Data Integration, High Performance Computing, and Scientific Visualization in the Geodynamics Workflow

Margarete A. Jadamec

NSF Postdoctoral Fellow
Dept. of Geological Sciences
Brown University

Collaborators:
Magali Billen, Donald Turcotte, Louise Kellogg, Oliver Kreylos, Marek Vanco, Karen Fischer

Resources: NSF, XSEDE, TACC, KeckCAVES

http://www.geo.brown.edu/People/Postdocs/Jadamec/

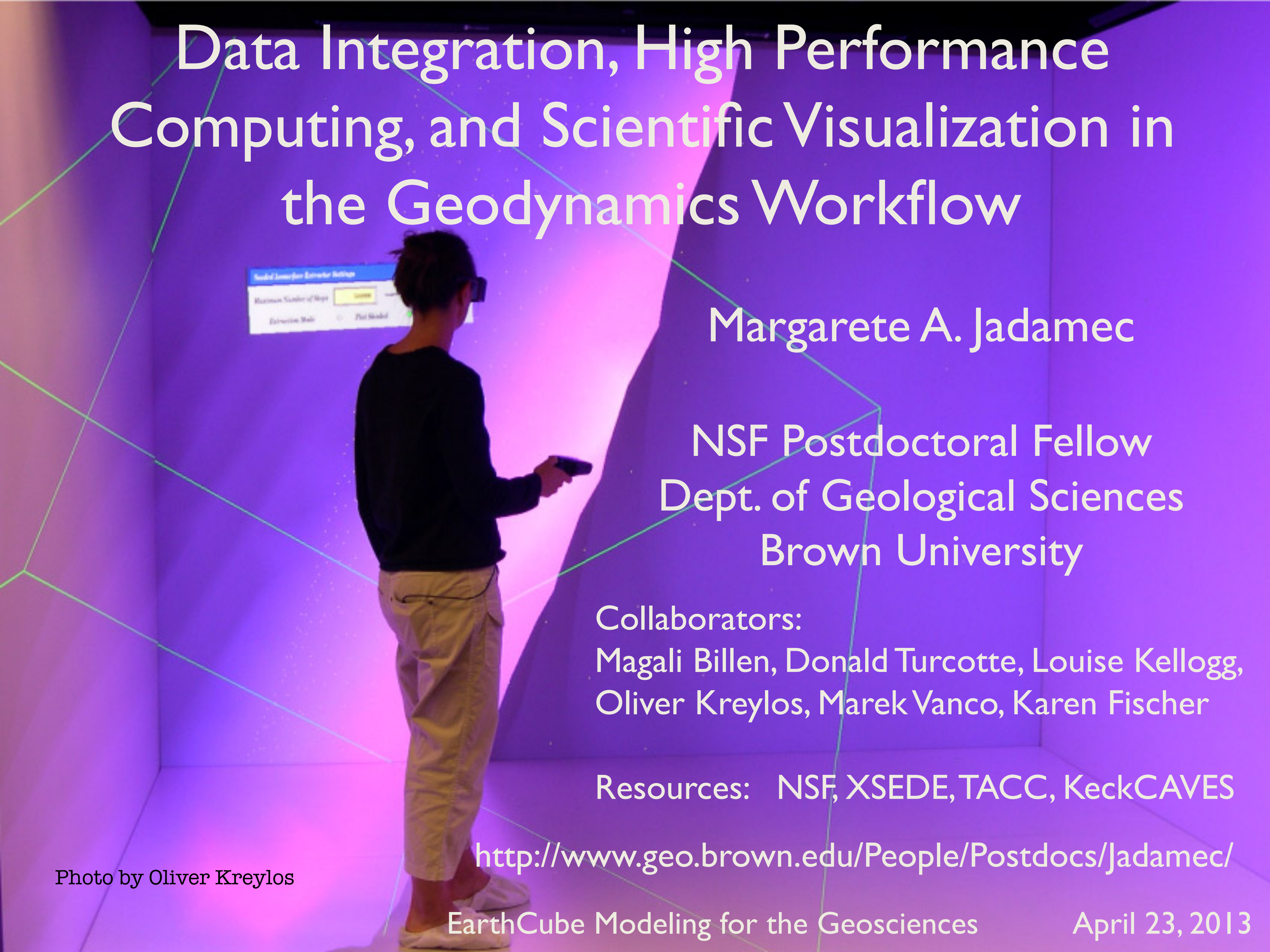
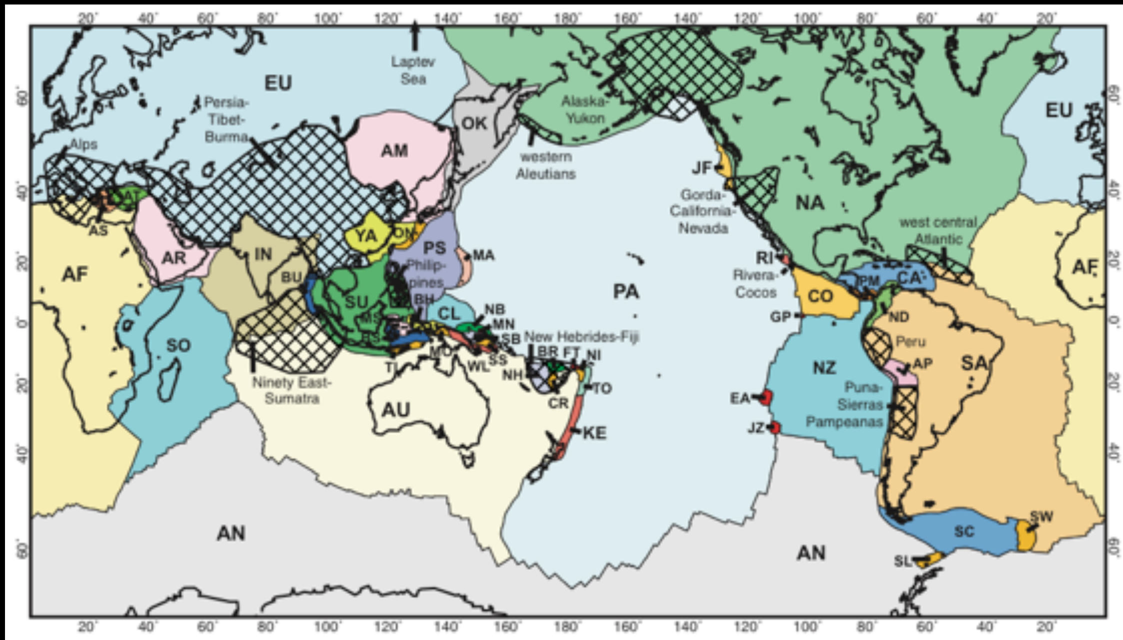


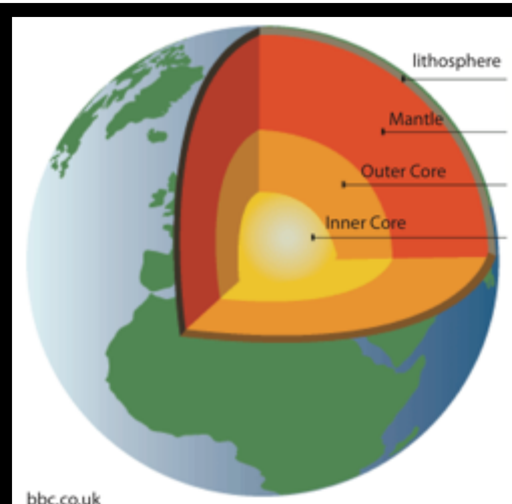
Photo by Oliver Kreylos

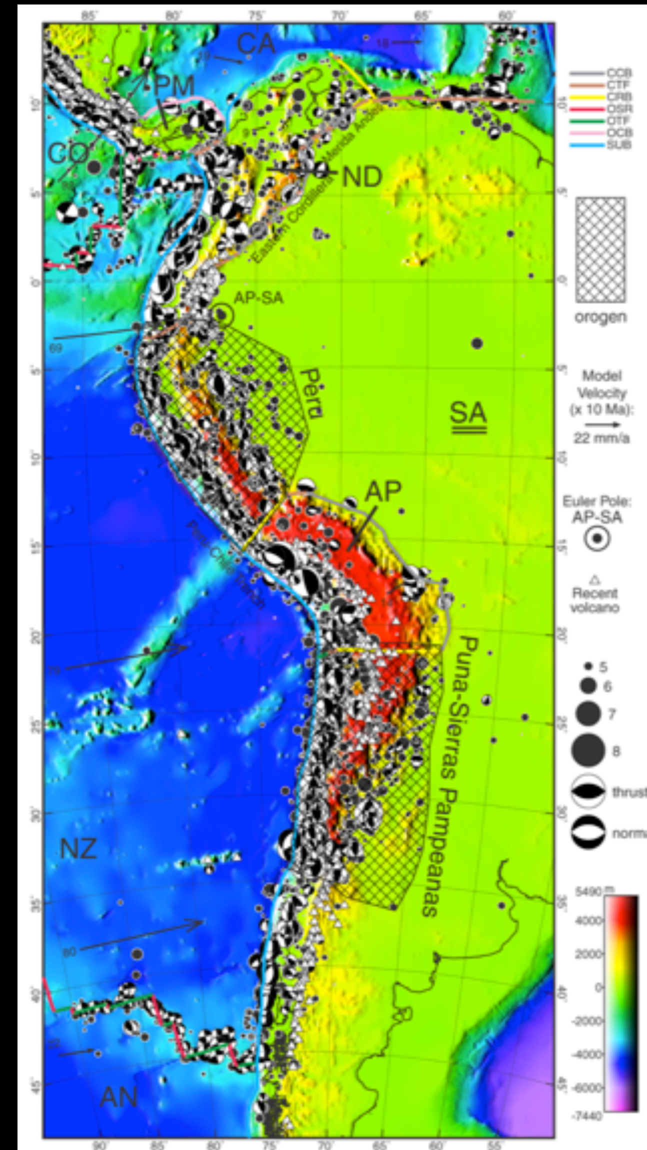
EarthCube Modeling for the Geosciences April 23, 2013

Plate Tectonics and Deformation at Plate Boundaries



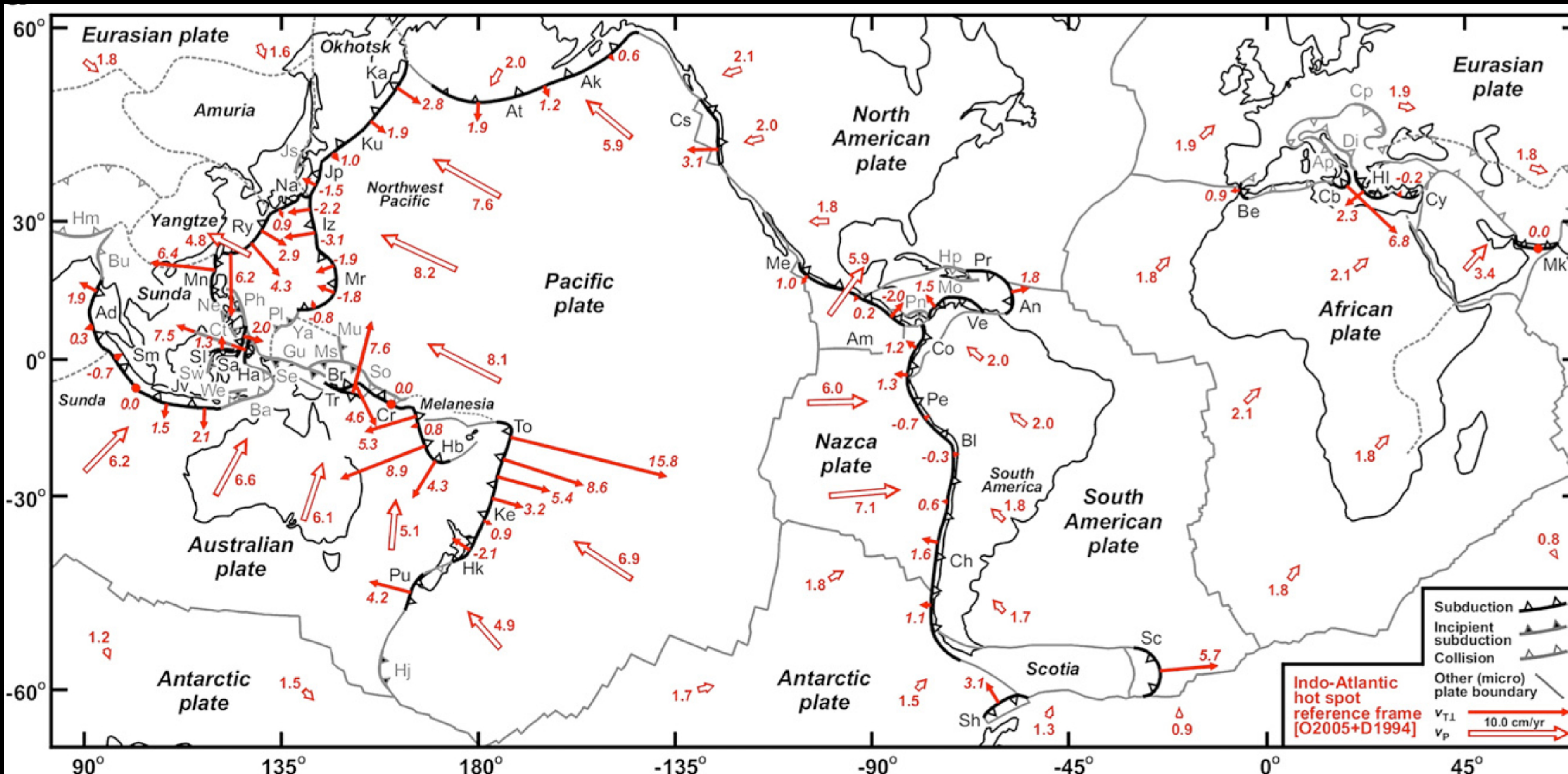
Rohr & Furlong, 95
Zhong & Gurnis, 96
Hall et al., 00
Billen et al., 03
Syracuse & Abers, 06
Kneller & van Keken, 07
Schellart et al., 07
Ammon et al., 08
Jadamec & Billen, 10





