Thermal-Mechanical Behavior of Oceanic Transform Faults

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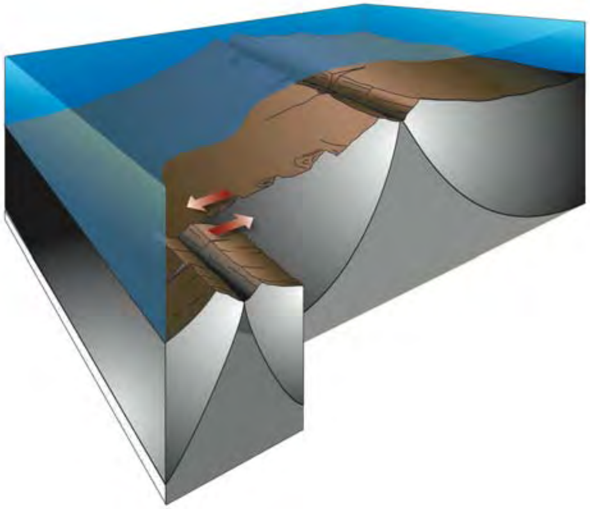
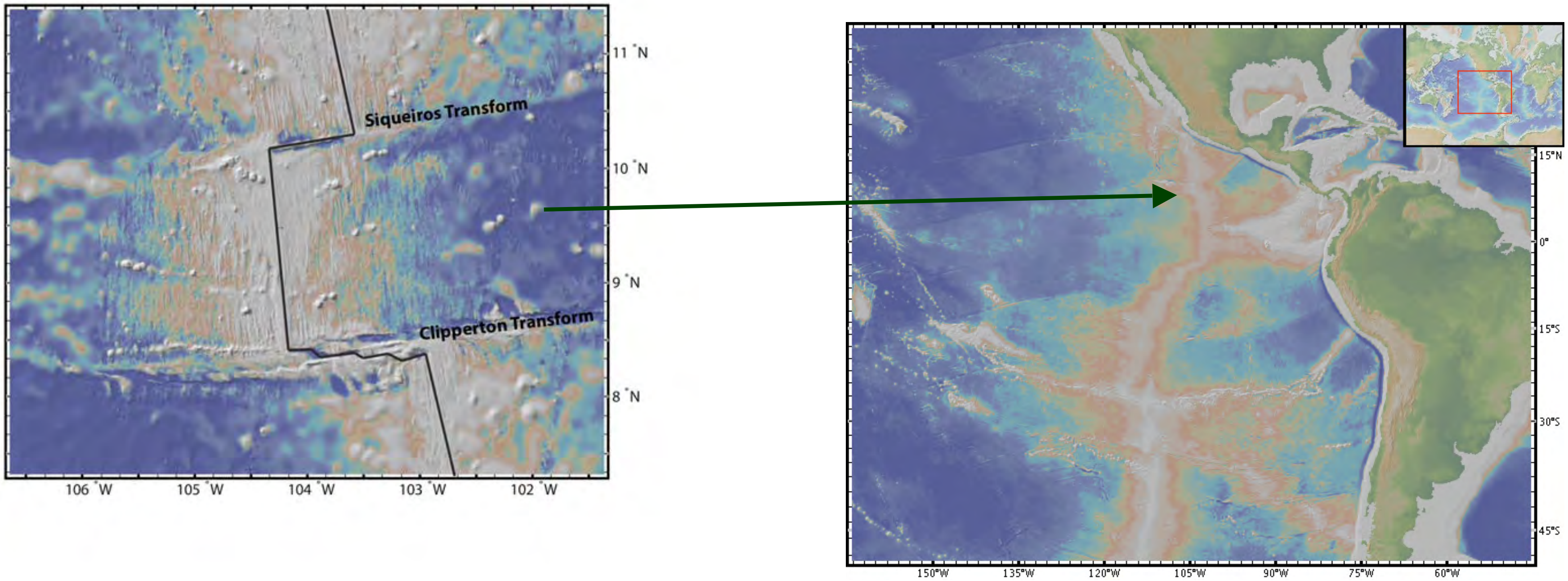
Mid-Ocean Ridge Transform Faults



Transform Faults Play Many Roles:

- Accommodate deformation on mid-ocean ridges worldwide
- Influence mantle flow
- Provide mechanism for fluid circulation:
  - Alteration
  - Hydration



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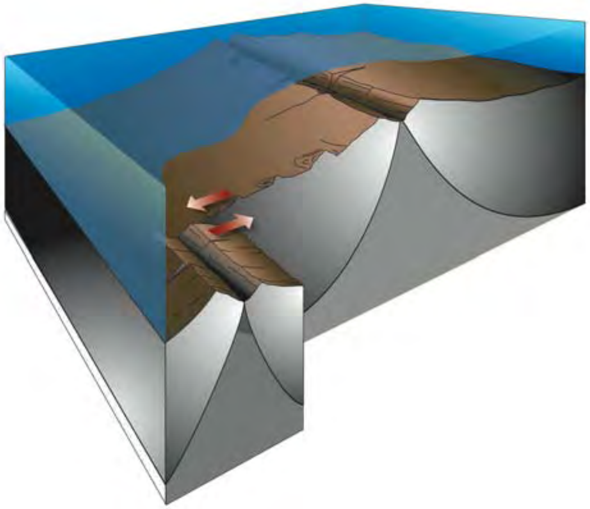

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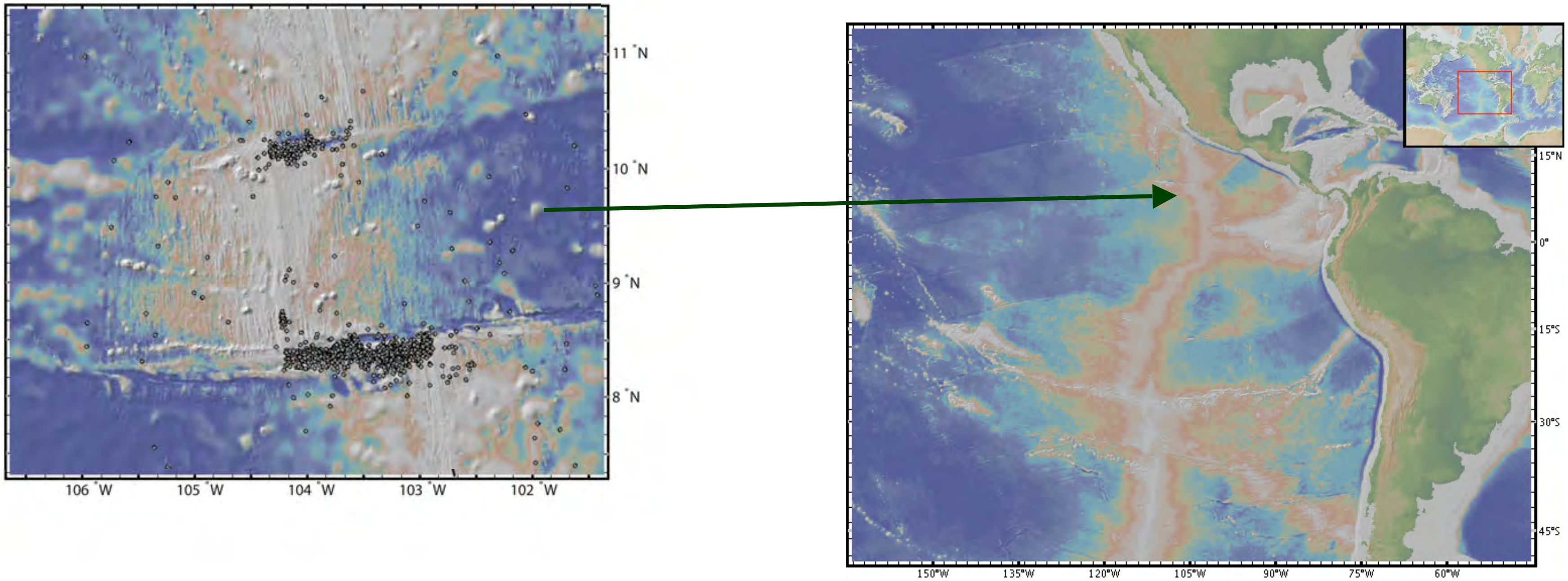
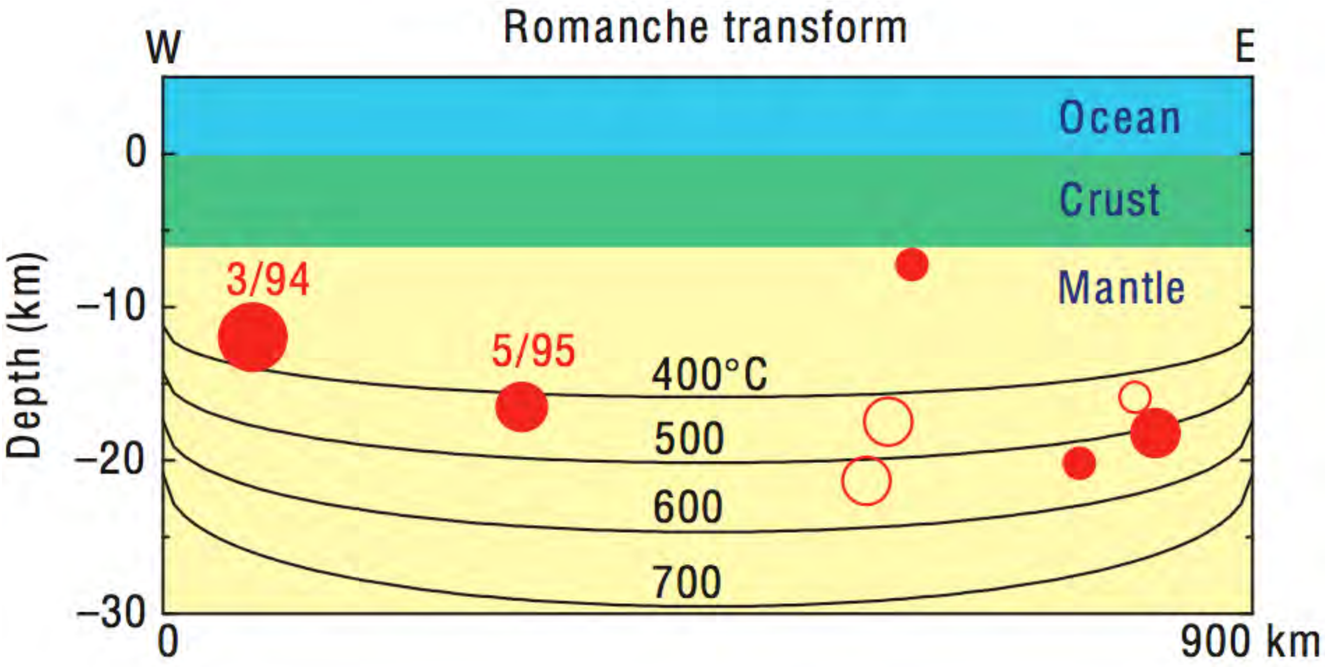


