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Mantle flow influence on the evolution of subduction systems.

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1. Summary

Evolution of the subducting slab has been widely investigated in the past two decades be means of numerical and laboratory modeling, including analysis of the factors controlling its behavior. However, until present, relatively little attention has been paid to the influence of the mantle flow. While for large subduction zones, due to the high slab buoyancy force, this effect might be small, mantle flow might be the primary factor controlling the evolution of a regional subduction zone.
Here we investigate the impact of prescribed mantle flow on the evolution of both generic (**Fig.1**) and real-Earth (**Fig.4**) subduction models by means of 3D thermo-mechanical numerical modeling. We implement two types of generic models. The first includes only a single subducting plate. The second has a subducting, overriding and two side plates. For the generic setup we test arbitrary mantle flow prescribed on one of the four side boundaries or for the combination of two boundaries.
To test the mantle flow influence on the dynamics of real-Earth subduction zone we adopt the numerical model from Chertova et al. (2014) for the evolution of the western Mediterranean subduction since 35 Ma. This model was tested with time-dependent estimates of the actual mantle flow in the region based on Steinberger (2016) given for every 1 My.
Our models demonstrate that for the western-Mediterranean subduction, the surrounding mantle flow is of second-order compared to the slab buoyancy in controlling the dynamics of the subducting slab. Introducing mantle flow on the side boundaries might, however, improve the fit between the modeled and the real slab imaged by tomography, although this may also trade-off with varying rheological parameters of the lithosphere and mantle.

2. Experimental settings. Generic models.

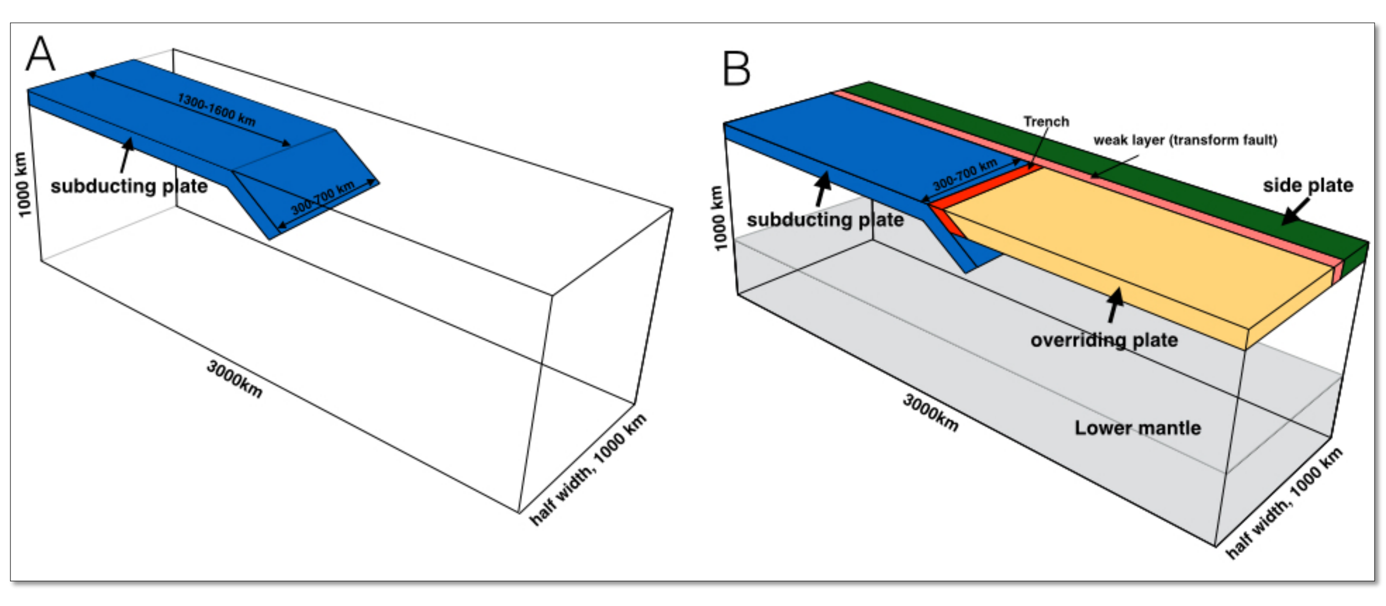


Fig. 1. A – Perspective view of the model setup with one plate for half-width of the model with respect to symmetry plane. B - Perspective view of the model setup with four plates for half-width of the model with respect to symmetry plane. Trench is located in 1400 km from the left boundary.

