Presented at the COMSOL Conference 2009 Milan

Modeling with COMSOL the Interaction between Subducting Plates and Mantle Flow

J. Rodríguez-González[1], A. M. Negredo[1], P. Petricca[2], E. Carminati[2,3]
1 Departamento de Geofísica y Meteorología, Facultad de CC. Físicas, Universidad Complutense de Madrid, Av. Complutense s/n, 28040 Madrid, Spain
2 Dipartimento di Scienze della Terra, Università di Roma “La Sapienza”, Roma, Italy
3 Istituto Geologia ambientale e Geoingegneria CNR, Roma, Italy

Abstract

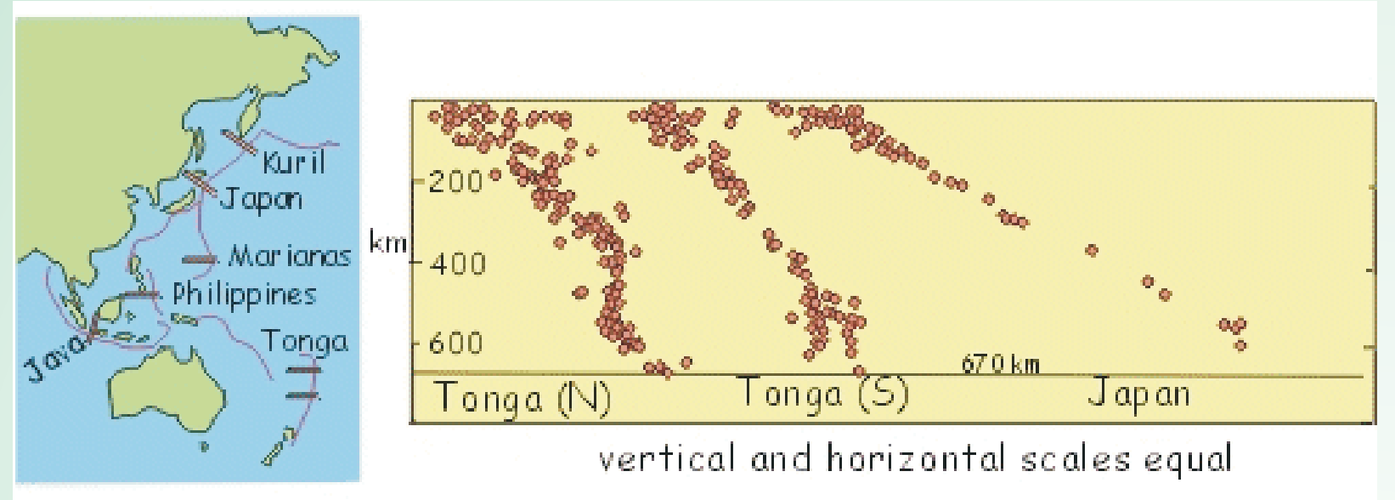
Subduction processes have great importance as are related to volcanism and earthquake occurrence. Old and cold plates are expected to subduct steeper than younger ones owing to the higher density contrast between the subducting slab and the surrounding mantle. However, there is a large variability of the observed subduction angles, which do not always correlate with the age of the plates (Cruciani et al., 2005; Lallemand et al., 2005).

Some researchers propose a global or net westward drift of the lithosphere relative to the mantle, but this assessment is still a matter of debate. The relative motion between lithosphere and underlying mantle would affect the geometry and angle of subduction. To test this influence, we have run several simulations in which the evolution during subduction is simulated by solving the equations of conservation of mass, momentum and energy for a high density and high viscosity fluid in 2-D. A horizontal flux has been imposed on the sublithospheric mantle to test its effect.

This flux has little effect on the subduction angle in the shallower part of the slab, but this effect becomes significant in the deeper region and in some cases it inhibits the penetration of the slab into the lower mantle.

