Time-varying subduction and rollback velocities in slab stagnation and buckling

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SLAB STAGNATION

Fukao et al., 2009
SLAB STAGNATION

Obayashi et al., 1997

Huang and Zhao, 2006

Widiyantoro, 1997
TRENCH ROLLBACK – ADVANCE

old slabs $\rightarrow$ cold and heavy $\rightarrow$ rollback

**BUT:** cold old slabs are stiff $\rightarrow$ good stress guide $\rightarrow$ advance  
(Gerault et al., 2012)

Husson, 2012 $\rightarrow$ rollback is controlled primarily by mantle drag, 
slab rheology plays only minor role
Fig. 3. Normal component of trench velocity $V_{\text{cm}}$ in four absolute reference frames: (a) hot spot reference frame of Gripp and Gordon (2002), which analyses the Pacific hot-spot track; (b) hot spot reference frame of Gordon and Jurdy (1986), which considers both the Indo-Atlantic and the Pacific hot-spot tracks; (c) hot spot reference frame of Steinberger et al. (2004), which investigates only the Indo-Pacific hot-spot tracks; (d) no-net-rotation reference frame (Gripp and Gordon, 2002). Reference velocity is indicated at the bottom-left of each panel.

Funiciello et al., 2008
NUMERICAL MODELING TRENCH ROLLBACK

**Target:** find the parameters of slabs (rheological parameters, age?) that may control the trench migration

**Main focus:** rheological description – effects of nonlinear rheology
NUMERICAL MODELING TRENCH ROLLBACK

**Target:** find the parameters of slabs (rheological parameters, age?) that may control the trench migration

**Main focus:** rheological description – effects of nonlinear rheology

??? FREE PARAMETERS OF RHEOLOGICAL DESCRIPTION ???
Activation parameters, lower mantle viscosity jump
Estimate of the lower mantle viscosity based on sinking speed of detached slabs

\[ \log \eta = 3000 + 20 \left( t_{\text{break}} - t_{\text{ini}} \right) \]
MODEL: COMPOSITE RHEOLOGY

Diffusion creep

\[ \dot{\varepsilon}_{\text{diff}} = A_{\text{diff}} \sigma \exp\left(-\frac{E_{\text{diff}} + pV_{\text{diff}}}{RT}\right) \]

Dislocation creep

\[ \dot{\varepsilon}_{\text{disl}} = A_{\text{disl}} \sigma^n \exp\left(-\frac{E_{\text{disl}} + pV_{\text{disl}}}{RT}\right) \]

Stress limiter

\[ \dot{\varepsilon}_{\text{sl}} = C_L \left( \frac{\sigma}{\sigma_L} \right)^{n_L} \]
MODEL: RHEOLOGICAL PARAMETERS

**Crust**
Constant viscosity $10^{20}$ Pa s

**Upper mantle**
Activation parameters according to Hirth and Kohlstedt (2003)
Yield stress 0.5 GPa

**Lower mantle**
Diffusion creep

- **A-family**
  \[ V_{\text{diff}} = 1.1 \times 10^{-6} \text{ m}^3 \text{ mol}^{-1} \]

- **B-family**
  \[ V_{\text{diff}} = 2.2 \times 10^{-6} \text{ m}^3 \text{ mol}^{-1} \]

(PPV: $\eta_{PPV} = 10^{21}$ Pa s)
MODEL: VISCOSITY INCREASE AT 660 km

**A-family**

**B-family**

S&C, 2006

F&M, 1996

M&F, 2004

P, 1999
MODEL: THERMAL EXPANSIVITY

Katsura (2010)
RESULTS

$t = 40$ Myr

CMB
RESULTS:

AGE vs. DEPTH

Čížková et al., PEPI 2012
RESULTS: BOTTOM AND TOP OF SLAB REMNANTS

Van der Meer et al. (2010)  Čížková et al., PEPI 2012
family A
preferred profile

log (η)

