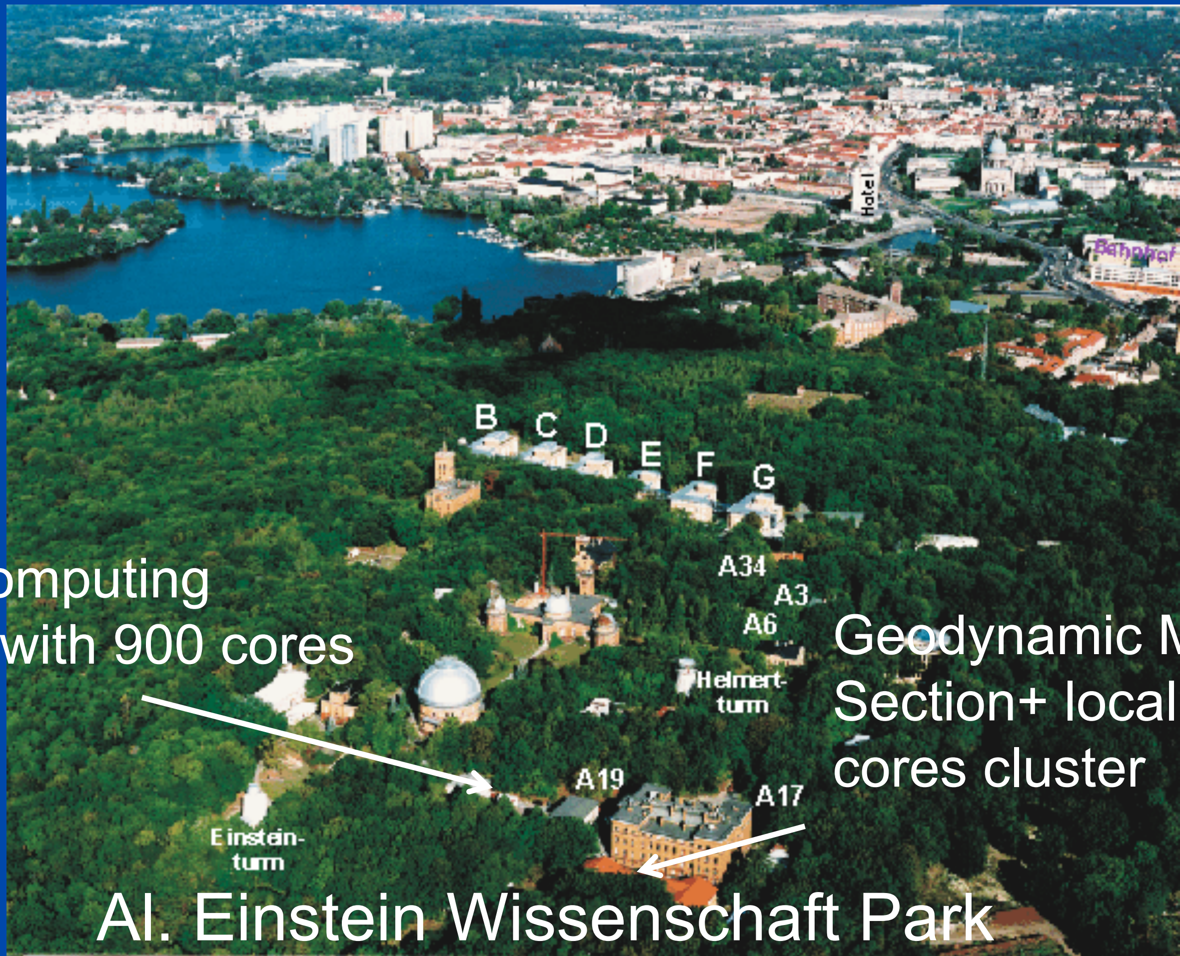
Three dimensional numerical modeling of lithospheric dynamics and transform fault tectonics

Stephan Sobolev and GFZ Geodynamic Modeling Section

GFZ POTSDAM

German Research Centre for Geosciences

GFZ-German Research Centre for Geosciences



GFZ Computing Center with 900 cores cluster

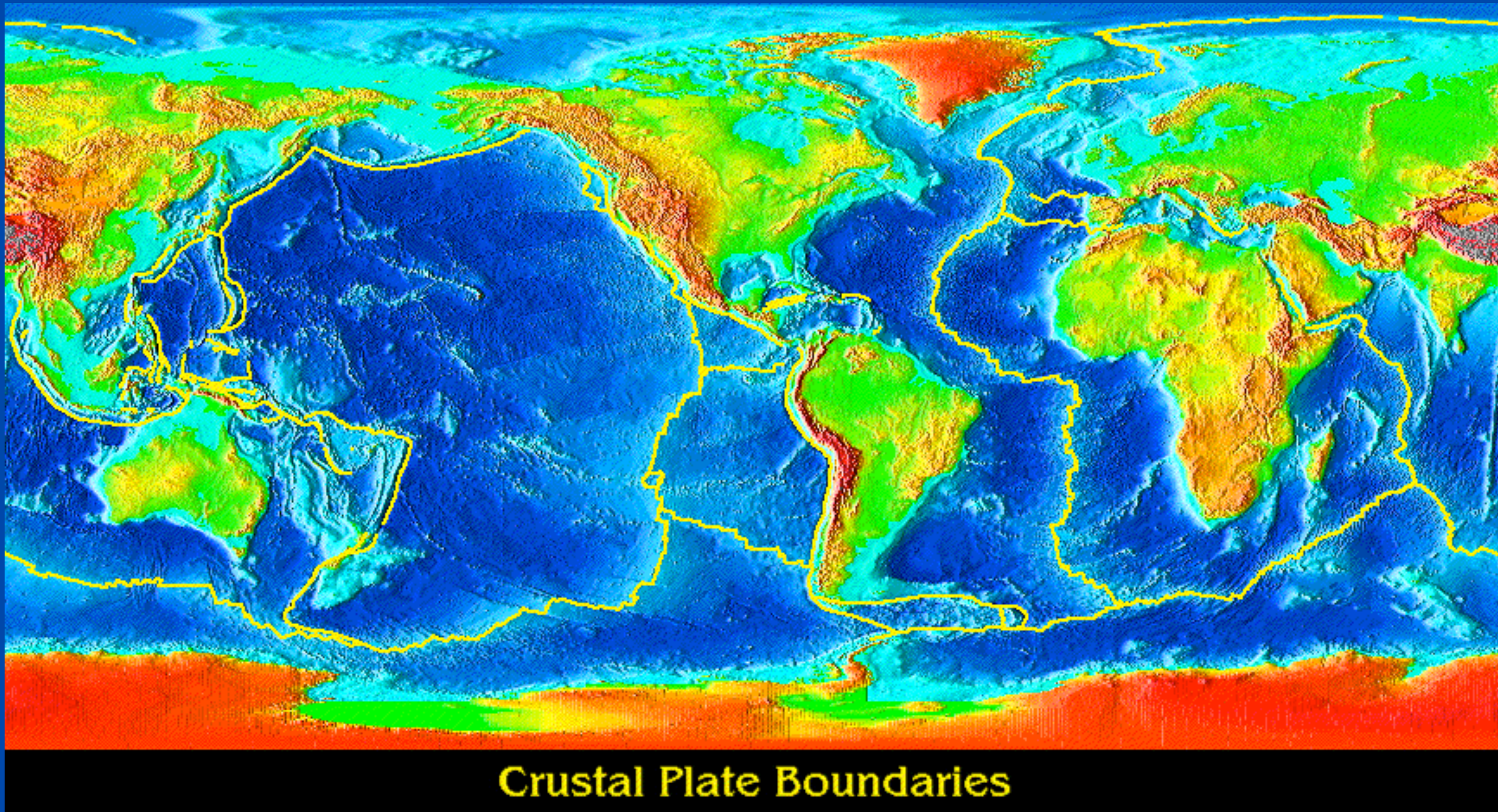
Geodynamic Modeling Section+ local 160 cores cluster

More than 900 employees; solid Earth focus including geodesy, geophysics, geology, geochemistry and geo-engineering

Outline

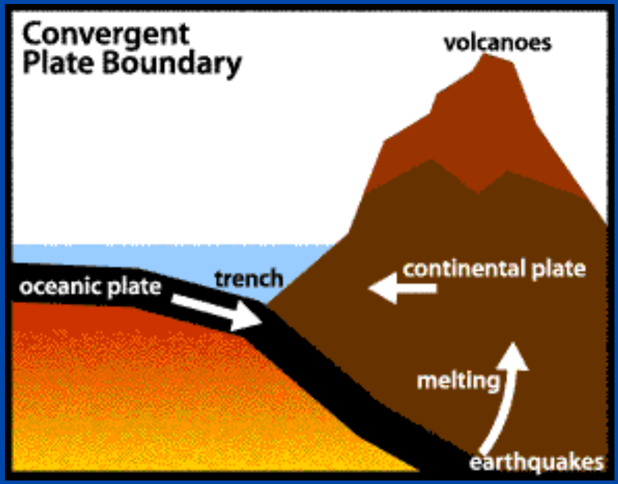
- Why modeling in 3D and with realistic rheology?
- Tools to model 3D deformation at plate boundaries
- Modeling birth and maturation of the transform plate boundary – *Dead Sea Transform in the Middle East*
- Global scale:
  - *How weak are the plate boundaries?*
  - *How weak is asthenosphere*

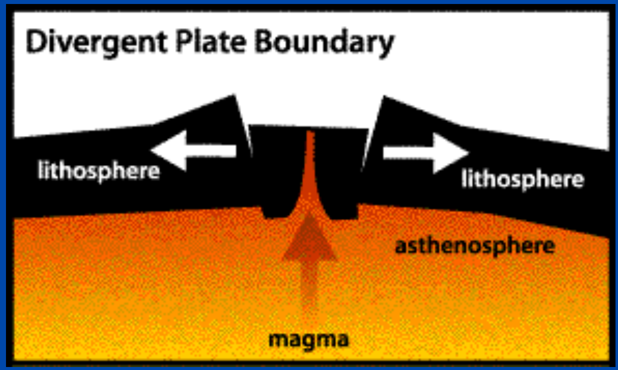
Plates



Earth is a plate-tectonics planet, where most of deformation at the lithospheric level goes at the plate boundaries.

Why 3D?

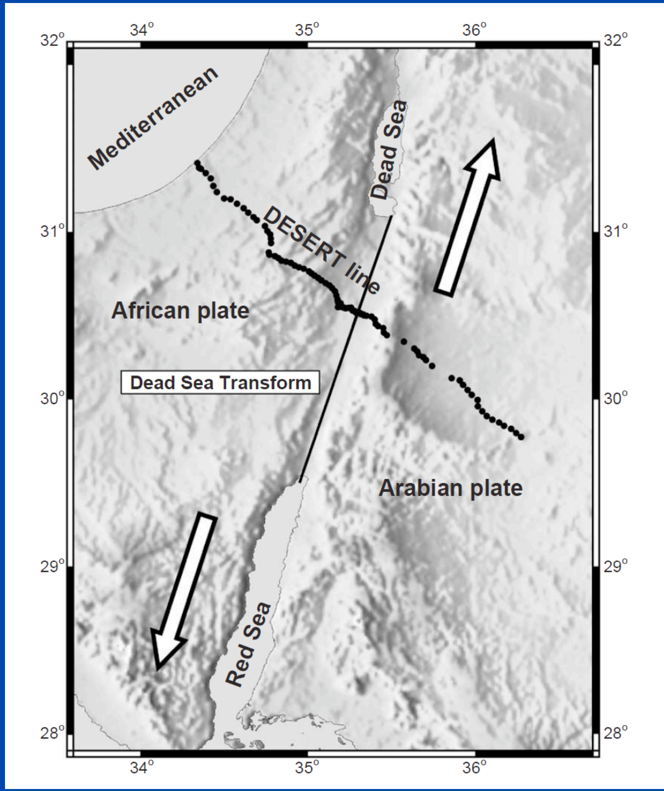




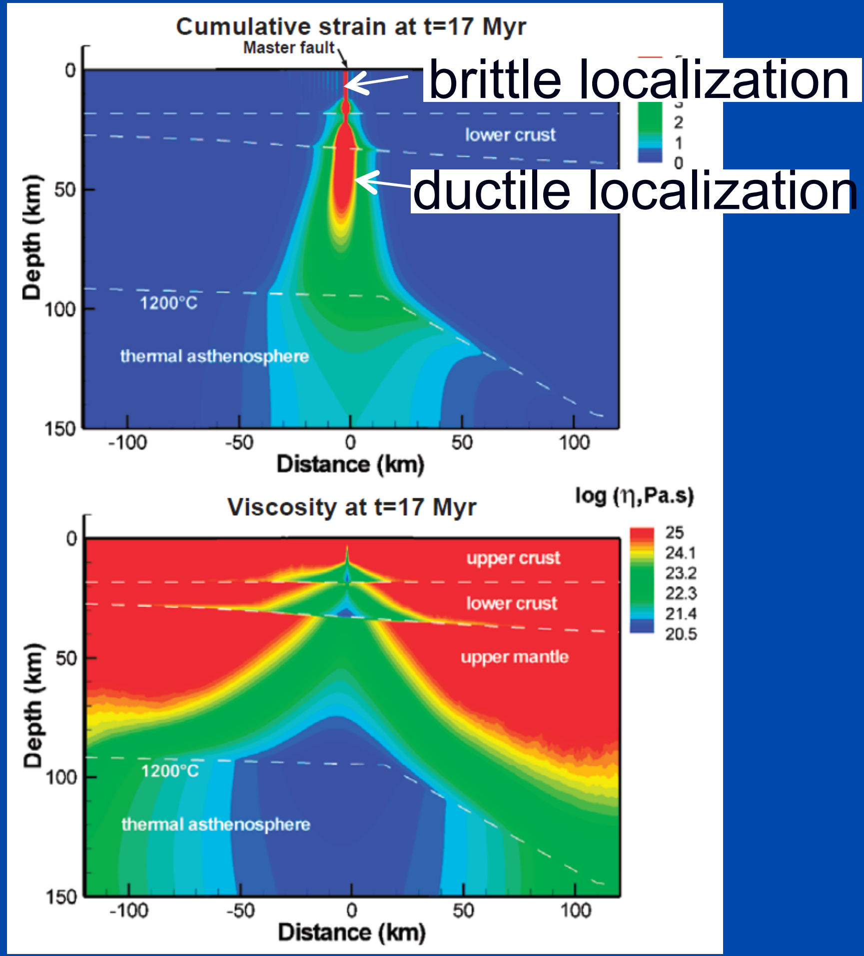
While a lot can be understand about convergent and divergent plate boundaries through 2D modeling, the transform plate boundaries are essentially 3D.

Global geodynamics is also essentially 3D, just because of the presence of plate boundaries and large lateral heterogeneities in the upper mantle

Why "realistic" rheology?



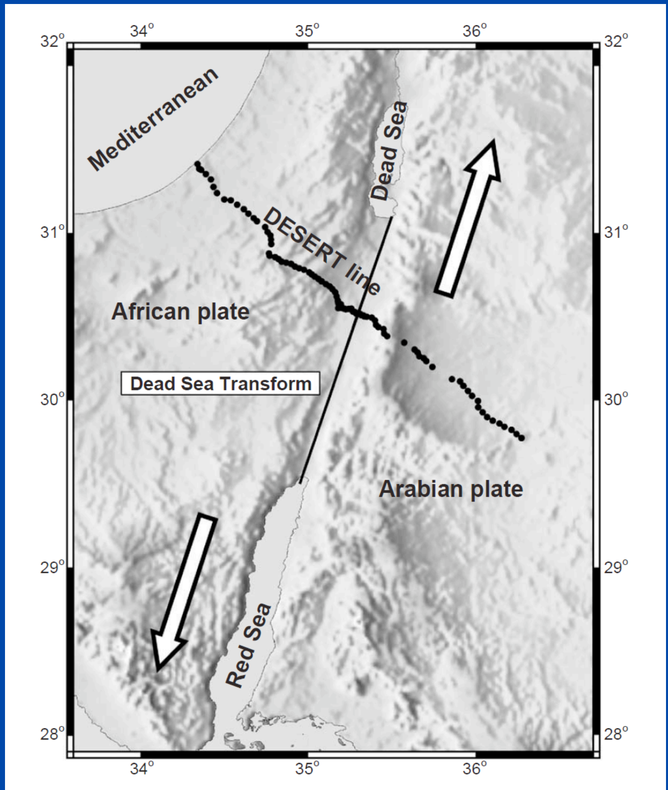
Sobolev et al. EPSL, 2005



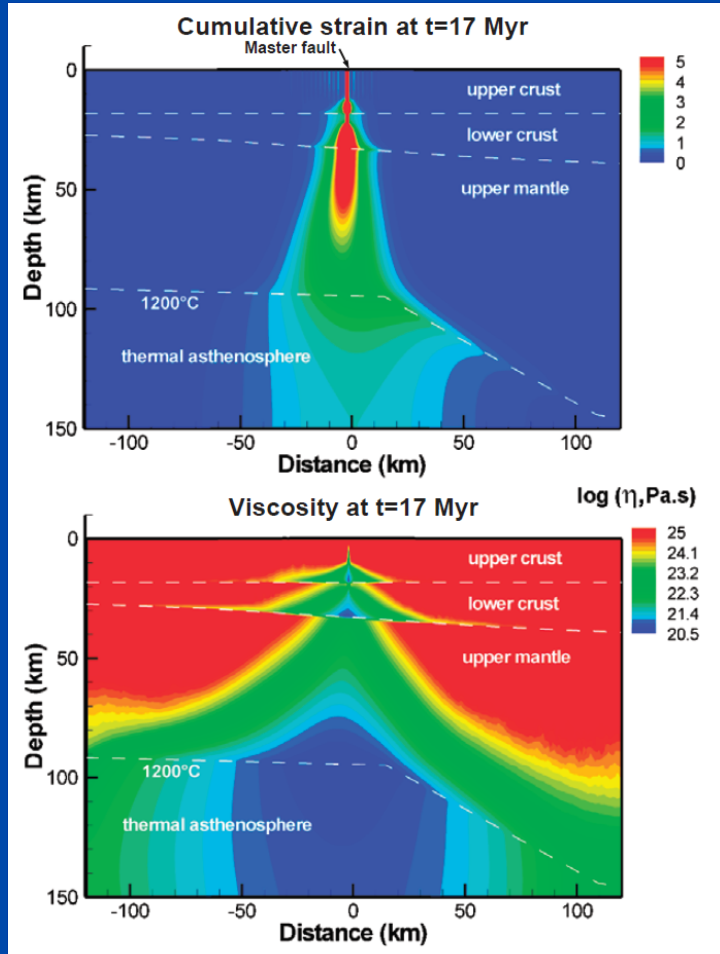
Essential are:

- **plastic rheology (for brittle localization)**
- **non-linear stress- and temperature-dependent ductile rheology (for ductile localization)**

Why "realistic" rheology?



Sobolev et al. EPSL, 2005



Essential are also:

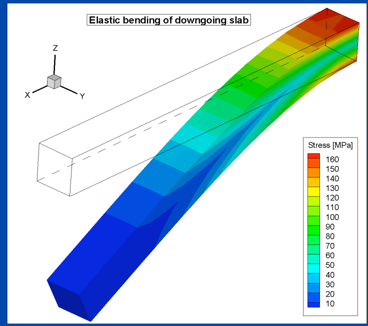
- **damage rheology (*to explain low observed friction at major faults, see poster by Meneses-Rioseco and Sobolev)***
- **elasticity (brings in stress history)**

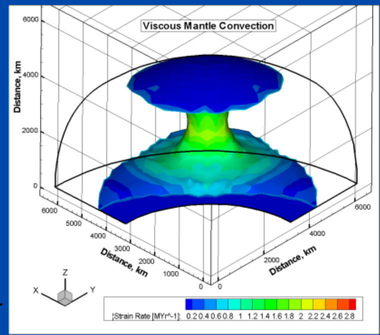
„Realistic“ rheology

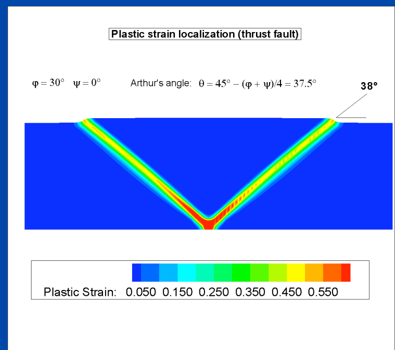
Balance equations

Momentum: $$\frac{\partial \sigma_{ij}}{\partial x_j} + \Delta \rho g\, z_i = 0$$

Energy: $$\frac{DU}{Dt} = -\frac{\partial q_i}{\partial x_i} + r$$







Deformation mechanisms

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{vs} + \dot{\varepsilon}_{ij}^{pl}$$

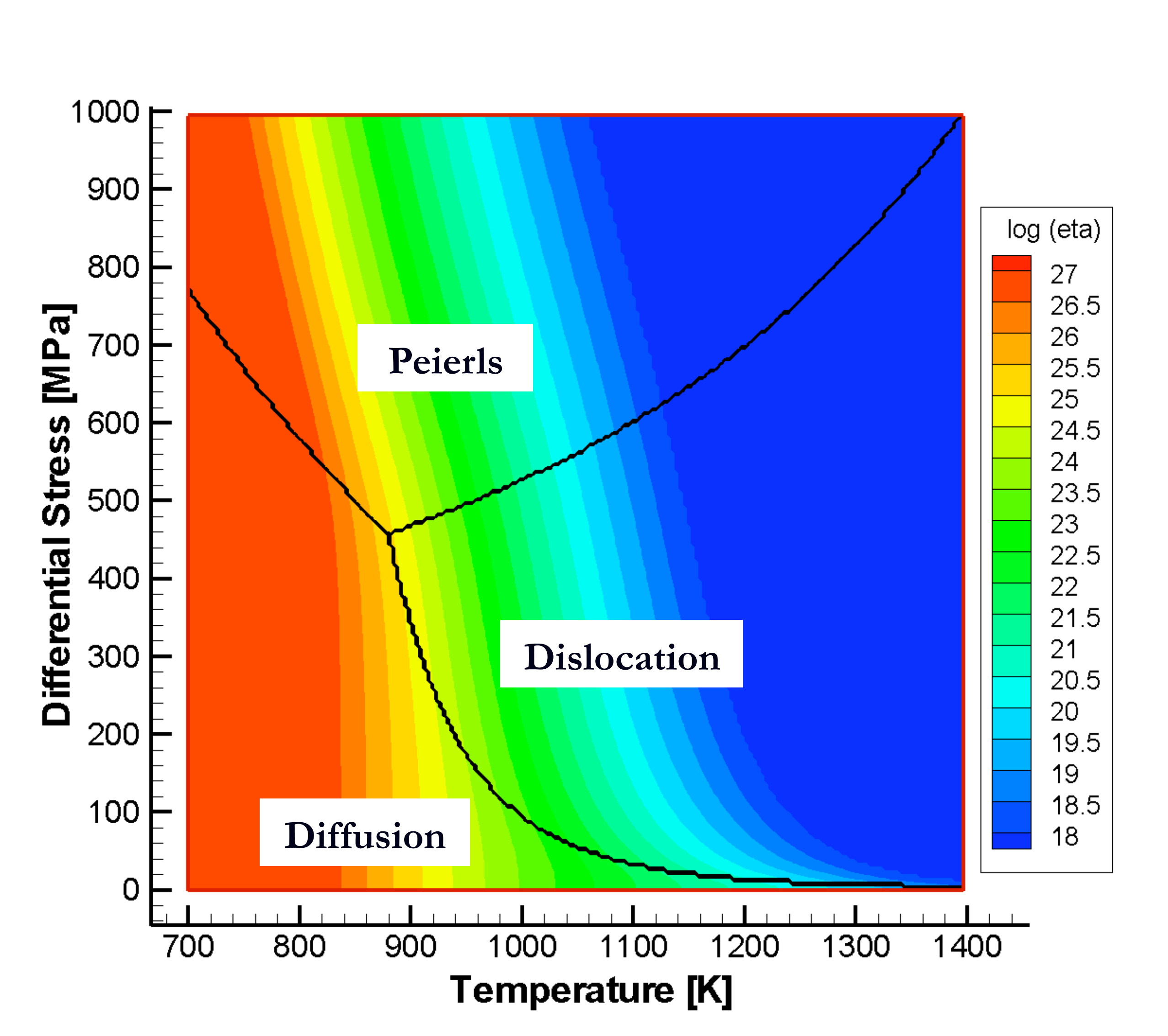
Elastic strain: $$\dot{\varepsilon}_{ij}^{el} = \frac{1}{2G}\hat{\tau}_{ij}$$

Viscous strain: $$\dot{\varepsilon}_{ij}^{vs} = \frac{1}{2\eta_{eff}}\tau_{ij}$$

Plastic strain: Mohr-Coulomb $$\dot{\varepsilon}_{ij}^{pl} = \dot{\gamma}\frac{\partial Q}{\partial \tau_{ij}}$$

Popov and Sobolev (PEPI, 2008)

Three creep processes



$$\eta_{eff} = \tfrac{1}{2}\tau_{II}\left(\dot{\varepsilon}_L + \dot{\varepsilon}_N + \dot{\varepsilon}_P\right)^{-1}$$

Diffusion creep

$$\dot{\varepsilon}_L = B_L\,\tau_{II}\exp\left(-\frac{E_L}{RT}\right)$$

Dislocation creep

$$\dot{\varepsilon}_N = B_N\left(\tau_{II}\right)^n\exp\left(-\frac{E_N}{RT}\right)$$

Peierls creep

$$\dot{\varepsilon}_P = B_P\exp\left[-\frac{E_P}{RT}\left(1-\frac{\tau_{II}}{\tau_P}\right)^2\right]$$

(Kameyama *et al.* 1999)

Mantle rheology

Mantle lithosphere: dry olivine rheology combining diffusion and dislocation creep

$$\dot{\varepsilon}_{II} = A d^{-m} \sigma_{II}^{n} \exp(-(E_a + PV_a)/RT)$$

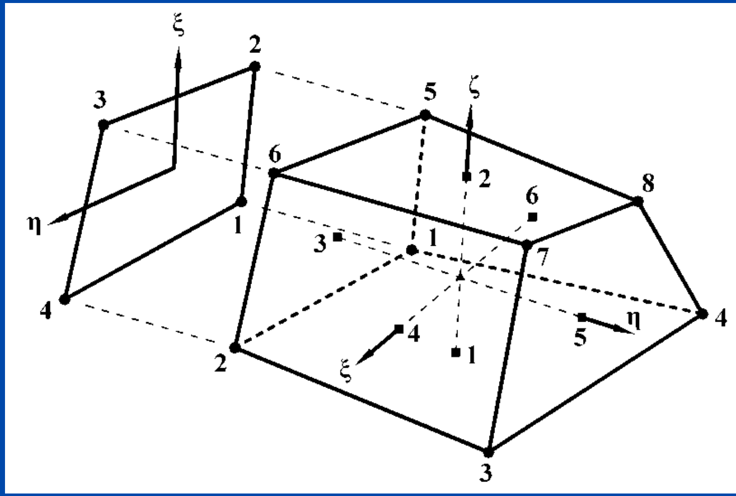
Asthenosphere: wet olivine rheology combining diffusion and dislocation creep

$$\dot{\varepsilon}_{II} = A d^{-m} C_{H2O}^{p} \sigma_{II}^{n} \exp(-(E_a + PV_a)/RT)$$

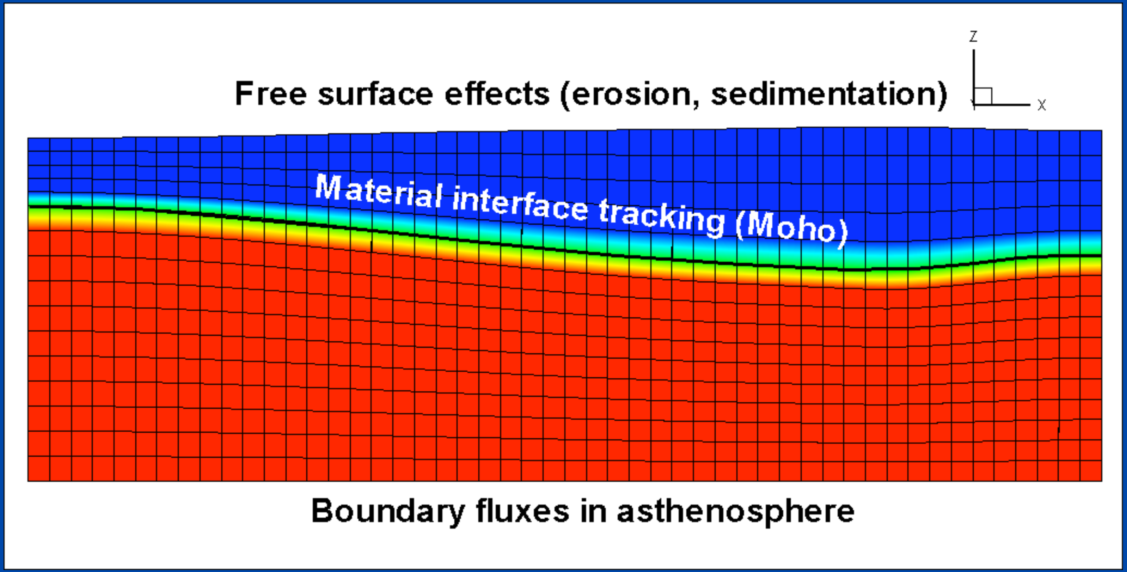
Parameters from Hirth and Kohlstedt (2003) and activation volume from Kawazoe et al. (2009).