Bird 2003

Observe Surface Plate Velocity (1-15 cm/yr)

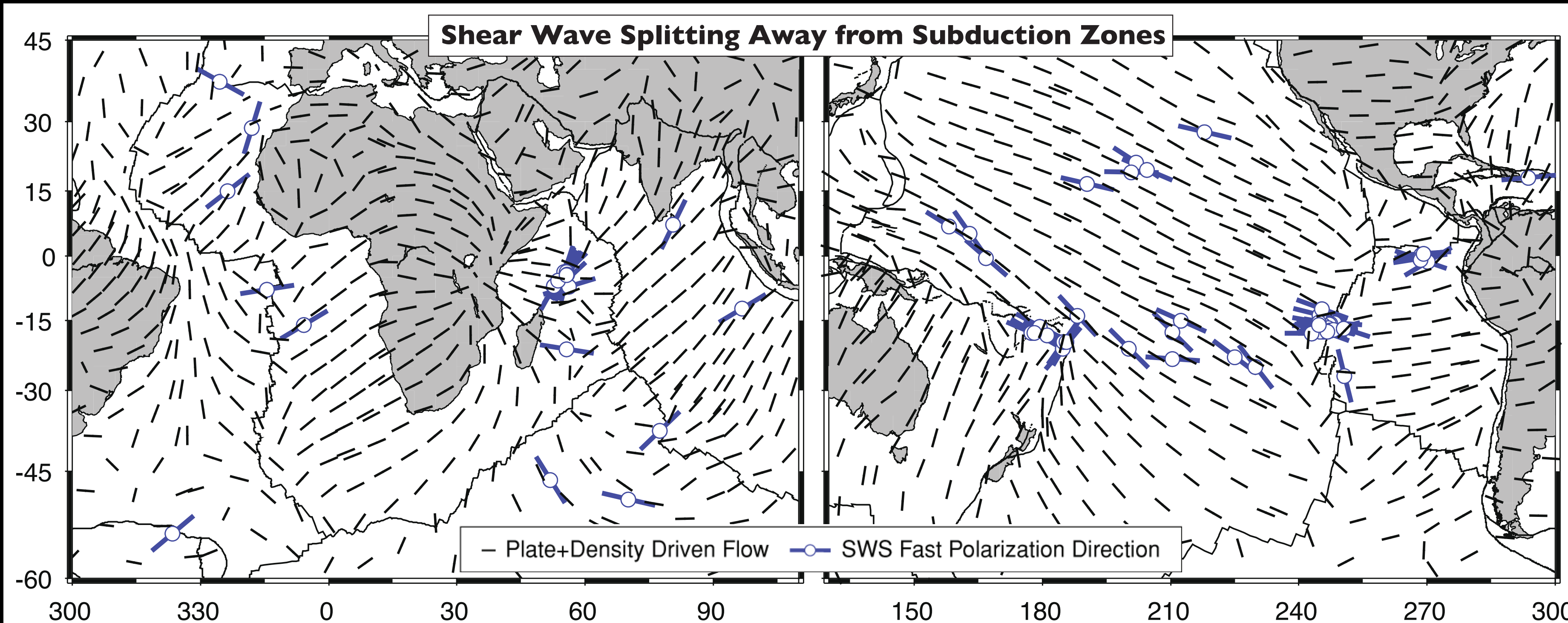


Schellart et al., G-Cubed 2008

Lithosphere (outer layer of Earth) ~15 (52) 'Plates' ~150 km thick
Motion of plates on Earth's surface from GPS measurements

(DeMets and Dixon, GRL 1999; Bird, G-Cubed 2003; Schellart et al., ESR 2008)

What About the Mantle Underneath the Plates?



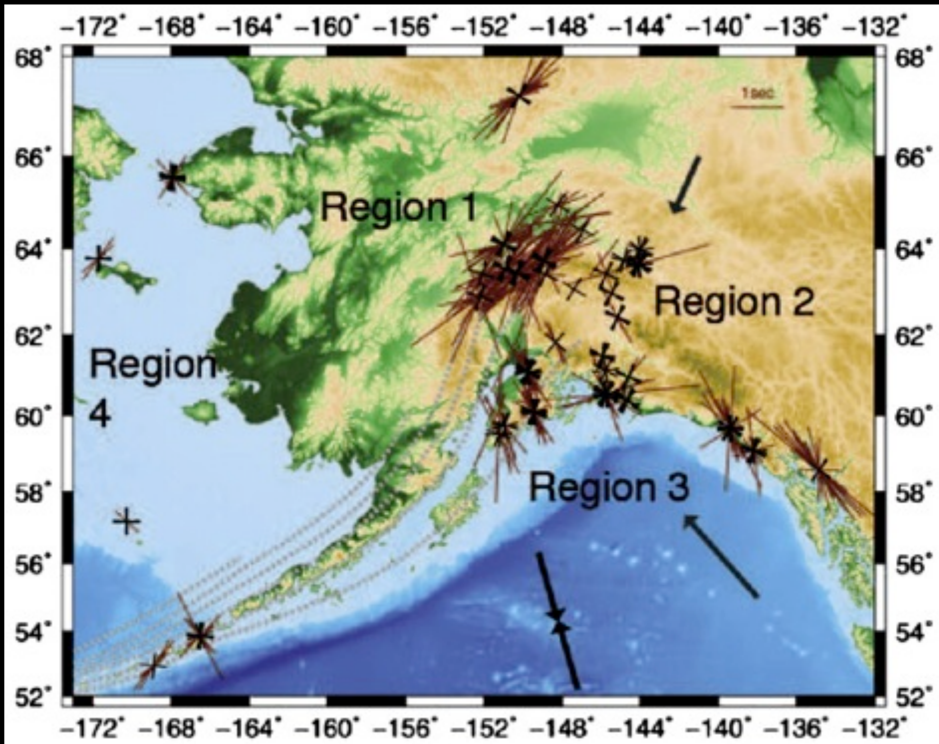
Hanna and Long, 2012

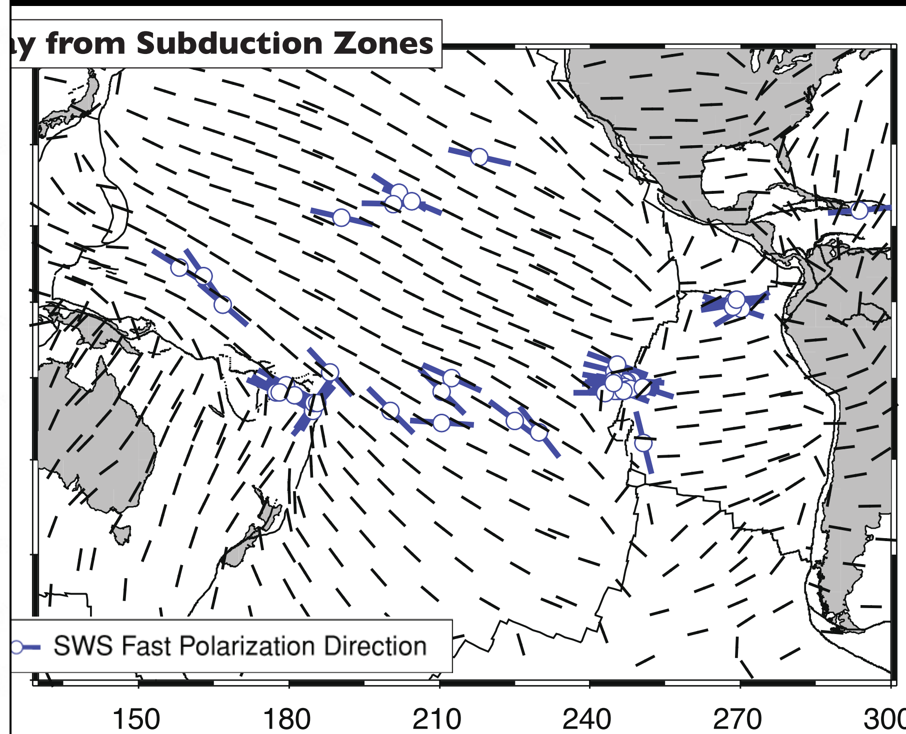
Conrad et al., JGR 2007; Long and Silver, Surv. Geophys. 2009

The fast seismic propagation axis indicates mantle flow is aligned with plate motion indicating **coupling** between the plates and mantle in the center of the tectonic plates

(assuming A type fabric in olivine, where the fast seismic axis is tracking the mantle flow)

What About the Mantle Underneath the Plates?



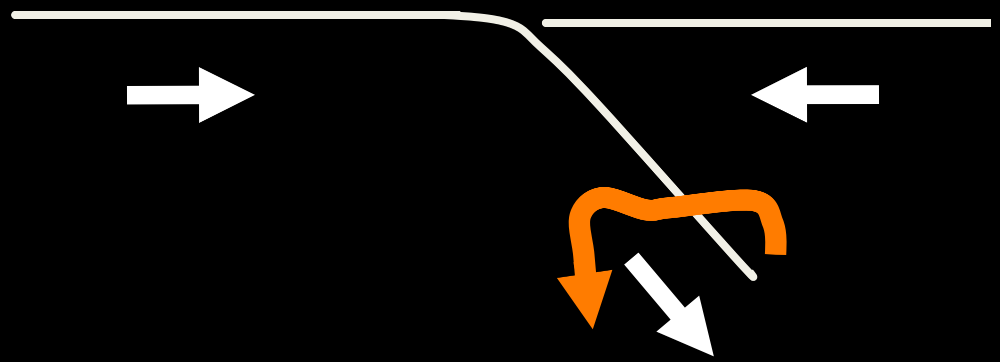


Hanna and Long, 2012

Conrad et al., JGR 2007; Long and Silver, Surv. Geophys. 2009

This is not the case at many subduction zones where the seismic fast axis is not aligned with surface plate motion, implying complex mantle flow in subduction zones and **decoupling** between the plates and mantle (assuming A type fabric in olivine)

How Explain Complex Mantle Wedge Flow & Decoupling?

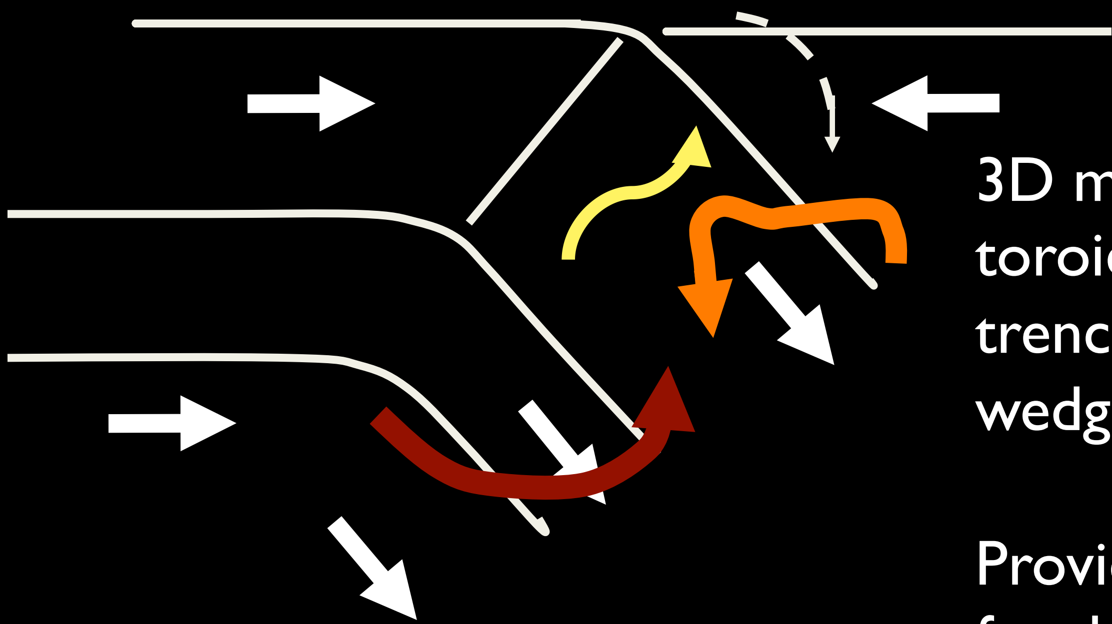


In 2D model, the material in the mantle wedge and that beneath the subducting plate are entrained by the slab, giving mantle flow aligned with plate motion

Thus, 2D models of subduction cannot explain the trench parallel flow implied by the seismic anisotropy

(Tovish et al., JGR 1978)

How Explain Complex Mantle Wedge Flow & Decoupling?



