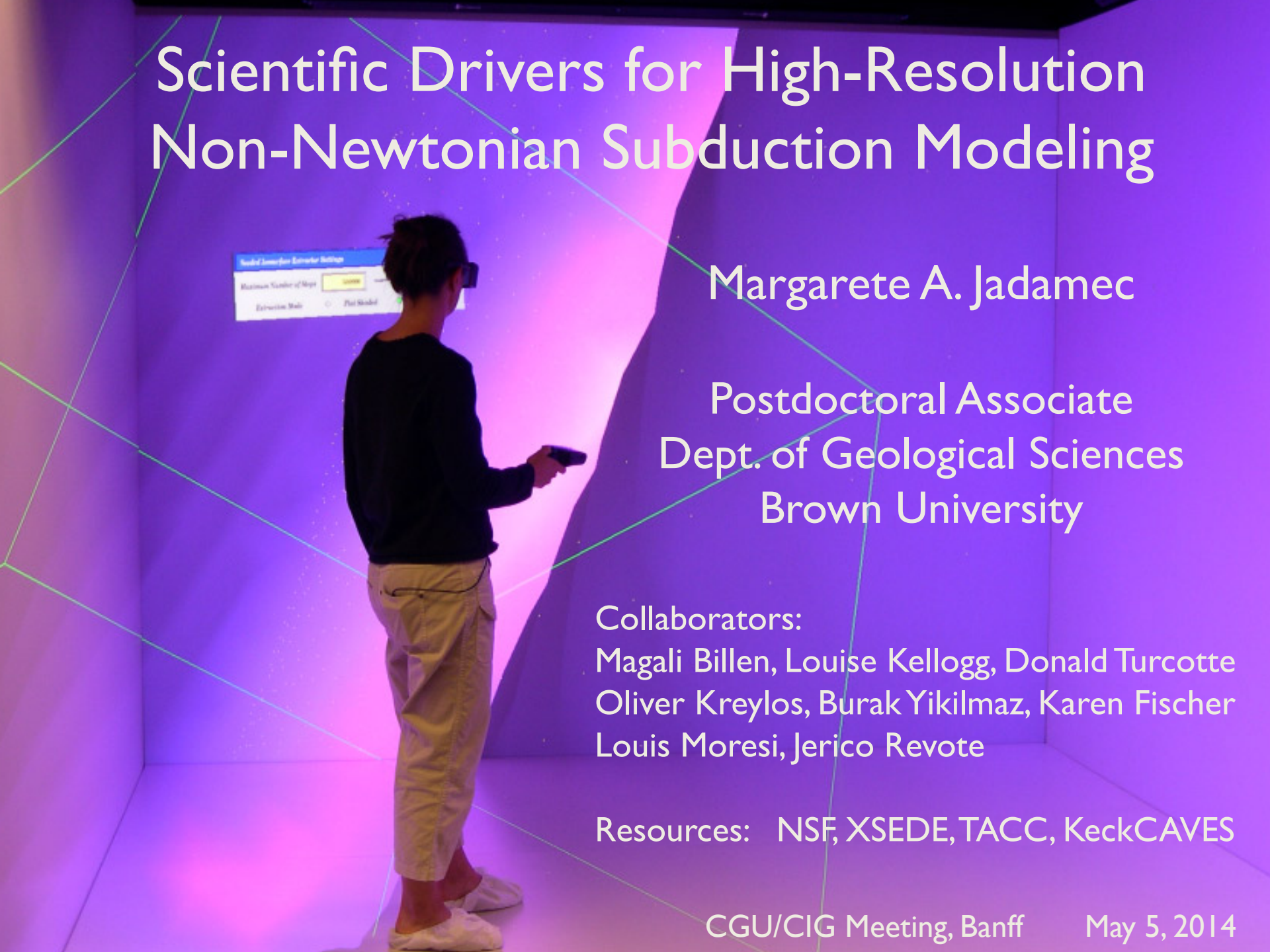
Scientific Drivers for High-Resolution Non-Newtonian Subduction Modeling



Margarete A. Jadamec

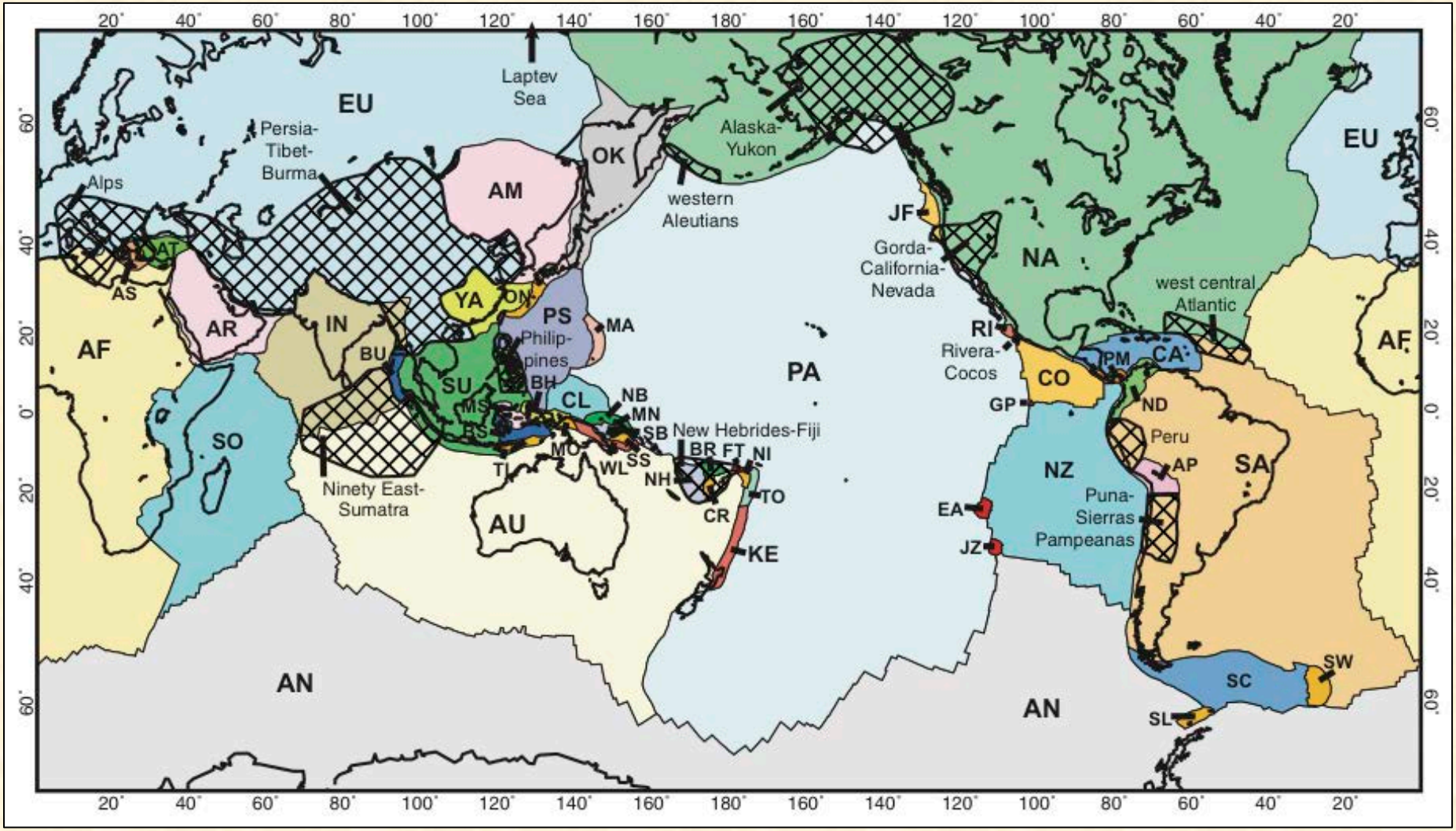
Postdoctoral Associate
Dept. of Geological Sciences
Brown University

Collaborators:
Magali Billen, Louise Kellogg, Donald Turcotte
Oliver Kreylos, Burak Yikilmaz, Karen Fischer
Louis Moresi, Jerico Revote

Resources: NSF, XSEDE, TACC, KeckCAVES

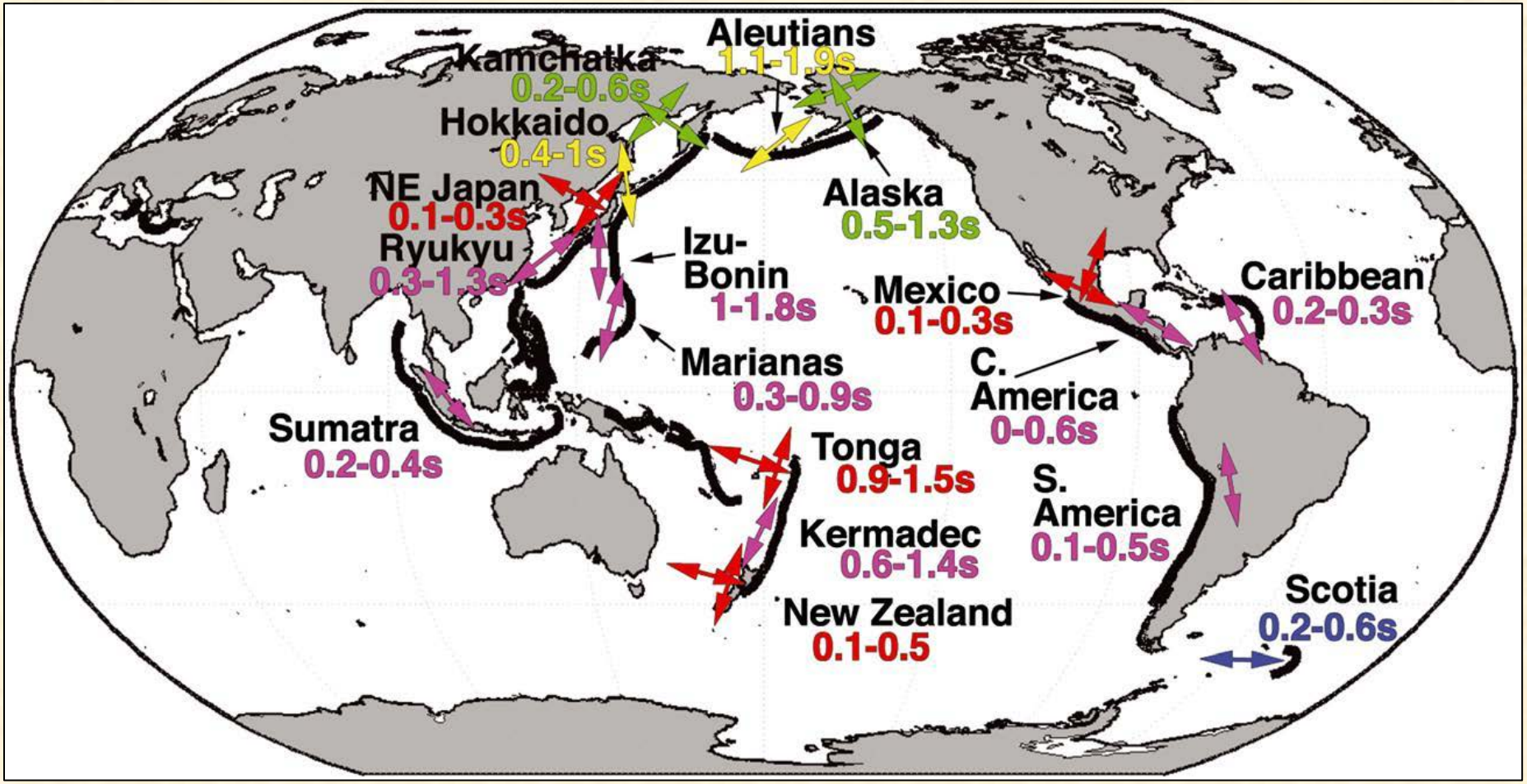
CGU/CIG Meeting, Banff May 5, 2014

Broad Zones of Lithosphere Deformation at Boundaries



Bird, G^3 2003

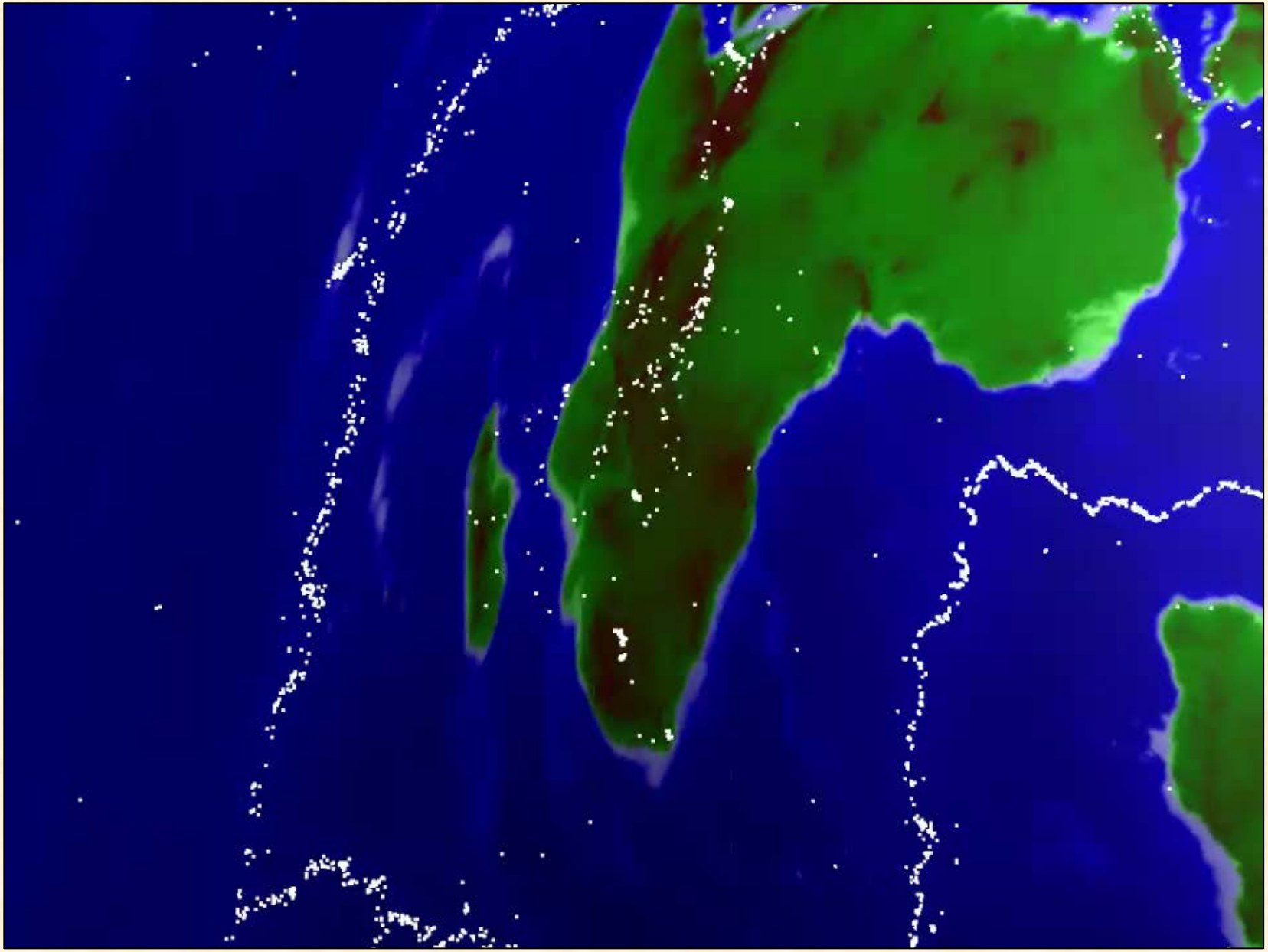
Broad Zones of Slab Driven Mantle Deformation



Summary of (Local S) Shear Wave Splitting in Mantle Wedge

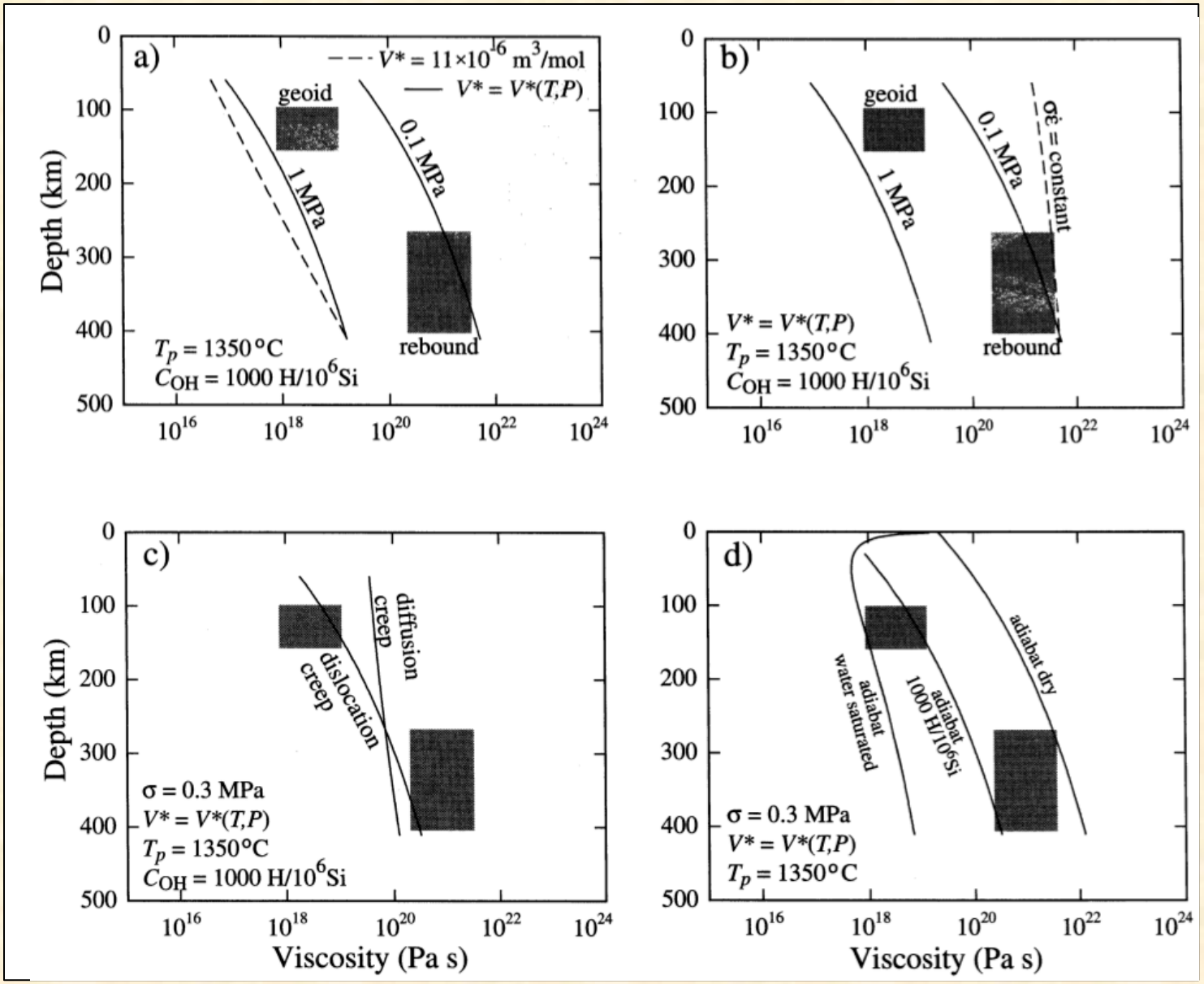
Long and Wirth, JGR 2013

Role of Slab Morphology in Driving Deformation



Revote, Jadamec, and Moresi, 3DALIVE Demo, 2010 (Software from Kreylos et al., 2006)

