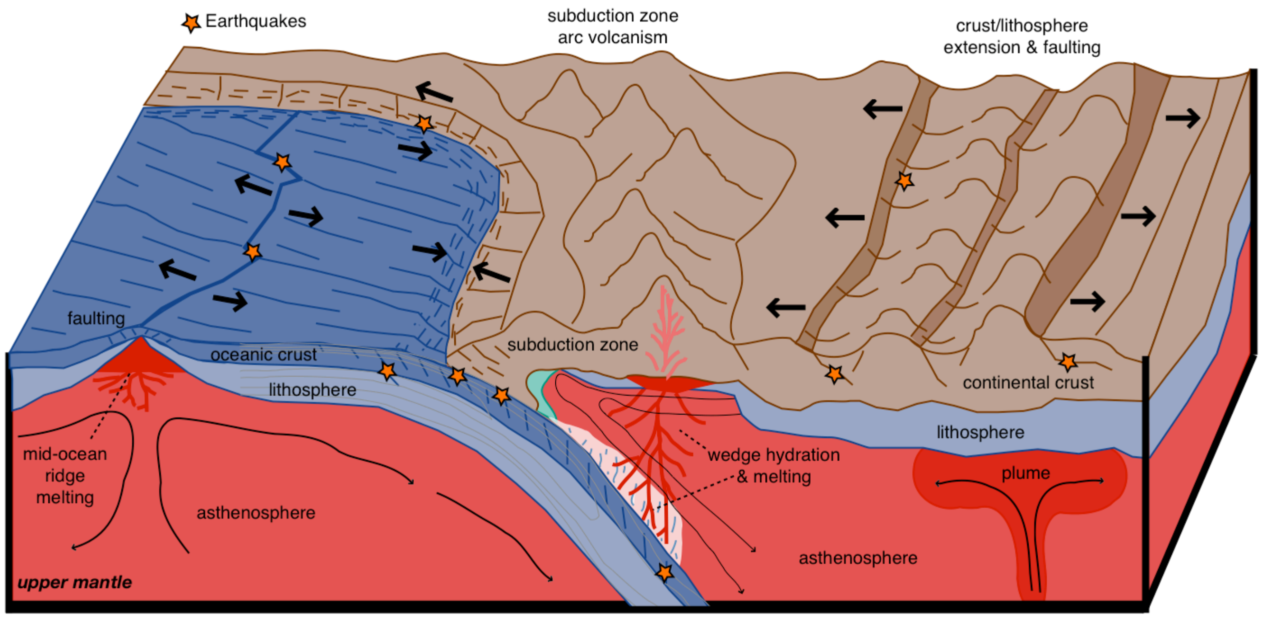
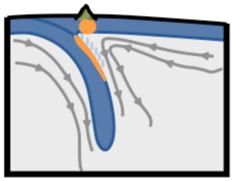
Subduction Zone & Slab Processes

11th International Workshop on Modeling of Mantle Convection & Lithospheric Dynamics

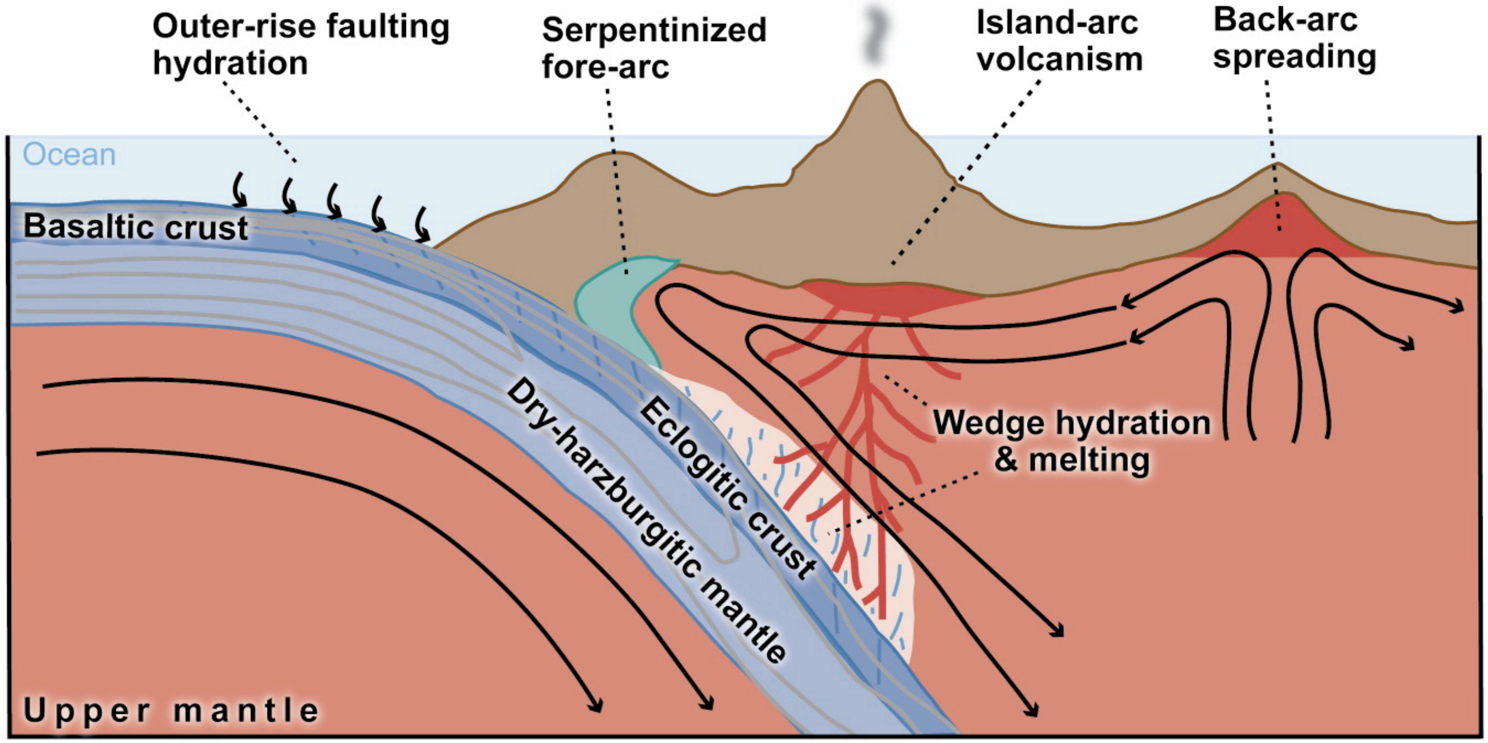
Braunwald, Switzerland



Magali Billen
Department of Geology
U.C. Davis

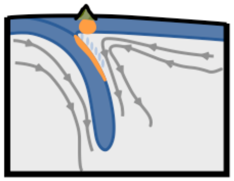


Regional View of the SZ



Billen MI. 2008.
Annu. Rev. Earth Planet. Sci. 36:325–56.

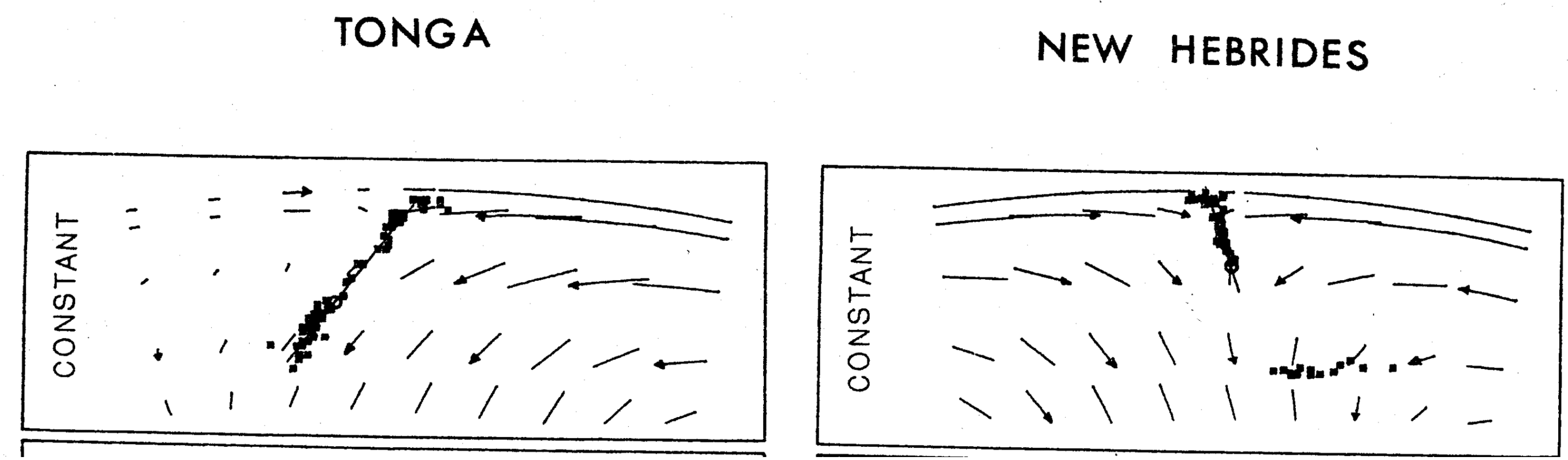
- ***How did we get to this picture?***
- ***What are we still missing?***



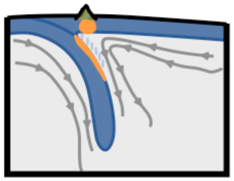
More Questions than Answers

- Some slabs appear to subduct into the deep lower mantle, while others get stuck in the transition zone and mid-mantle: why is it that, so far, only physical models with an unrealistically large clapeyron slope for the 660-km phase change and weak slabs can trap slabs in the mid-mantle?
- Rheological constraints predict that slabs should deform plastically at high effective viscosities: why are physical models with weak or moderately-strong slabs successful?
- Geological observations of surface deformation call for long-term coupling between overriding and subducting plates: why are models without an overriding plate successful?
- Rheological and seismological constraints predict that the upper mantle deforms by dislocation creep (non-Newtonian rheology): why are Newtonian models of slab dynamics successful?
- Tomographic images of slabs in the deep mantle imply significant thickening of slabs (5-10 x): why are most physically-modelled slabs so thin 1.5-2.0 x)?

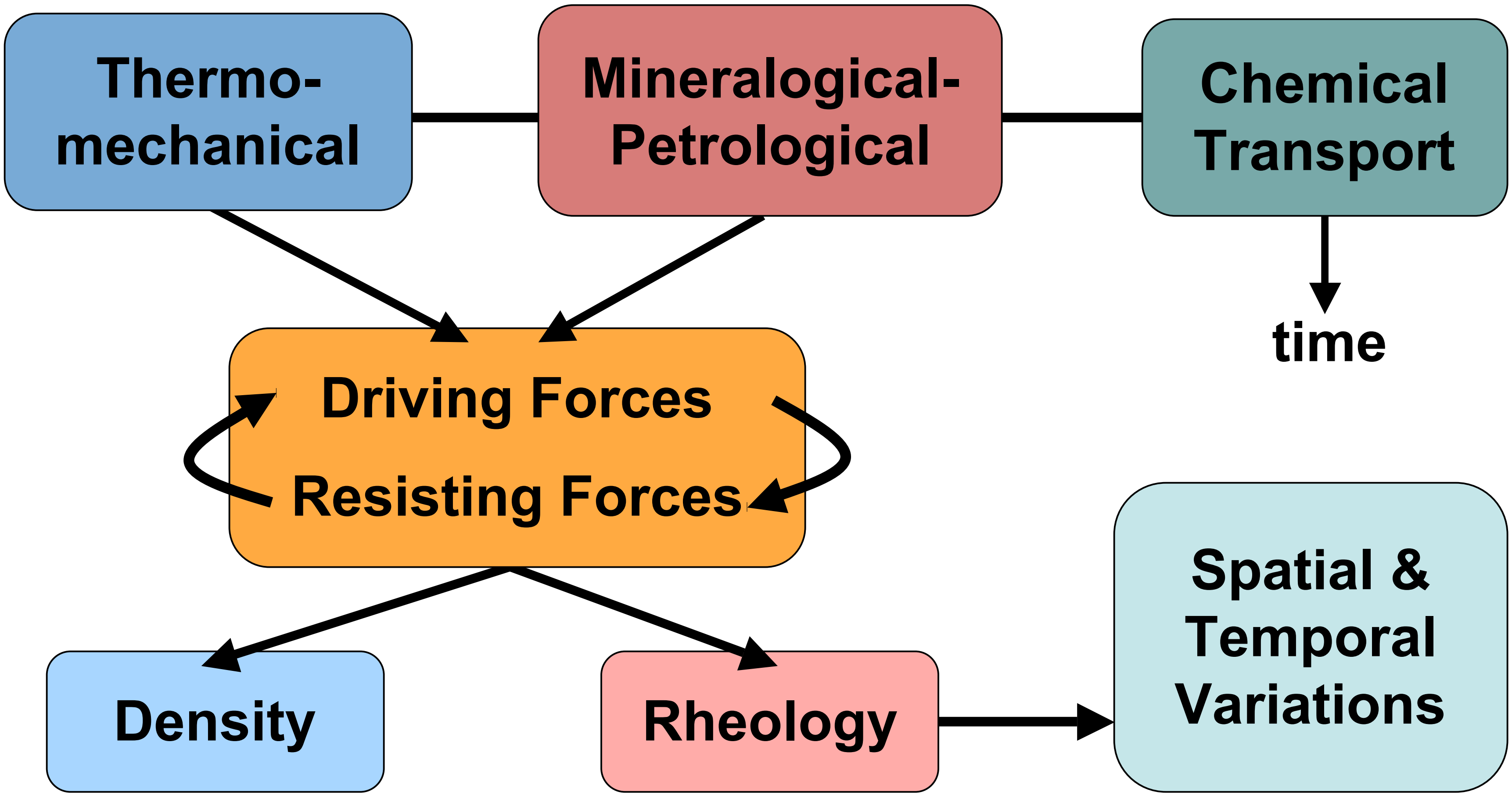
Why so many Questions?



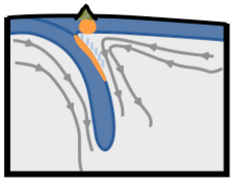
We know something is missing, but we still match observations.



The Dynamical System



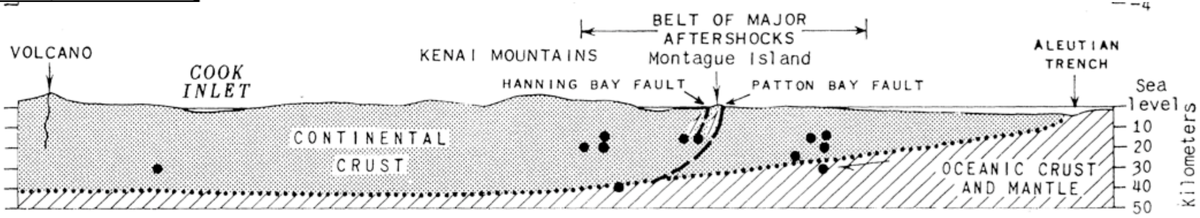
- Non-linear interactions & dynamic feed-backs.



Outline

- ***Historical Perspective***
  - ***Pre***-Plate Tectonics
  - ***Since*** Plate Tectonics
  - An ***Unprecendented*** Time for Subduction Models
- ***The Dynamical System***
  - Thermo-mechanical: driving & resisting forces.
  - Mineralogical-petrological: linking to **fluids**.
  - Chemical Transport ***- the importance of time.***
- ***Conclusions***
  - Transforming a kinematic theory of plate tectonics to a dynamic theory.