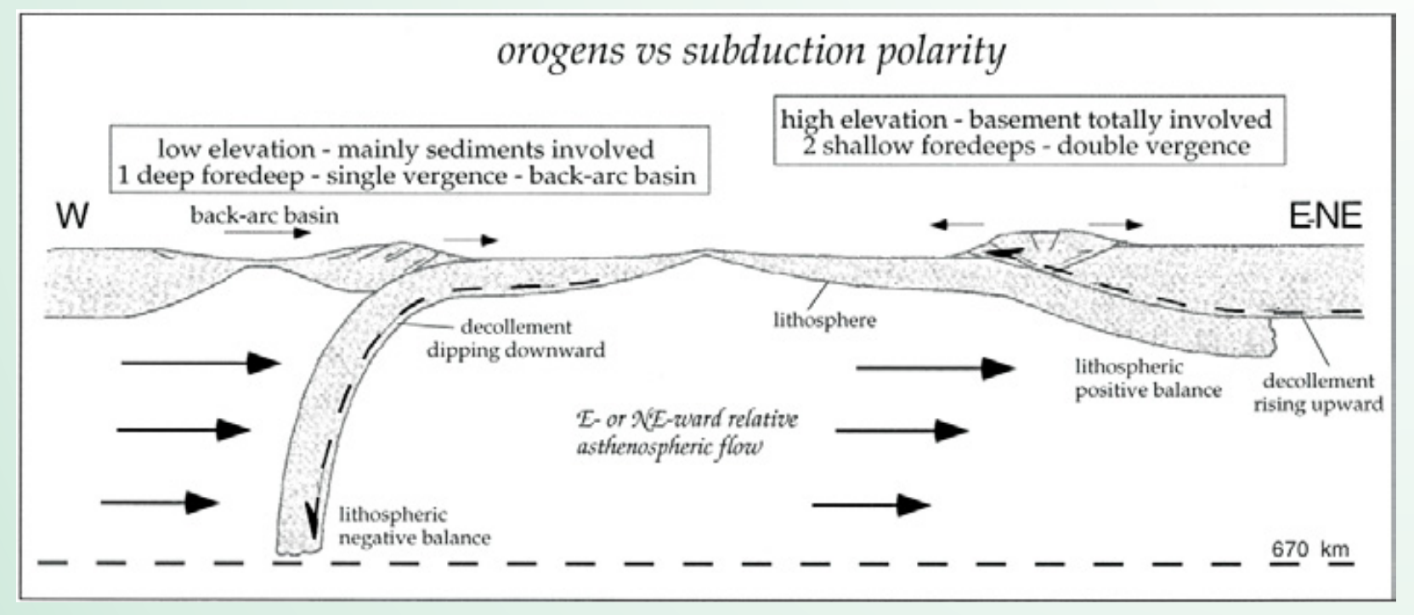
1. Introduction

1.1 Subduction angle variability.



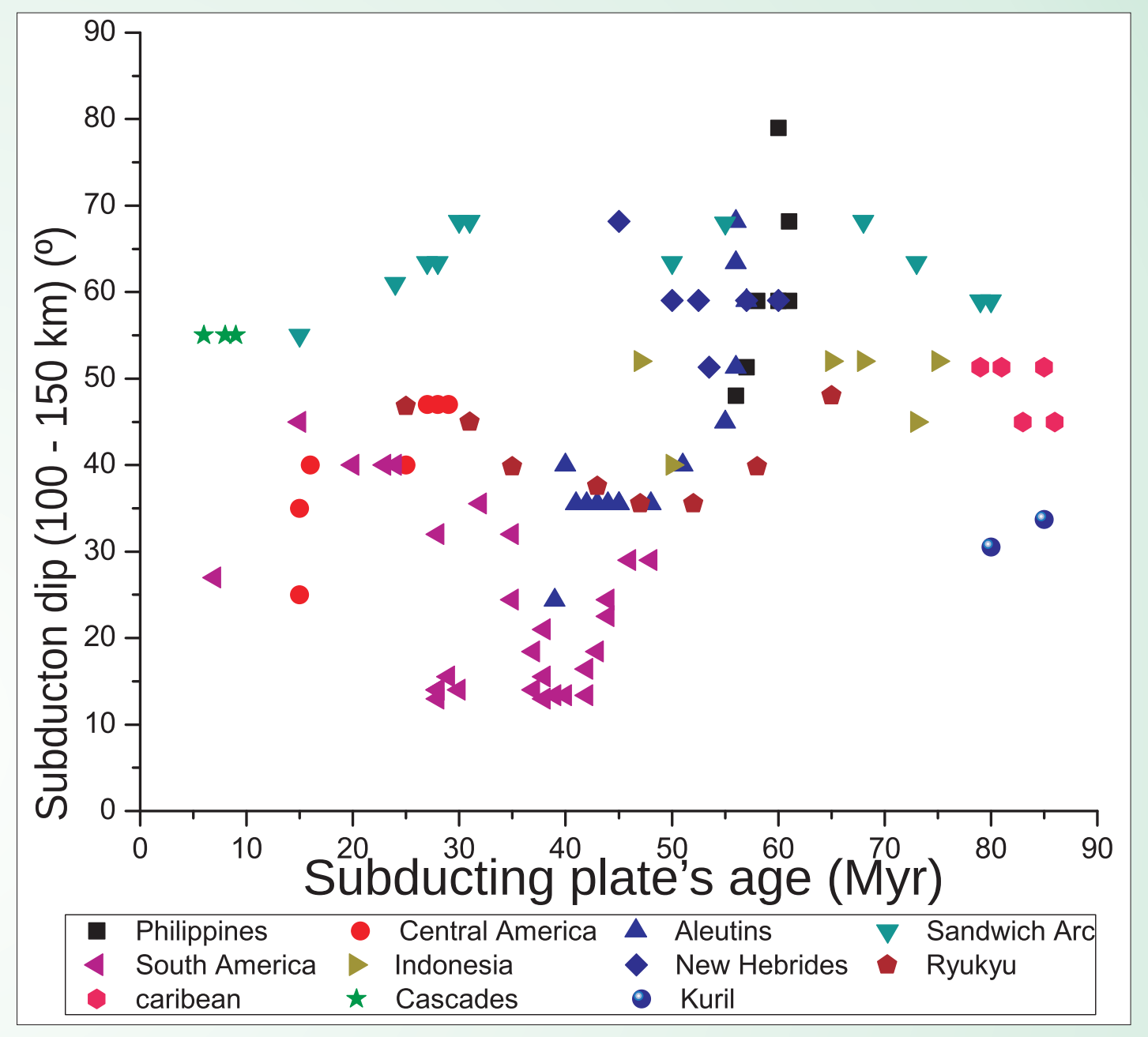
Examples of three subduction zones, where the dips of Wadati-Benioff planes show high variability (Buttler, 2001).