Numerical background

Discretization by Finite Element Method



Arbitrary Lagrangian-Eulerian kinematical formulation



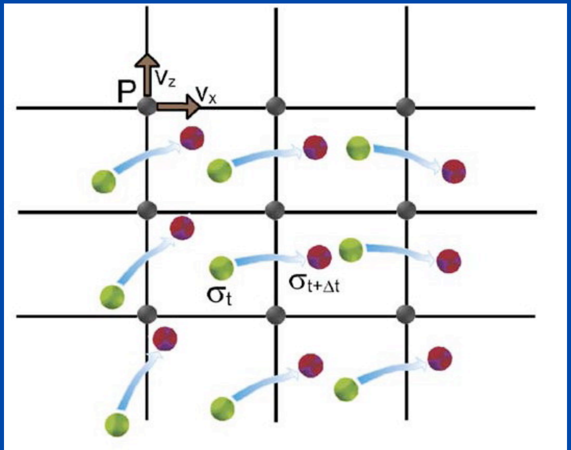
Fast implicit time stepping + Newton-Raphson solver

$$\mathbf{u}_{k+1} = \mathbf{u}_k - \mathbf{K}_k^{-1}\,\mathbf{r}_k$$

r – **Residual Vector**

$$\mathbf{K} = \frac{\partial \mathbf{r}}{\partial \Delta \mathbf{u}}$$ – **Tangent Matrix**

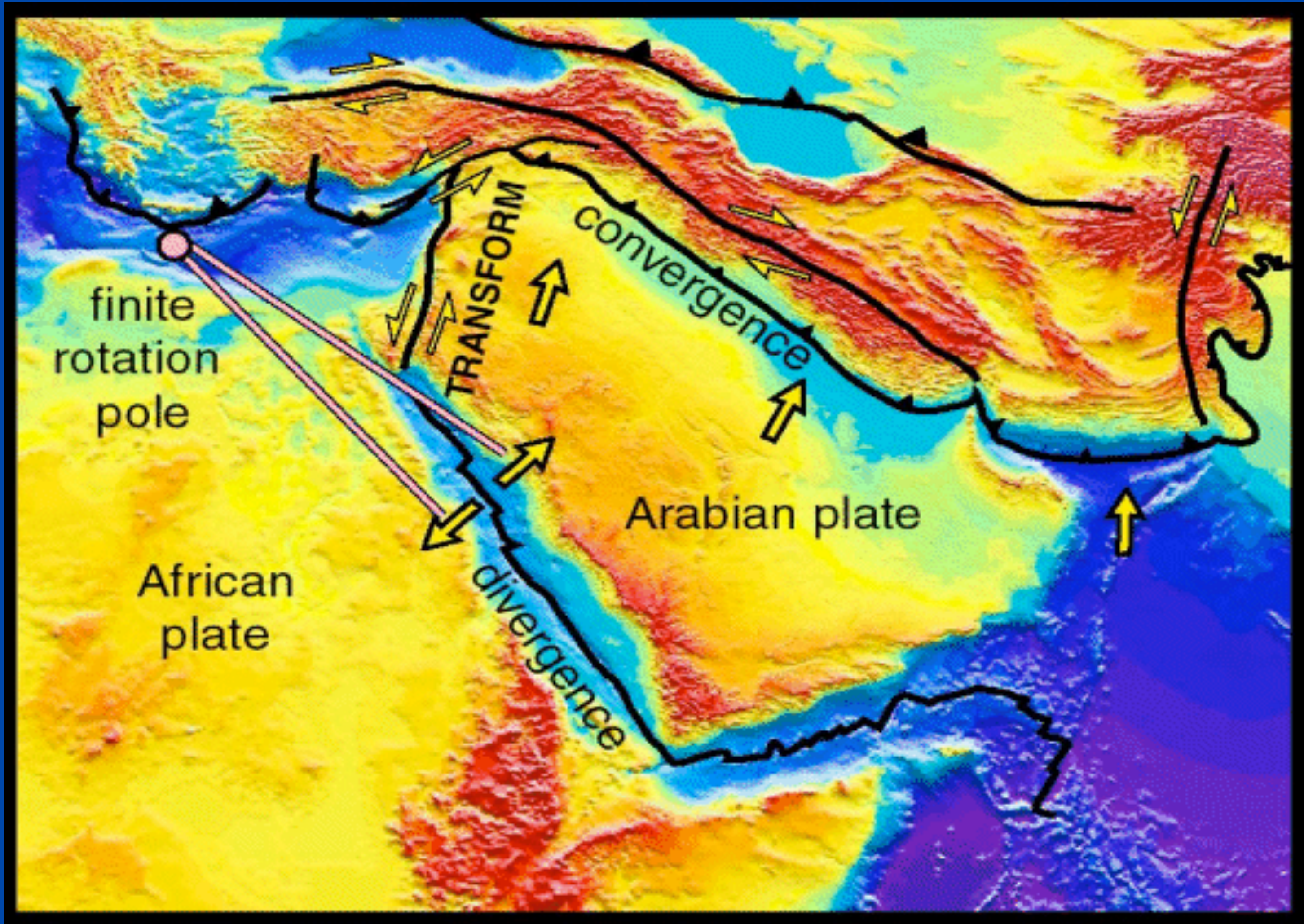
Remapping of entire fields by Particle-In-Cell technique



Popov and Sobolev (PEPI 2008)

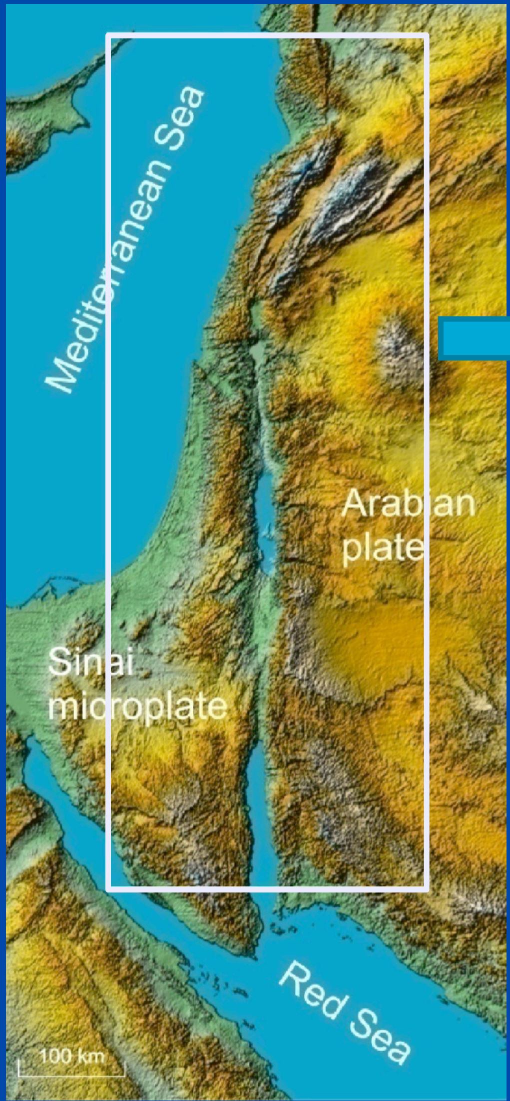
Transform Fault- case Dead Sea Transform

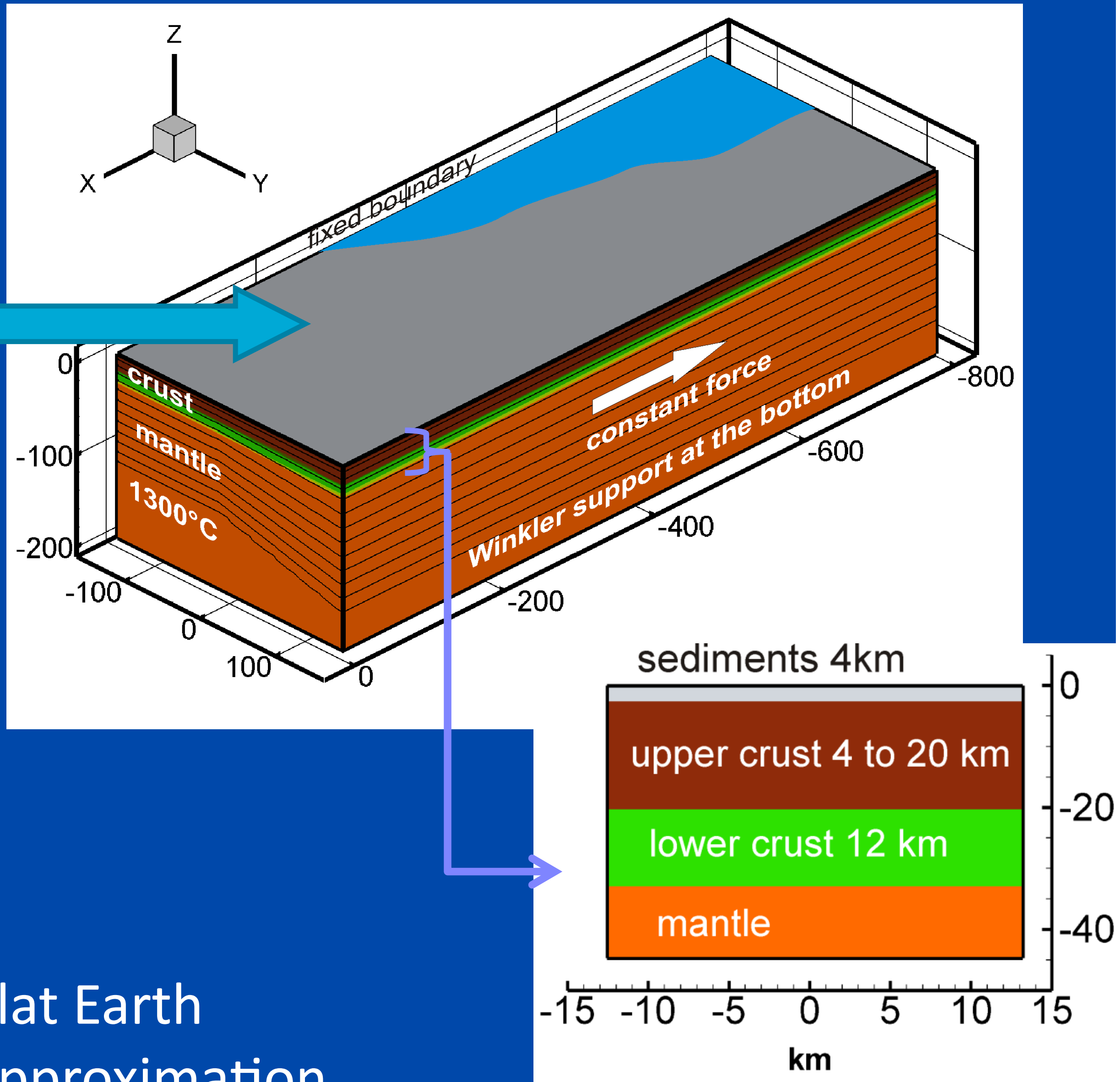
(In cooperation with A. Petrunin)



Why the Dead Sea DST is where it is, and how is it originated?

Model setup

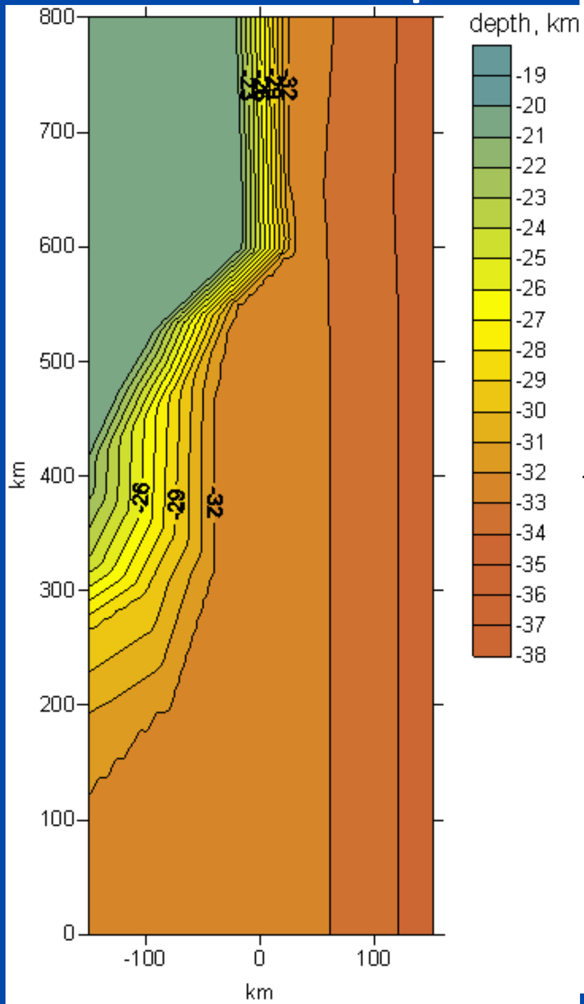




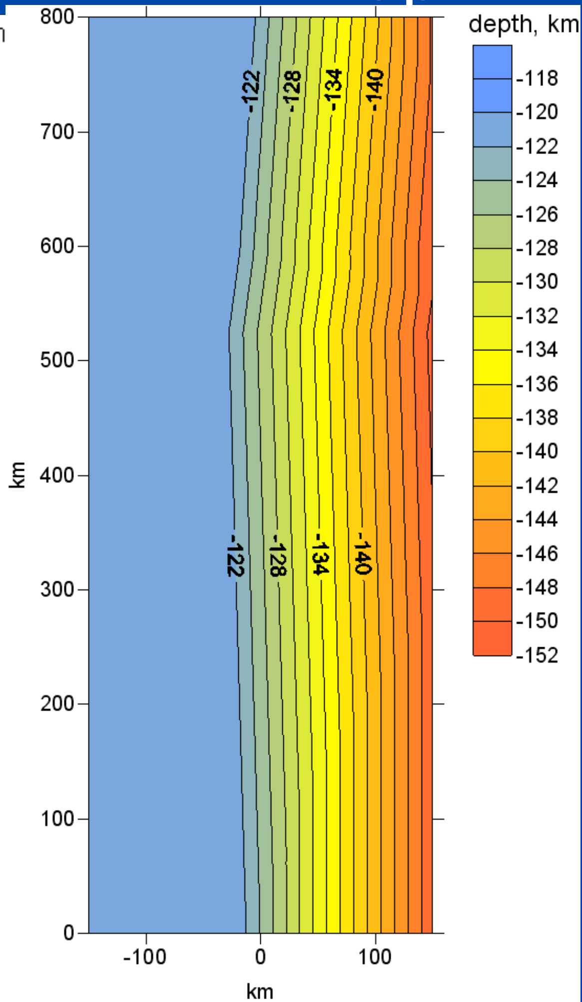
Flat Earth approximation

Initial lithospheric structure:

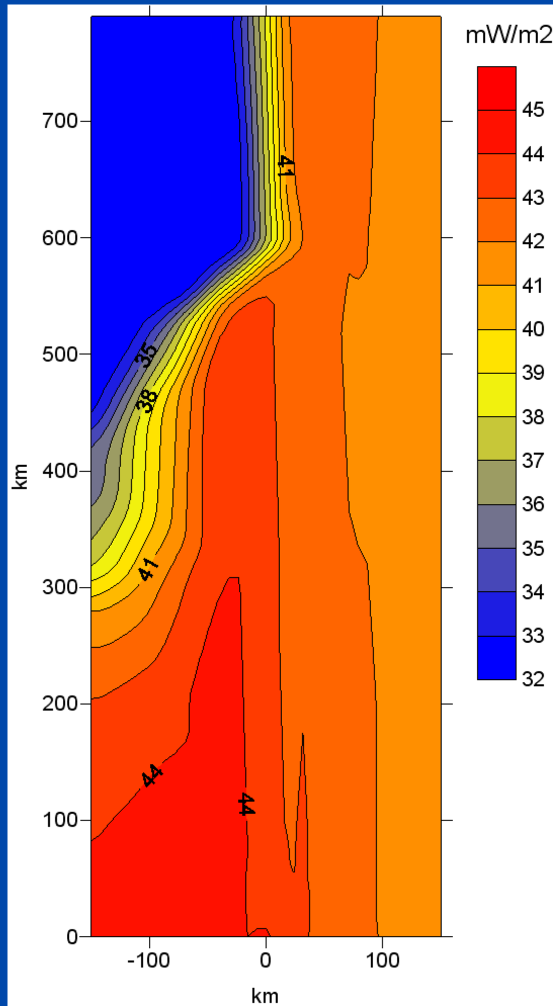
Moho map



LAB map



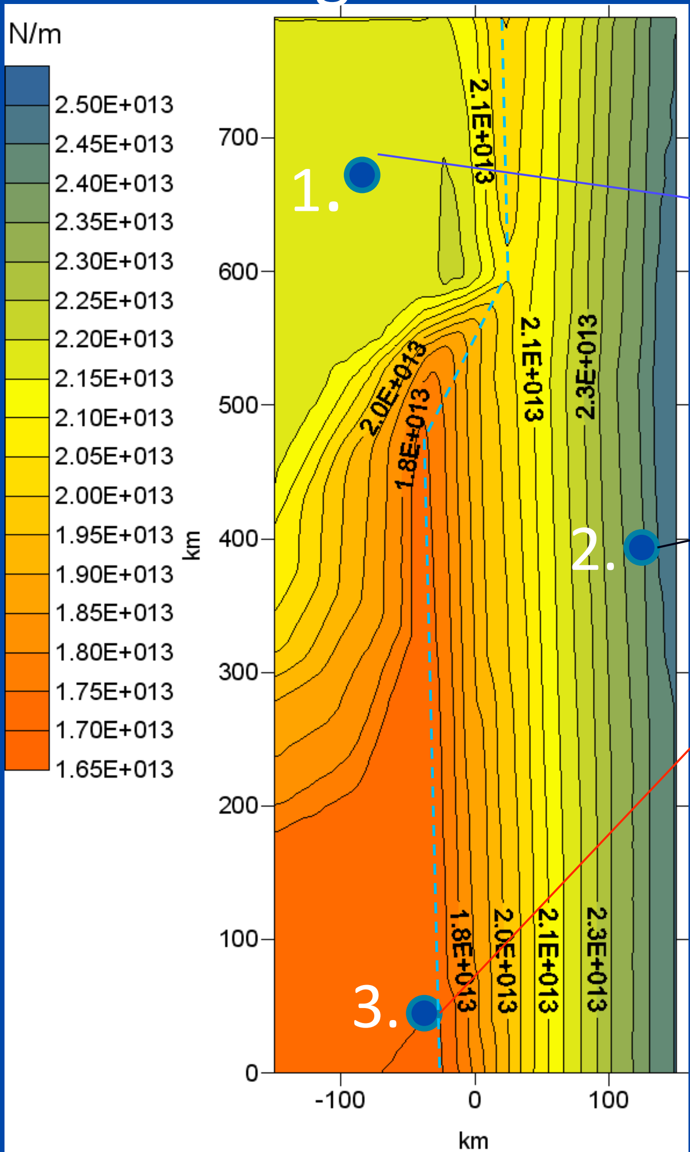
Heat flow

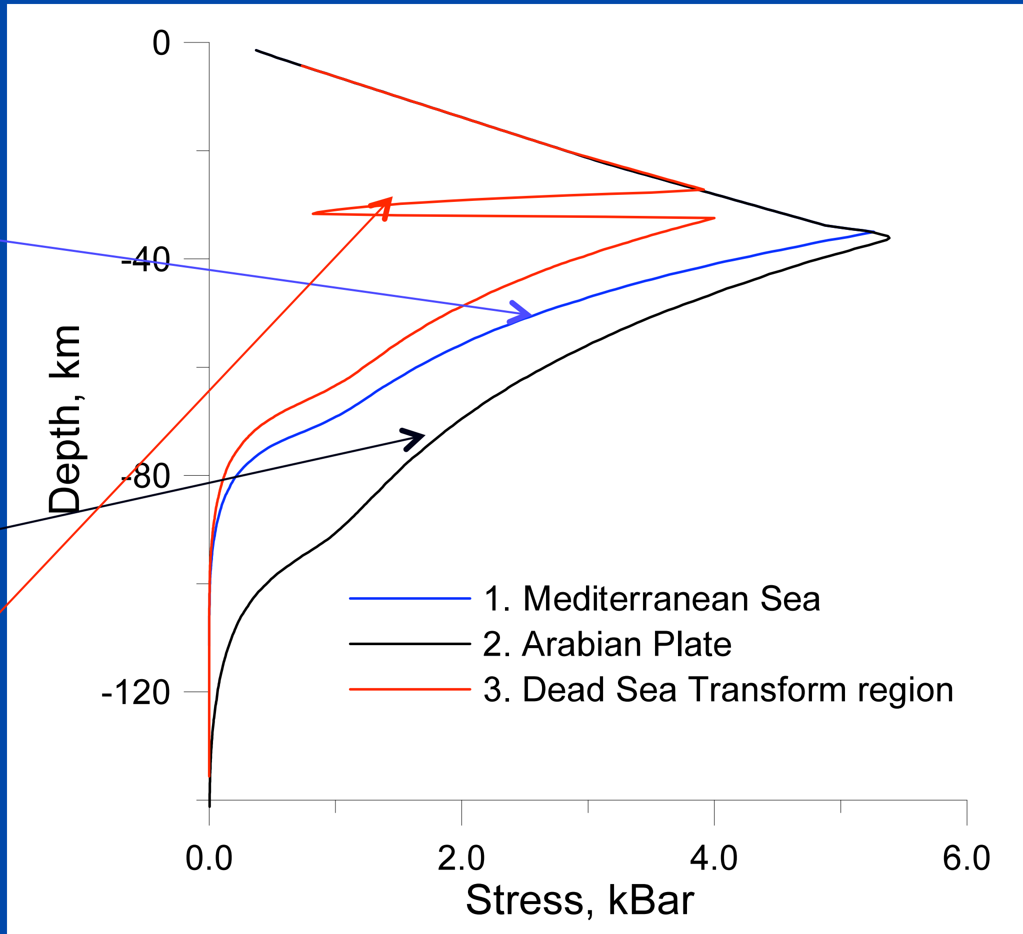


The regian is characterized with the very low heat flow, of less then 55 mW/m2

Initial lithospheric structure: rheology

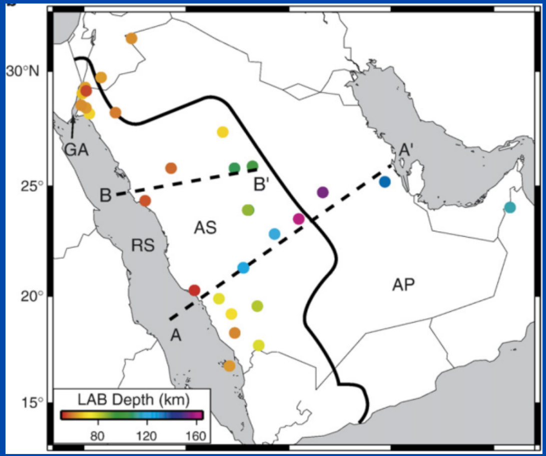
Net strength distribution



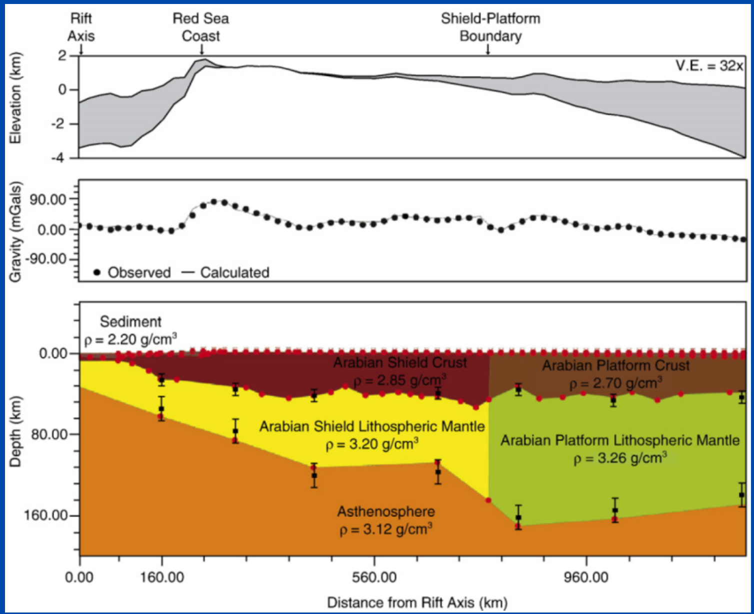


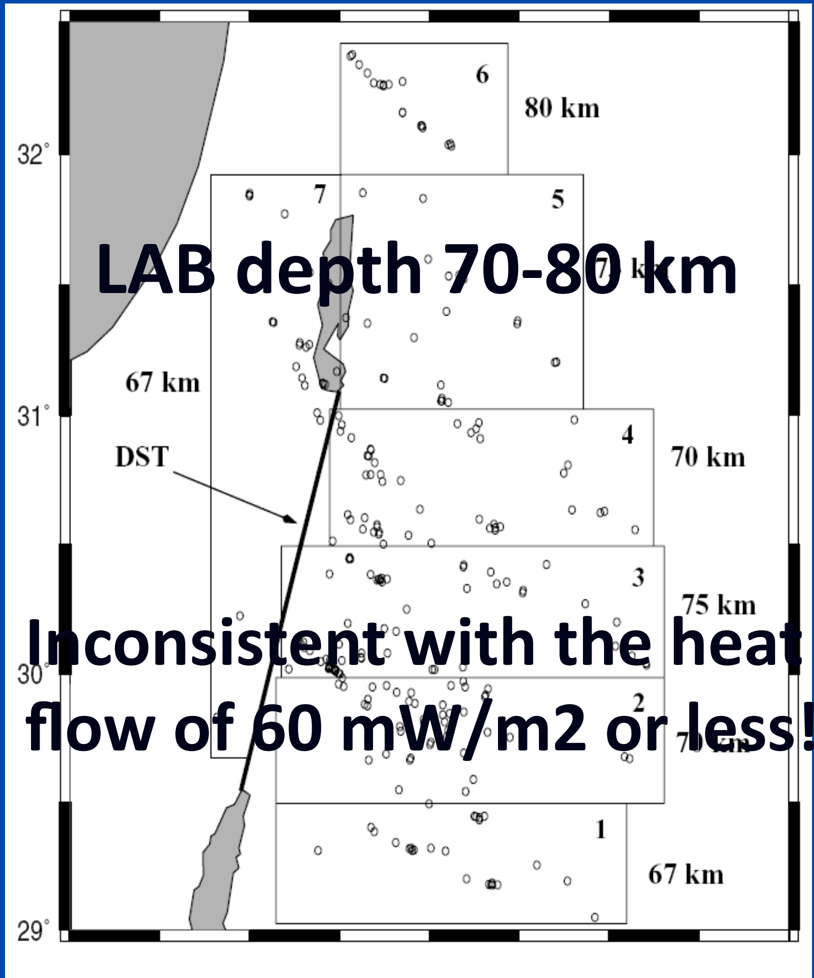
Net strength $= \int_0^{200\ km} \tau_{II}(\dot{\varepsilon}_{II} = 10^{-15} s^{-1}, P, T, \mu)\, dh$

Present day lithospheric thickness



Hansen et al., *EPSL 2007*





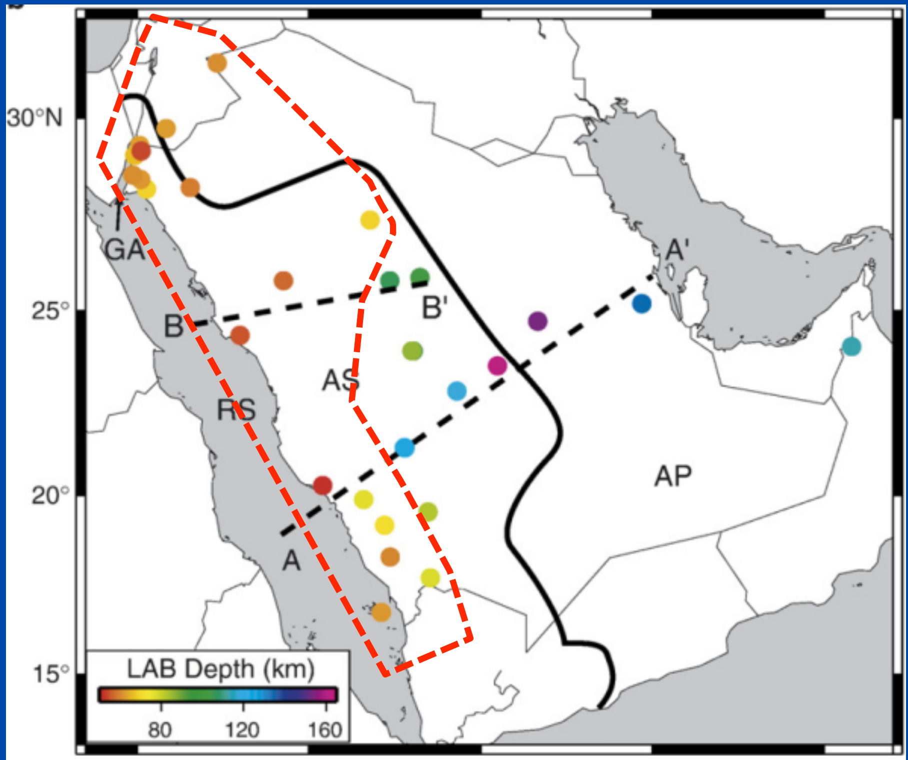
LAB depth 70-80 km

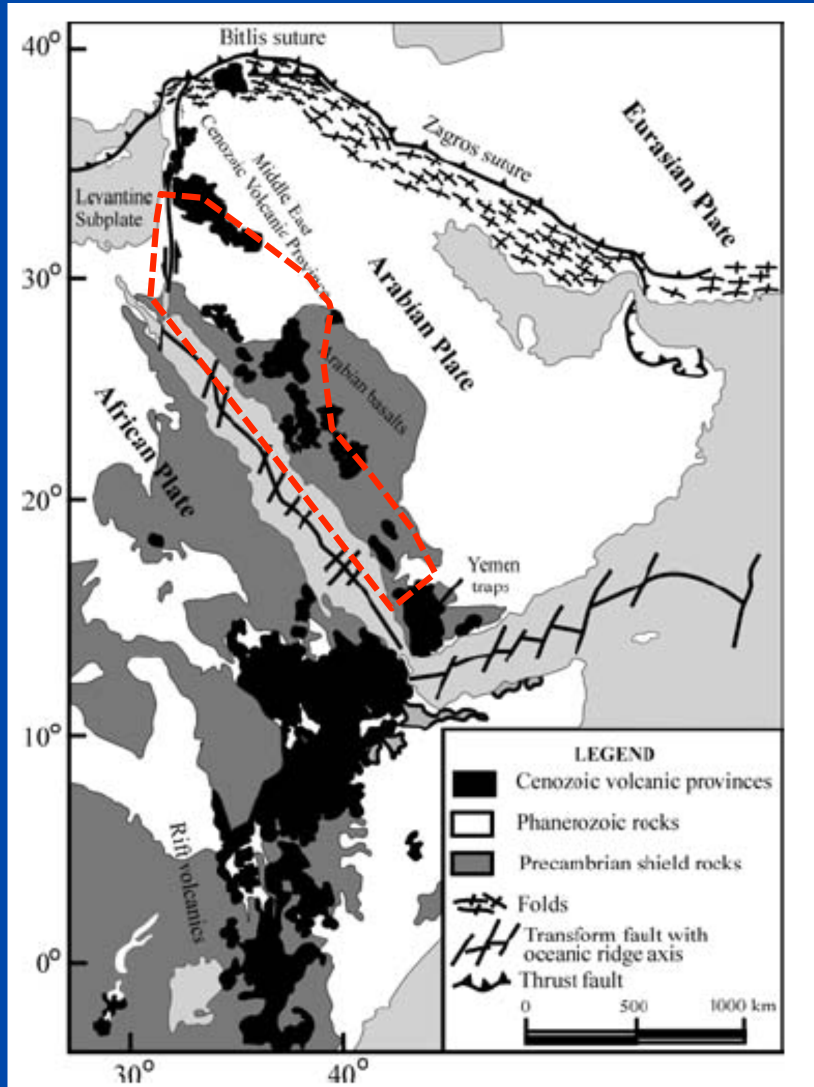
Inconsistent with the heat flow of 60 mW/m2 or less!

