova et al., 2014] with respect to the viscous forcing exerted on the slab
75 by remotely forced mantle flow.

76

77 2. Methodology

78 We carry out our 3-D numerical experiments using the finite element package SEPRAN [Segal and
79 Praagman, 2005]. As described in Chertova et al. [2014], we solve the equations of mass,
80 momentum and energy conservation and the transport equation for advection of non-diffusive
81 material properties using the extended Boussinesq approximation including two major phase
82 transitions at 410 km and at 660 km in the unperturbed mantle. Experiments are performed in a
83 Cartesian box with dimensions of length x width x height = 3000 km × 2000 km × 1000 km for the
84 generic model setup and 1800 km × 1300 km × 1000 km for the simulation of western Mediterranean
85 subduction.

86

87 2.1 Rheology and boundary conditions

88 Composite nonlinear rheology is used for all models and comprises diffusion creep, dislocation
89 creep, and a viscosity maximum, $\eta_{max}(2 \cdot 10^{23}$ or $5 \cdot 10^{23}$ Pas). For the geometrically more complex
90 western Mediterranean model setup also a stress limiter mechanism is used [Chertova et al., 2014].

91 The effective composite viscosity is defined as $\frac{1}{\eta_{eff}} = \frac{1}{\eta_{diff}} + \frac{1}{\eta_{disl}} + \frac{1}{\eta_y}$, with

$$92 \eta_{diff} = \mu A_{diff}^{-1} (b/d)^{-m} \exp[(E_{diff} + PV_{diff})/RT] \quad (2.1)$$

$$93 \eta_{disl} = \mu A_{disl}^{-\frac{1}{n}} \dot{\epsilon}^{\frac{1-n}{n}} \exp[(E_{disl} + PV_{disl})/nRT] \quad (2.2)$$

$$94 \eta_y = \frac{\tau_{max}}{2\dot{\epsilon}}, \quad (2.3)$$

95 where μ is the shear modulus, $A_{diff,disl}$ are diffusion and dislocation creep viscosity prefactors, b is
96 Burgers vector, d is the grain size, $\dot{\epsilon}$ is the second invariant of the strain-rate tensor, m is the grain
97 size exponent, $V_{diff,disl}$ and $E_{diff,disl}$ are activation volume and activation energy for diffusion and

98 dislocation creep, respectively, P is the lithostatic pressure, T is temperature, τ_{max} is the maximum
99 yield stress value, i.e. stress limiter. Used parameters for the rheology and phase transitions are
100 given in supplementary table 1. Lagrangian particles are used to define viscosity parameters. They
101 are placed randomly over the whole modeling domain and free inflow/outflow of particles is
102 allowed on side boundaries. The number of particles varies between 20 and 30 million during
103 computations. We use free-slip conditions for the top boundary and no-slip for the bottom
104 boundary. Different side boundary conditions are used: free-slip (closed, impermeable boundary),
105 open boundaries as developed in Chertova et al. [2012], or prescribed mantle flow at a subset of the
106 vertical sides, as detailed in the next section. For all boundaries we prescribe a stationary depth-
107 dependent adiabatic temperature profile during simulations. The mesh element size varies from 6
108 km in the top 200 km to 20 km at the bottom of the model.

109 To allow decoupling of the subducting slab from the free-slip top surface and overriding plate we
110 implement a 30 km weak crustal layer, as in Chertova et al. [2012, 2014], with a viscosity $2 \times$
111 10^{19} Pas in the generic models and 5×10^{19} Pas for the western Mediterranean subduction
112 modeling. This weak top layer facilitates vertical decoupling of the slab during the development of
113 subduction, which is driven by its slab buoyancy, and by the subducting plate motion that is
114 imposed on the side-boundary, both simulating geodynamic forcing that also occurs naturally.
115 Additional forcing comes from the mantle flow imposed on selected boundaries of the model of
116 which the effects on subduction evolution are topic of our investigation here.

117

118 2.2. Initial model setup for generic models

119 The initial model setup is illustrated in figure 1A and comprises the subducting and overriding
120 plates and two plates to either side. Table 1 lists the models we created with the various inflow
121 boundary conditions. All 4 plates have the same initial thermal structure determined from the
122 equation of a cooling semi-infinite half space for an oceanic lithosphere age of 80 My. The initial

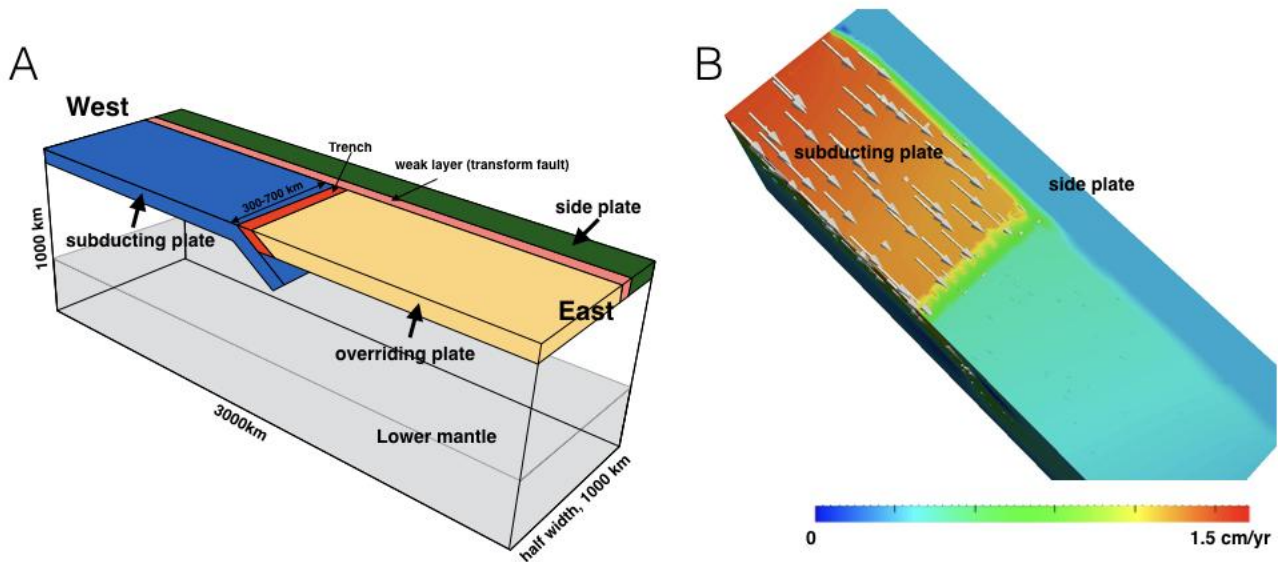
123 subduction angle is 45° and the slab extends to the depth of 300 km. Low viscosity deformation
124 zones of $3 \cdot 10^{20}$ Pas and 70 km wide (pink in figure 1A) are used as a weak mechanical coupling of
125 the plates (figure 1B). Figure 1B shows their motion decoupling effect between subducting and
126 side-plates in the initial model stage. Experiments are performed with a subducting plate width of
127 600 and 1400 km. These models include a viscosity increase in the mantle by a factor of ~ 10 to 10^{22}
128 Pas at a depth of ~ 660 km. The upper viscosity limit is set to $5 \cdot 10^{23}$ Pas. The activation energy for
129 dislocation creep and activation volume for diffusion creep for most models is set to 423 KJ mol^{-1}
130 and $3 \text{ cm}^3 \text{ mol}^{-1}$ respectively. But, for models M600.O*, M600.SE, M600.SW and M600.O/E/S a
131 slightly higher activation energy of 433 KJ mol^{-1} is used for reasons explained later. An example of
132 viscosity profiles away from the subducting slab is shown in supplementary figure 1. In all models,
133 we prescribe the speed of the subducting plate of 1.5 cm/yr on the western side boundary, which
134 ensures that the slab does not rollback too fast to this side boundary. Although this choice is
135 practical, it is not unnatural because slab pull and an independent component of advance velocity of
136 the subducting plate are natural drivers of many subduction zones [e.g. *Heuret and Lallemand,*
137 *2005; Schellart, 2008*].

138 For model comparison, we constructed two reference models of subduction evolution, M600.O and
139 M1400.O, in which 4 open boundaries are used and thus no mantle inflow is imposed. In separate
140 experiments uniform inflow of the mantle at a speed of 3 cm/yr is prescribed below the lithosphere
141 on either the western (left), eastern (right) or southern (frontal) model boundary keeping other
142 boundaries open (Table 1). Transitions between boundary conditions are taken up locally and
143 smoothly by the modeled mantle flow. Lastly, we created experiments where the prescribed mantle
144 flow of 3 cm/yr gradually changes direction from eastward to northward directed inflow during 10
145 My of subduction evolution and experiments where we prescribe mantle inflow from SW and SE
146 directions, i.e. under an angle of 45° to the subducting slab. In addition, to briefly assess the

147 influence of open versus closed boundaries we also used a free-slip condition on the northern and
148 southern boundaries of which results are presented as supplementary figure 3.

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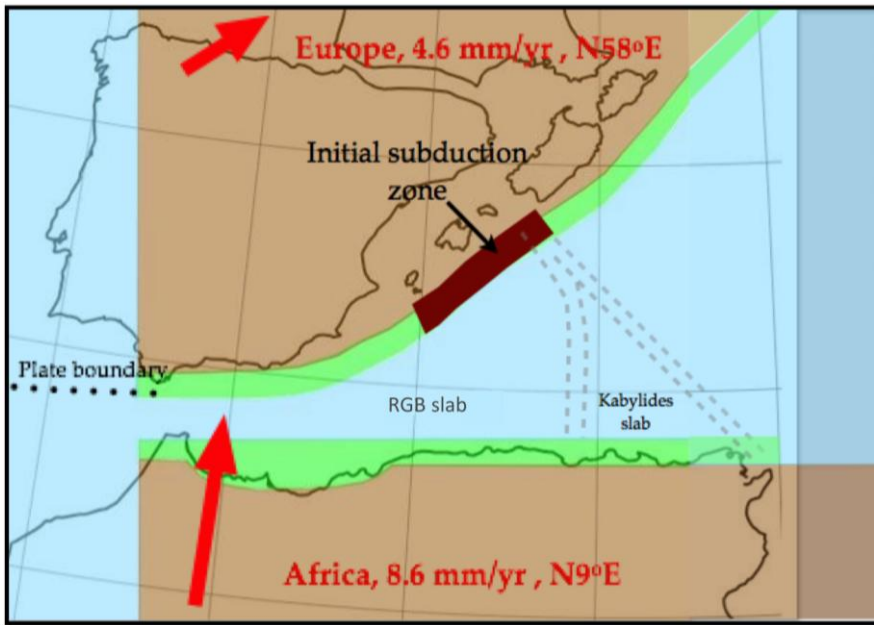
152 Figure 1. A - Model setup for models with four plates shown up to the symmetry plane (front). The
153 trench is located in 1400 km from the left boundary. B - Top view of the initial surface velocity
154 field of the model for a subducting plate velocity of 1.5 cm/yr imposed on the top of the western
155 model edge. Colors show the X-component (parallel to symmetry plane) of the velocity field and
156 arrows-total magnitude and direction.

157

158 2.3. Initial model setup for western Mediterranean models.