Role of Rheology in Modulating Plate Boundary Deformation



Hirth and Kohlstedt, Inside the Subduction Factory Geophysical Monograph, 2003

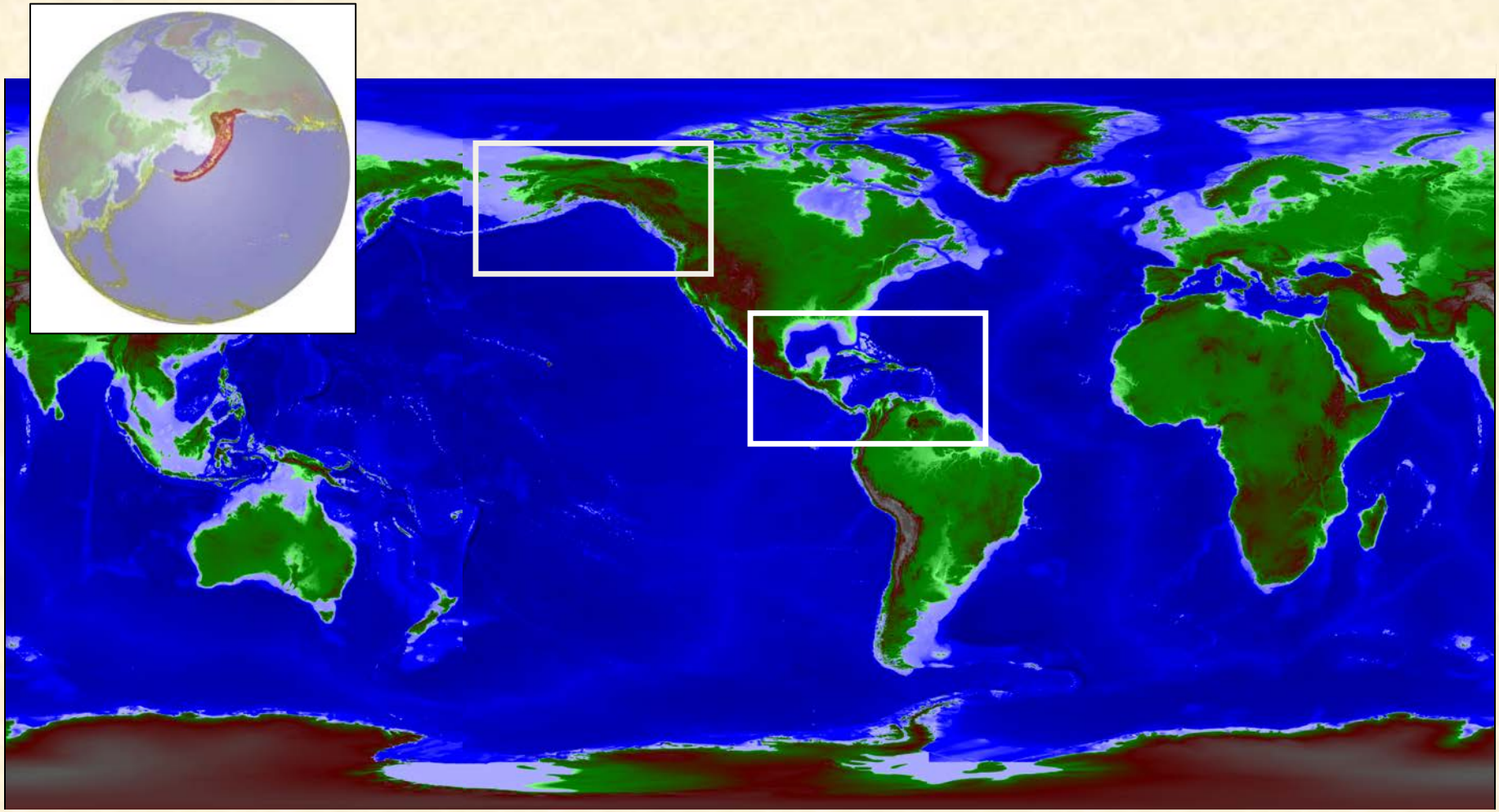
Outline:

① Intra-Continental Mountain Building

② Viscous (de)coupling of the Lithosphere to Mantle

- Methods: High-resolution 3D Regional Modeling
- Results: Predicted Plate Motion, Dynamic Topography
- Results: Predicted Plate and Mantle Velocity
- Conclusions & Looking Forward

Regionally Based 3D Model to Elucidate Process



Regional Model Design: Constraints on Slab Geometry

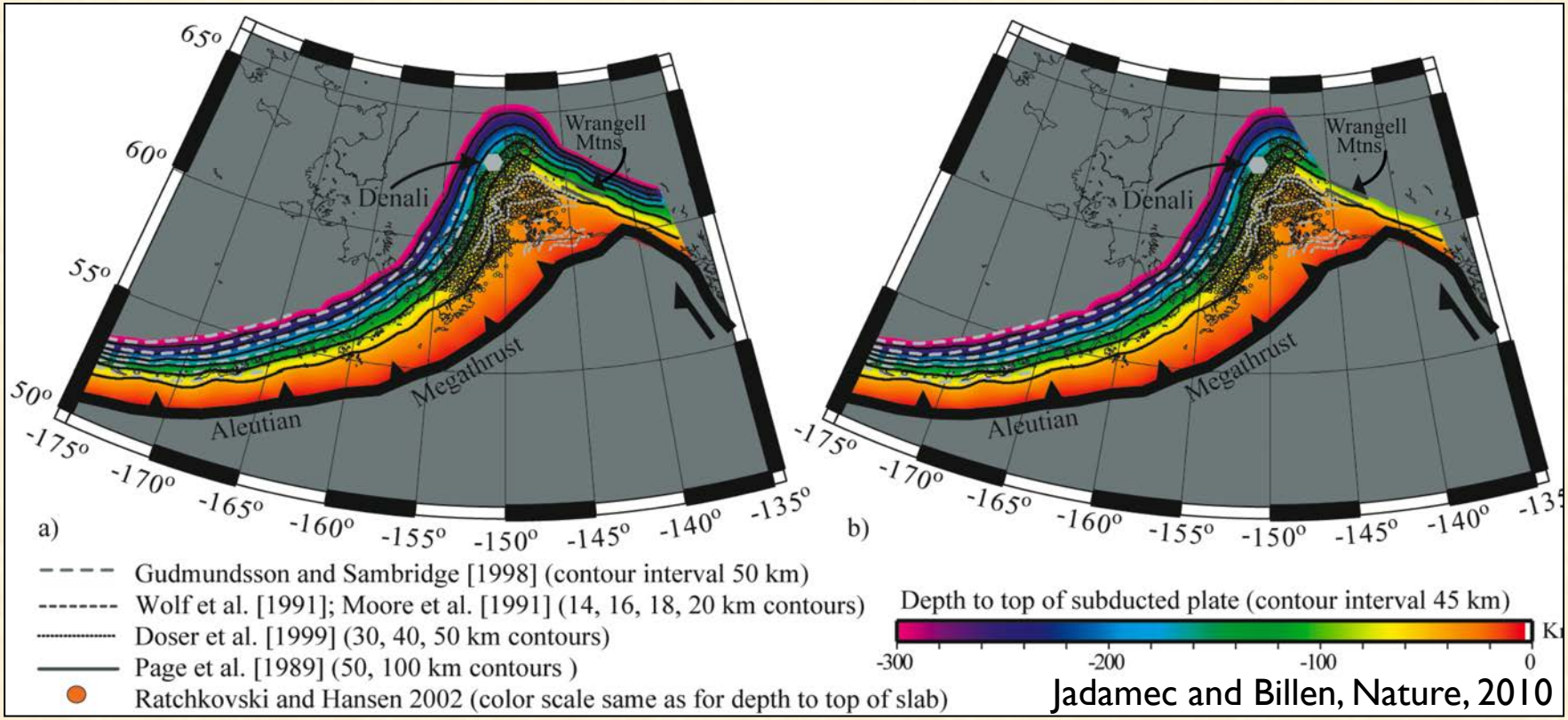
Data Integration | 3D Configuration | Solution

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 Slab Geometry



Jadamec and Billen, Nature, 2010

Regional Model Design: Constraints on Plate Temperature

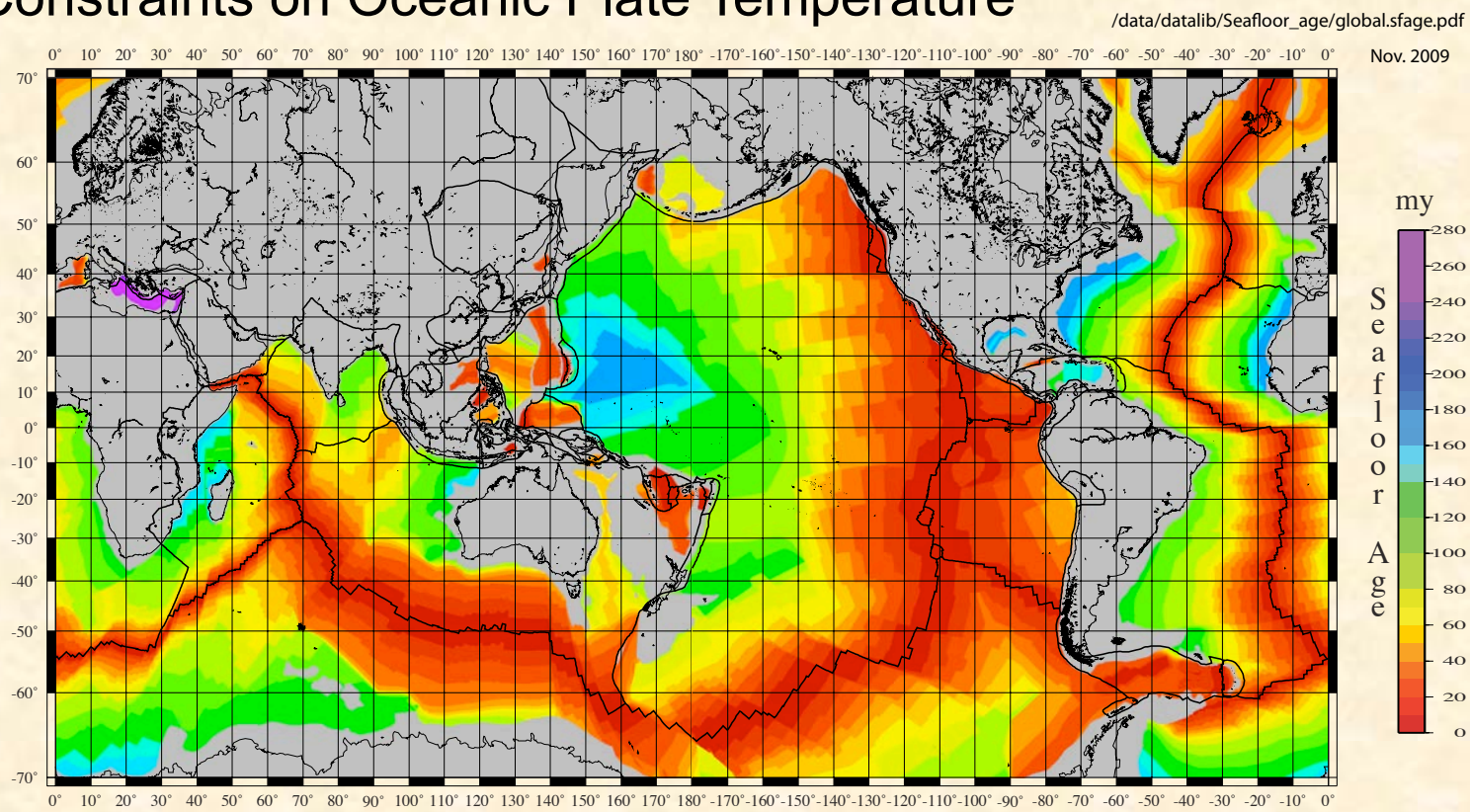
Data Integration | 3D Configuration | Solution

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 Oceanic Plate Temperature



Data from: Mueller et al. 2008

Regional Model Design: Constraints on Plate Temperature

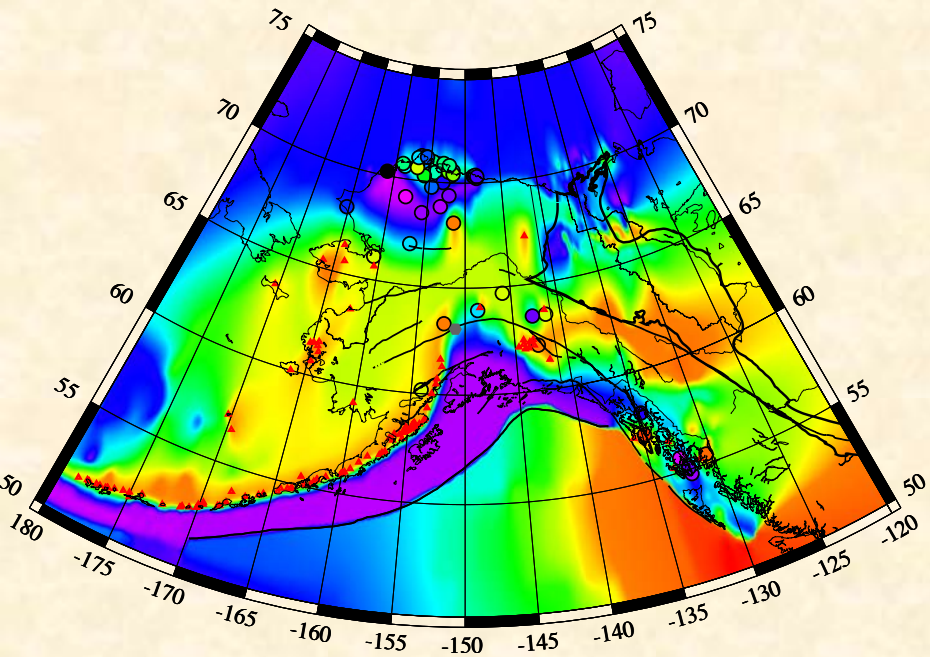
Data Integration | 3D Configuration | Solution

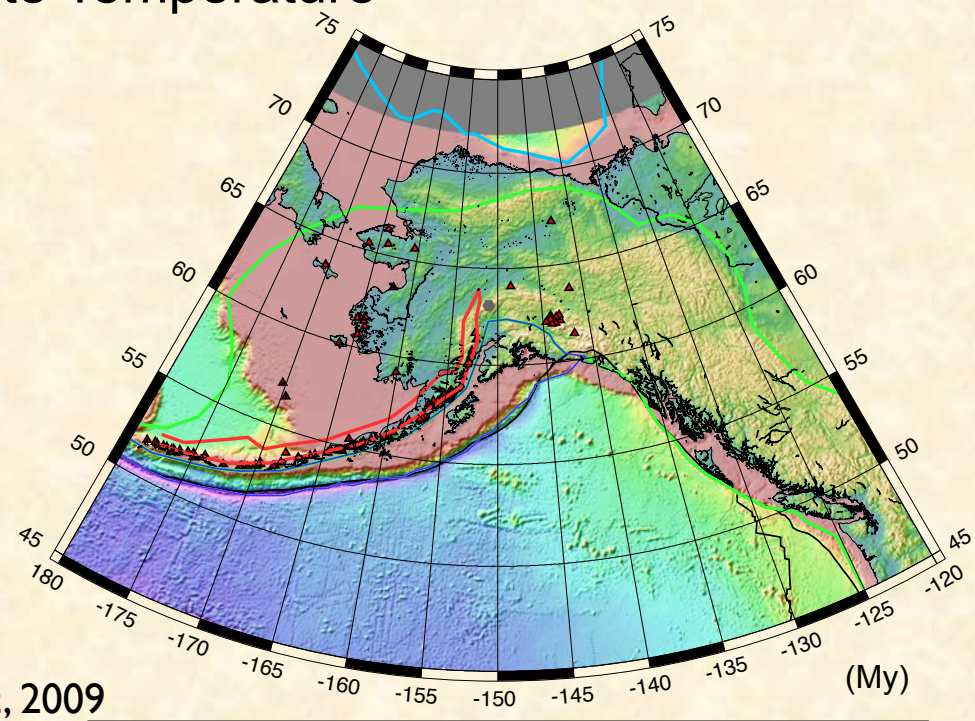
Slab Shape → SlabGenerator (Jadamec, 2009) → Mesh → CitcomCU (Zhong, 2006) → v, p

Plate Ages → SlabGenerator → Therm → CitcomCU → σ, ε

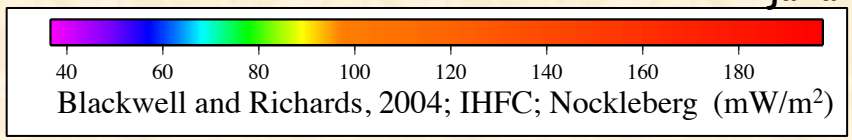
Plt Bndy → SlabGenerator → Weak → CitcomCU → η

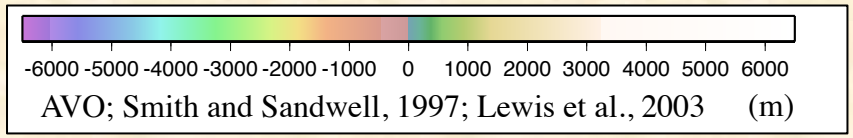
Plt Bndy → Constraints on Continental Plate Temperature