Mohsen et al., *Geophys. J. Int. 2006*

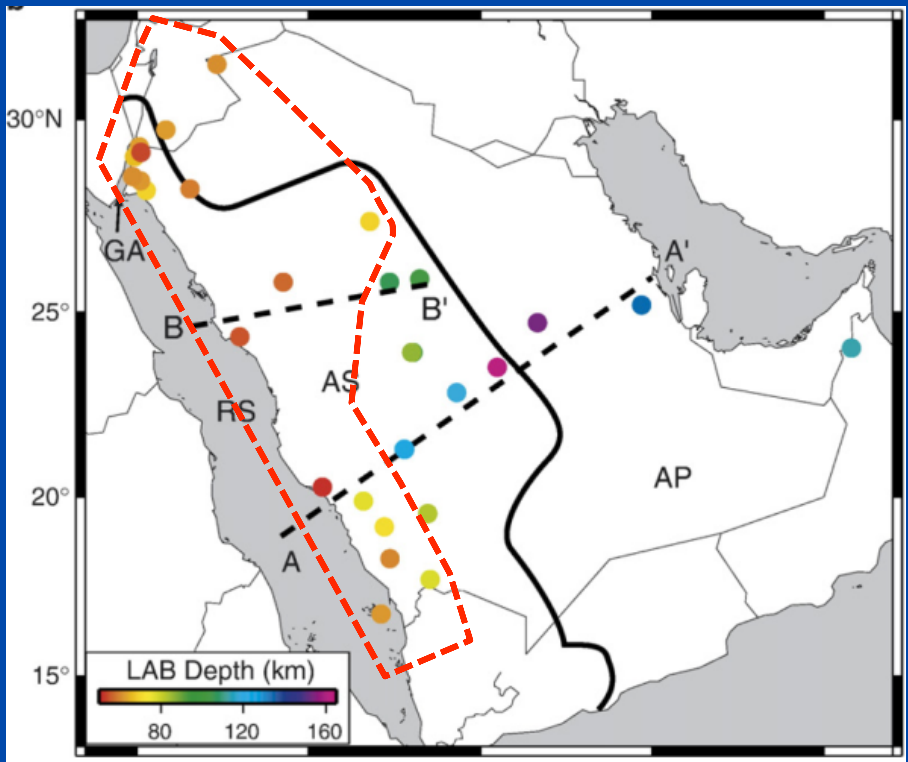
Lithospheric thickness and magmatism

Magmatism at 30-0 Ma

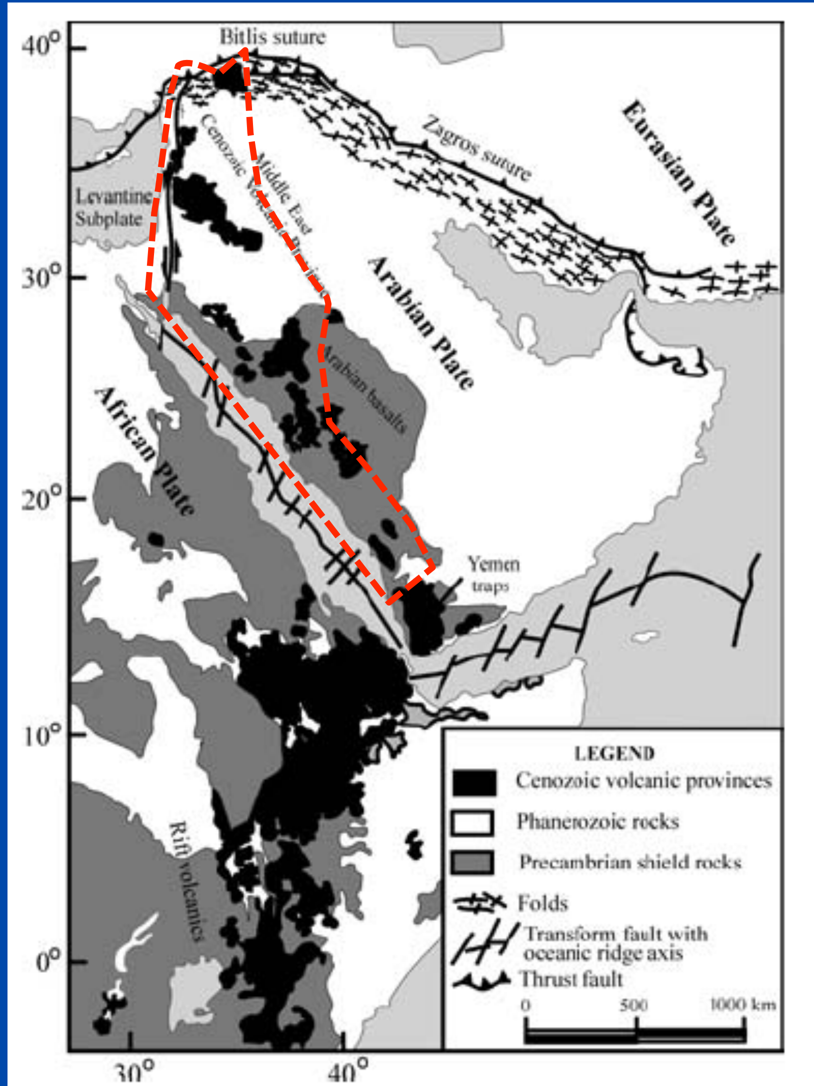




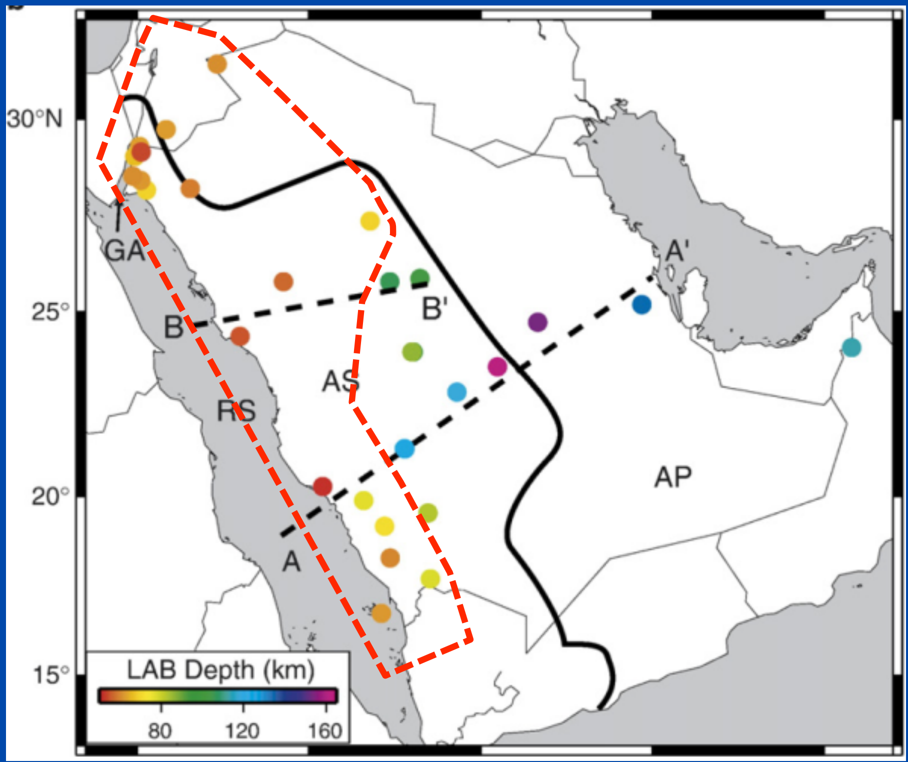
Lithospheric thickness and magmatism



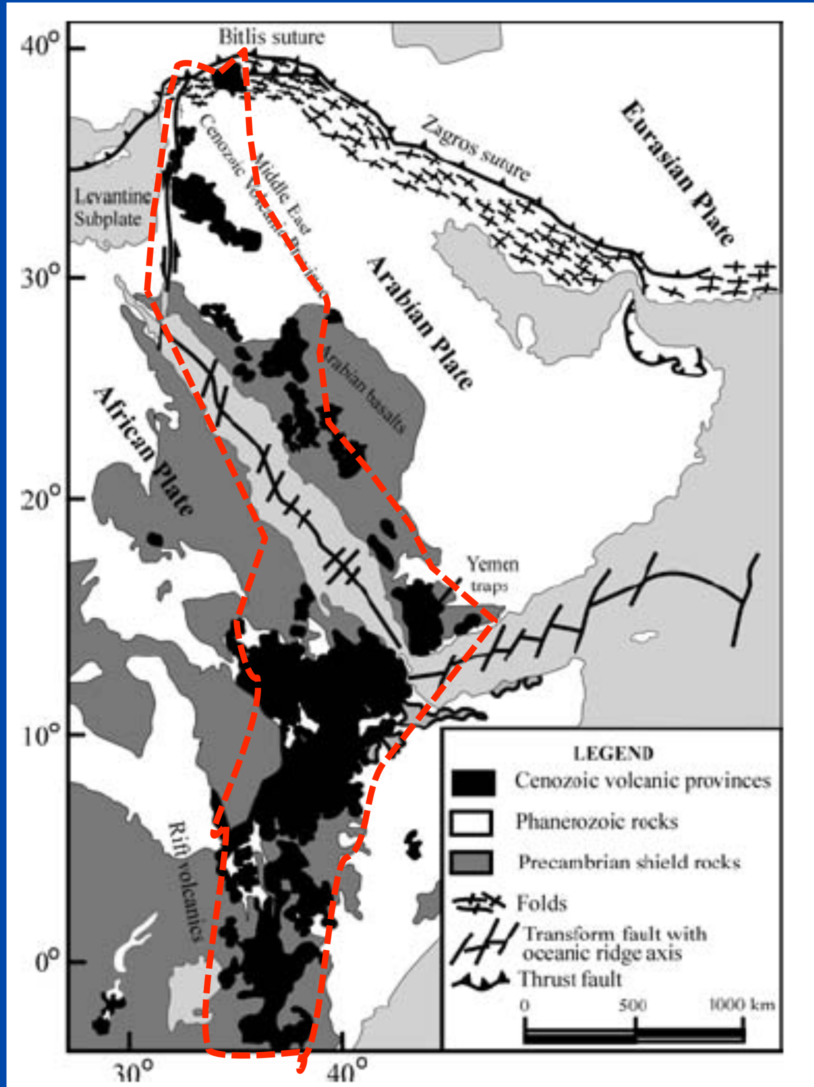
Magmatism at 30-0 Ma



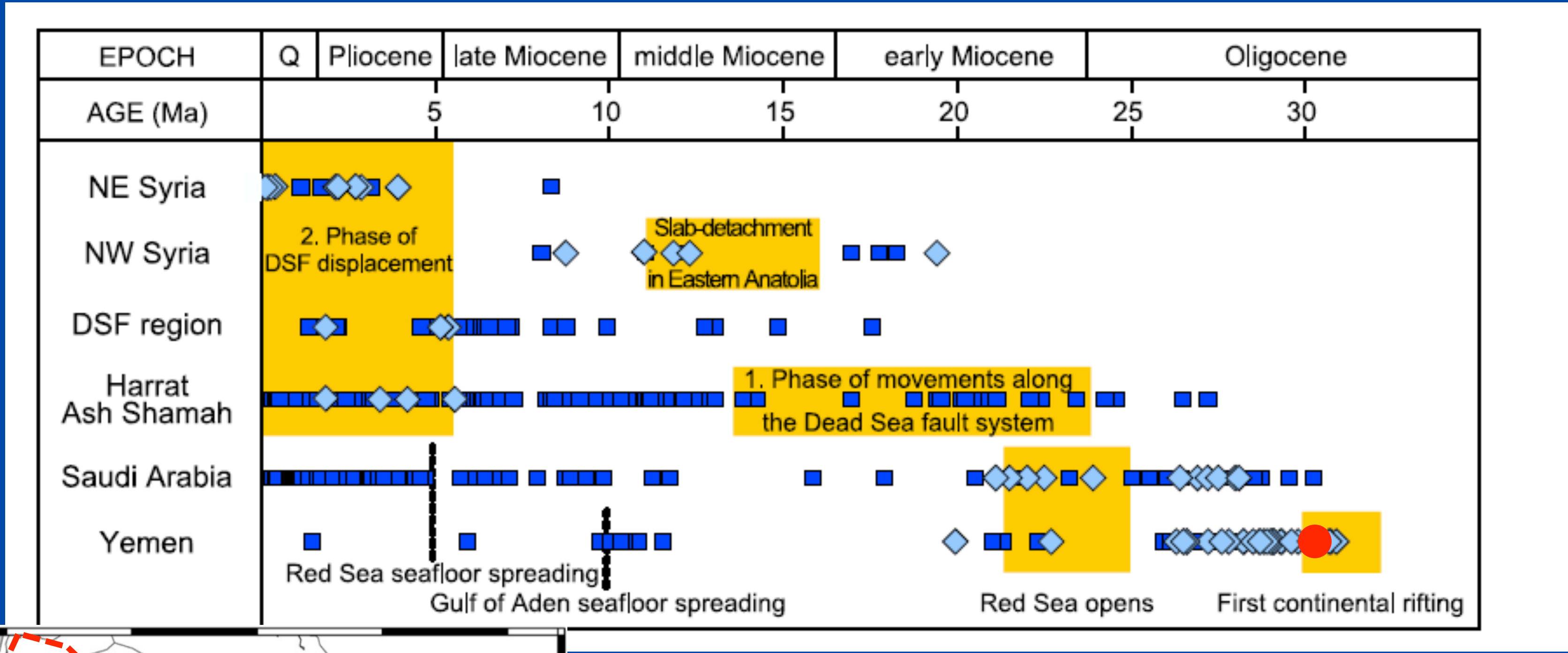
Lithospheric thickness and magmatism

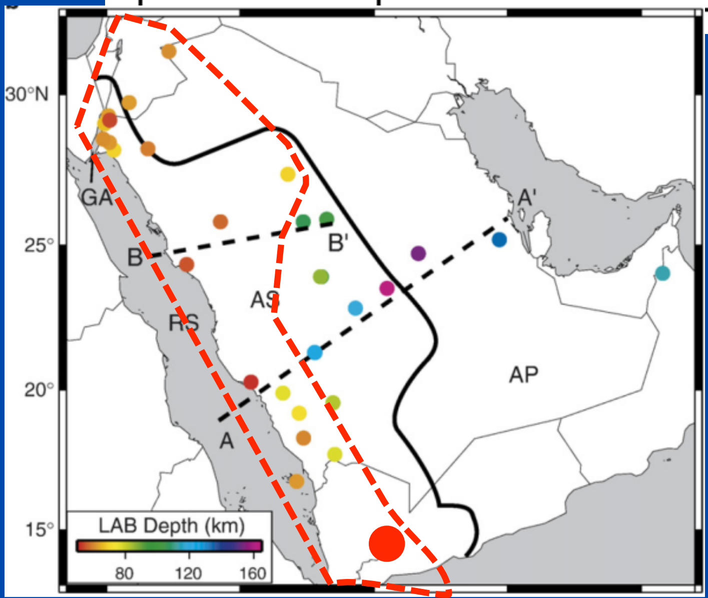


Magmatism at 30-0 Ma



Tectonic events and magmatism

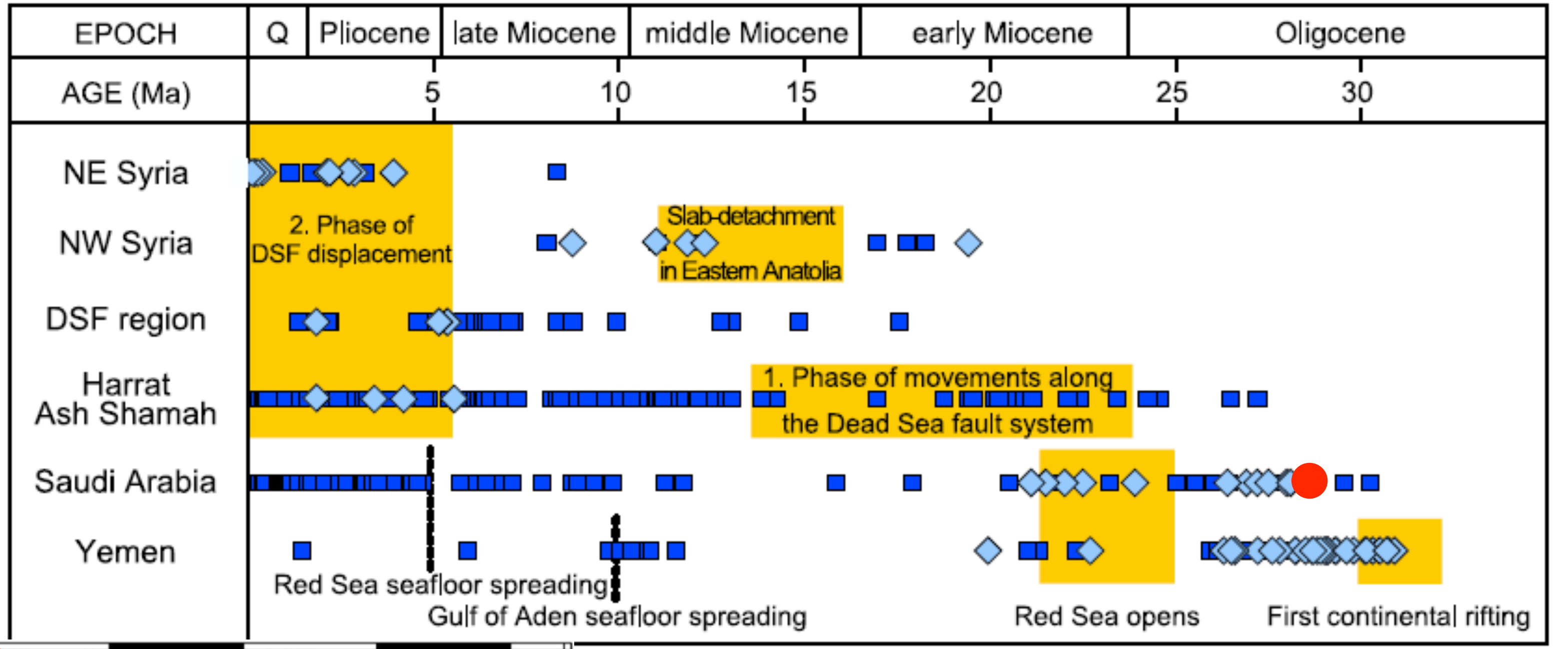


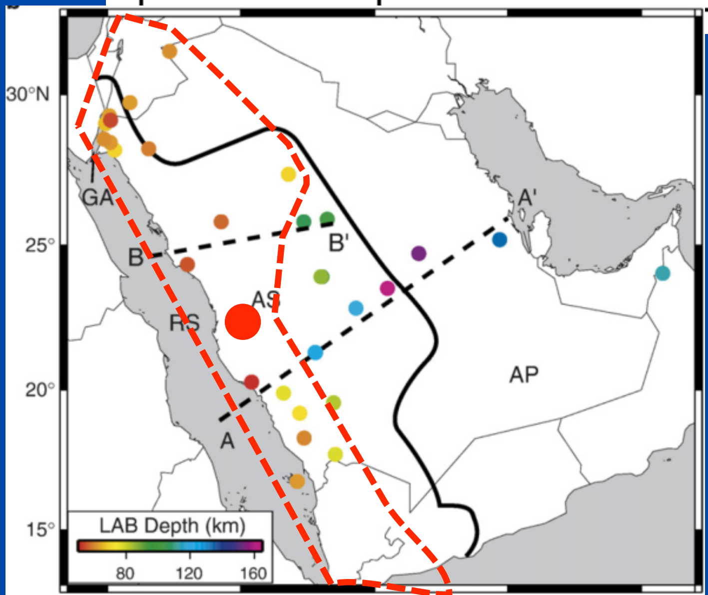


Krienitz et al, 2009

Magmatism at 30-0 Ma

Tectonic events and magmatism

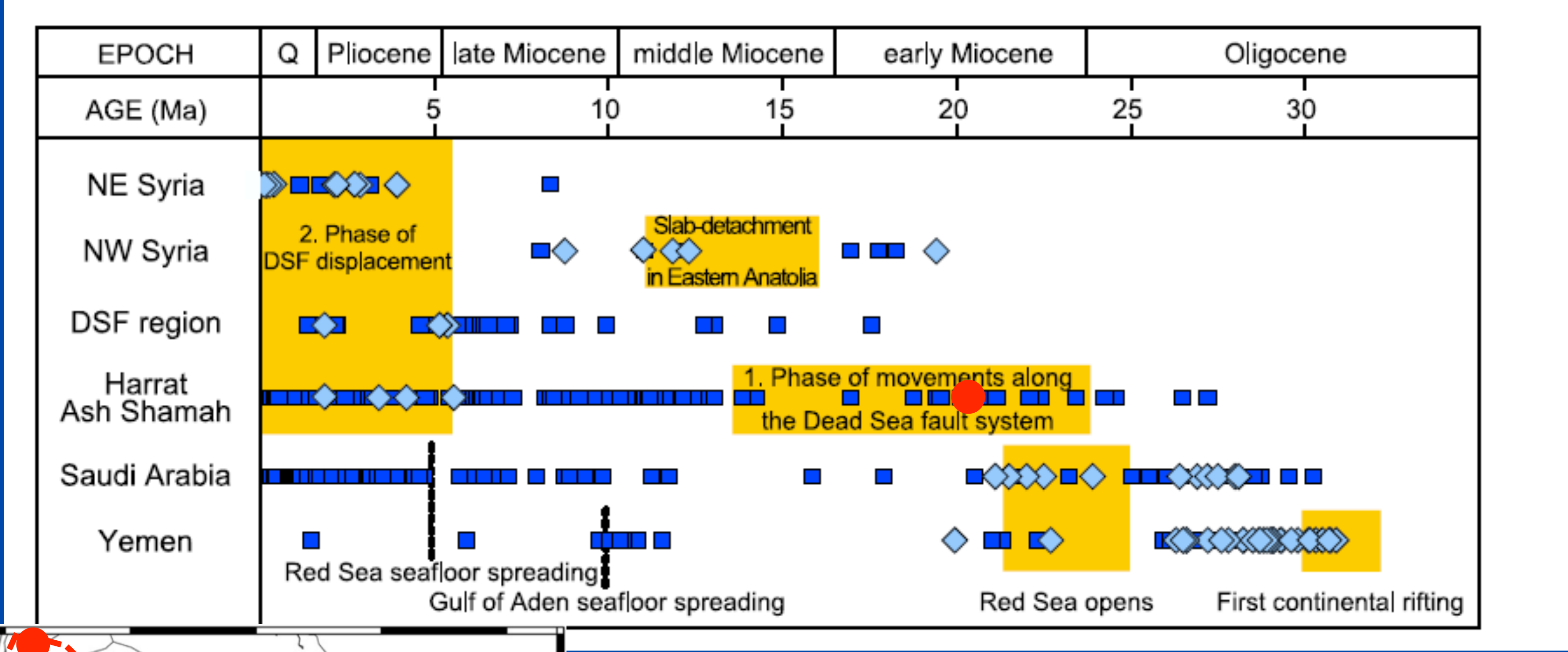


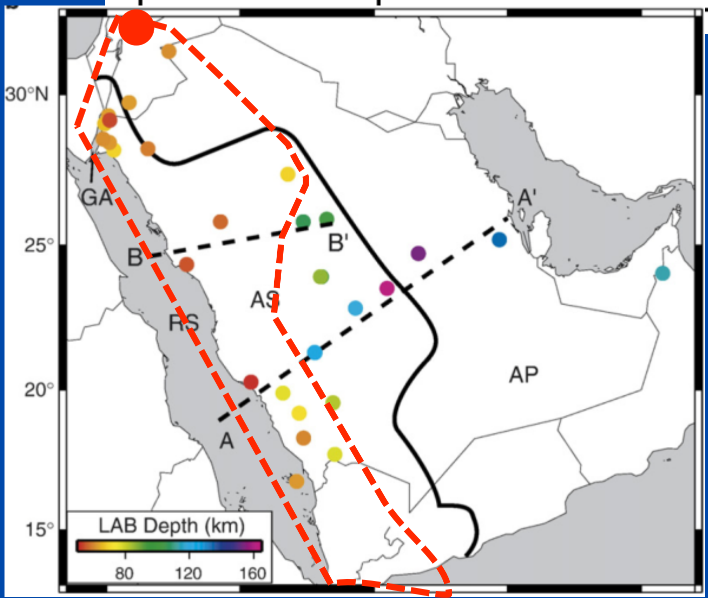


Krienitz et al, 2009

Magmatism at 30-0 Ma

Tectonic events and magmatism





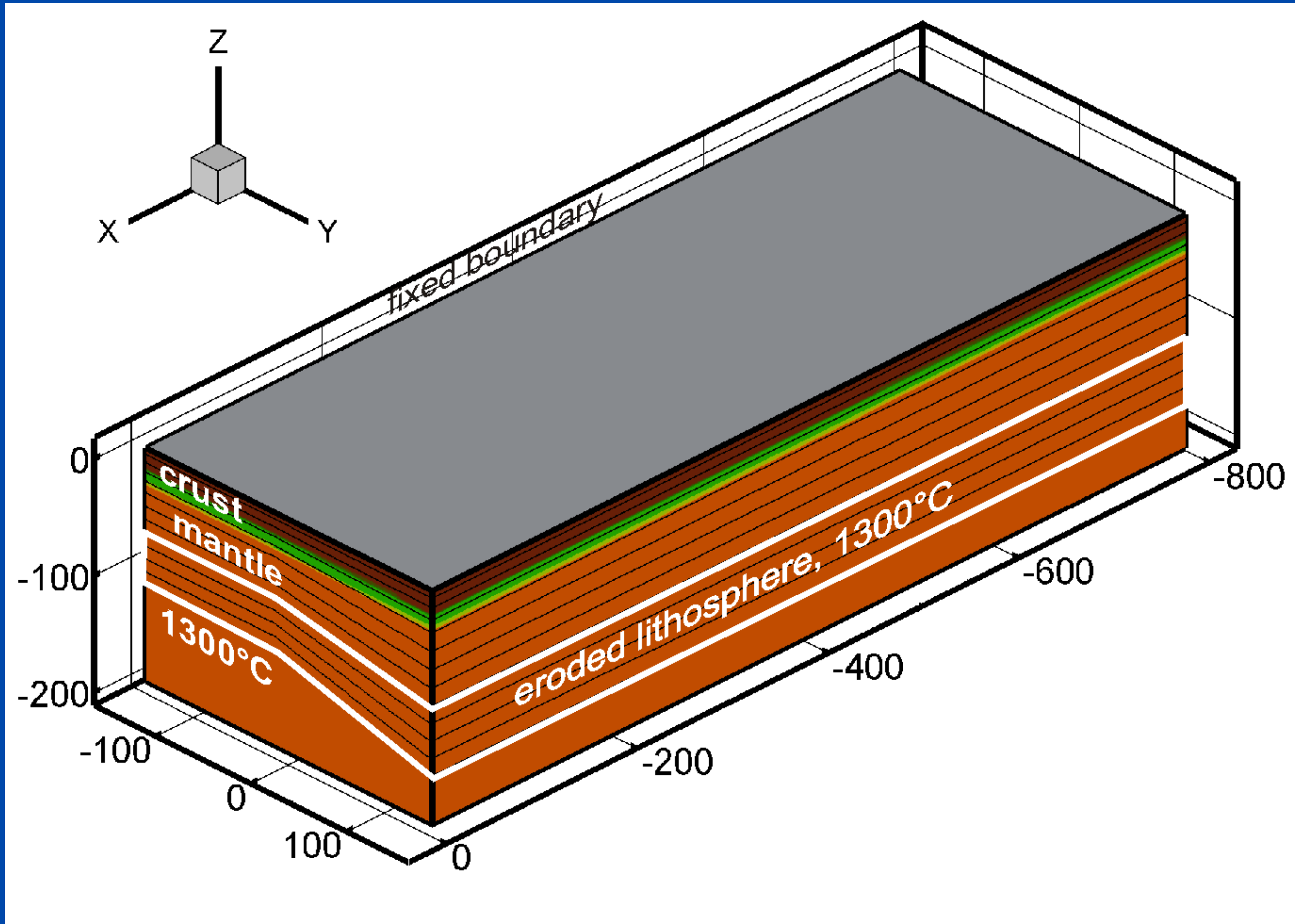
Krienitz et al, 2009

Magmatism at 30-0 Ma

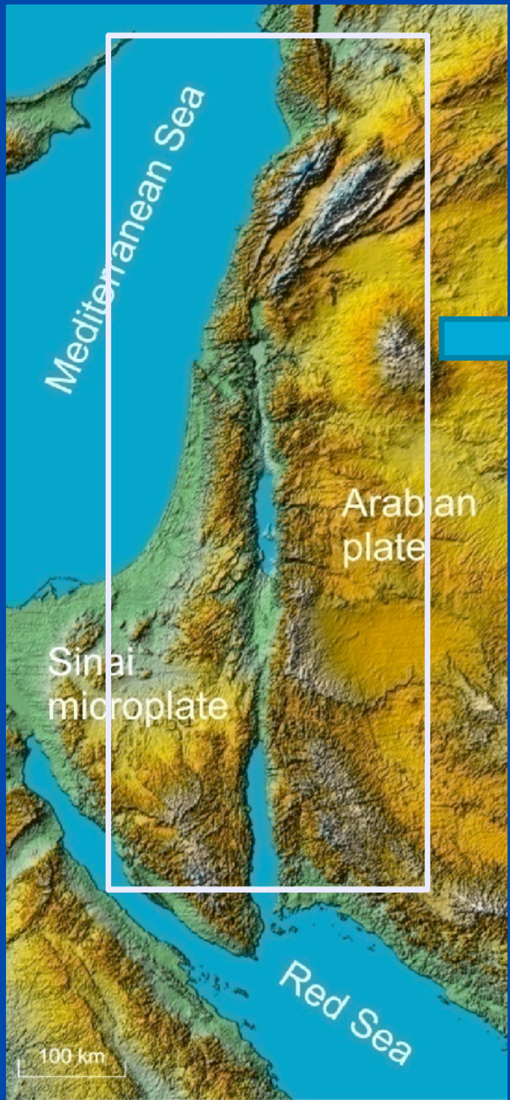
Conclusion

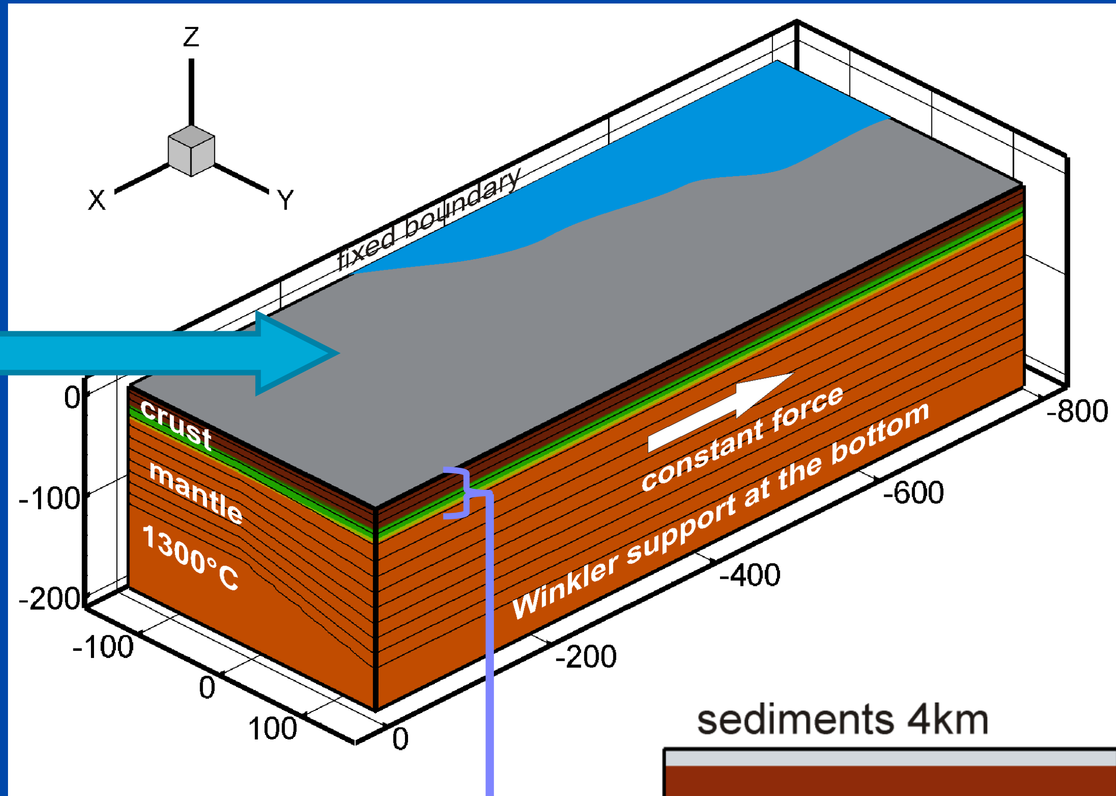