To investigate the influence of mantle flow on the evolution of the subduction zone, we implement different side boundary conditions, such as free-slip, open boundaries (Chertova et al. 2012) or prescribed mantle flow for which we use constant velocity of 3 cm/yr.
We perform two sets of experiments with different plate configurations(**Fig.1 A, B**). The first set incorporate one subducting plate while the second has 4 plates and includes phase transitions and a lower-mantle viscosity jump.
To ensure that the slab does not get close to the side boundary, we prescribe constant velocity for the subducting lithosphere in the range of 1.5-3 cm/yr.
Composite rheology is used for all model configurations comprises diffusion creep, dislocation creep and viscosity maximum of 10^{23}-10^{24} Pas. For the rheological settings we use the same values as for the western Mediterranean numerical setup, except the activation energy of dislocation creep. We vary this value between 430 and 450 KJ mol^{-1}.

3. Models with single subducting plate

Comparison between models with eastern, western flow of 3 cm/yr prescribed of two sides and the reference model *(transparent red)*. The speed of subducting plate for models is 3 cm/yr. For the reference model below the lithosphere side boundaries are open except the western boundary which has free-slip BC.

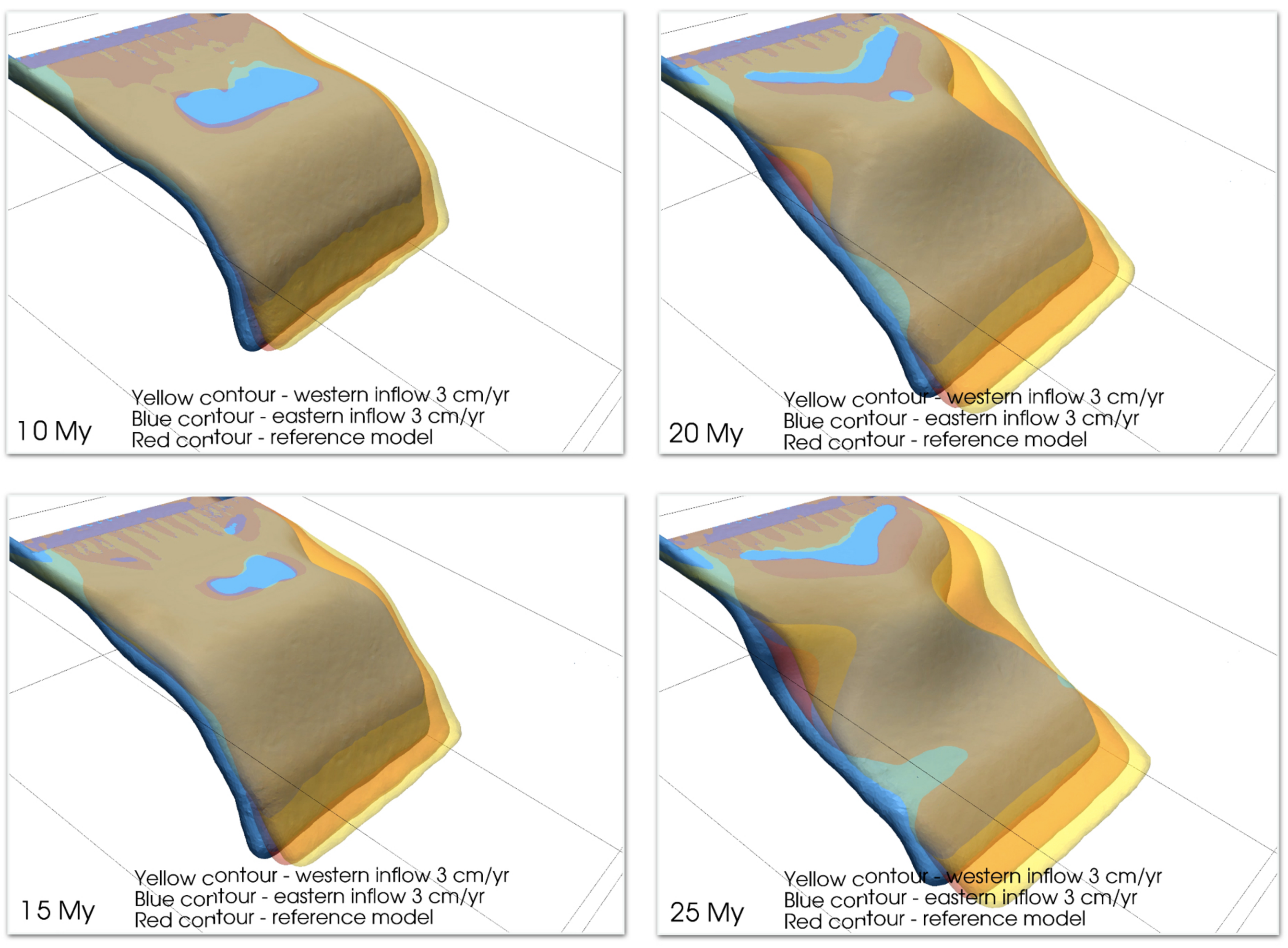


Fig. 2. Evolution of the model with eastern flow(co-directed with the subducting lithosphere), western flow(frontal flow) and reference model without prescribed mantle flow on domain boundaries; perspective view.

4. Experiments with 4 plates

We perform models with western, eastern and frontal inflow of 3 cm/yr and investigate their evolution in comparison with the reference model *(transparent blue)*. The speed of subducting plate is 1.5 cm/yr. For the reference model *all* side boundaries are open.