Need for improved fault models:



Abercrombie and Ekstrom, 2001

Simple half-space models: correlation between seismicity and temperature.

Neglect fundamental physical processes.

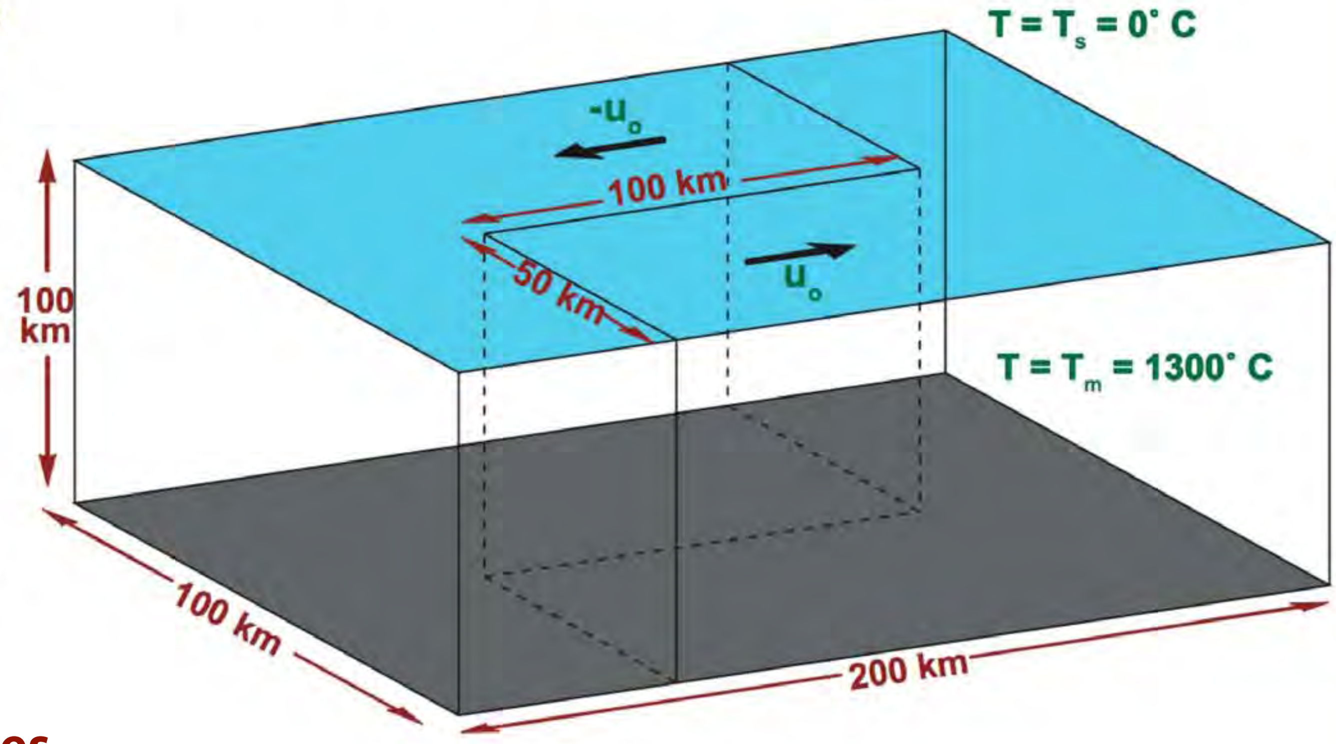
Our Study:

- Utilize finite element numerical models to characterize the temperature structure and mantle flow field of the transform environment.
    - non-Newtonian viscous flow & Brittle failure in shallow lithosphere
    - Thermal and Rheological feedbacks that result from the presence of fluids

Modeling Oceanic Transform Faults:

COMSOL 3.2 Finite Element Software Package

3-D, steady-state incompressible mantle flow thermal structure



Boundaries

Surface: Flow driven by imposed velocity, u_o: half slip rate

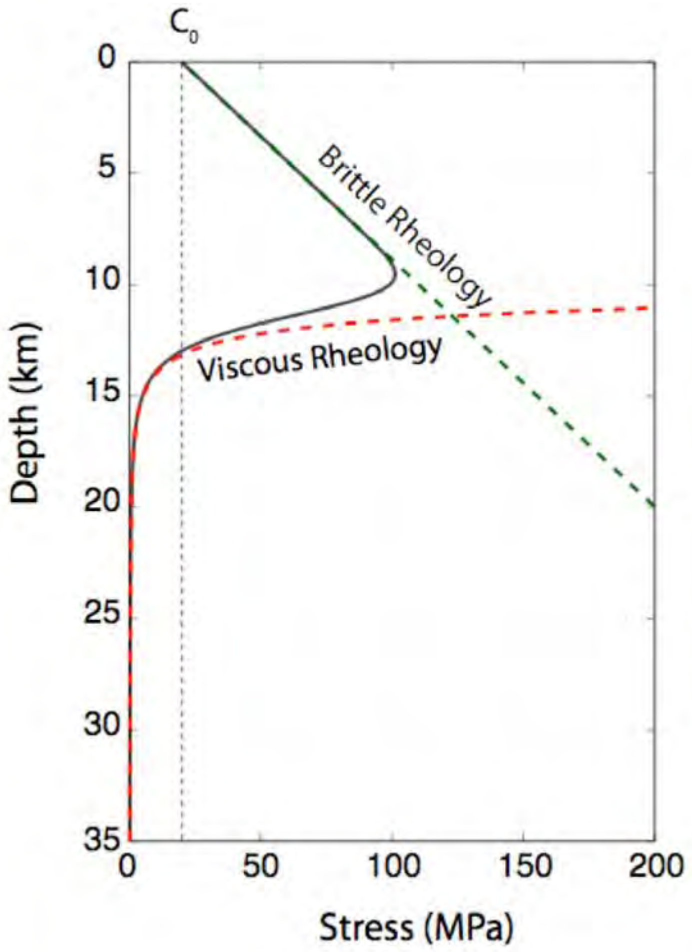
Temperature: $T_s = 0°$ C

Bottom: Stress Free (allowing mantle upwelling)