159 The initial model setup for the western Mediterranean plate boundary region is defined at 35 Ma
160 (figure 2) and follows that of Chertova et al. [2014]. The paleogeography is derived from van
161 Hinsbergen et al. (2014) and comprises the oceanic, or extremely stretched continental, basins that
162 eventually lead to the Rif-Gibraltar-Betic (RGB) slab and to the eastern Algerian Kabylides slab.
163 We use absolute plate motion estimates [Dobrovine et al., 2012] averaged over the past ~35 Myr
164 as kinematic boundary conditions for the top 150 km at the southern boundary for Africa (8.6

165 mm/yr) and at the northern boundary for Iberia (4.6 mm/yr) with directions as illustrated in figure 2.
166 For the remainder, the sidewalls are open boundaries and the bottom is no-slip.



167
168 Figure 2. The initial model for modeling western Mediterranean subduction (2000x1300x1000 km)
169 comprises two domains of continental lithosphere (Europe and Africa; brown), a continuous domain
170 of oceanic lithosphere (blue), two weak continental margins (green) and an initial subduction zone
171 located to the SE from the Balears with a slab length of ~200 km (dark red). The oceanic domains
172 labeled “RGB slab” and “Kabyrides slab” will be subducting in the model. Two double-dashed lines
173 indicate the position of weak decoupling zones that simulate transform faults and separate the RGB
174 (Alboran) and Kabyrides slab and the easternmost part of the oceanic domain. These weakness
175 zones constitute 60 Ma oceanic lithosphere with a viscous strength of $2 \cdot 10^{20}$ Pas to facilitate
176 decoupling between plates. Parameters used for the rheology were determined in Chertova et al.
177 [2014]. The initial temperature distribution within the oceanic lithosphere is determined from the
178 equation of cooling semi-infinite half space for an age of 100 My and for continental lithosphere we
179 use a constant temperature gradient of 10 K/km. For the mantle temperature, an adiabat with
180 potential temperature of 1573 K is used instead of a constant temperature gradient as in Chertova et
181 al. [2014]. For other details we refer to that paper.

182

183 3. Experiments with generic models

184 We start our modeling experiments with inflow normal to the trench from either the west or east and
 185 next parallel to the trench from the south for both a 600 km wide and 1400 km wide slab. Following
 186 are various experiments with mantle inflow oblique to the trench. The results are compared to the
 187 reference models with open side boundary conditions and between models. Reference model
 188 M1400.O is briefly illustrated in supplementary material 1.

	Mantle inflow conditions on the side boundary			
Model name	Left(W)	Right(E)	Front(S)	Back(N)
M1400.O	Open	Open	Open	Open
M1400.W	3 cm/yr	Open	Open	Open
M1400.E	Open	3 cm/yr	Open	Open
M1400.S	Open	Open	3 cm/yr	Open
M1400.W-S	3 cm/yr	Open	3 cm/yr	Open
M600.O	Open	Open	Open	Open
M600.W	3 cm/yr	Open	Open	Open
M600.E	Open	3 cm/yr	Open	Open
M600.S	Open	Open	3 cm/yr	Open
M600.O*	Open	Open	Open	Open
M600.O/E/S	variable	Open	variable	Open
M600.SE	Open	3 cm/yr	3 cm/yr	Open
M600.SW	3 cm/yr	Open	3 cm/yr	Open
M600.FS	Open	Open	Free-slip	Free-slip
M600.FS-W	Free-slip	Open	Open	Open

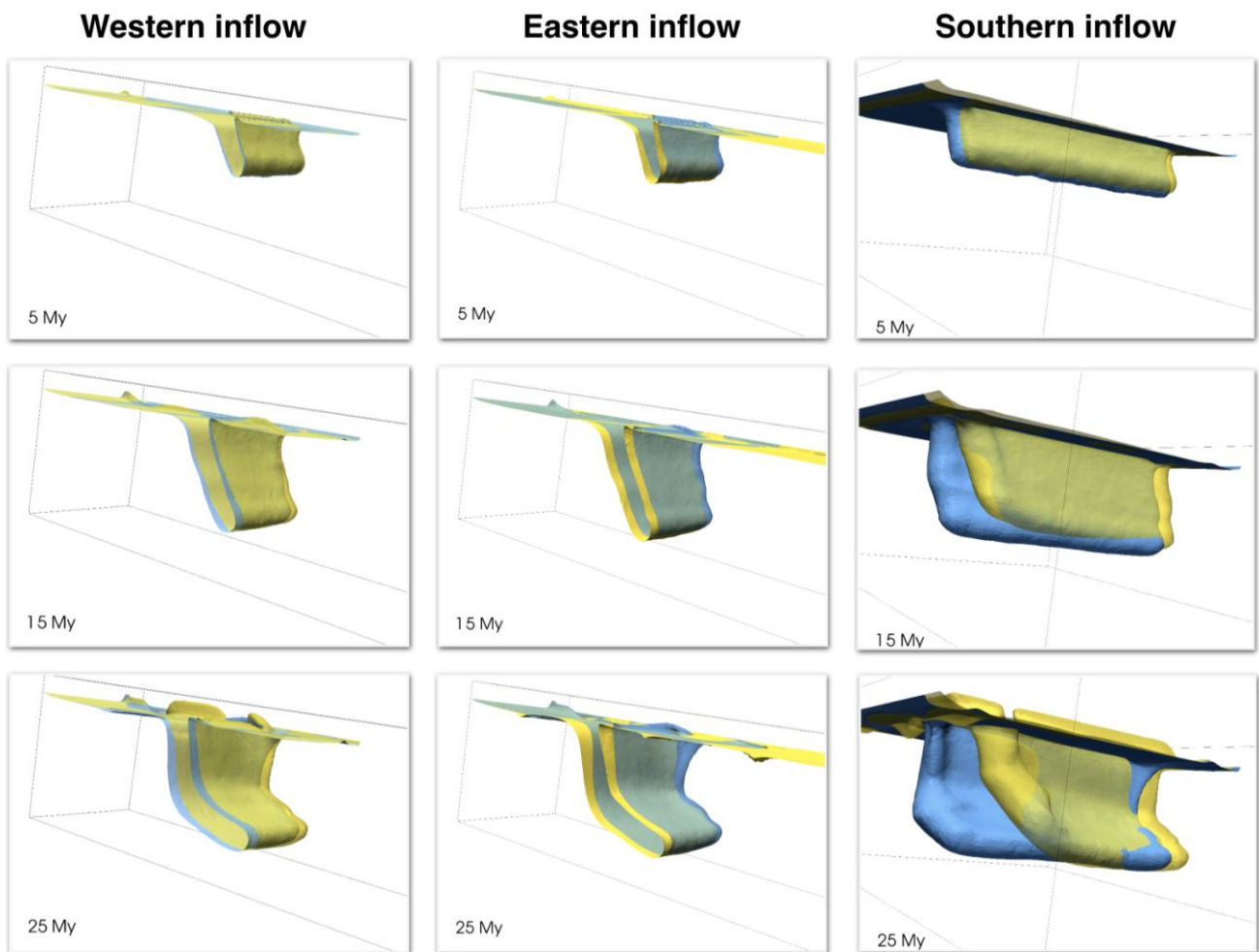
189 Table 1. List of numerical models. The number indicates the lateral width of the model slab. The
 190 letters after the “.” signify either open boundaries all around (“O”), or the model side where inflow
 191 occurs (“W”, “E”, “S”, “SW”, “SE”, for west, east, south, southwest, southeast, respectively). Western
 192 and eastern sides are indicated in figure 1 “W-S” denotes a model start starts with inflow from the
 193 west followed by inflow the south; “O/E/S” denotes a model that initially has open boundaries all
 194 around after which inflow occurs from the east gradually changing to inflow from the south; “FS”

195 denotes a model with 2 free-slip boundaries; and “O*” is a model with 4 open boundaries with
196 stronger rheology.

197

198 3.1 Influence of external mantle flow on the evolution of a wide subduction zone.

199 Figure 3 presents the evolution of three models with western (M1400.W), eastern (M1400.E) and
200 southern (M1400.S) mantle inflow, all for a wide slab of 1400 km and compared to the reference
201 model M1400.O (transparent blue).



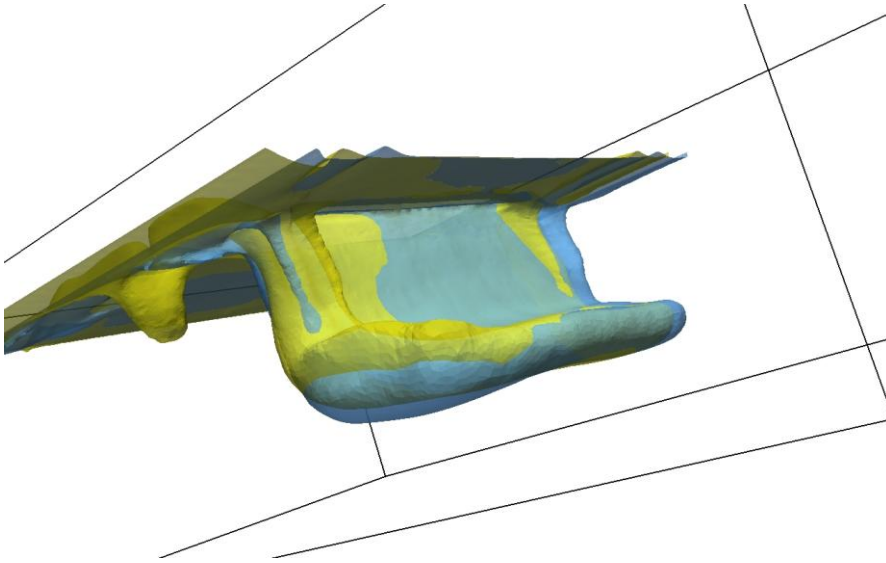
202

203 Figure 3. Evolution of models M1400.W (western inflow), M1400.E (eastern inflow) and M1400.S
204 (southern inflow); all in transparent yellow compared with the reference model M1400.O
205 (transparent blue). Models with western and eastern inflow are given for the half-width of the
206 modeling domain. The 1500 K isotherm defines the used contours.

207

208 In both M1400.W and M1400.E the slab position after 25 My of subduction evolution is displaced
209 by 30-50 km with minor changes in overall slab shape for M1400.W. For model M1400.E this
210 displacement occurs toward the west and a shallower subduction dip is observed in the top few
211 hundred km, both resulting from the push exerted by inflow from the east, which effectively leads
212 to a slight increase in slab rollback. In model M1400.W slab rollback is obstructed by the western
213 inflow in the sub-slab mantle but this does not change the overall slab morphology as compared to
214 the reference model.

215 For the model M1400.S with southern, trench parallel, mantle inflow we observe more dramatic
216 changes toward the final slab morphology. Slab curvature in the horizontal plane increases with
217 time and the slab is being transported to the north by the viscous coupling with the imposed mantle
218 flow. The southern slab edge is elevated and thickened due to the impact of mantle flow. This slab
219 deformation already starts during the initial subduction phase when the slab is still short (~300 km).
220 When a longer slab across the upper mantle is next subject to mantle inflow from the south, slab
221 deformation is less pronounced as is demonstrated with the model M1400.W-S. After 20 My of
222 subduction evolution under western mantle inflow, the direction of mantle inflow is changed to
223 inflow from the south. This led to ~150 km of northward slab transport in 10 Myr. Figure 4 shows
224 the difference in slab morphology that accumulates between 20 Myr and 30 Myr in models
225 M1400.W and M1400.W-S, where we have shifted model M1400.W to the north by 150 km to
226 compare the slab shape in more detail. Uplift of ~40 km of the southern slab edge is observed and
227 slab-edge thickening of the order of ~20 km compared to an original plate thickness 90-100 km.
228 The rest of the slab stays relatively undeformed although still being transported 150 km to the north
229 by the imposed mantle flow. This transport is accommodated by N-S shortening of the plate
230 decoupling zone and of the northern side plate.



