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The role of elastic compressibility in dynamic subduction models

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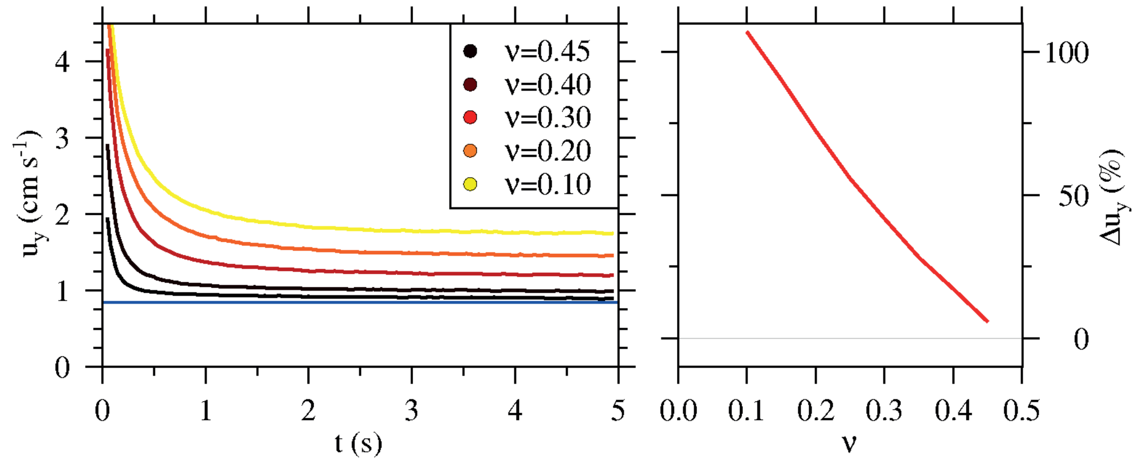
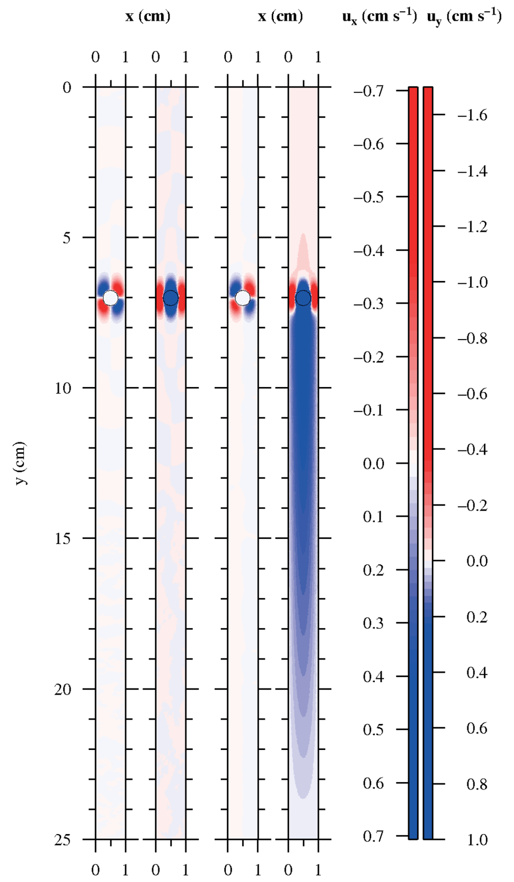
Introduction

The Earth has a complex rheology including an elastic, viscous and plastic response. For numerical models to be both accurate and fast simplifications needs to be made. Mantle convection models often ignore the effect of elastic deformation under the assumption that it is only significant on small time scales. Moreover, models that include elastic effects often ignores the effect of compressibility which contradicts rock mechanical experiments.
Here, the effect is tested for an Earth-like setting: the subduction of oceanic lithosphere underneath continental lithosphere and is the extension of the work done with a much simpeler setup (see below).