1.3. Horizontal asthenospheric flux



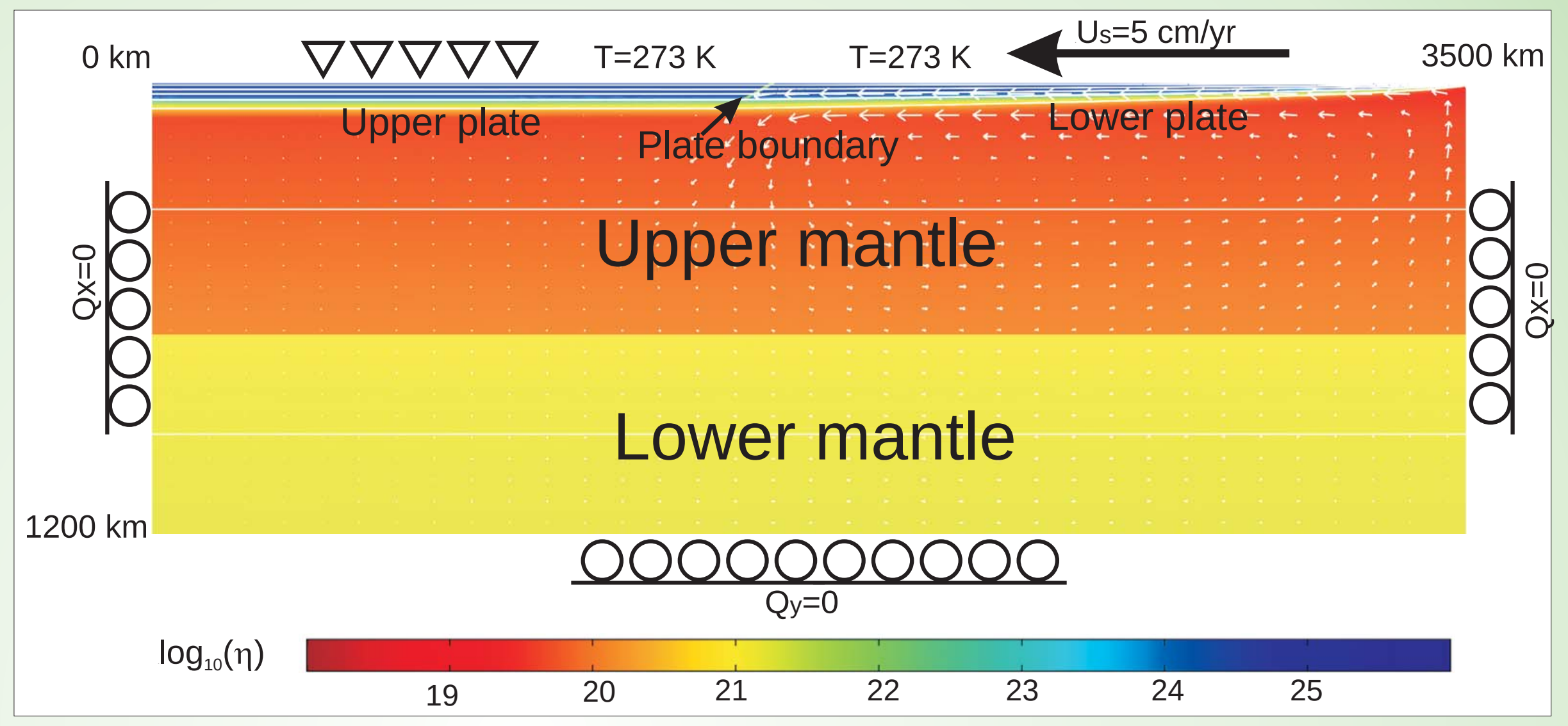
Eastward flow of the mantle relative to the overliying lithosphere proposed by different authors (e.g. Doglioni et al., 1999). This flow is expected to change the slab dip if it opposes or accompanies the relative mantle flow.