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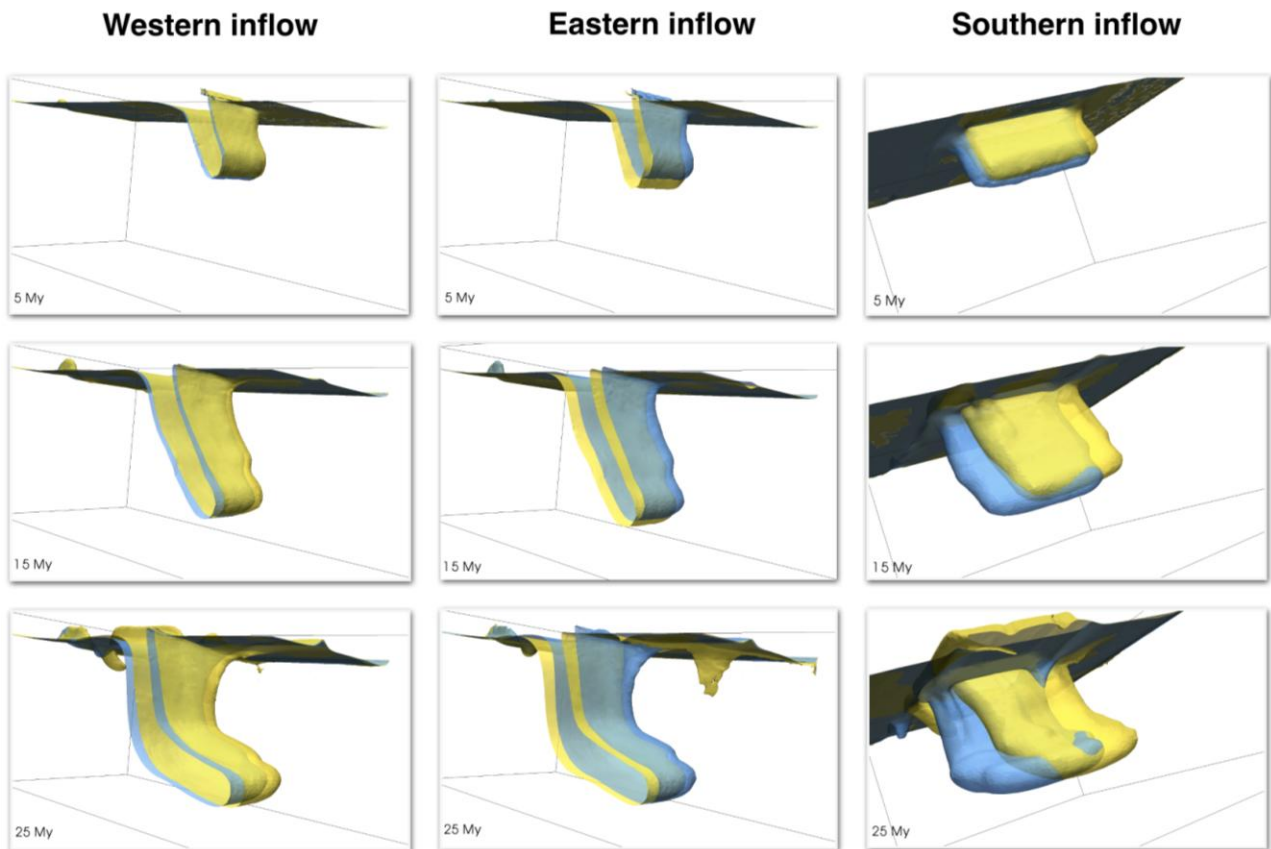
232 Figure 4. Comparison at 30 Myr between model M1400.W, shown in transparent blue and shifted
 233 by 150 km to the north and model M1400.W-S shown in transparent yellow. The 1500 K isotherm
 234 defines the used contours.

235

236 3.2 Influence of external mantle flow on the evolution of a narrow subduction zone.

237 Similar experiments were conducted with a 600 km wide subduction zone leading to models with
 238 western (M600.W), eastern (M600.E), and southern (M600.S) mantle inflow. In figure 5 results are
 239 compared to the reference model with open boundaries M600.O (transparent blue). With the same
 240 inflow conditions, model M600.O demonstrates slightly faster rollback that accumulates to ~60 km
 241 more westward displacement at 25 Myr than model M1400.O. For the 1400 km wide subduction
 242 zone, rollback is slower as it takes longer to move sub-slab mantle to both slab edges as also
 243 inferred previously [Schellart *et al.* 2007]. For the models M600.W and M600.E we observe a
 244 difference of about 50-60 km in final trench position compared to the reference M600.O model,
 245 which is similar to what we observed for the 1400 km wide subduction zone. Another similarity
 246 between corresponding *.E and *.W models concerns the slab shape. For the model M600.S with
 247 trench-parallel inflow the mantle flow influence is not stronger than for the M1400.S model. The
 248 results show a smaller difference between M600.S and M600.O than between models M1400.S and

249 M1400.O. The final slab in M600.S is less curved and less thickened and the tip of the slab is not
 250 uplifted as in the M1400.S model. However, the deeper part of the slab is transported more to the
 251 north than the top part as in the M1400.S model. The top 150 km of the side boundaries are fixed
 252 and deformation due to mantle flow is accommodated by the weak margins and by internal
 253 deformation of the side plates. In summary, the influence of prescribed western or eastern mantle
 254 inflow on the evolution of the narrow subduction zone is not stronger than for the wide subduction
 255 zone, except for a difference in rollback speed. We explain this by the fact that the total viscous
 256 coupling force exerted by mantle flow on the slab scales with the slab surface area.



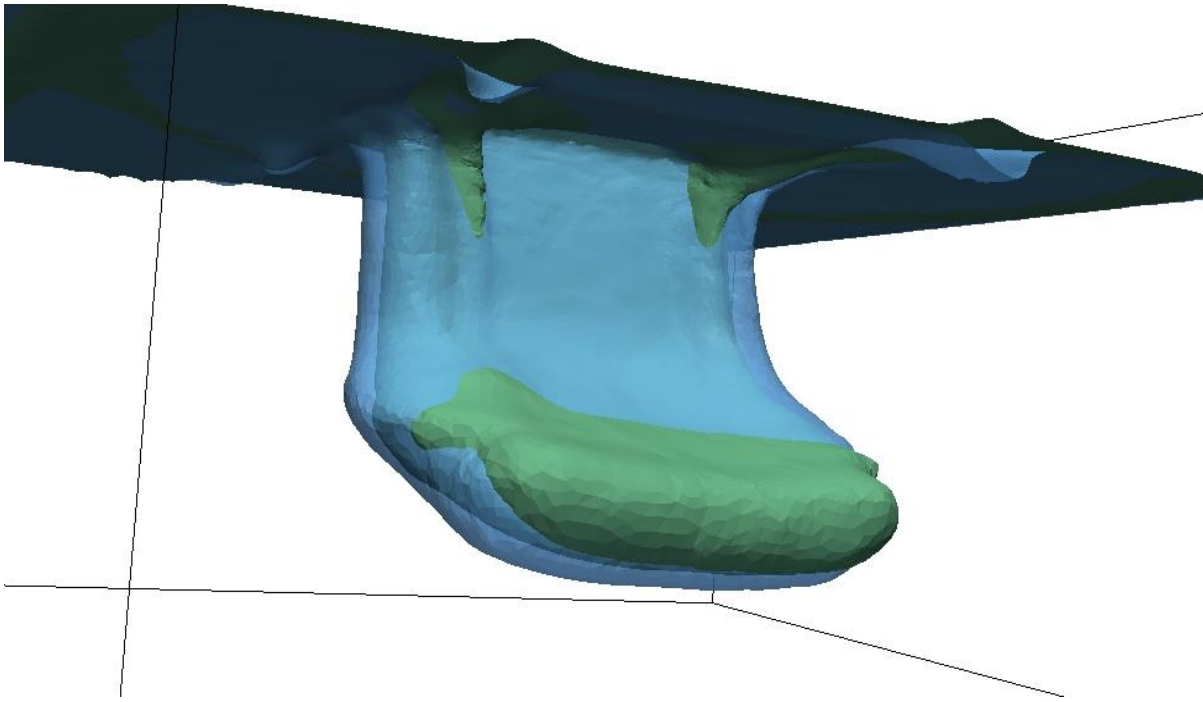
257
 258 Figure 5. Evolution of narrow-slab models M600.W (western inflow), M600.E (eastern inflow) and
 259 M600.S (southern inflow) compared to the reference model M600.O (blue transparent contour).
 260 Models with western and eastern inflow are given for the half-width of the modeling domain. The
 261 1500 K isotherm defines the used contours.

262

263 3.3 Slab evolution under directionally variable and trench-oblique mantle inflow

264 In previous experiments the imposed mantle flow was either perpendicular or parallel to the slab,
265 which is of course not necessarily mimicking natural conditions. To assess the influence of imposed
266 trench-oblique mantle flow we devised three models. In model M600.O/E/S imposed flow gradually
267 changes direction with time, while for models M600.SW and M600.SE the imposed flow is oriented
268 at 45° to the subduction zone inflowing from the SW and from the SE, respectively.

269 Figure 6 shows the difference between reference model M600.O and M600.O/E/S after 20 My of
270 subduction evolution. During the first 10 My model M600.O/E/S has the same open boundary
271 conditions as for the reference model. Next, we prescribe mantle inflow of 3 cm/yr that gradually
272 changes from eastward inflow to southern inflow between 10 My and 20 My. Model M600.O/E/S
273 exhibits several differences with the M600.O model. The slab in model M600.O/E/S bends, the
274 southern edge gets thicker, and the lateral width of the shallow part of the slab (to the depth of 300
275 km) decreases by ~50 km. This leads to increased curvature of the slab and its central part lies ~20
276 km to the west of the reference model. The position of the slab tip is ~10 km shallower than in the
277 reference model. Overall these differences with the reference model are relatively small (10-50 km),
278 compared to the scale of the subduction zone, but they do show sensitivity of the slab to oblique
279 time-variable mantle flow leading to complex slab morphology accumulating in only 10 Myr.