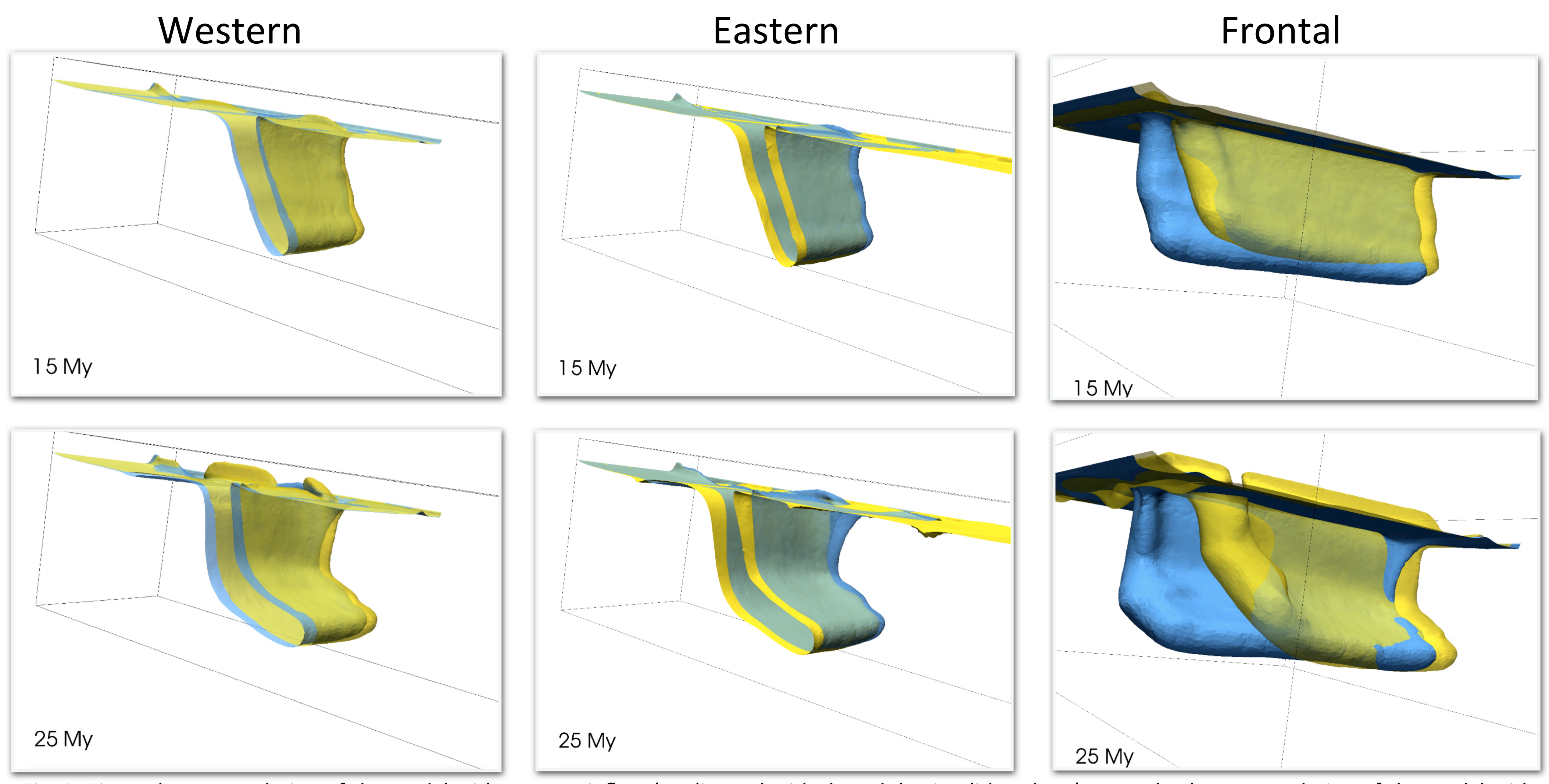


Fig. 3. First column – evolution of the model with western inflow (co-directed with the subducting lithosphere); second column - evolution of the model with eastern inflow (frontal flow) and third column – frontal mantle