Many full-text modeling papers and movies at section and my researchgate sites

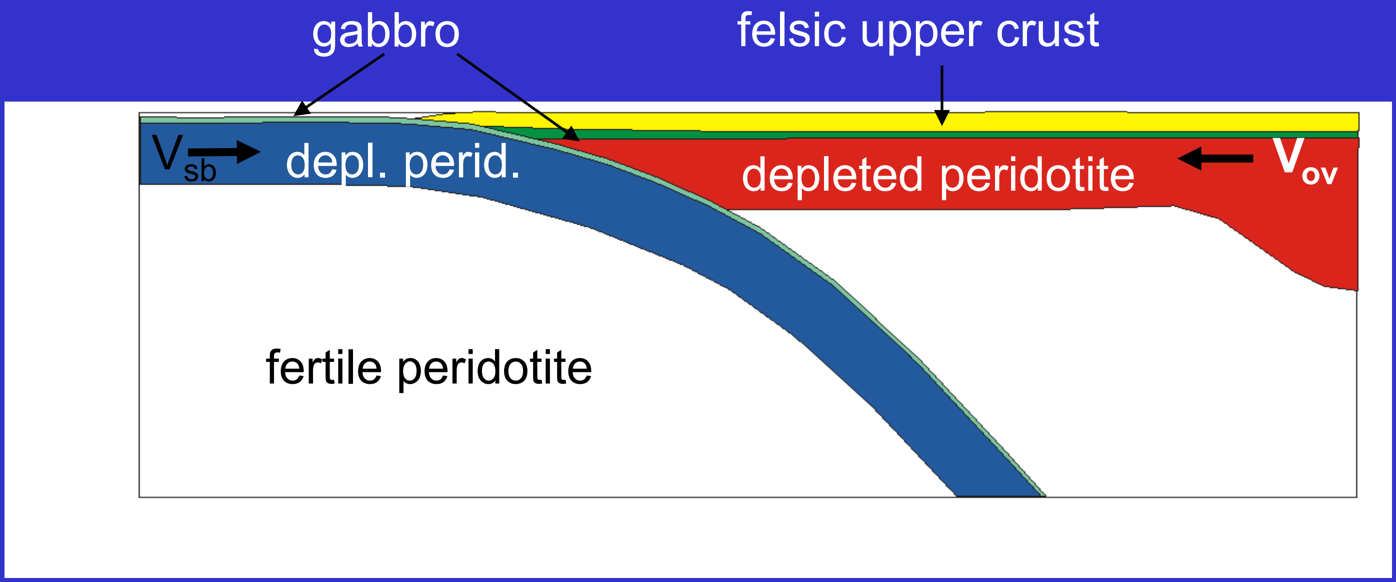
http://www.researchgate.net/profile/Stephan_Sobolev/

Lectures 6-7. Subduction and subduction orogeny

Outline

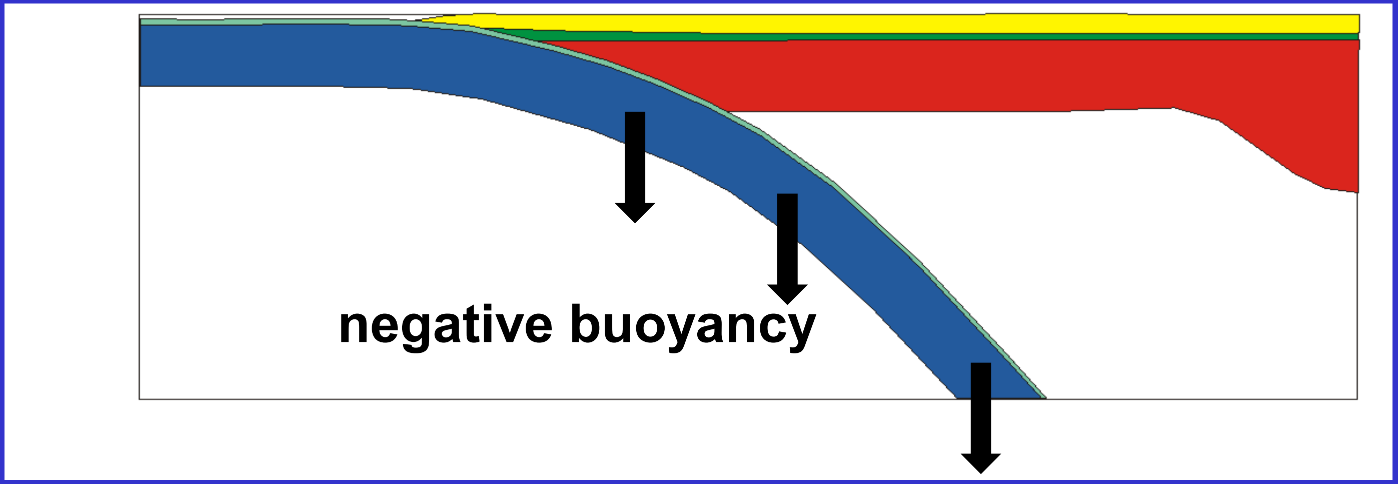
- Driving versus resisting forces- a key is subduction channel
- Role of subduction in generation of continental crust
- Subduction initiation –a key problem of plate tectonics
- Mature subduction-effect of mantle viscosity
- Subduction orogeny (Central Andes)
- Is low friction static or dynamic?
- Subduction in high resolution

Subduction

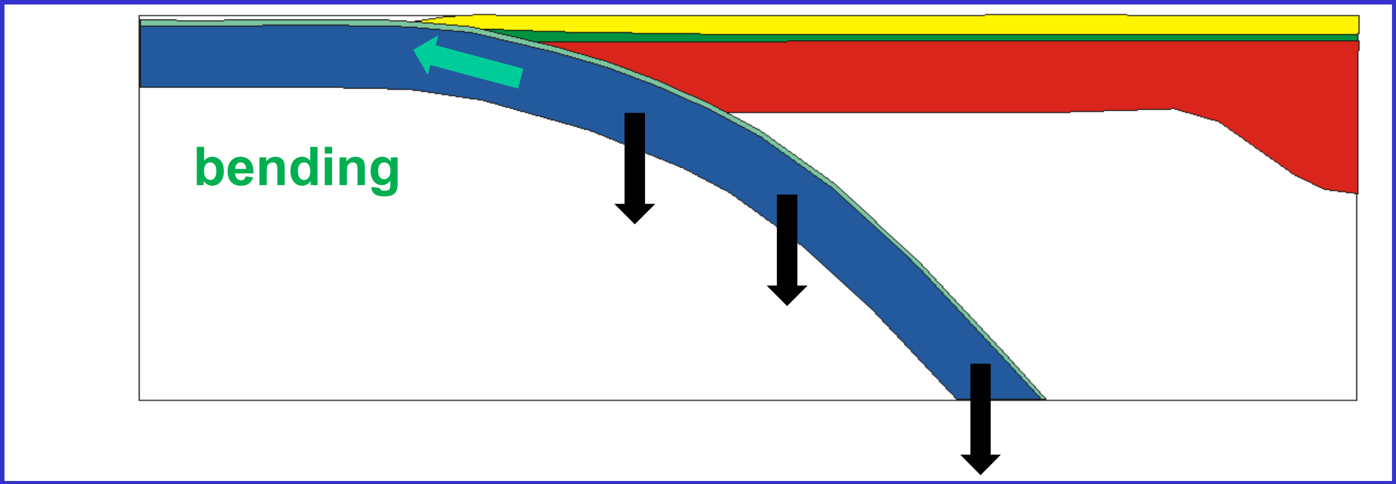


gabbro
felsic upper crust
V_{sb}
depl. perid.
depleted peridotite
V_{ov}
fertile peridotite