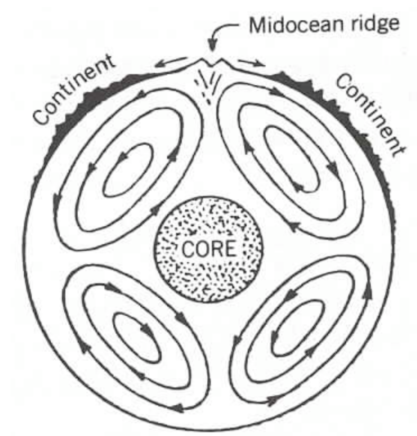
Pre - Plate Tectonics



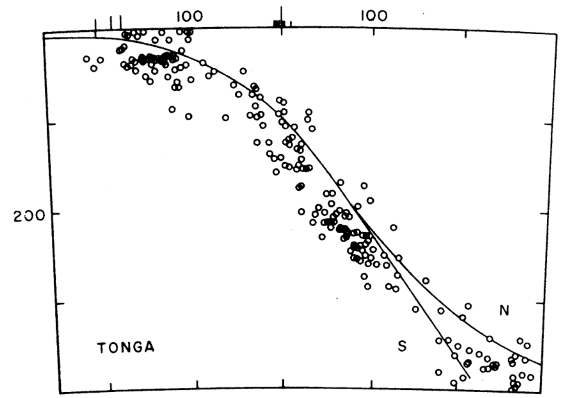
Internal deformation of subducted lithosphere.
- Isacks & Molnar, 1969

Deep planar fault zone
- Elsasser, 1968

Lithospheric thrusting
- Plafker, 1965



Mantle Convection
- Holmes, 1944



Mega-shear to 700 km
- Benioff, 1954

Crustal-scale thrusting
- Hess, 1962

1940s ***1950s*** ***1960s***

- ***Subduction into the mantle was one of the last pieces of the plate tectonics puzzle.***

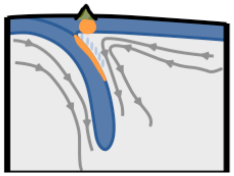
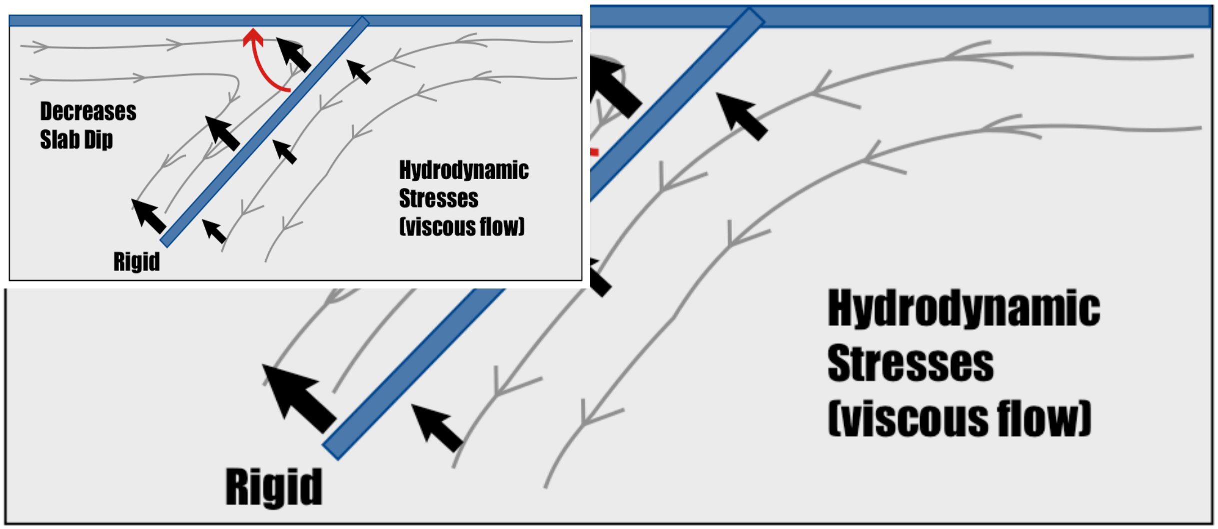
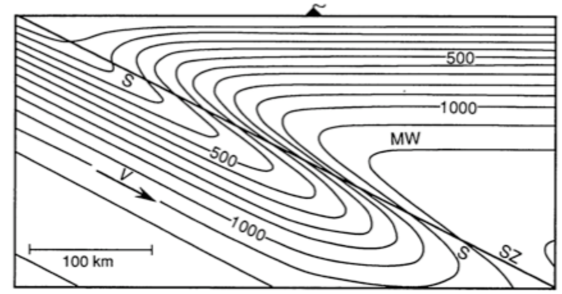


Plate Tectonics: in the SZ





Linking slab temp. to mineralogy & petrology
- Peacock, 1990

Corner-flow model.
- McKenzie, 1969

1960s

Dynamic topography from corner-flow
- Sleep, 1975

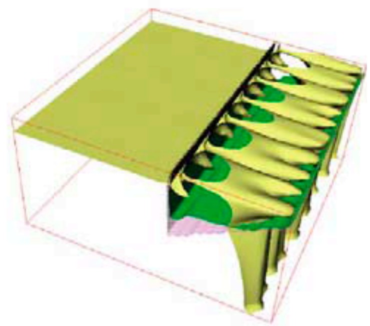
1970s → 1980s

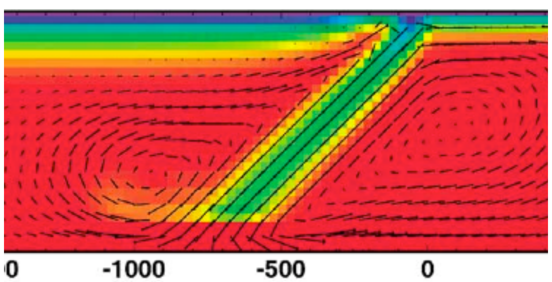
Slab thermal structure
-Toksov, 1971; 1973

1970s → 1990s

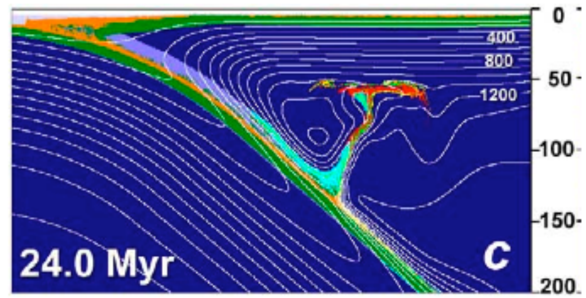
- ***Early analytic models capture major processes.***
  - ***Force balance on slab.***
  - ***Slab thermal structure.***

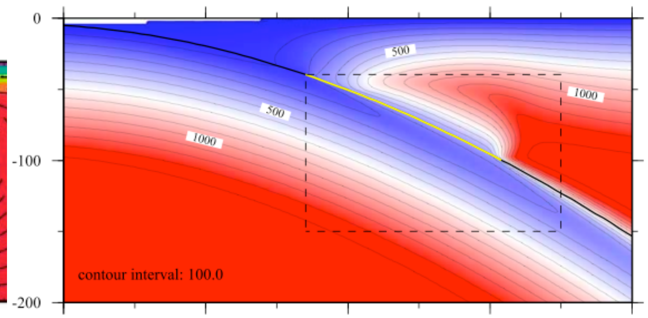
Kinematic Slab - Dynamic Wedge





Wedge/back arc flow
- Bodri & Bodri, 1978
- Toksov & Hsui, 1978





Convection in the wedge
- Ida, 1983
- Honda, 1985

3D, anisotropy implication
- Kneller & van Keken, 2007

Non-linear viscosity
- Kneller et al., 2007

Compositional & phase: density & viscosity
- Gerya & Yuen, 2003

Low viscosity wedge
- Honda & Saito, 2003

Temperature-dep. visc.
- Eberle, 2001

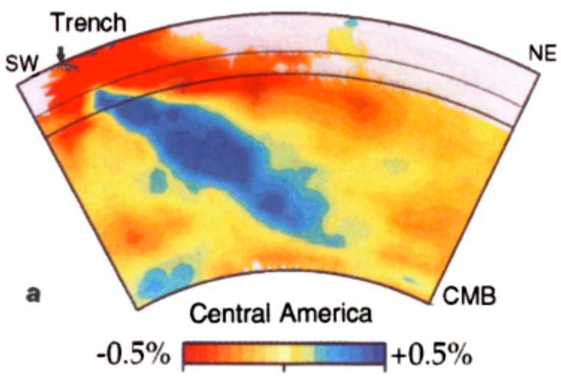
1970s

1980s

1990s → 2000s

- ***Slab & mantle wedge thermal/min./pet. structure.***
- ***Fluid transport***
- ***Seismic anisotropy.***

Observations



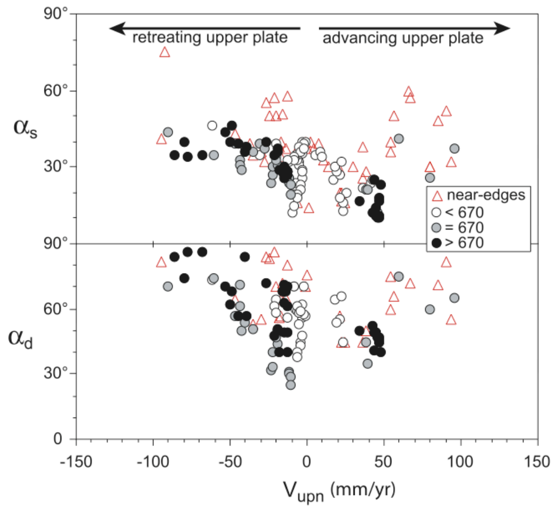


Plate kinematics & characteristics
- Mueller et al., 1997
- Lallemand et al., 2005

Seismic anisotropy
- Russo & Silver, 1994
- Fischer et al., 1998
- Long & Silver, 2008

Plate kinematics & characteristics
- Jarrard, 1986

Seismic tomography
- e.g., van der Hilst, 1997

Arc curvature, slab dip, subduction velocity.
- Tovish & Schubert, 1978

Geoid & dynamic topo.
- Hager 1984

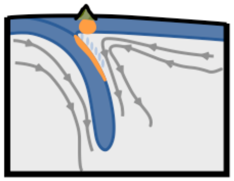
Plate tectonic reconsts.
- e.g., DeMets, 1990

1970s

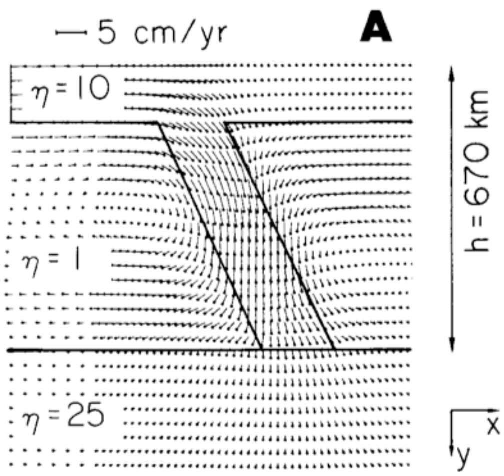
1980s

1990s → 2000s

- ***Connecting kinematics to dynamics.***

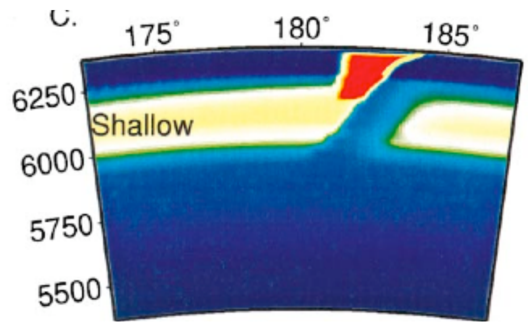


Instantaneous (quasi) Dynamic



Stress-state in slab
- Vassiliou, 1984

_1980s_



3D, Weak plate bndy, non-linear rheology
- Zhong & Gurnis, 1996

3D, Lateral (moderate) viscosity variations
- Moresi et al., 1996

2D, Faults & non-linear viscosity
- Zhong & Gurnis, 1992, 1994

_1990s_

2D, Overriding plate root geometry & slab suction

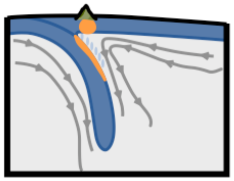
- Driscoll et al., 2009

3D, Slab strength effect toroidal & poloidal flow
- Piromallo et al., 2006

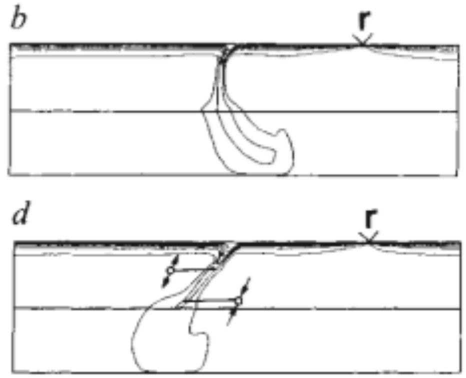
3D, Temp-dep, low viscosity wedge
- Billen & Gurnis, 2001

_2000s_

- ***Rheologic Structure:***
  - ***mantle, slab, plate boundaries, wedge, crust...***
- ***Surface deformation:***
  - ***topography, geoid, stress-state.***



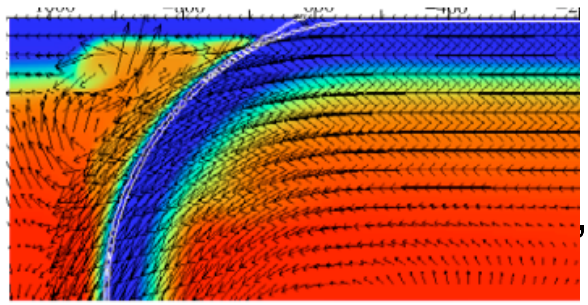
Fully Dynamic (t-dependent)



2D, Temp-dep,
- Gurnis & Hager 1988

2D, Phase trans. (mech)
- Christensen & Yuen, 1984

_1980s_



2D, Subduction initiation
- Toth & Gurnis, 1998

2D, Trench migration
- Olbertz et al., 1997
- Griffiths et al., 1995

2D, Phase trans. (T-dep. viscosity)
- King, 1991

_1990s_

2D, wedge rheology
- Arcay et al., 2008

3D, Slab width effects
- Stegman, 2006

2D, Slab detachment
- Gerya & Yuen, 2004

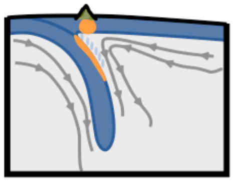
3D, Trench migration
- Funiciello et al., 2003

2D, Comp., grain-size-dep. slab visc
- Cizkova et al., 2002

2D, Oceanic plateaus
- van Hunen et al 2000

_2000s_

- ***Buoyancy forces: phase transition, slab, crust...***
- ***Rheologic structure: mantle, slab, wedge...***
- ***Geometry: 2-D, 3-D, slab edges, interactions...***



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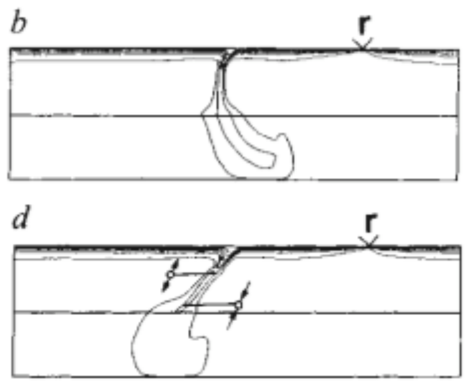

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- Gurnis & Hager 1988

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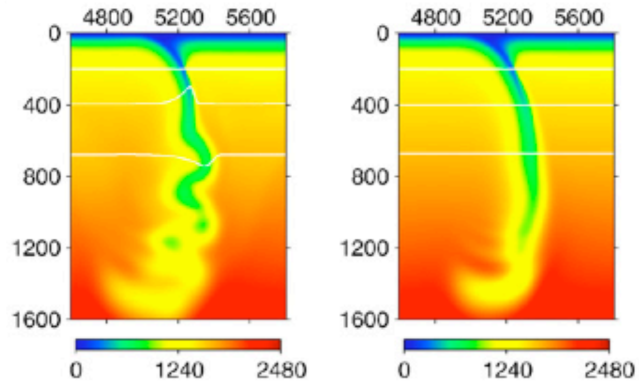
- Christensen & Yuen, 1984