Jadamec, 2009





Regional Model Design: Constraints on Plate Thickness

Data Integration | 3D Configuration | Solution

Slab Shape →
Plate Ages →
Plt Bndy →

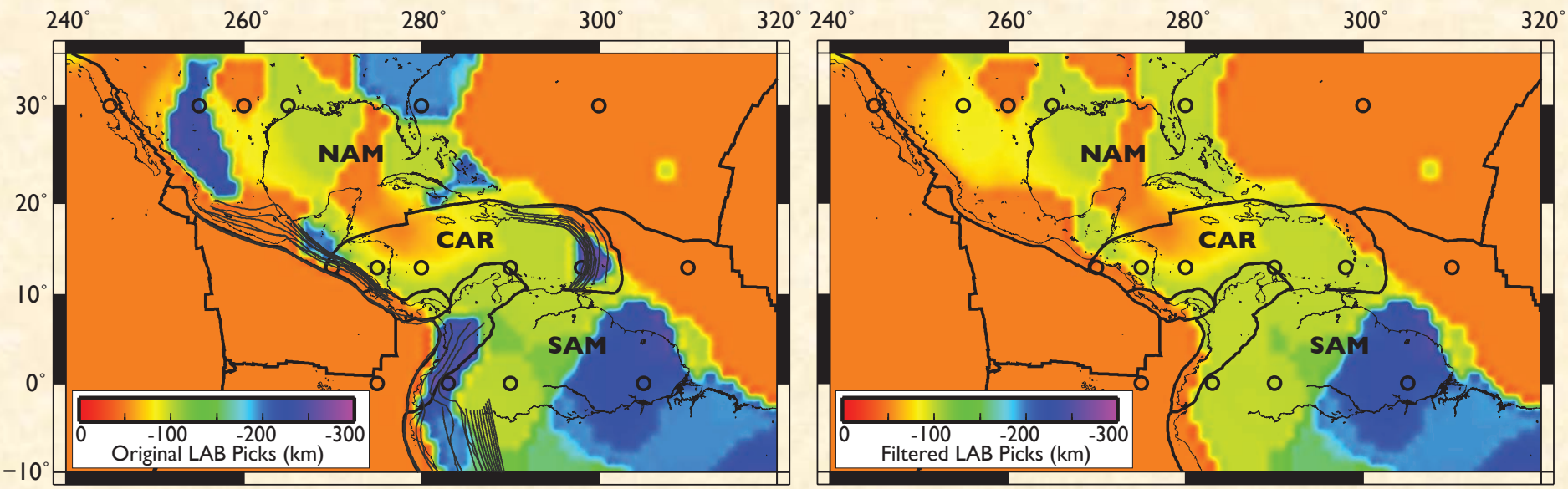
SlabGenerator (Jadamec, 2009)

→ Mesh →
→ Therm →
→ Weak →

CitcomCU (Zhong, 2006)

→ v, p
→ σ, ε
→ η

→ Constraints on Upper Plate Thickness (Depth to LAB)



LAB from absolute shear wave velocity

Lekic and Romanowicz, EPSL, 2011; Jadamec and Fischer, In Prep

Regional Model Design: Calculation of Initial Temperature

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

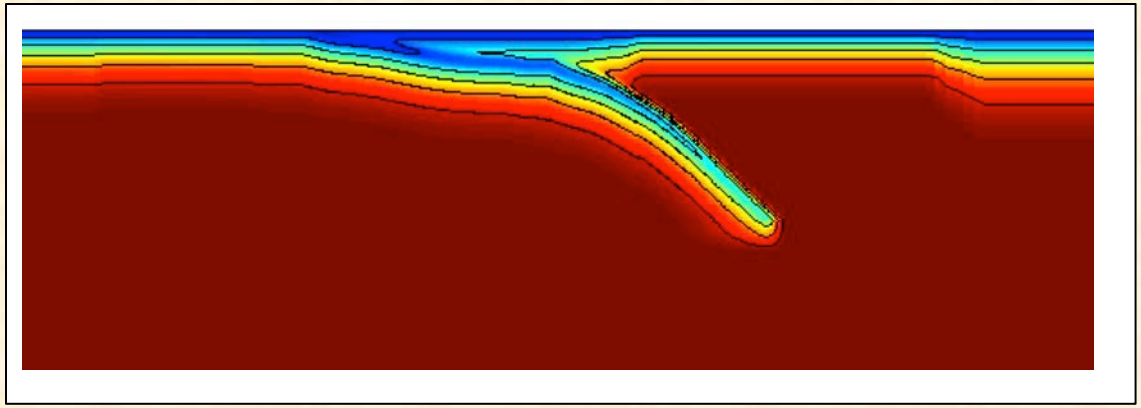
Slab Shape →
Plate Ages →
Plt Bndy →

SlabGenerator (Jadamec, 2009) → Mesh →
Therm →
Weak →

CitcomCU (Zhong, 2006) → v, p
→ σ, ε
→ η

$$T = (T_m - T_s)\,\mathrm{erf}\left(\frac{d}{2\sqrt{\kappa t}}\right) + T_s$$

$$T = T_s + (T_m - T_s)\left[\frac{y}{y_{Lo}} + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\exp\left(-\frac{\kappa n^2\pi^2 t}{y_{Lo}^2}\right)\sin\left(\frac{n\pi y}{y_{Lo}}\right)\right]$$



Jadamec and Billen, Nature, 2010; Jadamec et al. ,EPSL 2013

Regional Model Design: Calculation of Initial Temperature

Data Integration → 3D Configuration → Solution

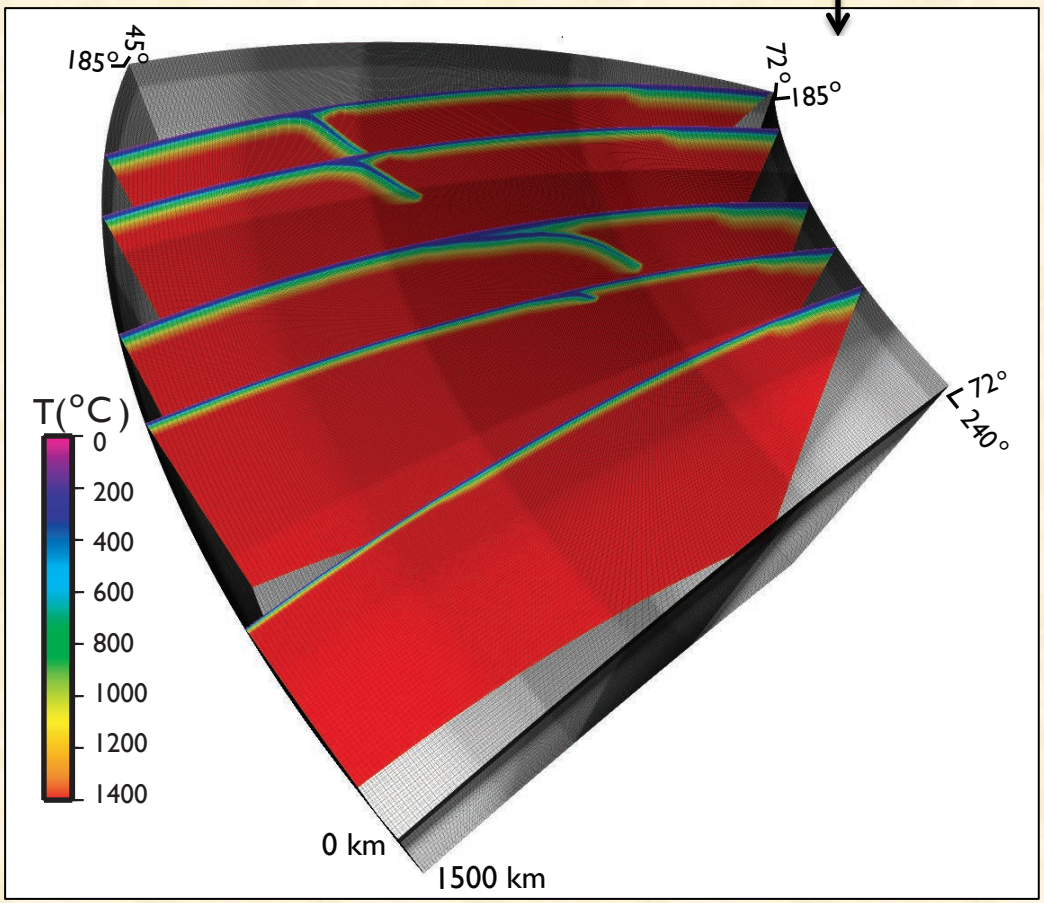
Slab Shape →
Plate Ages →
Plt Bndy →

SlabGenerator (Jadamec, 2009)

→ Mesh →
→ Therm →
→ Weak →

CitcomCU (Zhong, 2006)

→ v, p
→ σ, ε
→ η



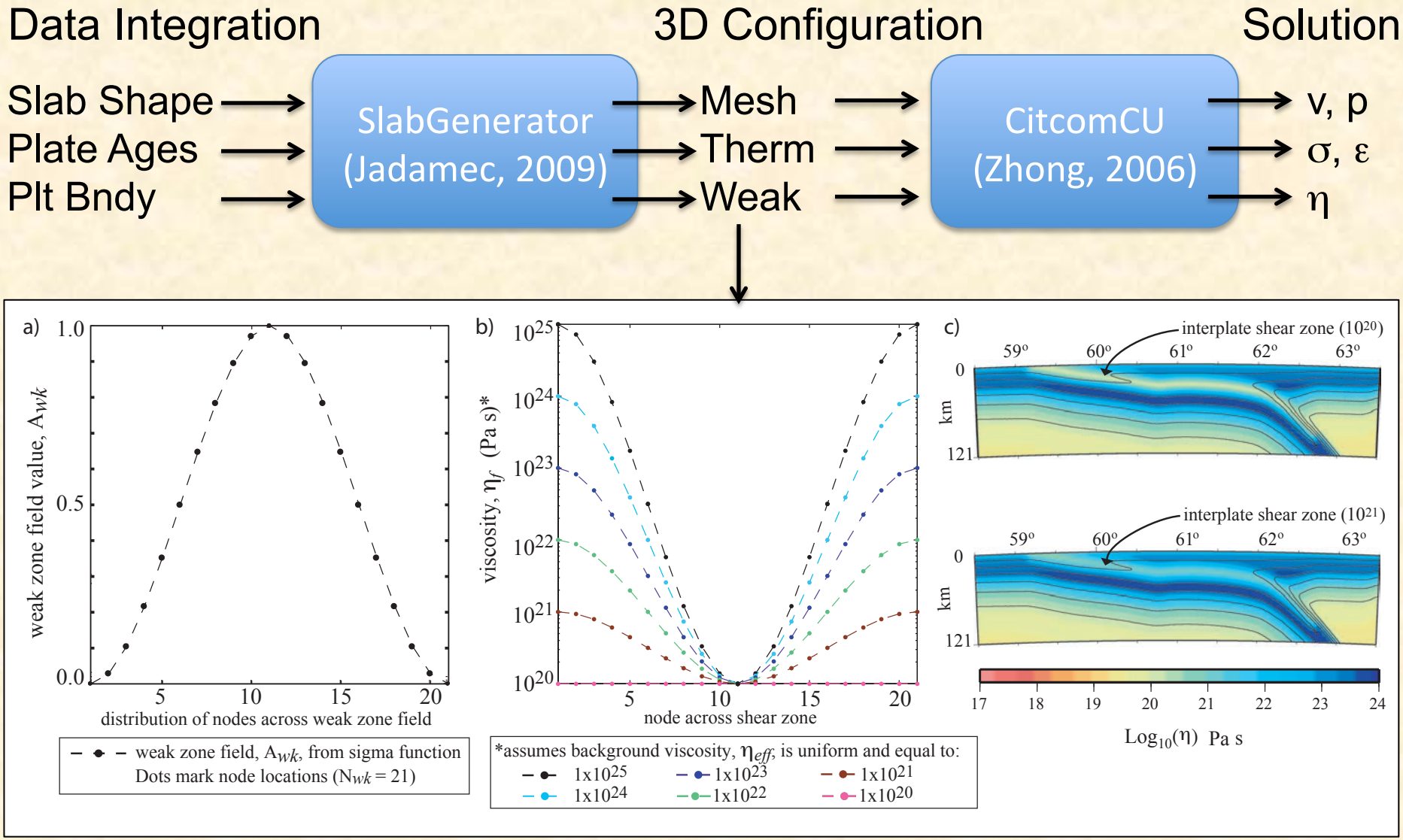
3D Models:
55° x 27° x 1500 km
El: 960 x 648 x 160
Res: 2.35 – 20 km

50° x 35° x 1000 km
El: 896 x 864 x 112
Res: 2.75 – 25 km

69° x 38° x 1500 km
El: 1536 x 1152 x 160
Res: 2.75 – 25 km

Jadamec and Billen, Nature, 2010
Jadamec and Billen, JGR, 2012
Jadamec et al., EPSL, 2013
Jadamec and Fisher, In Prep

Regional Model Design: Calculation of Initial Temperature



Jadamec and Billen, Nature, 2010; Jadamec et al., XSEDE 2012; Jadamec et al. ,EPSL 2013

Regional Model: Viscous Flow Code CitcomCU

Solves conservation equations for incompressible, creeping flow

$$\nabla \cdot \mathbf{u} = 0$$

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

(Moresi and Solomatov, Phys. Fluids, 1995; Moresi et al., PEPI, 1996; Zhong, JGR, 2006)

Composite Rheology

The composite rheology, η_{com}, is defined by

$$\eta_{\mathrm{com}} = \frac{\eta_{\mathrm{df}} \eta_{\mathrm{ds}}}{\eta_{\mathrm{df}} + \eta_{\mathrm{ds}}}$$

where the flow law for wet olivine* is

$$\eta_{\mathrm{df,ds}} = \left(\frac{d^p}{A C_{\mathrm{OH}}^r}\right)^{\frac{1}{n}} \dot{\varepsilon}^{\frac{1-n}{n}} \exp\left[\frac{E + PV}{nRT}\right]$$

Variable	Description	*df*	*ds*
A	pre-exponential factor	1.0	9×10^{-20}
n	stress exponent	1	3.5
d	grain size, μm (assuming A term is in μm)	10×10^3	–
p	grain size exponent	3	–
C_{OH}	OH concentration in H/10^6 Si	1000	1000
r	exponent for C_{OH} term	1	1.2
E	activation energy, kJ/mol	335	480
V	activation volume, m^3/mol	4×10^{-6}	11×10^{-6}

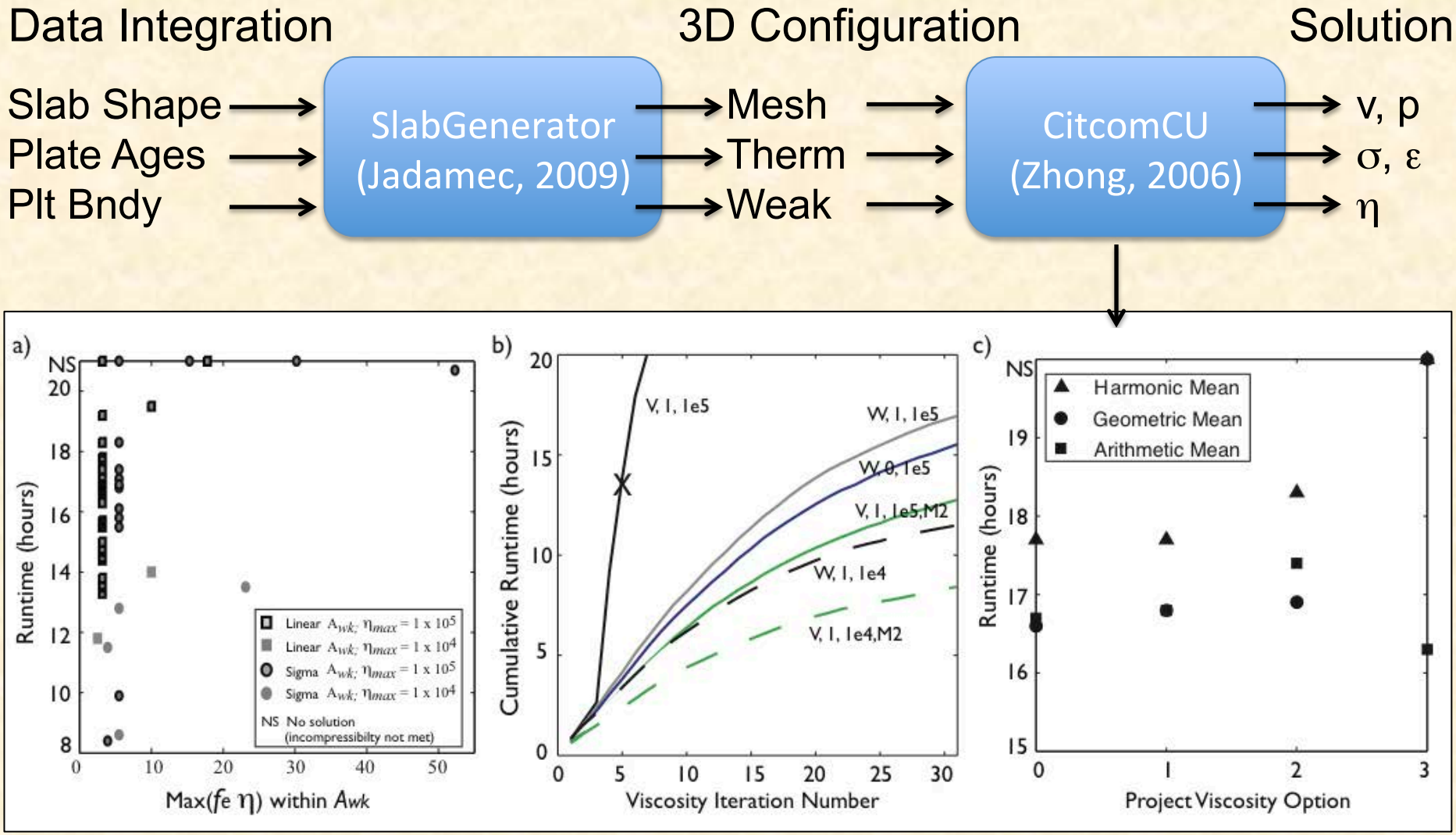
*flow law and parameters for wet olivine (Hirth and Kohlstedt 2003)

and a depth-dependent yield stress is applied such that if

$$\sigma > \sigma_y,\ \eta_{\mathrm{eff}} = \frac{\sigma_y}{\dot{\varepsilon}_{II}},\ \text{and if } \sigma < \sigma_y,\ \eta_{\mathrm{eff}} = \eta_{\mathrm{com}}$$

Hirth and Kohlstedt, Monograph, 2003; Billen and Hirth, G^3, 2007; Jadamec and Billen, Nature, 2010

Regional Model Tests: Effects on Model Runtime



Jadamec, 2009; Jadamec et al., XSEDE 2012

Methods: 3D Visualization of Temperature and Viscosity

Flat Slab Subduction, the Denali Fault, and Mountain Building in the Central Alaska Range

by Margarete Jadamec

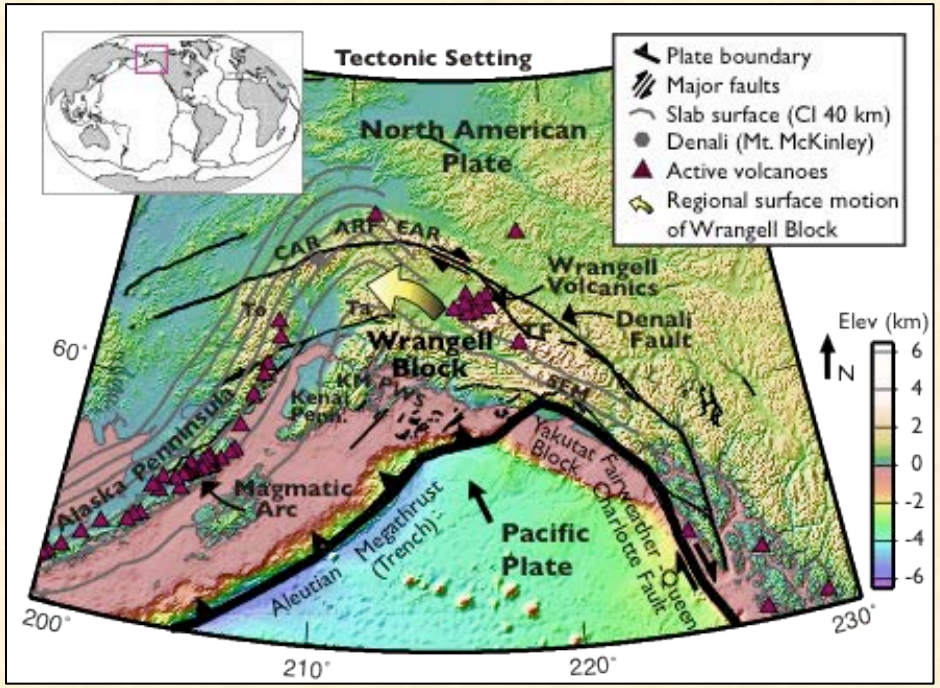
in collaboration with Magali Billen and Sarah Roeske