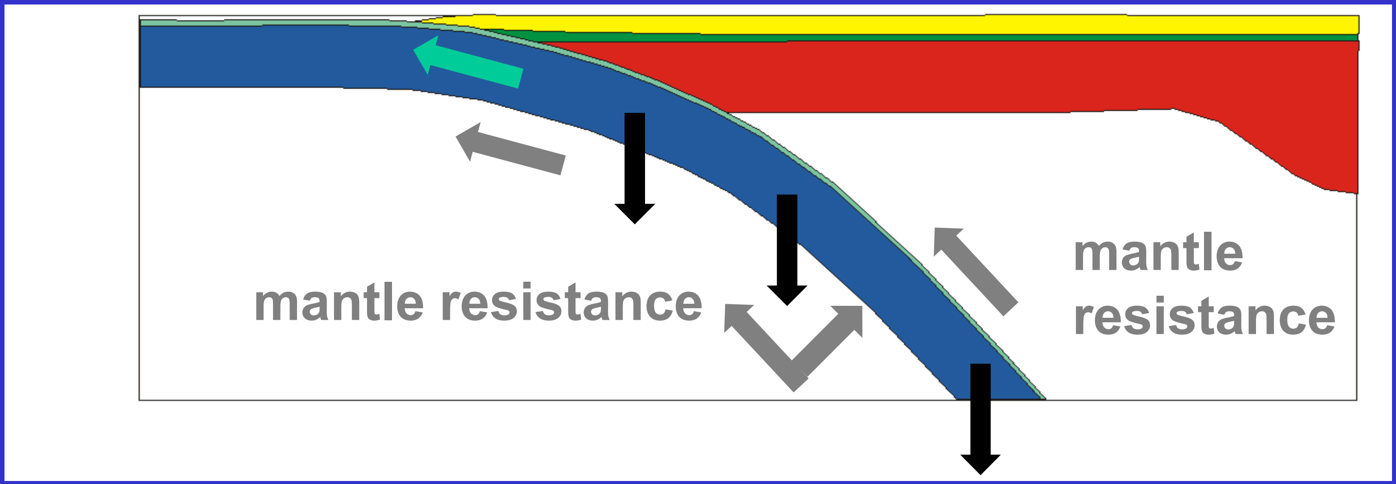
Subduction forces



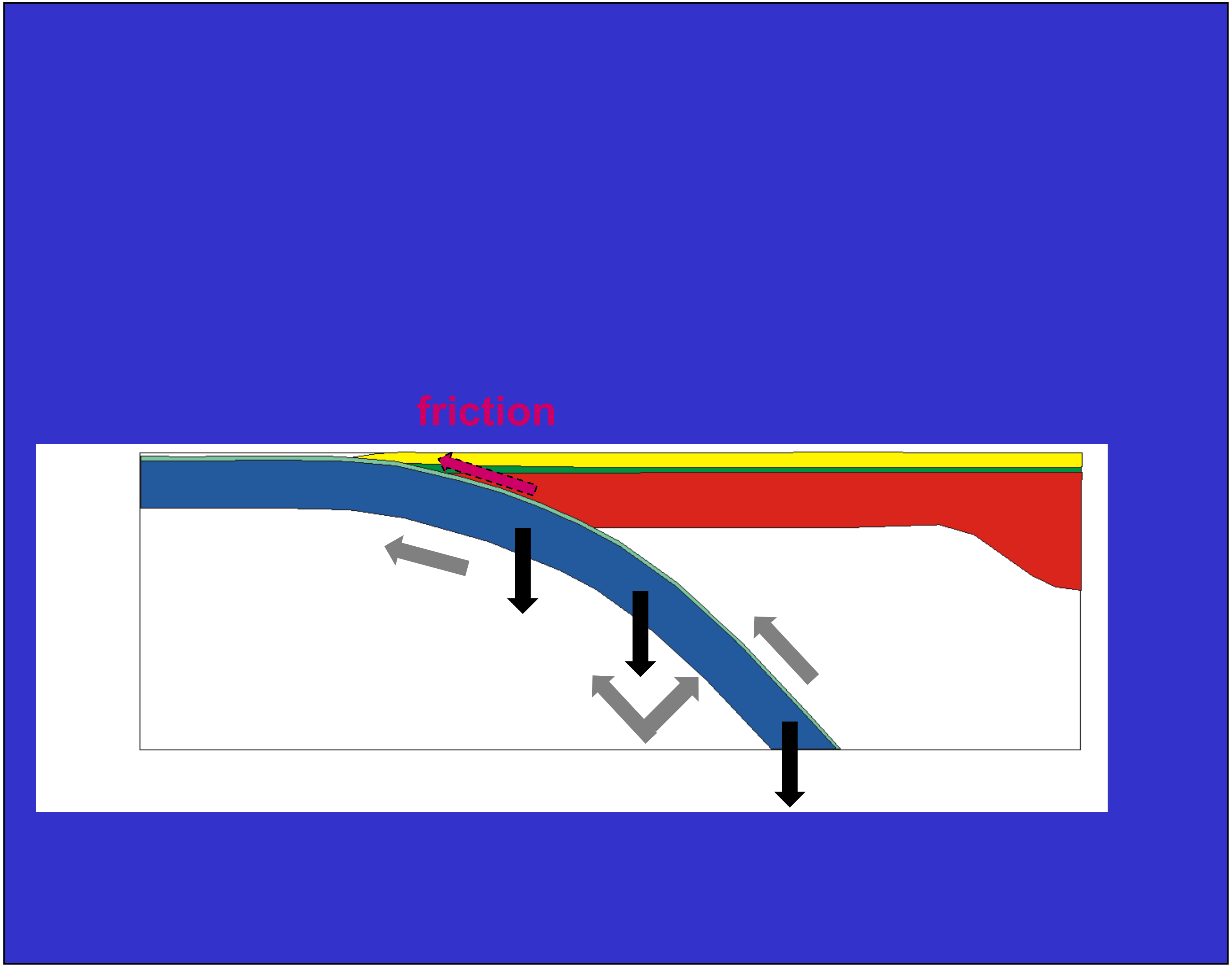
Subduction forces



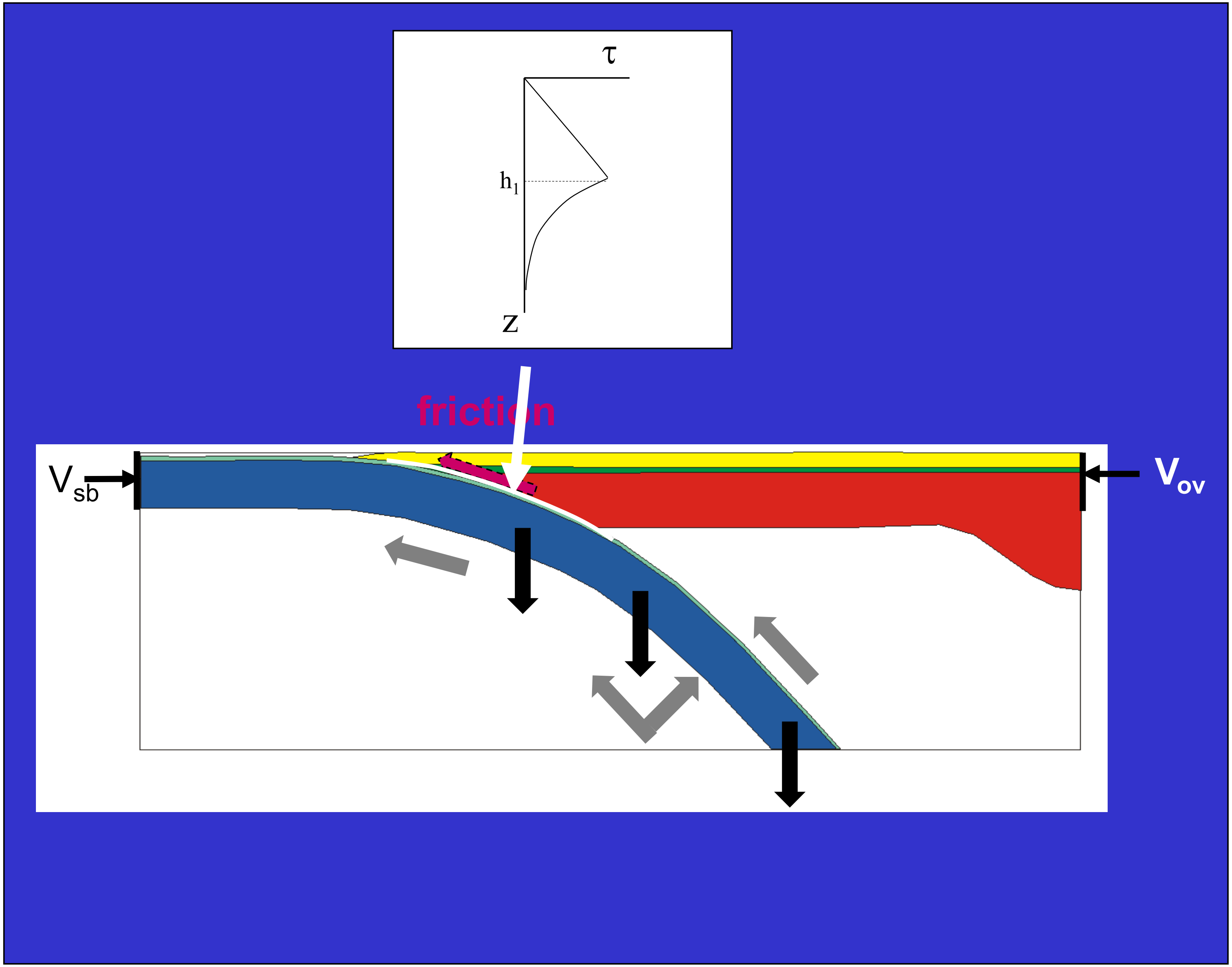
Subduction forces



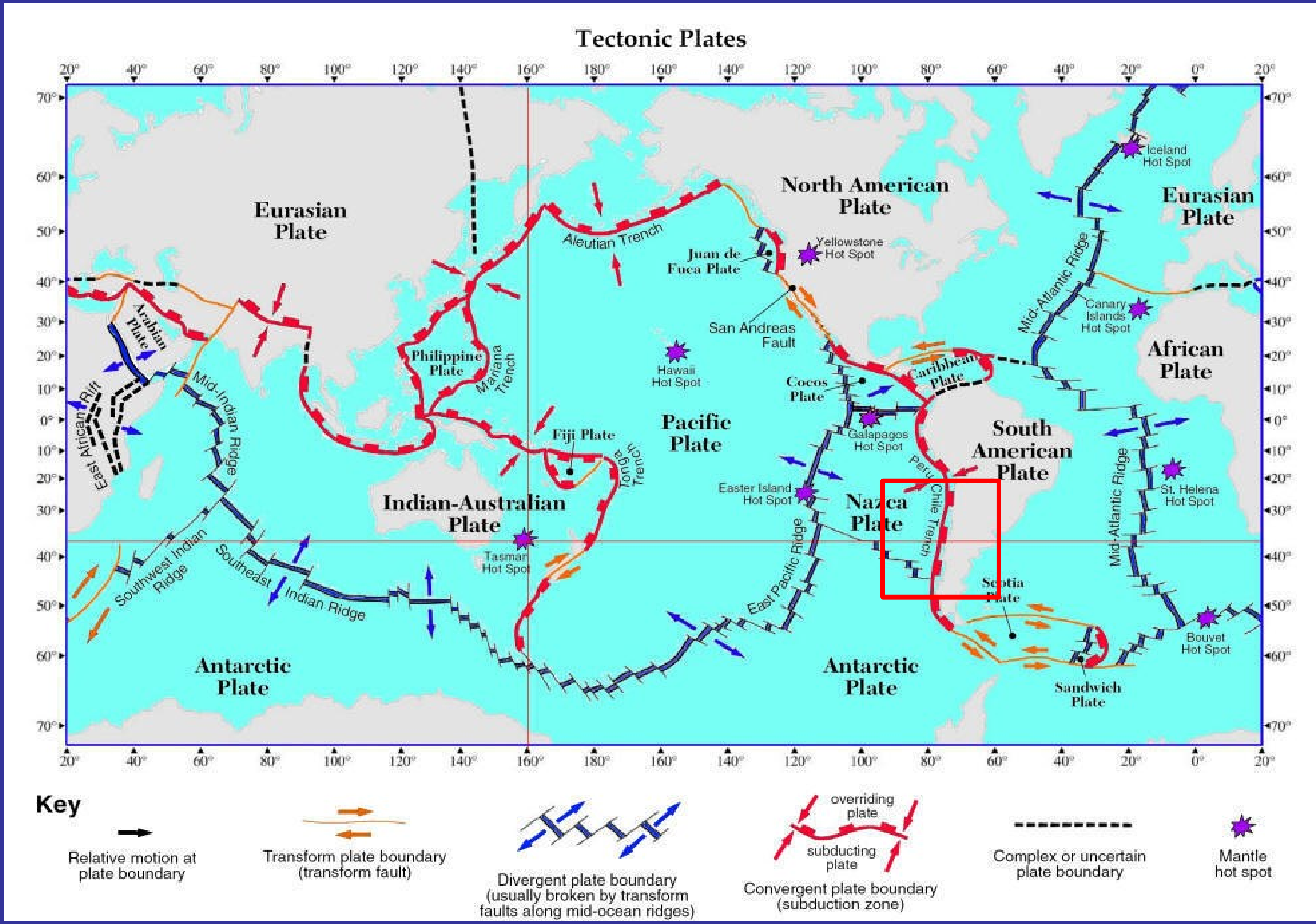
Subduction forces



Subduction forces

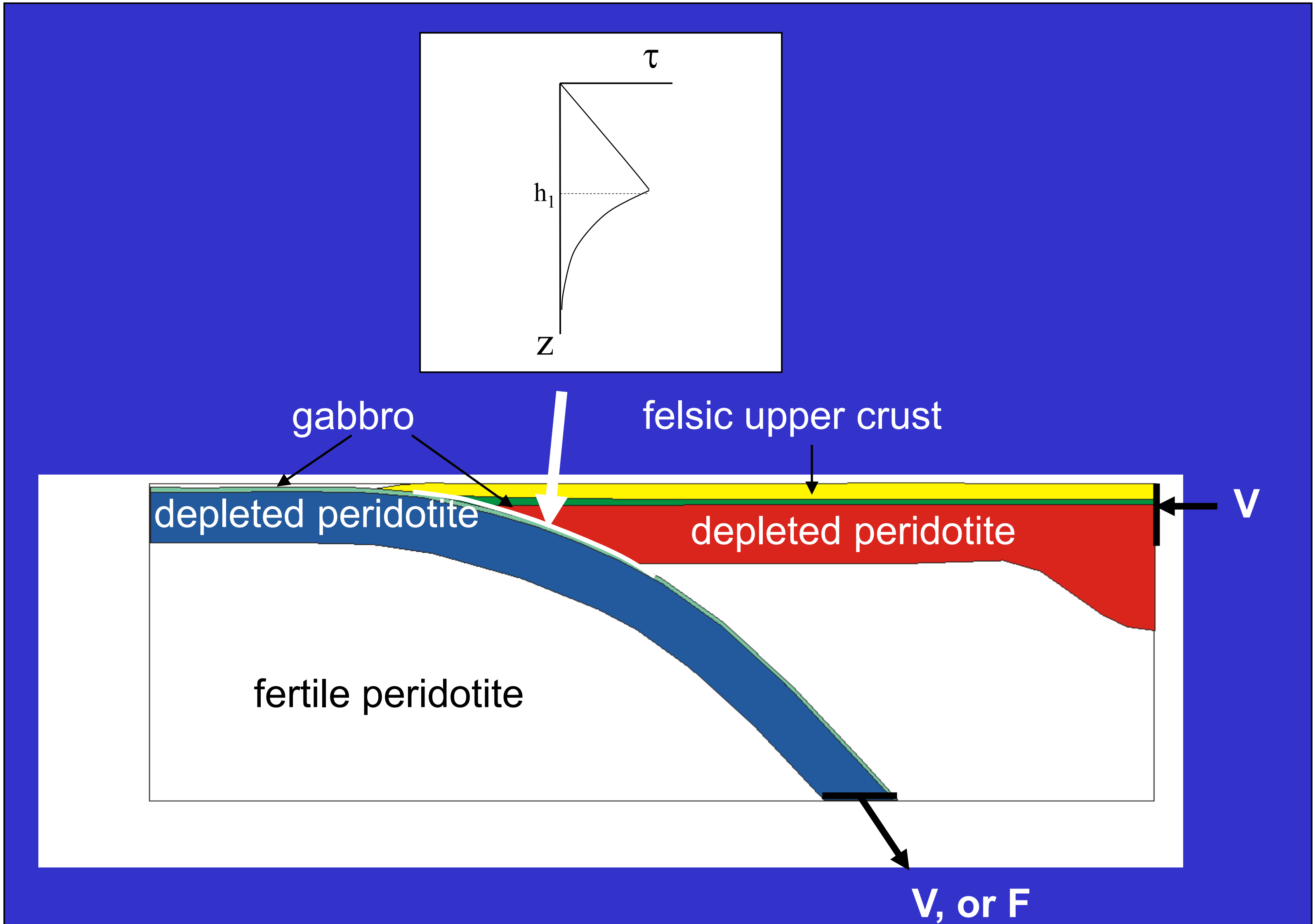


Subduction



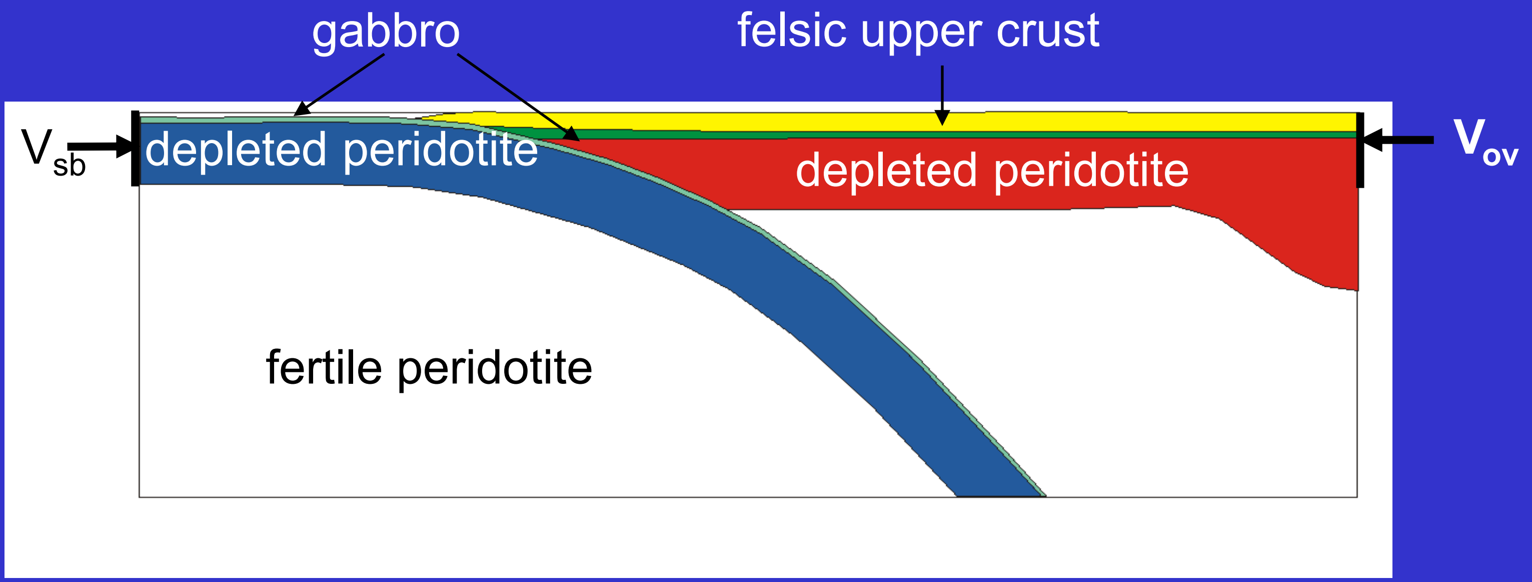
http://www.regentsearth.com

Subduction model setup

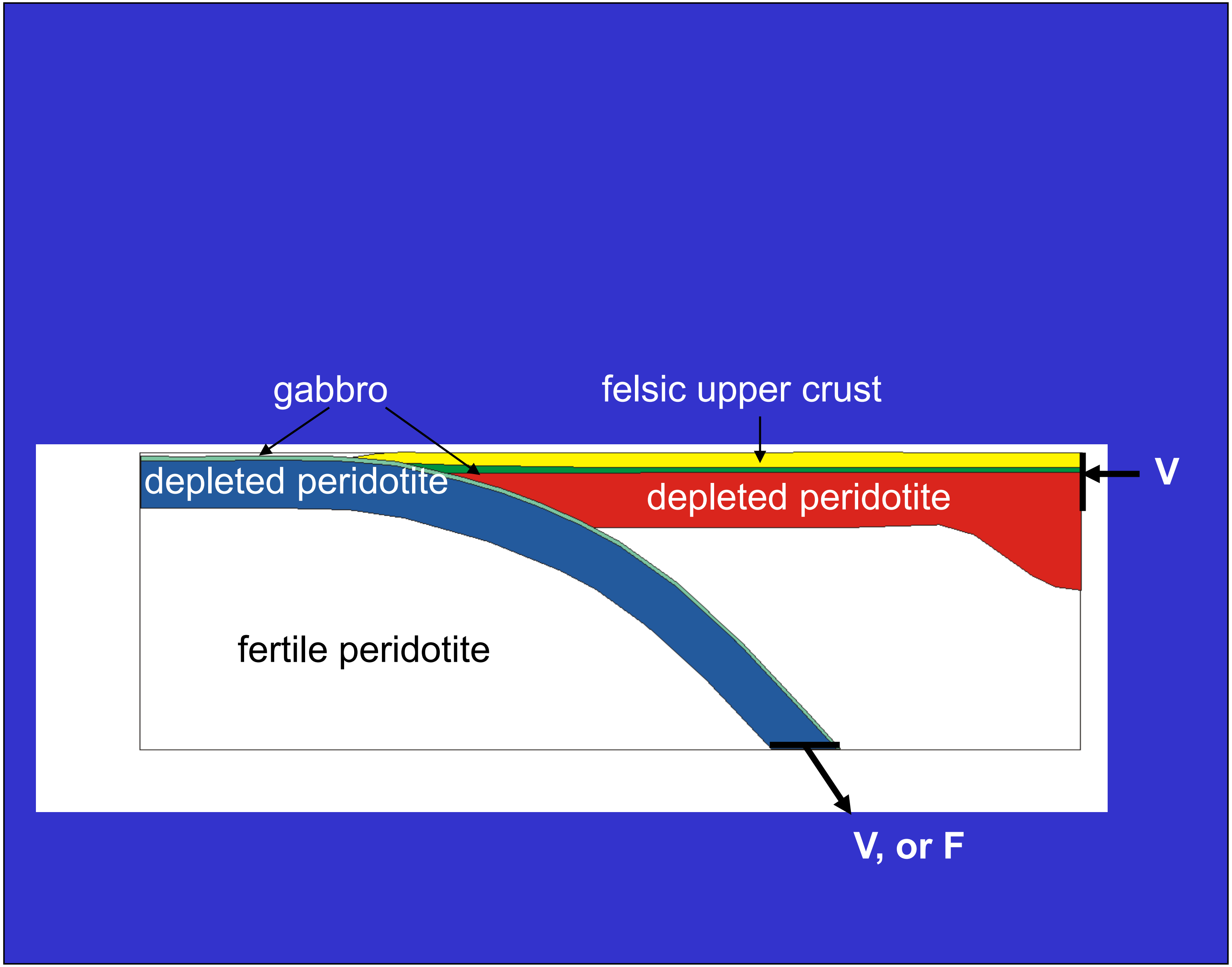


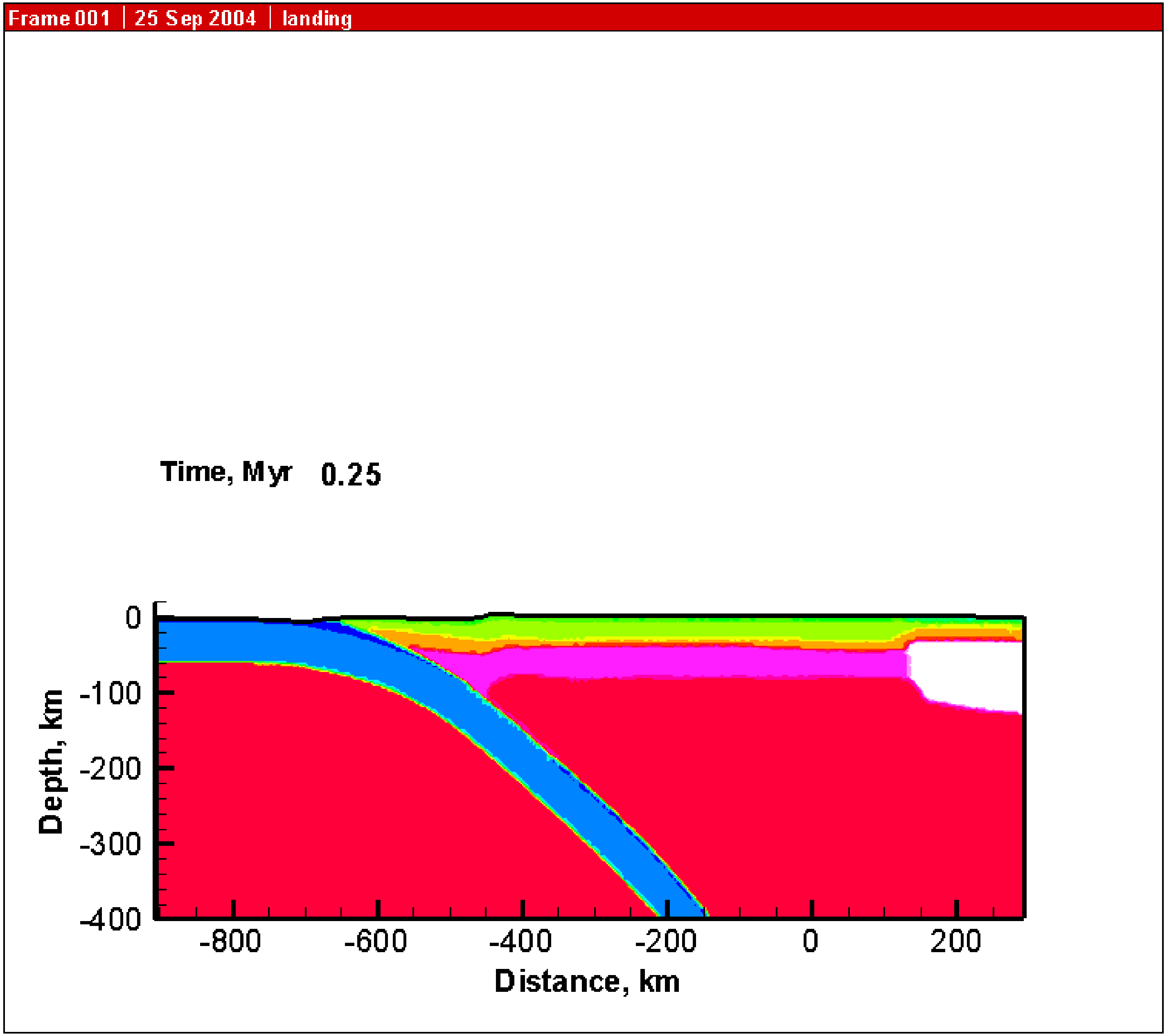
Sobolev and Babeyko, Geology, 2005

Appropriate model setup



Appropriate model setup




Frame 001 | 25 Sep 2004 | landing
Time, Myr 0.25
0
-100
-200
-300
-400
Depth, km
-800
-600
-400
-200
0
200
Distance, km

oceanic crust:

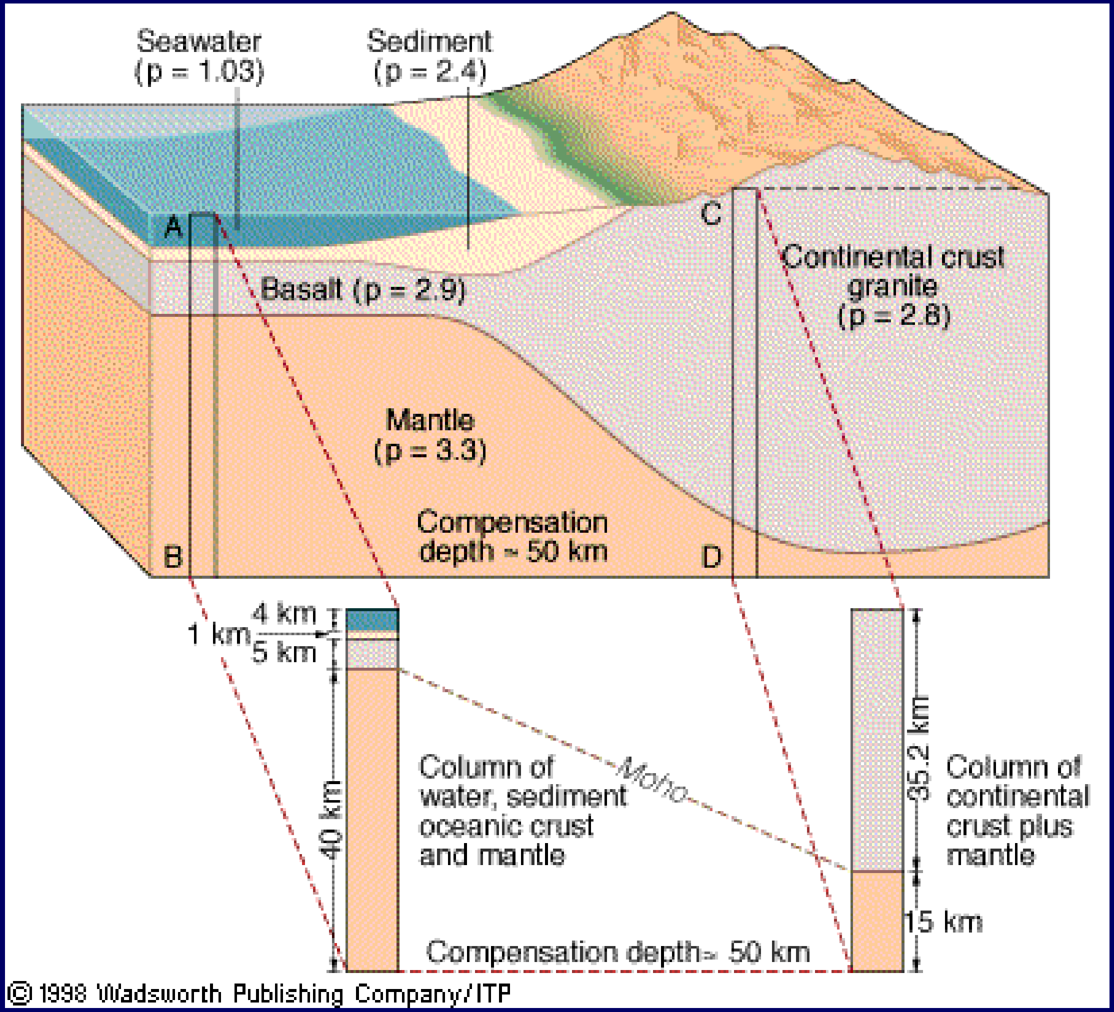
mafic; denser

continental crust:

felsic; less dense

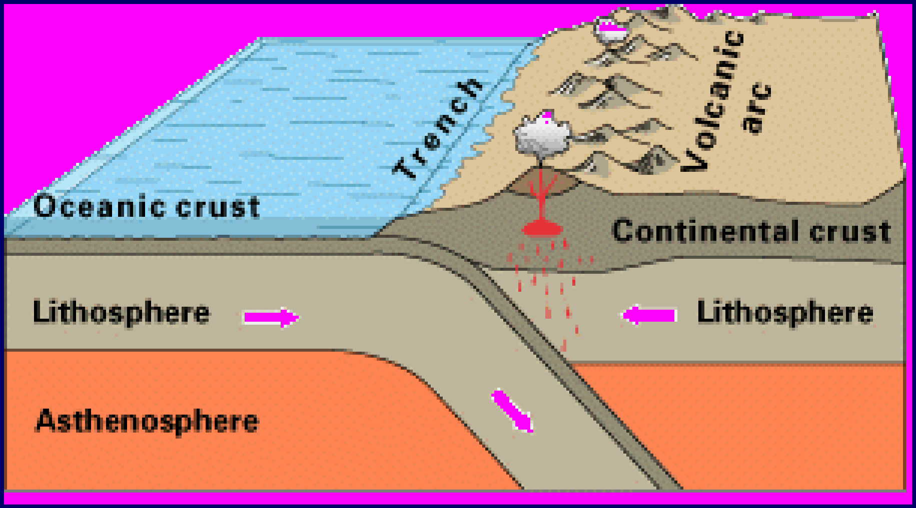
isostasy:

columns of mass must be the same at a certain depth (compensation depth) ~ 50 km



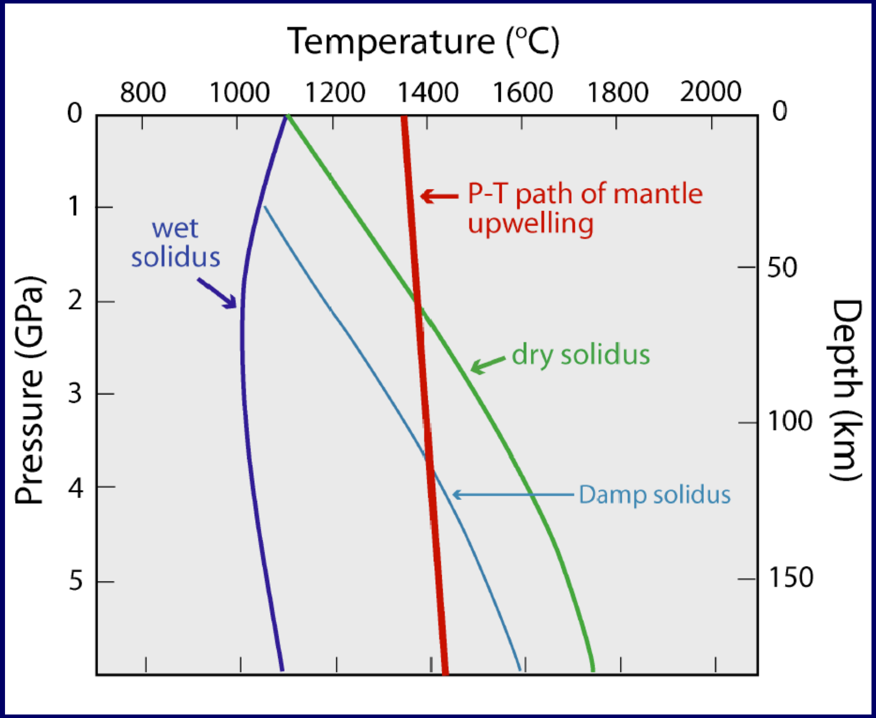
continents have roots and stick-up

Subduction zone

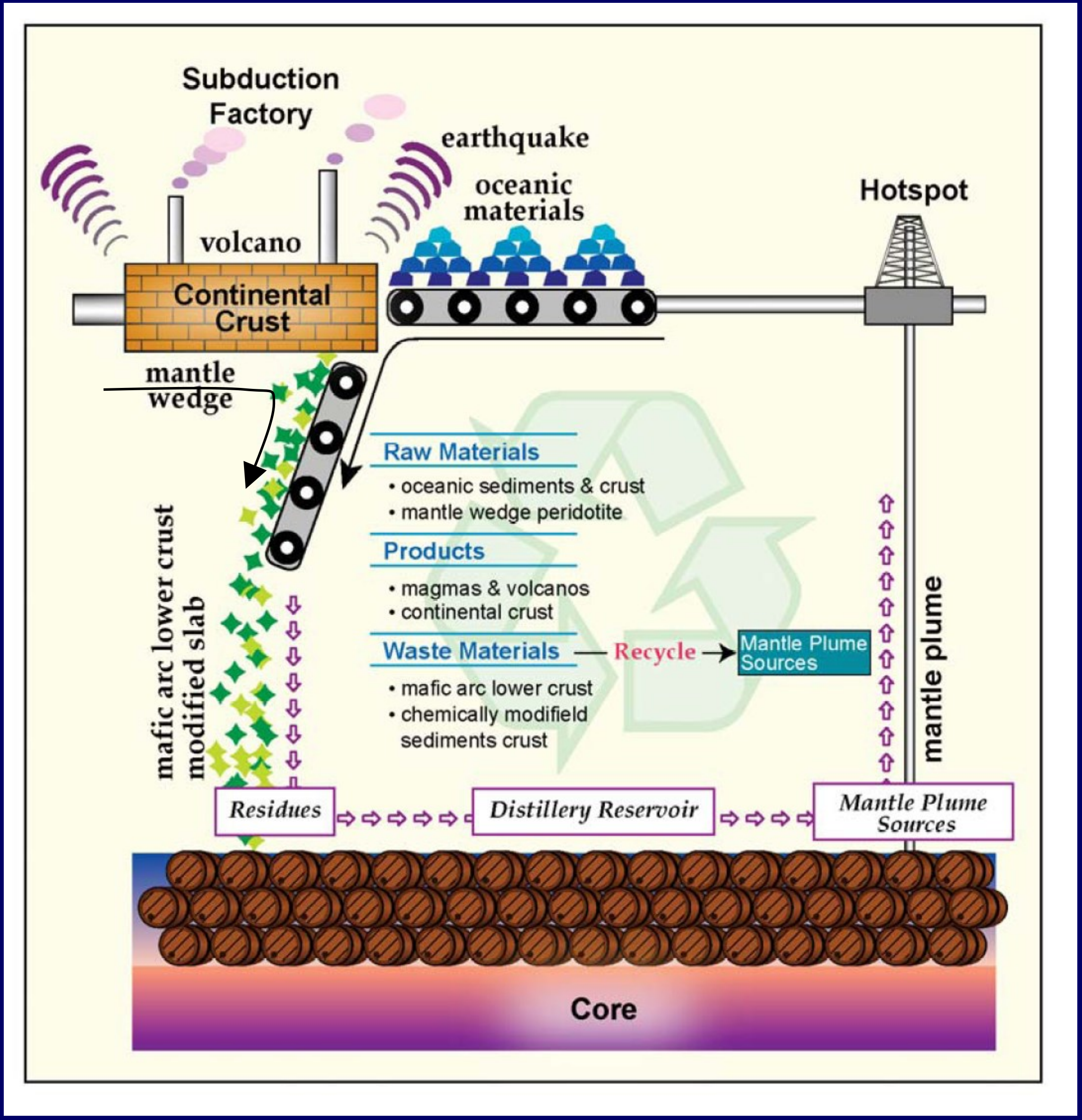


Because of water

Why volcanoes?



Making continental crust



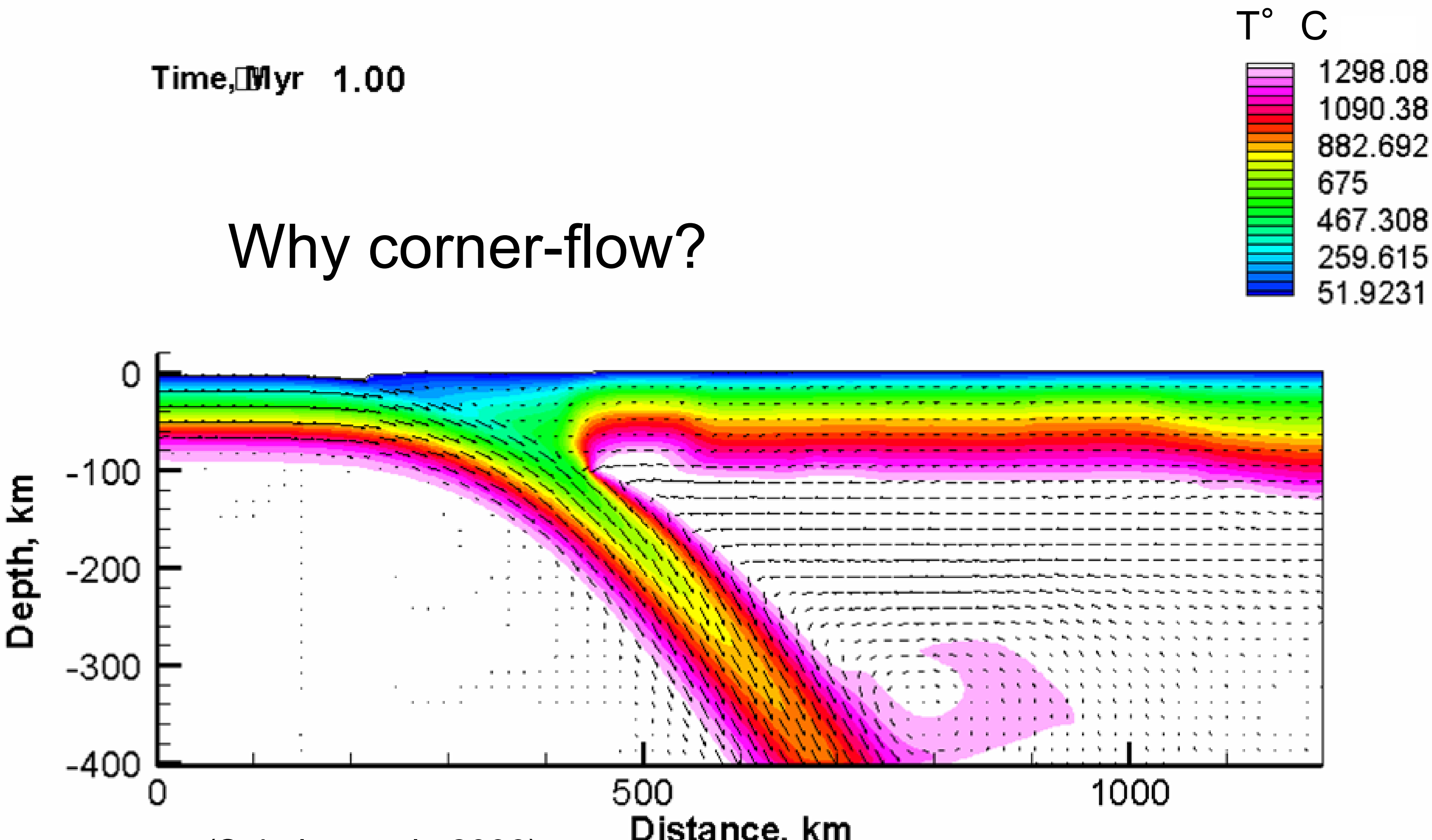
Arndt, 2015

A simple recipe for granite that should present no problems for even a starting chef.

Key factors to make continental crust

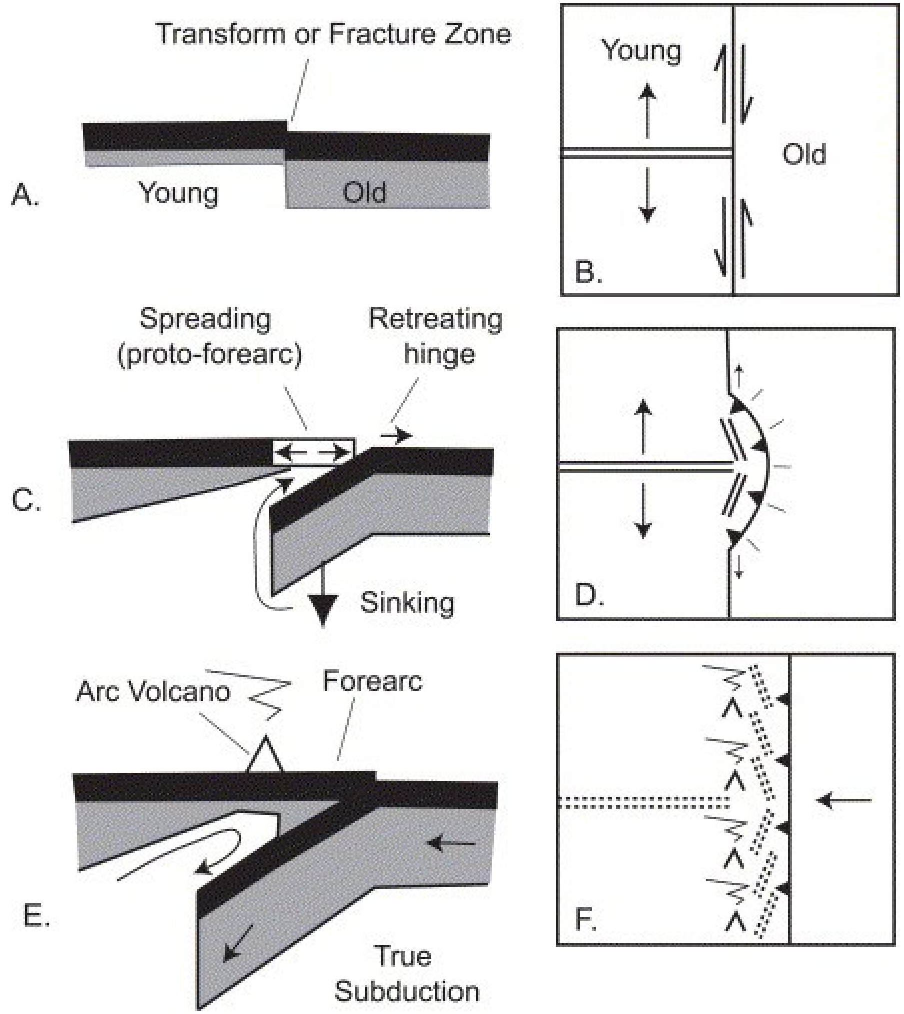
1. Permanent inflow of fluids, sediments and oceanic crust
2. Melting of mantle rocks enabled by water-rich fluid
3. Permanent inflow of „fresh“ mantle material = corner flow

Why corner-flow?



