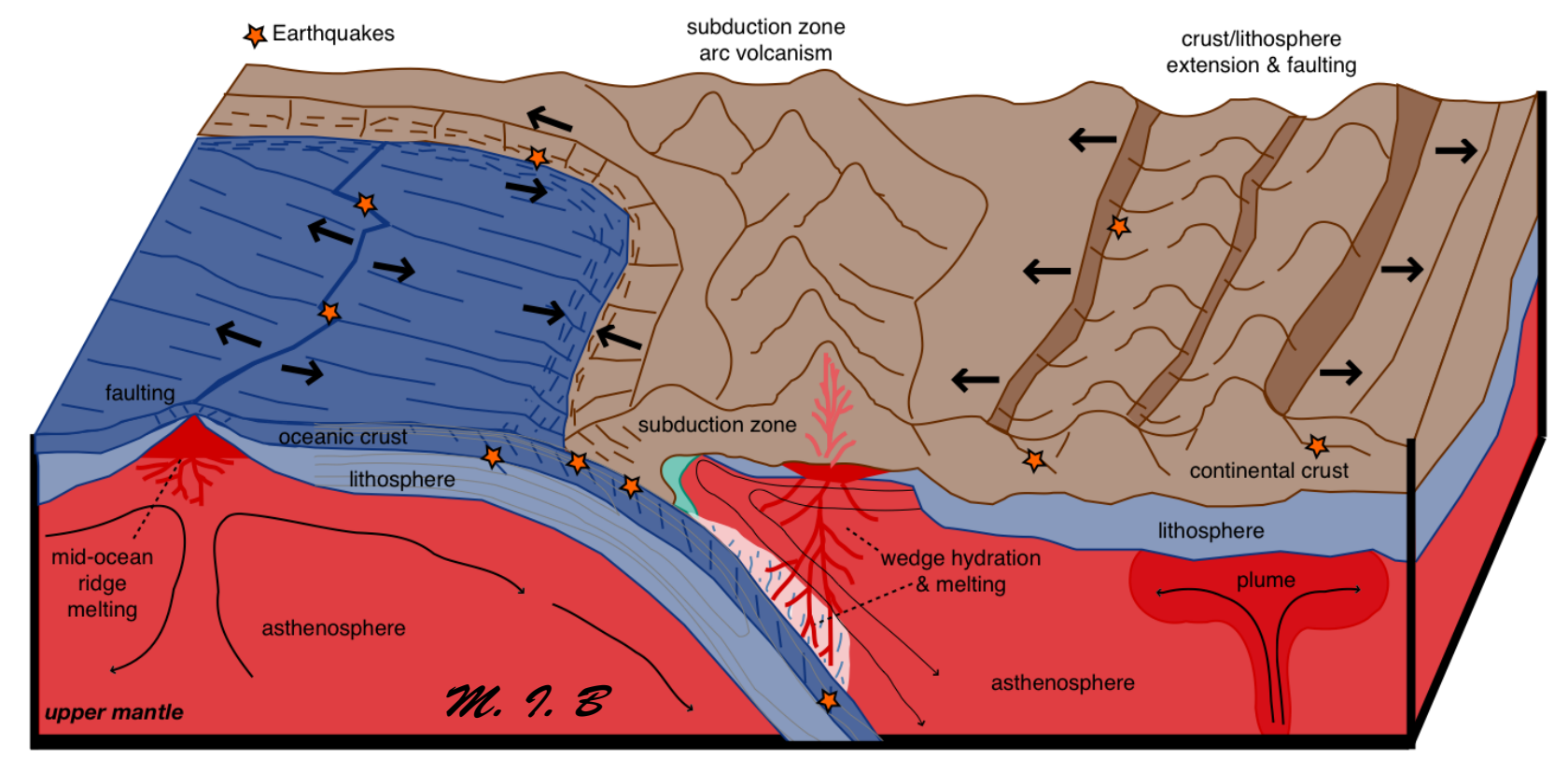
Geodynamics II: Subduction Dynamics

Magali Billen

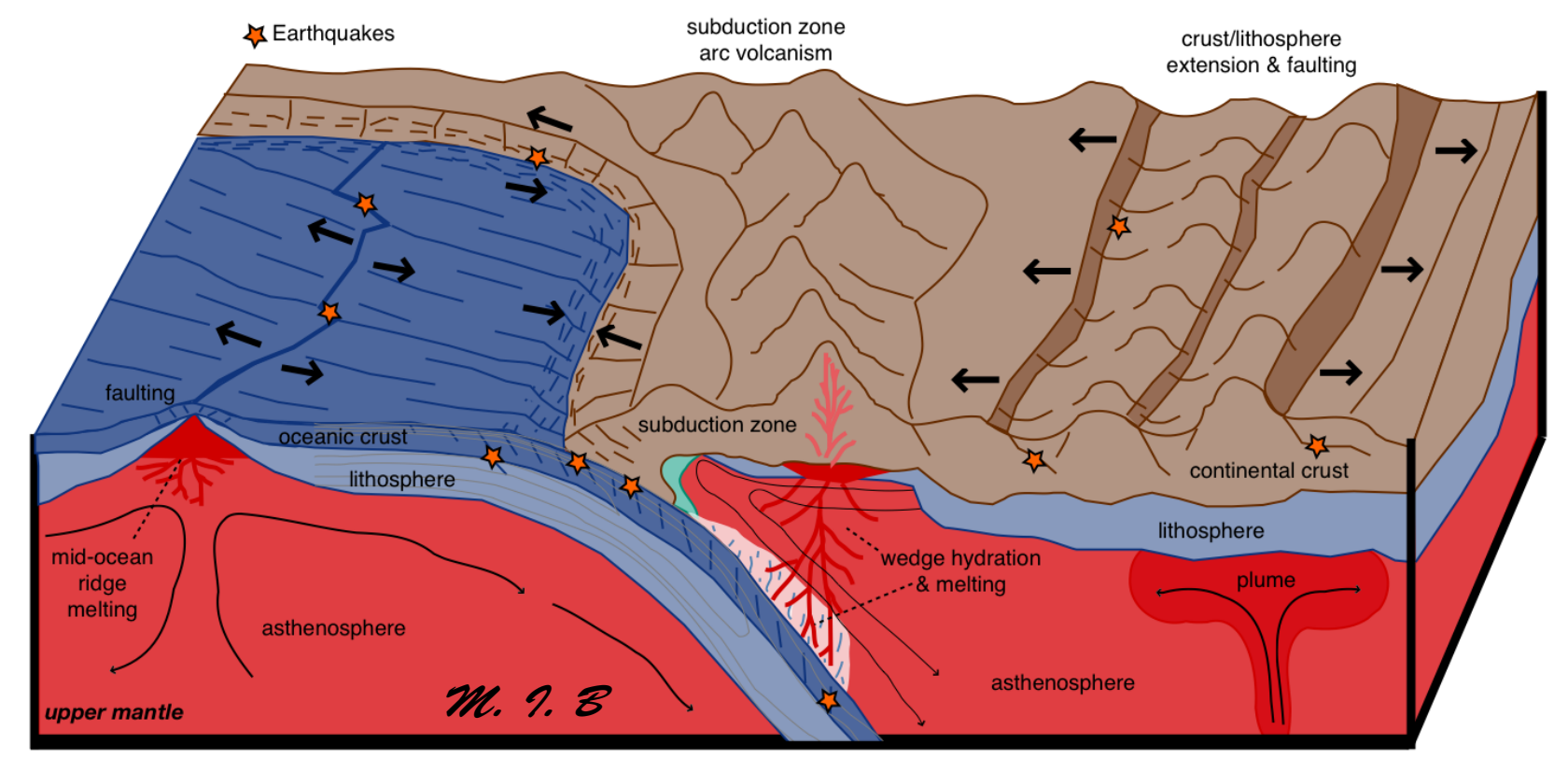
UC Davis

Overview of Subduction System



- Plate forms at spreading ridge (buoyant crust + harzburgite, dry)
- Cools and thickens (dense lithosphere) as it travels across ocean basin.
- Bends at trench → Sinks into the mantle

Overview of Subduction System



- What are the key observations that characterize subduction on earth?
- How can we use these observations to learn about the process active in the upper and lower mantle?

Outline

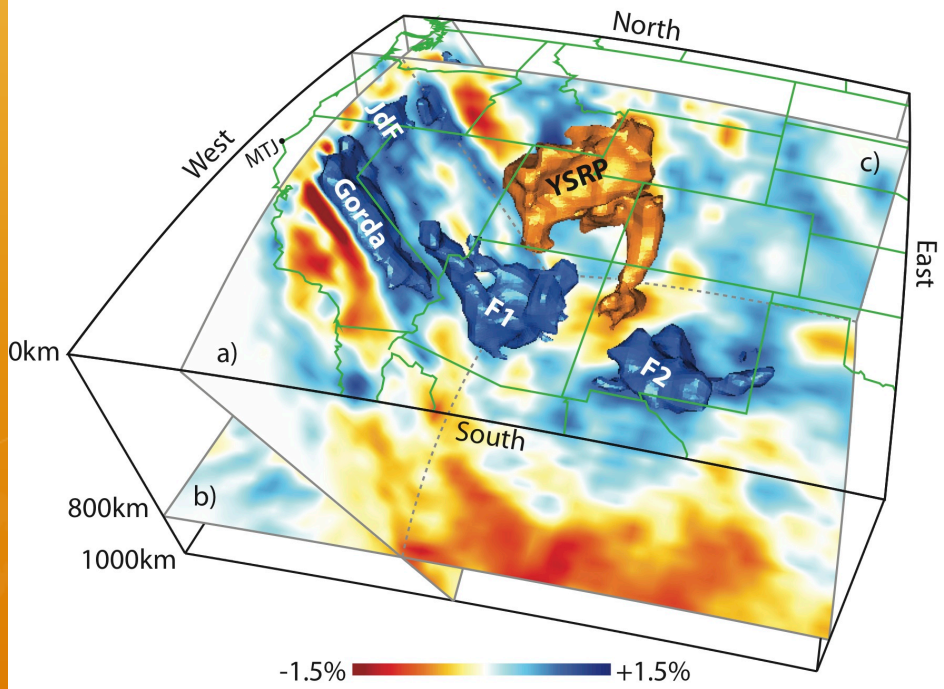
1. What are the key observations that constrain the dynamics of subduction?
2. How do end-member models inform our understanding of subduction?
3. Some key “simple” (temperature) approximations for asking/ answering questions about subduction.
4. What are the key processes during different stages of subduction?

1. Key Observations

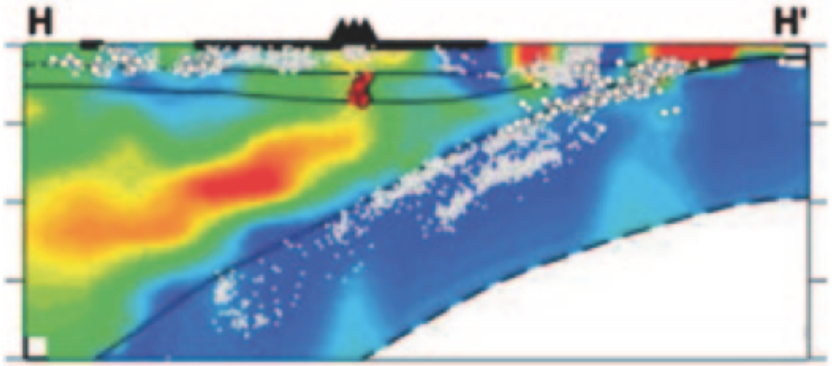
- One-sided subduction
- Surface topography
- Seismicity within slab
- Seismic imaging of the slab

One-Sided Subduction

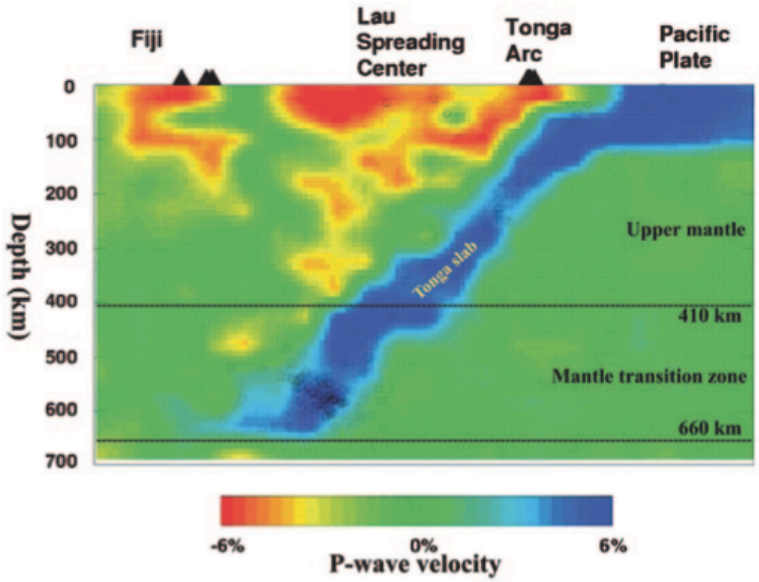
- One-sided subduction: only one plate subducts, even in oceanic-oceanic settings.



[from Richard Allen's Website]



D. Zhao et al., TectP., 2009

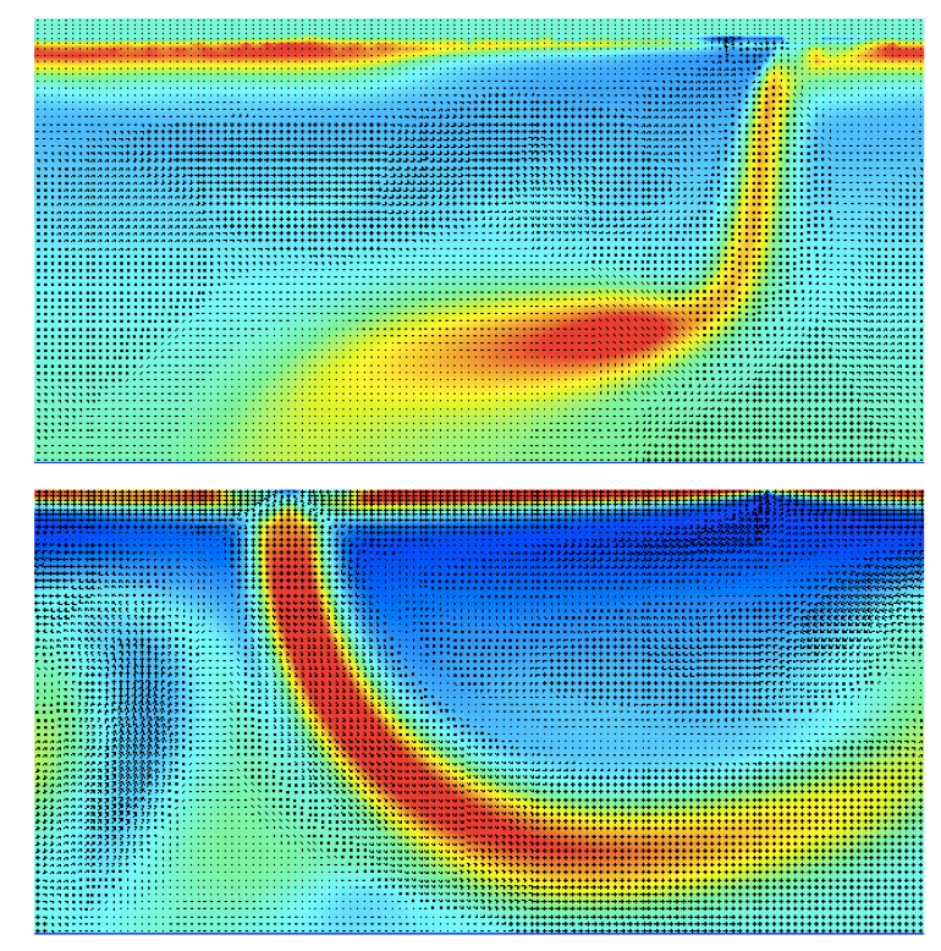


D. Zhao 1996, 1997

One-Sided Subduction

- Global models of plate tectonics typically show 2-sided subduction
- New models show 1-sided subduction. Key findings:
  - need to allow slab to bend naturally at upper boundary (free surface).
  - need a weak crustal layer to decouple flow from upper plate.