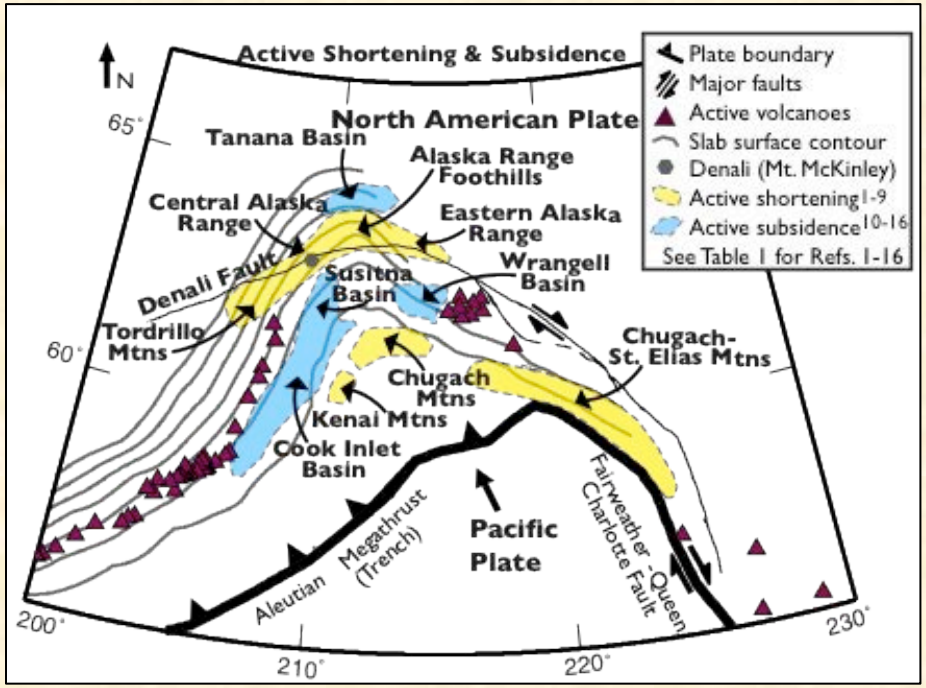
Filmed by Oliver Kreylos in the KeckCAVES

Edited by Margarete Jadamec

For additional Information See:
Jadamec, M. A., Billen, M. I., and Roeske, S. M., 2013, Three-dimensional numerical models of flat slab subduction and the Denali fault driving deformation in south-central Alaska. Earth and Planetary Science Letters, 376, p. 29-42, 2013. doi:10.1016/j.epsl.2013.06.009.

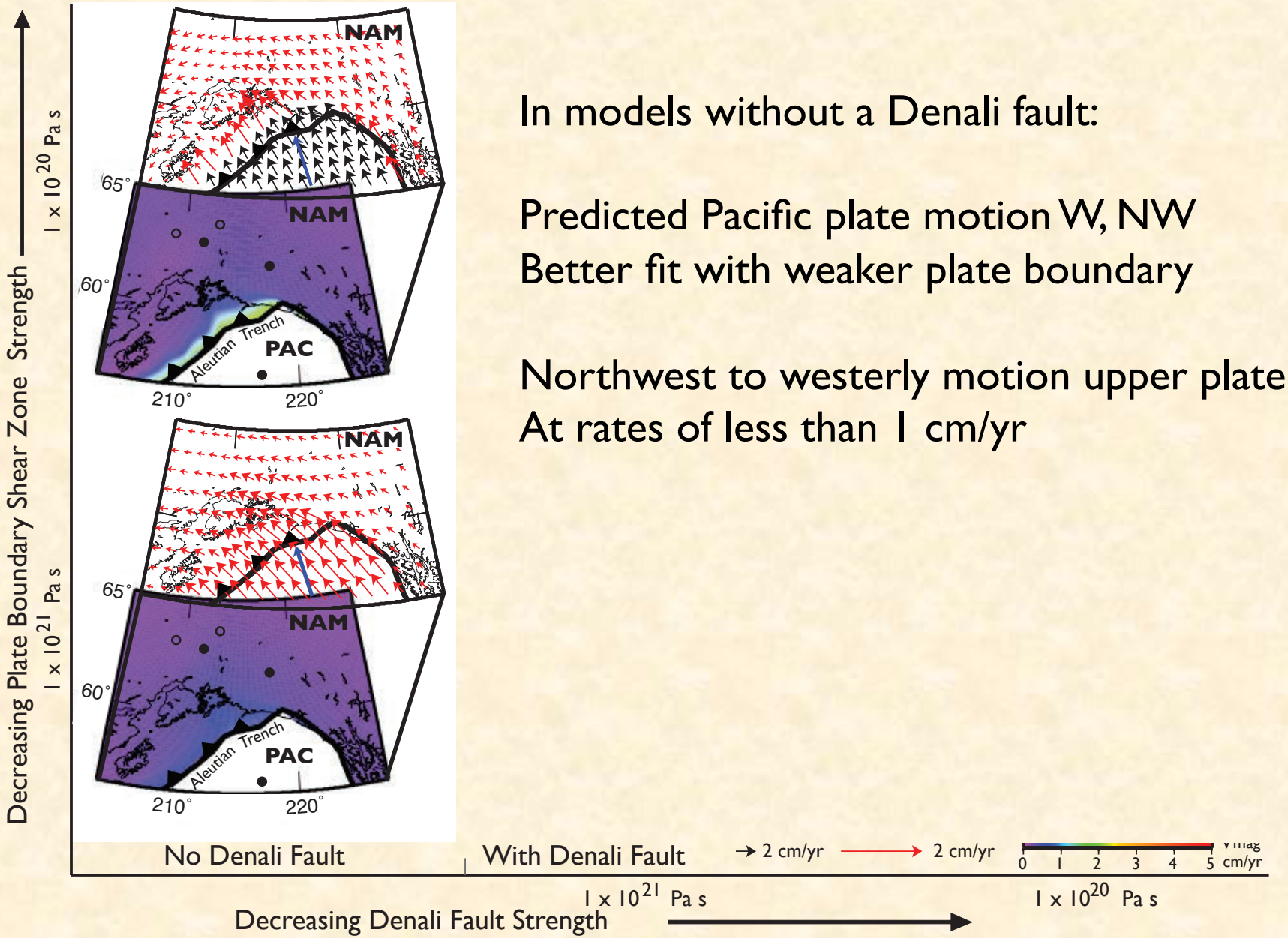
Tectonic Setting in South Central Alaska





Jadamec et al., EPSL, 2013

Newtonian Viscosity: Predicted Surface Velocity



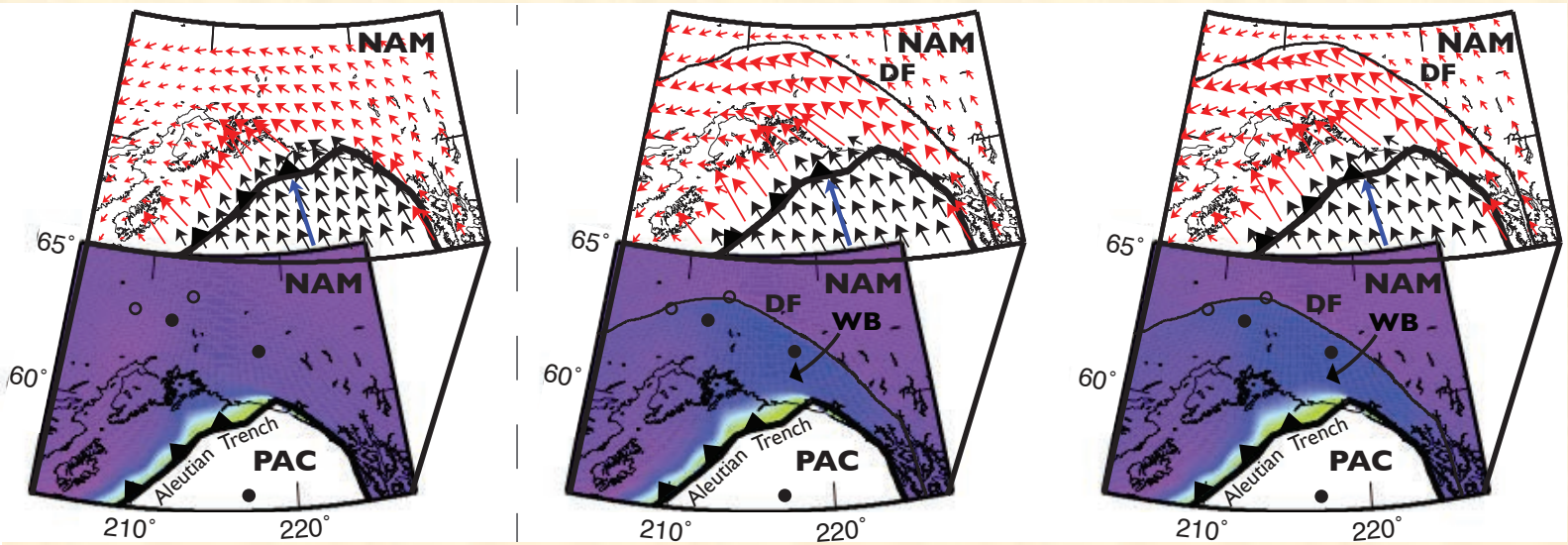
In models without a Denali fault:

Predicted Pacific plate motion W, NW
Better fit with weaker plate boundary

Northwest to westerly motion upper plate
At rates of less than 1 cm/yr

Jadamec et al., 2013

Newtonian Viscosity: Predicted Surface Velocity



Decreasing Plate Boundary Shear Zone Strength

1×10^{20} Pa s

1×10^{21} Pa s

With Denali fault :