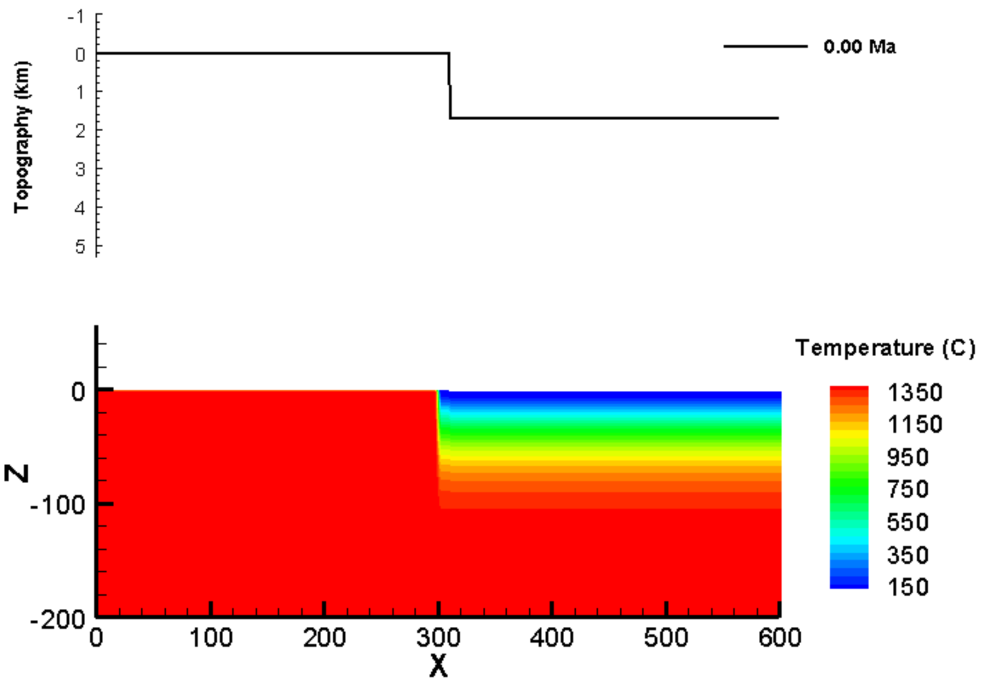
(Sobolev et al., 2006)

Spontaneous initiation at transform fault



Geological examples known (Stern, 2005) but was not confirmed by modeling (Gurnis et al., 2004)

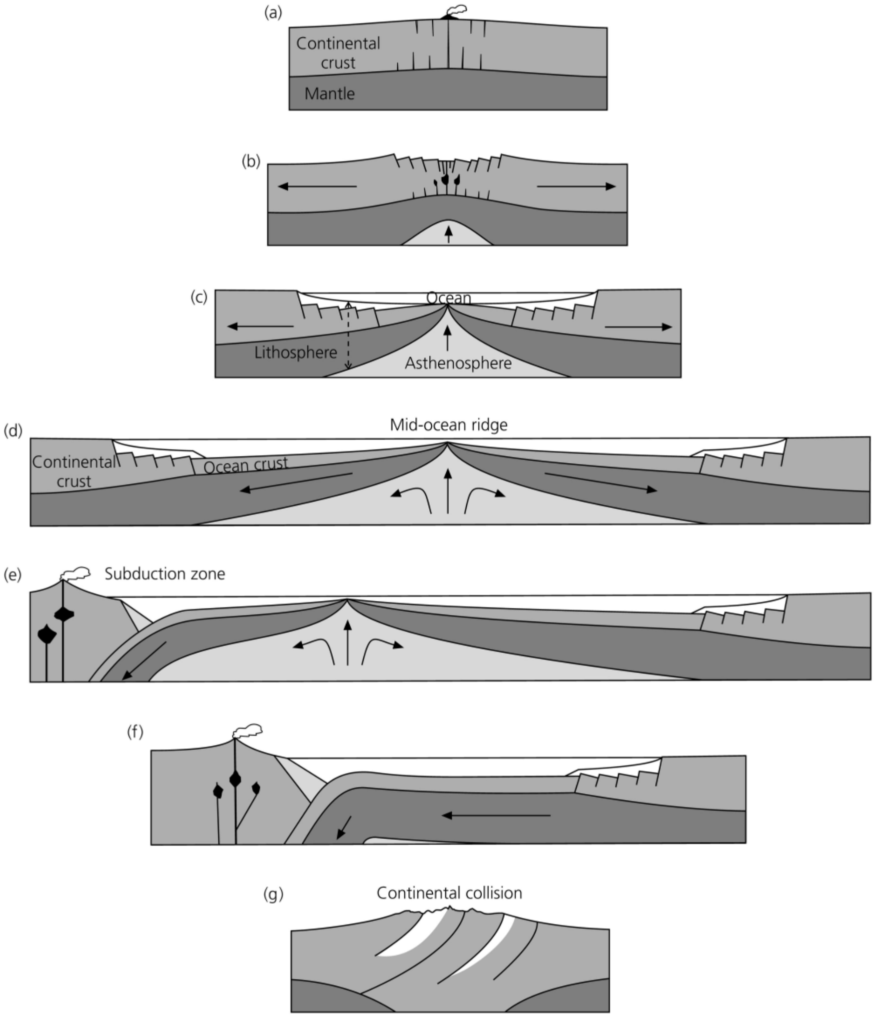
Forced initiation at transform fault



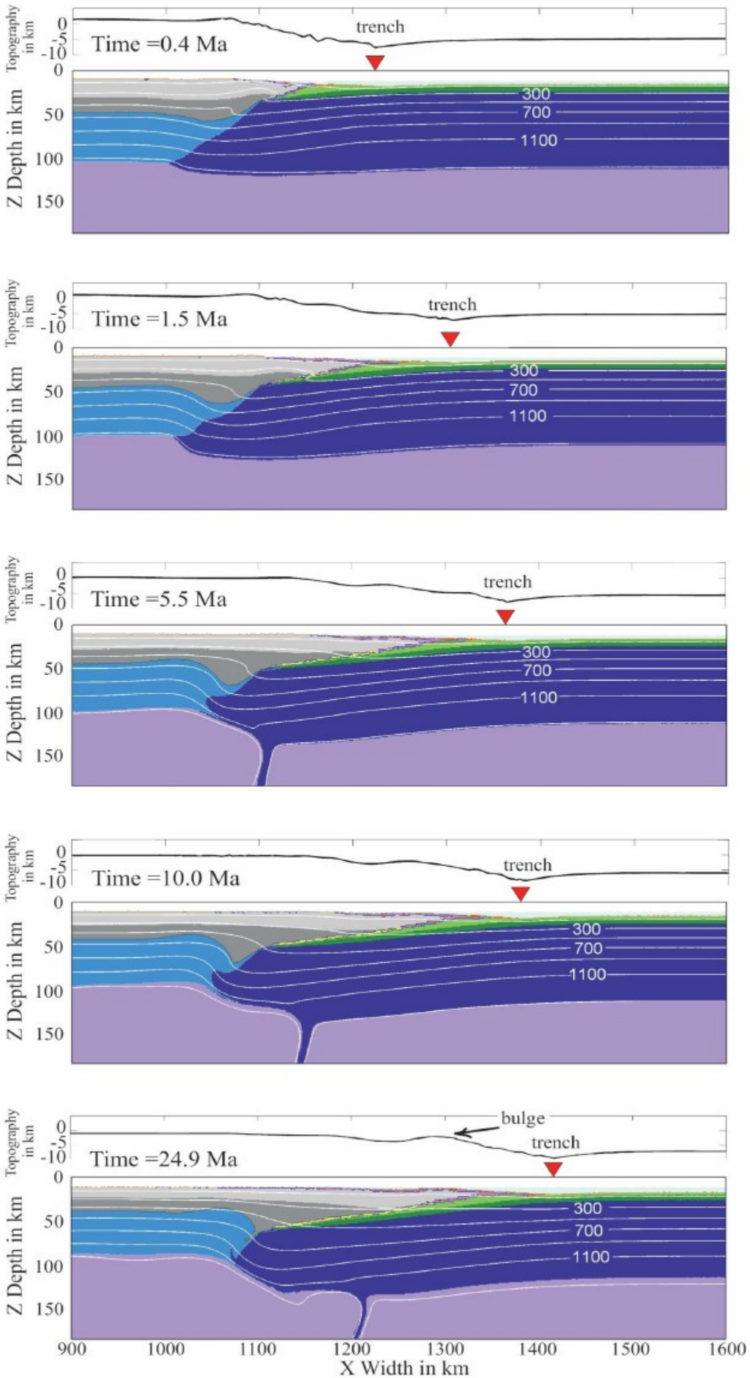
Problem 3D!

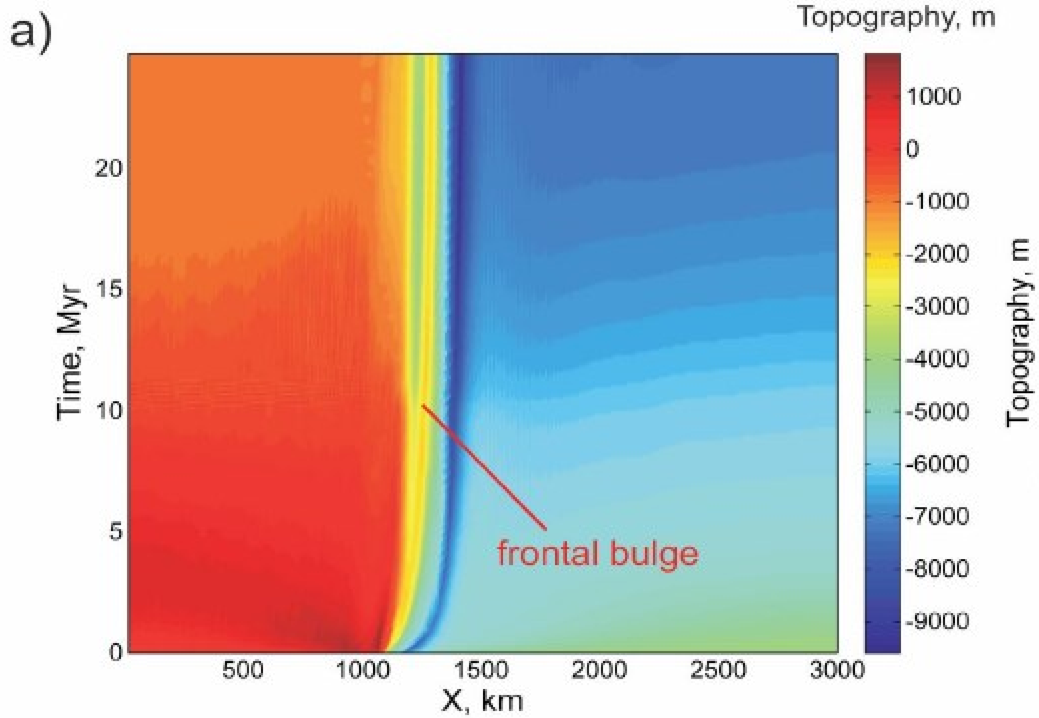
(Hall et al., 2003, Gurnis et al., 2004)

Wilson cycle



Initiation

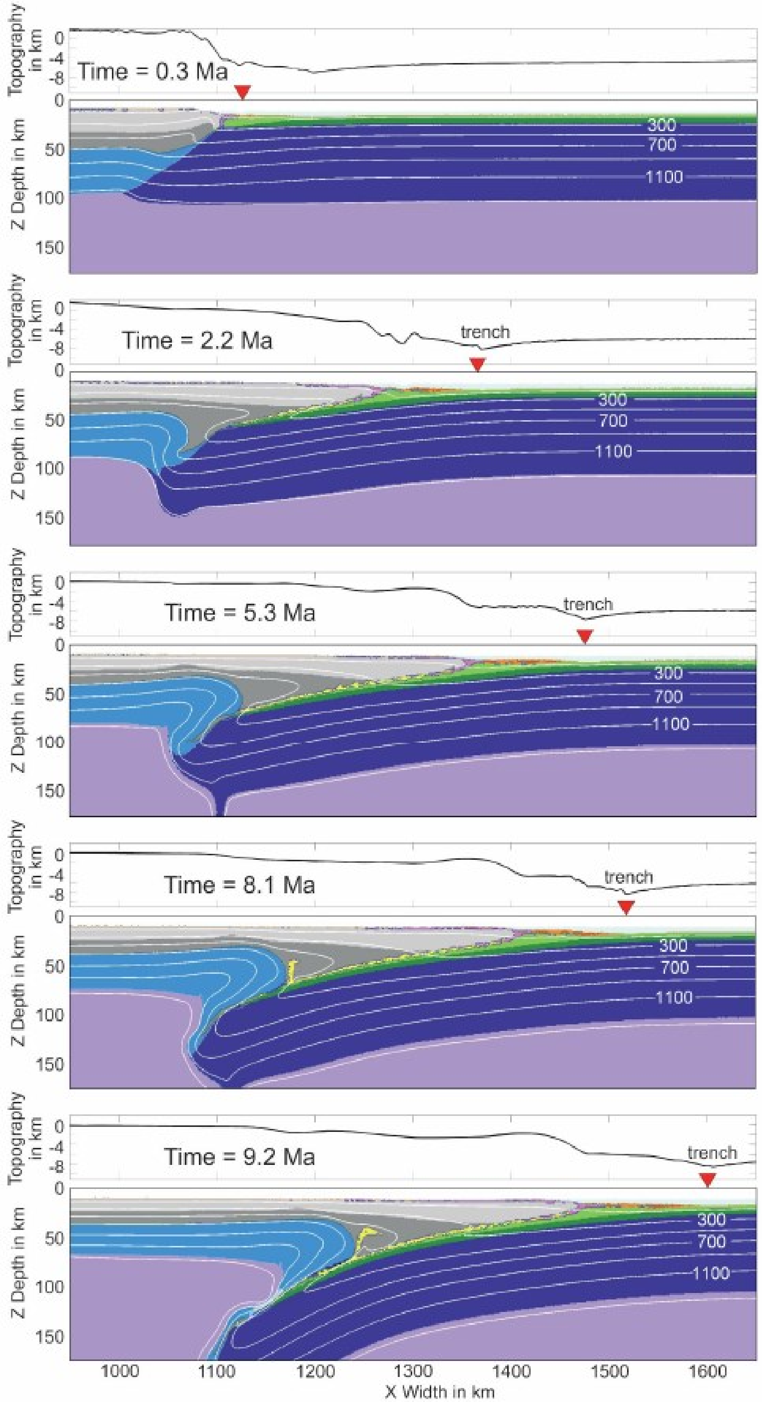


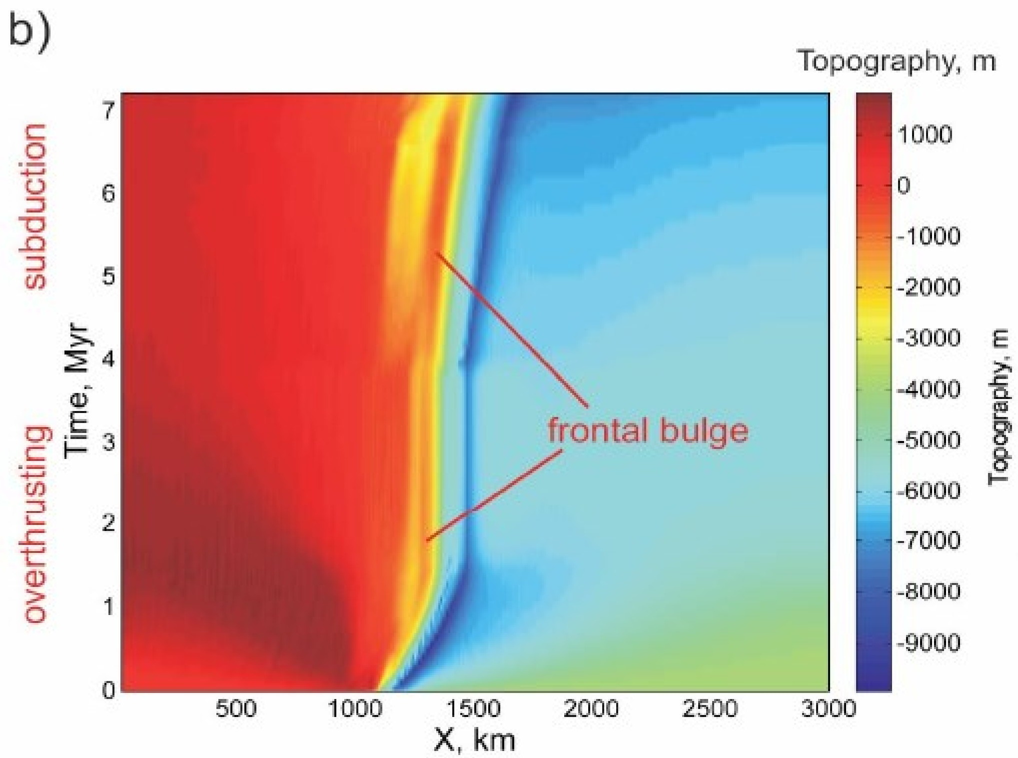


Implicit, Eulerian, FD, codes I2VIS, I2ELVIS, Gerya, ETH, Zürich

Nikolaeva et al, JGR , 2010

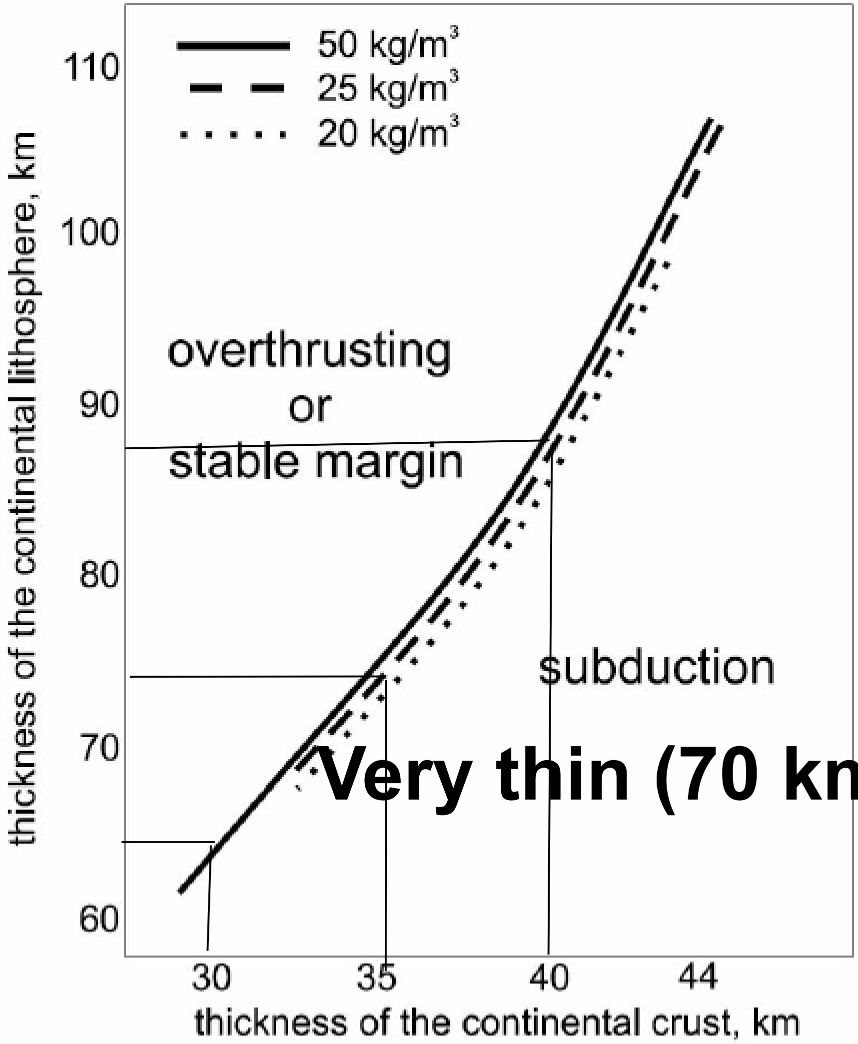
Initiation

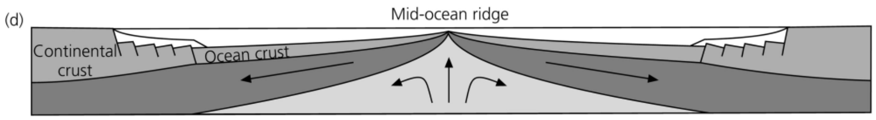




Nikolaeva et al, JGR , 2010

Initiation

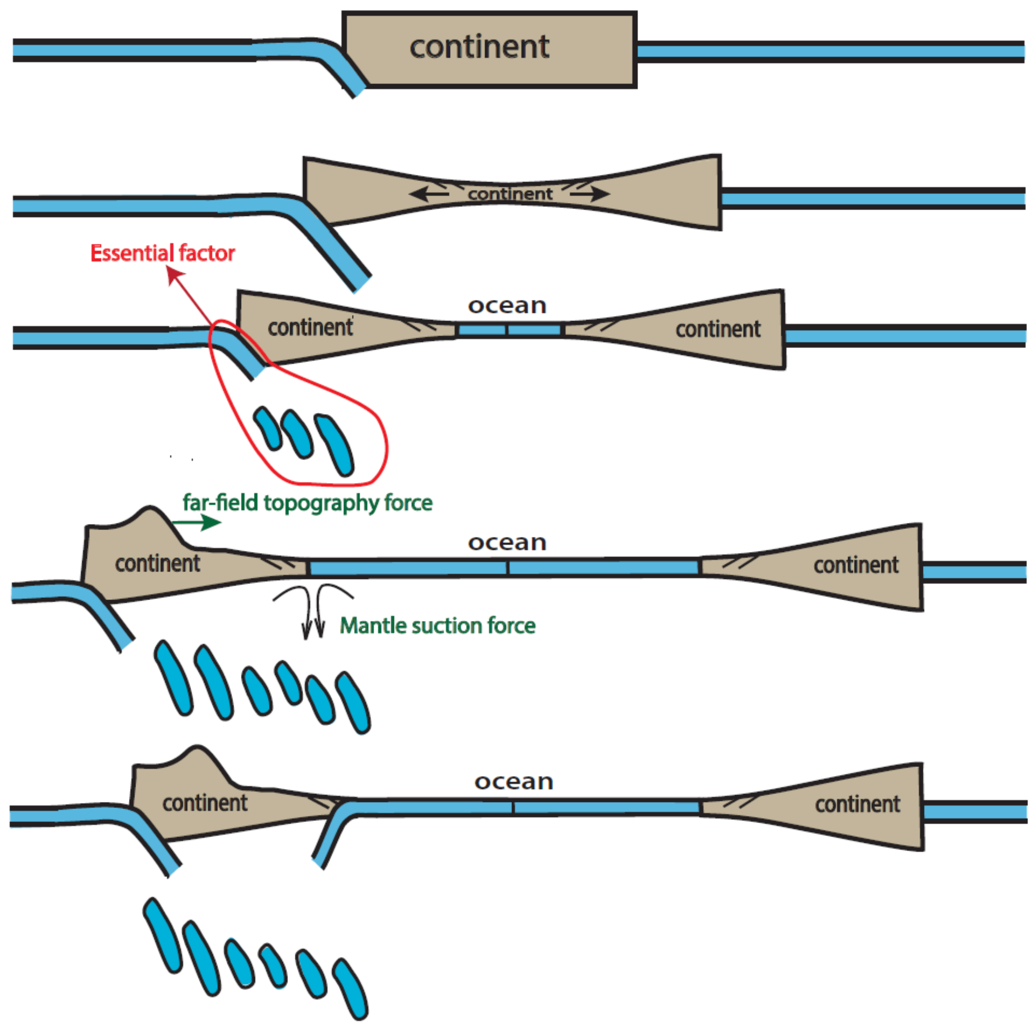


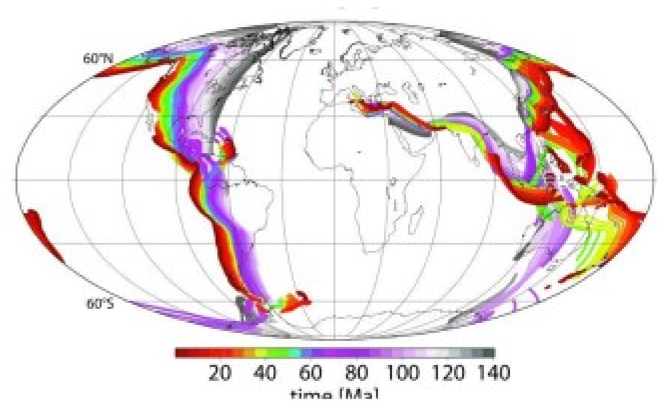


Very thin (70 km lithosphere) is required!

Nikolaeva et al, JGR , 2010

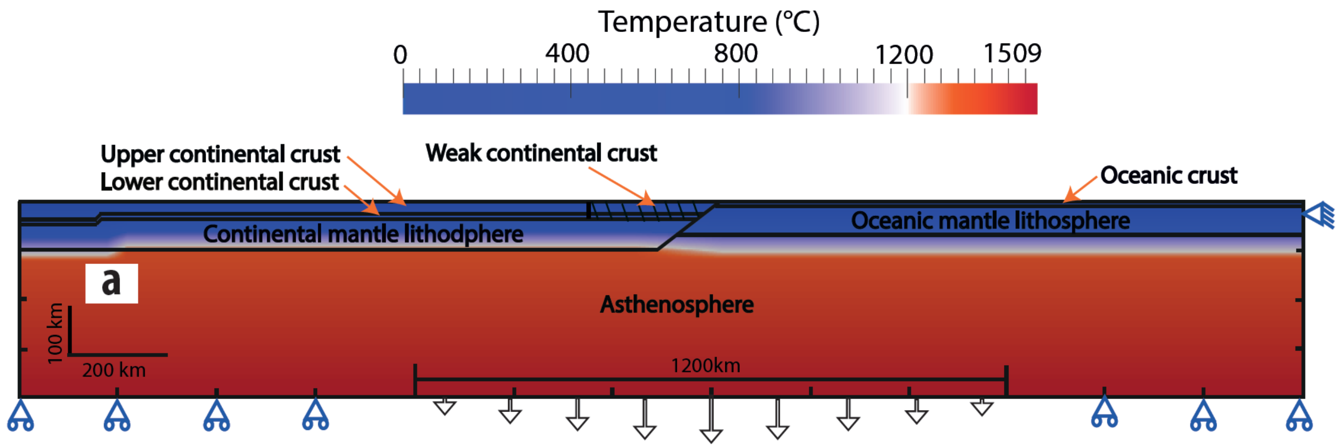
Pull from old subducted slab? *Initiation*





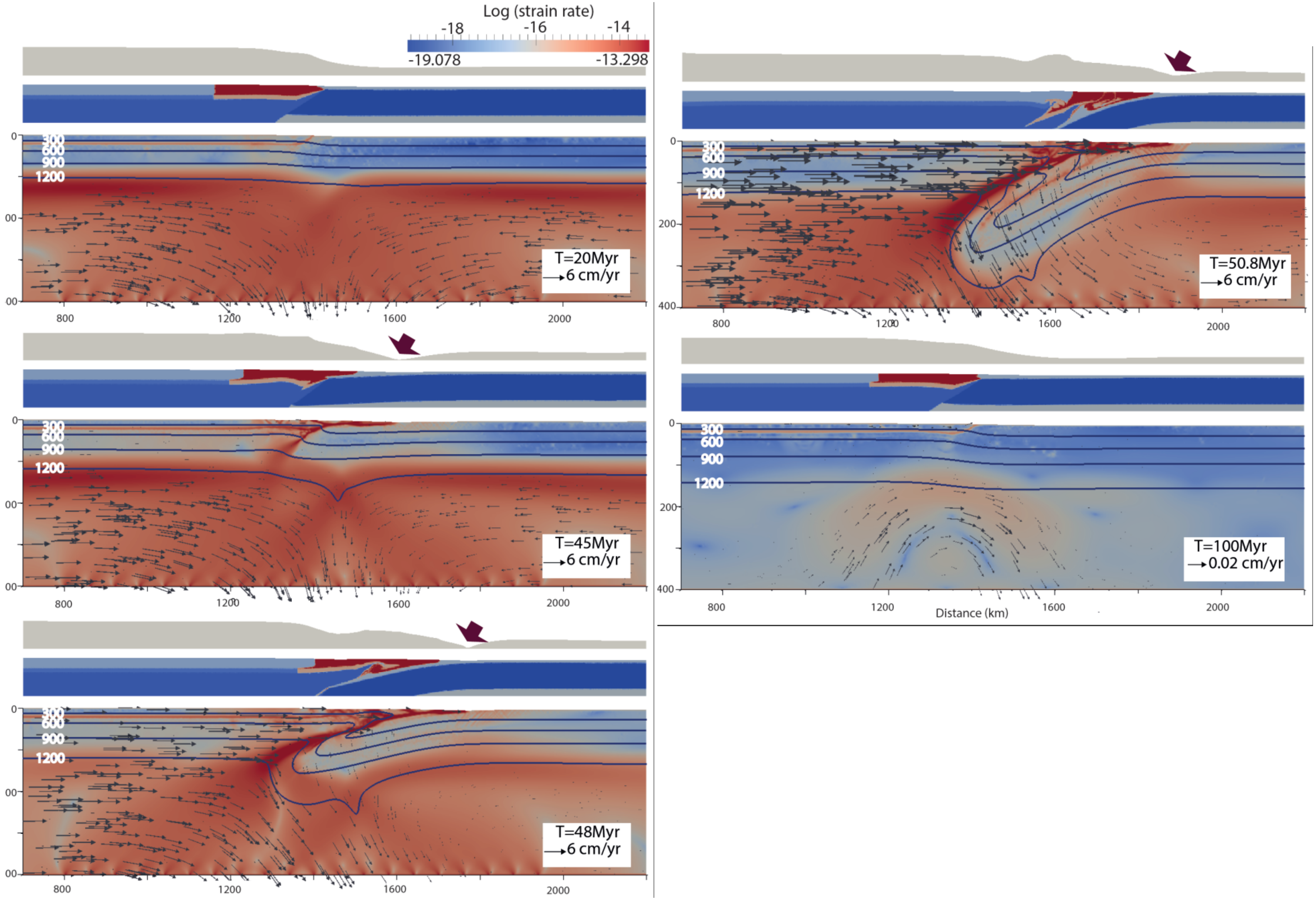
Pull from old subducted slab?

