GeoPRISMS

Geodynamic Processes
at Rifting and
Subducting
Margins

From the Outer Rise to the Transition Zone

Observations and Models of Plate & Mantle Deformation During Subduction

Magali Billen, UC Davis

What Is GeoPRISMS?

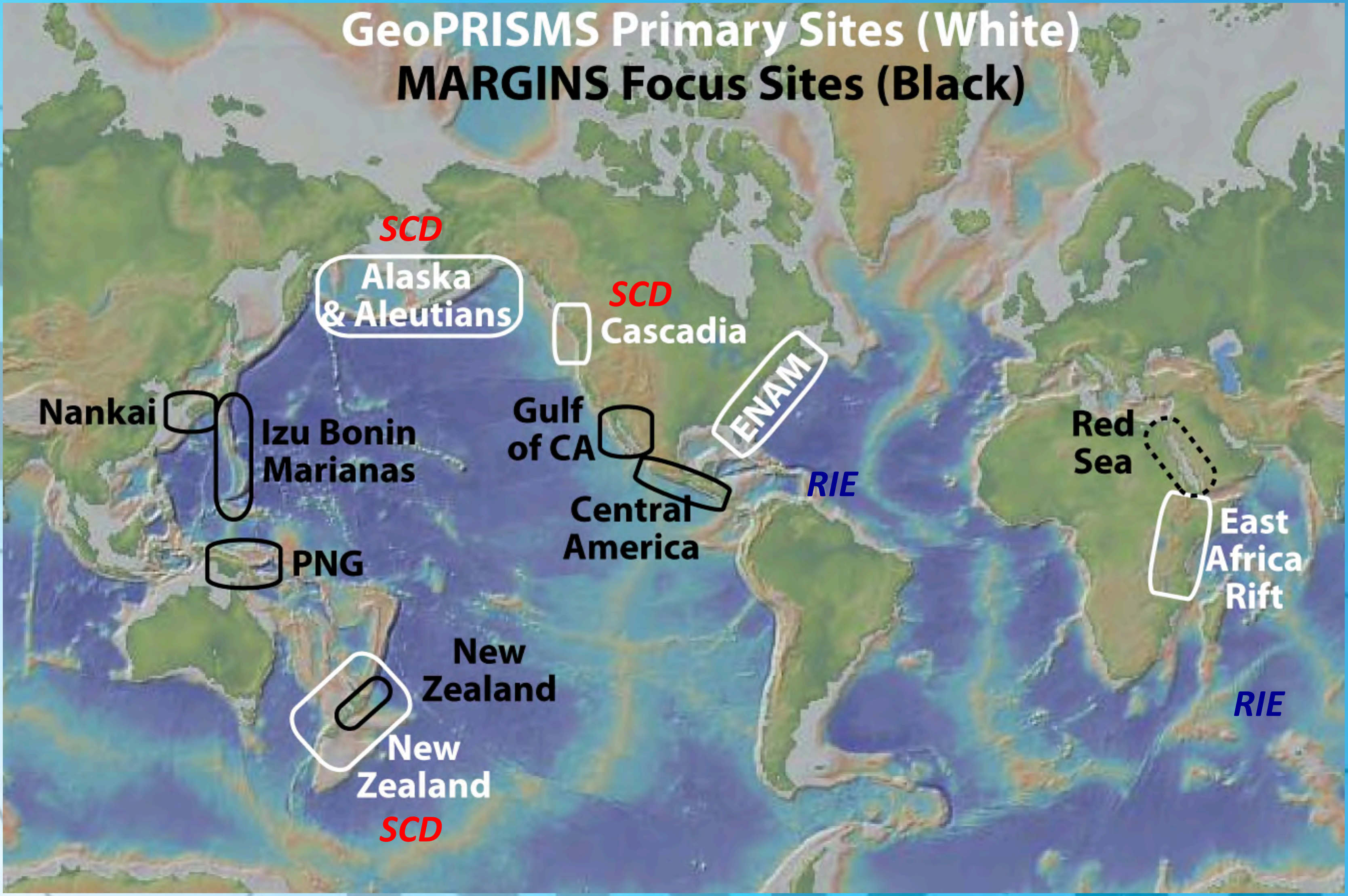
- **Successor to the decadal NSF MARGINS Program**
- **Studies of origin & evolution of continental margins**
  - Community-driven, interdisciplinary, cross-divisional NSF-funded
  - Integrating field, theory, experiment, and modeling
- **Focus on rifts and subduction zones**
  - Active geodynamic processes; formation of continental crust
  - Where geology and society intersect; many economic resources
- **Shoreline-crossing, i.e., "amphibious"**
  - Where most rifts and subduction zones occur
  - Geologic & geodynamic processes span the shoreline
  - Where focused, cross-divisional efforts are most needed
- **Two broadly integrated initiatives**

Subduction Cycles & Deformation

Rift Initiation & Evolution

- **Research at Primary Sites & through Thematic Studies**

Where GeoPRISMS Works



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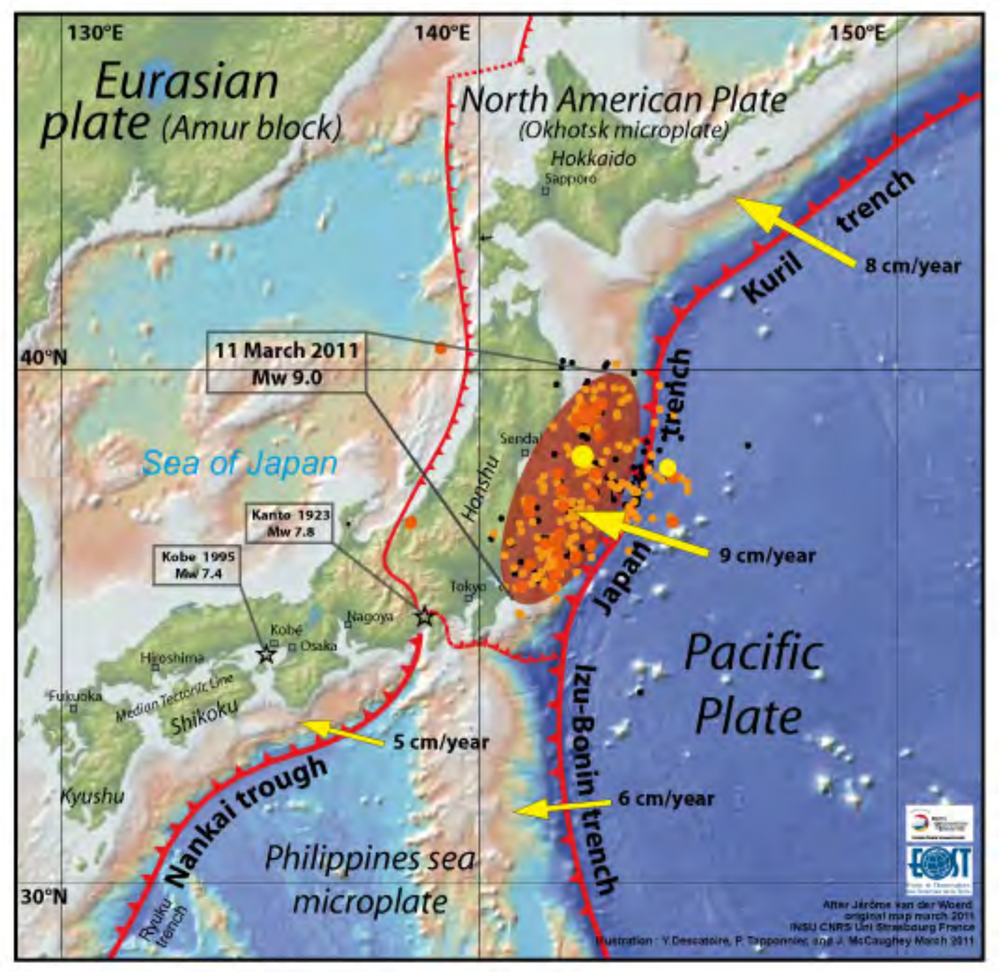
Why Study Subduction Zones?



Most Seismically Active Regions on Earth

- Tohuku Earthquake (9.0) and Tsunami
  - March 11, 2011

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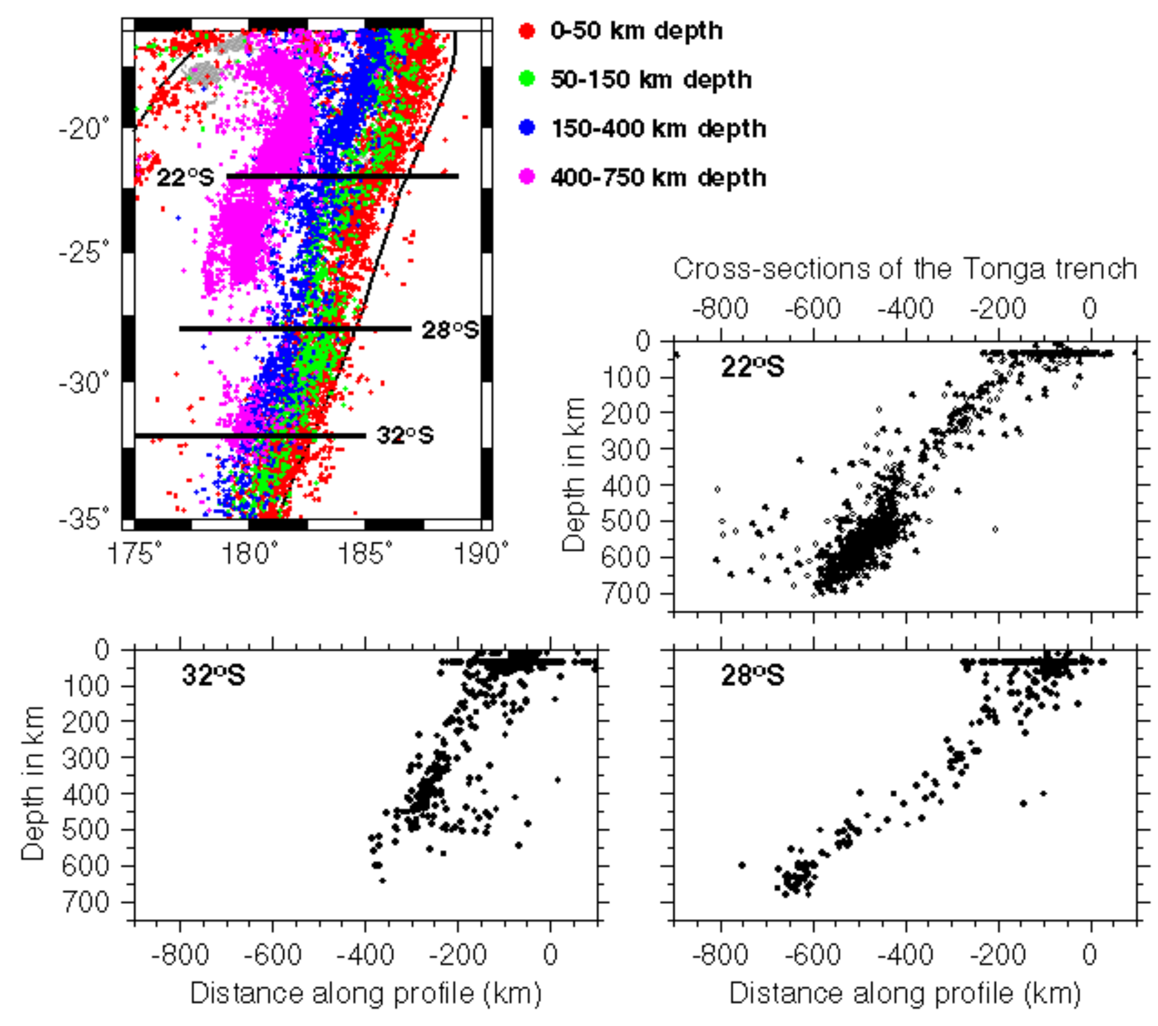
Evidence of Plate Descent & Deformation

Seismicity extends to depths of 660 km (300 miles).

Shows us the shape of the sinking tectonic plates within the earth

Variations in shape reflect deformation:
bending,
buckling,
stretching,
shortening.



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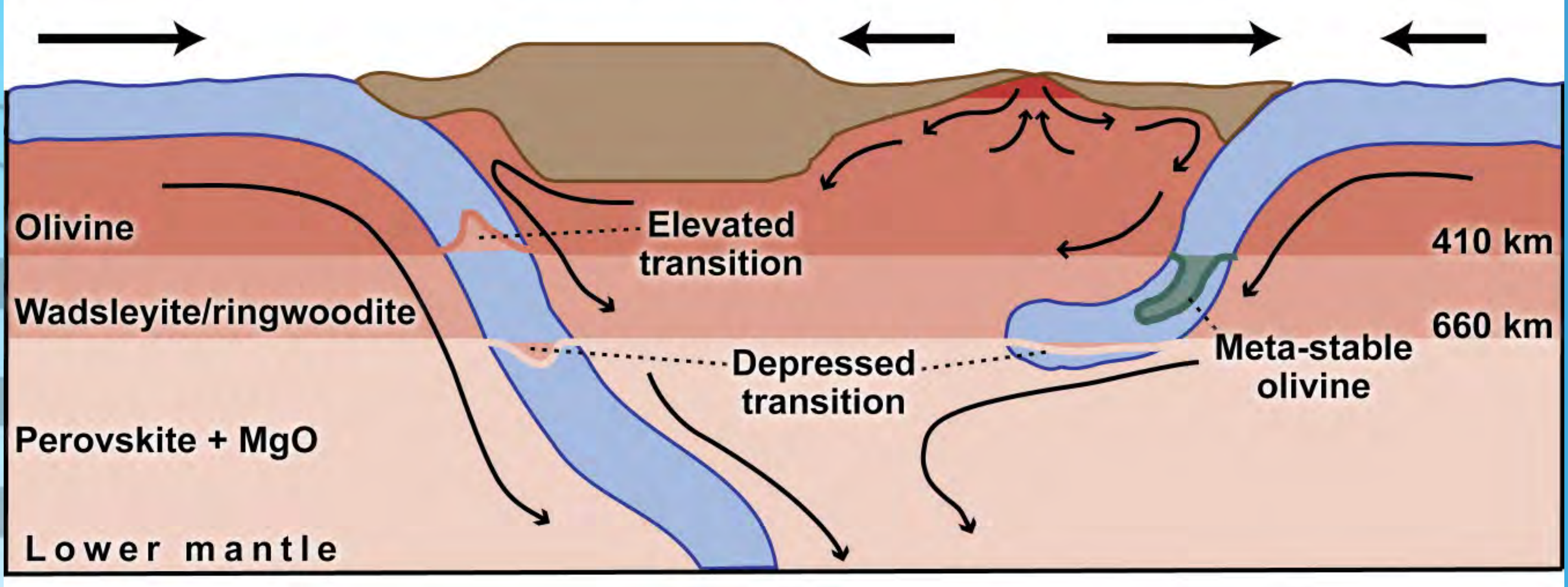
Overview of Subduction



- Oceanic plate sinks beneath an oceanic/continental plate: sinking plate is called a ***slab.***
- Plate can sink into the lower mantle or get stalled in the **transition zone** (region from 410-660 km)
- Sinking of plate entrains/drives flow in the surrounding mantle

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

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Subduction Zone Research Questions

1. Shallow Depths
   - What physical processes control the formation of outer-rise faults?
   - How much does the plate weaken as it bends into the mantle?
2. Deeper Processes
   - How do the changing forces on the slab affect its deformation in the mantle?
   - What combination of factors determines if a slab gets stuck in the transition zone?
3. Special Cases: Under what conditions does subduction fail?
   - Oceanic plateau subduction
   - Ridge-trench interaction