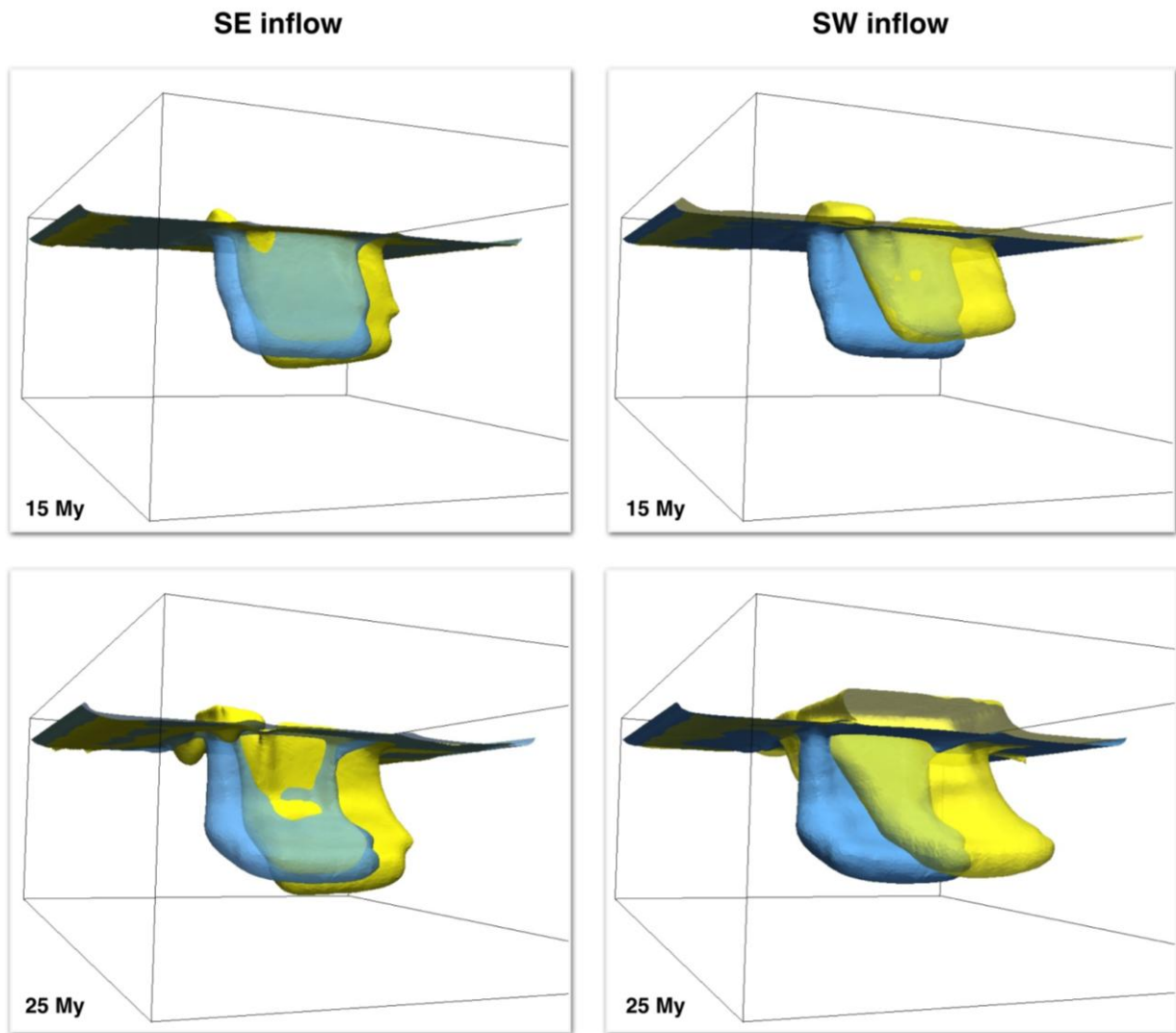
280

281 Figure 6. Reference model M600.O (transparent blue) and model M600.O/E/S (green) after 20 Myr
 282 of the subduction evolution. View from southeast. The 1500 K isotherm defines the used contours.

283

284 In figure 7 we show snapshots at 15 Myr and 25 Myr of two models with prescribed inflow, since 0
 285 Myr, from the SE (M600.SE) and SW (M600.SW) compared with the reference model M600.O*.
 286 These models are made with a slightly higher value of $E_{dis}=433$ KJ/mol to suppress some small-
 287 scale dripping we observed in the plate decoupling zones (figure 5; 25 Myr). We also used for these
 288 two models a free-slip bottom condition. Both models demonstrate significant differences in shape
 289 and slab position with the reference model after 15 Myr of the modeled subduction evolution and
 290 increasingly after 25 Myr. Along an E-W orientation the position of the slab tips for models
 291 M600.SE and M600.SW differs with the reference model by 200-220 km to the west and to the east
 292 respectively, while the trench position for all three models differs by ~20 km. At the depth of 660
 293 km the slab in model M600.SE is located ~250 to the north, while in the asthenosphere this is 150
 294 km exemplifying the strong lateral bending of the slab. For model M600.SW these differences are
 295 somewhat larger amounting to 300 km northward shift in the position of the slab tip. Experiments

296 with a no-slip condition on the bottom lead, as compared to a free-slip bottom (figure 7), to a
297 similar slab shape but to ~30 km less northward transport of the slab. Overall, these models with
298 imposed oblique mantle flow show the largest differences in the slab shape and position among all
299 conducted experiments and demonstrate a larger sensitivity of slab morphology evolution than
300 observed in the experiments with pure trench-perpendicular or trench-parallel mantle inflow. In
301 these latter experiments the non-obliqueness of the flow direction compared to the overall trench
302 and slab geometry apparently has a stabilizing effect on out-of-slab-plane deformation. In case of
303 trench-perpendicular inflow, the flow is by large equally deflected by the slab in directions south
304 and north and down-dip. For an initially long slab the trench-parallel inflow mostly led to viscous
305 flow coupling with the slab equally at its back- and top-side leading to lateral slab shortening and
306 lateral transport (figure 4). Only when an initially short slab is exposed to trench-lateral flow we
307 observed stronger slab deformation.



308

309 Figure 7. Comparison of models M600.SE (SE inflow) and M600.SW (SW inflow) with reference
 310 model M600.O* (blue) at 15 Myr and 25 Myr of slab evolution. The 1500 K isotherm defines the
 311 used contours.

312

313 We used the M600.O-model setup also for a brief excursion into testing if using open versus closed
 314 (free slip) boundaries would lead to a significant difference in modeling results. In model M600.FS
 315 we prescribe free-slip conditions on the northern and southern boundary while the west and east
 316 boundary remain open for mass balancing of the inflow of the subducting plate. The results,
 317 discussed in supplementary materials 1, show that the free-slip boundary condition leads primarily
 318 to ~50 km less rollback in 25 Myr compared to M600.O. This is likely tied in with differences in the

319 toroidal flow we observe around the slab edge revealing a complex 3D internal flow, which is
320 different for both boundary conditions.

321 We have also tested free-slip conditions with model M600.FS-W for which free-slip boundary
322 conditions on the western boundary were prescribed while all other boundaries were open. After 25
323 Myr the observed difference with reference M600.O model was of the order of ~10 km, which is
324 even smaller than in the case of M600.FS model. The differences between using open boundaries or
325 partly closed boundaries are much smaller than observed in 2-D subduction modeling (Chertova et
326 al. 2012), which suggests that these differences may diminish in 3D modeling if the boundaries are
327 placed at a large distance.

328

329 4. Influence of external mantle flow on the evolution of the RGB and Kabyldes
330 slabs.

331 Departing from the relatively “rectangular” plate configurations in previous experiments, here we
332 advance on an earlier developed 3-D subduction model of western Mediterranean subduction
333 leading to the Rif-Gibraltar-Betics (RGB) slab and the Kabyldes slab in which we used open side
334 boundaries [Chertova et al., 2014]. The slab evolution of the RGB slab involves trench rollback in
335 which the trench rotates by more than 180 degrees and where the trench is generally highly oblique
336 to the subducting plate motion. The evolution of this reference subduction model, WMED.O, are
337 described in detail in the supplementary material 1.

338 The prescribed time-dependent mantle flow is determined from back-advection of a density and
339 temperature model derived from the global tomographic model P06_CSloc [Amaru, 2007] and
340 surface plate velocities [Torsvik et al., 2010], and expanded to spherical harmonic degree 63. We
341 convert seismic velocity anomalies to density anomalies, first assuming they are both due to
342 temperature anomalies and hence using a thermal conversion factor shown in supplementary figure
343 7. However, we remove any strong positive anomalies in the continental lithosphere, which are

344 most likely not due to temperature anomalies, with a procedure described in Steinberger et al.
345 (2015). Mantle flow is computed with an extension of the method of Hager and O'Connell (1981)
346 that accounts for compressibility, depth-dependent gravity and phase boundaries, with a suitable
347 radial viscosity structure shown in supplementary figure 1. Based on this flow field we use
348 downwind differencing to compute derivatives of density with respect to time at grid points. Time
349 integration is done with a fourth-order Runge-Kutta scheme. Other details of the computation are
350 explained in the supporting information of Steinberger et al. [2015]. We also compared the
351 predicted mantle flow from model P06_CSloc with that predicted from three other tomographic
352 models and found general agreement on the style, in- or outflow, and good agreement in the average
353 amplitude for all boundaries (supplementary figure 8).

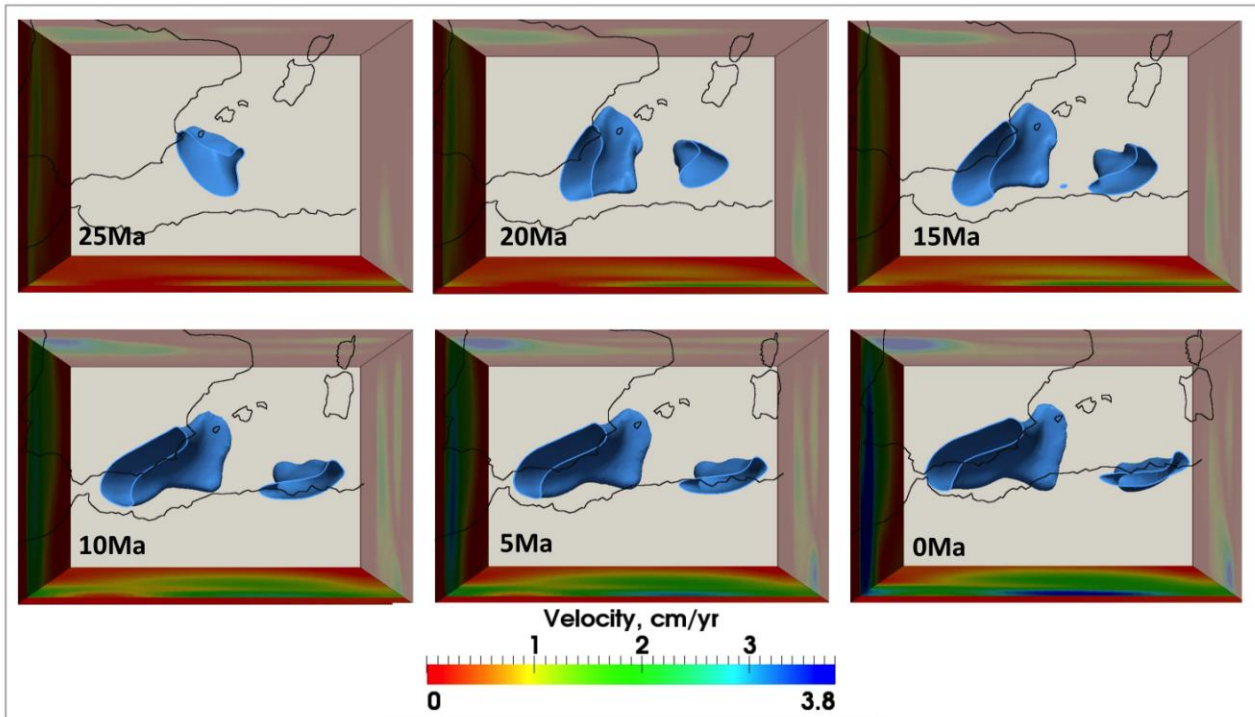
354 The mantle flow prescribed on 4 side boundaries is shown in supplementary movie 1. Although this
355 model features the tomographic image of the RGB slab, the locally predicted flow may still not be
356 consistent with the numerically modeled slab for which a no-slip condition at the bottom of the
357 model is used. Imposing flow at all boundaries combined with net inflow of the lithosphere plates
358 violates mass balance. Proper attention for conservation of the model mass balance is required and
359 therefore we impose the calculated flow at only two adjacent sides per experiment, treating the
360 other two sides as open boundaries.

