THE
LIFE TECTONIC

CIDER 2012 (Geodynamics V):

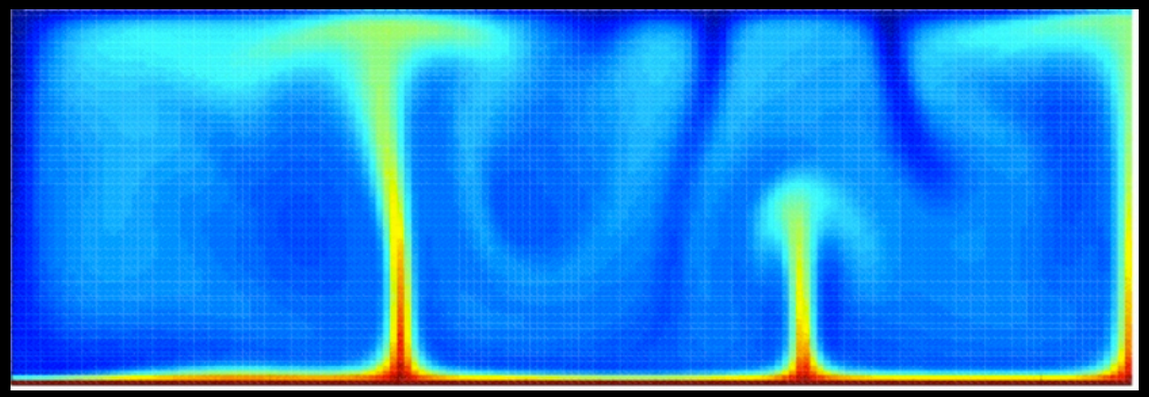
Subduction (sounds better with a french accent)

THE LIFE TECTONIC

devl

Mantle Convection vs Subduction

symmetric and two-sided flow



Quelle and Schmelling, 2002

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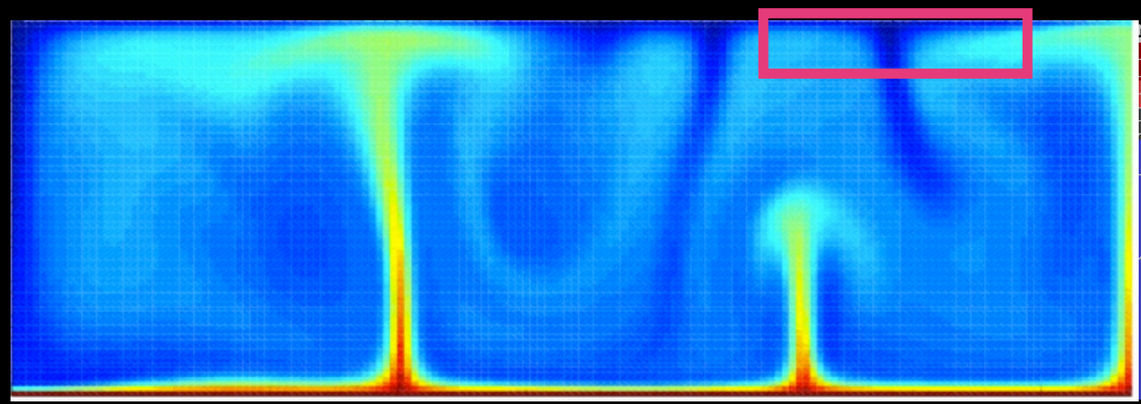

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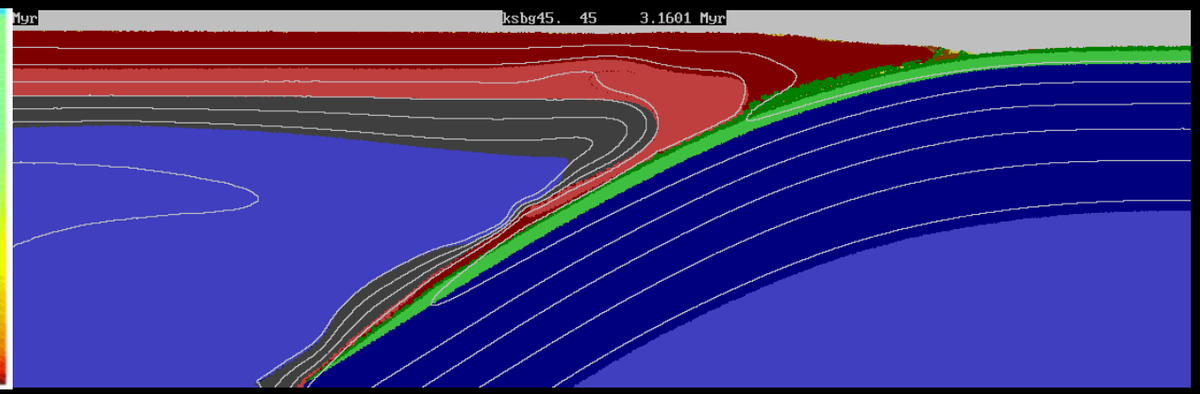
asymmetric and one-sided flow



Nikolaeva et al., 2010

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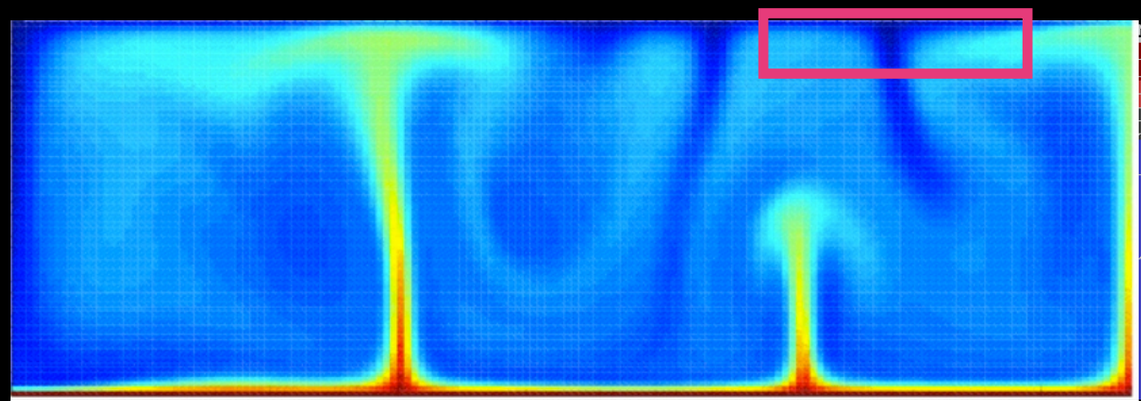

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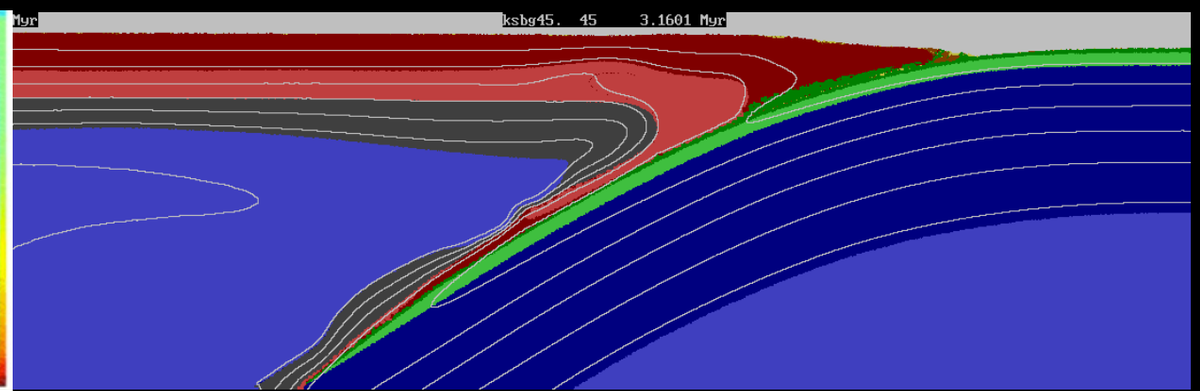


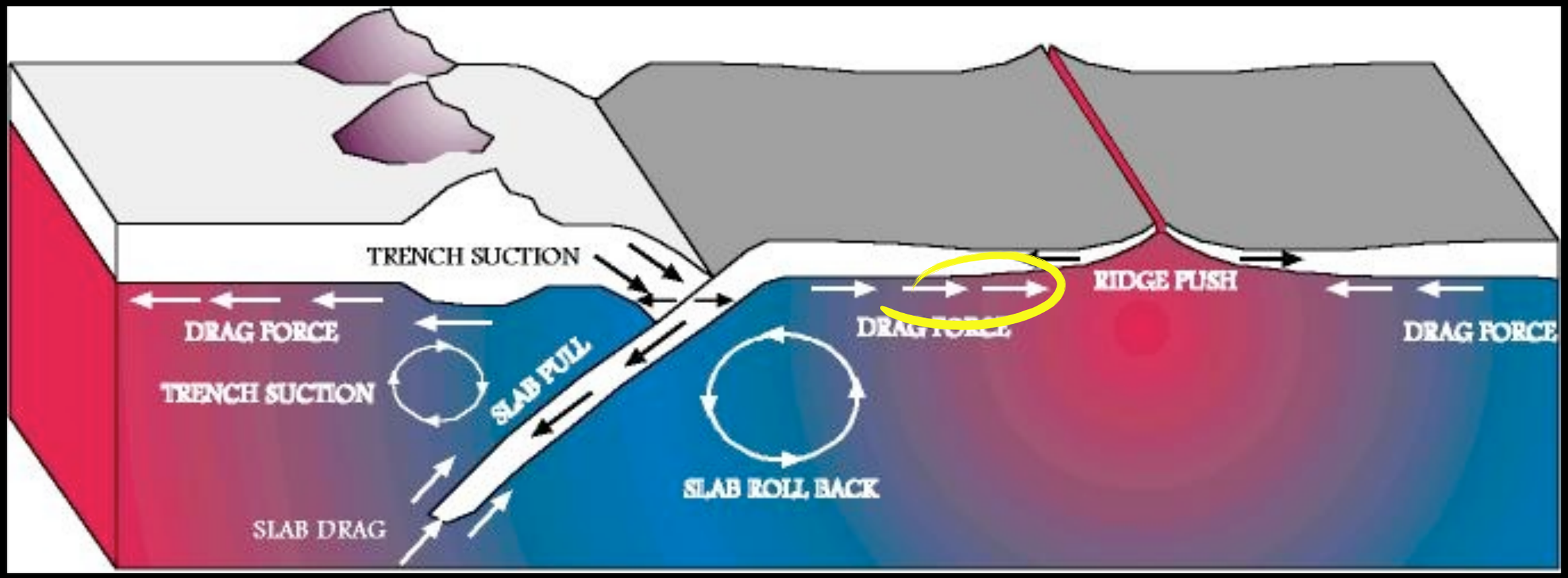
Nikolaeva et al., 2010

- **heat transfer in the mantle**
- **thermal evolution**
- **cold thermal boundary layer**
- **fluid dynamics**

- **deformation / recycling of lithosphere**
- **tectonic evolution**
- **tectonic plates (including continents)**
- **multi-scale and multi-physics**

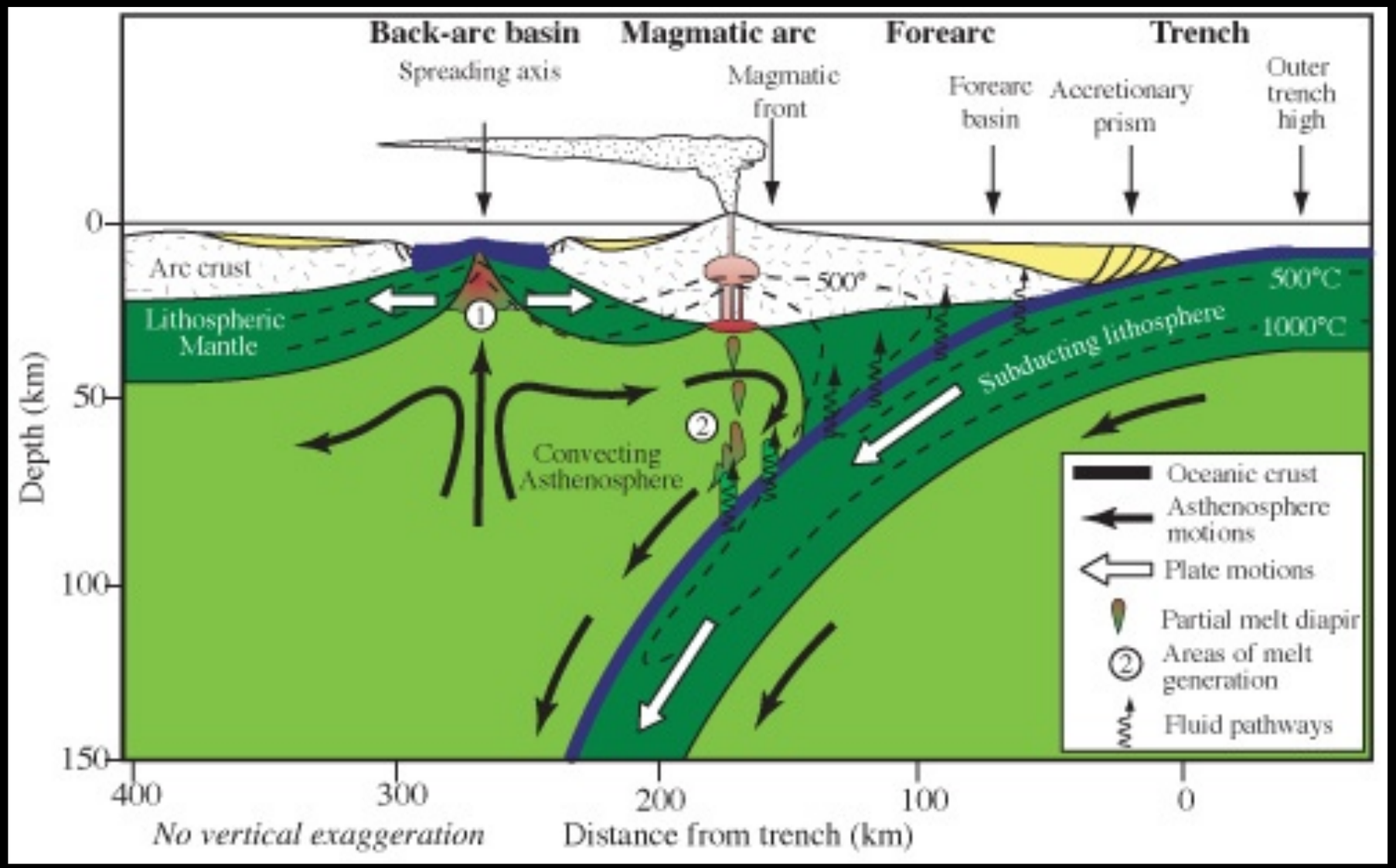
Forces that drive plate motion

- driving forces: slab pull, ridge push, slab suction (from the lower mantle)
- resisting forces: mantle drag, slab drag, trench suction

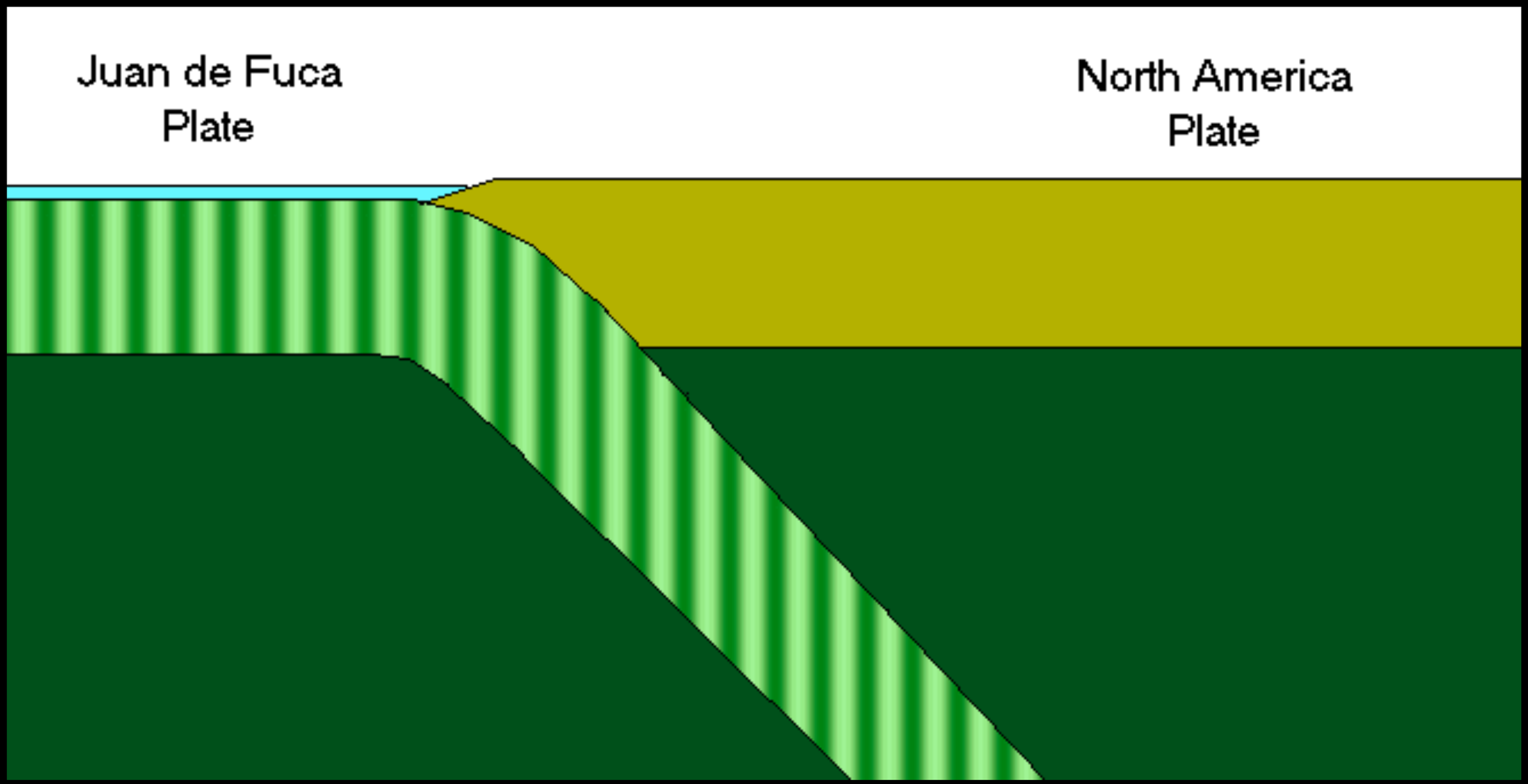


after Forsyth and Uyeda., GJI, 1975

Anatomy of a subduction zone



How subduction works



Questions still unanswered

- **Why do plates subduct the way the do?**

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- When did plates start subducting like they do today?
- How did plate tectonics operate in the past?
- Is Earth-like subduction unique to Earth?

If we want to think about plate tectonics on early Earth, we better start by figuring out how plate tectonics works in the present day

CHAPTER 1

KINEMATICS: plate motions and trench migration

CHAPTER 2

TWO MODES OF SUBDUCTION: partitioning

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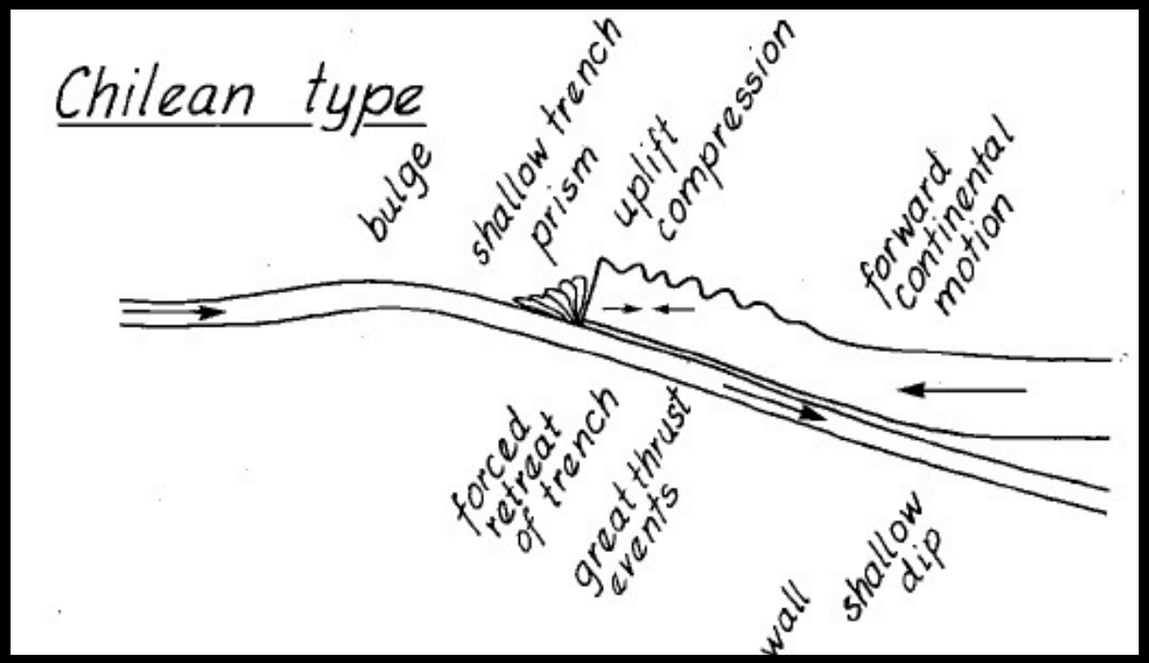
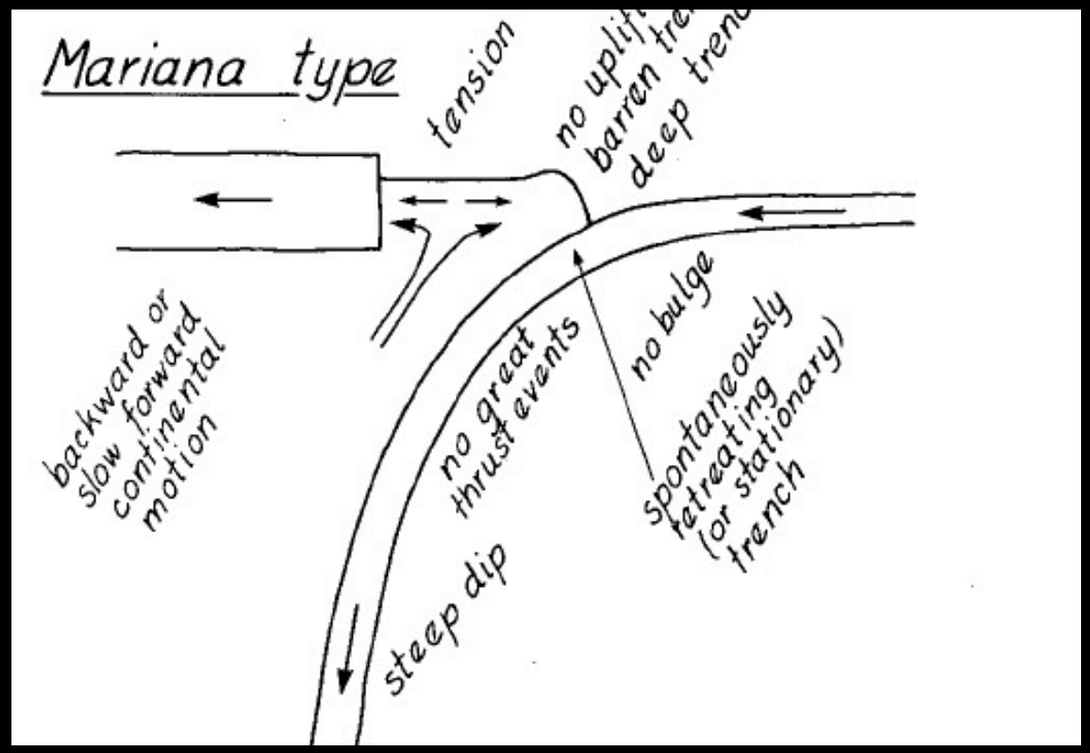
Chilean vs Mariana Types





- upper plate in compression
- shallow dipping slab
- usually has continental upper plate
- forward-moving subducting plate

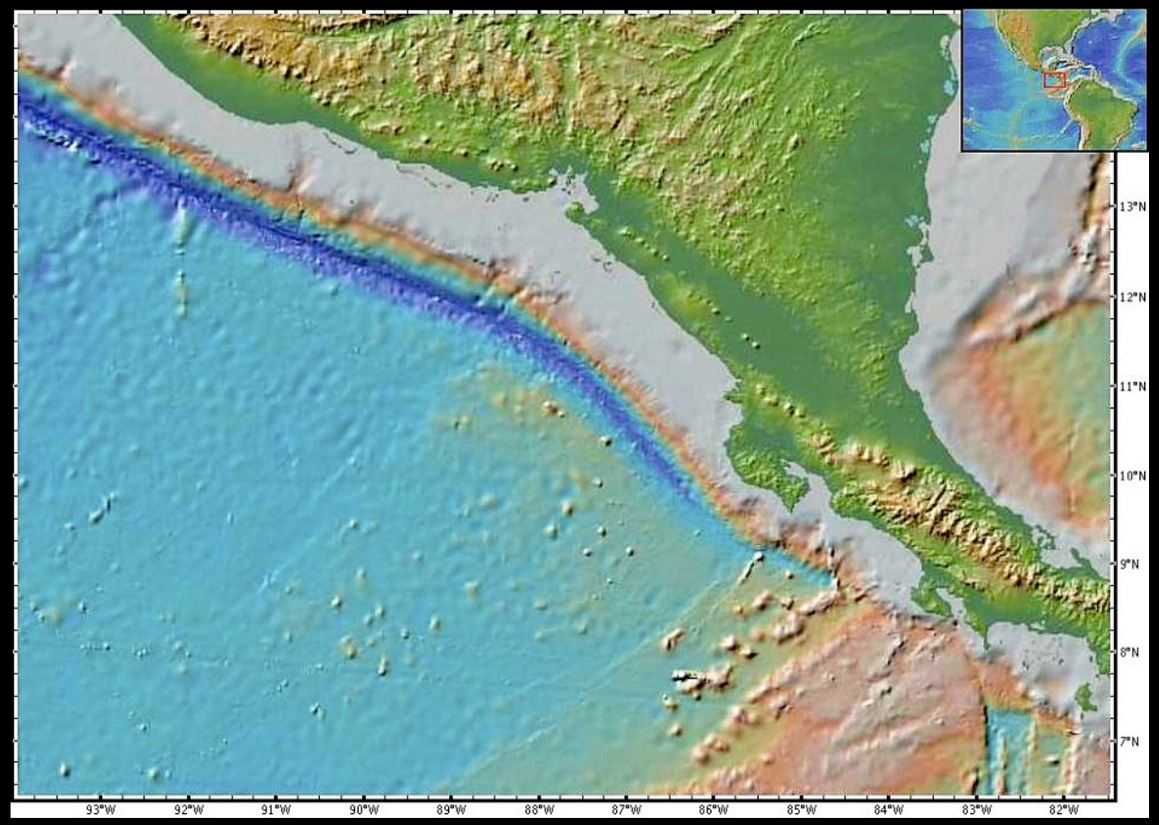
- upper plate in tension/extension
- steeply dipping slab
- usually has oceanic upper plate
- subducting plate has more rollback

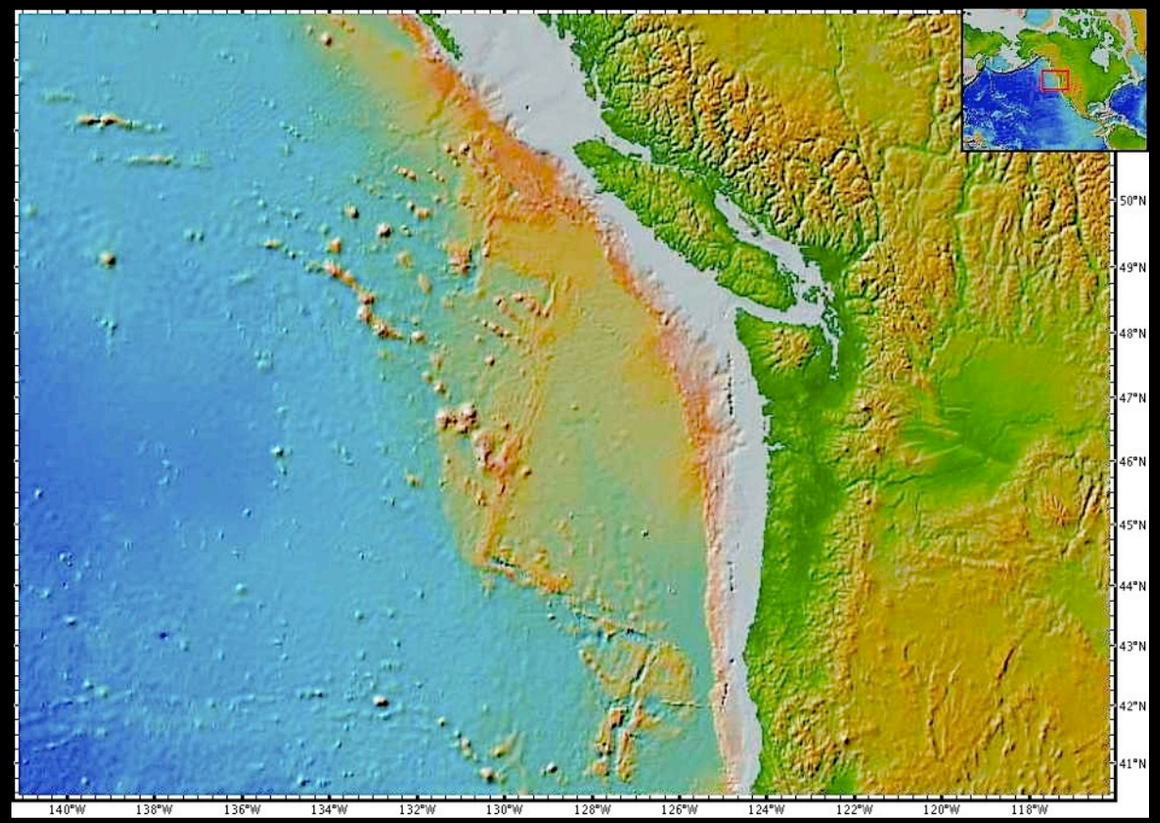
Uyeda and Kanamori, 1979

Erosional vs Accretionary Types

- no prism, evidence for erosion
- clear topographic expression of trench, easily identified

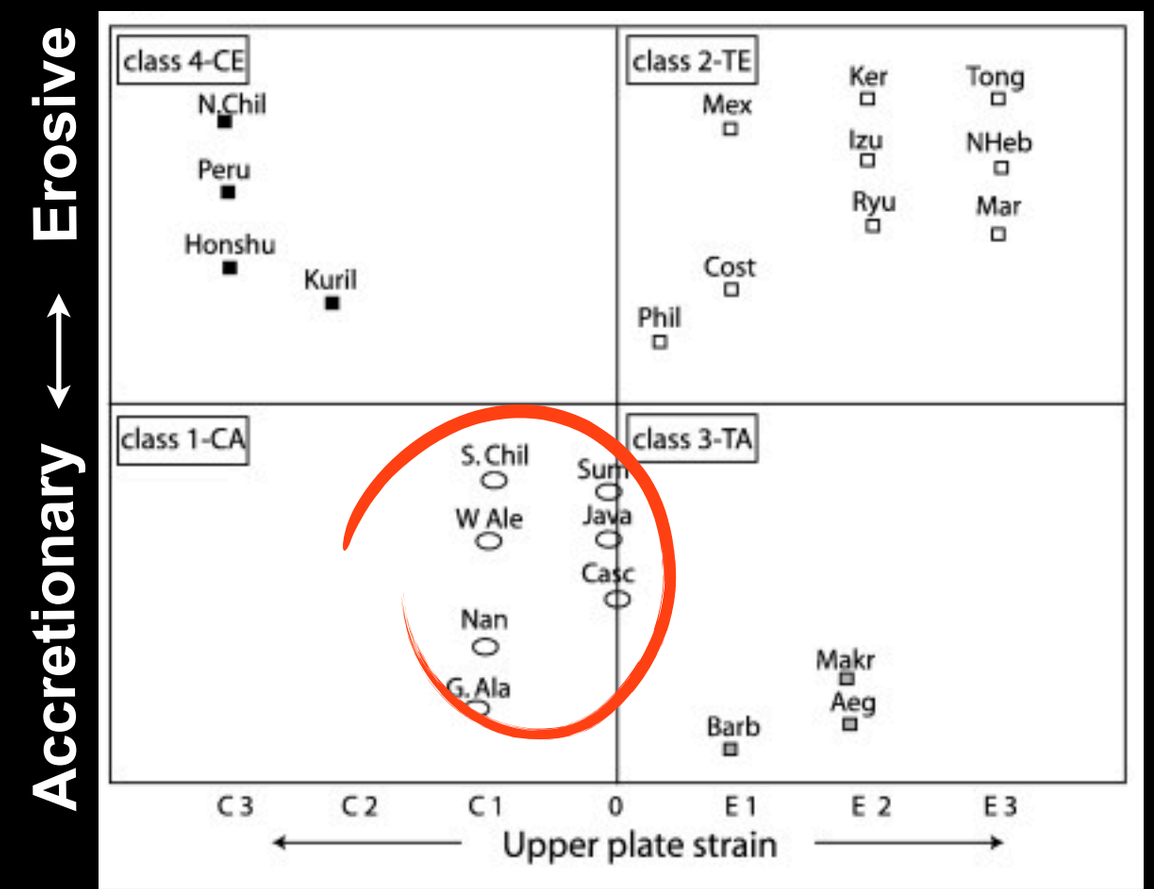
- large accretionary prism
- deep trench filled up and covered over by sediments





Classification of subduction zones

Subduction zone	Seismic moment magnitude	Class
SChile (S.Chil)	9.5	1-CA
Alaska (Ala)	9.2	
Aleutians (W.Ale)	9.1	
Sumatra (Java-Sum)	9.1	
Cascadia (Casc)	9.0	
Japan (Nan)	8.4	
Central America (Mex-Cost)	8.1	2-TE
New Hebrides (NHeb)	7.9	
Marianas (Mar)	7.8	
Izu-Bonin (Izu)	7.2	
Philippines (Phil)	7.9	
Tonga (Tong)	8.0	
Kermadec (Ker)	7.4	
Ryukyus (Ryu)	8.0	
Lesser Antilles (Barb)	7.5	3-TA
Aegean arc (Aeg)	7.1	
Makran (Mak)	8.0	
Peru (Peru)	8.4	4-CE
Japan (Honshu)	8.4	
Kurile (Kur)	8.5	
N.Chile (N.Chil)	8.5	

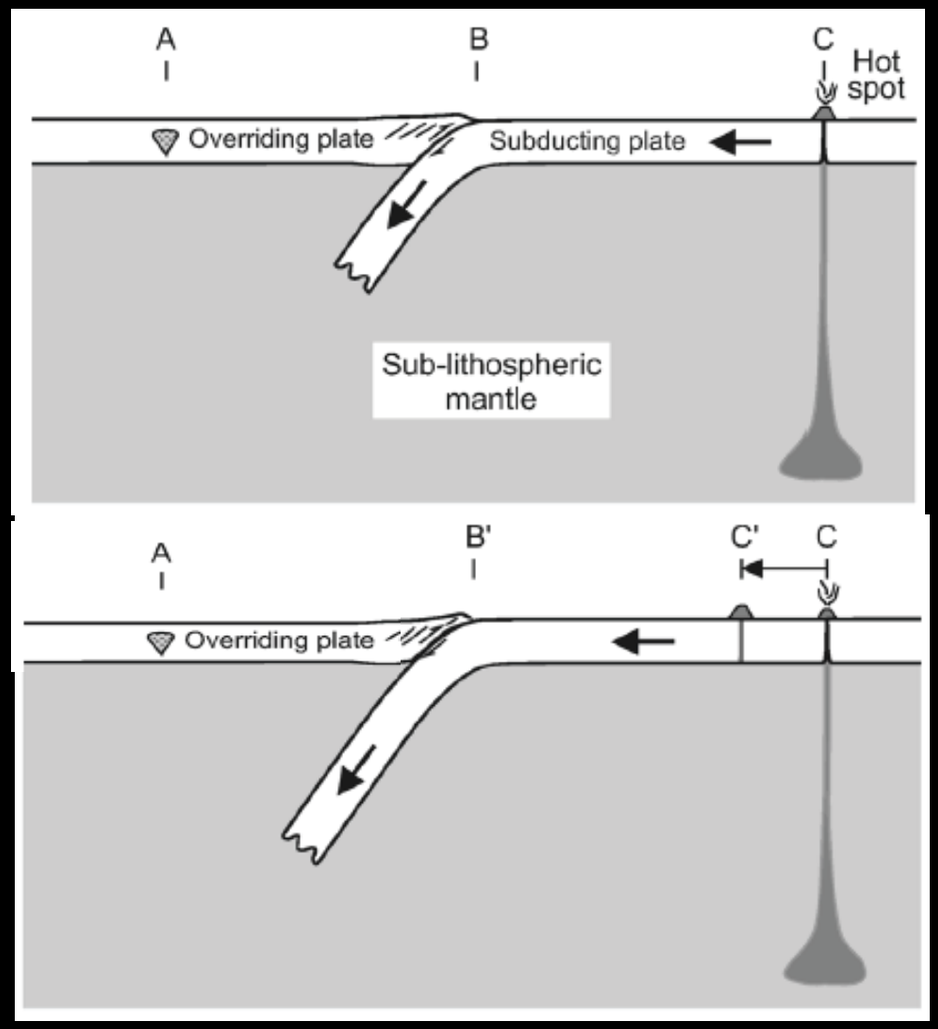


Chilean type ⟷ Mariana type

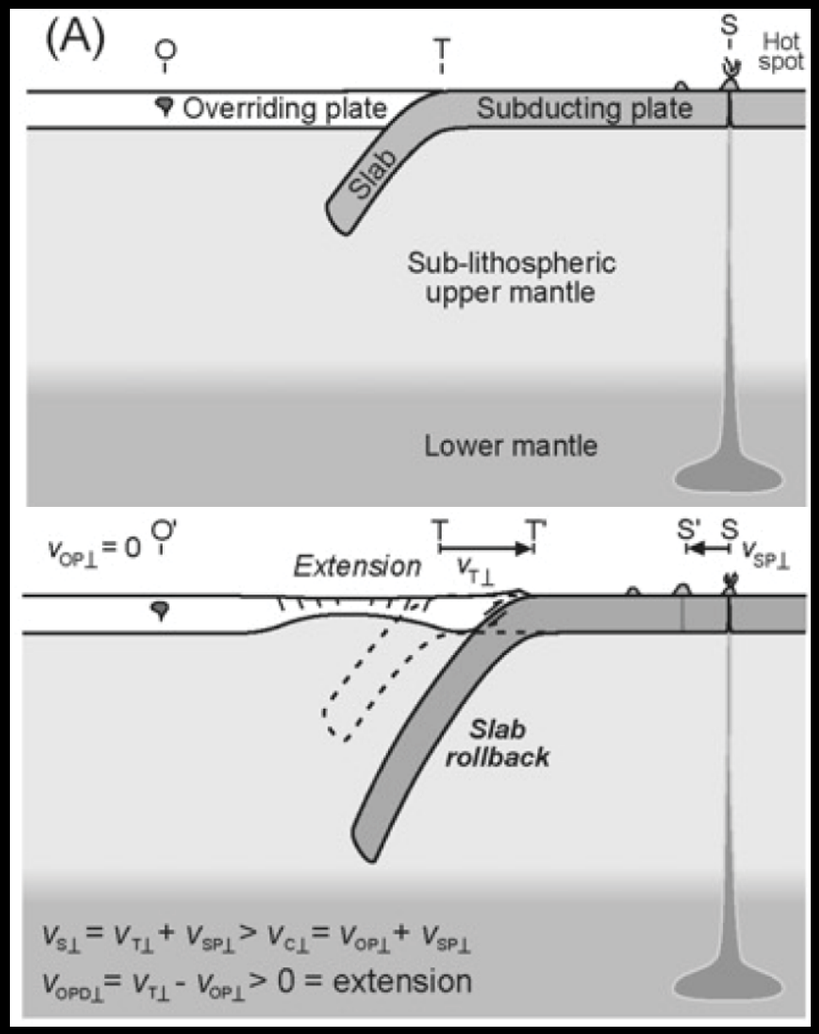
De Franco, Govers, and Wortel, EPSL, 2008