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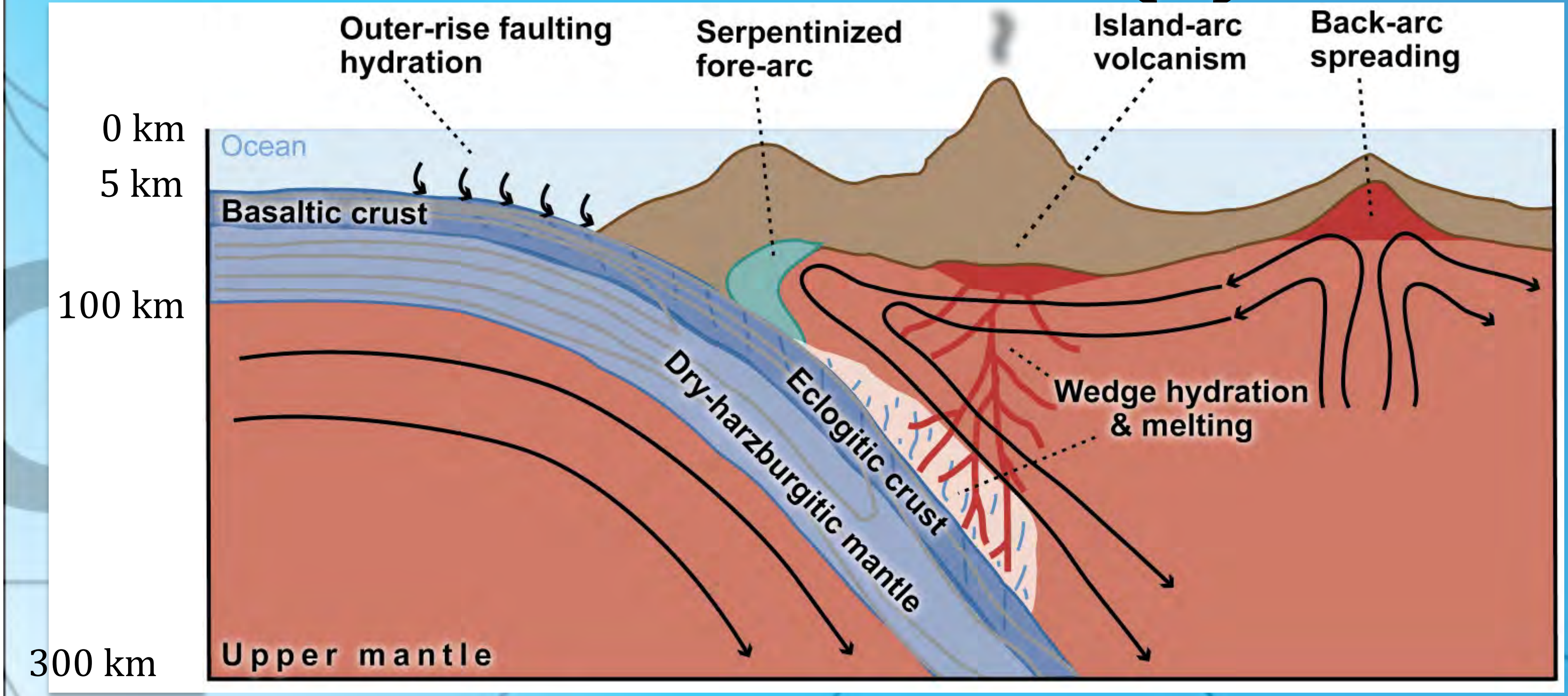
Shallow Processes (1)



- Subducting plate bends at the trench to sink into the mantle: ***outer-rise faulting*** hydrates the crust & lithosphere.
- Slab warms as it sinks & dehydrates, sending fluids into the ***mantle wedge***, forming serpentinite & causing melting.

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

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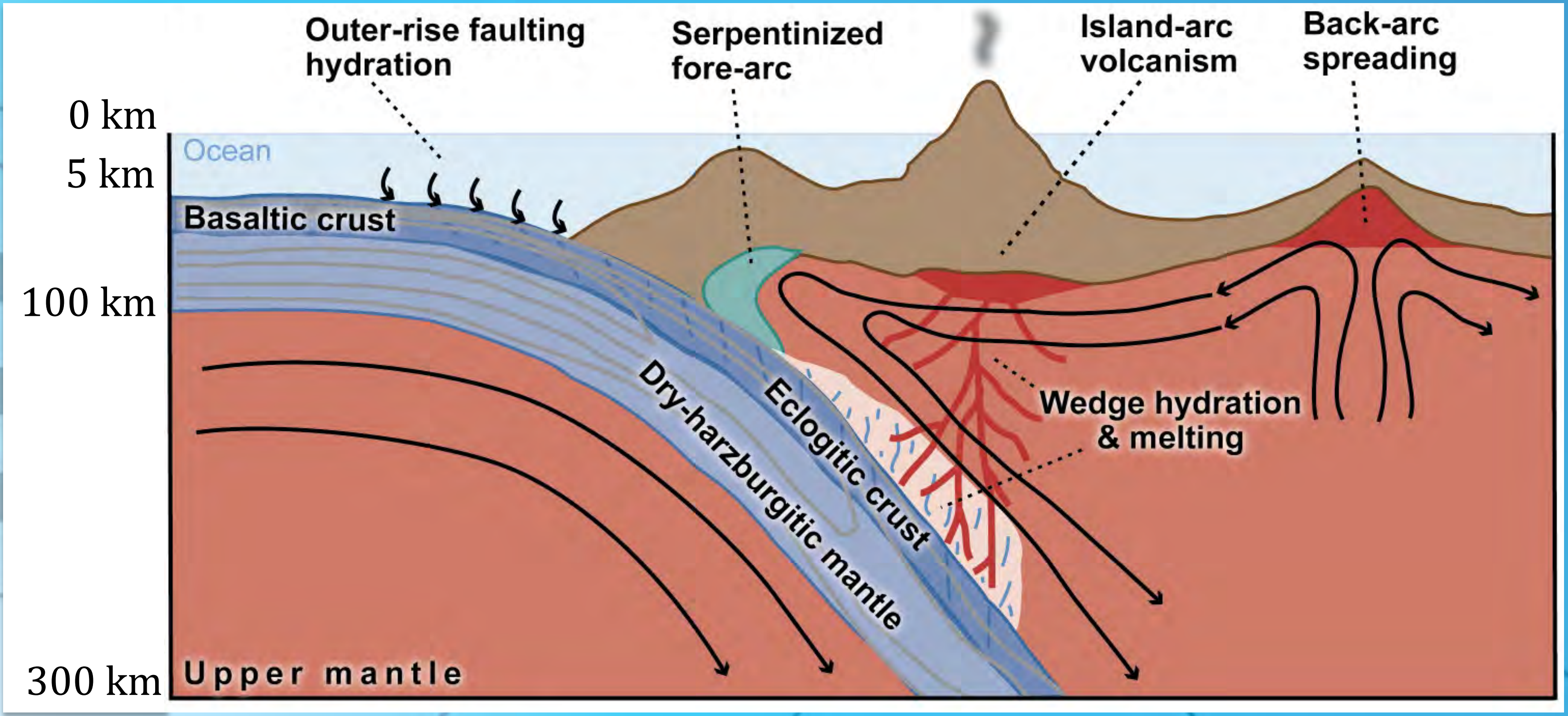
Shallow Processes (2)



- Coupling between subducting & overriding plate causes major earthquakes & limits rate of subduction.
- ***Basaltic*** crust undergoes phase transitions becoming a <u>denser</u> and <u>stronger</u> ***eclogitic*** assemblage.

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

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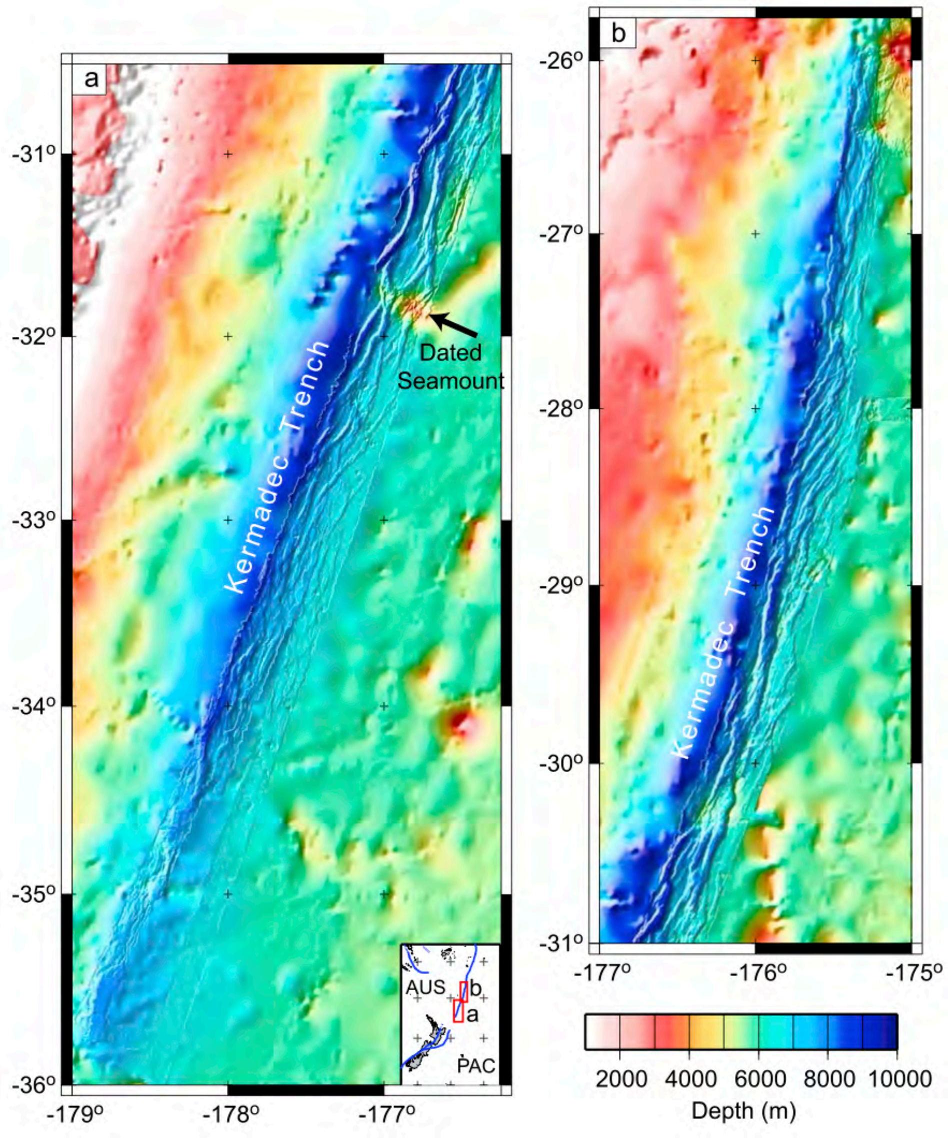
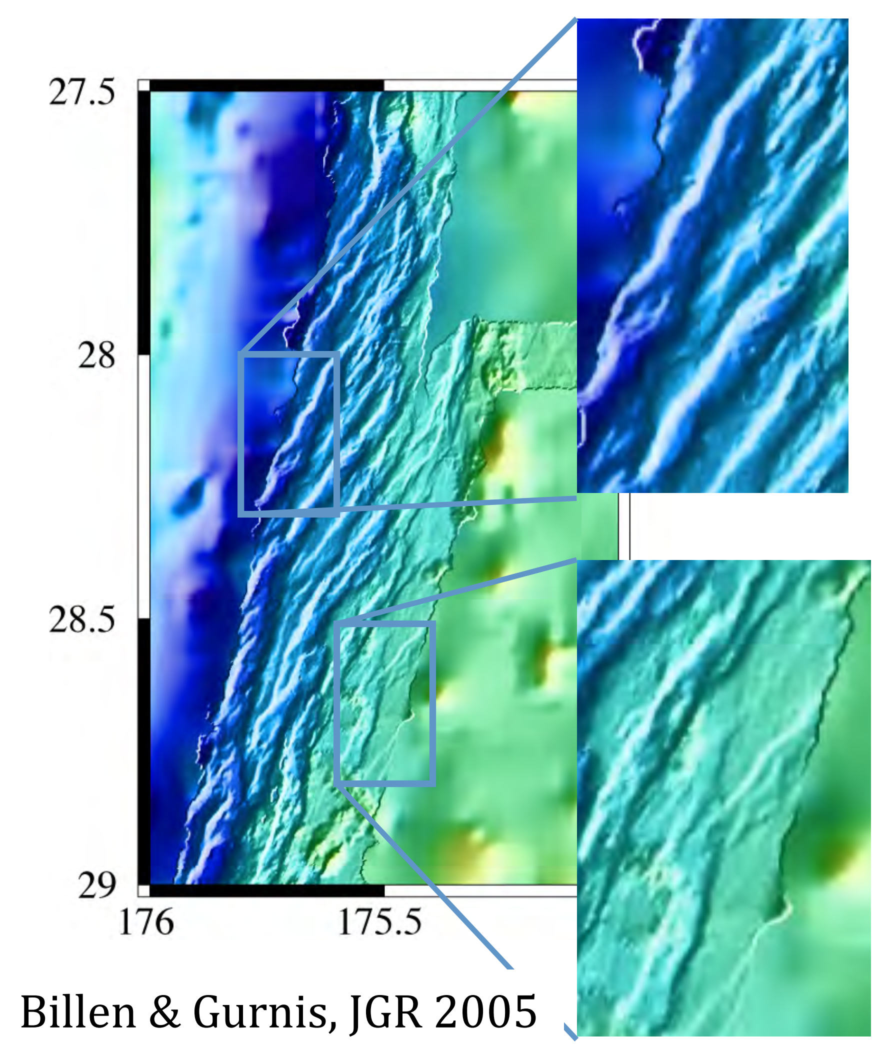
Observations of the Outer-rise: Swath Bathymetry Mapping

- Tonga-Kermadec
  - Just north of New Zealand.
  - Mapping seafloor bathymetry using swath sonar.
  - Gives much more detail on features including faulting.
  - Drive ship parallel to the trench axis on the subducting plate.



Billen & Gurnis, JGR 2005

Observations of the Outer-rise: Swath Bathymetry Mapping



Billen & Gurnis, JGR 2005

- Tonga-Kermadec
  - Faults form sub-parallel to trench
  - Abyssal-hill fabric is sub-perpendicular (Billen & Stock, 2001).
  - New & active faults along trench wall.
  - Offsets grow from outer rise towards trench

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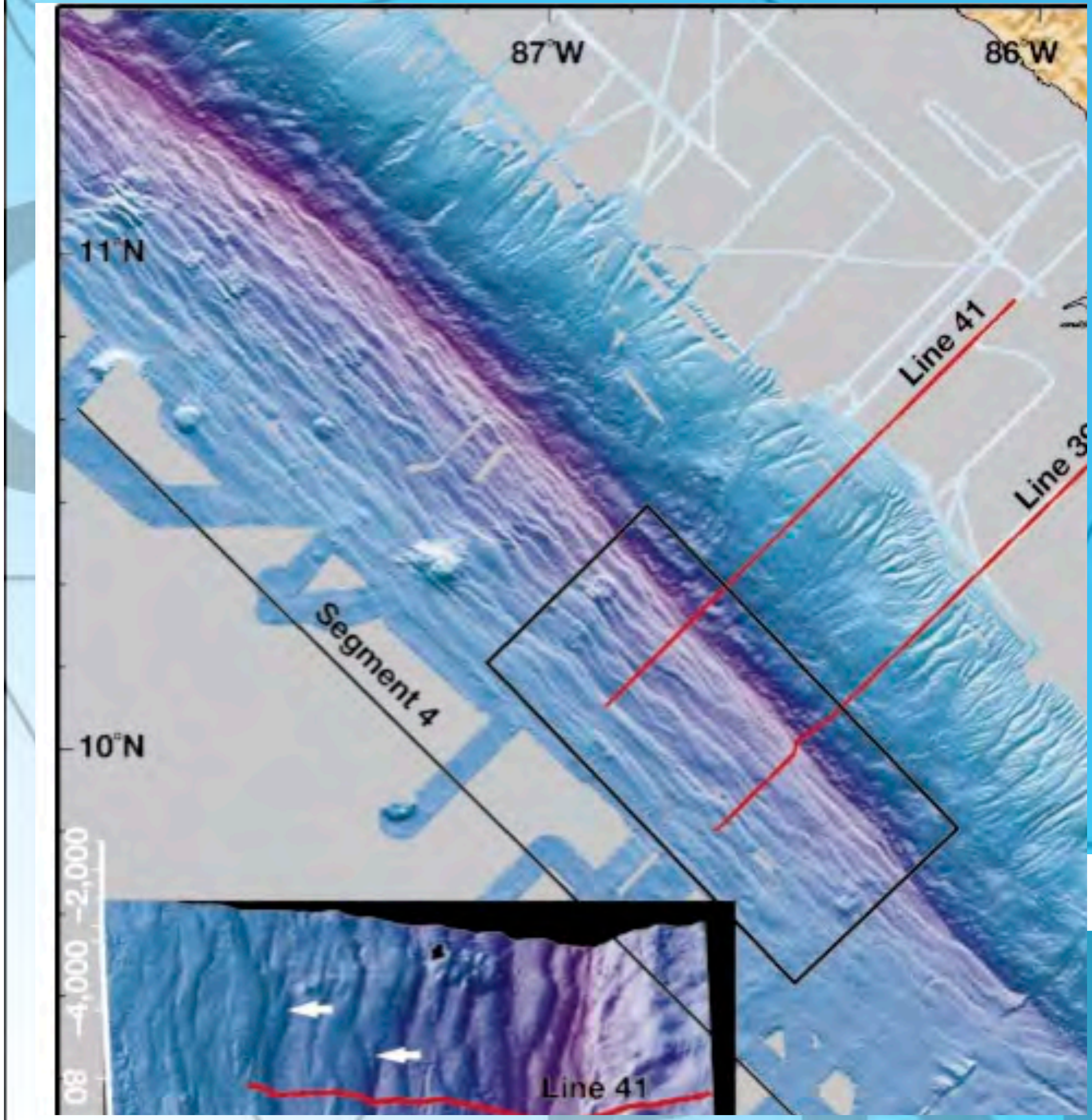
Observations of the Outer-rise: Swath Bathymetry Mapping



- Costa Rica:
  - Seafloor fabric is parallel to trench
  - Outer-rise faults reactivate seafloor fabric
  - How deep do these faults go?