1.2. Lack of correlation angle/age



Slab dip measured along different transects plotted against their lower plate age. The lack of correlation is in contrast with the idea of an older, and therefore colder and heavier, plate subducting with a higher angle than a younger one. Data from Cruciani et al. (2005).

2. Numerical method



Vertical section parallel to the subduction direction. Boundary conditions and initial viscosity distribution for the reference model (without horizontal asthenospheric flux) are shown.

Subduction is reproduced by imposing a low viscosity channel on the plate boundary and a velocity of 5 cm/yr at the surface of the subducting

To reproduce horizontal mantle flow, an inlet velocity is applied at one of the lateral boundaries, from 95 to 670 km depth, while the same outlet flux is imposed on the opposite boundary.

The Navier-Stokes (ns) and convection and conduction (cc) equations are solved by using PARDISO solver from the software COMSOL Multiphysics:

$$\rho\frac{\partial\vec{u}}{\partial t}-\nabla\left[\eta\left(\nabla\vec{u}+(\nabla\vec{u})^{T}\right)\right]+\rho(\vec{u}\nabla)\vec{u}+\nabla P=\vec{F}$$

$$\rho C_{P}\left(\frac{\partial T}{\partial t}+\vec{u}\nabla T\right)-\nabla(\kappa\nabla T)=Q$$

The viscosity has the expression (Hirth and Kohlstedt, 2003):

$$\eta_{df,ds}=\left(\frac{d^{p}}{AC_{OH}^{r}}\right)^{1/n}\dot{\epsilon}_{II}^{\frac{1-n}{n}}\exp\left[\frac{E+P_{lit}V}{nRT}\right]$$

