Large-scale Synthesis Model of the Lithosphere and Upper Mantle in Alaska

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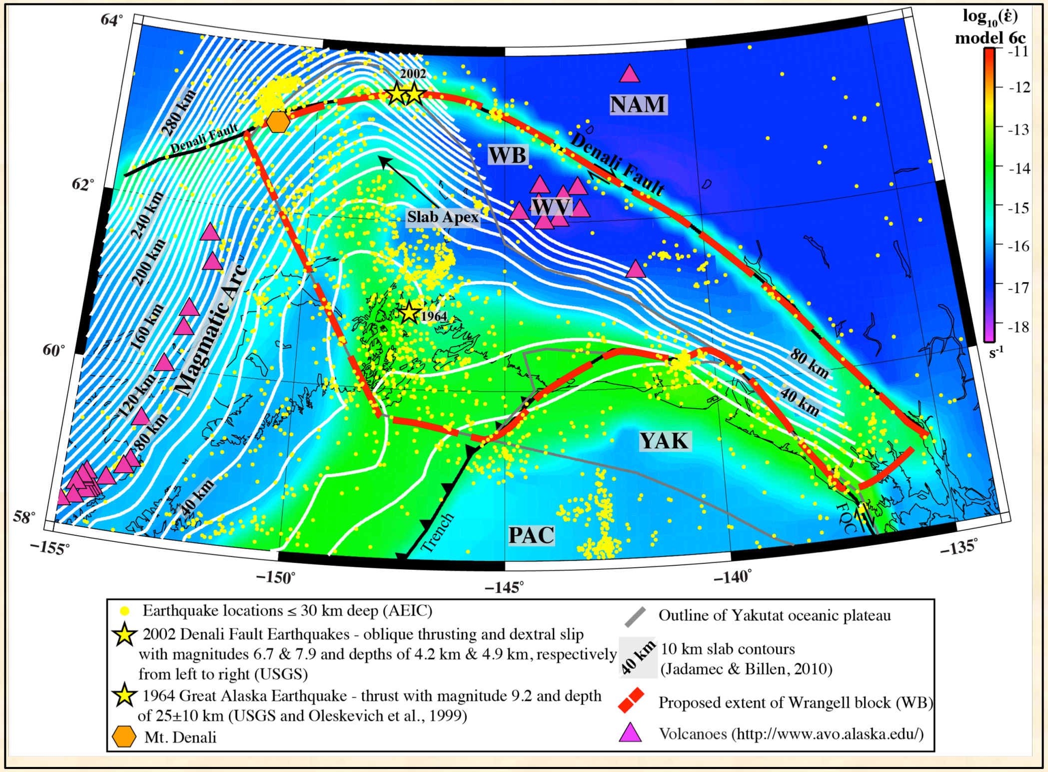


Collaborators:

Kirstie Haynie, Magali Billen, Louise Kellogg, Sarah Roeske Donald Turcotte, Oliver Kreylos, Burak Yikilmaz, Ben Chang, Nicole Pham, Alberto Carballo

Resources:

National Science Foundation, TeraGrid-XSEDE, TACC UH Geodynamics Cluster KeckCAVES

EarthScope National Meeting May 17, 2017

Use High-resolution 3D Model of Specific Regions to Constrain Process: Alaska Specific Questions

- Initial 3D Slab, Mantle, Lithosphere Structure of Alaska (AlaskaModel 1.0)

- What is the slab geometry in Alaska?

- What is the mantle flow field in southern Alaska?

- Why is there localized mountain building in Central Alaska Range over 500 km from the plate boundary?

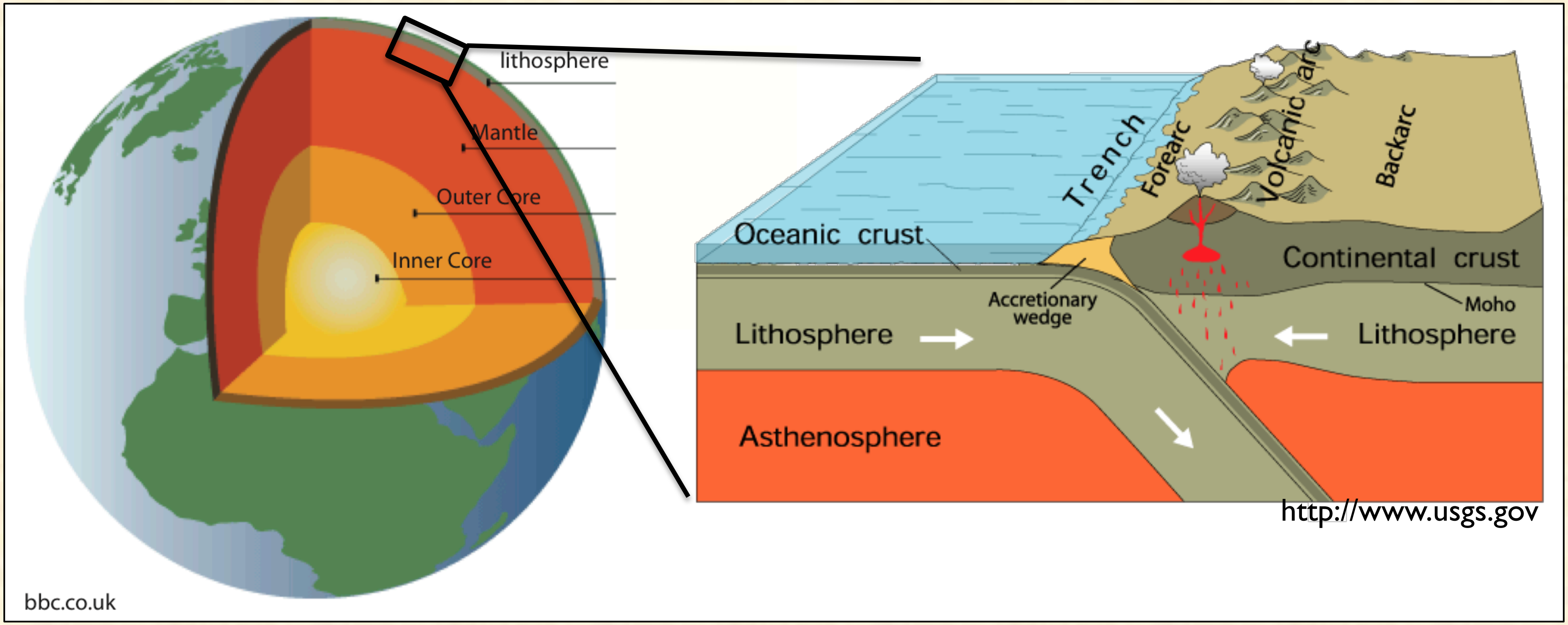
- What controls Wrangell Block (fore-arc sliver) motion in Alaska?