2D, Trench migration
- Olbertz et al., 1997
- Griffiths et al., 1995

2D, Phase trans.
(T-dep. viscosity)
- King, 1991

3D, Slab-edge flow & slab depth
- Honda, 2009

2D, Slab Buckling LM.
- Behounkova & Cizkova 2008

2D, Double-slab sub.
- Mishin et al., 2008

2D, 1-sided subduction
- Gerya et al., 2008

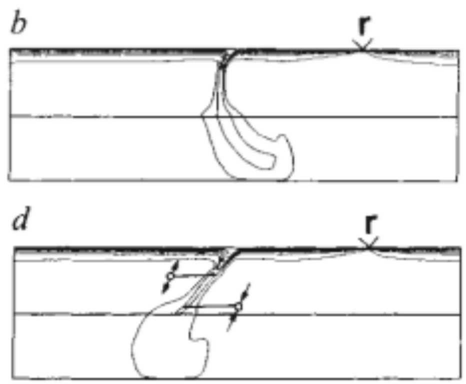
2D, Flat slabs & LVC
- Manea & Gurnis, 2007

2D, wedge rheology
- Arcay et al., 2008
3D, Slab width effects
- Stegman 2006
2D, Slab detachment
- Gerya & Yuen, 2004
3D, Trench migration
- Funiciello et al., 2003
2D, Comp., grain-size-dep. slab visc
- Cizkova et al., 2002
2D, Oceanic plateaus
- van Hunen et al 2000

1980s ***1990s*** ***2000s***

- ***Buoyancy forces: phase transition, slab, crust...***
- ***Rheologic structure: mantle, slab, wedge...***
- ***Geometry: 2-D, 3-D, slab edges, interactions...***

Fully Dynamic (t-dependent)



2D, Temp-dep,
- Gurnis & Hager 1988

2D, Phase trans. (mech)
- Christensen & Yuen, 1984

1980s

2D, Meta-stable olivine,
- Schmeling, 1999

2D, Subduction initiation
- Toth & Gurnis, 1998

2D, Trench migration
- Olbertz et al., 1997
- Griffiths et al., 1995

2D, Phase trans.
(T-dep. viscosity)
- King, 1991

1990s

2D, Compressibility
- Lee & King, 2009

2D, Ridge-trench int.
- Burkett & Andrews, 2009

2D, Coupled/uncoupled continental collision
- Faccenda et al., 2009

3D, Slab-edge flow & slab depth
2D, Slab Buckling LM.
- Honda, 2009
2D, Double-slab sub.
- Behounkova & Cizkova 2008
2D, 1-sided subduction
- Mishin et al., 2008
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2D, Oceanic plateaus
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2000s

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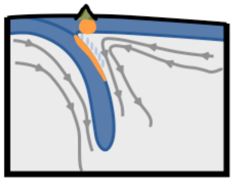
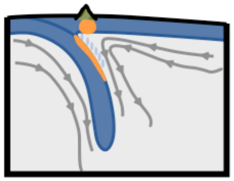


A Multi-variate System

- ***Geometrical Variables***
  - 2D vs. 3D
  - Over-riding plate
  - Interaction w/ other plate boundaries.
- ***Mineral-/Petro-logical***
  - Compositional variation
    - Density
    - Rheology
- ***Physical Properties***
  - Rheology
  - Thermal parameters (α,κ)
  - Compressibility
- ***Coupled Systems***
  - Solid phase changes
  - Hydration/dehydration
  - Melting

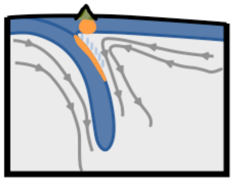
Link to Observations & Time Evolution

Transform a kinematic theory to a <u>dynamic theory.</u>

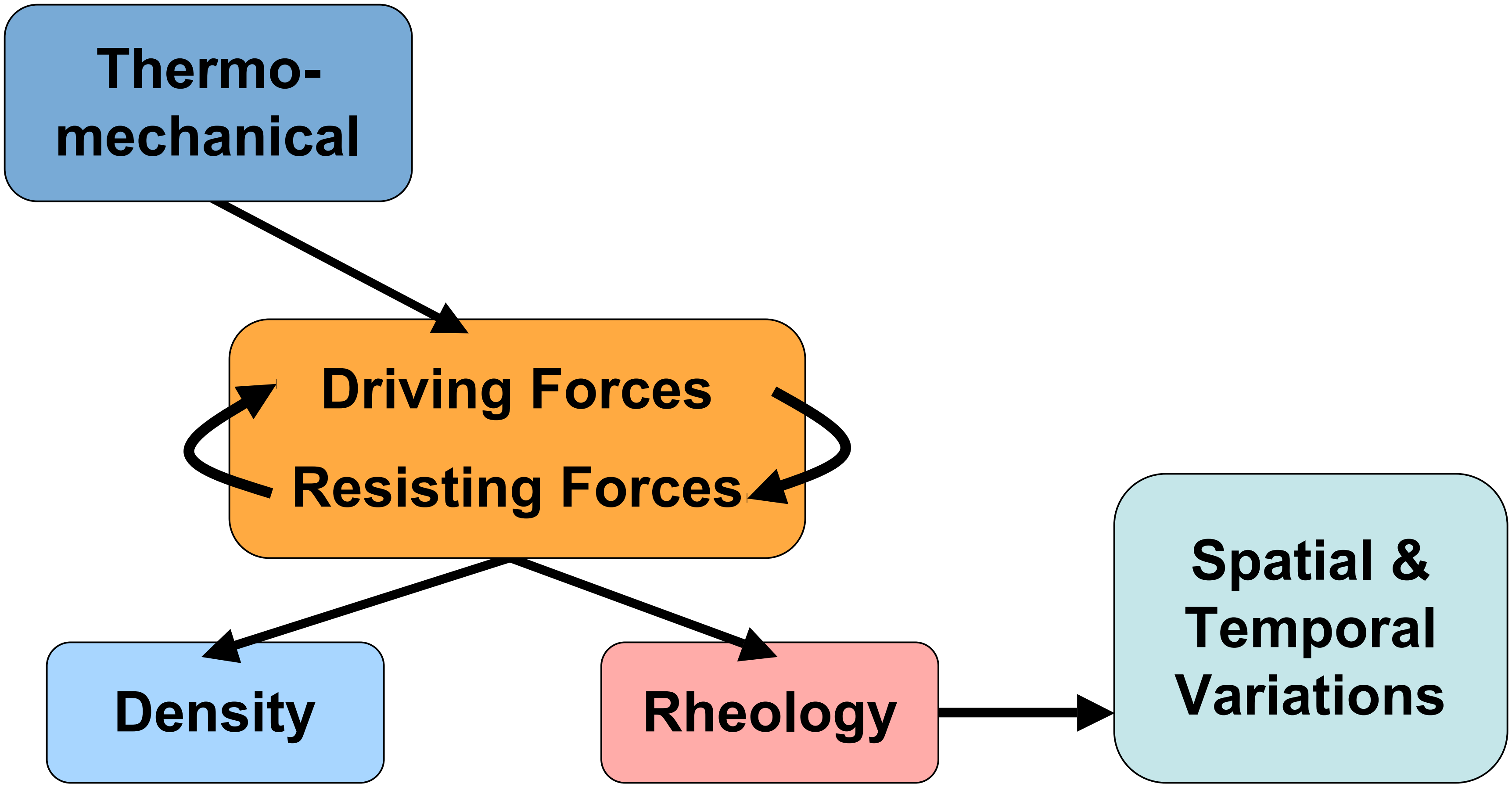


An *Unprecedented* Time

- ***Access*** to new & more complete observations on kinematics & geometry
  - plate tectonic reconstructions, seismic observations on slab shape, seismic anisotropy constraints on flow patterns.
- ***Advances*** in numerical & analogue methods
  - CPU-speed, RAM, parallel processing, better solvers; imaging techniques, materials...
- ***Ability*** to link dynamics to observations/ data/ processes from other disciplines
  - petrology, geochemistry (origins, process/transport times), geology-structures, thermo-barometry.



The Dynamical System



Thermo-Mechanical

- **Conservation Equations**

– Conservation of Mass:

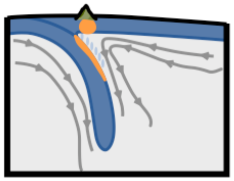
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0$$

– Conservation of Momentum:

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} \right) = \nabla \cdot \vec{\sigma} - g\rho\vec{z}$$

– Conservation of Energy:

$$\frac{\partial C_p T}{\partial t} + \vec{v} \cdot \nabla C_p T = \frac{1}{\rho} \nabla \cdot k \nabla T + H$$



Thermo-Mechanical

- **Common simplifications.**

– Conservation of Mass (incompressible; $\delta\rho = 0$):

$$\nabla \cdot \vec{v} = 0$$

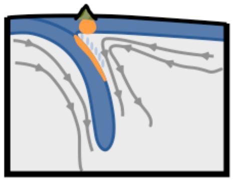
– ***Compressibility: minor effects in shallow mantle (Lee & King, 2009).***

– Boussinesq Approximation ($\delta\rho << \rho$):

$$\rho = \rho_o(1 - \alpha(T - T_o))$$

– Constituitive Equation (incompressible):

$$\sigma_{ij} = \eta \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) - p\delta_{ij}$$



Thermo-Mechanical

- *Simple Equations. Complexity comes from:*
  - *Geometry, material properties & variation in materials.*
  - Conservation of Mass (incompressible; $\delta\rho = 0$):

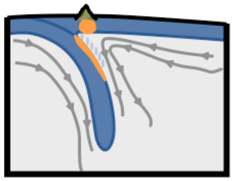
$$\nabla \cdot \vec{v} = 0$$

  - Conservation of Momentum:

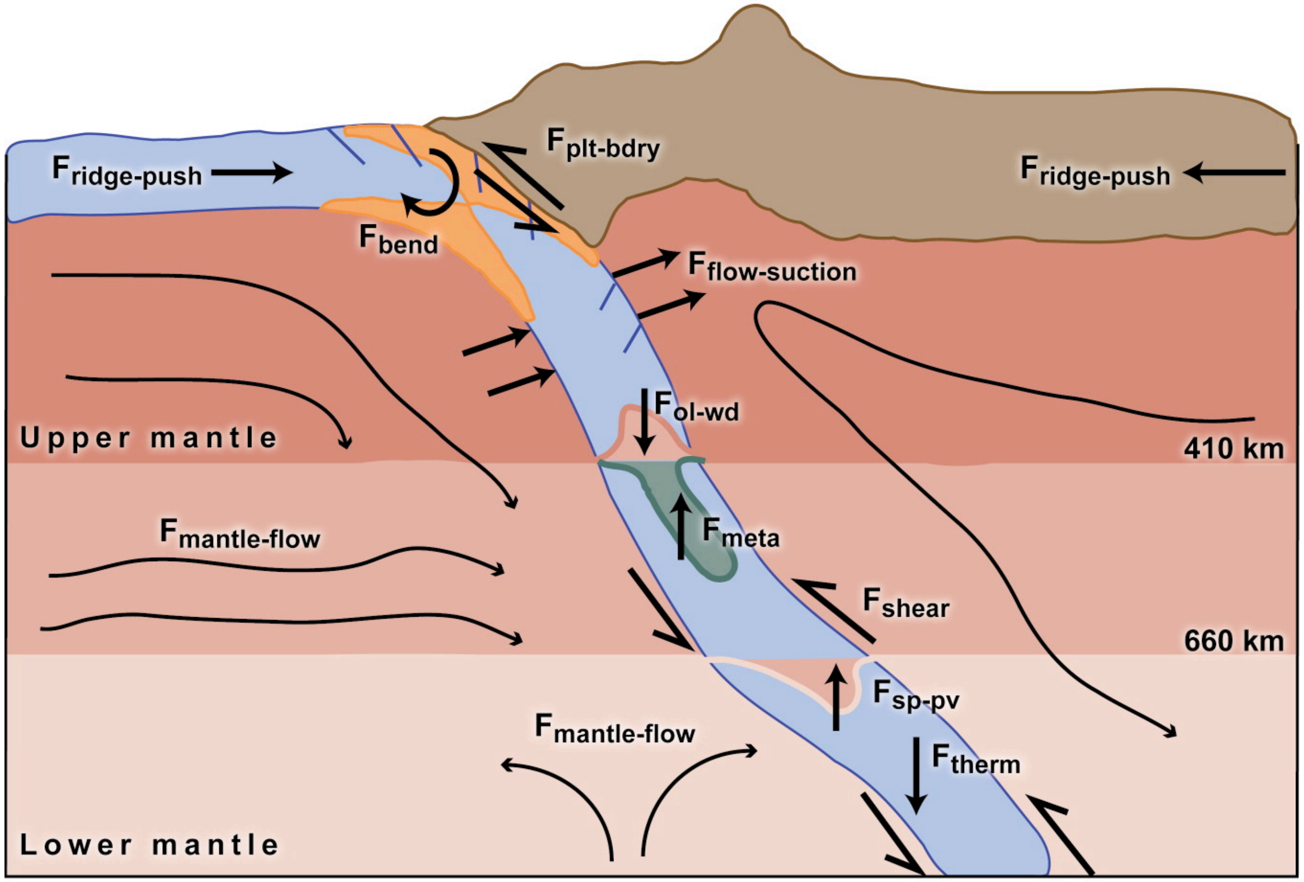
$$\rho \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} \right) = \eta \nabla^2 \vec{v} - \nabla p - g\rho\vec{z}$$

  - Conservation of Energy (constant C_p, κ; $H = 0$):

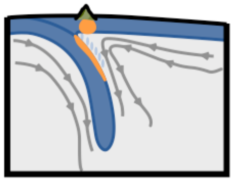
$$\rho \left(\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T \right) = \kappa \nabla^2 T + \frac{H}{C_p}$$



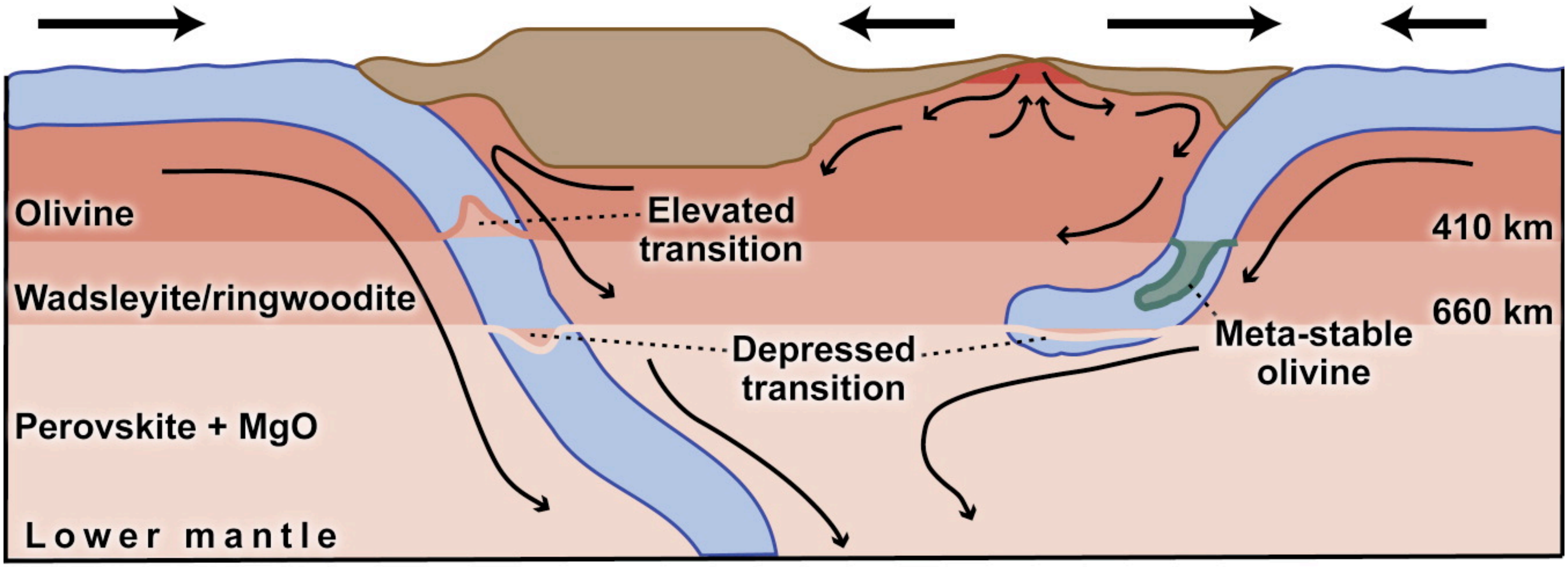
A *Dynamic* Slab



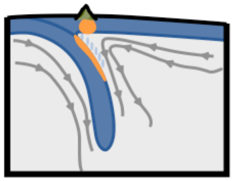
Driving forces vs. resisting forces...