Two modes of subduction

- forward plate advance
- stationary trench

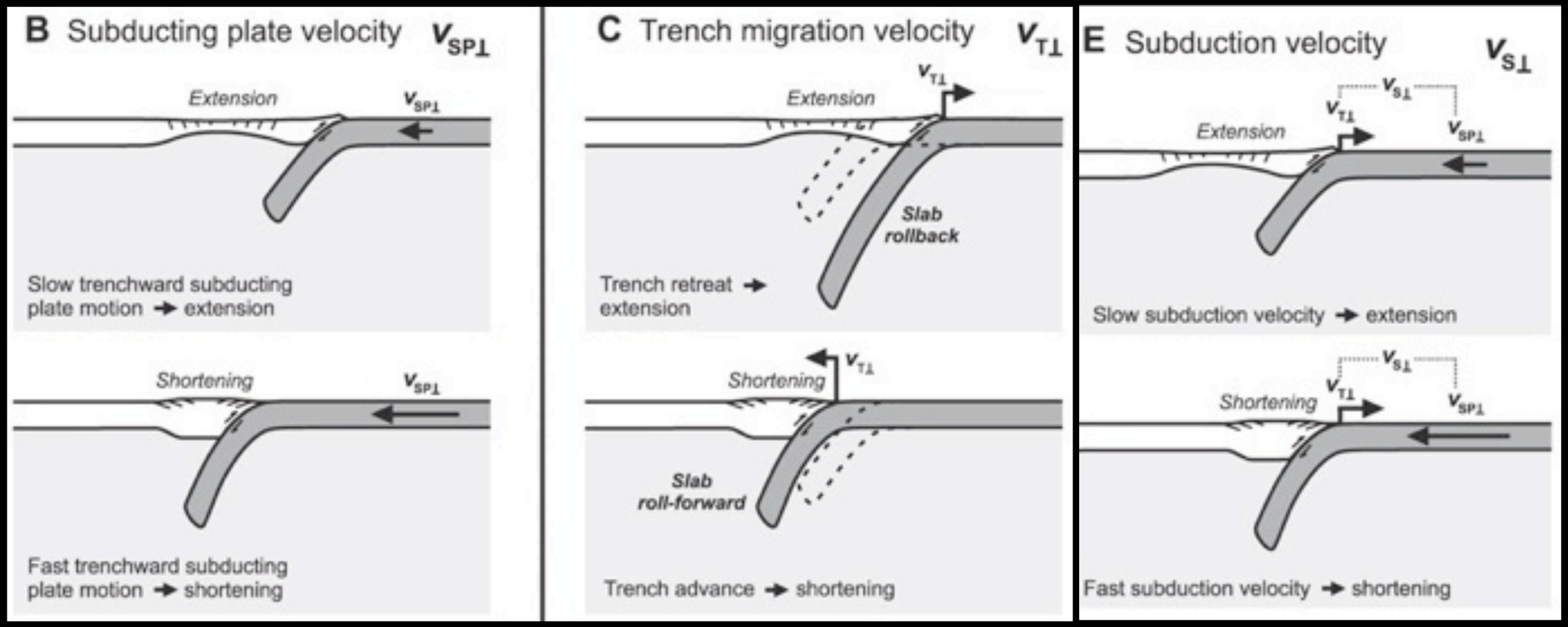


- slab rollback
- retreating trench



after Schellart (2006; 2008)

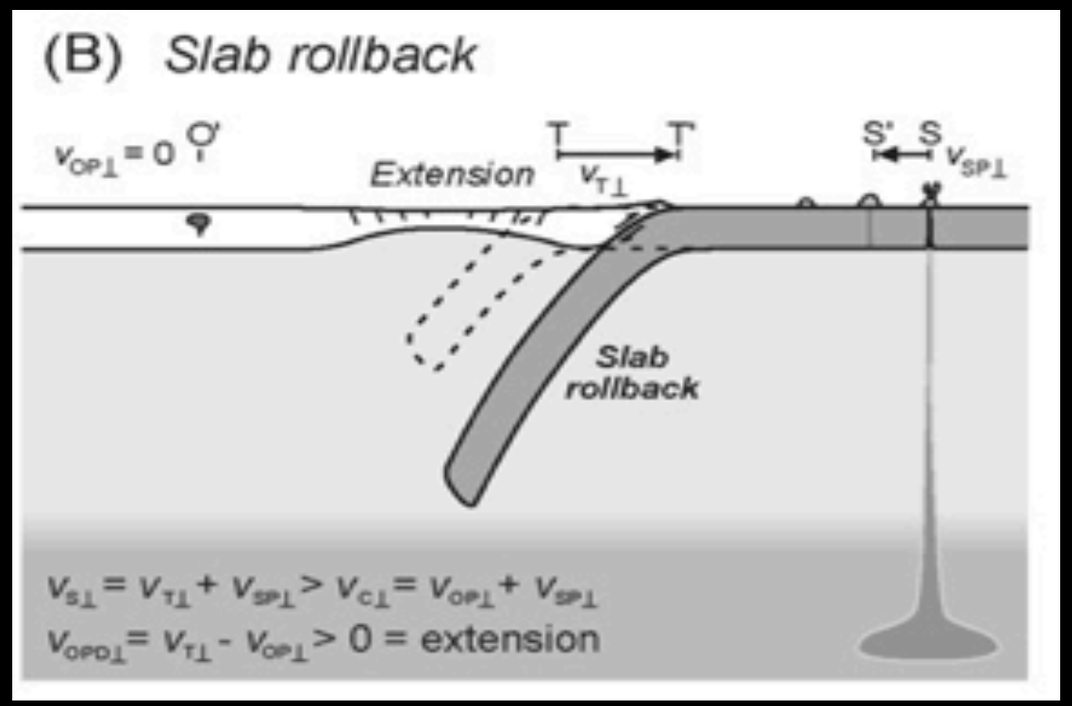
Kinematics of subduction zones



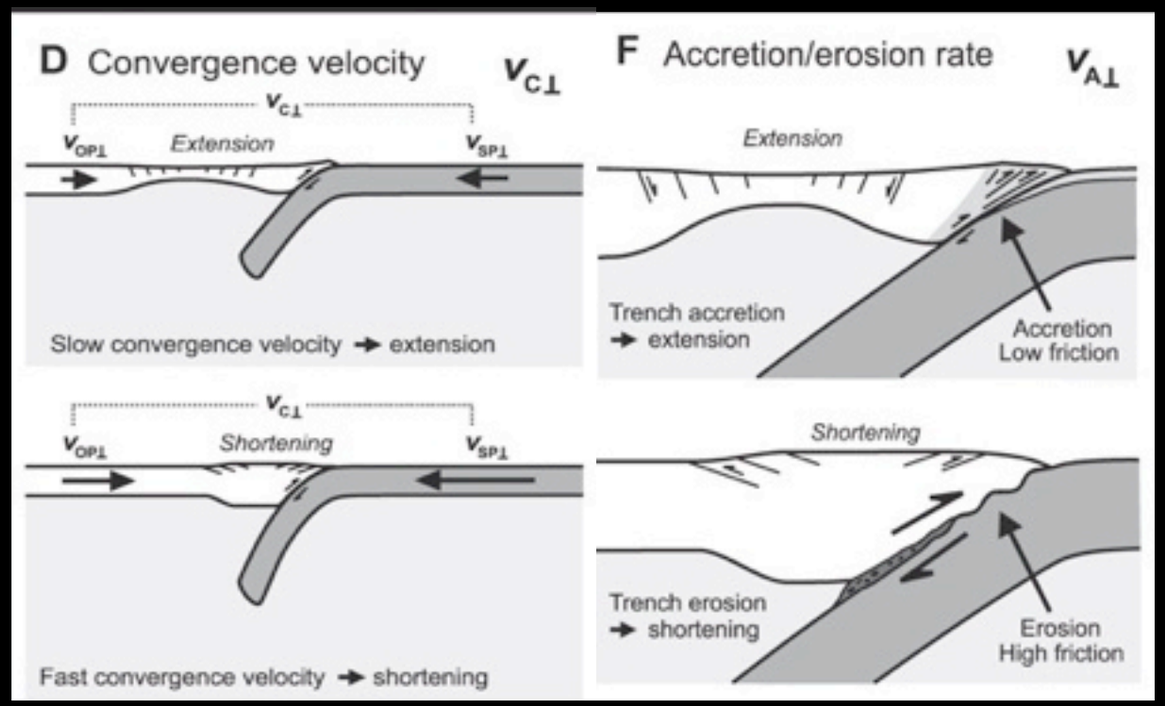
Schellart, GSA Bulletin, 2008

Kinematics of subduction zones

- **plate/trench motions depend on reference frame**



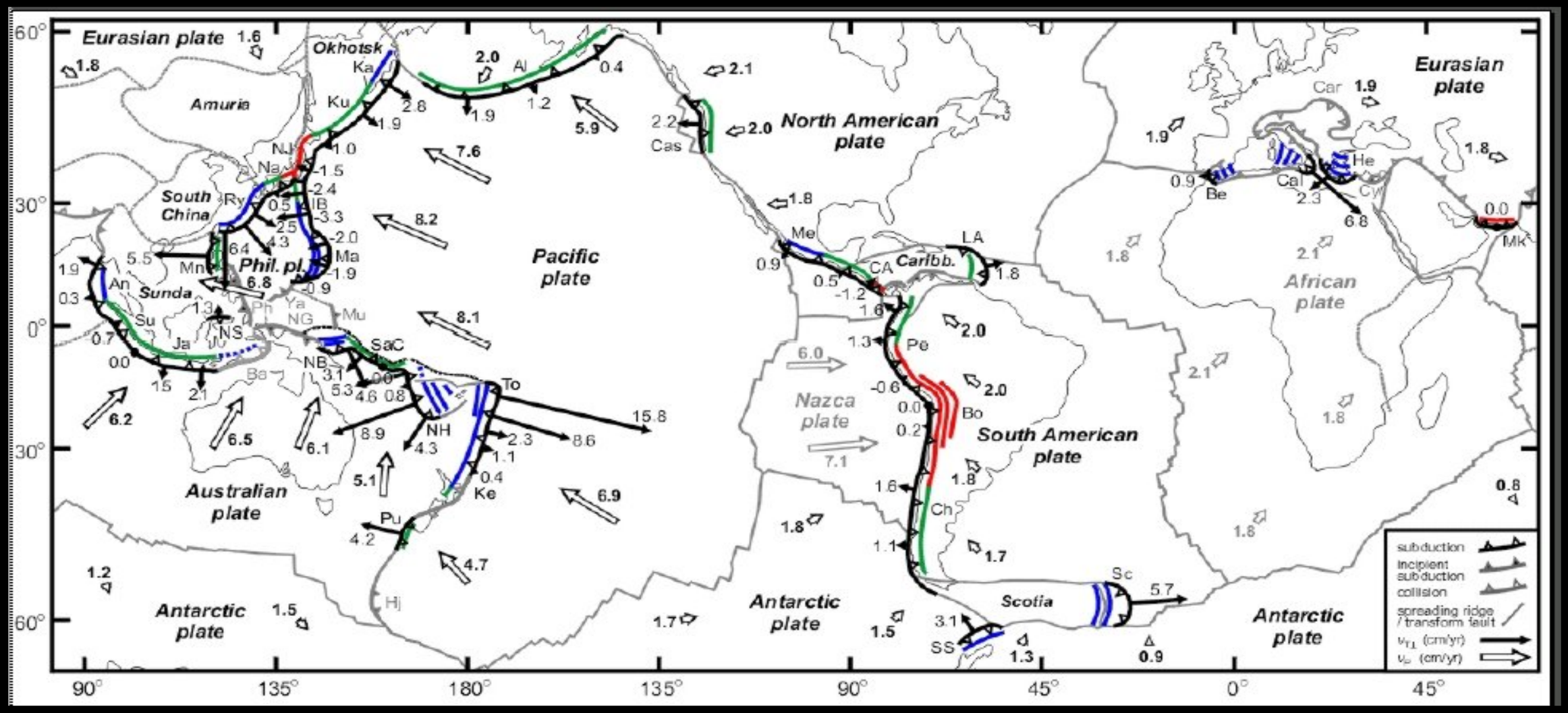
- **total rates independent of reference frame**



Schellart, GSA Bulletin, 2008

Diversity of subduction zones

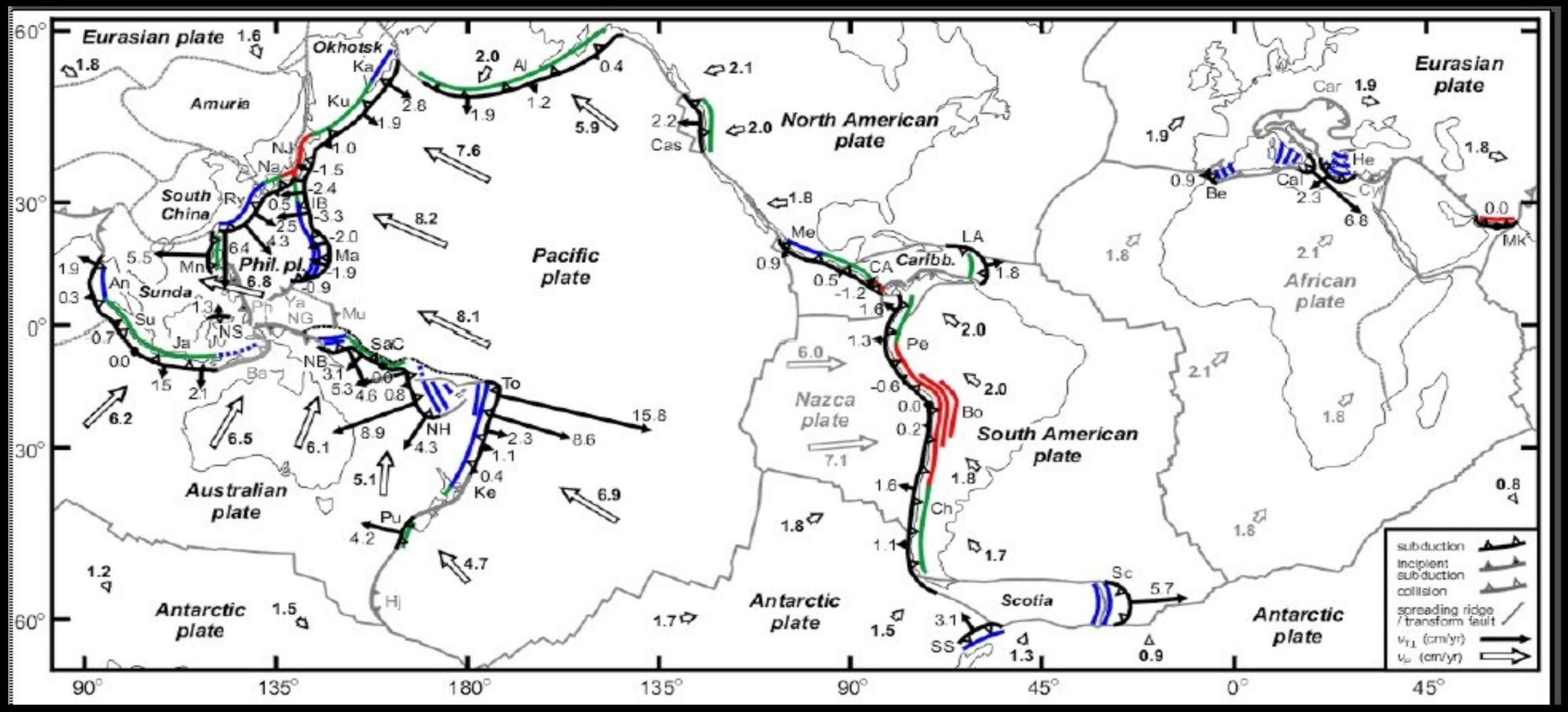
- **24 distinct subduction zones**
  - **Some are *retreating*, some are *stationary*, few are *advancing***



Schellart, Stegman, and Freeman, Earth Sci. Rev., 2007

Diversity of subduction zones

- **24 distinct subduction zones**
  - **vary in lateral extent between 200-6000 km**



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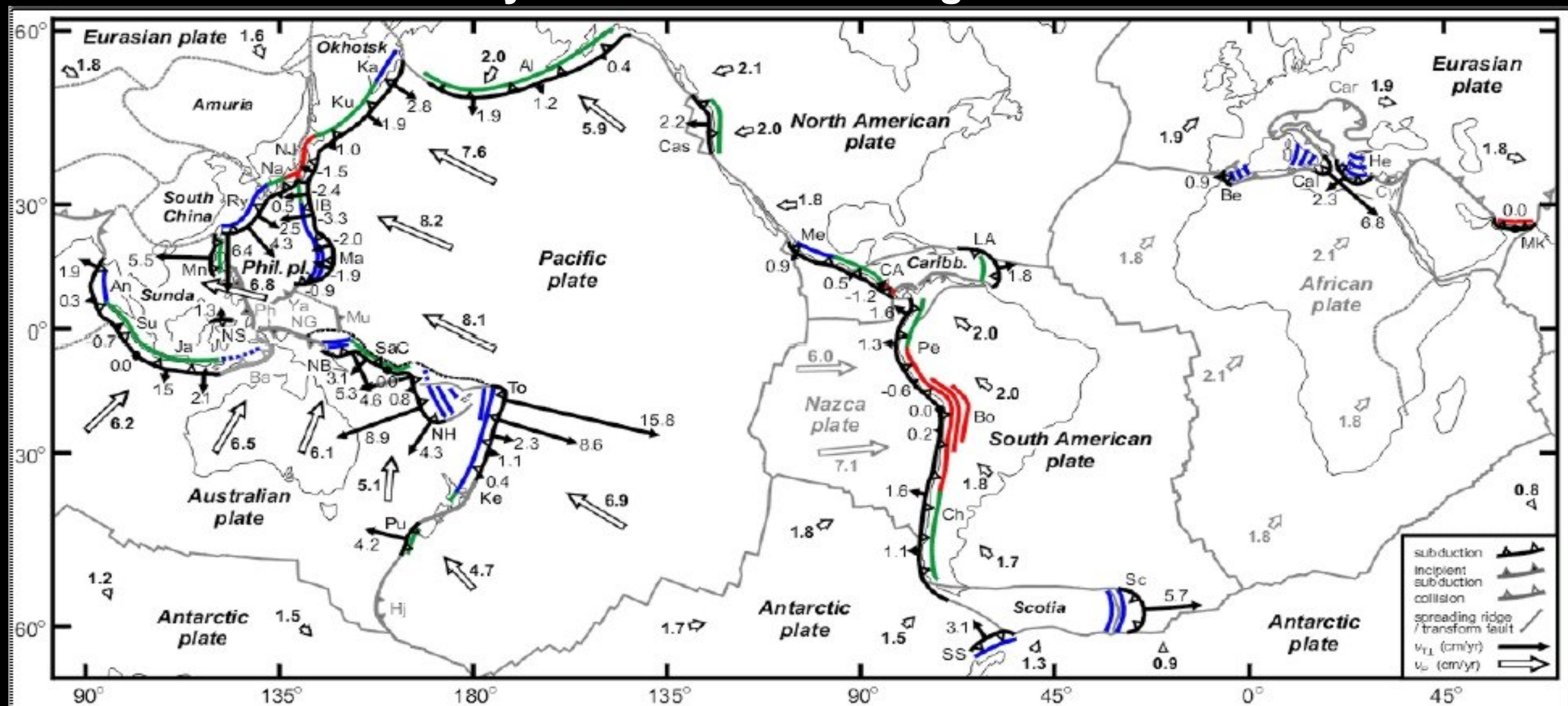
Global Diversity of Subduction Zones

- **Individual subduction zones have variable trench curvature, variable dip along the trench, variable dip with increasing depth, and evolve with time**

- **Subduction zones are dynamic features arising from slab-mantle interaction**



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Controls on subducting plate motions

- plate-scale segmentation
- 16 subduction zones - 16 segments

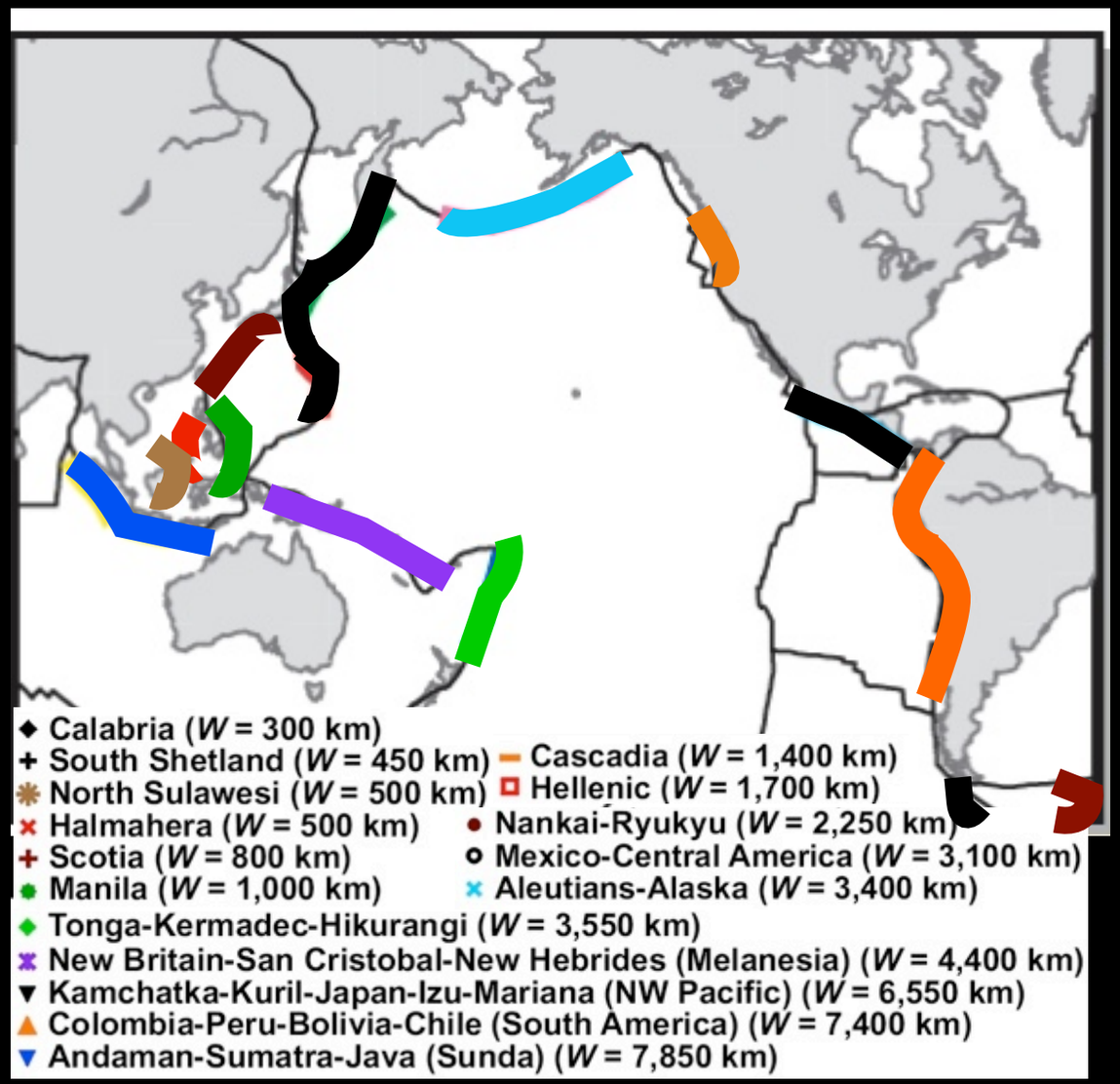
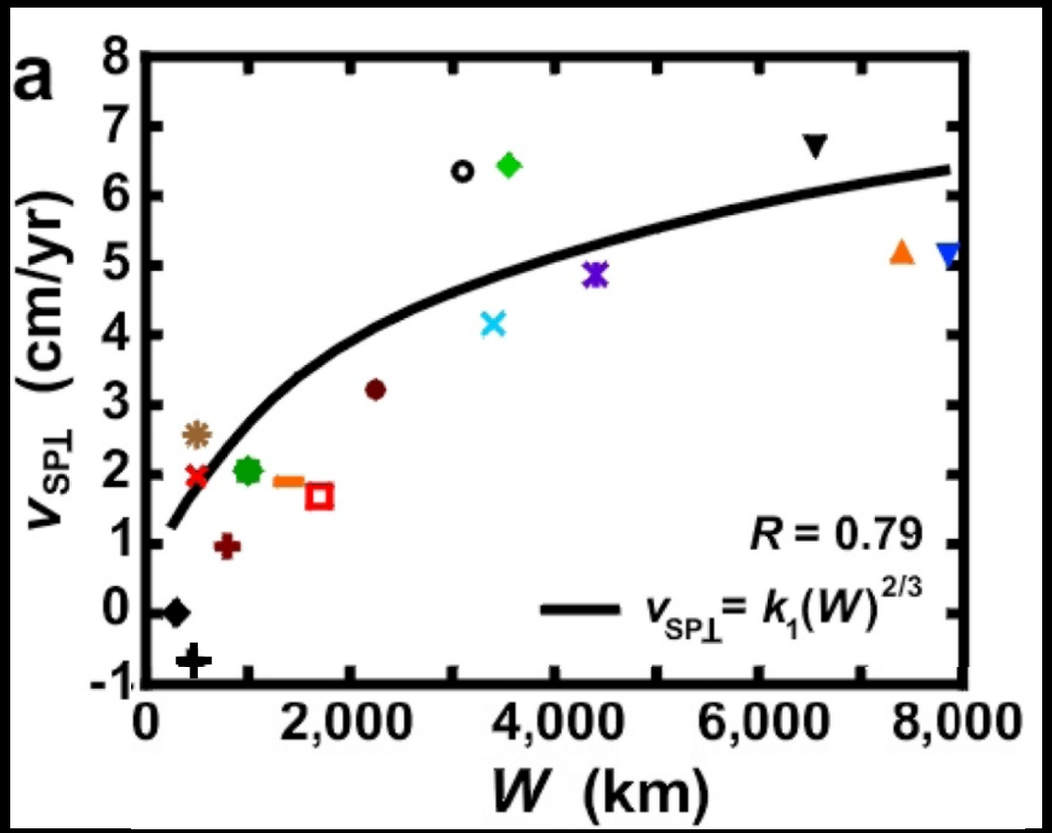


Plate velocity vs slab width



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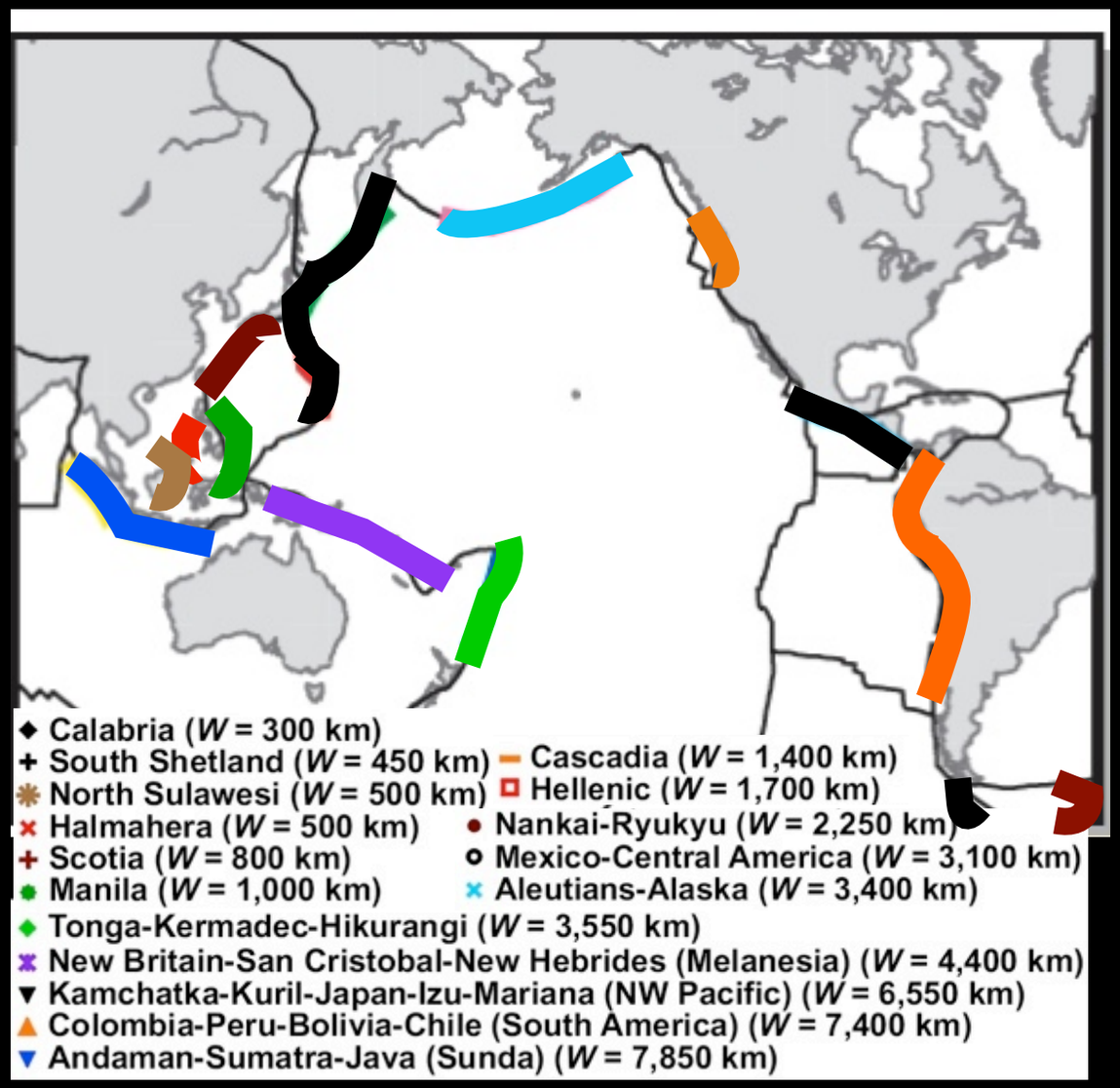
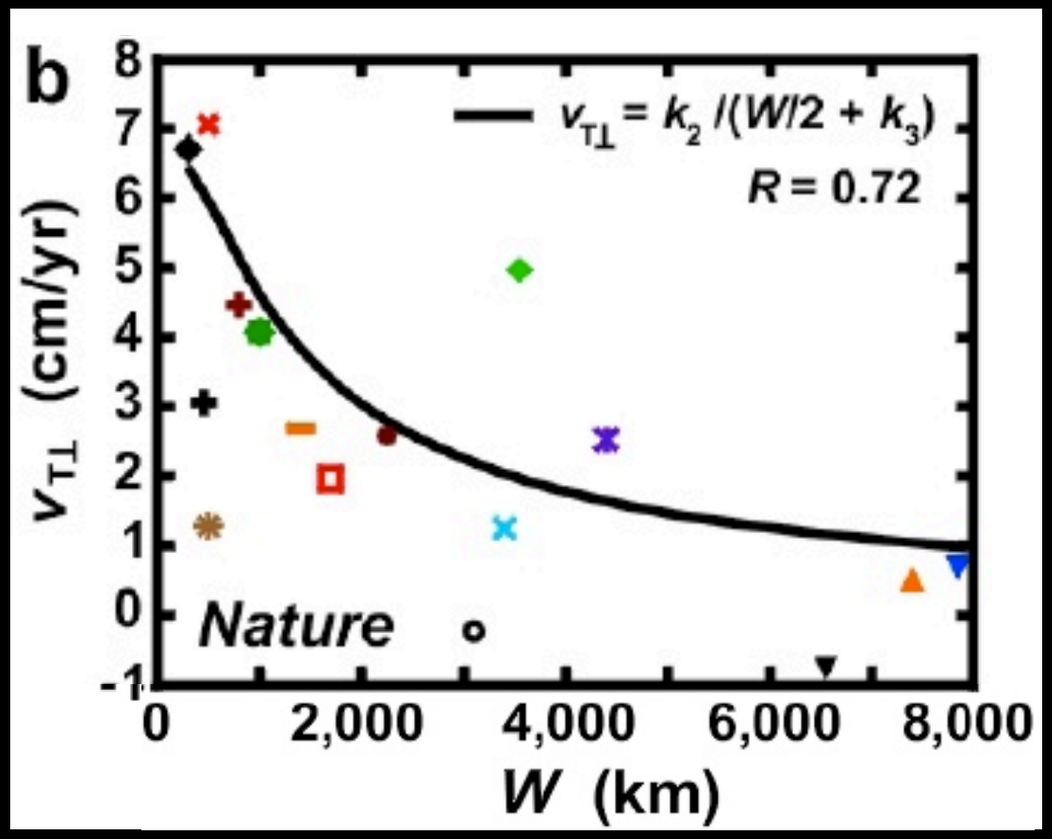


Trench retreat vs slab width



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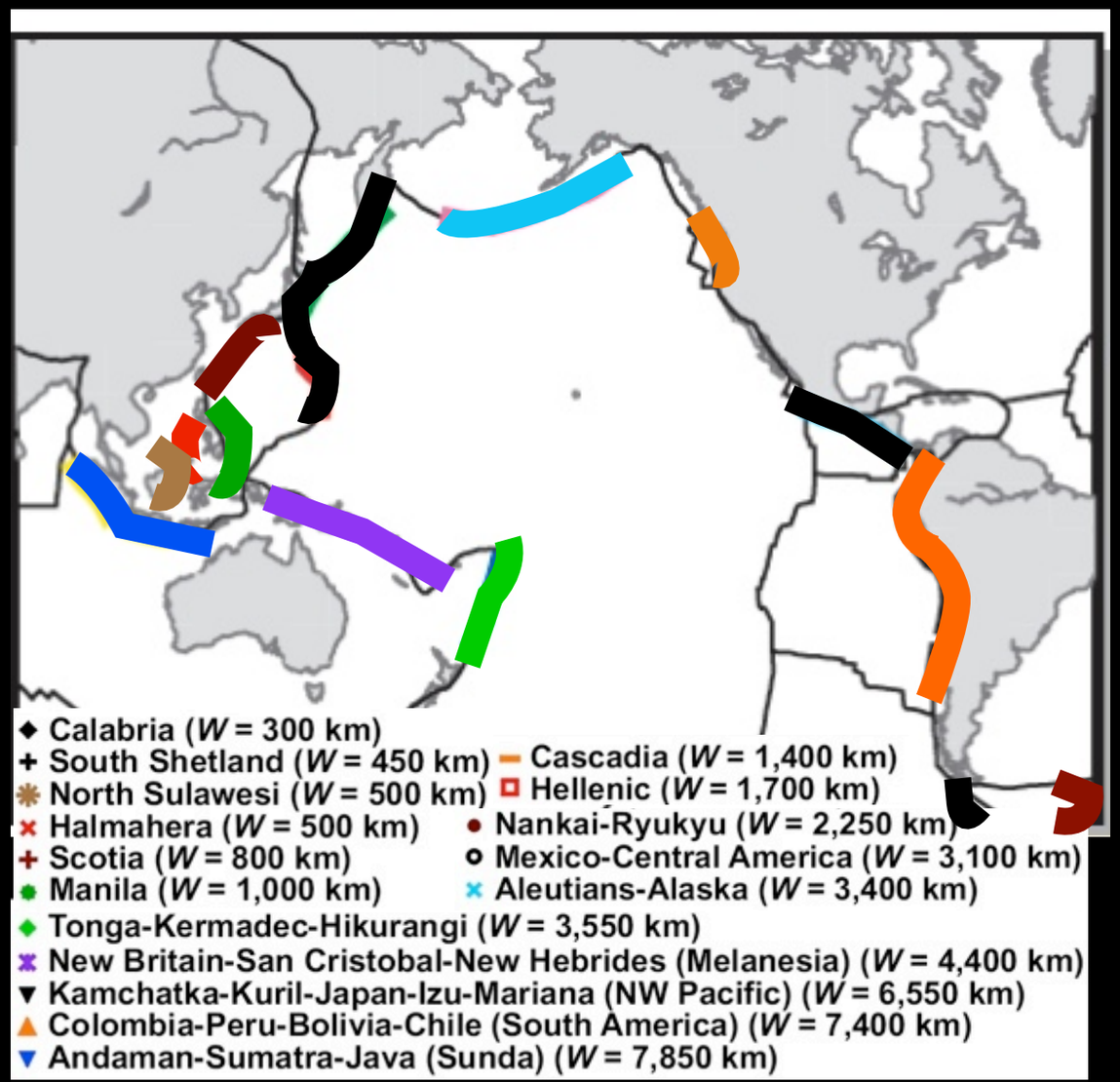
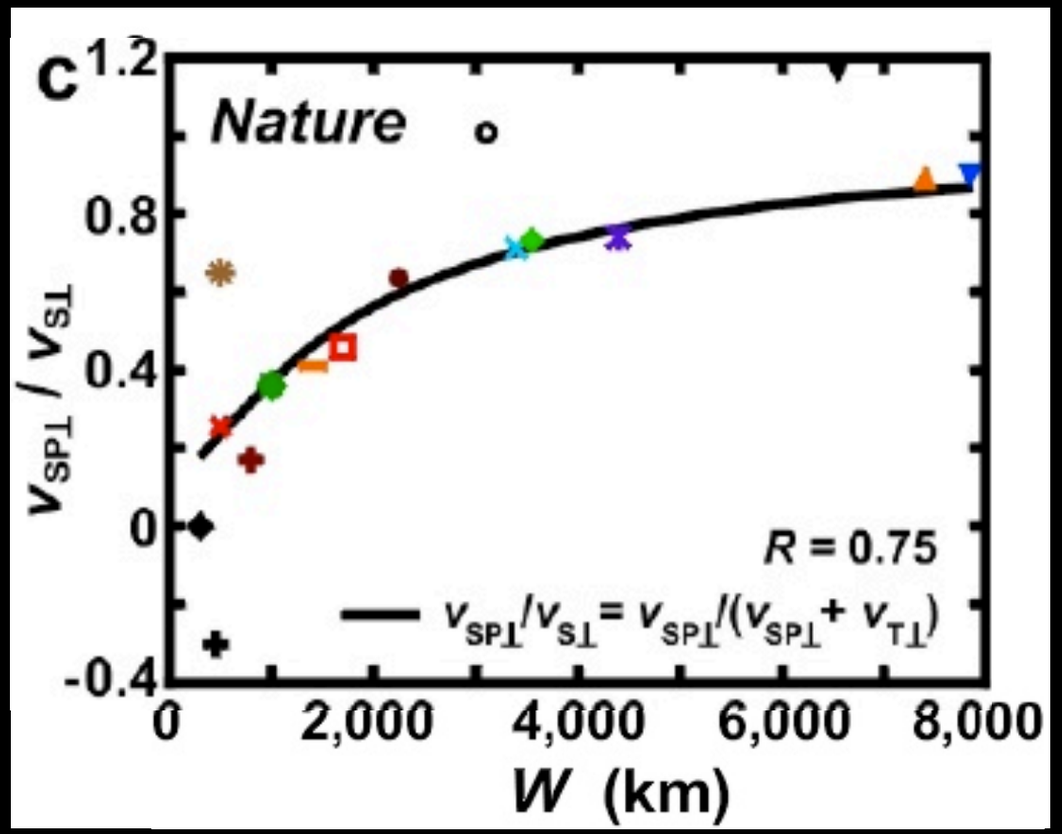