- What are implications of slab structure on hazards in Alaska?

Use High-resolution 3D Model of Specific Regions to Constrain Process: General Questions

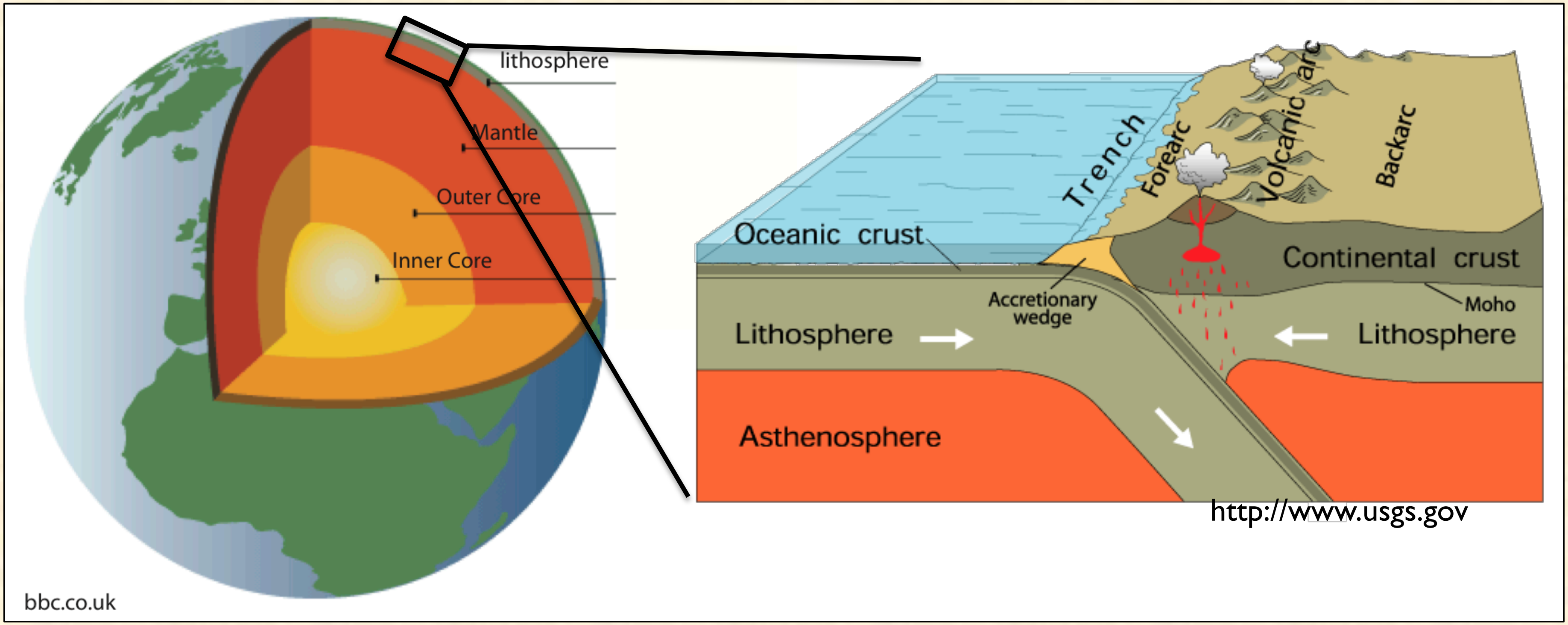
- What are the length-scales of plate-mantle coupling?
- What is the nature of 3D mantle flow in subduction zones?
- How do slabs couple into deformation of the upper plate in 3D?
- What controls intra-continental mountain building?
- What are implications of slab structure on tectonic hazards?
- How is scientific discovery advanced by High Performance Computing & Data assimilation?

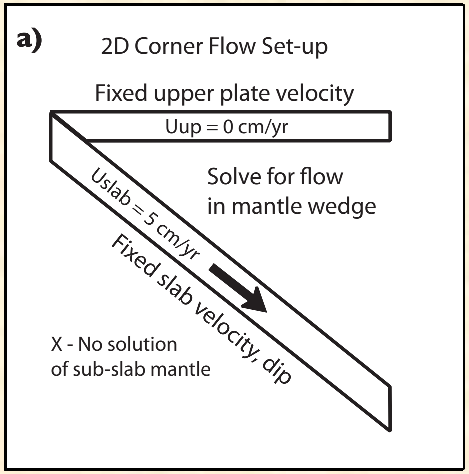
Plate Tectonics & Subduction Zone Type Boundaries



