State of the art numerical subduction modelling with ASPECT

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CEED The Centre for Earth Evolution and Dynamics

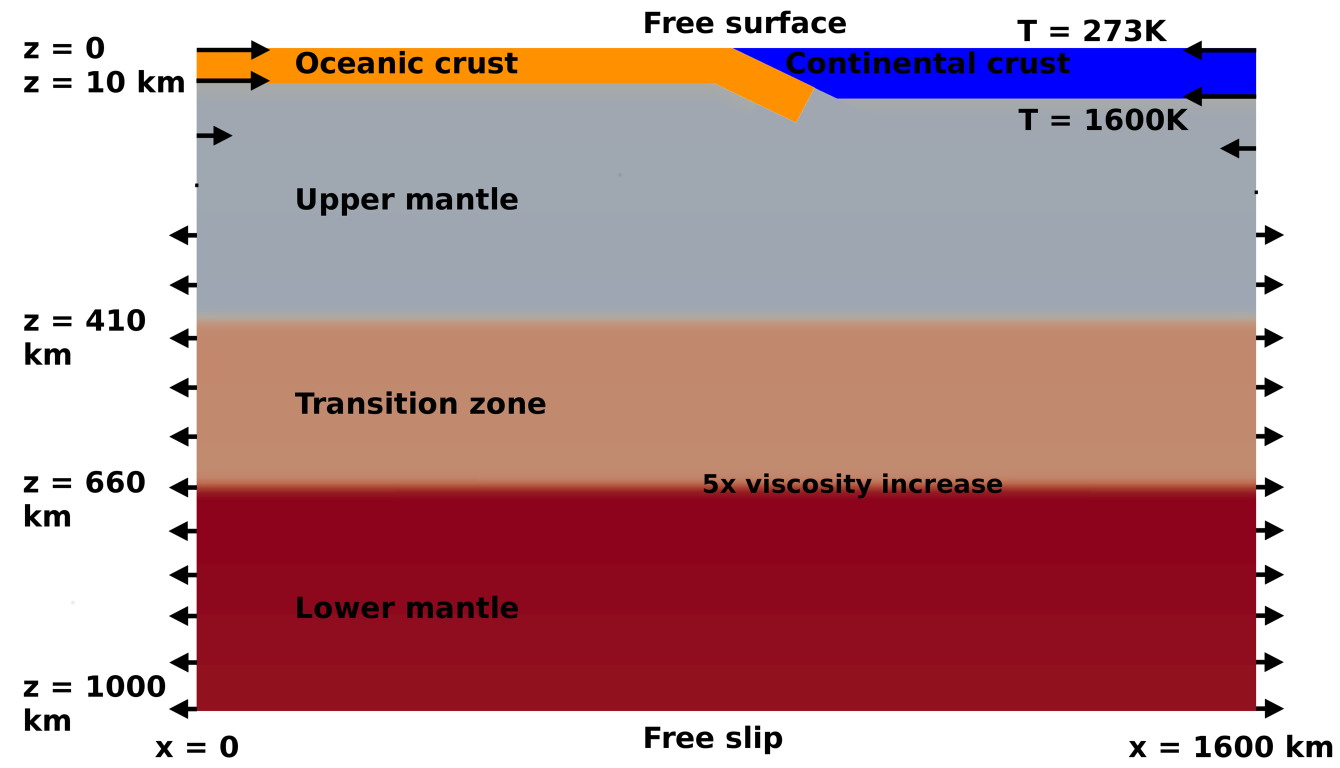
Introduction

Increasingly powerful computers allow for more realistic models resulting in more parameters to be investigated. To comprehend a complex subduction system, the effects of individual processes should be understood (Gerya, 2011). Here, we investigate several processes by addressing the following questions:

- What are the effects of compressibility on a subduction setting?
- What are the effects of mantle phase transitions on a subducting slab?
- How do boundary conditions, especially open boundaries, affect subduction geometry and mantle flow?

To this end, we run a thermo-mechanically coupled subduction model with a visco-plastic rheology (Glerum, in prep. and Fraters, 2014) using ASPECT (short for Advanced Solver for Problems in Earth's ConvecTion, Bangerth et al., 2014). The viscosity profile with depth is in accordance with Steinberger and Calderwood (2006) and Cizkova et al. (2012).

