Geodynamic model of Late Oligocene subduction initiation in the Western Mediterranean

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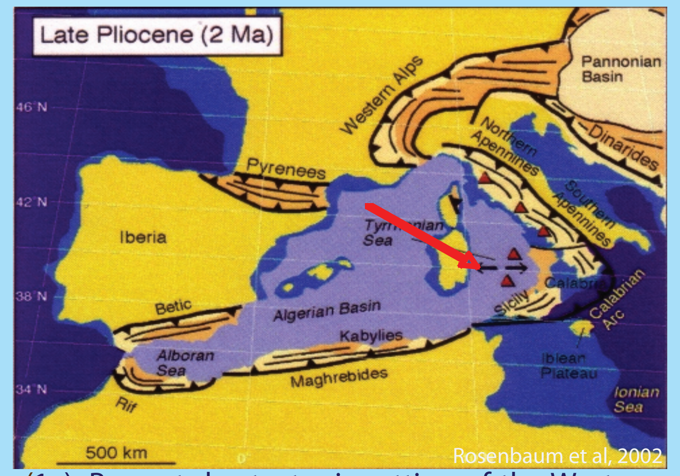
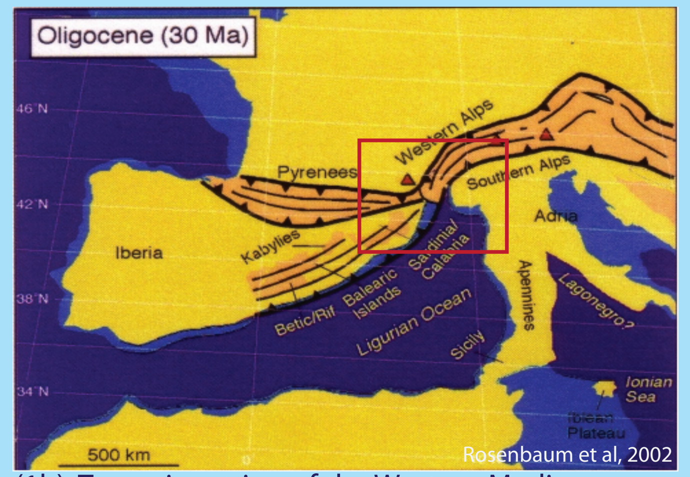
Objective

We study potential causes for initiation of subduction in the Western Mediterranean area in the Late Oligocene - Early Miocene. Two scenarios have been proposed for the initiation of subduction in the region: 1) subduction initiation at a pre-existing fault along former Iberian passive margin, and 2) polarity reversal of former Alpine subduction zone. We aim to investigate these scenarios using 2-D finite element models. Here we present the results of our numerical experiments for the first scenario.

1) Introduction



(1a): Present day tectonic setting of the Western Mediterranean. The red line shows the direction of the slab roll-back



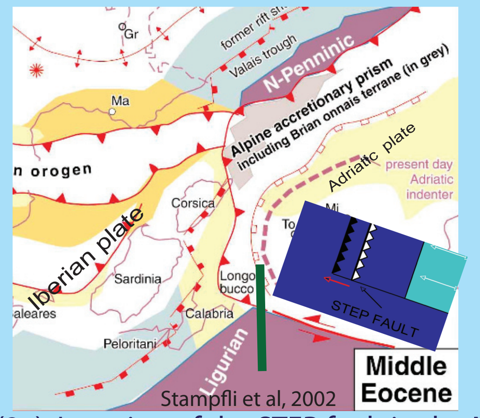
(1b): Tectonic setting of the Western Mediterranean in the Late Oligocene. Inset shows the approximate location of figure (2a).

The Western Mediterranean is located in the convergent plate margin between Africa and Eurasia. The region formed as a result of south-eastward retreating of the subduction and formation of extensional basins in the back-arc which was started at ~ 30 Ma (Fig. 1a) .

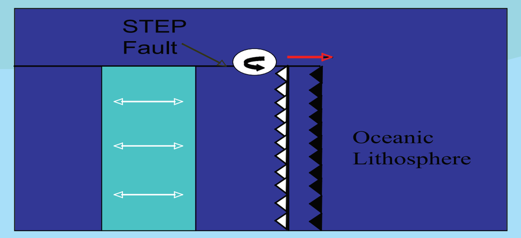
Subduction in this region began in the Late Oligocene with the sinking of the Jurassic age Ligurian ocean beneath Iberian plate (Fig. 1b).