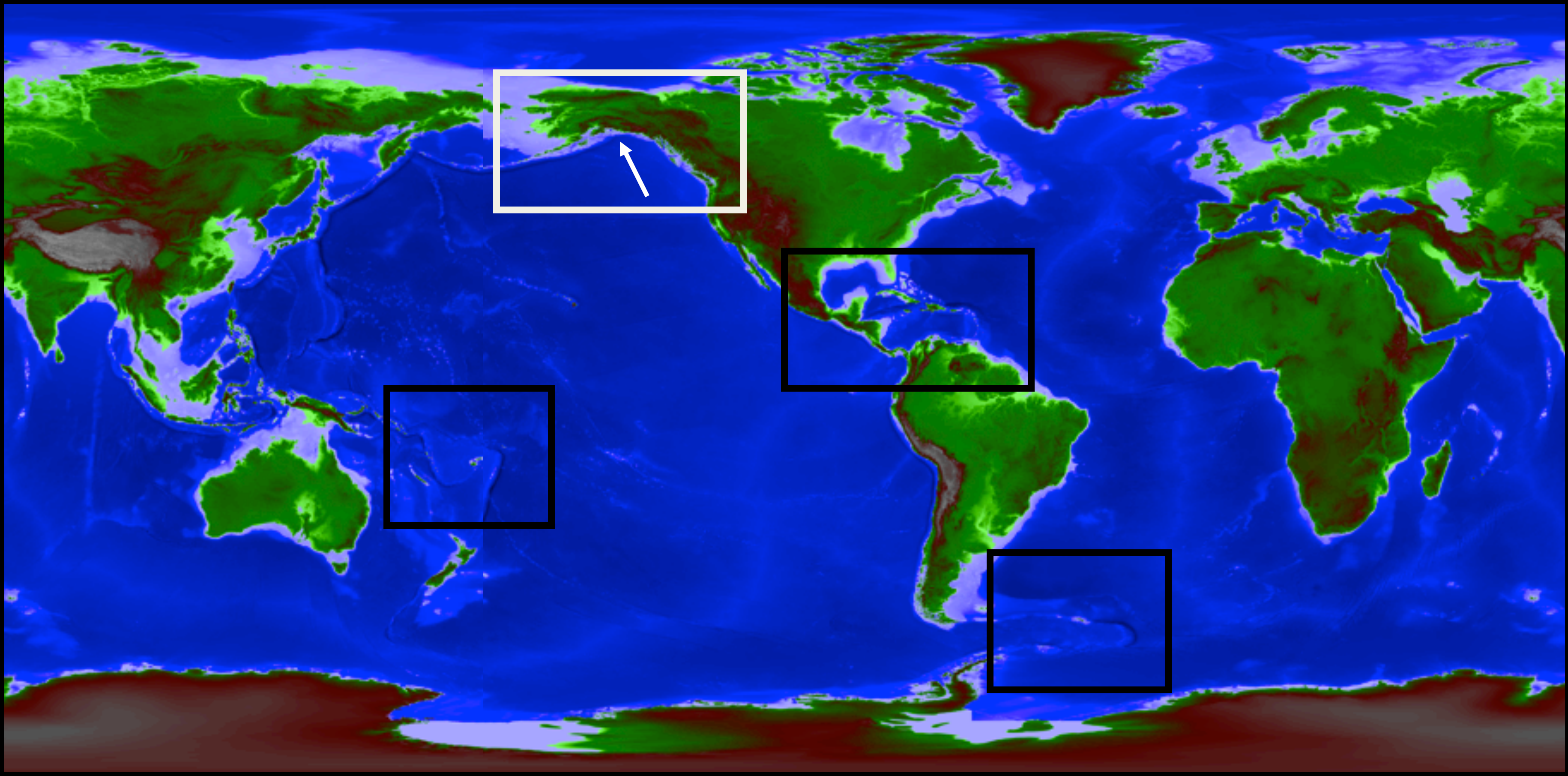
Zhong and Gurnis (Nature, 1996); Buttles and Olson (EPSL, 1998); Kincaid and Griffiths (Nature, 2003); Schellart (JGR, 2004); Funiciello et al (JGR, 2006); Stegman et al. (G cubed, 2006); Piromallo et al. (GRL, 2006); Kneller and van Keken (Nature, 2007); Jadamec and Billen (Nature, 2010); Jadamec and Billen (JGR, 2012)

3D models show slabs pivoting, toroidal flow at lateral slab edges, trench-parallel sub-slab and mantle wedge flow

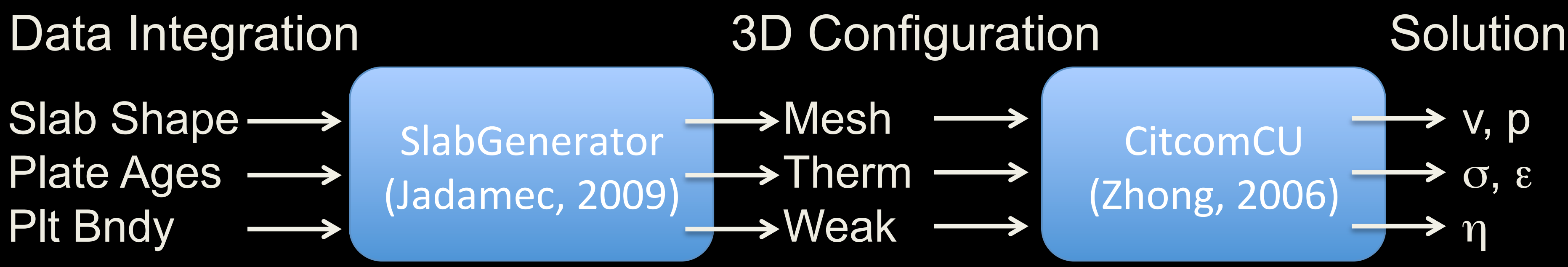
Provide fluid dynamics mechanism for decoupling in direction, but what about in velocity magnitude?

What is the role of rheology in controlling the magnitude of the decoupling?

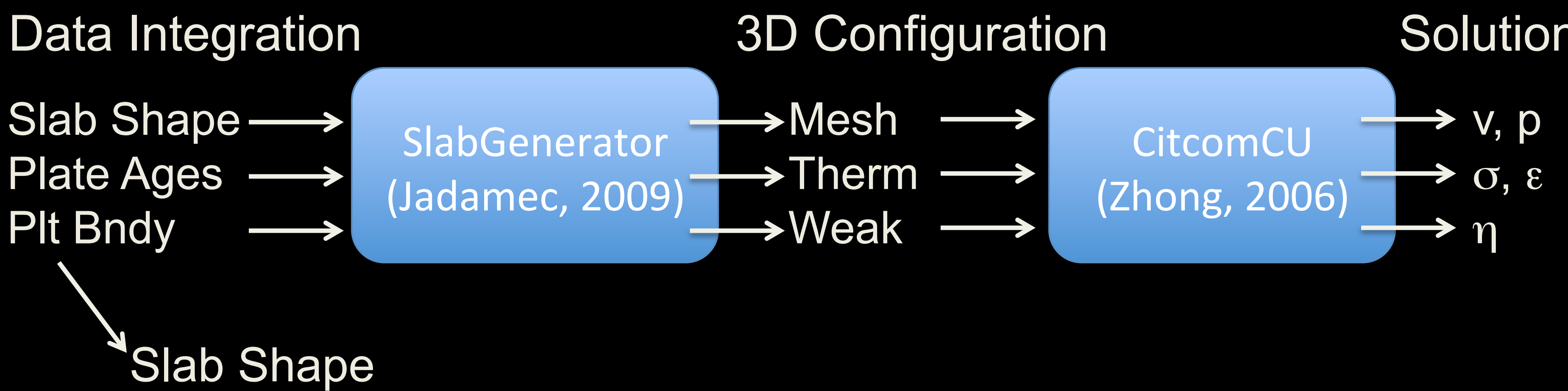
Regionally Based 3D Model to Elucidate Process

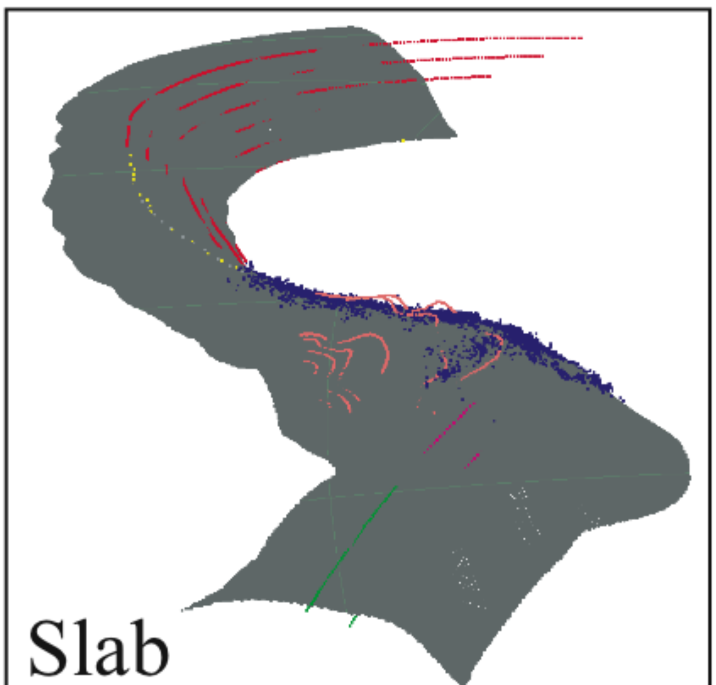


Approach for 3D Numerical Modeling of Plate Boundaries



Approach for 3D Numerical Modeling of Plate Boundaries

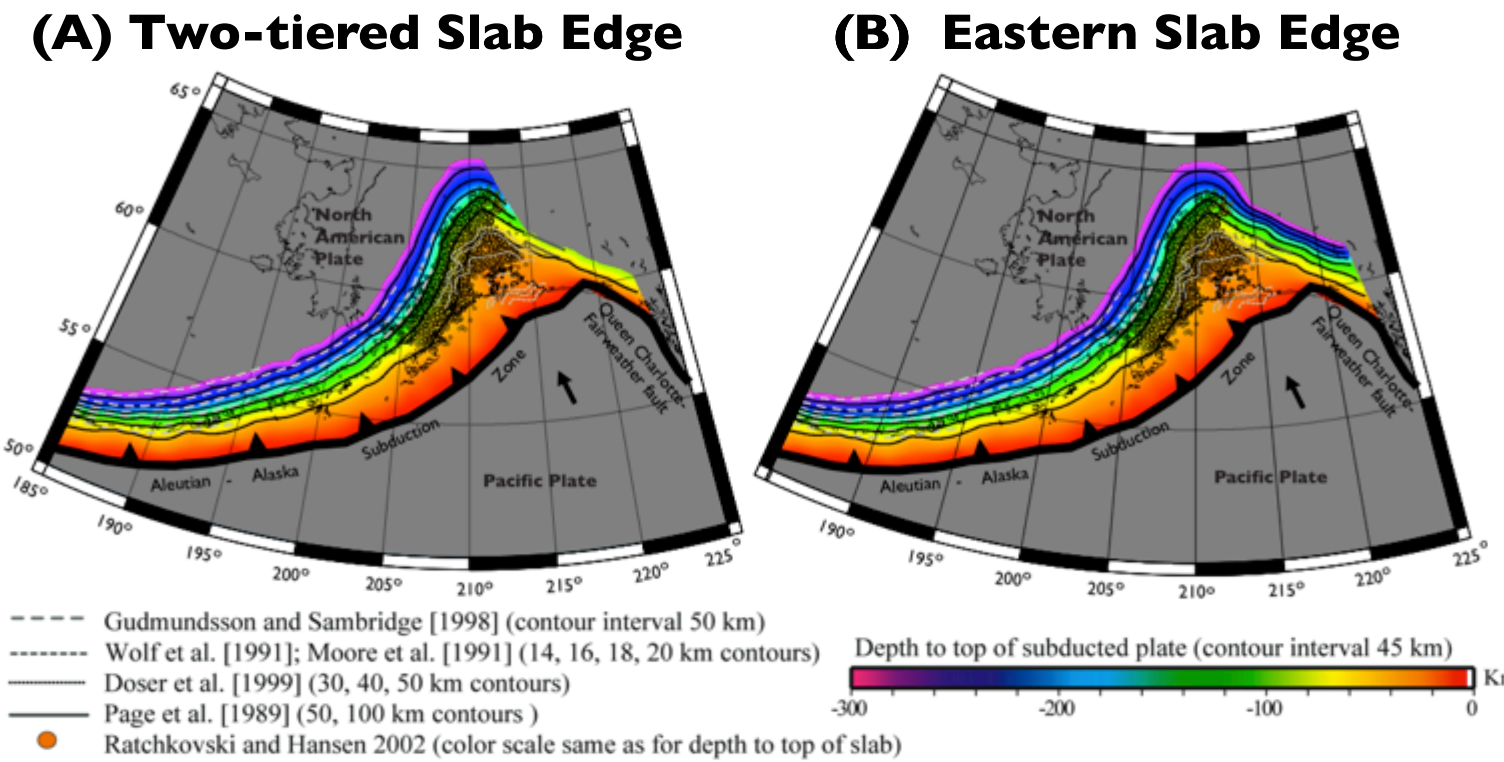




Data for Slab Surface (gray)