361 We first test effects of mantle in/outflow at the northern and eastern sides of the model and next at
362 the southern and western parts. Figure 8 shows the evolution of both slabs when mantle in/outflow
363 is prescribed on the southern and western boundaries (model WMED.SW). The amplitude of the
364 prescribed mantle in/outflow is shown in color on the domain boundaries. Mantle in- and outflow is
365 also shown in the supplementary movie 1. The subduction of both slabs evolves in a similar way as
366 in model WMED.O (supplementary figure 5) and in both models the RGB and Kabyldes slabs
367 reach their present-day position after 35 Myr of slab evolution, while the overall shape of the slabs
368 is similar (figure 9A). In model WMED.SW the amount of lithosphere tearing for the RGB slab

369 along the east Iberian margin since ~10 Ma is smaller than in the reference model. This effect
370 correlates with the strong inflow at the western boundary since 10 Ma. This mantle flow supports
371 the slab from below and counteracts the downward slab pull leading to reduced tearing of the
372 Iberian margin. The external flow also leads to a slightly more easterly position of the deep slab and
373 a slight shallowing in overall slab tilt (figure 9A). This effect is similar to that observed in our
374 earlier generic models where westward slab rollback was counteracted by opposite mantle inflow in
375 the sub-slab region (e.g. model M600.W; figure 5).

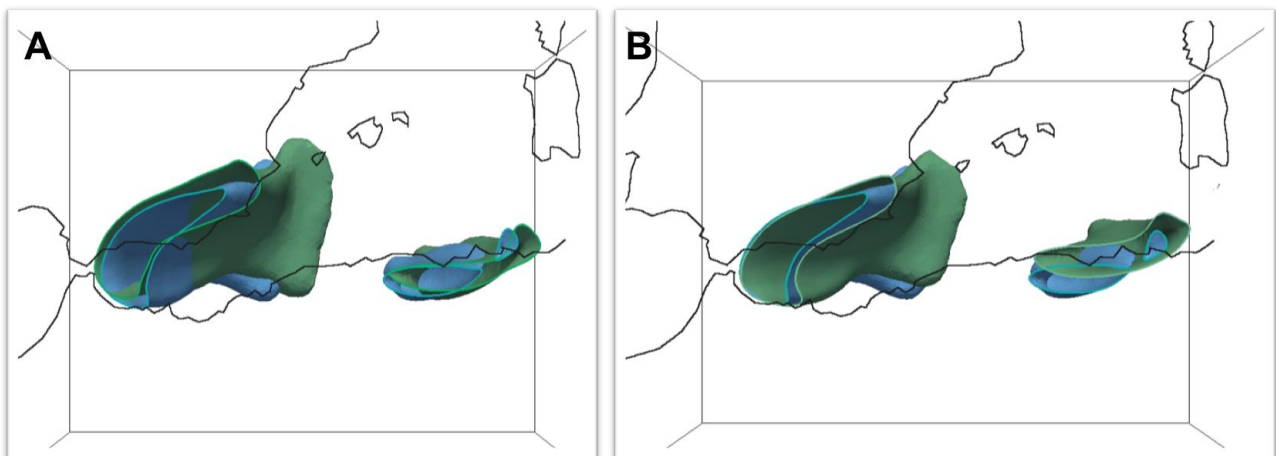
376 In figure 9B we show the comparison with model WMED.NE, which is based on predicted
377 in/outflow from the north and east, with the reference model WMED.O at the final stage reached
378 after 35 Myr of model evolution. Also, here the overall position and shape of the slabs are similar,
379 while lithosphere tearing under the Iberian margin has also started to develop in model WMED.NE.
380 Also now a change in slab tilt is observed although somewhat smaller than in model WMED.SW.
381 The Kabyldes slab is located more to the north, which is in better agreement with its tomographic
382 image [*Chertova et al.*, 2014].

383 The differences between WMED.SW, WMED.NE, and the reference model WMED.O are
384 generally of the order of 10-50 km, which is small compared to the overall distance travelled by
385 slab rollback and to the overall match in slab position and morphology. The difference in eastward
386 slab tilt leads to an eastward shift of the slab geometry in the transition zone of ~100 km. Important
387 for our previous work [*Chertova et al.*, 2014] is that this demonstrates the robustness of the overall
388 slab position and geometry of the RGB and Kabyldes slabs obtained after 35 Myr of modeled
389 subduction evolution with respect to the influence of external mantle flow.



390

391 Figure 8. Model WMED.SW: Evolution of the western Mediterranean subduction under the
 392 influence of mantle in/outflow through the southern and western sidewalls. In color the total
 393 amplitude of the imposed boundary velocity field is shown. In/Outflow vector are shown in
 394 supplementary video 1. In transparent colors we plotted the resulting in/outflow through the open
 395 northern and eastern boundaries. The 1400 K isotherm delineates the slabs from 200 km depth
 396 downward. The initial, 35-25 Ma, stage is skipped, as both slabs are shallower than 200 km.



397

398 Figure 9. A. Comparison after 35 Myr of subduction evolution between the reference model
 399 WMED.O (blue) and model WMED.SW (green) with prescribed in/outflow on the southern and

400 western sidewalls. B. Comparison after 35 Myr of subduction evolution between the reference
401 model WMED.O (blue) and model WMED.NE (green) with prescribed in/outflow on the northern
402 and eastern sidewalls. The 1400 K isotherm delineating the slabs is shown from 200 km depth
403 downward.

404

405 5. Discussion and Conclusions

406 Using 3D numerical thermo-mechanical modeling within a regional model domain we investigated
407 the influence of remotely forced mantle flow on subduction and slab morphology evolution. The
408 nonlinear composite rheology we used is adopted from Chertova et al. [2014] and conforms to the
409 present-day knowledge of mantle rheology [e.g. *King*, 2016]. Experiments were performed for both
410 a generic setup similar to that used by others and for a natural example in the western
411 Mediterranean with a complex spatial-temporal slab evolution. Within each geometric setting
412 similar effects of external mantle flow on subduction evolution could be observed which mostly
413 concerned various morphological changes on the scale of 10-50 km and appreciable differences in
414 total rollback of order of 50 km, all accumulating in 25 Myr of modeled subduction, or 35 Myr for
415 the western Mediterranean subduction systems.

416 Mantle flow perpendicular to the trench, from either direction, proved the least influential on
417 internal slab deformation, apart from slight changes in slab dip, which can be explained by the fact
418 that such flow is deflected trench-parallel to both sides and thus affects the slab equally along its
419 width. We observed no strong (e.g. tens of degrees) change in the dip of the narrow or wide slab
420 resulting from trench-perpendicular mantle flow. This is in contrast with observations from 2-D
421 subduction modeling with an imposed horizontal mantle flow of similar amplitude (3 cm/yr) used
422 for investigating the effects on slab dip of a proposed eastward directed global mantle flow
423 (Rodriguez-Gonzalez et al., 2014; Ficini et al. 2017). In our 3-D experiments, slab lateral mantle

424 flow and toroidal mantle flow around provide lateral transport of mantle material at either side of
425 the slab without strongly affecting the slab dip.

426 Trench-parallel inflow led to large ~150 km trench-parallel transport of the slab, which in our
427 models is taken up in the weak plate-coupling zones at either side of the subducting and in lateral
428 deformation of the side plates. On Earth this lithosphere motion is likely more restricted which
429 suggests instead an amplification of the slab bending and thickening effects we observed in the
430 various experiments in response to the viscous coupling with slab-parallel or obliquely impacting
431 flow. In reality slab deformation due to trench-parallel flow may also impact on the crustal
432 evolution in the overlying crust potentially leading to trench-parallel shortening or stretching above
433 slab edges.

434 We also observed that narrow (660 km) slabs are comparably affected as wide (1400 km) slabs,
435 which is an expression of the fact that the total frictional force acting on the slab scales with its
436 surface area while the detail of slab morphology change is caused by viscous tractions of similar
437 amplitude. Long slabs that reached the transition zone before the onset of trench-parallel flow
438 experience less morphology change, although they are still transported over 150 km or more.
439 Various experiments with mantle flow impacting obliquely on the slab surface proved to have much
440 larger impact on slab deformation giving rise to strong out-of-plane slab bending of more than 200
441 km and changes in overall slab tilt.

442 In our last experiments concerning simulations of natural subduction in the western Mediterranean
443 during the past 35 Myr, we imposed past mantle flow determined from a tomographic model of
444 present-day mantle structure. Apart from the complexities and uncertainties that are entailed in
445 determining this past flow, we observed for the predicted spatially and temporally varying mantle
446 flow that the overall position and slab morphology of the RGB and Kabyrides slabs are rather robust
447 with respect to 35 Myr of external flow impact on subduction evolution. The differences between

448 the three simulations concern slab tilt and morphological changes of the scale of 10-50 km, which is
449 still an important scale to be considered for orogenic geological processes in the overlying crust.
450 All our experiments suggest that during a long period of subduction the slab forcing by external
451 mantle flow is of secondary importance with respect to the forcing by slab buoyancy and imposed
452 plate motions that control the first-order aspects of long-term subduction evolution. However, we
453 have shown that various aspects of slab morphology (e.g. slab bending, slab edge thickening, slab
454 tilt) and subduction evolution (e.g. rollback speed and trench deformation) can result from the
455 continuous impact of remotely forced mantle flow. At present these aspects may be difficult to
456 discern from other processes that determine slab morphology, e.g. subduction of trench-parallel
457 lithosphere heterogeneity [e.g. *Moresi et al.*, 2014; *Duretz et al.*, 2014] or other complexity of the
458 geodynamic subduction setting [e.g. *Boutelier and Cruden*, 2013; *Chertova et al.*, 2014]. An
459 additional complexity is that the still large uncertainty in mantle rheology allows for trade-offs in
460 numerical modeling between variations in mantle flow and mantle rheology. Still the contribution to
461 slab deformation from long-term impact of remotely excited mantle flow cannot be ignored when
462 considering the crustal evolution overhead. To make steps forward, deciphering the various
463 contributions requires more detailed numerical modeling that includes the crustal response as well
464 as numerical simulation of natural subduction constrained by independent observations from
465 geology, geodesy, and geophysics, for instance by higher-resolution seismic tomography models
466 and by spatially dense observations of seismic anisotropy.