2) Subduction initiation at a pre-existing fault

One of the scenarios which we examine is that subduction was initiated at a pre-existing fault in the Late Oligocene. Previous studies show the existence of a STEP (Subduction-Transform Edge Propagator) fault along the Adriatic plate in the Oligocene (Stampfli 2002). According to the proposed scenario a new subduction was initiated at this STEP fault in the North-East part of the Western Mediterranean and propagated towards South-West along the former Iberian passive margin.



(2a): Location of the STEP fault in the Middle Eocene - Oligocene along the Adriatic plate. Inset illustrates the direction of STEP propagation. The green line shows the approximate location of the cross section selected for the FEM.

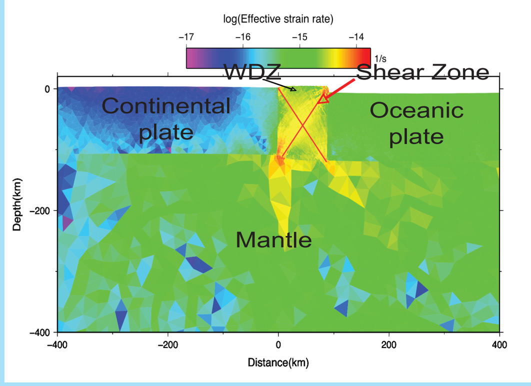


(2b): Map view of a schematic evolution of the STEP. Subduction retreating results in propagation of STEP fault. White and black sawteeth indicate the location of the subduction zone before and after retreating and red line shows the direction of STEP propagation. Green region represents extensional back arc area resulting from slab roll-back.

Remark:

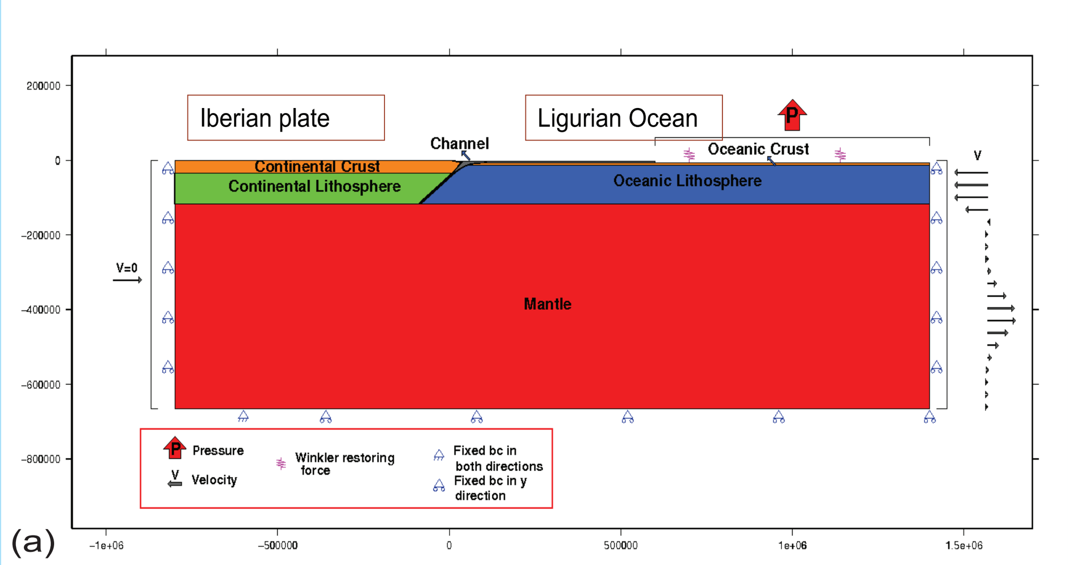
Most subduction zones have tearing regions at their horizontal termination which propagate through the lithosphere due to relative motion of the trench/overriding plate (red line in Fig. 2b). These tearing transform segments are named STEP (Subduction-Tranform Edge Propagator) faults (Govers et al, 2005).