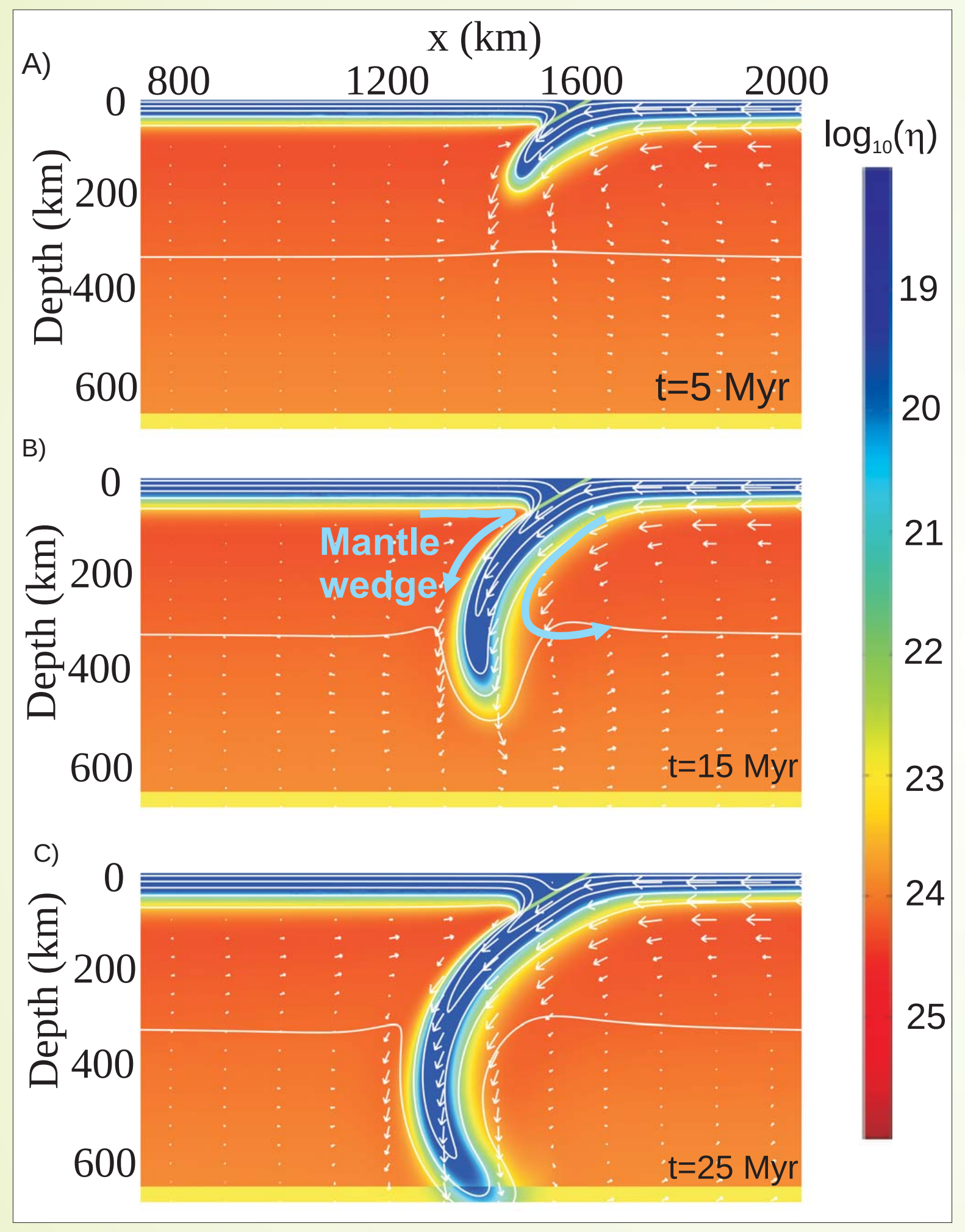
n=1 → Linear rheology

n>1 → Non linear rheology

A grid of 15000 to 30000 triangular (advancing front) elements has been used. The density of the mesh varies from one node every 2 km in the plate boundary area to one every 150 km on the lower mantle.