Initiation

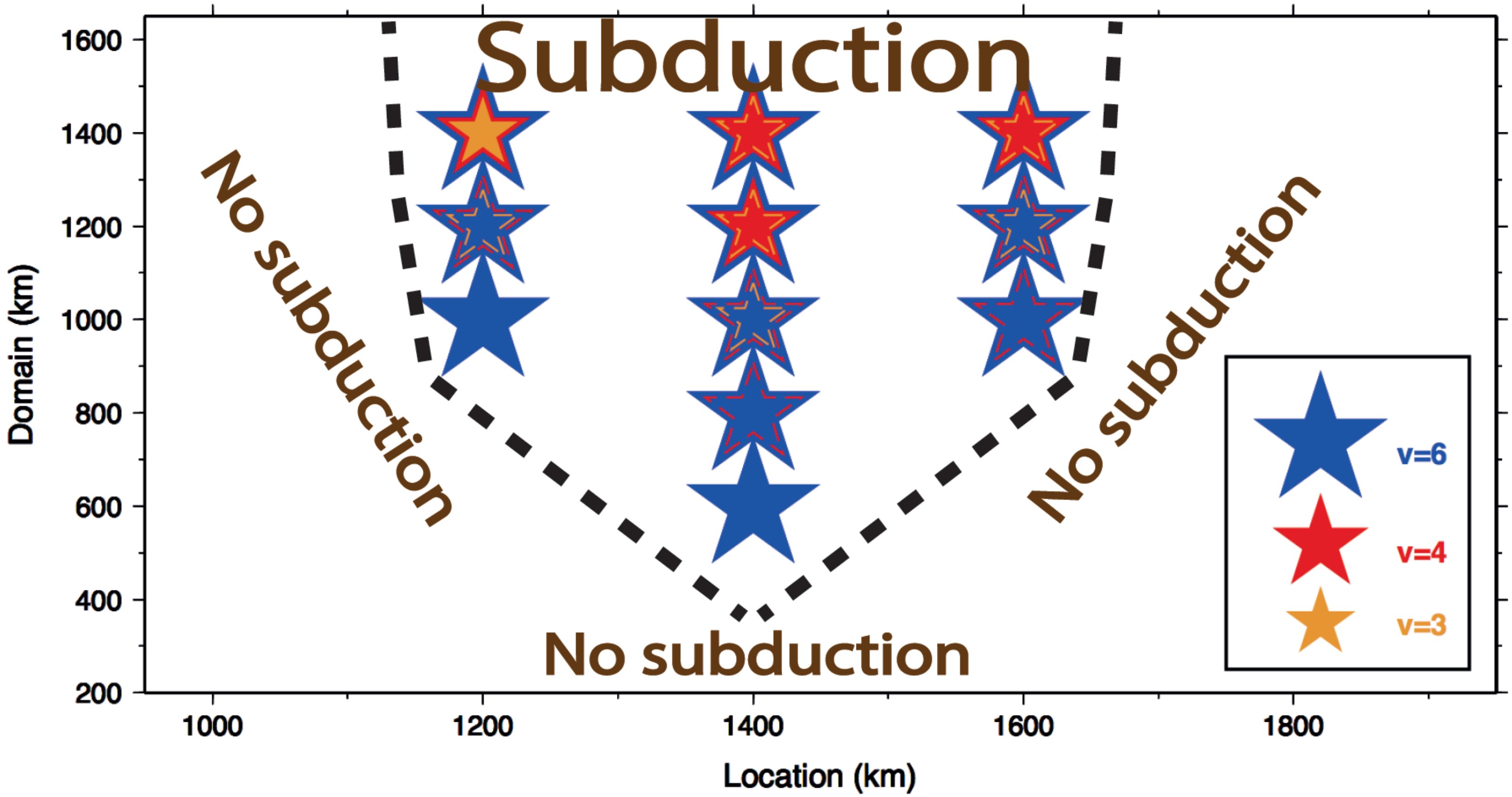


Setting the model up

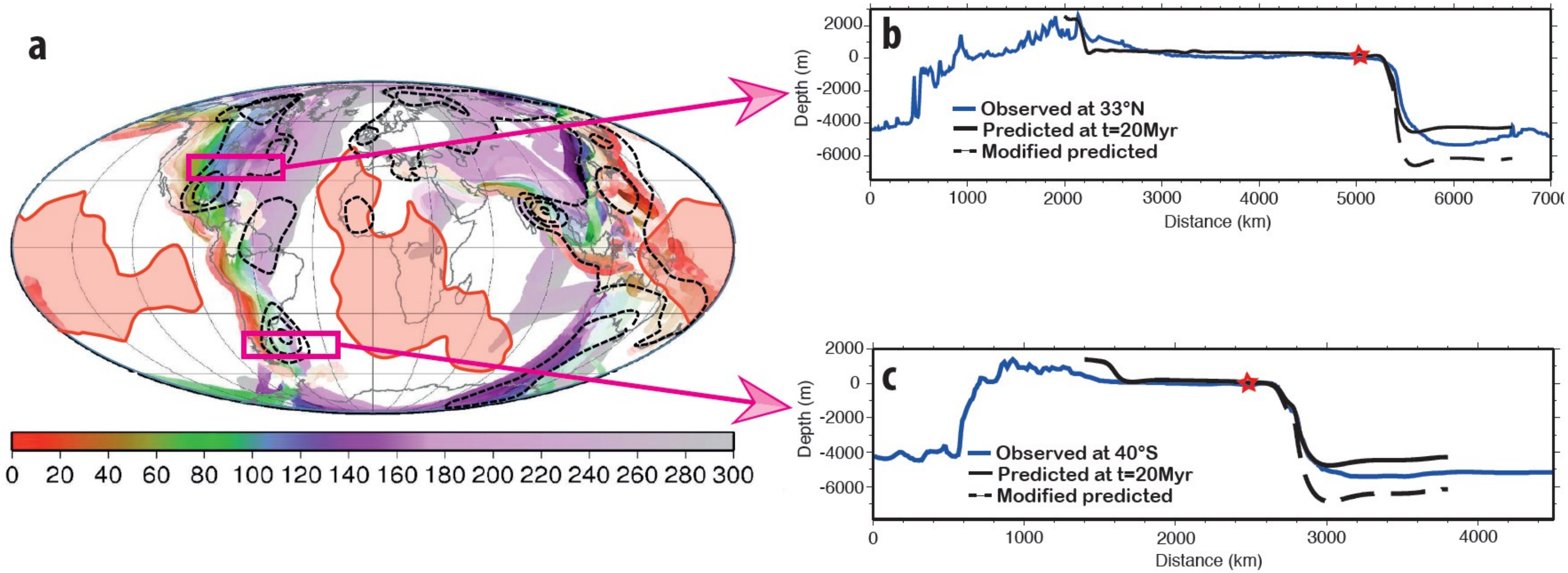
Pull from old subducted slab? *Initiation*



Pull from old subducted slab? *Initiation*

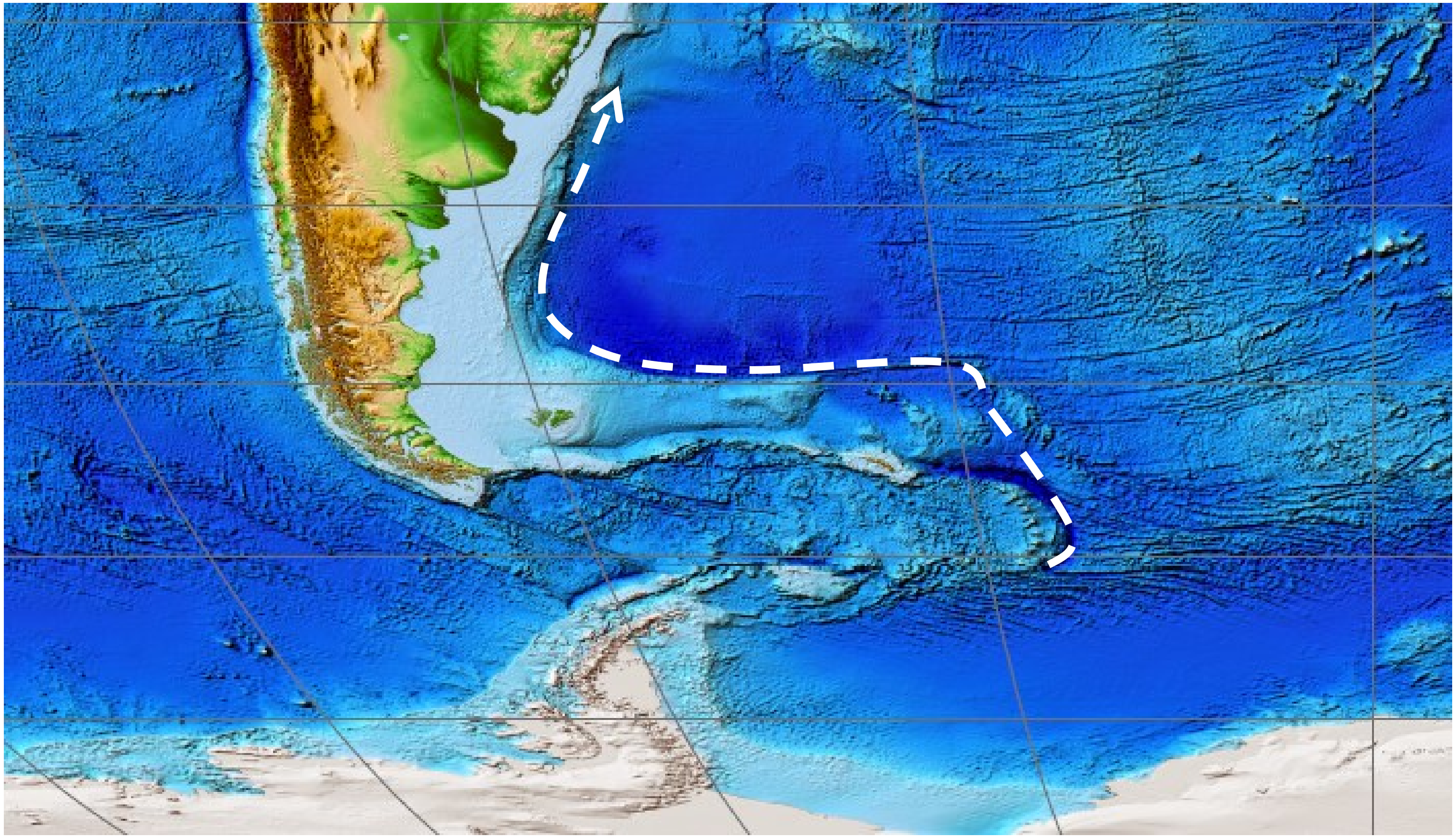


Pull from old subducted slab? *Initiation*

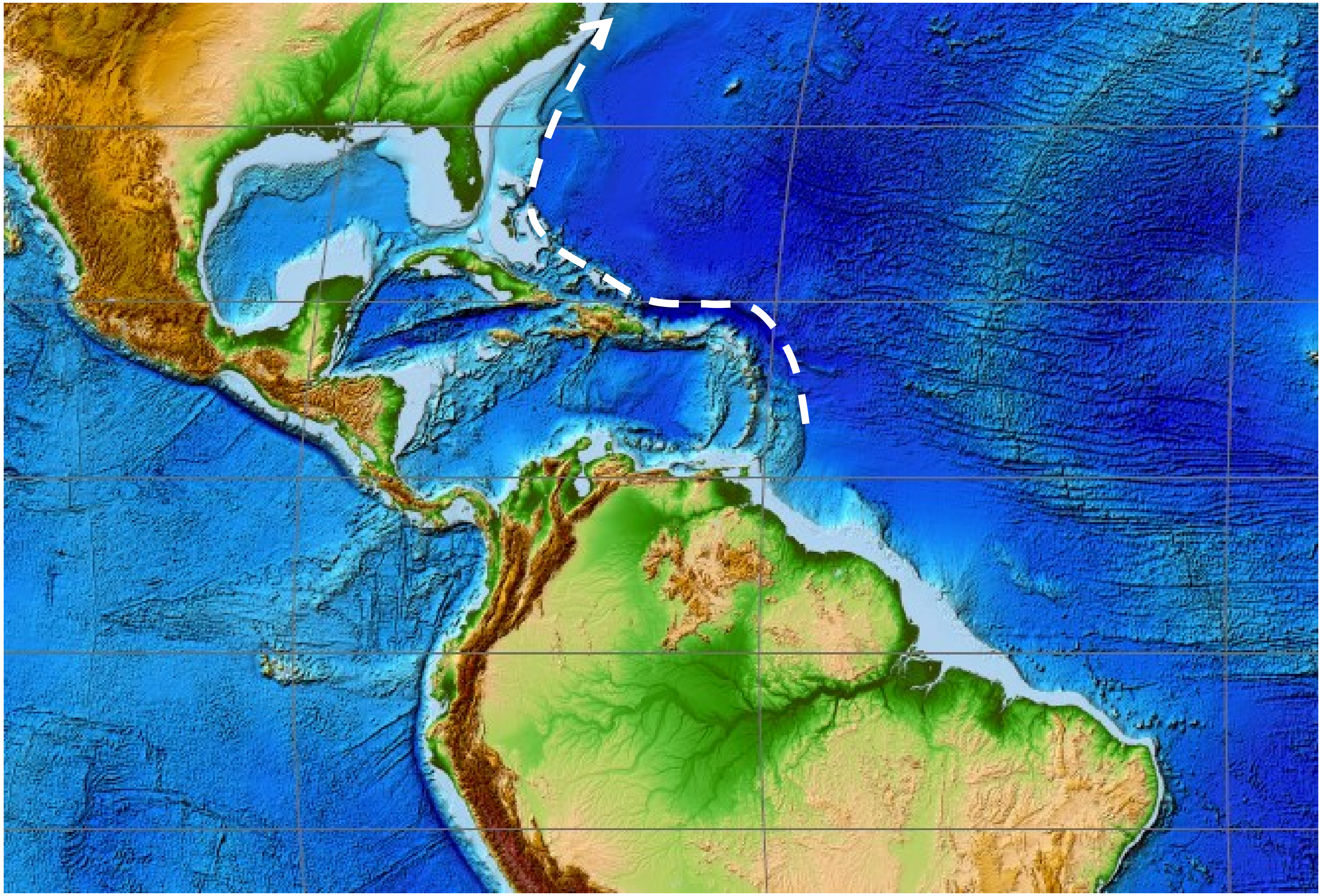


Problem 3D!

Possible subduction initiation in Atlantics



Possible subduction initiation in Atlantics

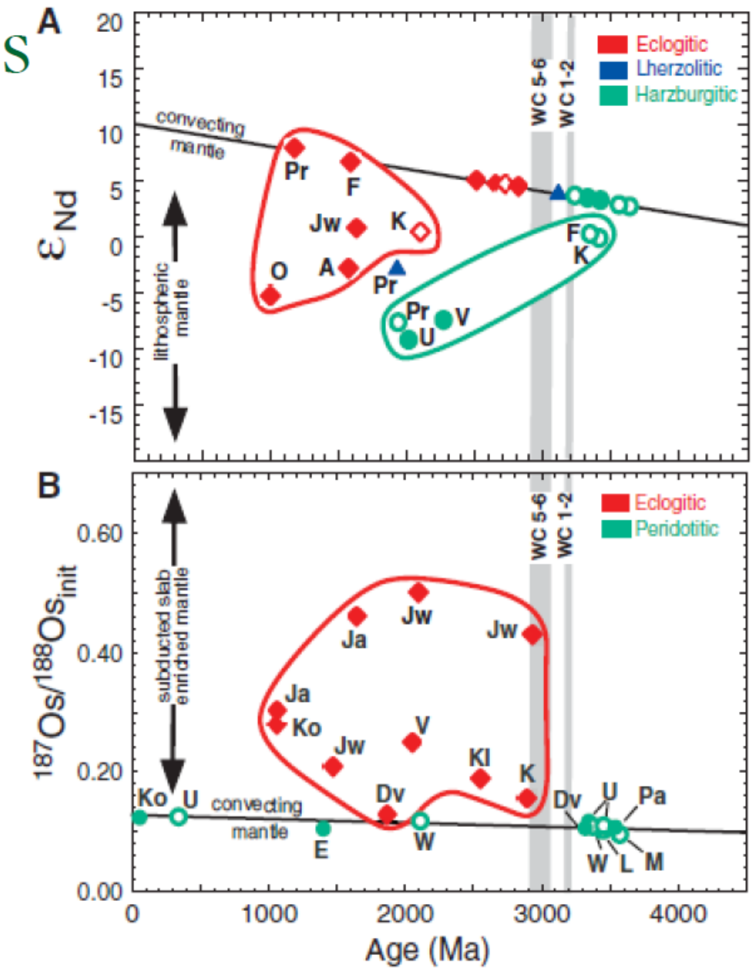


When the plate tectonics started on Earth?

Diamond inclusions

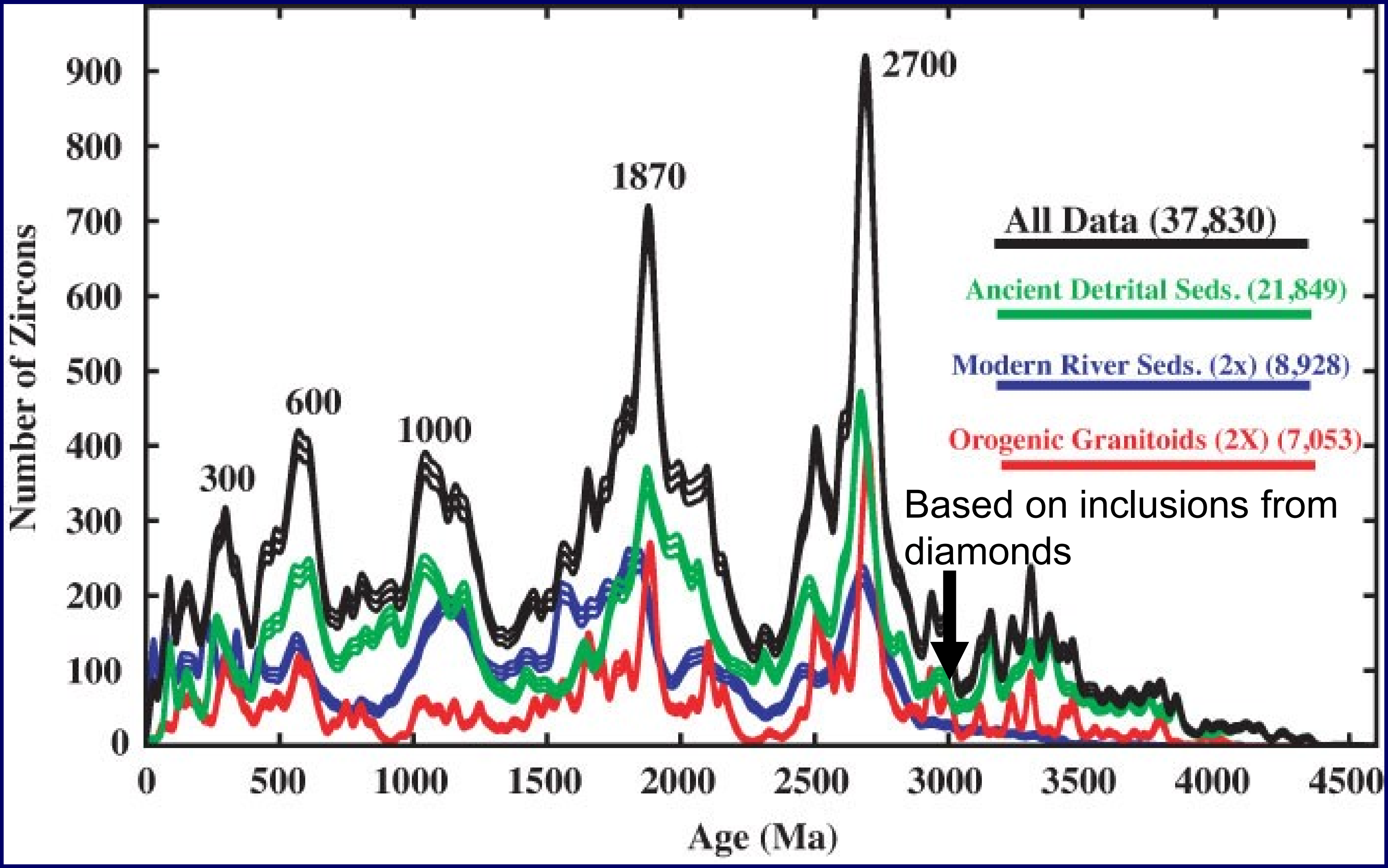
- > 3 Ga: peridotitic
- < 3Ga: eclogitic + peridotitic

→ Plate tectonics started ~ 3Ga



(Shirey & Richardson, 2011)

Zircon Age Distribution through time. Monitor of Continental Crust growth



What do these age peaks indicate?

Condie & Aster, 2009

First subduction

LETTER

doi:10.1038/nature13728

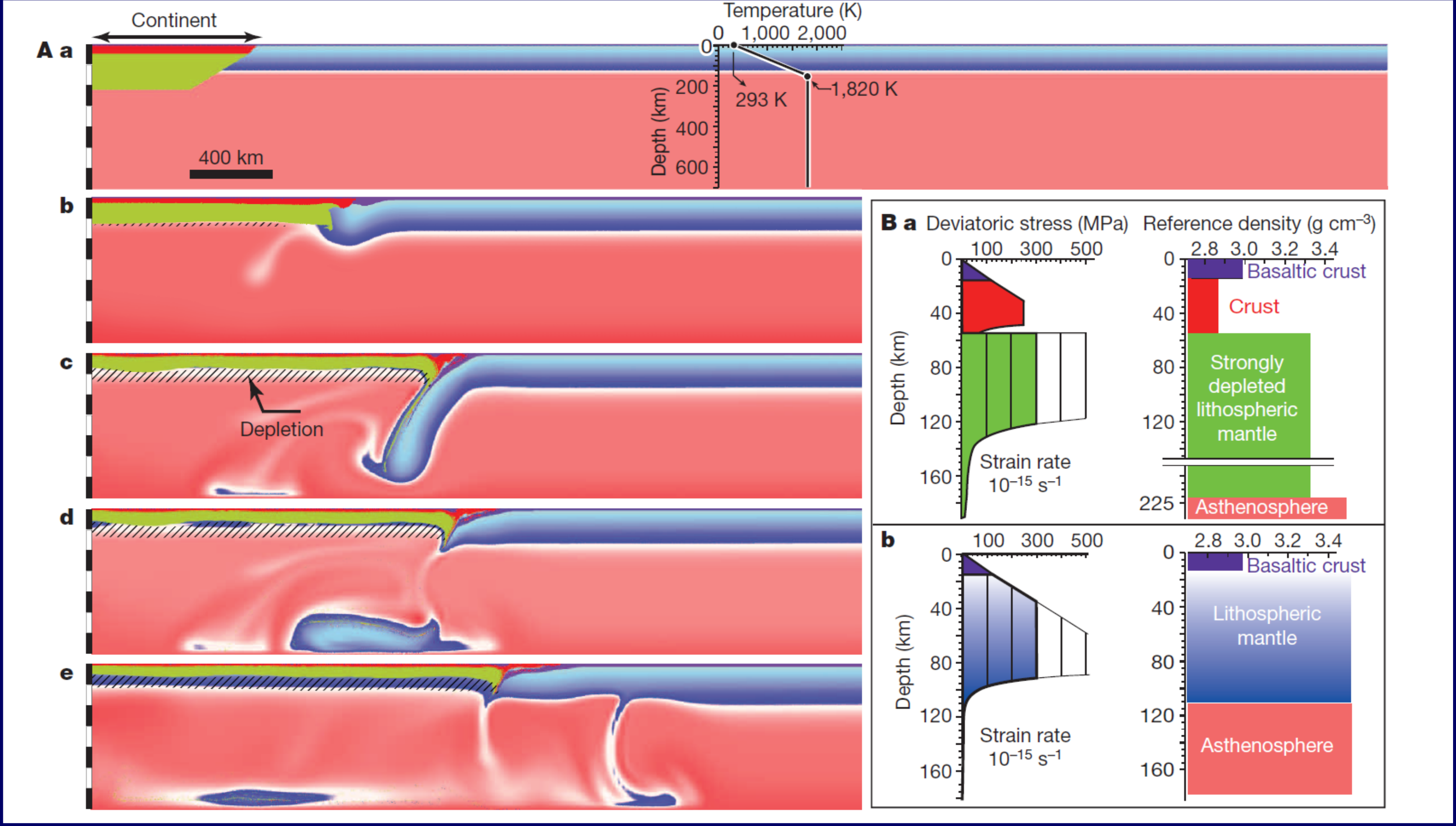
Spreading continents kick-started plate tectonics

Patrice F. Rey[1], Nicolas Coltice[2,3] & Nicolas Flament[1]

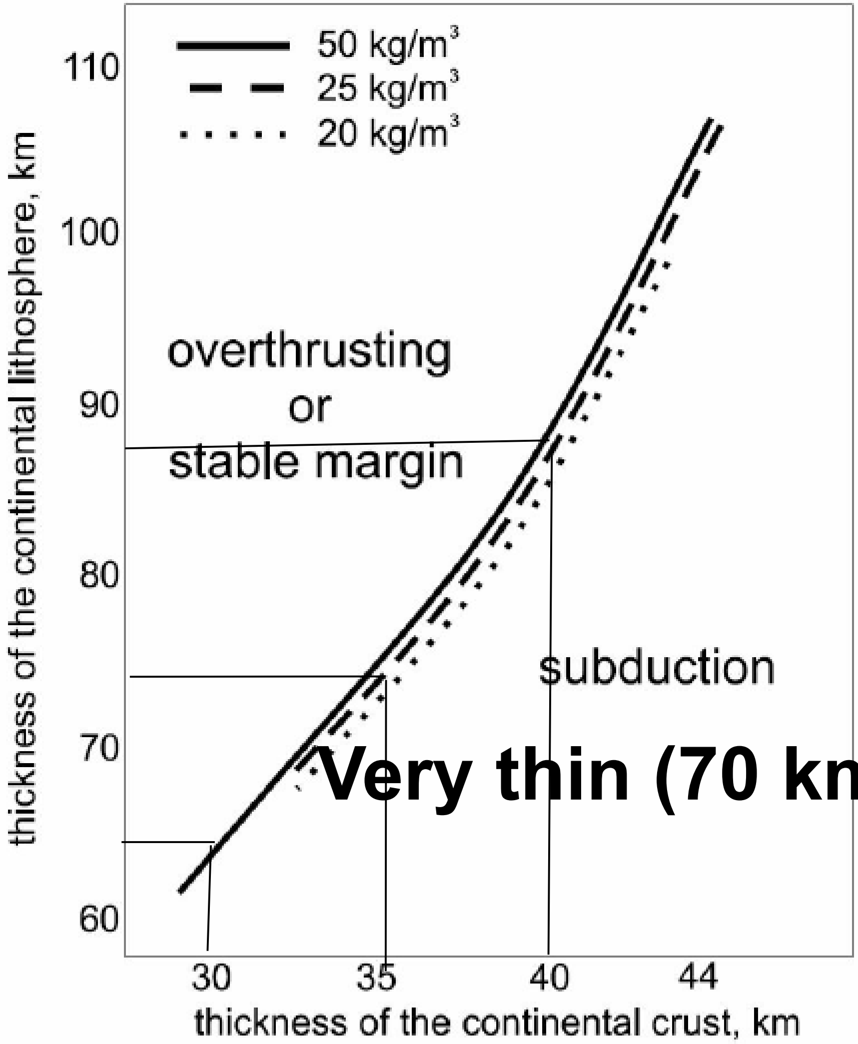
Stresses acting on cold, thick and negatively buoyant oceanic lithosphere are thought to be crucial to the initiation of subduction and the operation of plate tectonics[1,2], which characterizes the present-day geodynamics of the Earth. Because the Earth's interior was hotter in the Archaean eon, the oceanic crust may have been thicker, thereby making the oceanic lithosphere more buoyant than at present[3], and whether subduction and plate tectonics occurred during this time is ambiguous, both in the geological record and in geodynamic models[4]. Here we show that because the oceanic crust was thick and buoyant[5], early continents may have produced intra-lithospheric gravitational stresses large enough to drive their gravitational spreading, to initiate subduction at their margins and to trigger episodes of subduction. Our model predicts the co-occurrence of deep to progressively shallower mafic volcanics and arc magmatism within continents in a self-consistent geodynamic framework, explaining the enigmatic

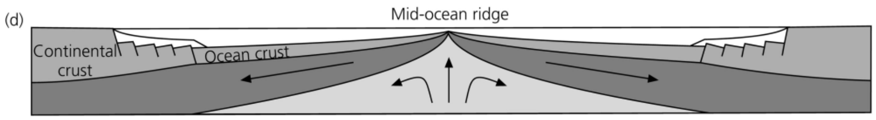
that of present-day tectonic forces driving orogenesis[1]. To explore the tectonic impact of a thick and buoyant continent surrounded by a stagnant lithospheric lid, we produced a series of two-dimensional thermo-mechanical numerical models of the top 700 km of the Earth, using temperature-dependent densities and visco-plastic rheologies that depend on temperature, melt fraction and depletion, stress and strain rate (see Methods). The initial temperature field is the horizontally averaged temperature profile of a stagnant-lid convection calculation for a mantle ~200 K hotter than at present (Fig. 1A, a and Extended Data Fig. 2). The absence of lateral temperature gradients ensures that no convective stresses act on the lid, allowing us to isolate the dynamic effects of the continent. A buoyant and stiff continent 225 km thick (strongly depleted mantle root 170 km thick overlain by felsic crust 40 km thick; see Fig. 1B, a) is inserted within the lid, on the left side of the domain to exploit the symmetry of the problem (Fig. 1A, a). A mafic crust 15 km thick covers the