Effect on a Sinking Cylinder





The effect of elastic compressibility on the settling velocity of a gravity driven cylinder is examined with a finite element code that solves the mechanical equilibrium equation for a Maxwell viscoelastic rheology (Austmann et al. in prep). The fluid is homogeneous and bounded by no-slip conditions.
In the left panels are the horizontal and vertical velocity field for the incompressible (left) and compressible (right) solution displayed. A downward motion of the cylinder is observed, which compresses the fluid in the region below the cylinder. Thereby, the resistance on the cylinder is decreased. The vertical velocity through time for different Poisson ratios is displayed in the top panel.

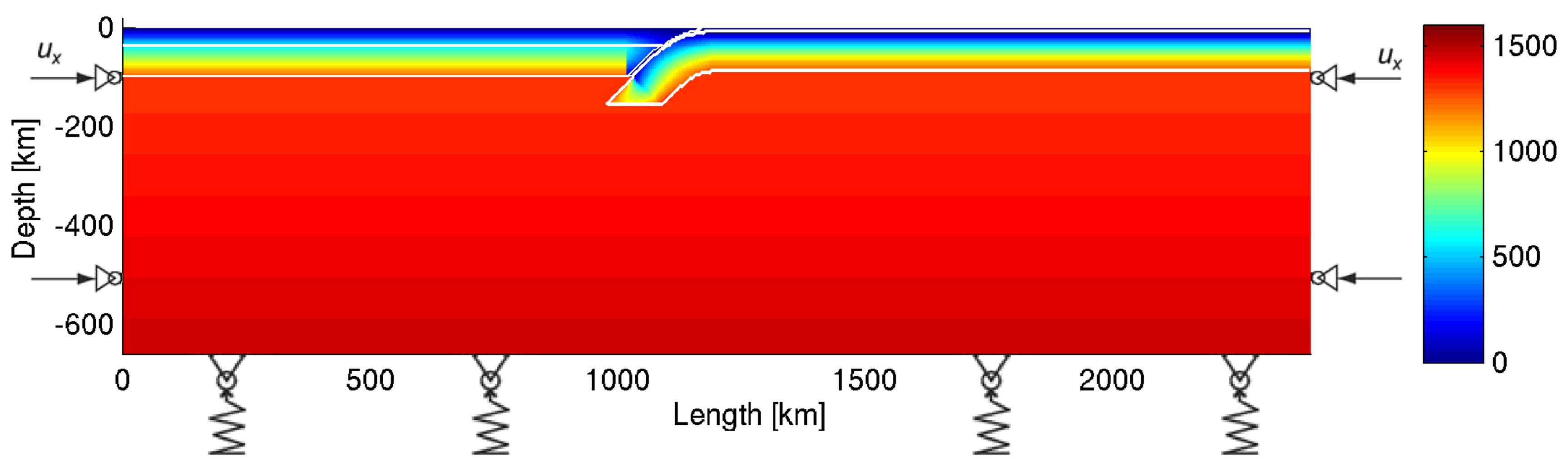
We conclude that the effect of elastic compressibility is significant for the case of a sinking cylinder in a bounded medium: an Earth-like Poisson ratio of ν=0.3 results in an increase of the sinking spreed by 40%.

Elastic Compressibility in terms of Poisson Ratio (ν)