Ranero et al., Nature 2003

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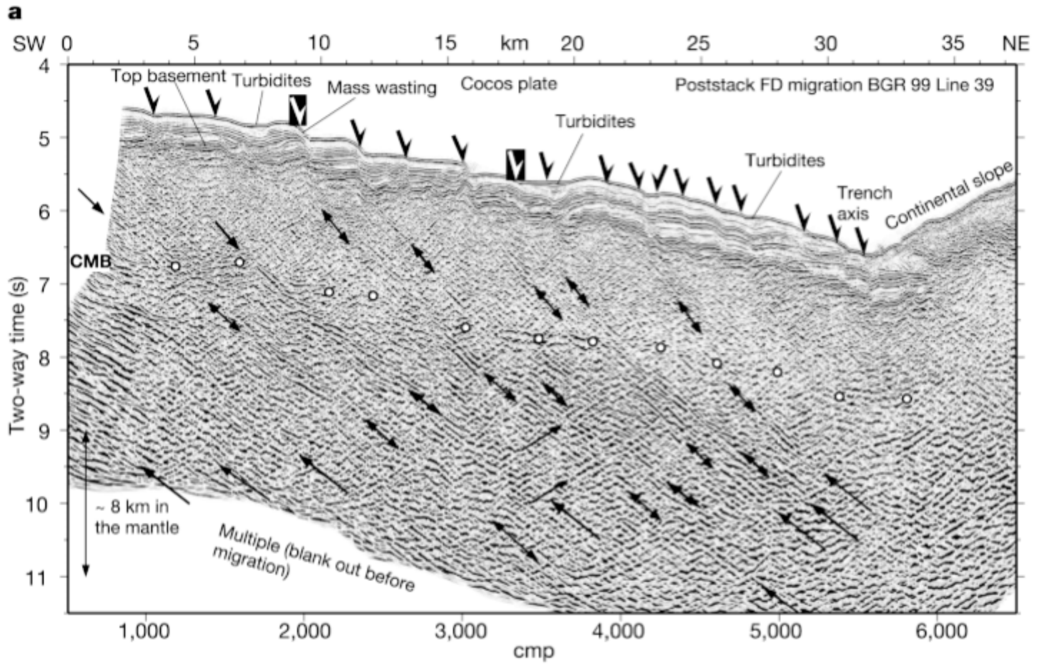
Observations of the Outer-rise: Seismic Imaging

- Costa Rica
  - Bright reflectors line-up with faults observed at the seafloor
  - Some reflectors clearly go beyond the crust-mantle boundary (CMB) and likely up to 8 km into the mantle portion of the plate.
- Some outer rise earthquakes may break on faults reaching > 50 km depth.



Ranero et al., Nature 2003

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Characteristics of Outer-rise Faults

- **Questions?**
  - What controls formation of new versus reactivated faults?
  - Does faulting depend on plate characteristics, dip, coupling, fault friction?
  - How does faulting affect plate strength?

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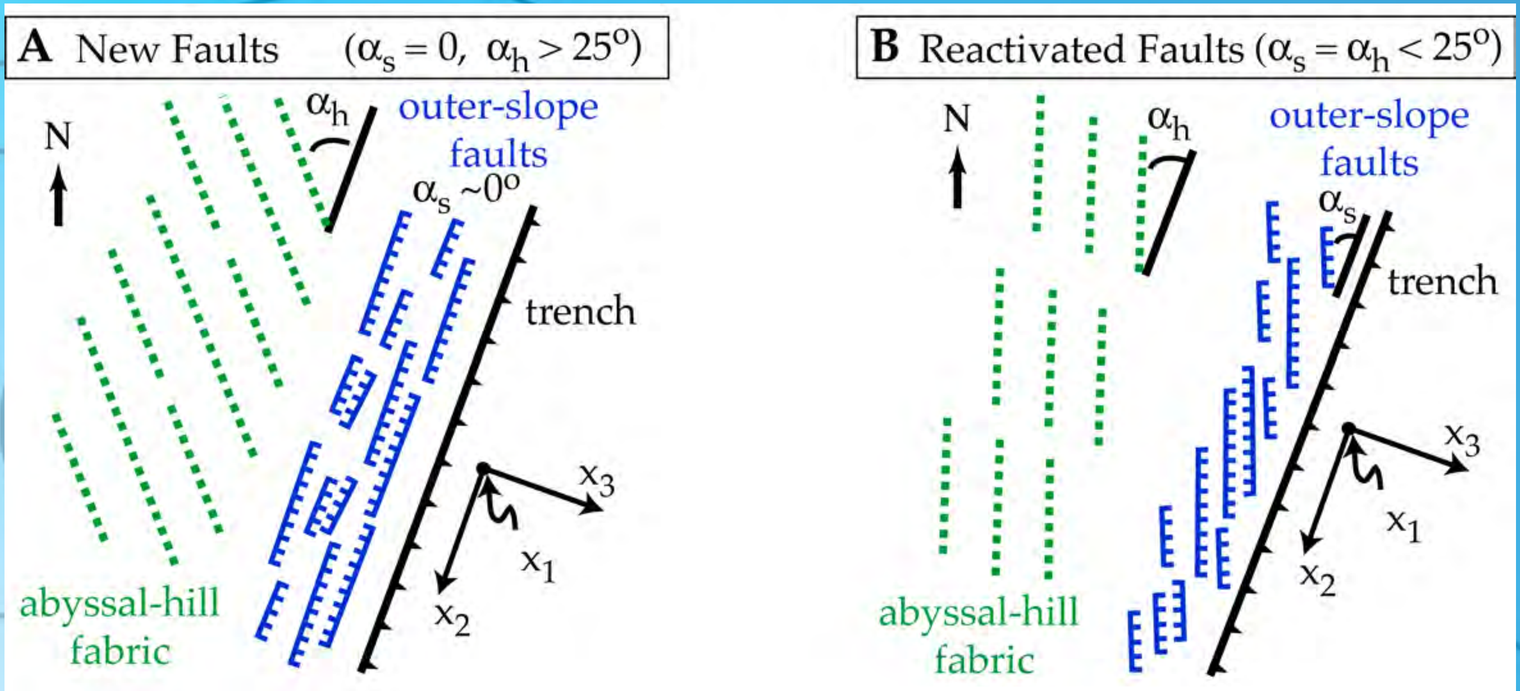
Frictional Strength of Outer-rise Faults



Billen, Cowgill, Buer, Geology, 2007

- Transition angle:
  - New faults form when seafloor fabric is ***mis-aligned*** by more than 25 degrees from trench-parallel.
  - **This works like a cleavage plane in a rock.**

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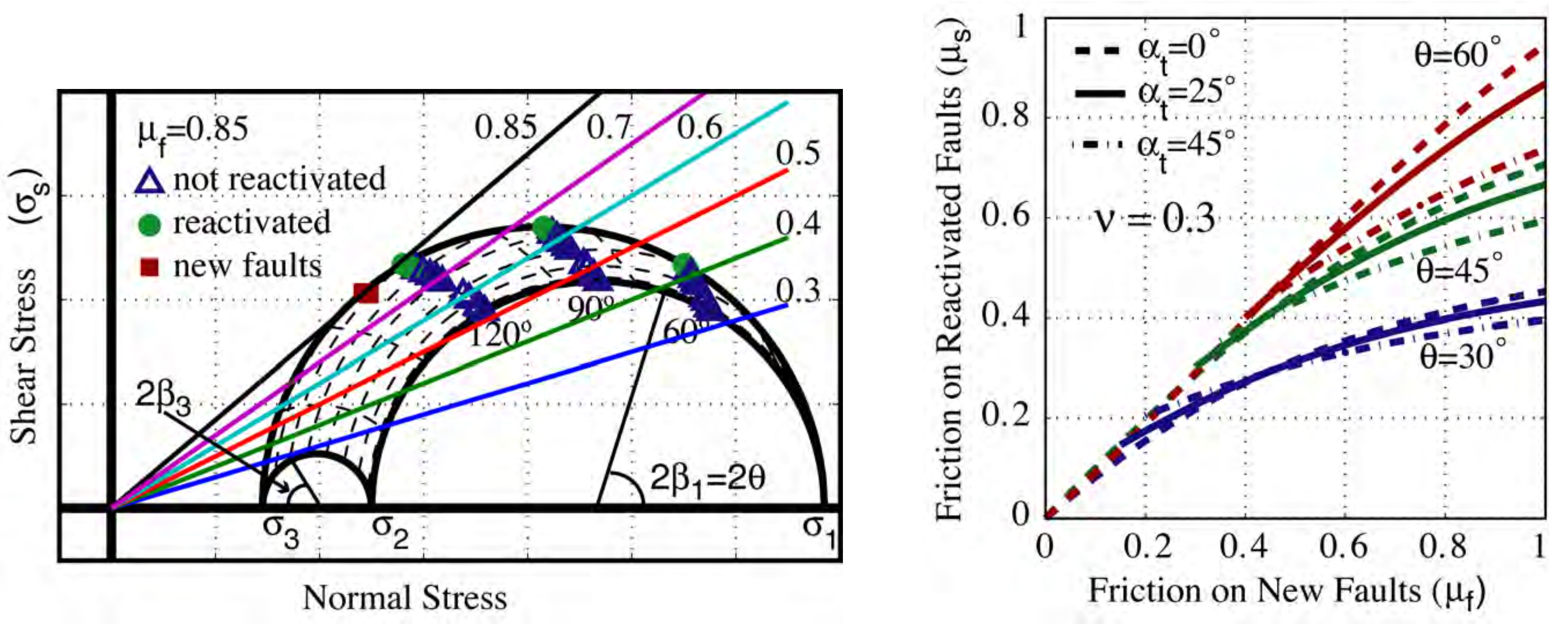
Frictional Strength of Outer-rise Faults



- Analysis of state-of-stress and observed transition angle
- Reactivated faults are **only 30% weaker** (0.6) than the rock in general (0.85): no indication of clay, serpentinite…
- Stresses are large enough to break crust/mantle without pre-existing weakening of the plate.

Billen, Cowgill & Buer, Geology, 2007

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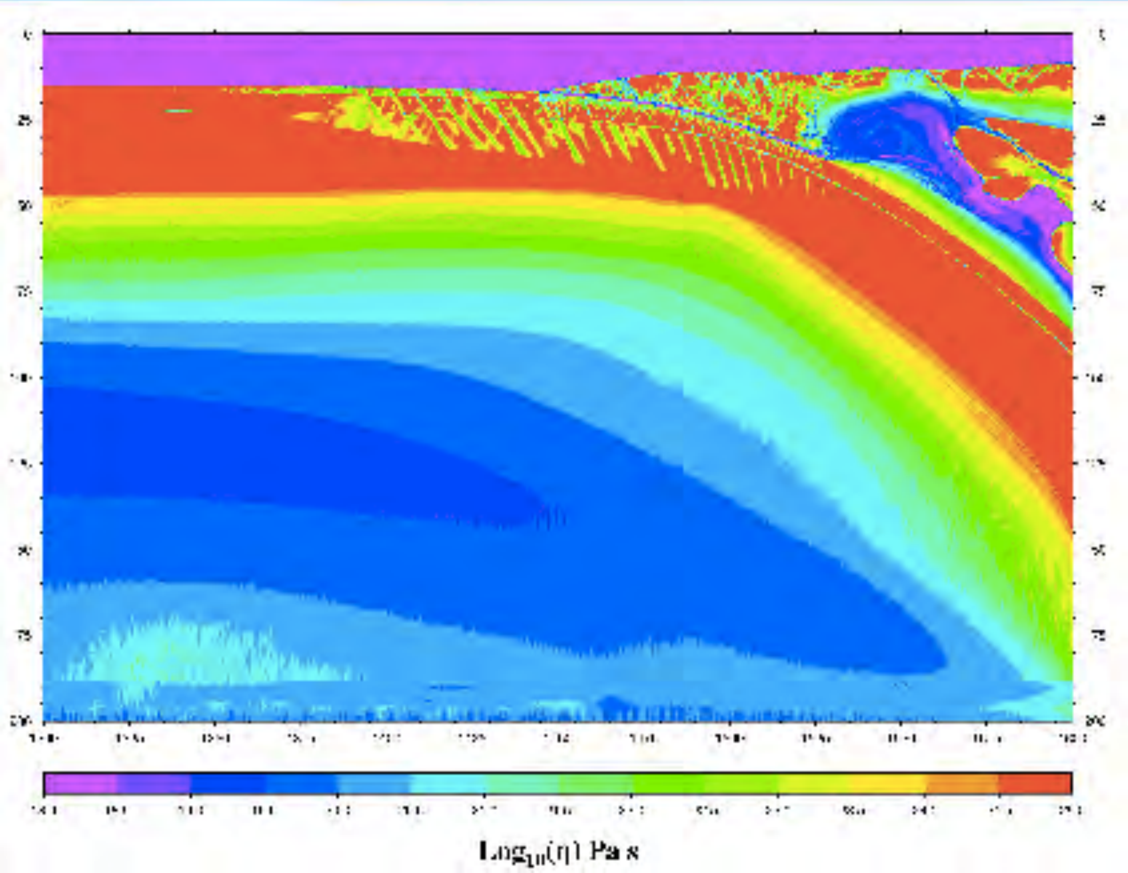
Numerical Modeling of Outer-rise Faulting



Colors:

viscosity strength

Red:

strong (10^{25} Pa-s)

Blue/purple:

weak

(10^{18}-10^{19} Pa-s).

Naliboff et al., in revision

- Oceanic subducting plate; Continental overriding plate (weak lower crust)
- Pushing subducting plate at 5 cm/yr near ridge, but plate boundary is free to evolve.