467

468

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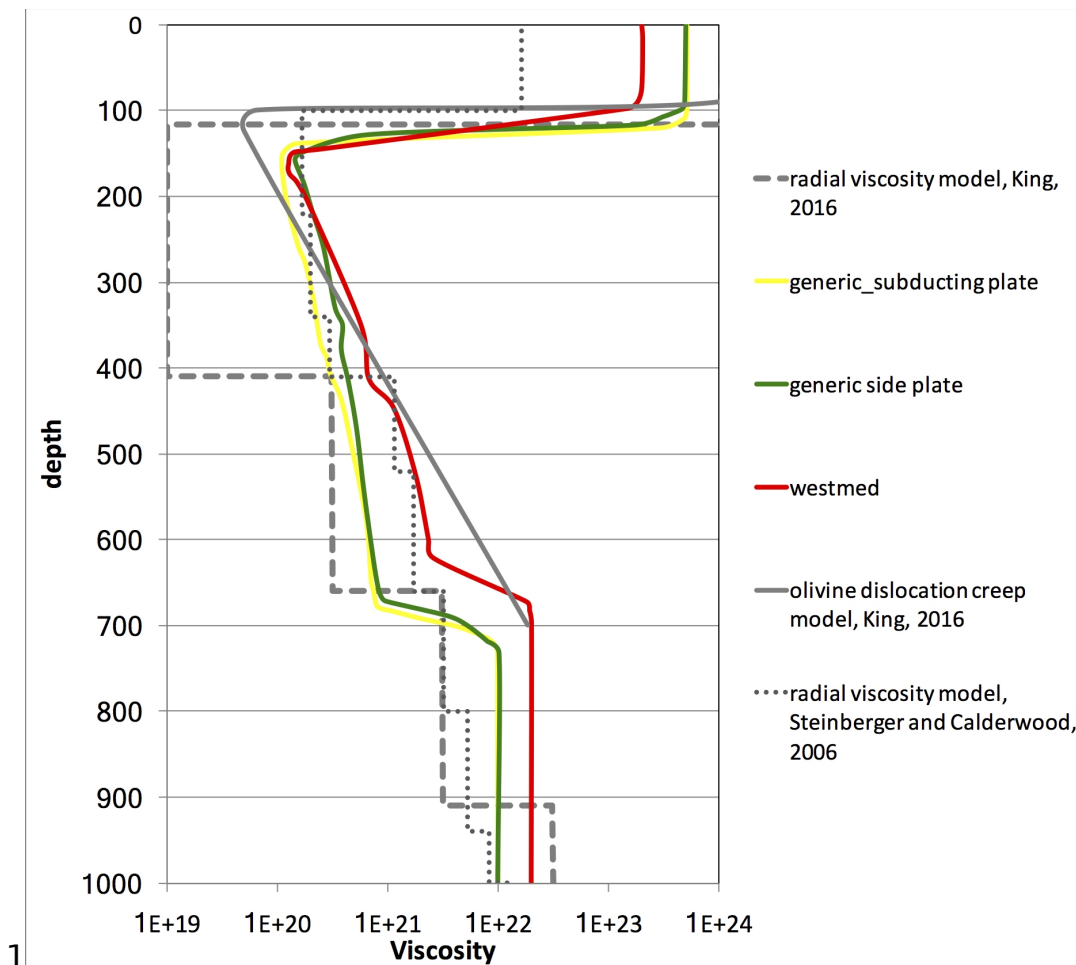
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Supplementary table 1. List of model parameters.

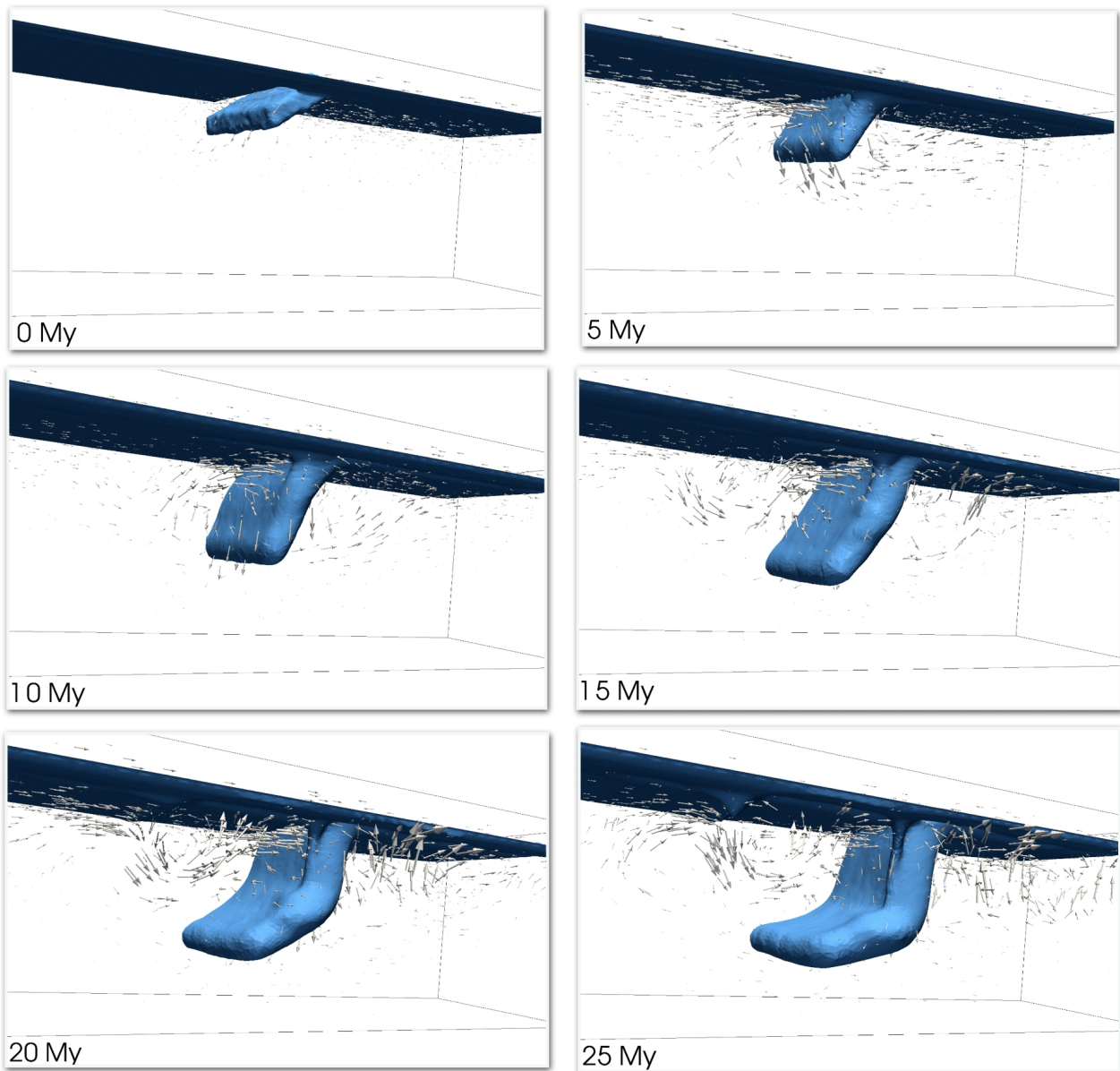
Symbol	Meaning	Value	Dimension
$a \times b \times c$	Dimensions of the generic models	$1 \times 3 \times 2$	1000 km
$a \times b \times c$	Dimensions of the western Mediterranean model	$1 \times 1.8 \times 1.3$	1000 km
w	Slab width, generic models	0.6-1.4	1000 km
η_0	Reference viscosity	10^{21}	Pa s
γ_1	Clapeyron slope (410 km)	4.1	MPaK ⁻¹
$\delta\rho_1$	Density contrast (410 km)	273	Kg m ⁻³
γ_2	Clapeyron slope (660 km)	-1.9	MPaK ⁻¹
$\delta\rho_2$	Density contrast (660 km)	342	Kg m ⁻³
η_{LM}	Viscosity of the lower mantle, generic models	10^{22}	Pa s
η_{LM}	Viscosity of the lower mantle, western Mediterranean	2×10^{22}	Pa s
A_{diff}	Diffusion prefactor	5.3×10^{15}	s ⁻¹
A_{disl}	Dislocation prefactor	2×10^{18}	s ⁻¹
V_{diff}	Activation volume for the diffusion creep	3-4	cm ³ mol ⁻¹
V_{disl}	Activation volume for the dislocation creep	8-9	cm ³ mol ⁻¹
E_{diff}	Activation energy for the diffusion creep	240	KJ mol ⁻¹
E_{disl}	Activation energy for the dislocation creep	423-433	KJ mol ⁻¹
b	Burgers vector	5×10^{-10}	m
d	Grain size	10^{-6}	m
R	Gas constant	8.314	J mol ⁻¹ K ⁻¹
m	Grain size exponent	2.5	-
n	Stress exponent dislocation creep	3	-
γ	Yield stress gradient	0.3	-
η_{max}	Maximum viscosity limit	$2-5 \times 10^{23}$	Pa s



Supplementary figure 1. Example viscosity profiles away from the subducting slab for the model with 4 plates. Green and yellow lines denote the profile for the side- and subducting plates, respectively. The differences between the two profiles for the generic models is caused by the different strain rate fields. The viscosity profile (“westmed”) for the model of the western Mediterranean region (Section 4) exemplifies a region with well-developed mantle flow. The viscosity parameters for subduction modeling in the western Mediterranean region result from tuning the mantle rheology such that the Rif-Gibraltar-Betics slab matches the observed slab geometry after 935 My of subduction evolution [Chertova et al., 2014]. For comparison a viscosity profile computed from olivine dislocation creep parameters listed in King [2016] is shown in solid grey. Dashed grey denotes the radial viscosity model from King [2016] based on a dry transition zone. In dotted-grey the radial viscosity model from Steinberger et al. [2015] is shown.

13

14 Reference generic model



16 Supplementary figure 2. Evolution of the model M1400.O. View from the northeast. Isotherm of
17 1500 K is shown in blue. Arrows indicate the direction and magnitude of the velocity field.

18
19 The evolution of the 4-plates model with open boundaries and a prescribed subducting plate velocity
20 of 1.5 cm/yr (M1400.O) is shown in supplementary figure 2. Trench retreat develops in the model
21 only after 8 Myr of nearly stationary subduction. The subduction angle gradually increases until the

22slab reaches the viscosity jump at 660 km at ~15 My. We note that in our modeling the viscosity
23jump by about a factor 10 (supplementary figure 1) proves of much larger influence on slab
24flattening than the resistance due to the phase change with a Clapeyron slope of -1.9 MPaK^{-1} . The
25deeper slab bends and flattens while the shallow portion of the slab keeps high subduction angles. In
26the horizontal plane the slab is almost straight. The flow in the mantle wedge area is directed toward
27the slab until the slab reaches the 660 boundary at ~15 My. During the later stages and between 200
28and 500 km depths, mantle flow is mostly parallel to the slab. After 24 My of the evolution, when
29the slab is lying on 660 boundary and rollback is very slow, two convection cells develop in the
30modeling domain: one beneath the overriding plate and another in the sub-slab area. These
31convection cells propagate from the symmetry plane to the slab edges and ~100 km beyond these.