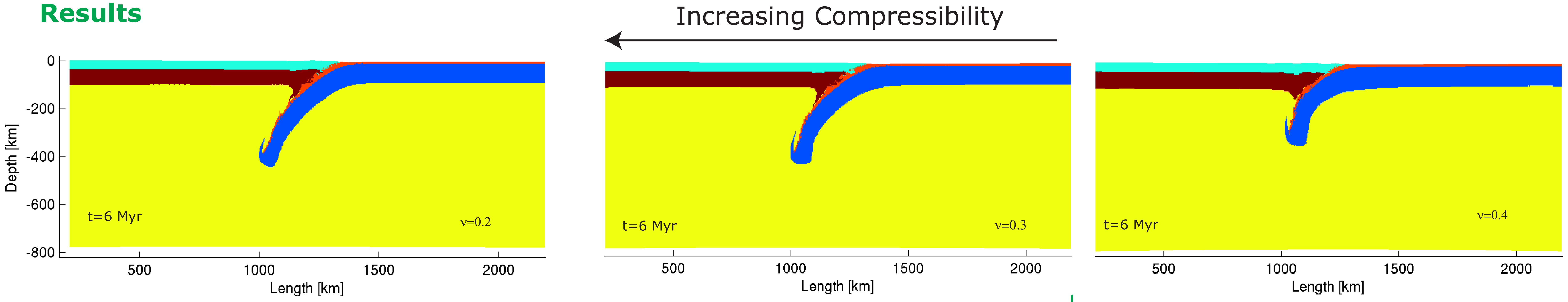
Elastic compressibility is measured in terms of the Poisson's ratio (ν), defined by the ratio of the transverse and the axial strain rate. A Poisson's ratio of 0.5 means a purely incompressible fluid, which is representative for fluids like water. Crustal rocks have a Poisson ratio in the range 0.1-0.4 and Mantle rocks have a Poisson ration 0.2-0.3 (Turcotte et al. 2002).
In this study, for simplicity, we assume a constant Poisson's ratio throughout the whole domain.

Model Setup

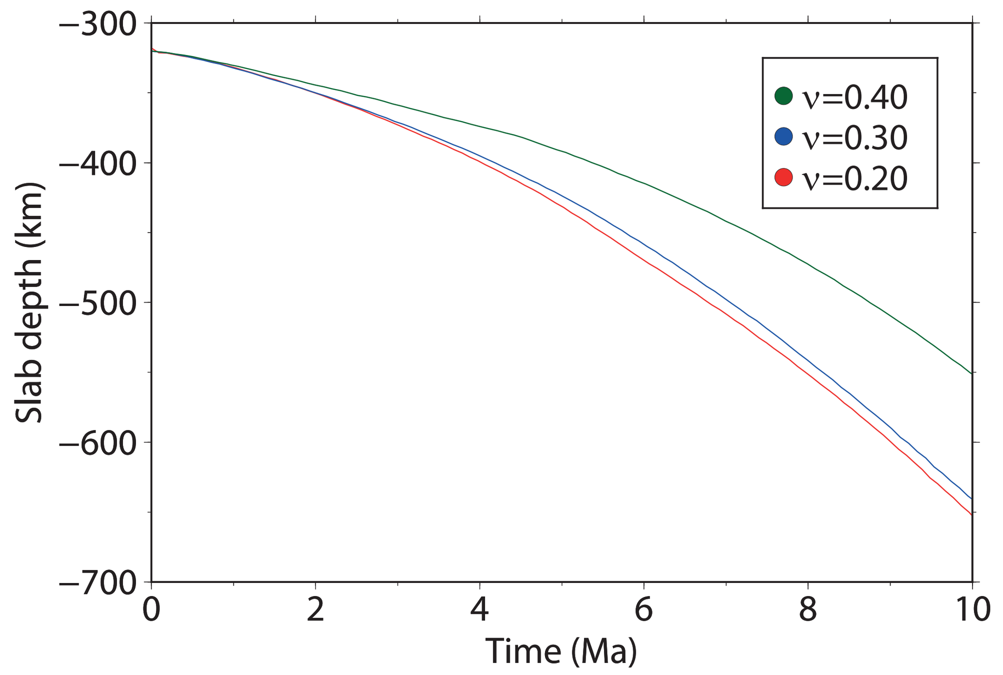
We study the ongoing subduction of oceanic lithosphere underneath a continental lithosphere. Initially the plate has been subducted to a depth of 150km. The oceanic plate consists of a 8km thick crust overlying a 80km lithosphere. The temperature is calculated using the Plate Model with an age of 33Myr at the right side of the domain.
The continental plate is made of a 35km thick crust and a 65km lithosphere and has a steady state geotherm with a 65 mW/m surface heat flow. The heatflow decreases near subducting plate, representing the cooling by the subducting plate.
The convergence velocity between the two plates is 6.9 cm/yr. On the bottom a Winkler condition is applied. The plate boundary is represented by a low-viscosity channel.