flow (trench-parallel)); perspective view. In the first and the second column the half-width of the modeling domain is imaged.

5. Model setup for the western Mediterranean region.

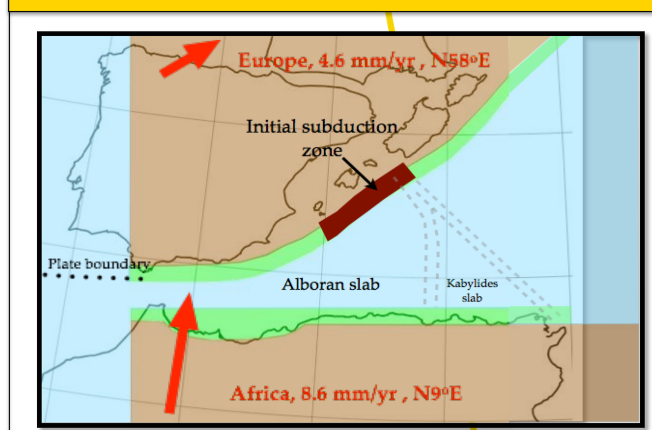
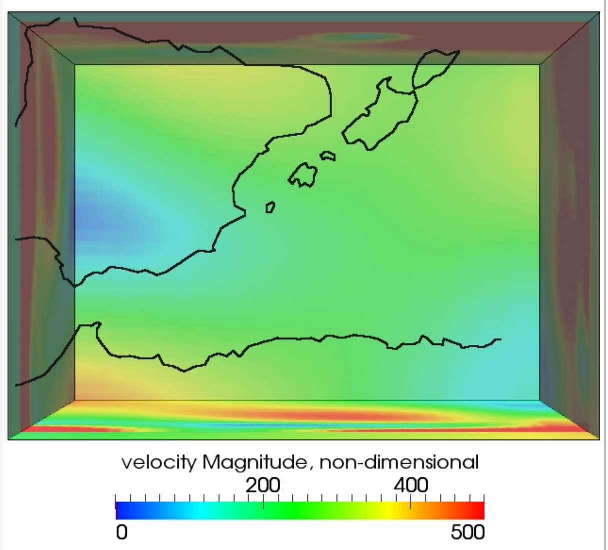