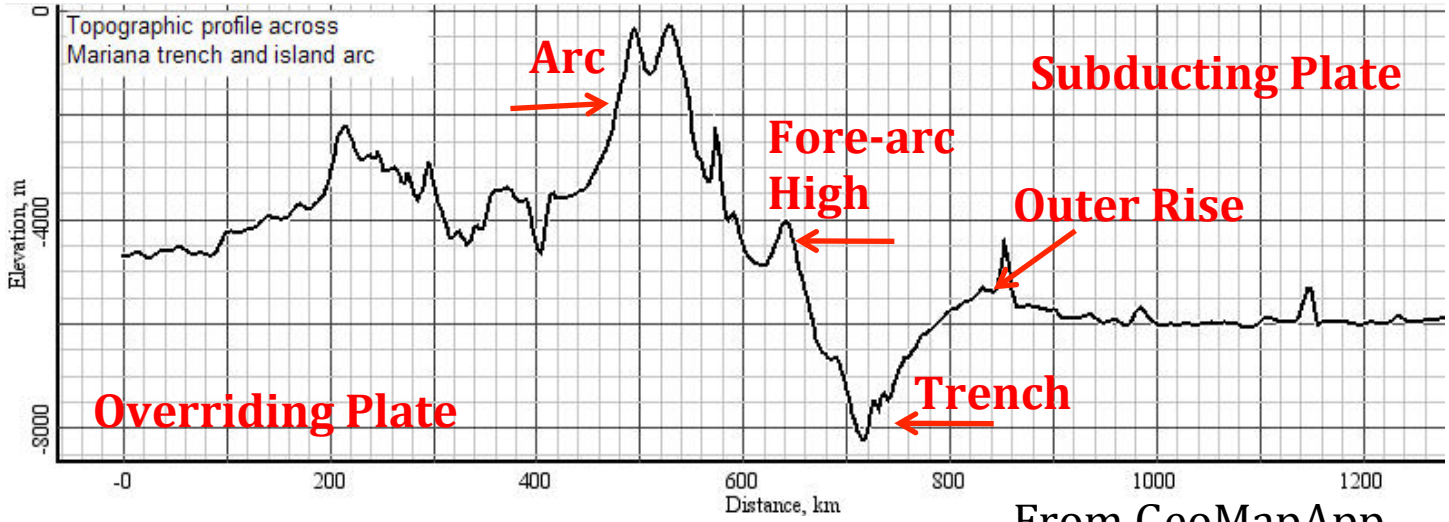
  [Crameri et al., 2012]
- **Key Point**: Always ask "What are the Boundary Conditions?"



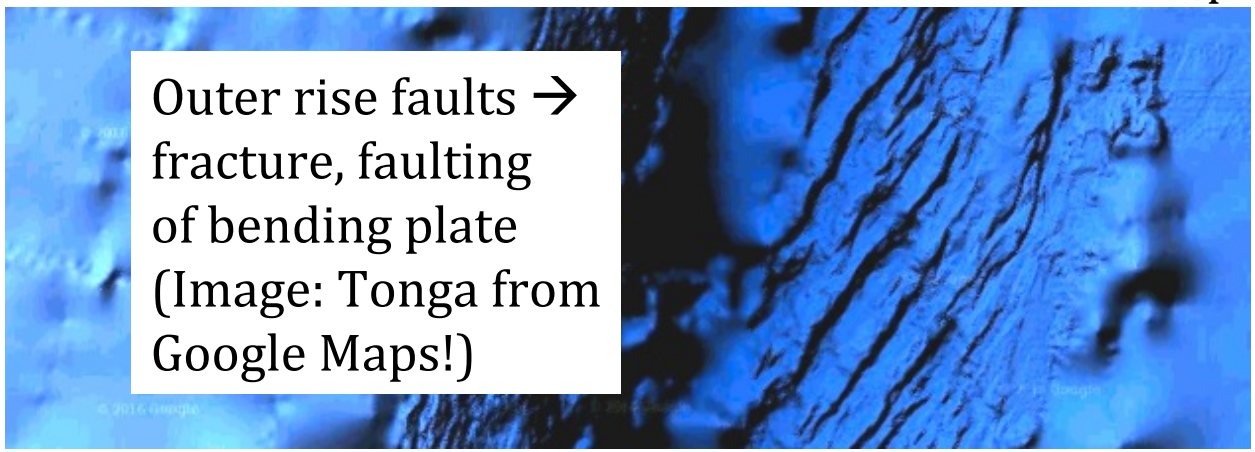
Becker Comment: this may not be "the" requirement, but having a free surface is more realistic.

Key Observations: Topography

- Topography → small outer rise (+ 200 m), deep trench (-3000 m), small fore-arc high, volcanic arc.



From GeoMapApp



Outer rise faults → fracture, faulting of bending plate (Image: Tonga from Google Maps!)

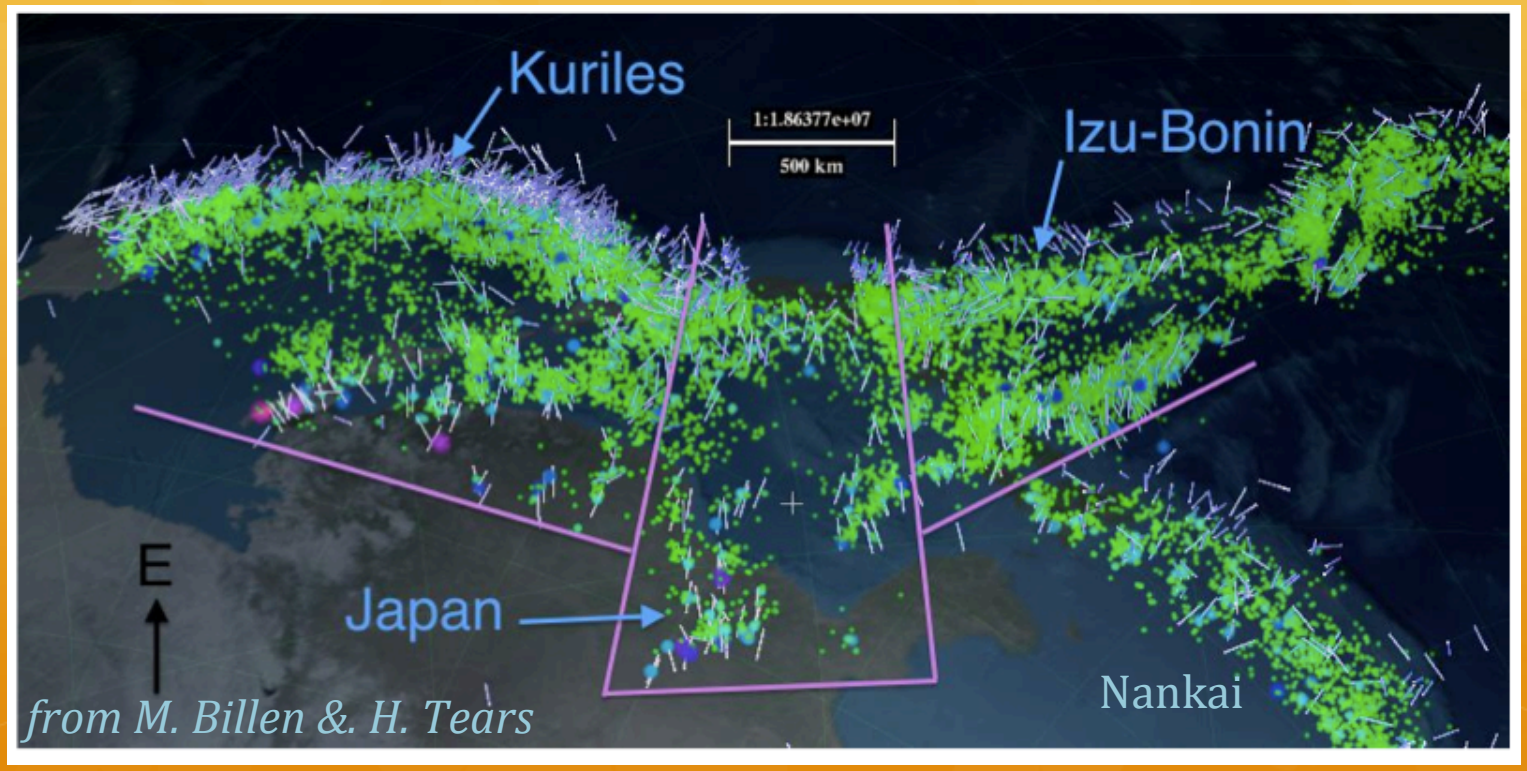
Key Observations: Earthquakes

Images from KeckCAVES: ShowEarthModel

- Next image is looking down into the Earth at seismicity in slabs beneath the surface shown in the figure.

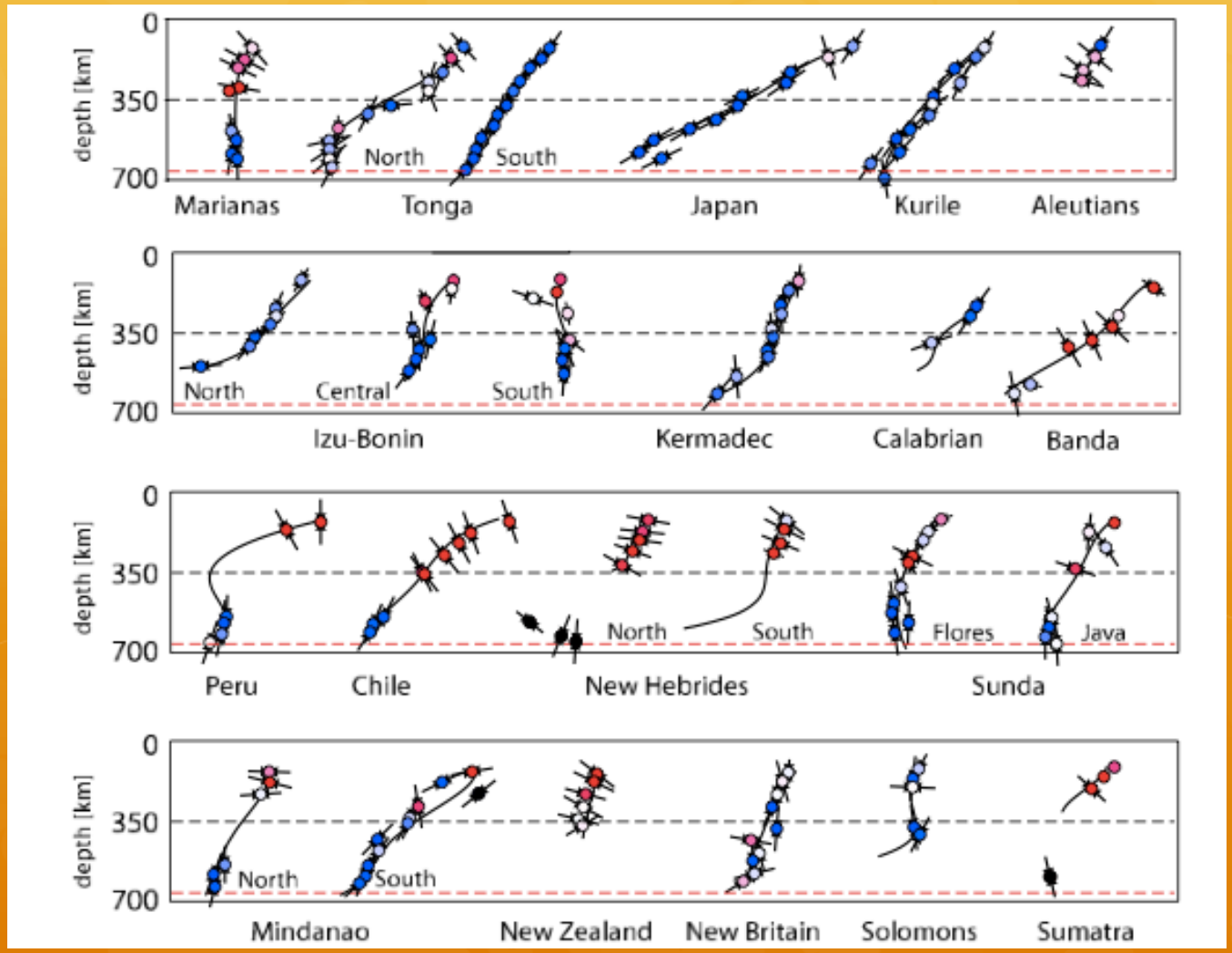
Key Observations: Earthquakes

Dots: earthquakes → Green, blue, purple pink, red →M= 5, 6, 7, 8, 9



- Earthquakes → delineate slab shape; stop abruptly at about 660 km; activity has minimum at ~350 km; activity varies a lot between slabs

Key Observations: Slab Shape & Moment Tensors

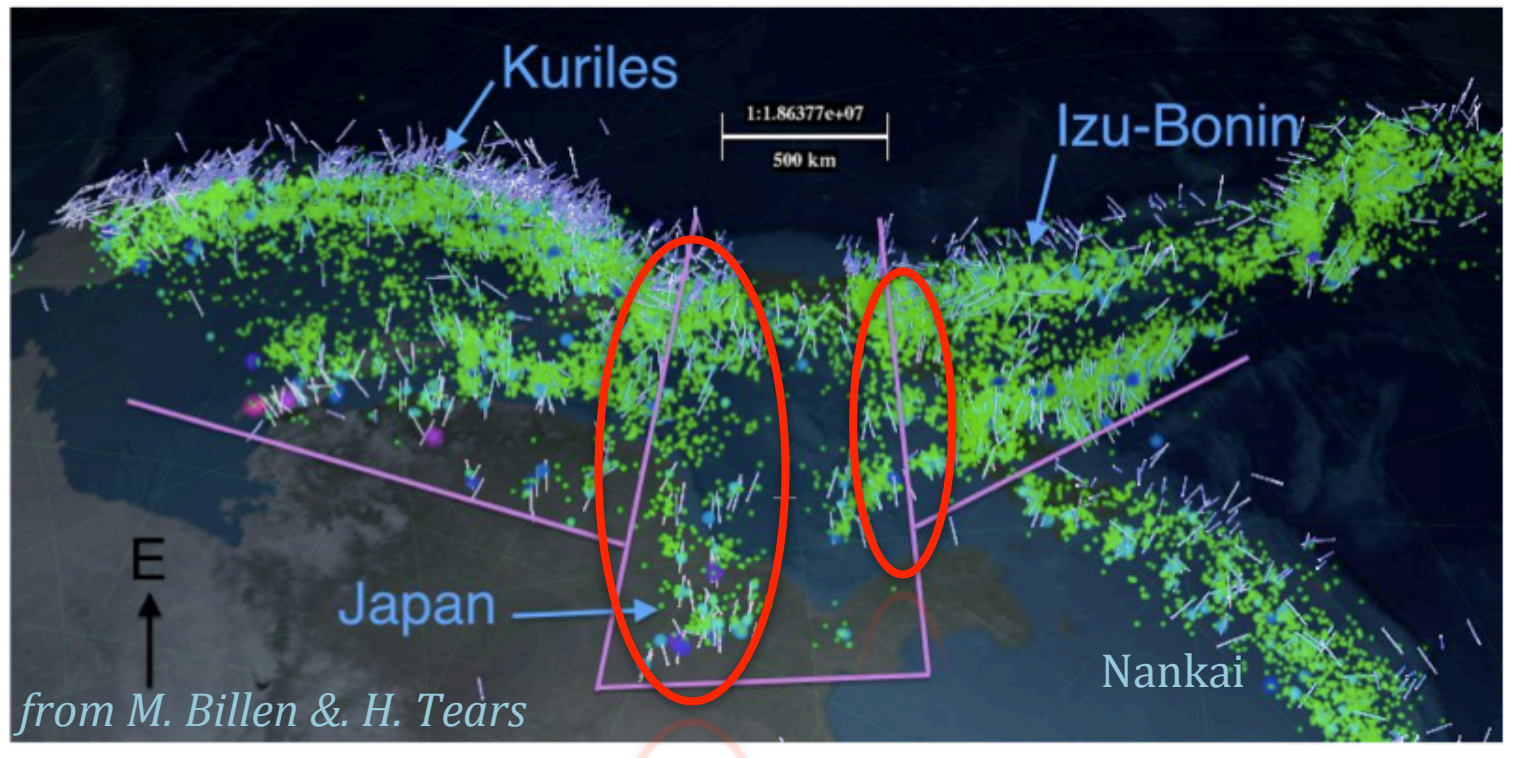


Alpert et al, G-cubed, 2010

- Moment tensor → internal deformation (shortening, stretching)