- Doser et. al. (1999)
- Gudmundsson and Sambridge (1998)
- Page et al. (1989)
- Plafker et al. (1994)
- Ratchkovski and Hansen (2002)

Data Integration: Slab shape



Study	Data Type	d_{aleut} (km)	d_{akp} (km)	d_{scak} (km)	d_{wr} (km)
Qi et al. [2007]	3D teleseismic tomography	–	> 400	300-400	90
Eberhart-Phillips et al. [2006]	3D tomography	–	> 200	160-180	50-60
Zhao et al. [1995]	3D tomography	–	> 190	165	> 90
Kissling and Lahr [1991]	3D tomography	–	–	120-150	–
Fuis et al. [2008]	Seismic reflection, refraction earthquake hypocentral locations	–	240	175	100
Ferris et al. [2003]	Teleseismic receiver function analysis	–	–	150	–
Ratchkovski and Hansen [2002]	Earthquake hypocentral locations	–	210	165-185	–
Page et al. [1989]	Seismic reflection, refraction earthquake hypocentral locations	–	–	–	> 100
Engdahl and Gubbins [1987]	Simultaneous travel time inversion	400	–	–	–
Stephens et al. [1984]	Earthquake hypocentral locations	–	–	–	85
Boyd and Creager [1991]	Local seismicity and teleseismic residual sphere analysis	600	–	–	–
Gudmundsson and Sambridge [1998]	RUM seismic model	300	250	150	–

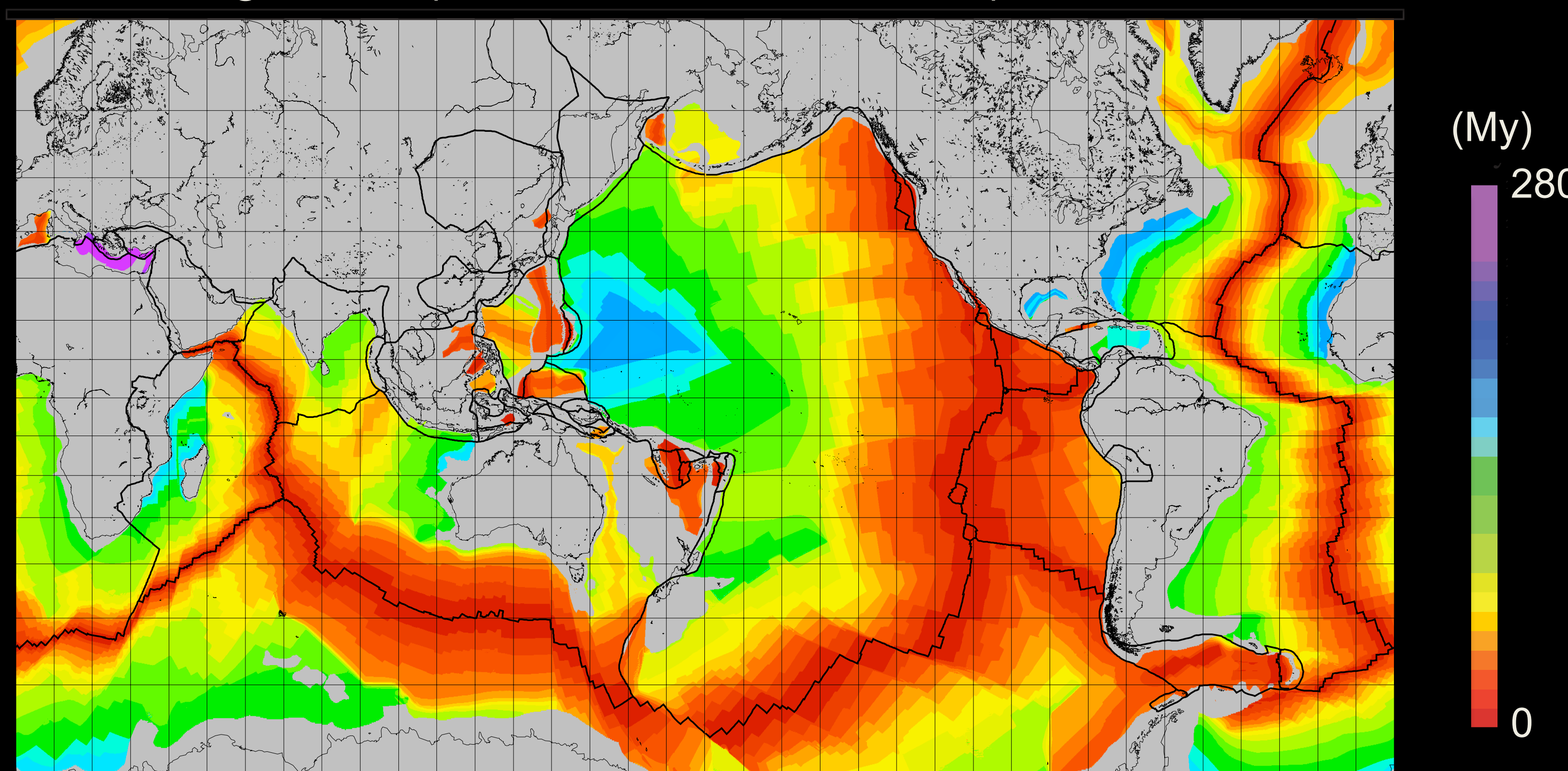
Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012

Approach for 3D Numerical Modeling of Plate Boundaries

Data Integration → **3D Configuration** → **Solution**

Slab Shape →
Plate Ages → **SlabGenerator (Jadamec, 2009)** → Mesh, Therm, Weak → **CitcomCU (Zhong, 2006)** → v, p; σ, ε; η
Plt Bndy →

Plt Bndy → Seafloor Age Grid (Muller et al., 1997, 2008)

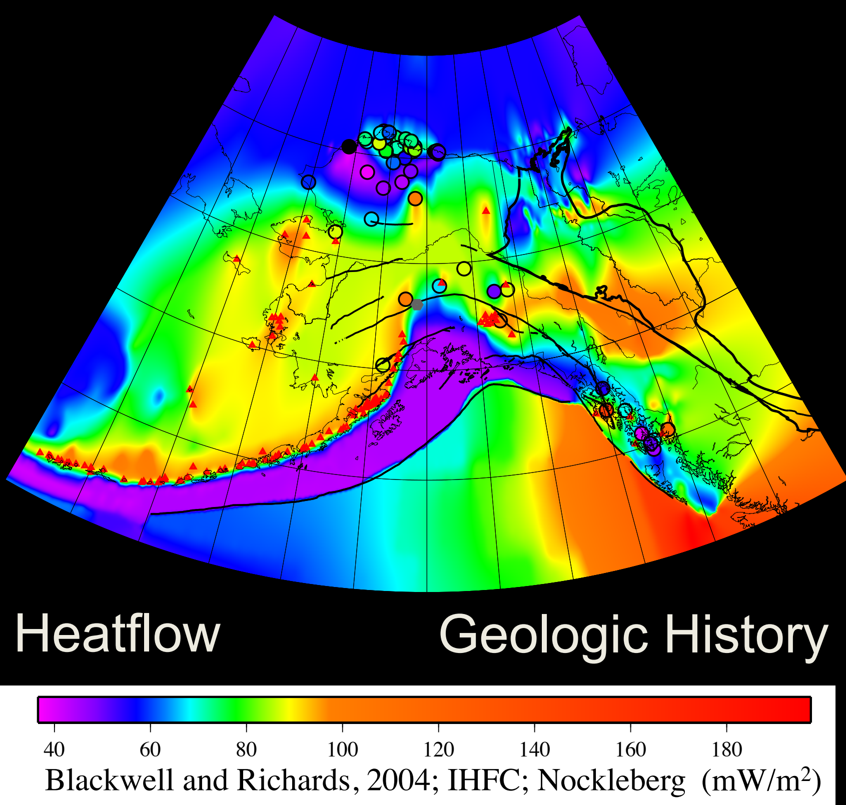


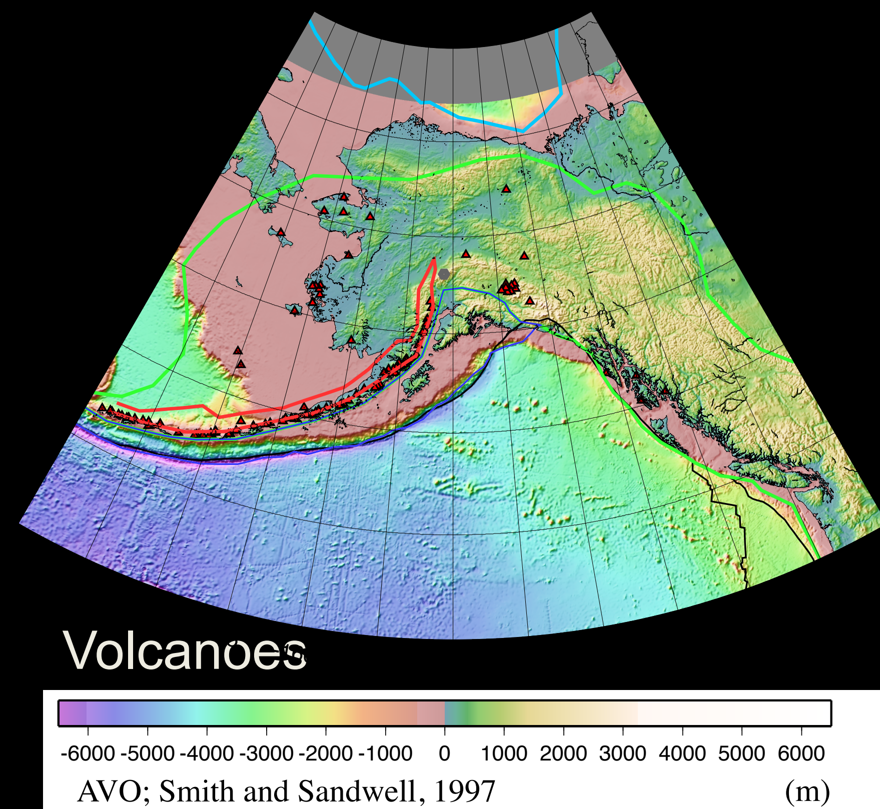
Approach for 3D Numerical Modeling of Plate Boundaries

Data Integration → SlabGenerator (Jadamec, 2009) → 3D Configuration → CitcomCU (Zhong, 2006) → Solution

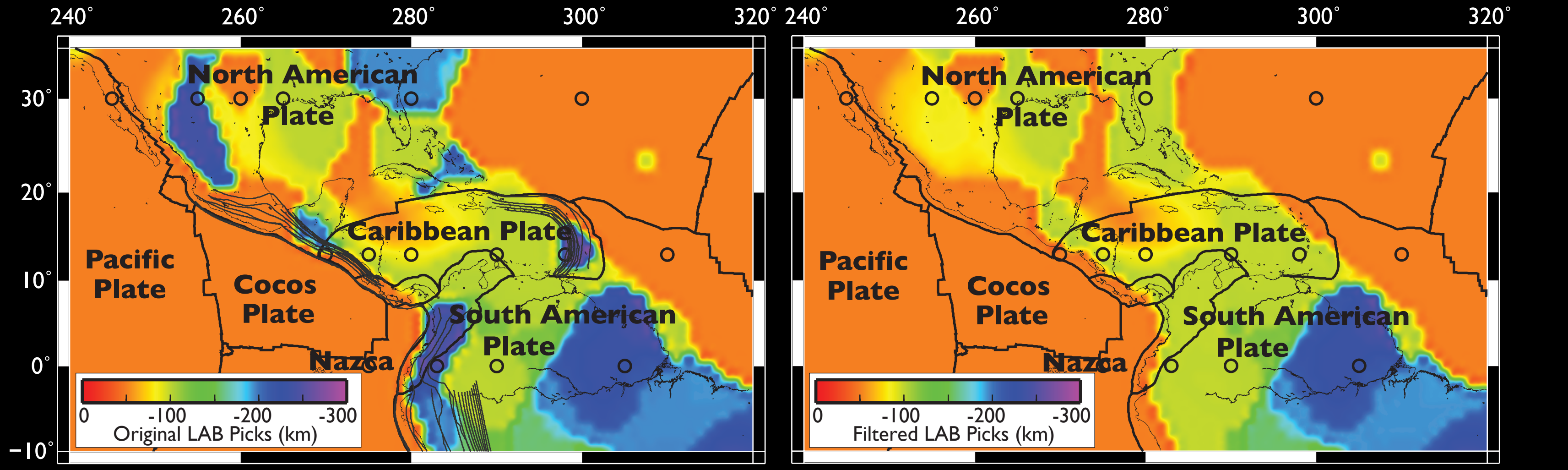
- Slab Shape → SlabGenerator (Jadamec, 2009) → Mesh → CitcomCU (Zhong, 2006) → v, p
- Plate Ages → SlabGenerator (Jadamec, 2009) → Therm → CitcomCU (Zhong, 2006) → σ, ε
- Plt Bndy → SlabGenerator (Jadamec, 2009) → Weak → CitcomCU (Zhong, 2006) → η