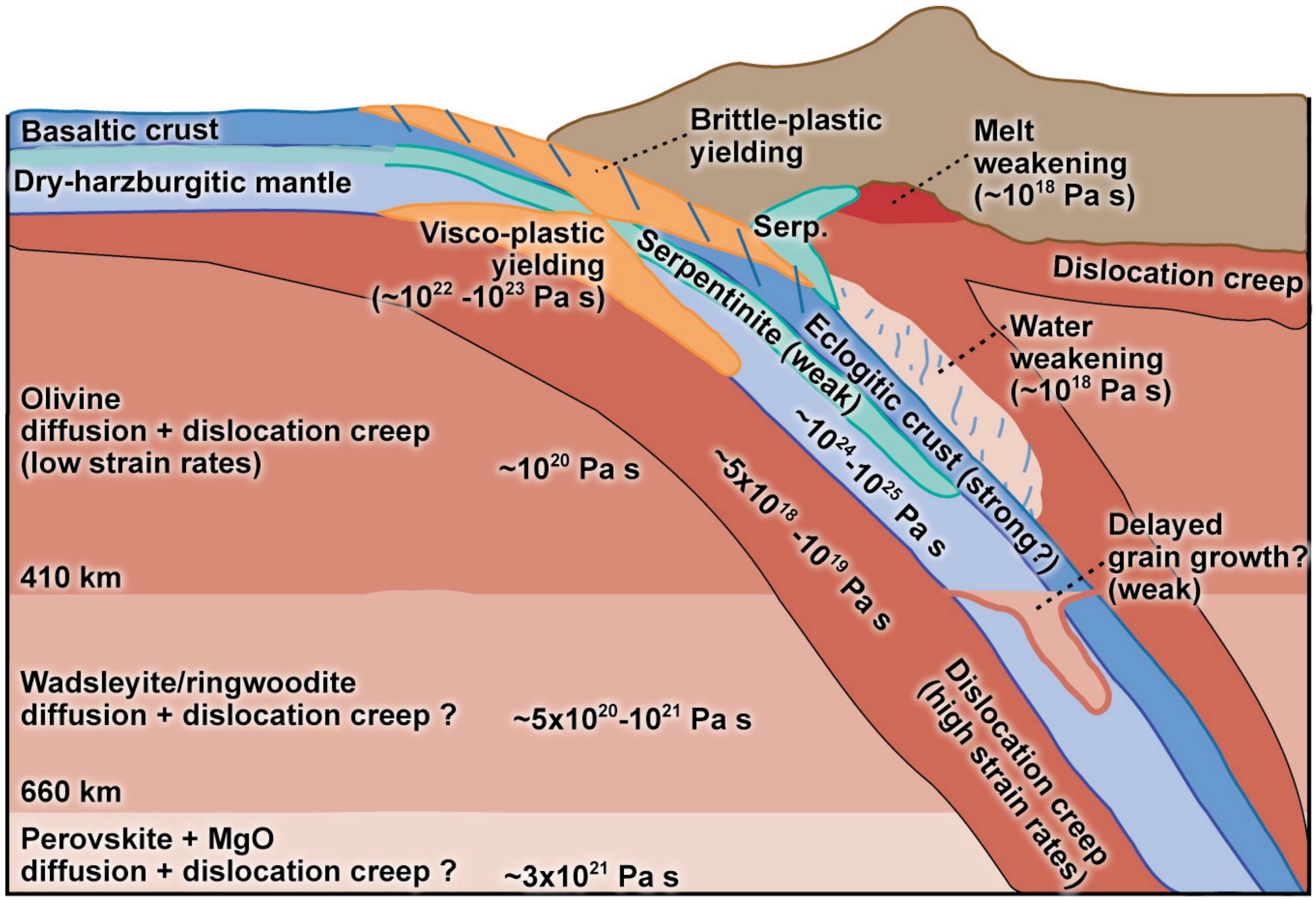
Material Properties: Density

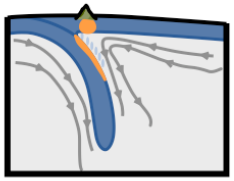


- *Previous, recent, models on*
  - *phase transitions, meta-stable olivine*
  - *mantle wedge dynamics*
  - *oceanic plateau subduction*
- *Lack of recent models evaluating*
  - *Local density variation in 3D (linked to composition).*



Material Properties: Rheology





Material Properties: Rheology

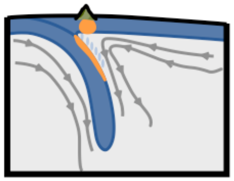
Laboratory experiments: large temperature, strain-rate & grain-size dependence.

- Viscous flow law (for each mechanism):

$$\eta = \left(\frac{d^p}{A e^{(a\phi)} C_{OH}^r} \right)^{\frac{1}{n}} \dot{\epsilon}_{II}^{\frac{1-n}{n}} \exp\left[\frac{E + P_{lc} V}{n R T_t} \right]$$

where,
$T_t = T + T_{ad}$.
P_{lc} is the lithostatic pressure, including a compressibility gradient.

For dislocation (ds) creep $p = 0$, $n = 3.5$.
For diffusion (df) creep $p = 3$, $n = 1$.



Material Properties: Rheology

- Dislocation (ds) & diffusion (df) creep accommodate total strain-rate:

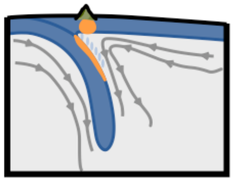
$$\dot{\epsilon} = \dot{\epsilon}_{df} + \dot{\epsilon}_{ds} \tag{2}$$

- For deformation at constant stress, the effective viscosity is:

$$\eta_{ef} = \frac{\eta_{df}\eta_{ds}}{\eta_{df} + \eta_{ds}} \tag{3}$$

For a background upper mantle viscosity of $\eta_o = 10^{20}$ Pas (at 250 km):
– Transition strain-rate ($\dot{\epsilon}_{df} = \dot{\epsilon}_{ds}$): $\dot{\epsilon}_t = 10^{-15}$ s^{-1}
for $C_{OH} = 300$ ppm-H/Si & $d = 10$ mm.

Dislocation creep decreases viscosity where the strain-rate is more than the transition value.



Material Properties: Rheology

- Plastic yield stress, σ_y, limits the stress (and viscosity). If,

$$\sigma_y > \eta_{df}\dot{\epsilon}_{II}$$

then,

$$\eta_y = \sigma_y/\dot{\epsilon}_{II}$$

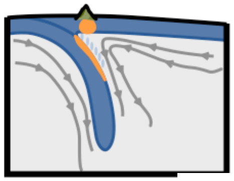
- Composite viscosity:

$$\eta_{comp} = \min(\eta_{ef}, \eta_y)$$

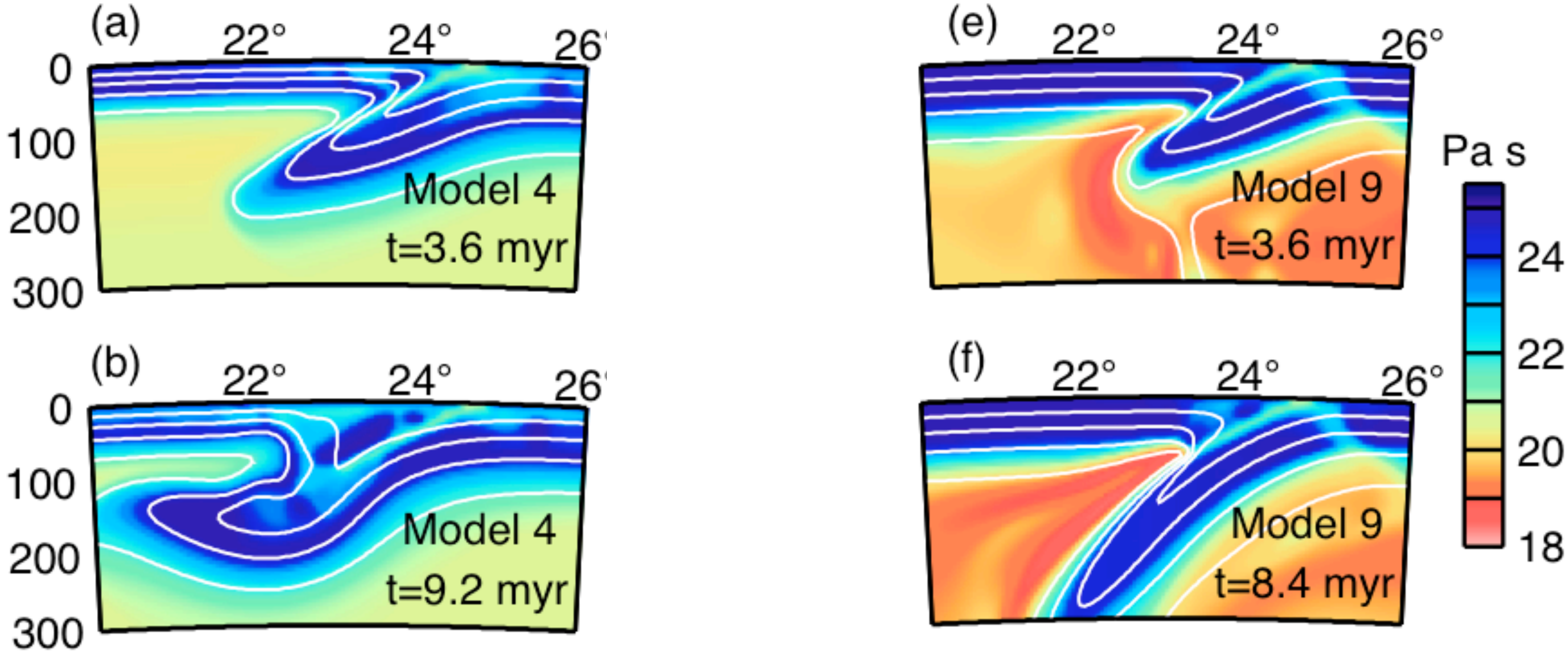
- ***Non-deforming regions remain highly viscous.***
- ***Yielding concentrates deformation.***

Rheology: Examples

- ***Subduction initiation***
- ***Long term subduction***
- ***3D instantaneous flow***
  - *Margarete Jadamec (PhD 2009)*
- ***Ridge-trench interaction***
  - *Erin Burkett (PhD, exp. 2010)*

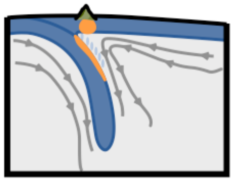


1. 2D Subduction Initiation

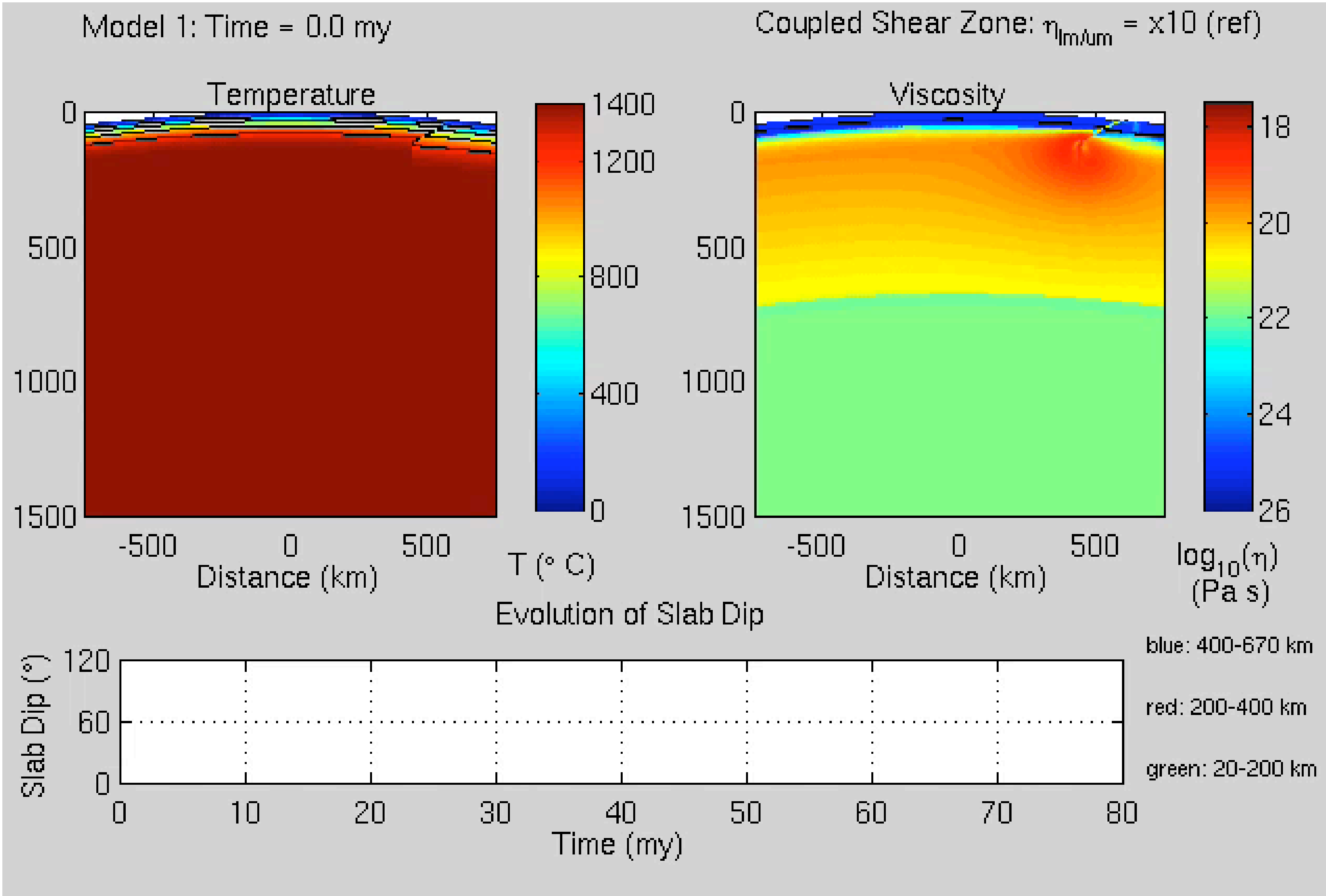


Newtonian **Composity Viscosity**

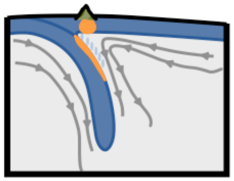
- ***Strain-rate weakening can counteract temperature-dependent strengthening.***