Model setup



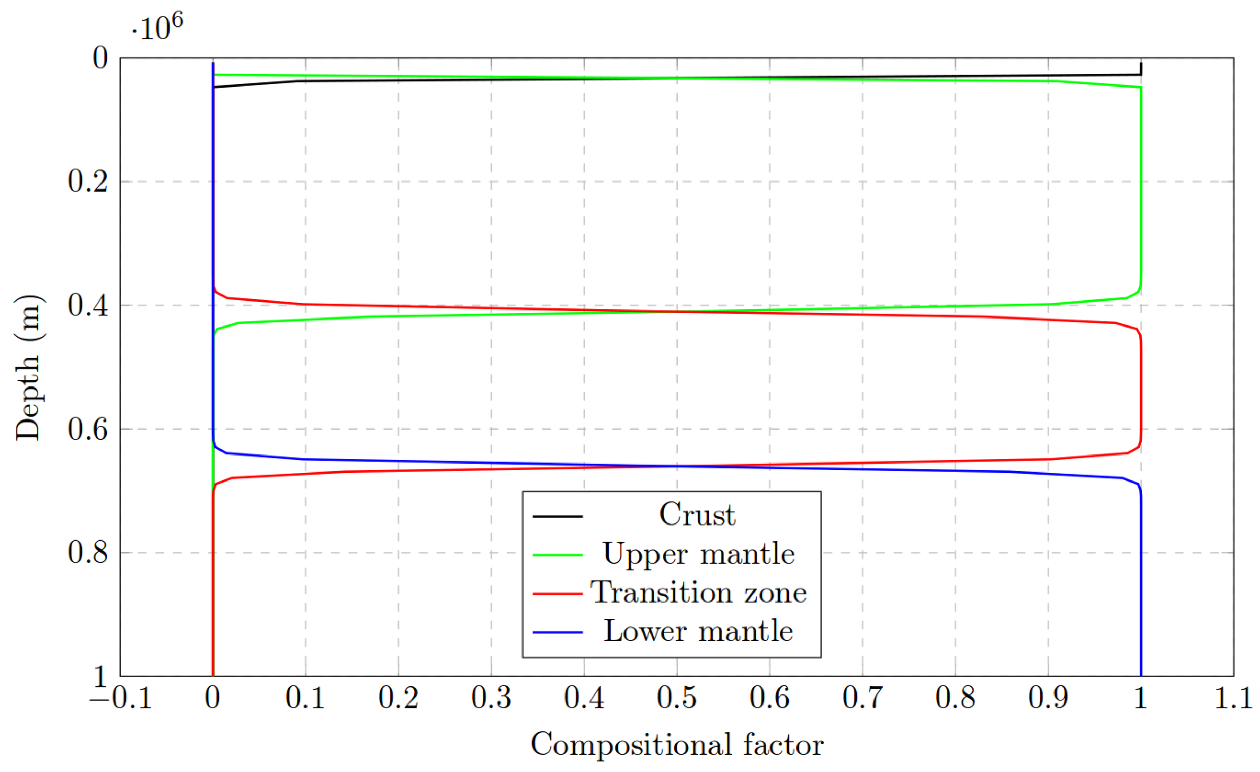
- 2D Cartesian box.
- Five initial compositional fields + two more compositional fields when a subducting slab crosses the phase transitions.
- The surface is defined by either a free slip or a free surface boundary condition.
- The sidewalls can be defined by free slip, prescribed velocity or true open boundary conditions.
- At the 410 km phase transition $\Delta\rho = 273$ kg.
- At the 660 km phase transition $\Delta\rho = 342$ kg and the viscosity increases 5 times.

Implementing phase transitions

Phase transitions have been implemented using the formula below which is based on a pressure dependent formula by Richter (1973). The pressure dependence has been rewritten into a depth dependence for two reasons. First, a pressure dependence causes compositional instabilities when the pressure is negative (e.g. due to a free surface). Second, the depth of the phase transitions does not change over time when the pressure changes.

$$\pi = \frac{1}{2}\Big[1 + tanh\Big(\frac{z - z_t - \gamma\frac{z_t}{P_t}(T - T_t)}{d\frac{z_t}{P_t}}\Big)\Big]$$