Temperature: $T_m = 1300°$ C

Sides: Stress Free - open to convective flux

Rheology Model



Non-Newtonian viscous mantle Rheology:

$$\eta_{disl} = B\,\dot{\varepsilon}^{\frac{1-n}{n}} \exp\left(\frac{E}{nRT}\right)$$

Visco-plastic Approximation for brittle weakening:

maximum shear stress in the lithosphere

$$\sigma_{\max} = C_0 + \mu(1-\lambda)\rho g z \qquad \eta_{brittle} = \frac{\sigma_{\max}}{2\dot{\varepsilon}}$$

Chen and Morgan, 1990

Composite Rheology Law

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

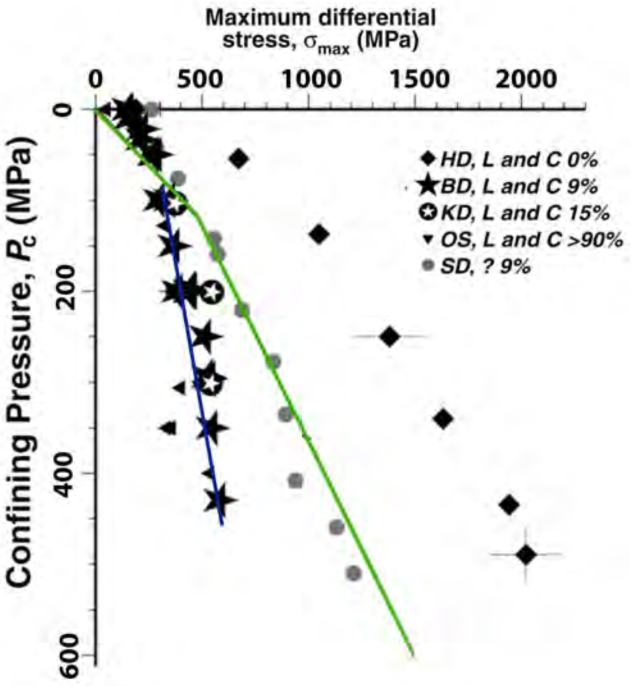
Weakening due to alteration:

$$\sigma_{\max} = C_0 + \mu(1-\lambda)\rho g z$$

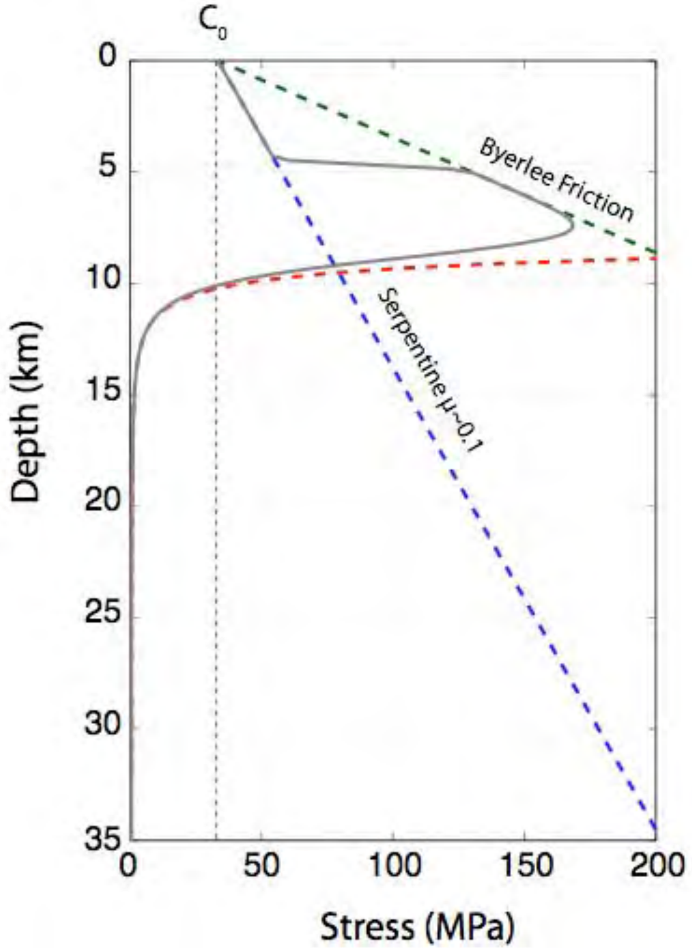
Serpentinization of peridotites:

- lizardite and chrysotile serpentines have low coefficients of friction

- $\mu = 0.1\text{-}0.45$



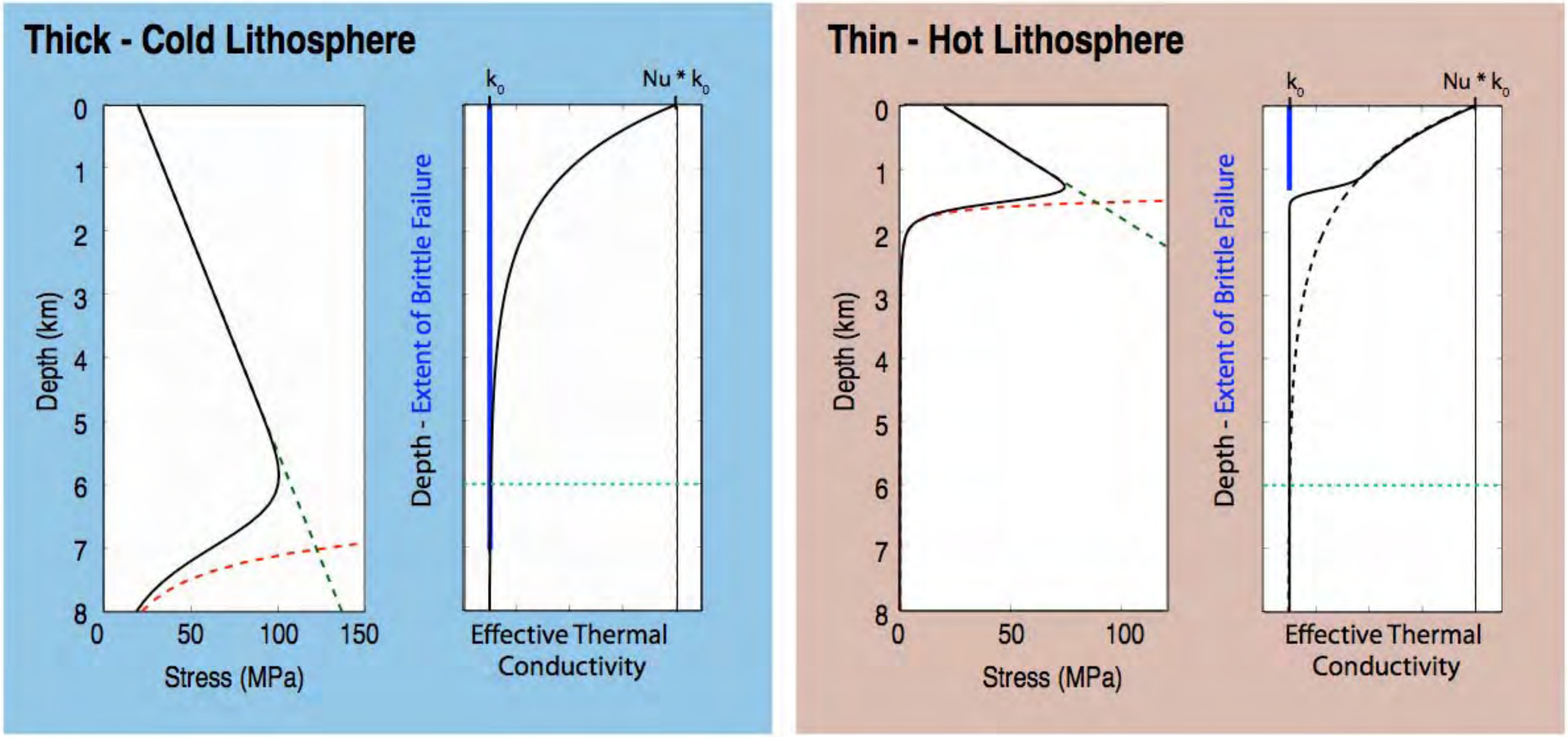
Escartin et al., 2001



Hydrothermal Circulation:

- Hydrothermal heat transport as enhanced thermal conductivity
- *Nusselt Number (*Nu): ratio of hydrothermal heat transport within a permeable layer to heat transport by conduction alone (*Phipps Morgan and Chen, 1993)*

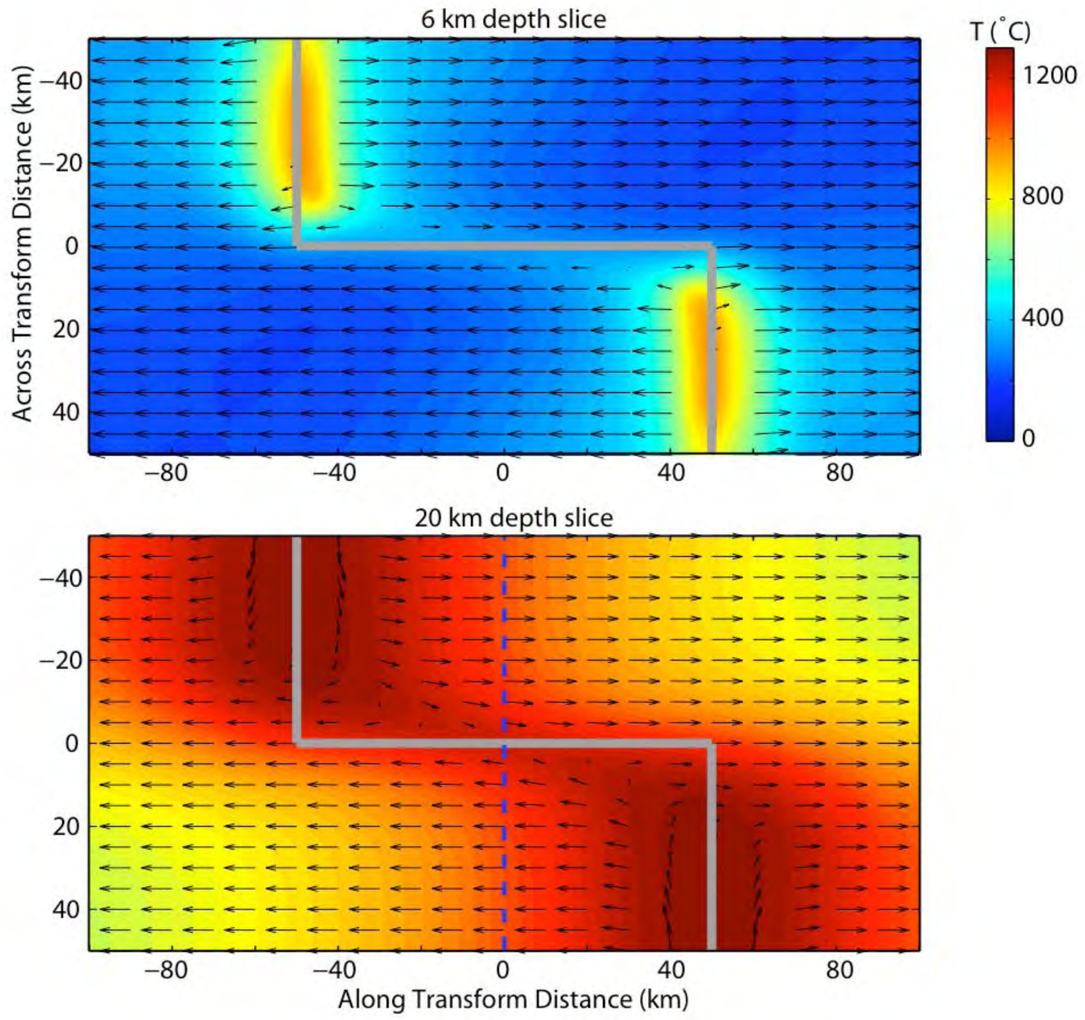
$$k_{eff} = k_0 \times \left[1 + \overbrace{(Nu - 1)}^{\text{Efficiency of Circulation}} \times \overbrace{\exp\left(\frac{z}{z_{ref}}\right)}^{\text{Empirical: Permeability with Depth}} \times \overbrace{\mathrm{erf}\,(z - z_{brittle})}^{\text{Smoothing across Brittle Zone}}\right]$$

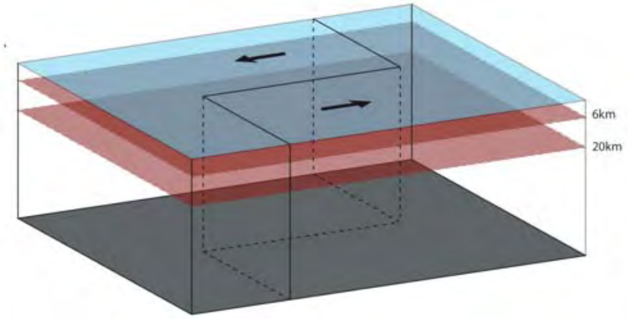


Thick - Cold Lithosphere

Thin - Hot Lithosphere

Model Results





Temperature Solution:

u_0 = 1.5 cm/yr

hydrothermal cooling: *Nu* = 8

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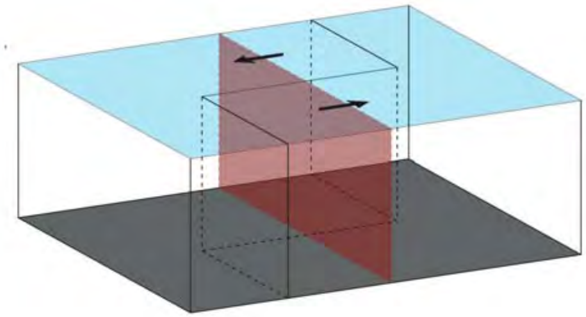
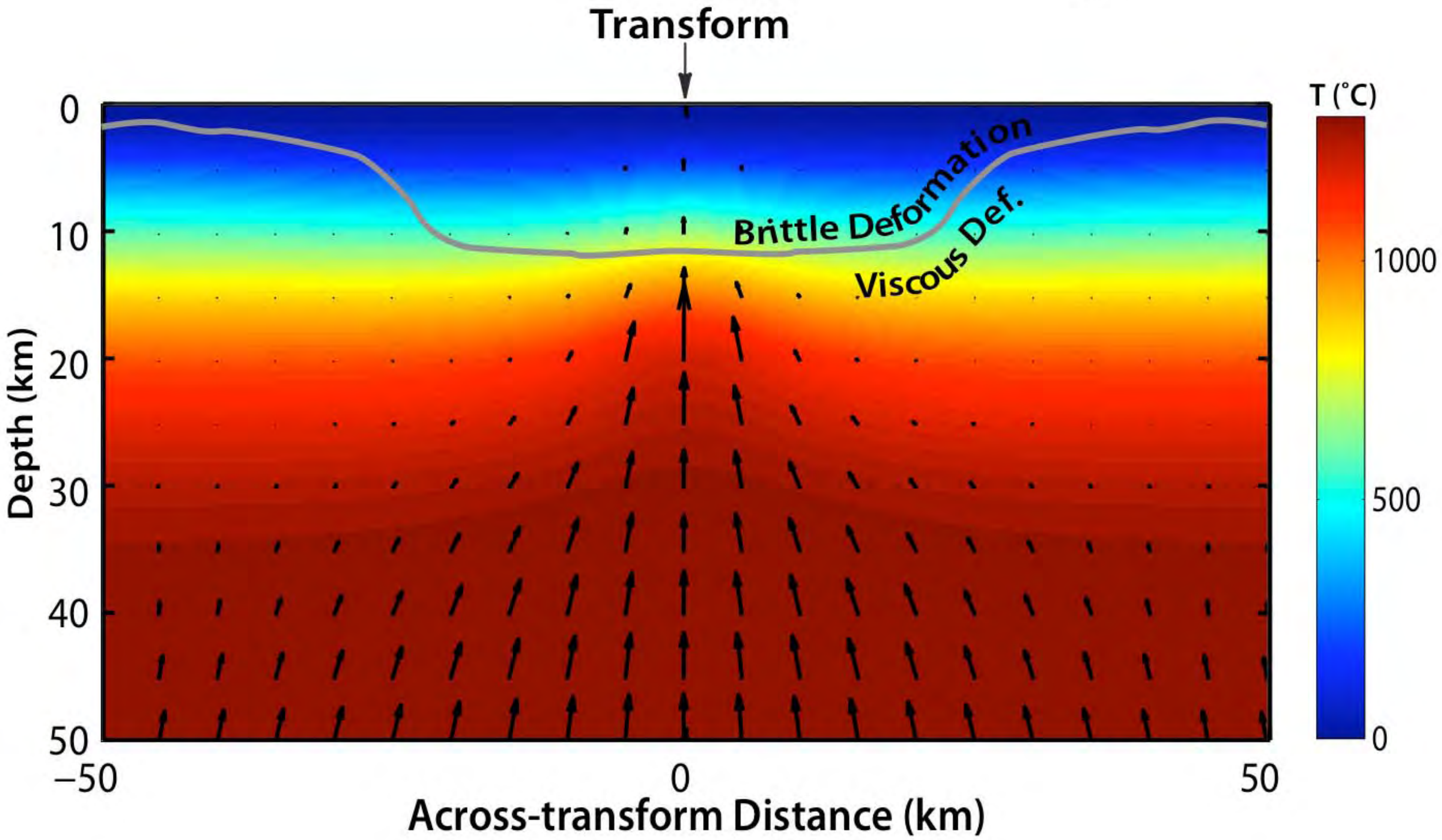
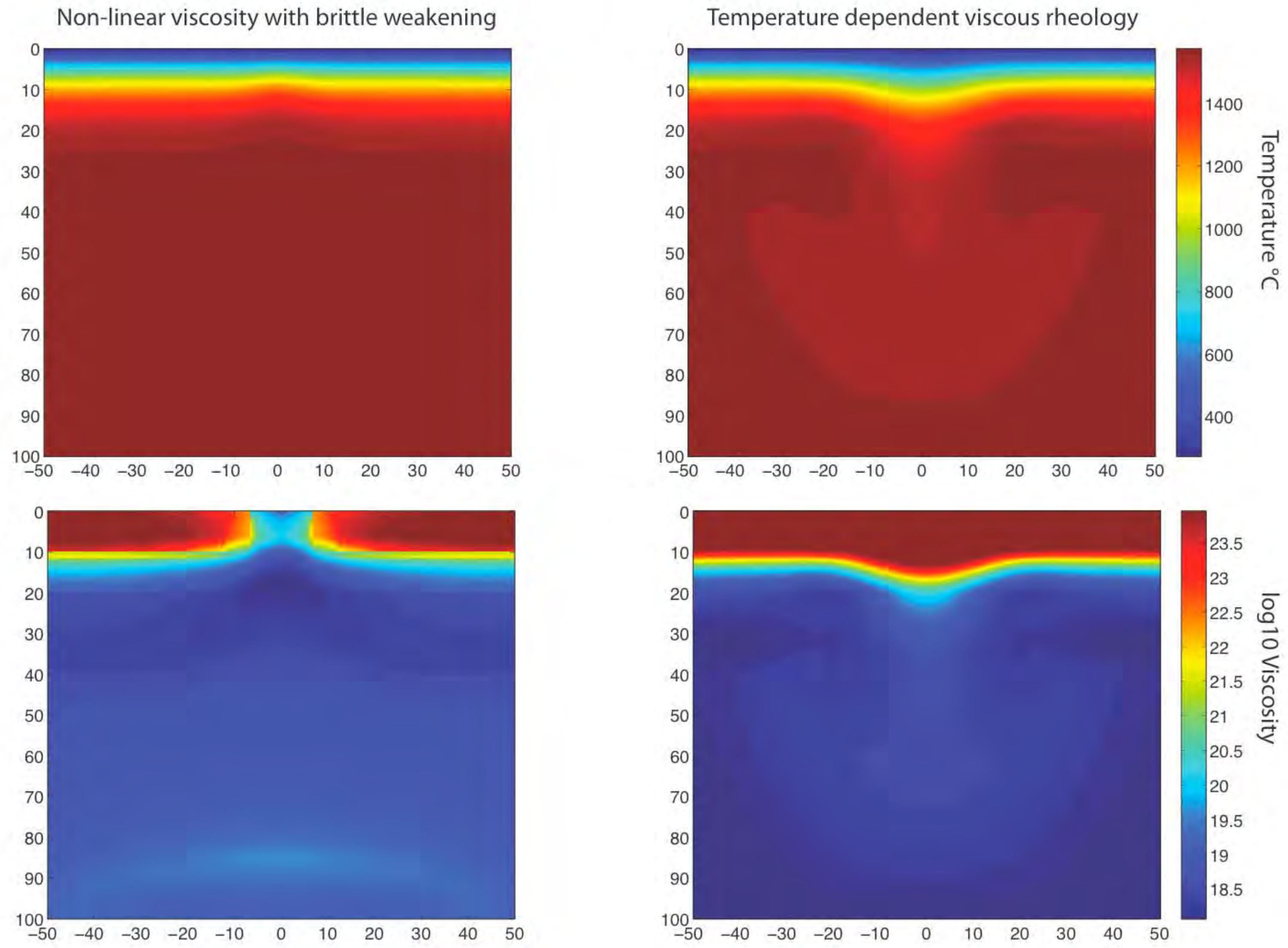




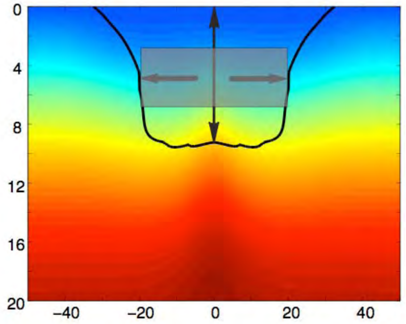
Lower Effective Viscosity Increased Mantle Upwelling



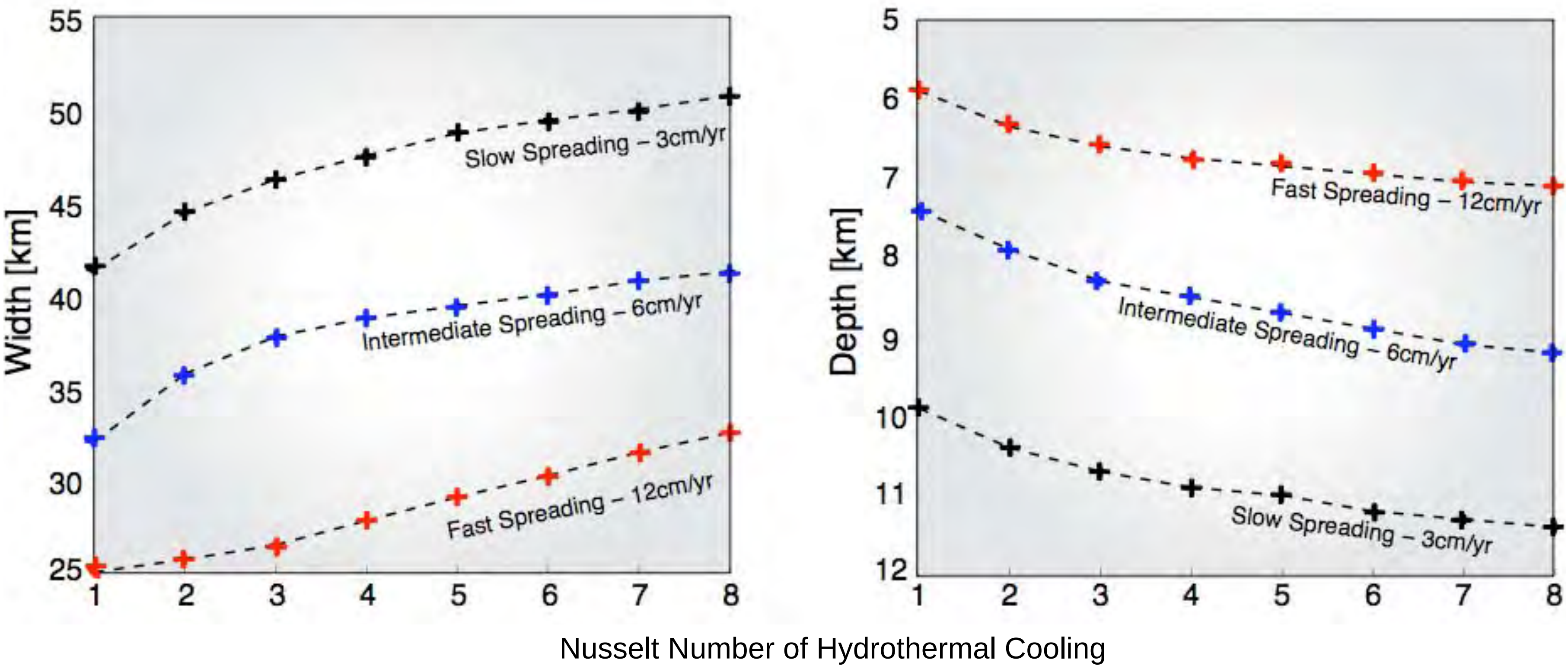
Non-linear viscosity with brittle weakening