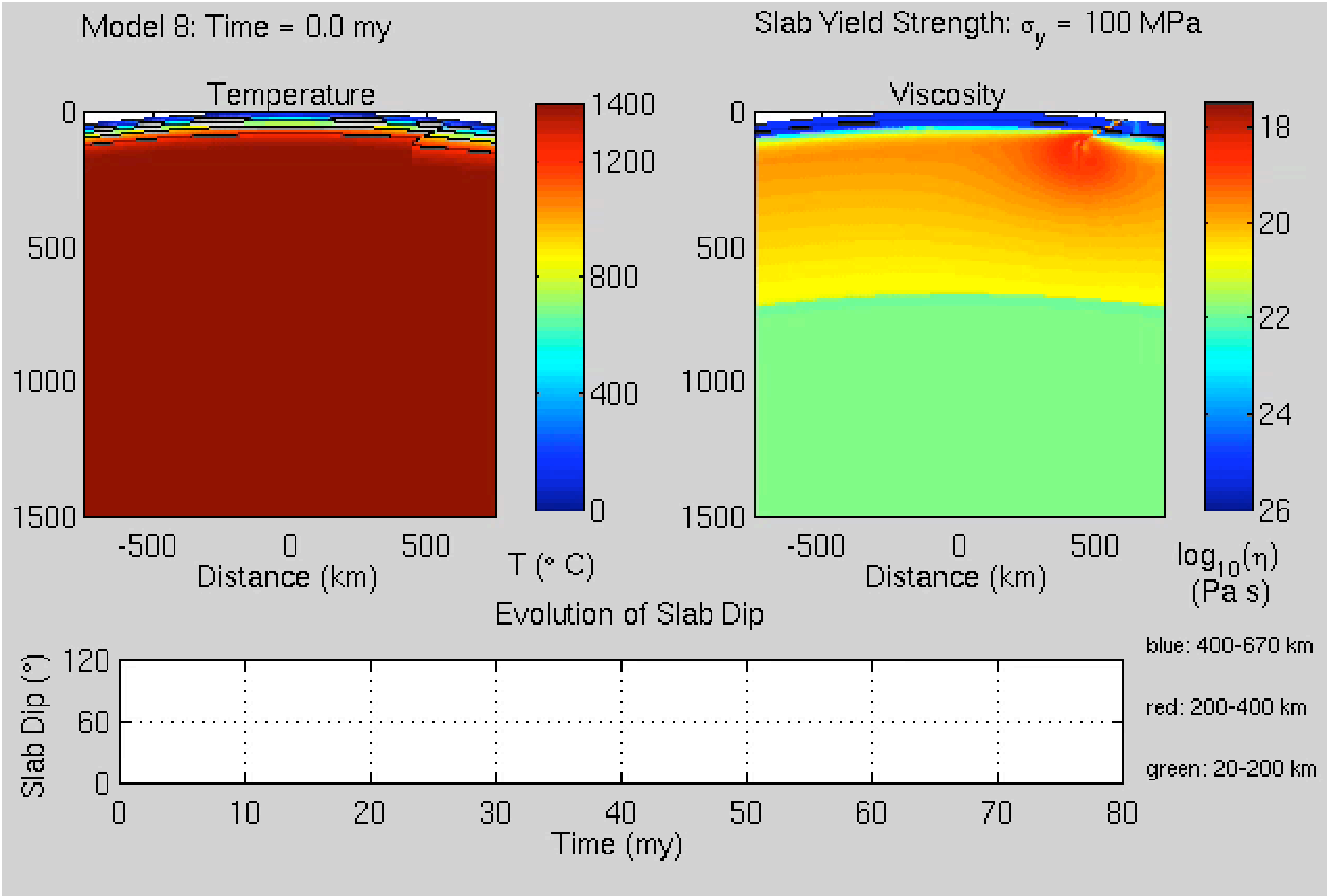


2. 2D Long Term Subduction

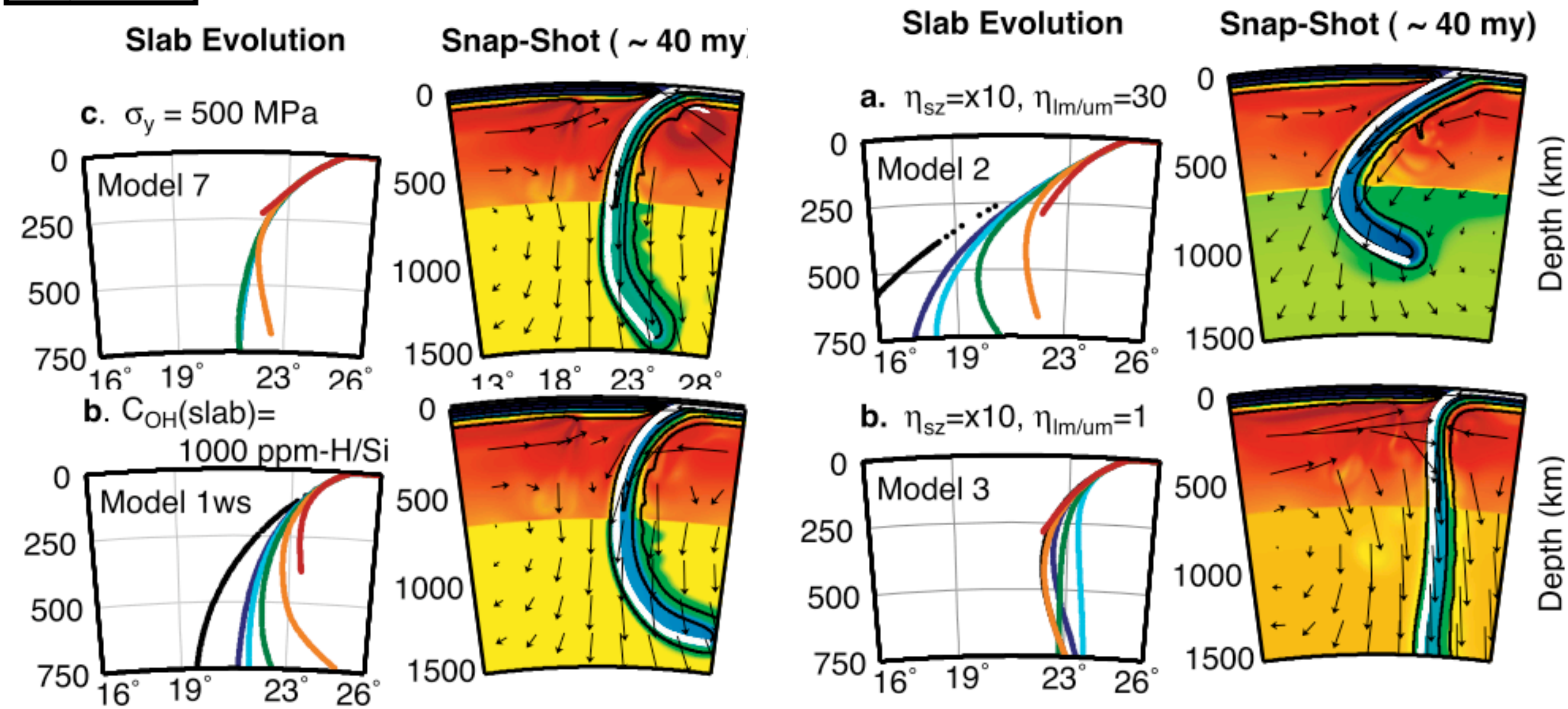


2. 2D Long Term Subduction

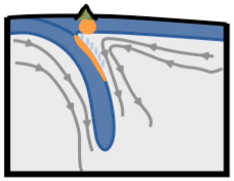




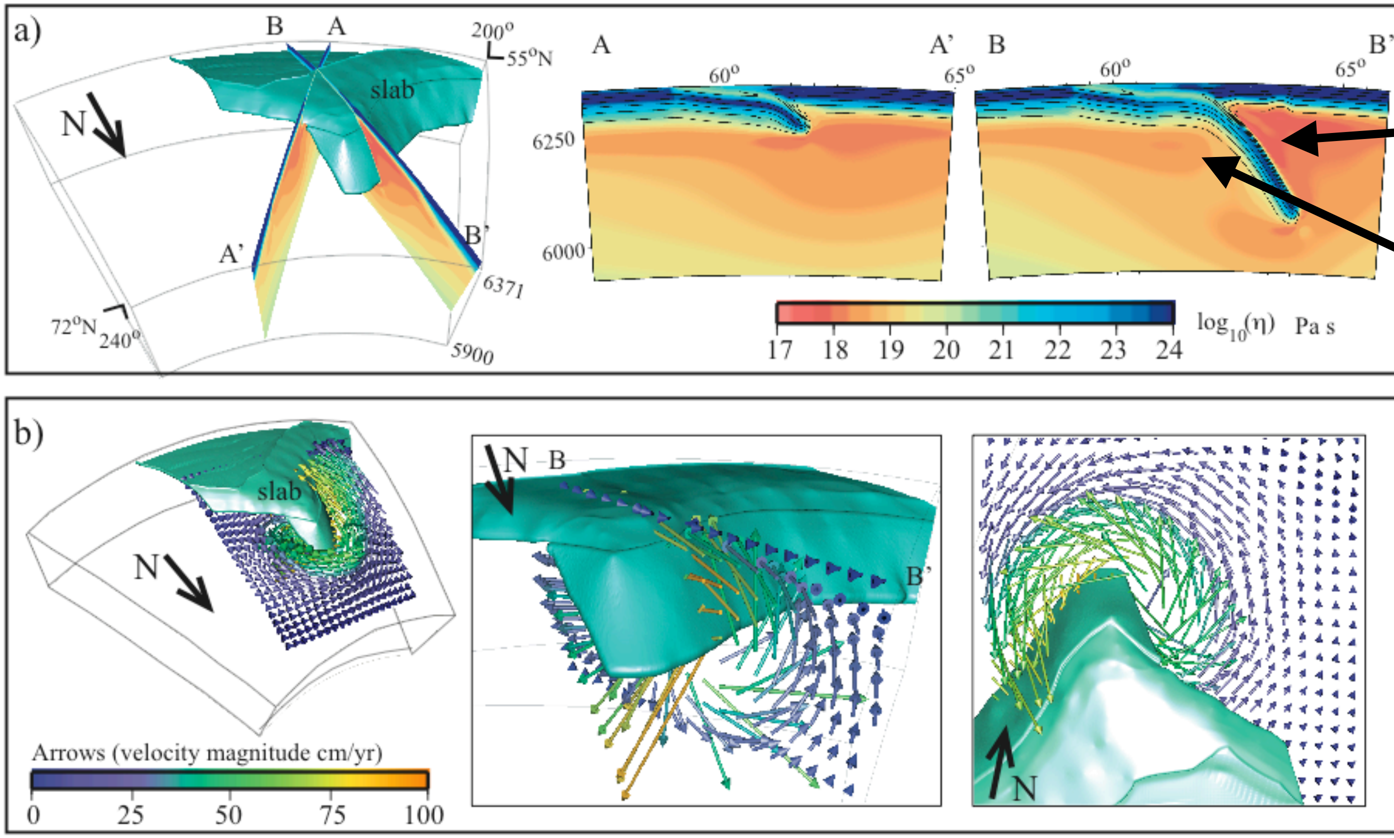
2. 2D Long Term Subduction



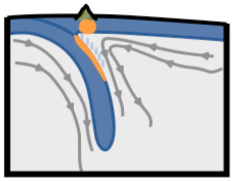
- ***High yield stress allows slab to:***
  - ***Better support own weight; Transfer stress along slab***
  - ***But depends on lower mantle viscosity***



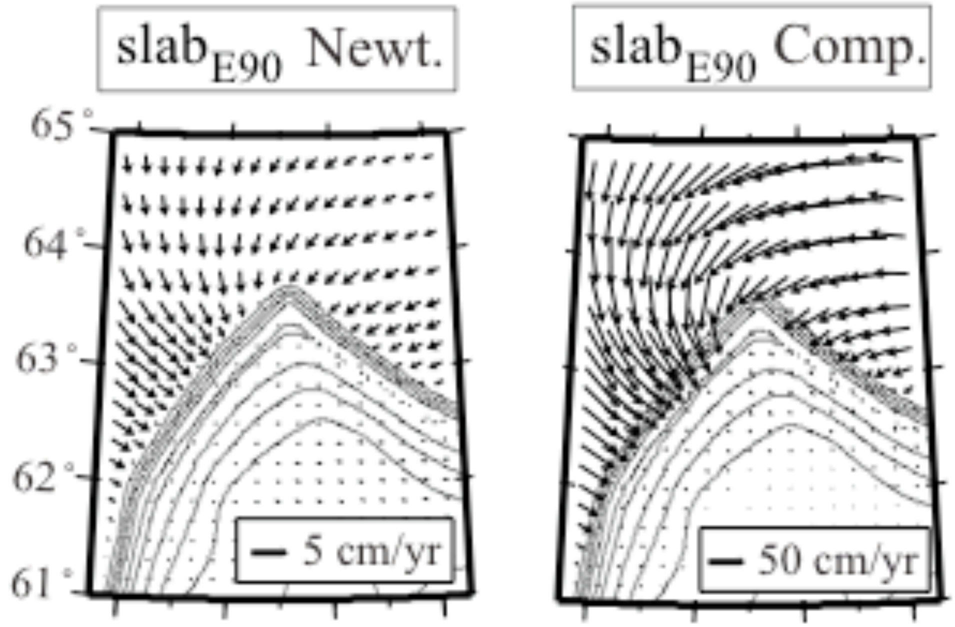
3. 3D Flow at a Slab Edge



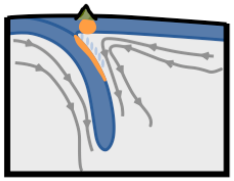
- ***Strain-rate weakened region provides little viscous support for upper-mantle slab.***
  - ***Slab is steepening (transient state of UM slabs?)***
  - ***Strong coupling between toroidal and poloidal flow.***



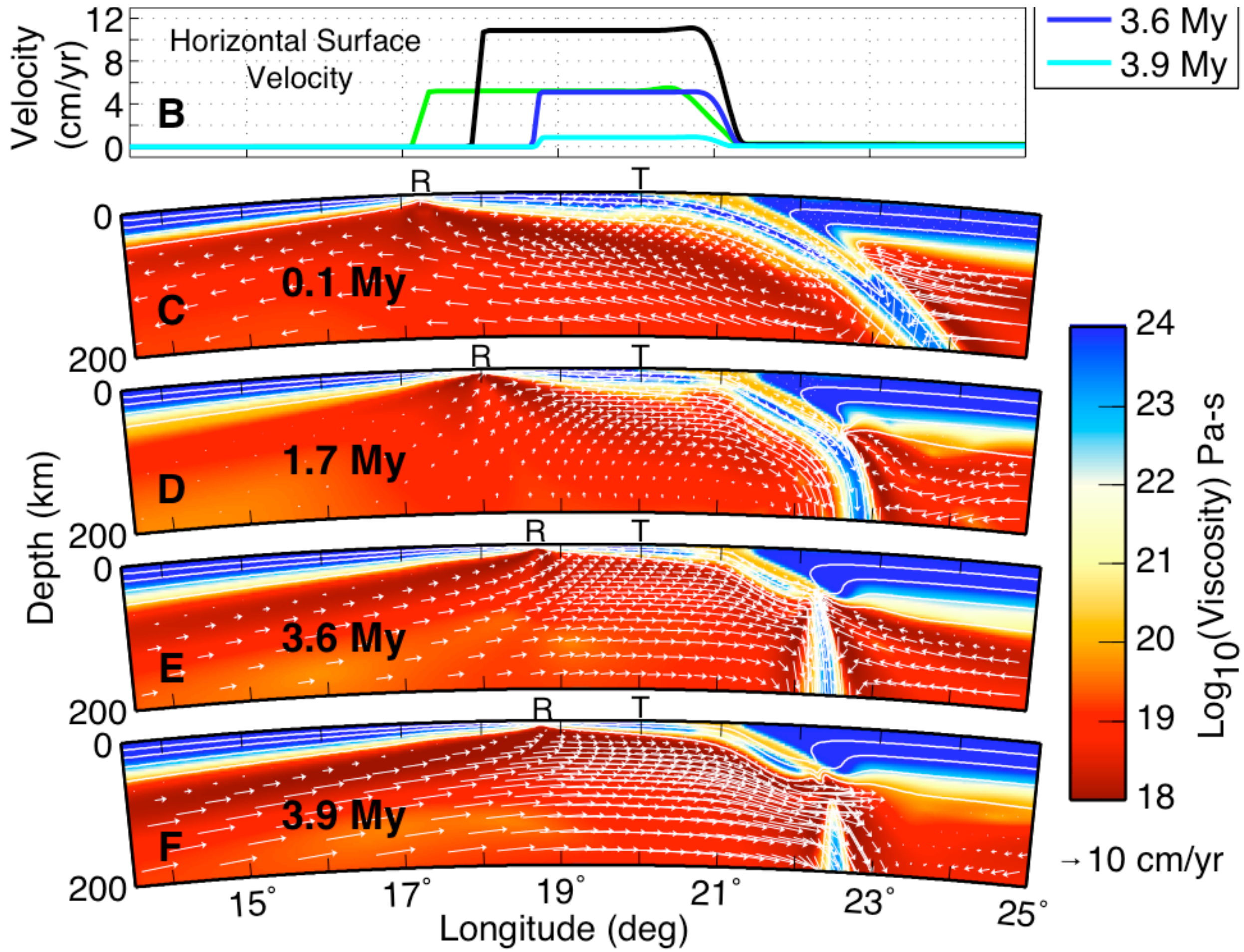
3. 3D Flow at a Slab Edge



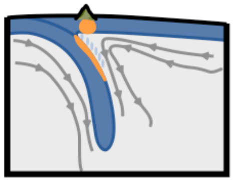
- ***Newtonian vs non-Newtonian flow:***
  - *Similar pattern, but stronger toroidal component.*
  - *Flow rate is 10-80 times faster.*
  - *Decouples surface plates from mantle flow (transient?)*