Partitioning vs slab width



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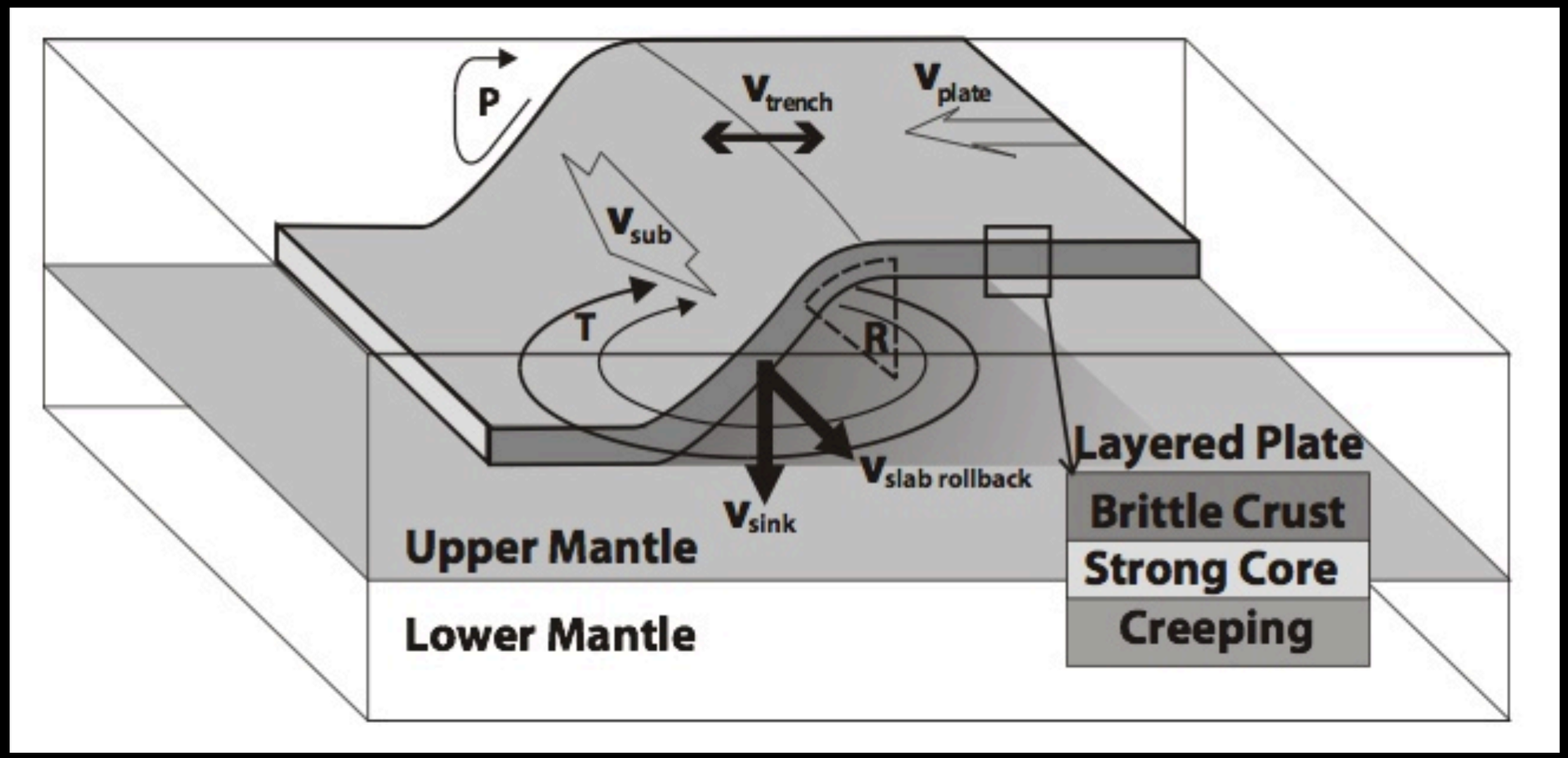
Top-down model of free subduction



Stegman et al., Tectonophysics, 2010a

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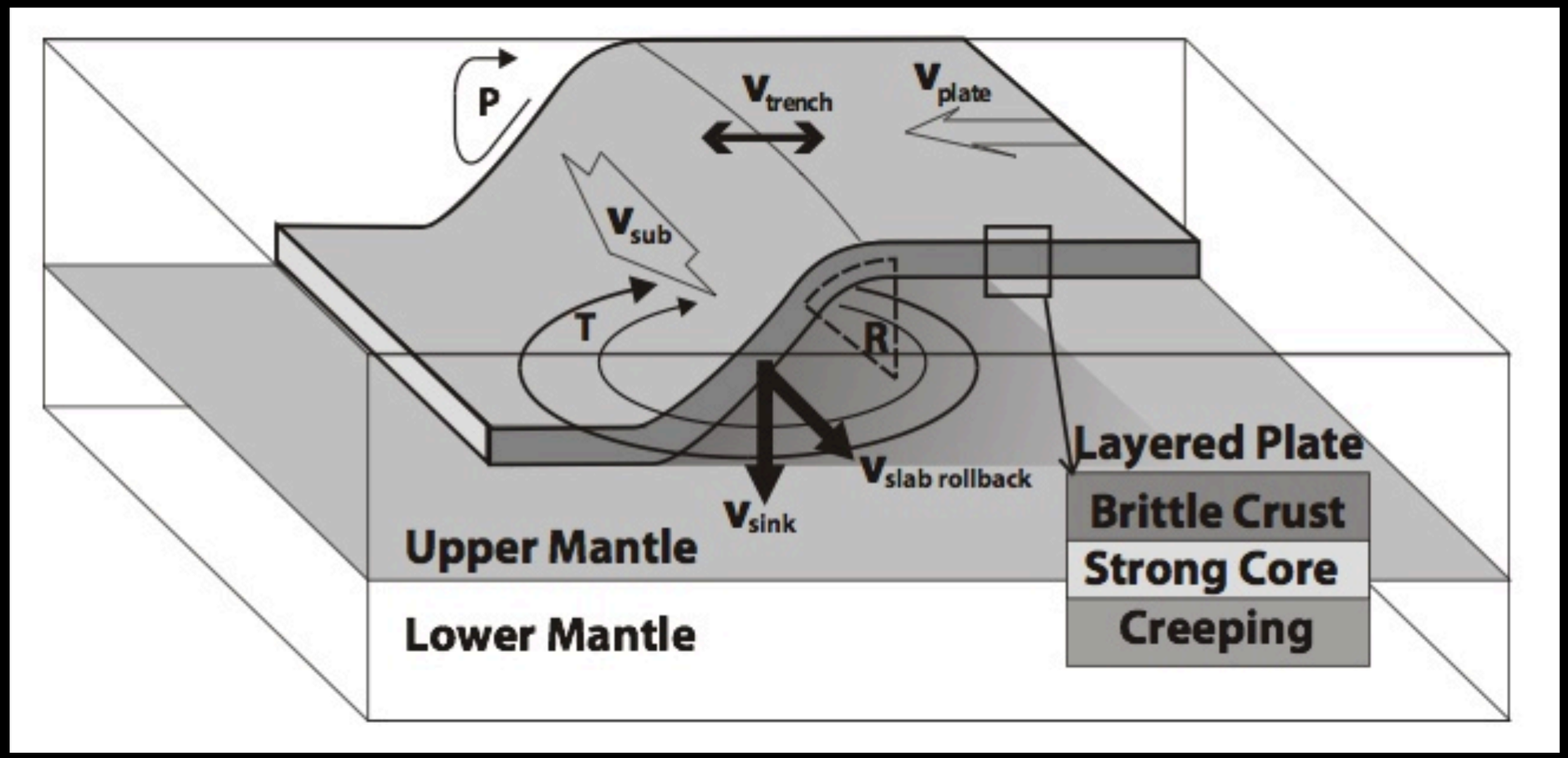

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$$0 = -\nabla P + \eta \nabla^2 \vec{u} - \rho g \hat{z}$$

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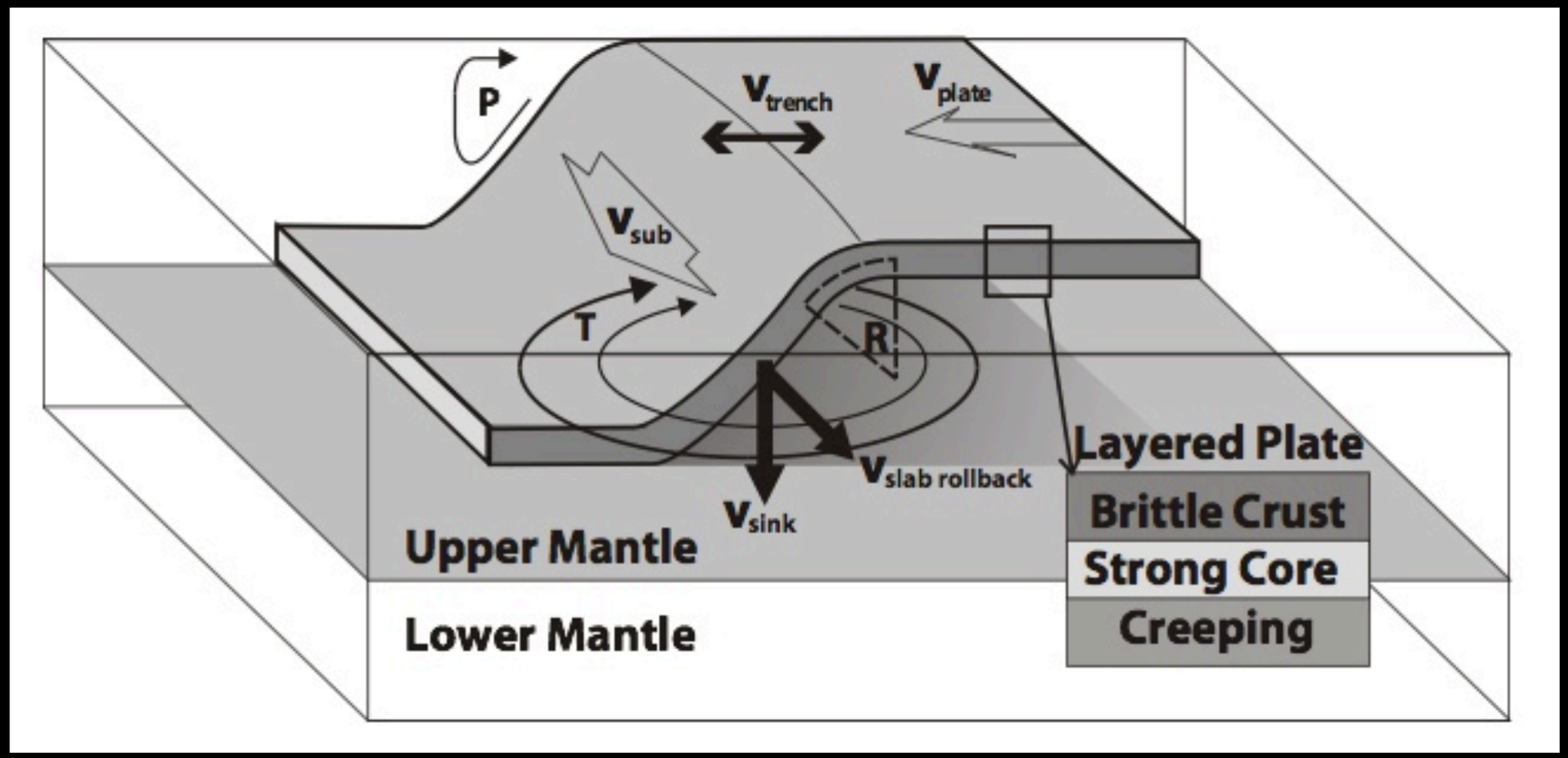

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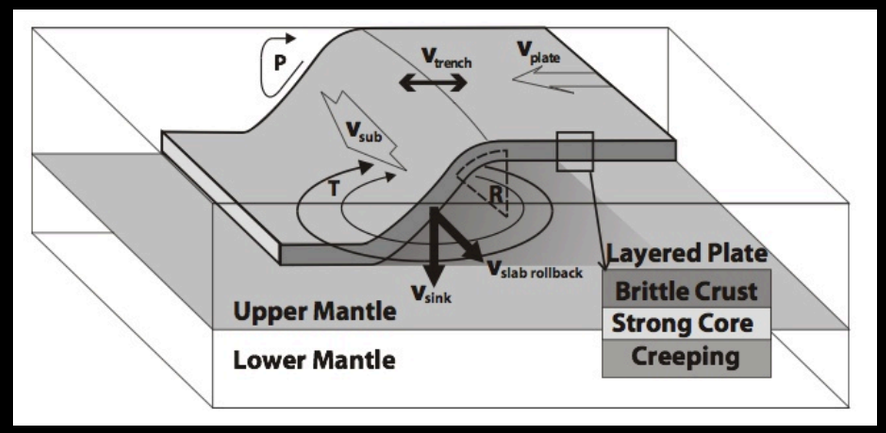
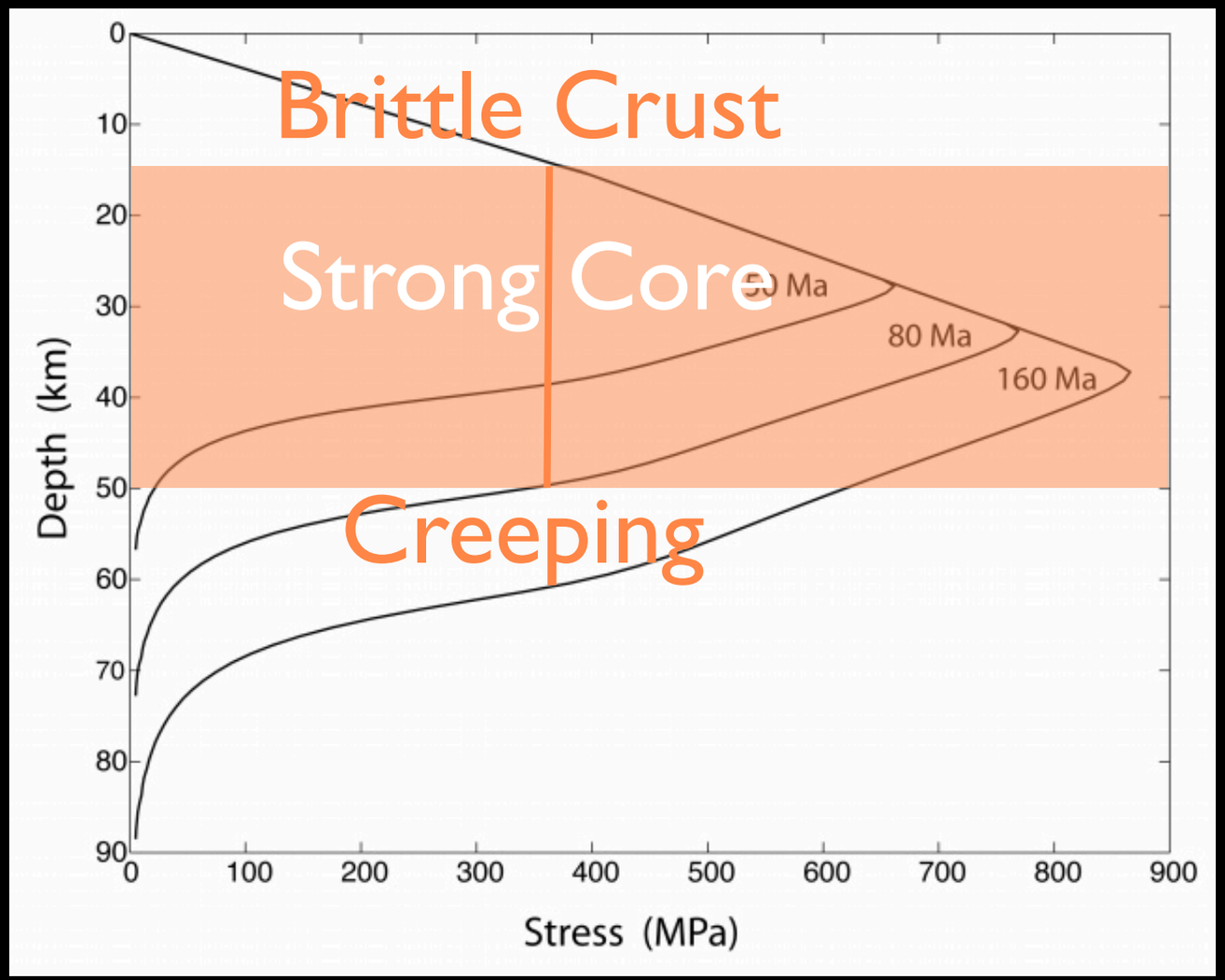


- 3-D mechanical model of a lithosphere with a layered structure



Buffett and Becker, JGR, 2012

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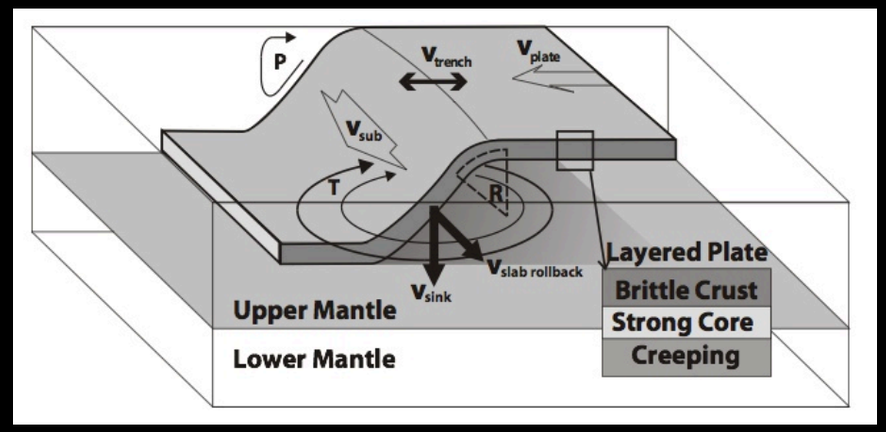

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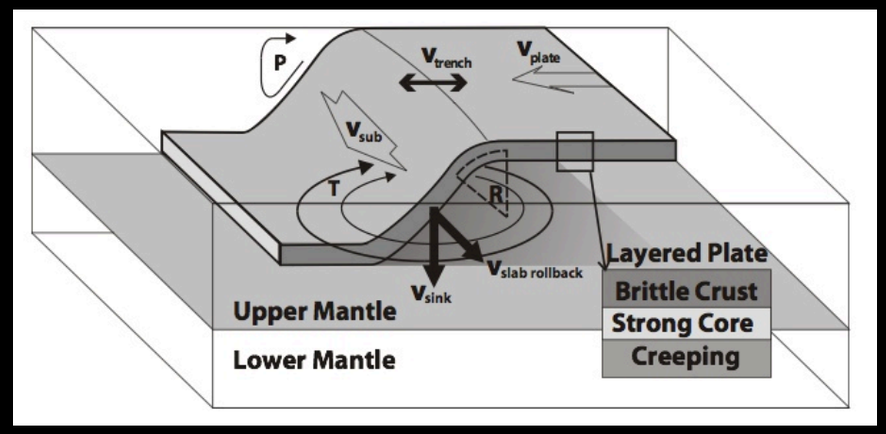

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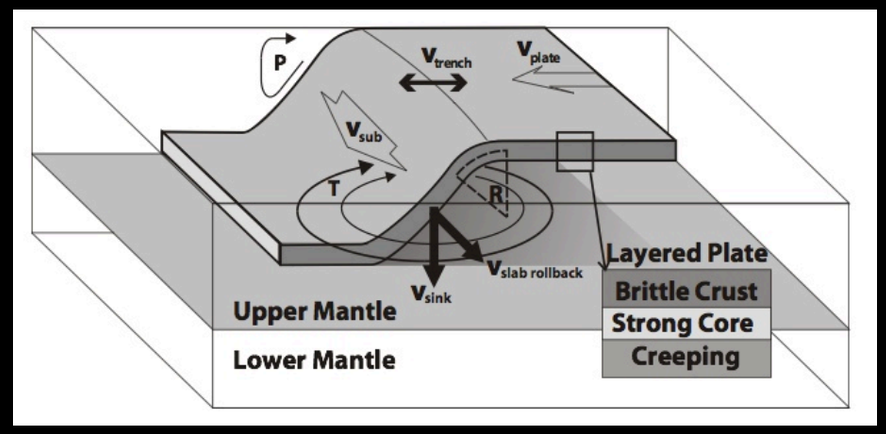

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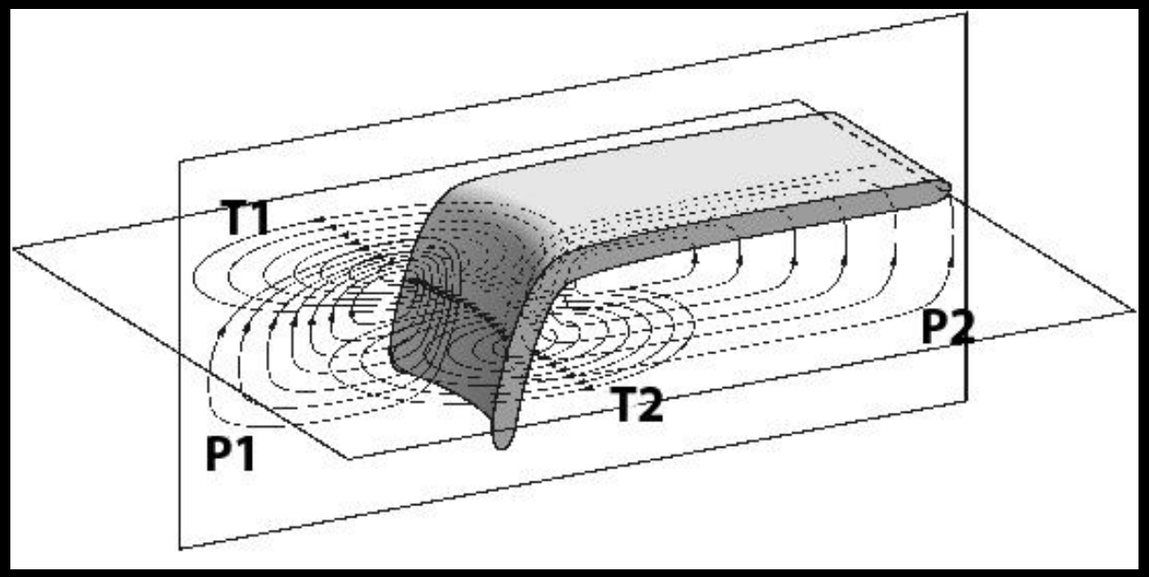
- assumptions: Earth is flat, the mantle is a cube, thermodynamics do not exist in the cube, plate subducts in isolation of any other plates, mantle viscosity is Newtonian

Coupled lithosphere-mantle system



after Schellart et al., 2004, Stegman et al., 2006

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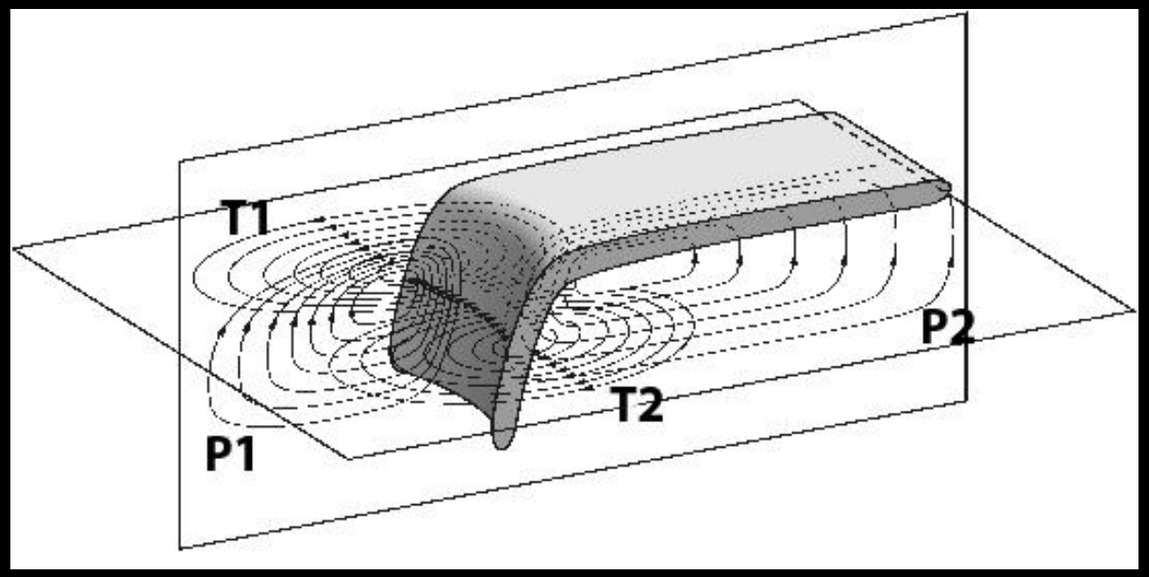

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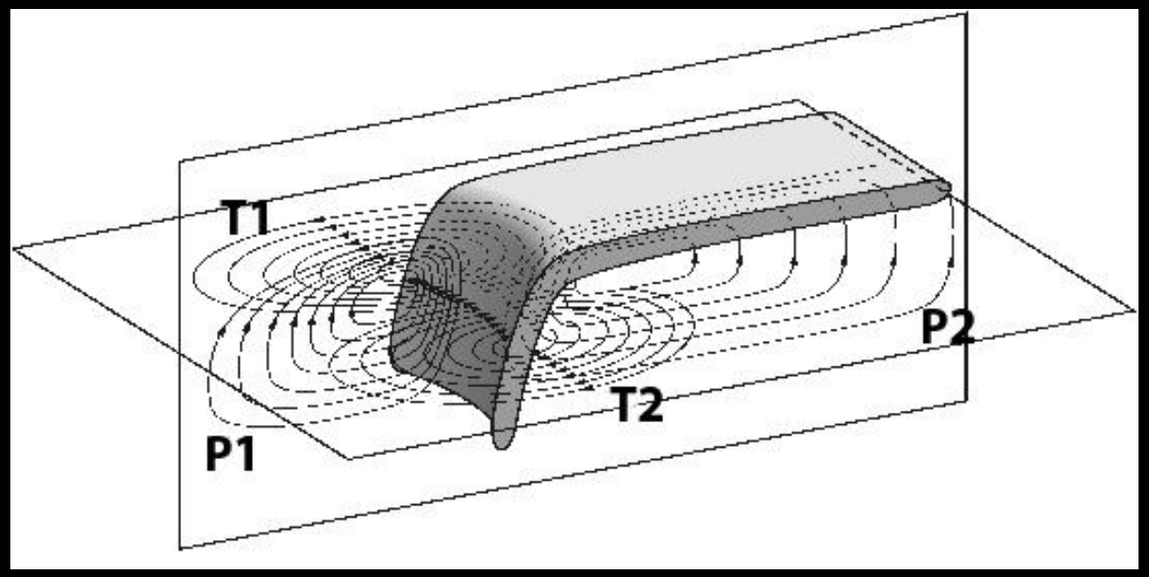

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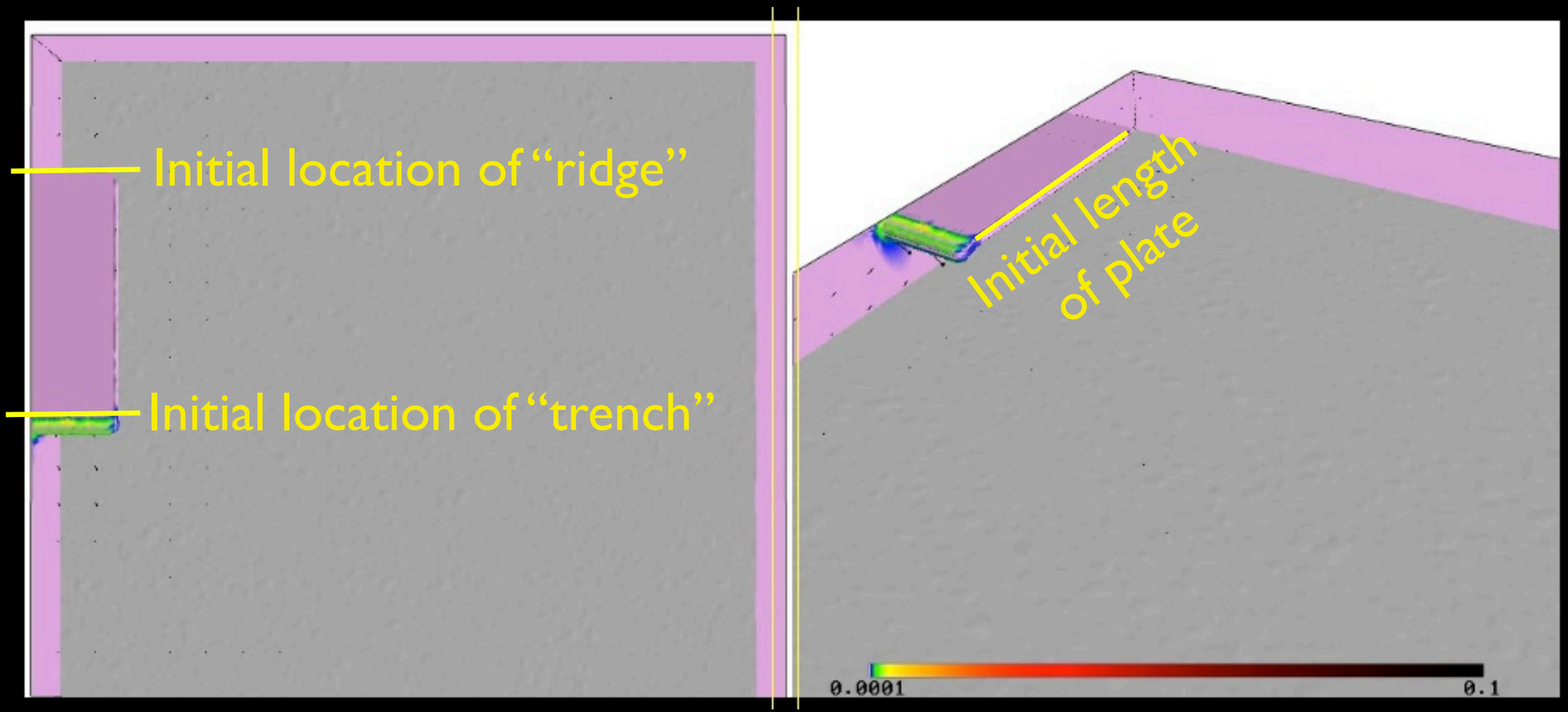
- **3-D geometry and variable viscosity of slab induces toroidal flow (T1, T2)**
- **Toroidal flow diminishes cornerflow**
- **Trench curvature arises from slab interaction with induced flow**

Two modes of subduction

- **Plates that are 1500 km or less in lateral extent predominantly subduct through slab rollback and trench retreat (Scotia, Calabria, Hellenic)**



Schellart, Stegman, et al., Science, 2010

Narrow plates have retreating trenches

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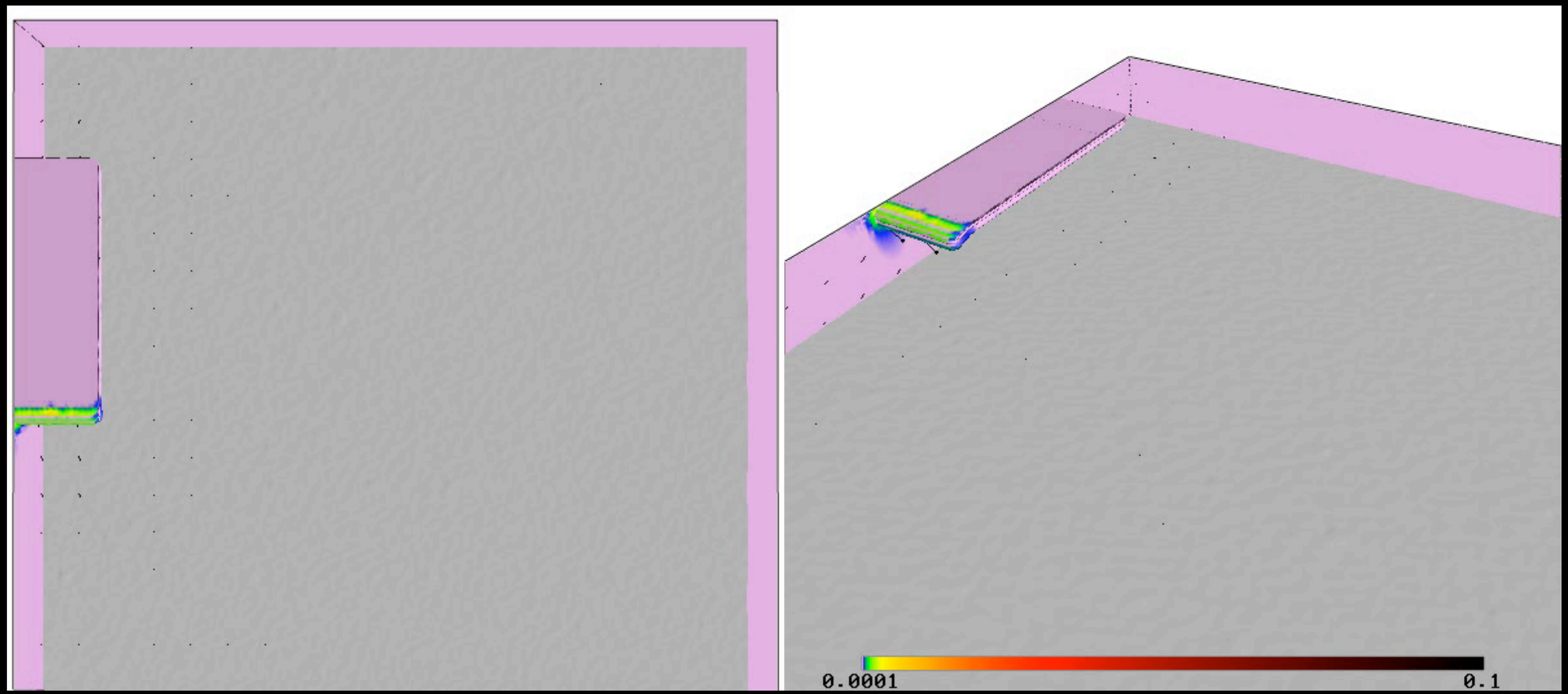

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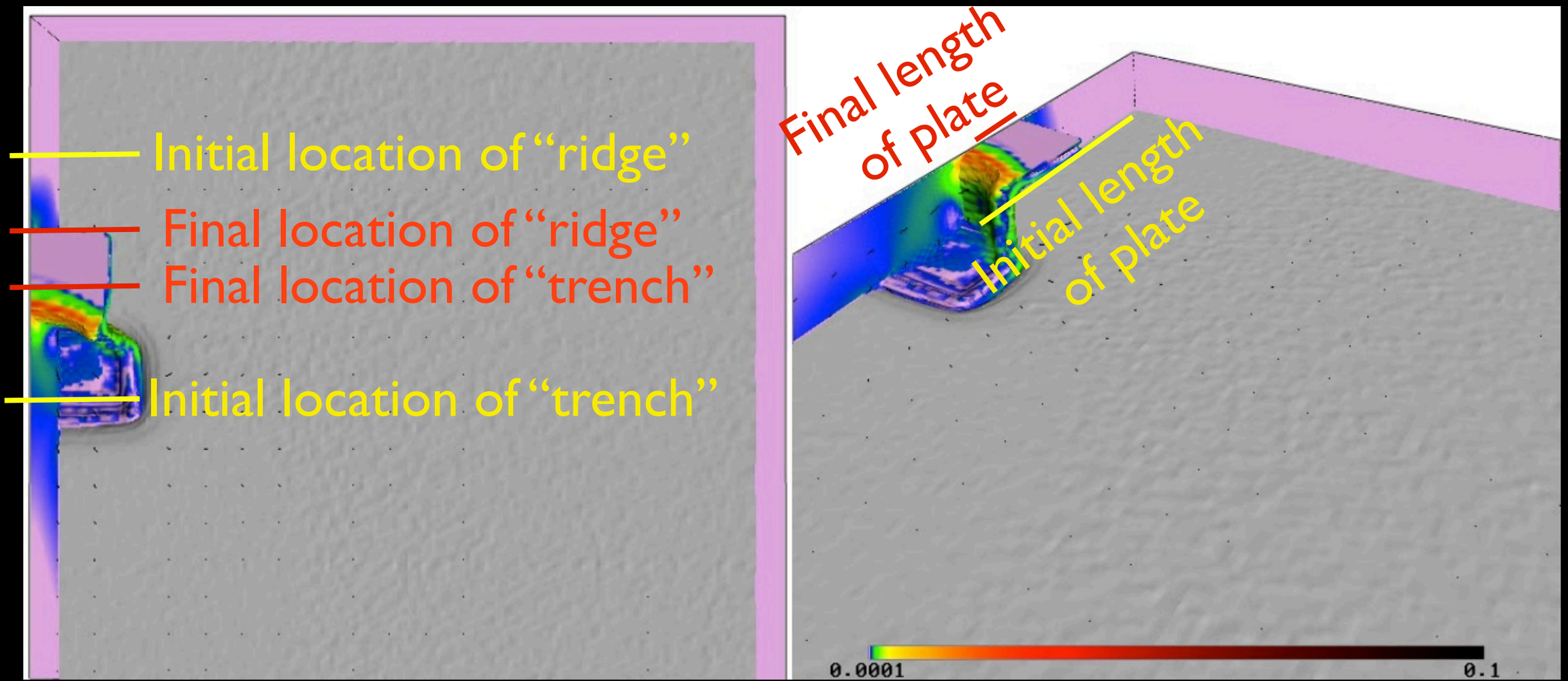
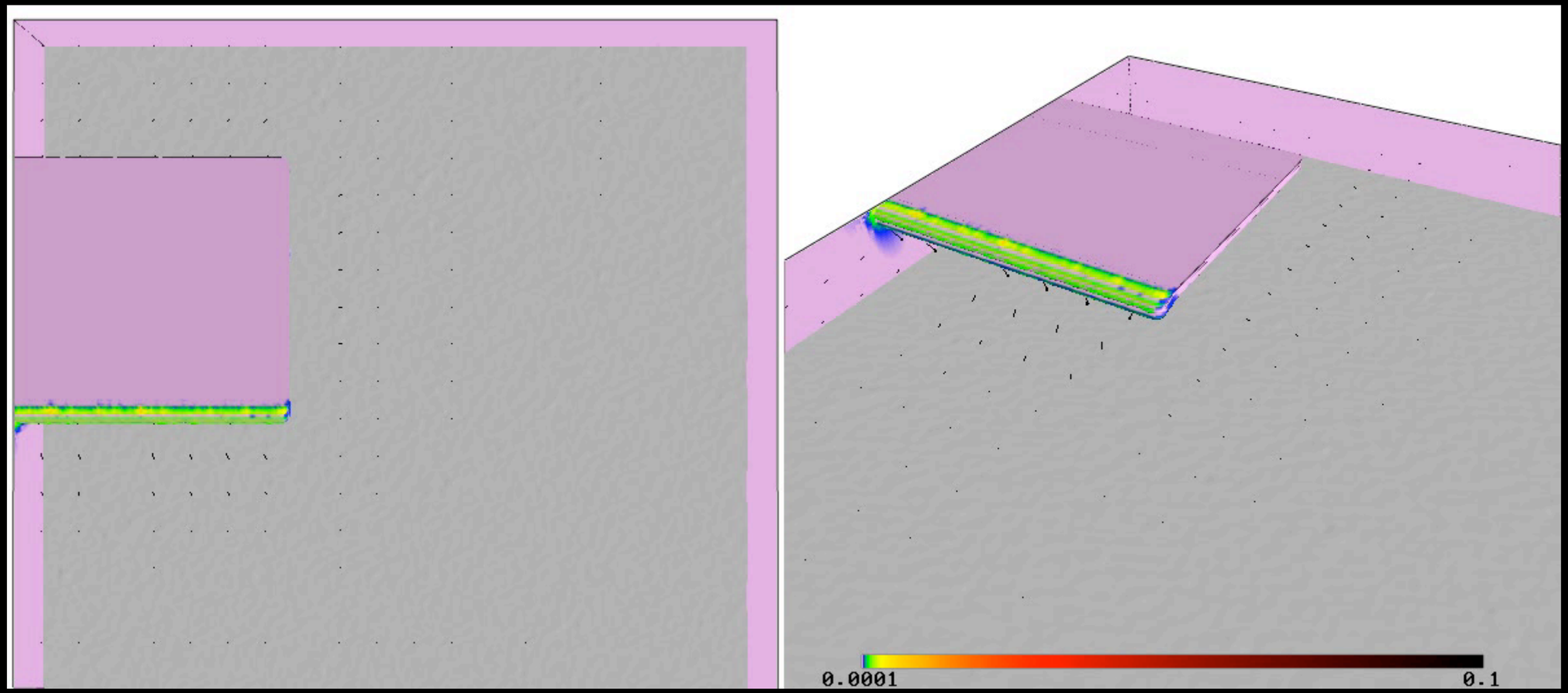