3. Reference model

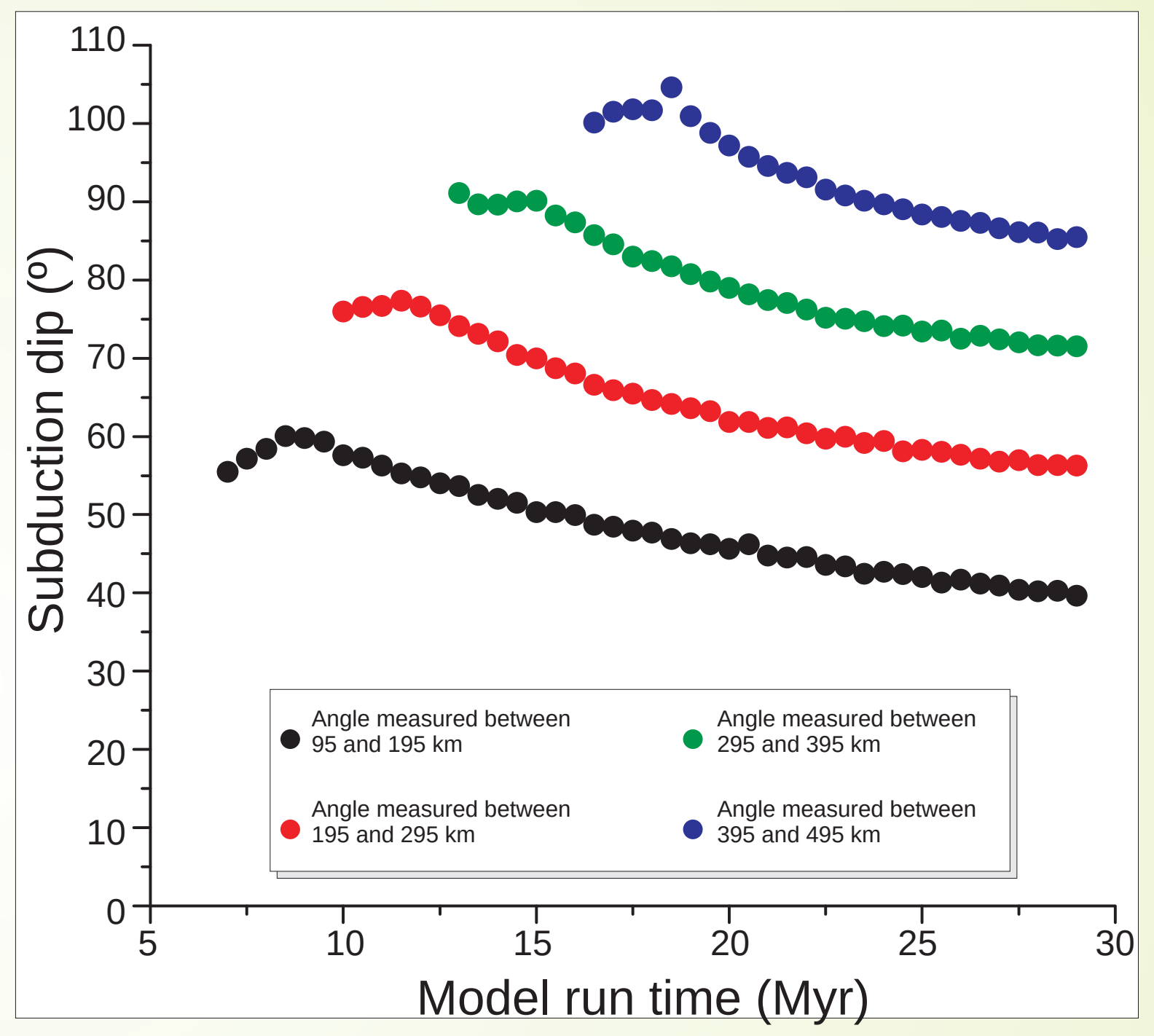
3.1 Evolution of the simulations



A) At the beginning of the simulation, the lower plate bends initiating subduction.

B) and C) The cold slab penetrates into the hotter mantle and an intense flow is created on the mantle wedge, generating suction forces.