First subduction



Initiation

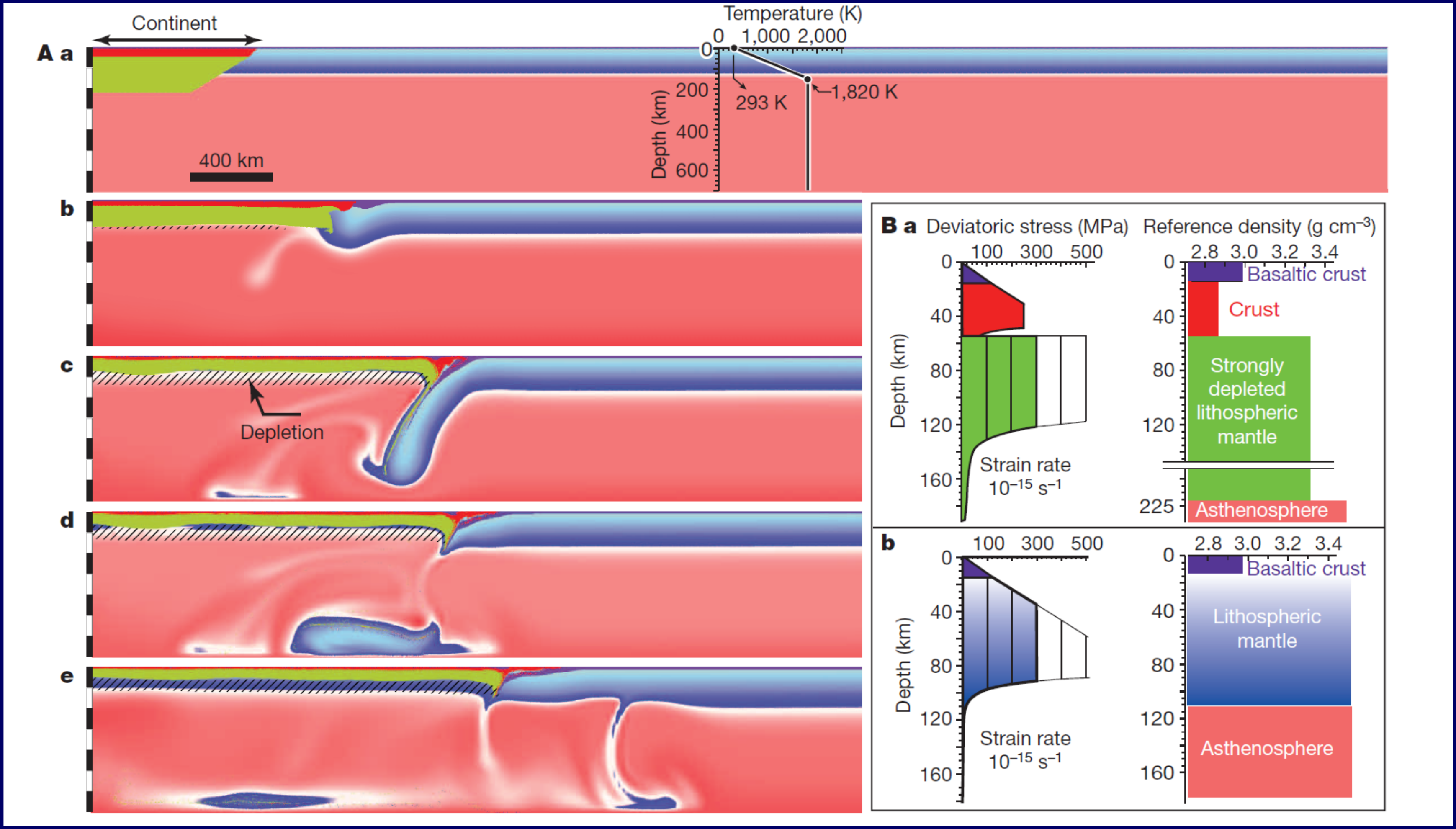




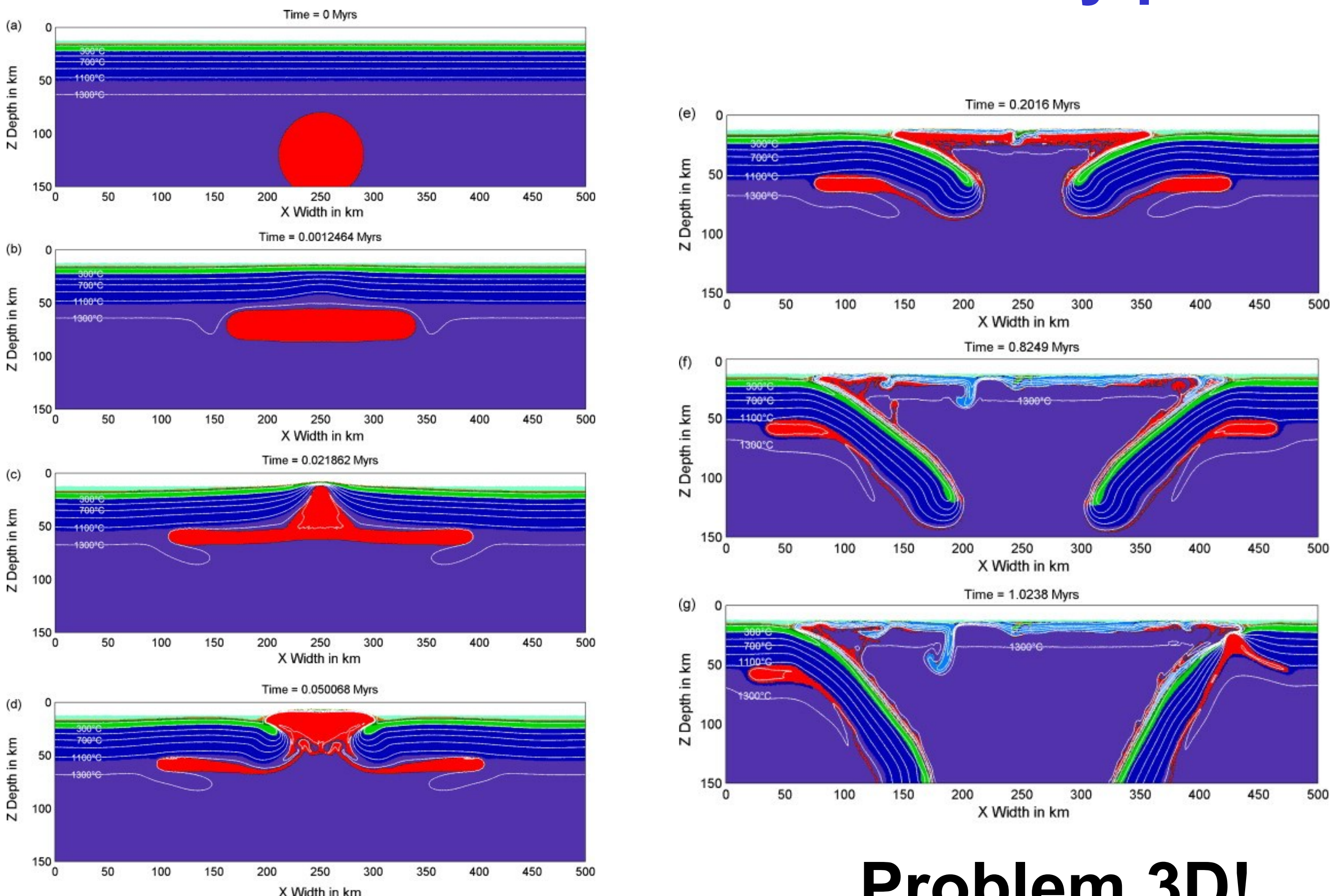
Very thin (70 km lithosphere) is required!

Nikolaeva et al, JGR , 2010

First subduction



First subduction: Initiation by plume



Problem 3D!

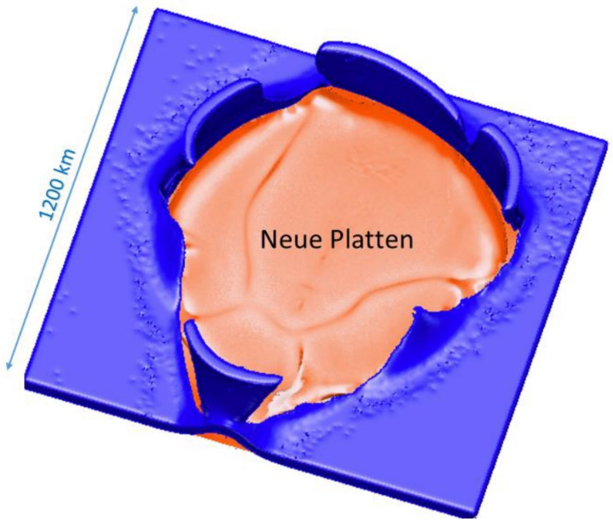
Implicit, Eulerian, FD, codes I2VIS, I2ELVIS, Gerya, ETH, Zürich

Ueda, Gerya, Sobolev (2008)

Initiation

First subduction: Initiation by plume 3D model

(Gerya et al. Nature 2015)



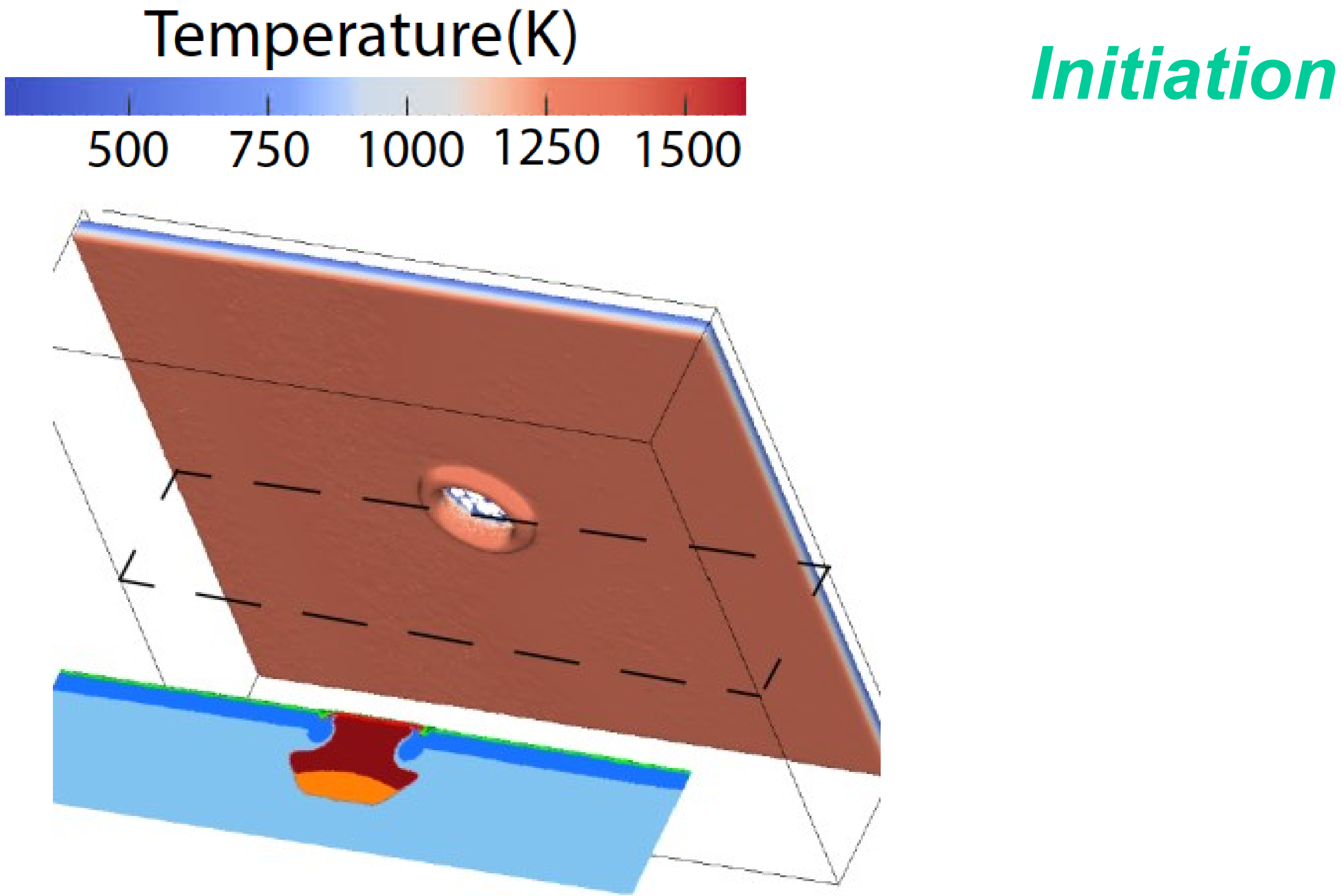
3D Code I3EVIS (Eulerian, FD) by Gerya, ETH, Zürich

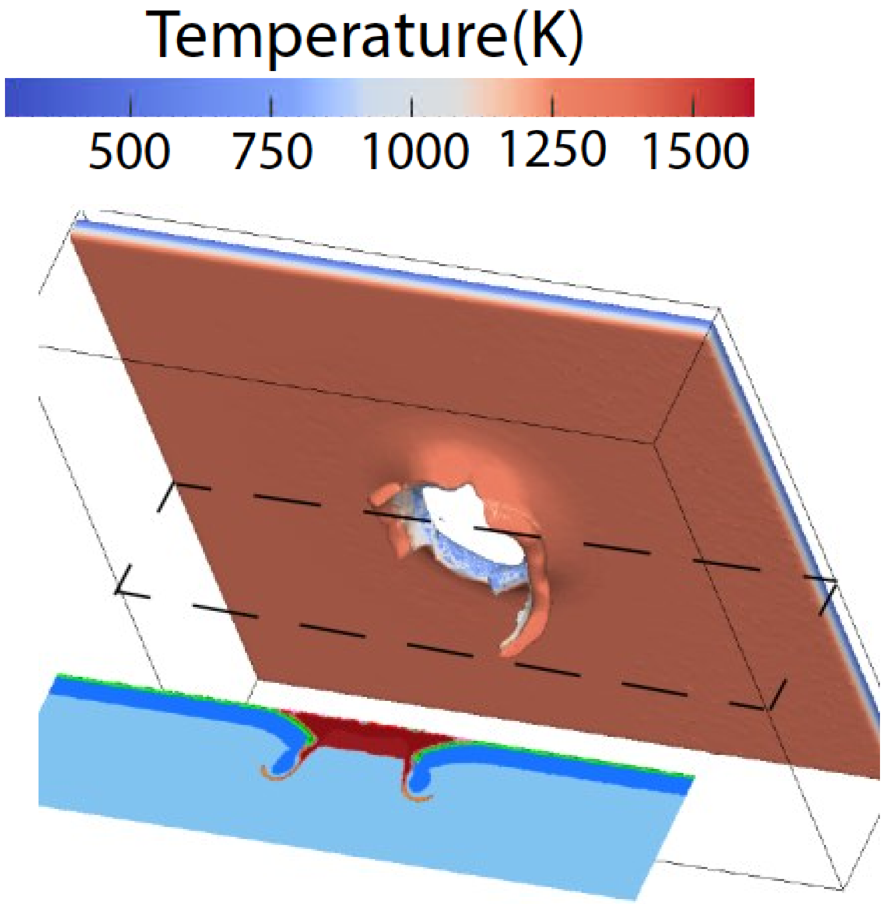
LETTER

doi:10.1038/nature15752

Plate tectonics on the Earth triggered by plume-induced subduction initiation

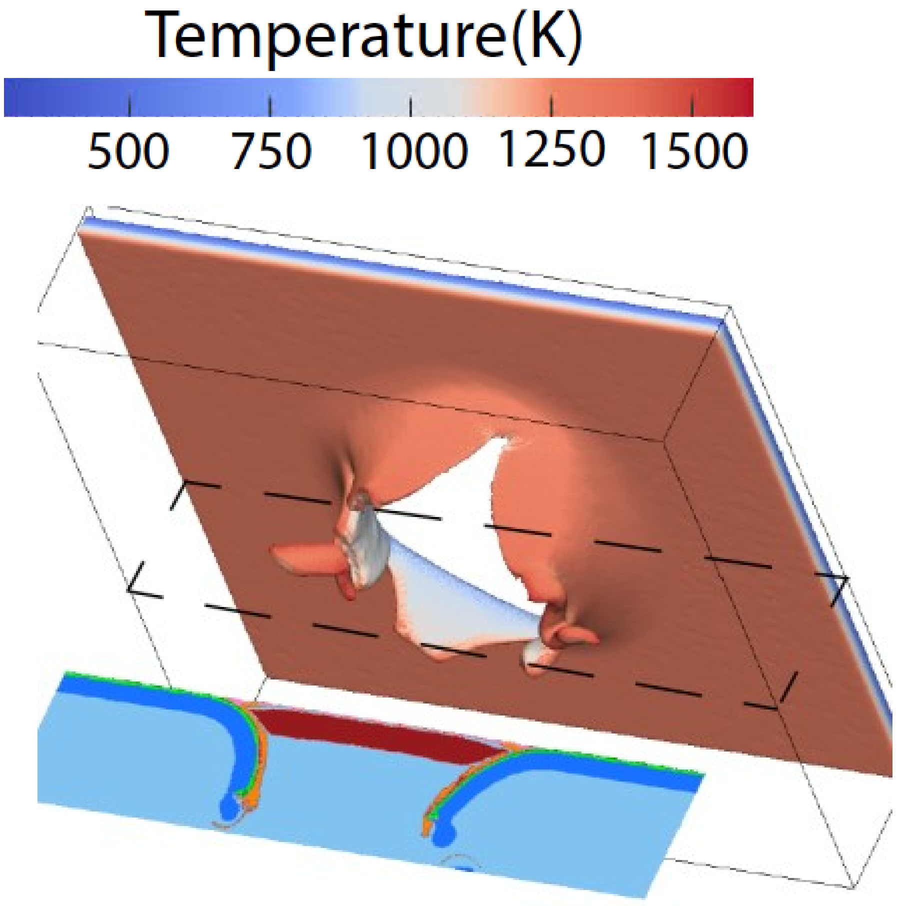
T. V. Gerya[1], R. J. Stern[2], M. Baes[3], S. V. Sobolev[3,4] & S. A. Whattam[5]


Temperature(K)
500
750
1000
1250
1500
Initiation



Initiation

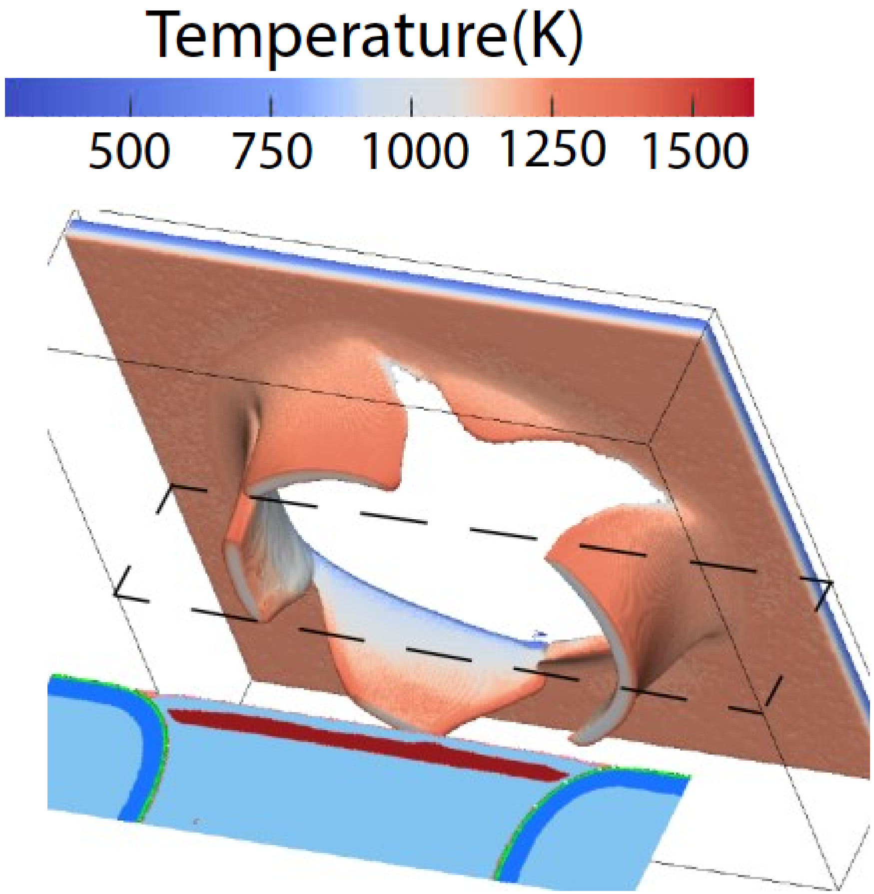
Formation of an incipient trench and a descending nearly-circular slab at the plateau margins



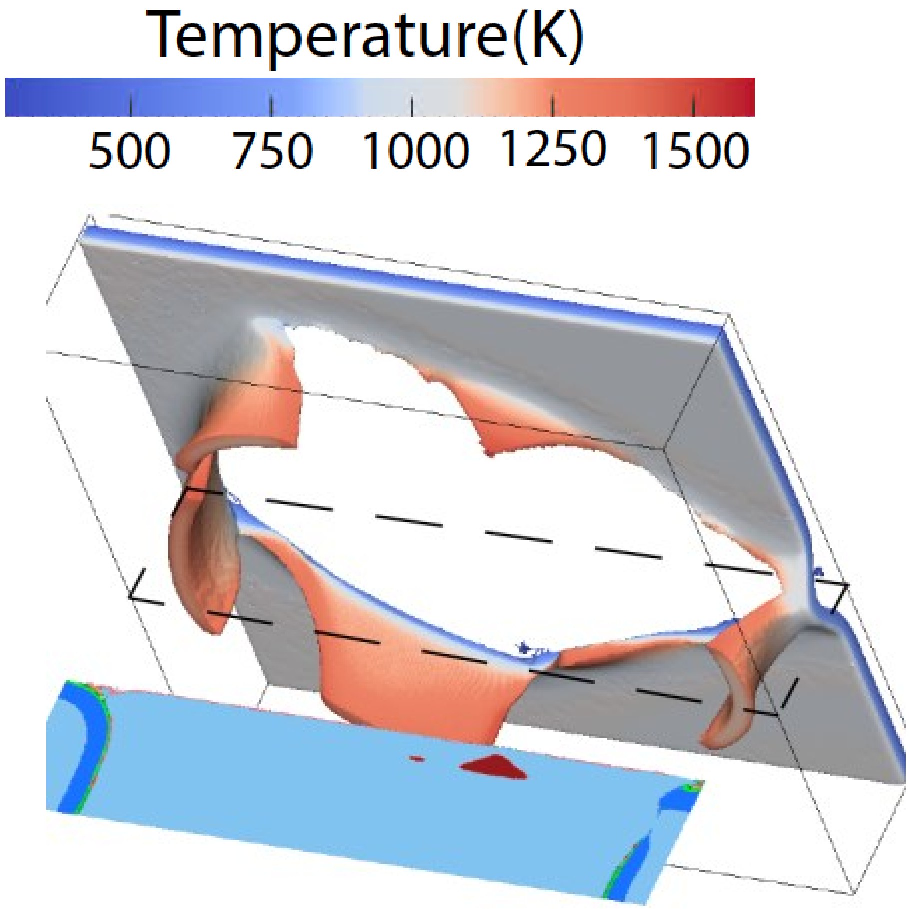
Initiation

Tearing of the circular slab under its own weight

Initiation



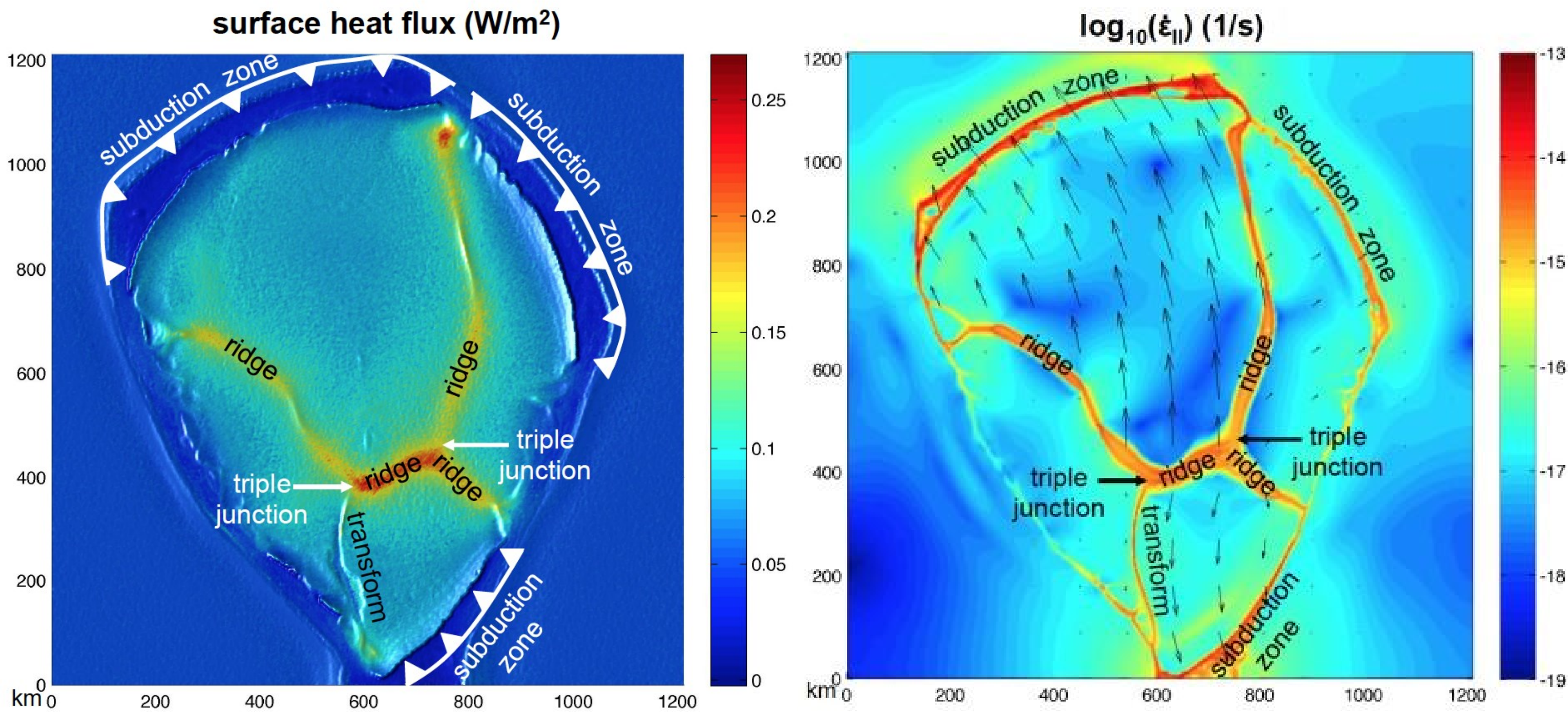
Formation of several self-sustained retreating subduction zones



Initiation

Cooling of the new plate, initiation of spreading centers and transform boundaries within this plate

Regional PT cell with retreating subduction zones



Gerya et al. (2015)

Mature

Study of effect of TZ and lower mantle viscosity and phase transformations on self-consistent slab dynamics