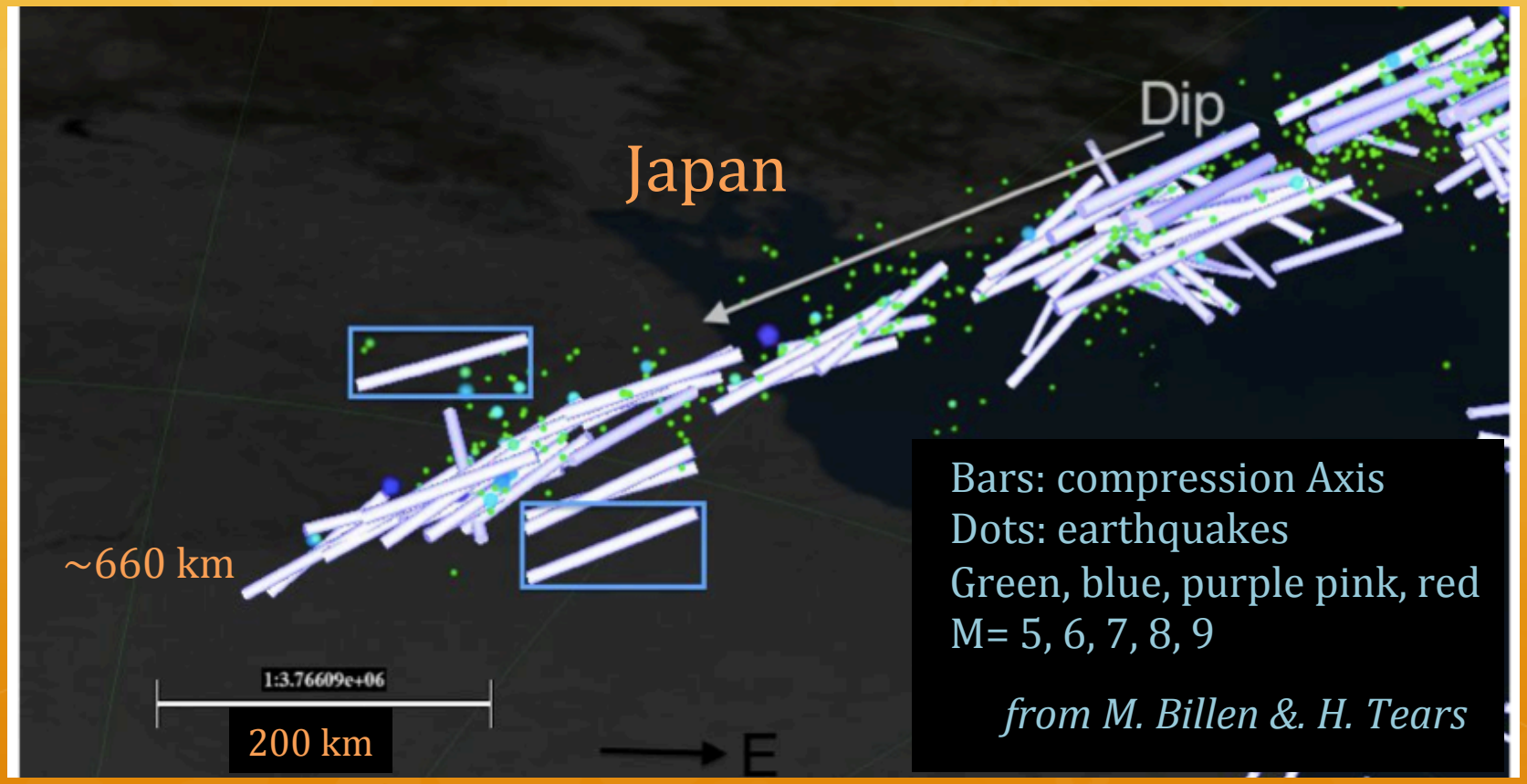
Example: Moment Tensors

Dots: earthquakes → Green, blue, purple pink, red →M= 5, 6, 7, 8, 9



- 3D View: Looking East down into the Earth"
  - Earthquakes (M>4): dots
  - Compression Axis from Moment Tensor: blue bars

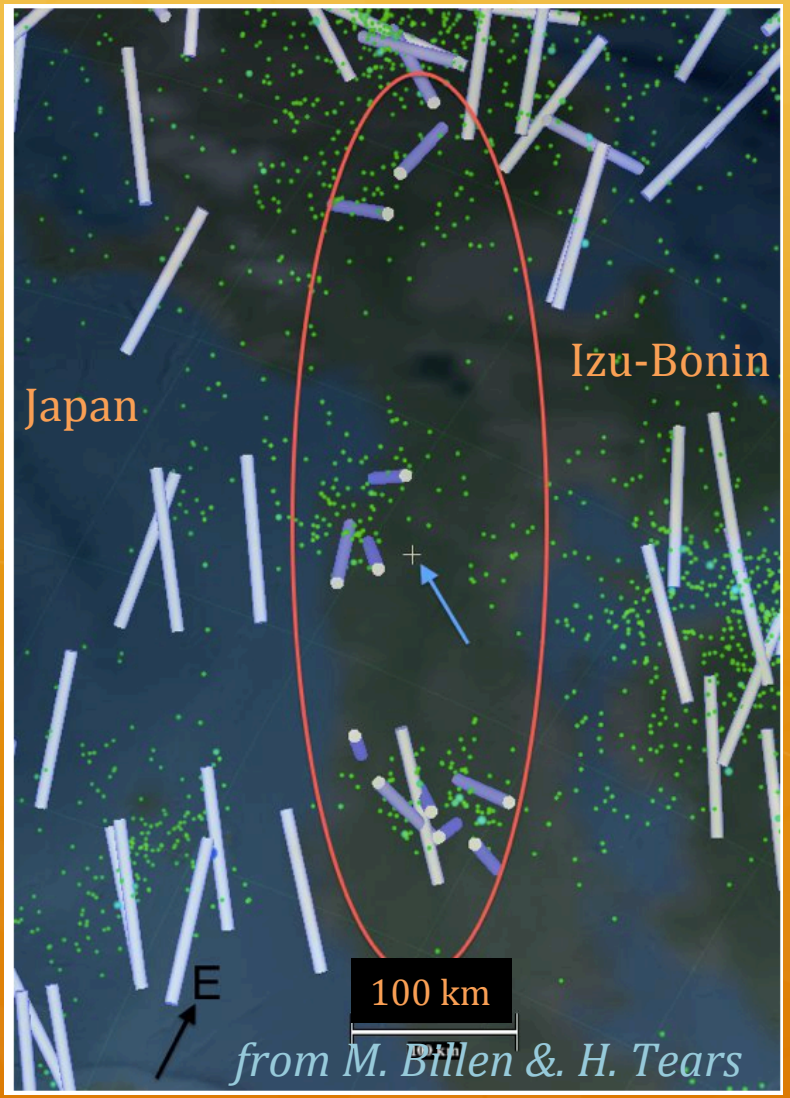
Example: Moment Tensors



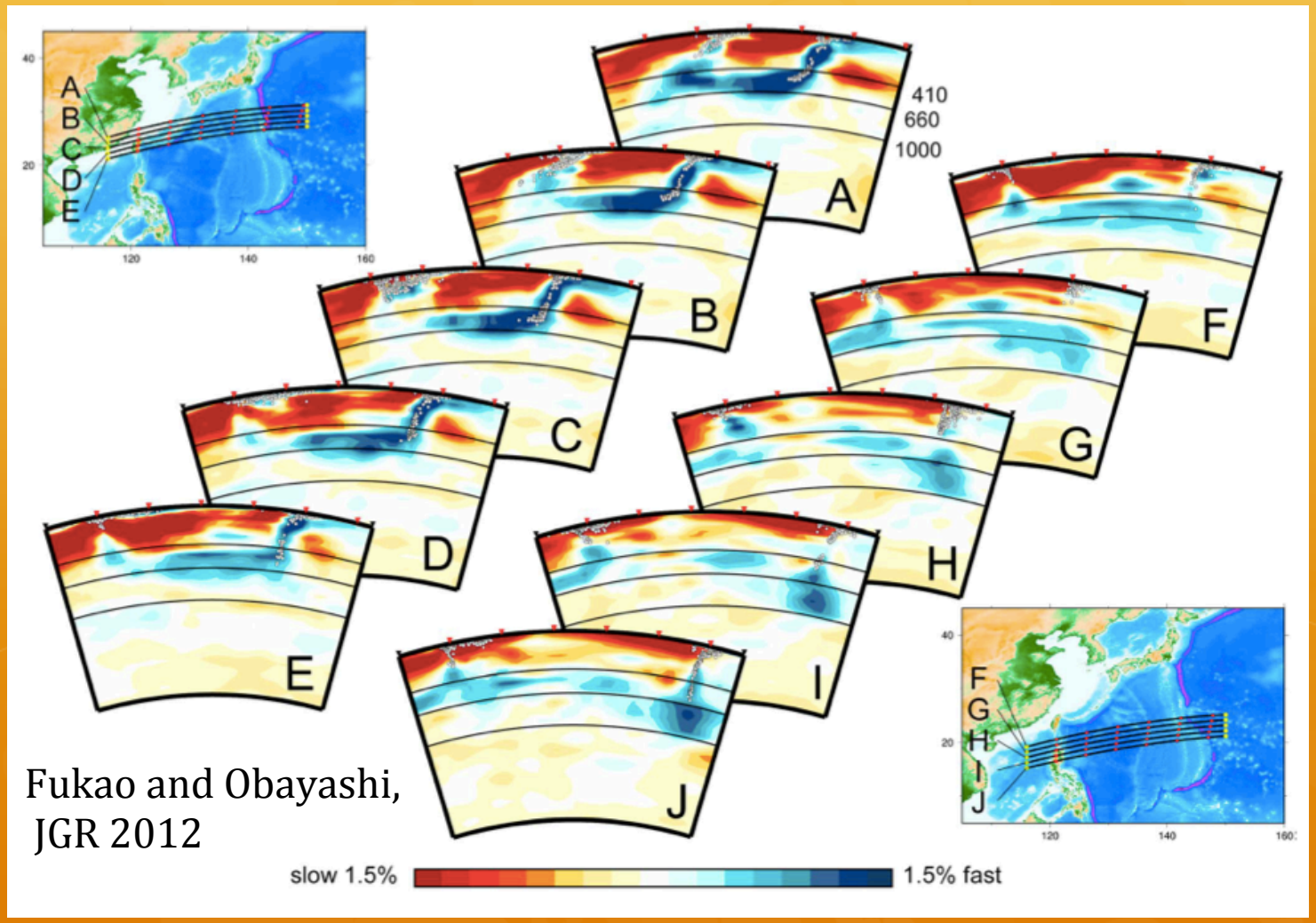
- Central Japan Slab: very uniform down-dip compression in shallow dipping slab (max depth ~660 km)
- Some outliers from central band in seismicity: significance?

Example: Moment Tensors

- Face-on view looking east
- Boundary between Japan and Izu-Bonin
- Clear rotation in compression axis in 100 km wide region.
  - Possible region of bending, stretching of slab
- **Key Point**: there is more information here about how slabs deform in the upper mantle → effects how they sink into the lower mantle.



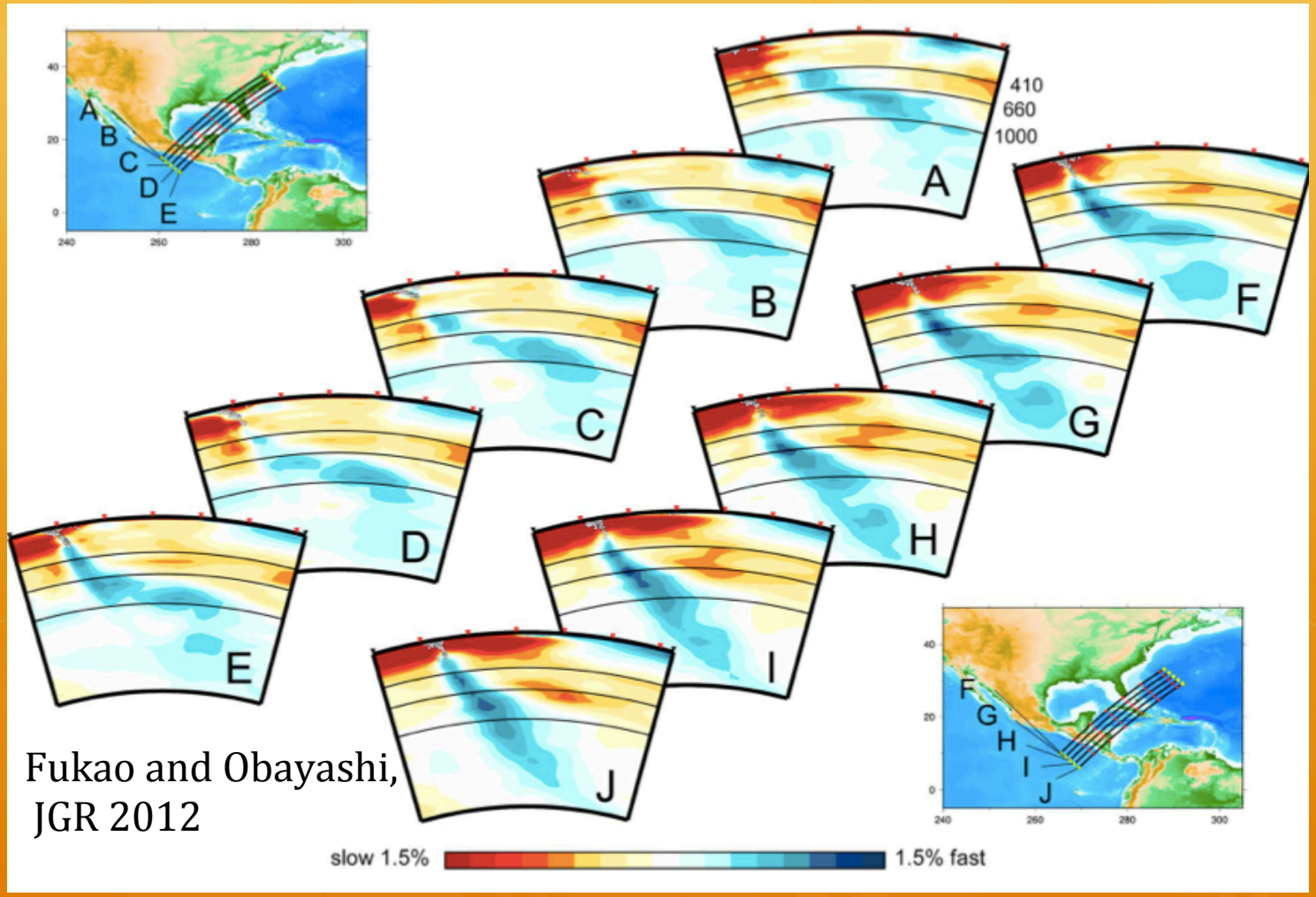
Key Observations: Seismic Tomography



Fukao and Obayashi, JGR 2012

- Seismic Tomography → slab shape (shallow & deeper).

Key Observations: Seismic Tomography



Fukao and Obayashi, JGR 2012

- Sinking into the lower mantle is… complicated.

Tomographic Images

- Give complex view of subduction into lower mantle.
- What causes differences in observed shape of slabs?
  - Different stages of interaction with transition zone and lower mantle?
  - Differences in slab properties?
  - Differences in surrounding mantle properties?
  - Differences in surrounding mantle flow?
- To answer these questions, need to use models to make predictions and compare to observations.

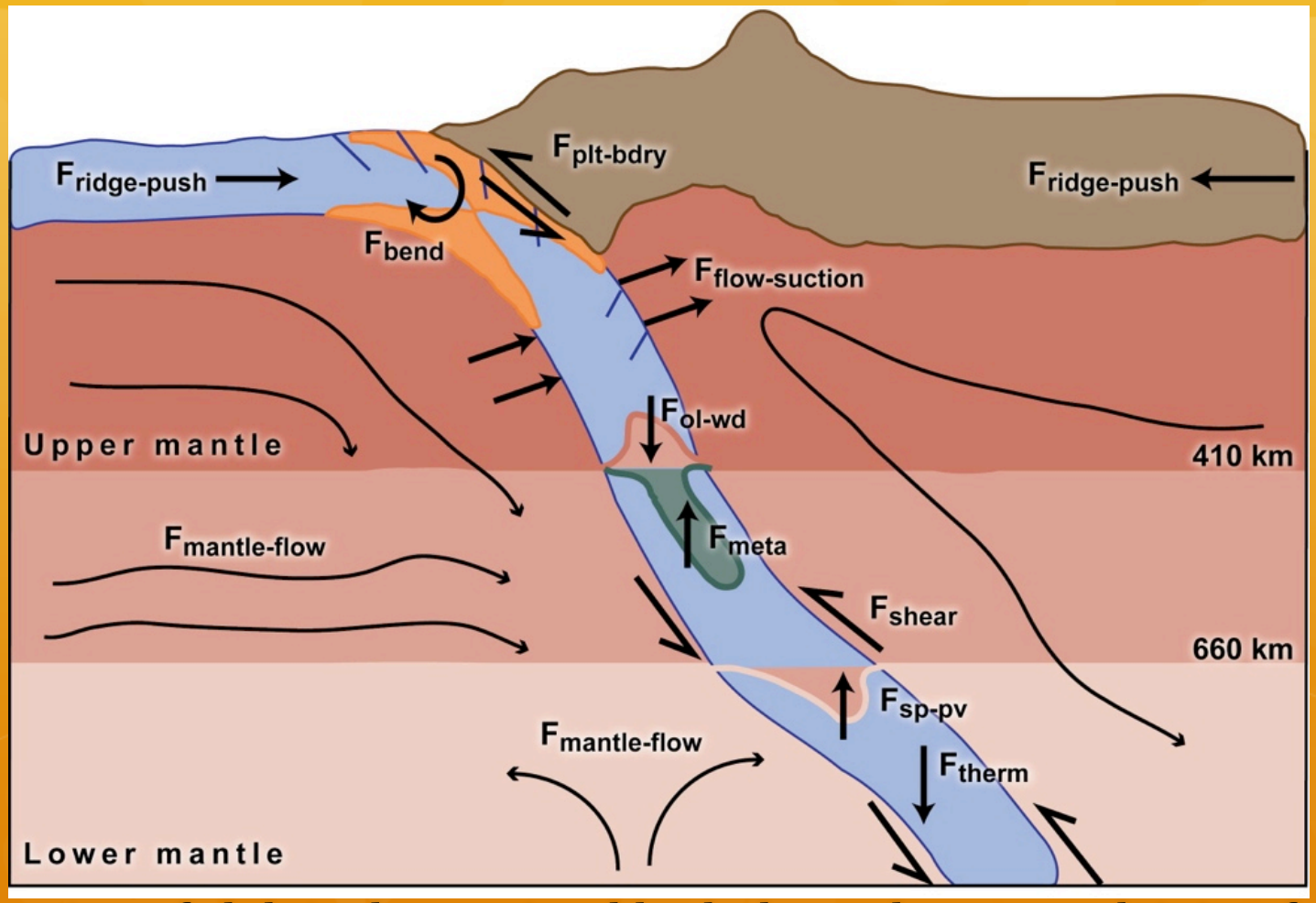
2. End-Member Models

- Rigid Slab → Corner Flow
  - What is the model?
  - Why is it useful?
  - What are the assumptions/simplications?