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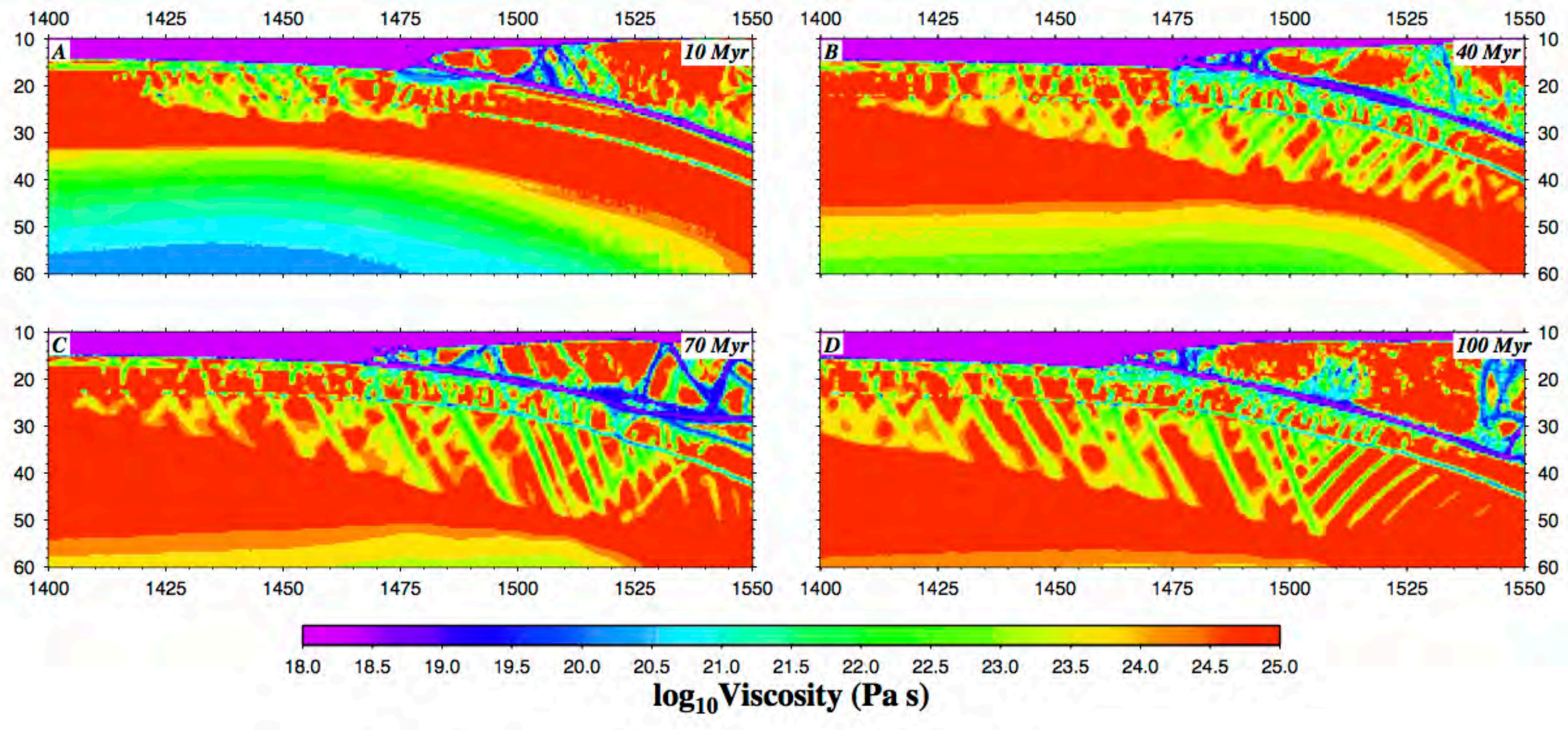
Outer-rise Faulting: Dependence on Plate Age



Naliboff et al., in review

- Younger-to-older plates:
  - Number of faults increases (but spacing is roughly constant)
  - Extent (width) of faulting region is larger
  - Faults extend deeper

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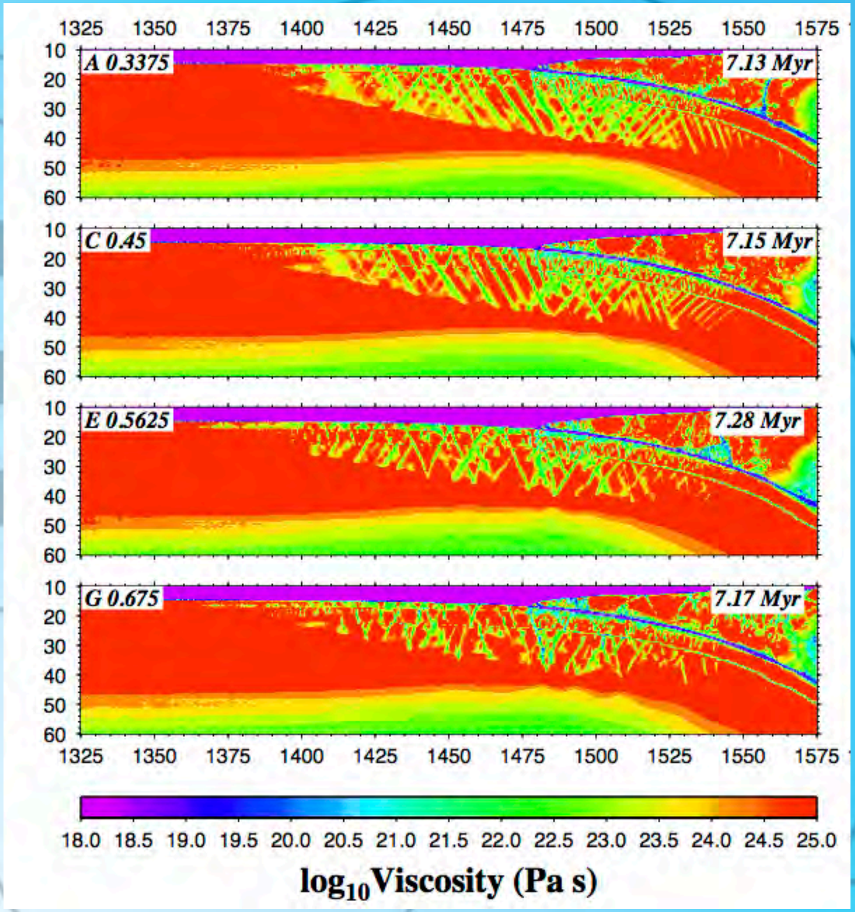
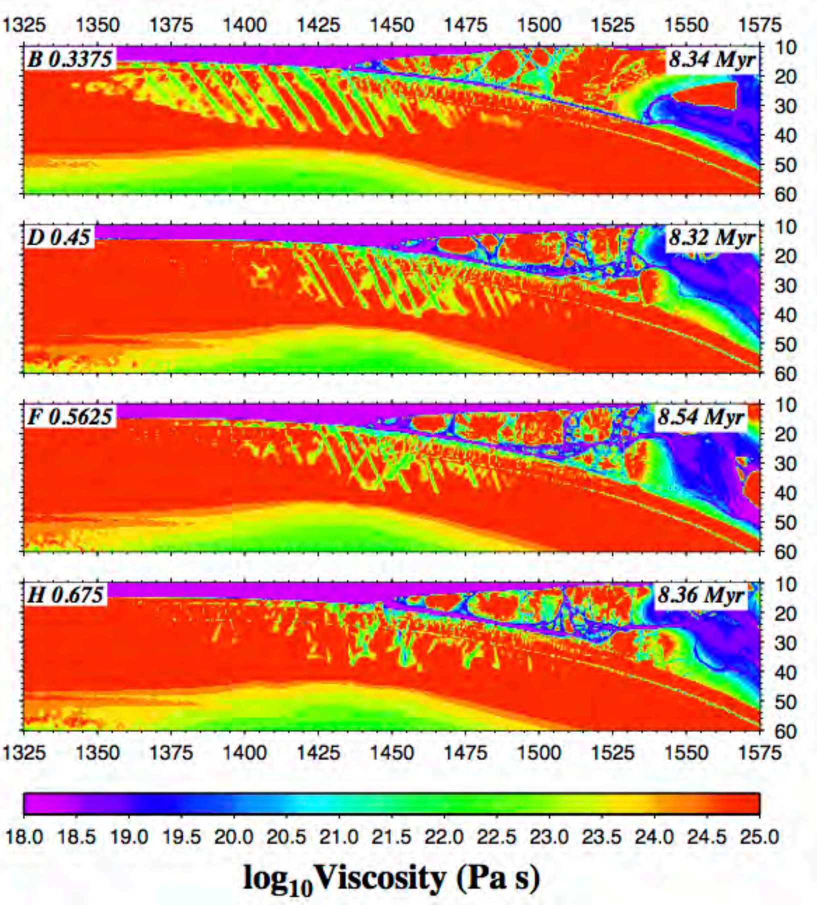
Outer-rise Faulting: Dependence on Fault Friction





- **Weak dependence on fault friction**: difference in fault friction, can lead to different faulting patterns, but there's ***more variation*** in a single model ***as a function of time***.

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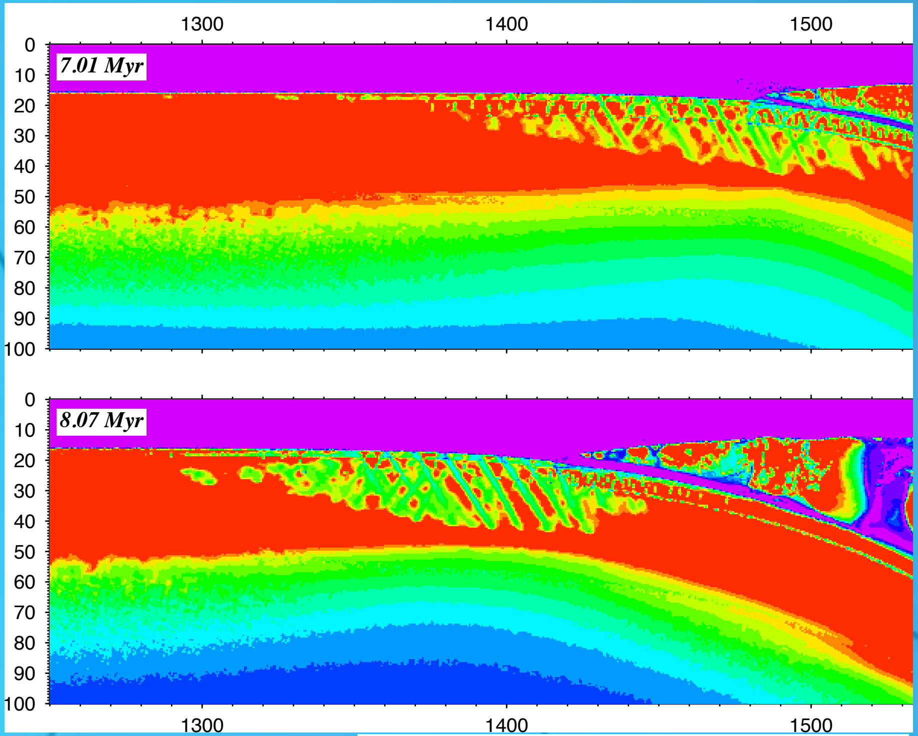
Weakening of the plate due to faulting

- Shear weakening leads to 25 to 200 times drop in average plate strength in region of faulting
  - Viscosity of 10^{25} drops to 10^{22} to 10^{23} Pa-s
- Reduces amount of slab-pull directly transmitted to surface-plate.



Naliboff et al., in revision

Is there independent evidence for this weakening of the plate?

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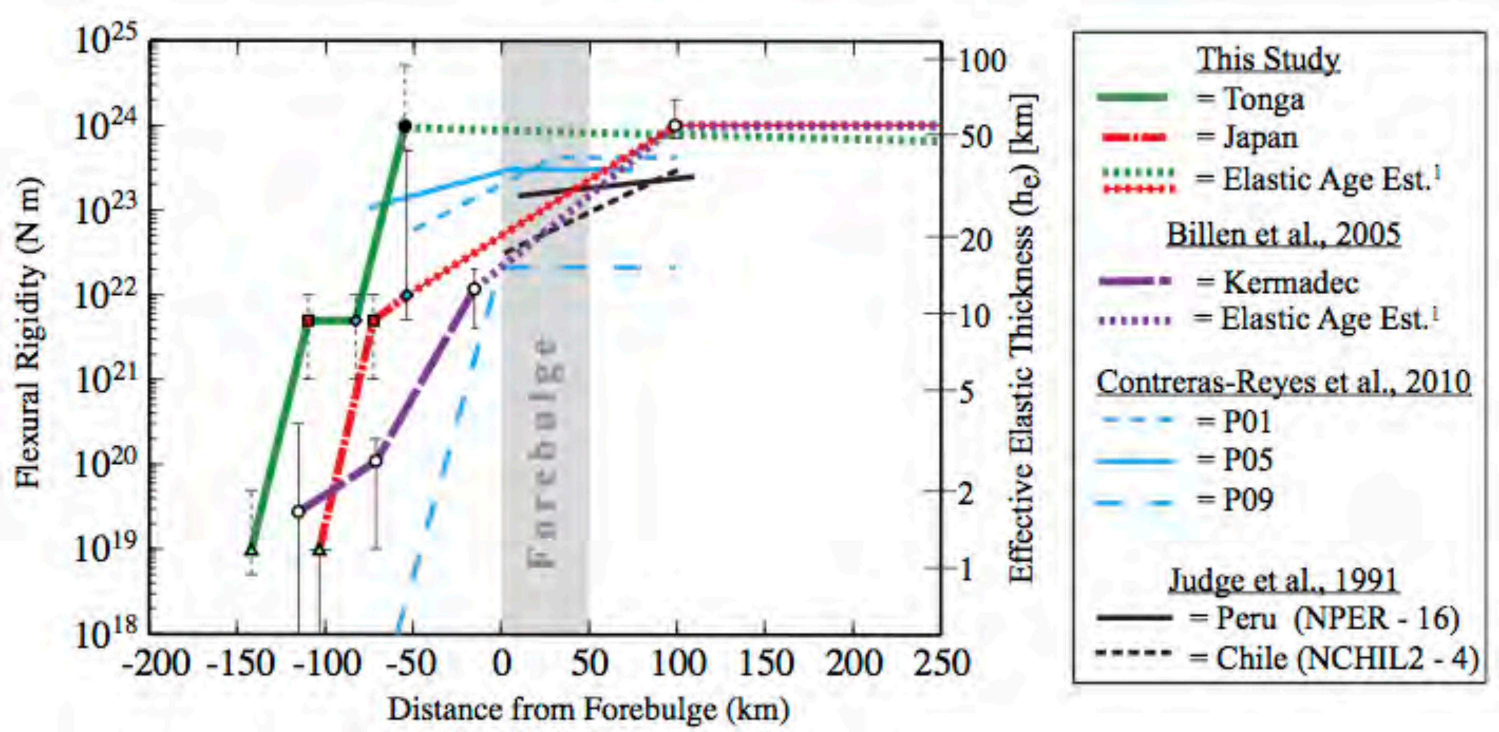
Weakening of the plate due to faulting



Arredondo & Billen, 2011

- Find decrease in flexural rigidity of 3-5 orders of magnitude.
- Equivalent to decreasing elastic plate thickness from 50 km to less than 5-10 km.
- Reduction is evidence of non-elastic behavior
  - Faulting, plastic yielding

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Summary of Outer Rise Deformation

- Ubiquitous outer-rise faulting
- Reactivated faults are not *very* weak
- Plate bending stresses are more than sufficient to break new faults.
- Faulting characteristics depend on
  - plate age (mechanical thickness)
  - But not frictional parameters
- Substantial weakening of the plate occurs from the outer rise to the trench.

Weakening of the plate, through outer rise faulting & deeper shear weakening, is the process that allows normally rigid plates to bend & sink back into the mantle.