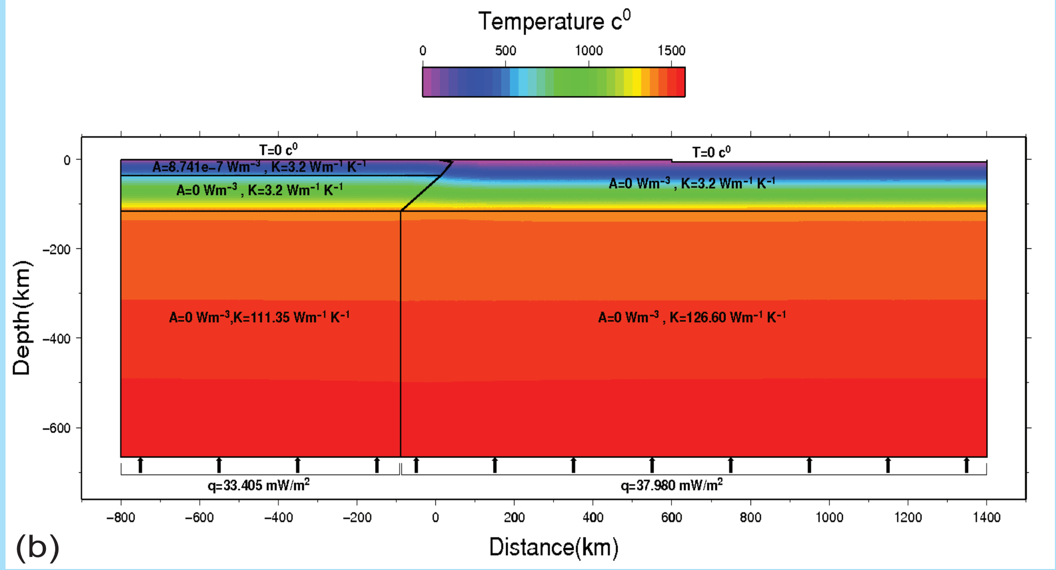
Unlike transform faults which usually dip vertically, STEP faults are not necessarily vertical. In addition, a STEP fault can be a single fault or a wide deformation zone (WDZ) consisting of a group of faults located next to each other. To investigate the orientation of shear zone formed in a WDZ, we make a simple 2-D FEM. Model consists of Oceanic and continental plates, which were separated from each other by a WDZ, and the upper mantle (Fig. 2c). A convergence rate of 2 cm/yr is imposed in the right side of the model to push oceanic plate towards continental one. After 1 Myr of convergence, viscous weakening allows formation of two localized shear zones in the WDZ (red lines in Fig. 2c). Due to foundering of the oceanic plate into the mantle, eventually only the shear zone which dips towards the continental plate remains active. The dip of this shear zone depends on the width of the WDZ.



(2c): Effective strain rate distribution showing formation of shear zones in a WDZ. Red lines indicate location of the shear zones.