Denali fault decouples part of Alaska (WB) from rest of NAM

Models with Denali fault - Sharp velocity gradient across DF

WB motion sub-parallel to motion of underlying flat slab and DF

Weaker Denali fault, faster Wrangell Block velocity

No Denali Fault | With Denali Fault

→ 2 cm/yr → 2 cm/yr

0 1 2 3 4 5 cm/yr

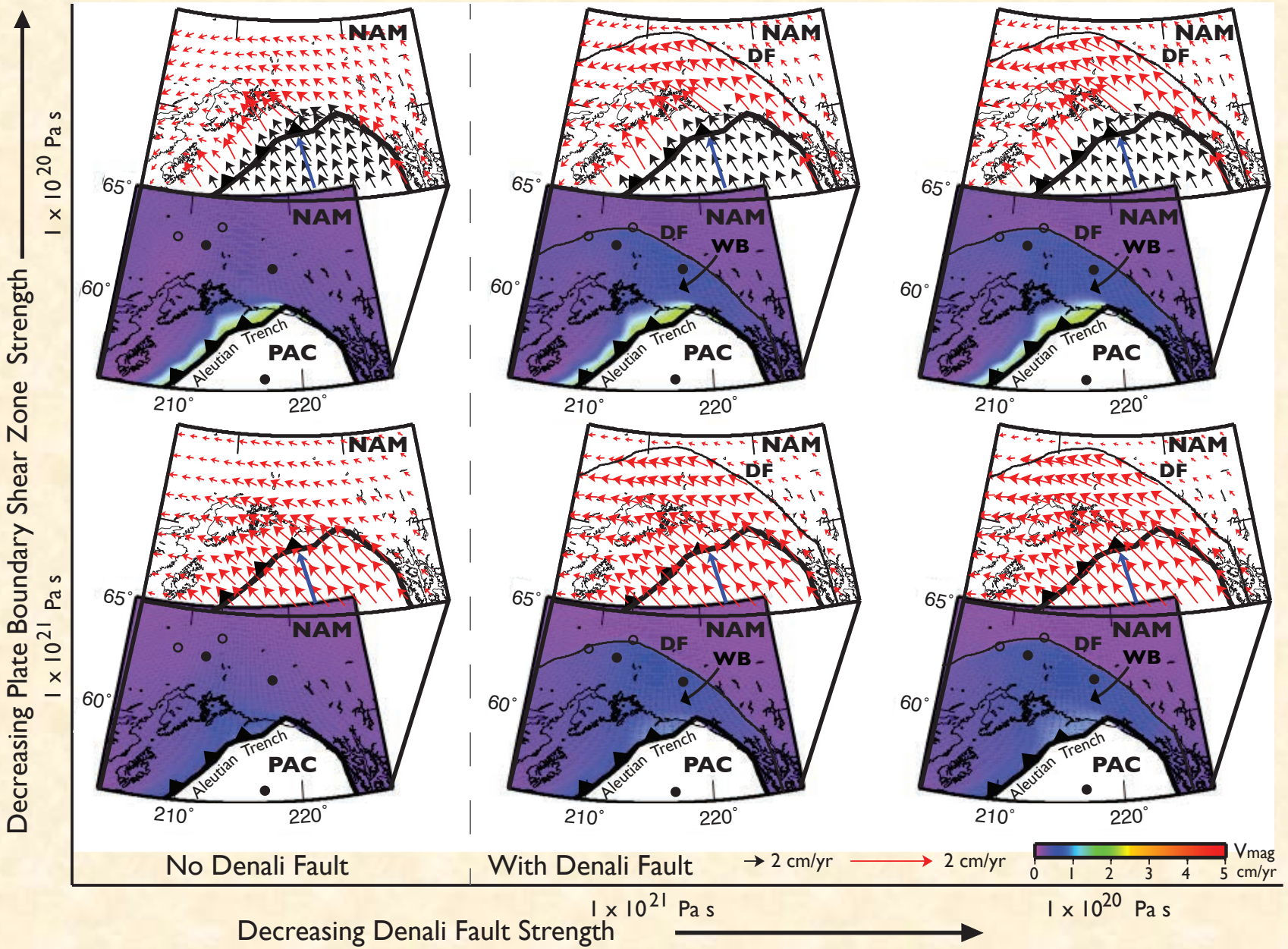
1×10^{21} Pa s

1×10^{20} Pa s

Decreasing Denali Fault Strength →

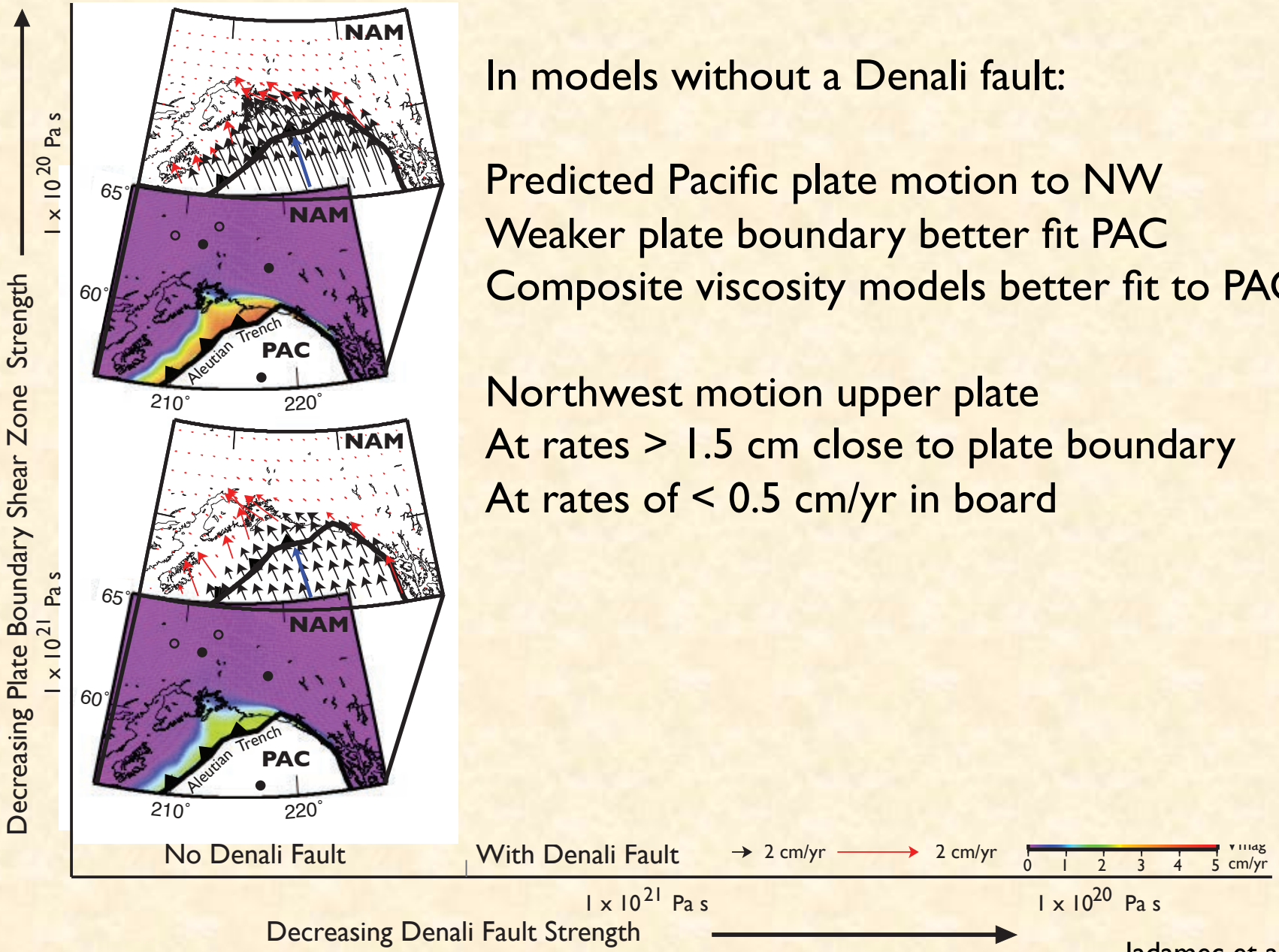
Jadamec et al., 2013

Newtonian Viscosity: Predicted Surface Velocity



Jadamec et al., 2013

Non-Newtonian Viscosity: Predicted Surface Velocity



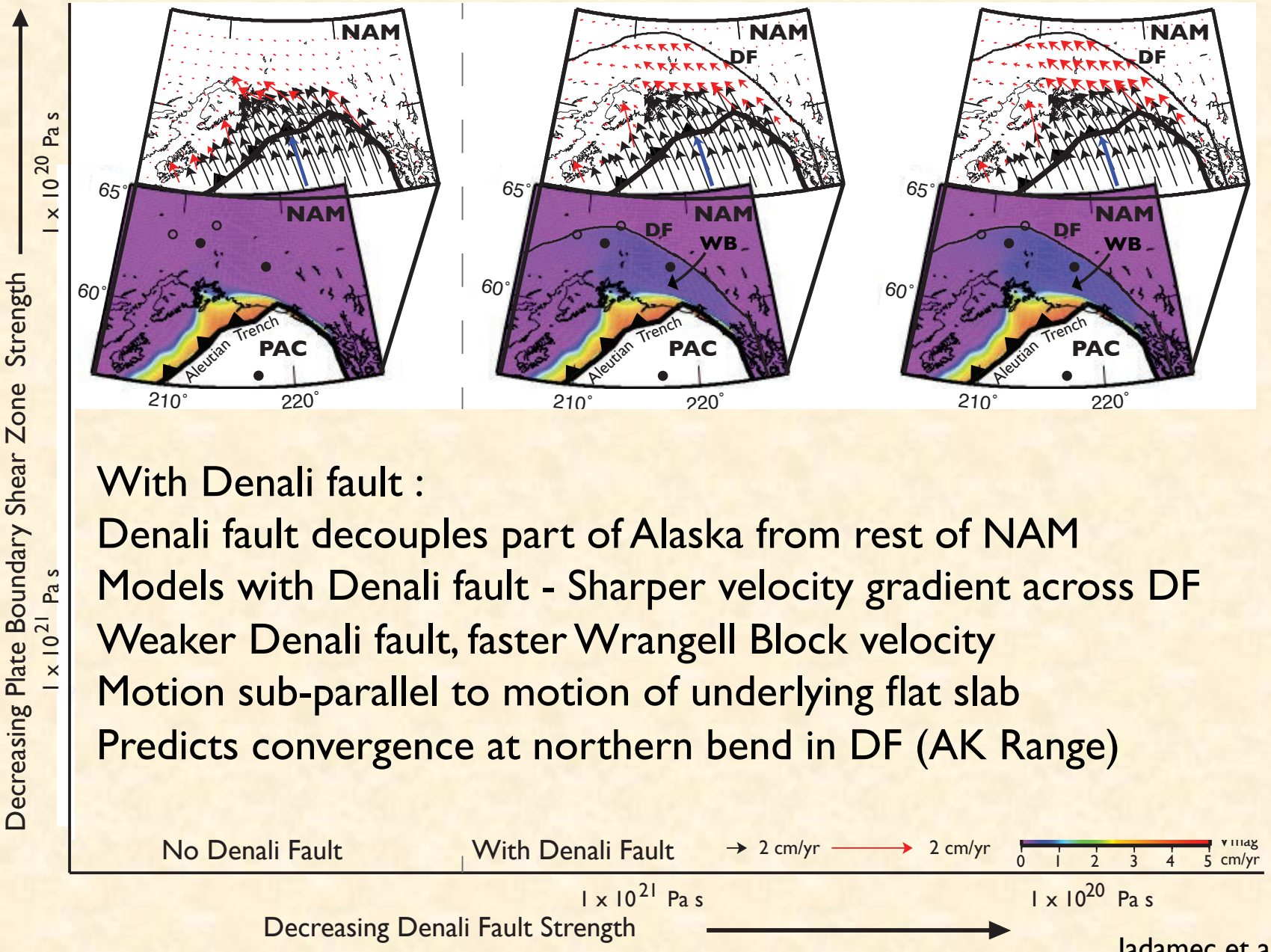
In models without a Denali fault:

Predicted Pacific plate motion to NW
Weaker plate boundary better fit PAC
Composite viscosity models better fit to PAC

Northwest motion upper plate
At rates > 1.5 cm close to plate boundary
At rates of < 0.5 cm/yr in board

Jadamec et al., 2013

Non-Newtonian Viscosity: Predicted Surface Velocity



With Denali fault :

Denali fault decouples part of Alaska from rest of NAM

Models with Denali fault - Sharper velocity gradient across DF

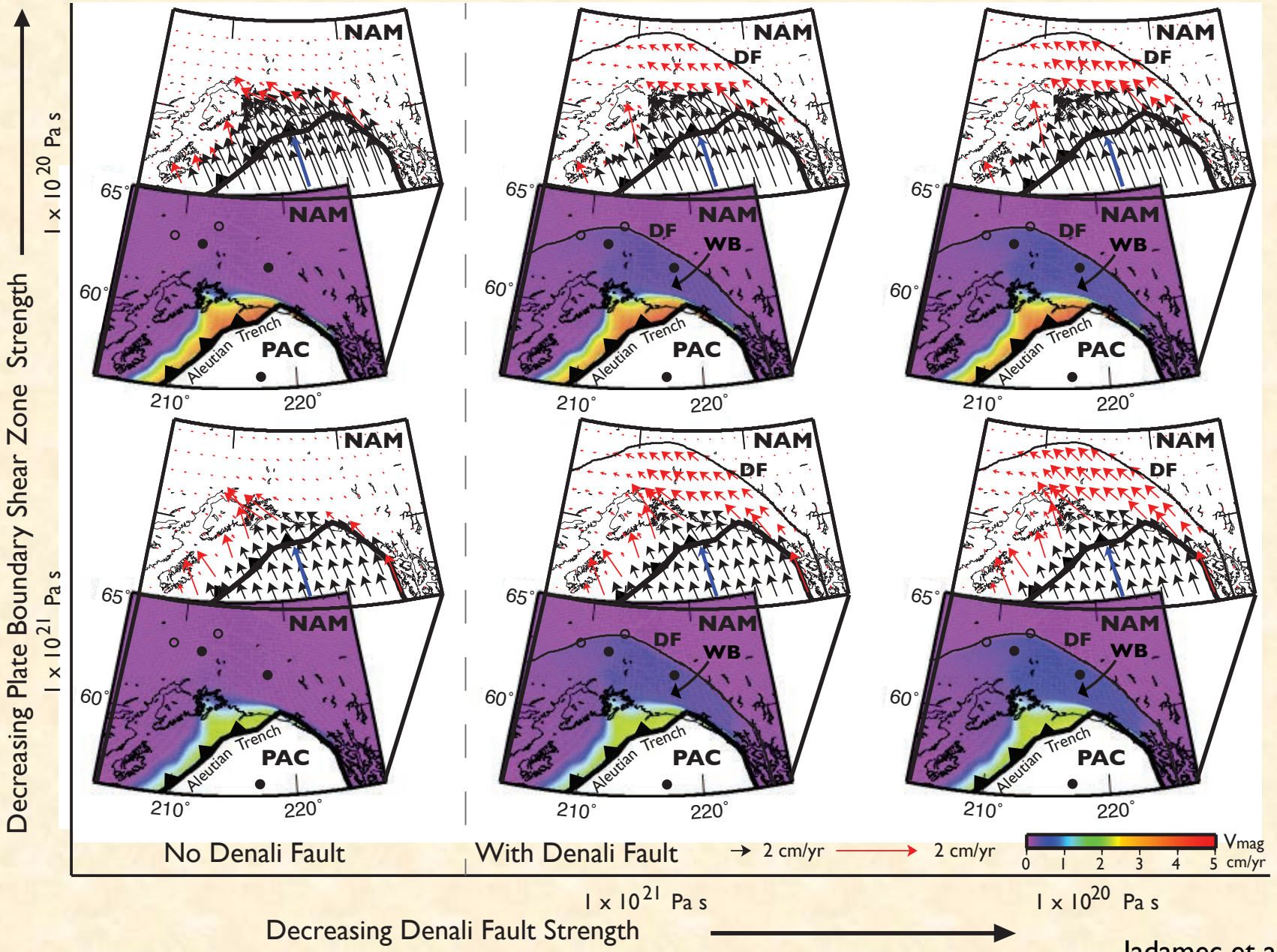
Weaker Denali fault, faster Wrangell Block velocity

Motion sub-parallel to motion of underlying flat slab

Predicts convergence at northern bend in DF (AK Range)

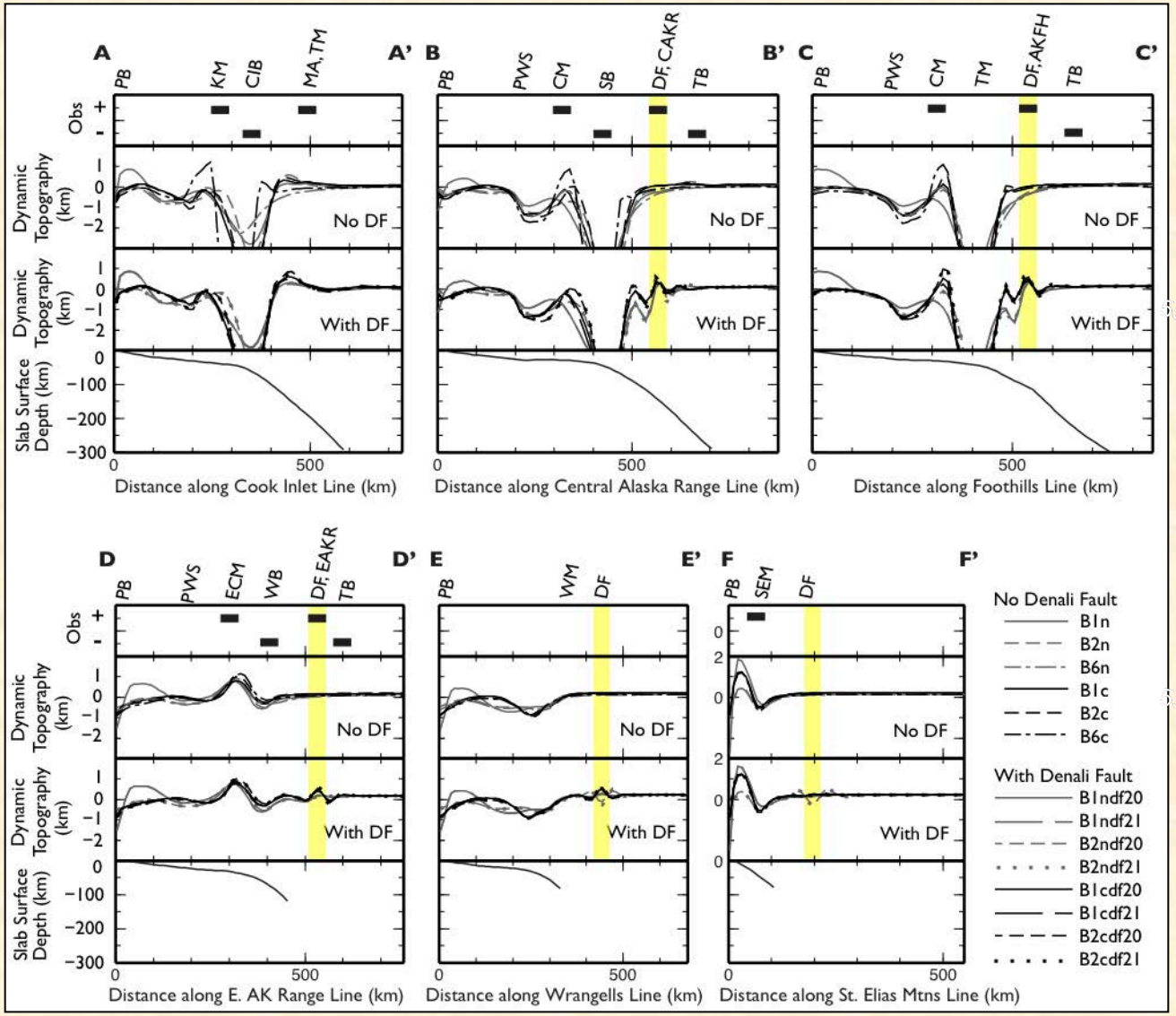
Jadamec et al., 2013

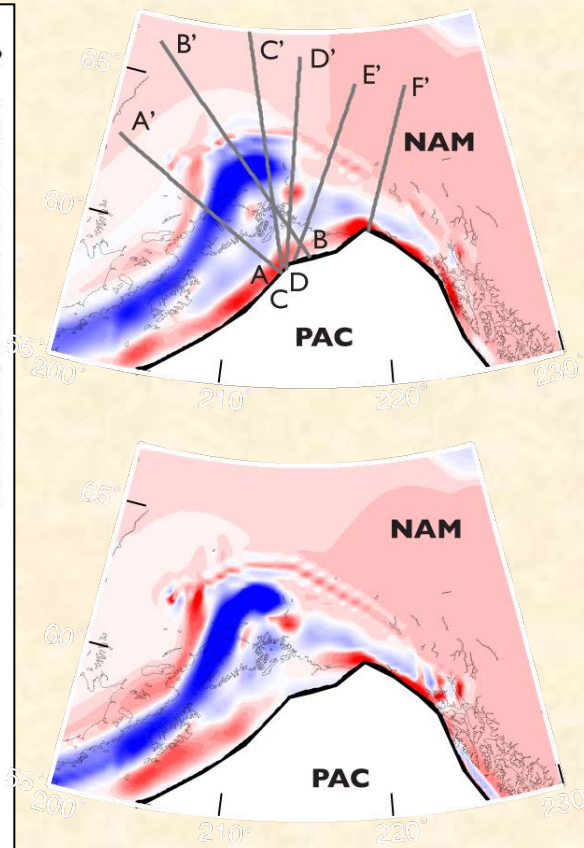
Non-Newtonian Viscosity: Predicted Surface Velocity



Jadamec et al., 2013

Effect of Denali Fault on Uplift of the Central Alaska Range

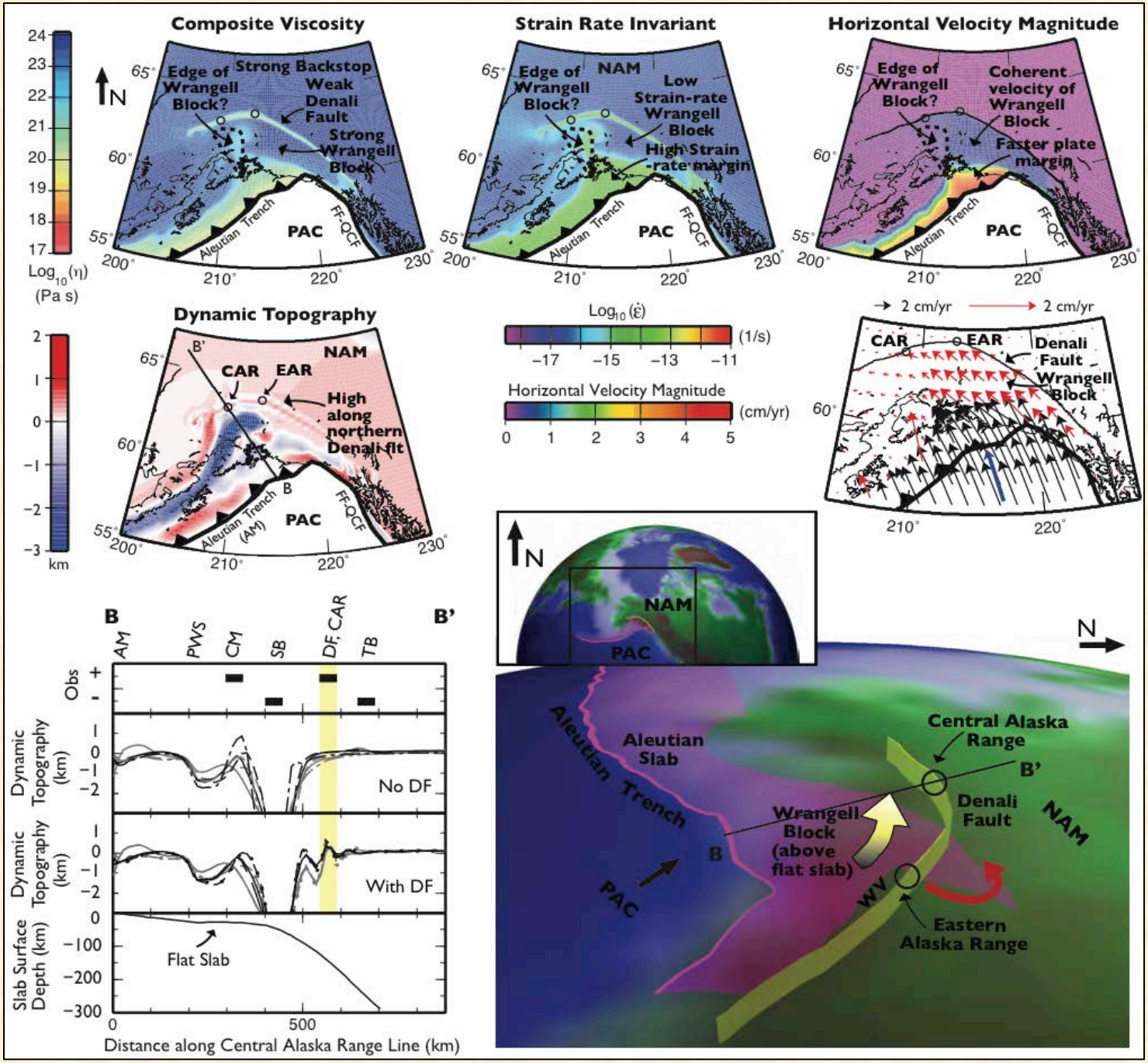




Denali fault localizes uplift in Alaska Range
(greater in models with composite viscosity)