- Outer layer of Earth composed of ~ 15 plates (~150 km thick)
- Plates in motion with respect to one another
- Deformation concentrated at the plate boundaries
- Subduction zones occur at convergent plate margins where one plate descends beneath another plate into the viscous mantle

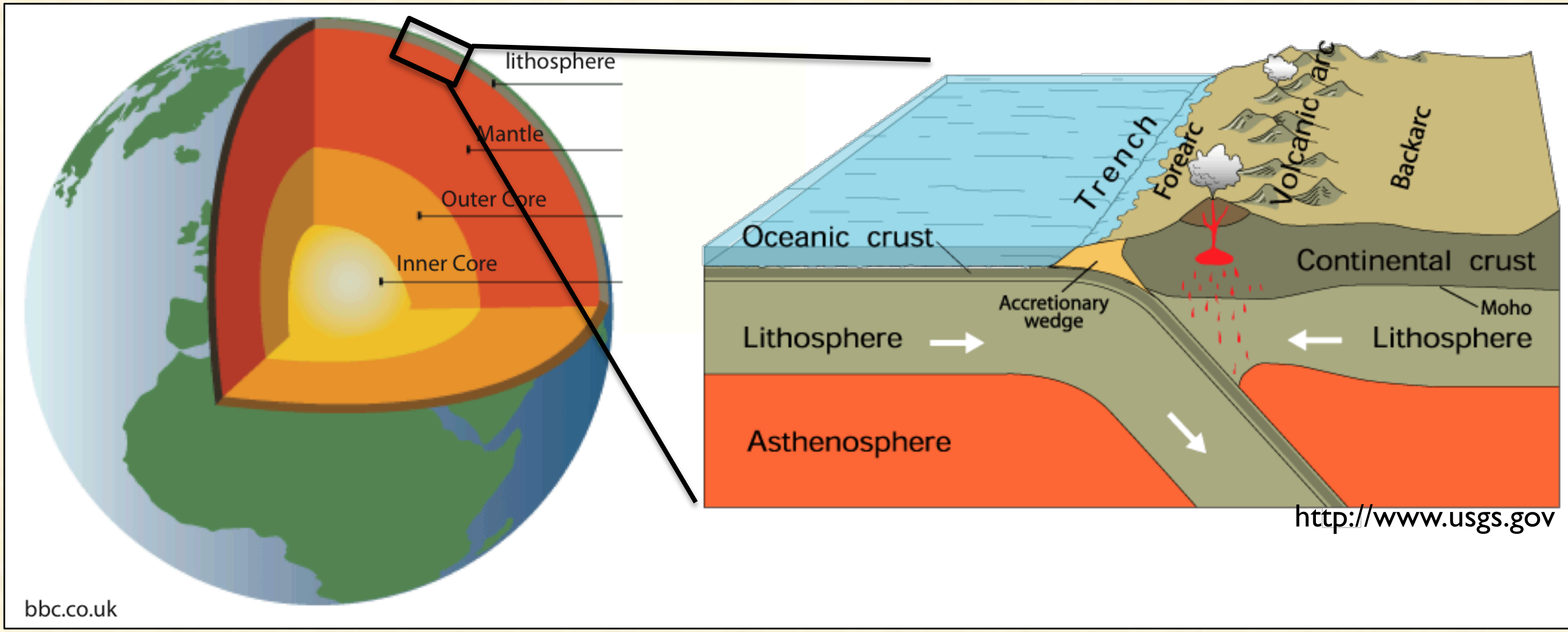
Plate Tectonics & Subduction Zone Type Boundaries