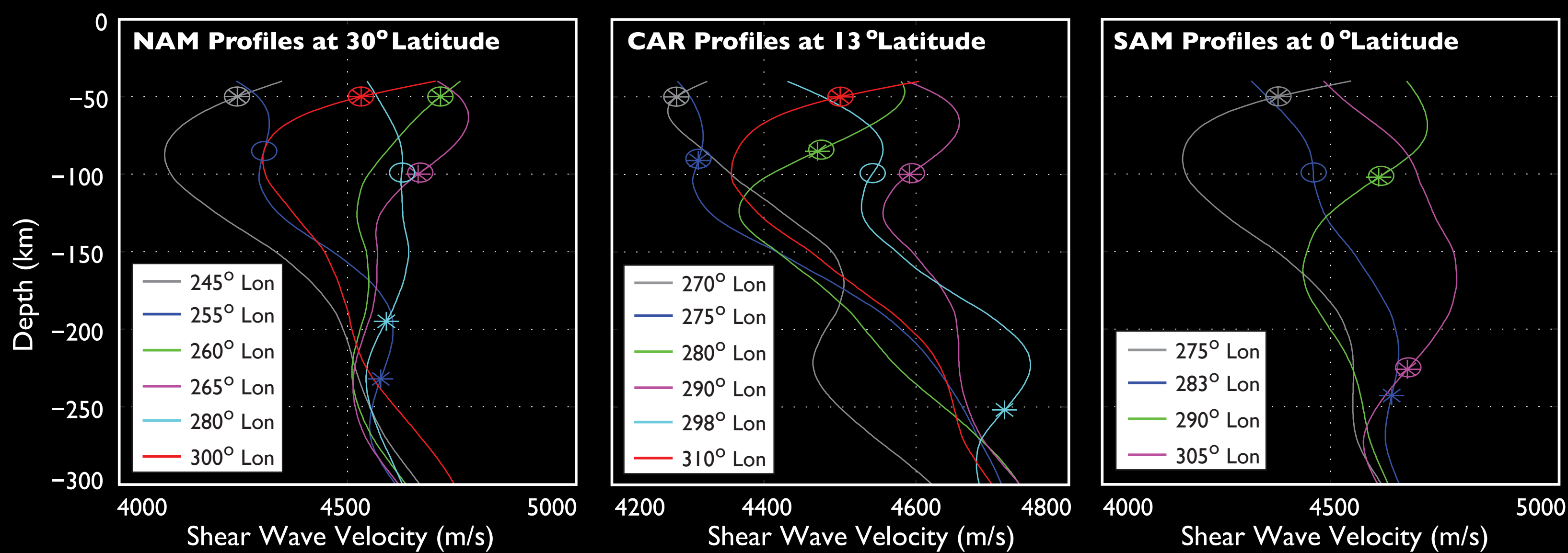
Plt Bndy ↘ Constraints on Upper Plate Temperature





Use Shear Wave Velocity to Constrain Plate Thickness

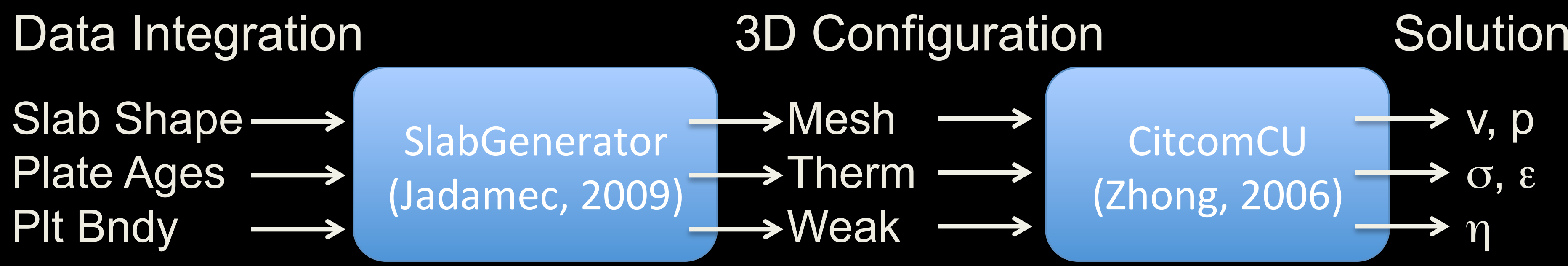




Jadamec and Fischer, In Prep. 2013

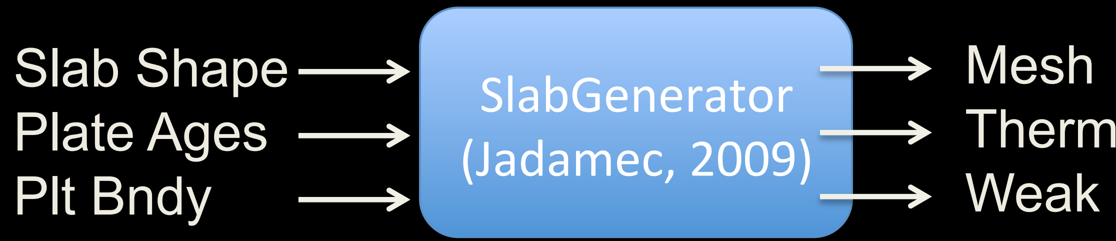
Data: Lekic & Romanowicz, 2011; Bird, 2003; Syracuse & Abers, 2006; Gudmundsson & Sambridge, 1998

Approach for 3D Numerical Modeling of Plate Boundaries



Model Configuration

C/C++ Program for Geodynamics Workflow



	Mesh Generation	Temperature	Shear Zone	Visualization
Input Files	modelA_param.lon modelA_param.lat modelA_param.rad	slab_shape.dat slab_edge.dat seafloor_ages.dat region.poly* polyregion.exp*	plate_interface.dat	
Output Files	mesh_vects.ascii	modelA_therm.bin	modelA_weak.bin	modelA_CT.dat

Model Configuration

C/C^{++} Program for Geodynamics Workflow

Slab Shape → SlabGenerator (Jadamec, 2009) → Mesh
Plate Ages → → Therm
Plt Bndy → → Weak

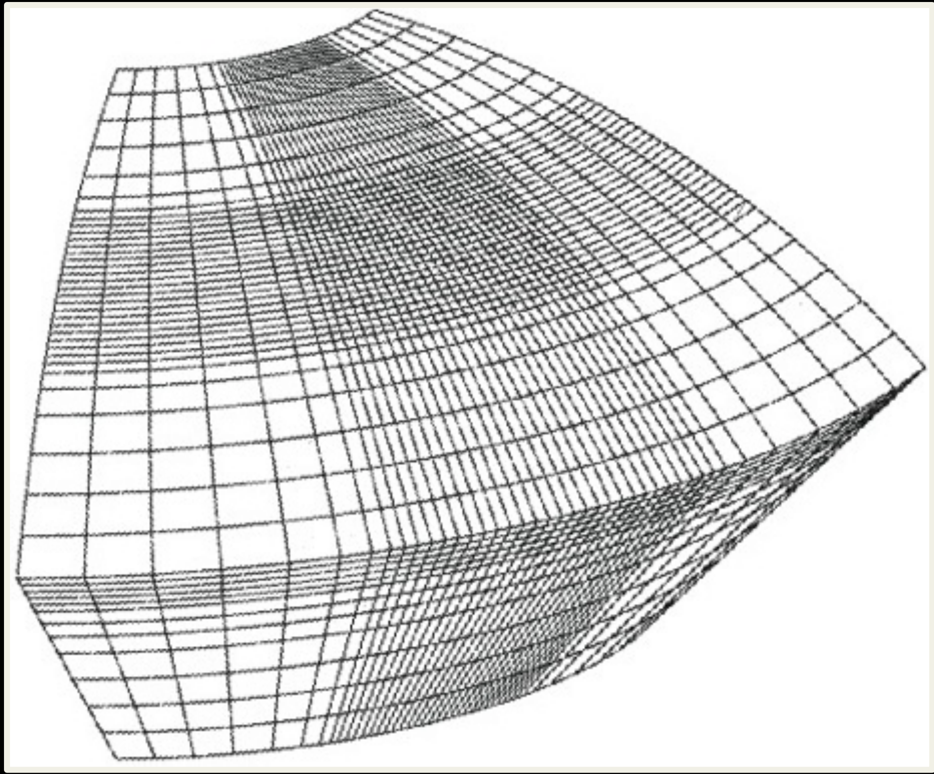
Mesh Generation

Input Files

```
modelA_param.lon
modelA_param.lat
modelA_param.rad
```

Output Files

```
mesh_vects.ascii
```



Model Configuration

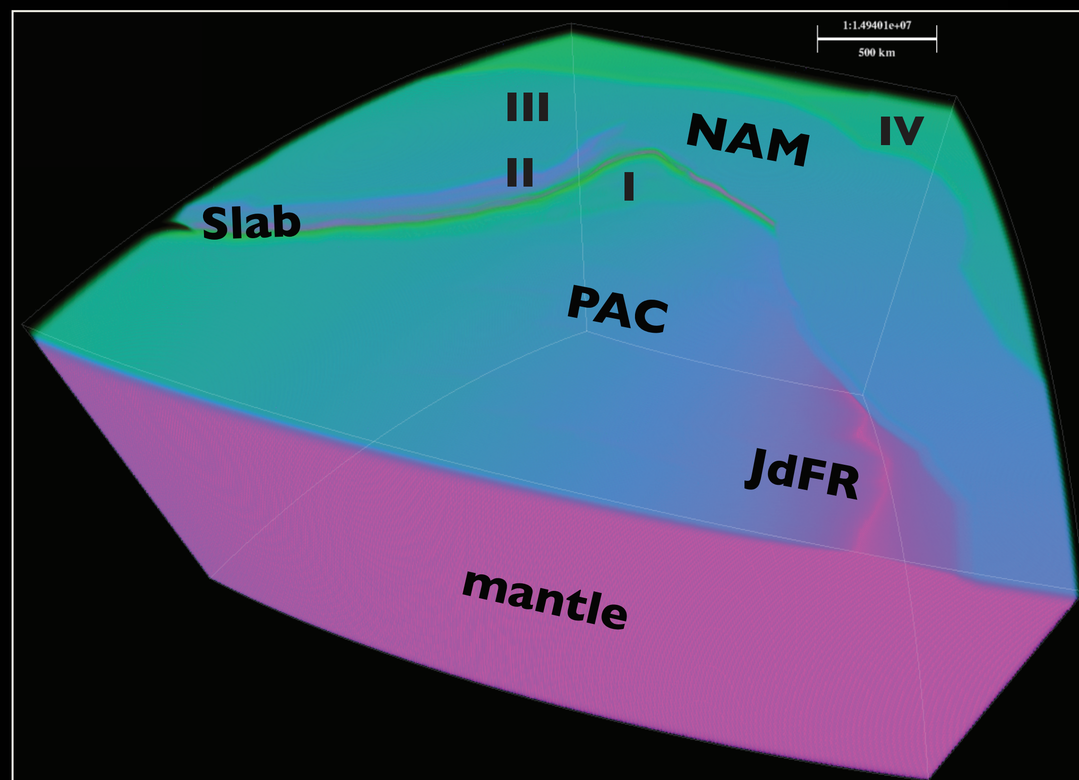
C/C^{++} Program for Geodynamics Workflow

Slab Shape → SlabGenerator (Jadamec, 2009) → Mesh
Plate Ages → Therm
Plt Bndy → Weak

Temperature

```
slab_shape.dat
slab_edge.dat
seafloor_ages.dat
region.poly*
polyregion.exp*

modelA_therm.bin
```



C/C++ Program for Geodynamics Workflow

Model Configuration

Slab Shape → SlabGenerator (Jadamec, 2009) → Mesh
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Temperature