Schellart, Stegman, et al., Science, 2010

Intermediate and wide plates

- **Subduction of plates that are intermediate in width (2000-3000 km) is accommodated with both forward plate advance and trench retreat, with increasing more plate advance for wider plates (>4000 km)**



Schellart, Stegman, et al., Science, 2010

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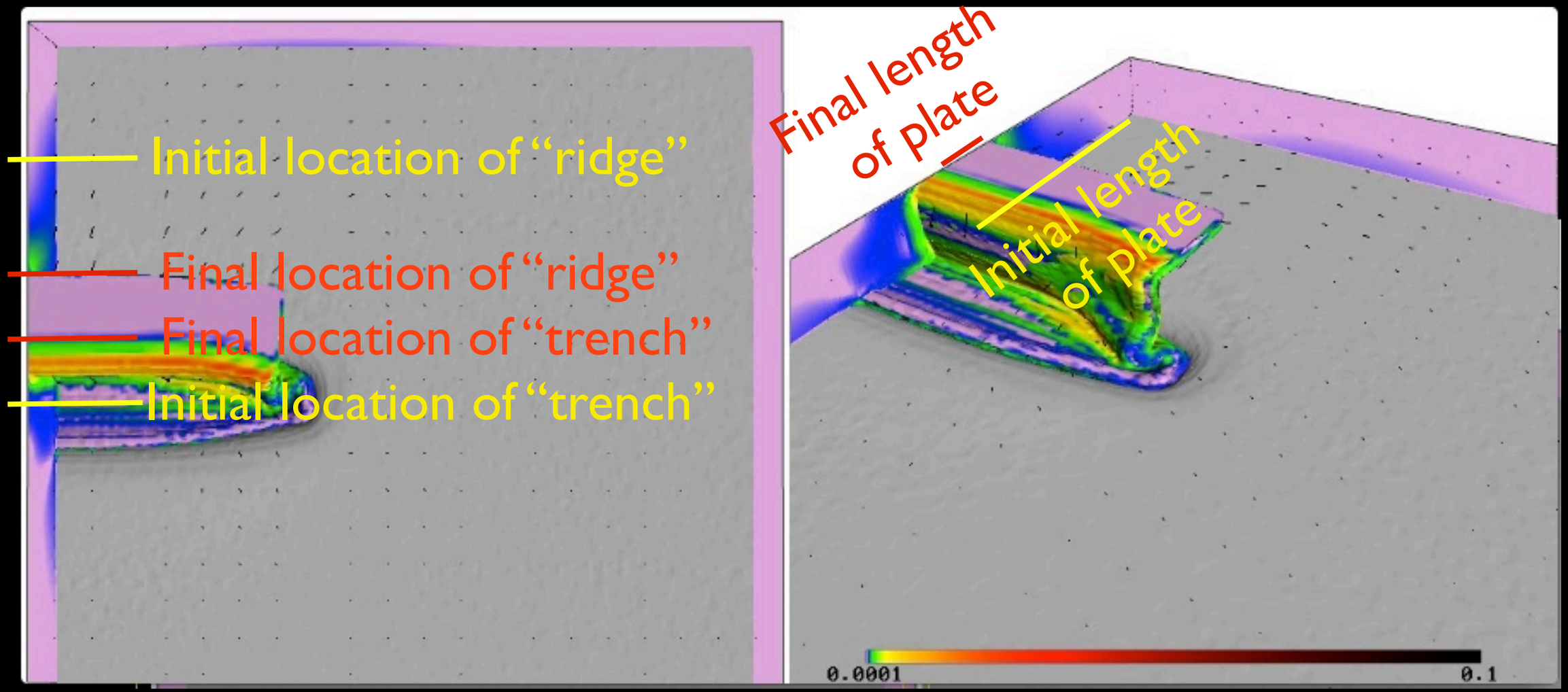
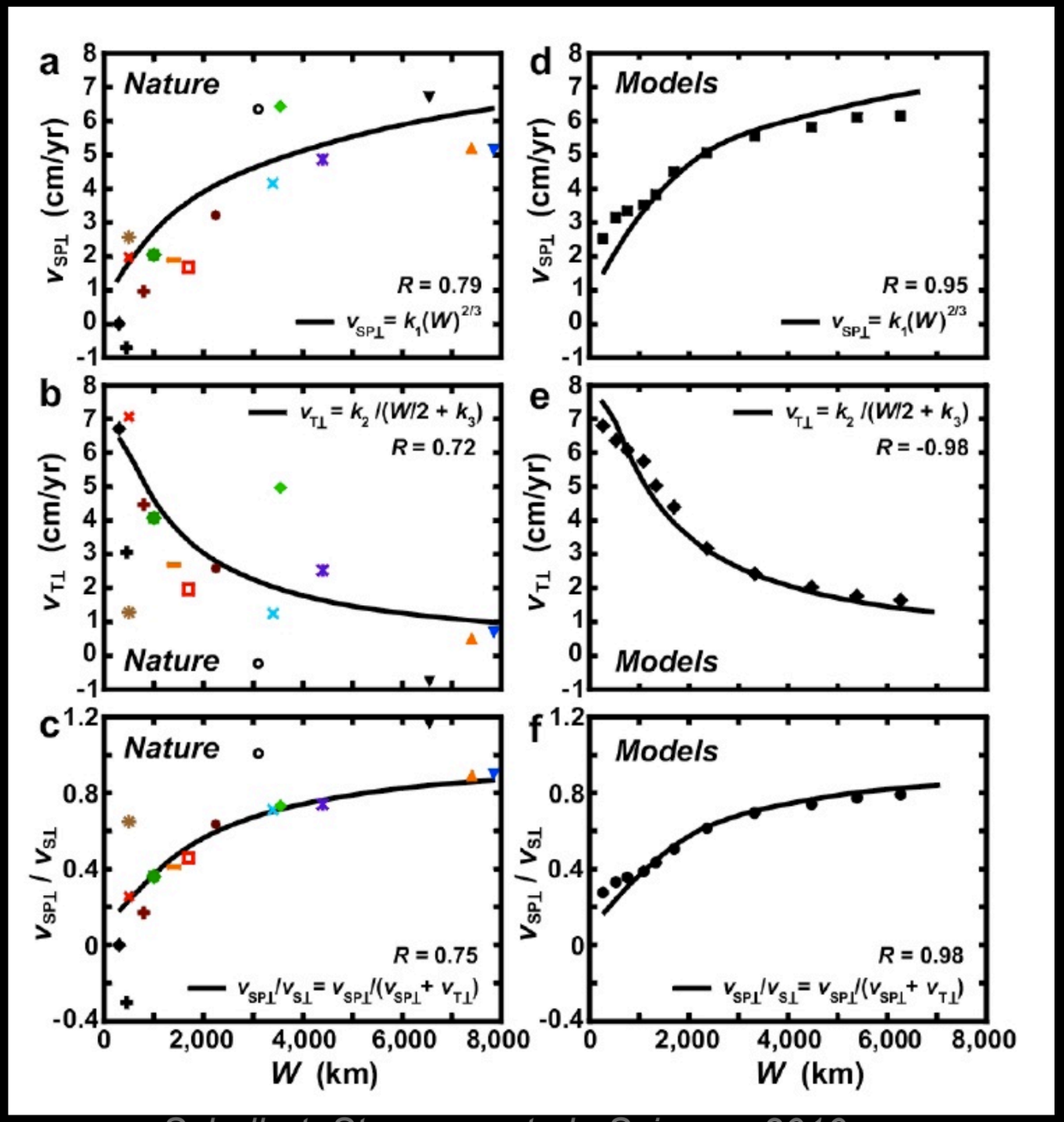


Schellart, Stegman, et al., Science, 2010

Slab pull alone explains plate motions



Schellart, Stegman, et al., Science, 2010

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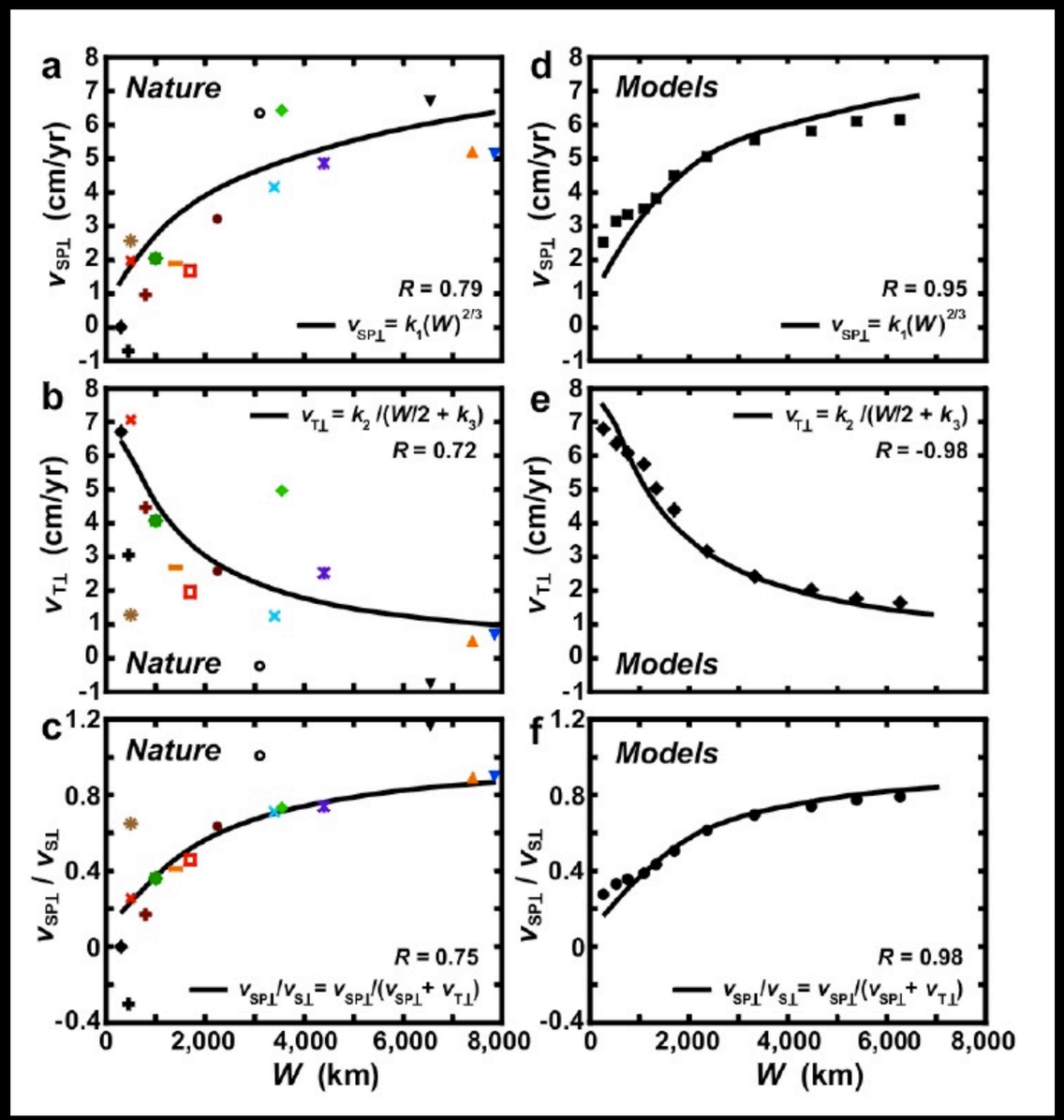

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Schellart, Stegman, et al., Science, 2010

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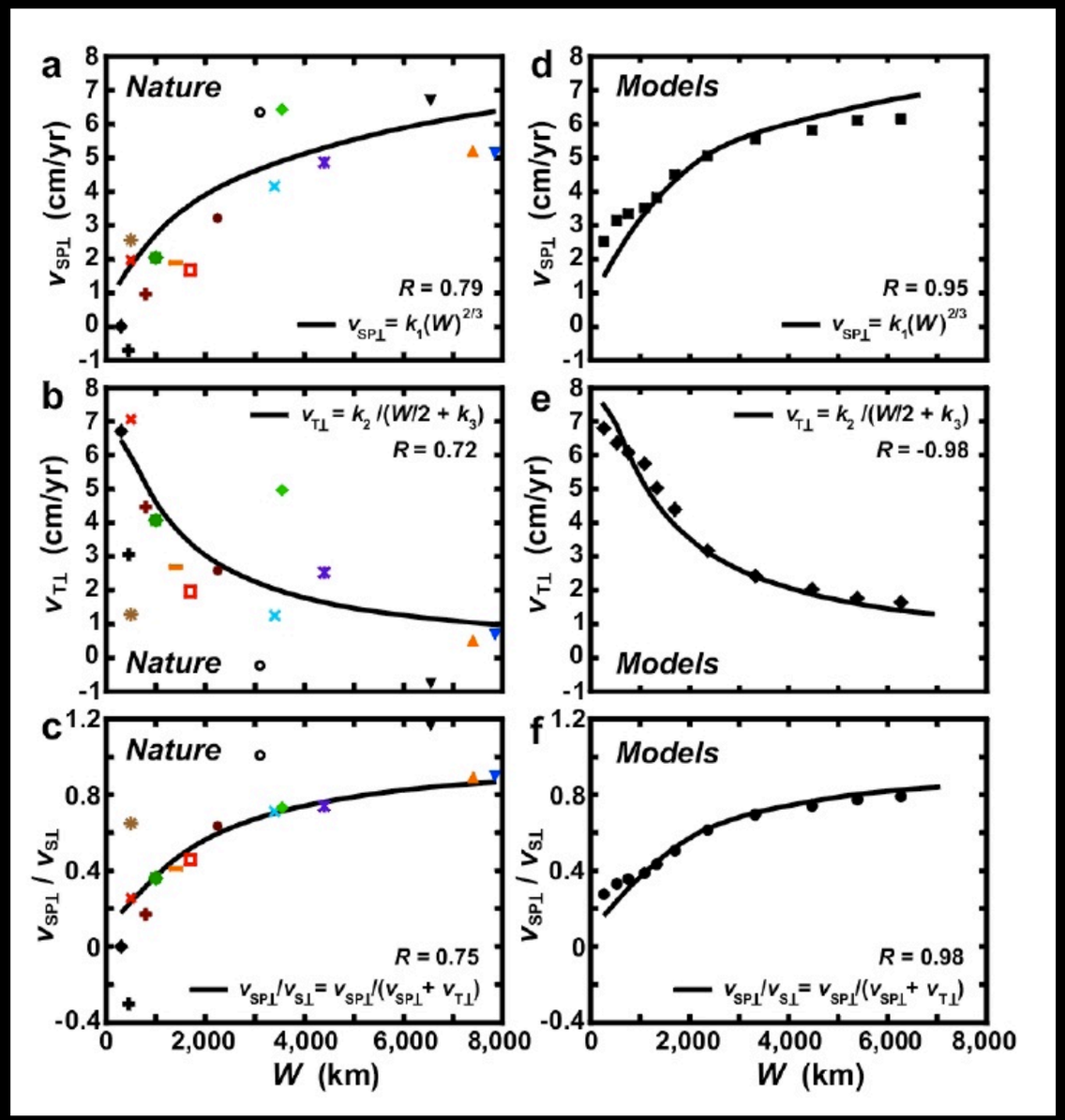

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Schellart, Stegman, et al., Science, 2010

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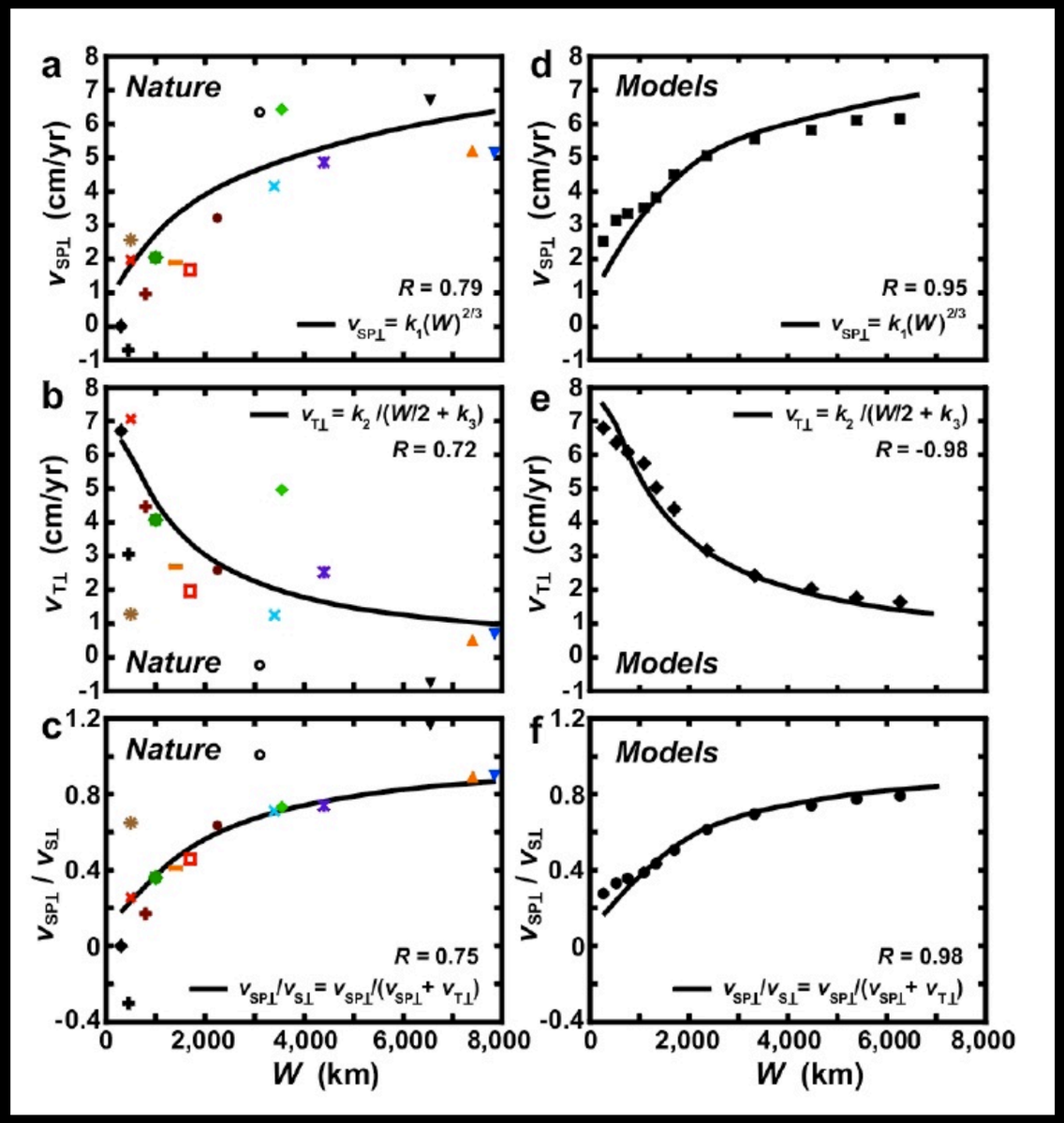

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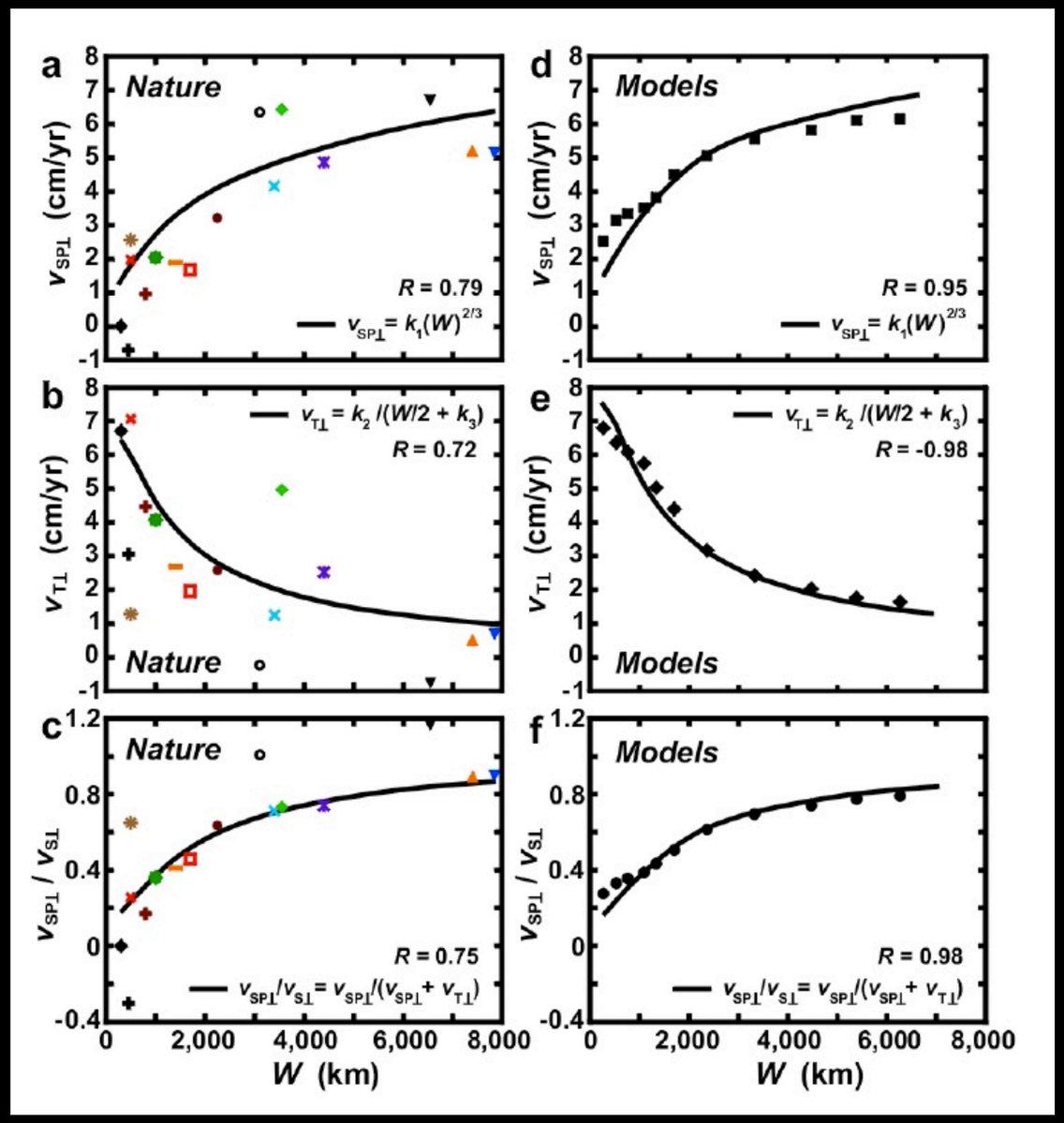
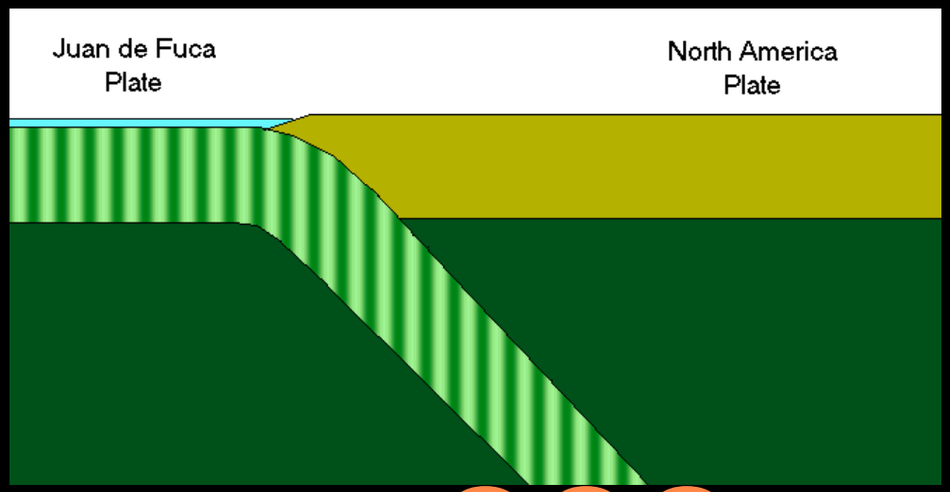


- partitioning of subduction motions strong dependence on slab width
- simple dynamical scaling relations for a sinking oblate ellipsoid
- increasing importance of drag from toroidal component of flow around slab edges for narrow plates
- origin for narrow plates favoring trench retreat over plate advance

Schellart, Stegman, et al., Science, 2010

The Myth of how subduction works..



???

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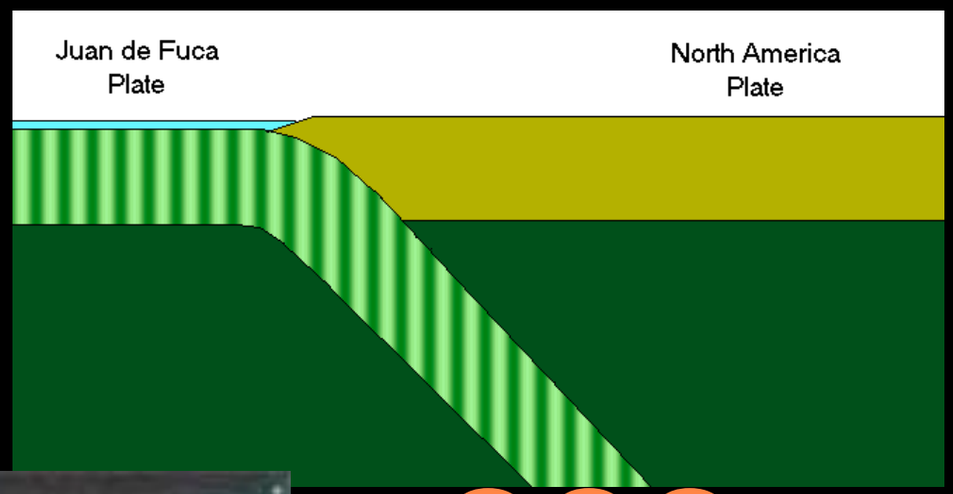

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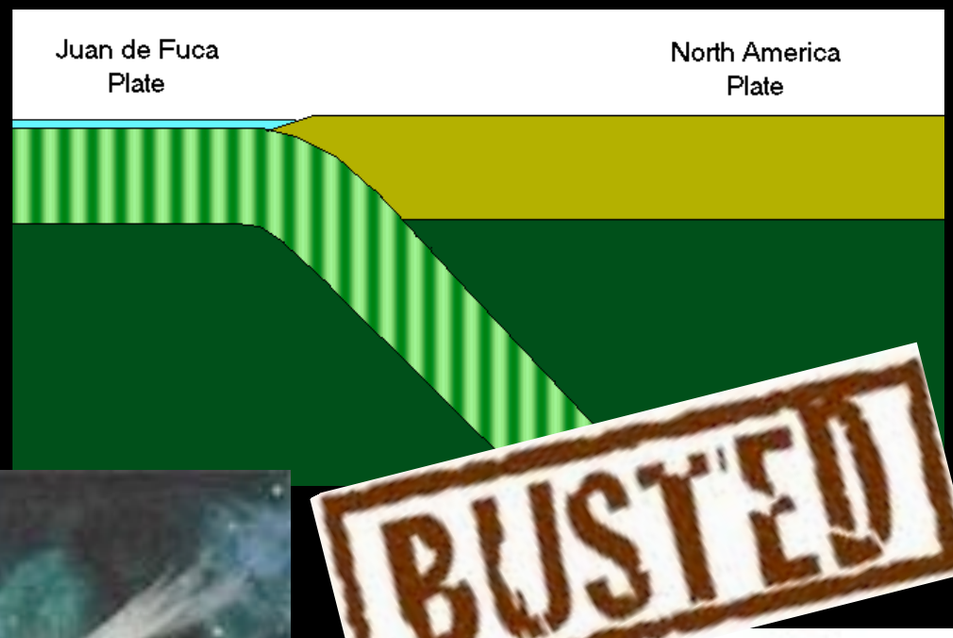

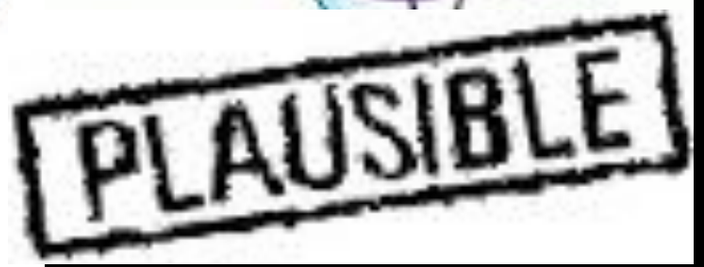

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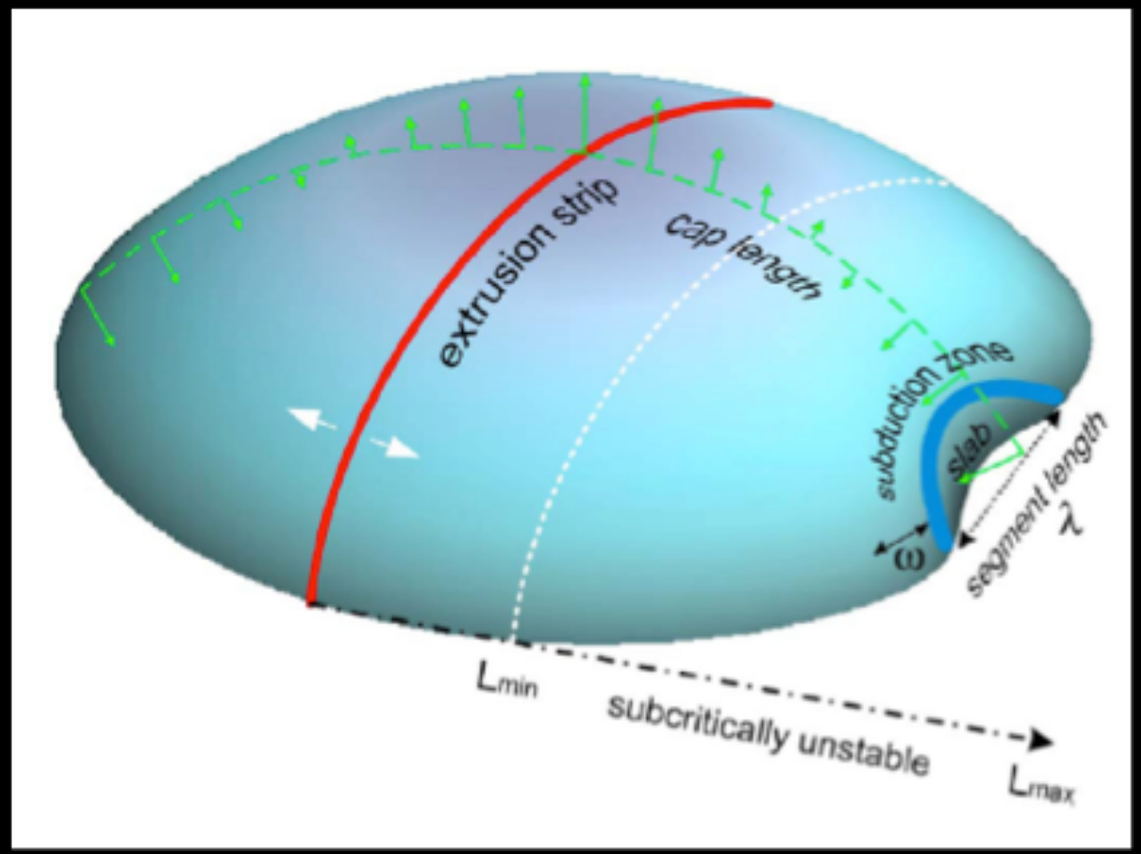
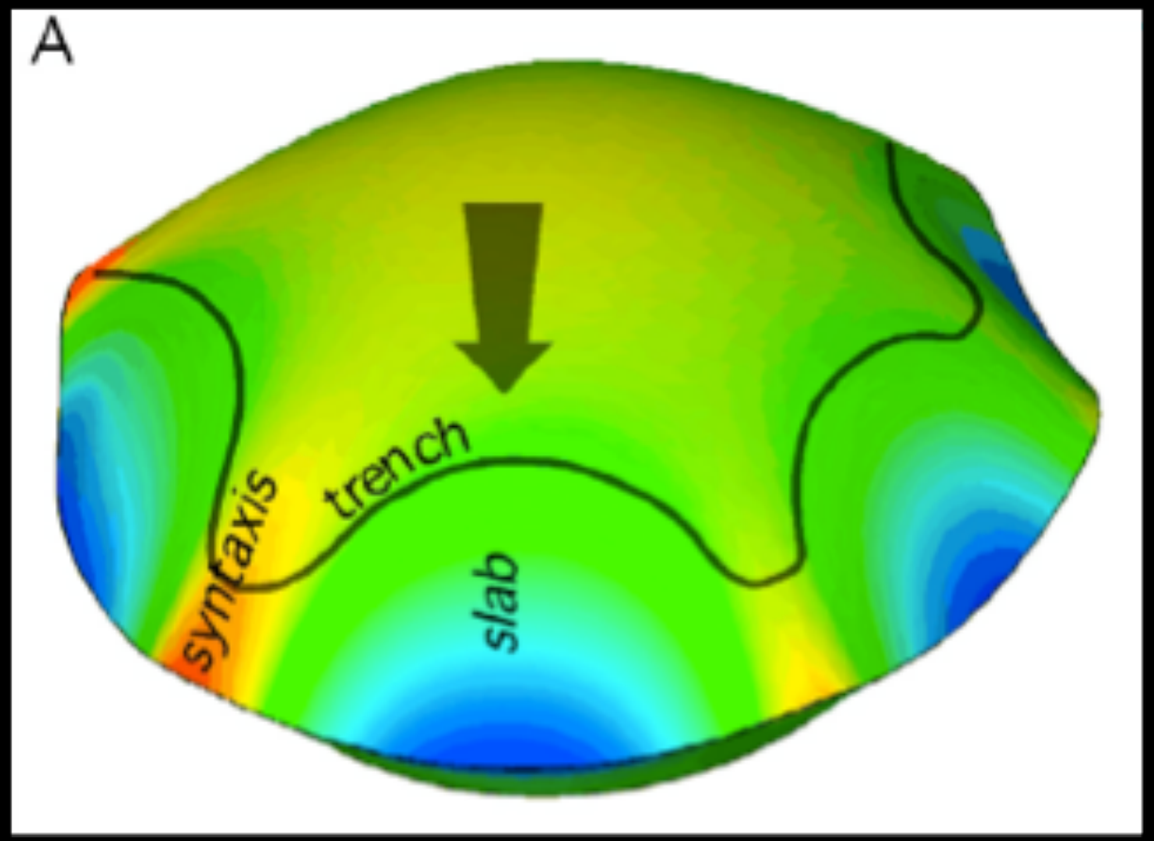
Why are subduction zones curved?