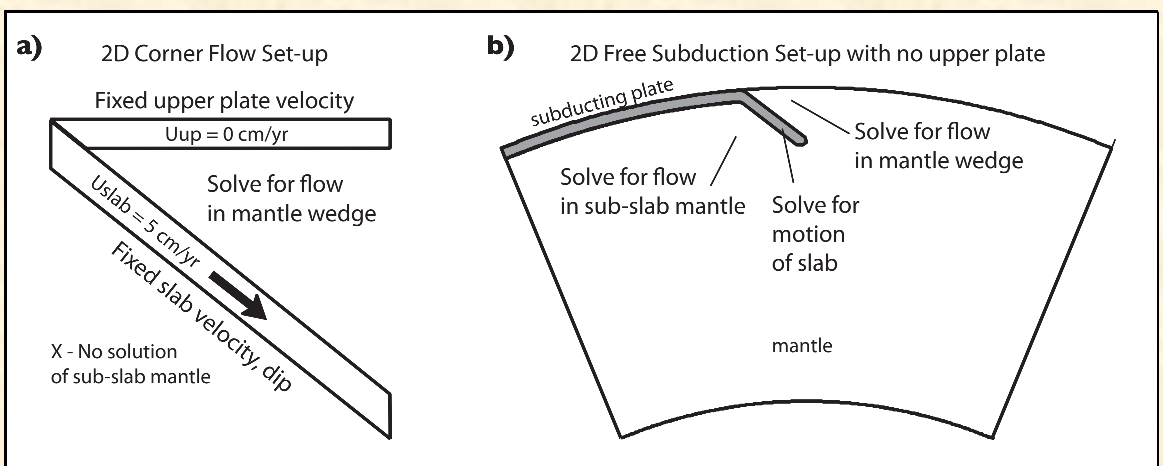




Jadamec, 2016, Journal of Geodynamics

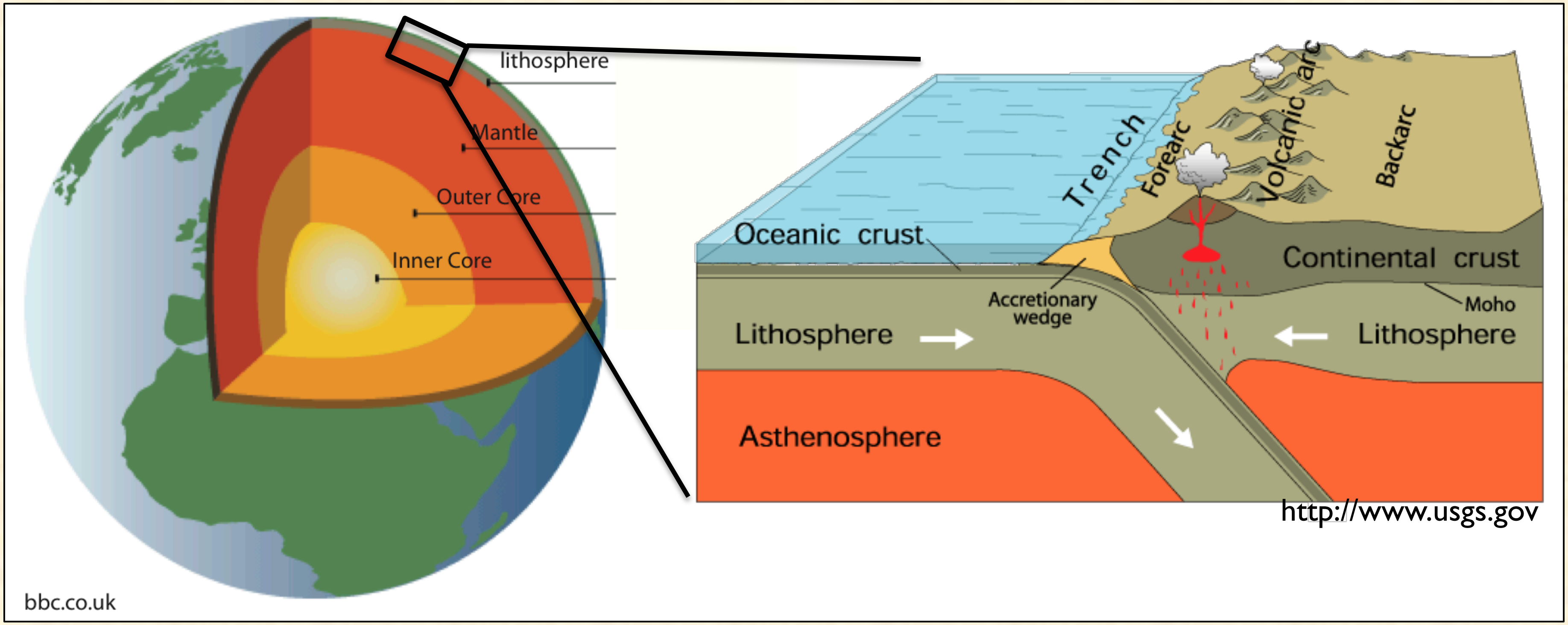
Plate Tectonics & Subduction Zone Type Boundaries

