Zemětřesení v subdukovaných deskách v přechodové oblasti

Hana Čížková

Craig Bina, Arie van den Berg, Junqing Liu, Jakub Pokorný, Jiří Zahradník
1. Extended transition zone

2. Slab stagnation above/below 660-km boundary – why?

3. Implications for deep slab seismicity
Mantle transition zone between the upper and lower mantle – complex area due to
1. Mineralogy – phase transitions
2. Rheology – increase of viscosity, presumably change of deformation mechanism
Mantle transition zone between the upper and lower mantle – complex area due to
1. Mineralogy – phase transitions
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Rheological transition between the upper and lower mantle traditionally coupled to the
disproportionation of ringwoodite to an assemblage of ferropericlasse and bridgmanite
which was mostly assumed to occur in a narrow depth interval around 660 km depth
Most of the interesting actions about slab deformation were therefore supposed to happen in the transition zone at the base of the upper mantle as was also documented by seismic tomography.

Recent seismic tomographic models however suggest that several subducting slabs seem to stagnate in the shallow lower mantle below the phase boundary → extended transition zone.

Why should that happen (rheological transition shifted at 1000 km?), how does this possible rheological shift affect slab deformation and stress evolution, comparison with the deep earthquakes.
Seismic tomography

- Slabs in some subduction regions stagnate below the 660-km boundary

Fukao and Obayashi (2013)
Seismic tomography

- Slabs in some subduction regions stagnate below the 660-km boundary
Seismic tomography
• Slabs in some subduction regions stagnate below the 660-km boundary

Fukao and Obayashi (2013)
SLAB STAGNATION BELOW 660 KM

Seismic tomography
- Slabs in some subduction regions stagnate below the 660-km boundary

Numerical models of subduction
- Slabs stagnate above the phase transition boundary at 660-km due to combined effects of an endothermic phase transition and/or abrupt viscosity increase

Slab stagnation above 660 km – combined effects of endothermic phase transition and (abrupt) viscosity increase at 660 km depth

Stagnation at 1000 km depth – why?
Seismological indications for a discontinuity (Niu and Kawakatsu, 1997)
Deeper rheological layering?
• Geoid inversion: viscosity increase at 800-1200 km (Rudolph et al., 2015)
• Mineral physics – gradual transformation of ringwoodite to ferropericlase and bridgmanite (Faccenda a Dal Zilio, 2017)
• Experiments with ferropericlase – increase of dislocation creep viscosity at ~900 km (Marquart a Miyagi, 2015)

Could the shift of the rheological interface between the upper and lower mantle into ~1000 km explain deep slab stagnation?
Model parameters to be tested

- Viscosity interface upper-lower mantle
- Viscosity of crustal decoupling layer
  \(\text{constant } \eta_{\text{crust}} = 10^{20}, 5.10^{20}, 10^{21} \text{ Pas}\)
- Major phase transitions
- Subducting plate age (50, 100, 150 Myr)

Nonlinear slab and mantle rheology

- Diffusion, dislocation creep, power-law stress limiter
- Lower mantle: Čížková et al. (2012)
- Yield stress 0.5 GPa

Čížková and Bina, EPSL 2019
EFFECTS OF VISCOSITY INTERFACE

Snapshot at 80 Myr

Sharp 660km

Smooth 1000 km

\( \eta_{\text{crust}} = 10^{20} \text{ Pas} \)

\( \eta_{\text{crust}} = 5 \times 10^{20} \text{ Pas} \)

\( \eta_{\text{crust}} = 10^{21} \text{ Pas} \)

Čížková and Bina, EPSL 2019
**EFFECTS OF VISCOSITY INTERFACE**

**Stagnation/penetration controlled by petrological buoyancy associated with the 660-km phase transition**

1. Lateral extent of flat-lying part (rollback)

2. Tip penetrating through 660-km boundary before rollback is initiated

Čížková and Bina, EPSL 2019
• Slab dynamics at the base of the upper mantle is close to threshold – any small change of parameters can decide whether the slab stagnates or penetrates

• Rheology of crust that decouples the plates plays an important role

• Subduction models often use entrained weak layer with either constant viscosity (e.g. Běhounková and Čížková, 2008; Chertova et al., 2012; Holt et al., 2015; Agrusta et sl., 2017) or nonlinear rheology (e.g. Garel et al., 2014; Crameri and Tackley, 2014; Liao et al., 2017)

• The magnitude of crustal viscosity was reported to affect plate velocities (Androvičová et al., 2013; Holt et al., 2015) and higher crustal viscosity inhibits rollback (Čížková and Bina, 2013; Arredondo and Billen, 2017; Holt et al., 2015)