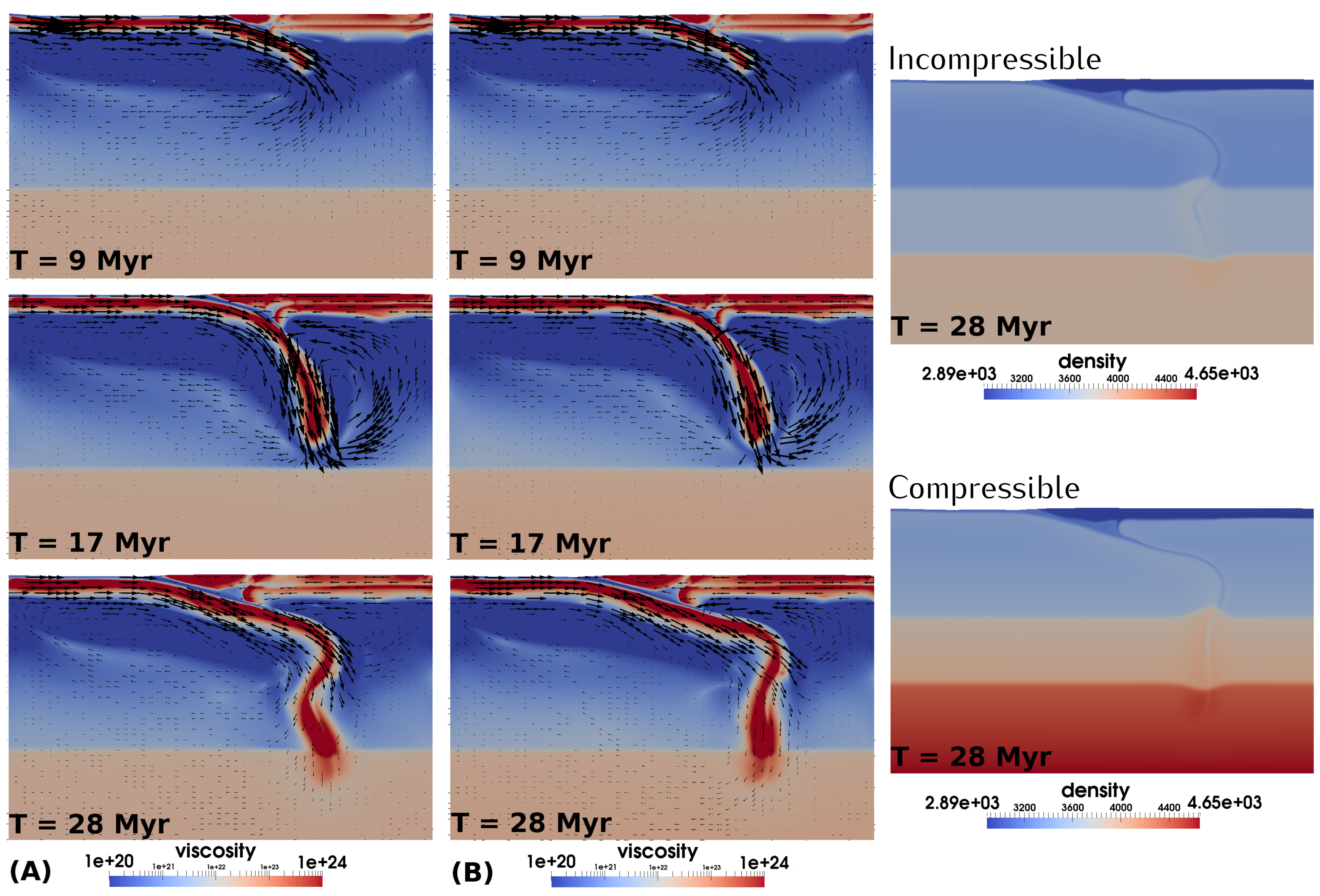
In this formula π is the phase transition function, z the depth, γ the Clapeyron slope, P the pressure and d is half of the transition width. The subscript t denotes the phase transition number. The figure below shows the initial distribution of the compositional fields with depth. Phase transitions are located at depths where two lines intersect.



Phase transitions and compressibility

Both models have a free surface and a prescribed inflow on the left (0.04 m/yr) and right (-0.02 m/yr) boundaries. Only when the slabs hit the 660 km phase transition, a noticeable dissimilarity can be observed between the incompressible model (A) and compressible model (B). The density field of the compressible model shows a more pronounced slab (i.e. a larger density contrast) which subducts more vertically into the lower mantle compared to the incompressible model.