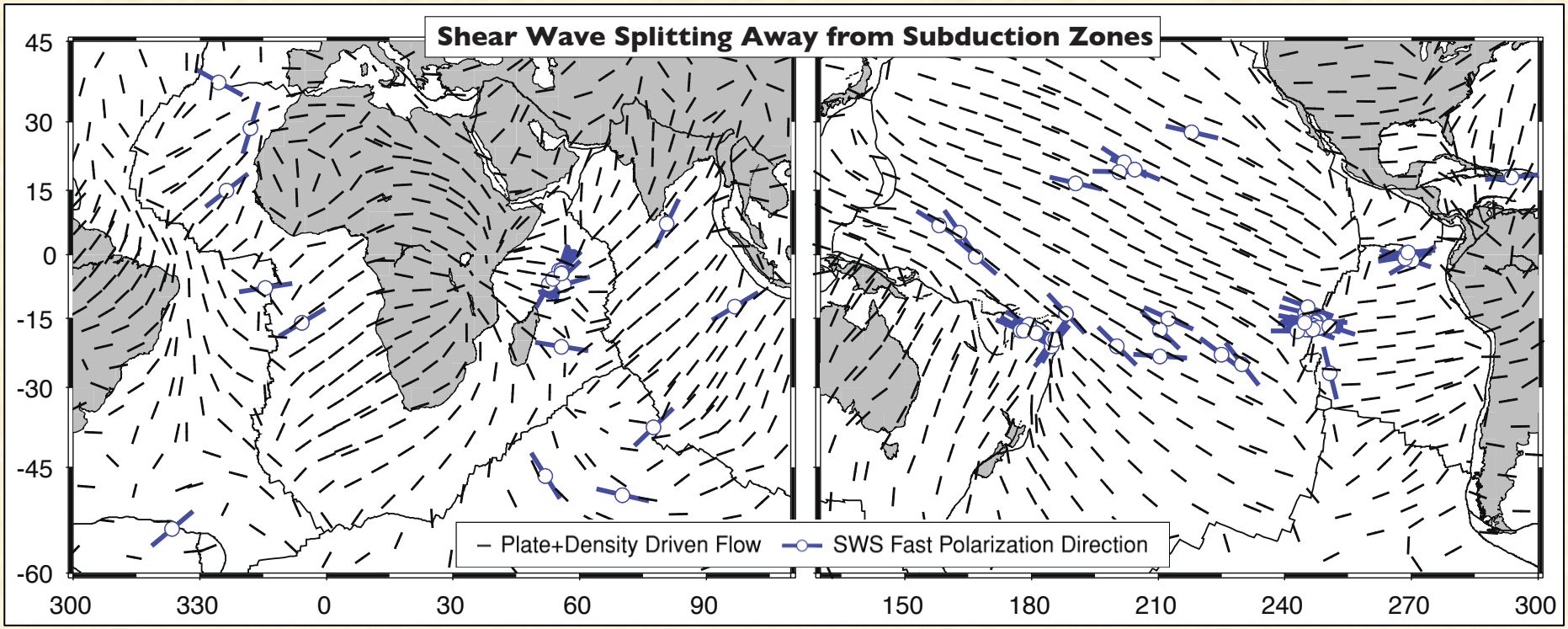
Jadamec et al., 2013

Slab driving overriding plate deformation in South Central Alaska



Jadamec et al., 2013

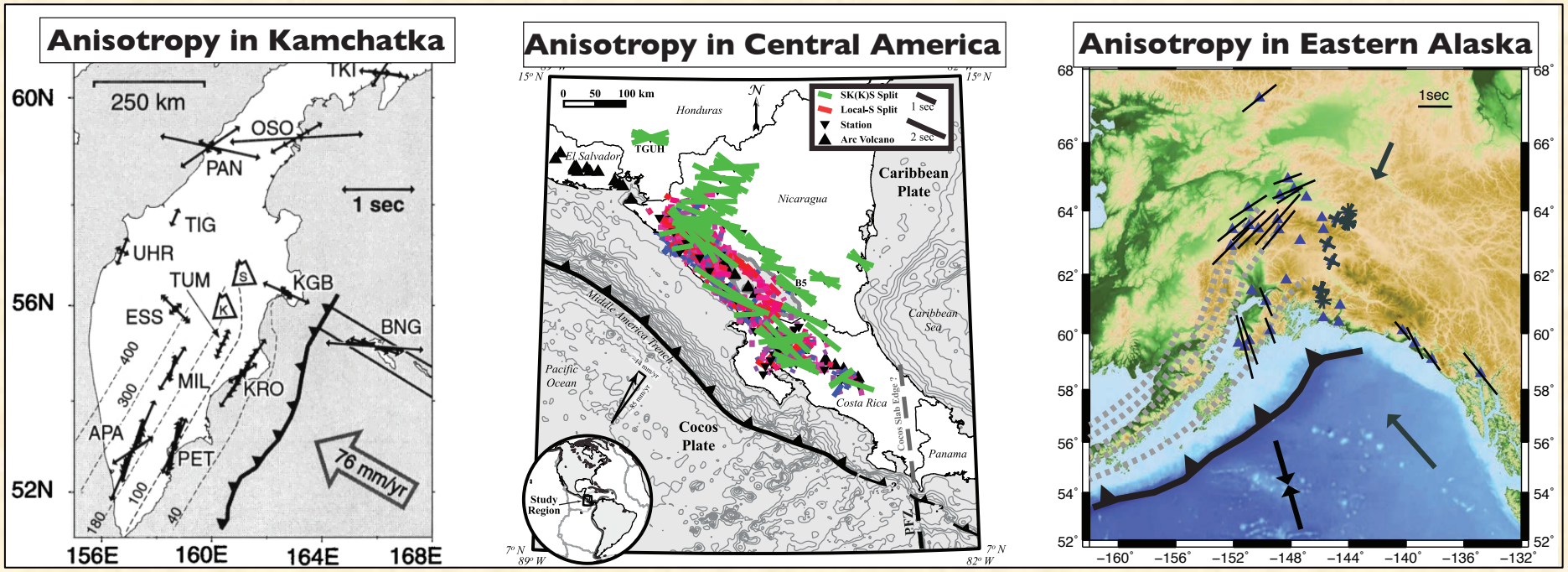
What About the Mantle Underneath the Plates?



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

Away from subduction zones, the surface motion of oceanic plates is well correlated with the fast axis of seismic anisotropy implying **coupling** between the plates and mantle (assuming A type fabric in olivine)

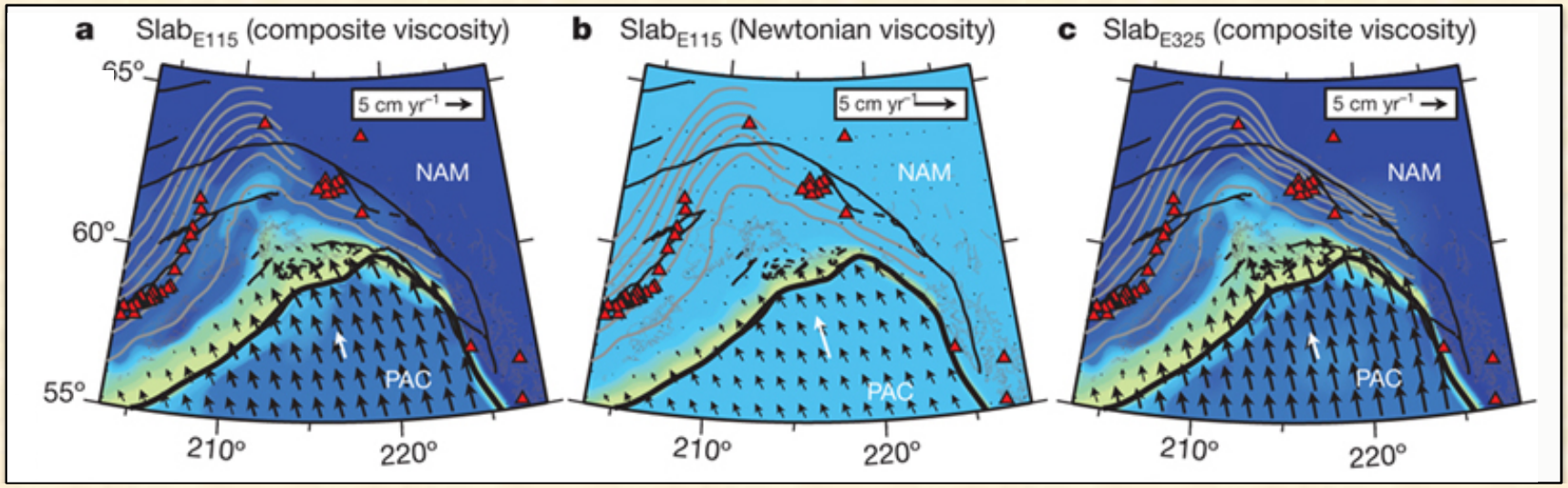
Plate Mantle-(de)coupling & Is Complex Flow Common?

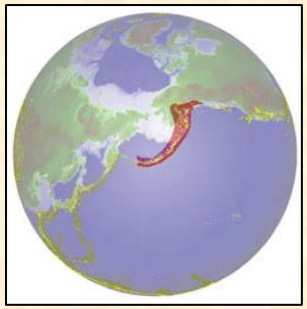


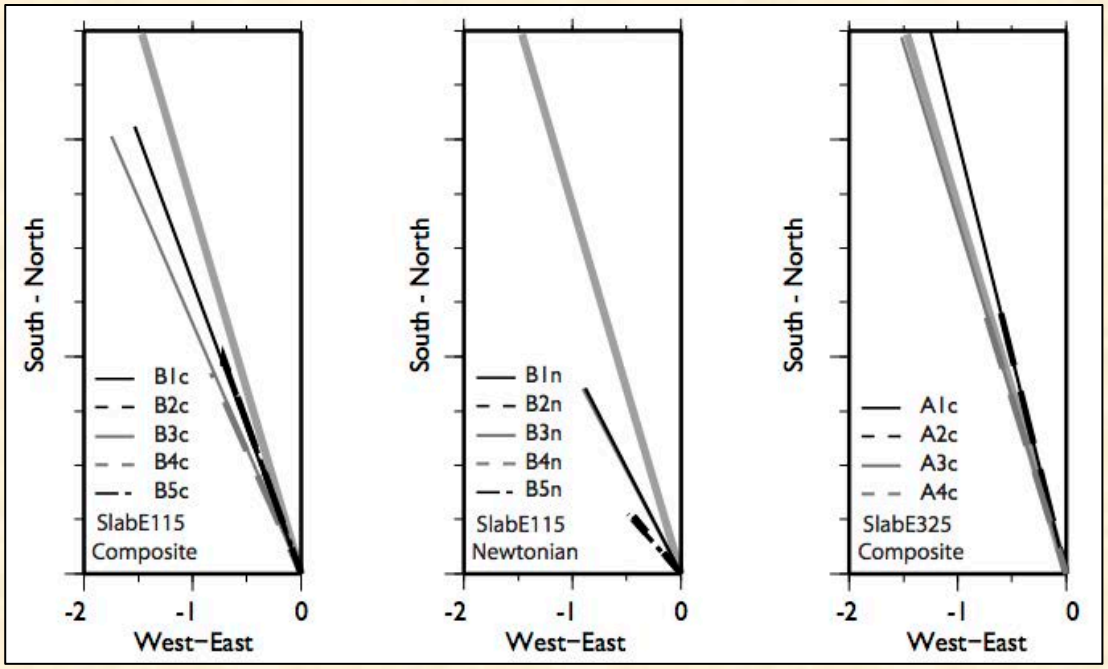
Peyton et al., GRL 2001 | Abt et al., JGR 2010 | Hanna and Long, Tect. 2012

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)

Results: Viscosity and Predicted Pacific Plate Motion



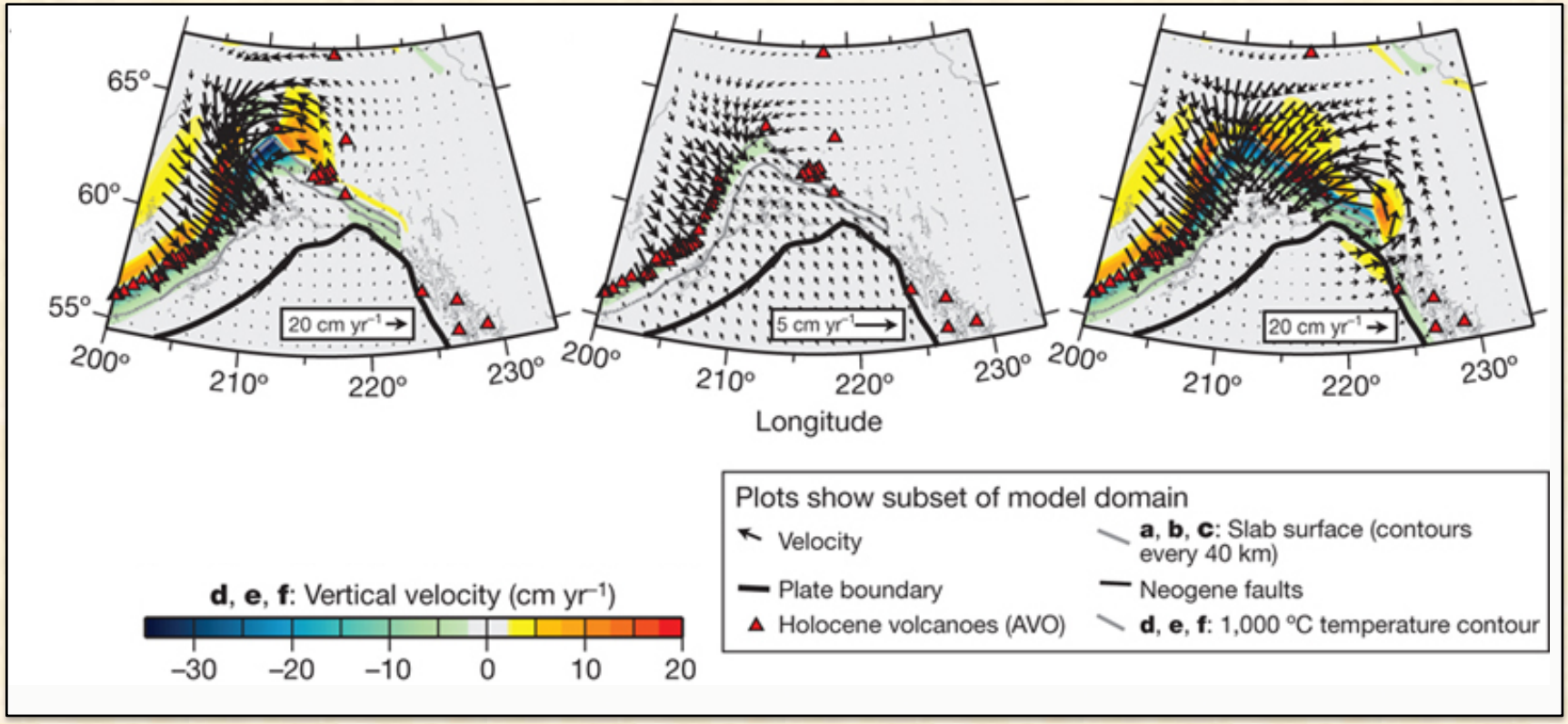




Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012

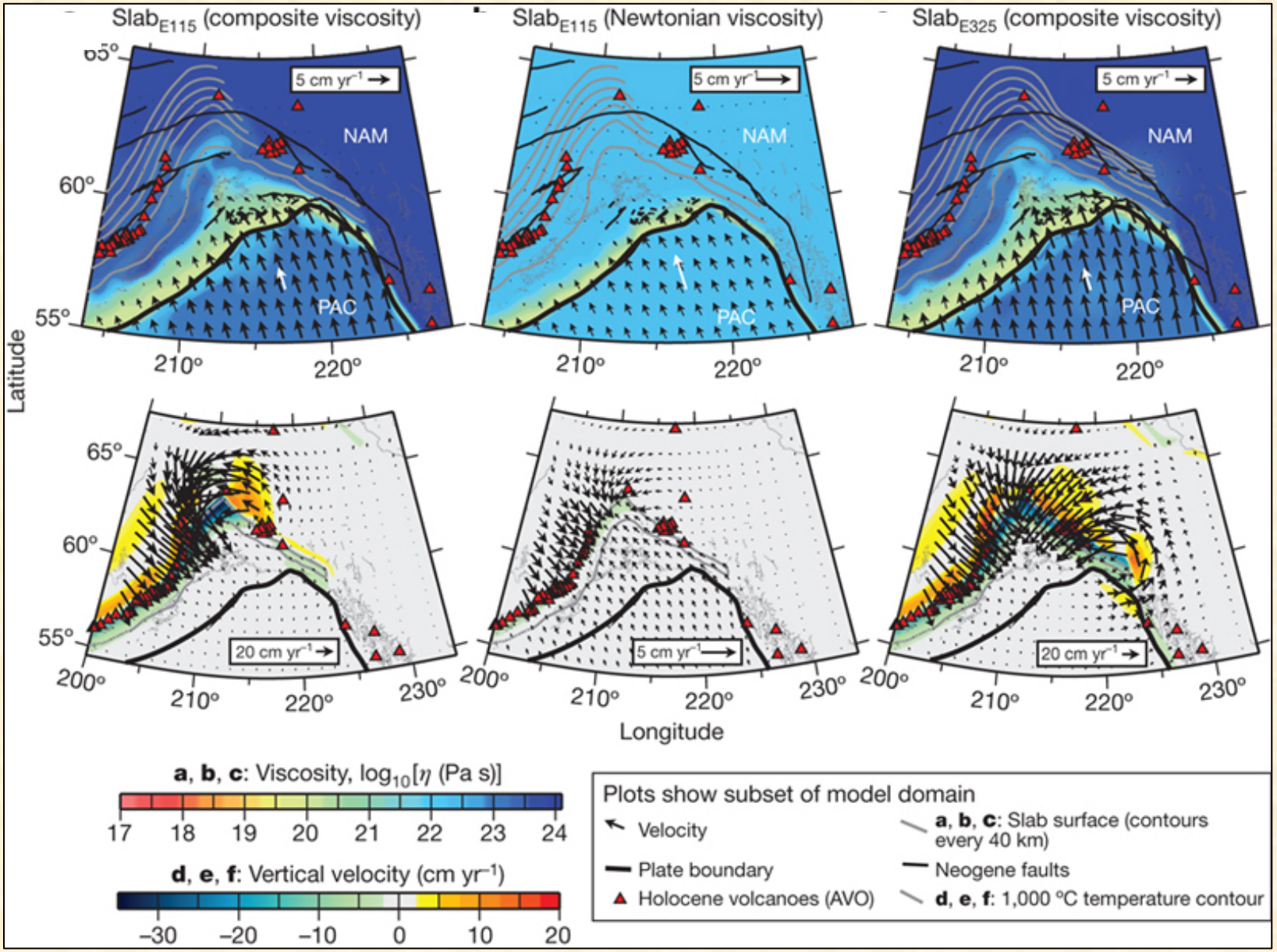
Results: Predicted Mantle Velocity at 100 km Depth

Toroidal flow around slab edge
Upward component of flow associated with slab edge (> 5 cm/yr)
Localized fast mantle flow velocity magnitudes (> 50 cm/yr)
Location of toroidal flow shifts with position of slab edge