Lithosphere around DST was thinned in the past (between 25-15 Ma), such that related high heat flow had not enough time to reach the surface

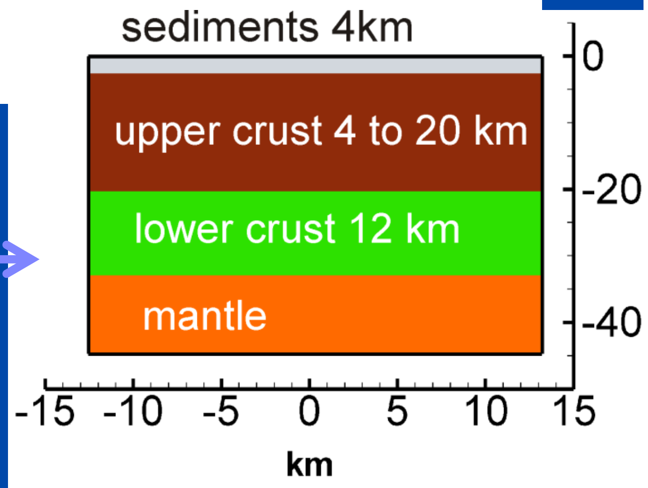
Assuming thermal erosion of the lithosphere



Model setup

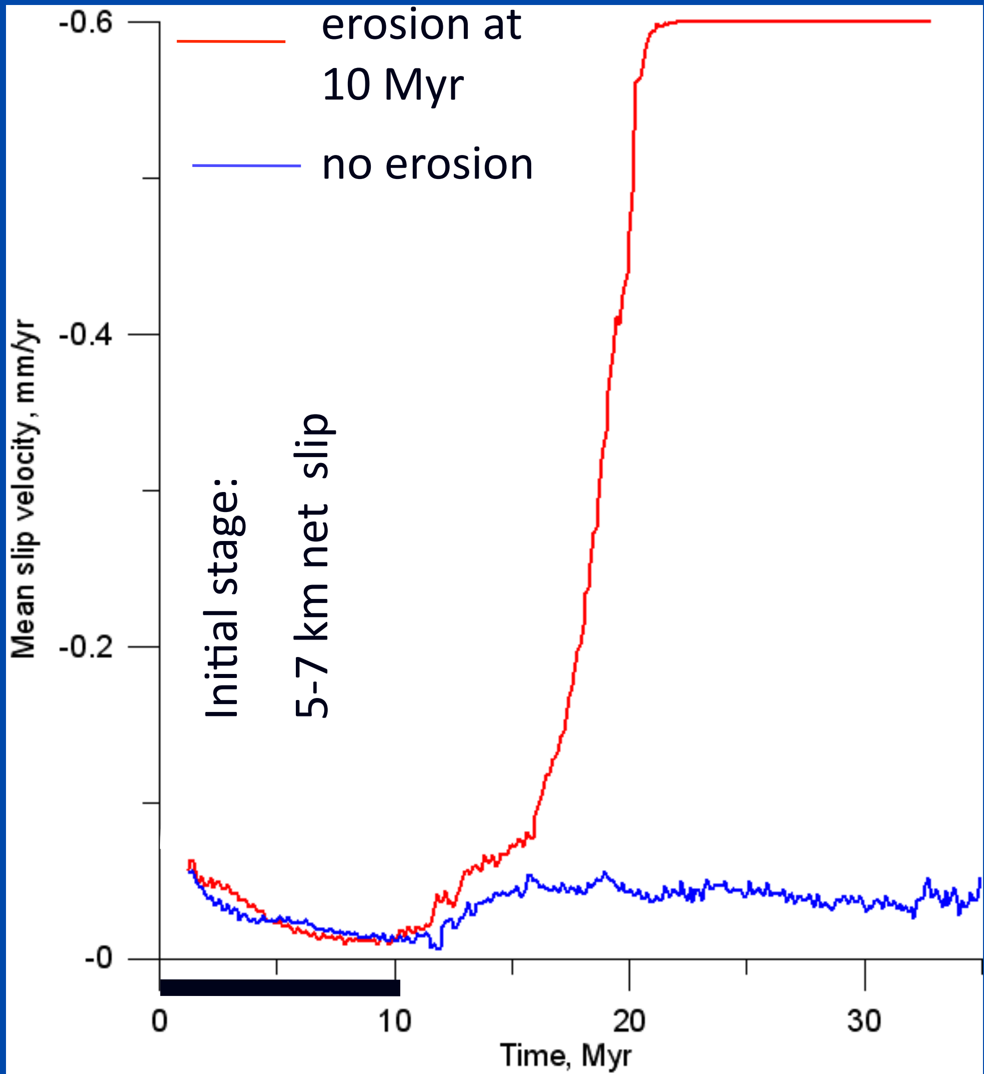


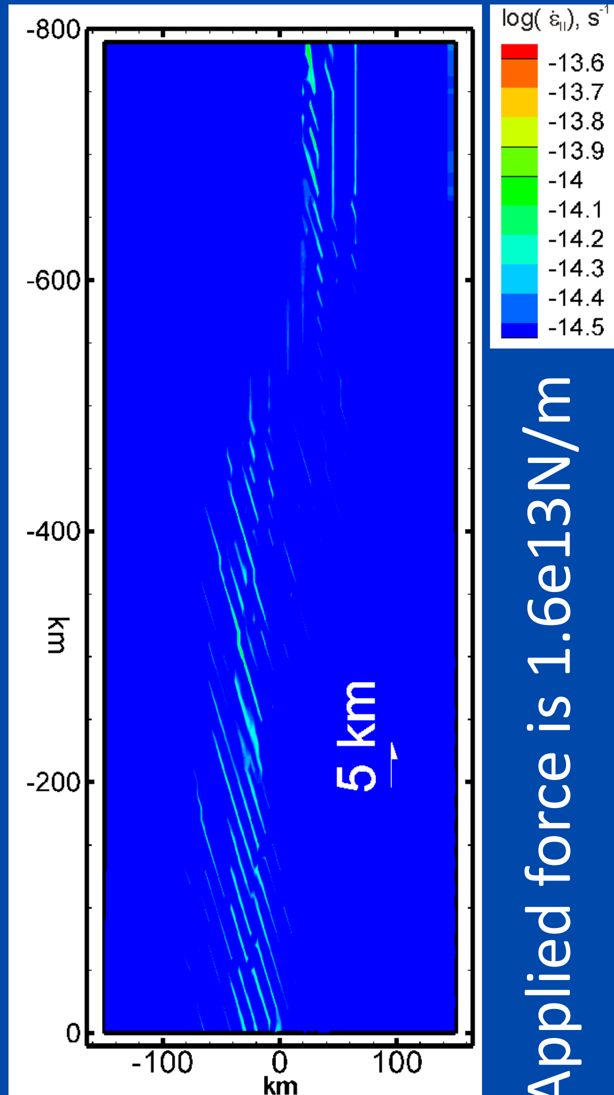




Flat Earth approximation

30-20 Ma rifting and beginning of opening of the Red Sea, thinning of the lithosphere in Saudi Arabia

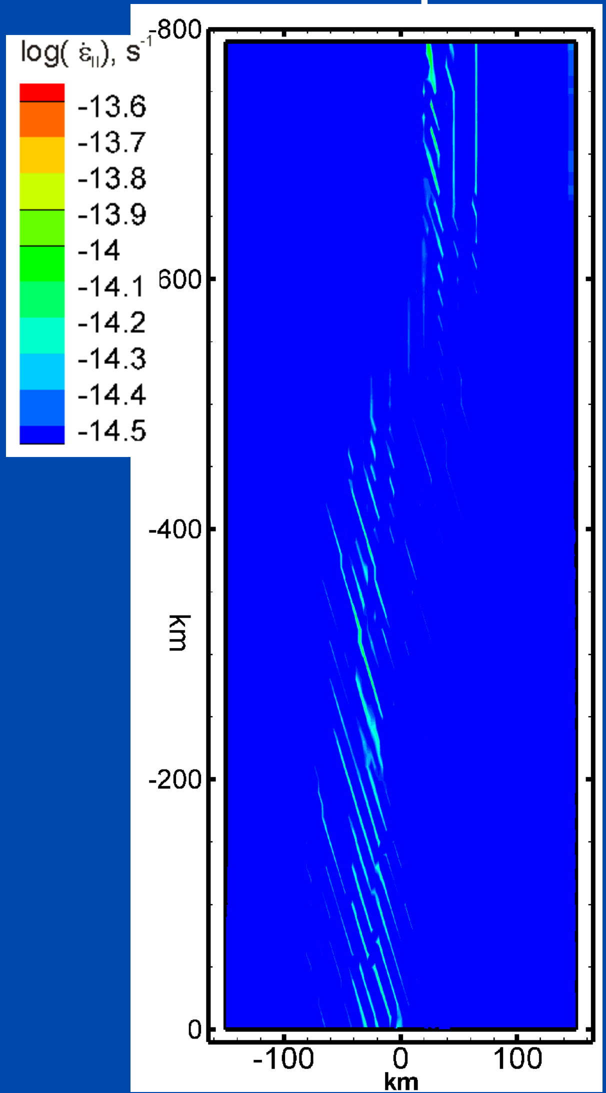




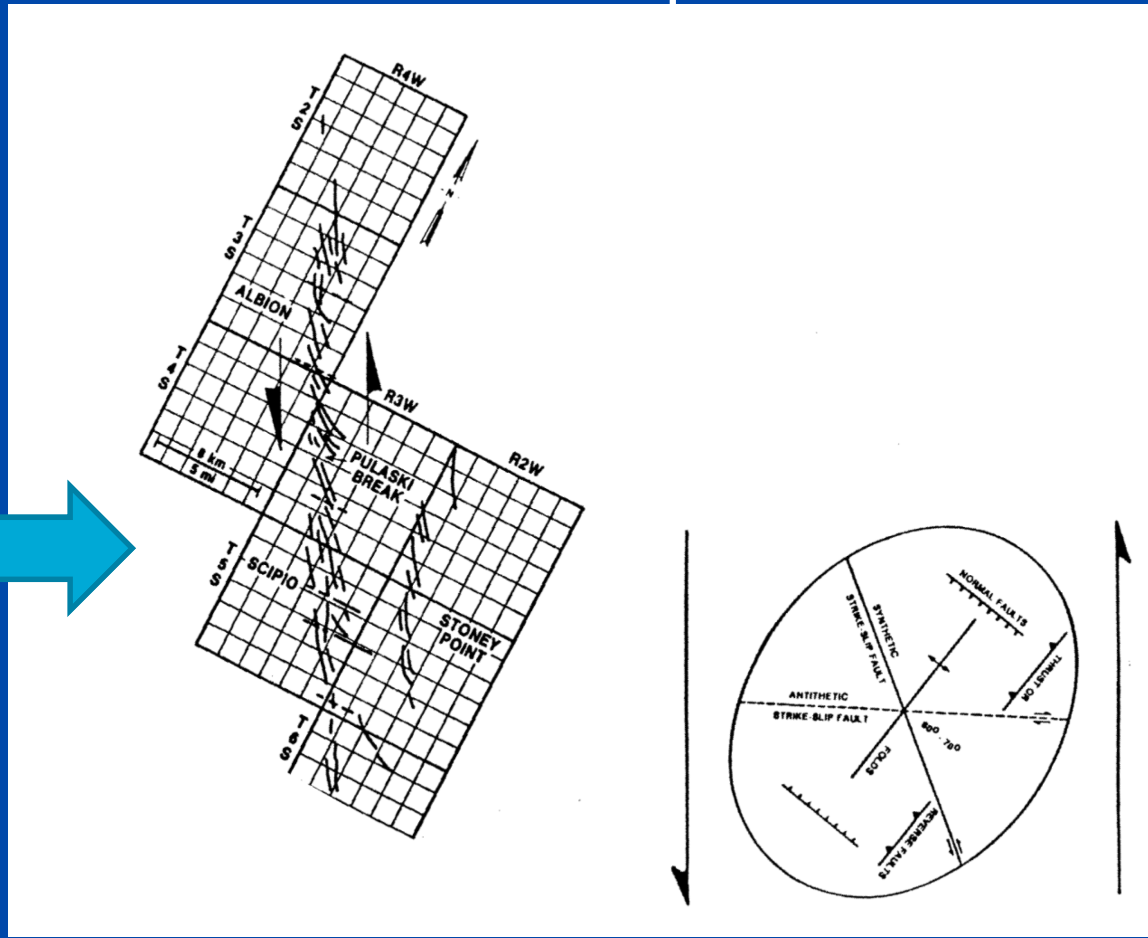
Applied force is 1.6e13N/m

Fault initiation

Model example



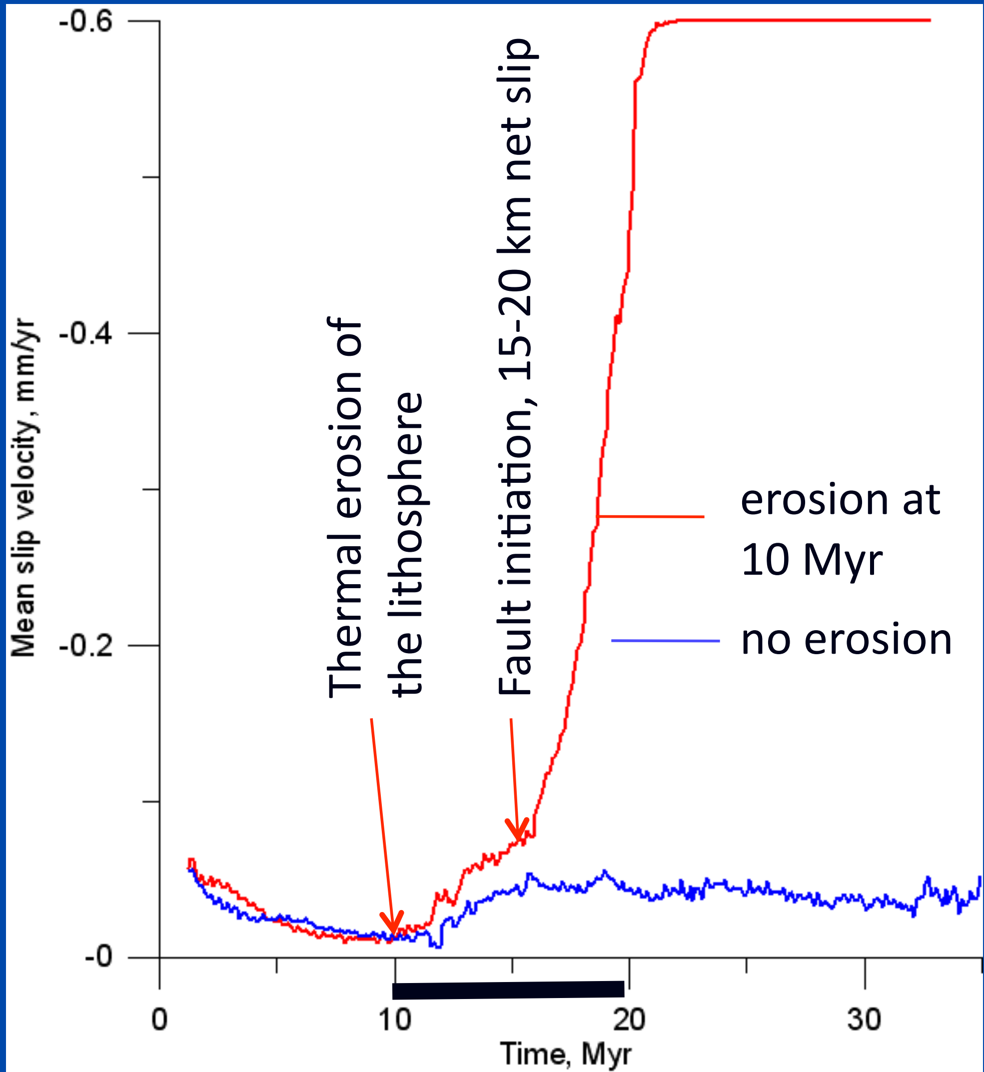
Natural example

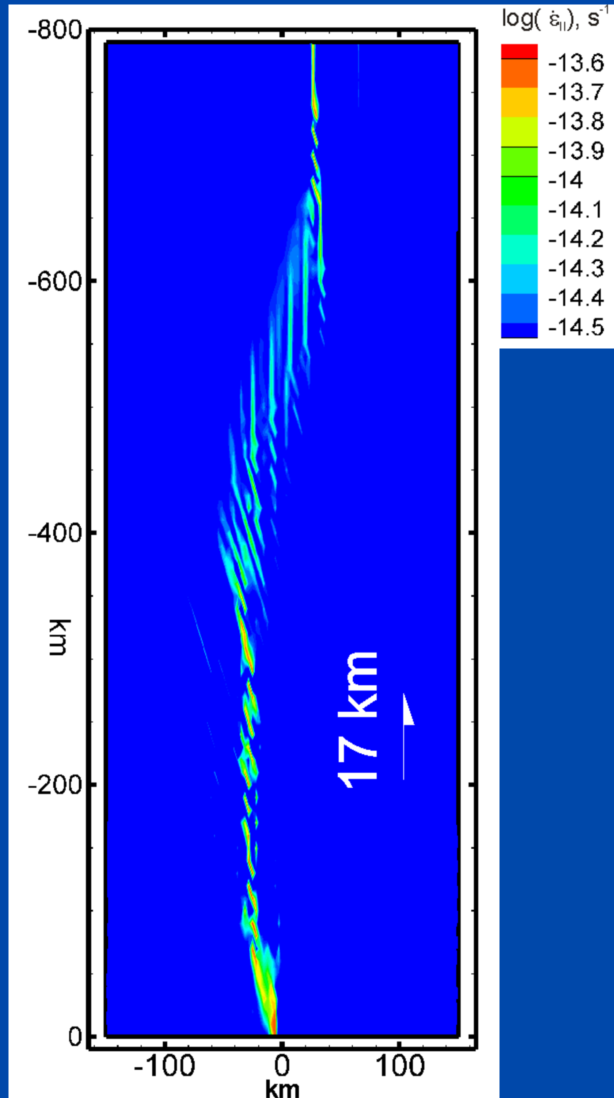


Albion-Scipio and Stoney Point Fields-U.S.A. Michigan Basin,

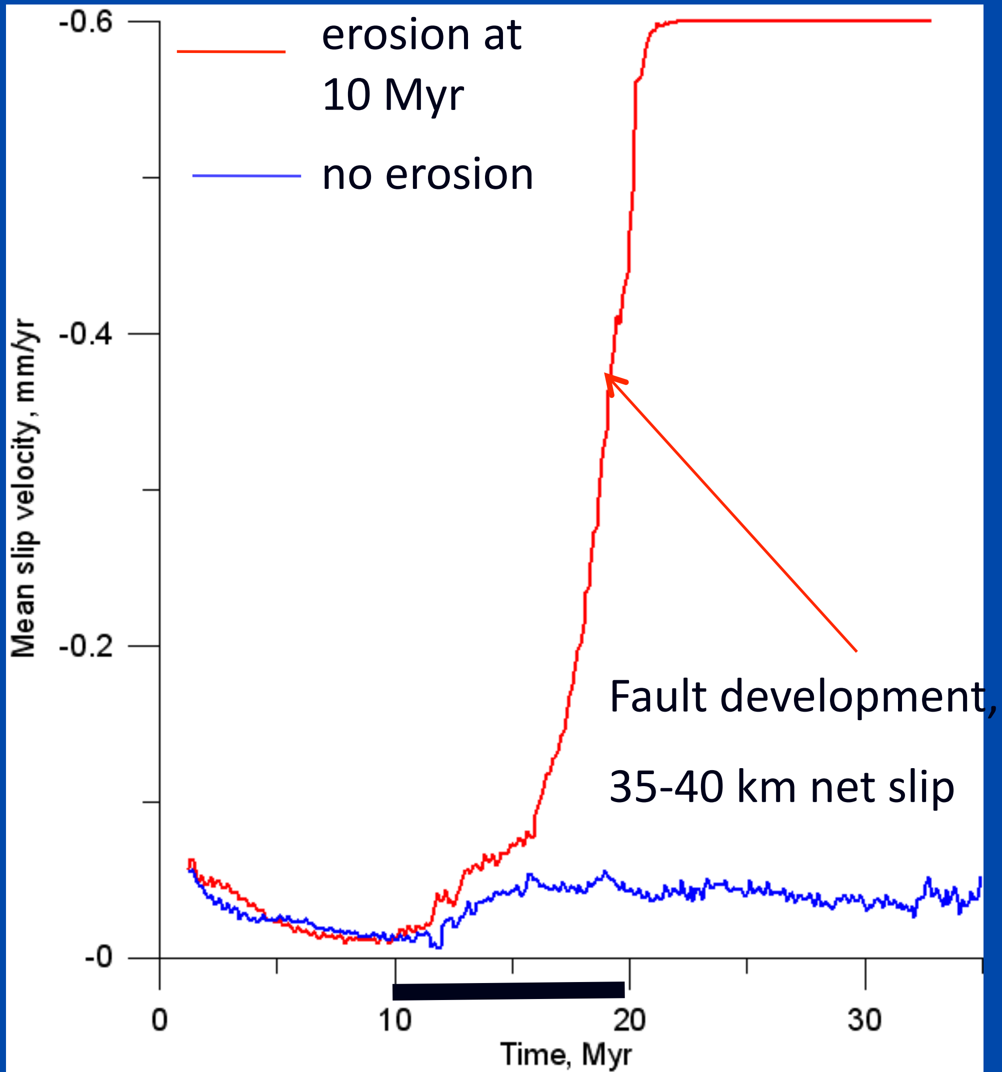
From: Versical, 1991, M.S. Thesis, W.M.U

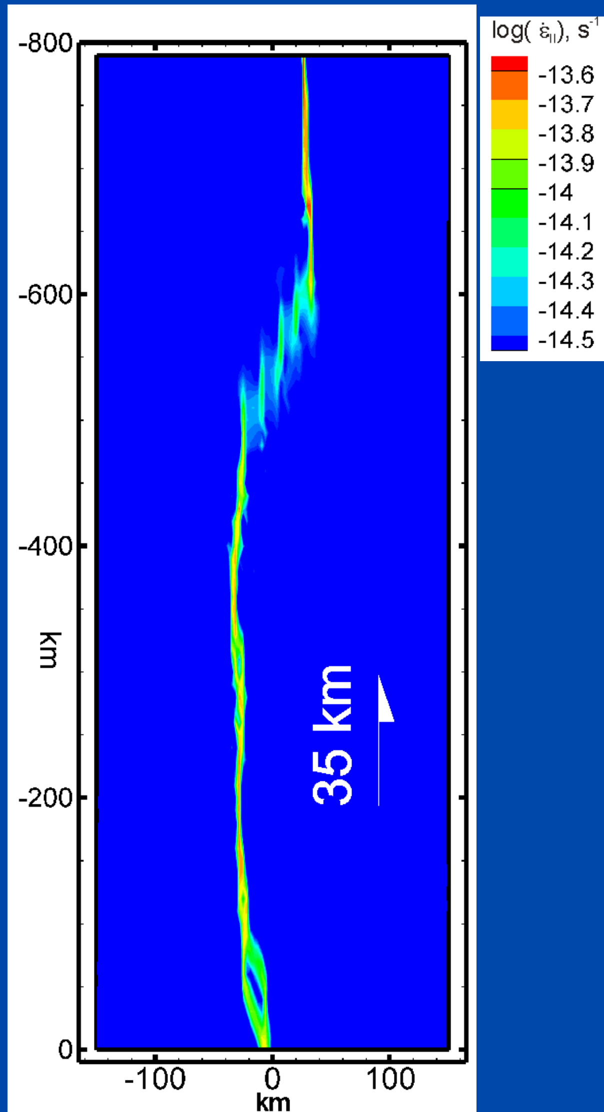
20-10 Ma thinning of the lithosphere around DST and localization of the DST