• The lubrication effect of the weak crustal layer is further affected by its thickness which evolves with time. In constant crustal viscosity models its transient thinning may hamper lubrication especially if the thinned layer is not properly resolved (Sandiford and Moresi, 2019)

Here we demonstrate that apart from affecting the plate velocity and trench migration, the efficiency of the lubrication of the contact between the subducting and overriding plate is also crucial for slab stagnation/penetration at 660-km depth and (temporary) stagnation between 660 km and 1000 km depths
APPLICATION: DEEP FOCUS EARTHQUAKES
EXAMPLE 1: SEISMICITY IN WESTERN PACIFIC
SEISMICITY WESTERN PACIFIC

No seismicity in flat-lying part

Fukao and Obayashi (2013)

Stagnation above 660 km boundary
Analysis of seismic stresses
39 events between 300 and 600 km, $M_w$ 5-6.9

Downdip compression in the dipping part of the slab
Dip angle $\sim 27^\circ$
Free subduction model of Pacific subduction with ageing plate

- EB, nonlinear composite rheology
- Major phase transitions
- Viscosity increase at 660 km or 1000 km
- Weak and buoyant oceanic crust
- Initial setup following Yang et al. (2018)

Can we fit dip angle, flat-lying part above 660 km depth, downdip compression? Indication for missing seismicity in flat part?
Free subduction model of Pacific subduction with ageing plate (following Yang et al., 2018)

- Nonlinear composite rheology
- Constant crustal viscosity
- Major phase transitions
- Viscosity increase at 660 km or 1000 km
- Weak and buoyant oceanic crust
MODEL STRESSES

Free subduction model of Pacific subduction with ageing plate

$\Delta \rho_{cr} = -200 \text{ kg/m}^3$, weak ph. trans.

$\Delta \rho_{cr} = 0$, weak ph. trans.

$\Delta \rho_{cr} = -200 \text{ kg/m}^3$, strong ph. trans.

$\Delta \rho_{cr} = 0$, strong ph. trans.

Čížková et al., submitted to EPSL
MODEL DIP ANGLE

Free subduction model of Pacific subduction with ageing plate

![Graph showing dip angle over time for different scenarios with annotations for each line.]

- $\Delta \rho_{cr} = 0$, weak p.t.
- $\Delta \rho_{cr} = 0$, strong p.t.
- $\Delta \rho_{cr} = -200 \text{ kg/m}^3$, weak p.t.
- $\Delta \rho_{cr} = -200 \text{ kg/m}^3$, strong p.t.
- $\Delta \rho_{cr} = -200 \text{ kg/m}^3$, weak p.t., sm1000
MODEL STRESSES

Free subduction model of Pacific subduction with ageing plate

\[ \gamma_{410} = 1 \text{ MPa/K}, \quad \gamma_{660} = -1.5 \text{ MPa/K} \]
DIP ANGLE EVOLUTION

Amplitude of maximum compressional stress

Dip-angle of maximum compressional stress

Depth (km)

σ_{\text{max comp}} (MPa)

δ_{\text{max comp}} (deg)
MODEL FIT SEISMICITY

Free subduction model of Pacific subduction with ageing plate

- Slab shape in agreement with tomography
- Explains seismogenic stress
- Nature of rheological transition between the upper and lower mantle not important (models with a sharp boundary at 660 km depth and models with smooth transition at 1000 km depth yield similar results)

Fukao and Obayashi (2013)  Čížková et al., submitted to EPSL
EXAMPLE 2: NAZCA SLAB
Acre, 24.11.2015
- earthquake doublet $M_w \sim 7.6$
- depth $\sim 600$ km
- downdip compression

Zahradník et al. (2017)
Geodynamic model of Nazca slab subducting below South America:

Could we obtain vertical compression at the base of the upper mantle?

NAZCA SUBDUCTION

Acre, 24.11.2015

- earthquake doublet $M_w \sim 7.6$
- depth $\sim 600$ km
- downdip compression

Fukao and Obayashi, (2013)

Stagnation below 660 km boundary
Geodynamic model of Nazca slab subducting below South America

Zahradník et al. (2017)
Viscosity interface between upper and lower mantle has to be shifted to 1000 km

Zahradník et al. (2017)
CONCLUSIONS

• In free subduction models it is not only slab and mantle rheology, but also the rheology of the decoupling crust that has primary effects on slab deformation

• Intermediate crustal viscosity together with rheological transition shifted to 1000 km depth results in (temporary) stagnation below 660 km depth

• Effects of nonlinear rheology and phase transitions explain seismogenic stresses derived from deep earthquakes

• Variety of slab deformation patterns as indicated by tomography may be related to differences in plate decoupling among different subduction zones (Behr and Becker, 2018) as well as to lateral variations of lower mantle viscosity structure with possible effects of compositional heterogeneity (Waszek et al., 2018)

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