Subduction Zone Research Questions

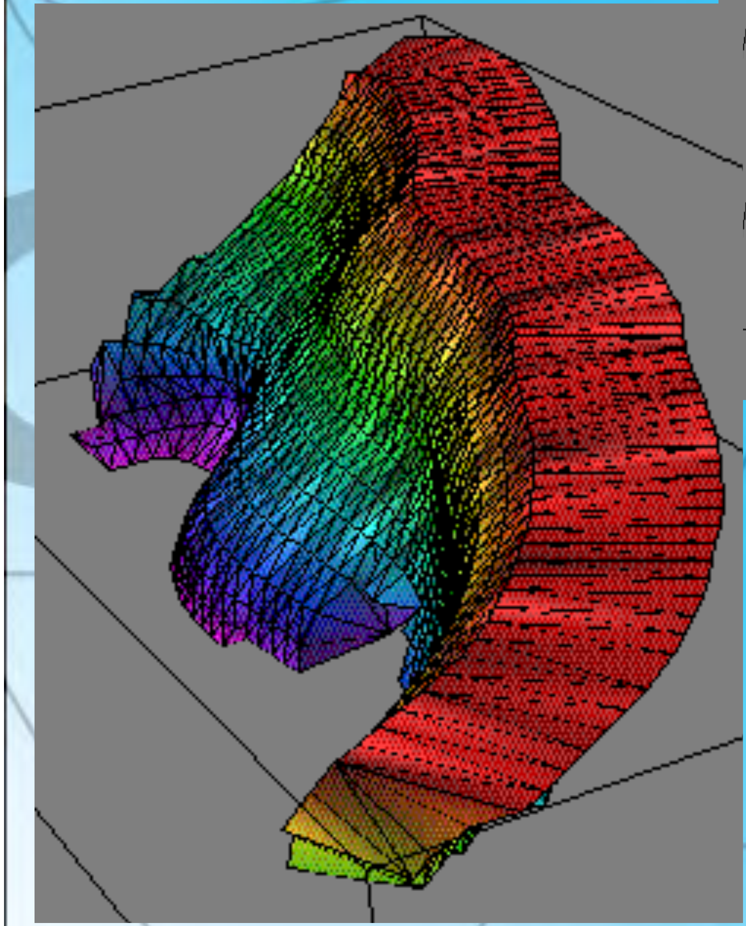
1. Shallow Depths
   - What physical processes control the formation of outer-rise faults?
   - How much does the plate weaken as it bends into the mantle?

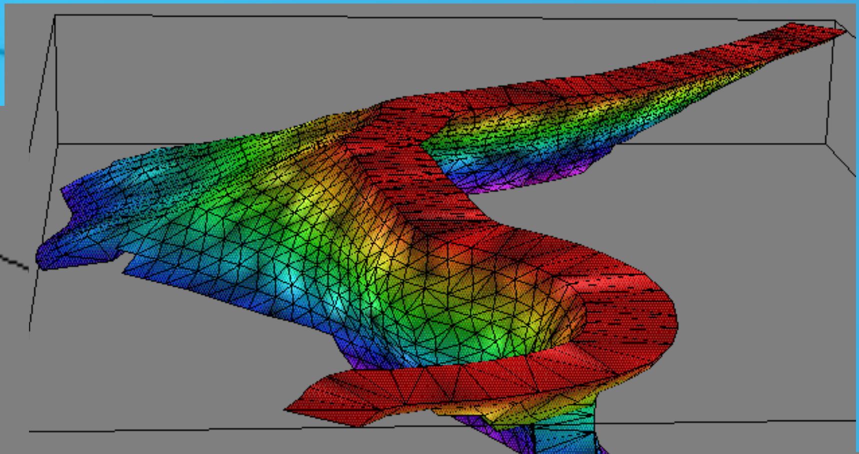
2. Deeper Processes
   - How do the changing forces on the slab affect its deformation in the mantle?
   - What combination of factors determines if a slab gets stuck in the transition zone?

3. Special Cases: Under what conditions does subduction fail?
   - Oceanic plateau subduction
   - Ridge-trench interaction

Seismic Observations of Slab Shape

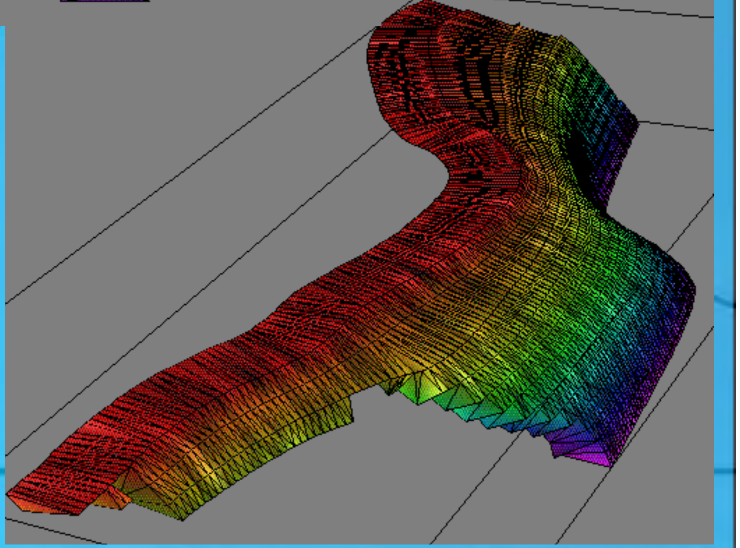
Tonga





Kuriles,
Japan,
Izu
Marianas

South
America



- 3D view of slabs based on seismicity (to 660 km) and seismic tomography (whole mantle).

Gudmundsson & Sambridge, RUM Model 1996

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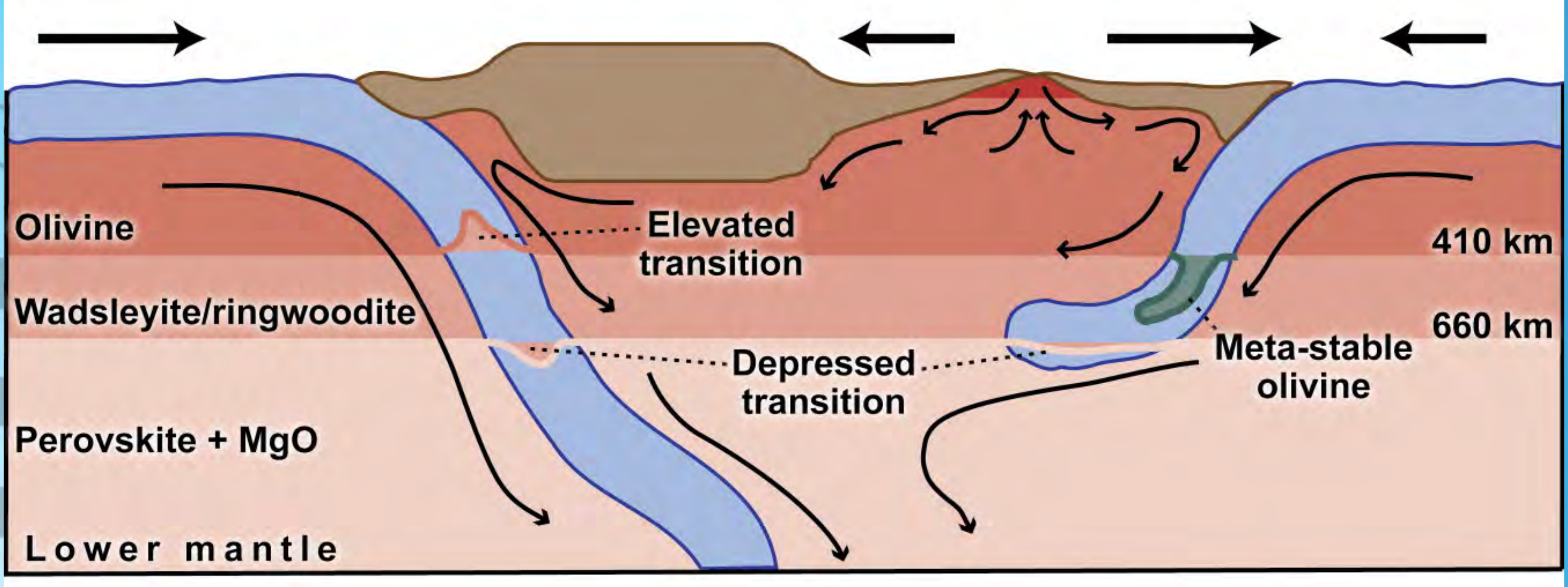
Deeper Processes (1)

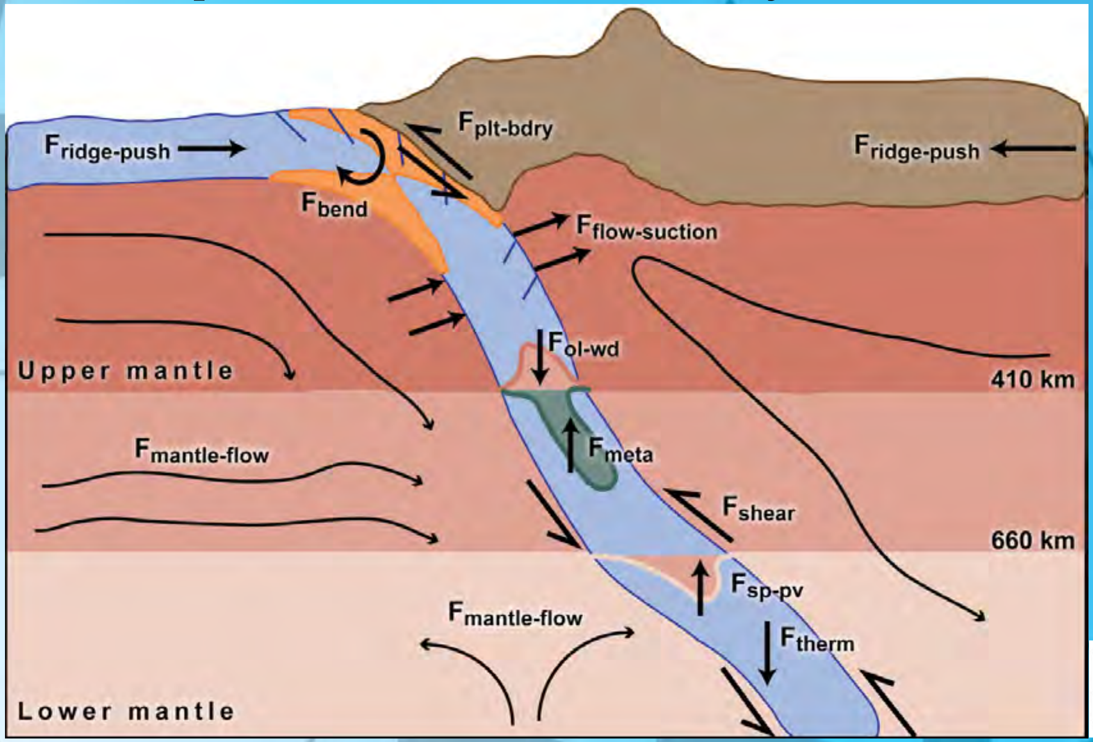


- Sinking plate undergoes ***phase transitions***
  - Increased pressure changes mineral structure to a closer-packed, denser form.
    - Example: olivine becomes wadsleyite (4% or ~150 kg/m^3 denser).
  - Series of transitions occur from 410 to 660 km
    - This is the ***transition zone.***

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

Forces Helping & Hindering Subduction

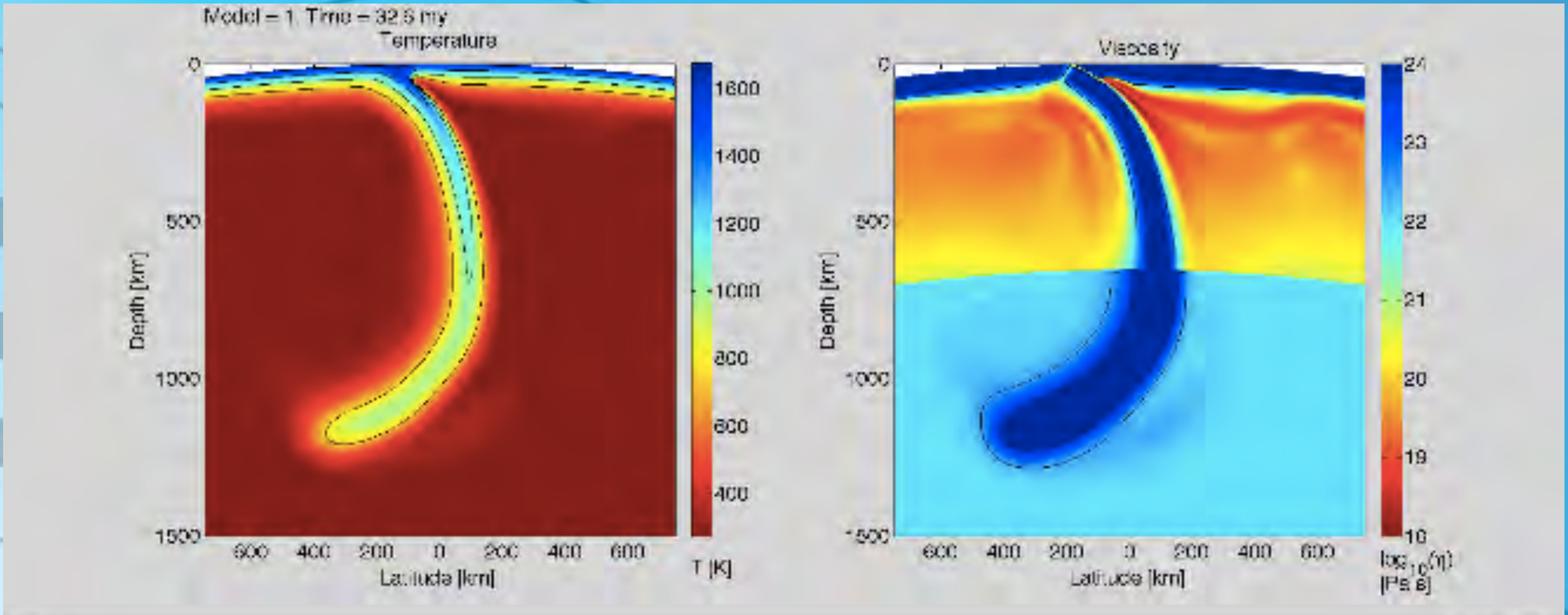
- Depth of phase transitions is temperature dependent: occurs at different depths inside cold slab.
  - If <u>shallower</u>, adds extra density to slab, **helps sinking.**
  - If <u>deeper</u>, makes slab more buoyant, **hinders sinking.**



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

- Fate of slab depends on many factors:
  - strength variations, phase transitions, coupling to surface plate motion, 3D geometry.

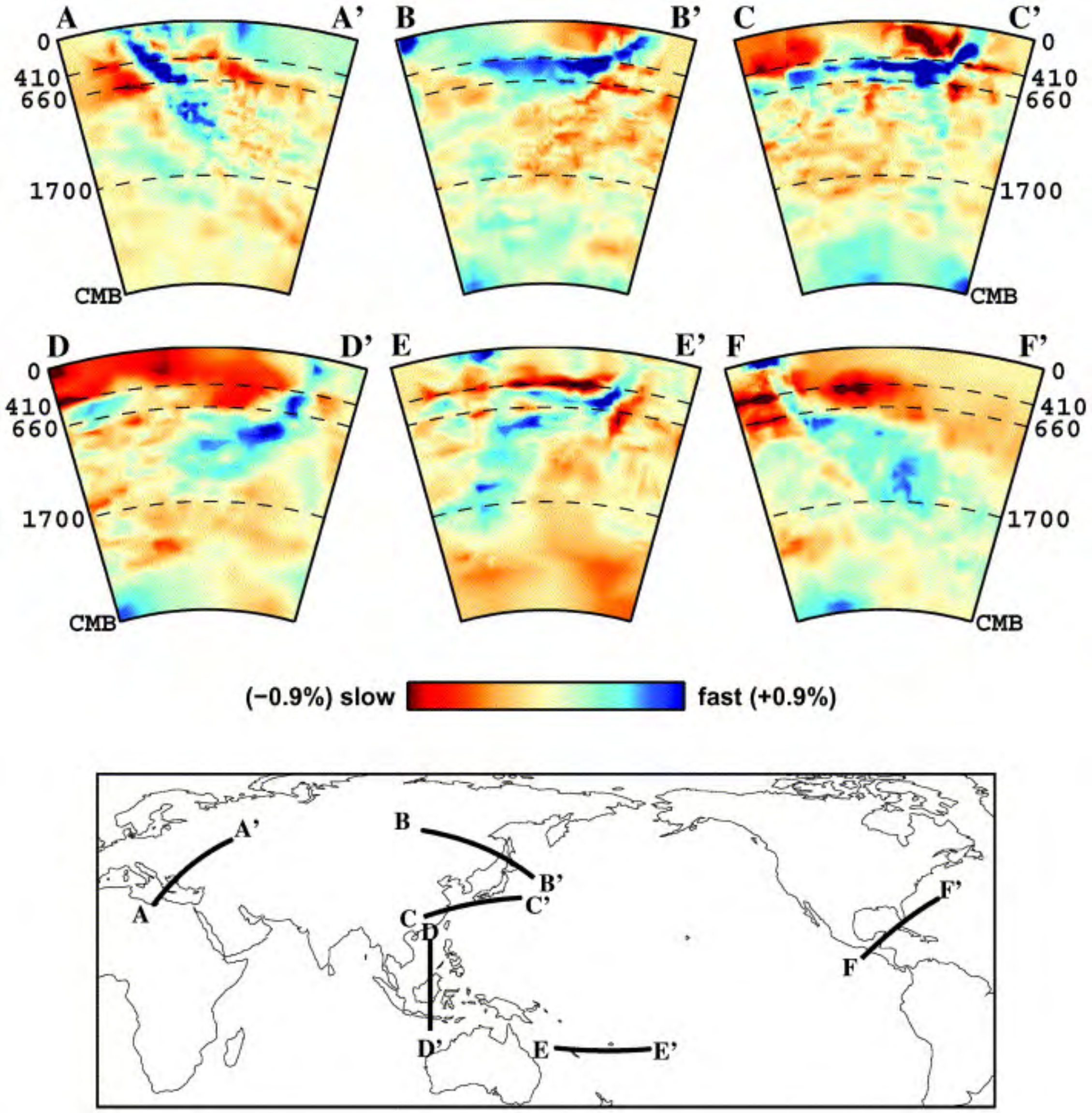
2D Numerical Models of Subduction



Billen & Hirth, 2007

- Fixed overriding plate
- Subducting plate moves at 5 cm/yr
- Stress-dependent rheology: note weak regions around slab
- No phase transitions
- Higher viscosity lower mantle supports slab
  - Shallows with time.