4. Ridge-Trench Interaction

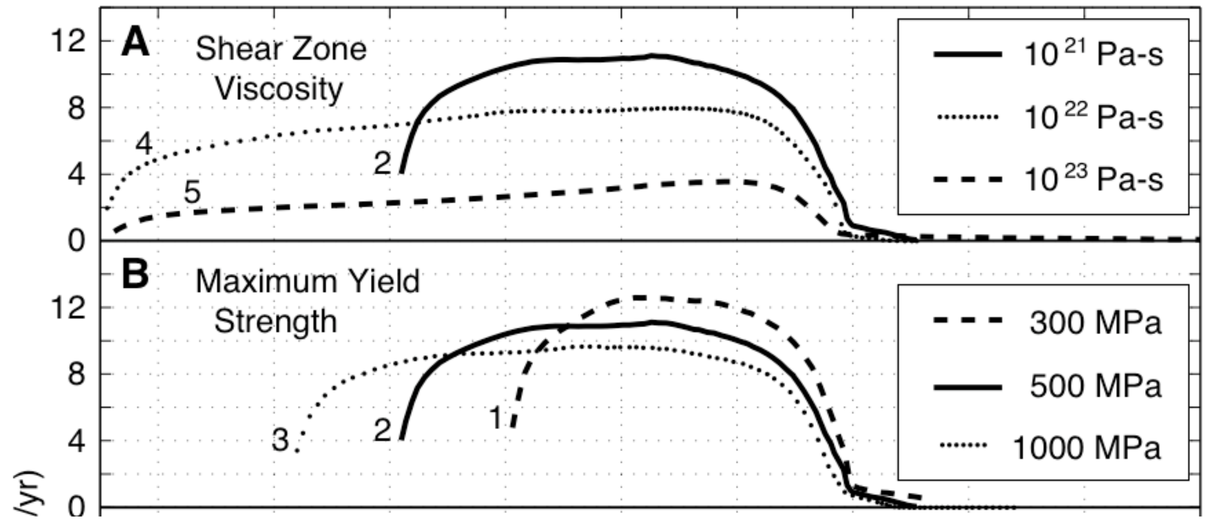


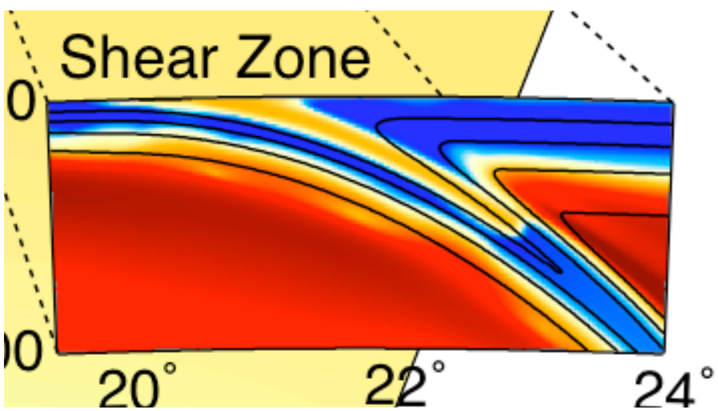
- *High yield stress & non-Newtonian viscosity leads to plate-like motion of young lithosphere.*



4. Ridge-Trench Interaction

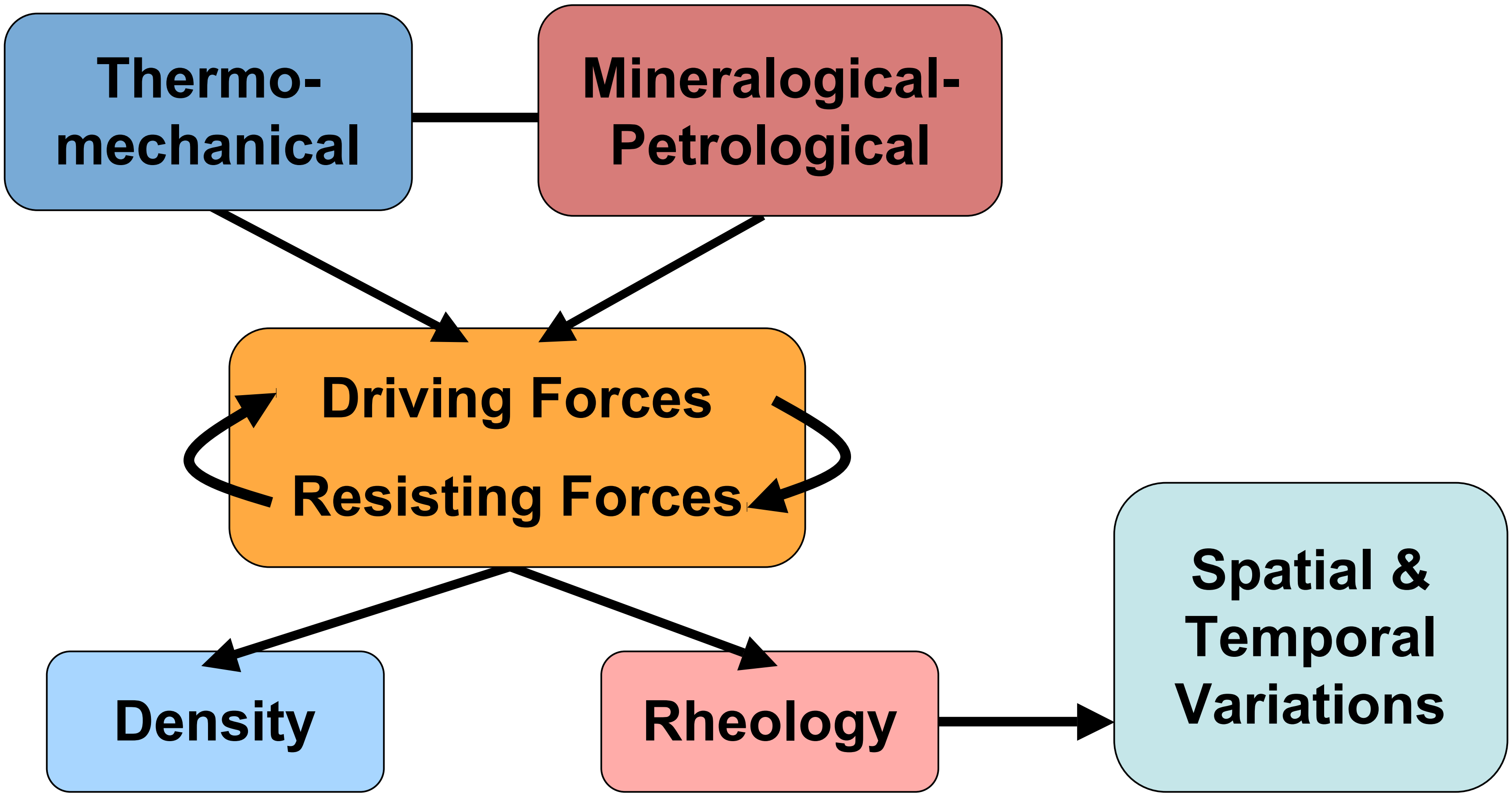
- ***Yielding within slab leads to slab detachment before ridge subduction.***

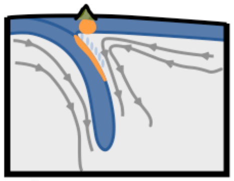




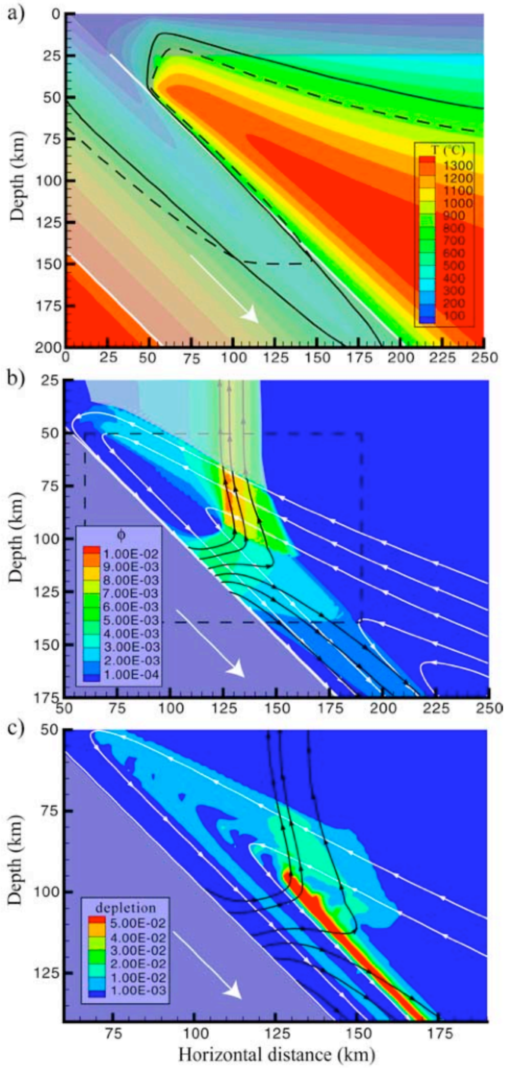
- ***Young plates have insufficient slab-pull to drive subduction in Newtonian mantle.***

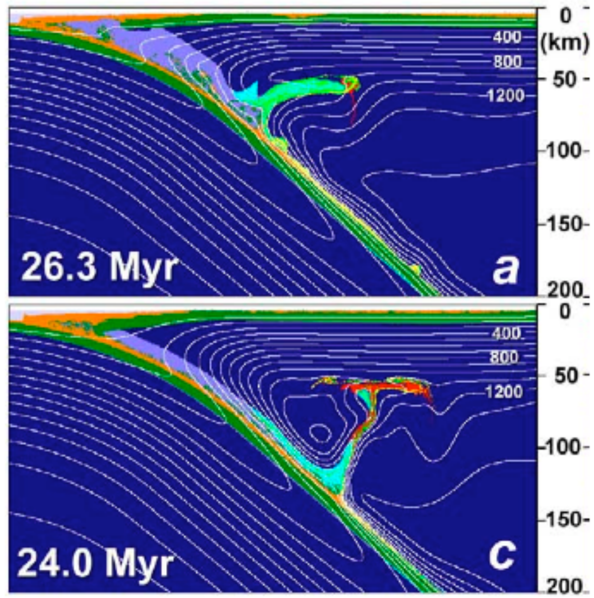
The Dynamical System





Mineralogical-Petrological





Fully-coupled mantle-wedge dynamics & petrology

- Baker-Hebert et al., 2009

Fluid transport, melting

- Cagniocle et al., 2007

Composite crust-mantle density & rheology in wedge

- Gerya & Yuen, 2003

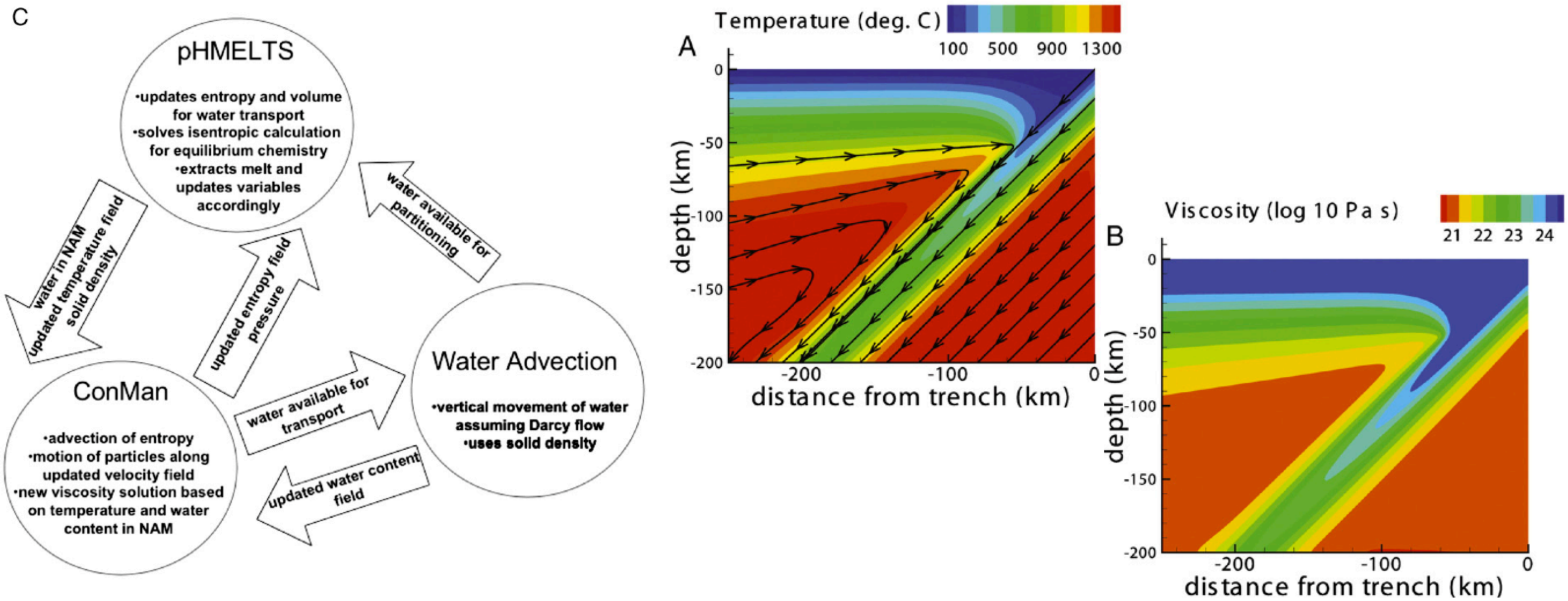
Min./pet. implications

- Davies & Stevenson, 1992

1990s → 2000s

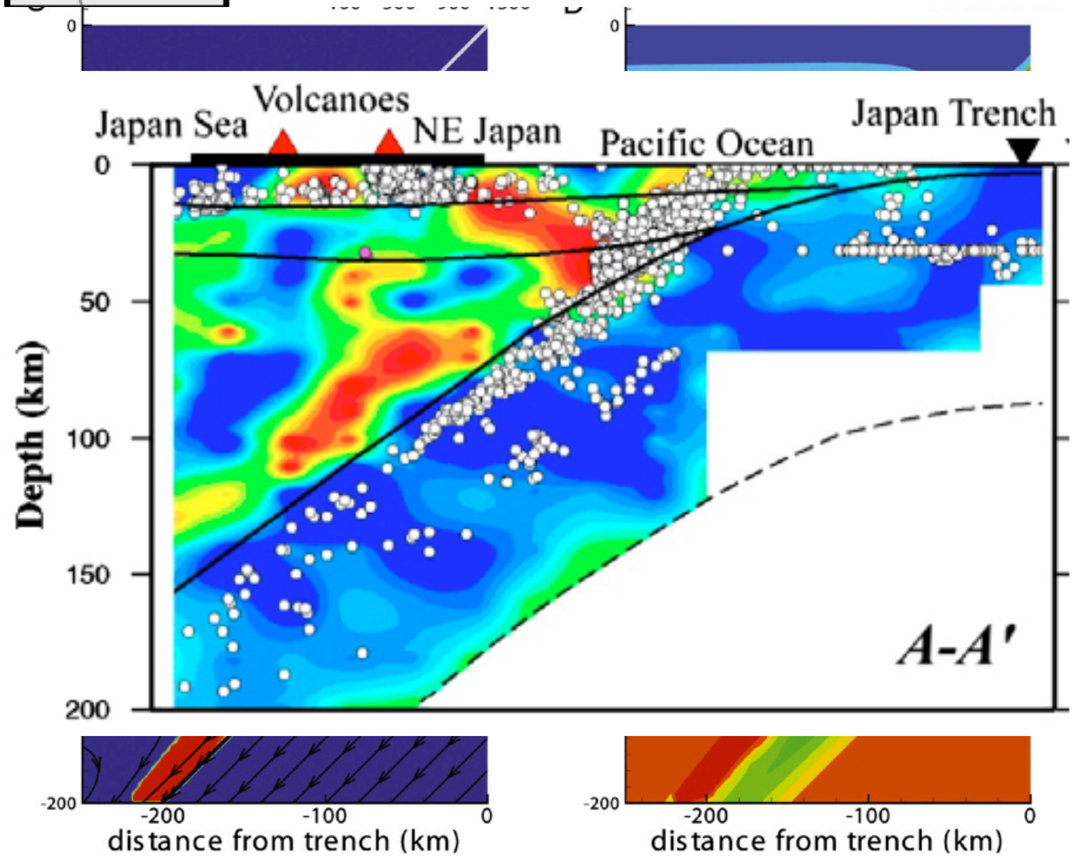
- ***Need coupled solid & fluid flow, density & rheology, detailed tracking of composition & phase.***