3) 2-D finite element model



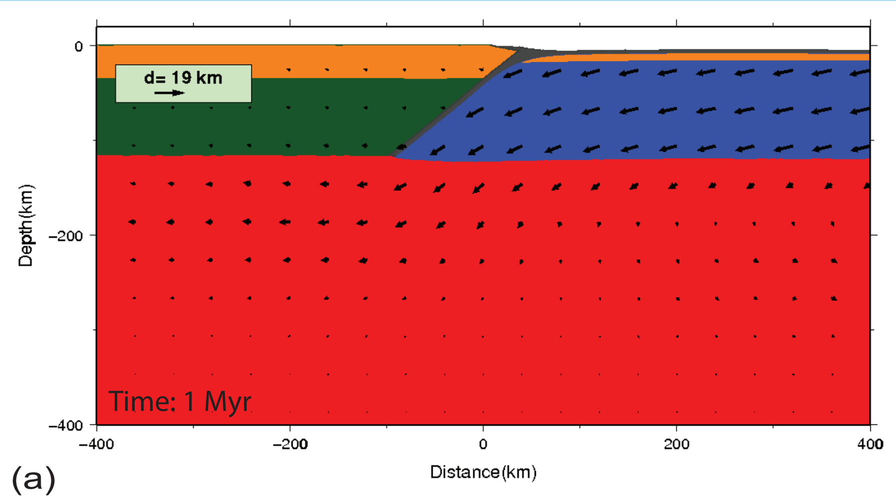


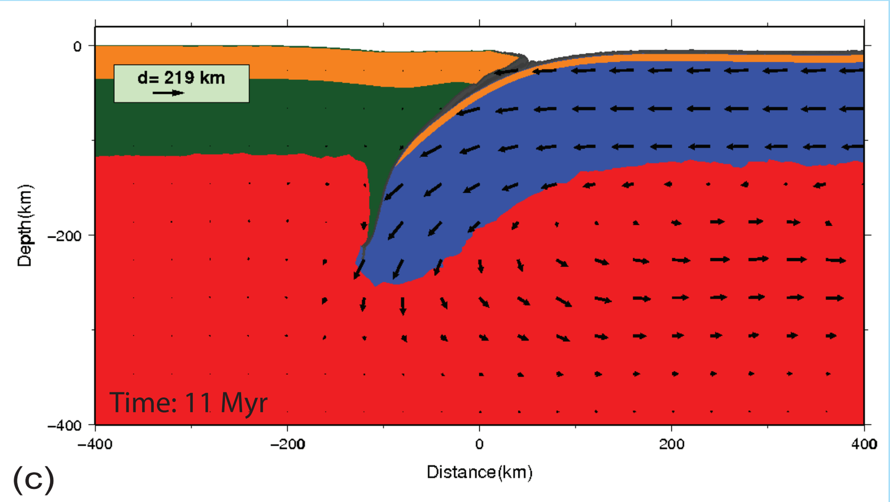
(3): Model setup for the subduction initiation at a STEP. a) boundary conditions for the mechanical solution, b) temperature distribution. Material properties and boundary conditions used for temperature calculations are also shown in the figure.

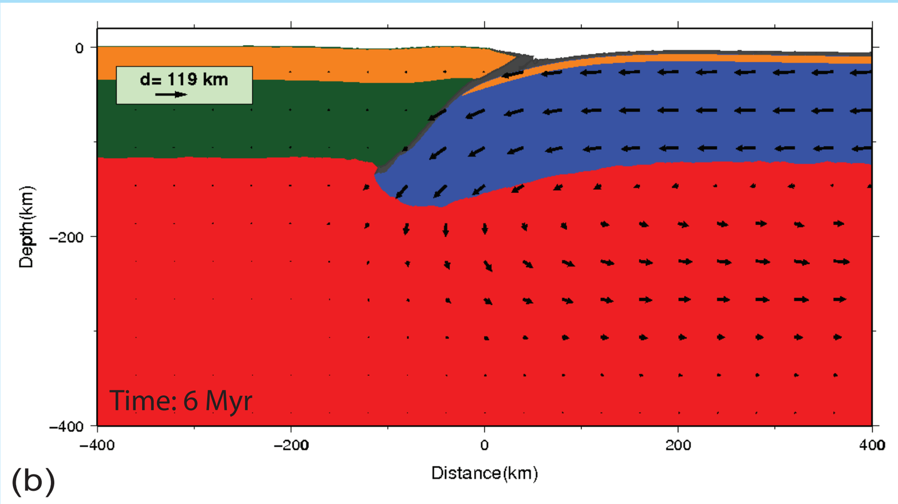
To investigate the scenario described in section 2, we select a cross section to make a 2-D elasto-viscoplastic model. The green line in Fig. 2a shows the approximate location of the cross-section, which we select for the model. Constraints on our model come from published geological data and paleogeographic reconstructions for the Late Oligocene - Early Miocene. The model domain covers an area of 2400 ×660 km. The oceanic plate is moving towards the continental plate with a convergence rate of 2 cm/yr (Fig. 3a). We select our reference model to have a channel width of 6km and dip angle of 40°. We later examine the sensitivity of the results to this choice.