Fig. 4. Initial kinematic boundary conditions and structure of modeling domain

Symbol	Meaning	Value	Dimension
A_{diff}	Diffusion prefactor	5.3×10^{1}	s^{-1}
A_{disl}	Dislocation prefactor	2×10^{18}	s^{-1}
V_{diff}	Activation volume for the diffusion creep	4	cm^3mol^{-1}
V_{disl}	Activation volume for the dislocation creep	8	cm^3mol^{-1}
E_{diff}	Activation energy for the diffusion creep	240	KJ mol^{-1}
E_{disl}	Activation energy for the dislocation creep	423	KJ mol^{-1}
γ	Yield stress gradient	0.3	
τ_{max_o}	Maximum yield stress, oceanic lithosphere	800	MPa
τ_{max_o}	Maximum yield stress, continental lithosphere	800	MPa
τ_{max_o}	Maximum yield stress, African margin	800	MPa
τ_{max_o}	Maximum yield stress, European margin	100	MPa
τ_0	Yield stress at the surface	40	MPa
$\dot{\varepsilon}$	second invariant of the strain-rate	-	-
μ	Shear modulus		
b	Burgers vector	5×10^{-10}	m
d	Grain size	10^{-6}	m
m	Grain size exponent	2.5	
P	Pressure	-	
T	Temperature	-	

We use the initial model geometry and rheological settings from our recent experiments on modeling of the western Mediterranean subduction system (Chertova et al., 2014a, **Fig. 3,table**). In **Fig.5** we show the example of prescribed mantle flow based on Steinberger, 2015. The mantle flow was subsequently changed each 1My.

Fig.5. Prescribed mantle flow on sides of the modeling domain and at the bottom at 35 Ma.



