Numerical models of slab deformation in the upper mantle

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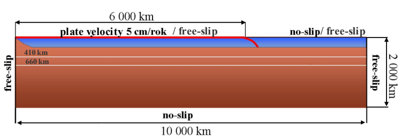
Abstract:

Processes within subduction zones have major influence on the plate dynamics and mantle convection. Subduction process is influenced by a combination of many parameters and there is no simple global relationship between the resulting slab geometry and deformation and any specific subduction parameter. In the present work we perform a parametric study of the slab dynamics in a two-dimensional model with composite rheology including diffusion creep, dislocation creep and stress limiting rheology or Peierls creep. The separation of the subducting and overriding plates is ensured by a layer of a low viscosity material - crust. We are particularly interested in the effect of the contact of subducting and overriding plate on the plate geometry in the upper mantle. We also study the influence of a surface boundary condition and the rheologic parameters of the plate.

Model domain:



Model:

- 2D Cartesian box
- incompressible, extended Boussinesq
- viscous composite rheological model (van den Berg et al., 1993)
- finite element code SEPRAN (Segal & Praagman, 2005)

Rheology

$$\eta_{eff} = \left(\frac{1}{\eta_{diff}} + \frac{1}{\eta_{disl}} + \frac{1}{\eta_p}\right)^{-1}$$

$$\eta_{diff} = A_{diff}^{-1} d^m \exp\left(\frac{E_{diff} + PV_{diff}}{RT}\right)$$

$$\eta_{disl} = A_{disl}^{-\frac{1}{n}} \dot{\varepsilon}_{disl}^{\frac{1}{n}-1} \exp\left(\frac{E_{disl} + PV_{disl}}{nRT}\right)$$

$$\eta_p = \dot{\varepsilon}_p^{\frac{1}{S_{(T)}}-1} \gamma \sigma_p A_p^{-\frac{1}{S_{(T)}}} \exp\left(g_p \frac{T_m(P)}{TS_{(T)}} (1-\gamma)^q\right) \quad \xrightarrow{\text{some models}} \quad \eta_y = \sigma_y \dot{\varepsilon}_y^{-\frac{1}{n_y}} \dot{\varepsilon}_L^{\frac{1}{n_y}-1}$$

$$S_{(T)} = \frac{g_p T_m(P)}{T} (1-\gamma)^{q-1} q\gamma$$

Parameters

$A_{diff} = 1.92 \times 10^{-10}\ Pa^{-1}.s^{-1}$
$E_{diff} = 3.0 \times 10^5\ J.mol^{-1}$
$V_{diff} = 4.5 \times 10^{-6}\ m^3.mol^{-1}$

$A_{disl} = 2.42 \times 10^{-15}\ Pa^{-n}.s^{-1}$
$E_{disl} = 5.4 \times 10^5\ J.mol^{-1}$
$V_{disl} = 14 \times 10{-6}\ m^3.mol^{-1}$

$A_p = 5.7 \times 10^{11}\ s^{-1}$

$E_p = 5.4 \times 10^5\ J.mol^{-1}$
$T_m(P) = 2100 + 1.4848\ z - 5.10^{-4}\ z^2$
$T_m(P) = 2916 + 1.25\ z - 165.10^{-4}\ z^2$

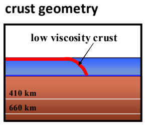
$\sigma_y = 10^8 - 10^9\ Pa$
$\varepsilon_y = 10^{-14}\ s^{-1}$

$\eta_{crust} = 10^{19} - 10^{21}\ Pa\ s$

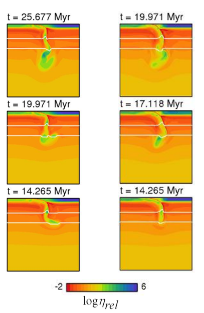
Results:

Effect of boundary condition

Initial setup: crust geometry



Crustal viscosity $\eta_{crust} = 10^{20}$ Pa s
Yield stress 10^8 Pa



Effect of yield stress

Crustal viscosity $\eta_{crust} = 10^{20}$ Pa s
Yield stress 10^9 Pa

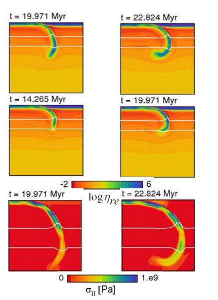
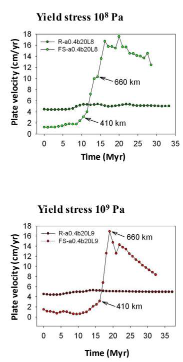
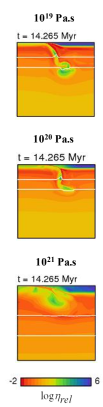


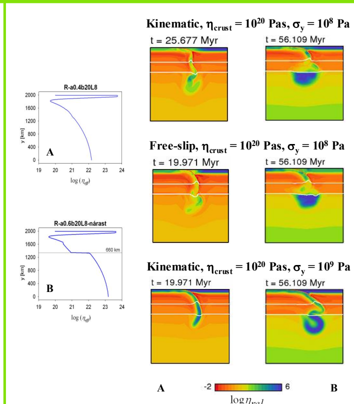
Plate velocity



Effect of crustal viscosity



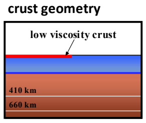
Effect of viscosity jump at 660 km



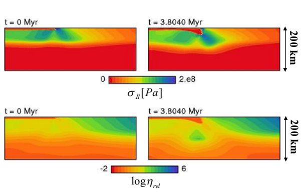
Results:

Effect of decoupling mechanism

Initial setup: crust geometry



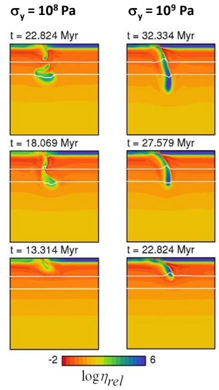
Subduction initiation: detail



Crustal viscosity $\eta_{crust} = 10^{20}$ Pa s

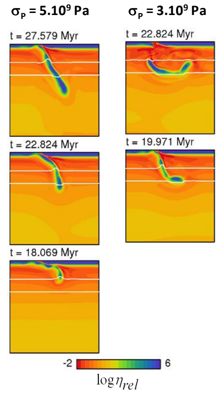
Stress limiter

$\sigma_y = 10^8$ Pa | $\sigma_y = 10^9$ Pa

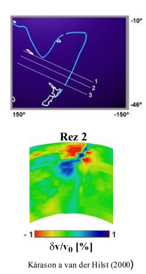


Peierls creep

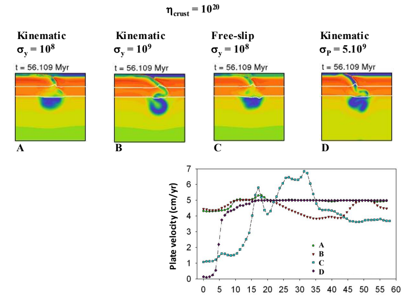
$\sigma_P = 5.10^9$ Pa | $\sigma_P = 3.10^9$ Pa



Kermadec region



$\eta_{crust} = 10^{20}$



Conclusions:

- Crustal viscosity of 10^{20} Pa s produces most reasonable slab morphologies
- Surface boundary condition plays relatively minor role in the models with predefined crustal arc
- In the models with kinematic boundary condition subduction develops without prescribing the initial contact geometry
- Rheological parameters of the plate have strong effect to slab deformation, especially in the models without predefined decoupling arc – the models with stress limiter produce different slab morphologies than models with Peierls creep
- An increase of viscosity at the depth of 660 km in necessary to produce the thickening in the lower mantle