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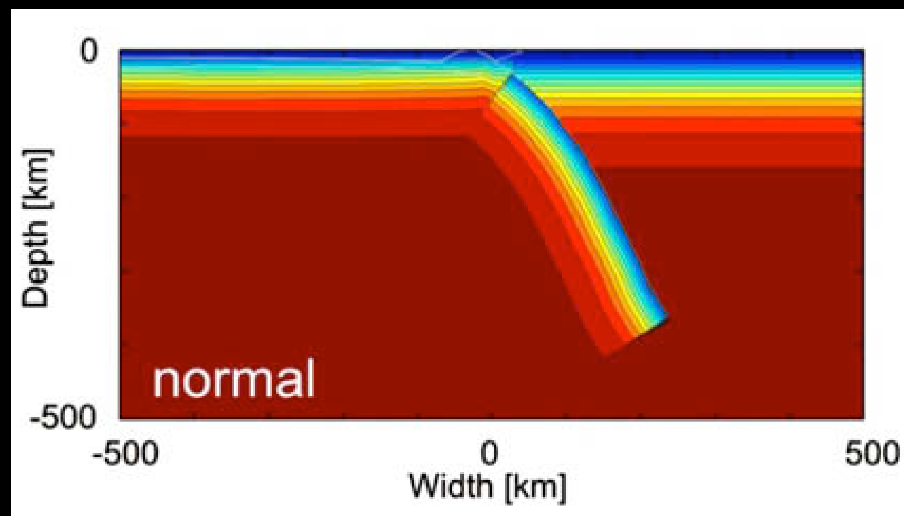
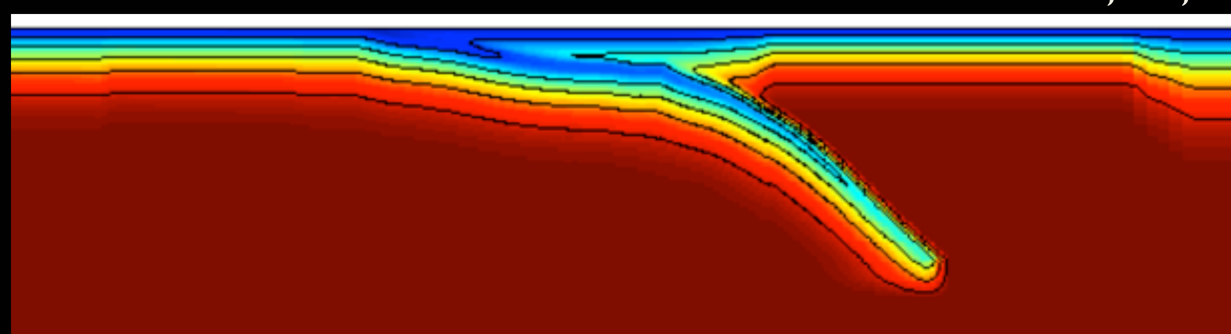
slab_shape.dat
slab_edge.dat
seafloor_ages.dat
region.poly*
polyregion.exp*