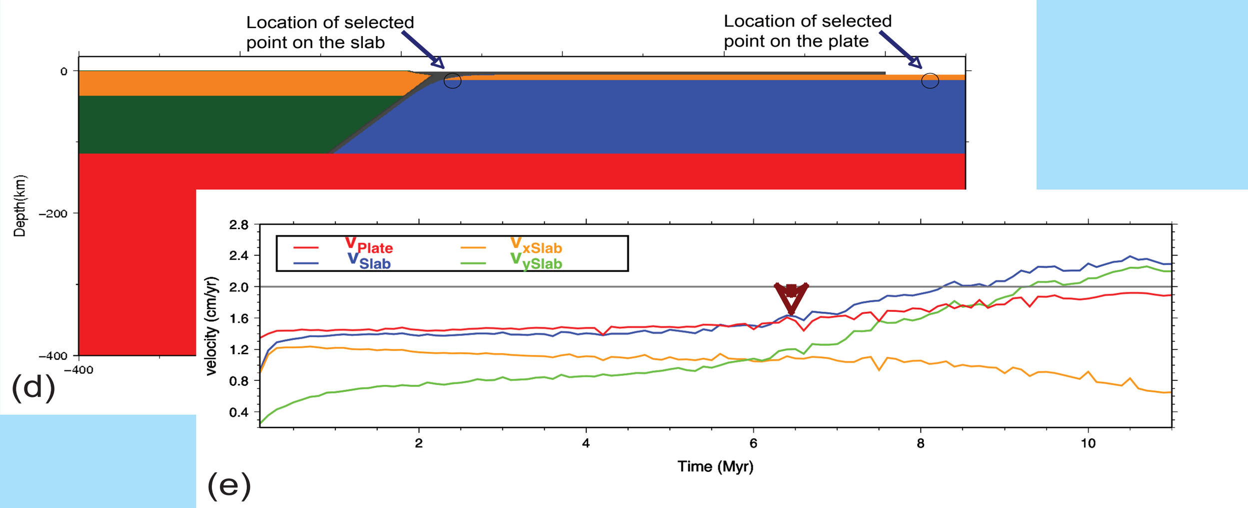
The initial geotherm for the oceanic plate is defined using the plate model, considering a plate with the age of 120 My and thickness of 110 km. The temperature in the continental plate is calculated based on steady-state diffusion equation. An adiabatic gradient of 0.3 K/km is selected for the mantel below the lithosphere (Fig. 3b).

4) Model results







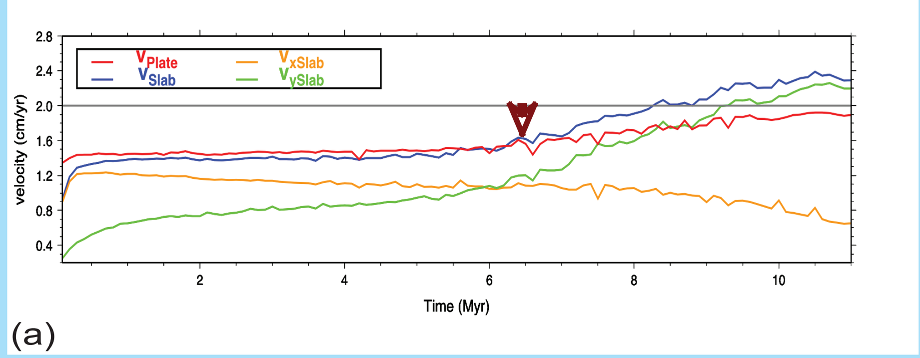


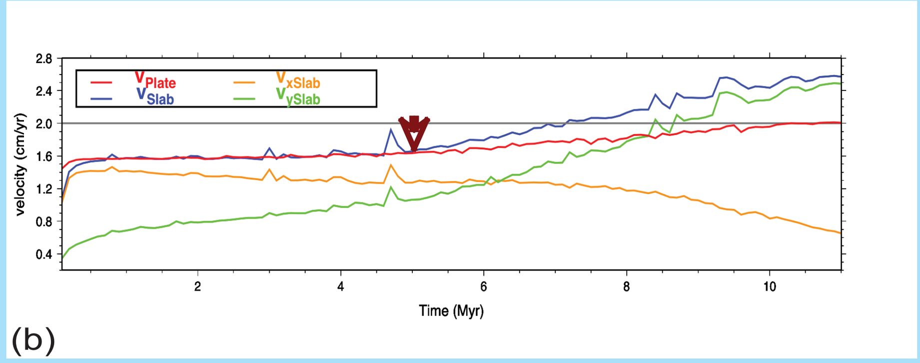
(4): Model results. a-c) displacement field at 1, 6, and 11 Myr, respectively. e) velocity of one point on the slab and one point on the oceanic plate against time. The location of selected points on the slab and oceanic plate is shown in figure d. Brown arrow in figure e indicates the time when subduction becomes self-sustained.