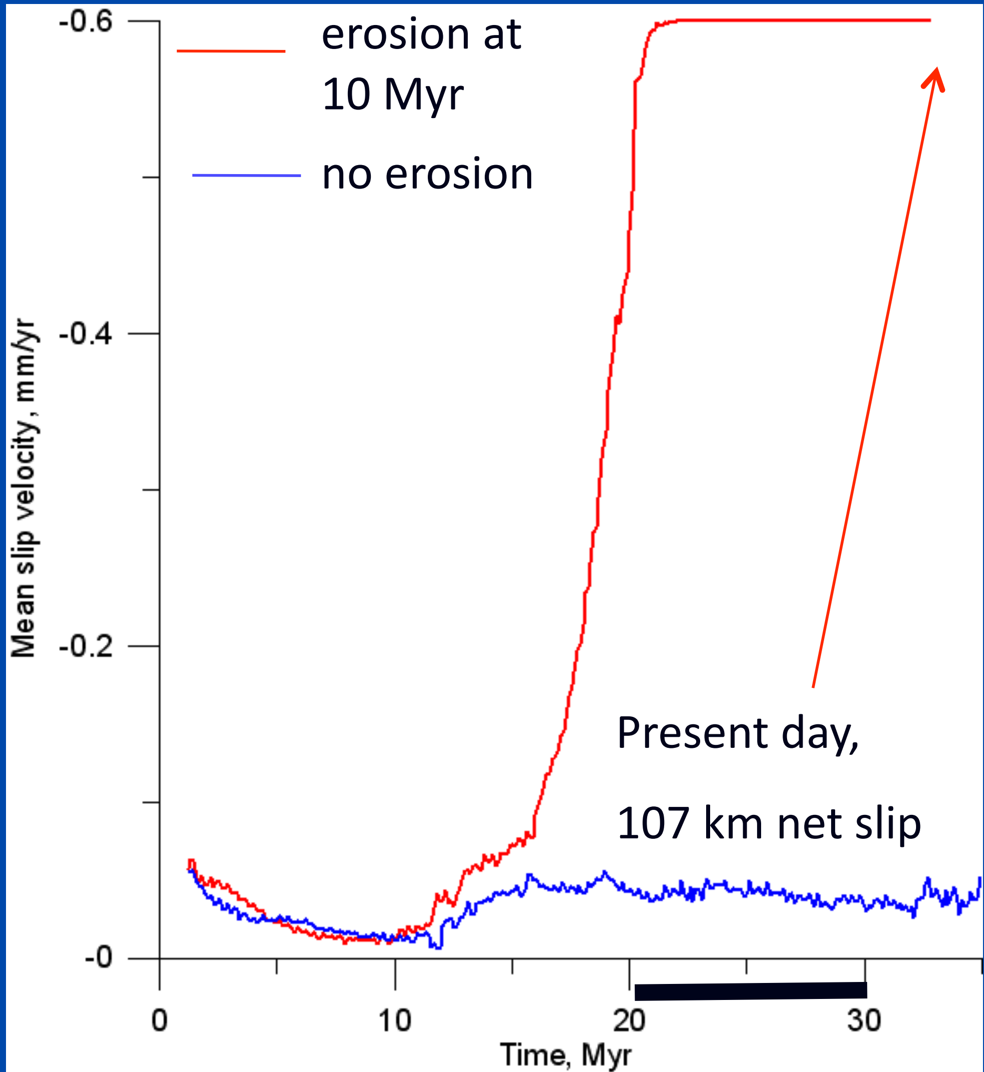


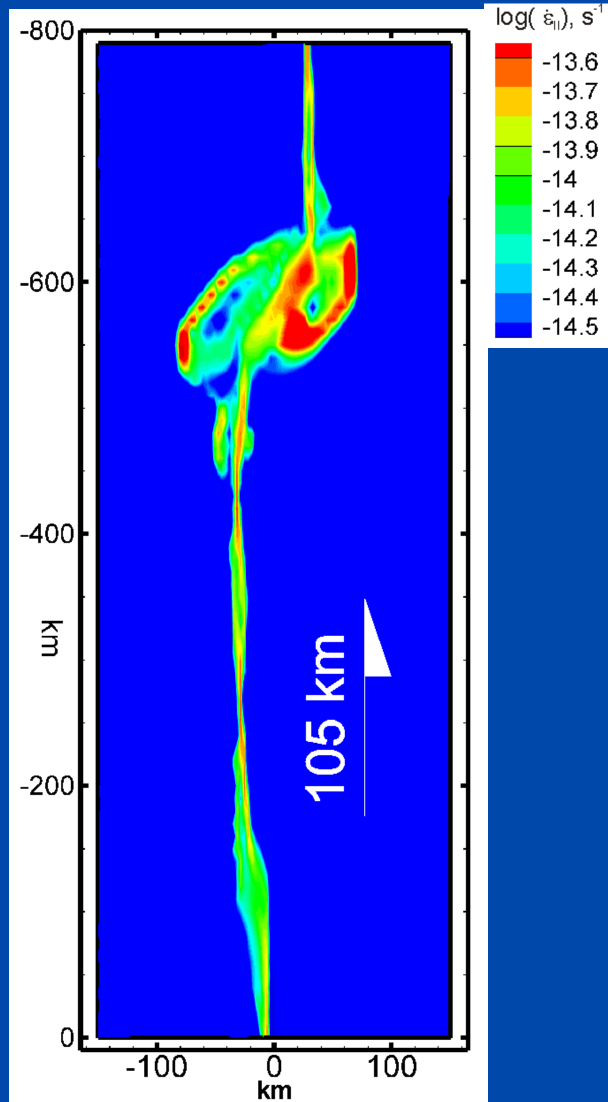
20-10 Ma thinning of the lithosphere around DST and localization of the DST





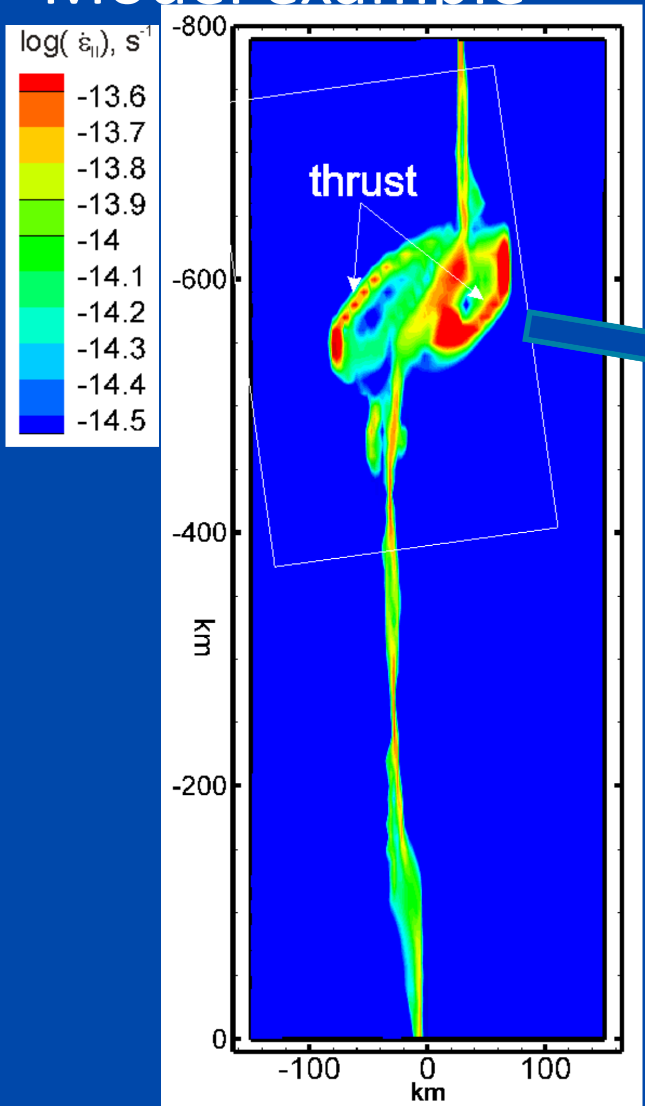
10-0 Ma mature DST, transpression and thrusting in Lebanon



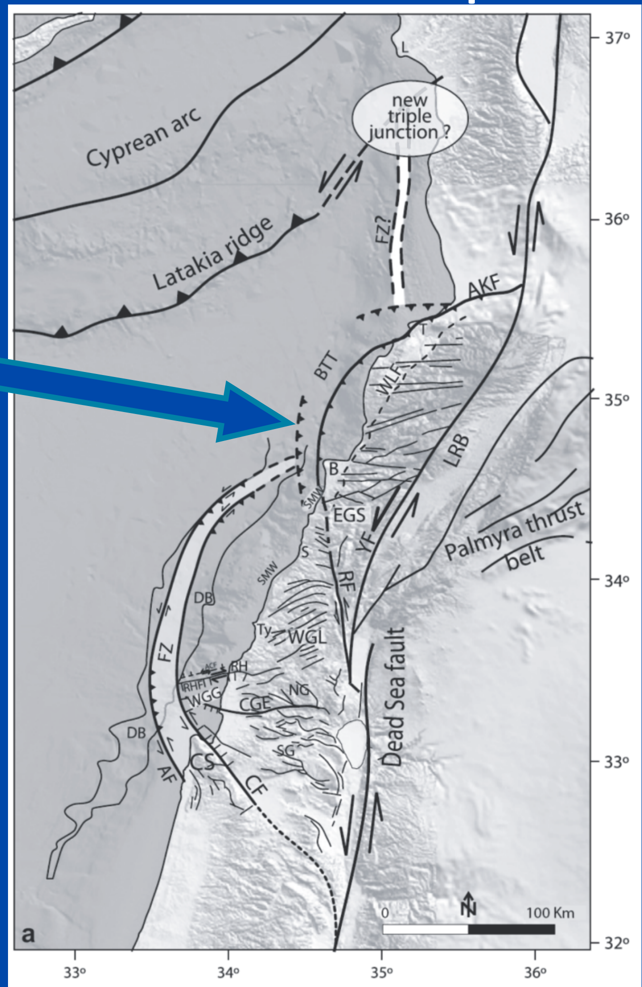


Lebanon Mountains structure

Model example



Natural example



Map summarizing the main tectonic elements

of the Lebanon Mountains (Schattner et al., 2006)

Conclusion

The DST has likely originated through “cooperation” of the plate-tectonic scale forces and Afar plume, which has thinned lithosphere at and around the Red Sea and triggered strain localization at the DST

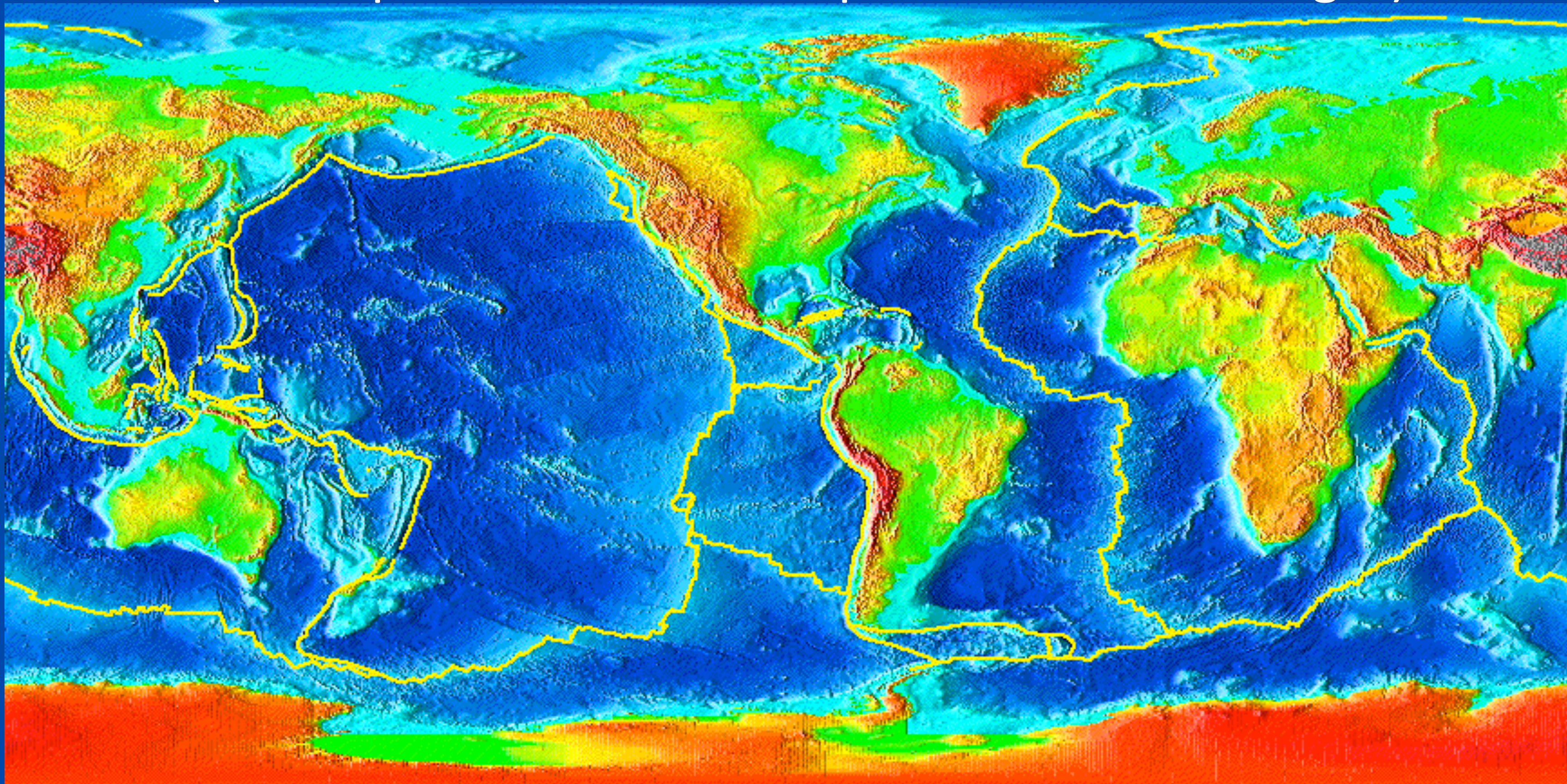
More on modeling of the **Dead Sea Transform**

see posters by **Petrunin et al.** and by **Meneses-Rioseco and Sobolev**

For modeling of the **San Andreas Fault System** see poster by **Popov and Sobolev**

Modeling Plate Velocities

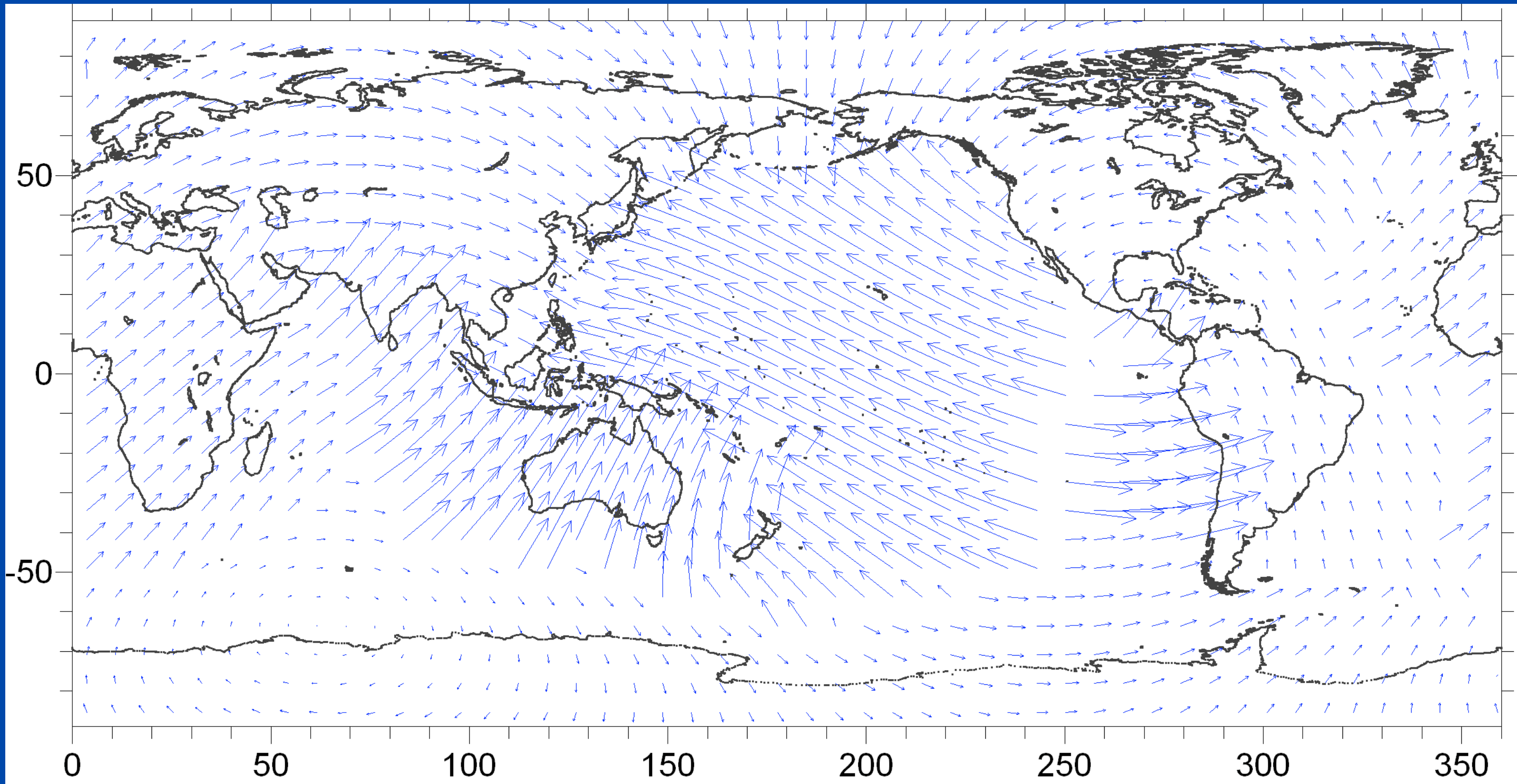
(In cooperation with A. Popov and B. Steinberger)



Crustal Plate Boundaries

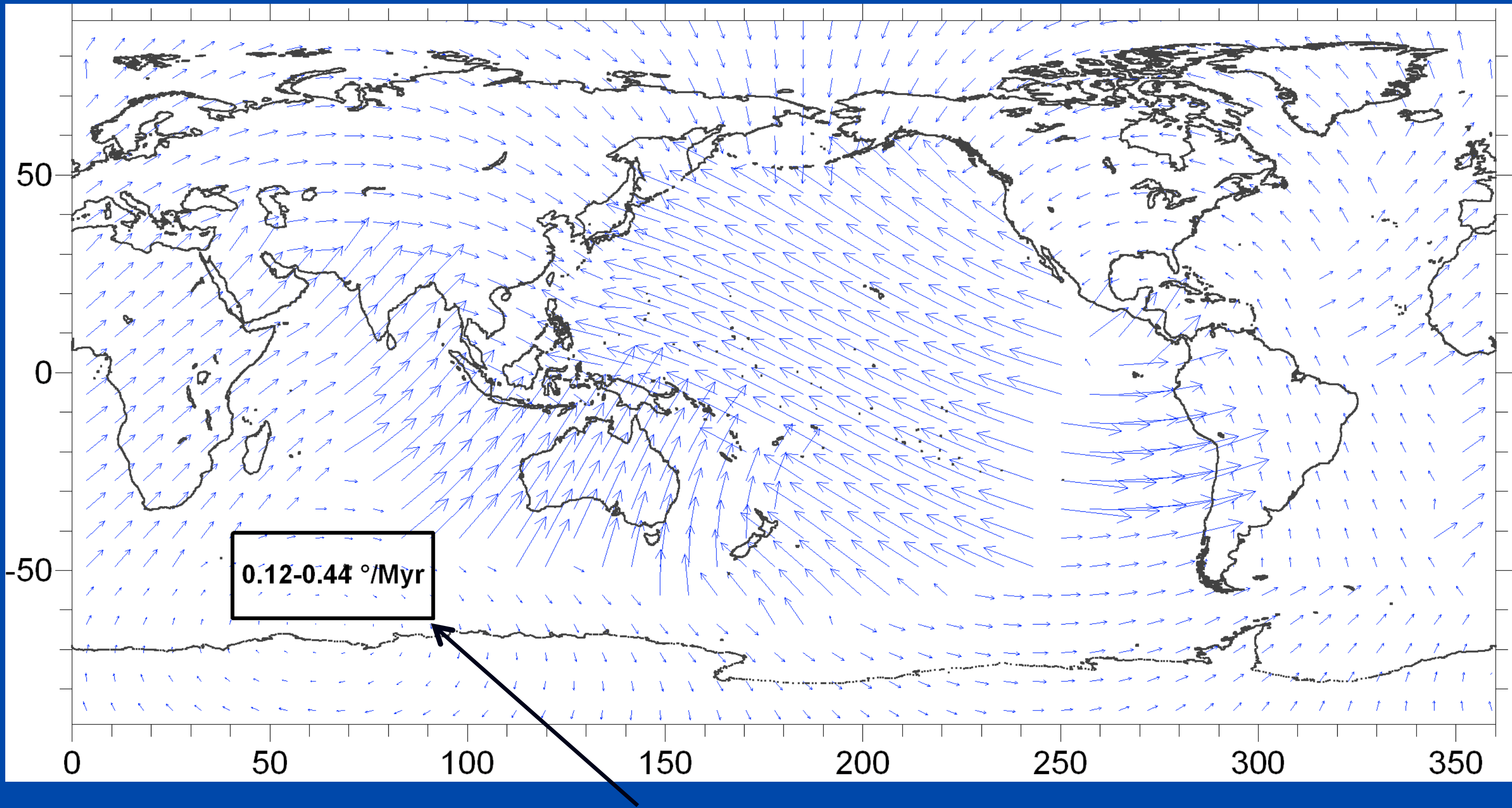
How weak are plate boundaries and how wet is the asthenosphere?

Plate velocities



Observed plate velocities in no-net-rotation (NNR) reference frame

Net rotation

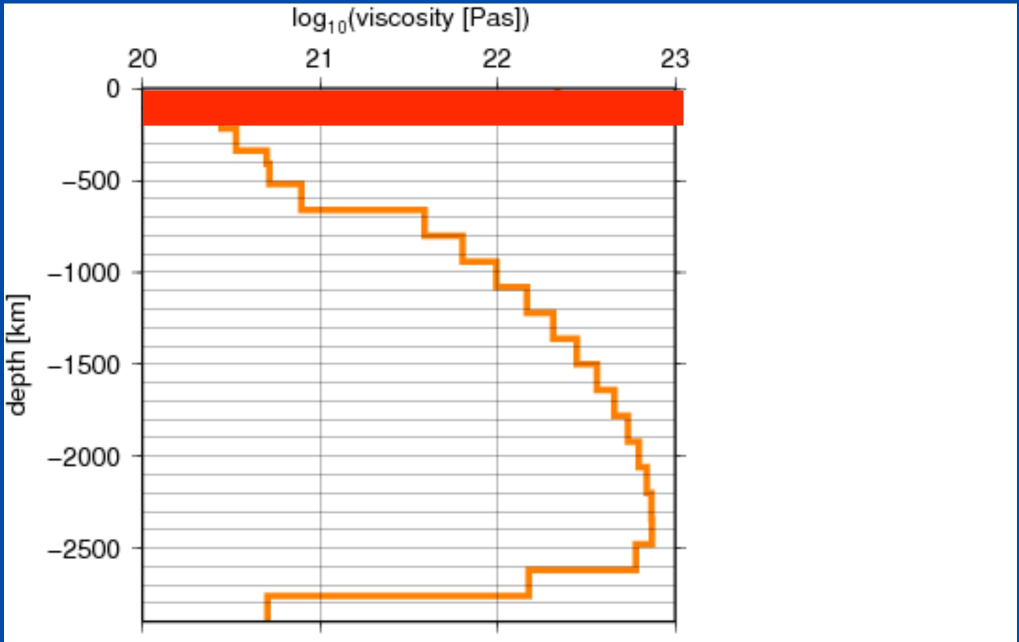


… and observed net-rotation (NR) of the lithosphere

Based on analyses of seismic anisotropy Becker (2008) narrowed possible range of angular NR velocities down to 0.12-0.22 °/Myr

Above 300 km depth

3D temperature and crust, numerical FEM technique (Popov and Sobolev, 2008) with 3D temperature- and stress-dependant visco-elasto-plastic rheology



Below 300 km depth

Spectral method (Hager and O'Connell,1981) with radial viscosity distribution from Steinberger and Calderwood (2006)

and 3D density distributions based on subduction history (Steinberger, 2000)

Mantle rheology

Mantle lithosphere: dry olivine rheology combining diffusion and dislocation creep

$$\dot{\varepsilon}_{II} = A d^{-m} \sigma_{II}^{n} \exp(-(E_a + PV_a)/RT)$$

Asthenosphere: wet olivine rheology combining diffusion and dislocation creep with water content as model parameter

$$\dot{\varepsilon}_{II} = A d^{-m} C_{H2O}^{p} \sigma_{II}^{n} \exp(-(E_a + PV_a)/RT)$$

Parameters in reference model by Hirth and Kohlstedt (2003) with **n=3.5 +-0.3** and activation volume from Kawazoe et al. (2009).

Modifications according to

$$\dot{\varepsilon}_{II}(n) = \dot{\varepsilon}_{II}(n_{ref})(\sigma_{II}/100MPa)^{n-n_{ref}}$$

Plate boundaries

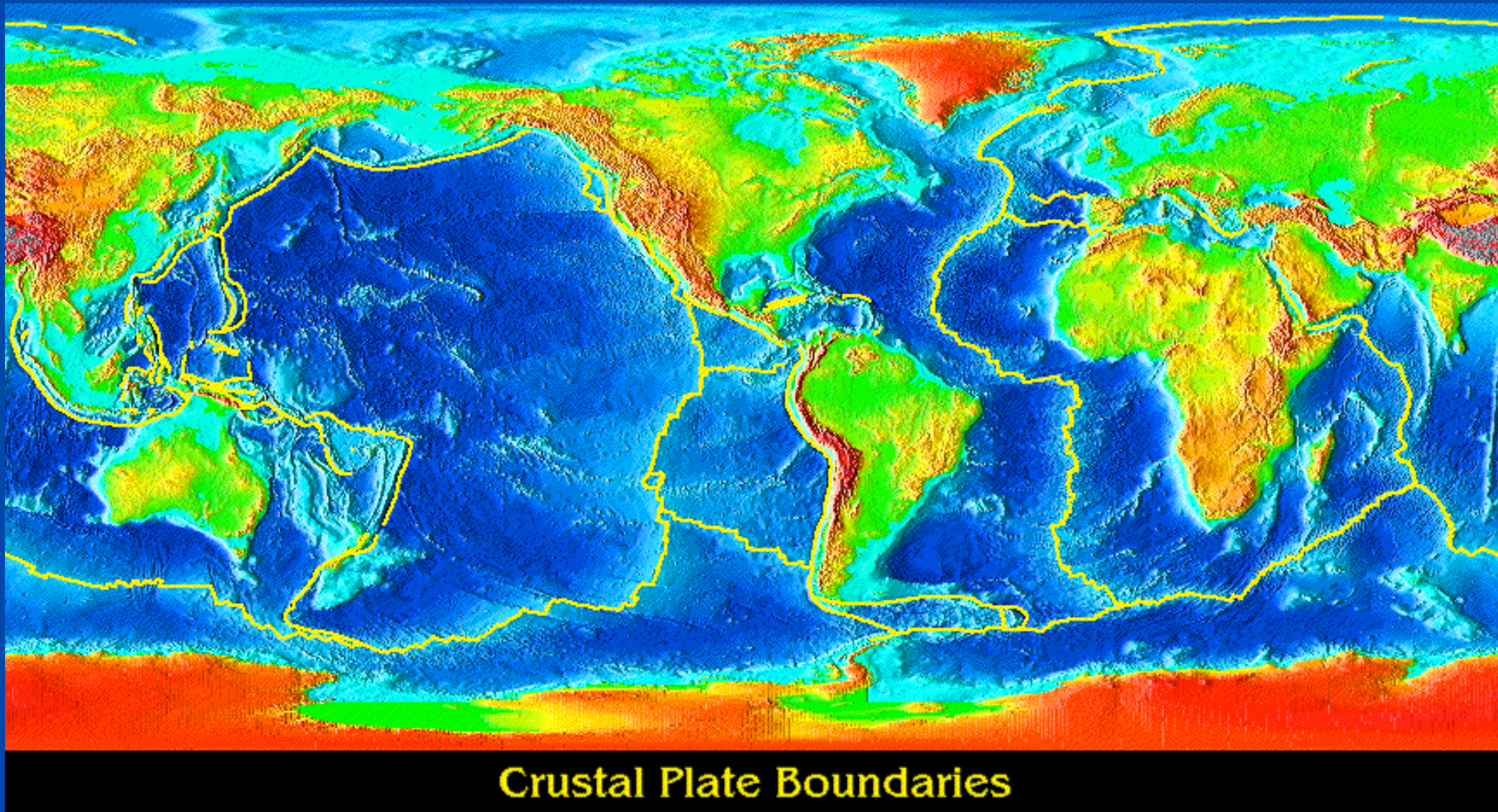
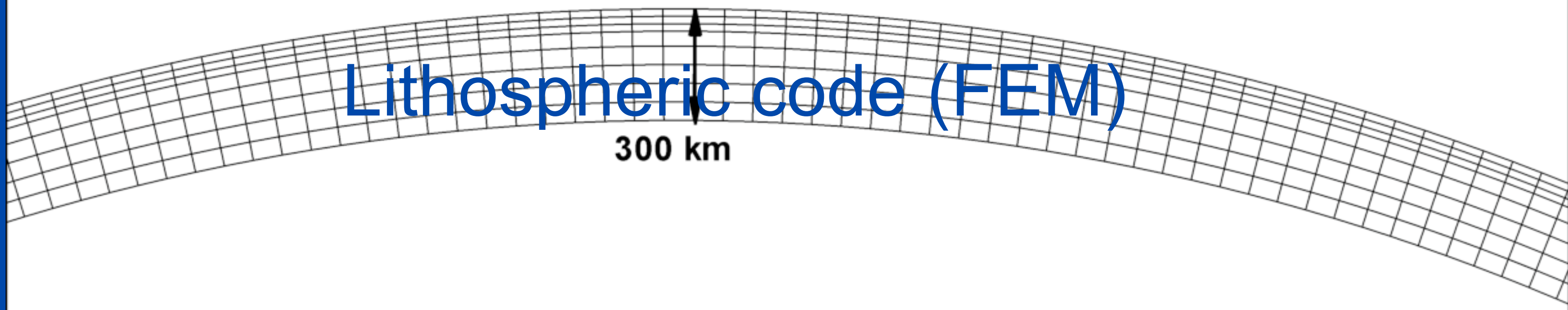
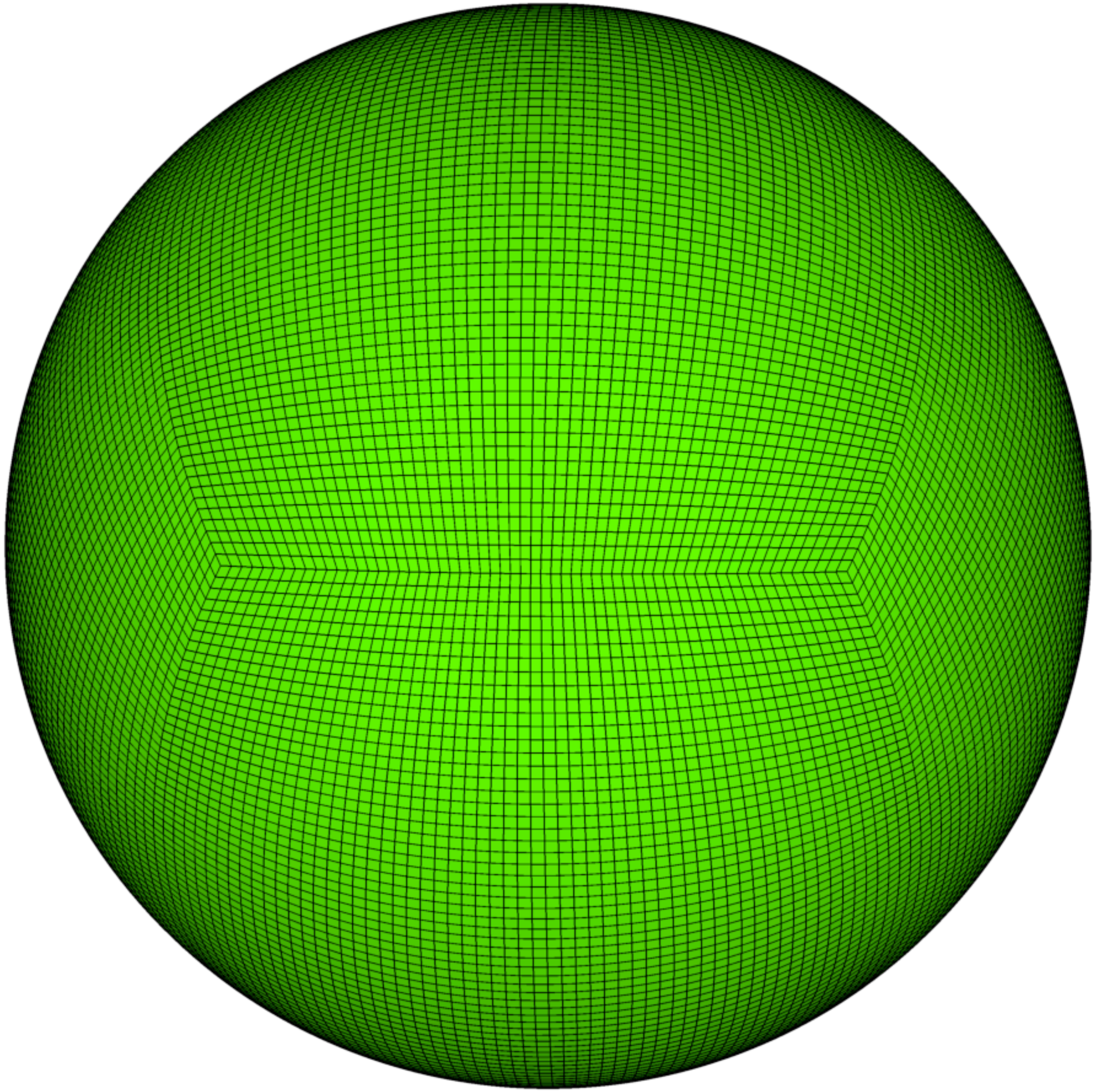