modelA_therm.bin
```



Kaus, et al., 09



Jadamec and Billen, 10, 12

C/C++ Program for Geodynamics Workflow

Model Configuration

Slab Shape → SlabGenerator (Jadamec, 2009) → Mesh
Plate Ages → → Therm
Plt Bndy → → Weak

Shear Zone

`plate_interface.dat`

`modelA_weak.bin`

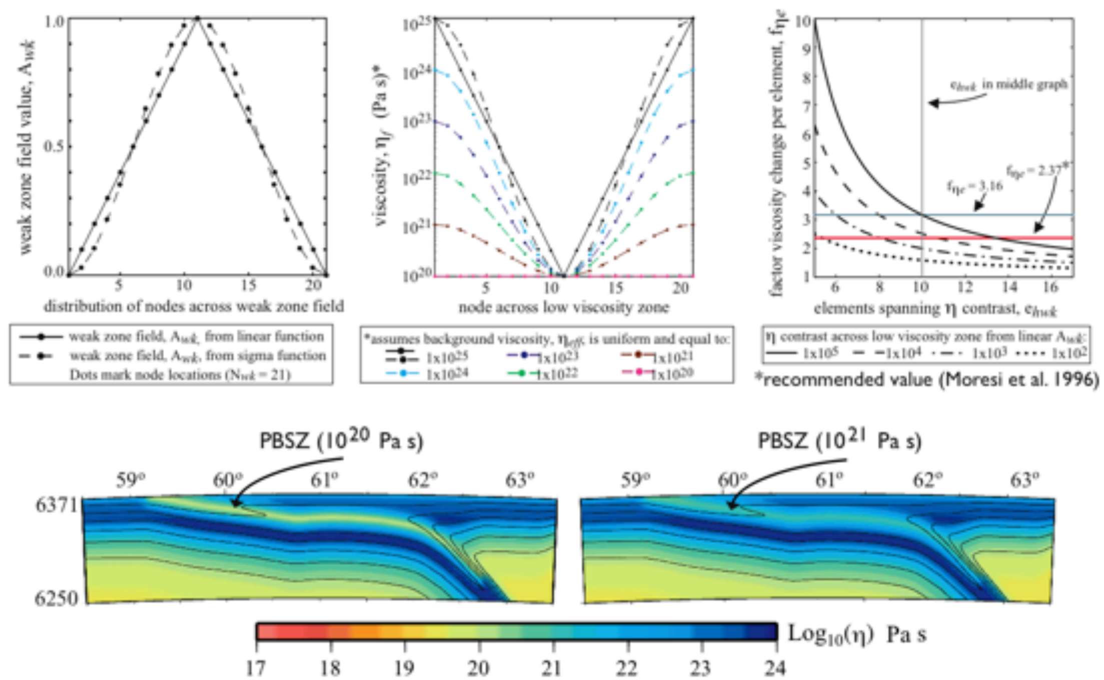
3D Plate Boundary Shear Zone

We then define a 3D low viscosity layer to separate the plates (plate boundary shear zone) where

$$\eta_{wk} = 10^{[(log_{10}(\eta_{eff}))(1-A_{wk})]}$$

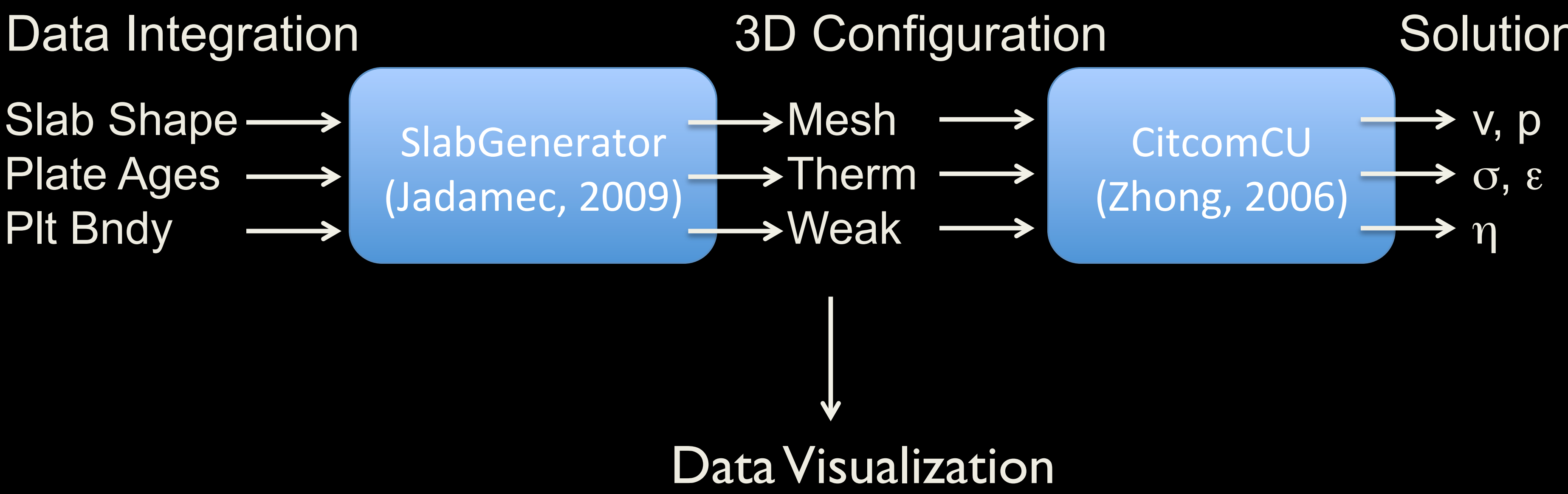
and the final viscosity becomes

$$\eta_f = min\,(\eta_{eff}, \eta_{wk})$$

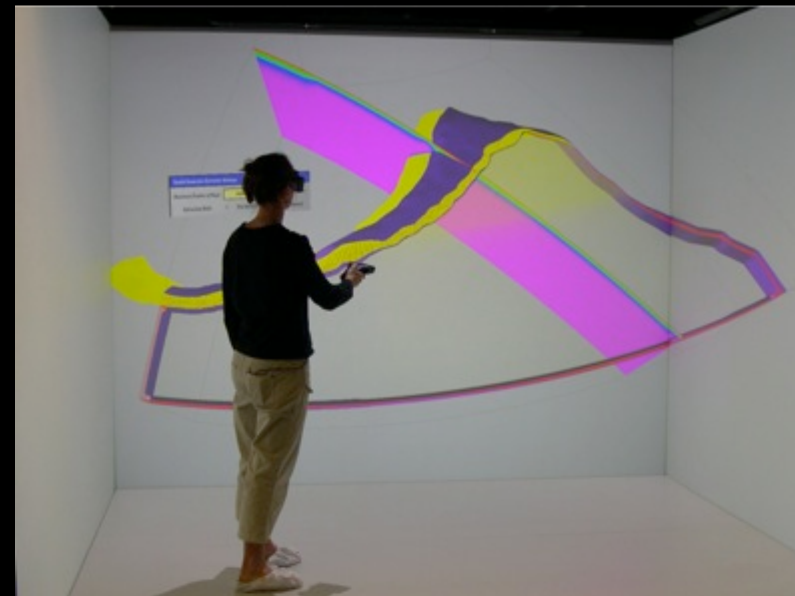


Jadamec and Billen, Nature 2010;
Jadamec and Billen, JGR 2012;
Jadamec et al., XSEDE 2012

Approach for 3D Numerical Modeling of Plate Boundaries



Three-dimensional Data Visualization

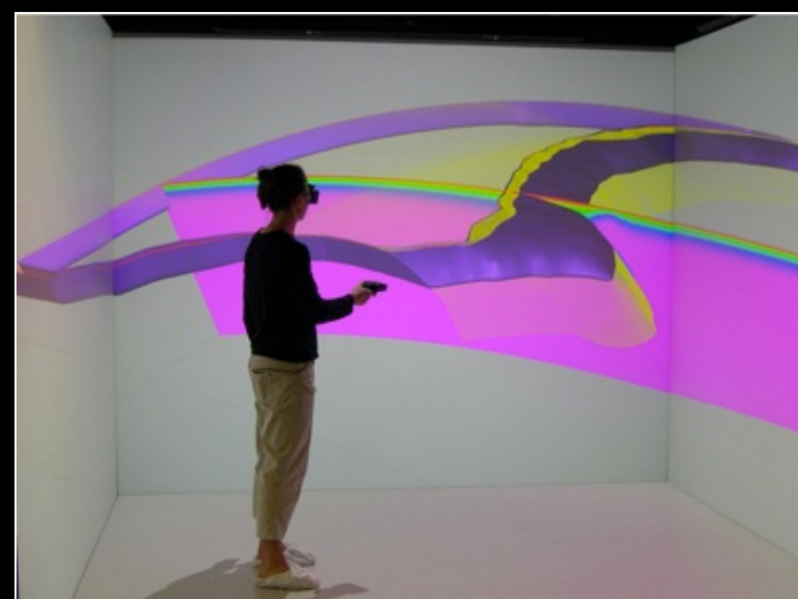


3D Immersive virtual reality

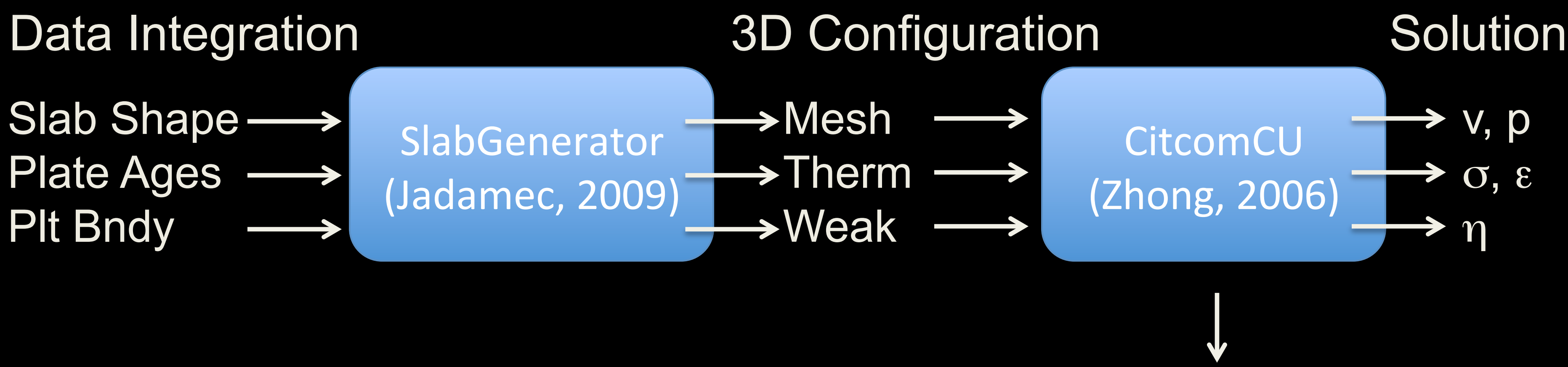
Interactive model exploration,
GB of data

Real-time evaluation of hypotheses

Kreylos et al. 2006; Kellogg et al. 2008



Approach for 3D Numerical Modeling of Plate Boundaries



Solves conservation equations (1,2) for viscous flow (Moresi et al. 96; Zhong, 06)

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\nabla p - \nabla \cdot [\eta_{\mathrm{eff}}(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})] = \rho_{\mathrm{o}} \alpha (T - T_{\mathrm{o}}) g \delta_{\mathrm{rr}} \quad (2)$$

Model Domain and Bounds

~30° x ~30° x 1500 km

On the order of 10^8 elements

2.5 to 25 km resolution

Computing Specifications

Run on XSEDE, TACC and PSC

~20,000 to ~45,000 Hours/job

100s to 1000s of cores

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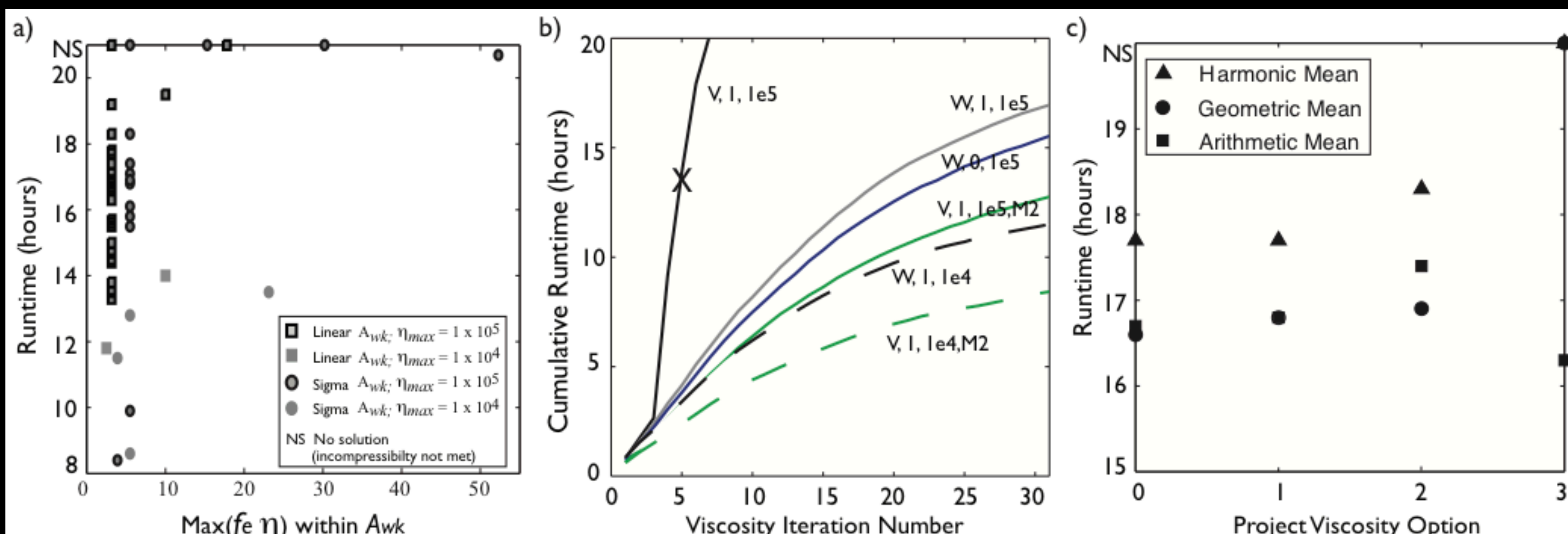
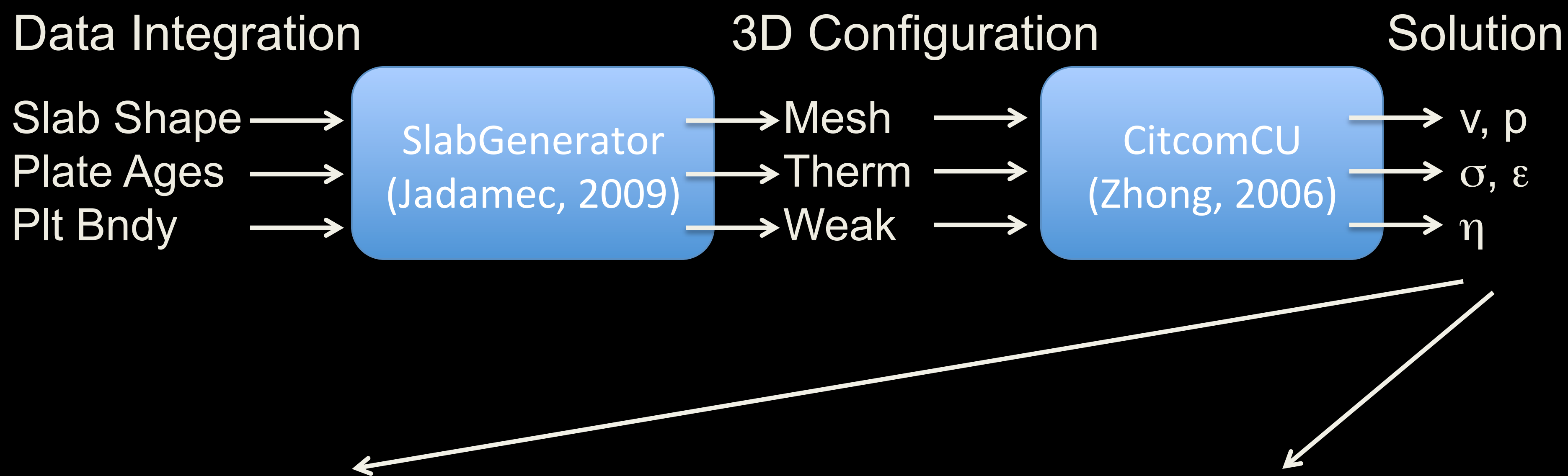