- **The physics that govern buckling in spherical geometry are more complicated than what Frank (1968) had originally proposed**





Mahadevan et al, Tectonics, 2010

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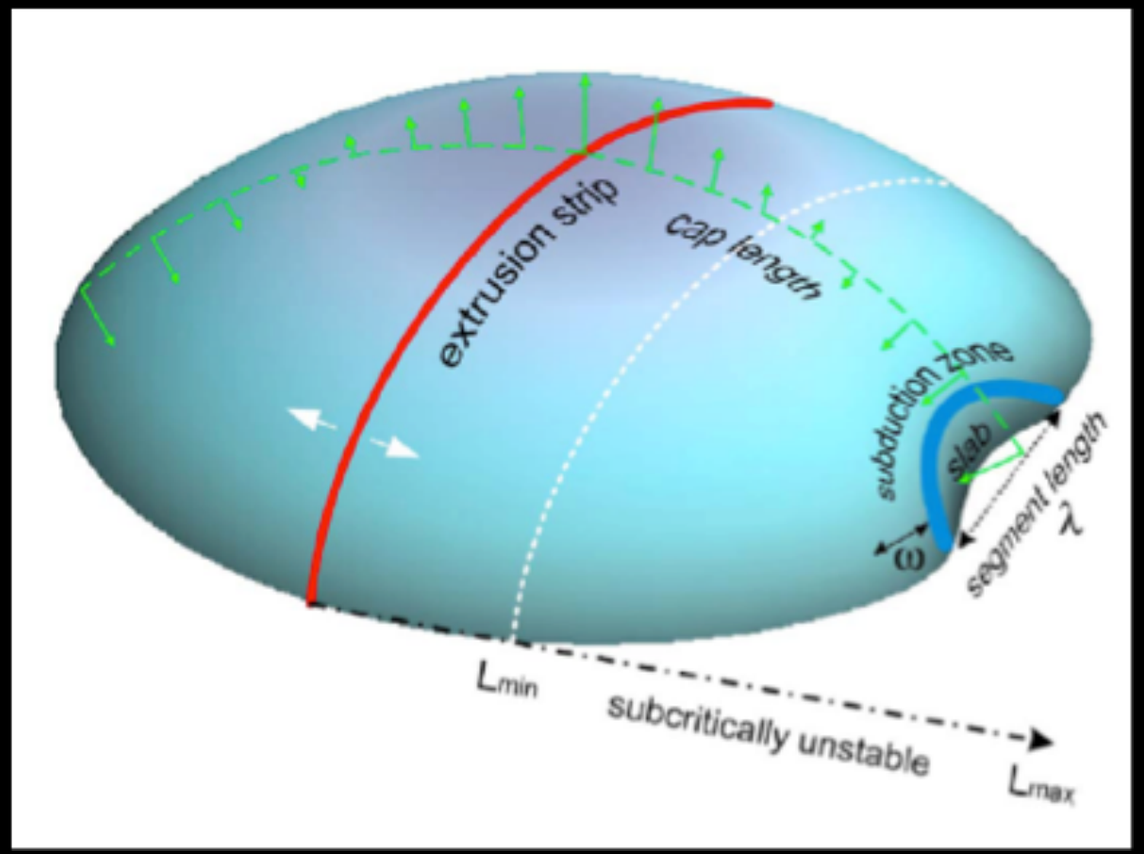
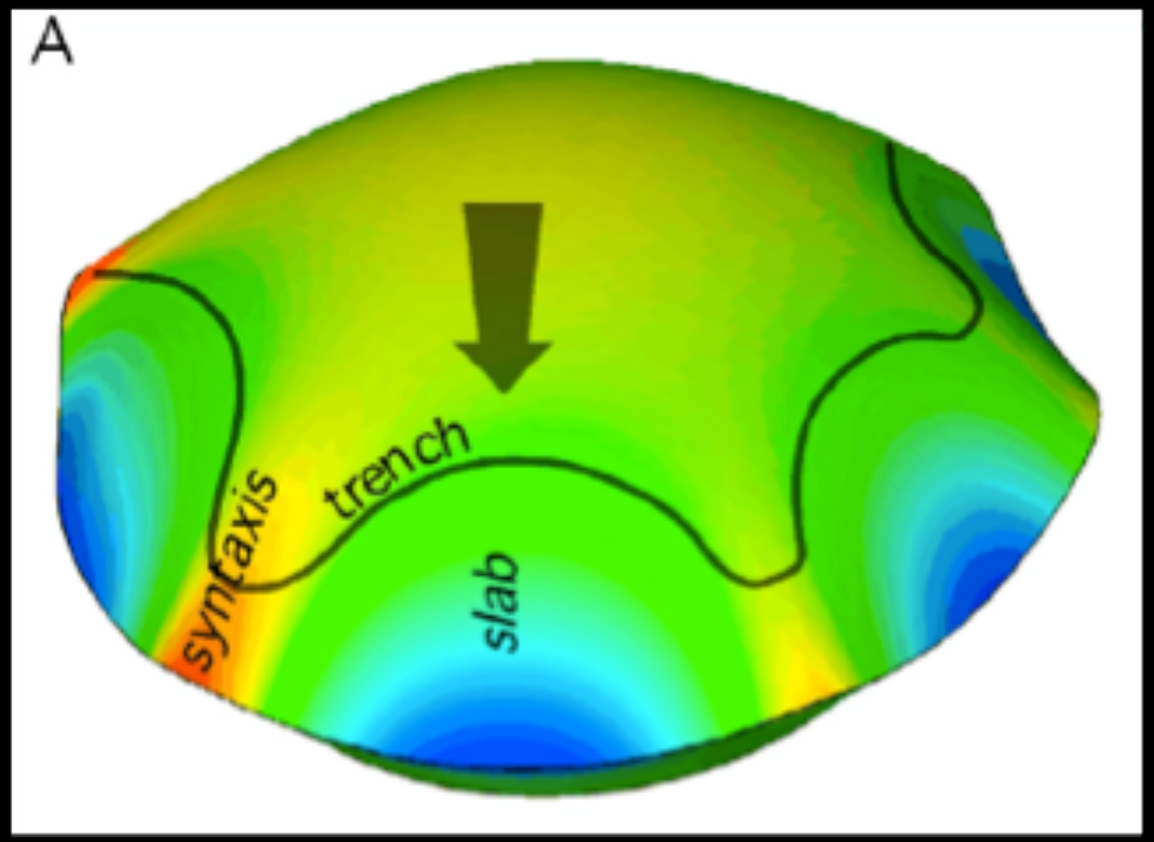


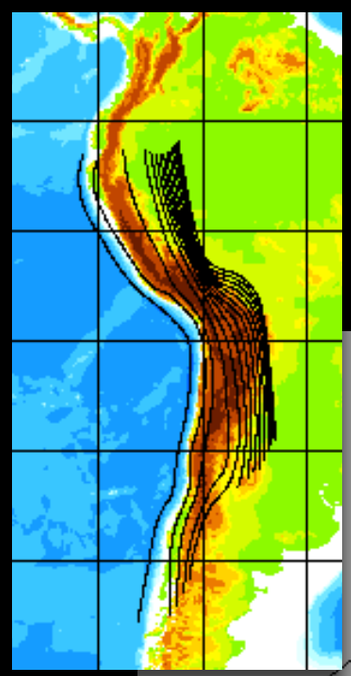


- stresses generated by buckling of viscous doubly curved shells take the form of a dimpling instabilities - wavelength of cusps related to material properties

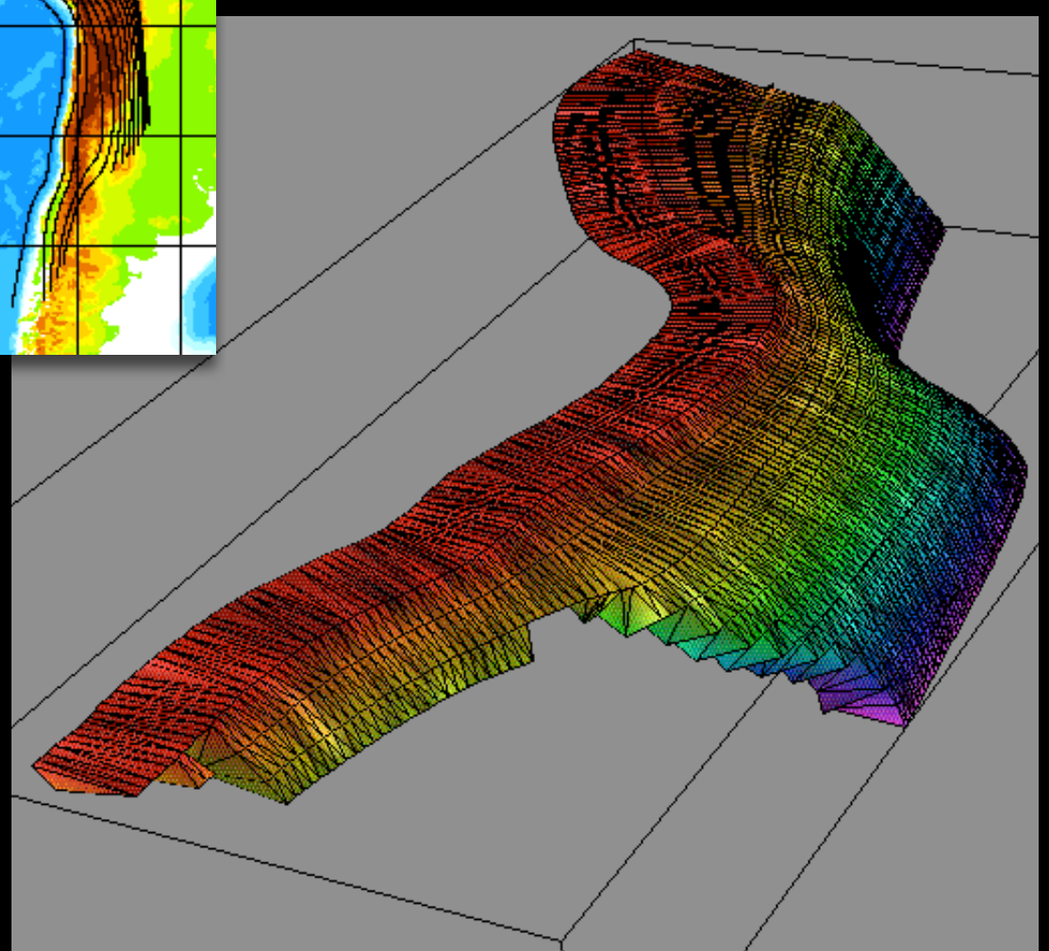
- no interaction with the underlying mantle --> still missing essential physics

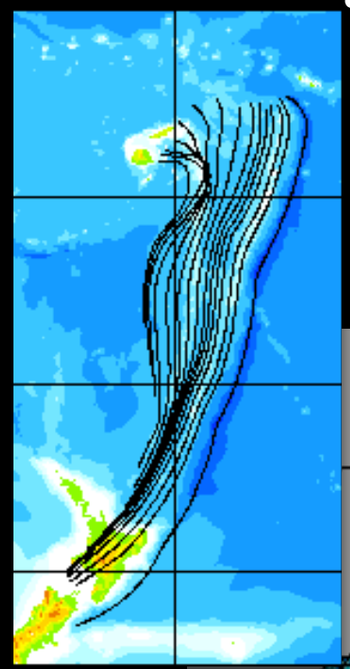
Mahadevan et al, Tectonics, 2010

Some arcs are curved the wrong way, others aren't curved at all...

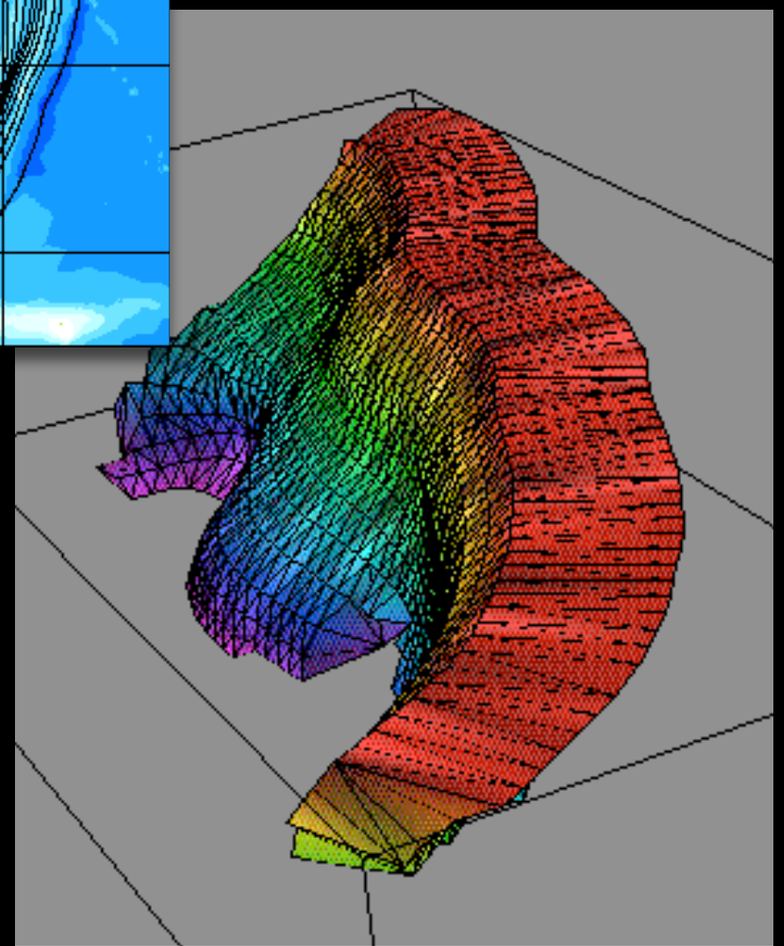


- South America the curvature changes from concave near Peru, to convex near Bolivia, back to concave in S. Chile





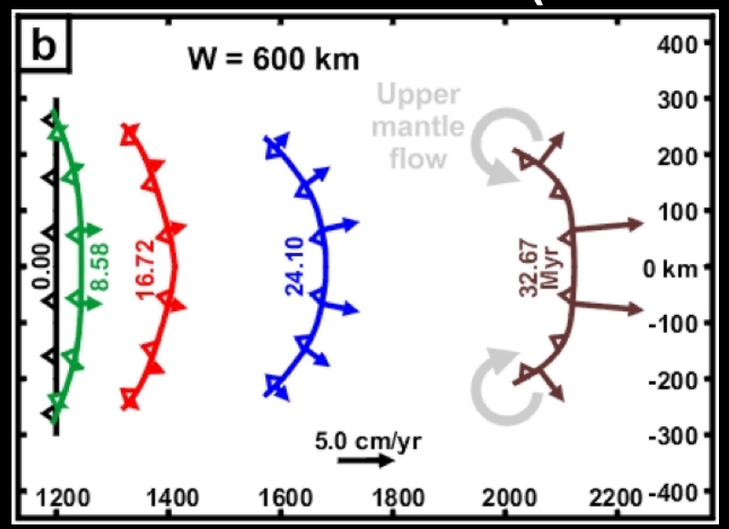
- Tonga-Kermedec is only curved in the very north, and is relatively straight towards New Zealand



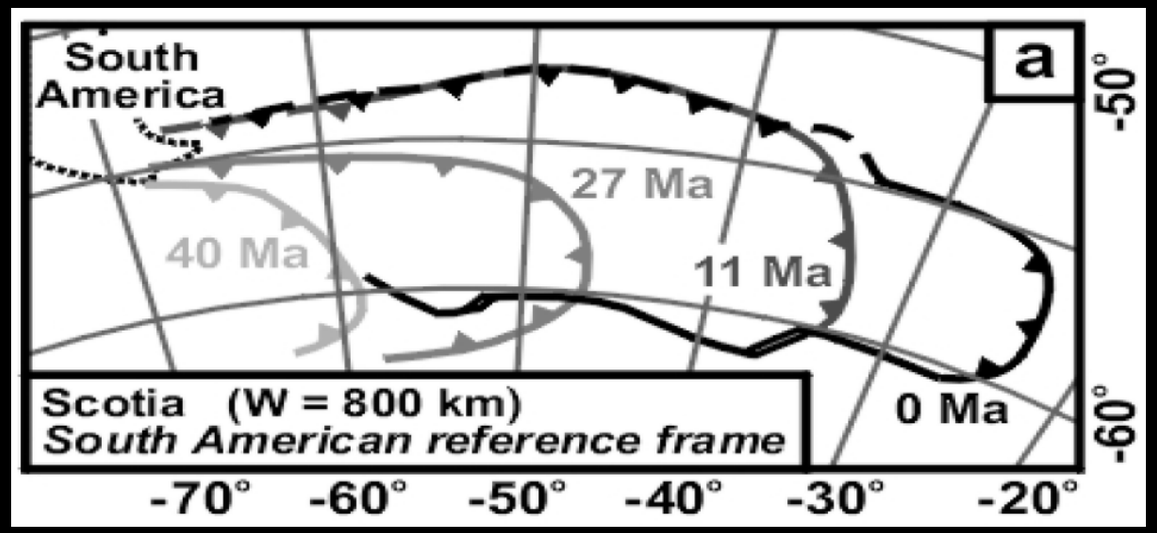
Gudmundsson and Sambridge, JGR, 1998

Narrow plates have retreating trenches

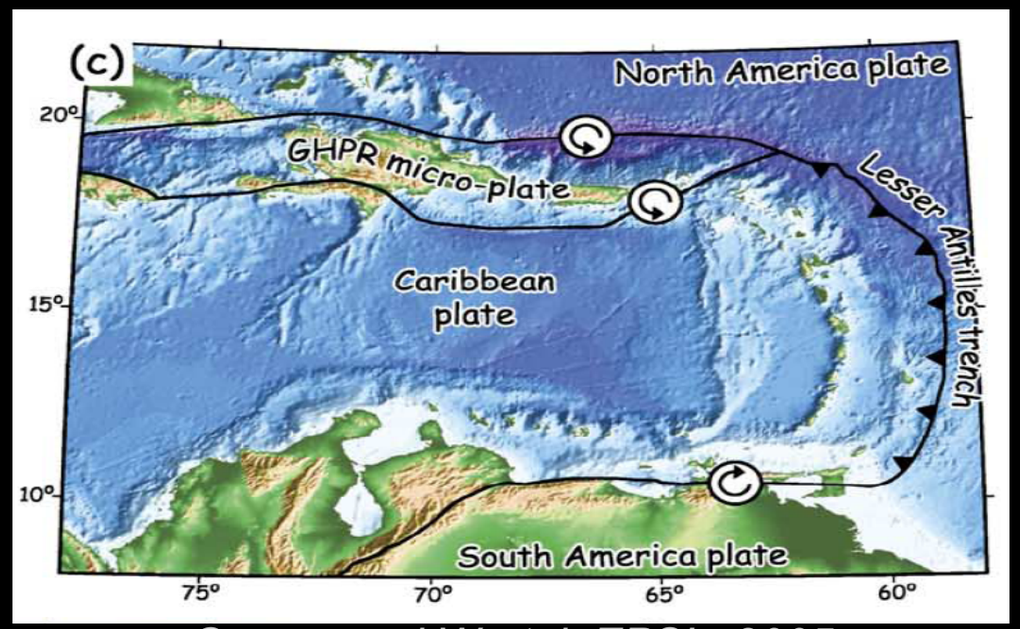
- **Numerical Model (600 km)**



- **Scotia (800 km)**

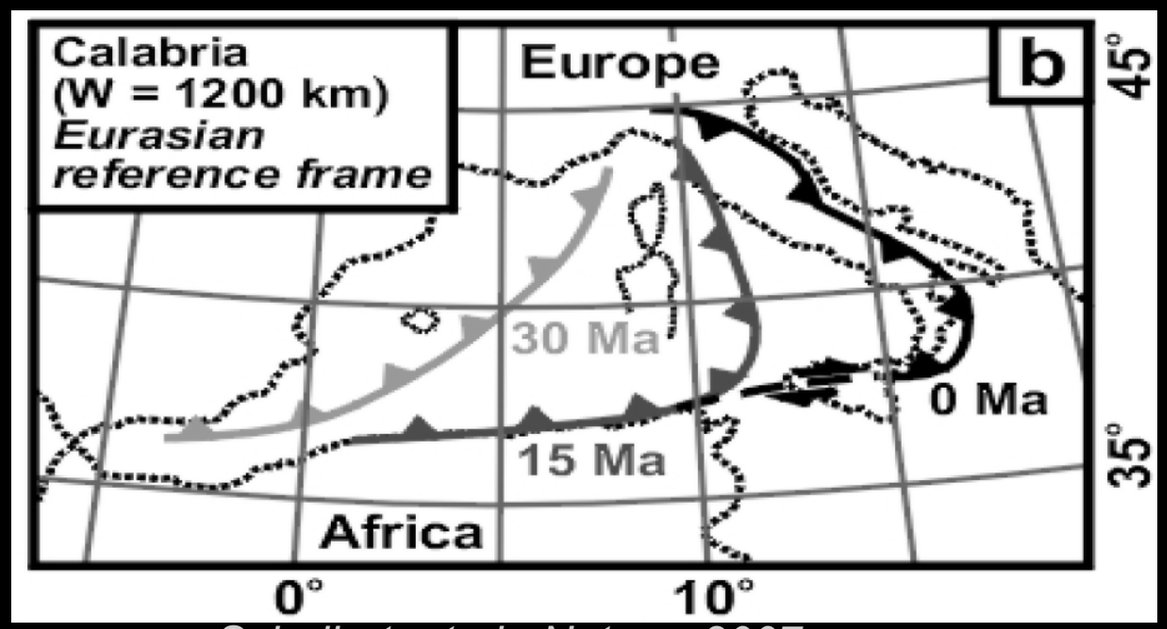


- **Caribbean (1900 km)**



Govers and Wortel, EPSL, 2005

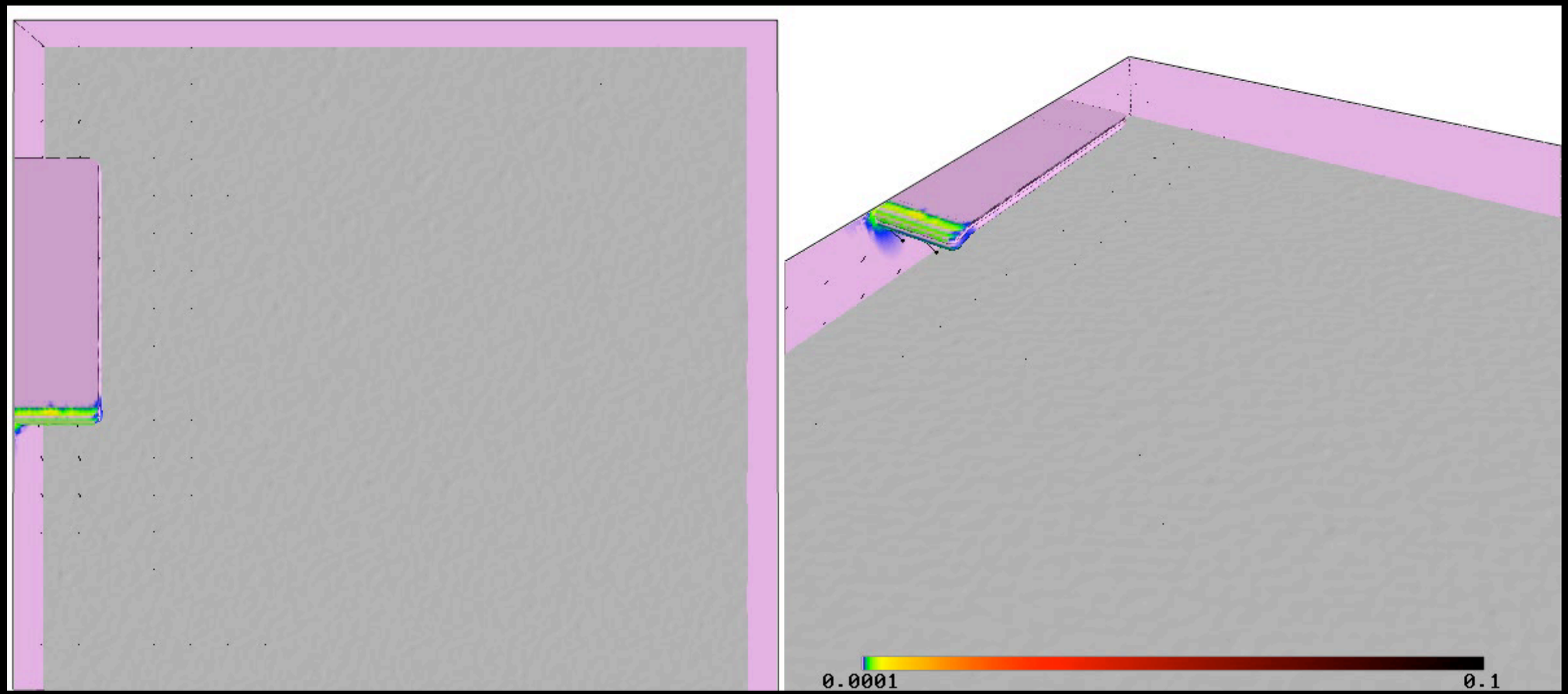
- **Calabria (1200 km)**



Schellart, et al., Nature, 2007

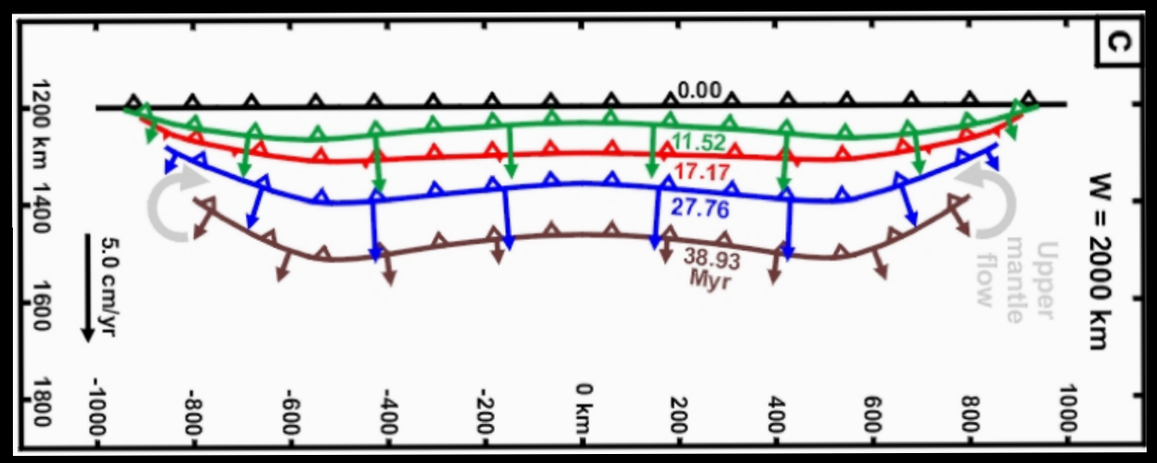
Narrow plates have retreating trenches

- **Plates that have retreating trenches become more curved over time and produce flat-lying slab geometries on top of the lower mantle**

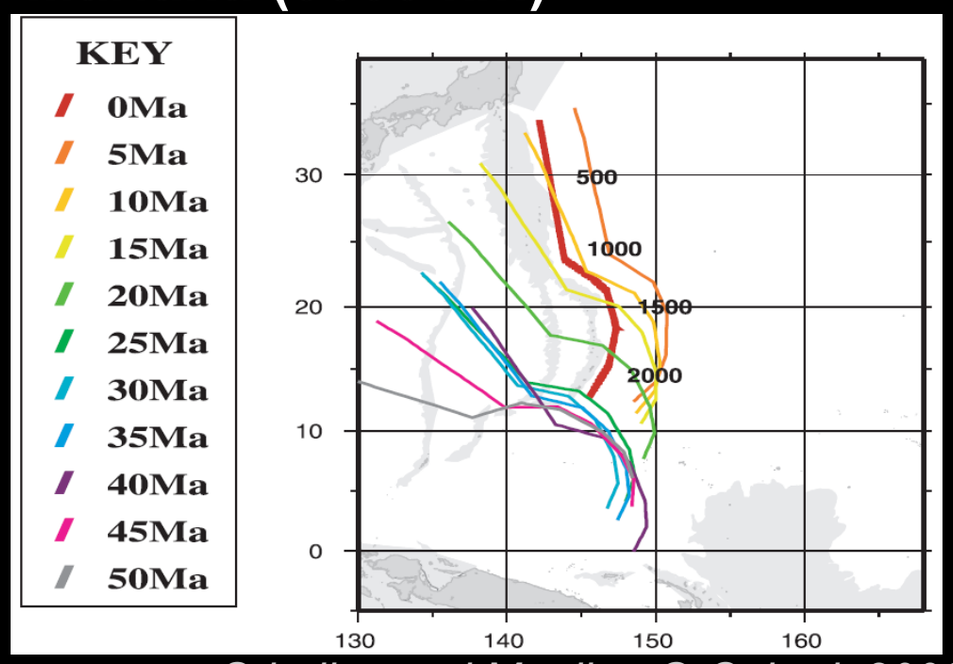


Wider plates have stationary trenches

- **Numerical Model (2000 km)**



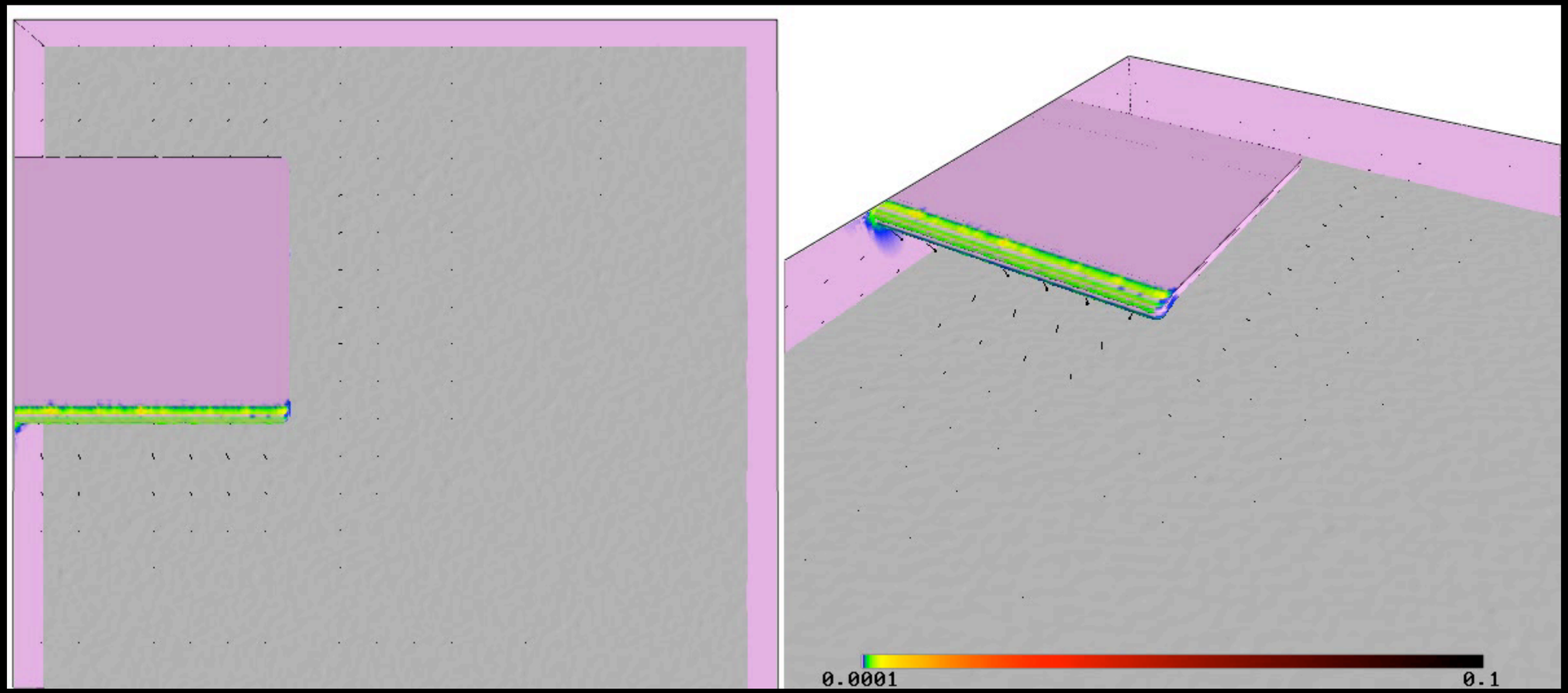
- **Mariana (3000 km)**



Sdrolias and Mueller, G-Cubed, 2006

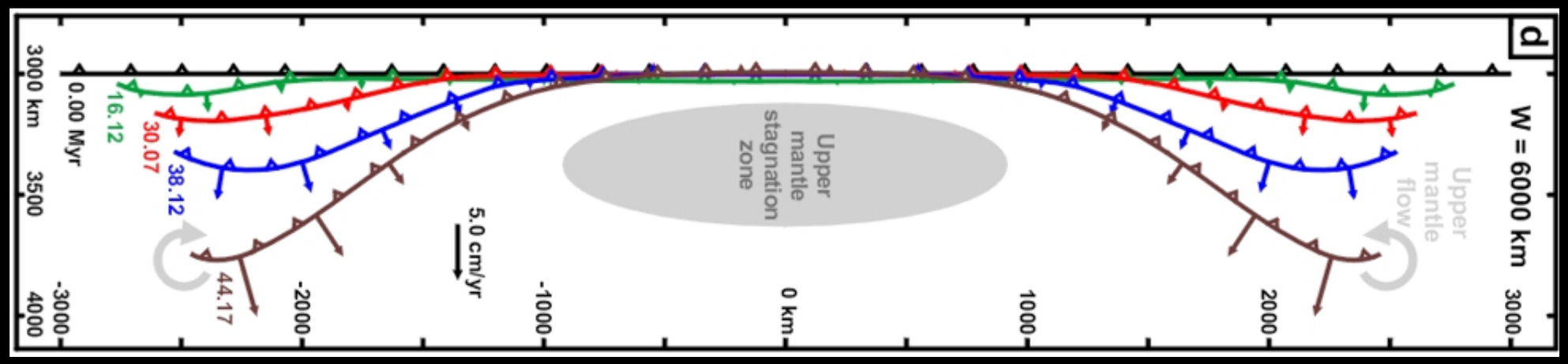
Intermediate and wide plates

- **Plates that have stationary trenches develop along-trench variations of curvature over time and produce piles of folded slab atop the lower mantle**

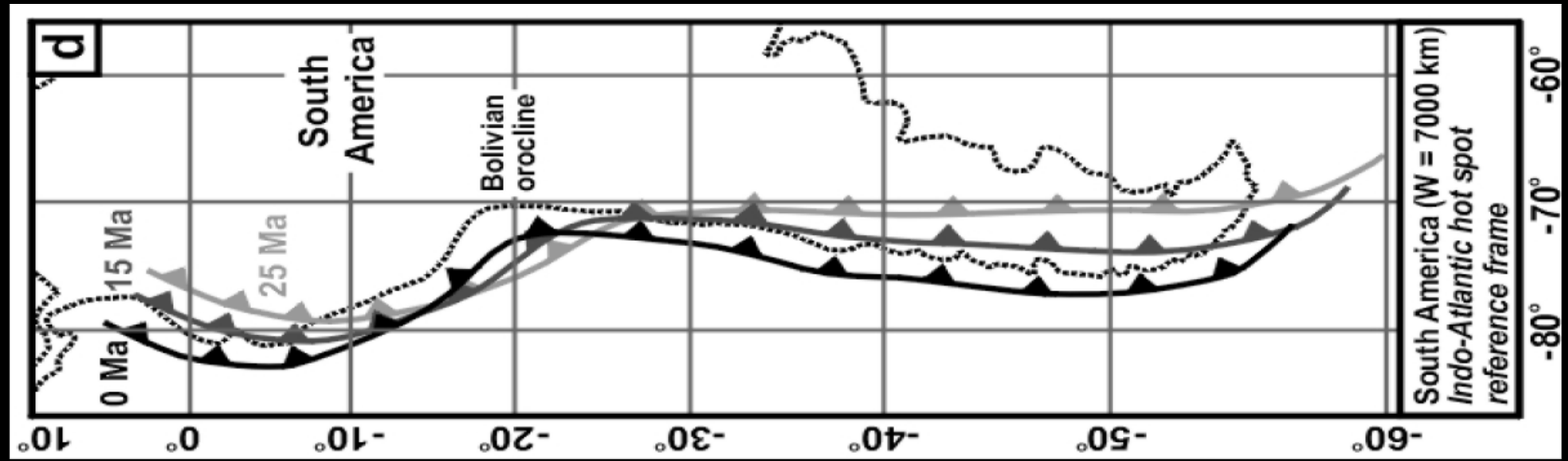


Very wide plates have retreating edges

- **Numerical Model (6000 km)**

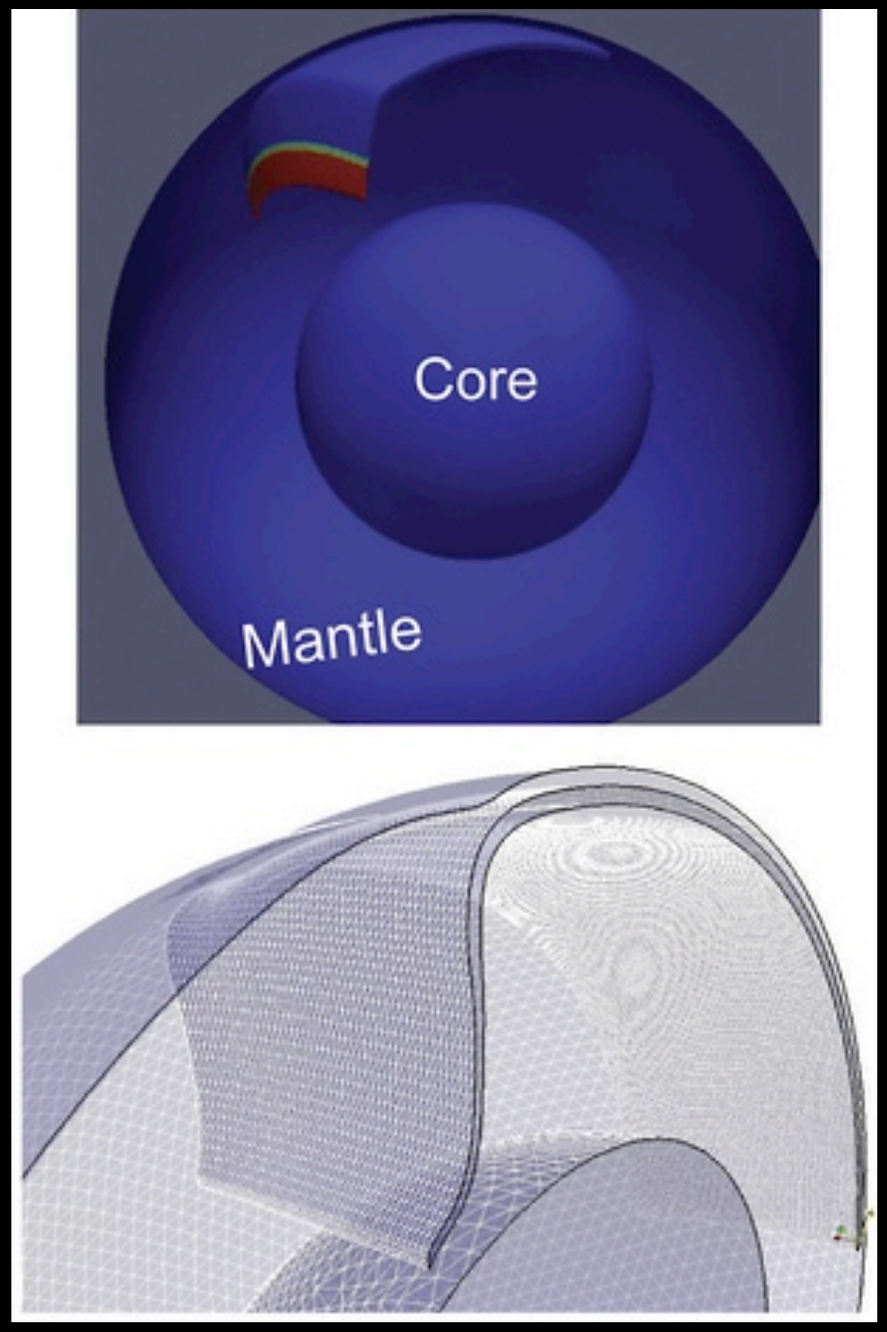


- **South America (6000 km)**



Schellart et al, Nature, 2007

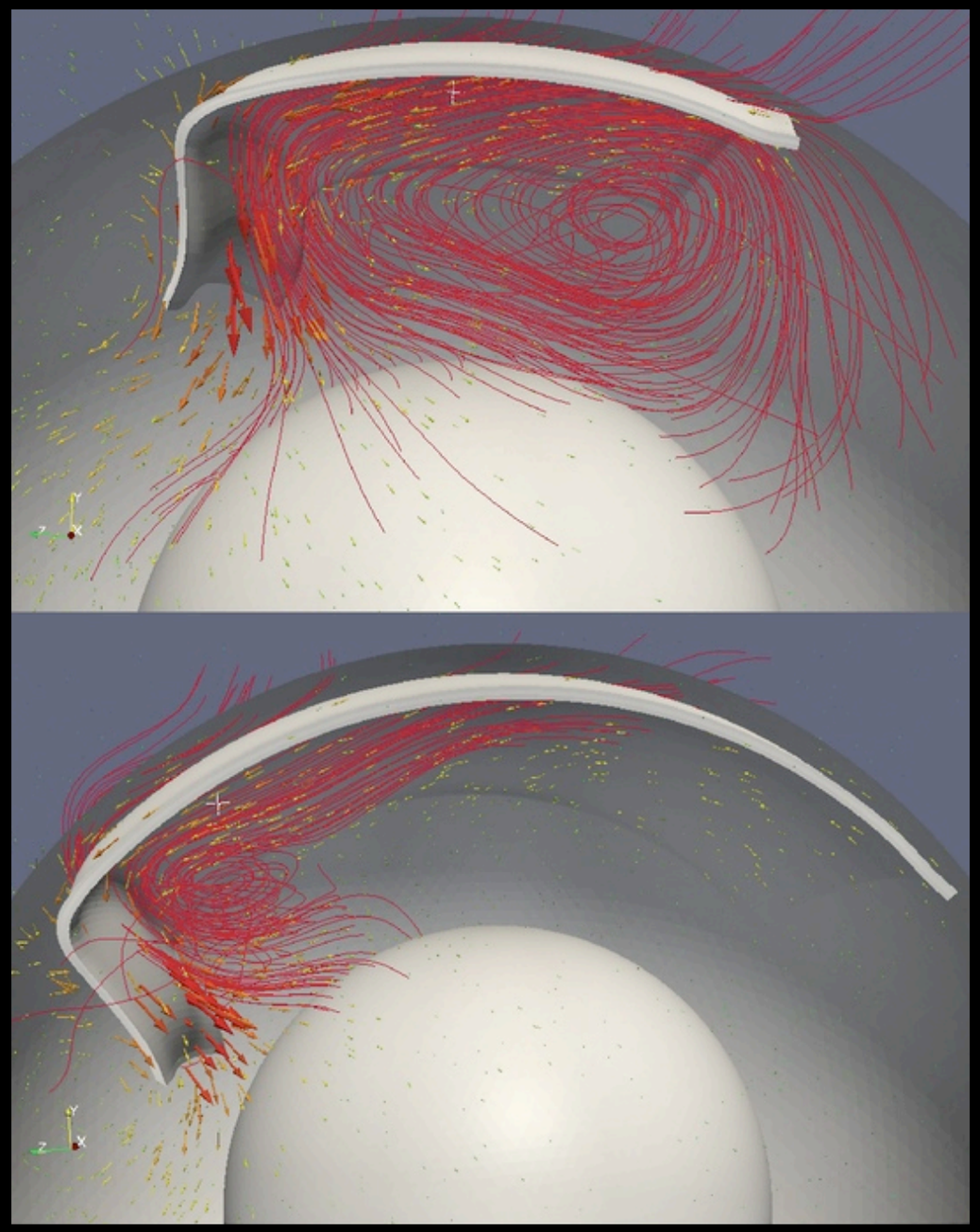
Development of trench curvature



Morra et al., G-Cubed, 2012

- **Free subduction model done in 3D spherical geometry**

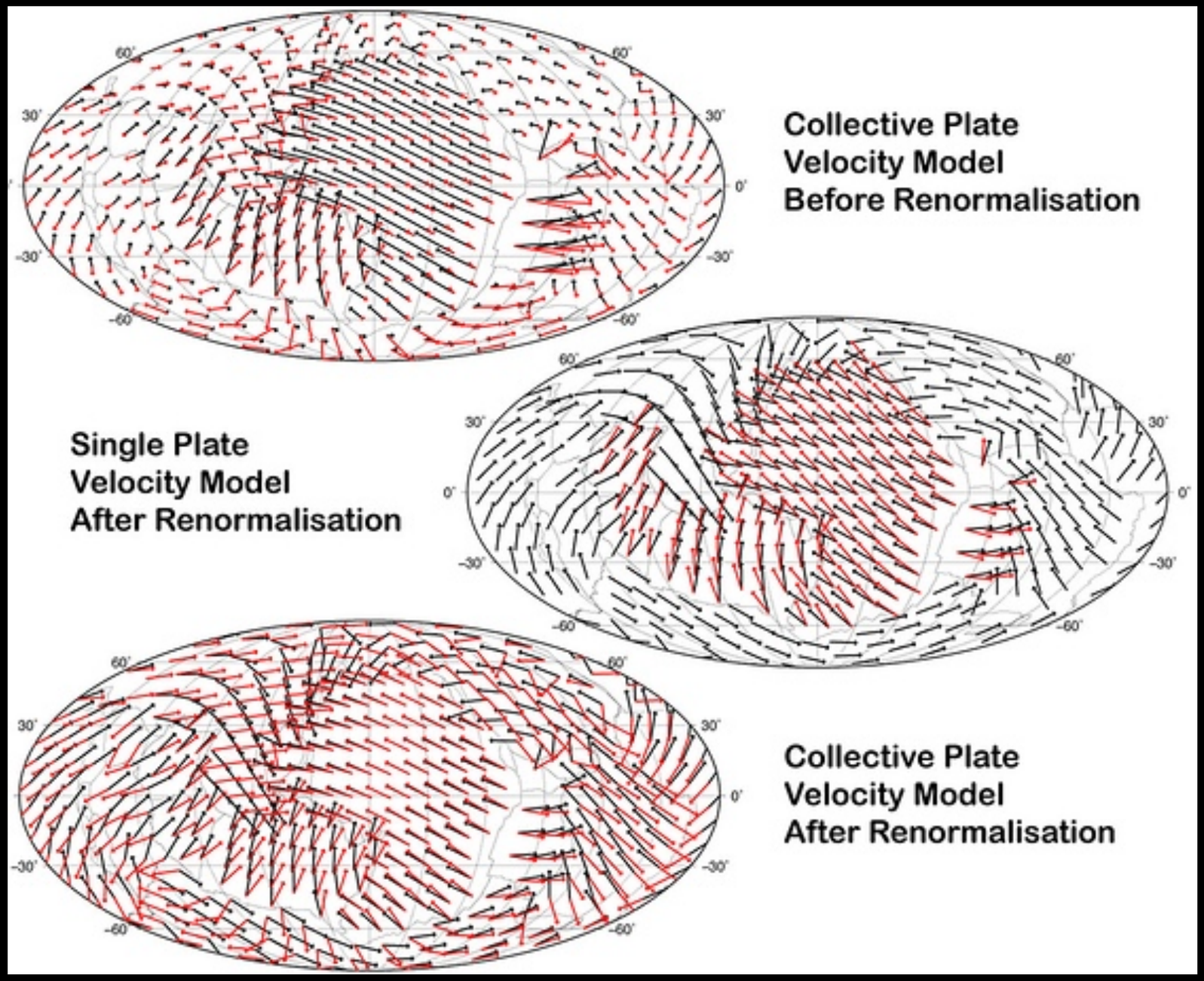
Development of trench curvature



Morra et al., G-Cubed, 2012

- Free subduction model done in 3D spherical geometry
- Lengthscale of induced mantle flow depends on length of plate
- Toroidal component of induced mantle flow dominant in determining shape of the slab (expressed as trench curvature at the surface)