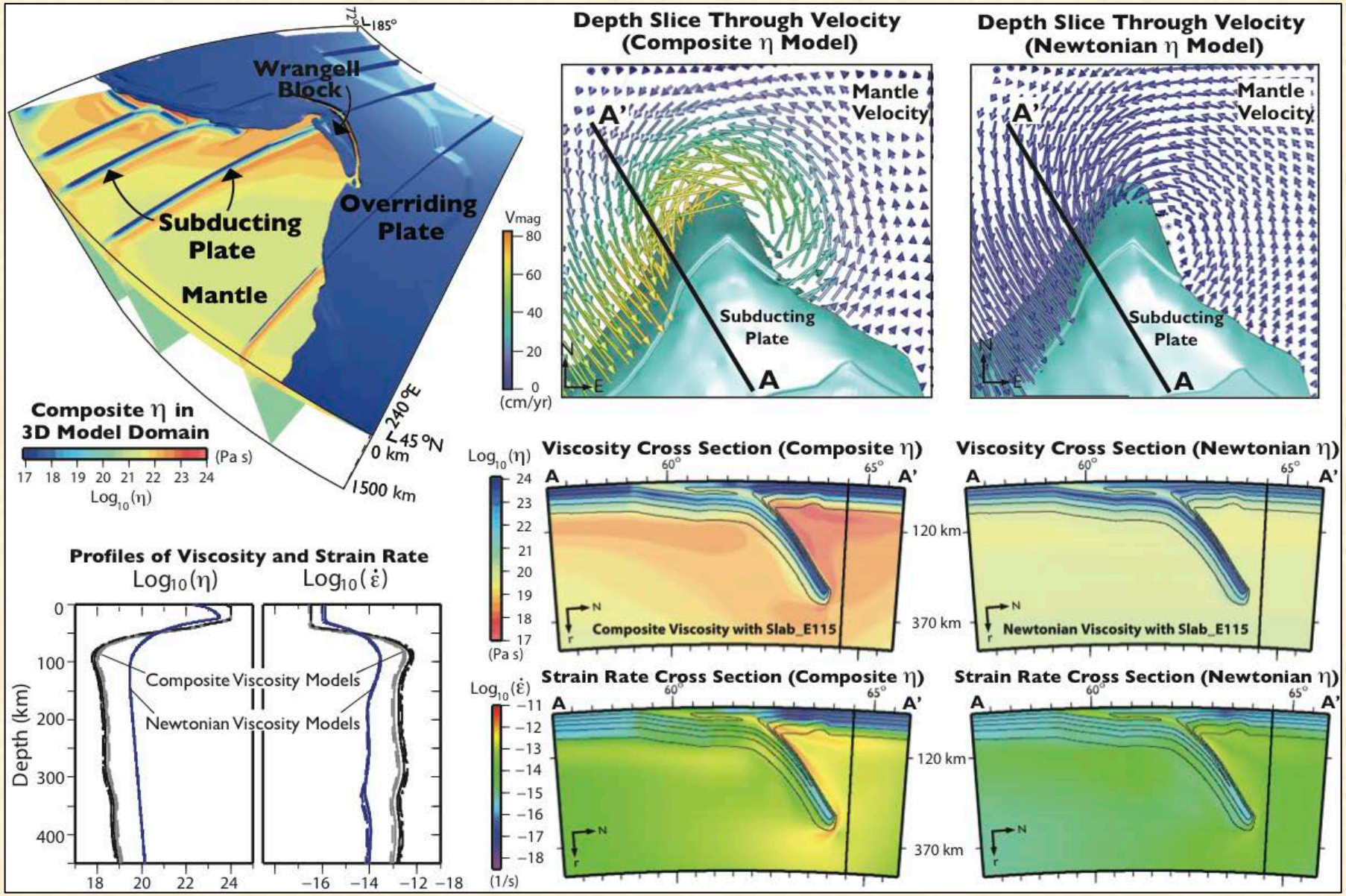
Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012

Rapid Mantle Flow Not Inconsistent with Plate Motions



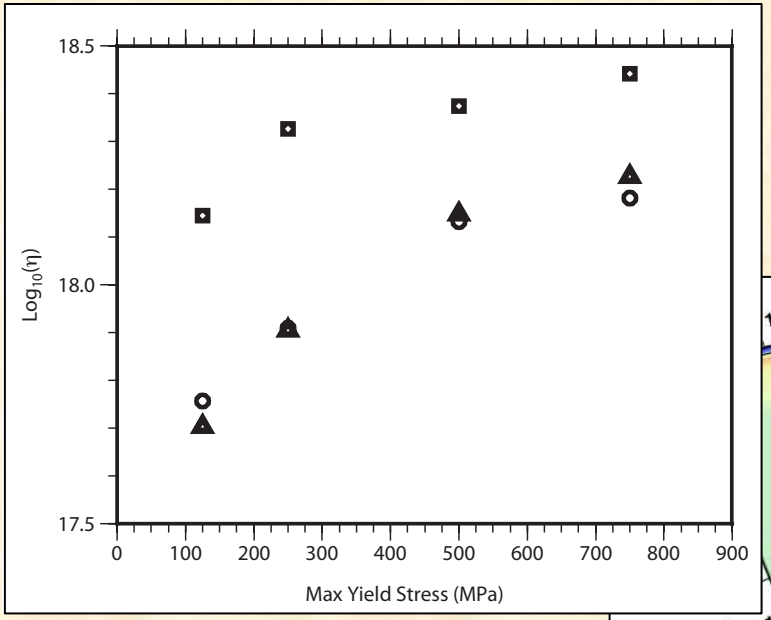
Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012

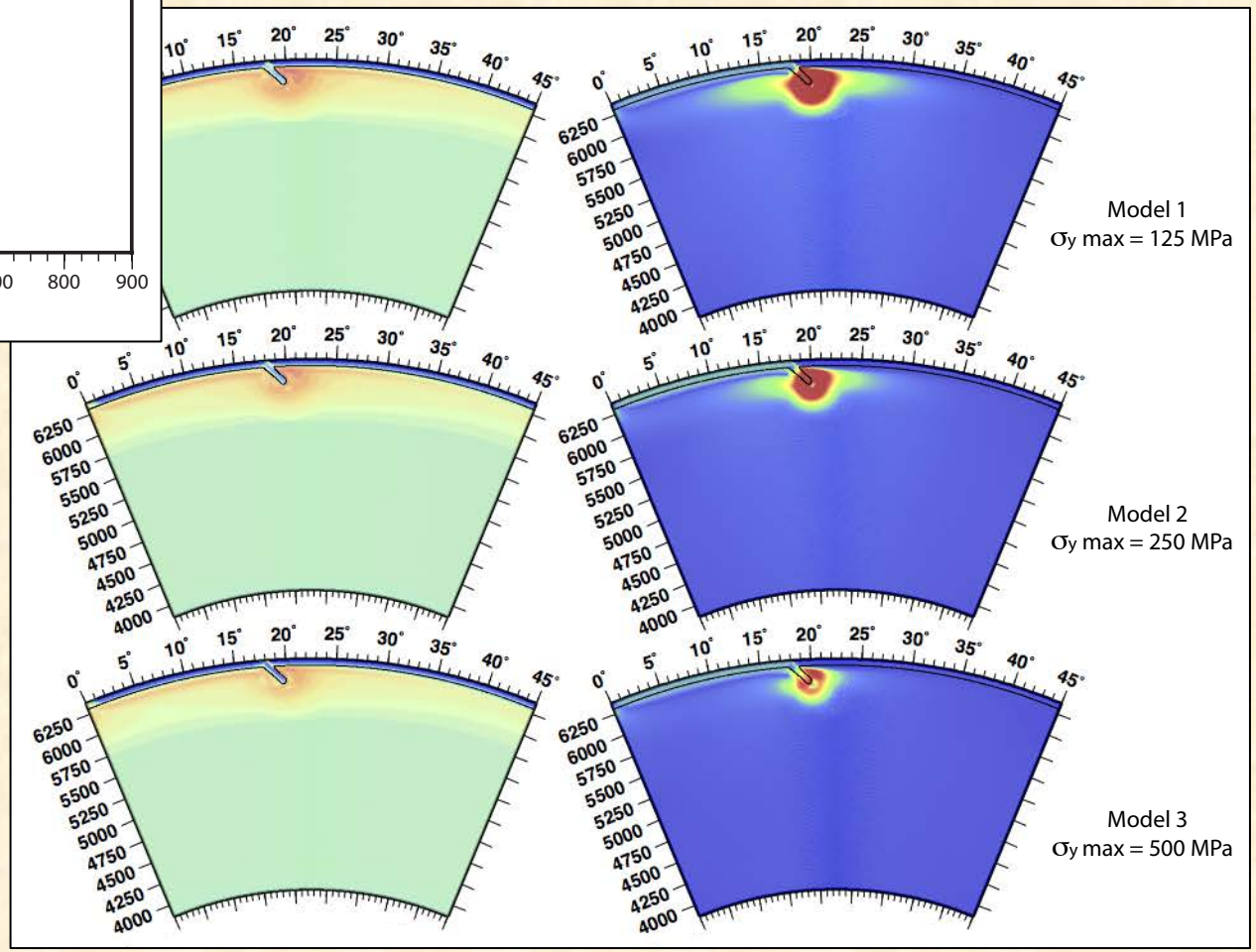
Results: Rheology and 3D Flow Around Alaska Slab Edge



Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012; Jadamec et al., 2013

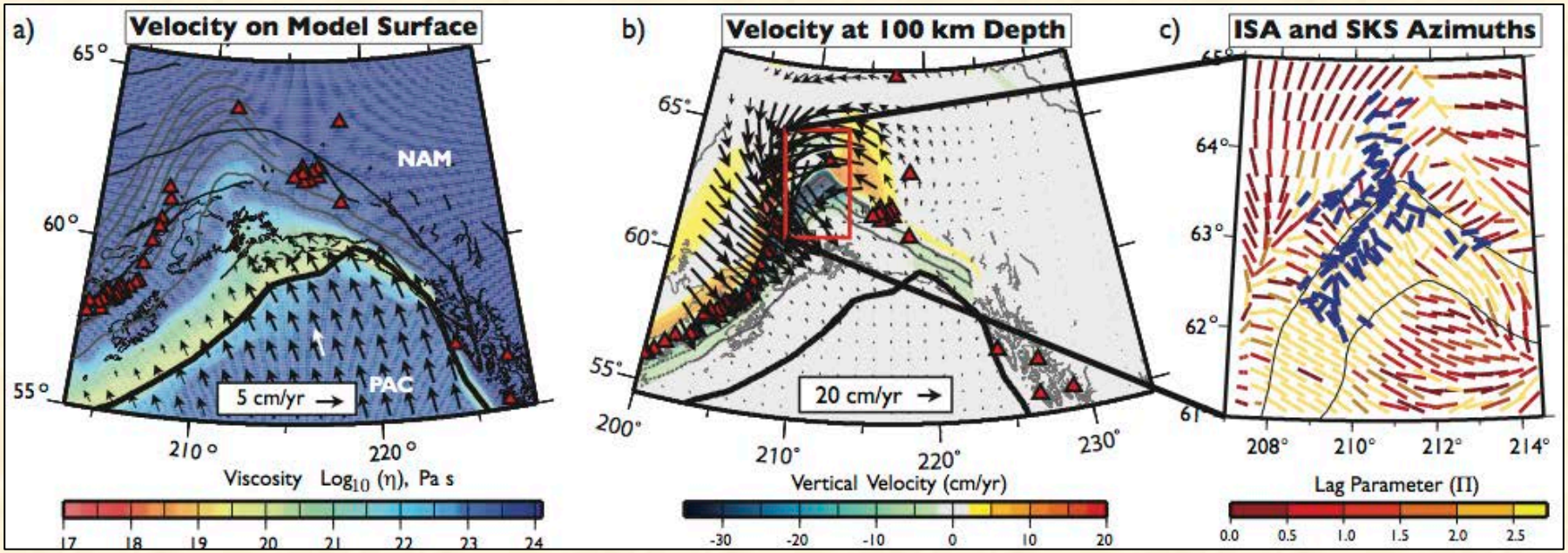
Results: Decreased Viscosity as a Function of Slab Strength





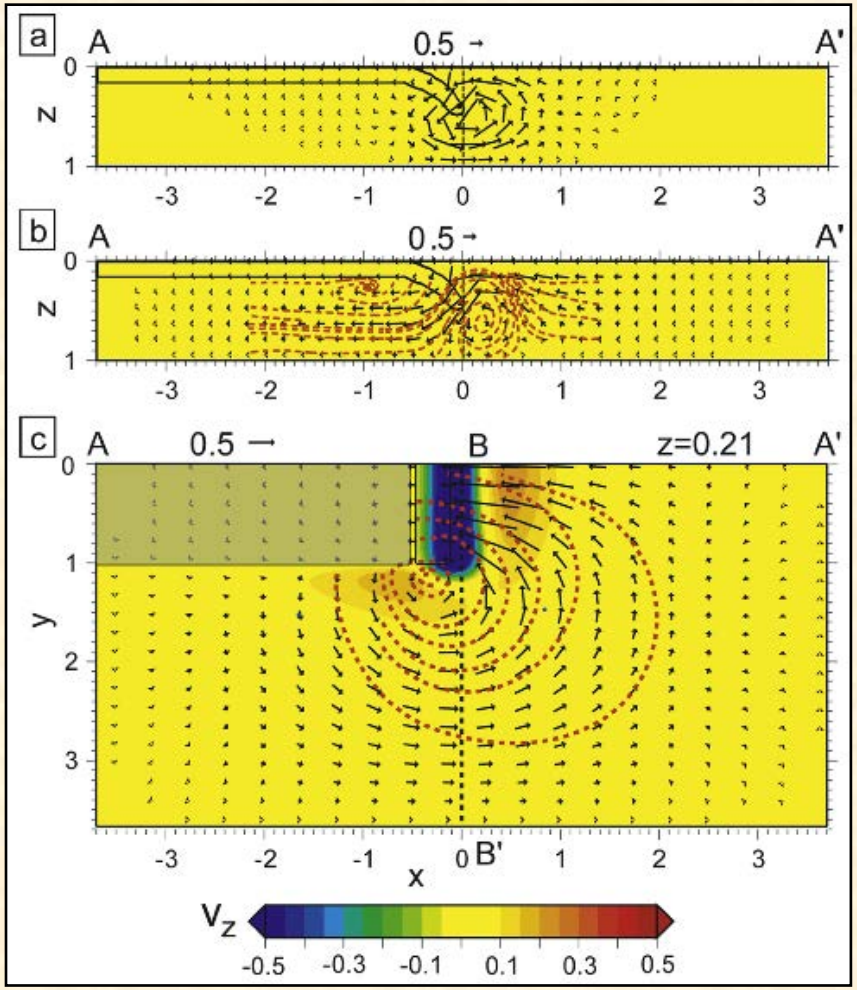
Jadamec, 2014 In Prep

Results: Differential Plate-Mantle Motion and SKS Splitting

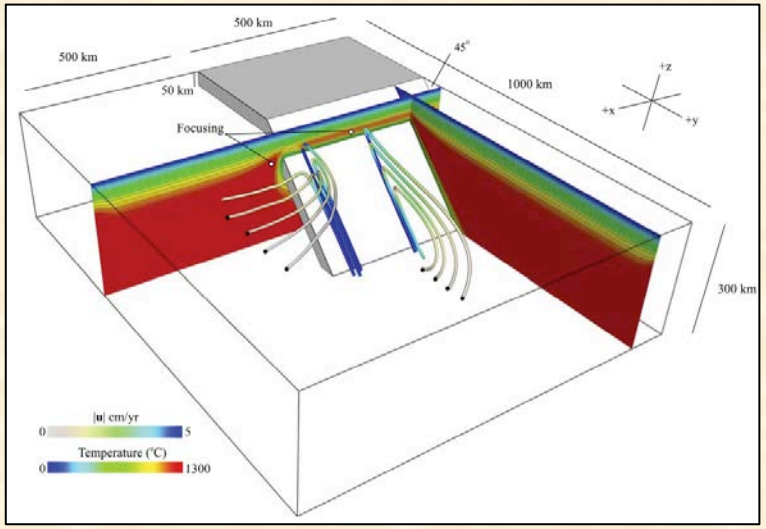


Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012; SKS from Christensen and Abers, 2010

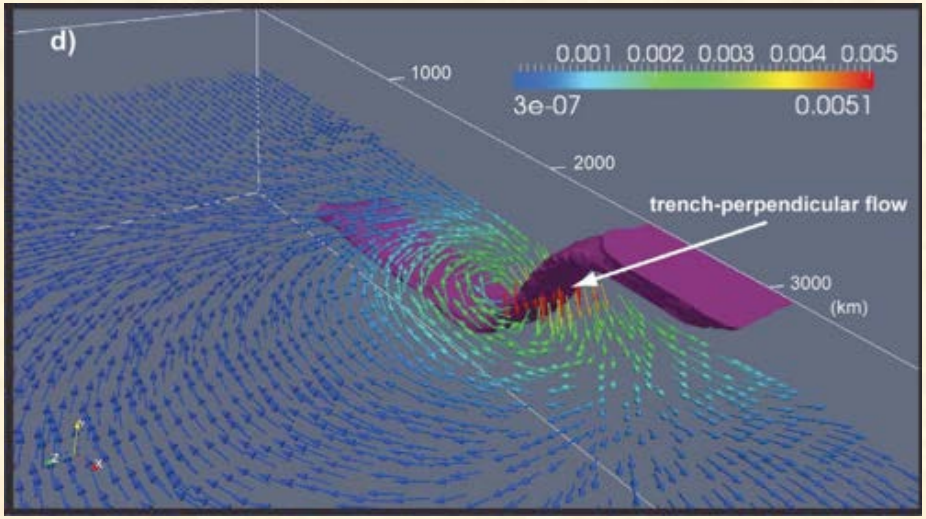
A Lateral Gradient in Velocity Consistent with Previous Models