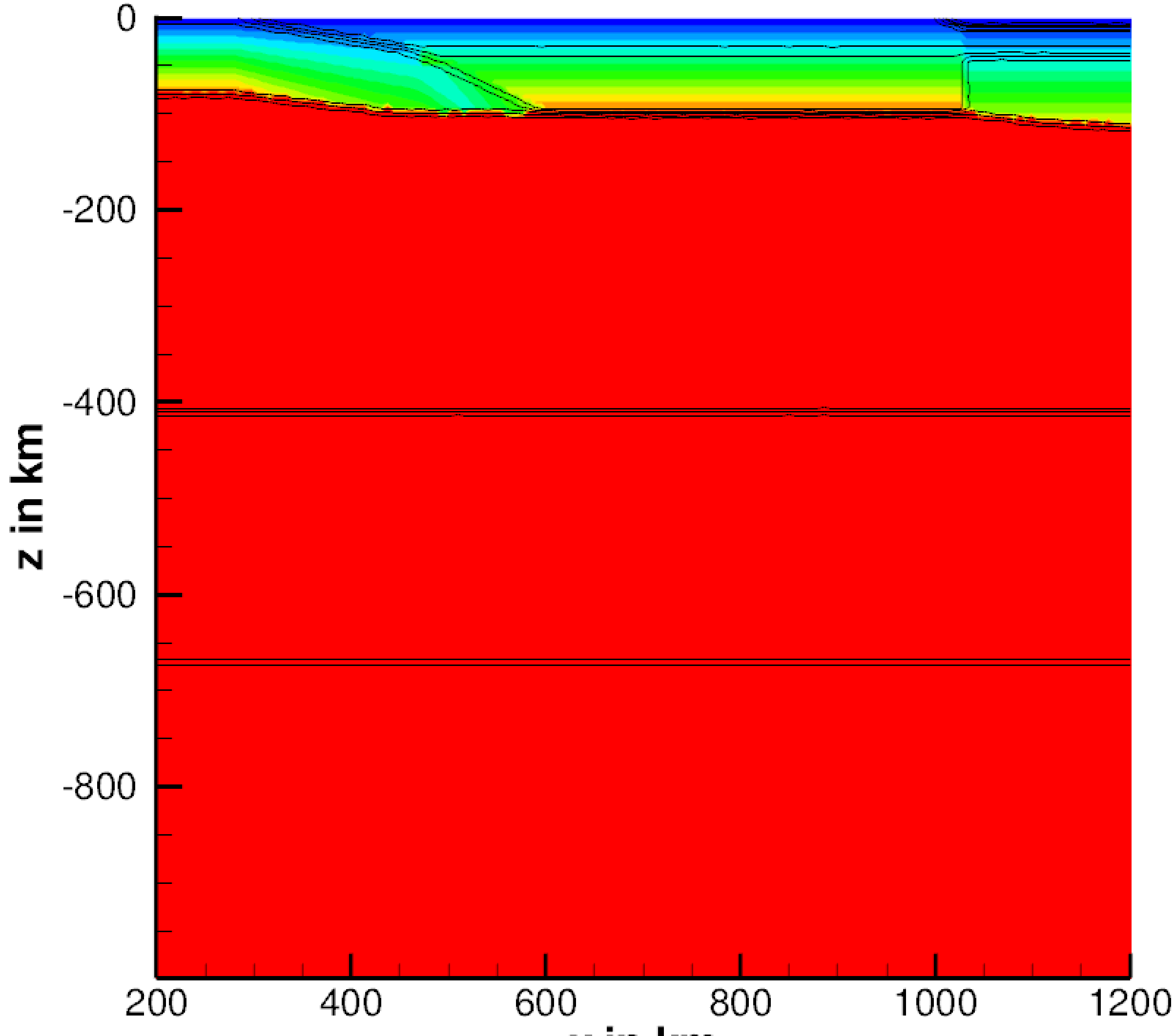
Code: elasto-visco-plastic, implicit (SLIM2D), disl. +dif.+P creep in upper mantle, TZ and lower mantle optional

Quinteros, Sobolev, Popov, 2010

Effect of TZ and lower mantle viscosity

Mature

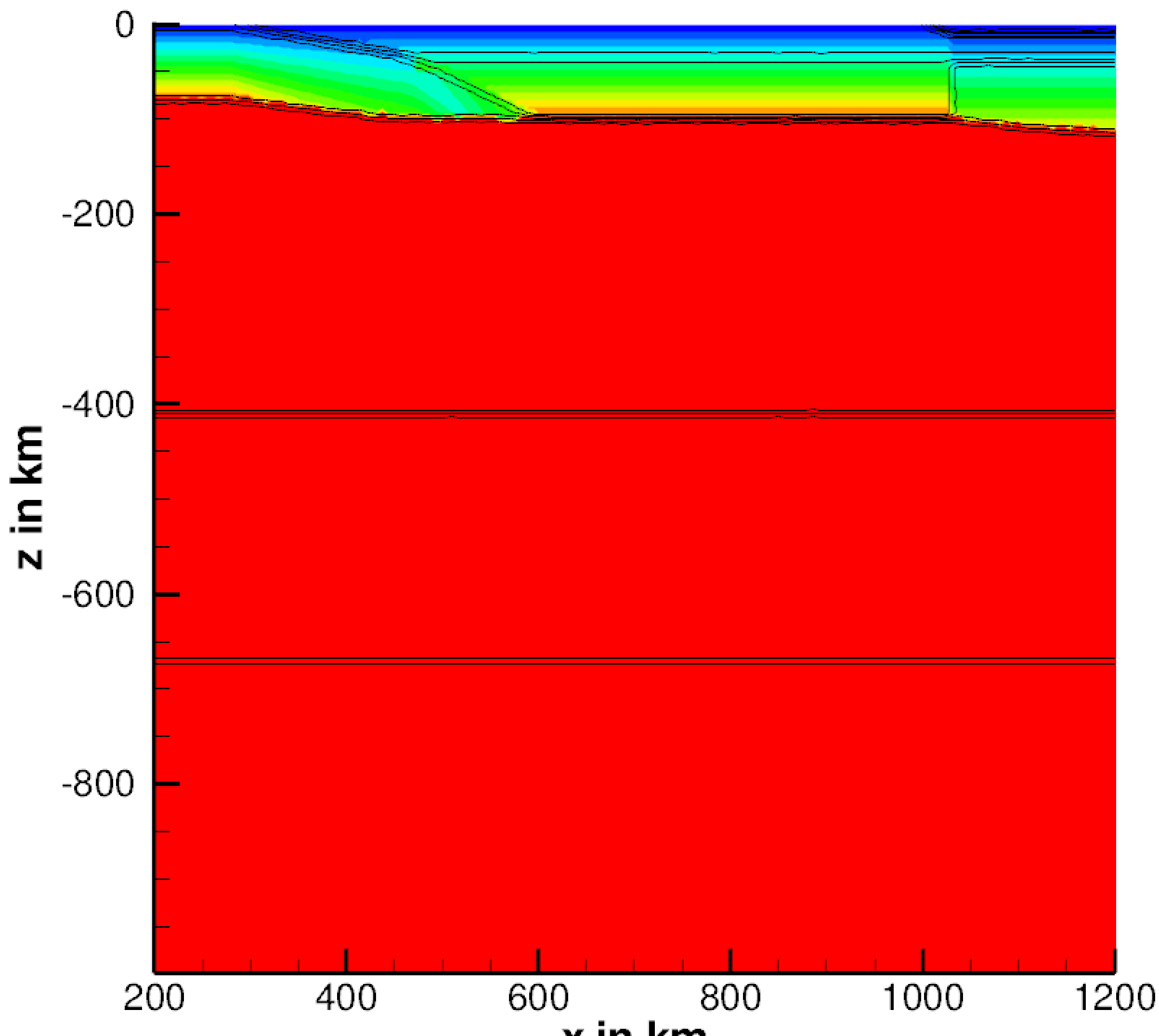
(viscosity in TZ 3*10^20, LM 3*10^21) Quinteros et al., 2010



Effect of TZ and lower mantle viscosity

Mature

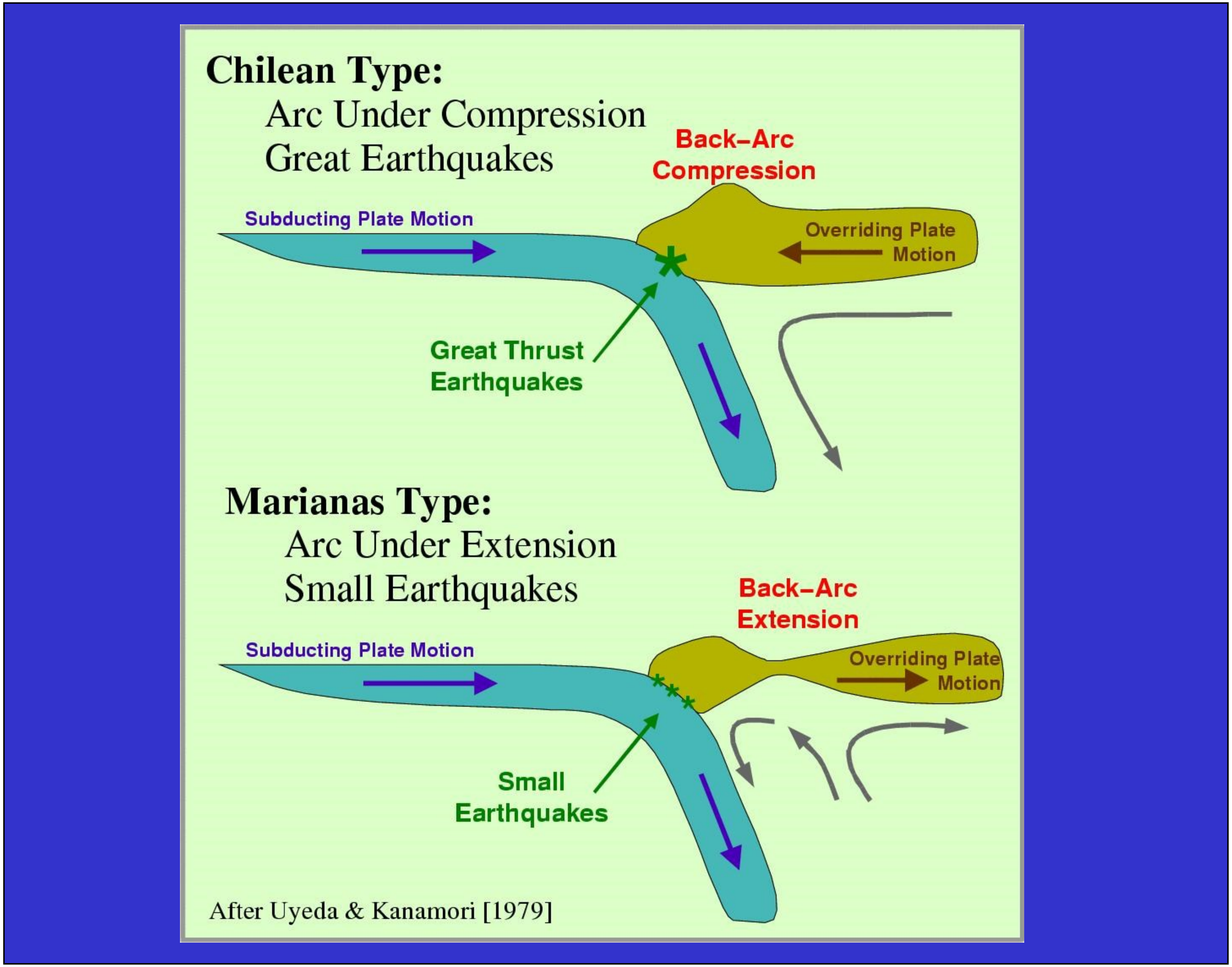
(viscosity in TZ 3*10^21,LM 1.5*10^22) Quinteros et al., 2010



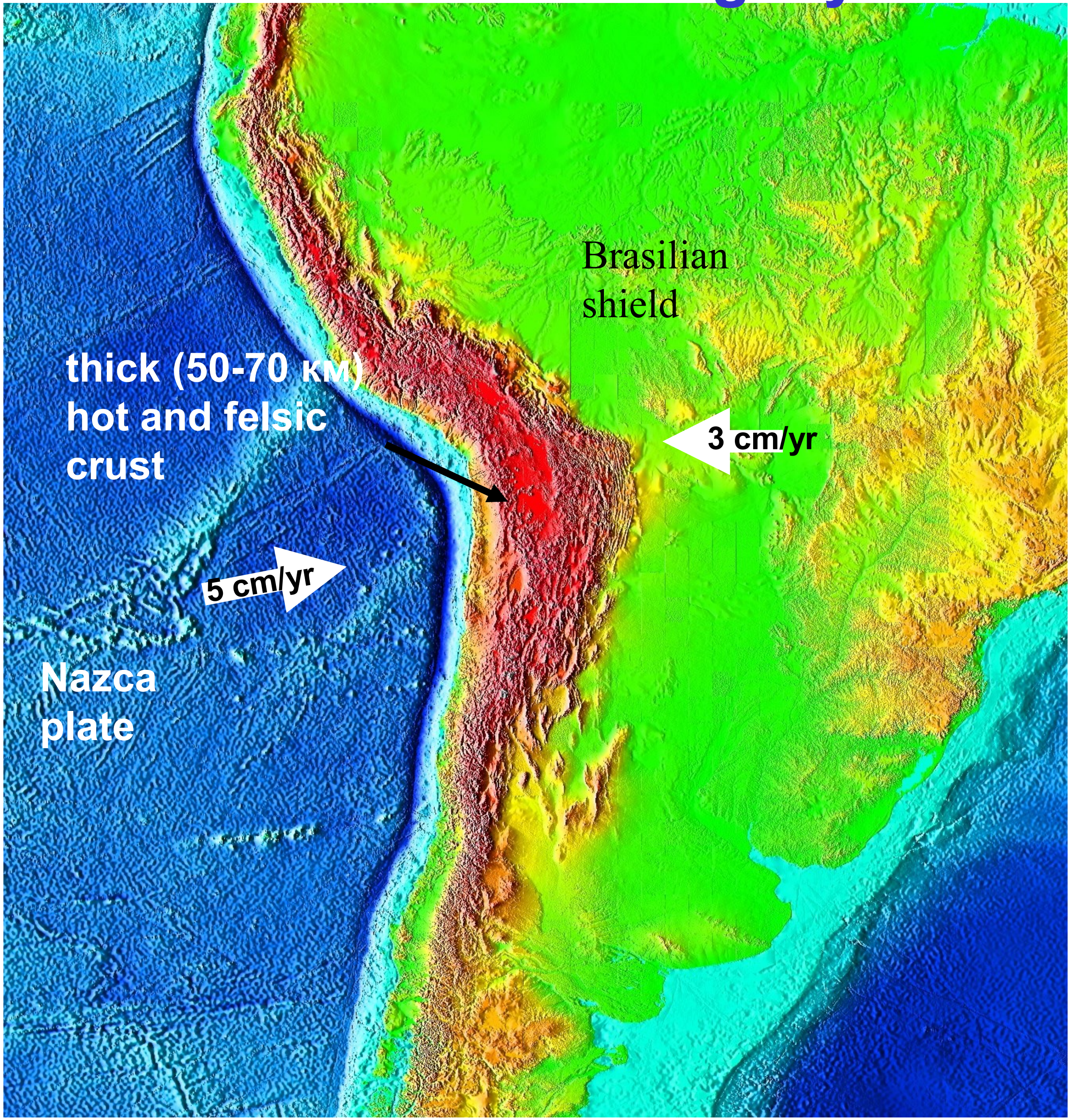
Conclusions

- Subduction survives only if friction in subduction channel is below 0.1 –need for high-pressure fluid in the channel
- Subduction initiation at passive margin (Wilson cycle) is unlikely unless there is strong mantle suction flow.
- Spontanios subduction initiation at transform fault is not yet confirmed by model., while modeling confirms forced initiation.
- First subduction at Earth might have been initiated by mantle plume.
- Style of internally consistent dynamic subduction is largely controled be lower mantle and TZ viscosity. Plausible range of TZ viscosity is 3*10^20-^10^21 and LM viscosity 5-10 times higher.

Mountains or back-arc basins?



Andean Orogeny



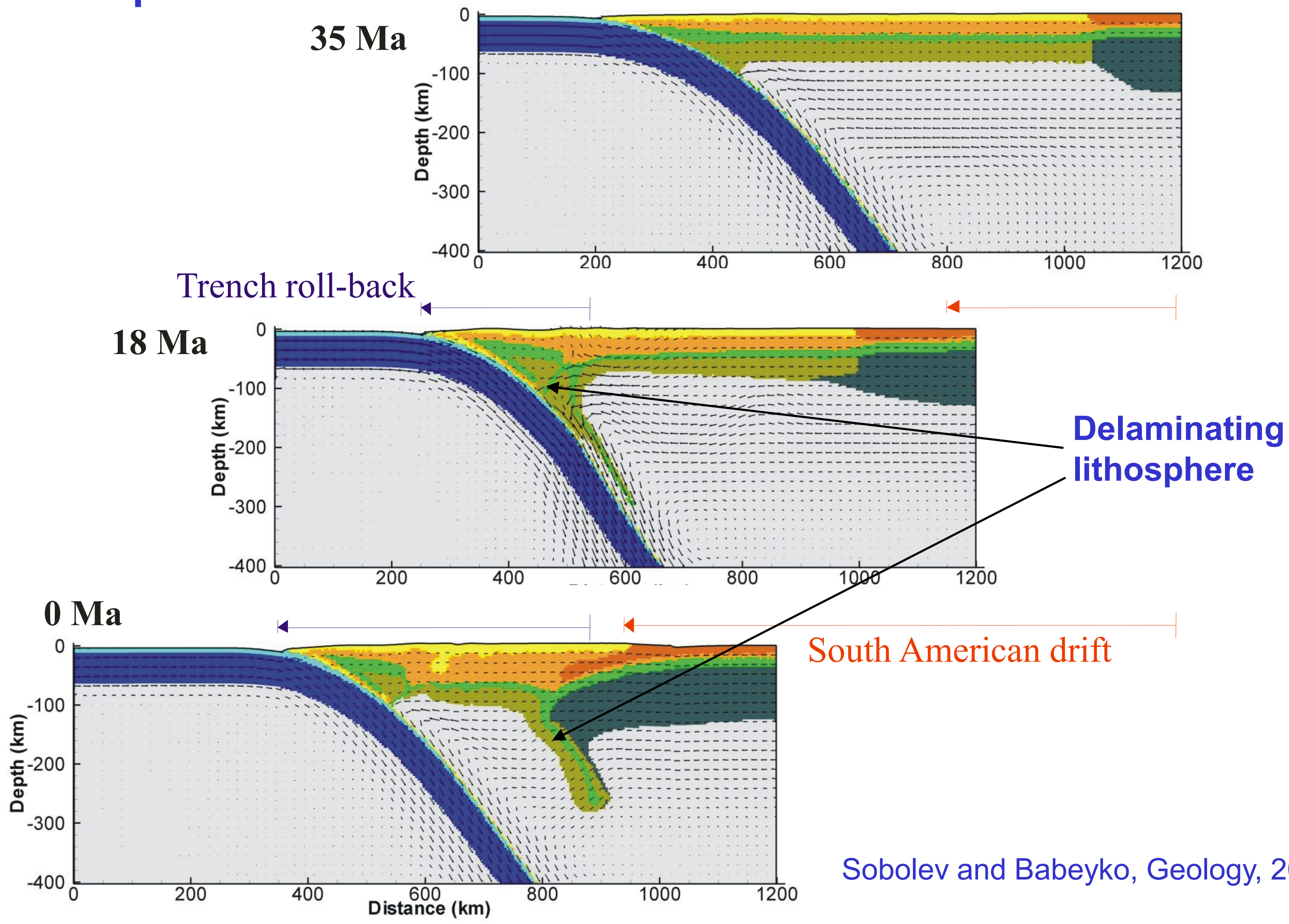
Orogeny

Why intensive orogeny occurred only in Cenozoic and only in the Central Andes?

The central Andes model

Orogeny

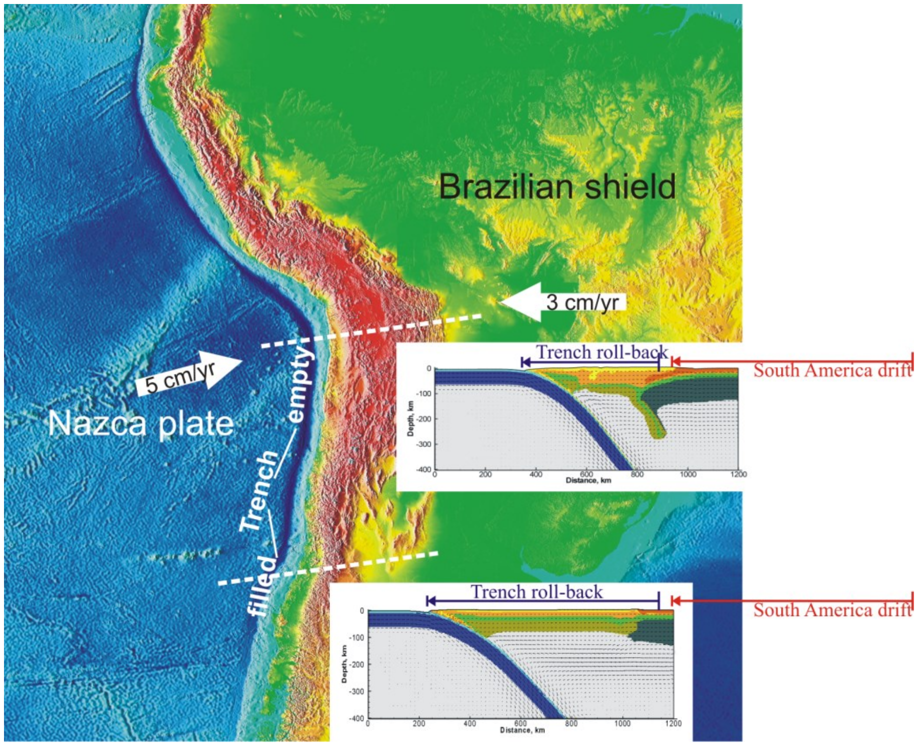
Friction μ = 0.05



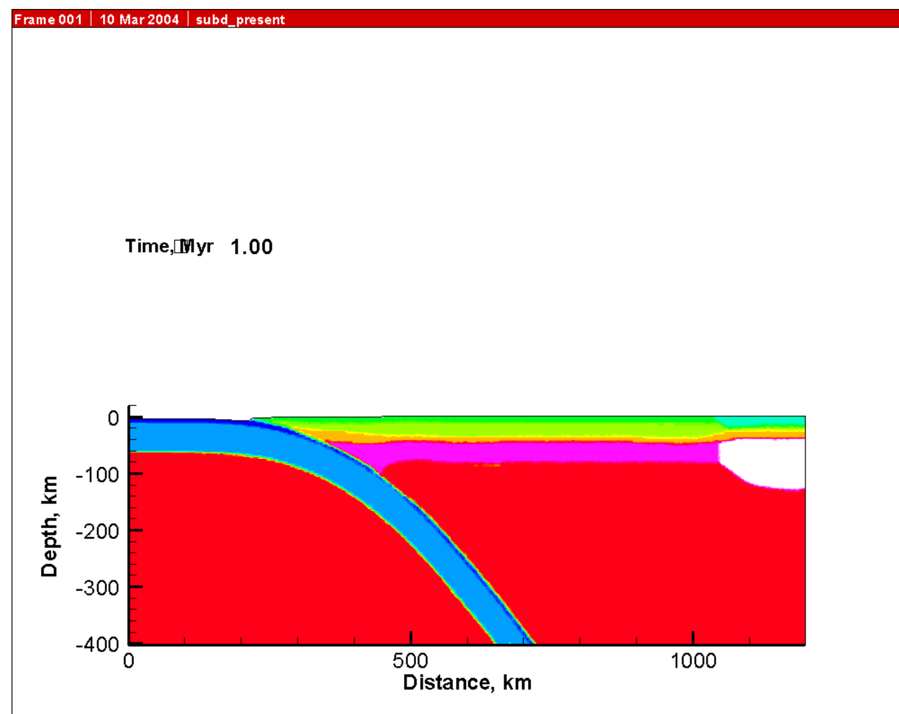
Sobolev and Babeyko, Geology, 2005

Factors controlling Andean orogeny

Orogeny



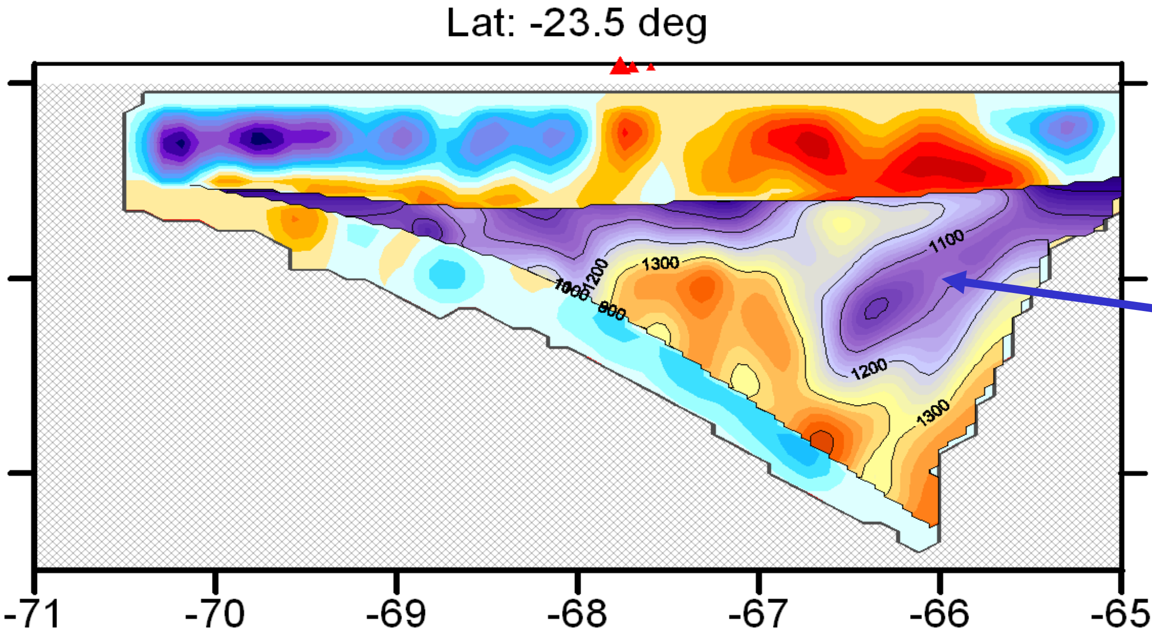
The key factors controlling Andean orogeny were:
(i) overriding rate of South America plate,
(ii) friction in subduction channel,
(iii) initial thickness of the upper-plate crust

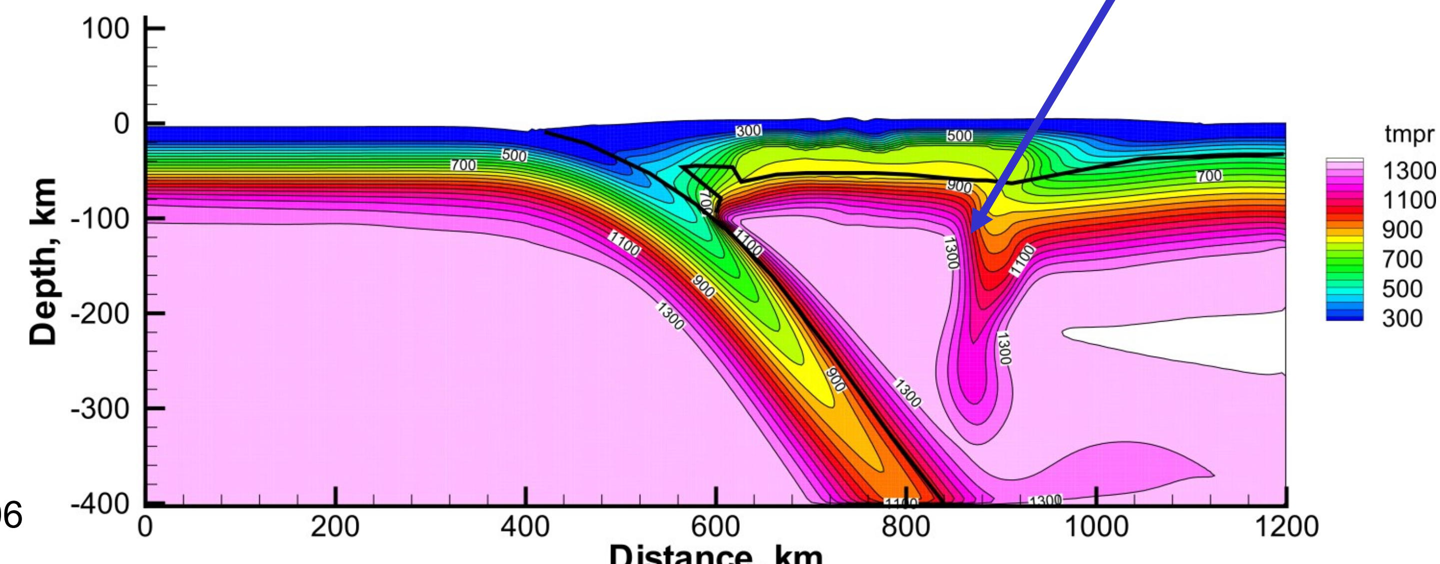


Babeyko and Sobolev, 2005, Babeyko et al., 2006, Sobolev and Babeyko, 2005; Sobolev et al., 2006