Top-down model of free subduction



Morra et al., G-Cubed, 2012

Styles of subduction

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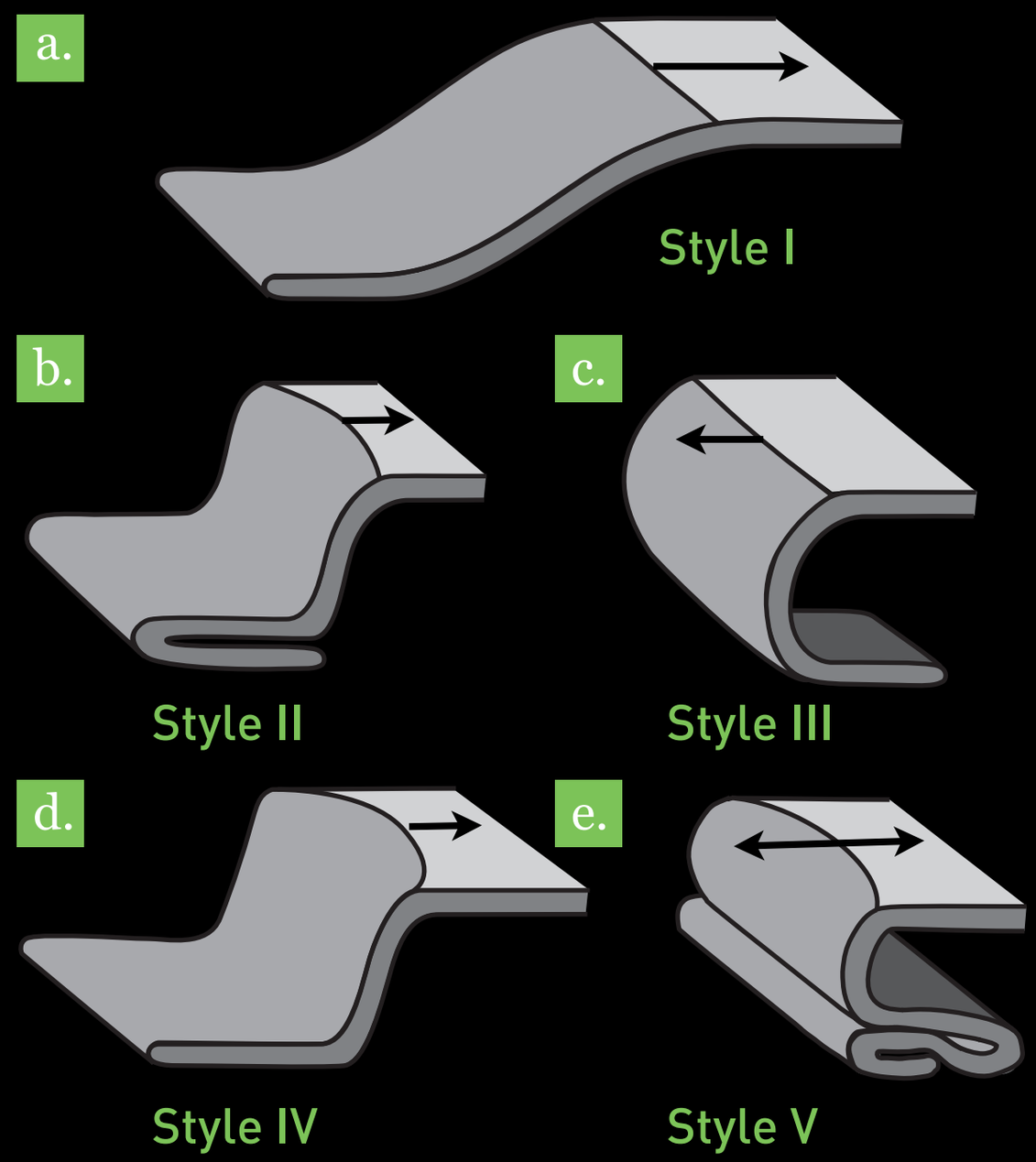

Stegman et al., Tectonophysics, 2010

- **subduction behavior characterized by 100's of previous experiments (both numerical and laboratory)**

  c.f work by Becker, Faccenna, Funiciello, Kaus, Ribe, Enns, Schellart, Capitanio, Morra, Goes, Kincaid, Bellahsen, Royden, Husson, DiGiuseppe, and many others

- **5 distinct subduction styles observed**

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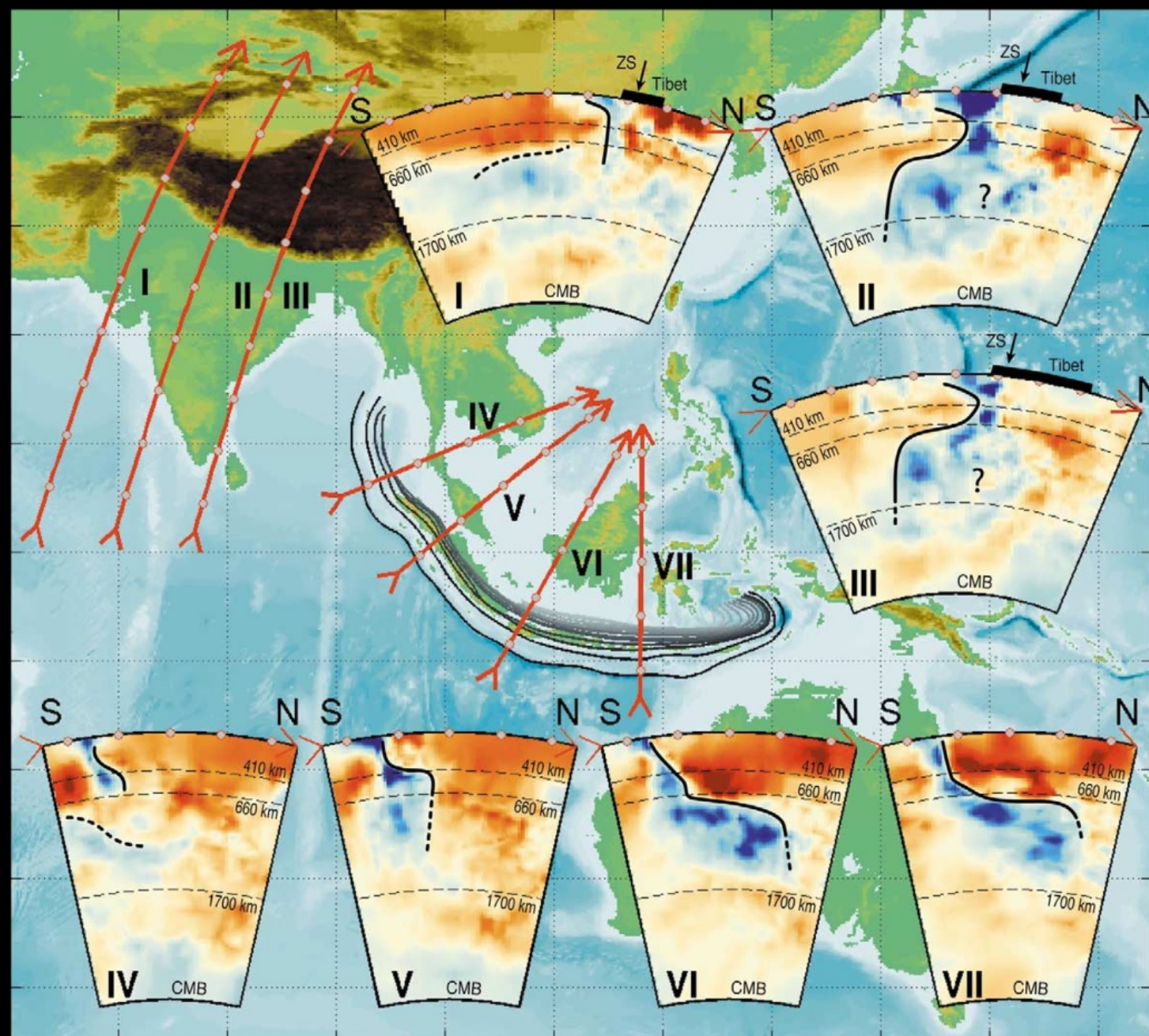
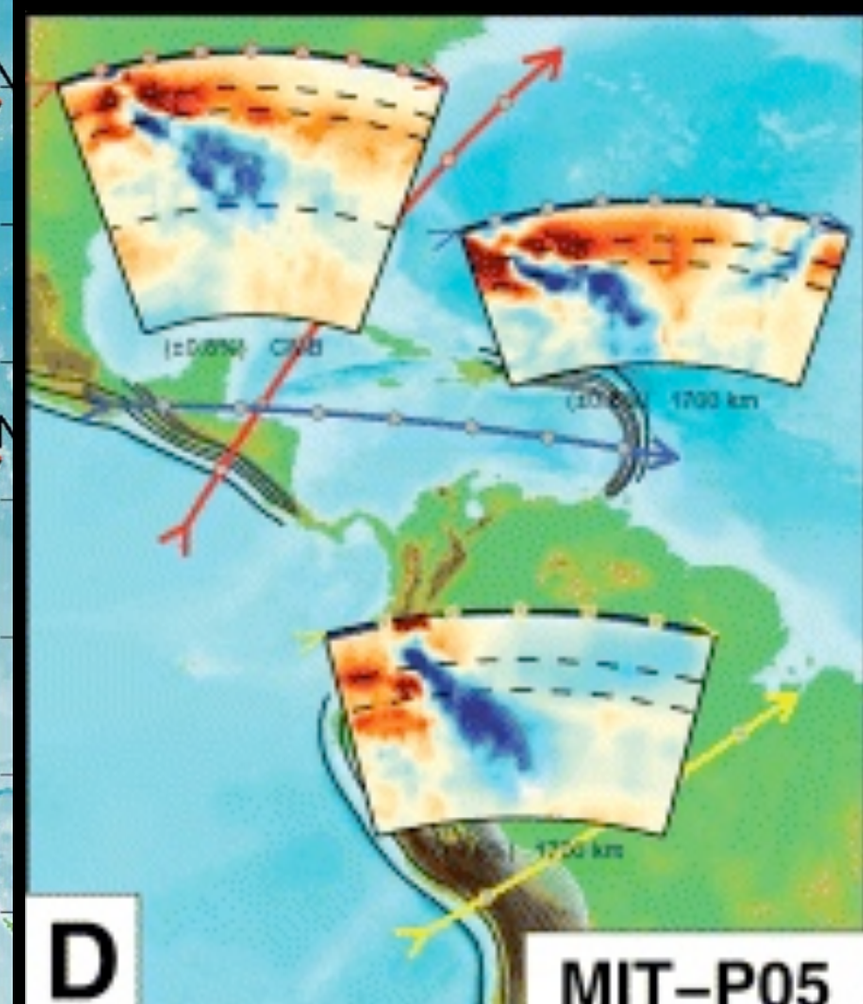
THE LIFE TECTONIC

devl

Slab Morphology: highly variable



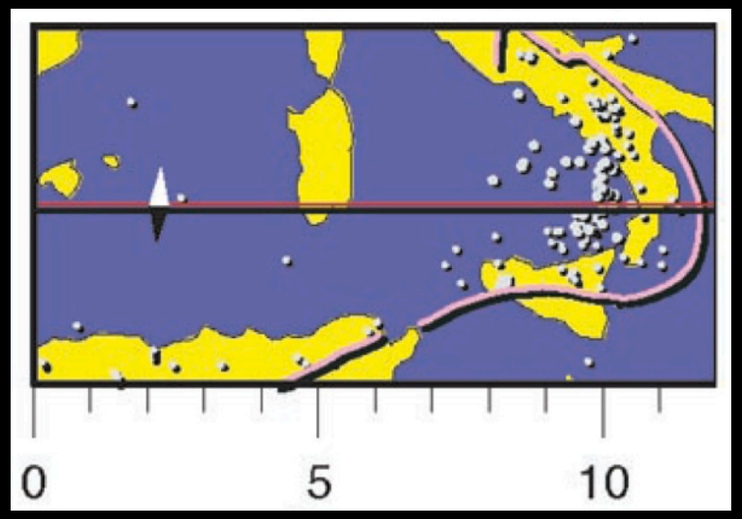
Replumaz et al, EPSL, 2004

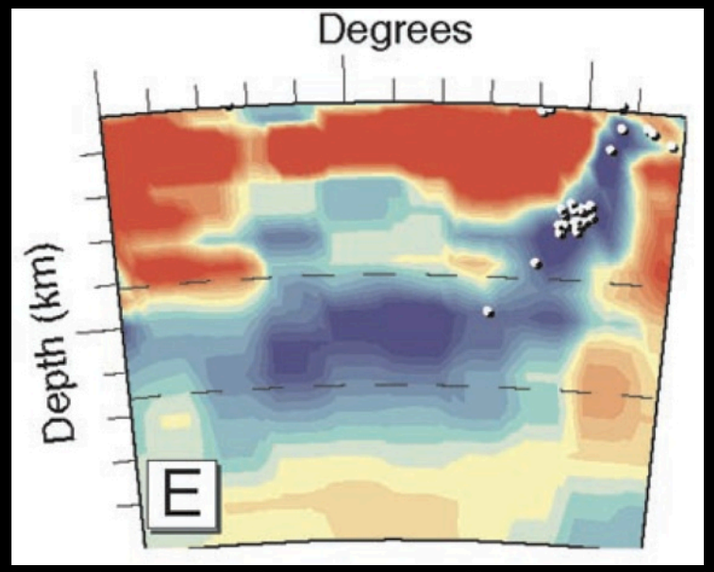


van der Hilst and de Hoop, GJI, 2005

Flat-lying slabs under retreating trenches

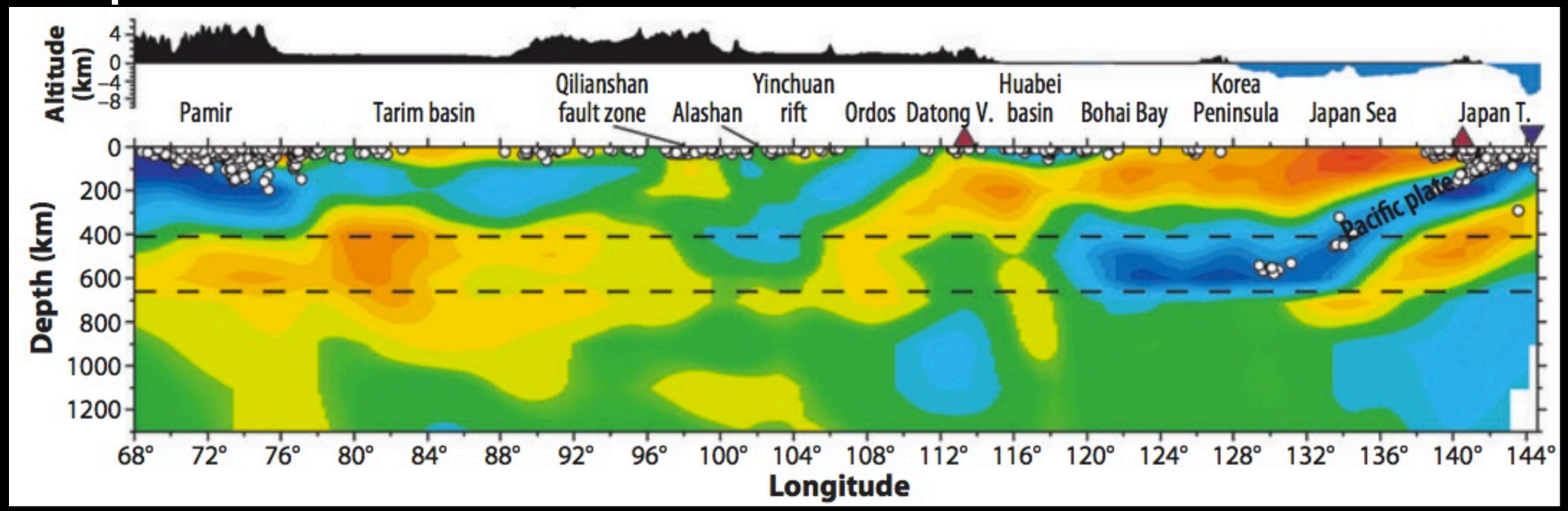
- **Calabria**





Wortel and Spakman, Science, 2000

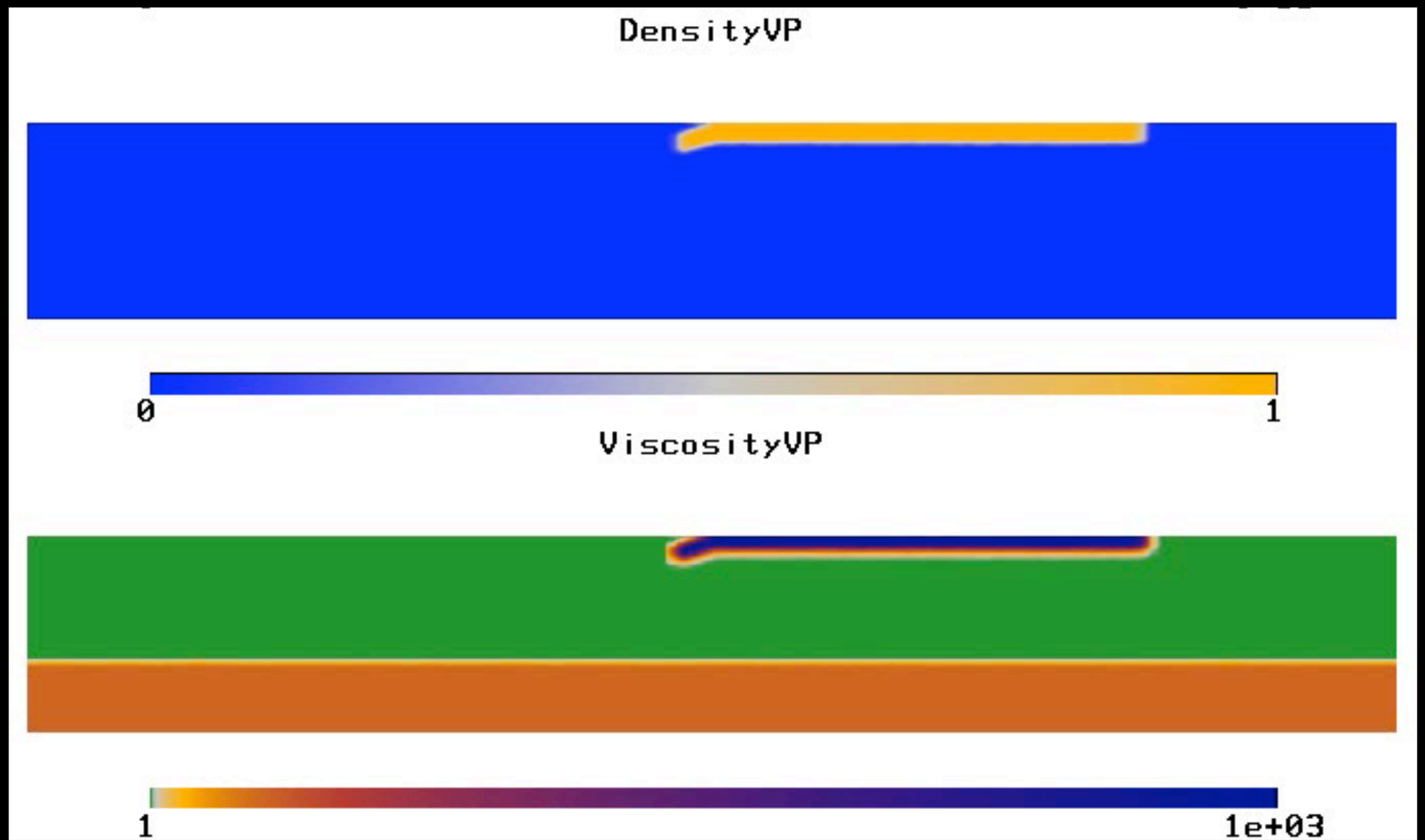
- **Japan Sea**



Fukao, et al., Annual Rev, Earth Sci 2009

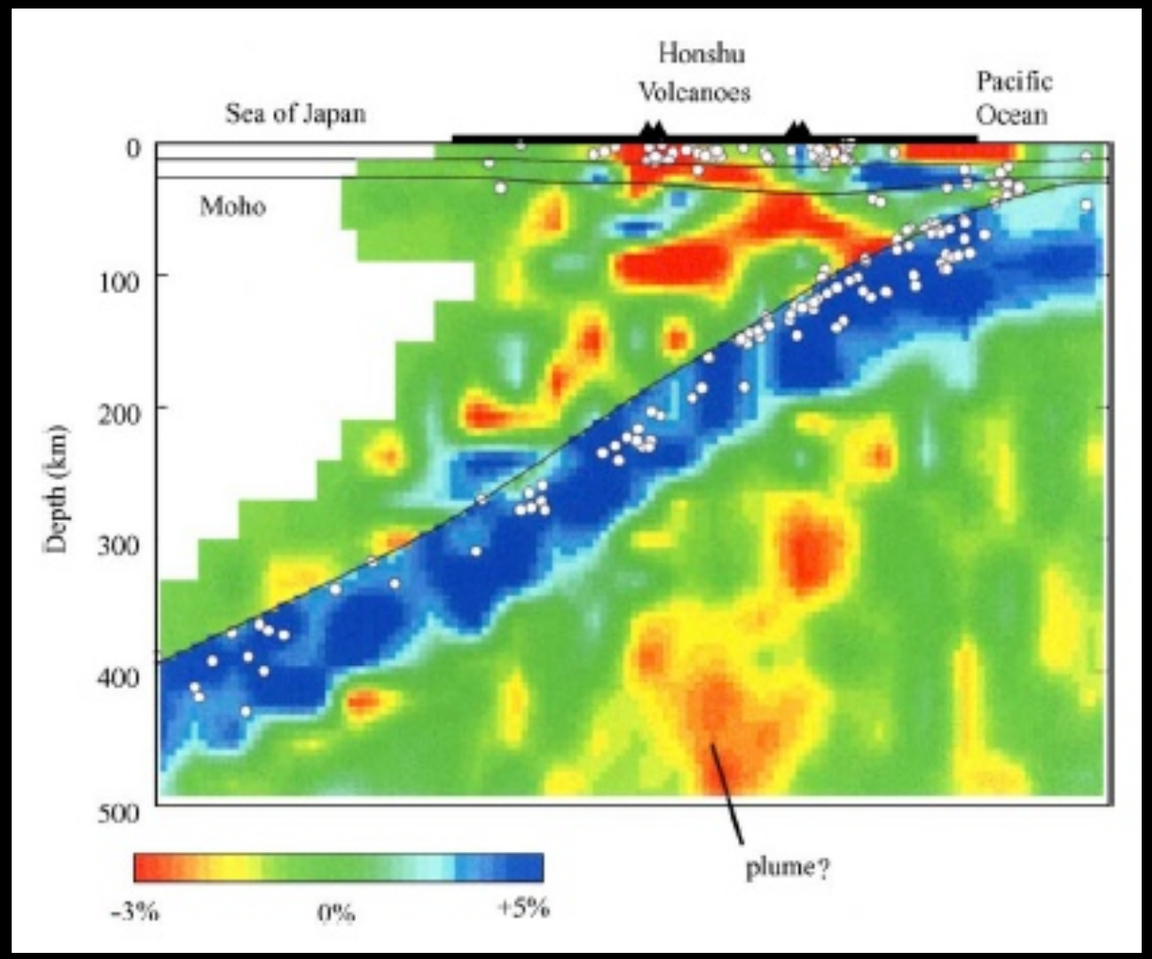
Flat-lying slabs under retreating trenches

- **Plates that have retreating trenches produce flat-lying slab geometries on top of the lower mantle**

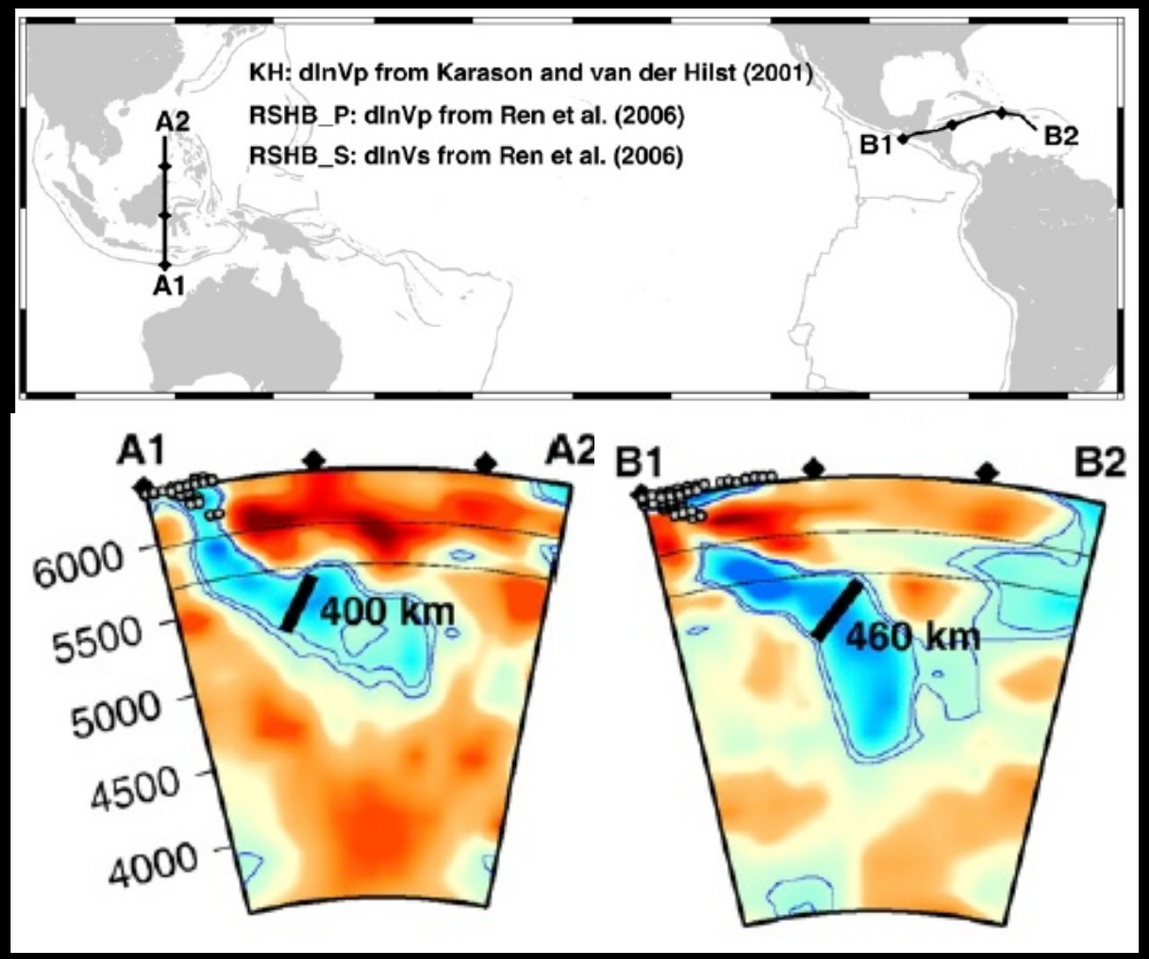


Slab morphology indicates folded piles

- slabs in the upper mantle are about 100 km thick as imaged by tomography (best with dense station coverage and high seismicity)
- slabs appear to become 3-5x thicker upon entering the lower mantle (is this due to the resolution of tomography or a physical effect?)