Temperature dependent viscous rheology

Effect of **Hydrothermal Cooling** and **Spreading Rate**-



Zone of Brittle Failure:



Potential for incorporating water into the mantle

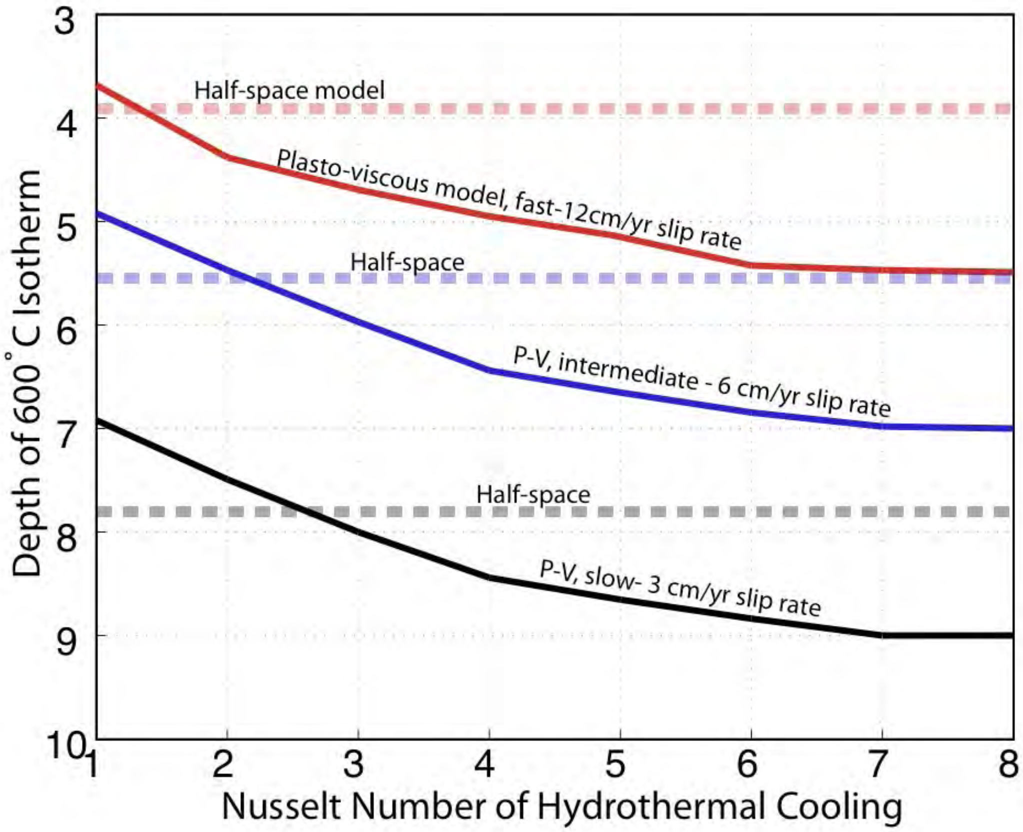
> brittle failure zone is depressed below crust (6km)

Comparison to Half-space model

600° C isotherm from simple half-space cooling model -

correlated with maximum depth of transform earthquakes

Abercrombie and Ekstrom, 2001



Conclusions

- Oceanic transform thermal models with brittle weakening show warm faults
  - Reduced effective viscosity leads to enhanced mantle upwelling
  - More consistent with seismologic observations, mechanical behavior
- Model results show secondary feedbacks influence thermal solution:
  - Altered minerals formed in brittle fault zone fail at lower shear stress
  - Increased heat transfer from hydrothermal circulation leads to cooler faults
- Implications for:
  - Seismologic and mechanical nature of oceanic lithosphere
  - mantle hydration: water budget estimates
  - Arc Volcanism where fracture zones are subducted

Thanks!

- Heat Equation

$$\nabla \cdot \left(-k\nabla T\right) = Q - \rho C_p u \cdot \nabla T$$

steady state conduction, convection,

- Navier Stokes -

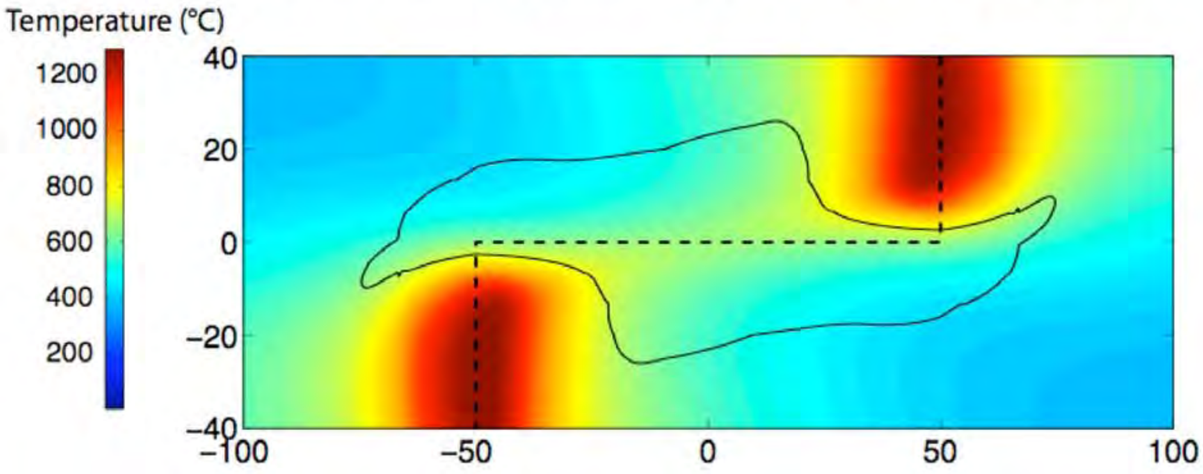
$$\nabla \cdot u = 0$$

Conservation of mass

$$\rho\left(u \cdot \nabla\right)u = \nabla \cdot \left[-pI + \eta\left(\nabla u + \left(\nabla u\right)^T\right)\right] + F$$

Convective acceleration, Pressure gradient, diffusion of momentum, body forces

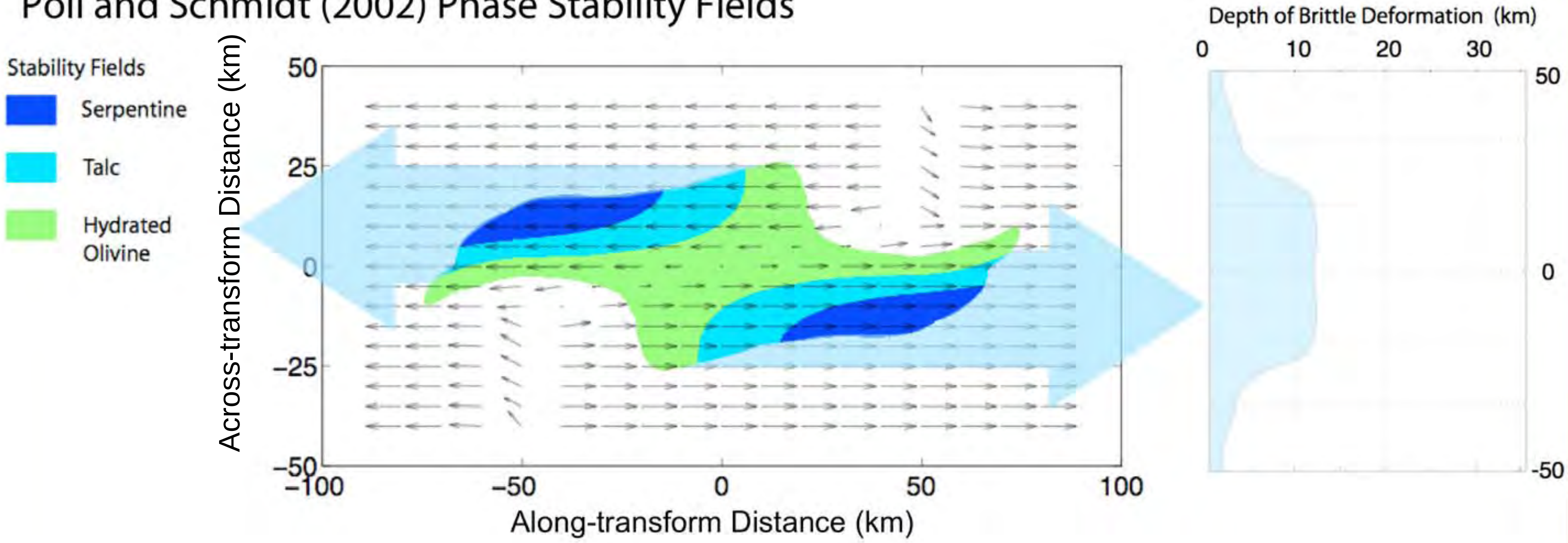
Extent of brittle failure formation of hydrated phases:



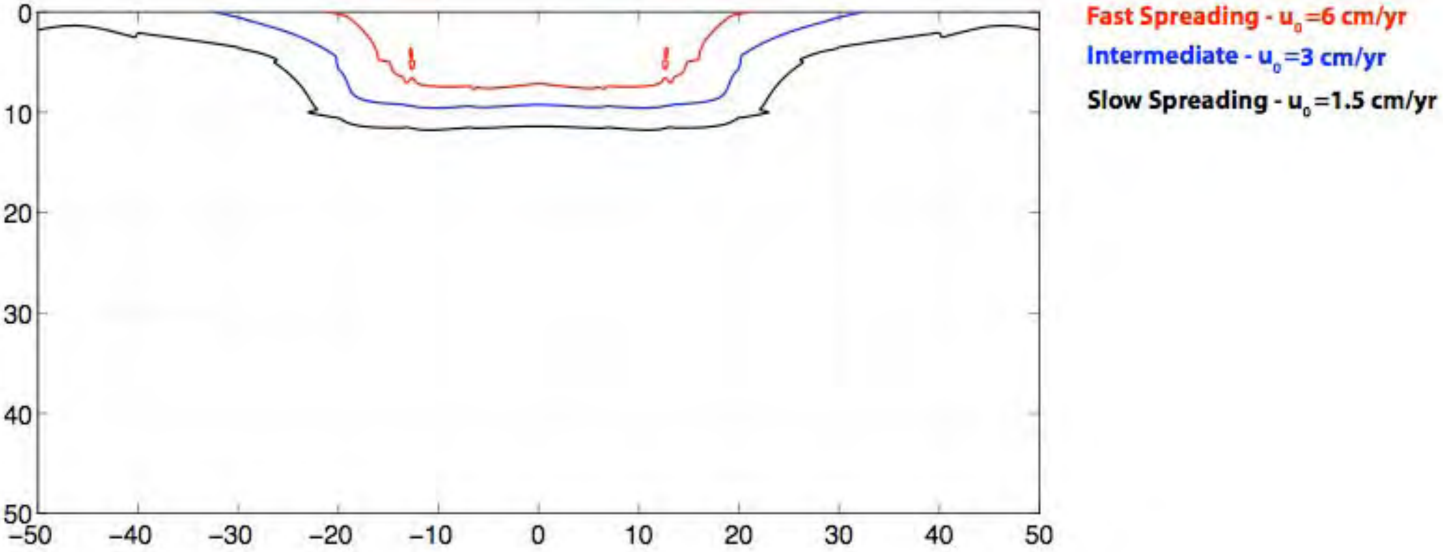
3 cm/yr full-spreading rate

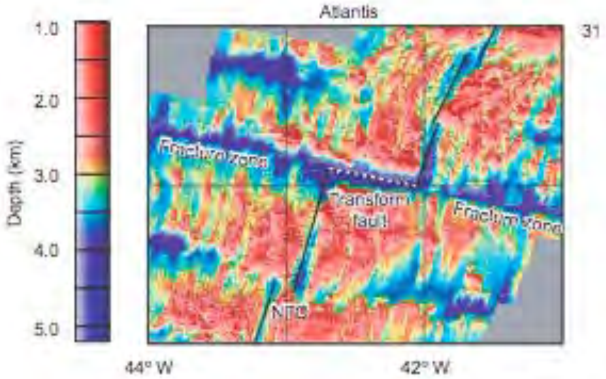
10 km depth

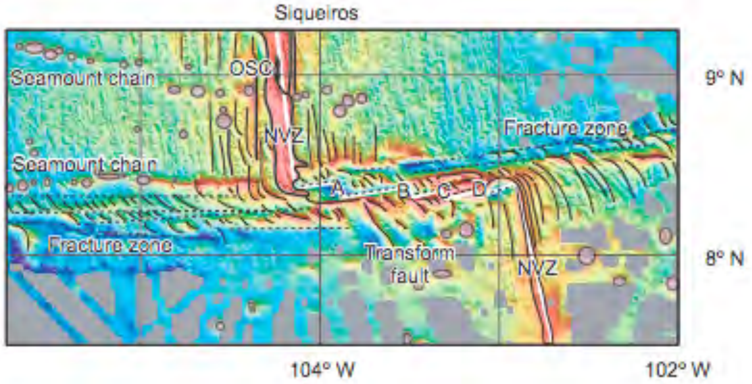
Poli and Schmidt (2002) Phase Stability Fields