Seismic tomography

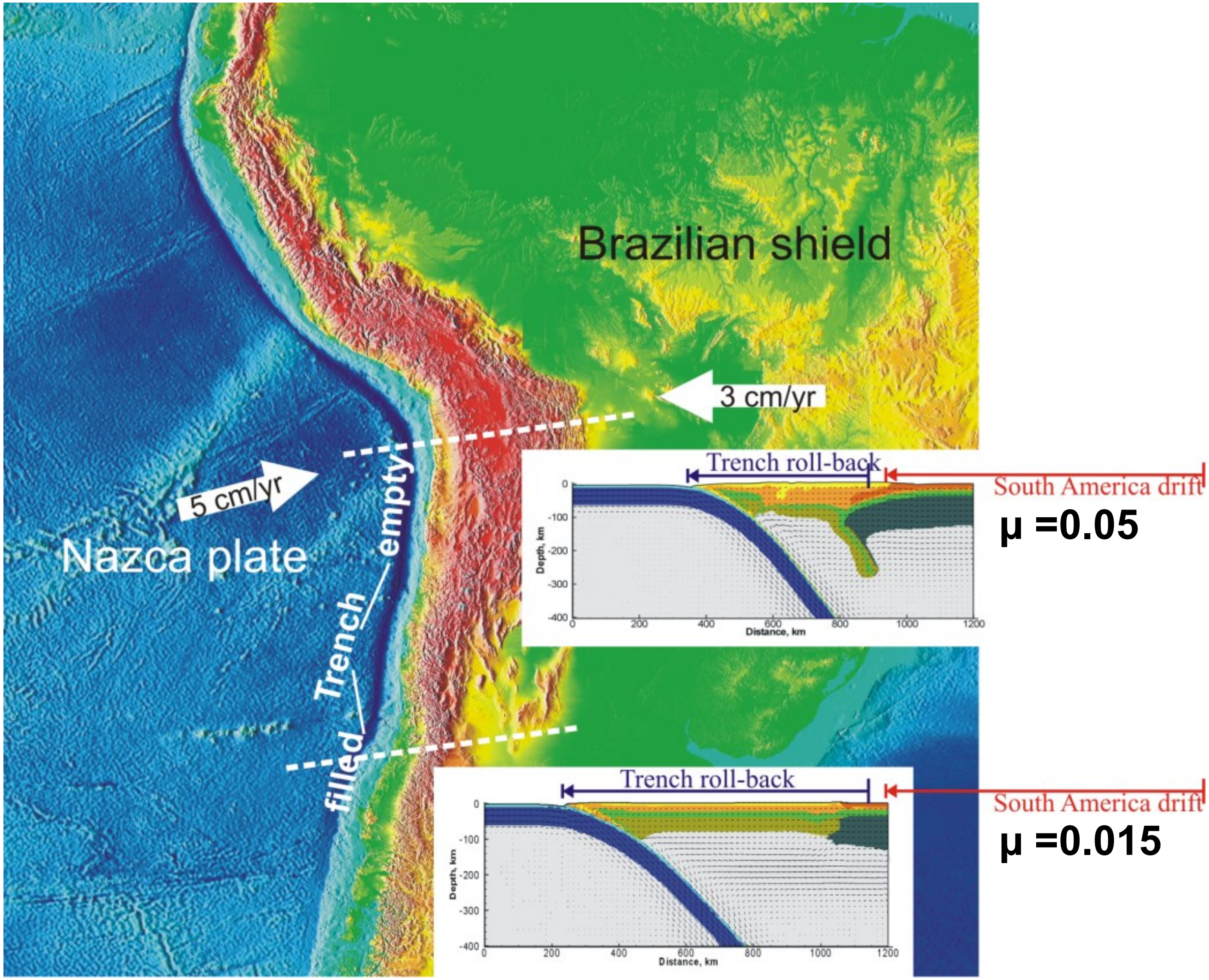
Delamination



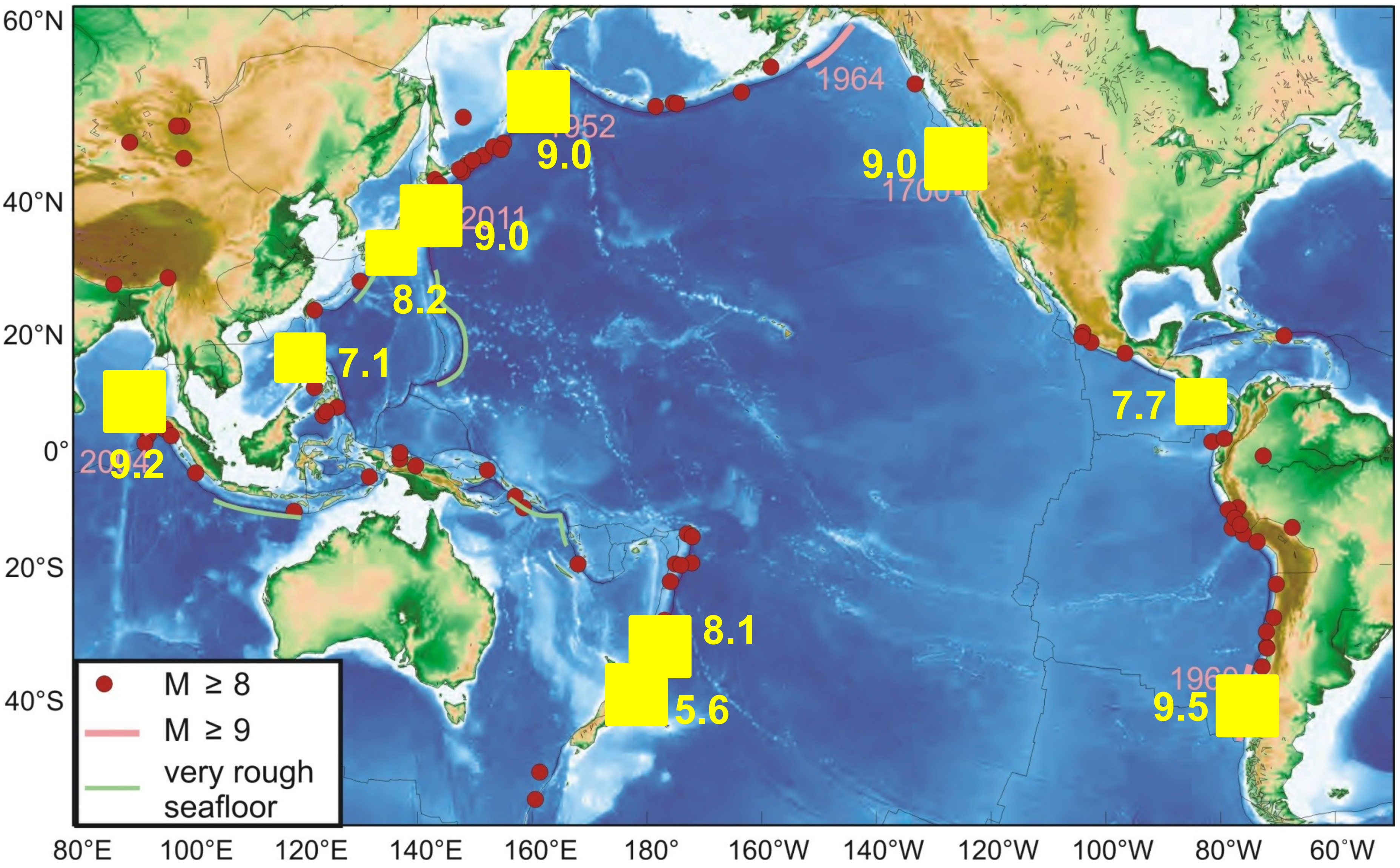


Sobolev et al., 2006

Subduction orogeny



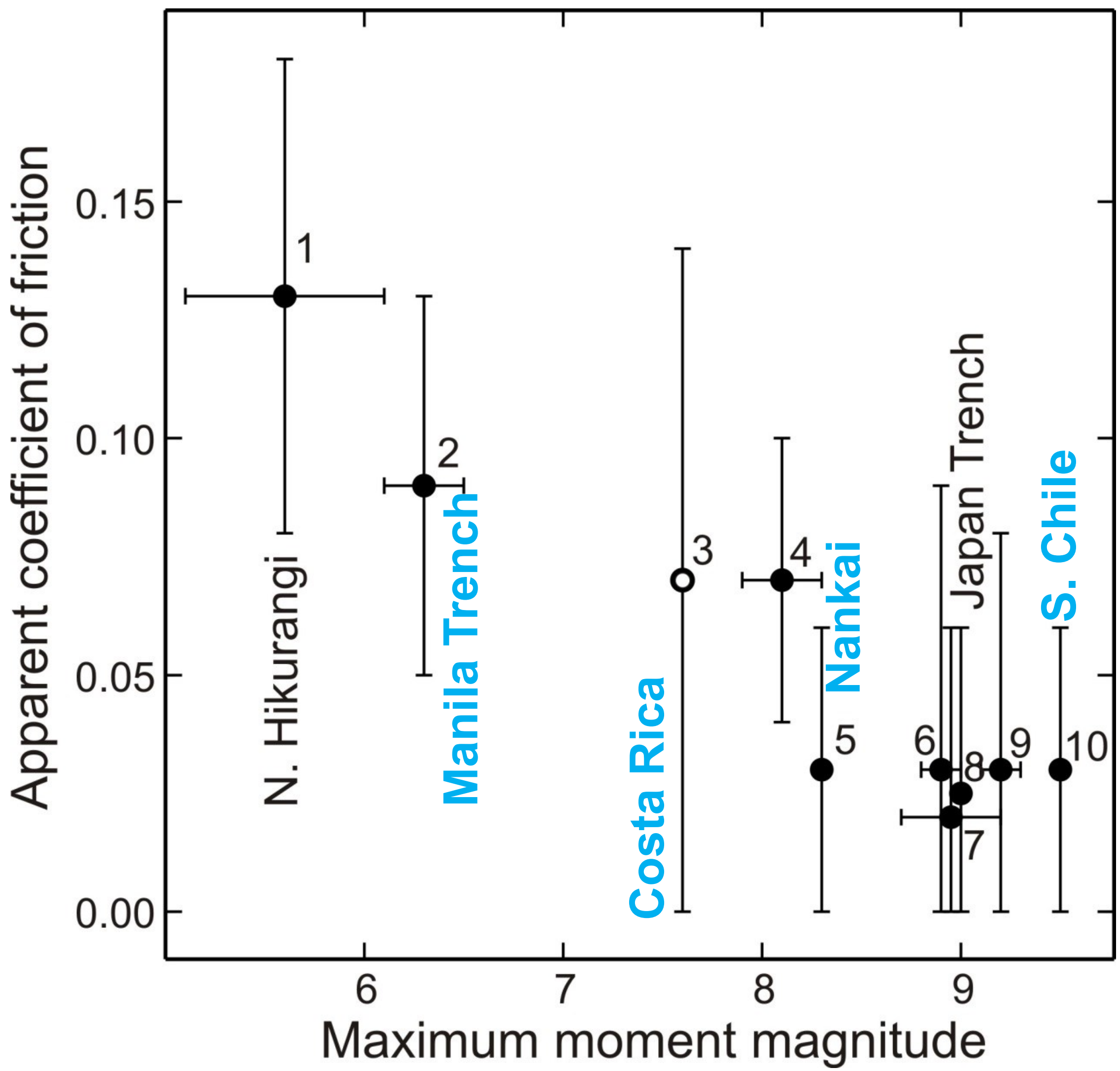
Sobolev and Babeyko, 2005, Sobolev et al., 2006



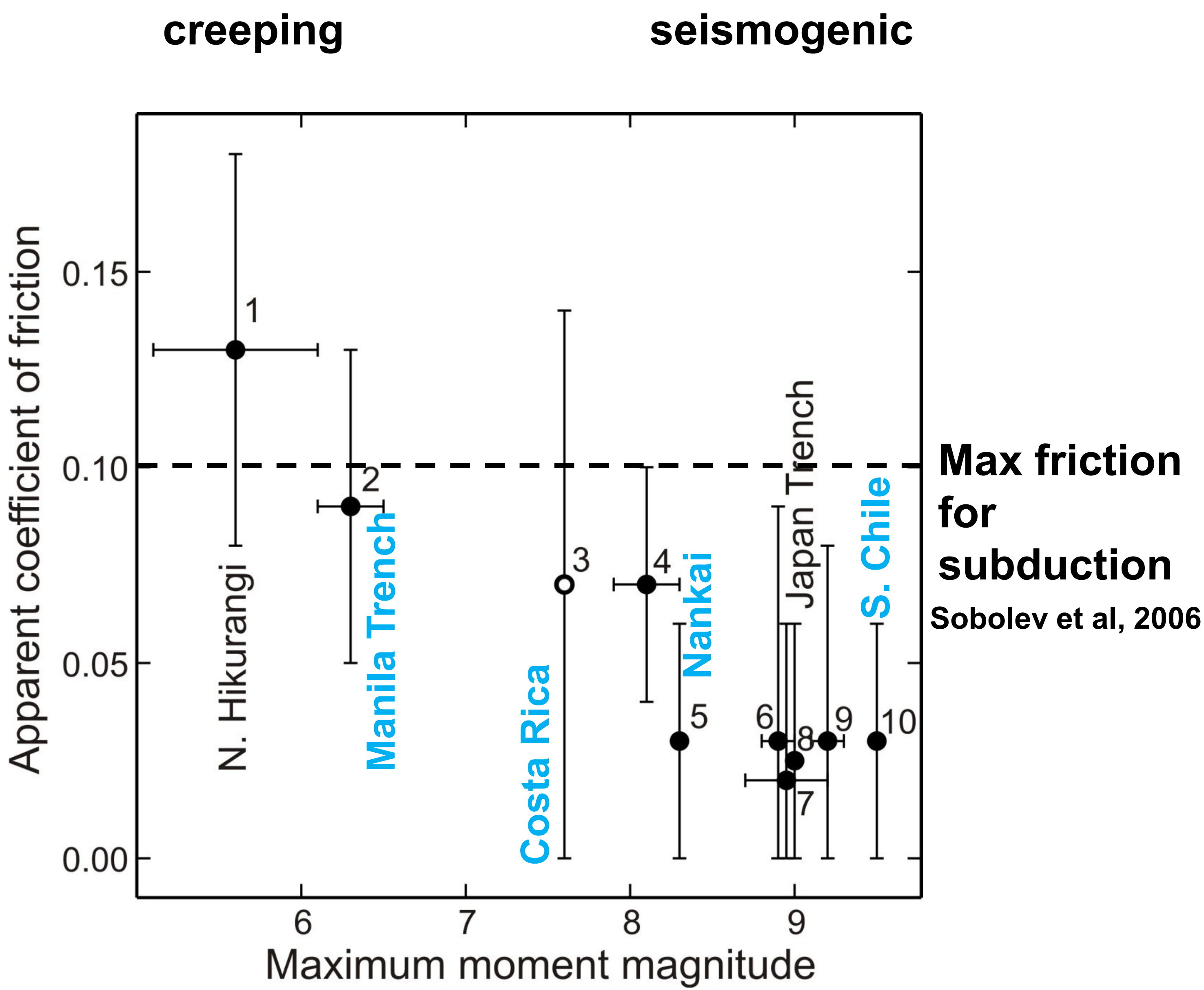
Subduction zones with adequate heat flow data to constrain frictional heating

Gao and Wang, Science, 2014

creeping **seismogenic**

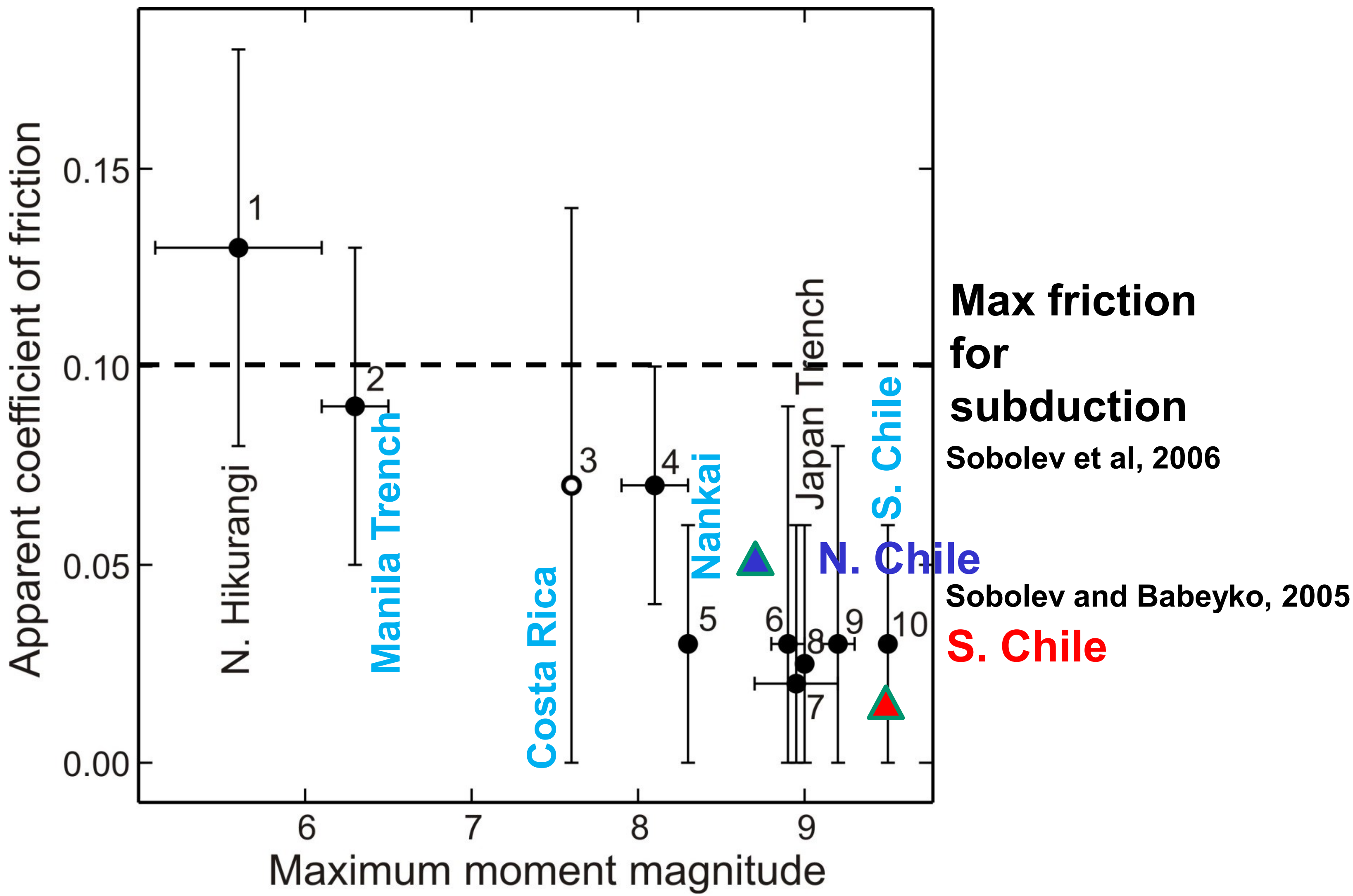


Gao and Wang, Science, 2014



Gao and Wang, Science, 2014

creeping **seismogenic**



Gao and Wang, Science, 2014

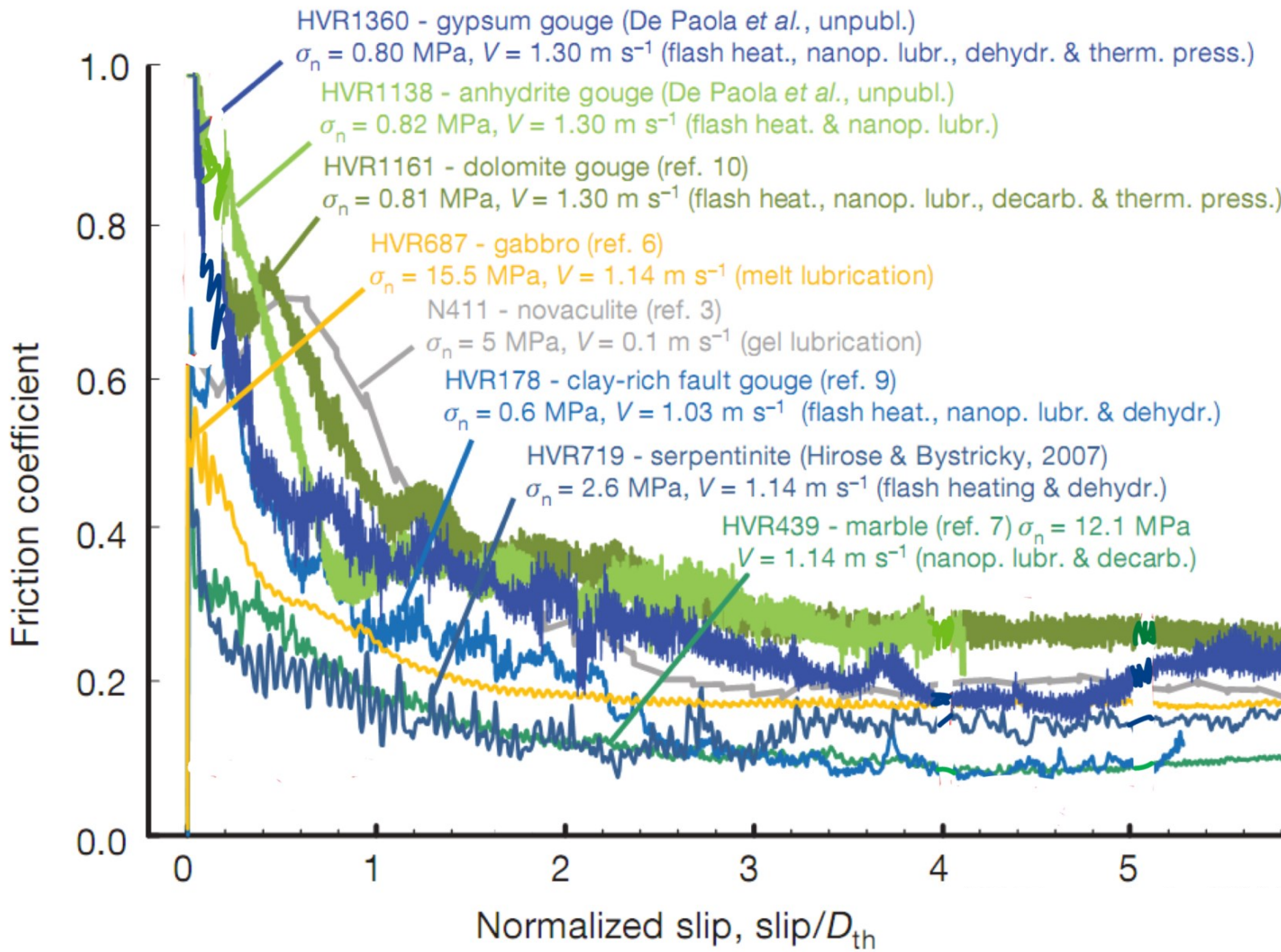
Conclusion

Estimates of low friction in subduction decoupling zones from geodynamic models is fully consistent with robust estimates of friction based on heat flow data

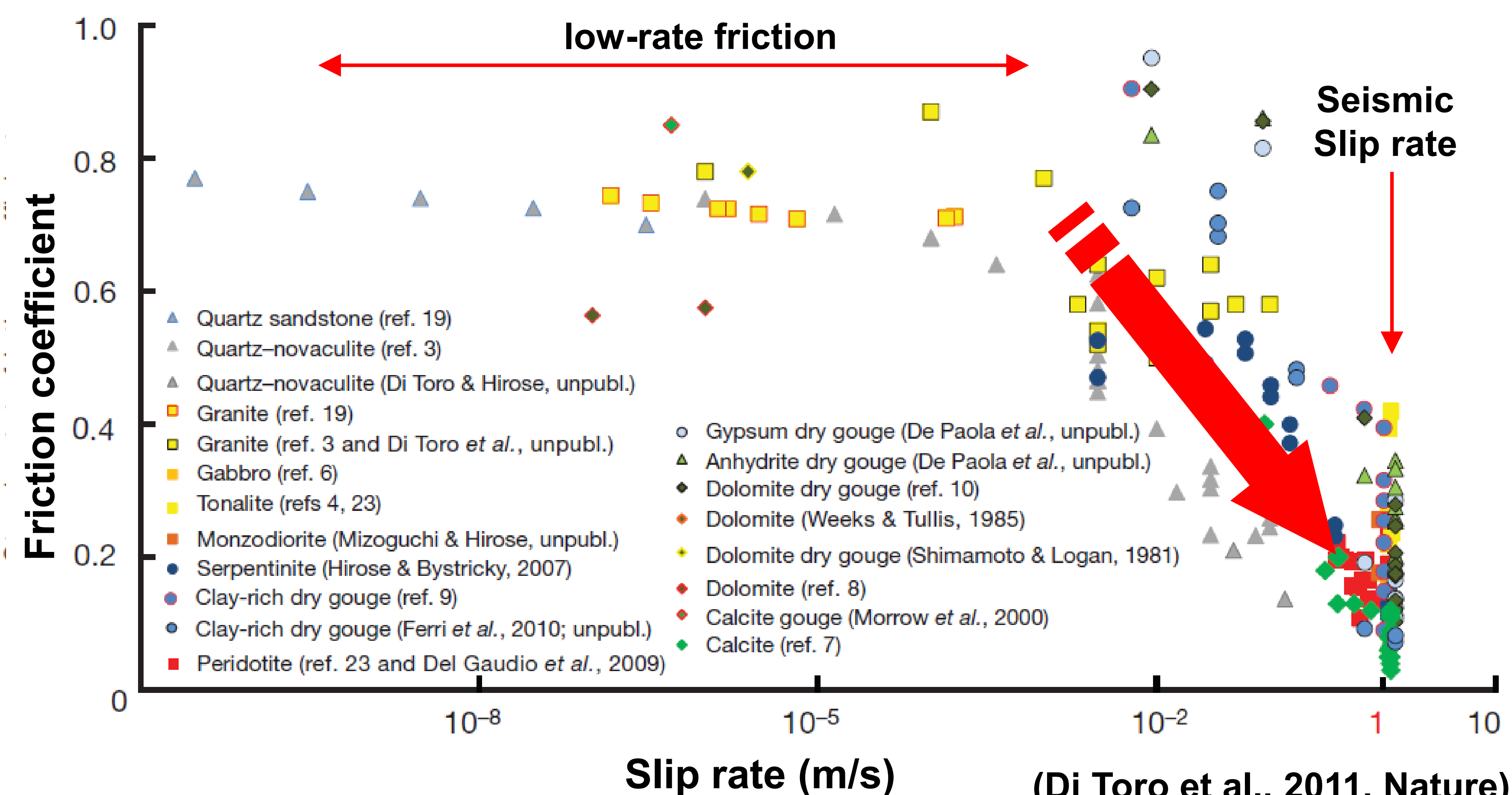
Question

Is that low friction static (effect of high pressure porous fluid) or dynamic (result of dynamic weakening)?