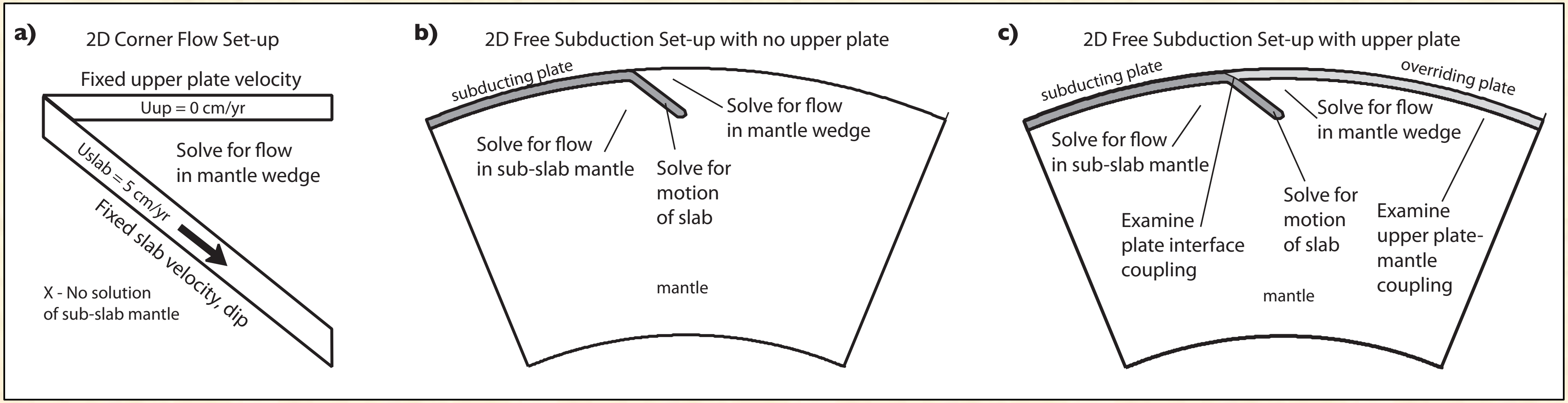




Jadamec, 2016, Journal of Geodynamics

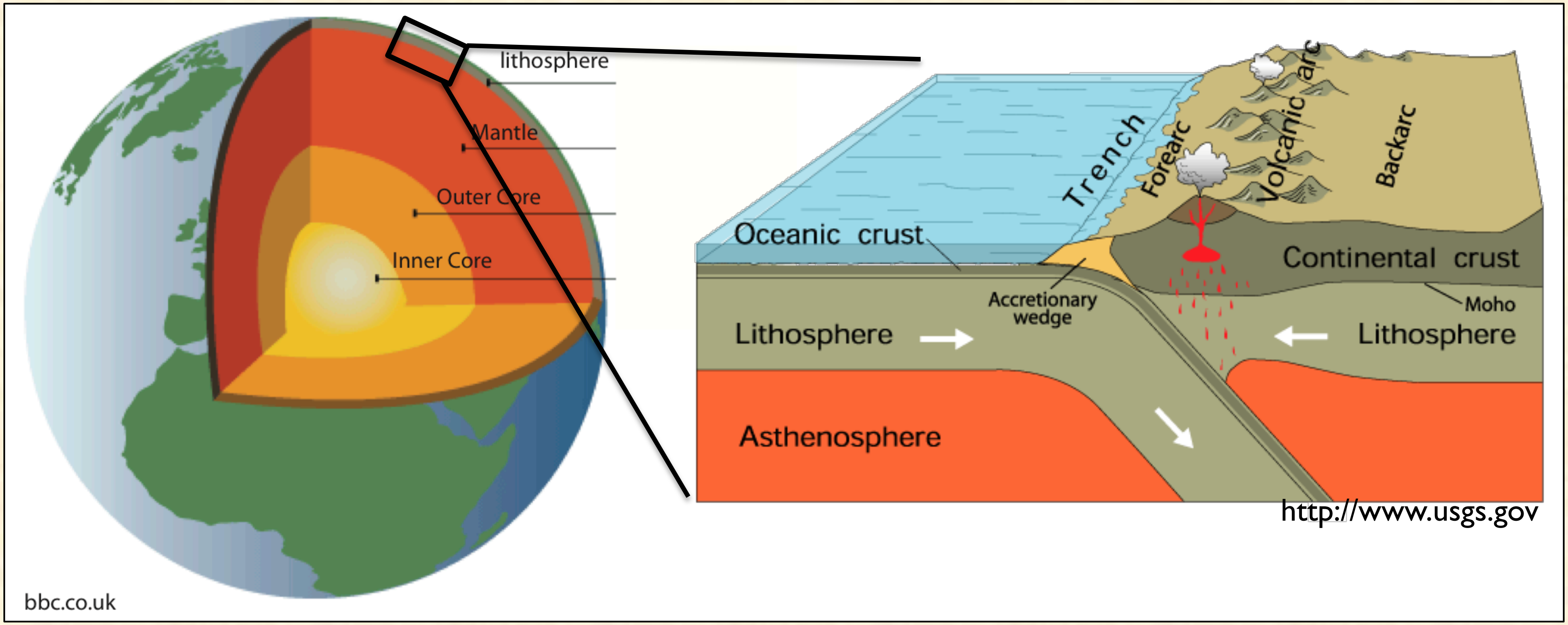
Plate Tectonics & Subduction Zone Type Boundaries