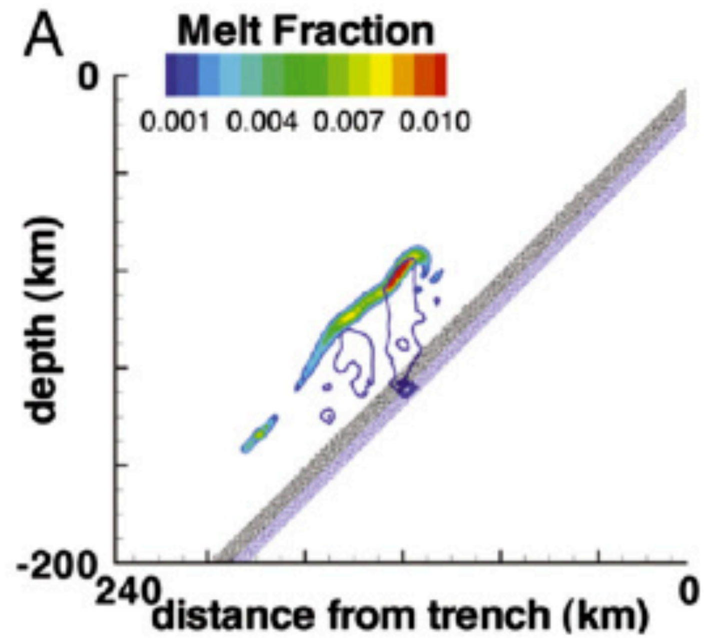
Coupled Solid-Fluid-Min.



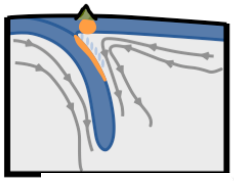
- Composition evolves including fluid & melt content.
  - Affects density (T, X) & rheology.
- Fluids move according to Darcy flow

Fluids Affect Solid Flow.

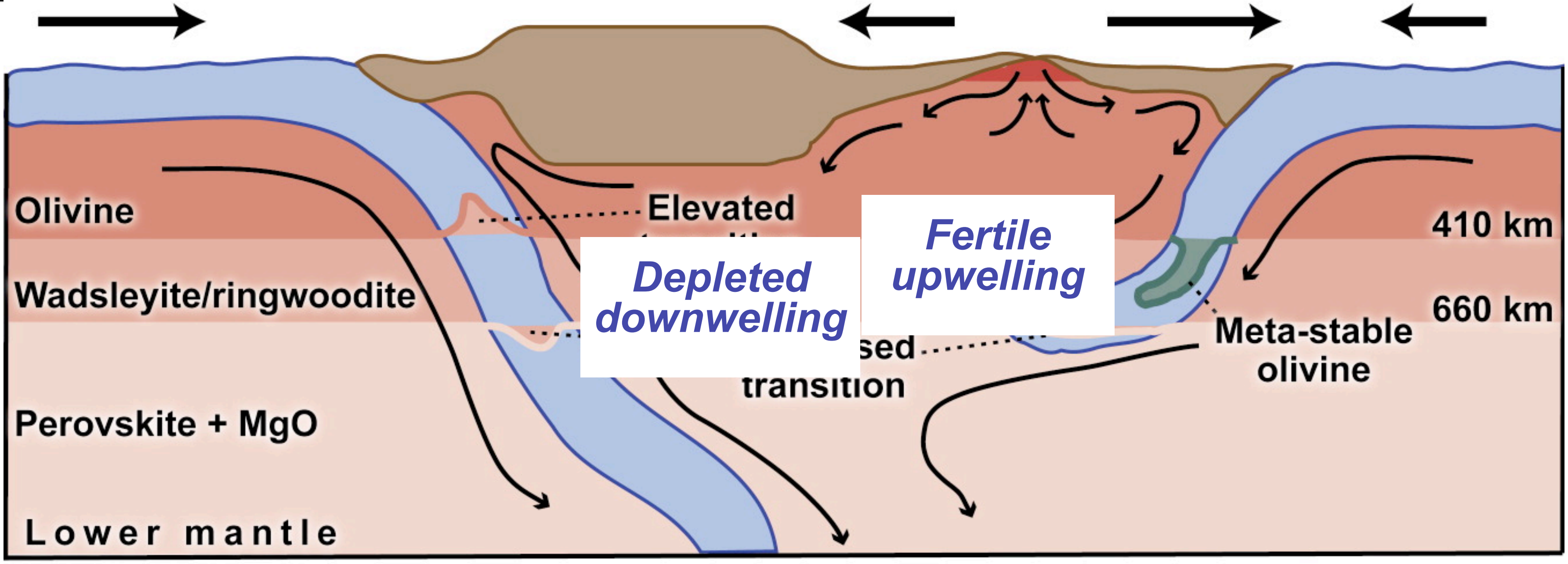




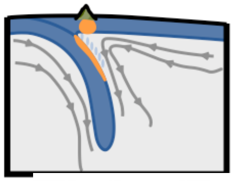
- ***Form low viscosity channel above slab.***
- ***Spatially & temporally variable melt fraction.***
  - ***Limits region of water effect on rheology.***



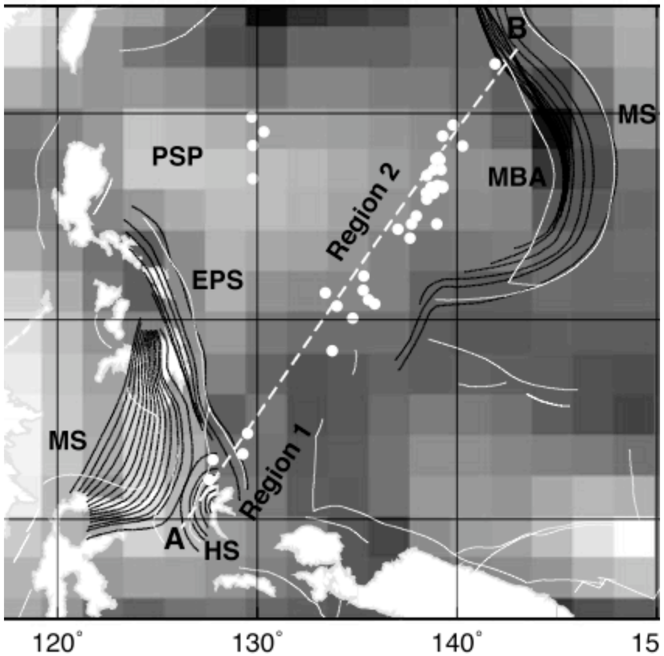
Mineralogical-Petrological

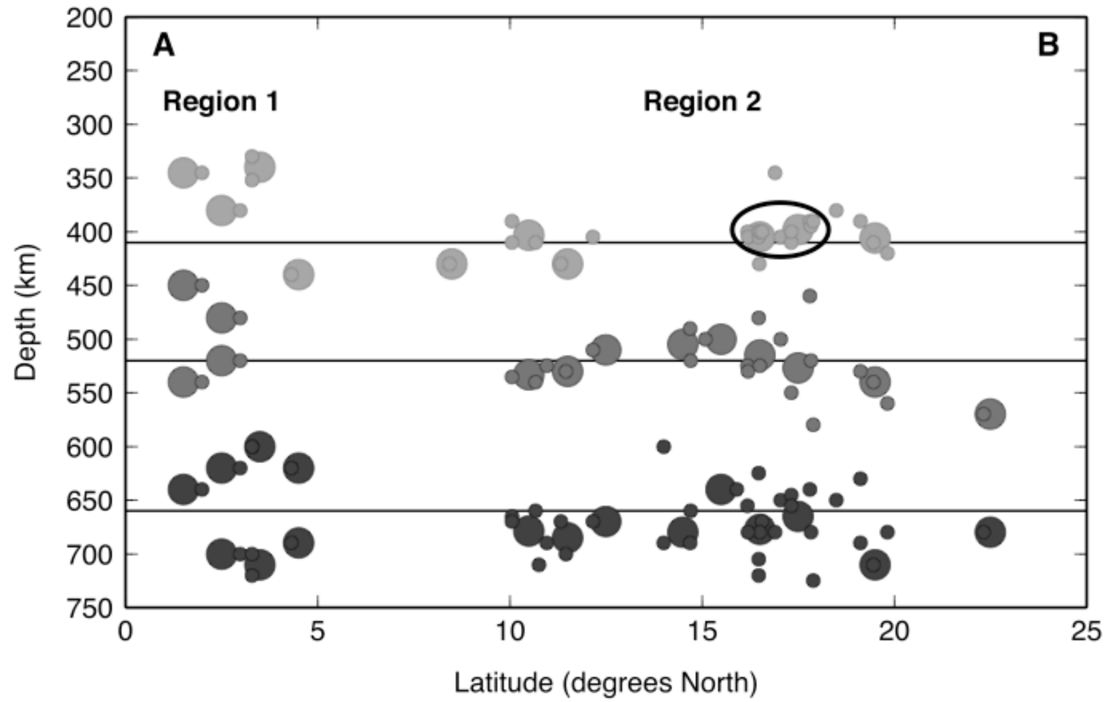


- *Expect compositional variation in the transition zone due to shallow mantle processes.*
  - *Density variations (Fe content, major ele. depletion)*
  - *Rheological variations (OH, grain growth & pinning)*

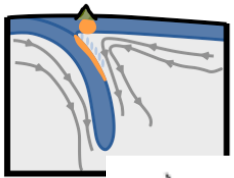


Mid-mantle Seismic Reflectors

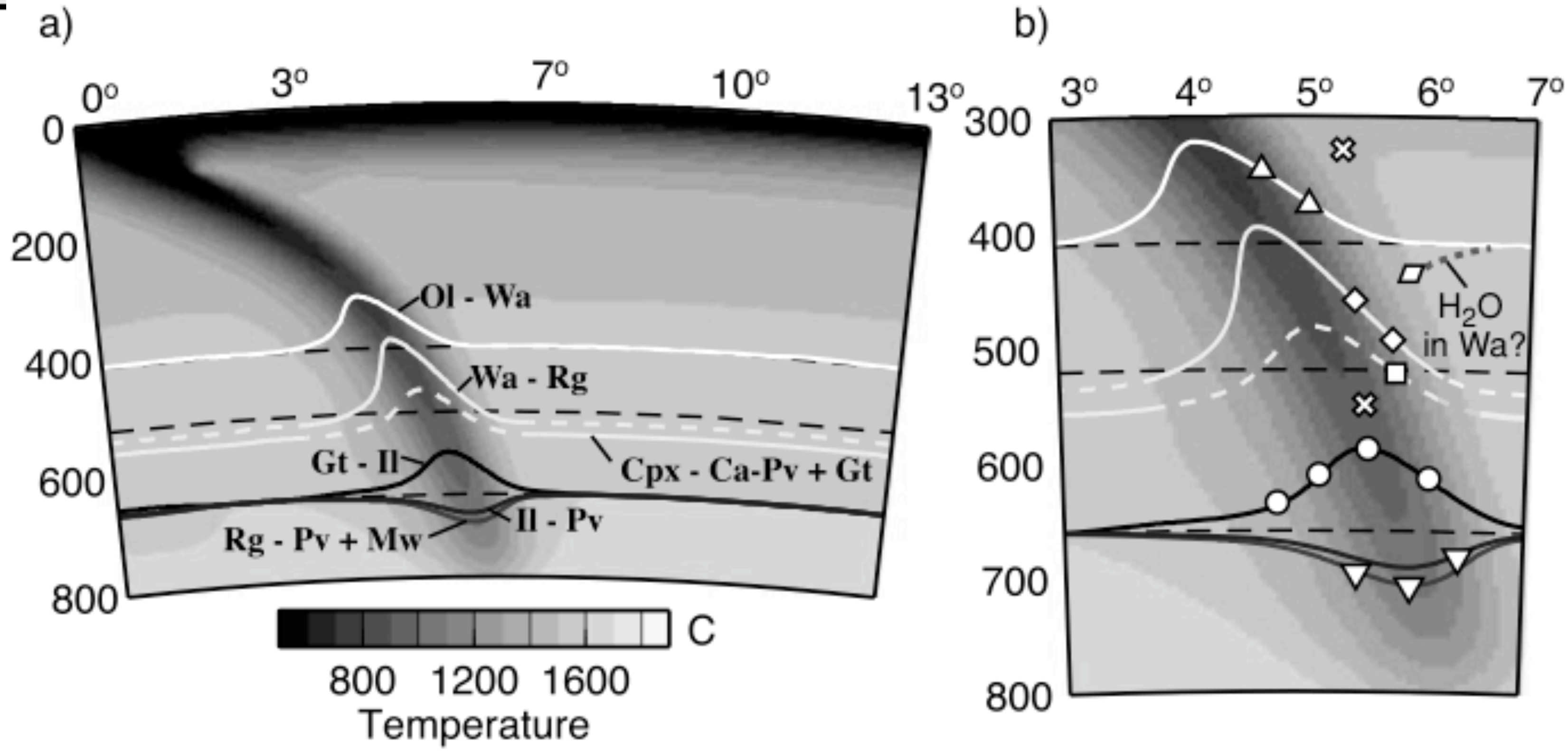




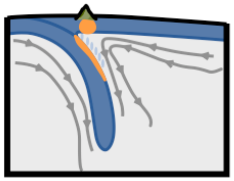
- ***Slab region: Shallow & deep 410 km (?), 520- km reflector, paired 660-km reflectors***
- ***Non-slab region: Hint of structure on 520-km reflector, 410 & 660 are confusing?***



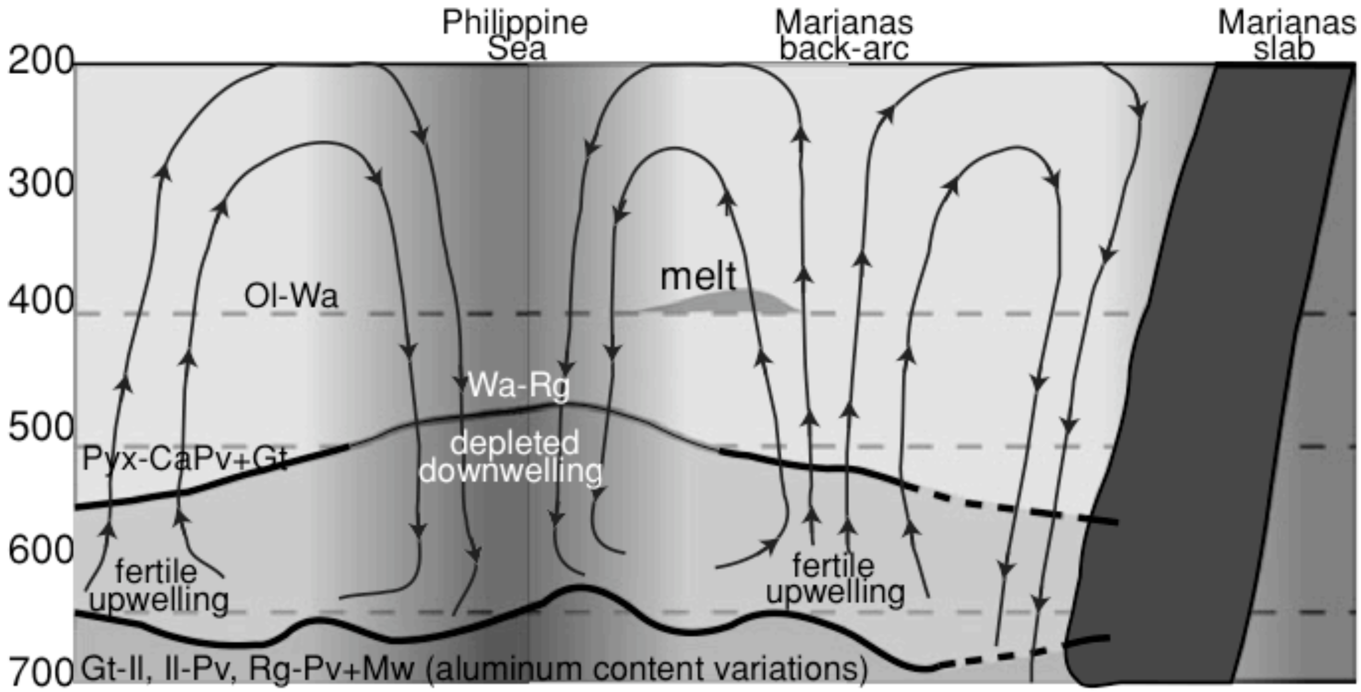
Mineralogical-Petrological



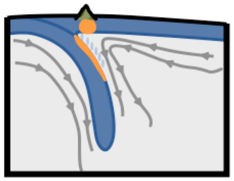
- *Laboratory data & dynamical models*
  - *Can see non-olivine component in slabs*