- Weak slabs → density controlled (Stokes Sinker)
  - What is the model?
  - Why is it useful?
  - What are assumptions/simplifications?

- **Key Point**: Behavior of slab is determined by balance between driving forces (buoyancy) and resisting force (viscosity/ strength

Forces Acting on the Slab

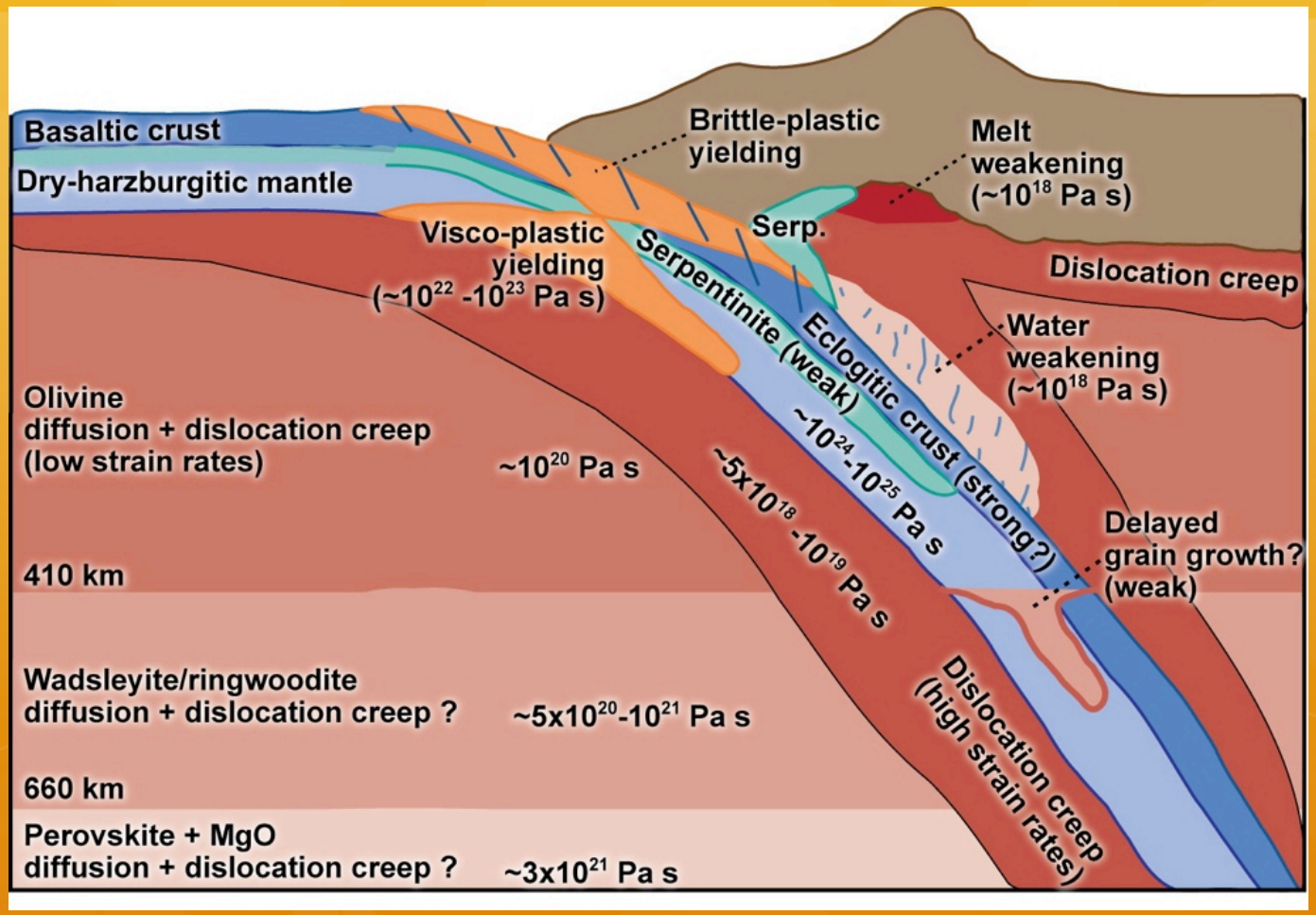


M. Billen, AREPS 2008

Behavior of slab is determined by balance between driving forces (buoyancy) and resisting force (viscosity/strength).

***** Bonus Question: Can you find the error in the figure?***

Rheologic Structure

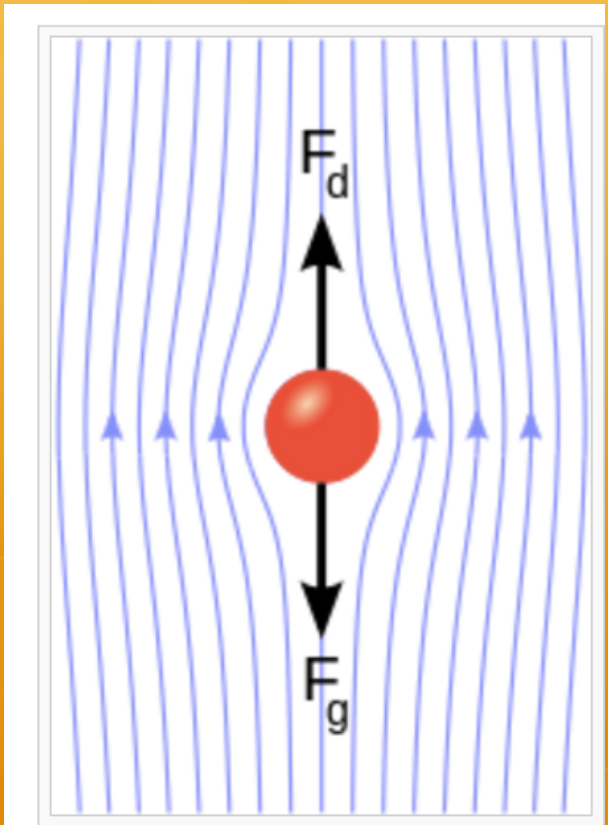


M. Billen, AREPS 2008

- Non-Newtonian Viscosity (e.g., $d\varepsilon/dt = \sigma^n$, yielding)
- Other factors: water, grain size, composition, melt, phase transitions.

Weak Slab Model

- Weak slabs → density controlled
- Prelude: consider a sinking sphere



$$F_d = 6\pi\,\mu\,R\,V$$

Drag Force
(Stress* Surface Area)

$$F_g = (\rho_p - \rho_f)\; g\,\frac{4}{3}\pi\,R^3$$

(buoyancy)

$$V = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2$$

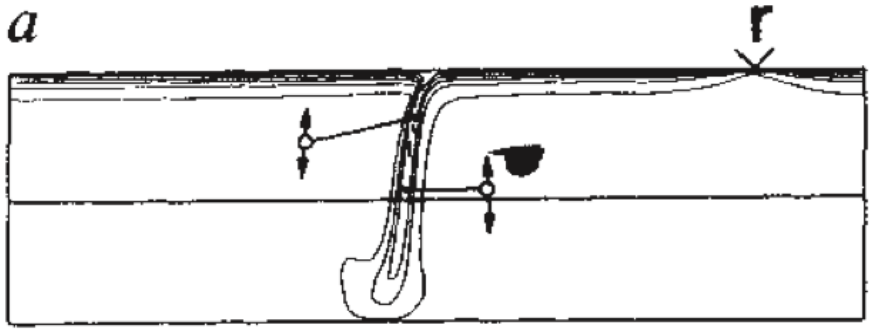
(Set equal, solve for V)

From Wikipedia page on Stokes Law: https://en.wikipedia.org/wiki/Stokes%27_law

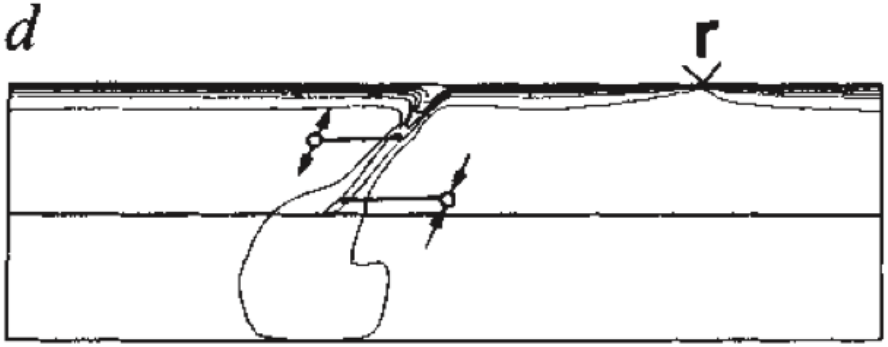
Weak Slab Models

- What is the model?
  - Small viscosity contrast 10-100 with surrounding mantle. (geoid/dynamic topography constraints)
- What does it predict?
  - Slab sink vertically into the mantle
  - Switch from all down-dip tension to deep down-dip compression at x 30.
  - Need trench motion to get non-vertical dip
- What are assumptions/ simplifications?
  - Strength is less than expected from experiments/rheology

$\eta_{slab}/\eta_{mantle} = 1$



$\eta_{slab}/\eta_{mantle} = 30$



Gurnis and Hager, GRL 1988

Rigid Slab Models

- Rigid Slab Model → strength controlled
- Prelude: Corner Flow
  - From Batchelor, 1967
  - Fixed Upper Plate
  - $U=U_o$ Lower Plate and Dipping Plane
  - Analytic solution for velocity, pressure
    - Solution to Conservation and Mass and Momentum with Boundary Conditions.
    - Can calculate stress, shear heating…

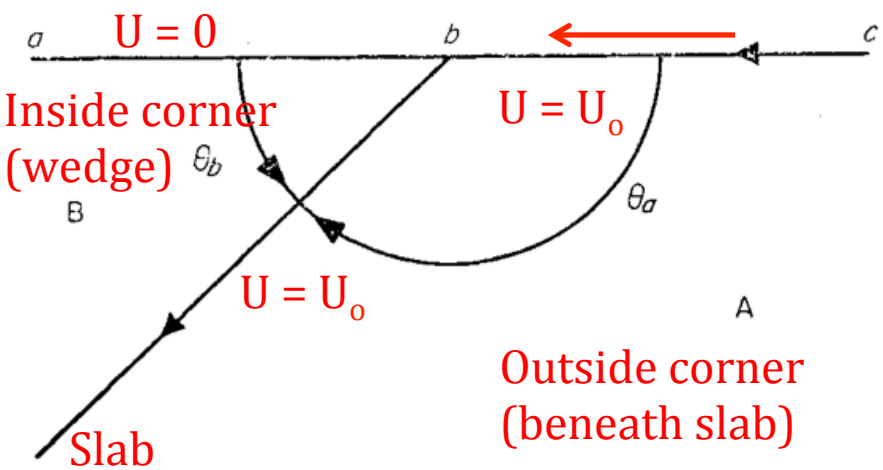
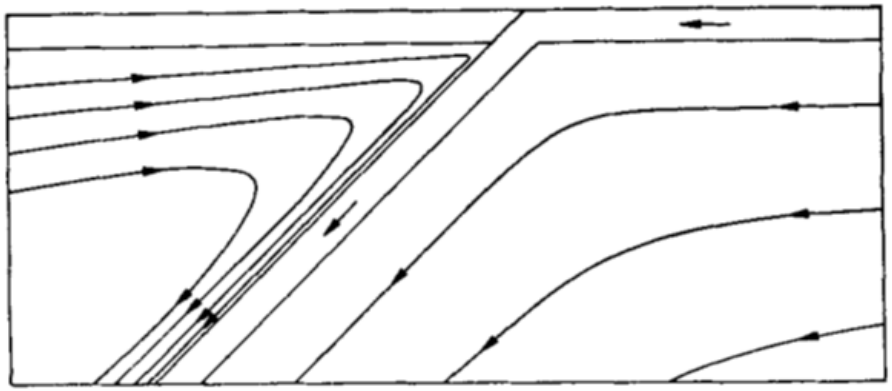


FIG. 5.



McKenzie, GJRAS, 1969

Rigid Slab Model

- What is the model?
  - Slab dip determined by balance between buoyancy and dynamic pressure (due to flow).

$$P_A(\theta) = \frac{2\mu U\,[\sin\theta - \sin(\theta-\theta_s)]}{r[(\pi-\theta_s)+\sin\theta_s]}$$

$$P_B(\theta) = \frac{-2\mu U\,[\sin\theta\sin\theta_s + \theta_s\sin(\theta_s-\theta)]}{r[\theta_s^2-\sin^2\theta_s]}$$

$$T_G = \int_0^L \Delta\rho\,(r)\,ghr\cos\theta_s\,dr$$

$$= \tfrac{1}{2}\,bL^2\cos\theta_s$$

$$b = gh\int_0^1 \Delta\rho\,(x)\,dx$$

$$T_H = \int_0^L [P_A(\theta_s) - P_B(\theta_s)]\,r\,dr$$

$$= 2\mu UL\left[\frac{\sin\theta_s}{(\pi-\theta_s)+\sin\theta_s} + \frac{\sin^2\theta_s}{\theta_s^2-\sin^2\theta_s}\right] \quad (2)$$

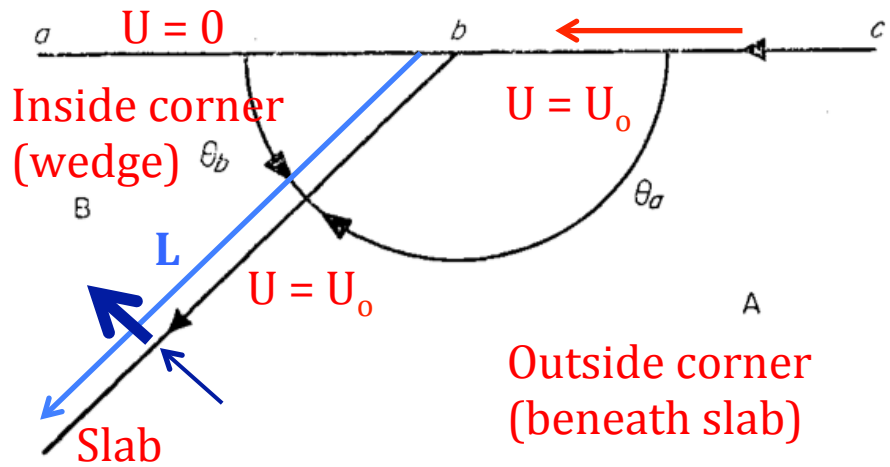
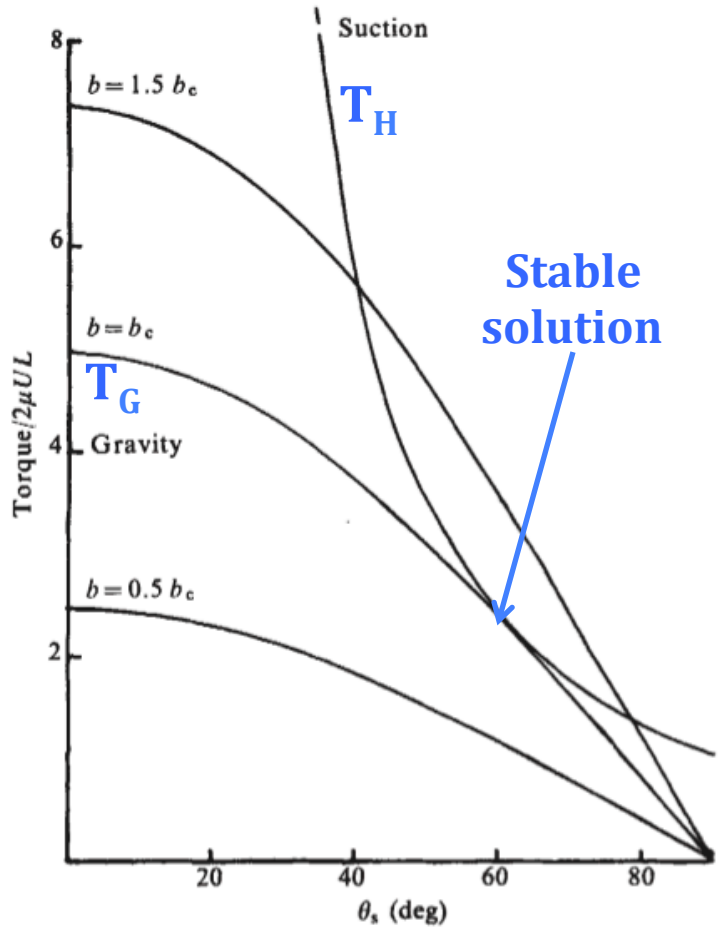


FIG. 5.