32

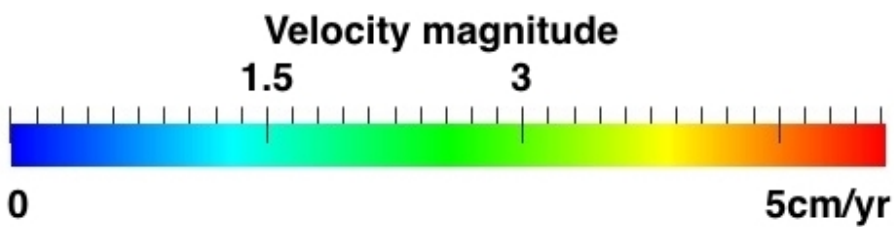
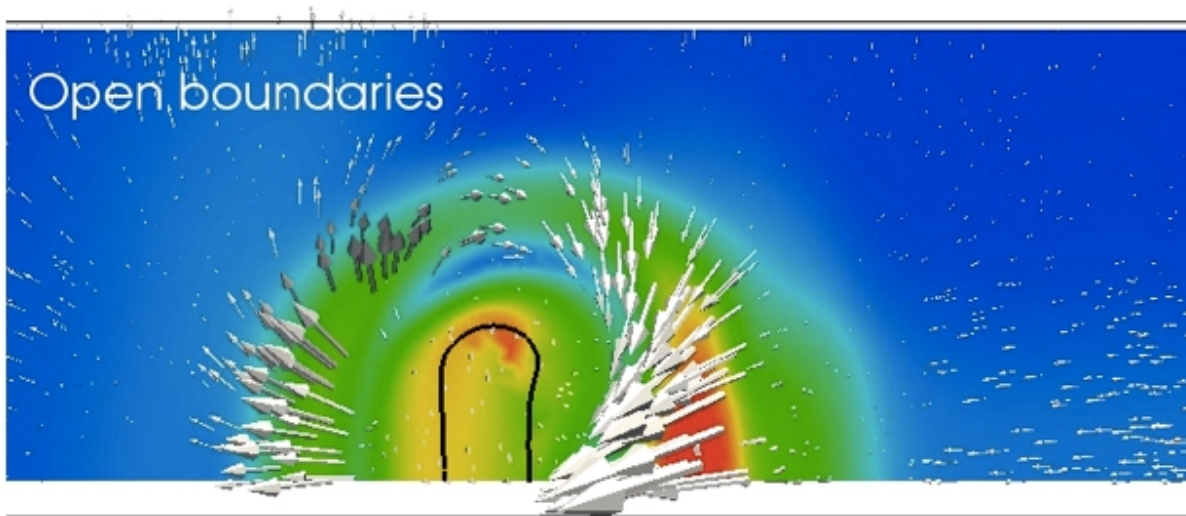
33**Toroidal flow in free-slip versus open boundary settings.**

34In subduction modeling free slip (closed) boundary conditions are often used on the sidewalls of the
35model domain, keeping the material in the model box, while we use open boundaries allowing for
36horizontal in/outflow. Importantly, we need to use open boundaries because it allows maintaining
37mass balance in our experiments with inflow from one side only. Here we briefly compare the effect
38of both types of BC on the development of mantle flow patterns around slab edges. We compare
39reference model M600.O to model M600.FS for which free-slip side boundary conditions are
40prescribed on the N and S boundaries. Because we have an inflow at the western boundary of the
41subducting plate with 1.5 cm/yr, we keep the western and eastern boundaries open to satisfy mass
42balance in the model.

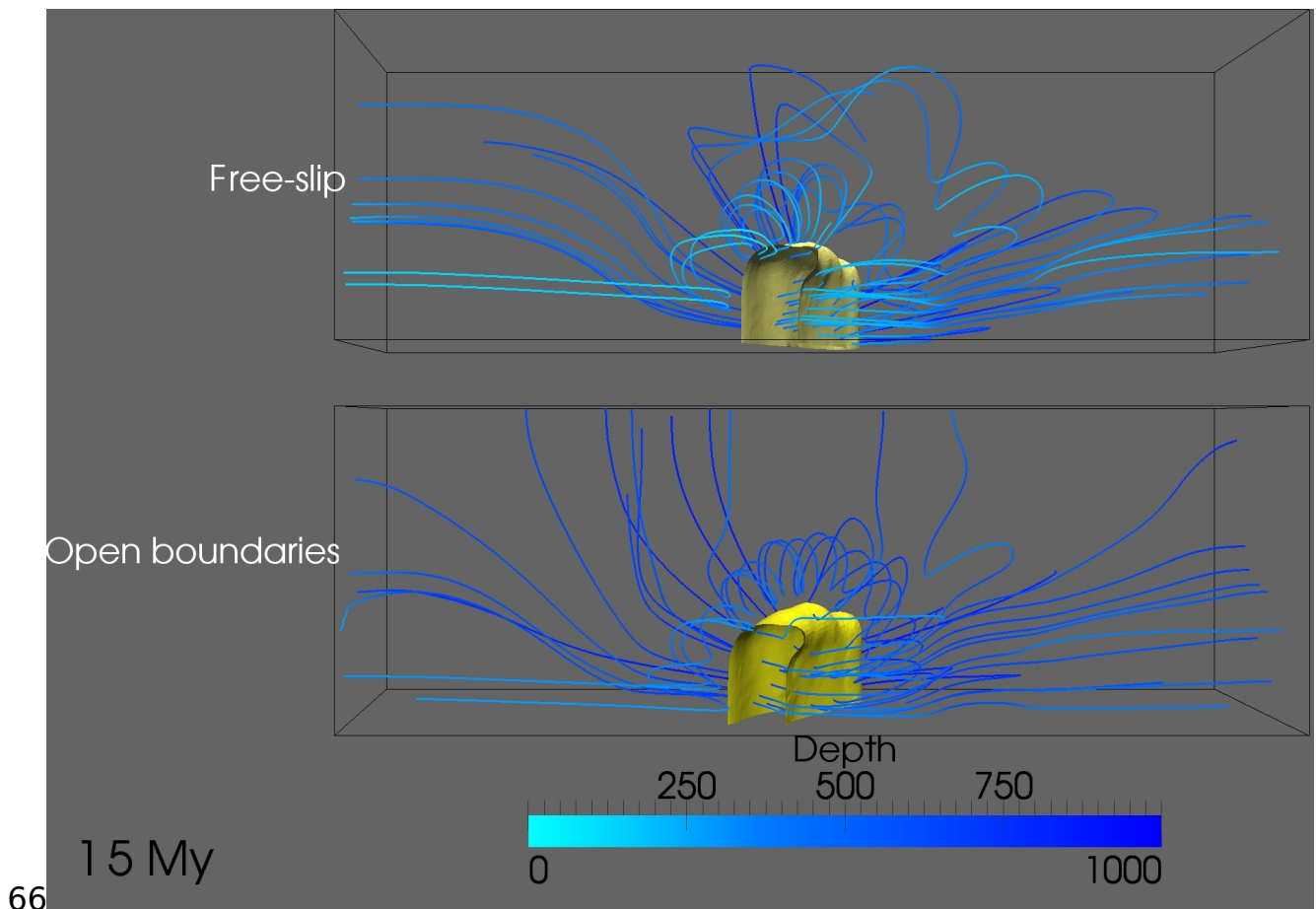
43Supplementary figure 3 shows the mantle flow for both models near the northern model boundary at
44the depth of 400 km after 15 My of the subduction evolution. In color we show the amplitude of the
45velocity field, arrows show the direction and the black contour line depicts the position of the slab
46given by the 1500 K contour. The general characteristics of the flow field are highly comparable but

47we do notice some differences. Rollback in model M600.FS is somewhat slower (~50 km difference
48at 25 My) as a result of the flow “reflecting” property of the free slip condition at the southern and
49northern sides that have an overall damping effect on slab rollback. The magnitude of the mantle
50flow around slab edges is similar for both models with small difference in orientation of the flow
51field. Supplementary figure 3 also suggests a vertical flow component implying more flow
52complexity than horizontal toroidal flow. In supplementary figure 4 we illustrate this for our models
53with open and closed boundaries by means of plotting some 3D streamlines of the velocity field that
54demonstrate complex spiraling flow adjacent to the slab edges. Streamlines extend across a
55significant 3D volume around the slab edge and across the entire upper mantle and highlight the
56difference between the flow fields obtained from using either open or closed side BC on the northern
57boundary. When compared to the very large effects of using either boundary condition in 2D
58subduction modeling (Chertova et al. 2012), even in the case of boundaries thousands km away from
59the slab, the differences in 3D modeling are considerably reduced when the boundary is only ~600
60km away.

61



62
 63Supplementary figure 3. Horizontal cross-section at 400 km depth for M600.O and M600.FS models
 64after 15 My of the subduction evolution. Grey arrows illustrate the 3-D mantle flow. The black
 65contour is the 1500 K isotherm delineating the slab.

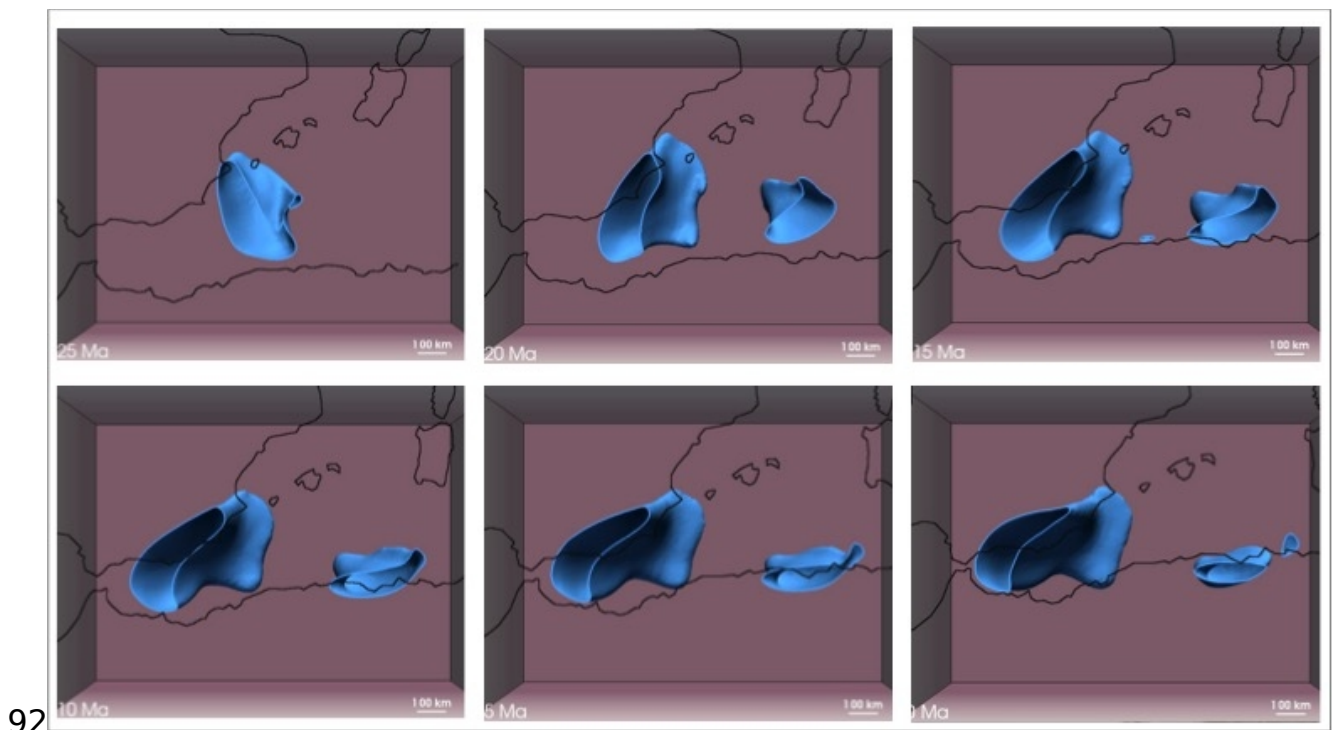


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67 Supplementary figure 4. Streamlines of the velocity field for models with open boundaries and free
68 slip. In yellow- 1400K isotherm delineating the slab from 200 km depth downward.