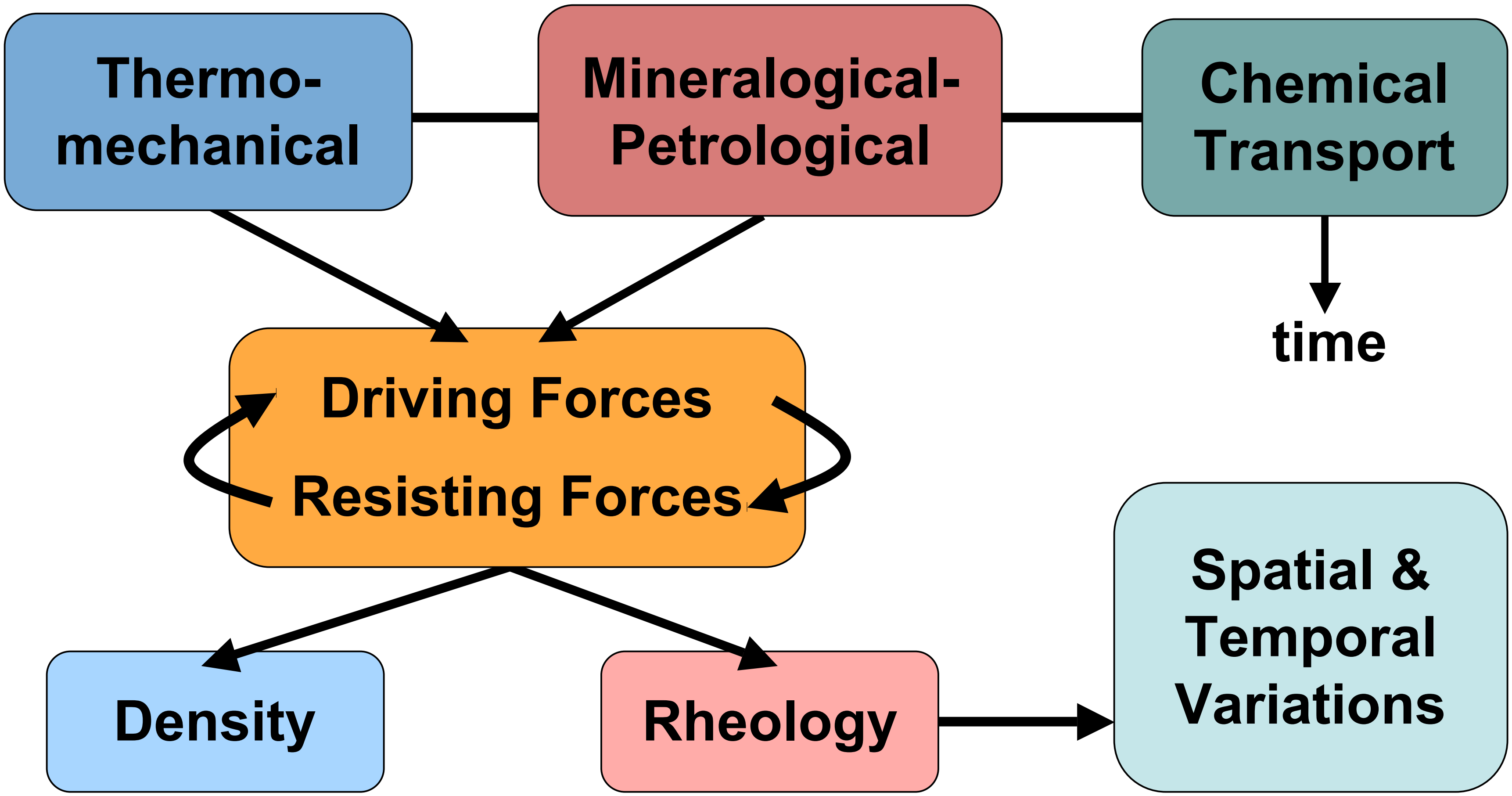
Mineralogical-Petrological



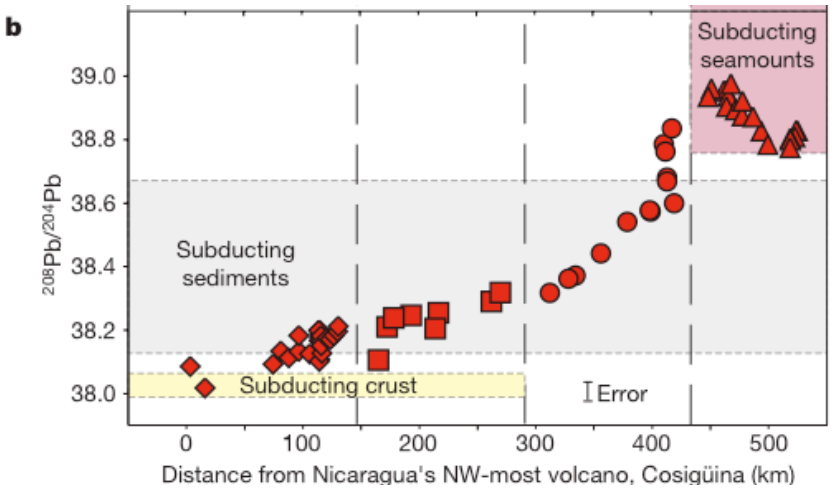
- ***Other variations can be interpreted in terms of surface tectonics & shallow mantle processes.***
  - ***Fertile upwelling (return flow from subduction)***
  - ***Depleted downwelling below back-arc spreading.***

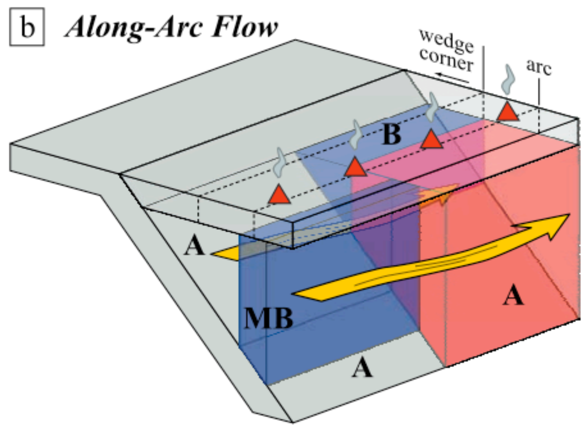


The Dynamical System

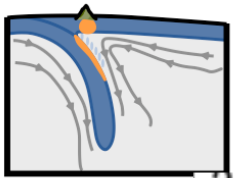


Chemistry Transport

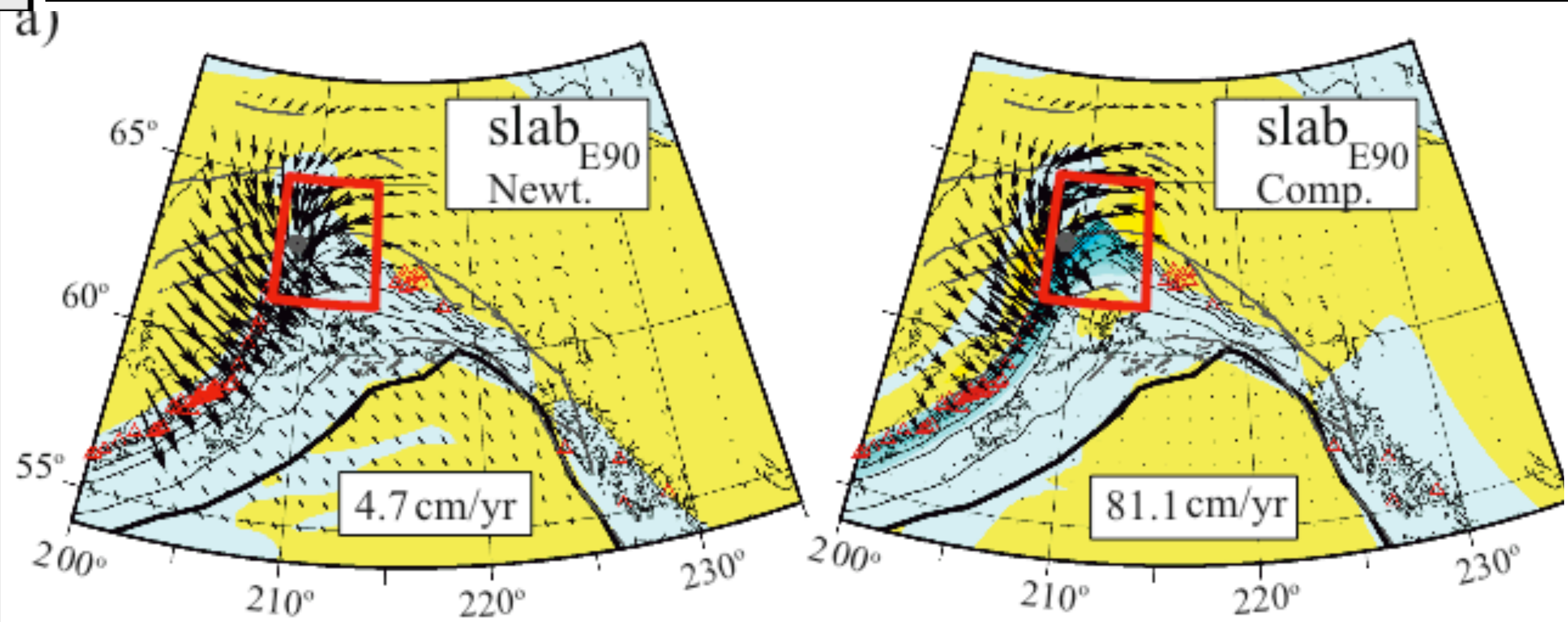




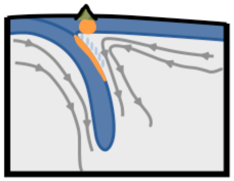
- ***Fast Rates:***
  - ***> 16 cm of trench-parallel flow***
  - ***2 x as fast as sub. plate rate.***
  - ***Implies even faster poloidal flow.***
  - ***Decoupling of surface plate & mantle flow.***
- ***Constraint on solid flow velocity***
  - ***Constraint on magnitude of viscosity.***



Chemical Transport

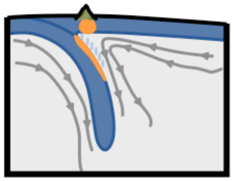


- ***3D model of Alaska (non-Newtonian) leads to decoupling & fast mantle flow rates, but...***
  - ***Don't get strong component of along-strike flow (different geometry?)***

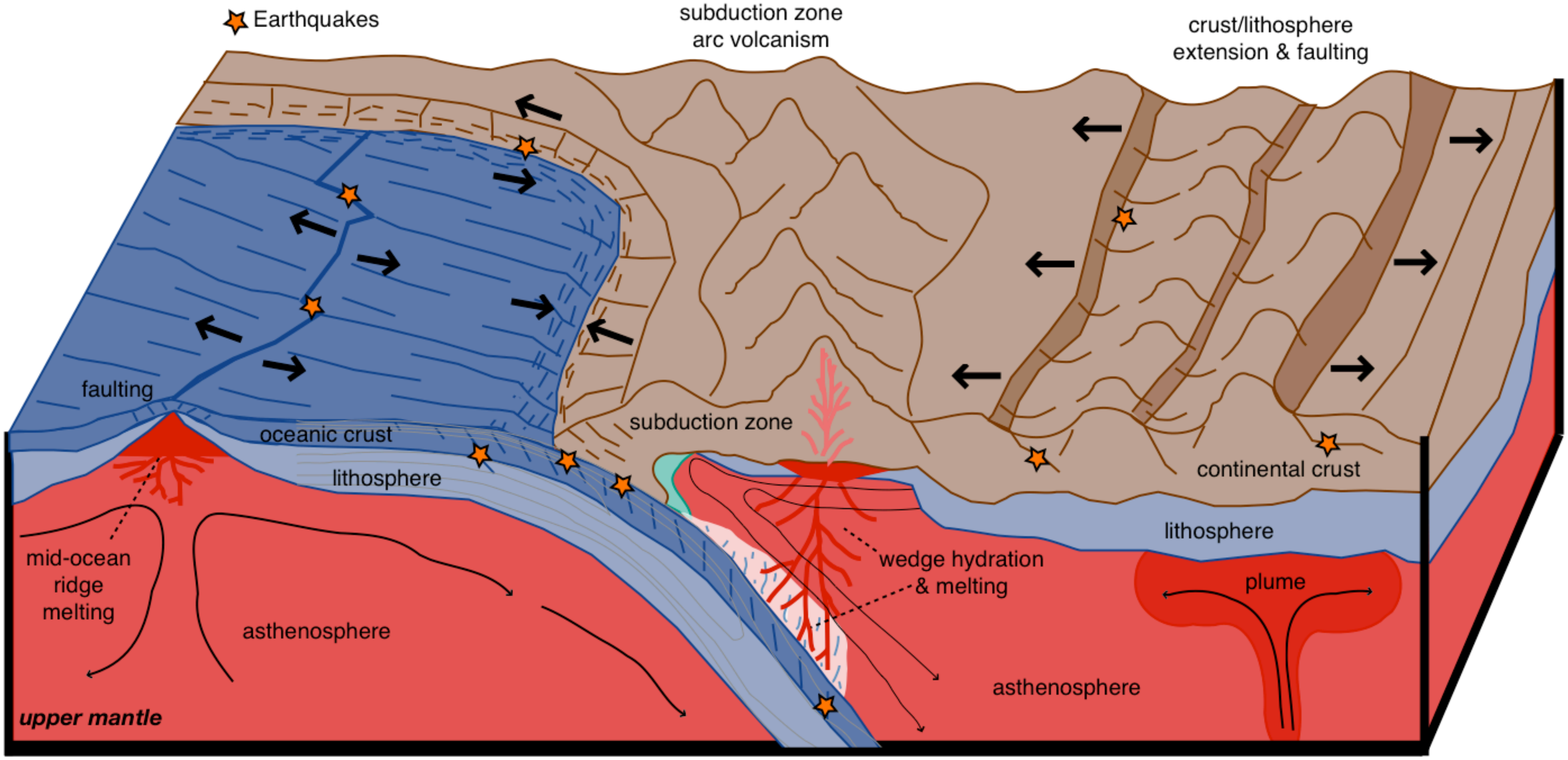


Conclusions

- ***Modeling of subduction dynamics is benefiting from,***
  - ***Access*** to new & more complete observations.
  - ***Advances*** in numerical & analogue methods.
  - ***Ability*** to link dynamics to other disciplines.
- ***New models are beginning to show how multi-processes are linked.***
- ***New results will challenge our standard view of mantle-plate coupling (flow patterns, flow rates).***



Conclusions



Using multiple observations to understand dynamics is key to determining what processes are important for a dynamic theory of plate tectonics.