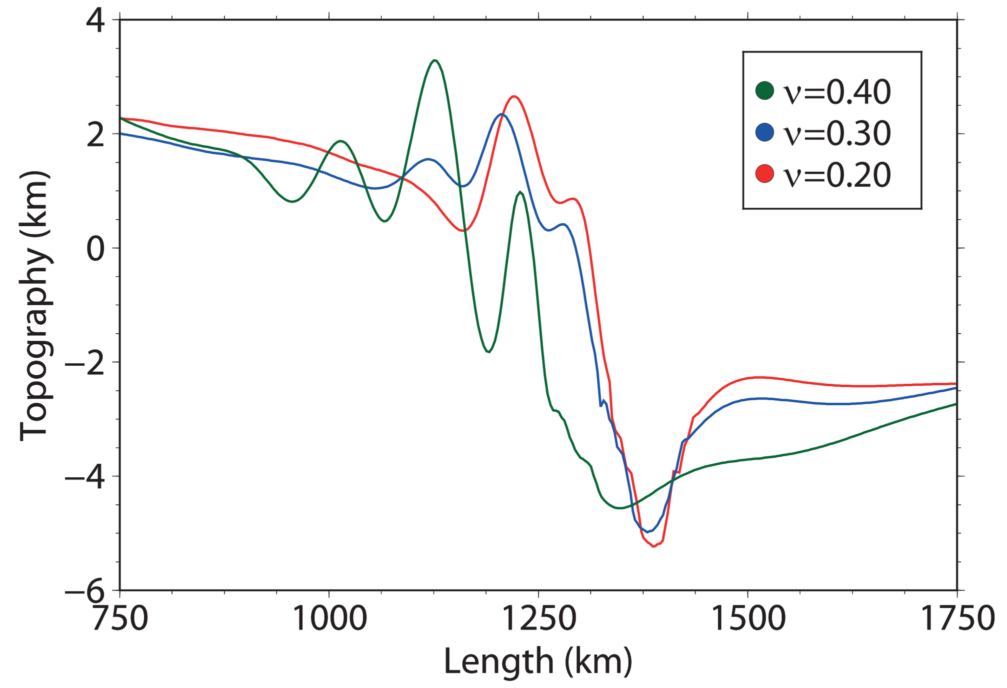


Results



In the three panels above are snapshots given of the model after 6 Myr. The only thing that is changed is the Poisson ratio (which is uniform in all models) increasing from left to right. The most important observation is the decrease in the sinking velocity of the slab for an increasing Poisson ratio. These observations are consistent with the results from the experiments with the sinking cylinder.
The depth of the slab tip is further evaluated in the figure on the right. Note that the differences between ν=0.2 and ν=0.3 are much smaller than the differences between ν=0.3 and ν=0.4
In the figure below is the topography for the different models displayed.





Numerical Code

The model is solved using the explicit time-marching Lagrangian code FLAMAR (e.g. Burov et al. 2008). It solves the momentum and heat equation for an elastic-viscous-plastic rheology. Elasticity is included by a Maxwell rheology, whereby the elastic part satisfies Hooke's Law.

Discussion

In all the models the driving force (i.e. gravity and convergent boundary conditions) is the same. However, the response is quite different. Hence, elastic compressibility has an important effect on the dynamics of the subduction zone of which the most important is that an decrease in the Poisson ratio leads to larger sinking velocities.

Since the Poisson ratio is varied uniformly throughout the whole model, it is difficult to pin down the mechanism for this. Based on the experiments with the sinking cylinder is seems reasonable that it is caused by the flow of subduction channel and the astenosphere. However, flexural response might also play a role.

Conclusion

Elastic compressibility can have a significant effect on the dynamics of a subduction zone. A decrease in the Poisson ratio leads to an increase in the sinking velocity of the slab.
Assuming an incompressible medium would results in an underestimation of the velocities in the models. Hence elastic compressibility does not only has an effect on small time scales, but also on the dynamics of the system at the time scales of mantle convection and hence elastic compressibility may not be ignored in the modelling of subduction zones.