(Stevenson & Turner, Nature, 1977)

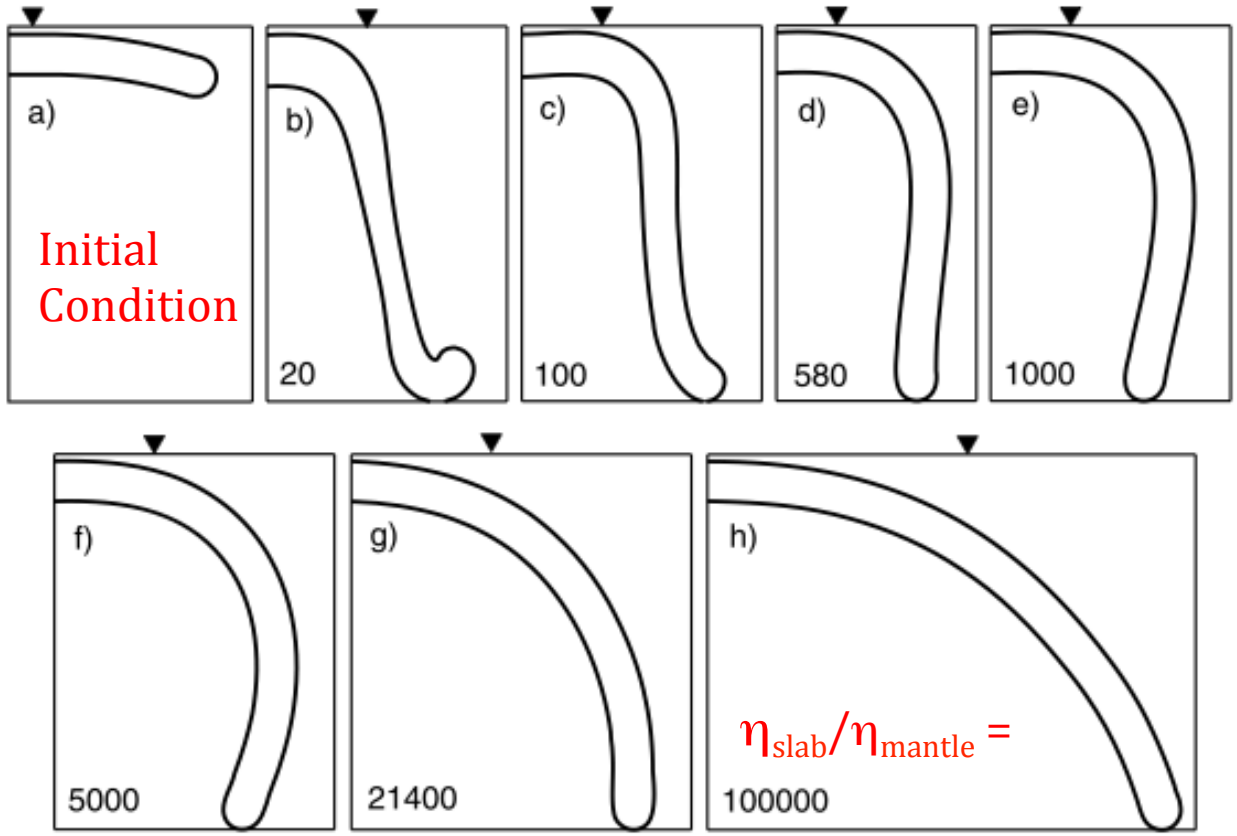
Rigid Slab Model

- What is the model?
  - Slab dip determined by balance between buoyancy and dynamic pressure.
- What does it predict?
  - Stable slab dip ~ 63°
  - Shallower dip for faster velocity, higher mantle wedge viscosity or less slab mass (lower density or less volume).
  - Unstable at very shallow dip → runaway flattening
  - Unstable at steep dip → runaway steepening
- What are assumptions/simplifications?
  - Perfectly rigid slab, can only pivot.
  - Sinks parallel to slab dip (steady-state dip)



Stevenson & Turner, Nature, 1977

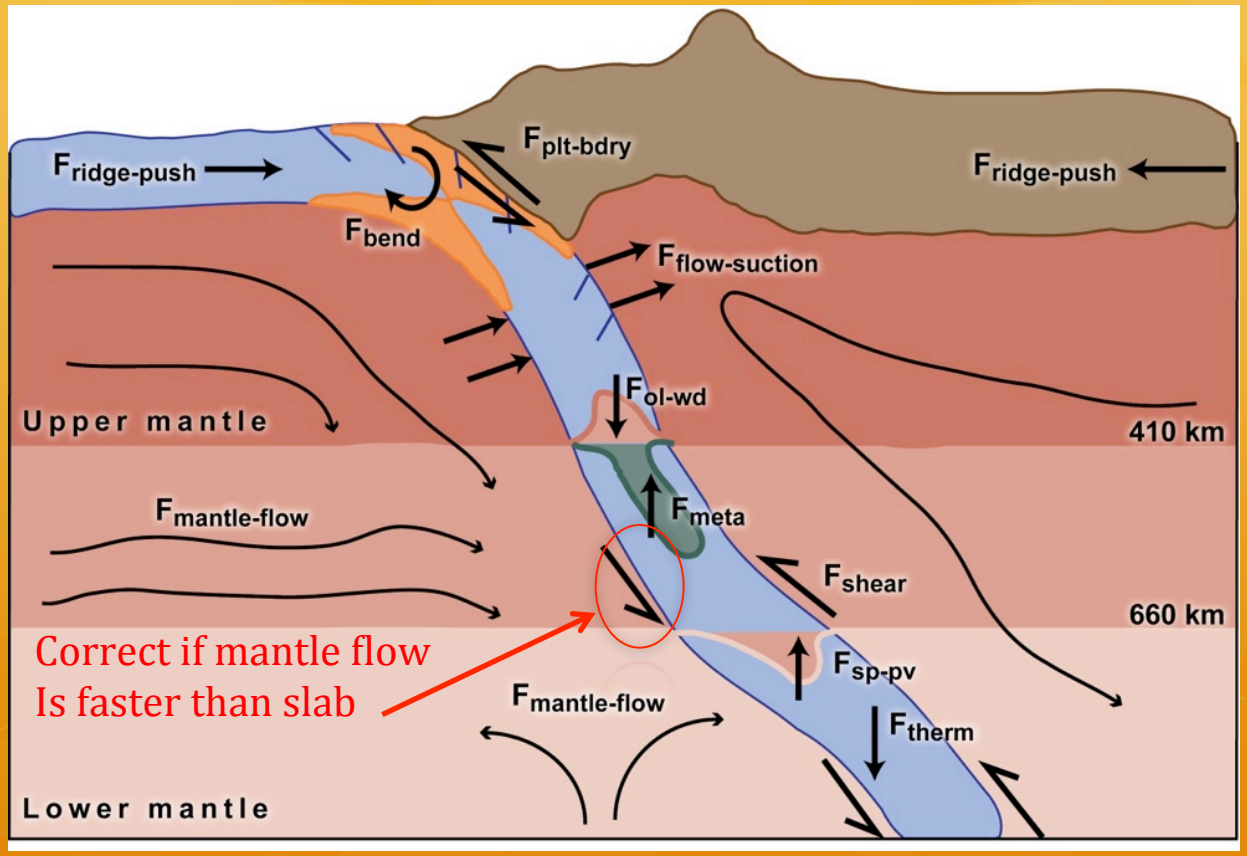
Earth's Subduction is Somewhere in Between



Ribe, GJI, 2010

- Slab shape is determined by balance between buoyancy induced sinking and slab strength → these depend on several other things.

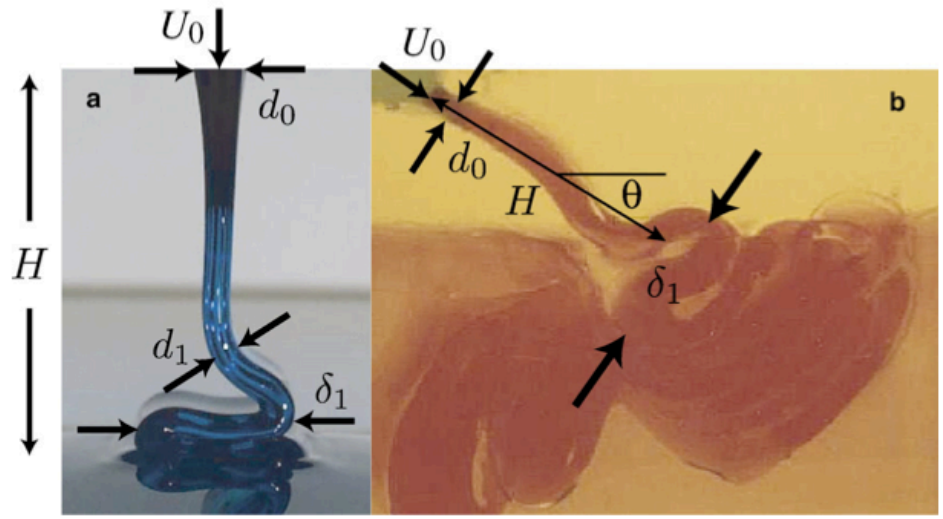
Forces Acting on the Slab



M. Billen, AREPS 2008

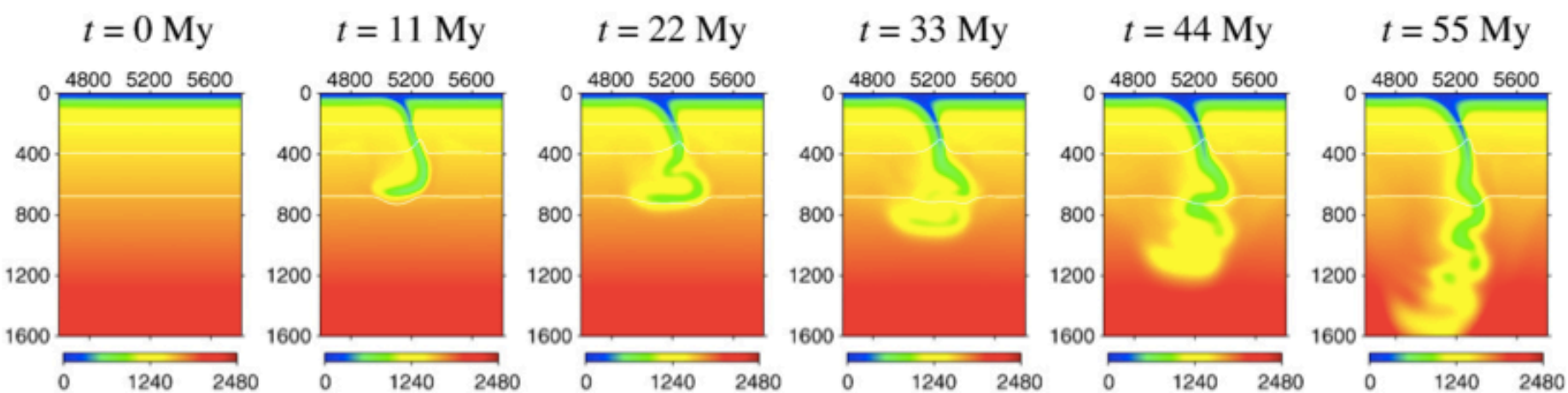
- Buoyancy: temperature, phase change anomalies (composition dependent)
- Strength: temperature, stress-dependence (bending, plastic flow), water, grain size.

Strong, Deformable Slabs Buckle and Fold



Ribe et al., EPSL 2007

- Moderate increase viscosity with/without phase change induces folding.
- Significant apparent thickening in lower mantle.

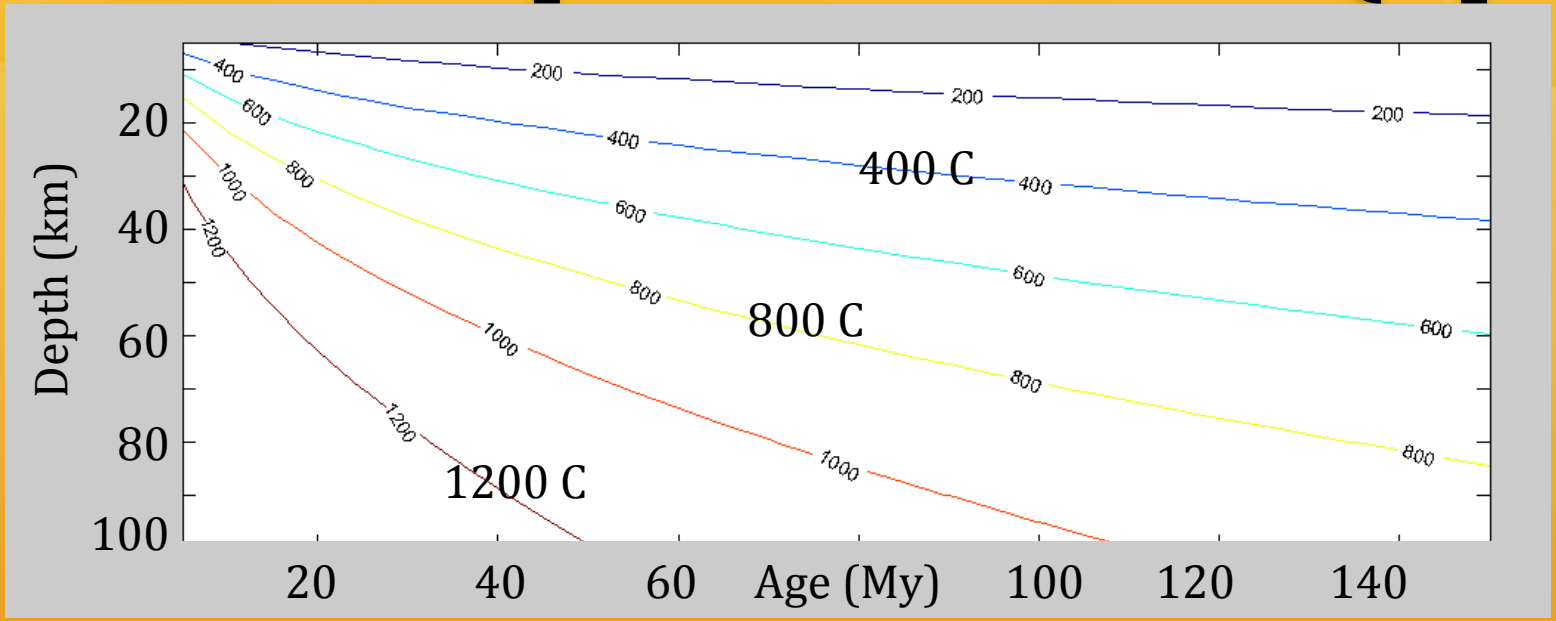


Behounkova and Cizkova, EPSL 2008

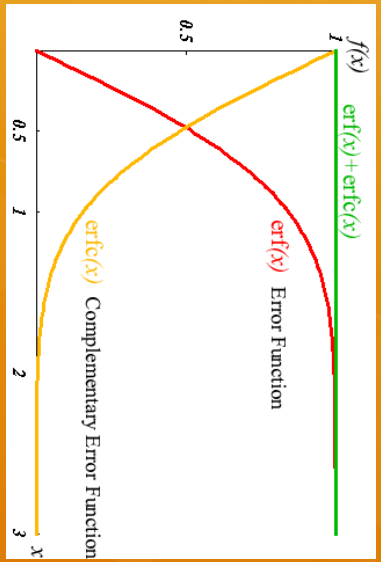
3. Simple Quantitative Approximations

- Temperature of the slab
  - Half-space cooling model
  - McKenzie (heating of a cold slab)
  - Corner Flow (newtonian vs. non-newtonian)
- Sinking Rate of Slab in Upper vs. Lower Mantle

Initial Temperature of Slab (Option 1)