Seismic Observations of Slab Shape



Karason & van der Hilst, AGU Monograph, 2000

- Slab shapes are heterogeneous
  - – Slab properties?
  - – Plate motion?
  - – Time-dependent behavior?
  - – Some combination?
- Blue – fast, cold
- Red – slow, warm or hydrated or melt.

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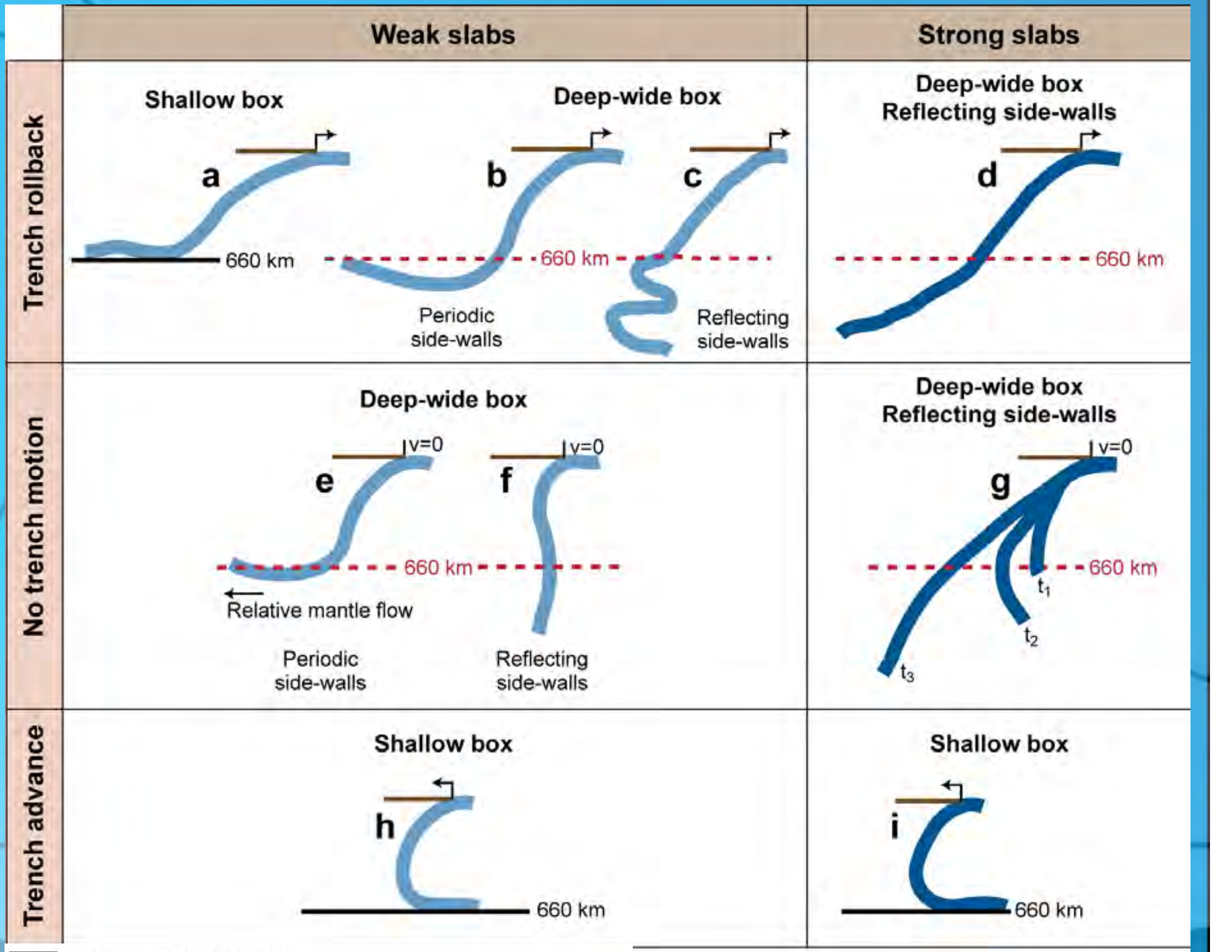
Summary of Previous Models of Subduction Behavior

- Trapped-slabs:
  - Need trench motion (roll-back).
  - Viscous resistance helps, but many models use rigid boundary at “660”
- Model domain boundary conditions can affect the slab dynamics.



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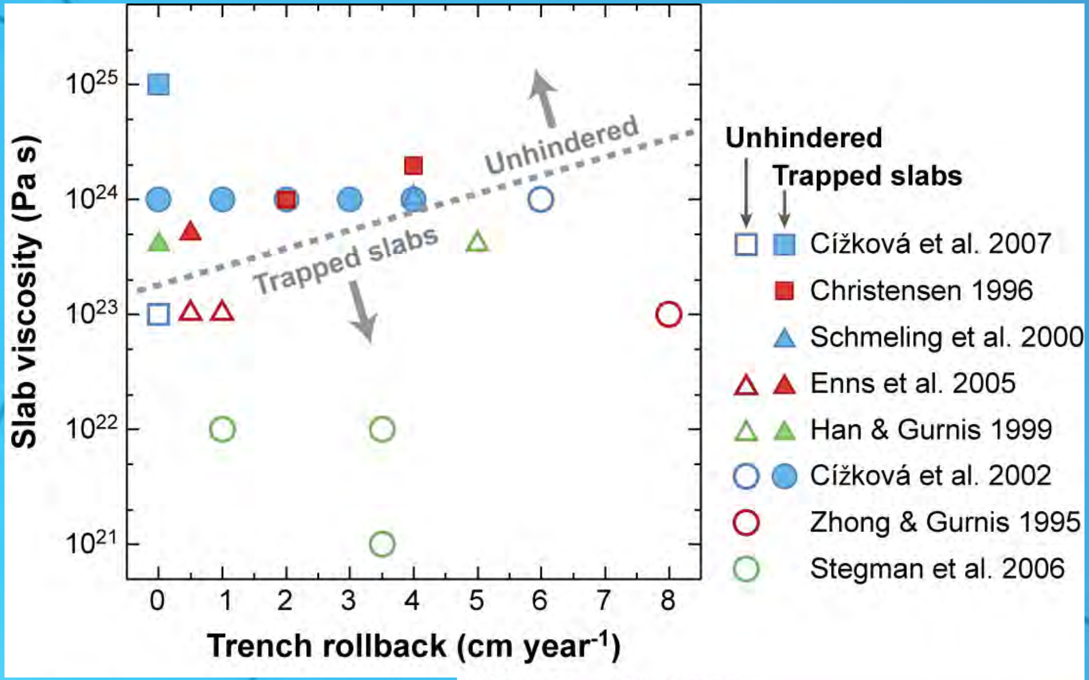
Summary of Previous Models of Subduction Behavior

- Trapped-slabs:
  - Need a moderately weak slab (or slab with weak parts)
- No previous models have, all:
  - overriding plate,
  - stress-dependent rheology,
  - **phase transitions**,
  - ***free trench motion***.



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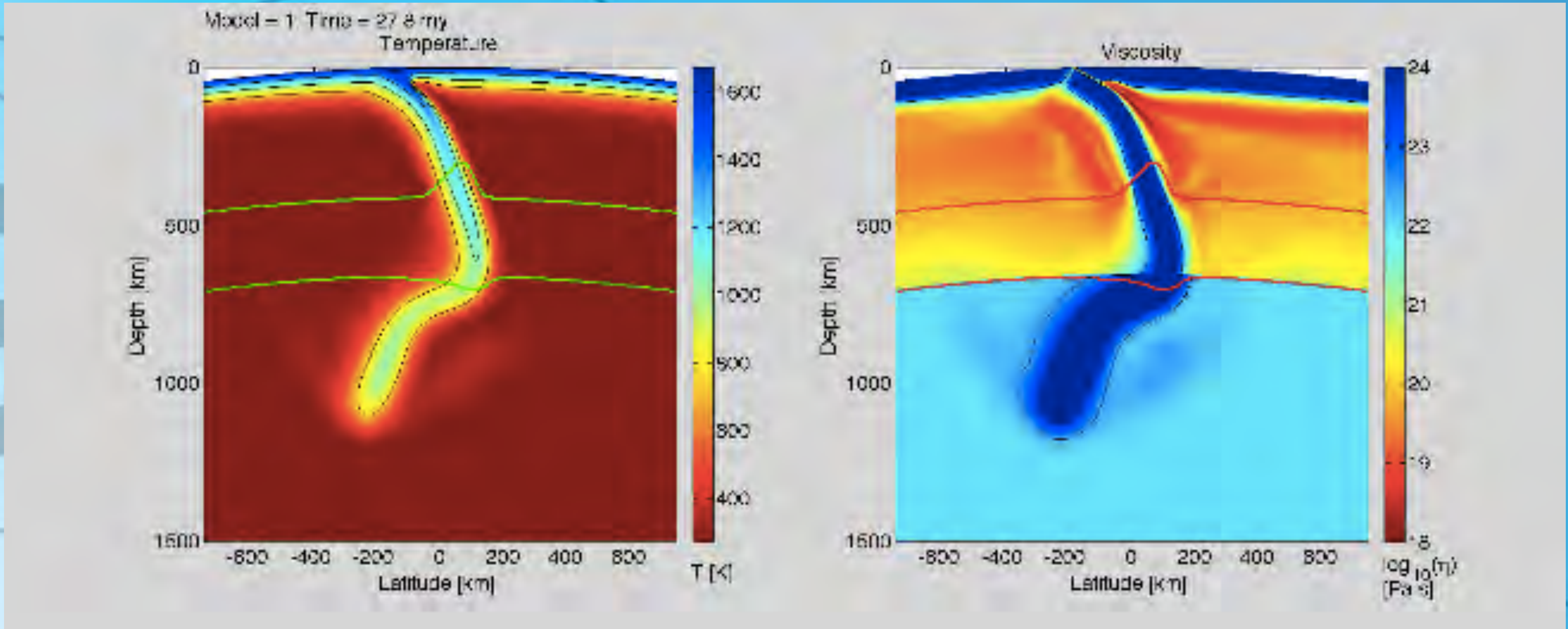
Current research project is bringing all these together in one model.

Adding Buoyancy Forces from Phase Transitions



Arredondo & Billen, in prep

- Two phase transitions (410 & 660 km)
  - hint of more deformation within slab
- Approximations:
  - Incompressible mantle with no shear heating or latent heat
  - Whole mantle is olivine
  - Only two phase transitions
  - Fixed trench

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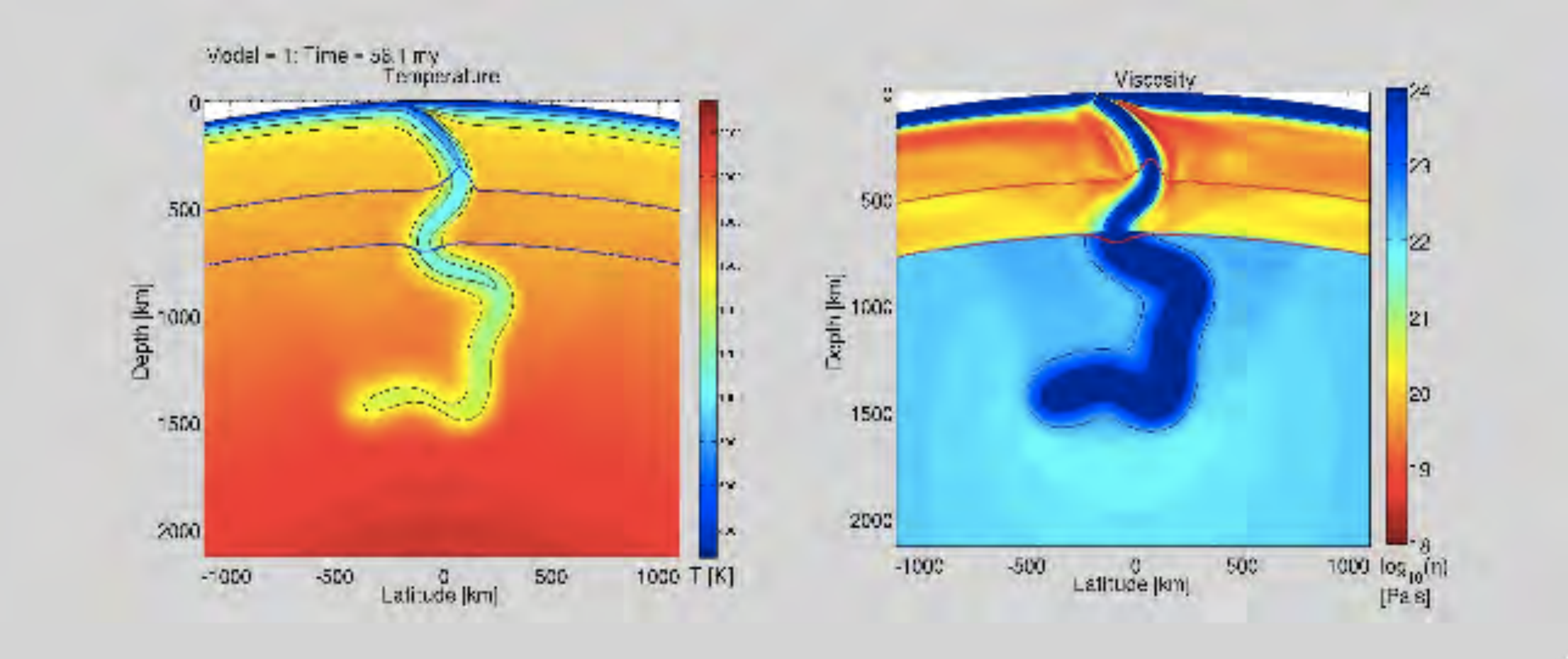
Two Phase Transitions, Shear heating & Latent Heat



Arredondo & Billen, in prep

- More folding & time-dependent behavior
  - Local weakening in slab coupled with local source of buoyancy (torques)
  - Limits transmission of stress through slab
  - ***How would this affect trench motion & plate motion at the surface?***