69
70
71 **Evolution of the reference model WMED.O of the western Mediterranean based on using open**
72 **boundaries.**

73 In supplementary figure 5 we show snapshots of the subduction evolution of the RGB slab and the
74 smaller Kabylides slab in reference model WMED.O. The initial slab only extends ~50 km below the
75 lithosphere and its buoyancy is still small. During the first 5 Myr the slab length is increased by only
76 ~30-40 km resulting from the northward advance of the African plate. Between 30 Ma and 25 Ma,
77 subduction rollback of the RGB slab sets in and subduction speed increases, the slab tears along the
78 predefined oceanic weakness zone and initially rotates clockwise by ~ 90° to a NW-SE strike

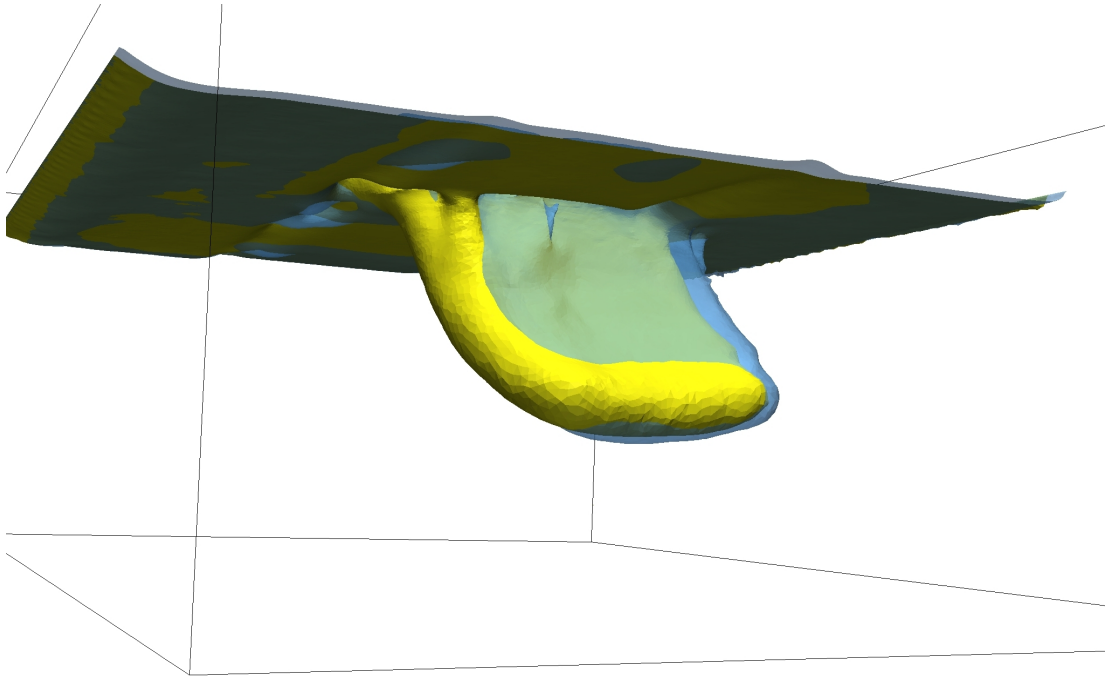
79direction. During 25-20 Ma, fast rollback occurs in a westward direction and lithosphere tearing
80under the African margin develops for the RGB slab. At 22-23 Ma subduction of the Kabyldes slab
81initiates by lithosphere tearing along the prescribed oceanic weakness zone. The subduction develops
82in SE direction and fast rollback leads at 20 Ma to a Kabyldes slab that reaches the depth of 350 km.
83From 20 to 10 Ma the RGB slab continues to roll back to the west with associated lithosphere tearing
84along the African margin and eventually the trench rotates in NW direction completing a $\sim 180^\circ$
85rotation of the trench during 35 My of subduction evolution; turning a NW dipping slab under the
86Baleares margin into a E-SE dipping slab under the south-Iberian margin [Chertova *et al.*, 2014]. The
87Kabyldes slab rolls back further to SE and later to S direction until it reaches the African margin.
88From 10 Ma onward the subduction process for both slabs slows down, lithosphere tearing starts
89under the Iberian margin and under the African margin for the Kabyldes slab. Both slabs are close to
90the present day position. At present, the position of both slabs in the mantle correlates reasonably
91well with the tomographic images for this region [Chertova *et al.*, 2014].



93Supplementary figure 5. Model WMED.O: Evolution of western Mediterranean subduction since 25
94Ma using open boundaries. Two slabs, the RGB slab (left) and the Kabyldes slab are modeled. The

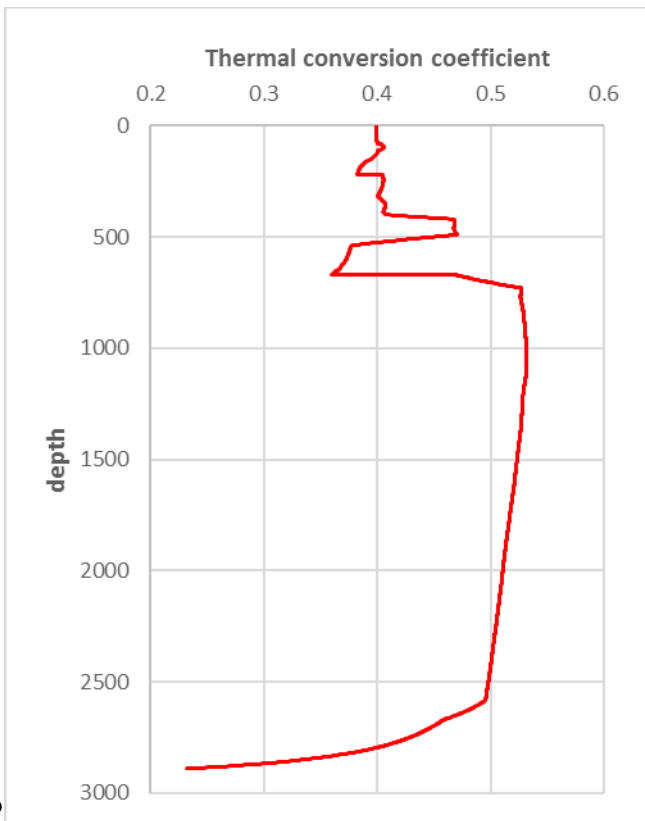
95 1400 K isotherm is shown from 200 km depth downward. The initial, 35-25 Ma, stage is skipped, as
96 both slabs are shallower than 200 km.

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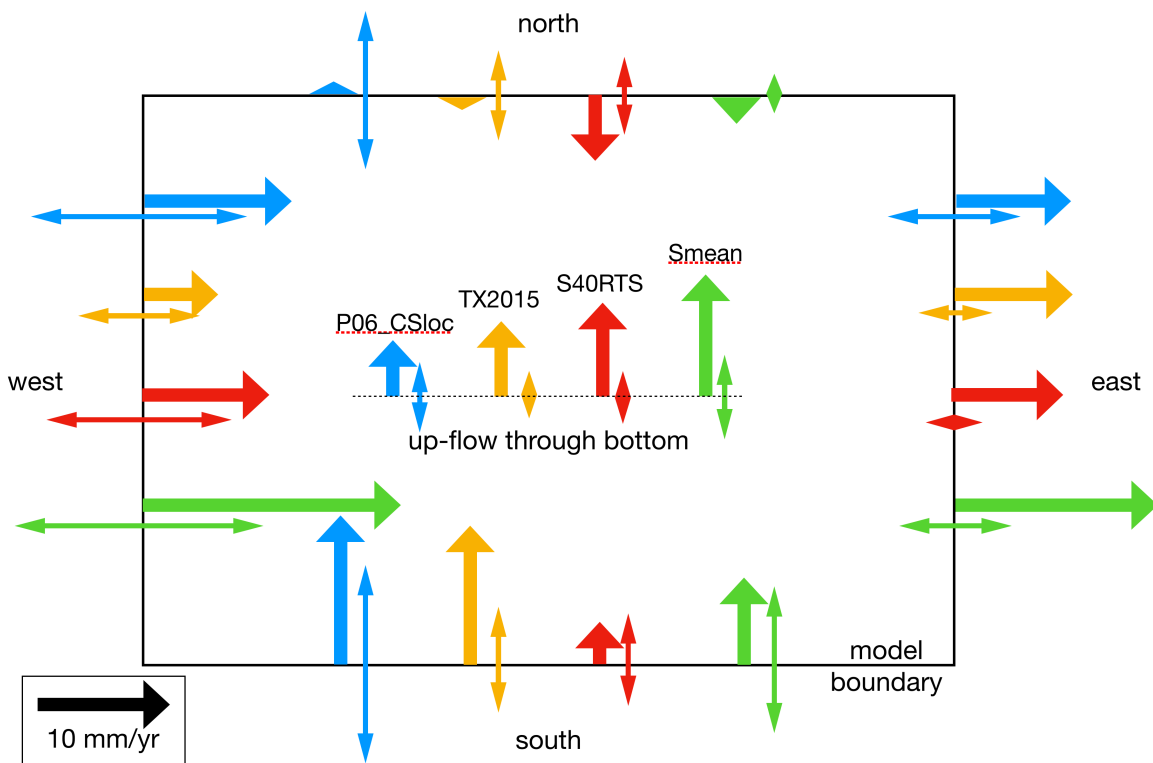
99 Supplementary figure 6. Model with SW mantle inflow with free-slip bottom
100 boundary conditions is shown in transparent blue. Model with SW mantle inflow
101 with no-slip bottom boundary conditions is shown in yellow.



102

103 Supplementary figure 7. Thermal conversion factor for mantle flow calculations.

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105

106 Supplementary figure 8. Predicted in- and outflow of mantle material across the boundaries of the
107 western Mediterranean model. Flow prediction perpendicular to the boundary (arrows) and standard
108 deviation (double ended arrows) are 35 Myr averages computed from back-advection of 4
109 tomography models: P06_CSloc (Amaru 2007) used here, Smean (Becker and Boschi 2002);
110 TX2015 (Lu and Grand 2016), and S40RTS (Ritsema et al. 2011). Although with variable
111 amplitudes, the flow predictions agree on western inflow, eastern outflow, southern inflow, and a
112 relatively low material exchange across the northern boundary. Generally, there is an upward flow
113 through the bottom.

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