3.2 Evolution ot the subduction dip measured at different depths

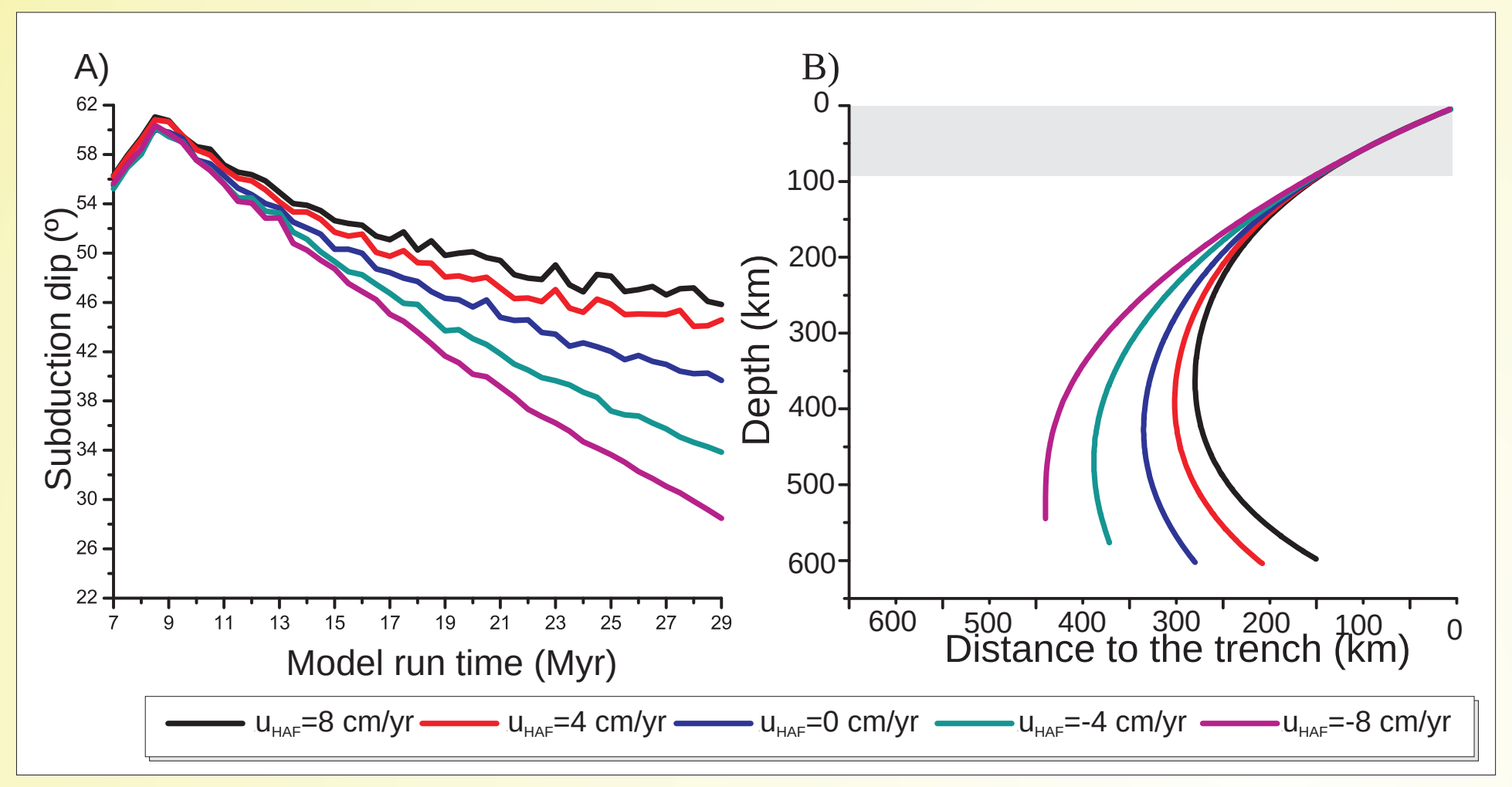


As the gravitational torque is higher in the deeper region of the slab the angle of this portion is also higher.

While the model evolves, the suction at the asthenospheric wedge increases and therefore, the angle of subduction decreases with time at all depths