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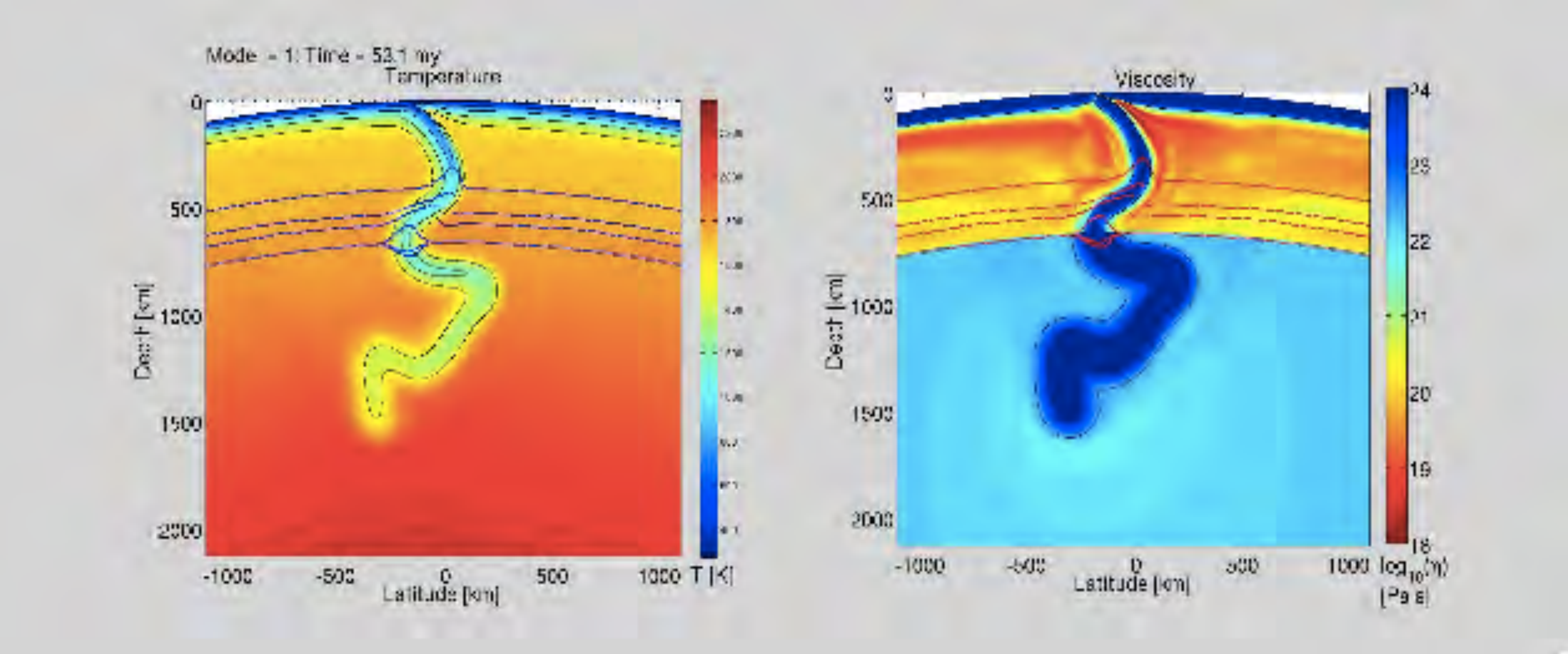
All Phase Transitions, Shear heating & Latent Heat



Arredondo & Billen, in prep

- Similar folding behavior
- Opportunity to compare deflection of multiple phase transitions (seismic discontinuities) with observational constraints.

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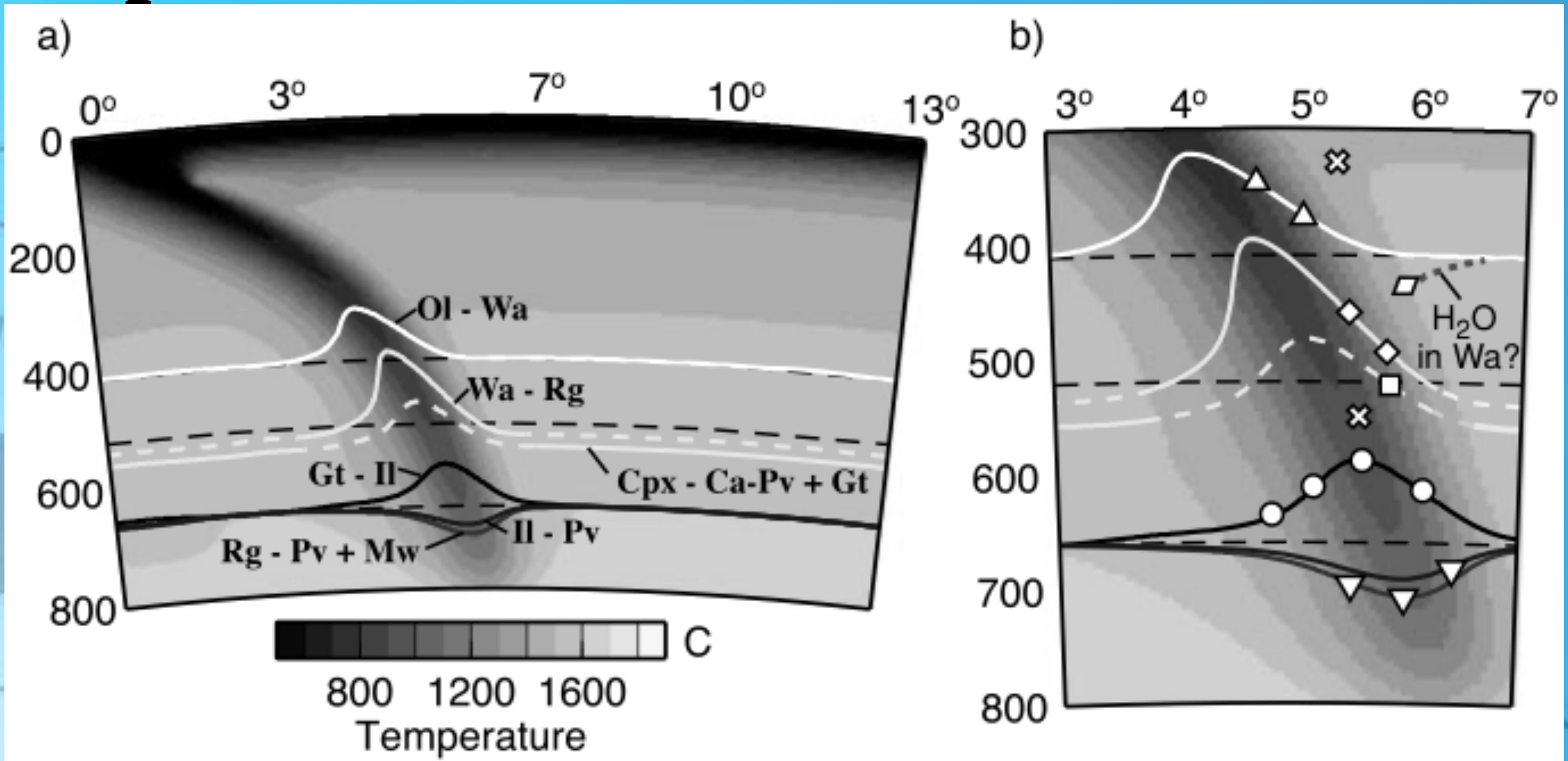
Comparison to Seismic Observations



Thomas & Billen, 2010

- Phase transitions predicted based on temperature.
- Symbols are observed under-side reflections of the Molucca sea slab.
- ***Can now do self-consistent models including all phase transitions & regional comparisons.***

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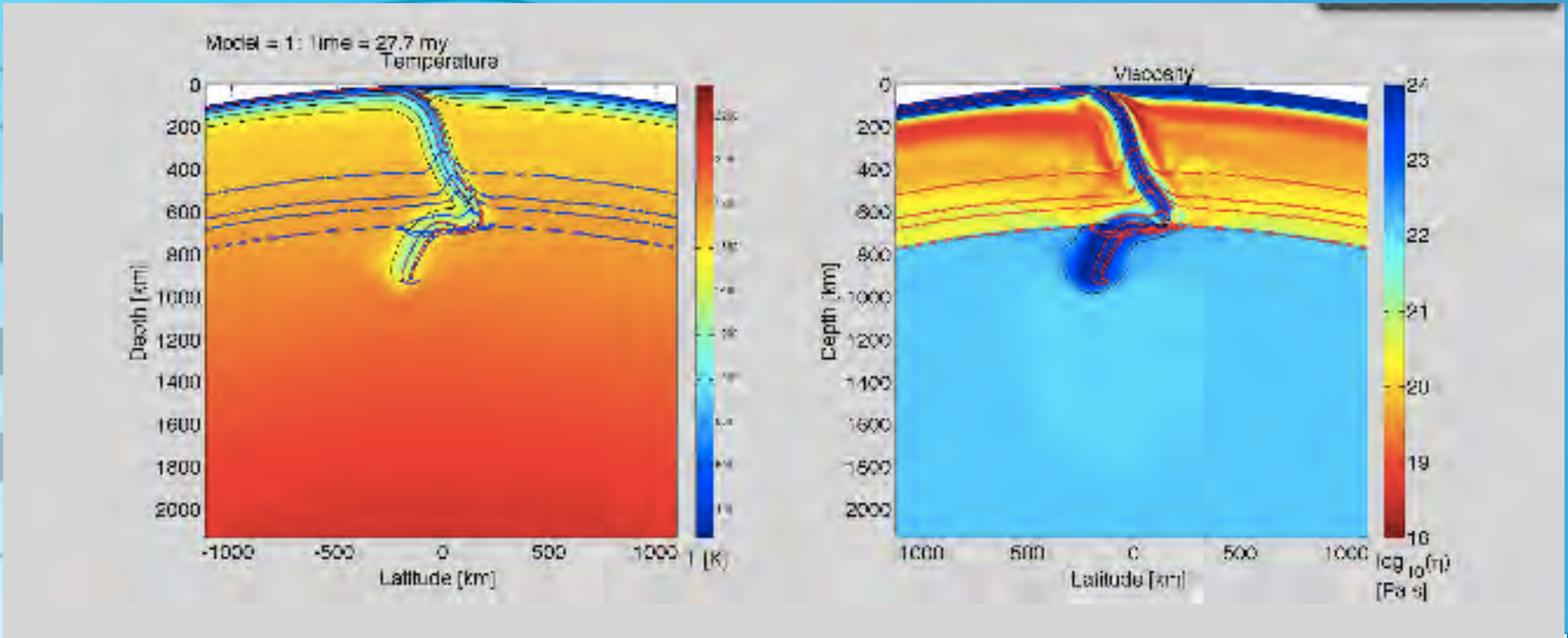
Add Compositional Layering



Arredondo & Billen, in prep

- Crust, residual layer & mantle
- Stronger eclogite layer with fewer phase transitions
- Less folding, but still strongly time-dependent.
- Break in slab above 660 km.

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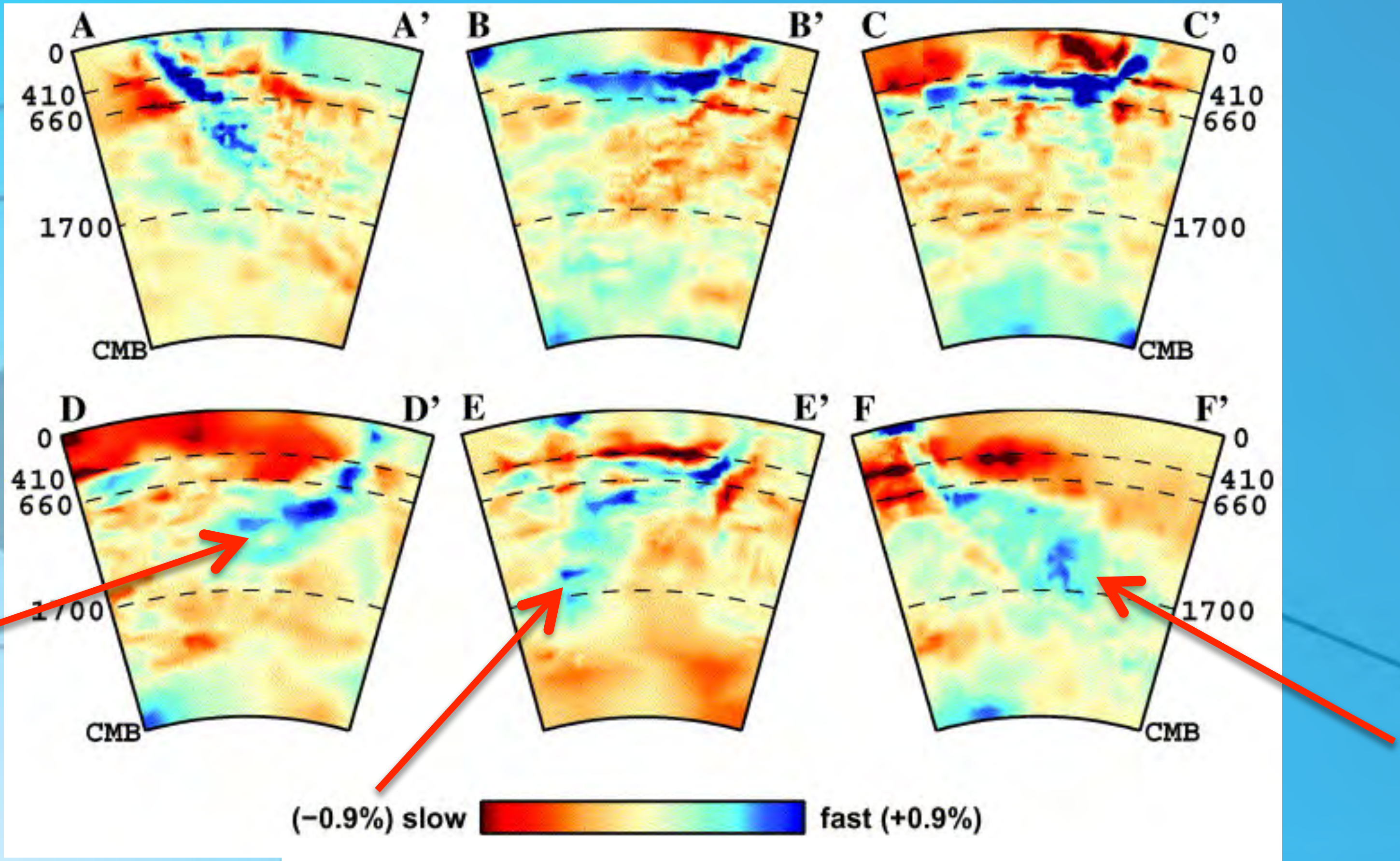
Evidence for Slab Folding?



Karason & van der Hilst, AGU Monograph, 2000

- Apparent thickening of slabs in the lower mantle??
  - Could be caused by “smearing” of folded slabs.