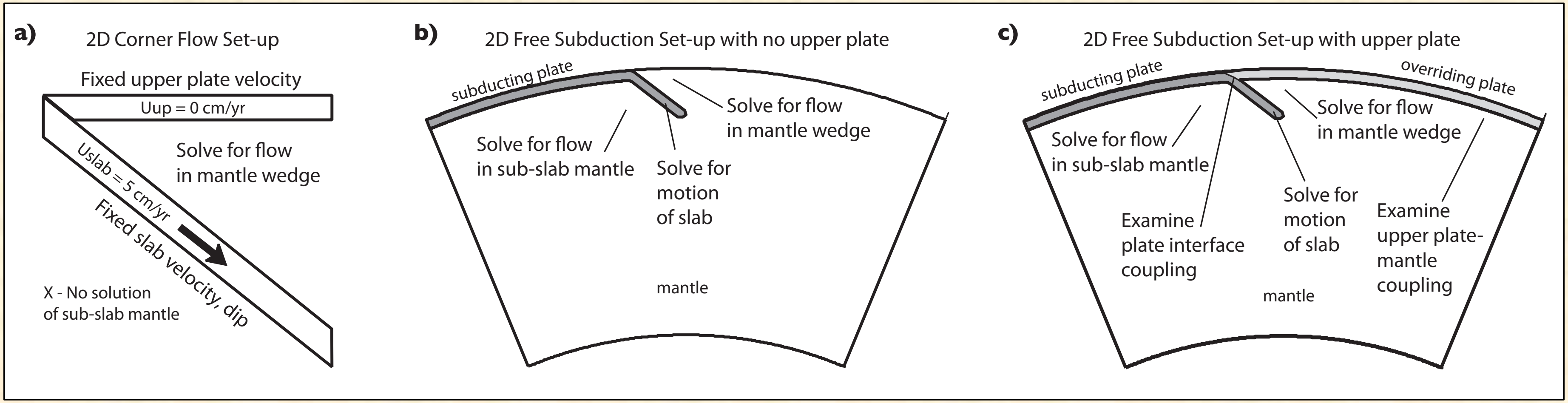




Jadamec, 2016, Journal of Geodynamics

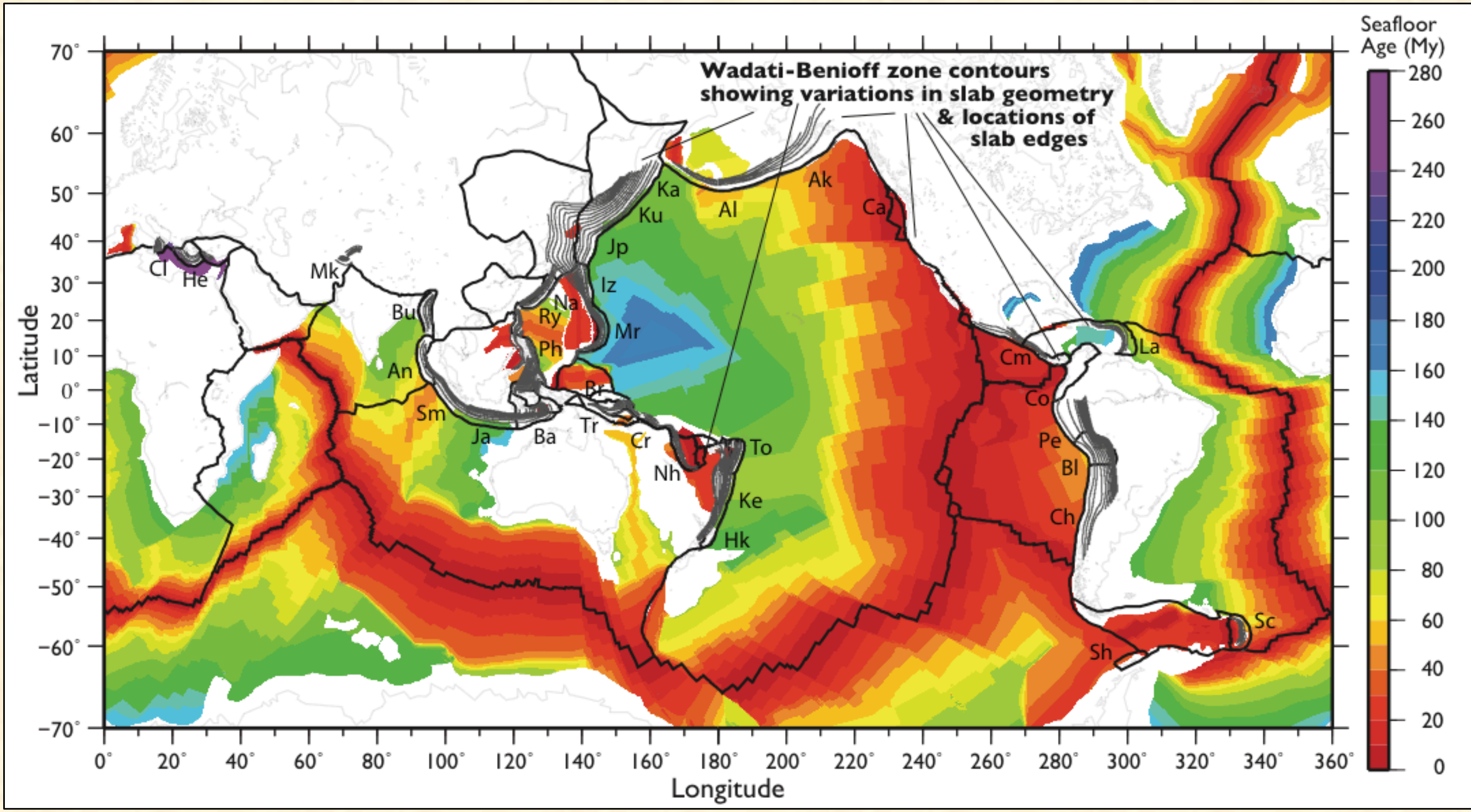
Plate Tectonics & Subduction Zone Type Boundaries





Jadamec, 2016, Journal of Geodynamics

Slabs are Inherently 3D and Important for Mantle Plate Def.