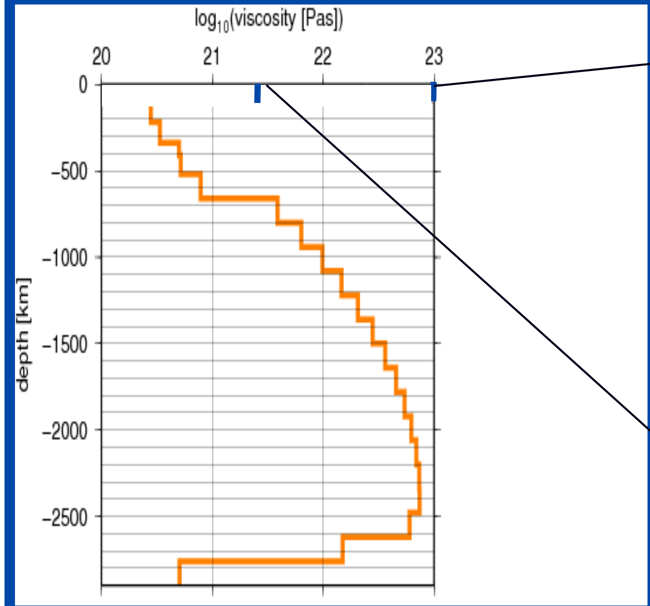
Plate boundaries are defined as narrow zones with visco-plastic rheology where friction coefficient is model parameter

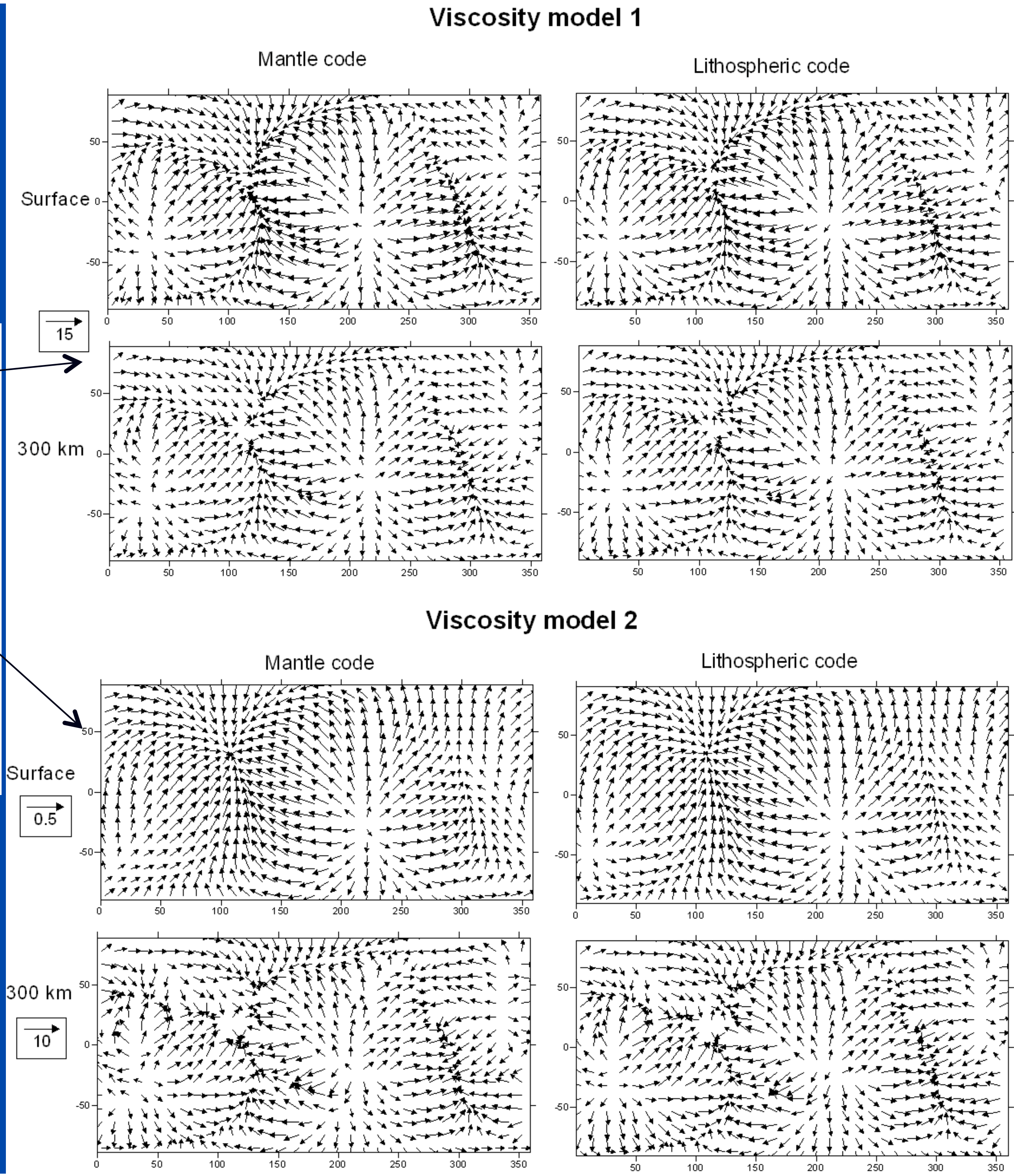


Mantle and lithospheric codes are coupled through continuity of velocities and tractions at 300 km.

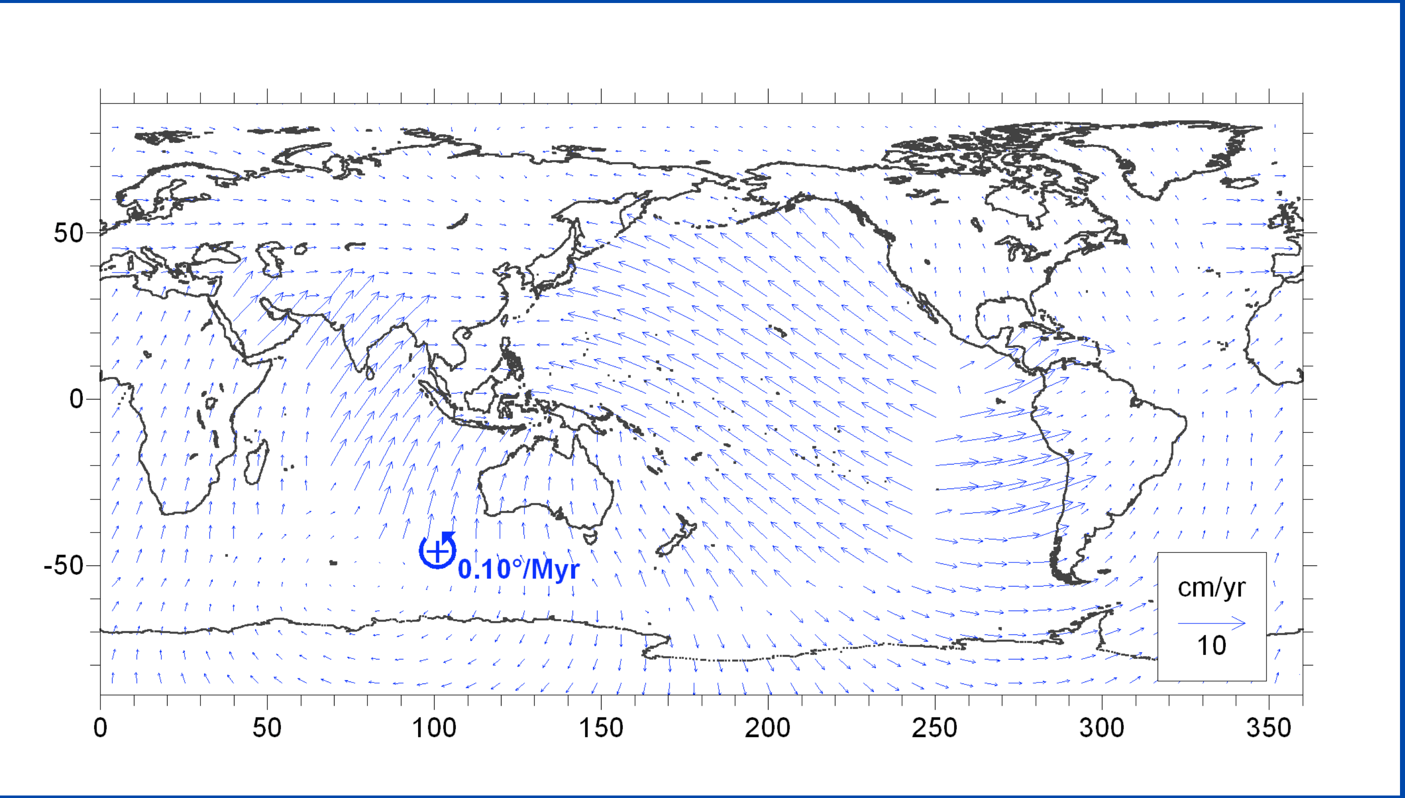


Benchmark test



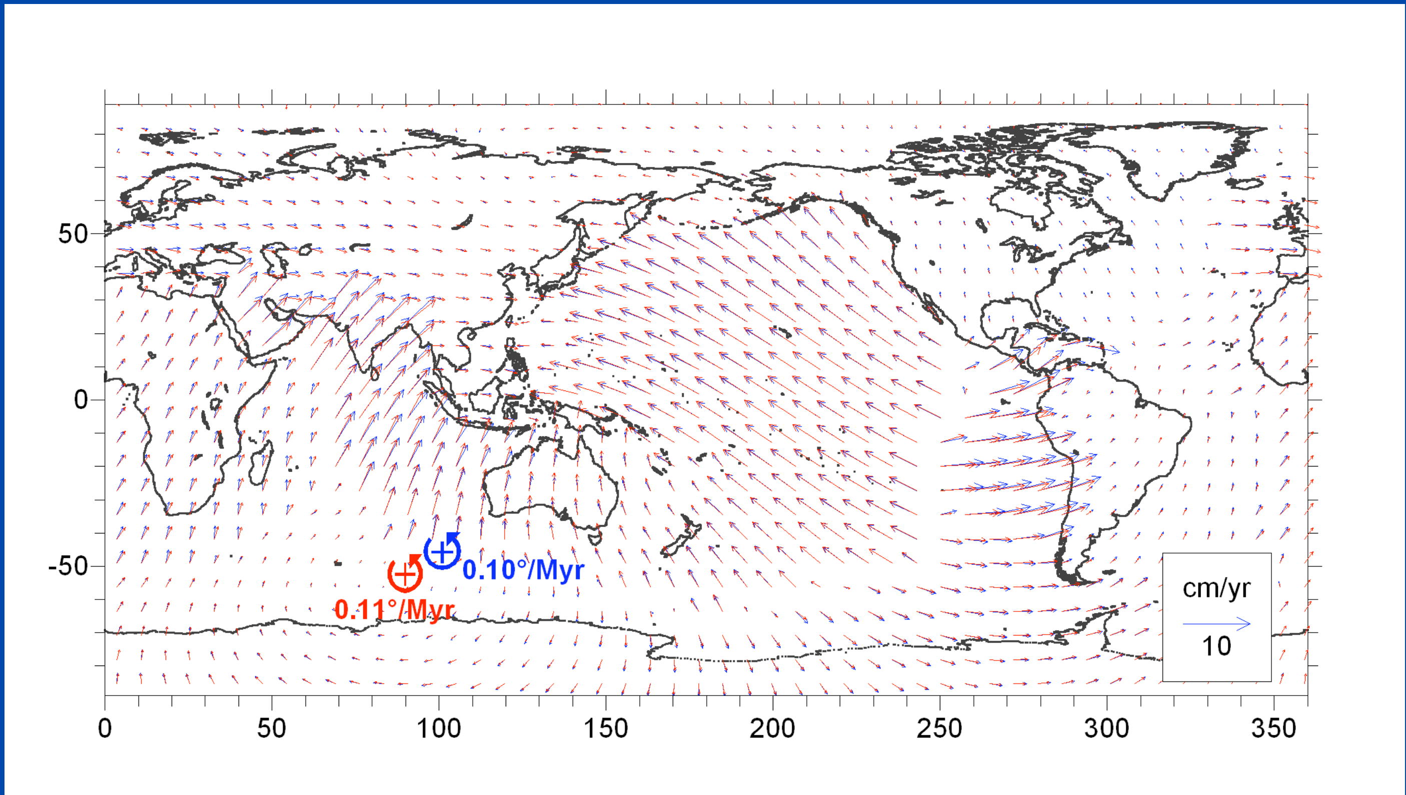


Model by Becker (2006)



CitcomS, 3-D temperature-dependant dislocation+diffusen rheology, **lateral viscosty variations** in the entire mantle, low-viscosty plate boundaries

Our model vrs. model by Becker (2006)



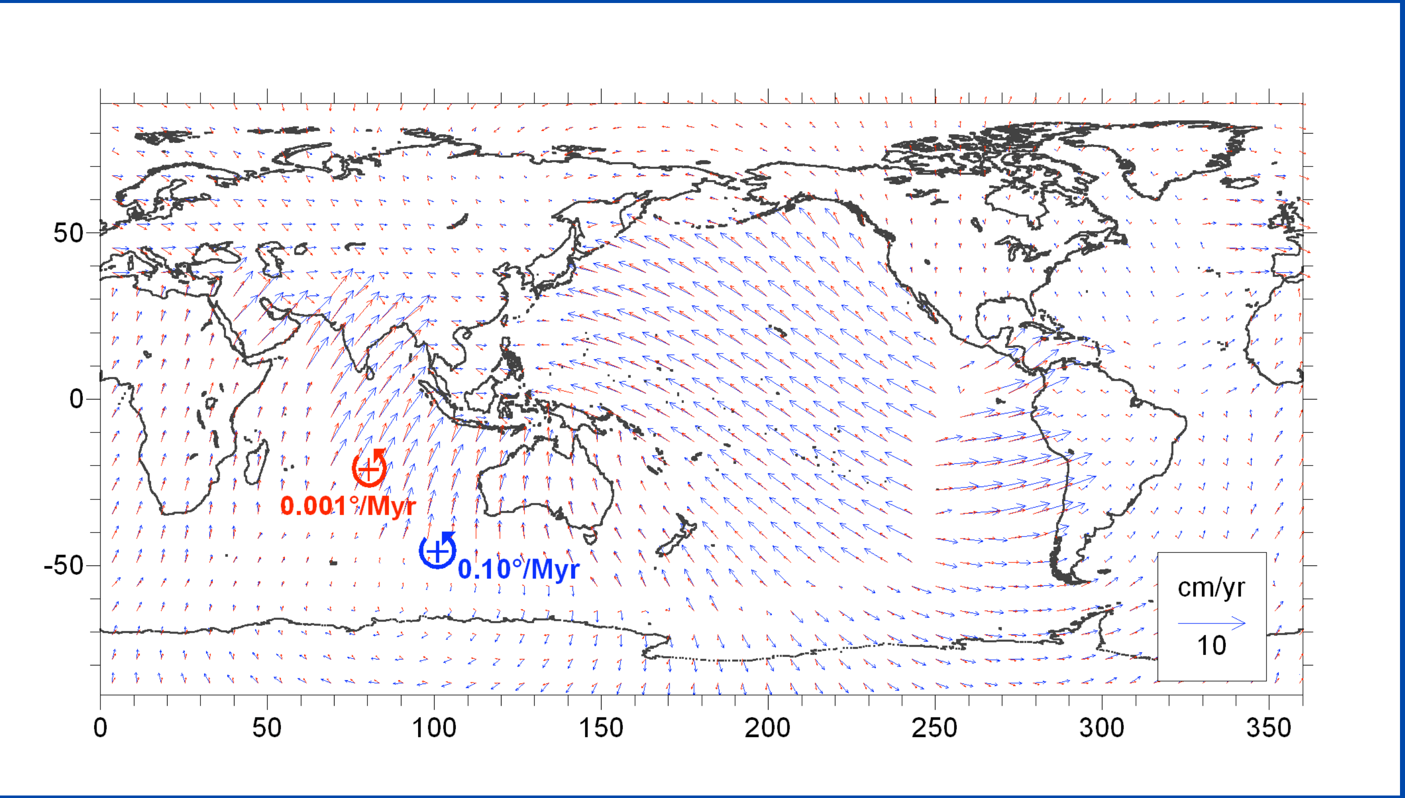
$$\text{Misfit}=\int \left\|\vec{v}_2-\vec{v}_1\right\| / \left\|\vec{v}_1\right\| dS = 0.19$$

Conclusion

Benchmark tests justify our hybrid-codes modeling approach and suggest that lateral viscosity variations **deeper than 300 km** may be ignored in modeling plate velocities

But what about lateral viscosity variations **shallower than 300 km?**

Radial UM viscosity vrs. 3D UM viscosity



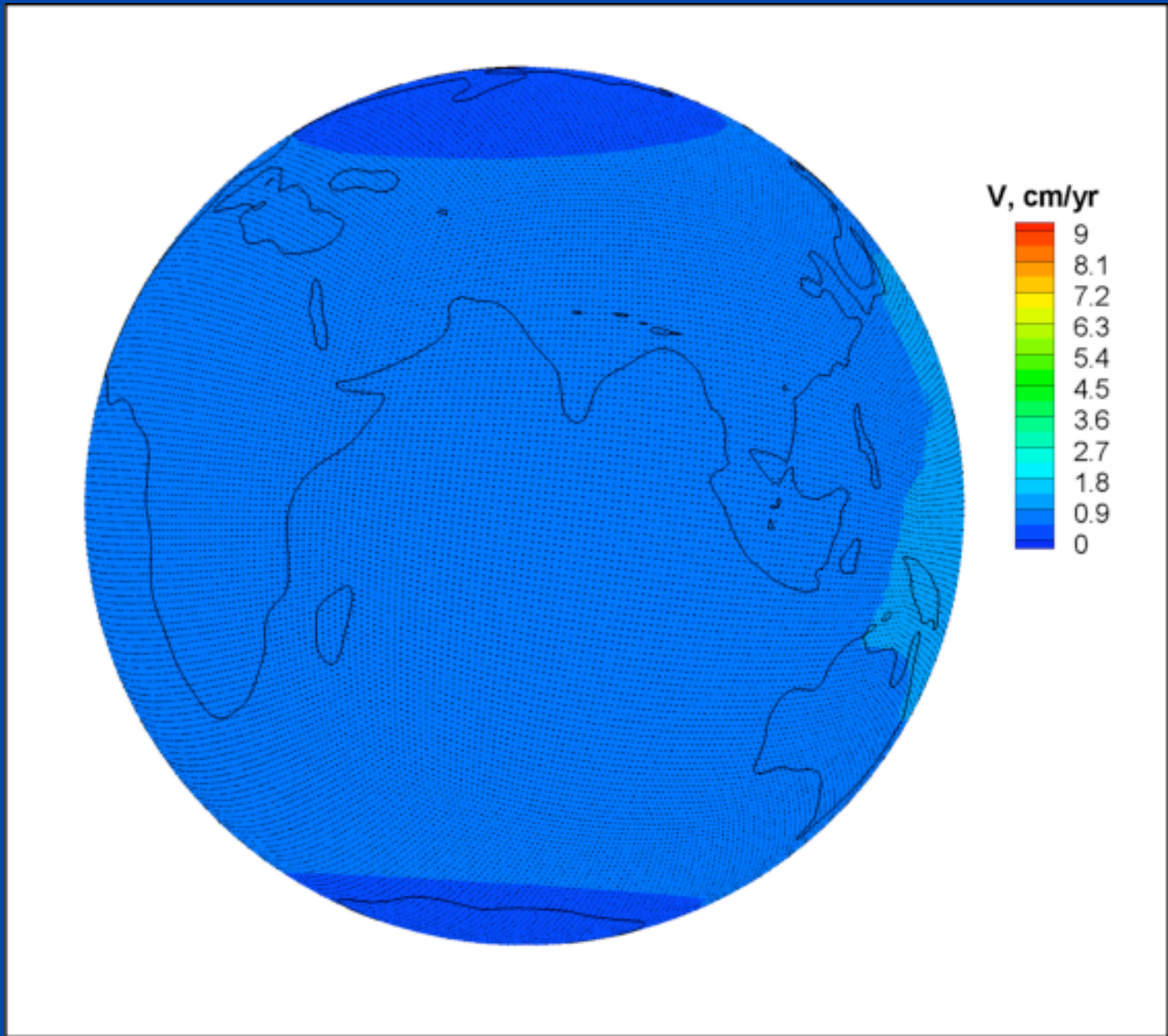
$$\text{Misfit}=\int \left\| \vec{v}_2 - \vec{v}_1 \right\| / \left\| \vec{v}_1 \right\| dS = 0.51$$

Conclusion

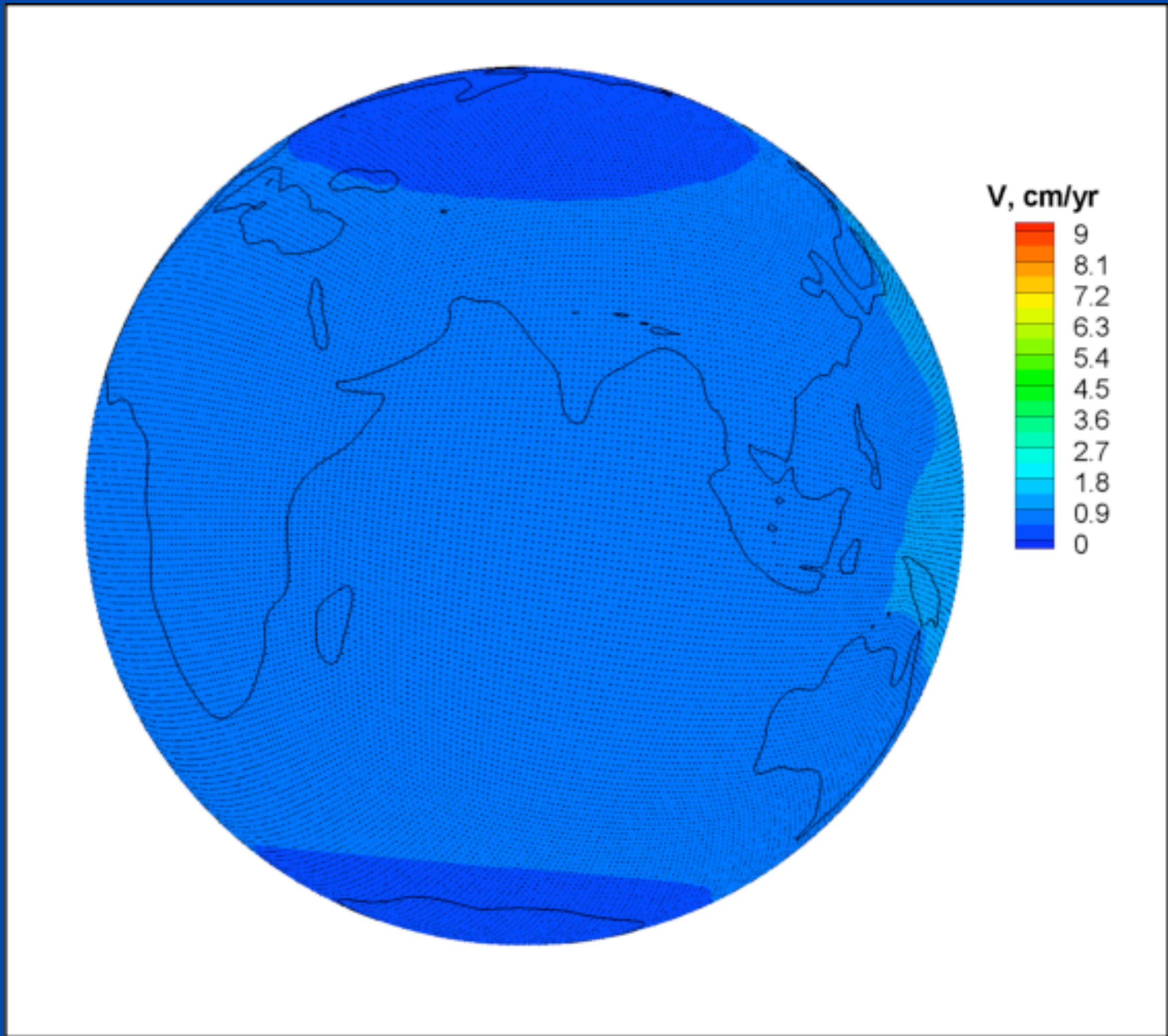
Lateral viscosity variations shallower than 300 km strongly affect magnitudes, but less directions of plate velocities