r (km)
MODEL SETUP – ROLLBACK AND SLAB STAGNATION STUDY

Sinking slabs

Rollback and stagnation

weak crust

locked overriding plate

impermeable free-slip

second ridge
MODEL SETUP – ROLLBACK AND SLAB STAGNATION STUDY

Initial position of the trench

surface

CMB

log $\eta$

19

26
MODEL SETUP – ROLLBACK AND SLAB STAGNATION STUDY

Initial position of the trench

log $\eta$

1450 km
RESULTS

rollback not allowed

rollback
RESULTS

- **Plate Velocity**
- **Rollback Velocity**

**Graph:**
- **Y-axis:** Plate / rollback velocity (cm/yr)
- **X-axis:** Time since passing 400 km (Myr)

**Log Scale:**
- **Log η:** Range from 19 to 26

**Images:**
- Multiple snapshots at different times (t = 10Ma, 20Ma, 30Ma, 40Ma, 50Ma)
- Color scale indicating log η values.
RESULTS

velocity

plate / rollback velocity (cm/yr)

horizontal

vertical

absolute value

± 7 cm/yr

± 7 cm/yr

0 - 10 cm/yr

0 - 10 cm/yr

± 7 cm/yr

0 - 10 cm/yr

plate velocity

rollback velocity

04 0 8 0

time since

assigning 400 km (Myr)

2900 km
RESULTS

- viscosity
- abs(velocity)
- stream function

Plate / rollback velocity (cm/yr)

Plate velocity

Rollback velocity

Time since subduction (Ma)
RESULTS: EFFECT OF THE LOWER MANTLE VISCOSITY
RESULTS – snapshot after 50 Myr

Effect of the lower mantle viscosity

\[ \eta_{LM} = 3 \times 10^{22} \]

\[ \eta_{LM} = 6 \times 2^{22} \]

\[ \eta_{LM} = 3 \times 10^{23} \]
RESULTS: EFFECT OF THE CRUSTAL VISCOSITY

\[ \eta_{\text{crust}} = 10^{21} \text{ Pas} \]

\[ \eta_{\text{crust}} = 5 \times 10^{20} \text{ Pas} \]

\[ \eta_{\text{crust}} = 2 \times 10^{20} \text{ Pas} \]

\[ \eta_{\text{crust}} = 10^{20} \text{ Pas} \]

\[ \eta_{\text{crust}} = 10^{19} \text{ Pas} \]
RESULTS – snapshot after 50 Myr

Effect of the crustal viscosity

snapshot after 90 Myr

penetrating slabs
RESULTS – snapshot after 50 Myr

Effect of the yield stress

age 70 Myr

age 100 Myr

age 150 Myr

\( \sigma_y = 2 \times 10^8 \)  \( \sigma_y = 5 \times 10^8 \)  \( \sigma_y = 10^9 \)
RESULTS – plate and rollback velocities

lower mantle viscosity

crust viscosity

yield stress
RESULTS – snapshot after 50 Myr

Effect of the Clapeyron slope

\( \gamma_{410} = 1 \text{ MPa/K} \)

\( \gamma_{410} = 2 \text{ MPa/K} \)

\( \gamma_{410} = 3 \text{ MPa/K} \)

\( \gamma_{410} = 4 \text{ MPa/K} \)
RESULTS – snapshot after 50 Myr

Effect of the Clapeyron slope

\[ \gamma_{410} = 1 \text{ MPa/K} \]

\[ \gamma_{410} = 2 \text{ MPa/K} \]

\[ \gamma_{410} = 3 \text{ MPa/K} \]

\[ \gamma_{410} = 4 \text{ MPa/K} \]
RESULTS – trench distance after 60 Myr

- Clapeyron slope: 410 km (MPa/K)
- Lower mantle viscosity: 1E+019, 1E+020, 1E+021 Pa s
- Crustal viscosity: 400, 800, 1200, 1600, 2000, 2400 km
- Trench retreat (km)
- Yield stress: 400, 800, 1200, 1600, 2000, 2400 km
- Clapeyron slope 410 km (MPa/K)
- Age: 150 Myr, 100 Myr, 70 Myr

Graphs showing the relationship between trench retreat and various parameters such as crustal and lower mantle viscosities, yield stress, and Clapeyron slope, with different markers for different ages.
CONCLUSIONS – SLAB STAGNATION AND ROLLBACK

- all modes display rollback (effect of ridge push?)
- relation between plate velocity and rollback
- most models predict slab stagnation in the transition zone
- slow slabs (due to higher friction on the contact) have slower rollback and penetrate to the lower mantle – effect of higher astenospheric viscosity?
- more negatively buoyant slabs have faster rollback
- stiffer slabs have faster rollback (no reduction due to the periods of increased subduction velocity)
- implications of rollback periodicity to exhumation