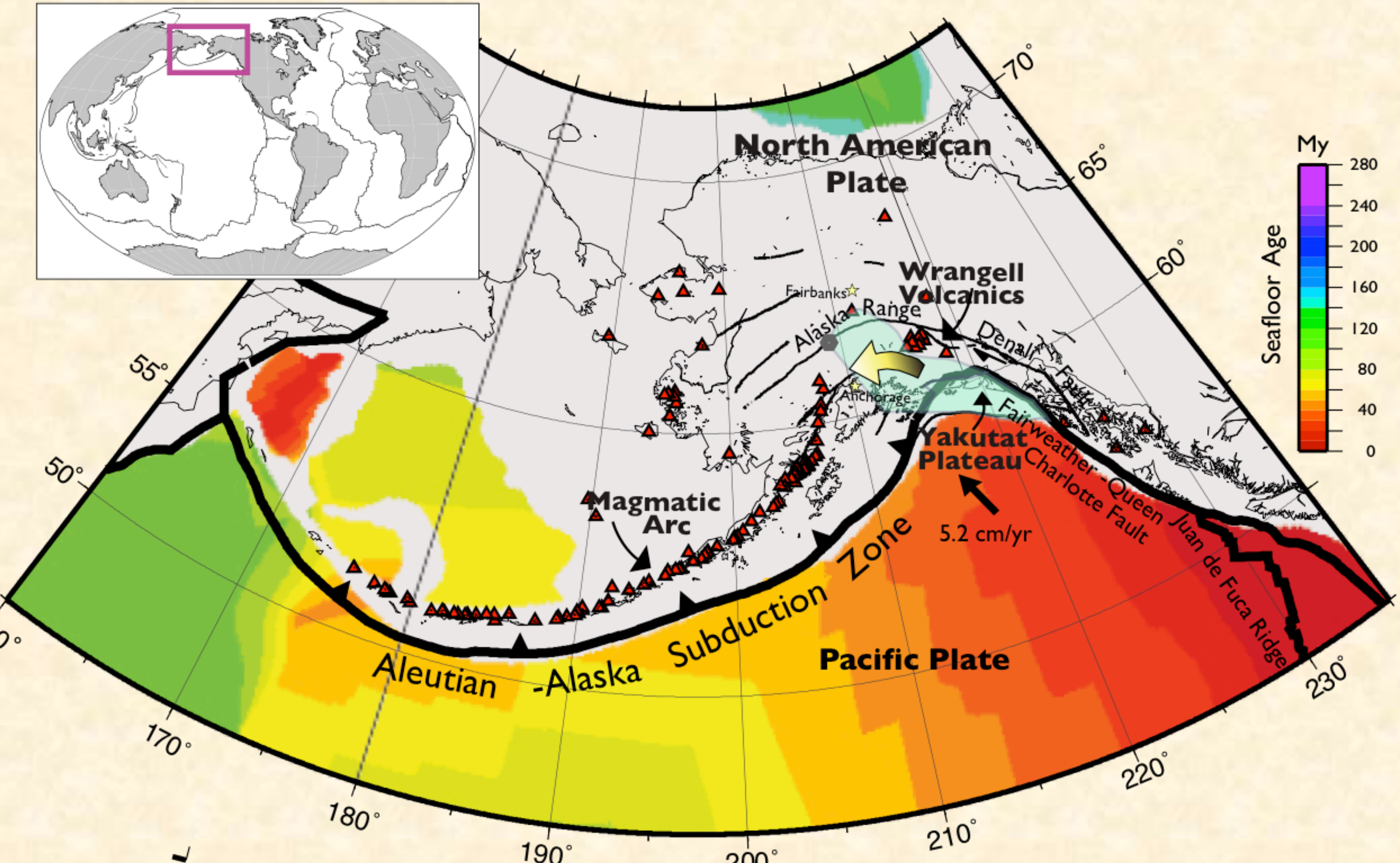


Jadamec, 2016, Journal of Geodynamics

Data Sources:

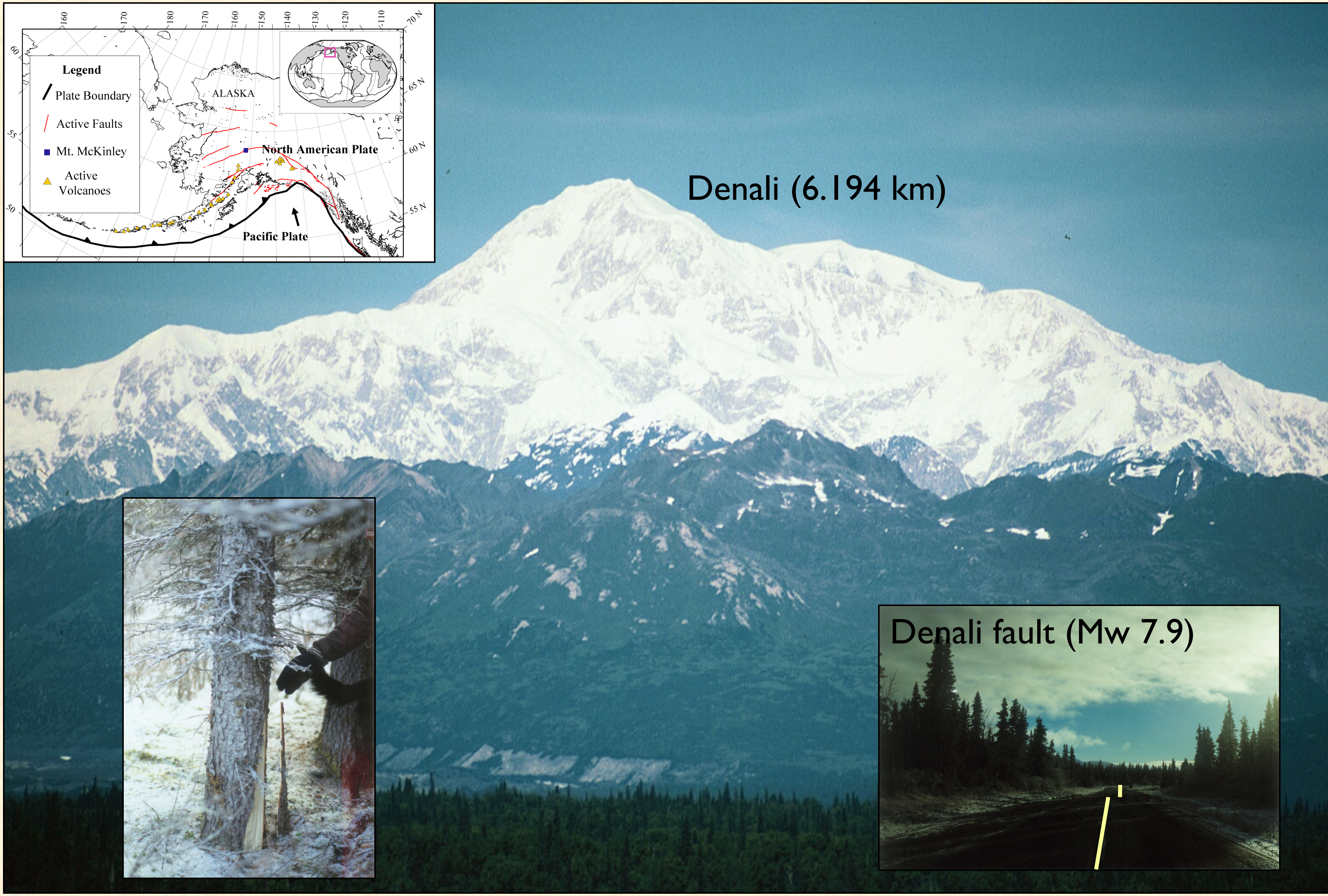
Mueller et al., 2008; Bird et al., 2003; Schellart et al., 2008; Gudmundsson and Sambridge, 1998