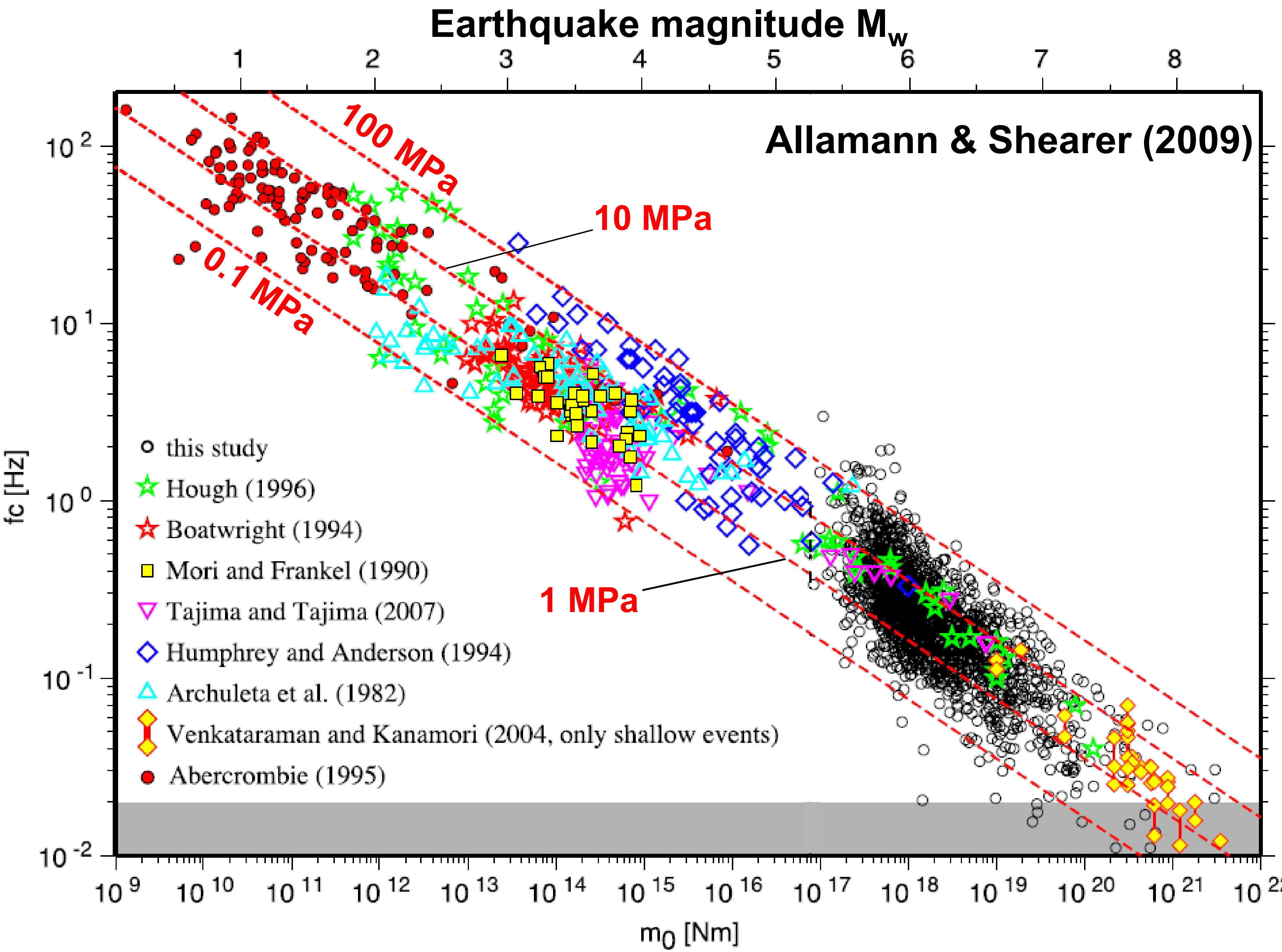
Experimental results on dynamic weakening



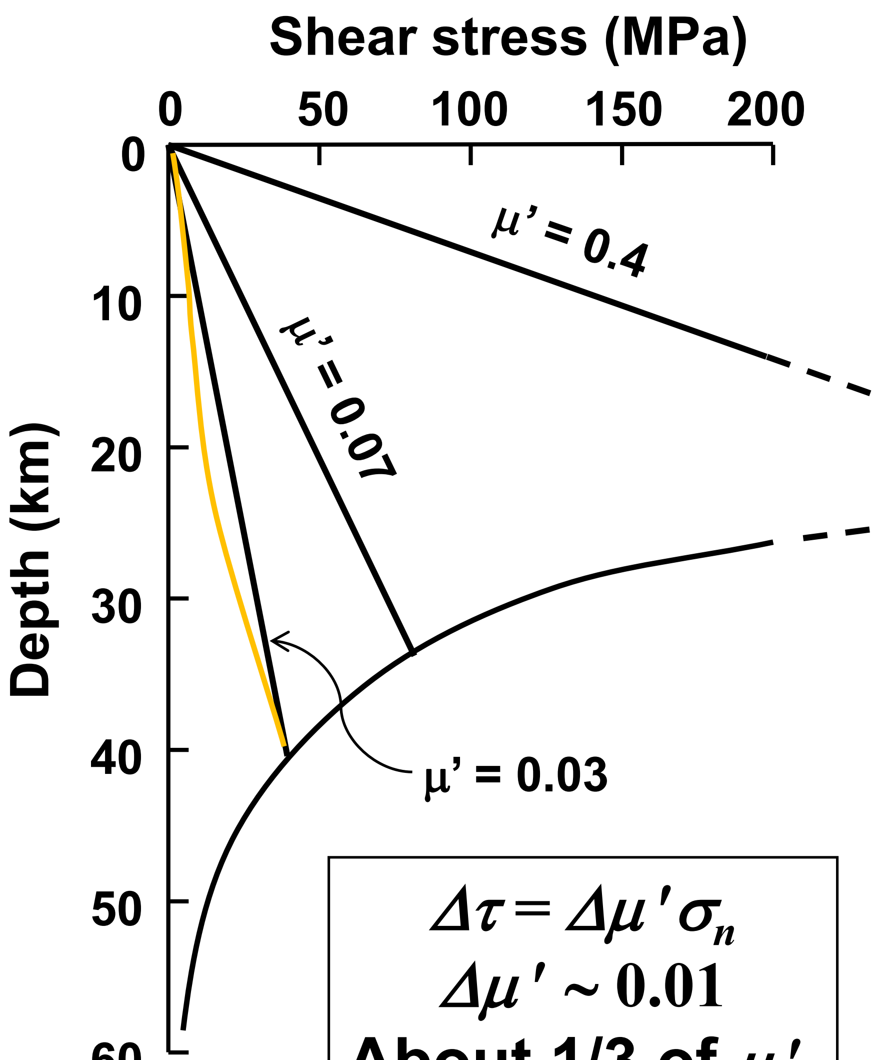
(Di Toro et al., 2011, Nature)

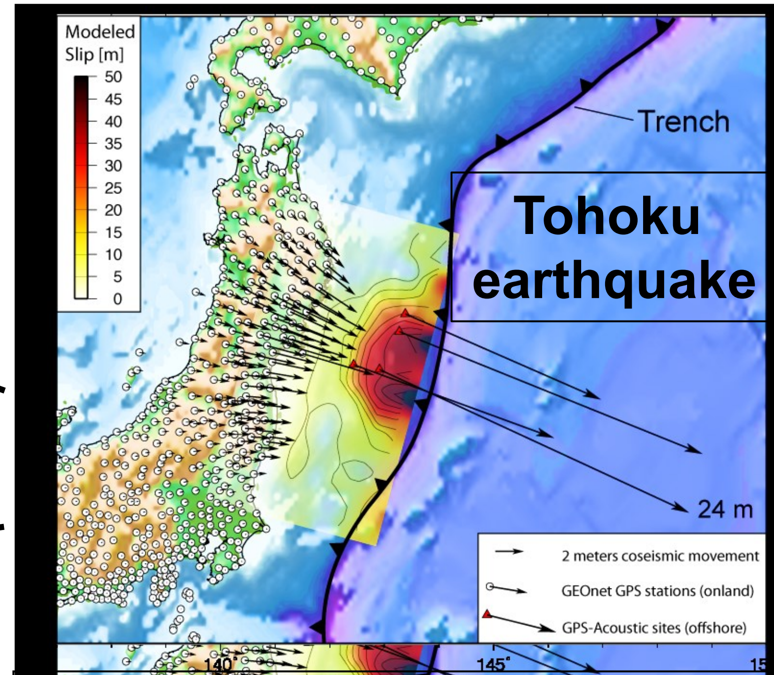


(Di Toro et al., 2011, Nature)



Gao and Wang, Science, 2014





$$\Delta\tau = \Delta\mu'\sigma_n$$
$$\Delta\mu' \sim 0.01$$
About 1/3 of μ'

Stress drop estimates:

Simons et al. (2011): 2-10 MPa

Koketsu et al. (2011): 4.8 MPa

Lee et al. (2011): 7 MPa

Kumagai et al. (2012): Locally up to 40 MPa

From GEOMOD 2014 presentation of K. Wang

Question

Is that low static friction (effect of high pressure porous fluid) or dynamic (result of dynamic weakening)?

Answer

Dynamic friction change in large earthquake is less than 0.01. It means that low friction in subduction channel has static reasons, e.g. high pressure fluid

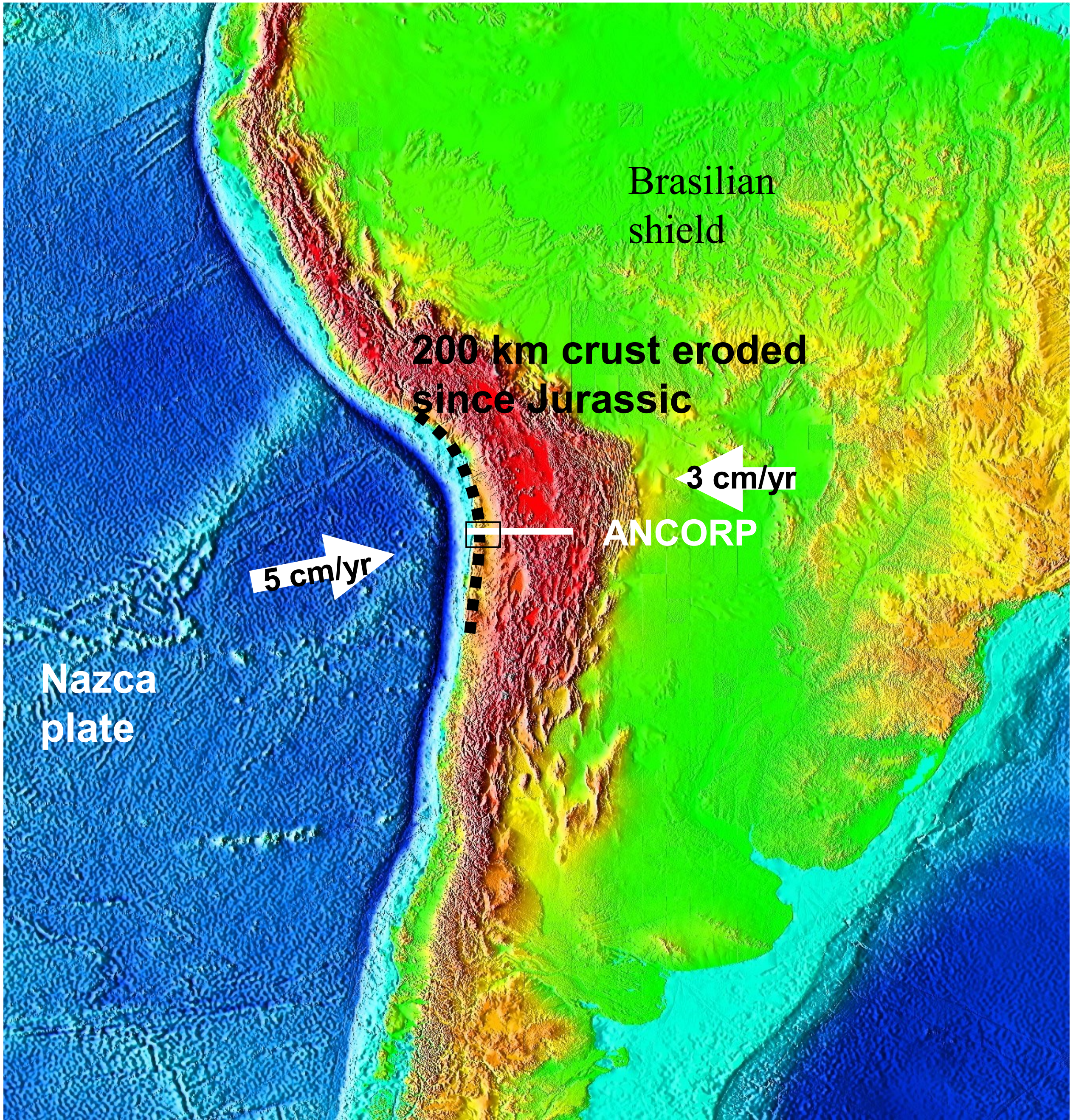
Subduction processes in high resolution

Outline

- Spatial "zoom-in" at subduction processes. Stress in the slab. Effect of gabbro-eclogite transformation and de-serpentinization.
- Effect of weakening of mantle wedge.
- Friction in subduction channel

Andean Orogeny

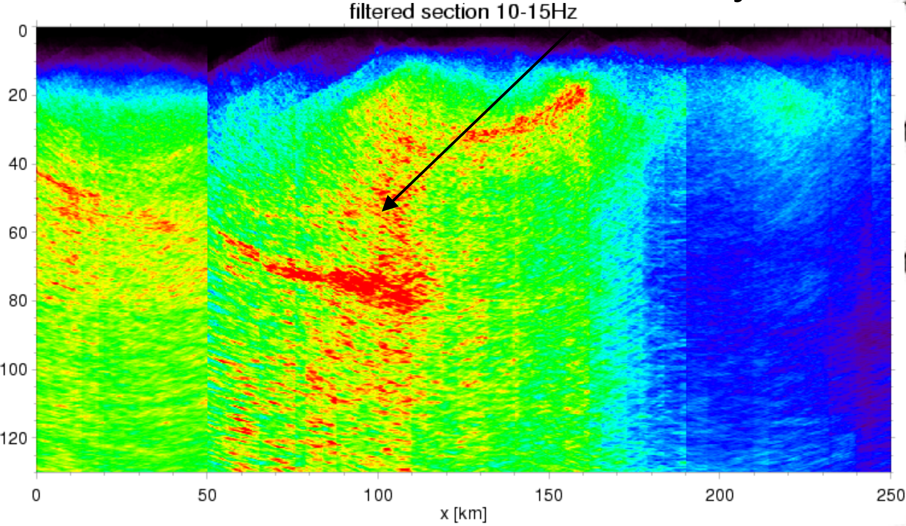
Wedge weakening



21°S

Wedge weakening

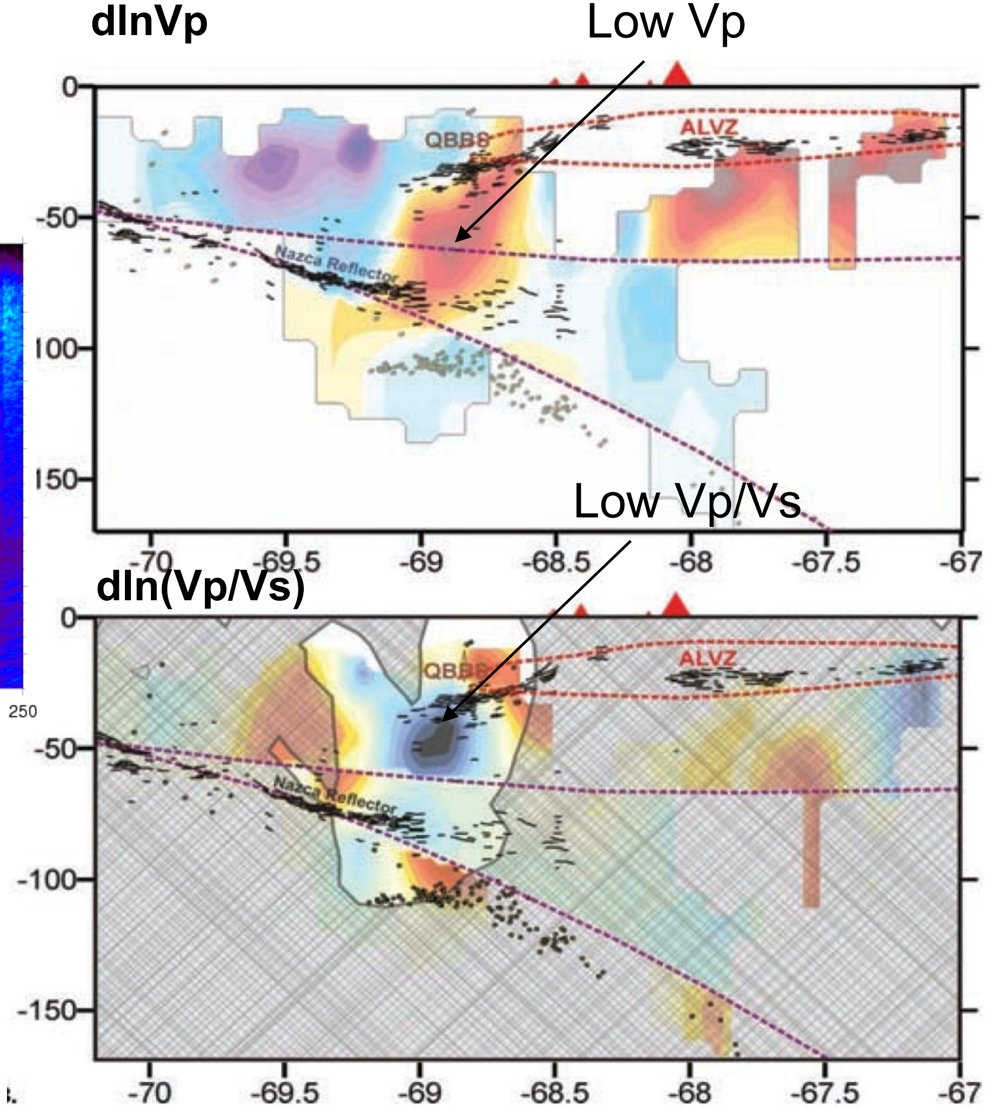
High reflectivity



Yoon et al. (2007)

Low Vp

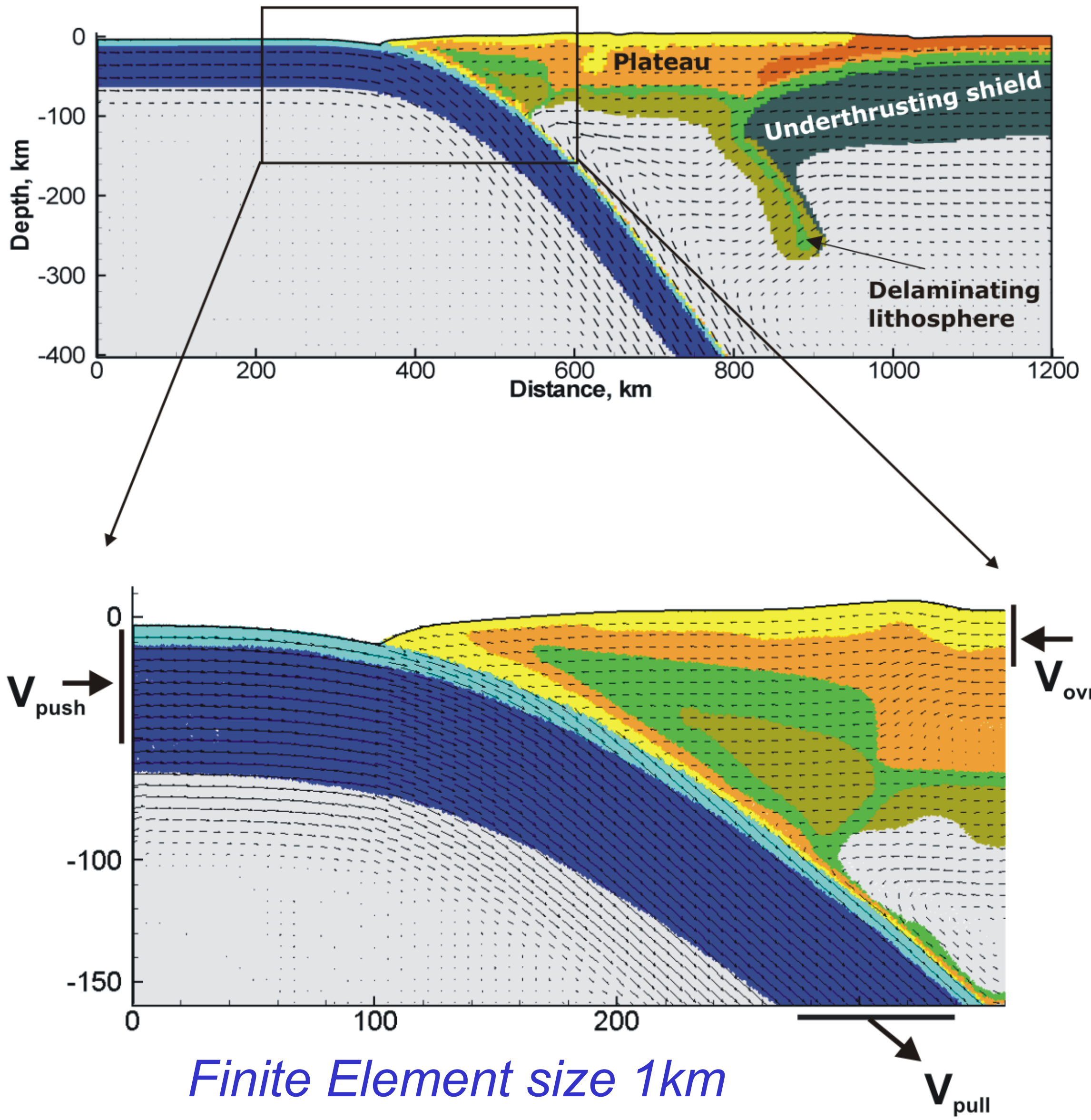
Low Vp/Vs



(Koulakov, Sobolev, Asch, 2006)

Spatial "zoom-in"

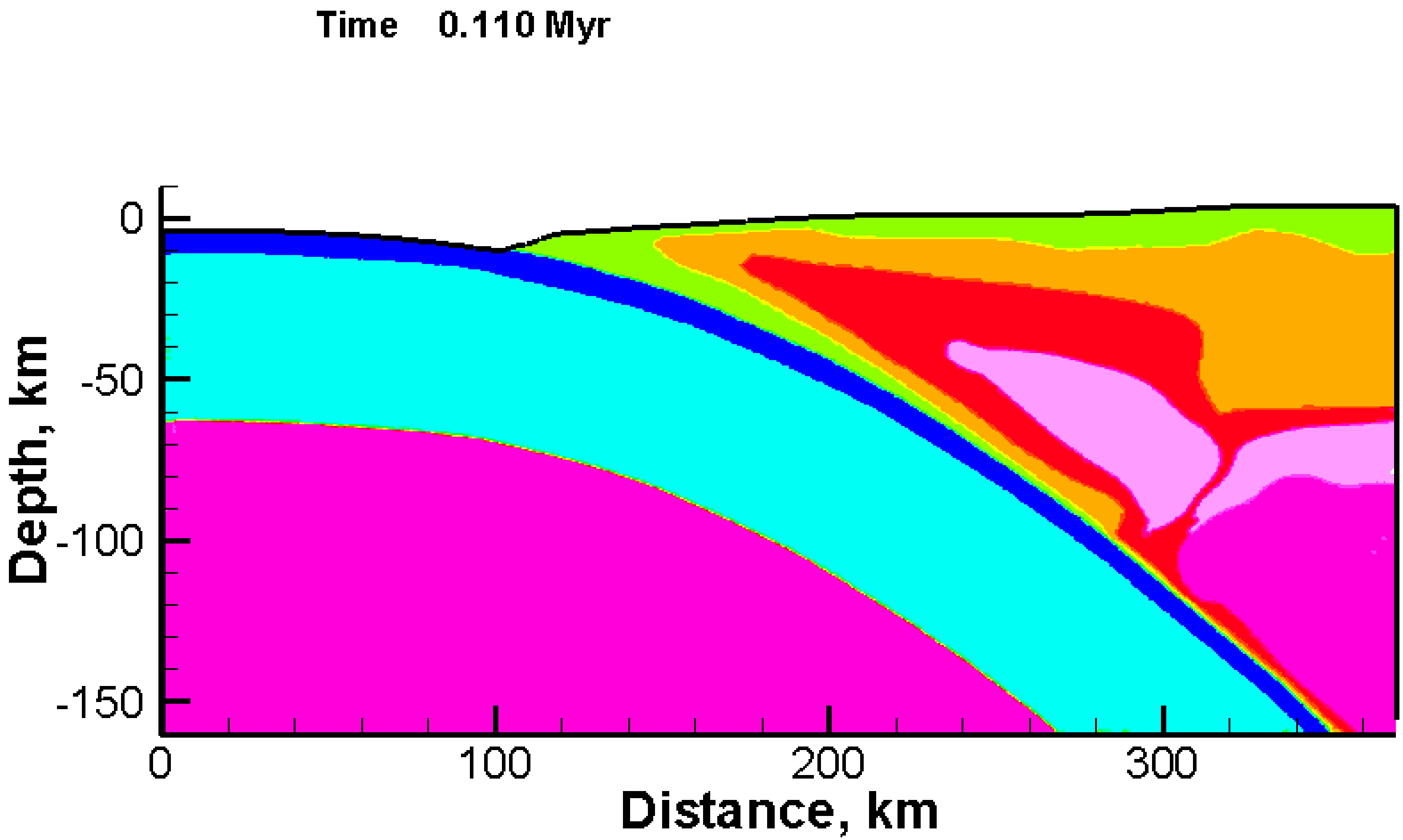
Wedge weakening



Finite Element size 1km

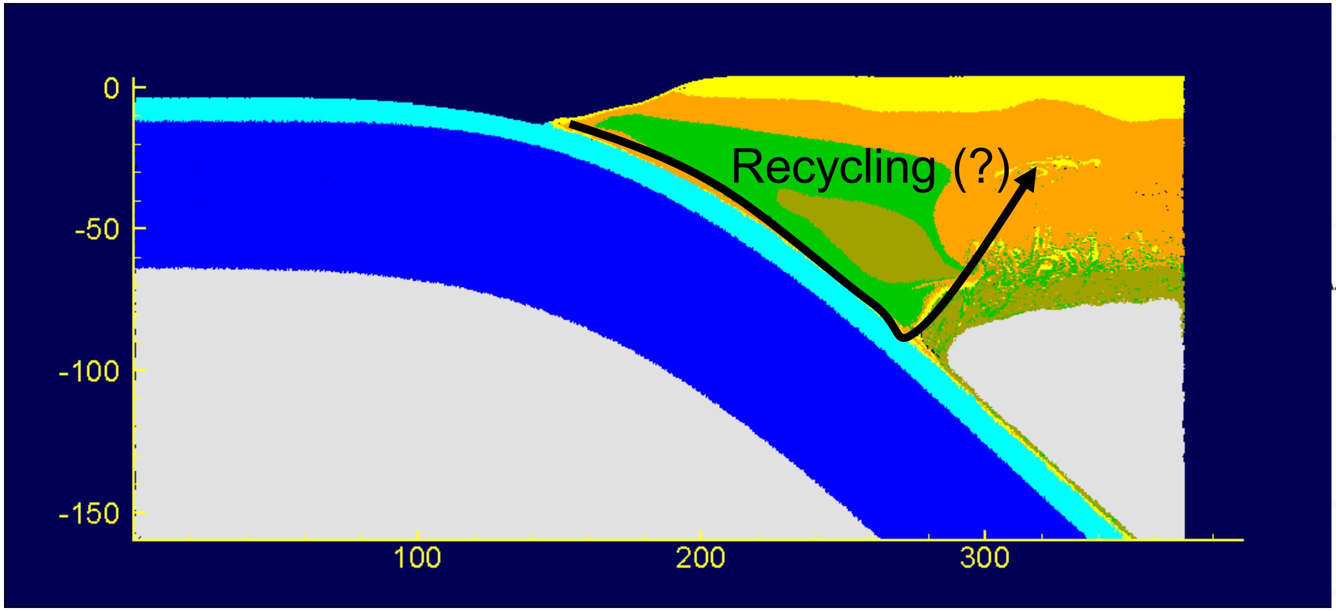
Wedge weakening

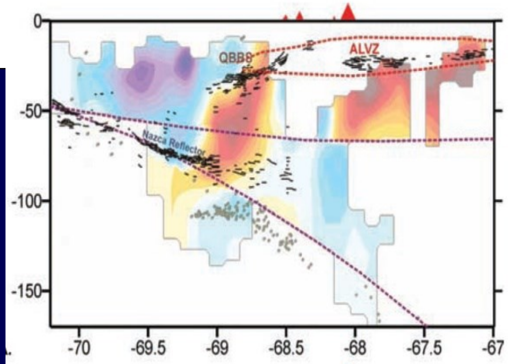
Mantle wedge weakening (1 km FE)

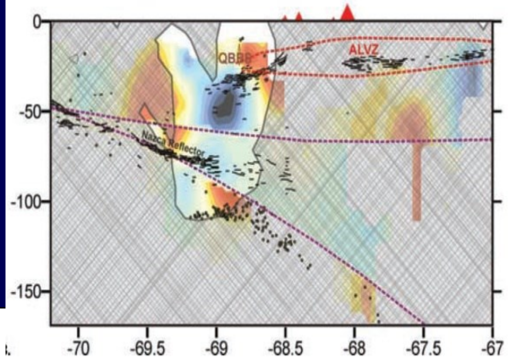


Wedge weakening

Mantle wedge evolution







Conclusions

- Spatial "zoom-in" technique allows to increase model resolution and to consider effects not detectable in the low-resolution models.
- Mantle wedge weakening may cause the recycling of the upper crust in the overriding plate