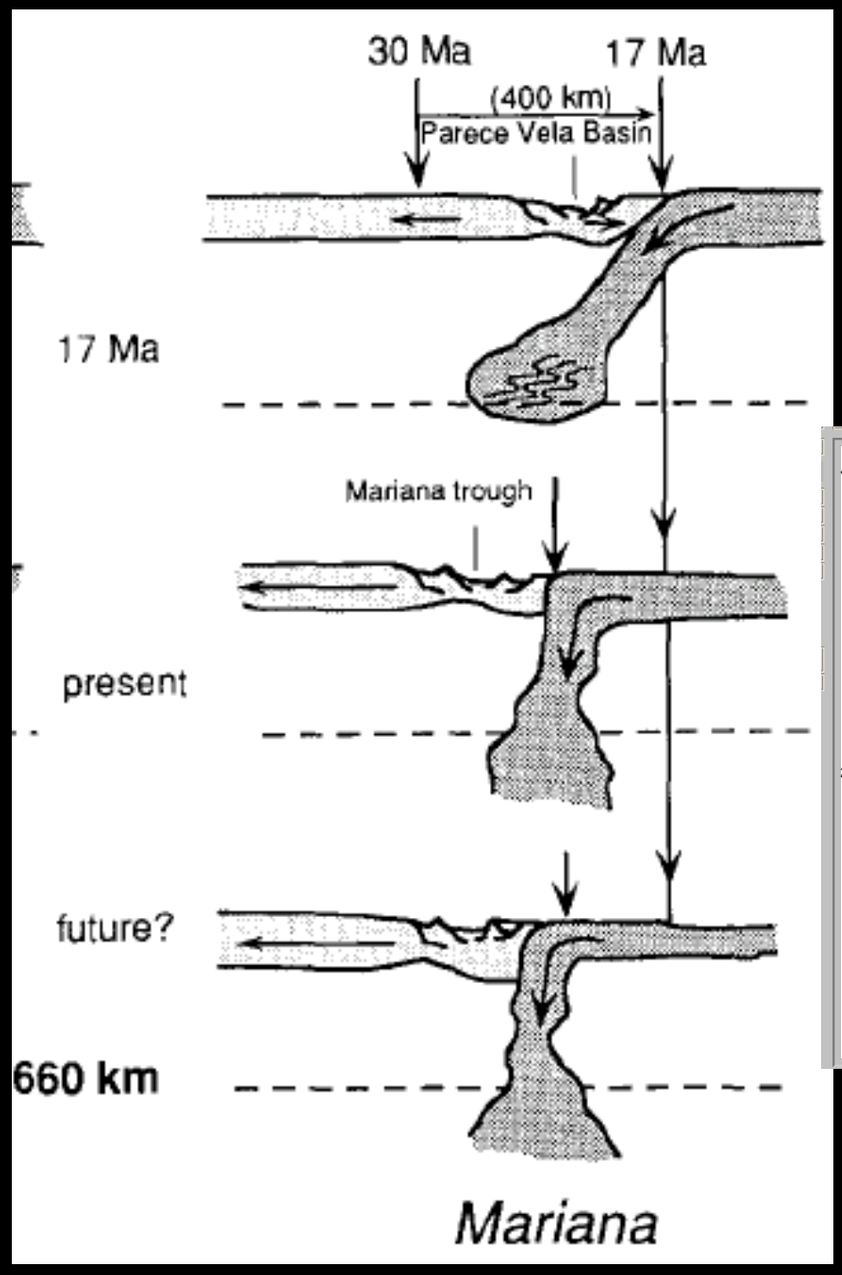


Zhao, PEPI, 2004



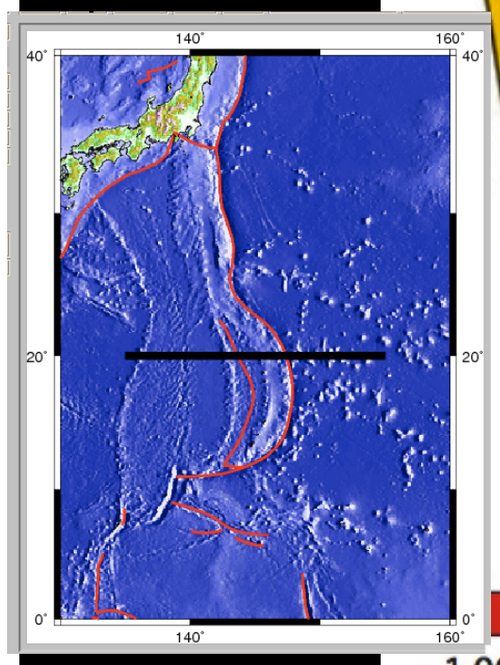
Ribe et al., EPSL, 2007

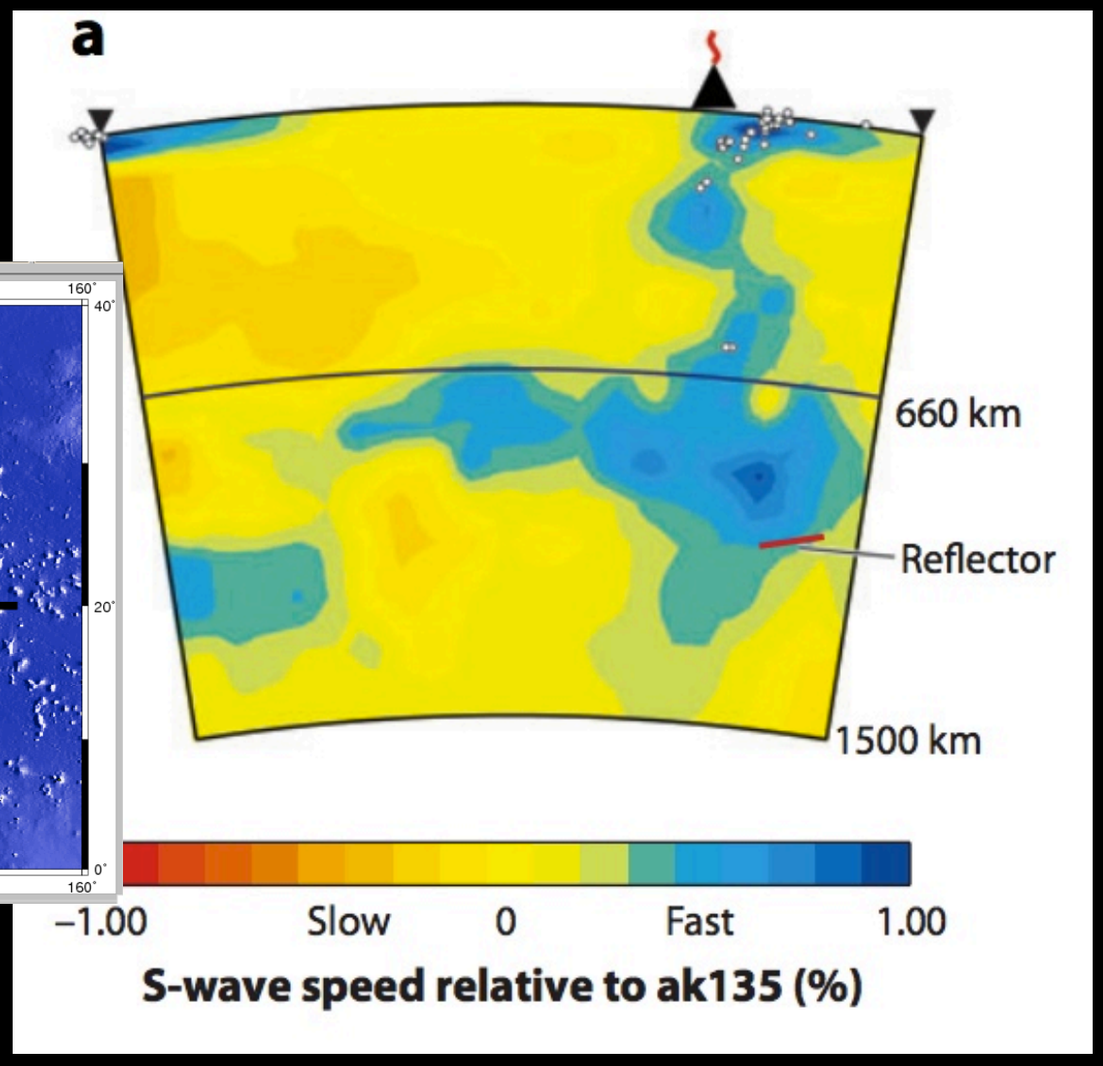
Folded slabs under stationary trenches



van der Hilst and Seno, EPSL, 1995

- **Stationary trenches lead to slab piles**

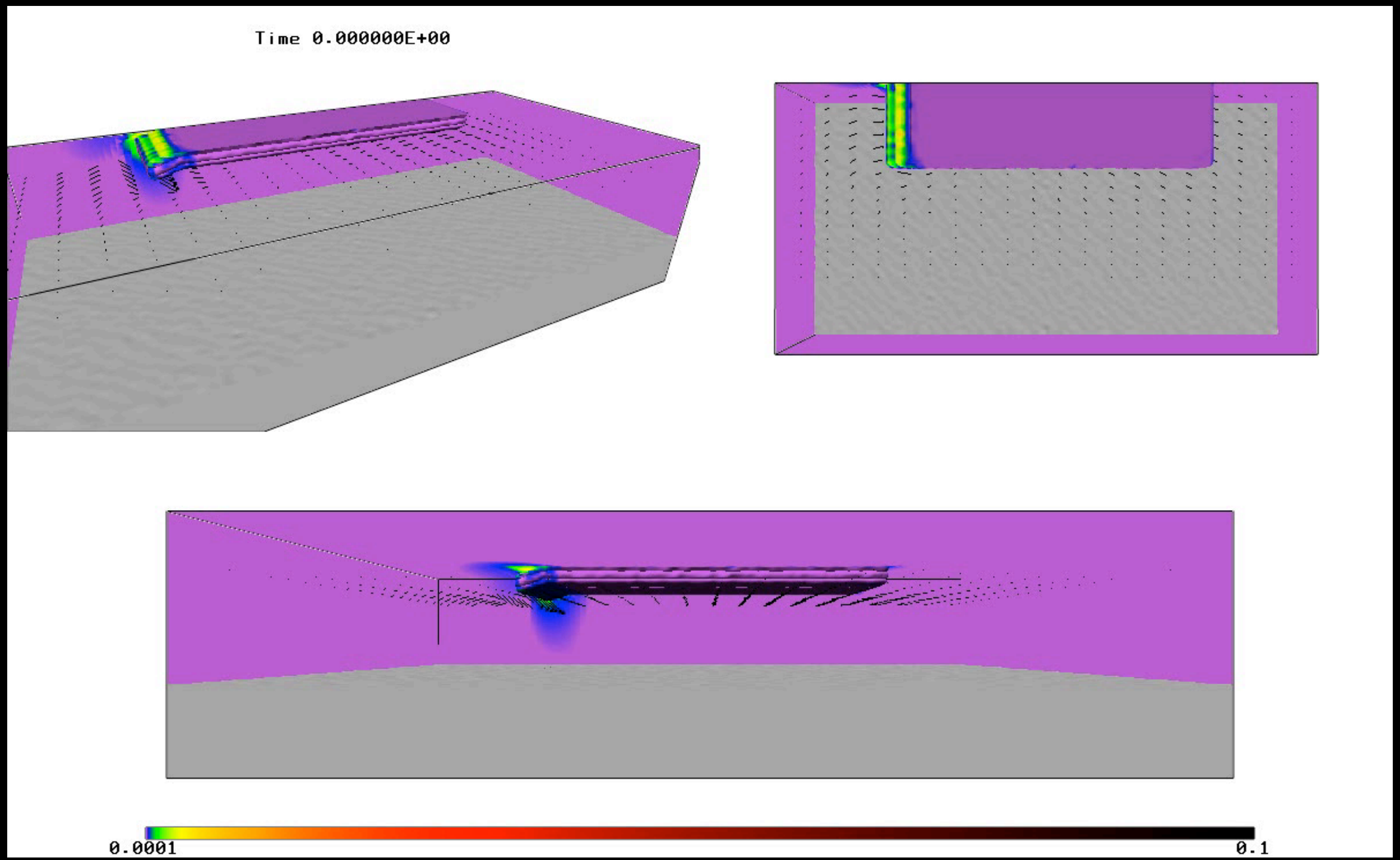




Widiyantoro et al, GJI, 2000

Widiyantoro et al. 2000

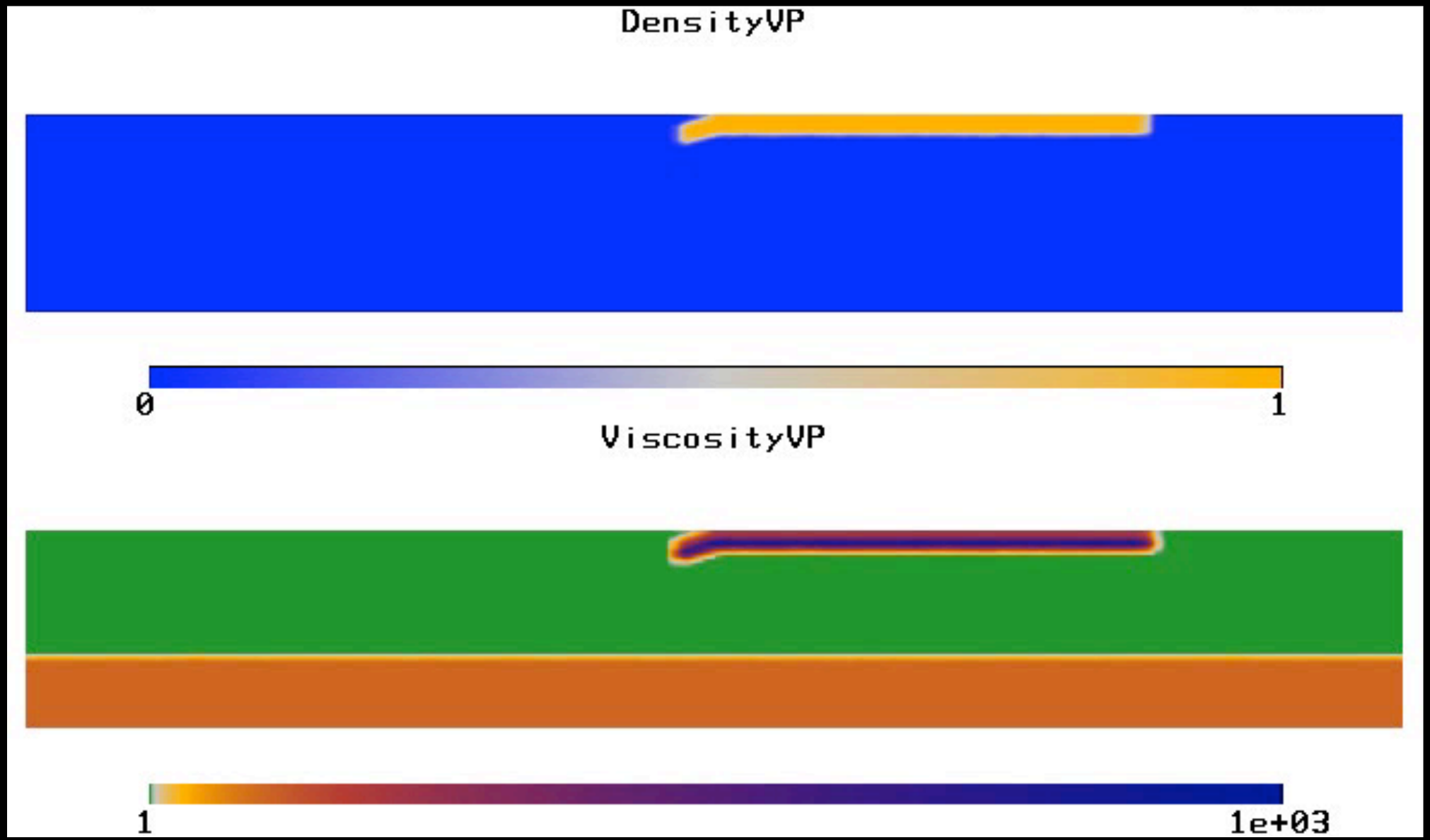
Slab folding and piling at 660 km



Stegman et al., Tectonophysics, 2010a

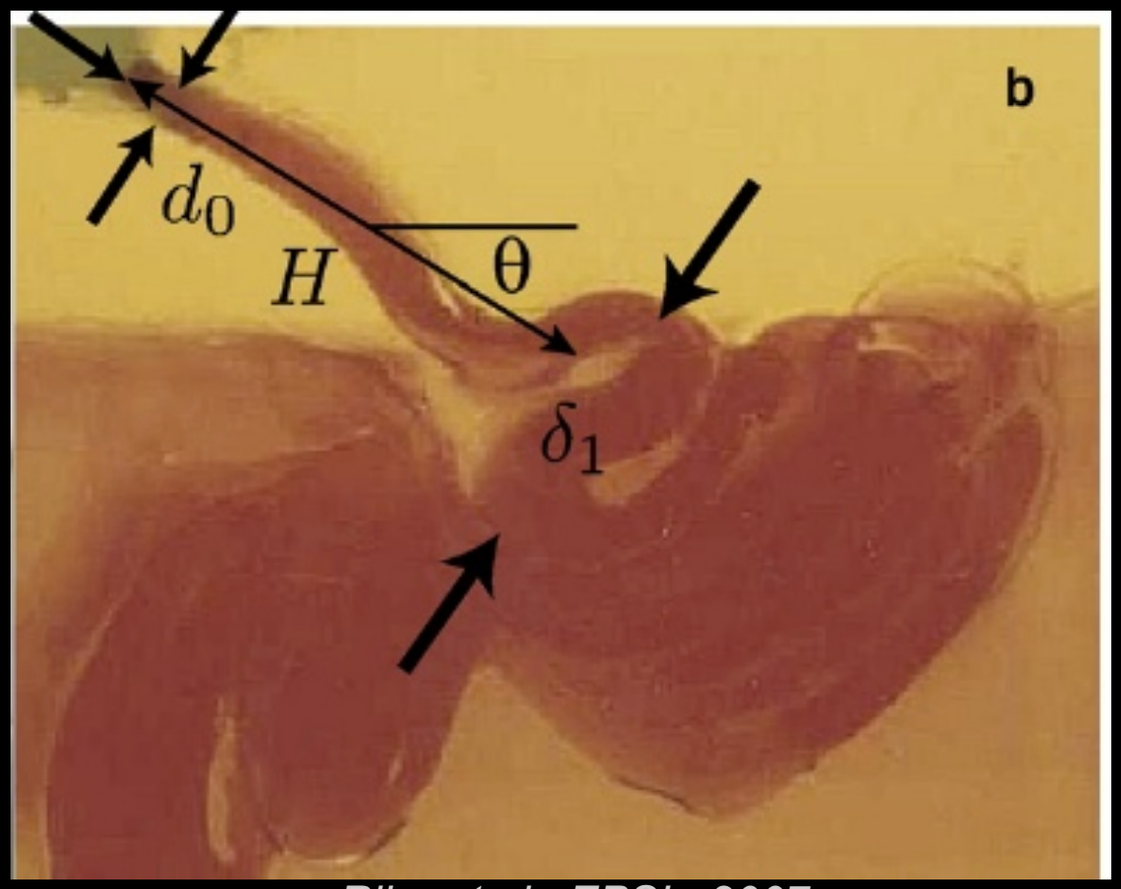
Folded slabs under stationary trenches

- **Plates with stationary trenches produce slab piles on top the lower mantle**



Folded slabs under stationary trenches

- Folding of weak slabs atop lower mantle due to increase in viscosity
- Increases diffusion time of thermal heterogeneities, concentrates buoyancy
- 660 km interface is low-pass filter



Ribe et al., EPSL, 2007

sinking velocity in upper mantle ~7cm/yr
slabs reach 660 km depth in 8 Myr
not diffusing too much in transit to 660

Summary of trench and slab behavior

slab morphology = f(radial layering of viscosity mantle, slab strength, plate width)

- **Narrow plates: trench retreat and flat-lying slabs**
- **Wider plates: quasi-stationary trenches and folded slab piles**
- **Weak slabs/bending regions indicated by development of lateral trench curvature and recumbent folding of slabs into piles**

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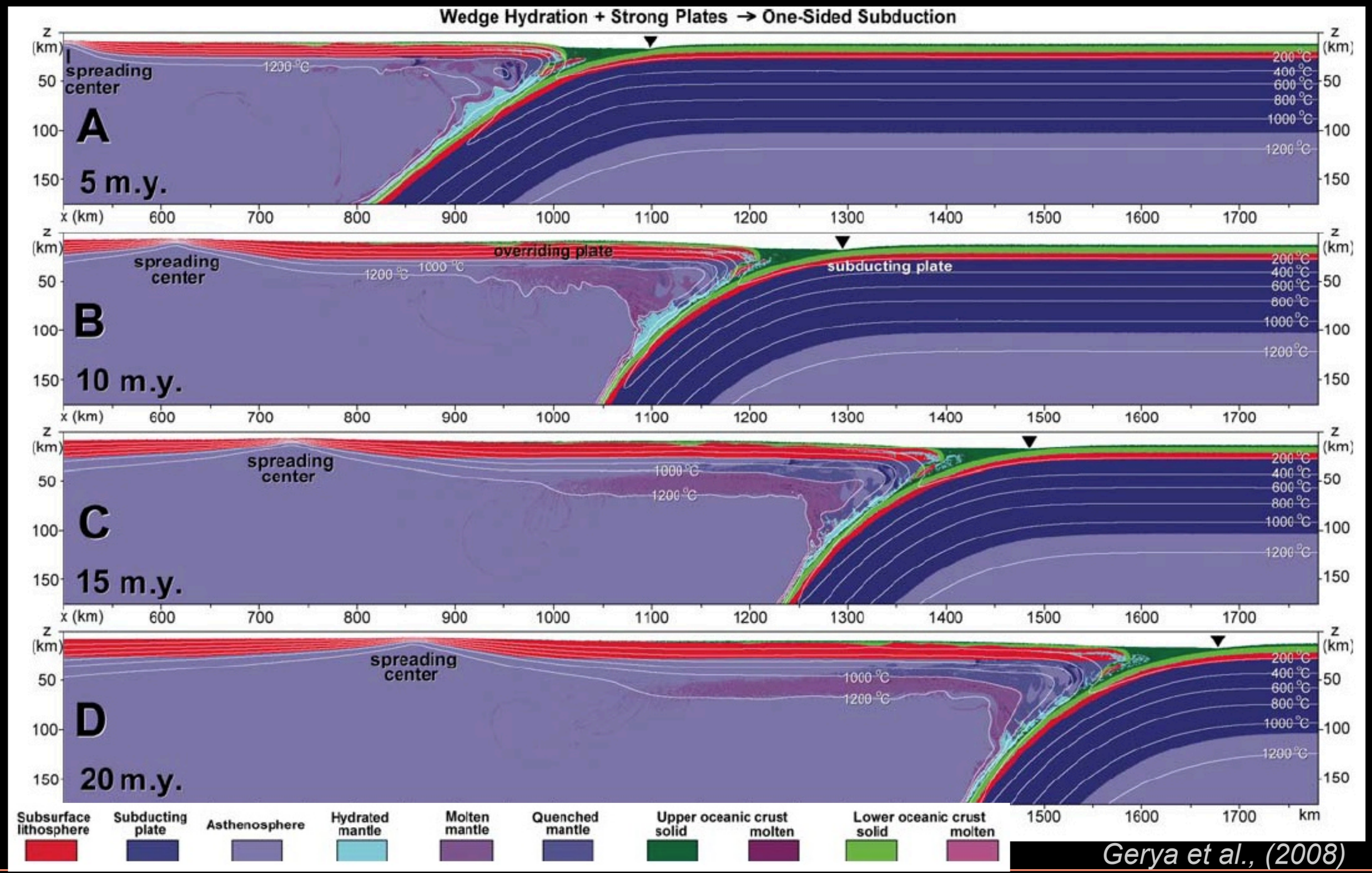
Ingredients for single-sided subduction

- weak subduction hinges (able to bend easily)
  - arising from brittle crust
- free surface (also promotes bending)
- strong core in slab (able to maintain stress guide to the trailing plate)
- low viscosity wedge (keep upper plate decoupled from subducting plate)
  - arises from dehydration of the slab and wet sediments

see Review paper by Gerya (2011), Journal of Geodynamics

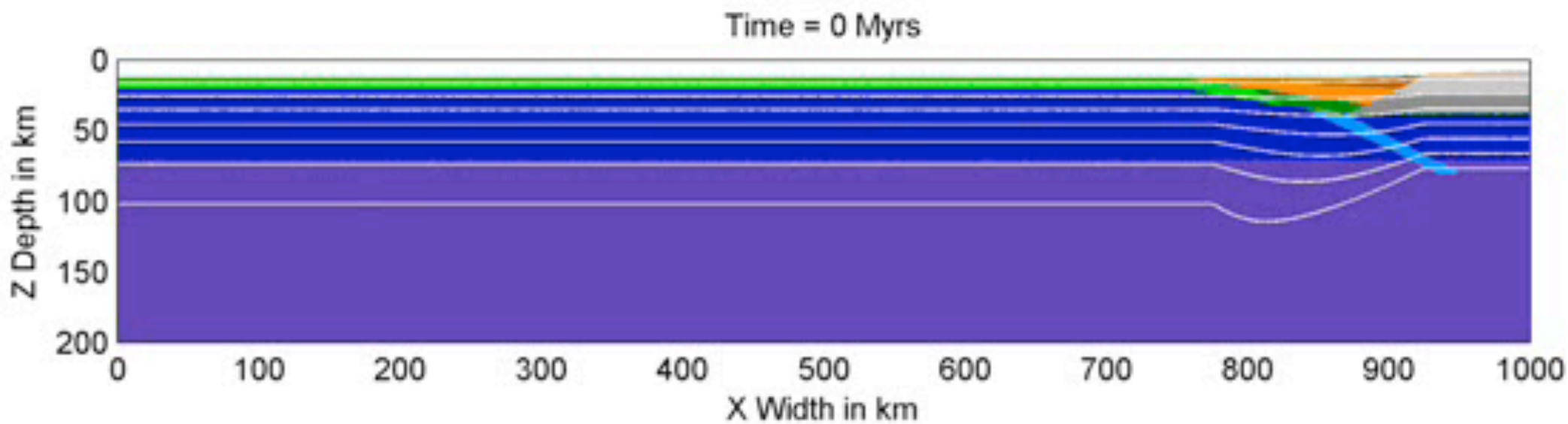
Gerya et al., (2008)

Wedge hydration -> one-sided subduction



Gerya et al., (2008)

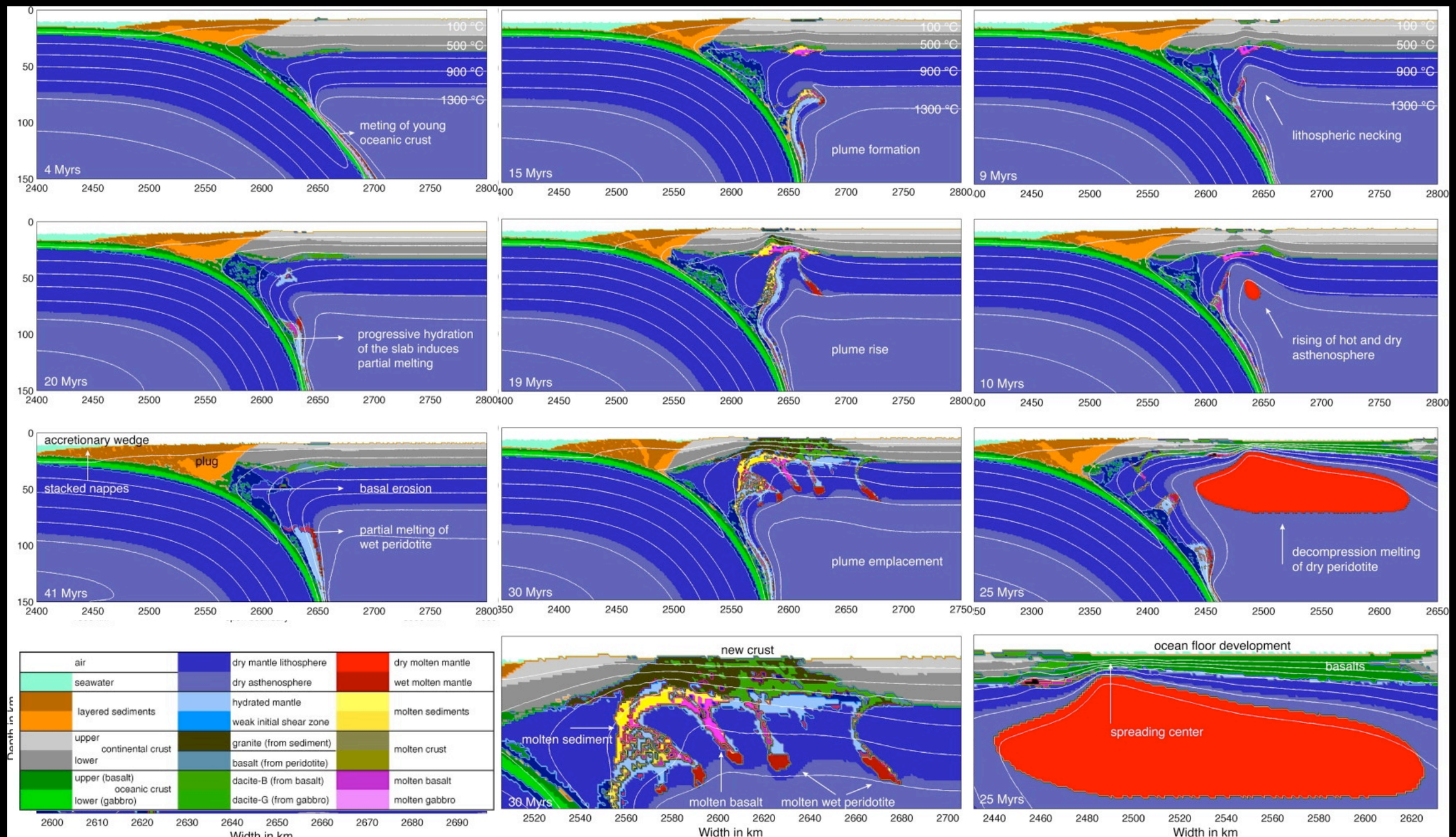
Development of back-arc basin



Model includes spontaneously bending slab, free erosion/sedimentation upper surface, variable non-prescribed subduction rate, visco-plastic pressure-temperature-stress-dependent rheology, non-steady temperature field, spontaneous extension of the overriding plate associated with back arc basin development, slab dehydration and water transport above the slab associated with progressive mantle wedge hydration, fluid fluxed and decompression melting of the mantle wedge, melt extraction and volcanic crust growth

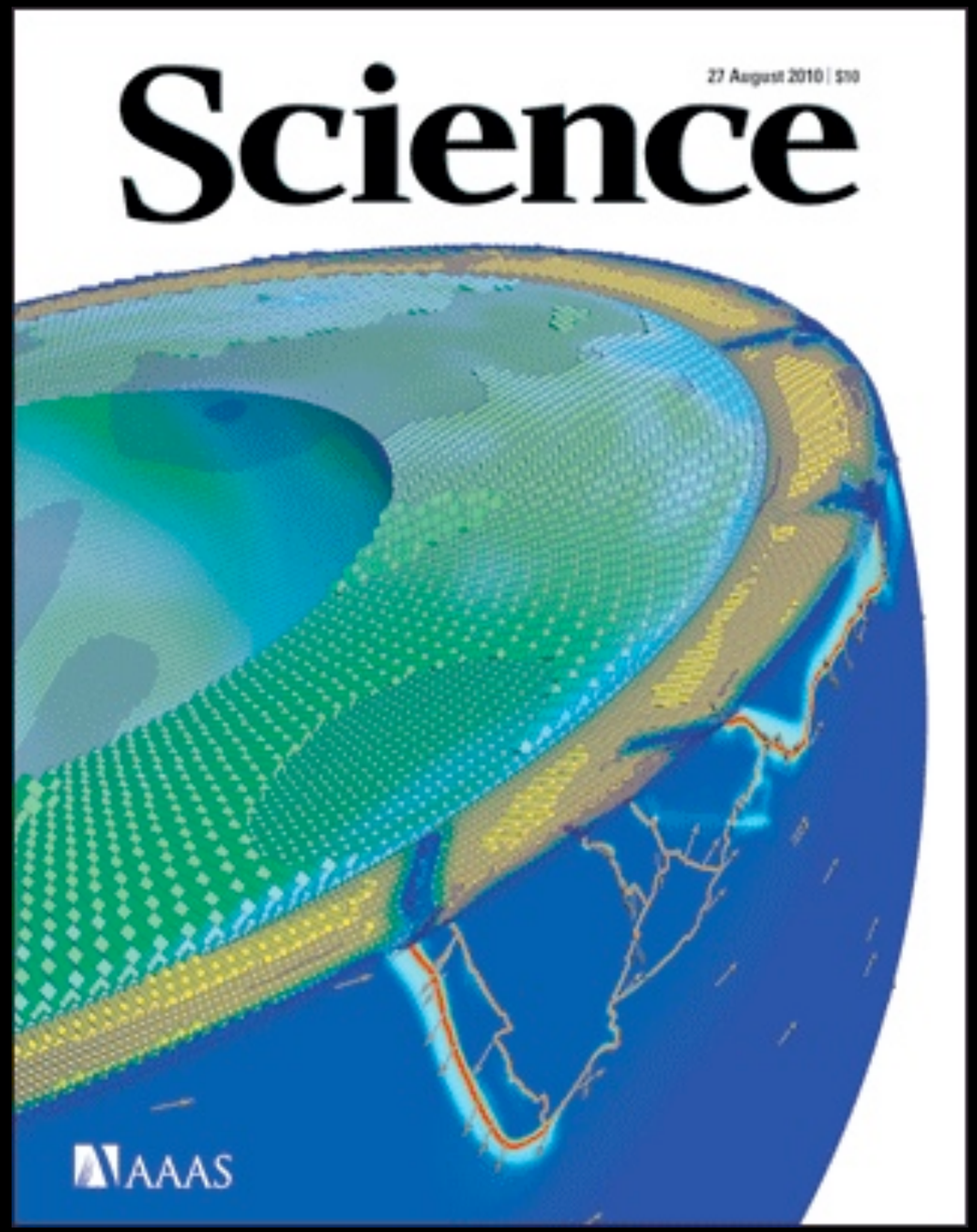
Gerya and Meilick, (2010)

Petrologic feedback and crustal growth

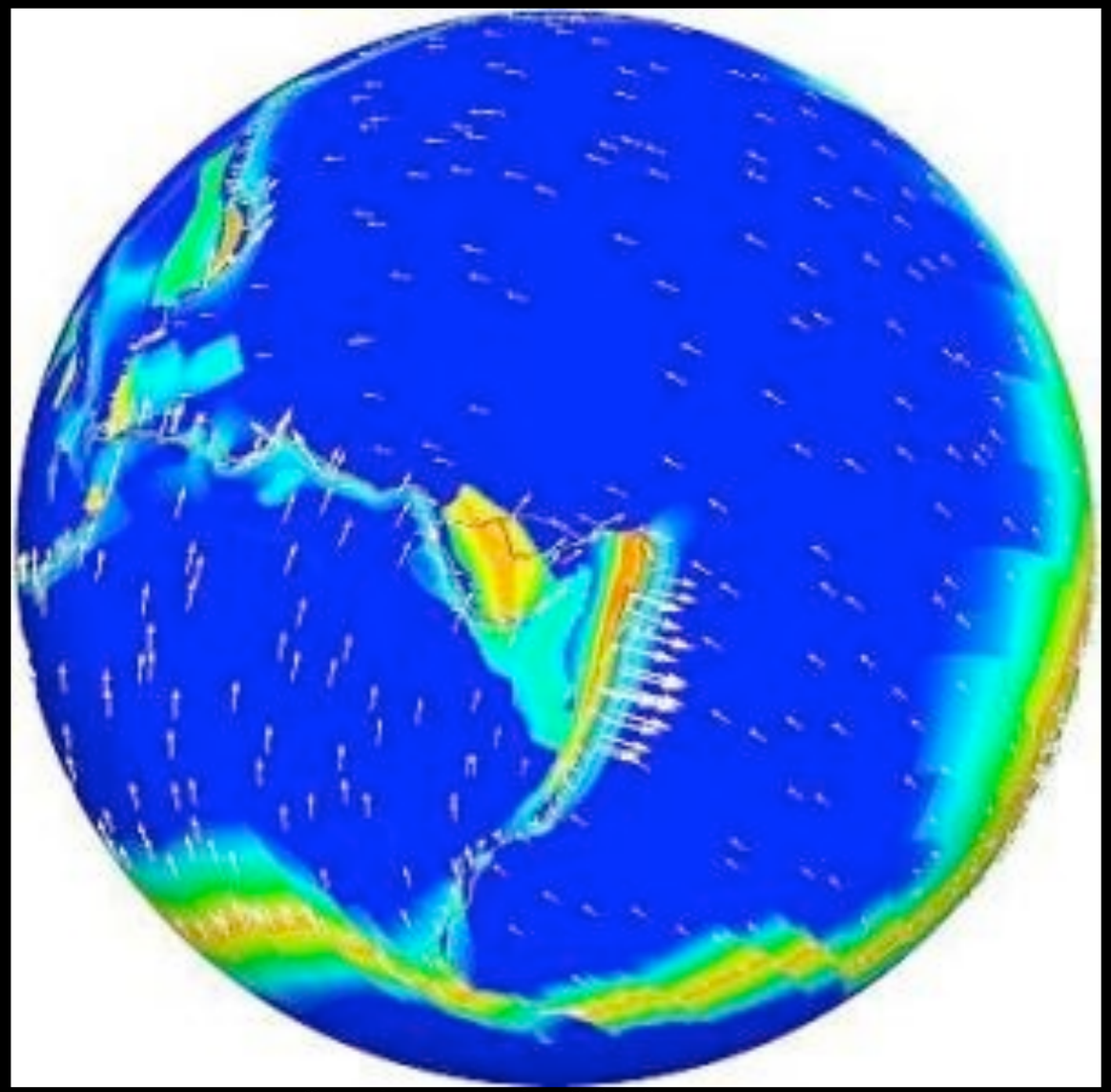


Vogt et al., (2012)

Predicting Plate Motions with Convection



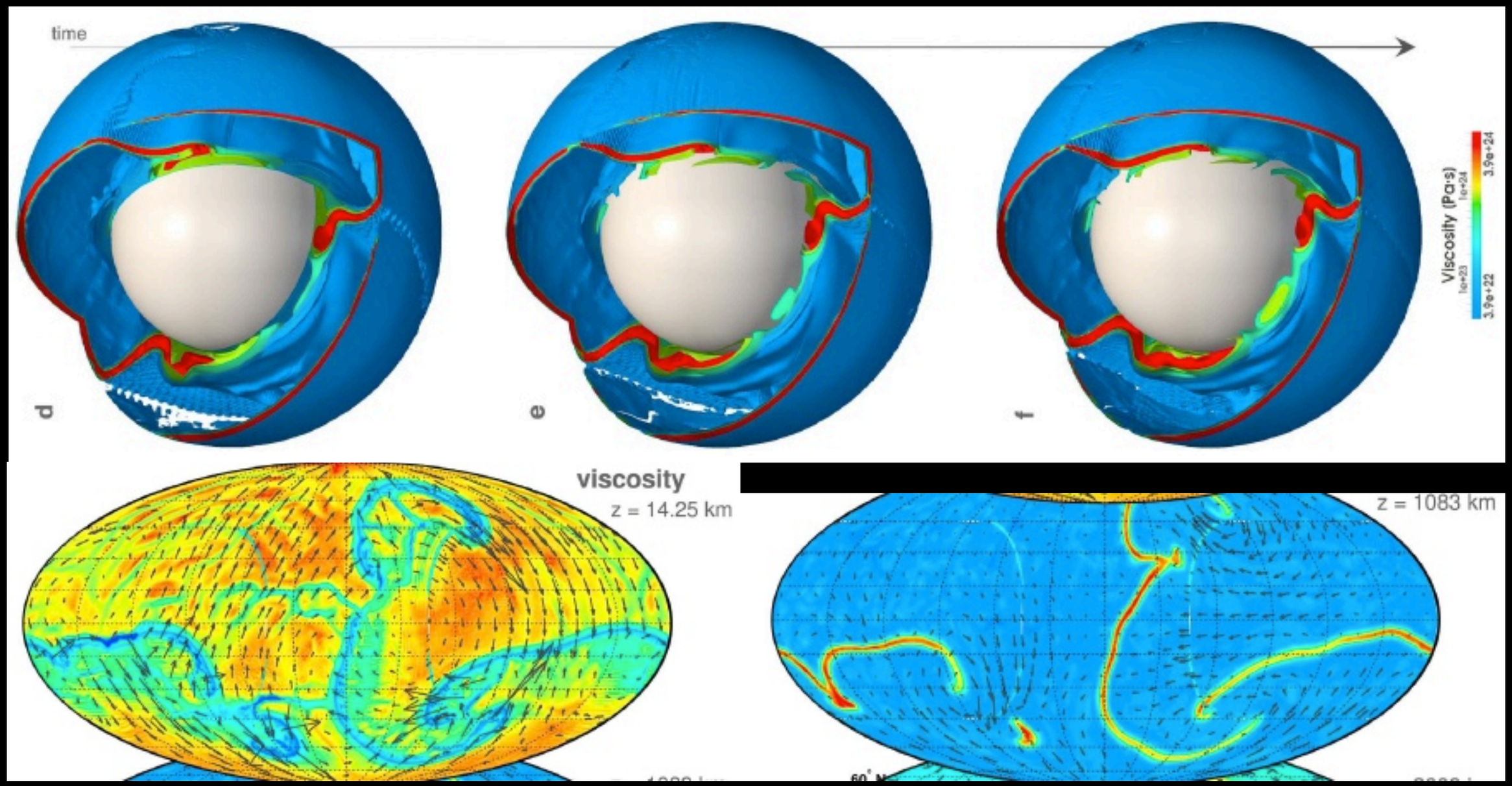
- **Turns out it is not an easy problem to solve at all, but there is progress**



Stadler et al., 2010

One-sided Subduction within Convection

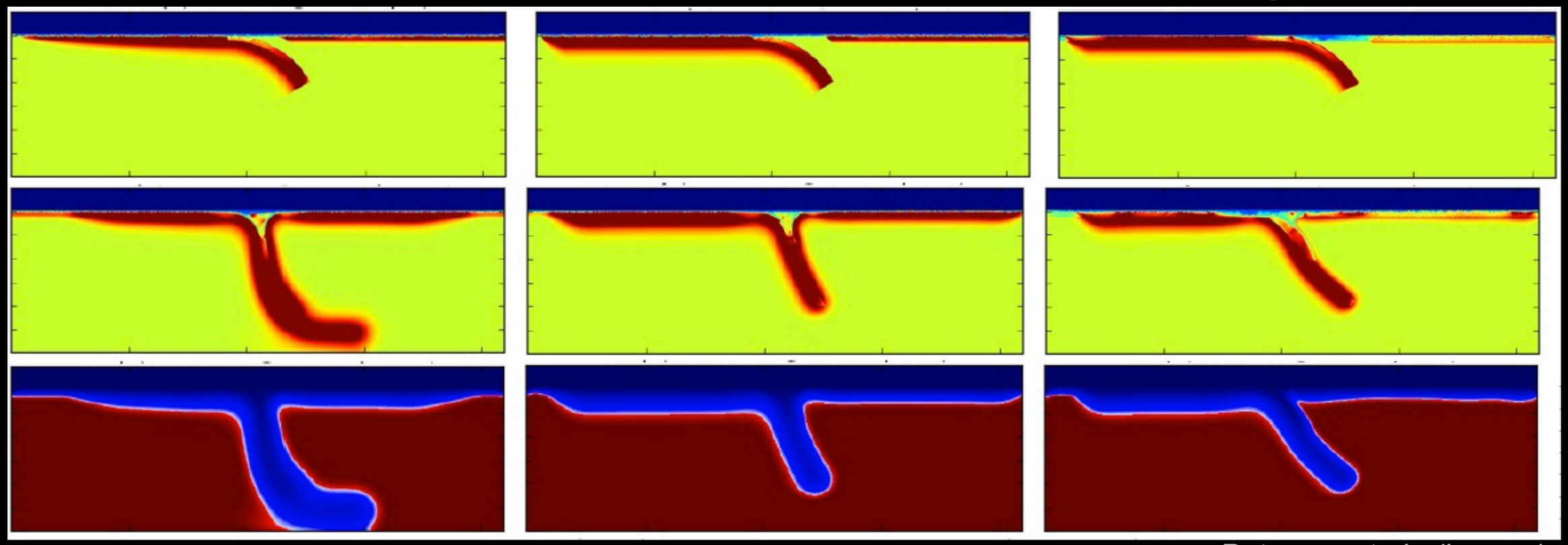
- ``Earth''-like subduction with strongly asymmetric, migrating downwellings



Crameri et al., 2012

One-sided Subduction within Convection

Two-sided, symmetric initial wedge size: 50 km | **Two-sided, asymmetric initial wedge size: 100 km** | **One-sided, asymmetric initial wedge size: 150 km**



Petersen et al., (in prep)

``Earth”-like subduction seems to require maintaining a low-viscosity wedge

most likely mechanism: slab dehydration

A different sort of laboratory

DEEP EARTH VIRTUAL LABORATORY

- simulation software
- visualization software
- high-performance computing
- develop computer models that help us understand planets