Figures 4a-c show the displacement field at different times. Results show that after a short time of resistance, oceanic plate starts to subduct beneath the continental plate. To identify the time when subduction becomes self-sustained, we track the velocity of one point on the oceanic plate and one on the slab (the location of selected points are shown in Fig. 4d). At about 6.5 Myr the velocity of the slab exceeds the plate velocity. At the same time the vertical component of slab velocity is increasing, indicating that subduction has changed to the self-sustaining state (Fig. 4e). This event happens after ~120 km of convergence which agrees well with the results of Hall et al, 2003.

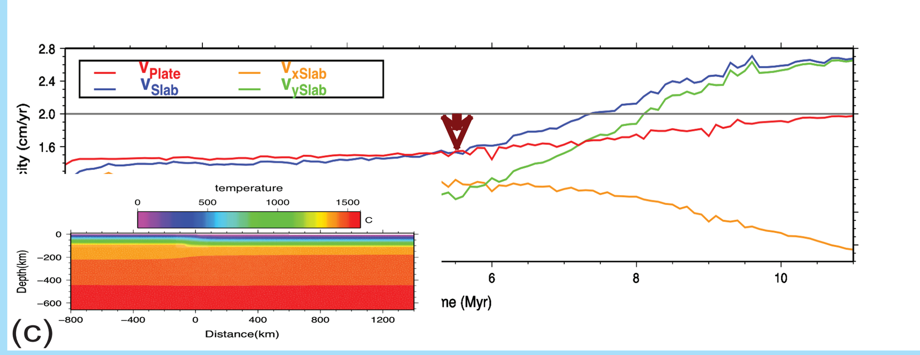
5) Sensitivity Analysis of the model results