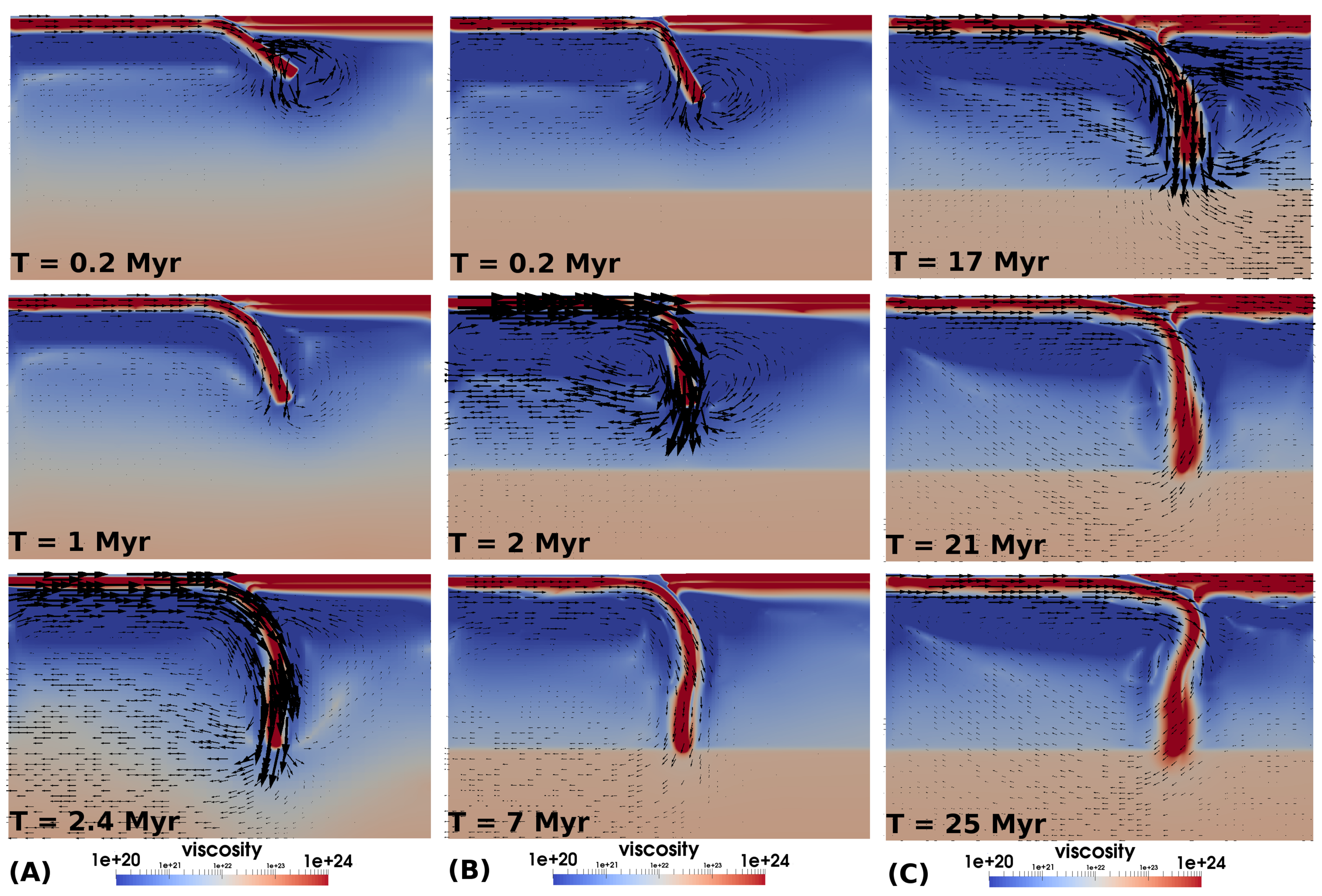
Incompressible | Compressible | Density profiles



Open boundary conditions

An open sidewall (A & B) allows the subduction velocity to increase until the slab reaches the bottom of the domain or approaches a phase transition. Also, mantle flow is limited to the depth to which the slab has subducted. A prescribed inflow combined with an open sidewall (C) may result in the continental plate moving in both directions at different times.

Top: free slip, Left: open boundary | Free surface, Left: open boundary | Free surface, left: prescribed velocity, right: open boundary



Conclusions

- When using prescribed inflow boundaries, the effect of compressibility on subduction modelling is only noticeable when a subducting slab hits the 660 km phase transition.
- When using open boundaries, the velocity of the subducting slab increases after it crossed the 410 km phase transition.
- A 5 times viscosity increase at the 660 km phase transition obstructs subduction greatly. Most of the slab is trapped at the phase transition and will start to fold.
- Open boundaries allow the velocity of the subducting and/or overriding plates to change freely depending on their buoyancy and mantle viscosity. A large viscosity increase at a phase transition may cease subduction if slab pull is the main driving force.
- Open boundaries limit mantle flow to the depth to which the slab has subducted. Lower velocities are observed in the lower mantle where viscosities are high.

References

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