Effect of strength at plate boundaries

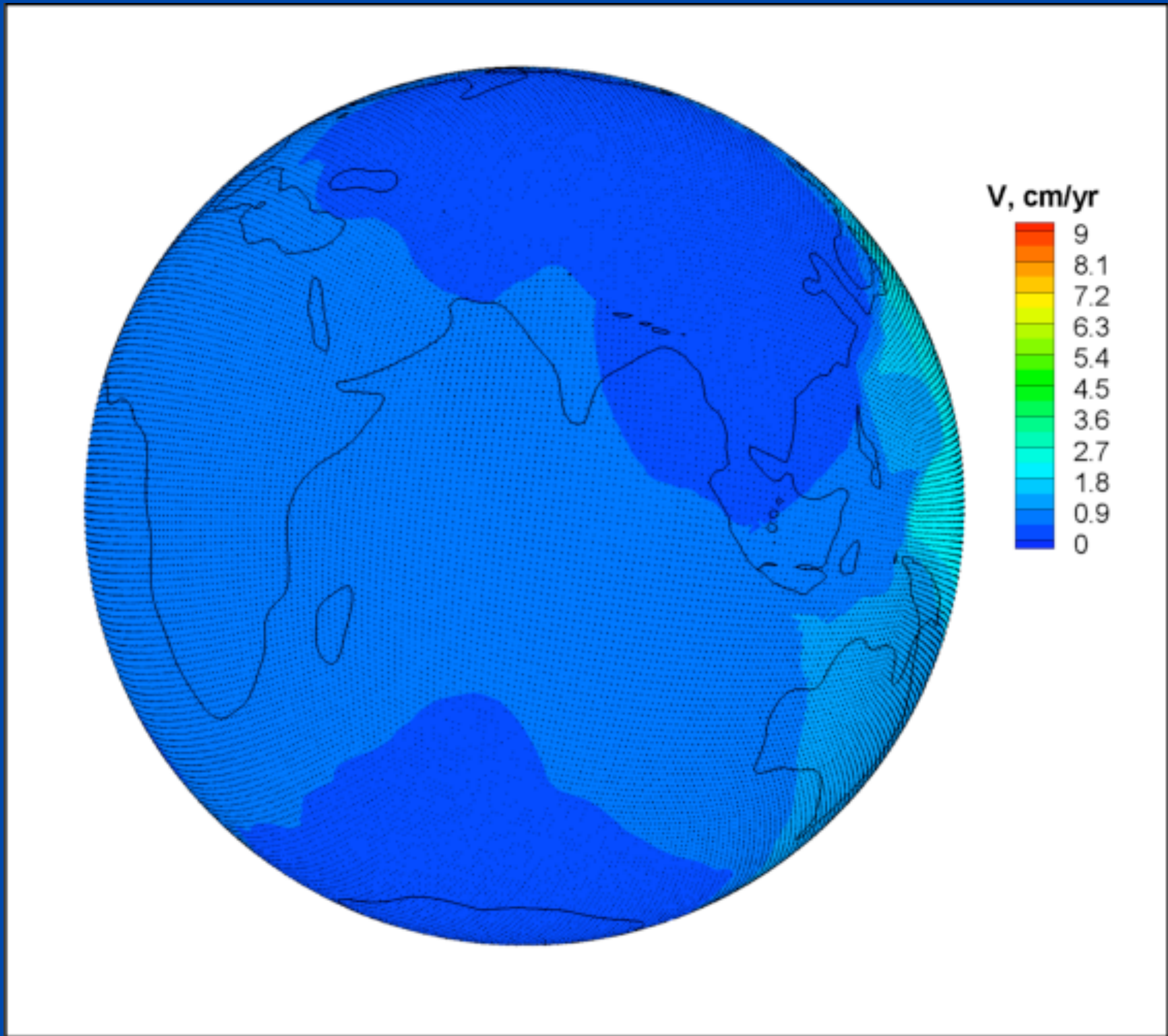
Friction at boundaries 0.4



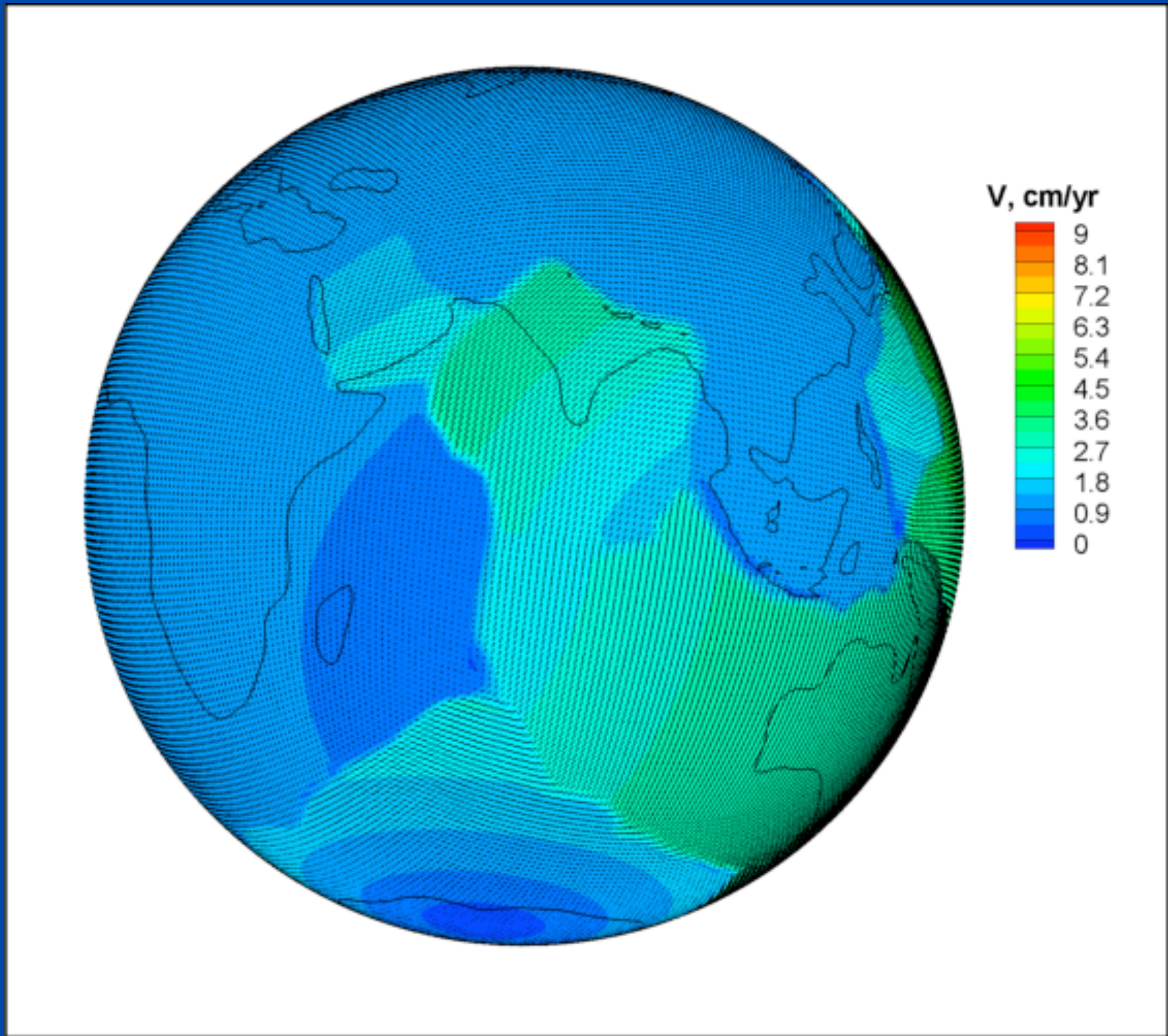
Friction at boundaries 0.2



Friction at boundaries 0.1

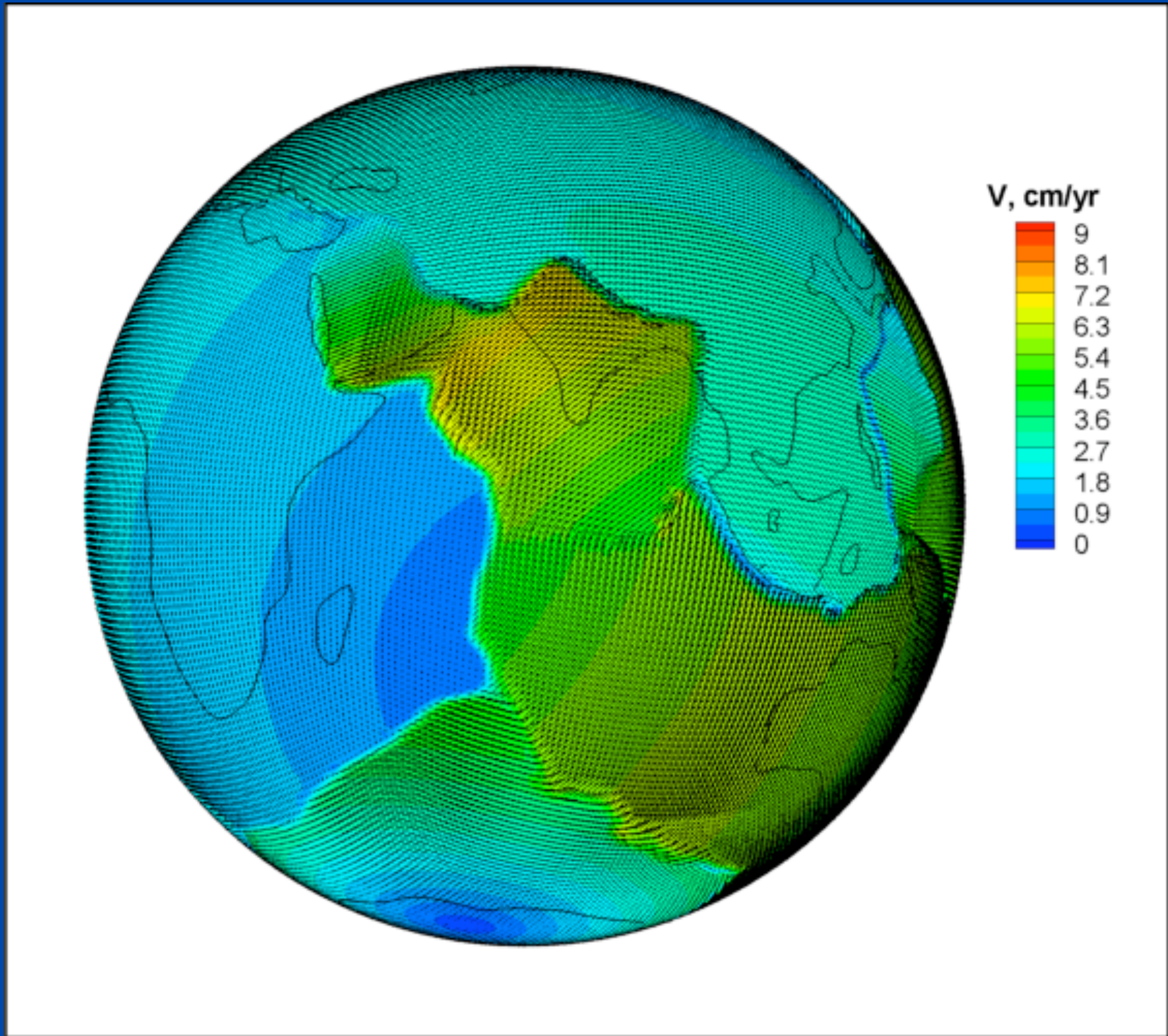


Friction at boundaries 0.05



too low velocities

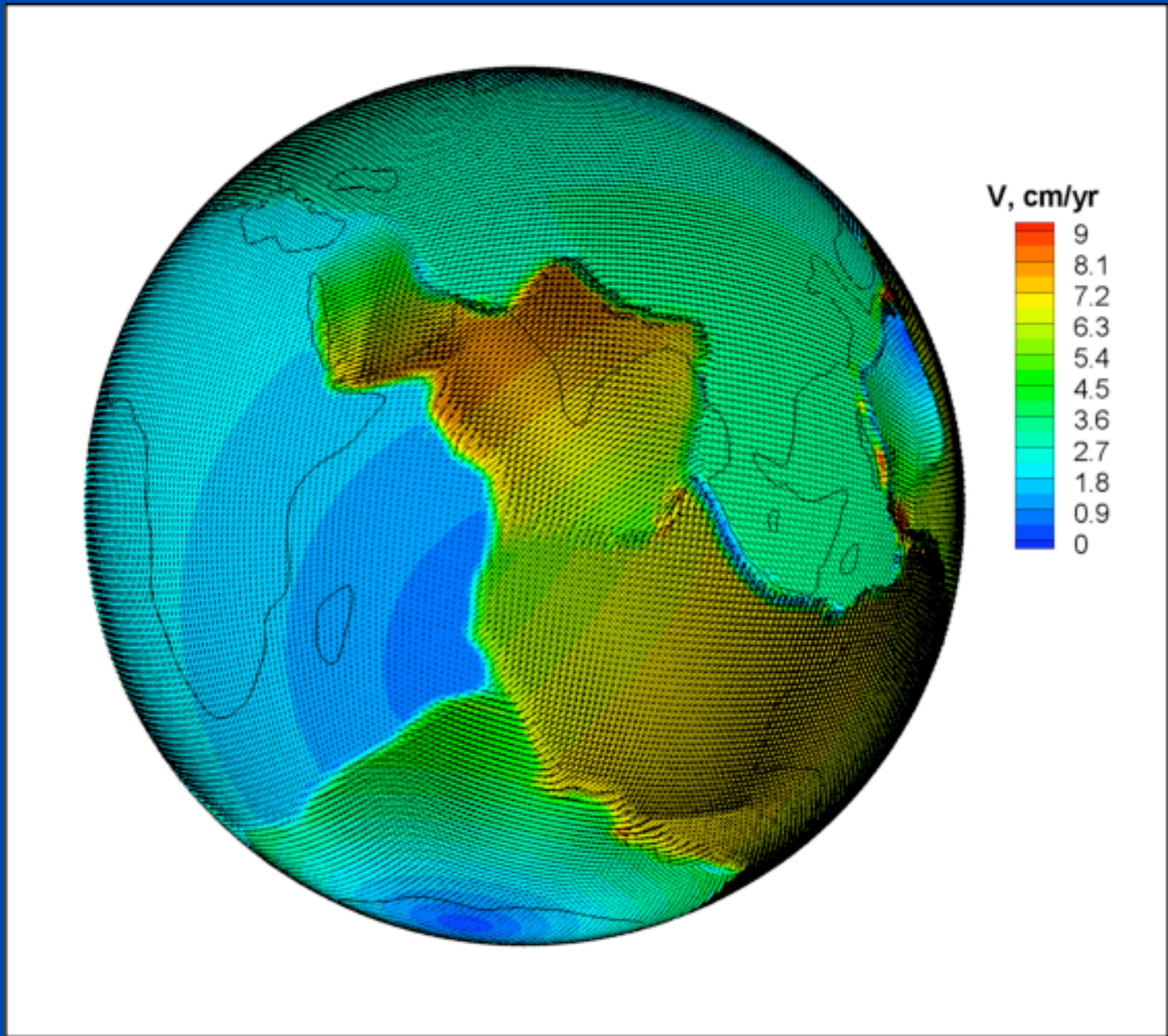
Friction at boundaries 0.02



about right magnitudes of velocities

Plates

Friction at boundaries 0.01



too high velocities

Conclusion

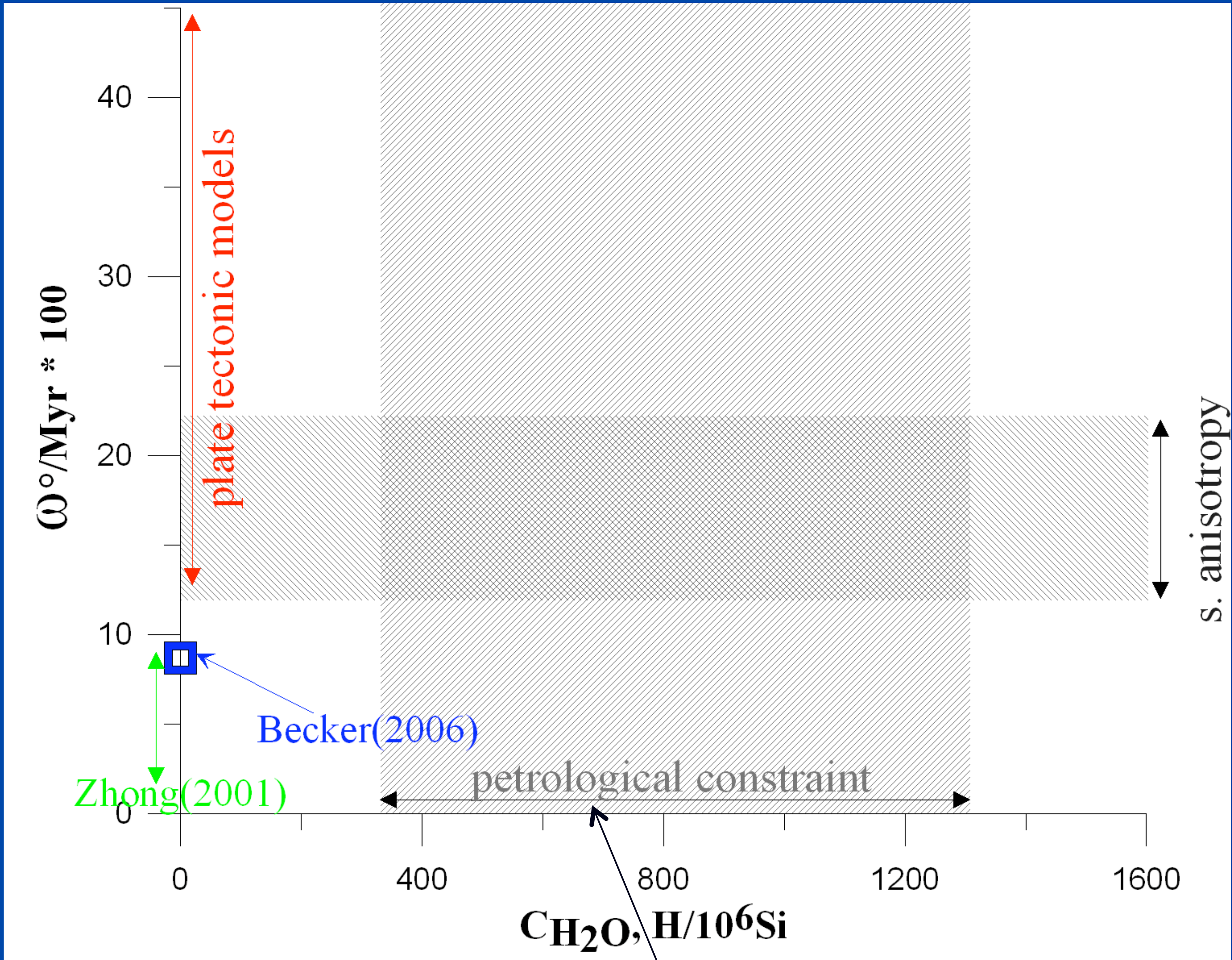
Strength (friction) at plate boundaries stronrly affect plate velocities and must be very low.

Modeling scheme

For every trial rheology (water content in asthenosphere) we calculate plate velocities varying strength (friction) at plate boundaries until we get best fit of observed plate velocities in the NNR reference frame

Next, we look how well those optimized models actually fit observations

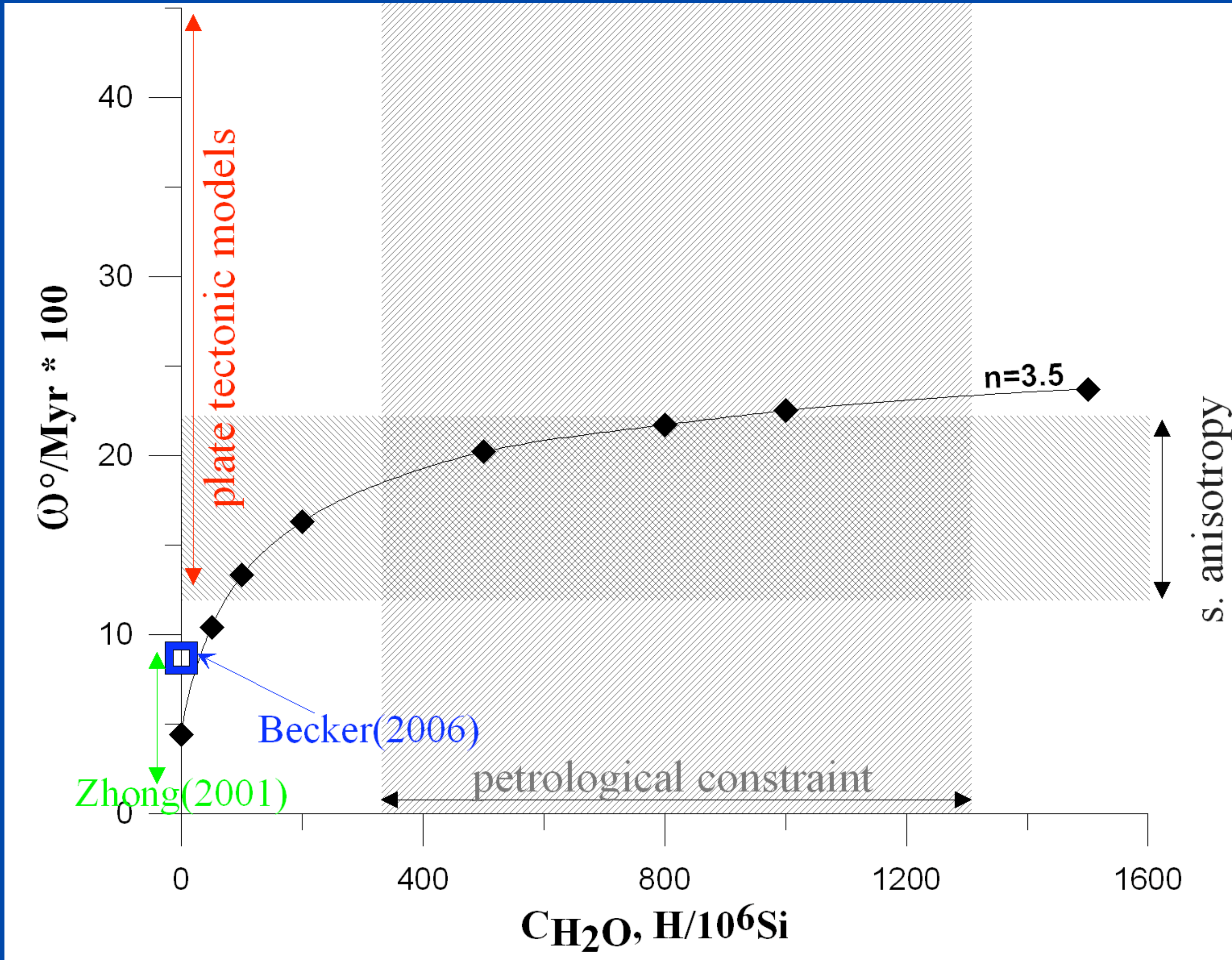
Lithospheric net rotation



Becker (2008)

Hirth and Kohlstedt (1996)

Lithospheric net rotation



Lithospheric net rotation

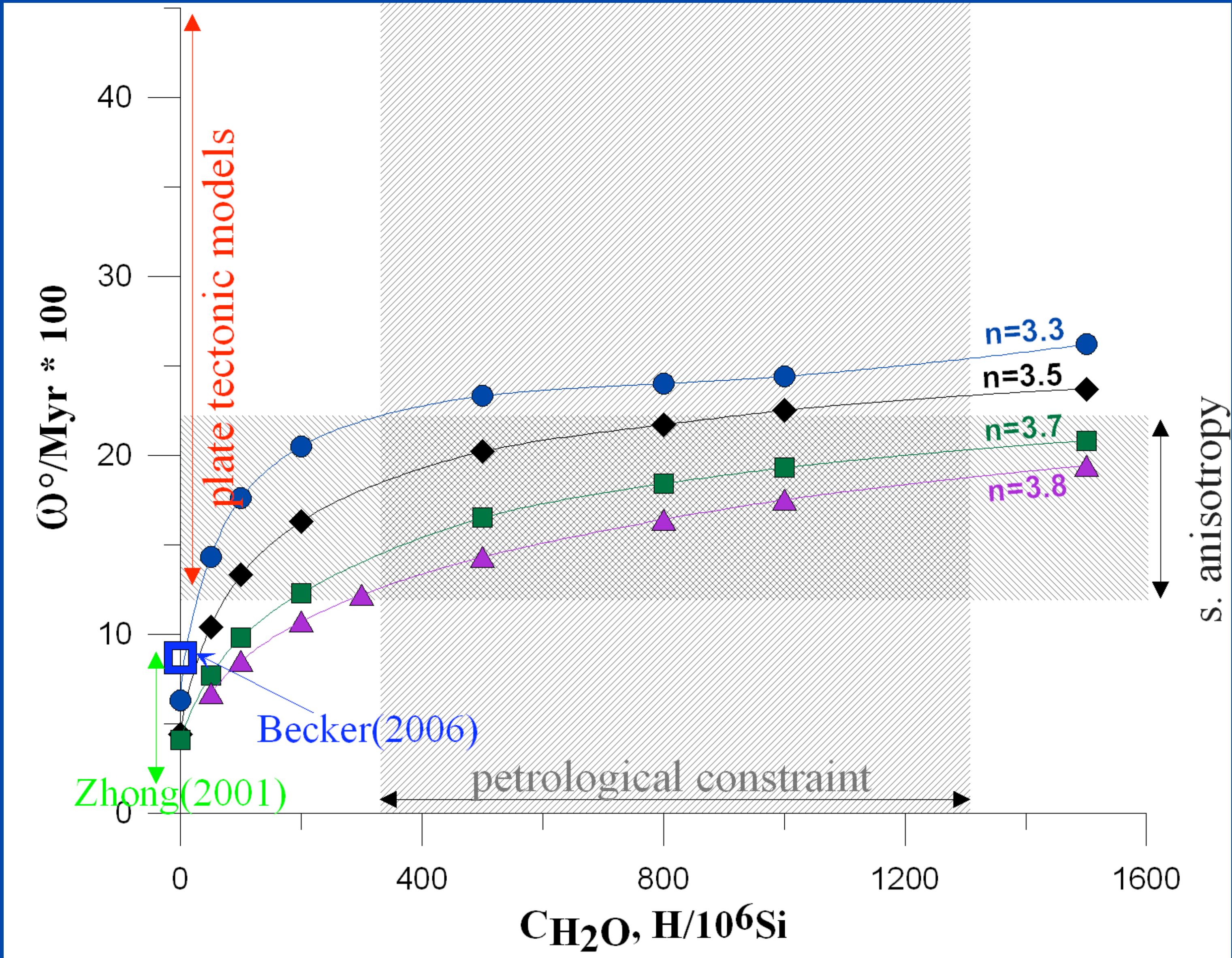
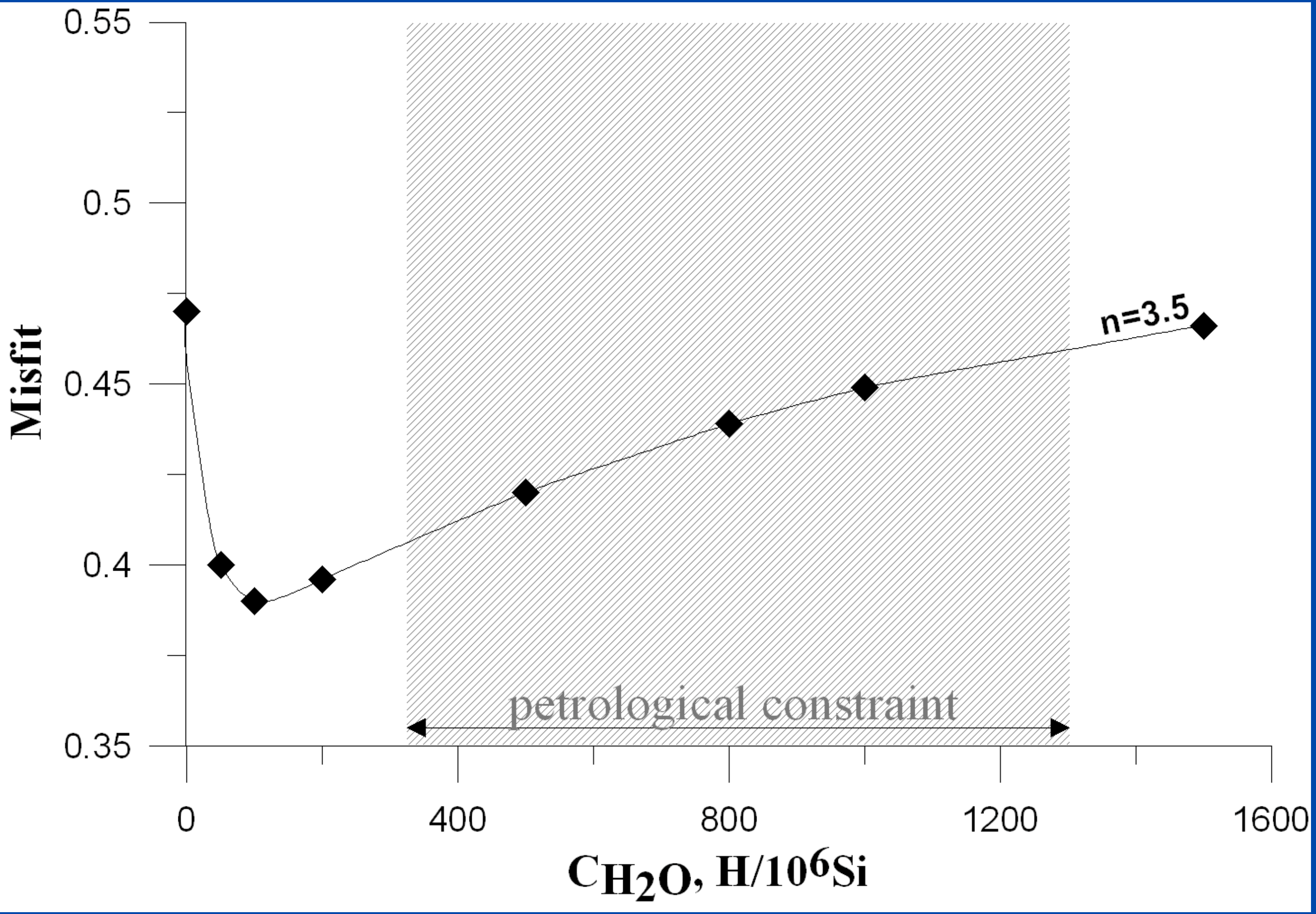
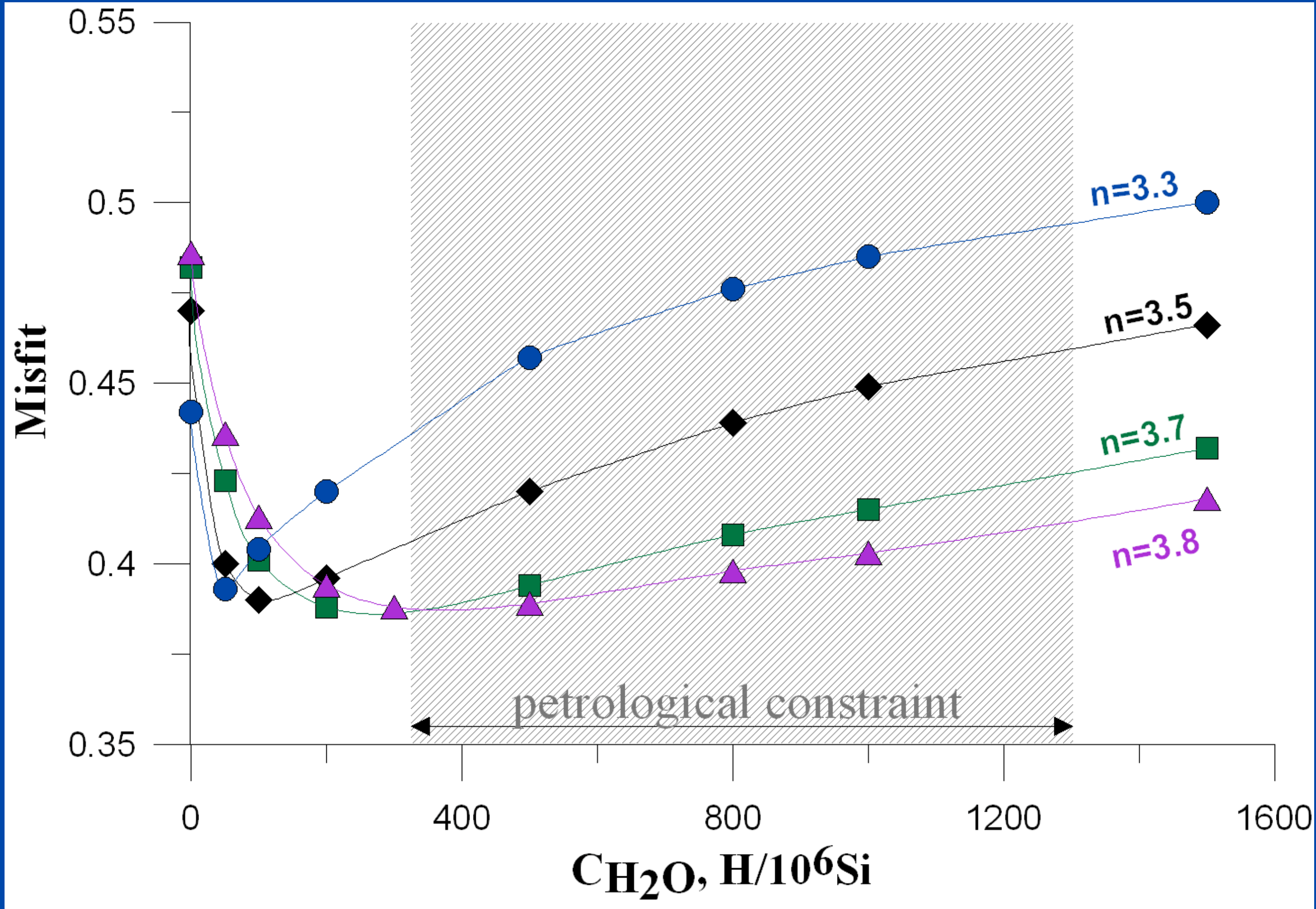