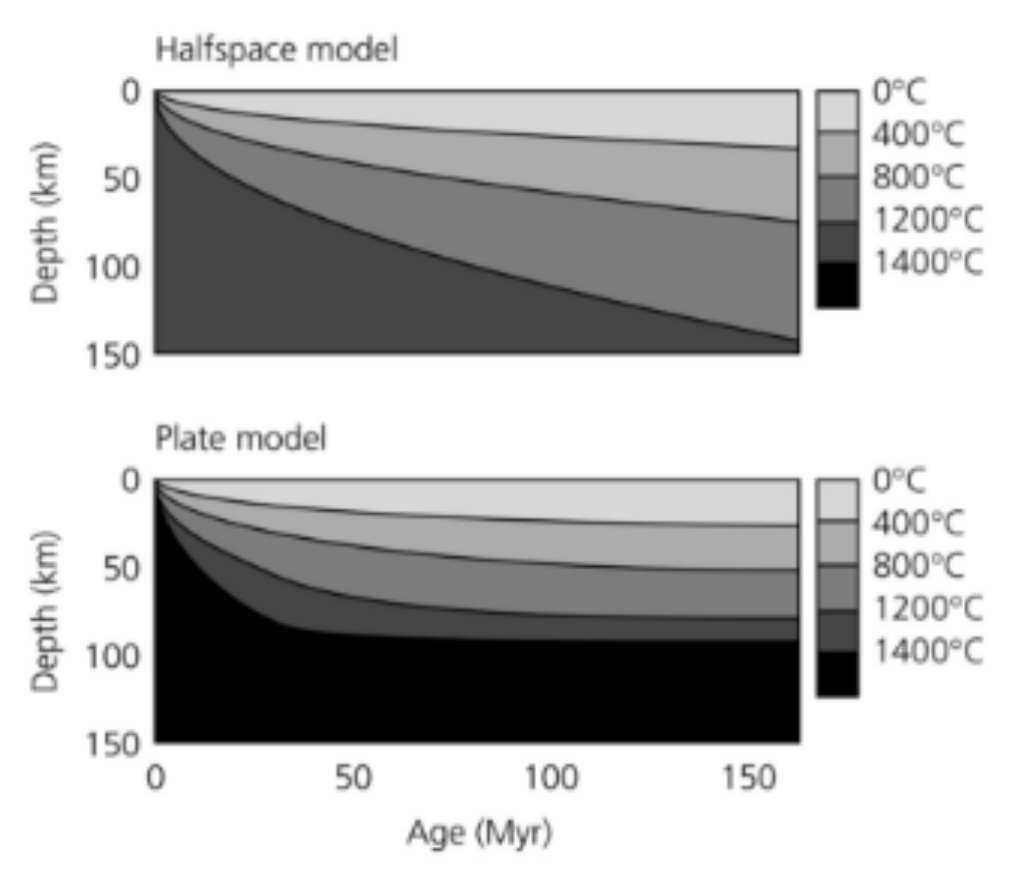


- Conduction of Heat: $dT/dt = \kappa\, d^2T/dy^2$
- Half Space Cooling model: $T \rightarrow T_{mantle}$ as $y \rightarrow$ inf
- $T = (T_{mantle} - T_{surf})\, \mathrm{erf}(y/2*\mathrm{sqrt}(\kappa\, t)) + T_{surf}$
  - Predicts broad thermal boundary layer
  - Slow diffusion of heat through most of this profile.



Initial Temperature of Slab (Option 2)

- Plate Model
  - Different boundary conditions.
  - Max thickness of plate is fixed.
  - (Mechanism for doing this in nature is unclear).
- Sharper temperature gradient → faster diffusion.



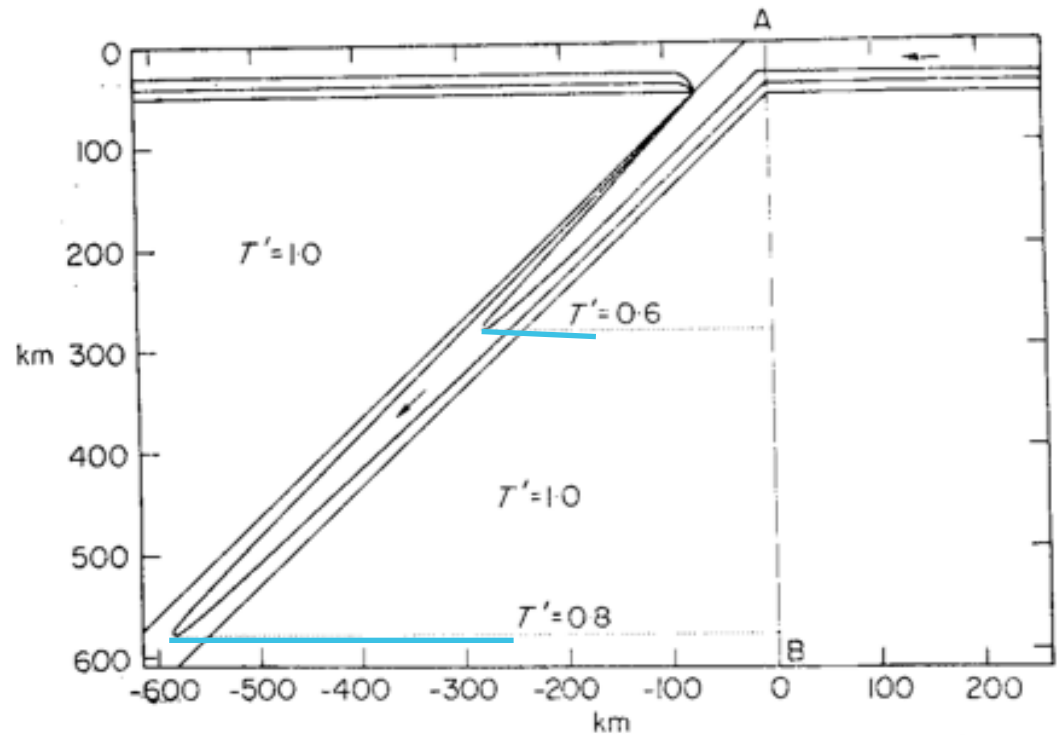
Early Model of Slab Temperature

- McKenzie, 1969:

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

$$\frac{\partial^2 T'}{\partial x'^2} - 2R \frac{\partial T'}{\partial x'} + \frac{\partial^2 T'}{\partial z'^2} = 0.$$

$$R = \frac{\rho C_p v_x l}{2\kappa}$$



BC: T' = 1.0 @ x' = +/-40 km

$$T' = 1 + 2 \sum_n \frac{(-1)^n}{n\pi} \exp\left[\left(R - (R^2 + n^2 \pi^2)^{\frac{1}{2}} \right) x' \right] \sin n\pi z'$$

Captures key process but slab warms up too quickly because of BCs.
Slab should cool down surrounding mantle → needed to conserve mass.
Slab is too warm and does not have enough total mass

Early Model of Slab Temperature

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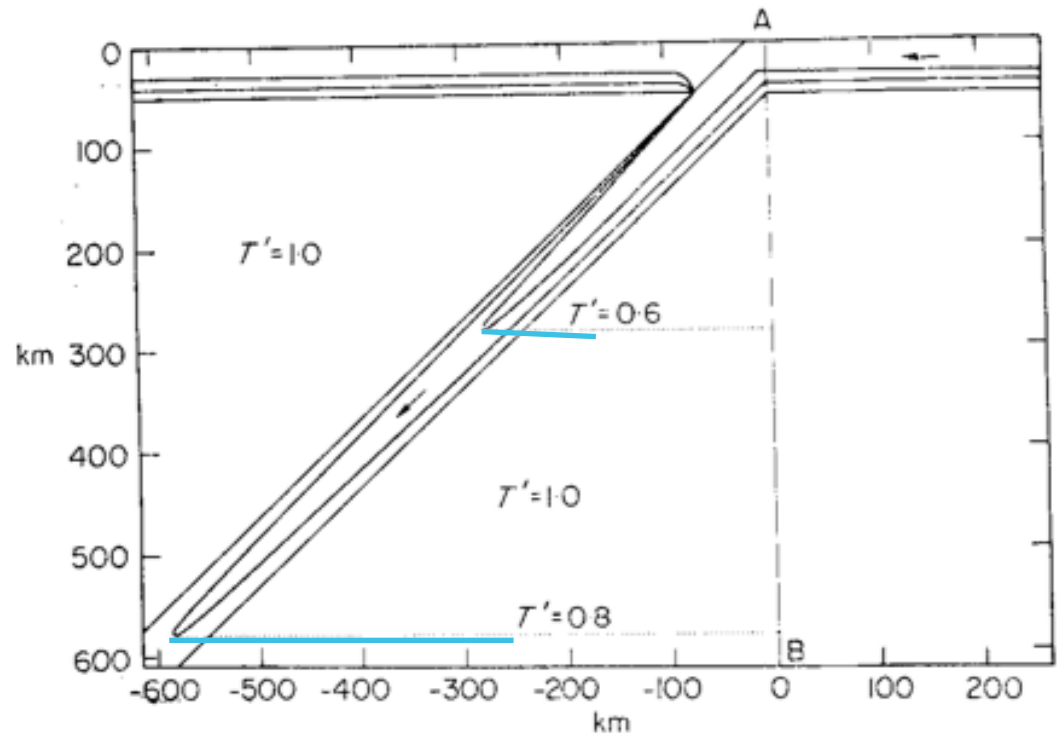

- Captures key process but slab warms up too quickly because of BCs.
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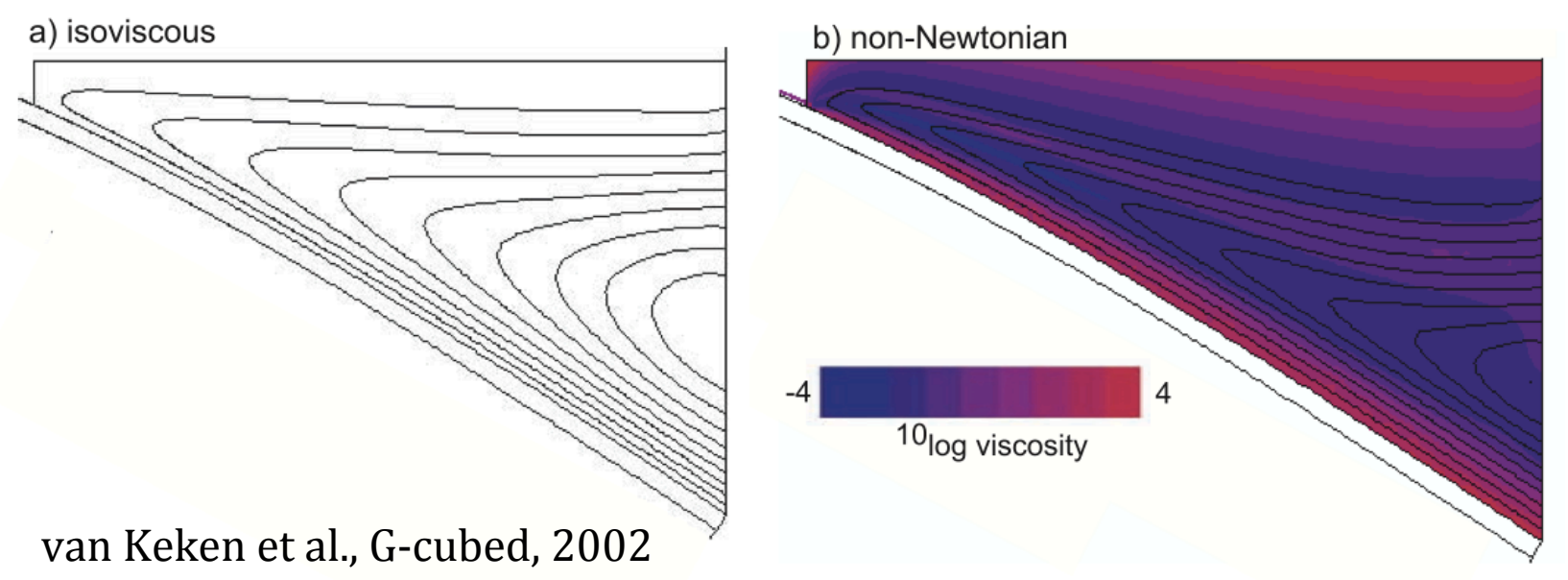
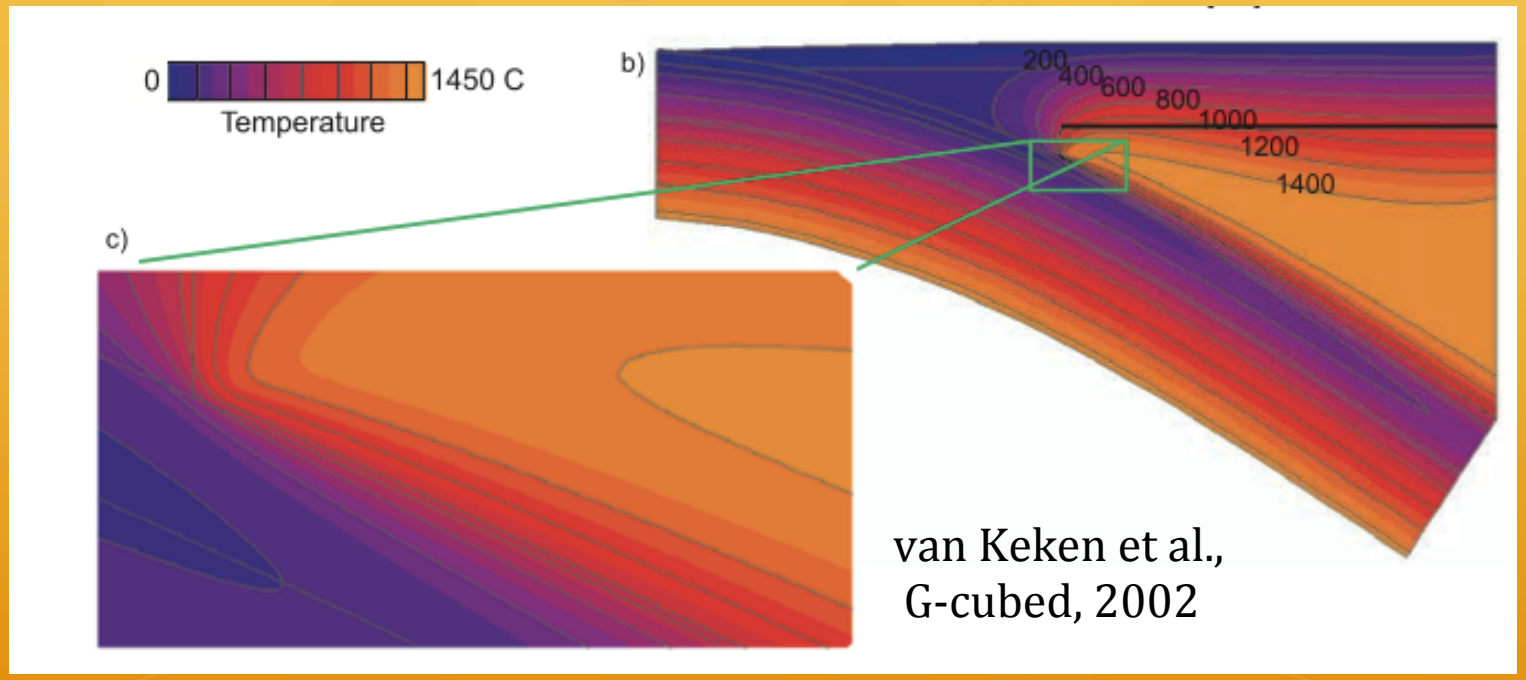
Improved treatment of Slab Temperature



van Keken et al., G-cubed, 2002

- Use corner-flow to advect initial plate temperature profile.
- Predict cooling of mantle of above slab
  - Less cooling for non-Newtonian mantle viscosity