Modeled transform fault properties - Observations



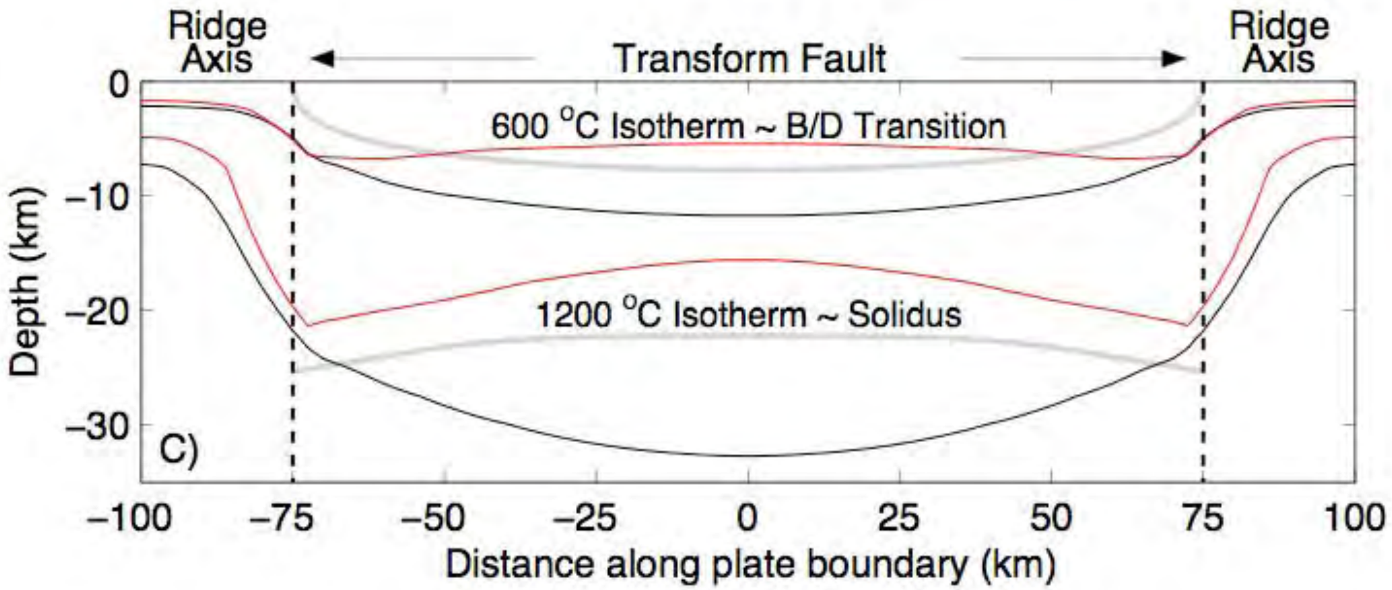




Evolution of the Transform Thermal Models

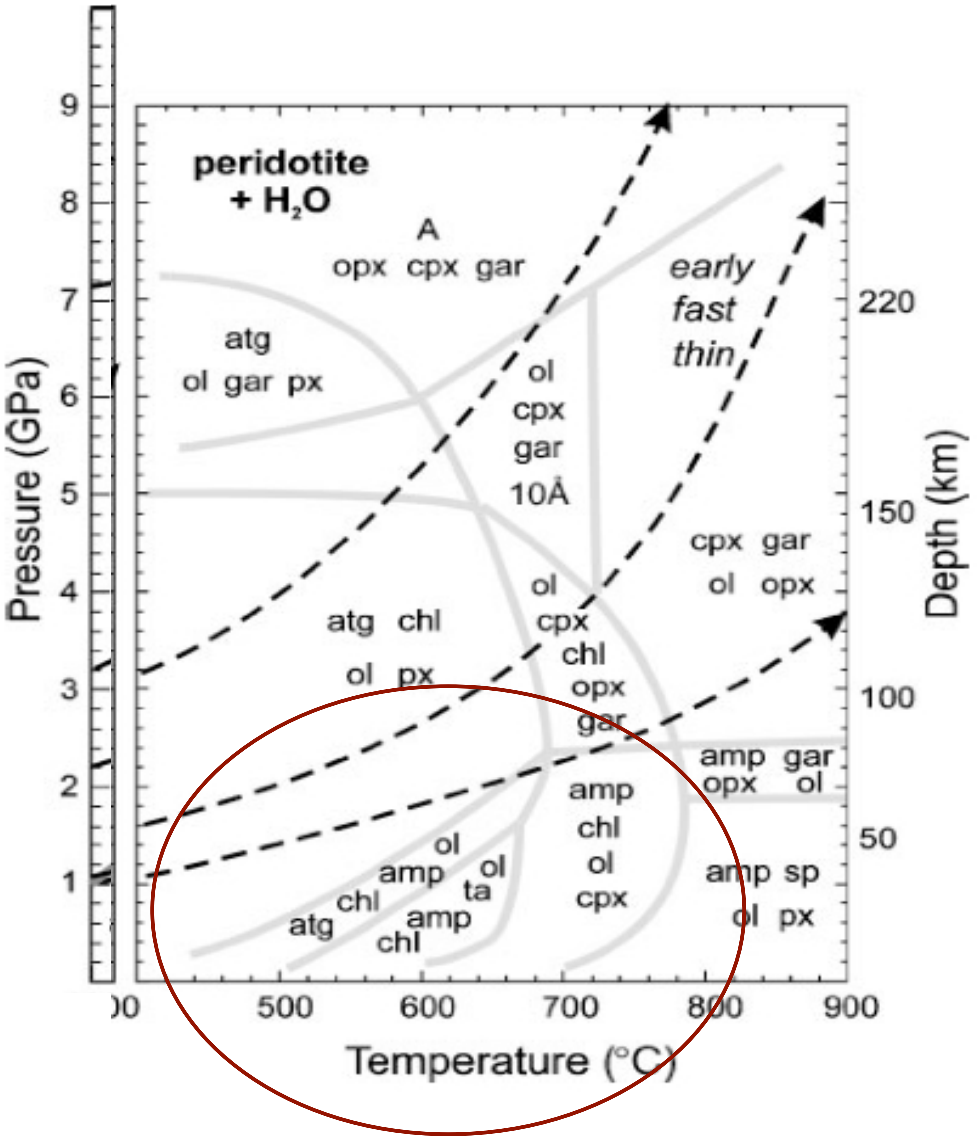
- Traditional 3D transform models are too cold to match a number of observations:
  - *Maximum depth of transform earthquakes*
  - *Mechanical behavior of faults relative to surrounding crust*
  - *Transform Morphology*

- Improved Rheological model to more realistically represent thermal structure
  - Brittle Rheology: weakens crust at shallow depths leading to enhanced mantle upwelling and warmer temperatures



Behn et al. 2007

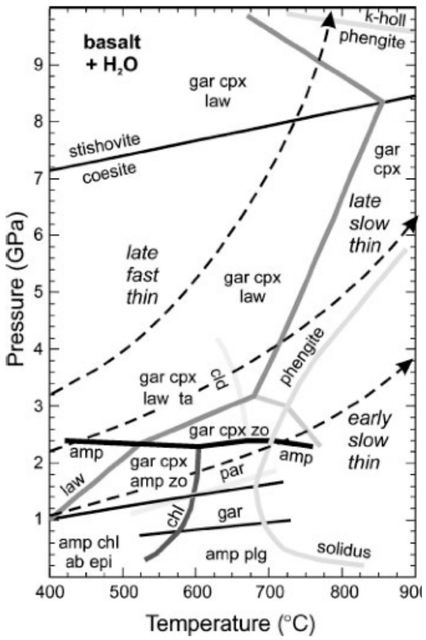
Phase Stability



lherzolite composition at H2O-saturated conditions,

after *Schmidt&Poli 1998*

tholeiitic basalt composition

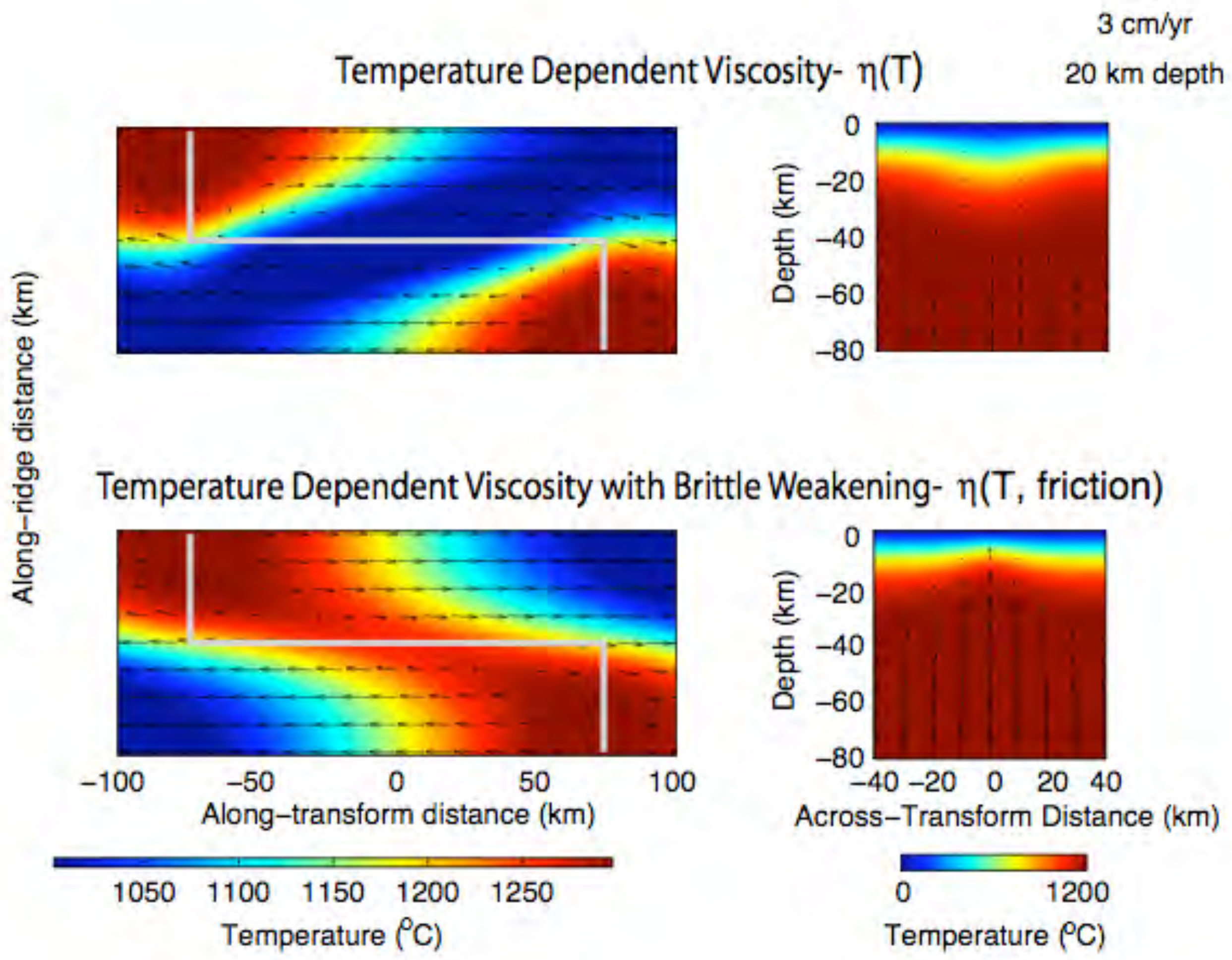


Transform Thermal Models

Previous models produced temperature structure too cold to match observations: Seismicity, Localized Deformation

More realistic Rheology:

- Shallow brittle mechanisms weaken transform
- Increase mantle upwelling - leads to warmer temperatures



Behn et al. 2007 - temperature dependent model results results of model with brittle weakening of the lithosphere