6. Evolution of the reference model.

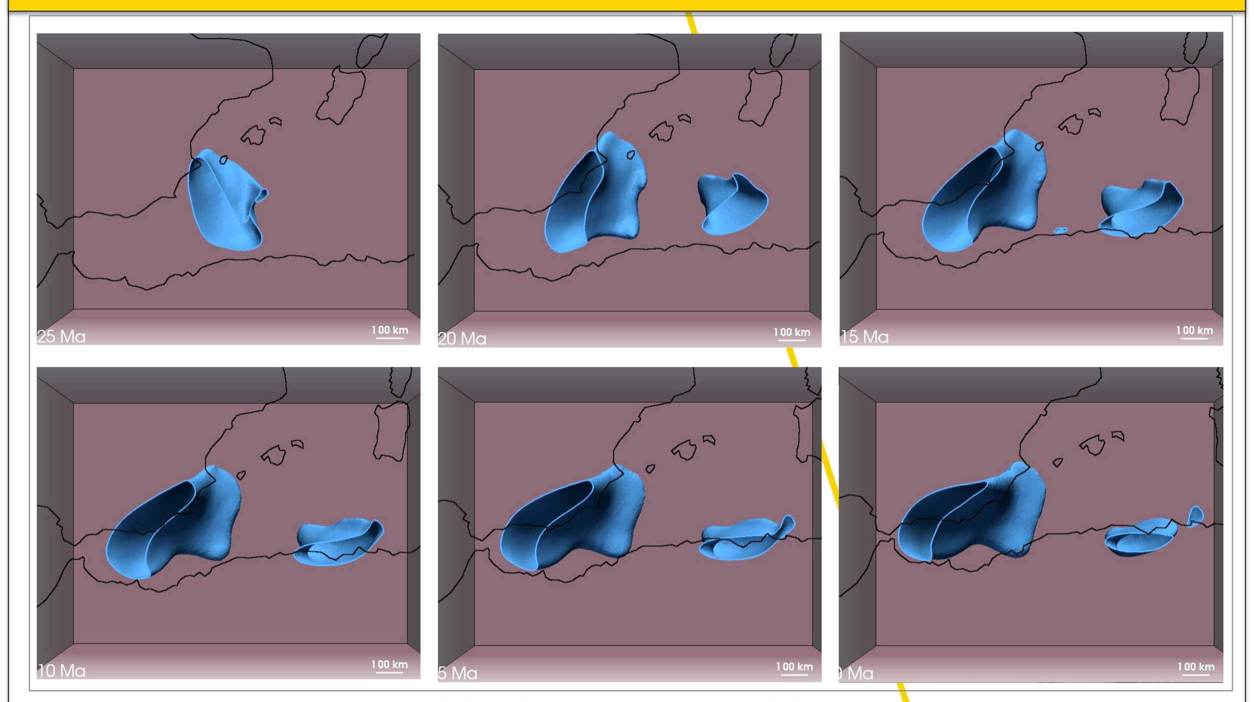


Fig. 6 Slab evolution in the model with Alboran and Kabylides slabs. Top view.

7. Mantle flow influence.

The subduction process in models with prescribed mantle flow on southwest (**Fig.7**) and northeast (**Fig.8**) domain sides demonstrates evolution similar to the reference model (**Fig.9**).

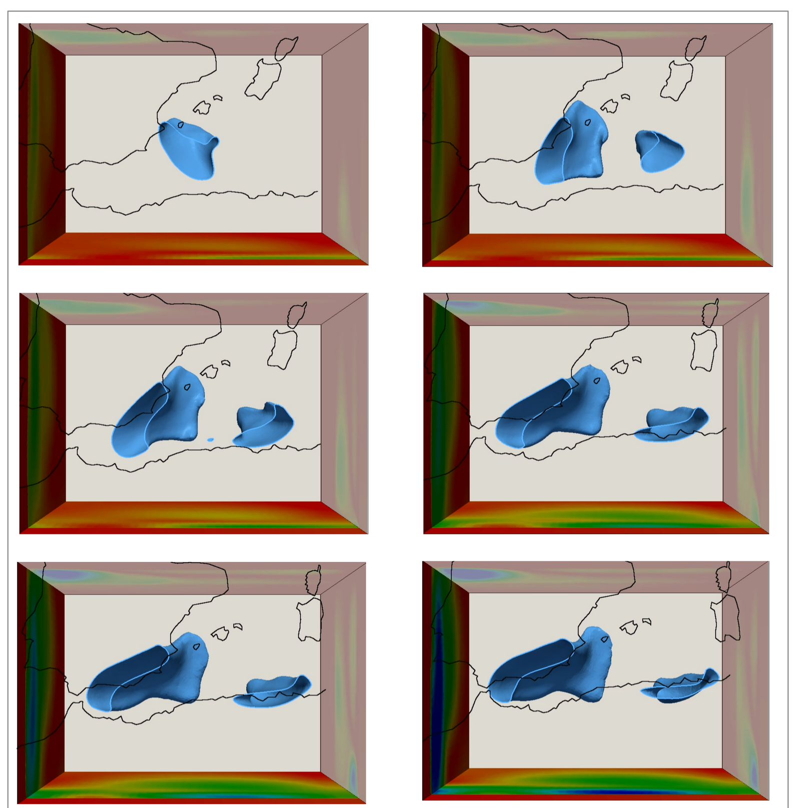


Fig. 7. Model with mantle flow prescribed on southern and western boundaries. Open boundaries shown in transparent.