Improved Treatment of Slab Temperature



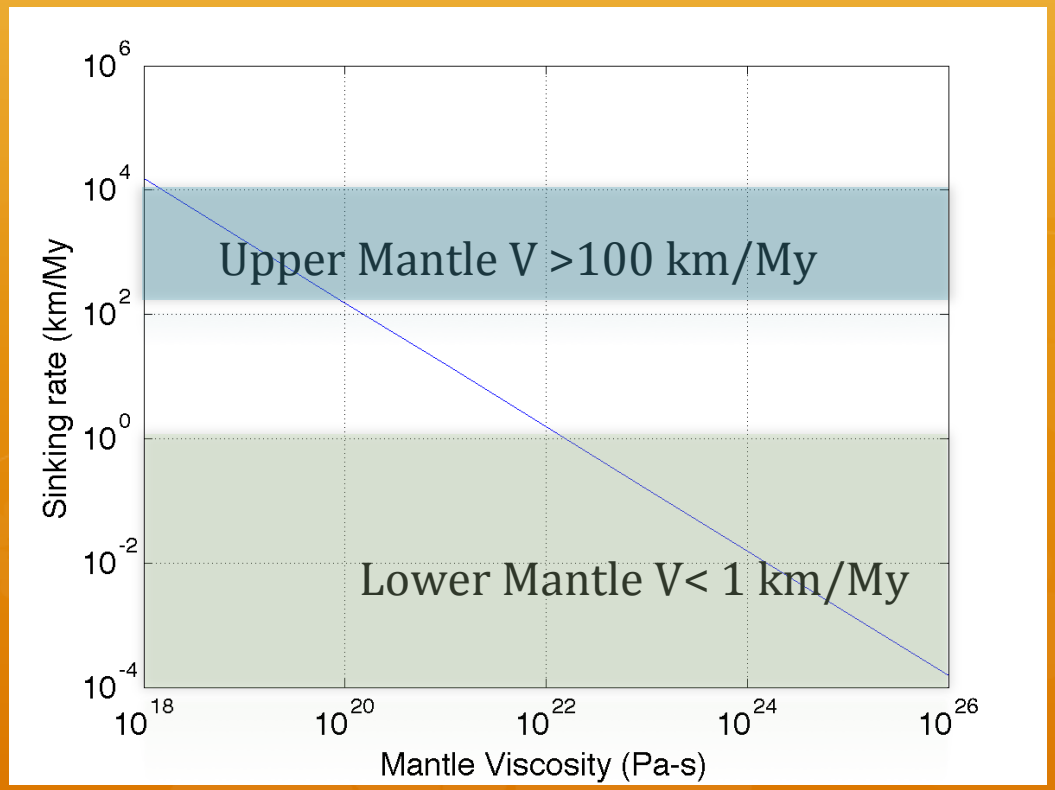
van Keken et al., G-cubed, 2002

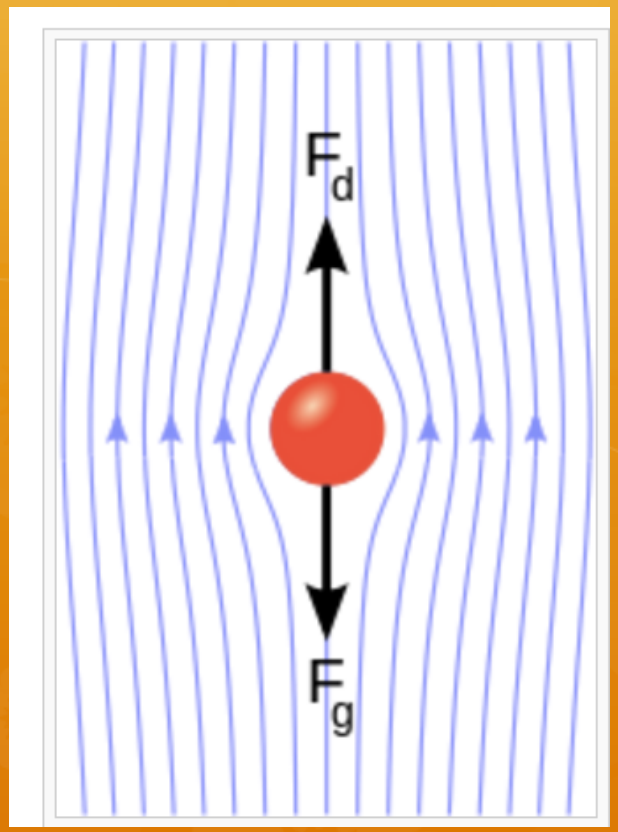
- Allow for dynamic flow in the mantle wedge & non-Newtonian rheology (and mechanical decoupling zone at shallow depth.
- Growth of thermal boundary layer above slab.
- Cross section of temperature becomes more symmetric with depth.

What is the sinking rate of slab?

- $\rho_p = 3350\ kg/m^3$
- $\rho_f = 3300\ kg/m^3$
- μ = 1e18 – 1e26 Pa-s

$$V = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2$$



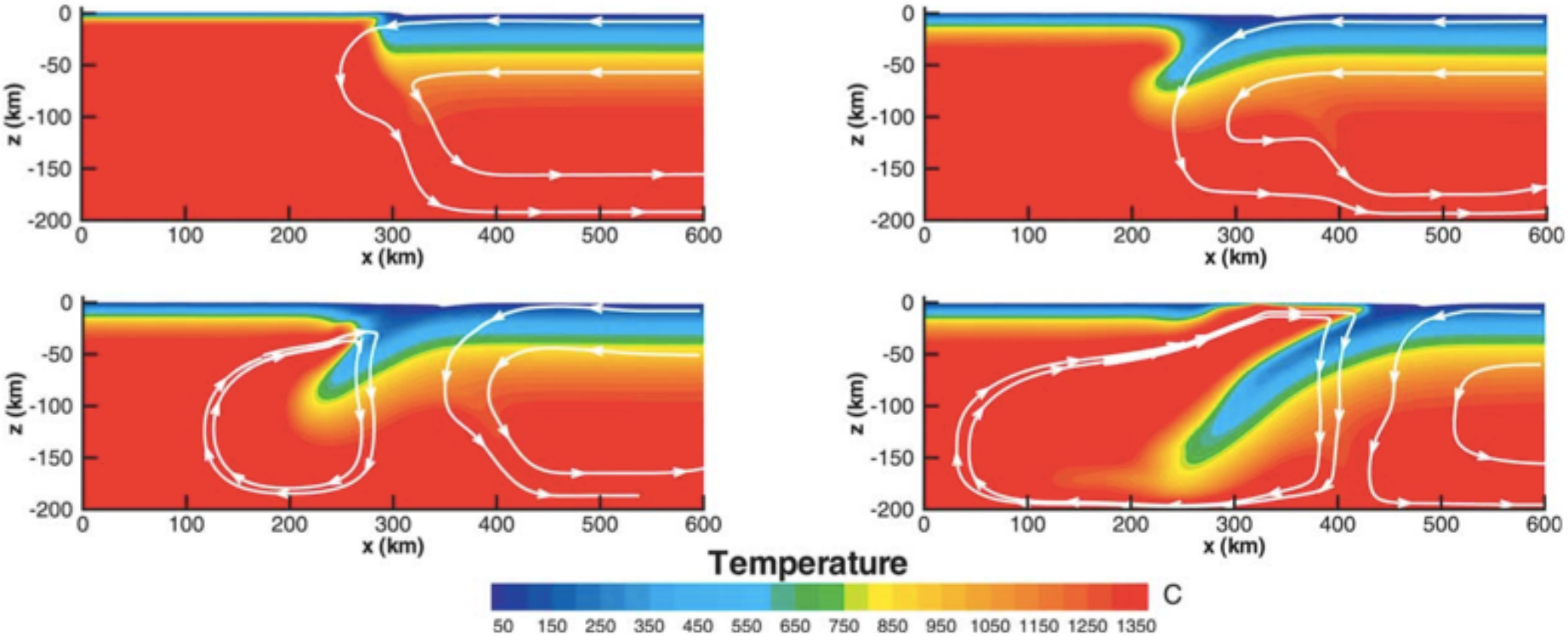


4. Phases of Subduction

- What are the key processes during different Stages?
  - Subduction Initiation → forced compression; slab is not driving this processes.
  - Juvenile → slab suction followed by increasing density driven sinking (shallow → steep)
  - Young Adult → Rapid descent through transition zone
    - Increase in density
    - Weakening of slab due shear & latent heat (stretching)
    - Weakening of surrounding mantle
  - Mid-Life Crisis → interaction with higher viscosity lower mantle
    - Folding, buckling, forced slab rollback, trapped slabs.
  - Senior → very slow sinking into lower mantle
  - Retirement → slab break-off (can happen earlier)

Subduction Initiation

- Forced compression; slab is not driving this processes.
  - Need > 100 km of "proto-slab" to attain self-sustaining subduction.



Hall and Gurnis, EPSL 2002

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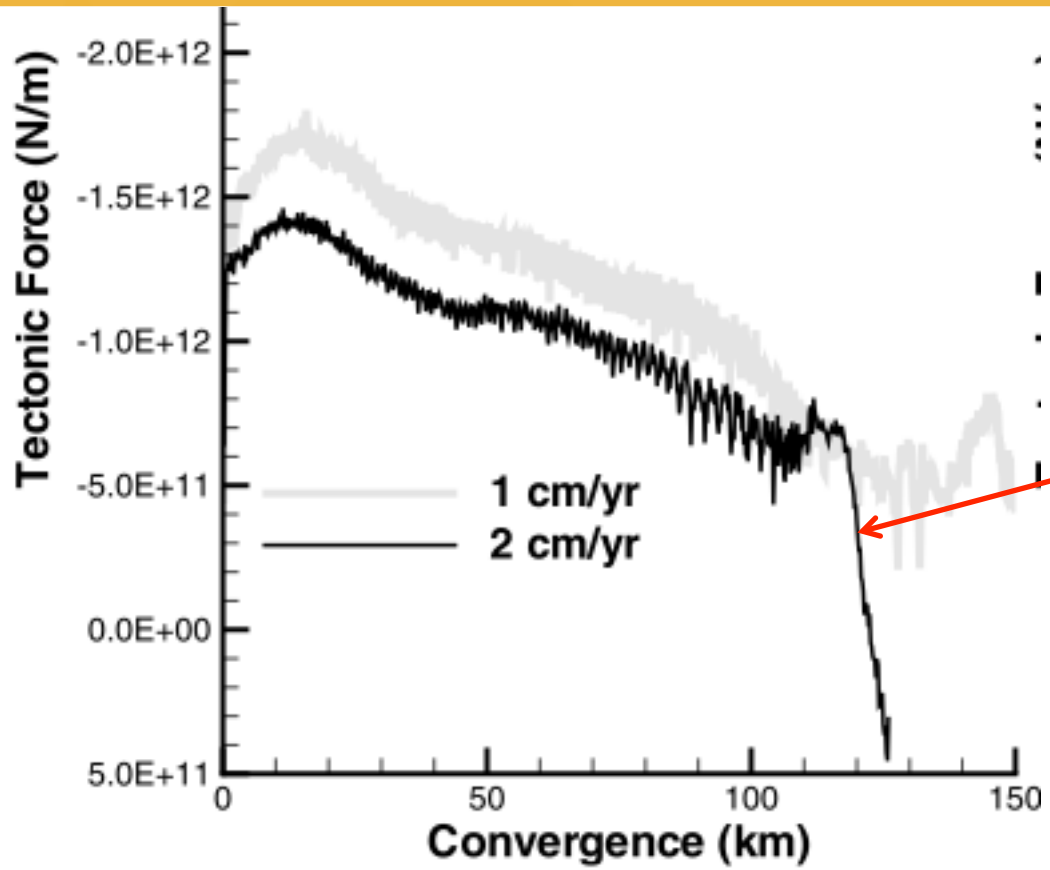
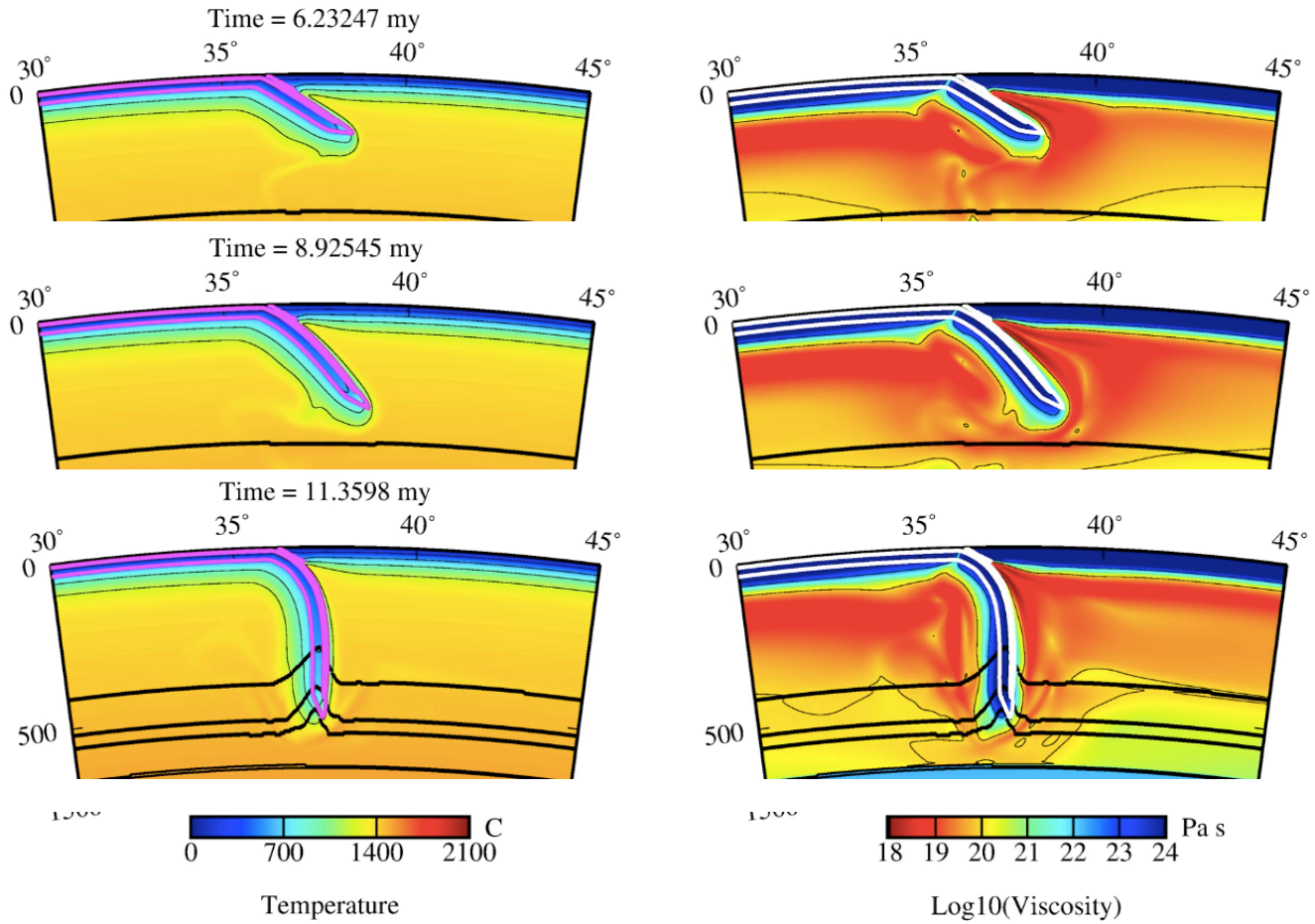


Onset of self-sustaining subduction is after 125 km of convergence

Hall and Gurnis, EPSL 2002

Juvenile Slab

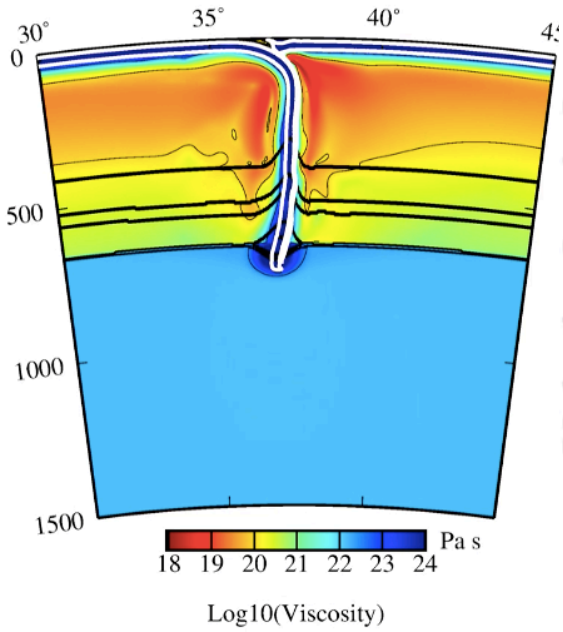
- Slab supported by wedge suction followed by increasing density driven sinking (shallow → steep)



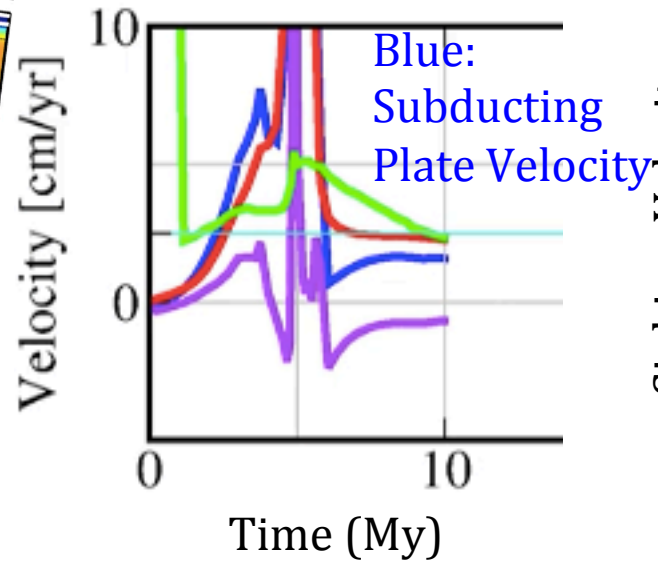
Arredondo & Billen, J. Geodynamics 2016

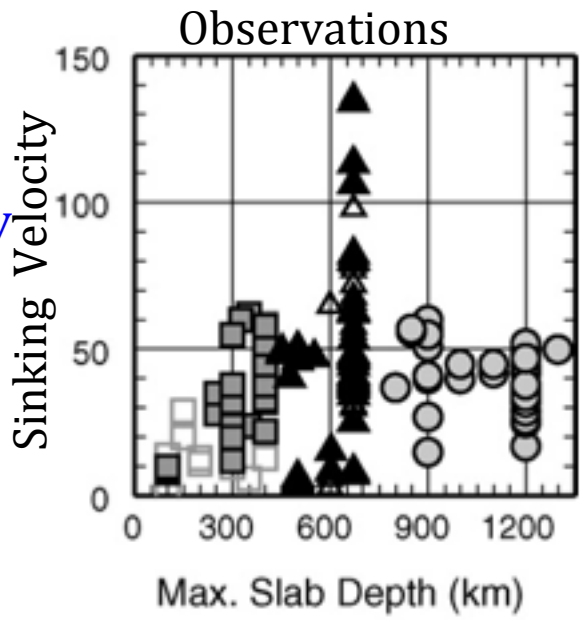
Young "Adult" Slab: Interaction with Transition Zone