Jadamec et al., XSEDE 2012

Large viscosity variations in Earth challenge for geodynamics codes
(Moresi and Solomotov, 1995; Tackley, 1996; May and Moresi, 2008; Jadamec et al., 2012)

Approach for 3D Numerical Modeling of Plate Boundaries



Mantle Deformation Constraints

Seismic Anisotropy
Mantle upwellings
Rock deformation experiments

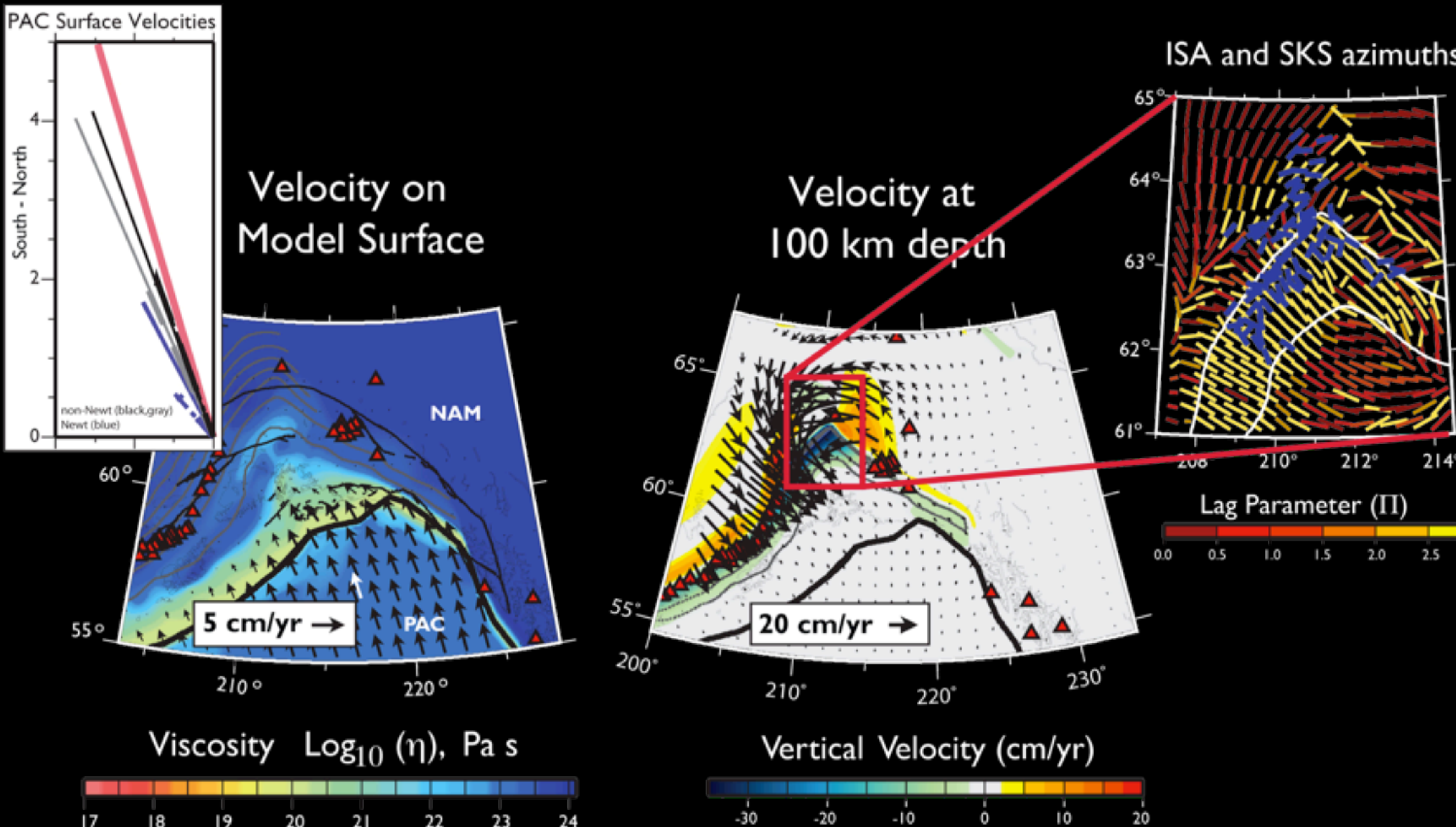
(Jadamec and Billen, Nature 2010)
(Jadamec and Billen, JGR 2012)
(Durance et al., AJES 2012)
(Jadamec and Moresi, In Prep. 2013)
(Jadamec and Fischer, In Prep., 2013)

Lithospheric Deformation Constraints

Pacific Plate velocity
GPS Wrangell Block
Exhumation/Subsidence
Global Strain Rate Model

(Jadamec et al., EPSL, In Rev., 2013)
(Jadamec et al., In Prep., 2013)

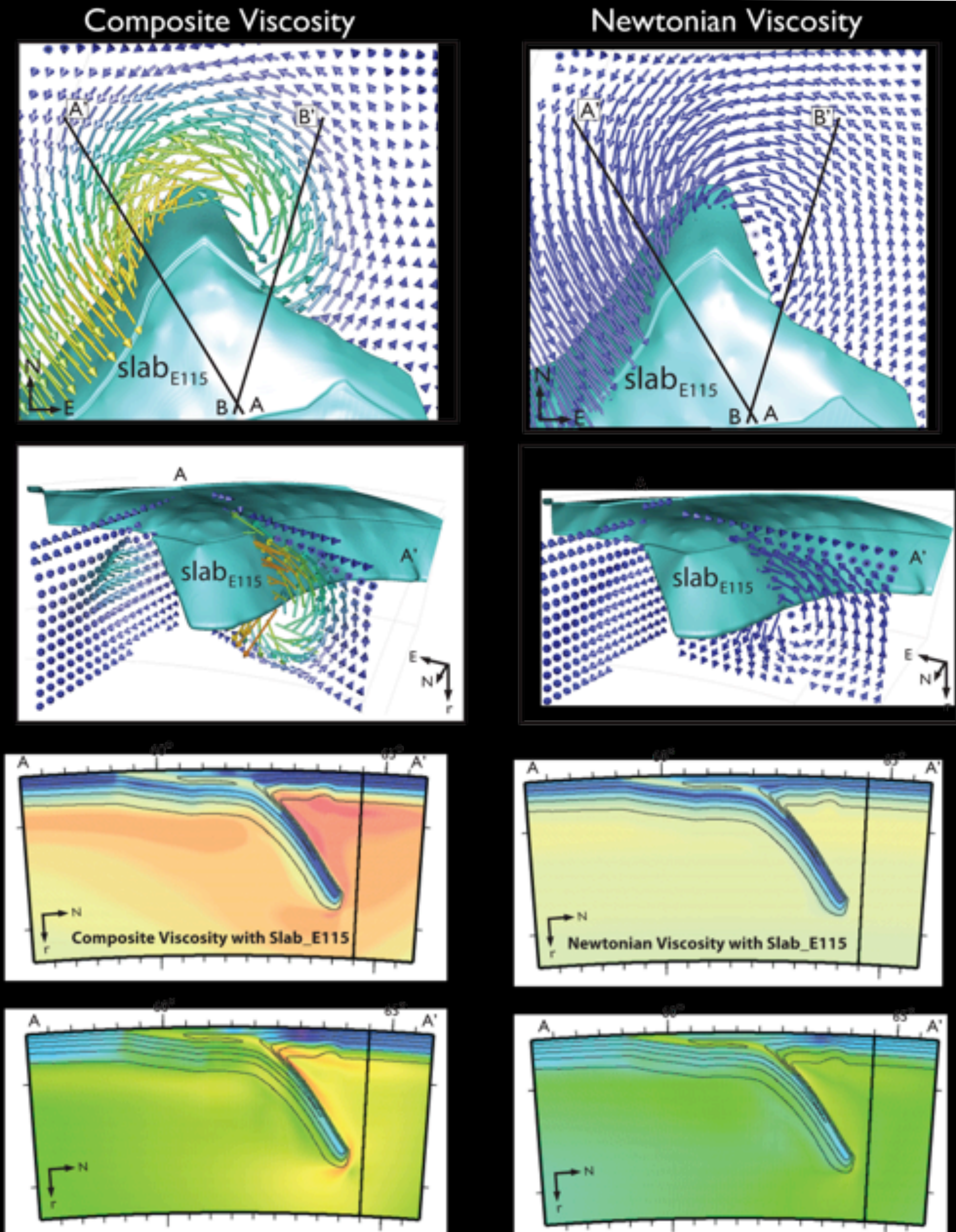
Models w/Rapid Mantle Flow Fit Plate Motions & Anisotropy

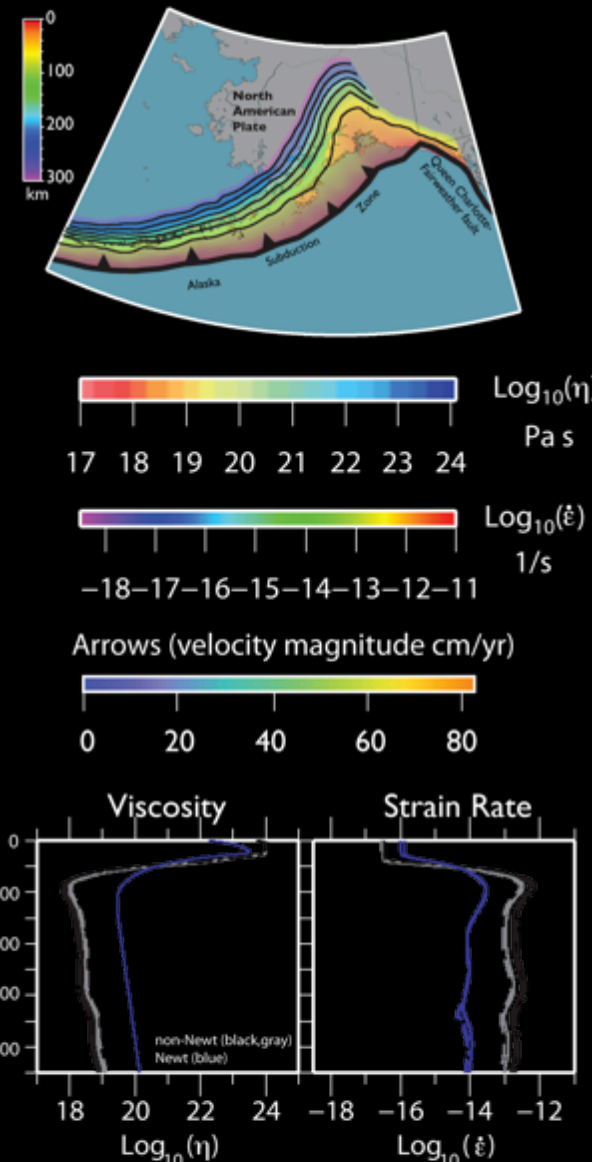


Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012

Plate Motion Constraints: DeMets and Dixon, GRL 1999
SKS Constraints: Christensen and Abers, JGR 2010

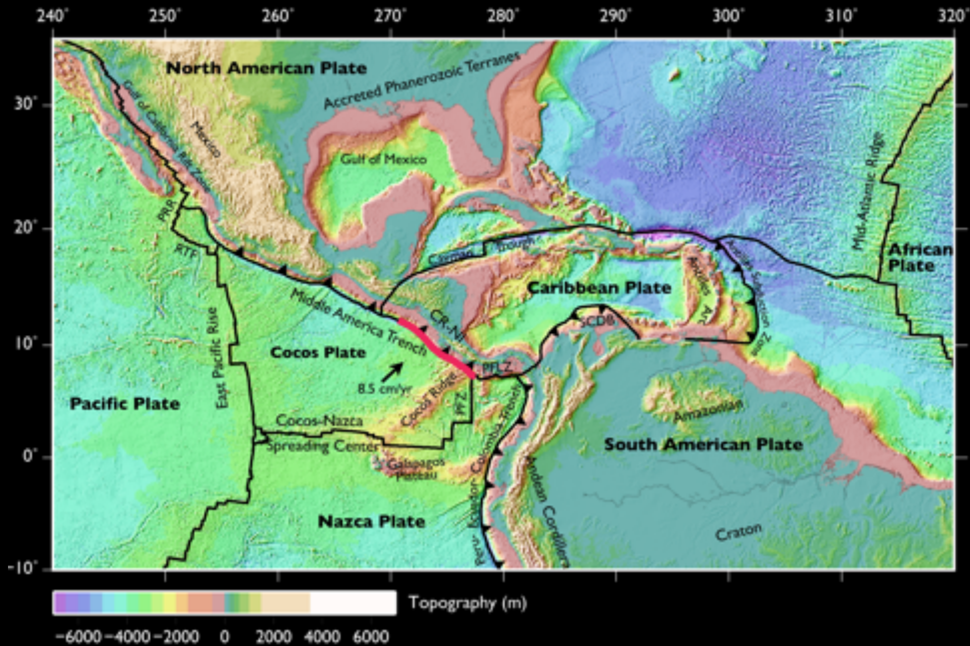
3D Mantle Flow Field Around the Alaska Slab Edge

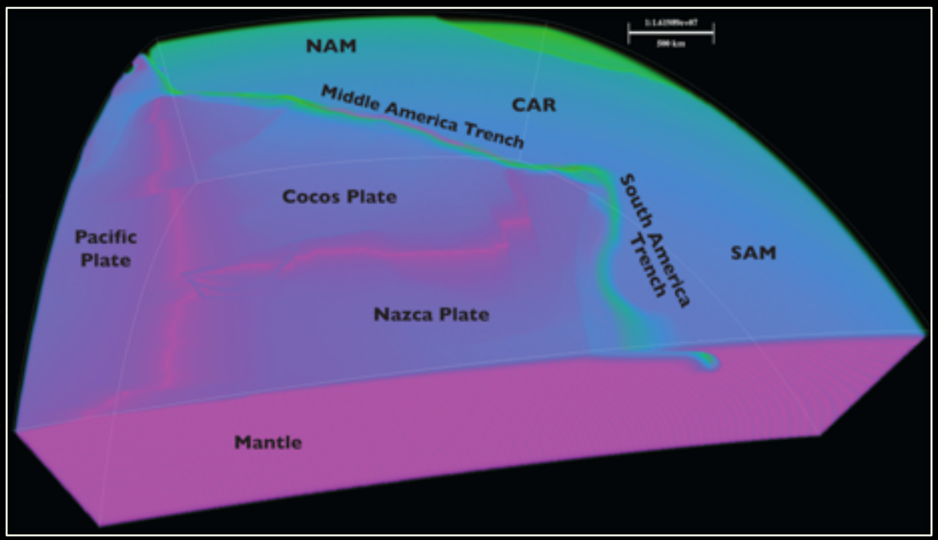


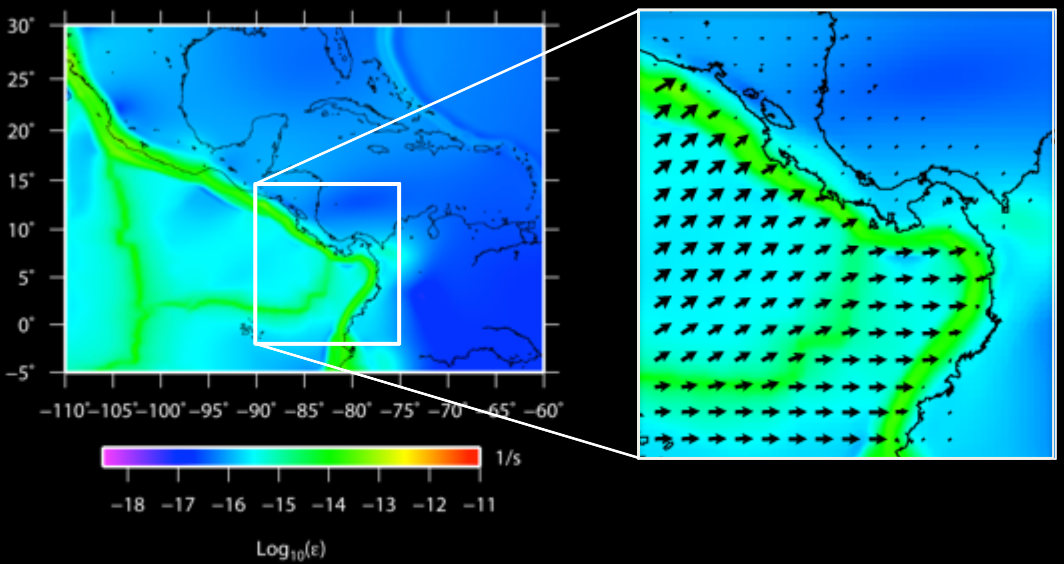


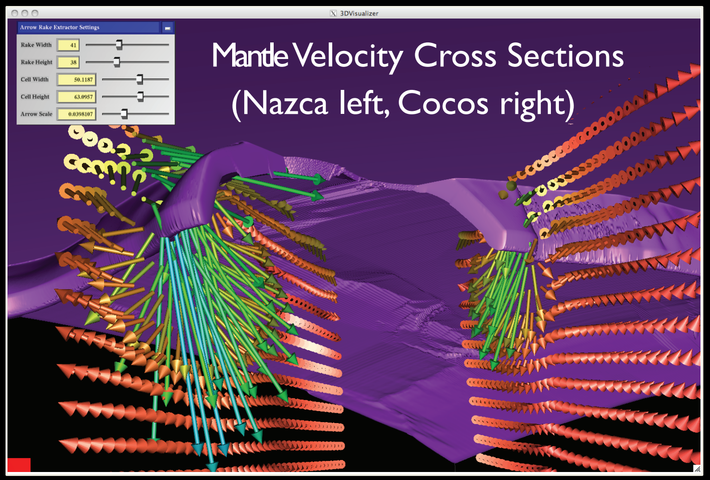
Jadamec and Billen, Nature 2010
Jadamec and Billen, JGR 2012

3D Numerical Models of Mantle Flow in Central America



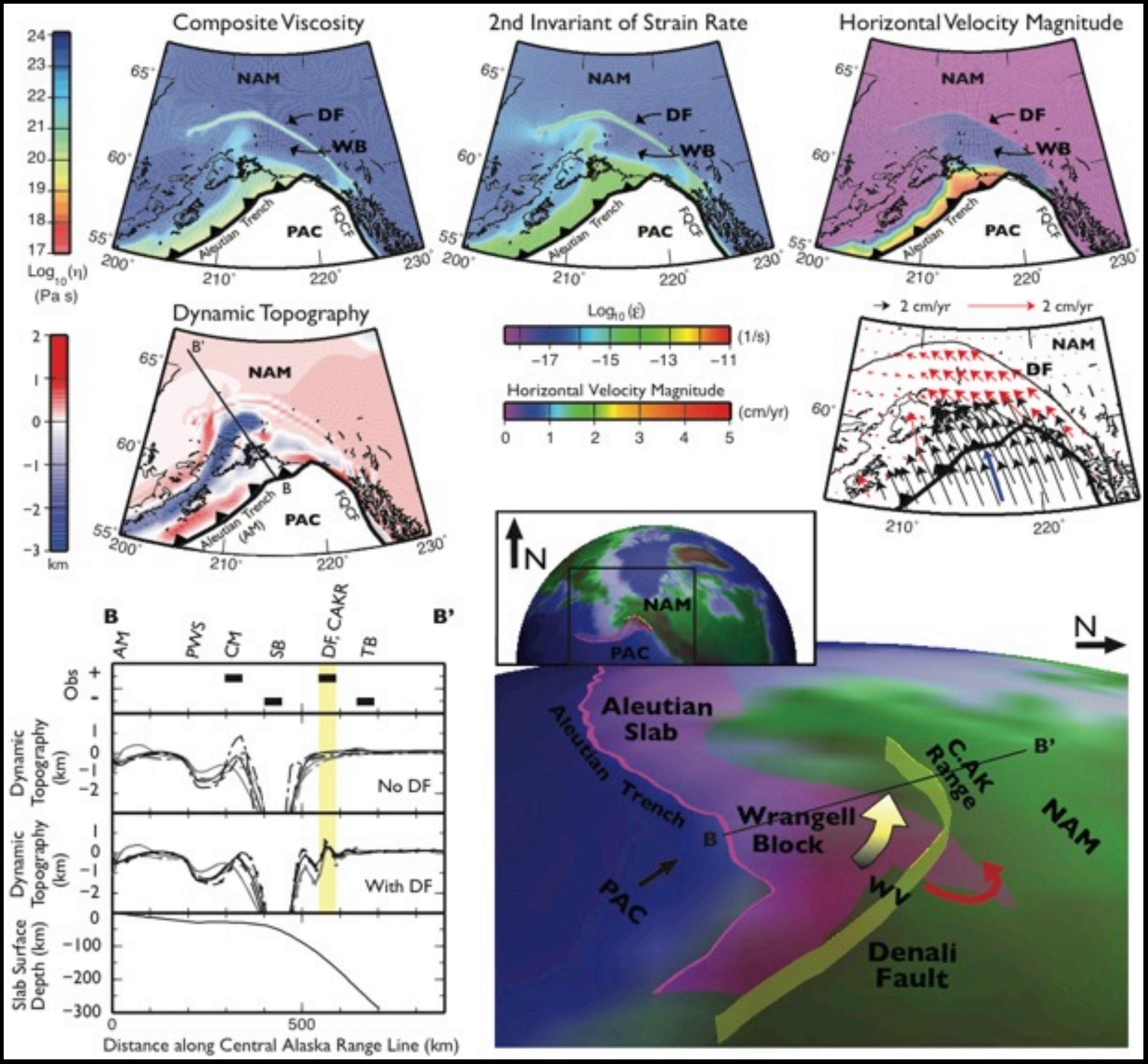






Jadamec and Fischer, In Prep. 2013

Flat Slab Subduction Driving Upper Plate Deformation



Jadamec, Billen, and Roeske, EPSL, In Revision 2013

Broader Impacts, Societal Impacts, Communication

Volcan Arenal, Costa Rica

Broader Impacts, Societal Impacts, Communication

Painting by Lynn Jadamec

Communication Among Scientists, EarthCube, Impacts

Thank You