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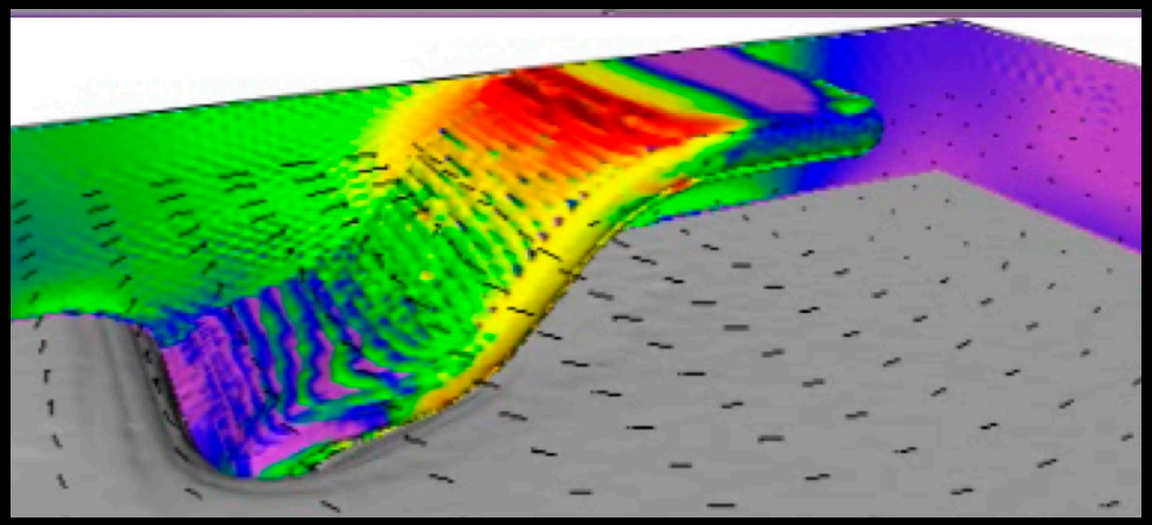
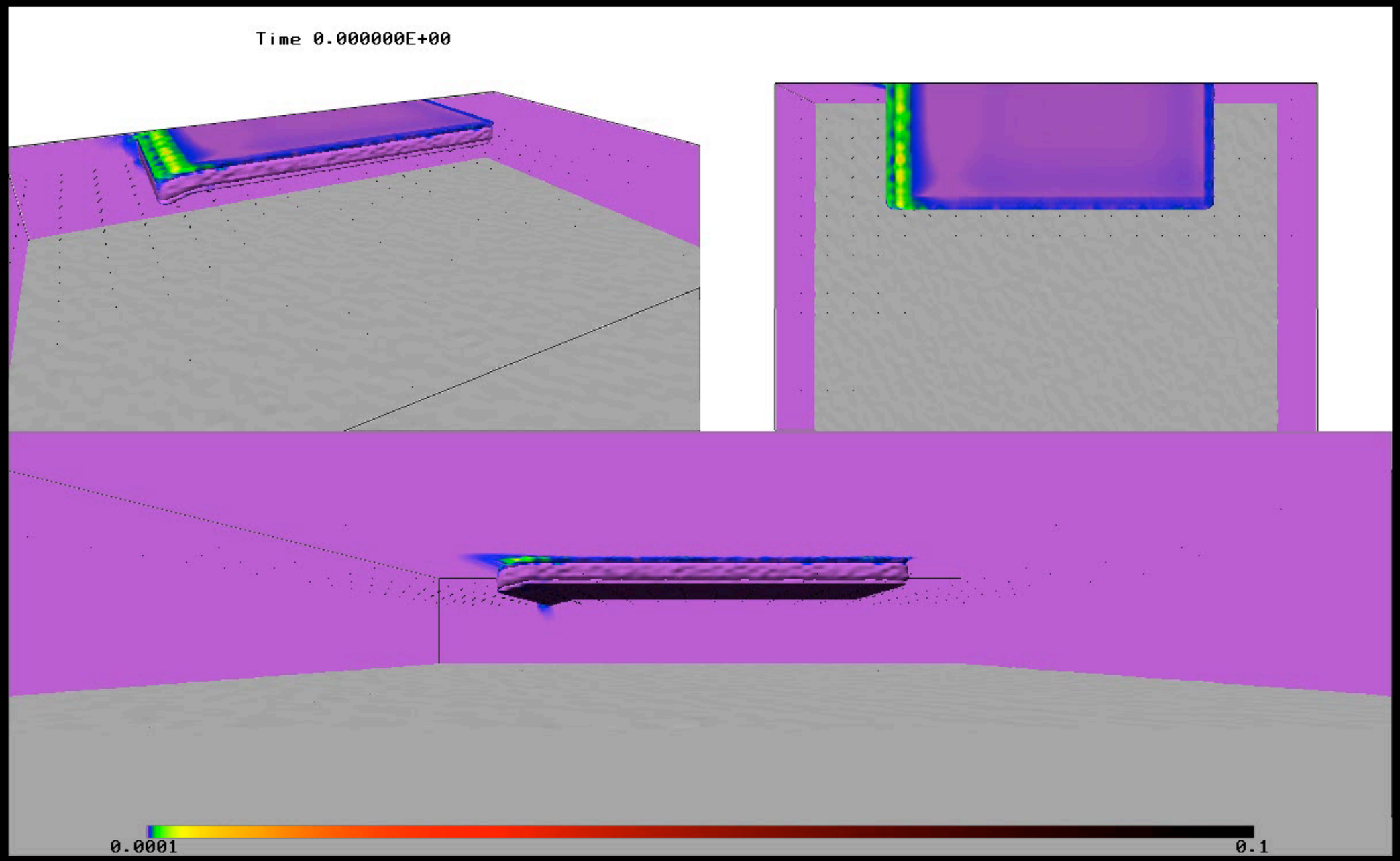
Regime I: Viscous beam mode



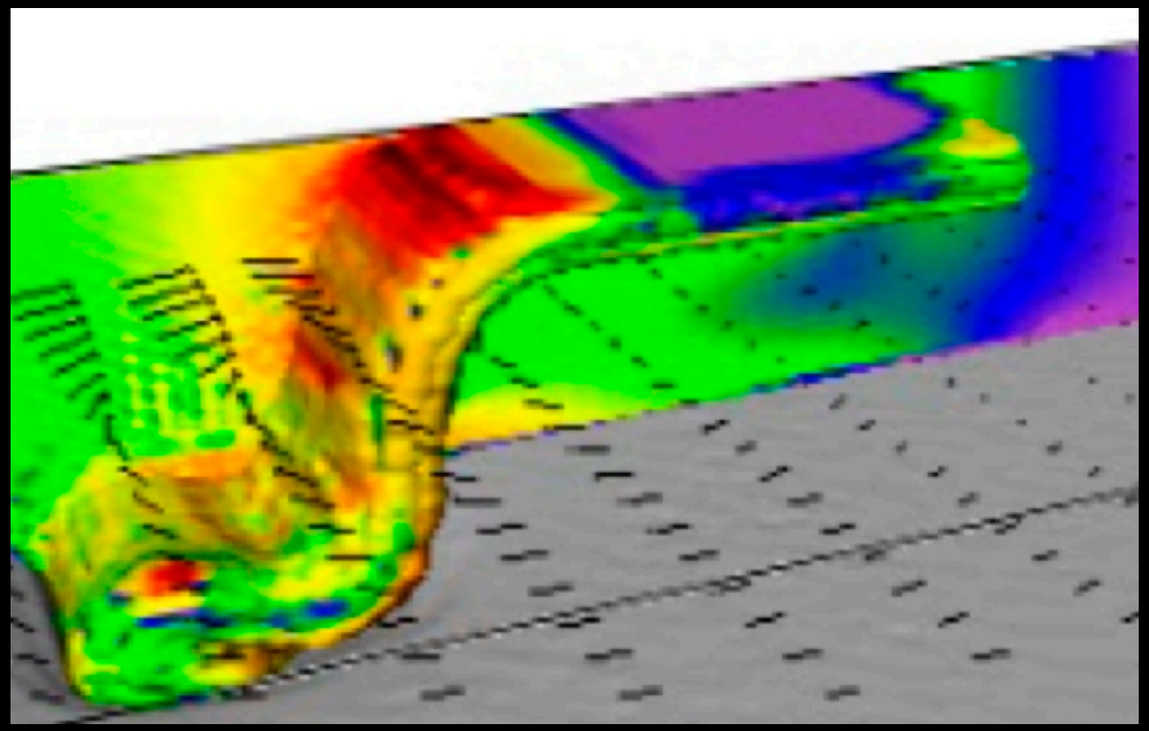
- Very Strong Slabs
  - fast subduction velocities
  - approx. 2-D, linear trench
  - trench retreat dominates
  - flat-lying slab
  - large radius of curvature

Regime I: Viscous beam mode



Stegman et al., Tectonophysics, 2010a

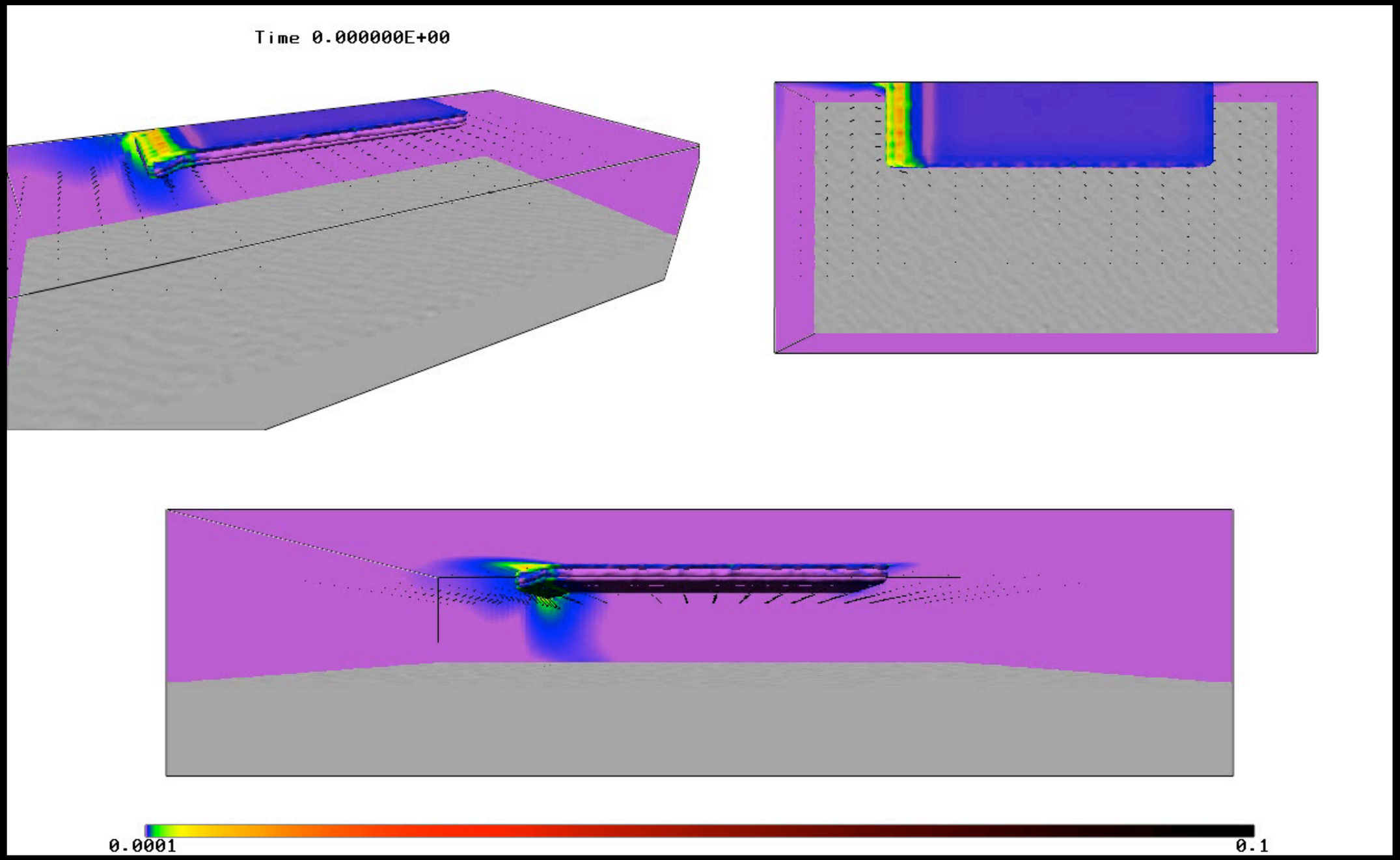
Regime II: Advance-Fold-Retreat mode



- Heavy, Strong Slabs
  - moderate subduction velocities
  - slightly concave trench
  - trench advance transitions into retreat
  - slab has a single recumbent fold
  - medium radius of curvature

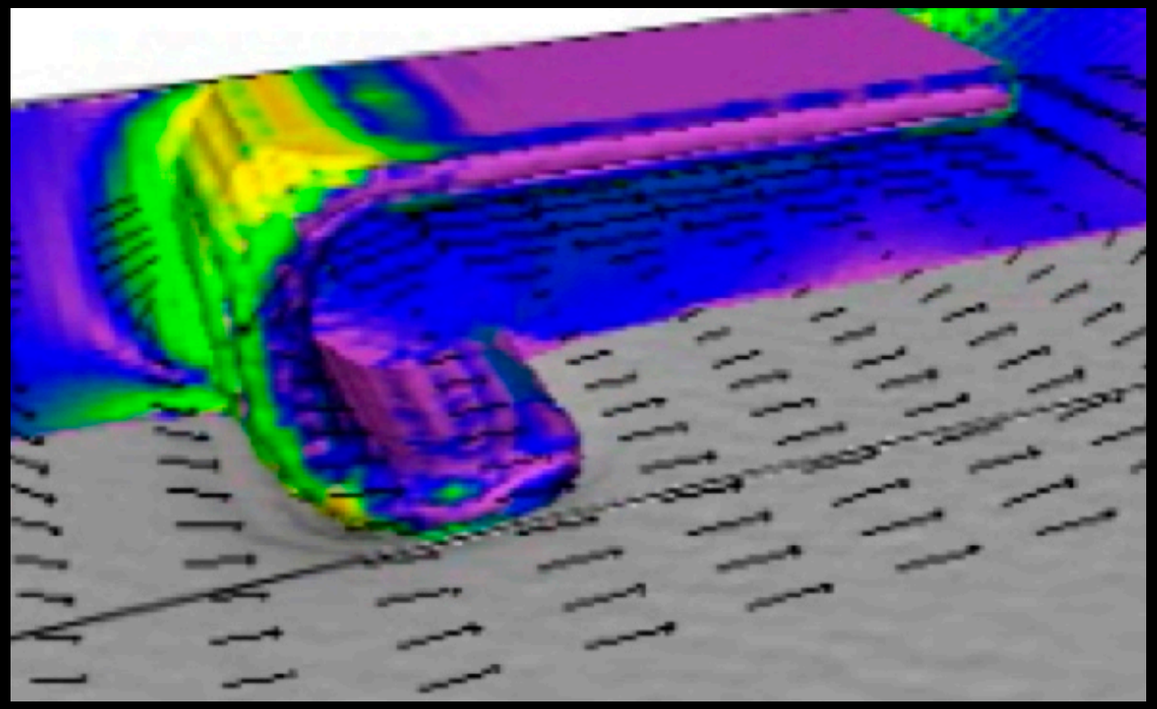
Stegman et al., Tectonophysics, 2010a

Regime II: Advance-Fold-Retreat mode



Stegman et al., Tectonophysics, 2010a

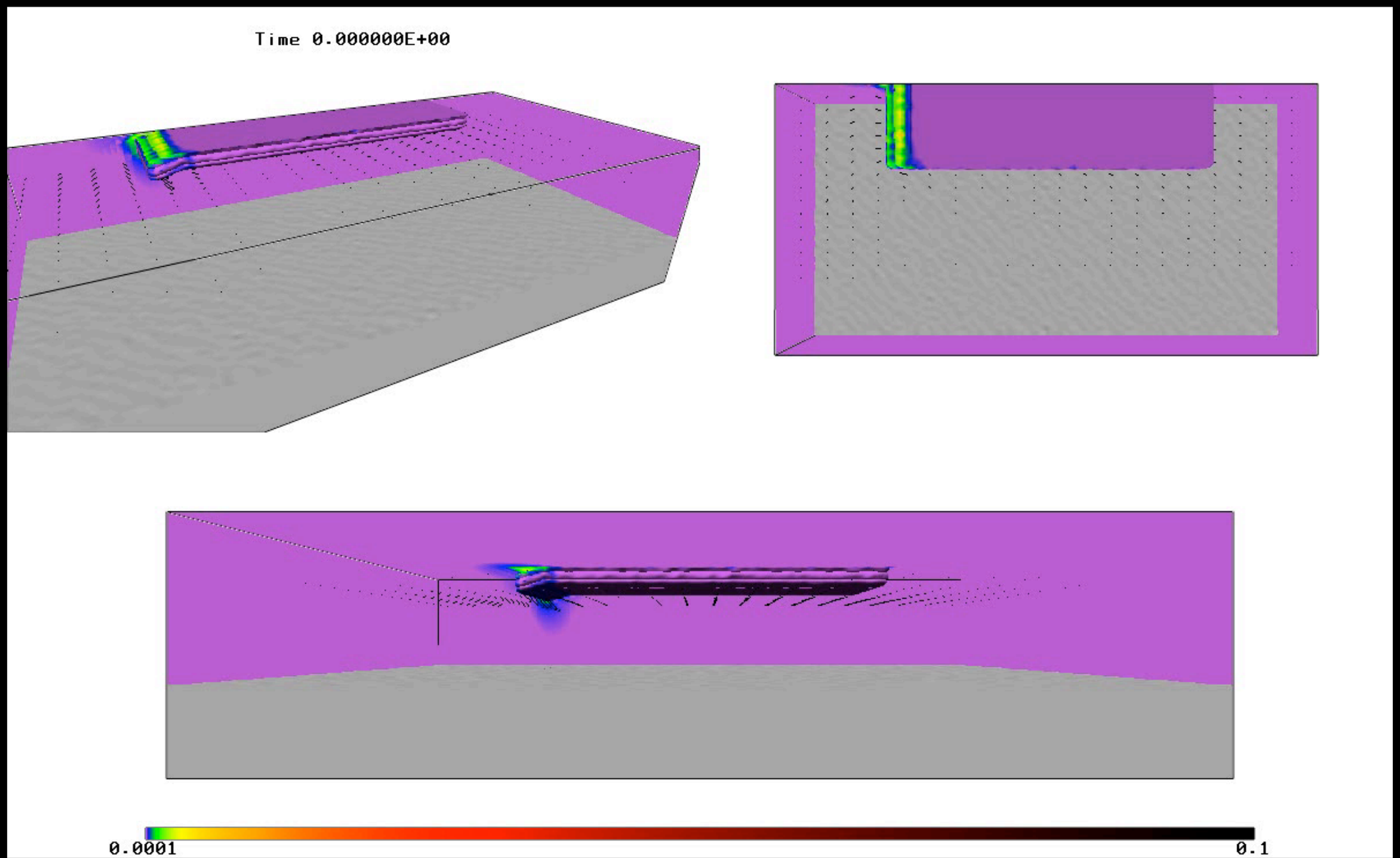
Regime III: Advancing mode



- Strong Slabs
  - moderate subduction velocities
  - slightly concave, advancing trench
  - strength of plate supports entire weight of the slab
  - slab rollover geometry produces after interaction with 660 km
  - medium radius of curvature

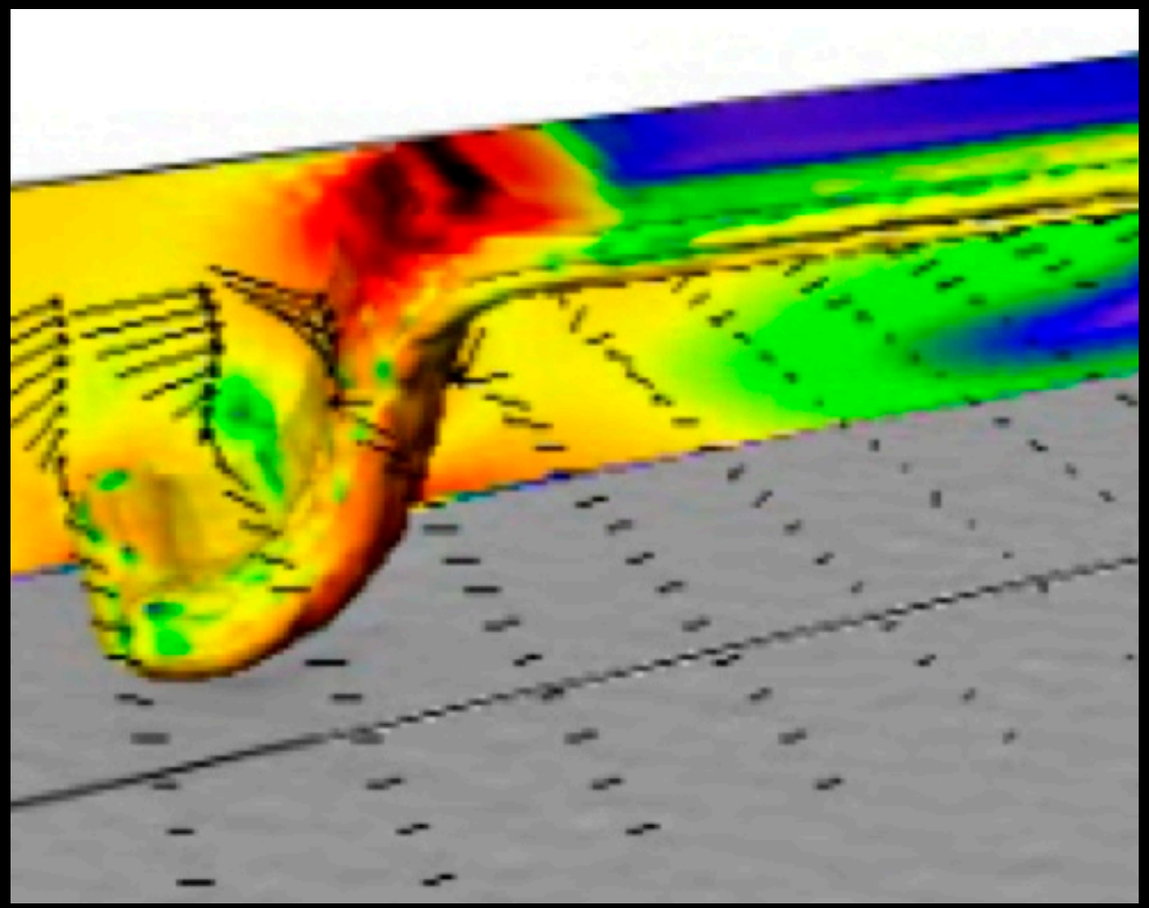
Stegman et al., Tectonophysics, 2010a

Regime III: Advancing mode



Stegman et al., Tectonophysics, 2010a

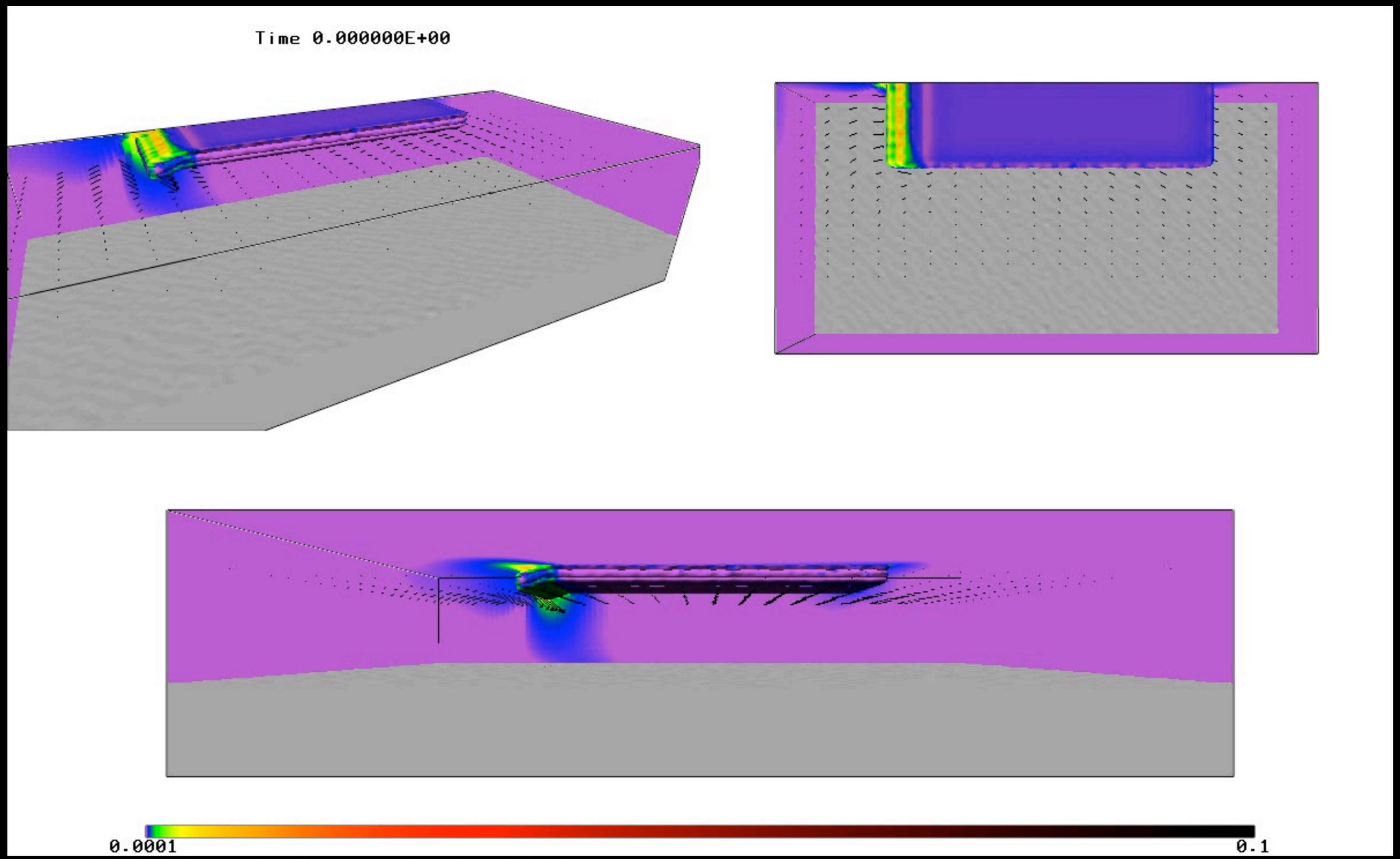
Regime IV: Retreating mode



- Heavy, Weak Slabs
  - faster subduction velocities
  - highly curved trench
  - dominated by trench retreat
  - flat-lying, backwards-draping slabs atop 660 km
  - medium radius of curvature

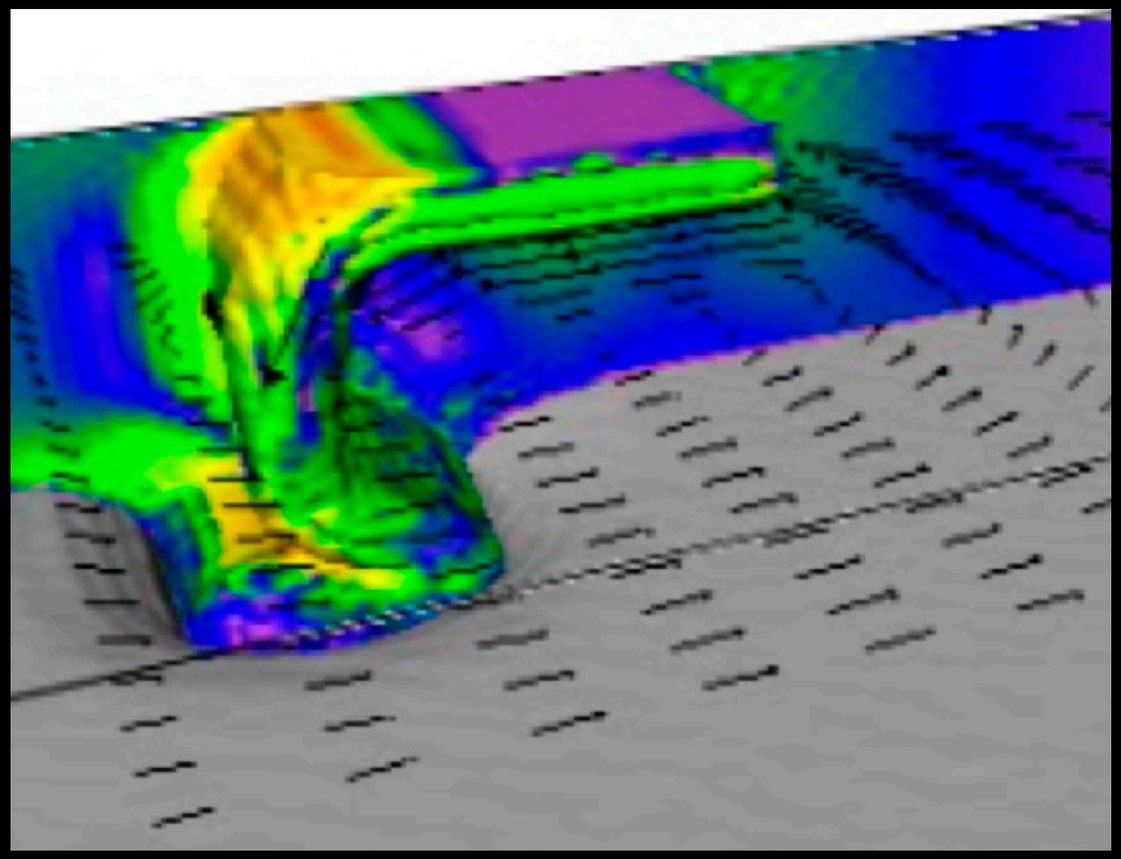
Stegman et al., Tectonophysics, 2010a

Regime IV: Retreating mode



Stegman et al., Tectonophysics, 2010a

Regime V: Folding mode

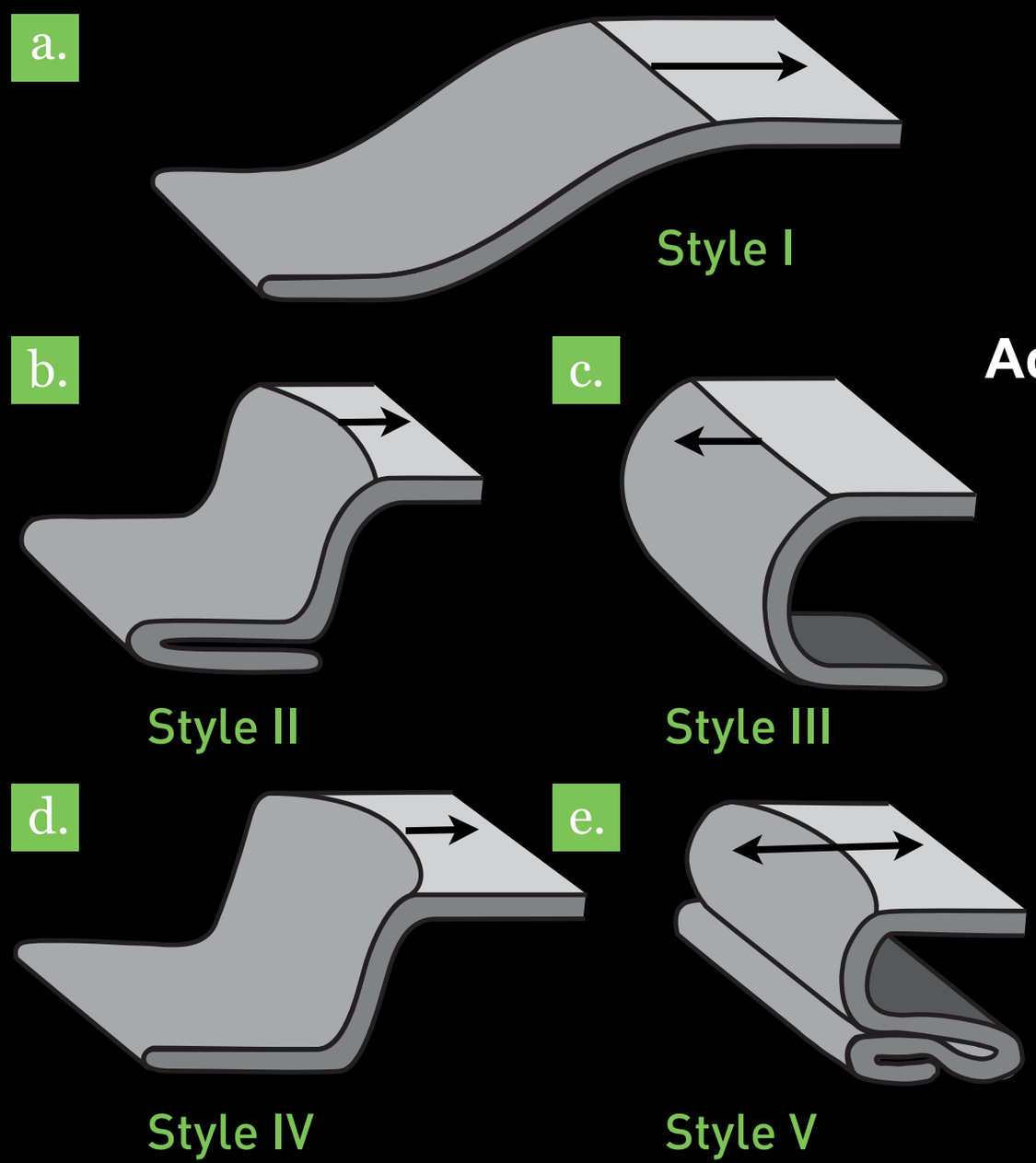


- Weak Slabs
  - faster subduction velocities
  - highly curved trench
  - subducts through trench retreat and plate advance (partitioning depends on plate width)
  - accumulation of recumbent folds into slab pile
  - small radius of curvature

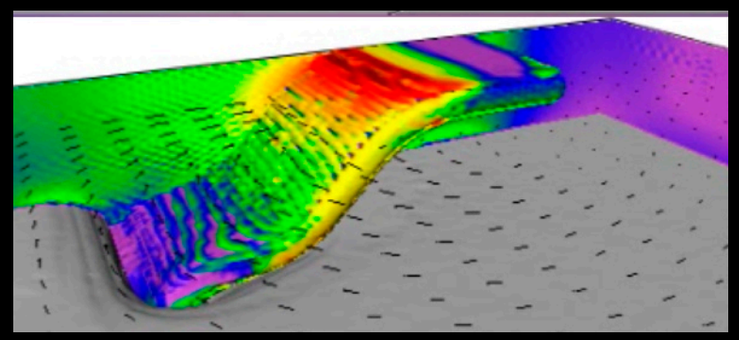
Stegman et al., Tectonophysics, 2010a

New suite of numerical models

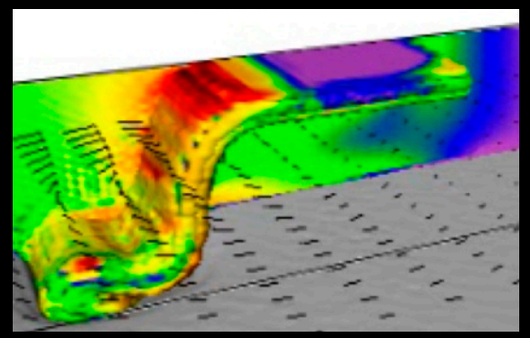
Styles of subduction



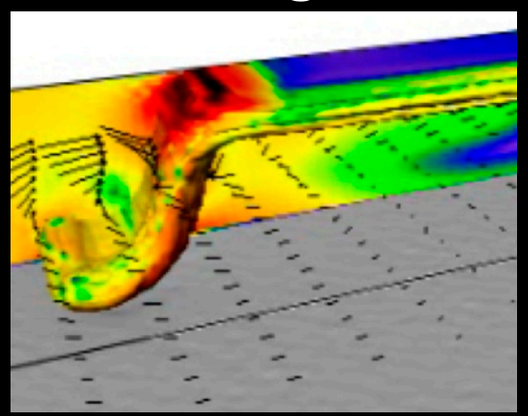
Viscous Beam Mode



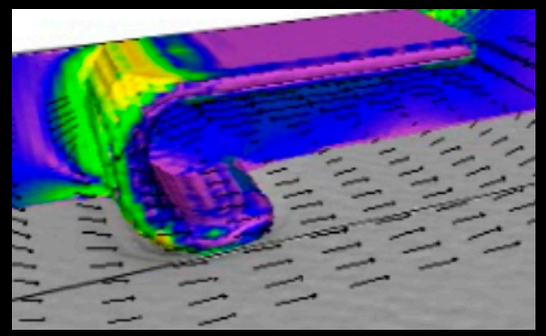
Advance-Fold-Retreat



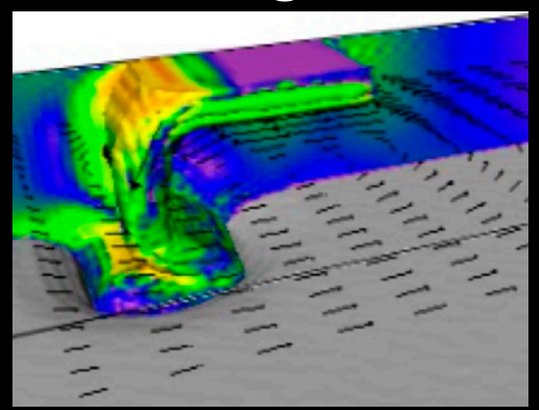
Retreating Mode



Advancing Mode

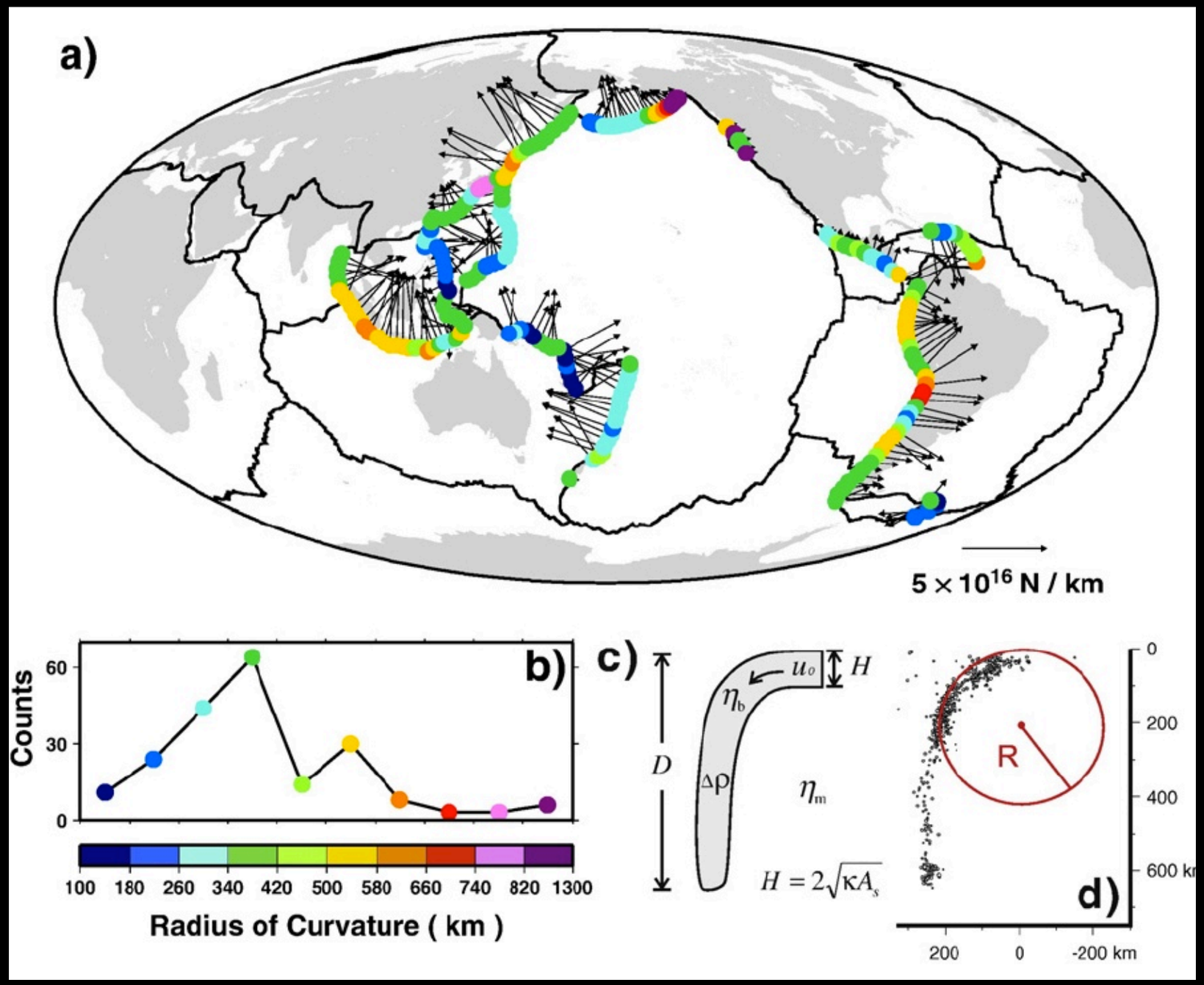


Folding Mode



Stegman et al., Tectonophysics, 2010

Observed radius of curvature in nature



Wu, Conrad, et al., EPSL, 2008