4. Effect of the horizontal asthenospheric flux

4.1 Simulations with horizontal asthenospheric flux

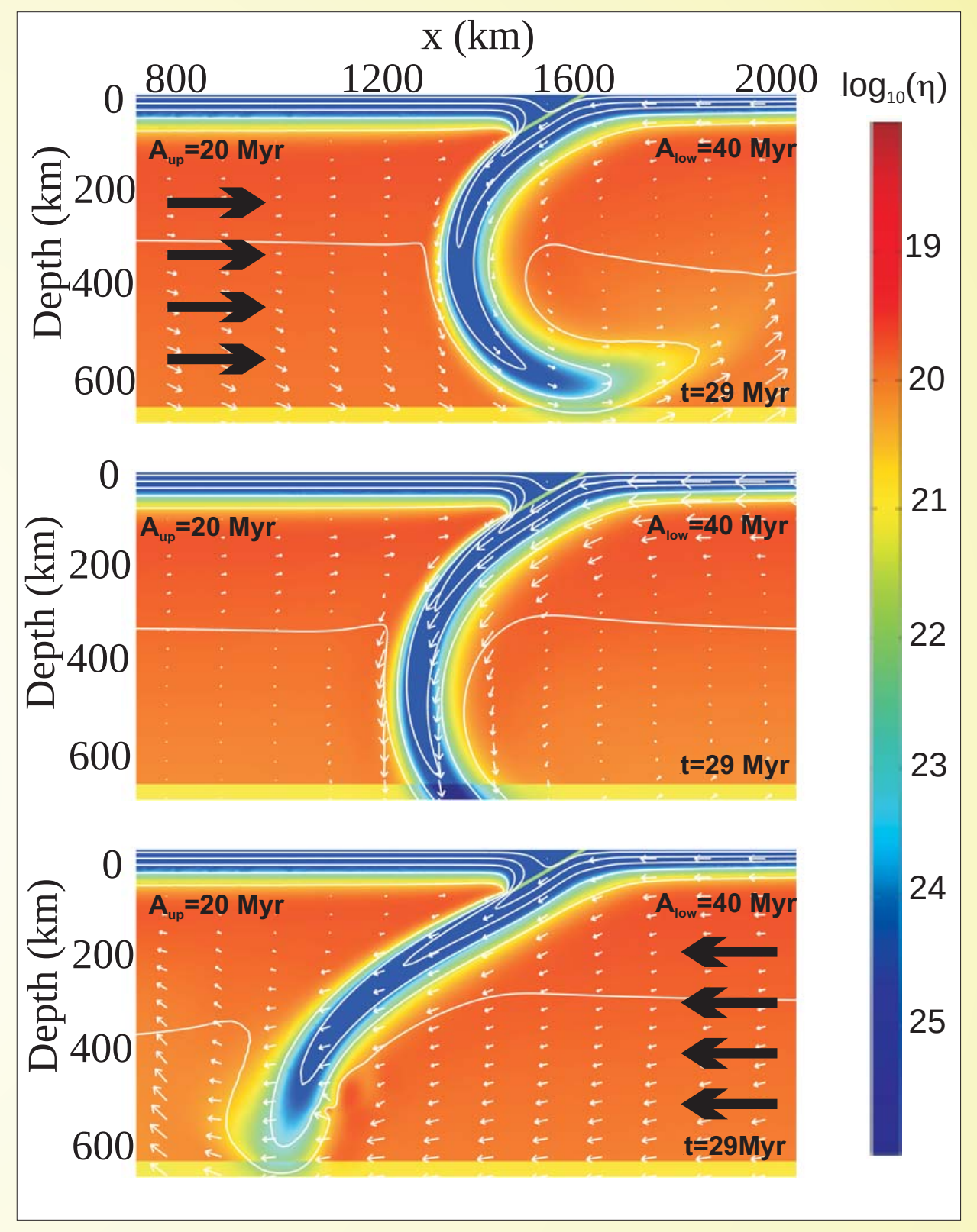


A) When a horizontal asthenospheric flux is imposed, during the first million years, the effect on the slab dip (measured between 95 and 195 km) is not significant.

However, as the slab reaches a deeper region, the flux is channeled between the slab tip and the more viscous lower mantle. Therefore the velocity of the flux increases and the efect of the asthenospheric flux also increases.

B) The effect of the flux, after 22 Myr, is greater for the deeper region of the slab (between 500 and 670 km), as the torque generated by the horizontal asthenospheric flux is higher there.

4.2 Penetration into the lower mantle



The slab penetrates into the lower mantle when no horizontal asthenospheric flux is imposed; this result is not reproduced if the flux is present. On the contrary, the penetration is inhibited when asthenospheric flux is imposed, due to high velocity arround the tip of the slab

5. Conclusions

- The presence of the horizontal asthenospheric flux has little influence on the dip of the shallower portion of the slab during the first million years of evolution.

- There is a significant influence of the asthenospheric flux on the deeper region of the slab. This influence becomes more important for longer evolution times and stronger fluxes.

- In some cases the horizontal asthenospheric flux inhibits penetration of the slab into the lower mantle.

6. References

- Butler, R., Dynamic Earth. (Http://www.see.leeds.ac.uk/structure/dynamicearth/index.htm)
- Cruciani, C., Carminati, E. and Doglioni, C., Slab dip vs. lithosphere age: no direct function. *Earth Planet. Sci. Lett.* **238**, 298310 (2005).
- Doglioni, C., Harabaglia, P., Merlini, S., Mongelli, F., Peccerillo, A., Piromallo, Orogens and slabs vs their direction of subduction. *Earth Sci. Rev.*, **45**, 167–208 (1999).
- Hirth, G., and Kohlstedt, D.L., Rheology of the upper mantle and the mantle wedge: A view from the experimentalists, in *Inside the Subduction Factory*, edited by J. Eiler , pp. 83– 105, AGU, Washington, D.C. (2003).
- Lallemand, S., Heuret, A., and Boutelier, D., On the relationships between slab dip, back-arc stress, upper plate absolute motion, and crustal nature in subduction zones, *Geochem. Geophys. Geosyst.*, 6, Q09006, doi:10.1029/2005GC000917 (2005).