Piromallo et al., GRL 2006

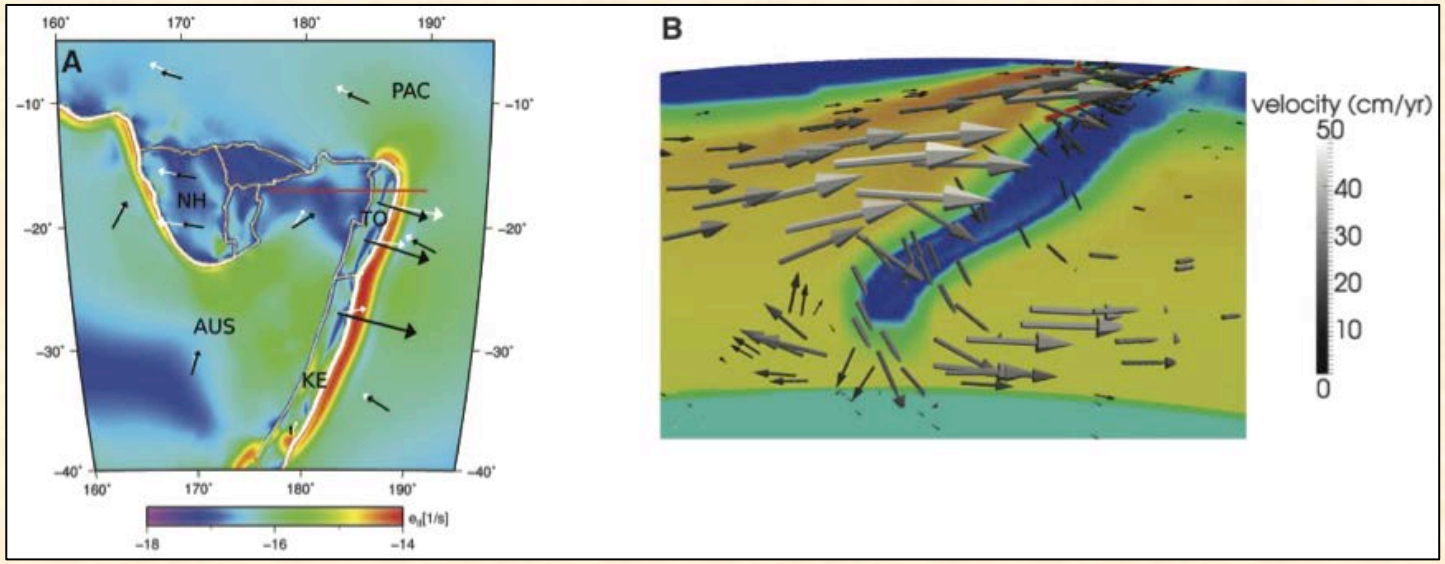


Kneller and van Keken, G^3 2007

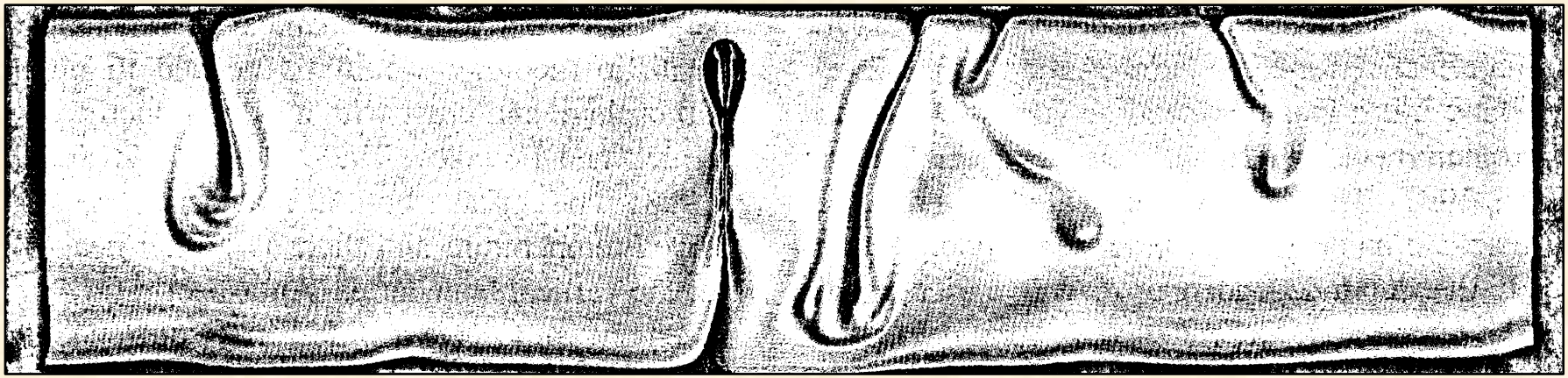


Faccenda and Capitanio, GRL, 2012

Large Velocity Magnitudes in Global Models and Plume Studies

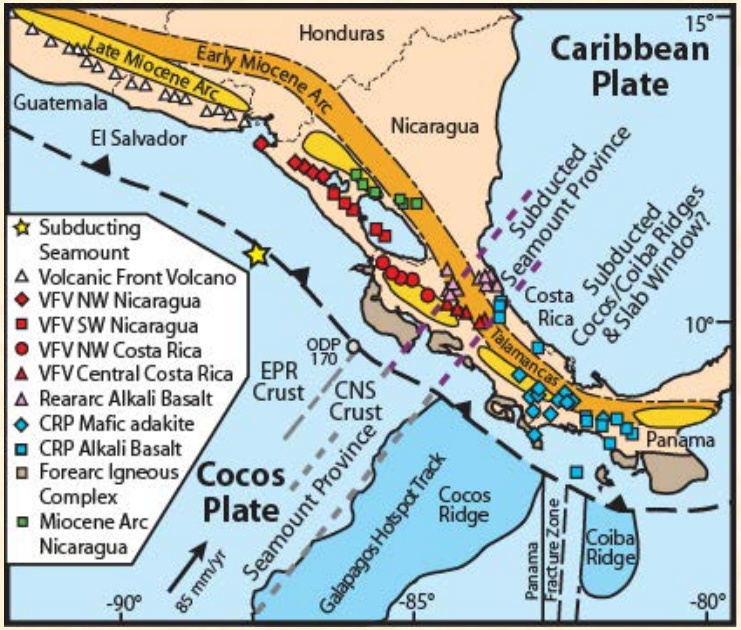


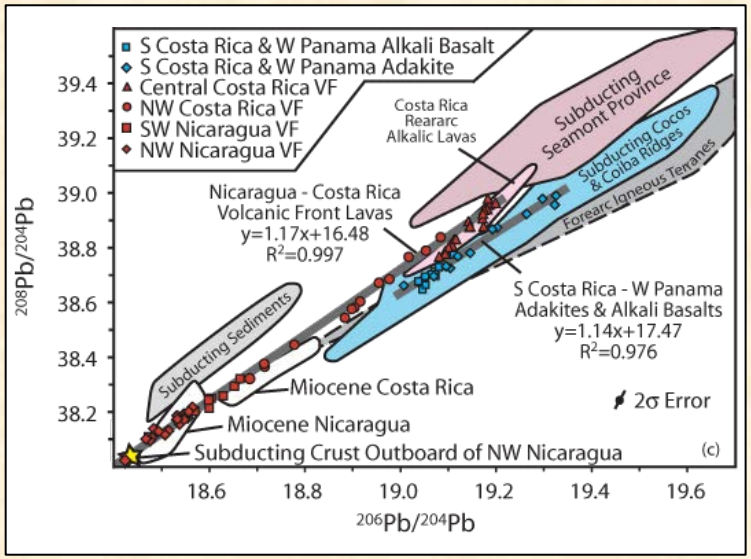
Stadler et al., Science, 2010

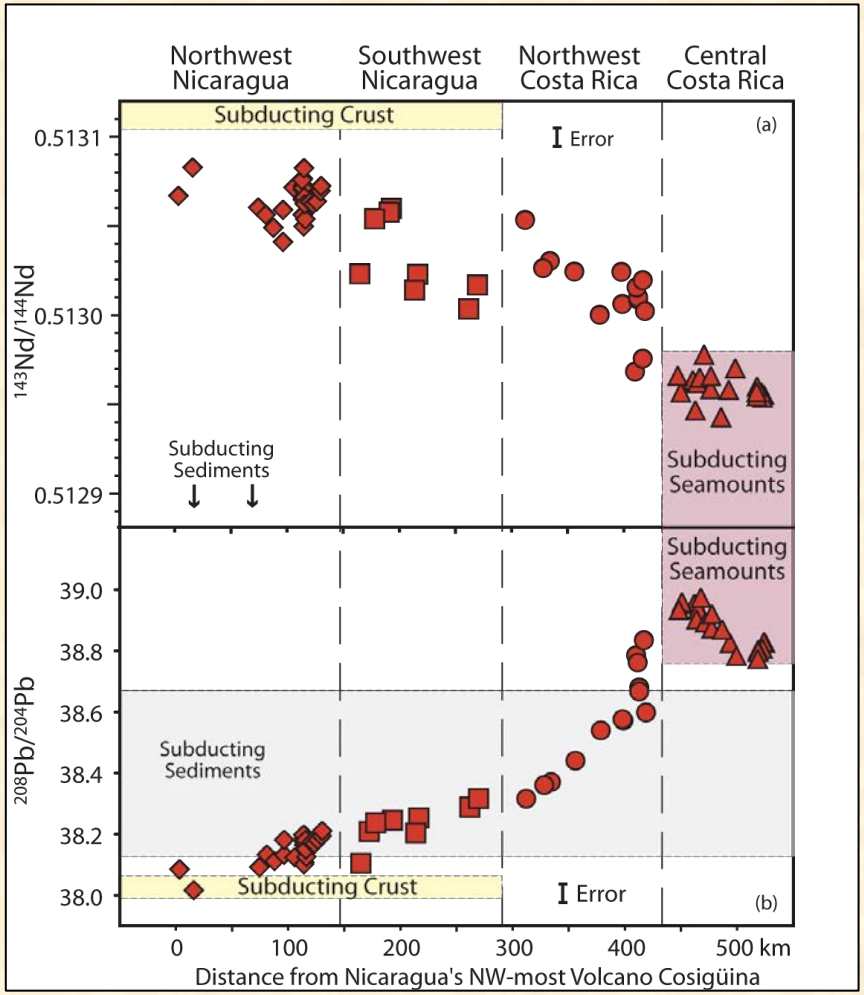


Larsen et al., Tectonophysics, 1999

Independent Observational Constraints on Mantle Flow Rates







Hoernle et al., Nature, 2008

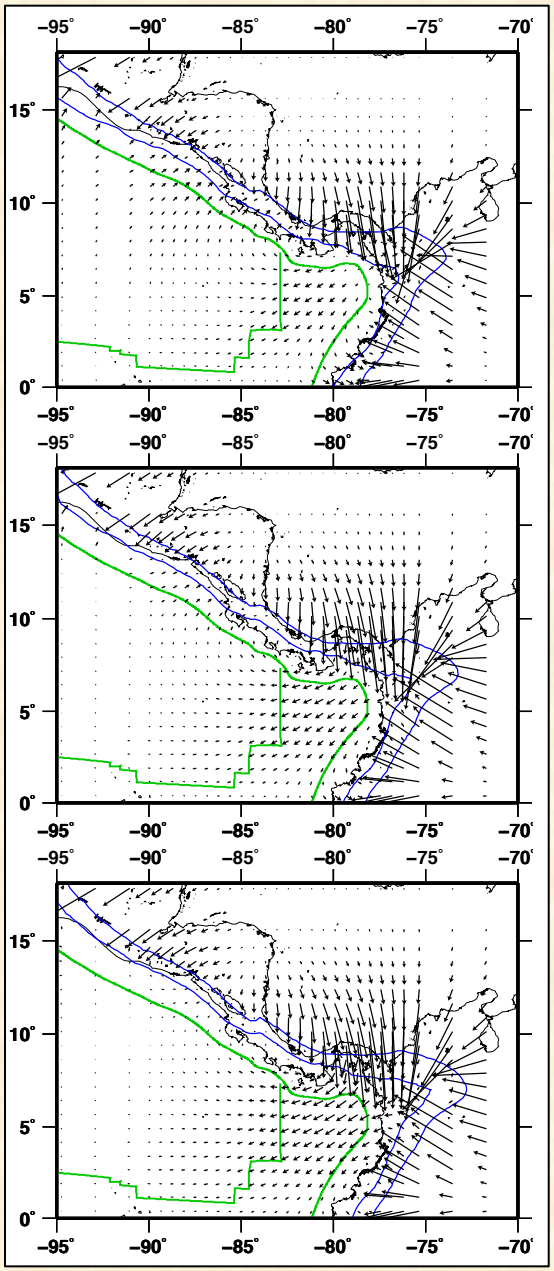
Predicted Mantle Flow Field in Central America System

No Gap Model:

100 km depth

120 km depth

140 km depth

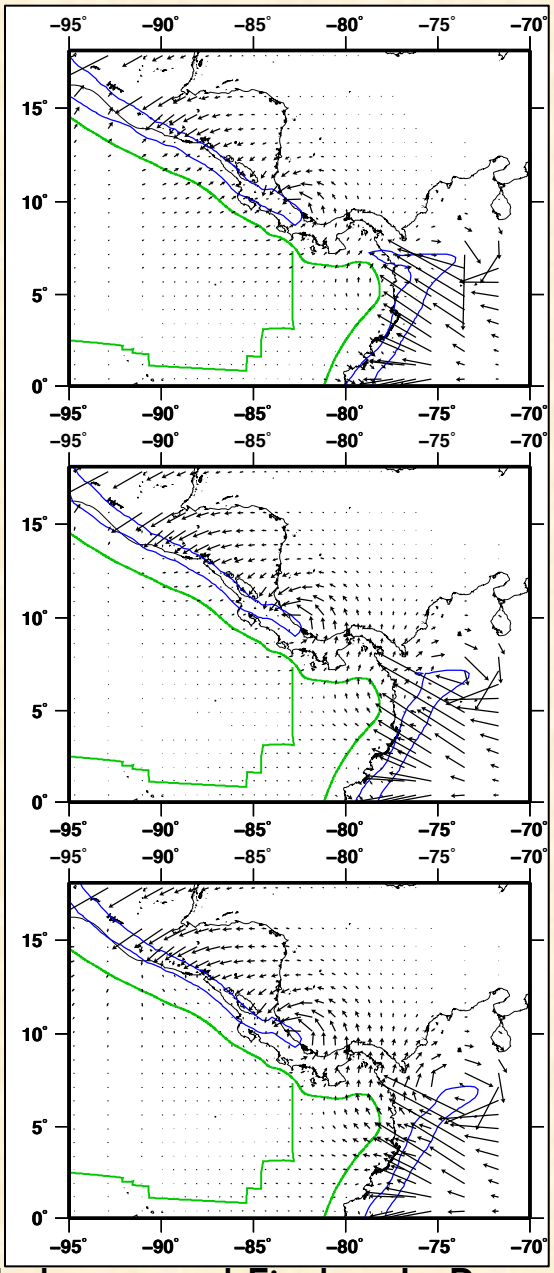


Gap Model:

100 km depth

120 km depth

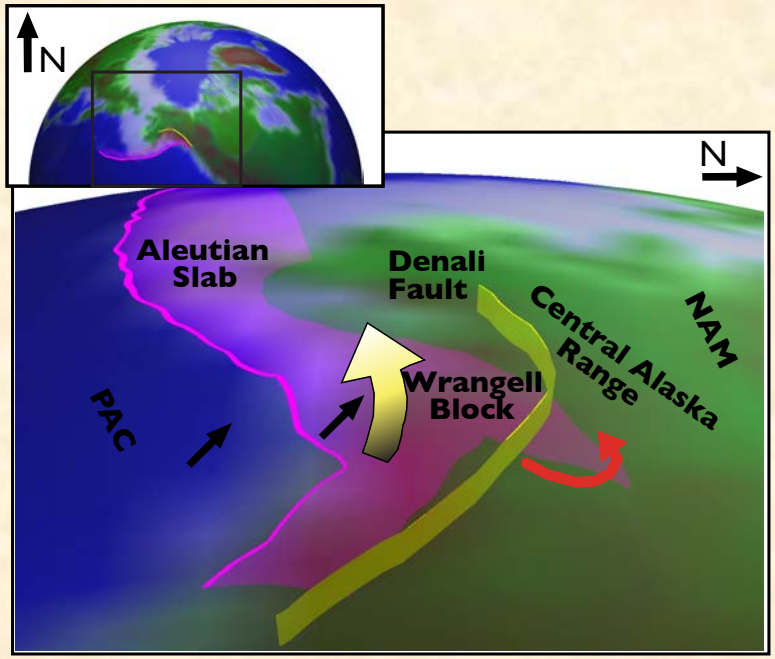
140 km depth



Jadamec and Fischer, In Prep

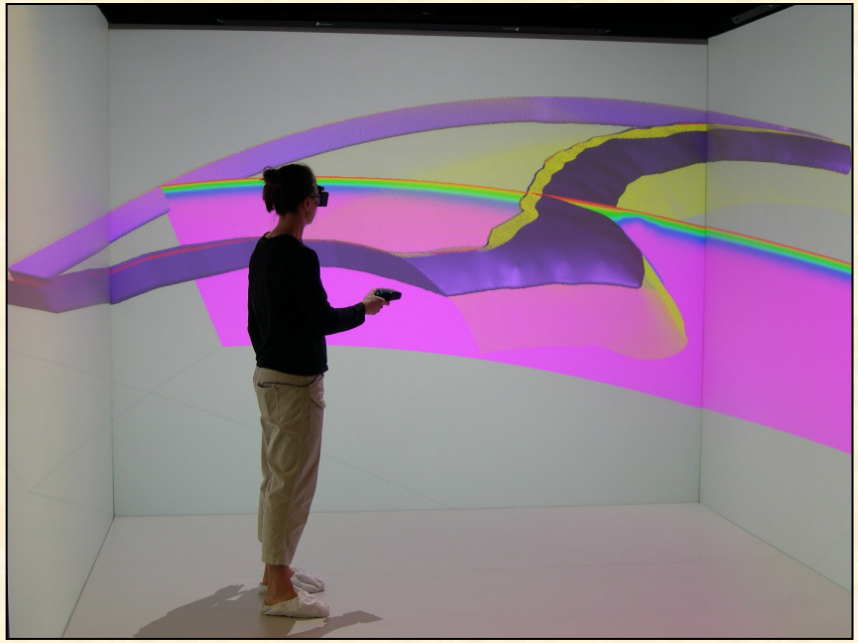
Conclusions & Looking forward

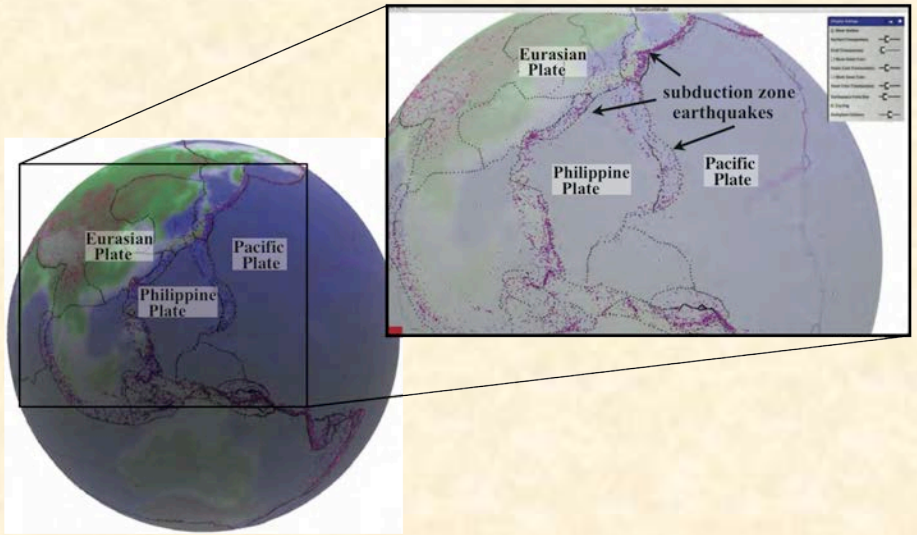
- 3D framework – slab driving deformation in lithosphere and mantle
- Power law (stress-dependent viscosity) decouples mantle from plates in subduction zones, leading to mantle flow rates over 10X plate motions, questions fixing slab velocity to plate motions
- Incorporation of geophysical complexity and large viscosity variations have high computational costs

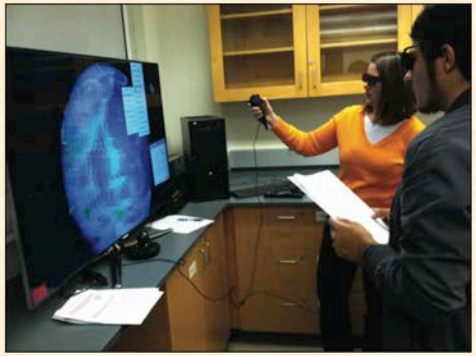


- Software and Hardware to render spatial complexities and Gigabytes of data
- Incorporation of disparate data sets, uncertainty quantification
- Data storage, archiving, libraries, code repositories, version control

Conclusions & Looking forward







Interactive Scientific Data Visualization:
Upper Left: KeckCAVES (UC Davis)
Lower Left: 3DALIVE (Monash)
Upper Right: In-Office (Brown)

Thank You