- Rapid descent ***INTO*** the transition zone
  - Increase in density due to phase transitions
  - Weakening of slab due to shear & latent heat (stretching)
  - Weakening of surrounding mantle



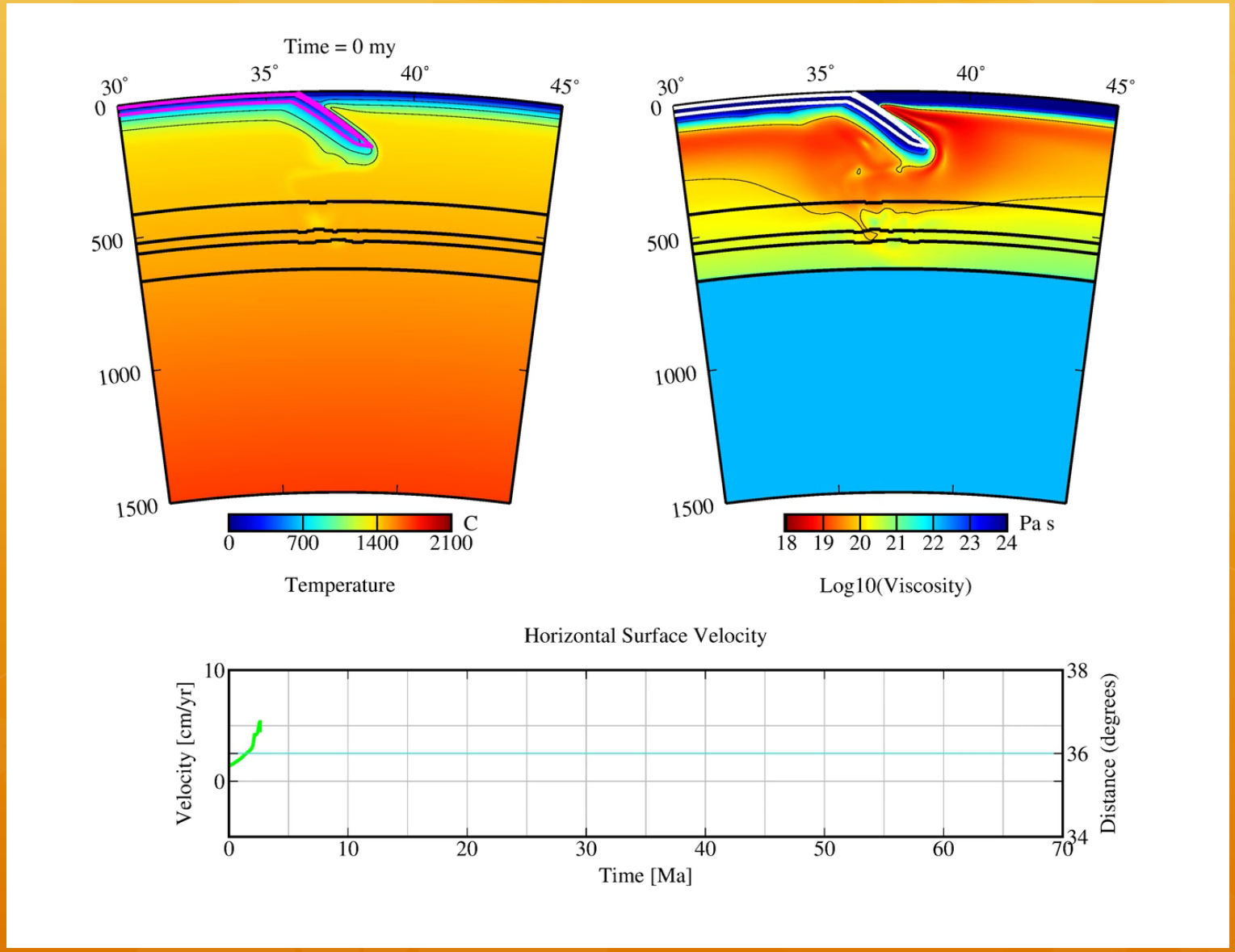
Arredondo & Billen, in review





Billen, PEPI, 2010

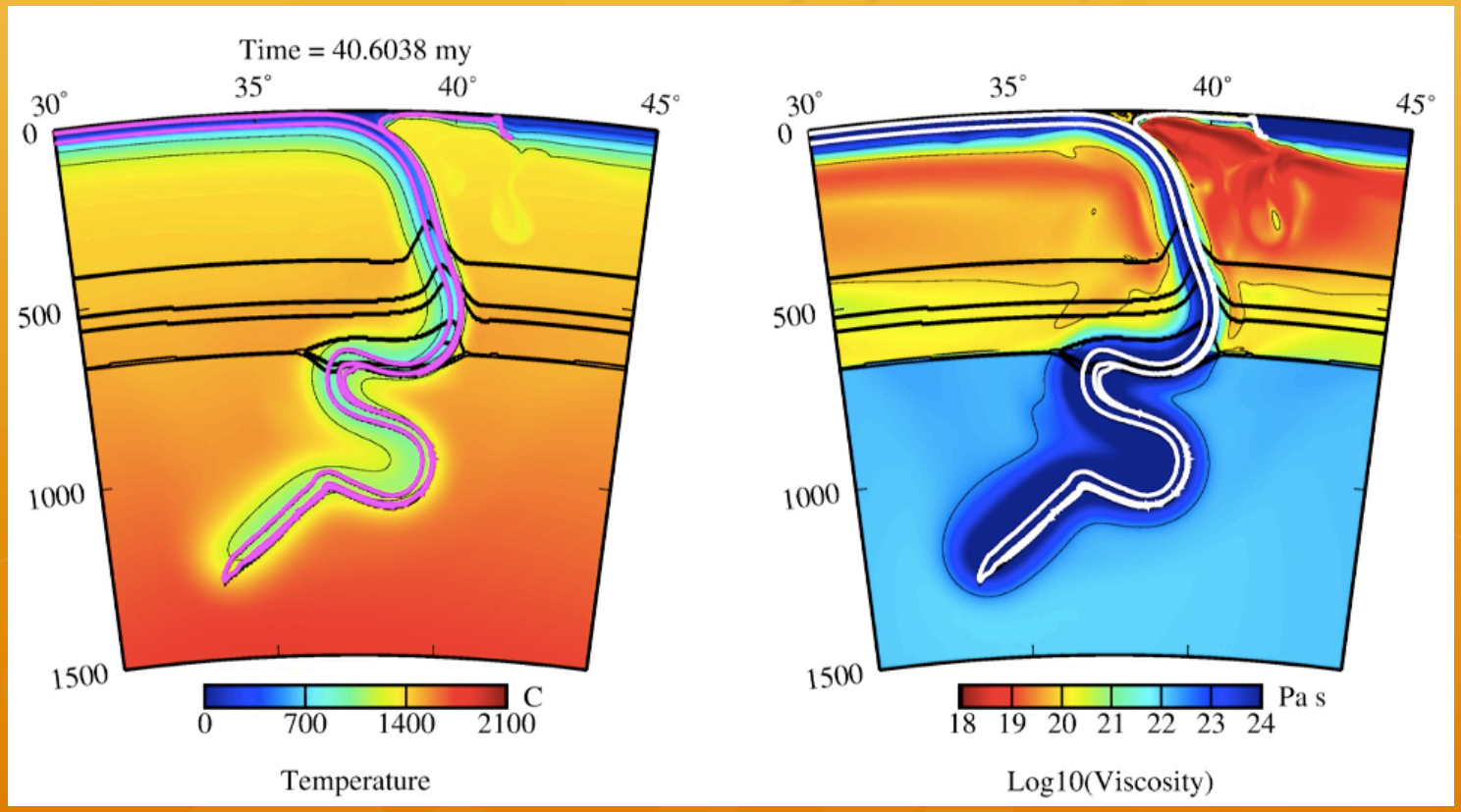
Midlife Crisis
Interaction with Transition zone



Arredondo & Billen, in review

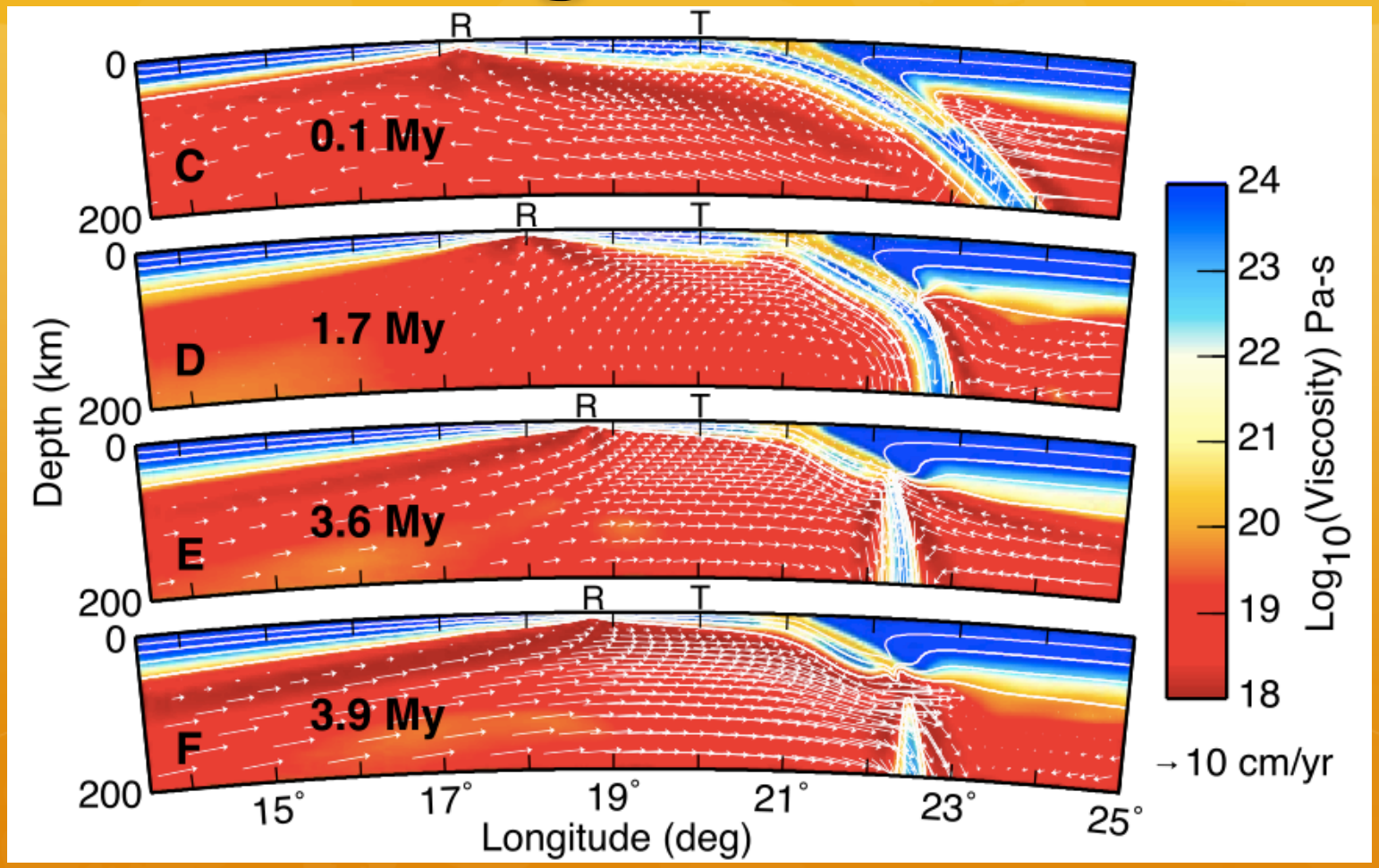
Senior Slab: Going into the Deep Mantle

- Very slow (<1 – 10 km/Myr sinking into lower mantle)
  - 2000 km takes ~100 - 200 Myr (or more)



Arredondo & Billen, in review

Ending Subduction



Burkett & Billen, JGR 2009

- Retirement → slab break-off (can happen earlier)
  - Example: ridge approaching the trench

Phases of Subduction

- What are the key processes during different Stages?
  - Subduction Initiation → forced compression; slab is not driving this processes.
  - Juvenile → slab suction followed by increasing density driven sinking (shallow → steep)
  - Young Adult → Rapid descent through transition zone
    - Increase in density
    - Weakening of slab due shear & latent heat (stretching)
    - Weakening of surrounding mantle
  - Mid-Life Crisis → interaction with higher viscosity lower mantle
    - Folding, buckling, forced slab rollback, trapped slabs.
  - Senior → very slow sinking into lower mantle
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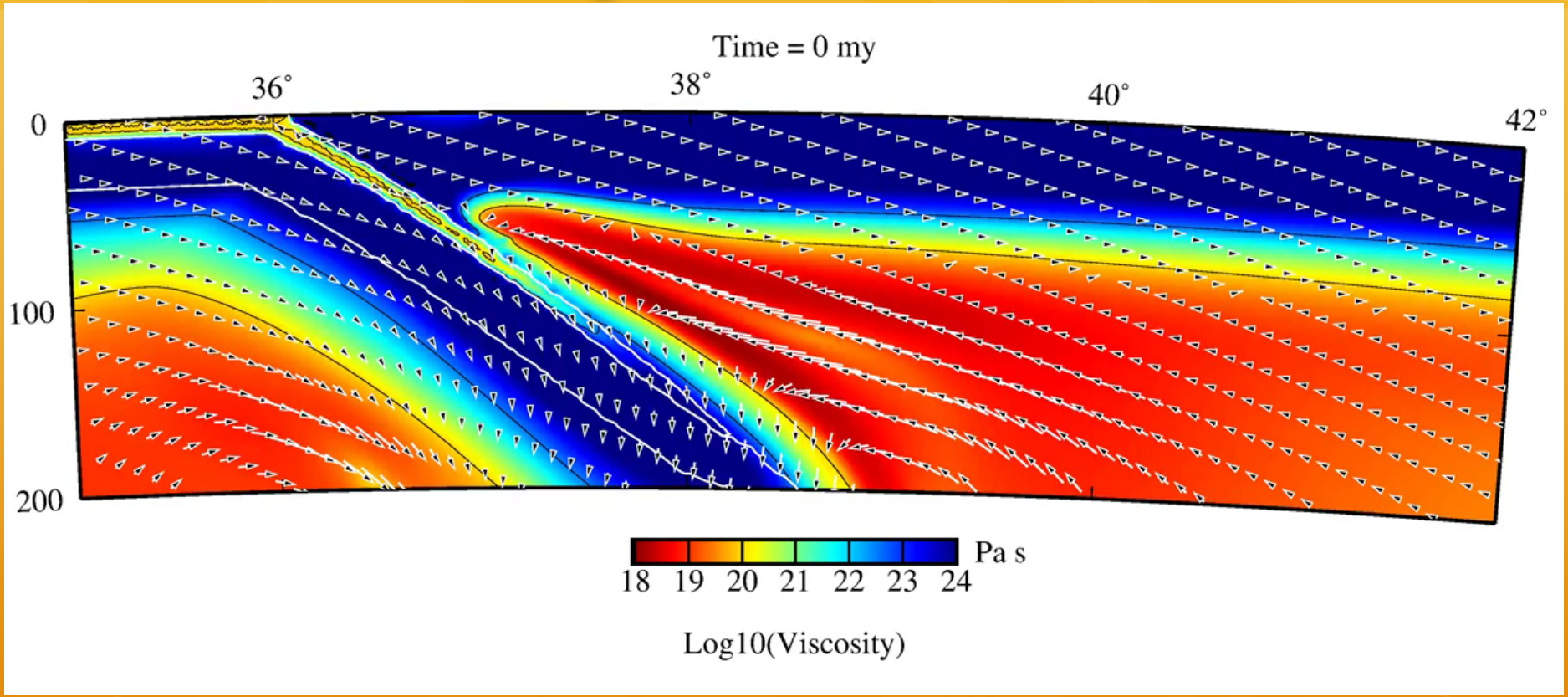
Summary

- Observations provide a lot of information on what is happening to the slab; while others remain enigmatic.
- End-member models are useful for thinking about trade-offs
- Use order-of-magnitude calculations to get at key processes.
- Subduction evolution goes through several stages that depend on the lower mantle structure, phase transitions, etc…

Questions?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