Plate-velocities misfit



$$\text{Misfit}= \int \left\| \vec{v}_2 - \vec{v}_1 \right\| / \left\| \vec{v}_1 \right\| dS$$

Plate-velocities misfit



$$\text{Misfit}=\int \left\|\vec{v}_2-\vec{v}_1\right\| / \left\|\vec{v}_1\right\| dS$$

Plate velocities in NNR reference frame

Model

Tp=1300°C,

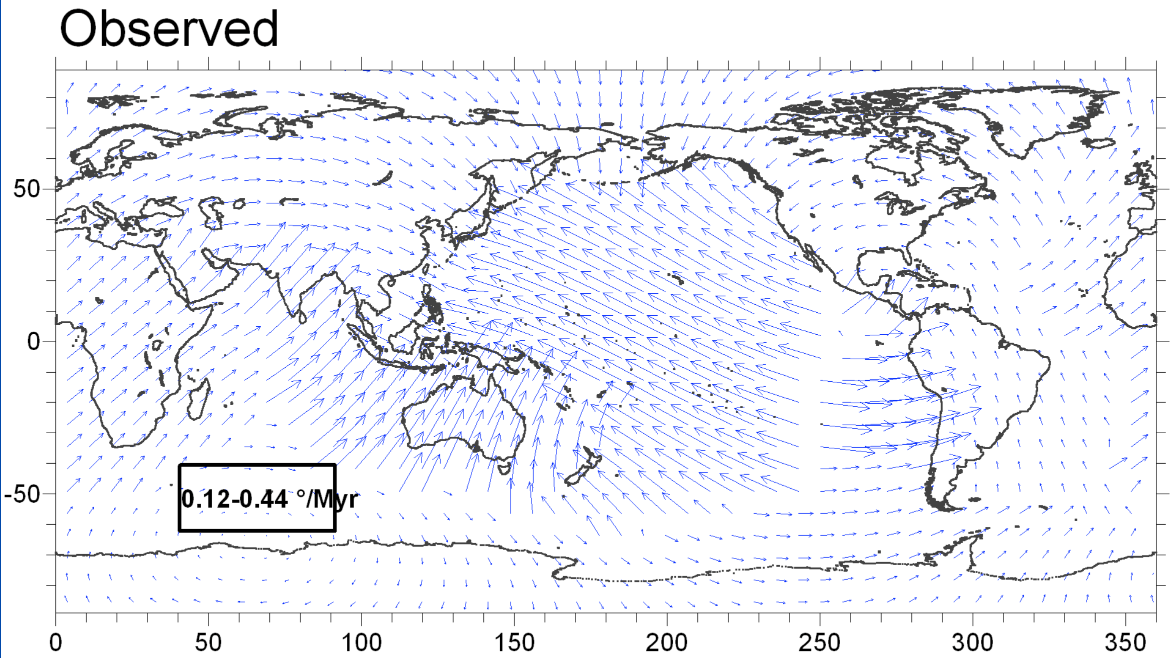
lith: dry olivine;

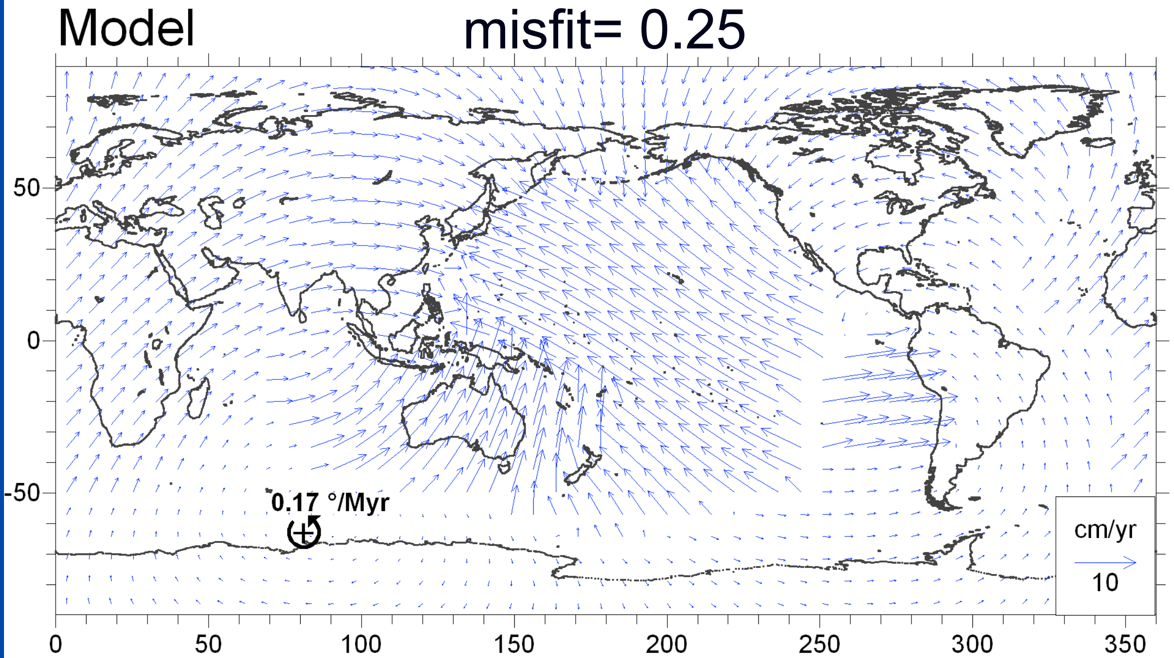
asth:1000 ppm H/Si in olivine, n=3.8

Plate bound. friction:

Subd. zones 0.01-0.03, other 0.05-0.15

misfit=0.25 (0.36 previous best by Conrad and Lithgow-Bertelloni, 2004)





Conclusions

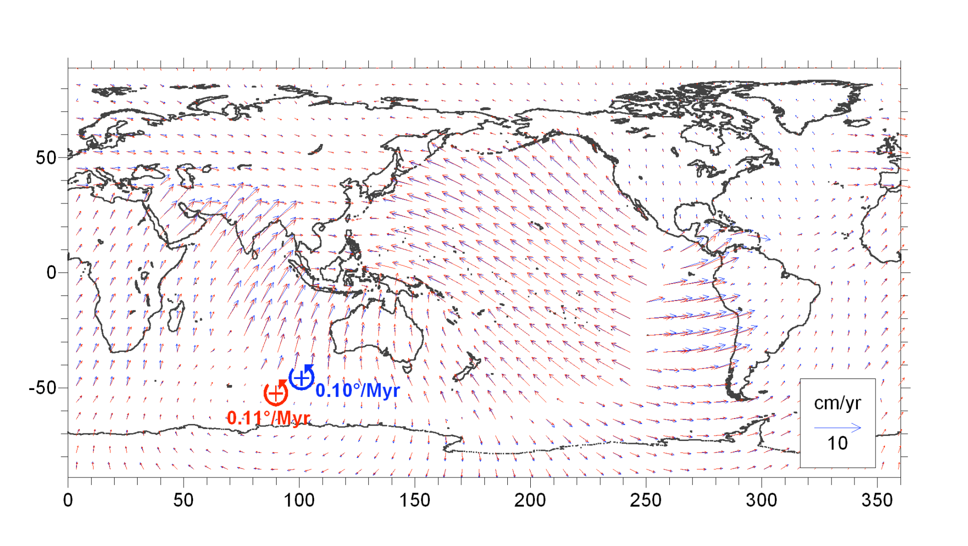
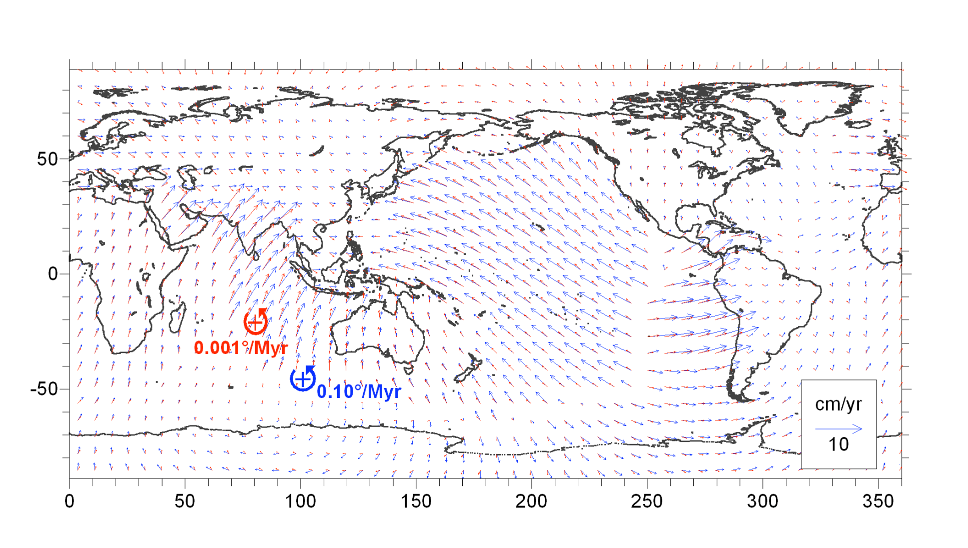
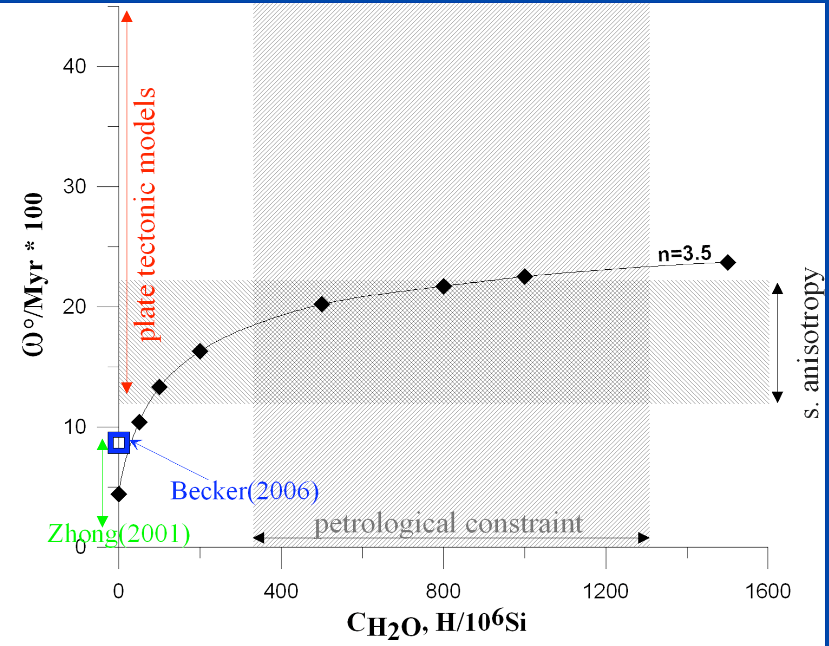


Plate velocities are not sensitive to the lateral viscosity variations deeper than 300 km

But their magnitudes are sensitive to the lateral viscosity variations shallower than 300 km

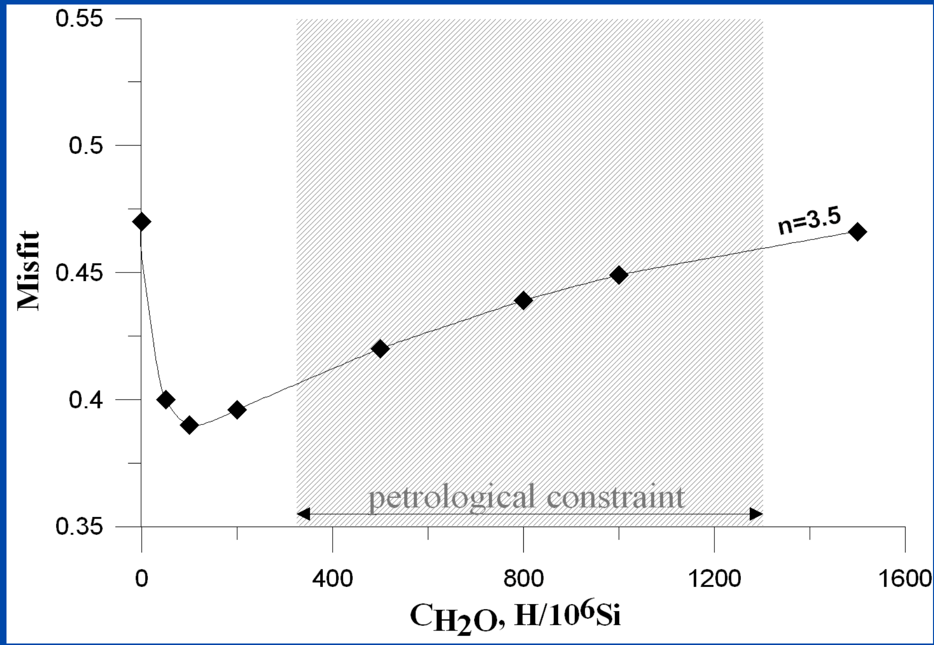


Conclusions

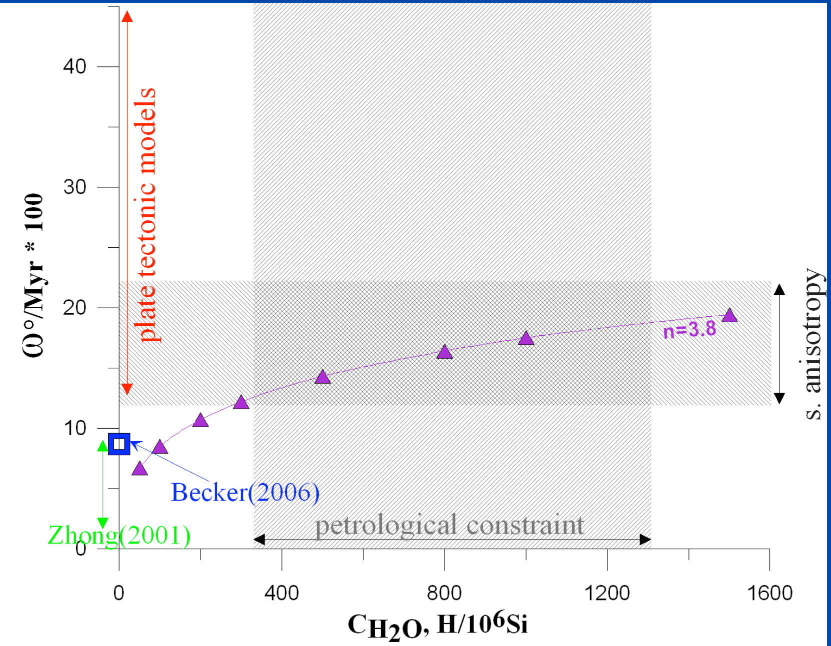


Magnitude of the lithospheric net rotation and quality of fit of plate velocities are sensitive to the water content of the asthenosphere

There is potential of estimating water content in the asthenosphere using plate velocities and net rotation

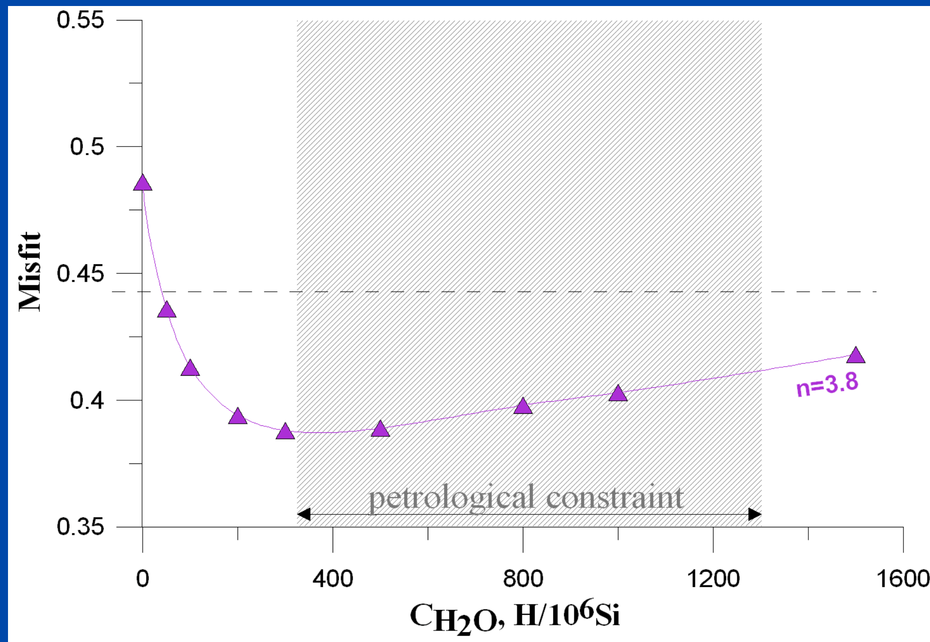


Conclusions



The current views on the rheology and water content in the upper mantle are consistent with the observed plate velocities

if the stress exponent *in wet olivine rheology and activation volume are* pushed to the highest experimentally allowed values of n=3.8, V=14 cc/mol



Conclusions

Distribution of dissipation rate

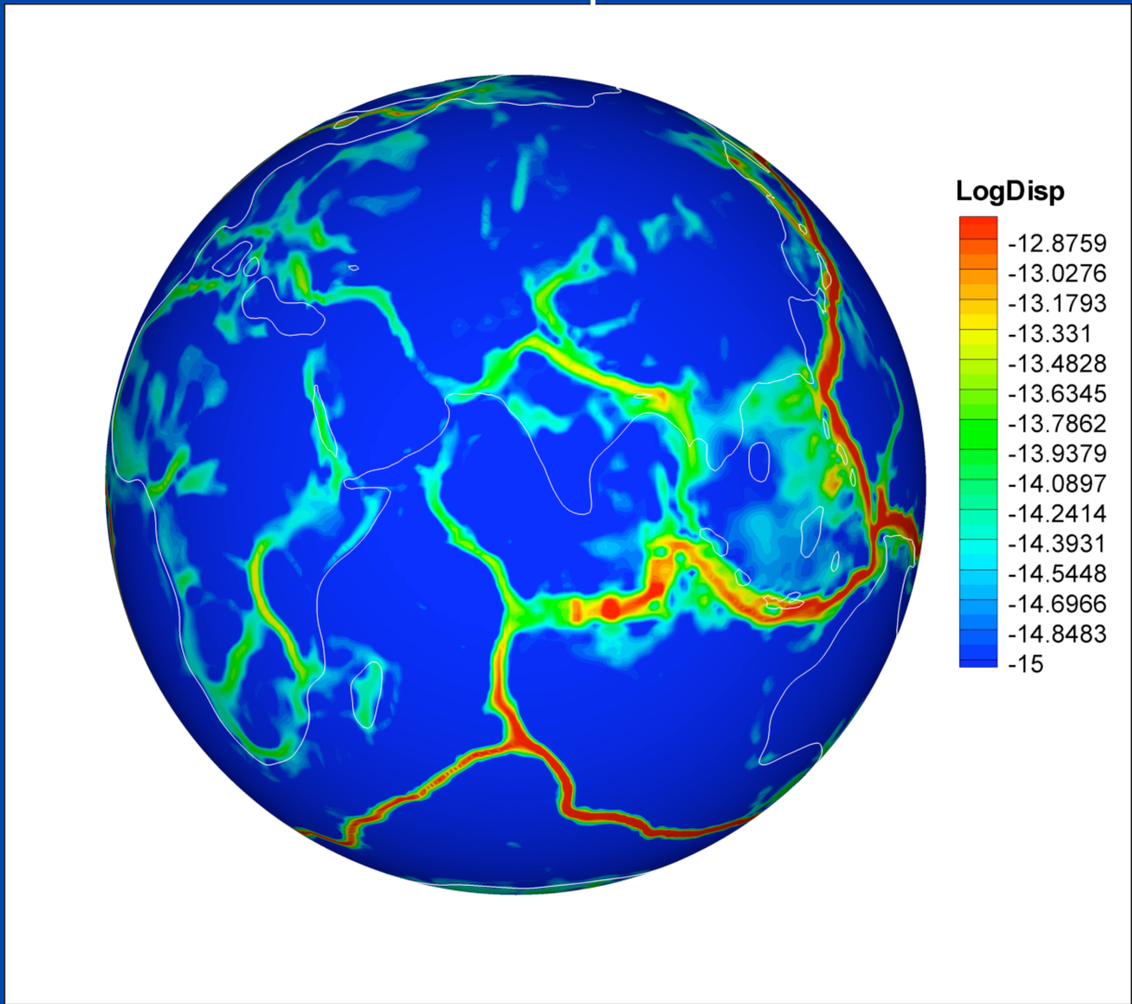


Plate boundaries must be very weak to allow for plate tectonics. Particularly, at subduction zones friction must be < 0.02 on average, just some 1/35 of the dry rock value.

Conclusions

Distribution of dissipation rate

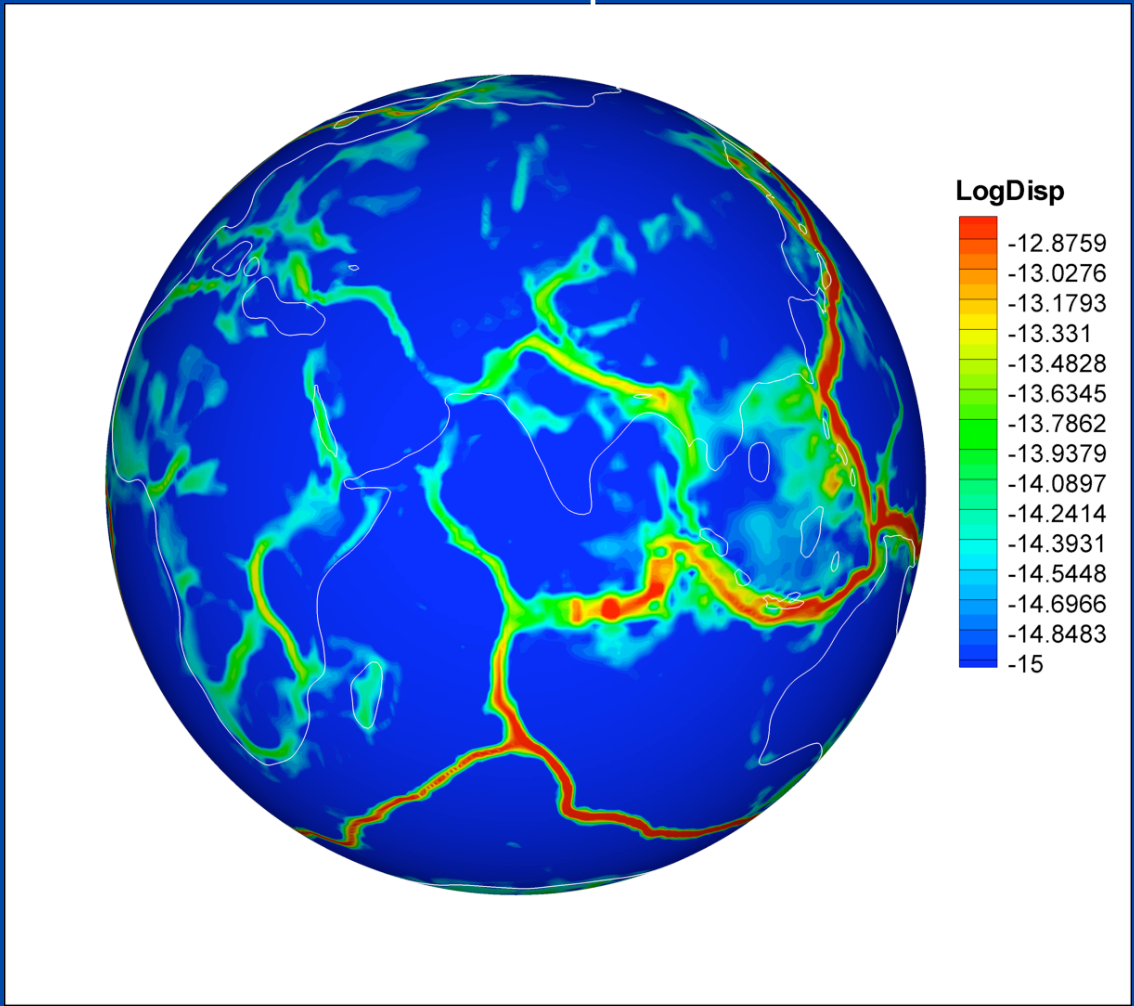


Plate boundaries must be very weak to allow for plate tectonics. Particularly, at subduction zones friction must be < 0.02 on average, just some 1/35 of the dry rock value.

That can be achieved only with high-pressure fluids in subduction channels.

Conclusions

Distribution of dissipation rate

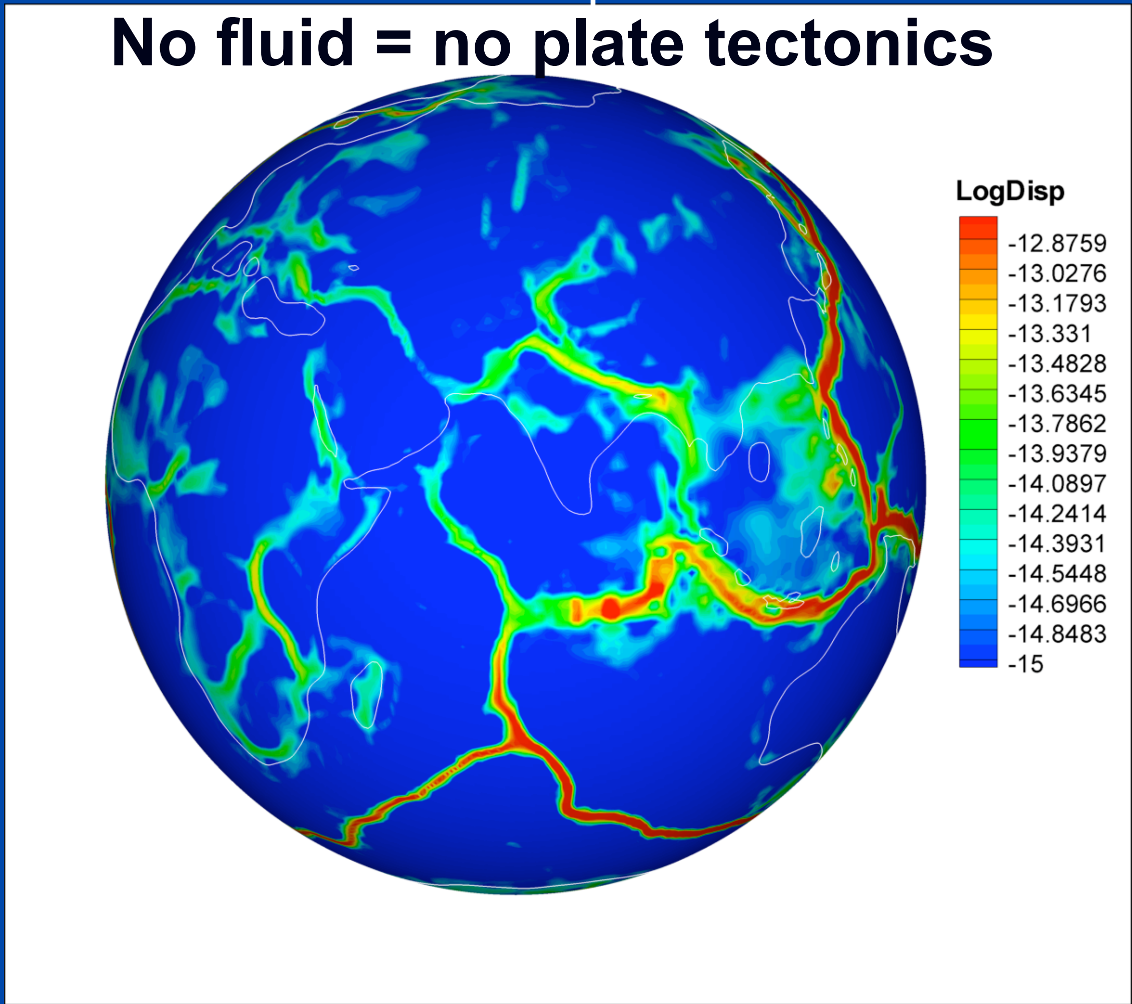


Plate boundaries must be very weak to allow for plate tectonics. Particularly, at subduction zones friction must be < 0.02 on average, just some 1/35 of the dry rock value.

That can be achieved only with high-pressure fluids in subduction channels.