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Summary of Dynamical Models

- Previous models hint at importance of phase transitions and boundary conditions
- Now possible to systematically increase realism of models to better understand controls on slab dynamics.
- Strongly time-dependent behavior with folding in transition zone and lower mantle
- Last Major Step: *add free trench (in progress)*

Subduction Zone Research Questions

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   - Oceanic plateau subduction
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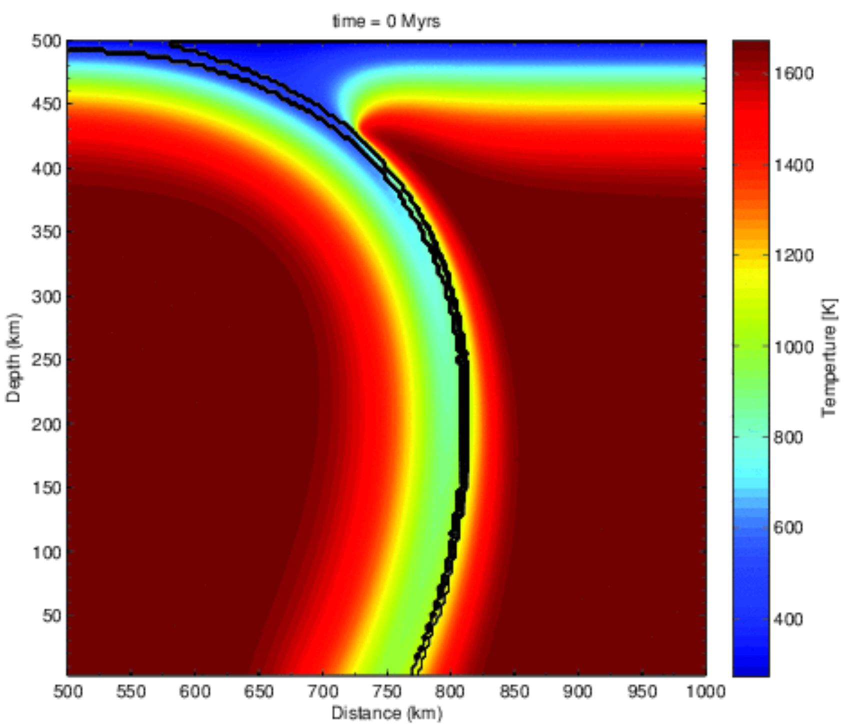
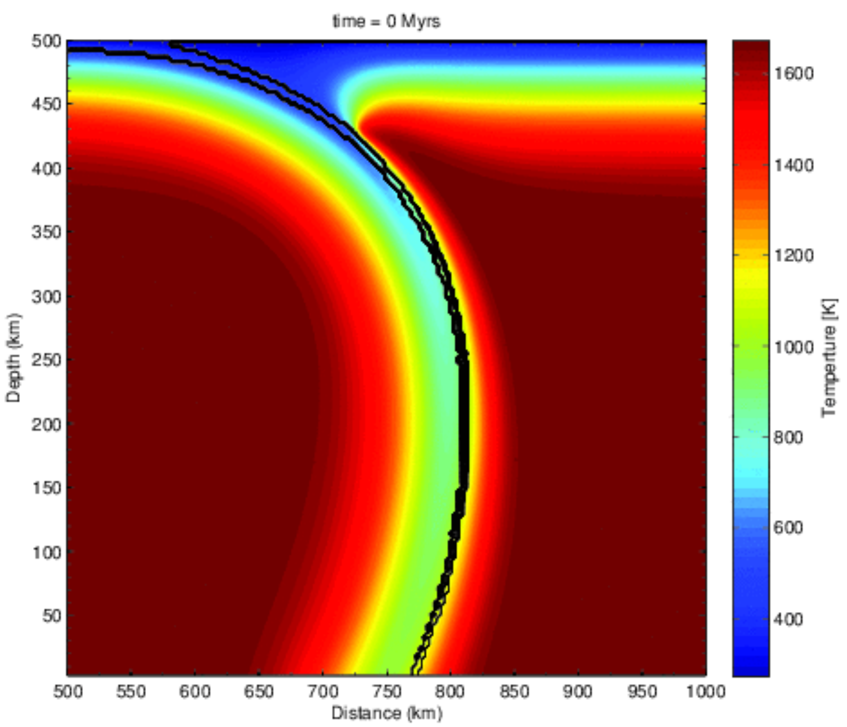
Oceanic Plateau Subduction (2D)

- 20 km thick, 300 km long
- Subduction slows, but plateau is subducted



- 25 km thick, 300 km long
- Trapped underplated plateau
- slab detaches



Arrial & Billen, EPSL 2013

Basalt-to-eclogite transition favors plateau subduction.

Stretching & Plastic yielding in slab causes Detachment and subduction fails.

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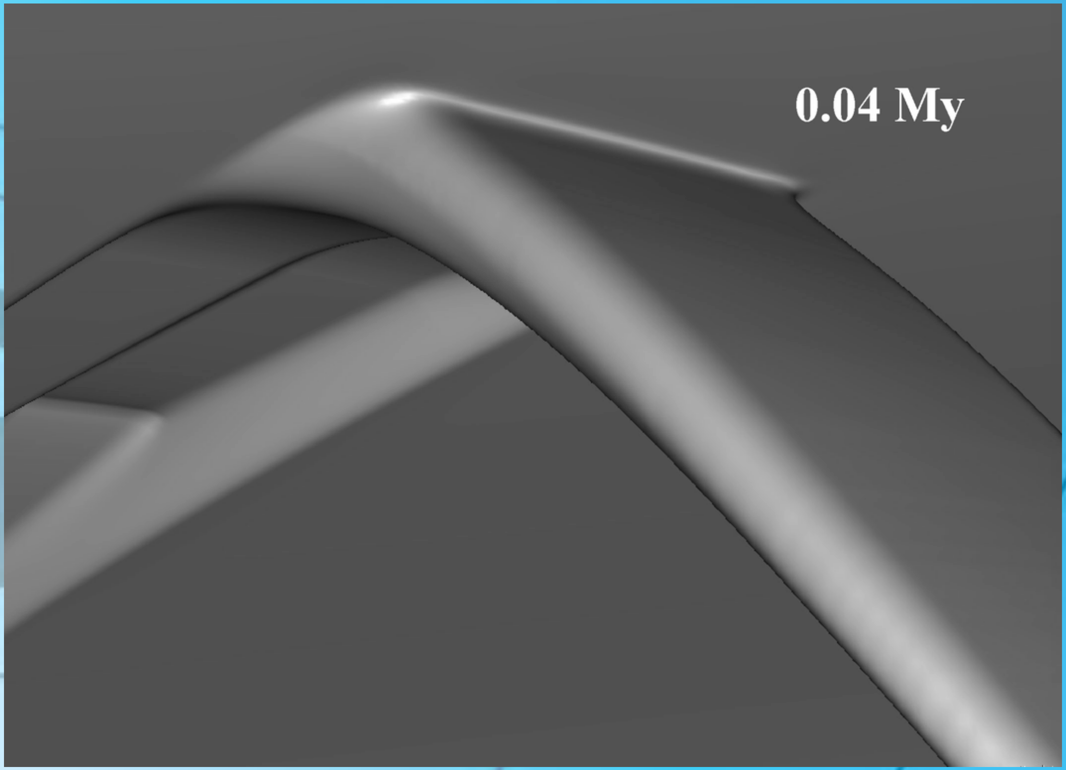
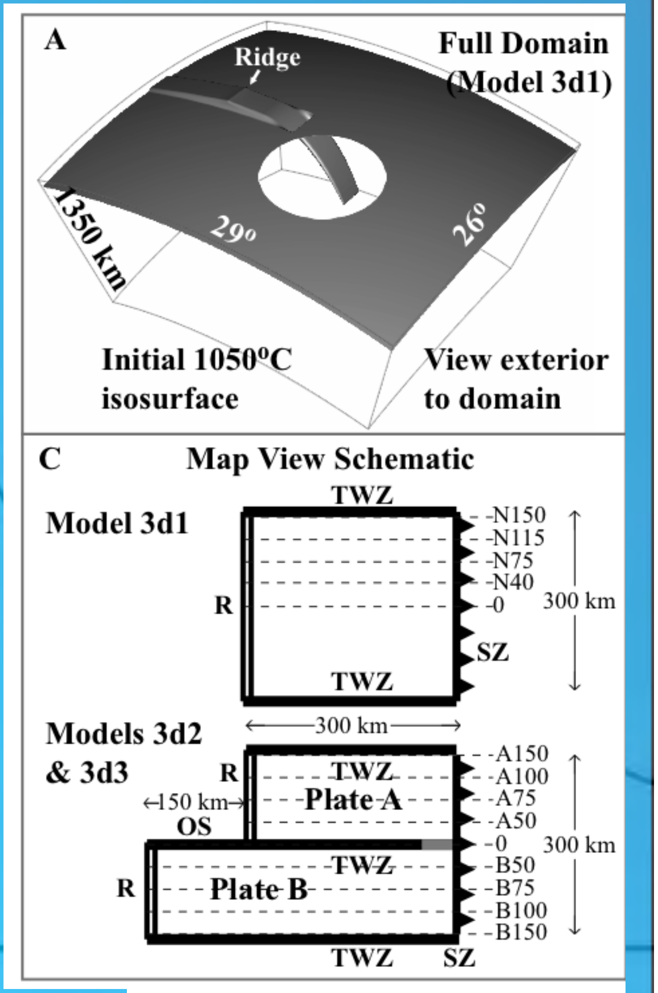
Ridge-Trench Interaction (3D)





Burkett & Billen, 2010

- Slab detaches along weakened fracture zone, propagates toward older plate side (plastic yielding)
- Loss of strength leads to detachment (not ridge buoyancy)

Conclusions

1. Outer-rise faulting is just the beginning of a rough journey for the slab
   - Significantly weakens the plate allowing it to bend into the mantle
2. Forces acting on slab in the mantle both help and hinder subduction
   - Phase transitions, shear heating, and latent heat cause time-dependent folding behavior
     - May be cause for broad slabs imaged seismically
     - Next step: allow free-trench motion
       - Time-dependent coupling to surface plate, trapped slabs?
   - Slab strength variations are biggest influence on dynamics: time-dependent behavior.
3. Each subduction zone has unique history
   - Special cases can cause subduction to fail
   - More difficult to interpret seismic images in terms of simpler subduction models.

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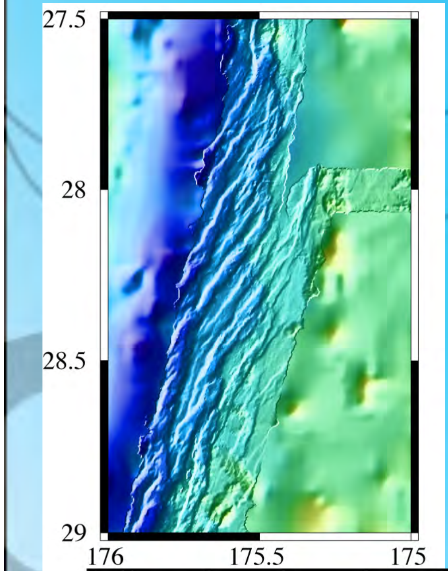
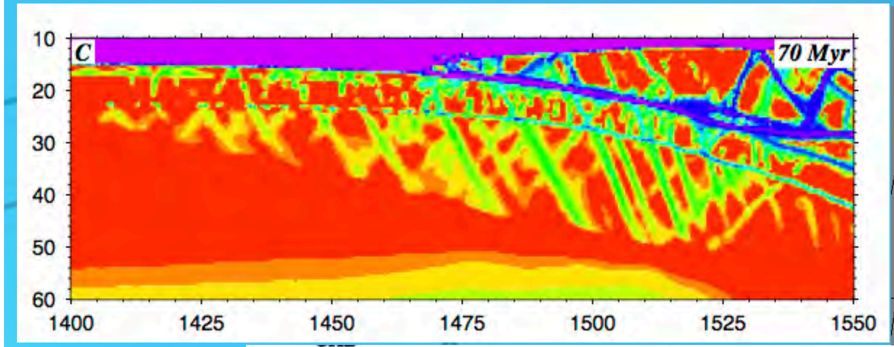
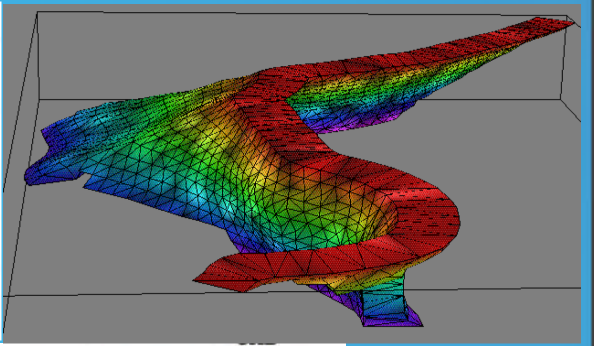
Collaborators & Students

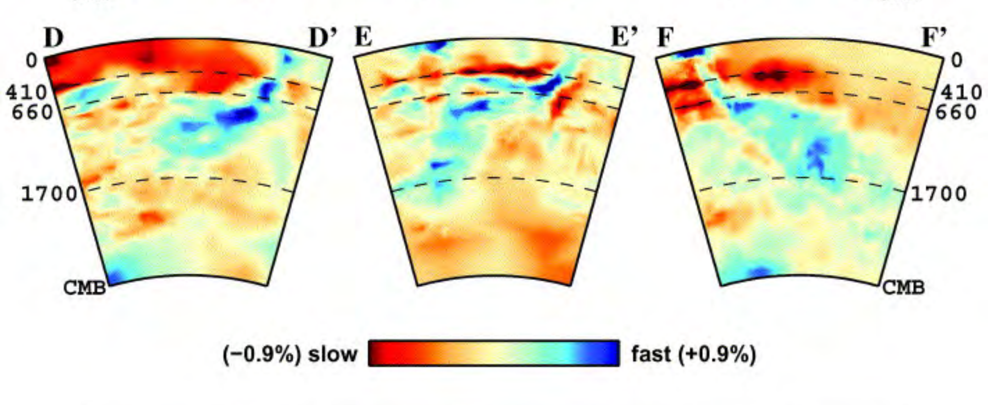
- Outer-rise Faulting:
  - Weakening of the plate (Dr. Mike Gurnis (Caltech), Katrina Arredondo (ugrad, grad),
  - Strength of faults: Dr. Eric Cowgill (UCD), Eric Buer (ugrad)
  - Fault characteristics: Jessie Saunders (ugrad)
  - Numerical Modeling: John Naliboff (postdoc)
- Subduction Dynamics (2D)
  - Rheological constraints: Dr. Greg Hirth & Dr. Peter Kelemen (WHOI)
  - Phase Transitions: Katrina Arredondo (grad)
  - Comparison to seismic obs: Dr. Tine Thomas (U. Muenster)
- Subduction Failure (2D & 3D):
  - Ridge-Trench Interaction: Erin Burkett (grad)
  - Oceanic-Plateau subduction: Pierre Arrial (post-doc)

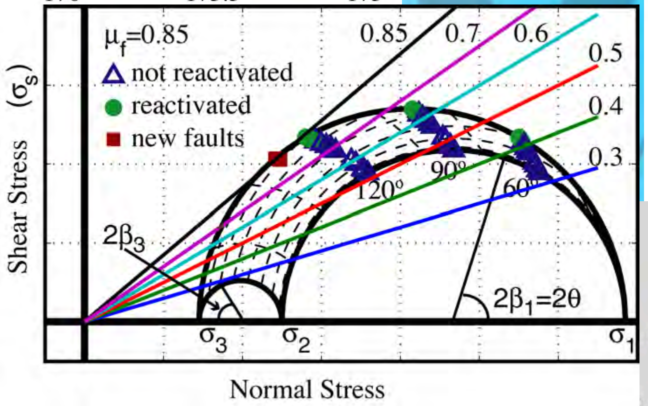
Thank you!

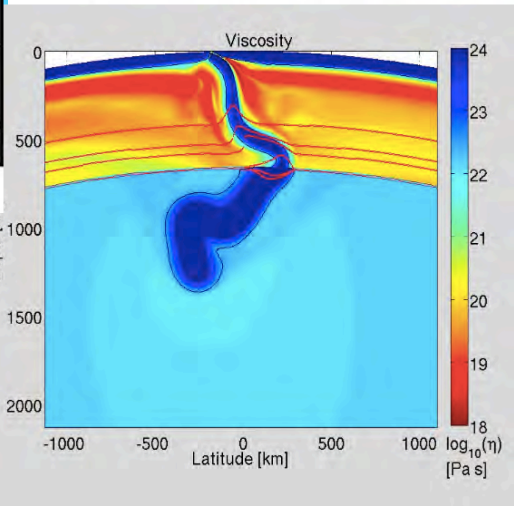


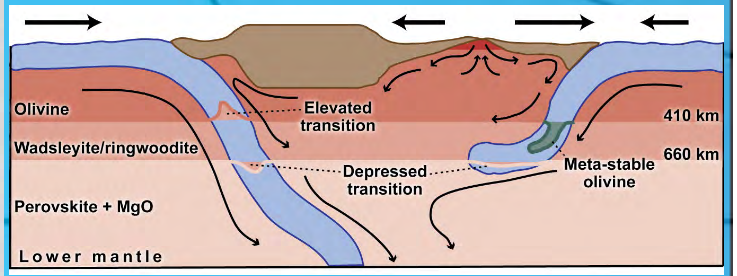


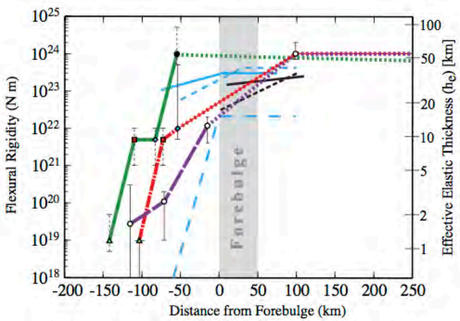












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