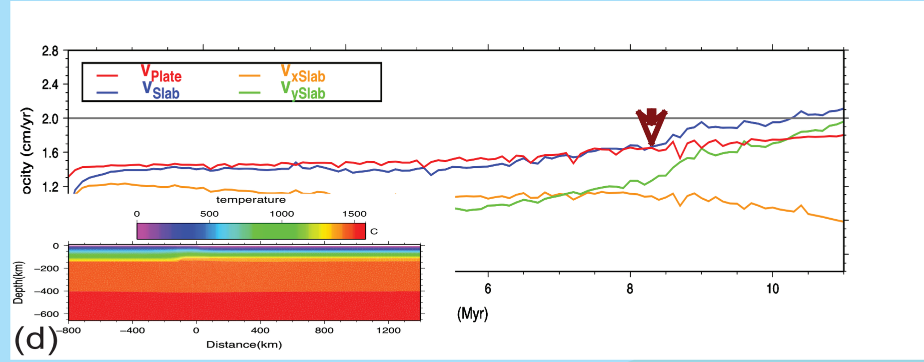
Channel width



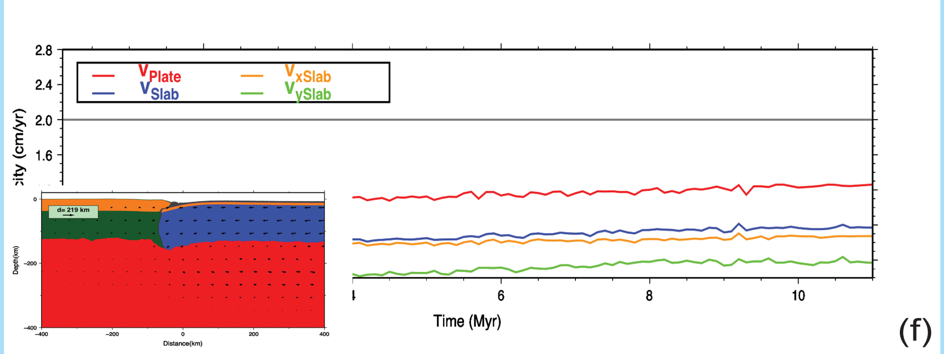


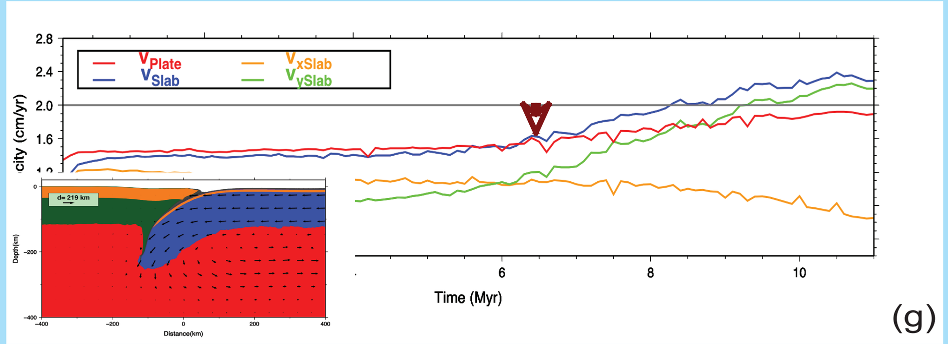
Thickness of continental plate

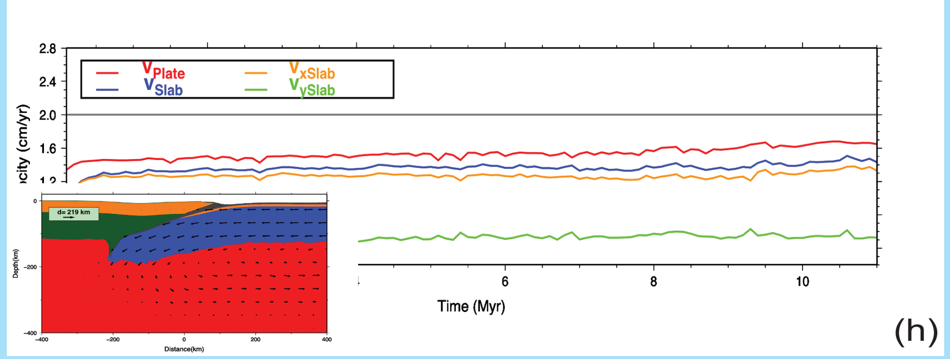




Channel dip angle

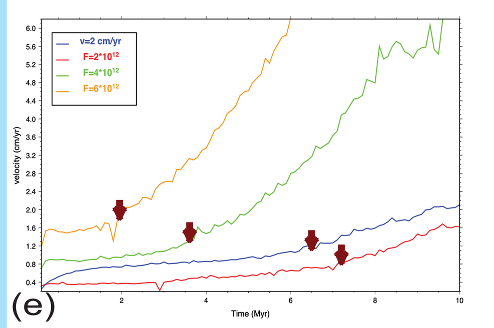






(5): Sensitivity of the model results. Slab velocity and plat velocity against time for a model with: a) channel width of 6km, b) channel width of 8km, c) continental plate of 90km, d) continental plate of 160km, f) channel dip angle of 80°, g) channel dip angle of 40°, h) channel dip angle of 20°. Insets in Figures c and d indicate the initial temperature distribution and Insets in Figures f, g, and h show the displacement field at 11Myr. Figure e shows the vertical component of slab velocity against time for different boundary conditions. In all figures the brown arrows point out the time when subduction becomes self-sustained

Force or velocity BC



We examine the influence of some initial parameters, which we chose in our reference model, on the results. In models with wider channel slab velocity exceeds the plate velocity sooner, indicating that subduction becomes self-sustained faster (Fig. 5a-b). Since in our models the base of the lithosphere is determined thermally, plates interface becomes hotter when the continental plate is thinner. As a consequence, the amount of coupling between two plates decreases which leads to speeding up the initiation process (Fig 5c-d). In models with very steep channel (with dip angle of ~80°) STEP doesn't convert into a subduction zone, even after 11Myr of convergence (Fig. 5f). On the other hand, reducing the channel dip angle to a very shallow dip (20°) doesn't facilitate initiation of subduction (Fig. 5h) . We find that the optimal channel dip angle, favorable for incipient subduction, is about 40°-60° (Fig. 5g). When oceanic plate is pushed towards the continental plate with forces larger than ridge push force (> 4×10^12), subduction becomes mature in less that 2 Myr (Fig. 5e).

Conclusions

Results of our numerical model show that:

- Subduction becomes self-sustaining after ~120km of convergence.
- A dip angle of 40-60 degrees facilitates subduction initiation.
- A wider channel speeds up the initiation process.
- Thicker continental plate results in increasing the amount of coupling between two plates, leading to slowing down the subduction process.
- A STEP fault converts into a subduction zone much faster when, in addition to the ridge push, integrated forces from adjacent subduction zones drive plates towards each other.

References

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