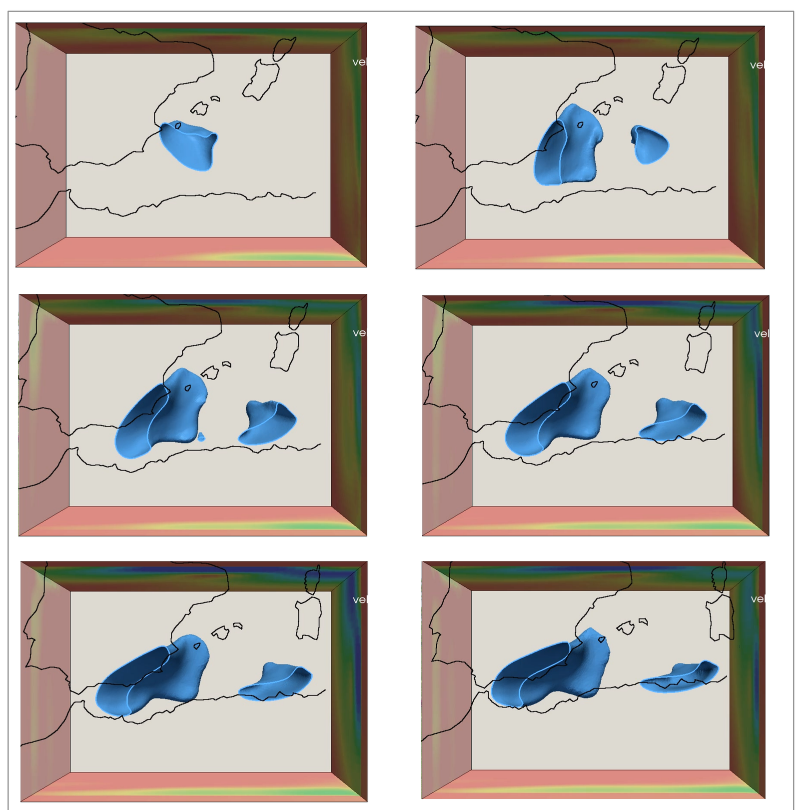


Fig. 8. Model with mantle flow prescribed on eastern and northern boundaries.

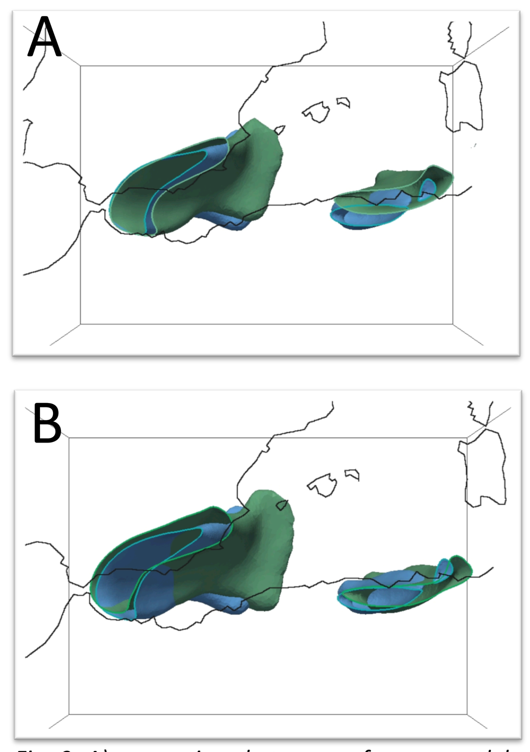


Fig. 9. A) comparison between reference model and model with northeast inflow B) comparison between reference model and model with southwest inflow. Reference model is shown in blue color.

8. Conclusions

- For the single plate generic models, mantle flow might significantly change the shape of the slab. Prescribing trench-perpendicular mantle flow leads to an initiation of spontaneous subduction on the slab sides due to the absence of side plates (**Fig. 1B**).
- For models, which include overriding and side plate, the prescribed mantle flow influences the evolution of subduction process to a lesser extent than for the model with single plate(**Fig.2, Fig.3**).
- Trench-parallel mantle flow has an impact on the evolution of the subduction zone only in the case of a short subducting slab; for the well developed subduction zone slab buoyancy controls subduction dynamics.
- For the model of the western Mediterranean subduction zone tomography derived (Steinberger, 2016) mantle flow on sidewalls of the modeling domain does not significantly disturb the subduction process(**Fig.9**); however, it decreases the amount of tearing under the Iberian margin and drags Kabylides slab to the north which provides better fit with tomographical constraints.

References

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