Use High-resolution 3D Model of Specific Regions to Constrain Process



Jadamec et al., In Prep

Far-field Mountain Building and Along Strike Variation

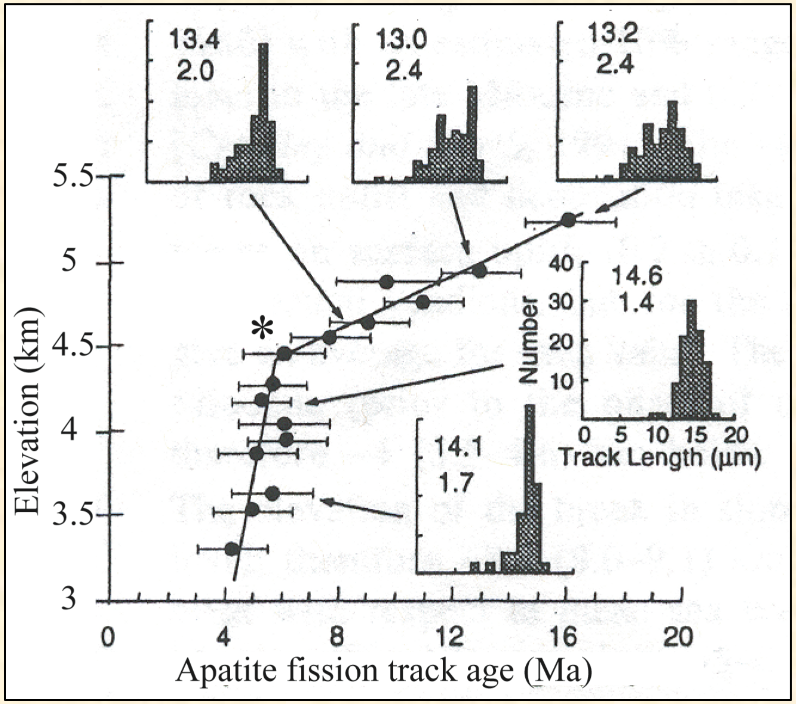


Photos by M. Jadamec

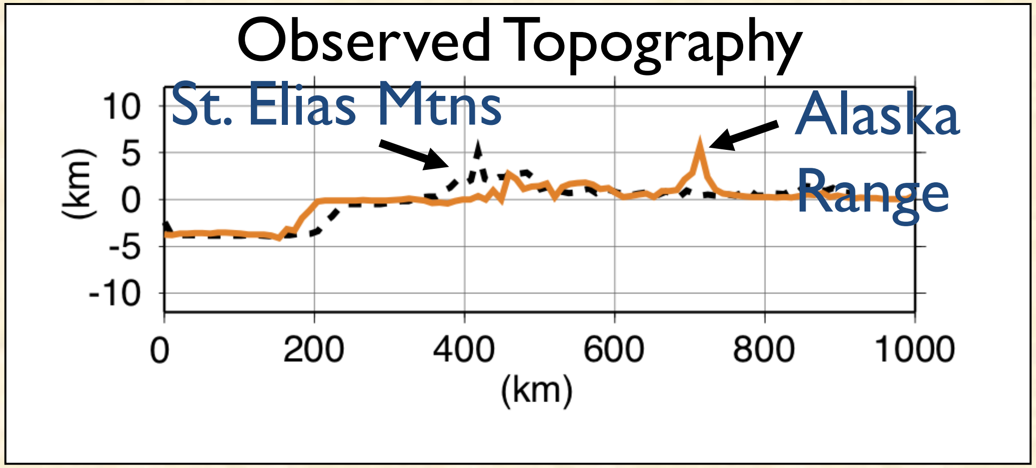
photos by M. Jadamec

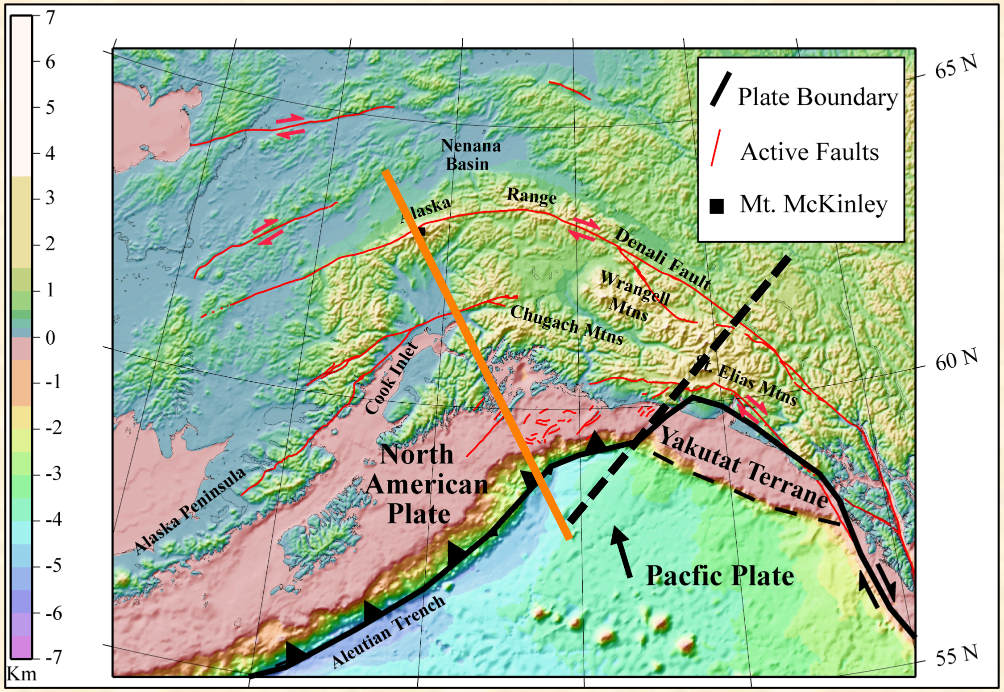
Far-Field Localized Deformation in Central Alaska Range

Onset Exhumation ~5 Ma

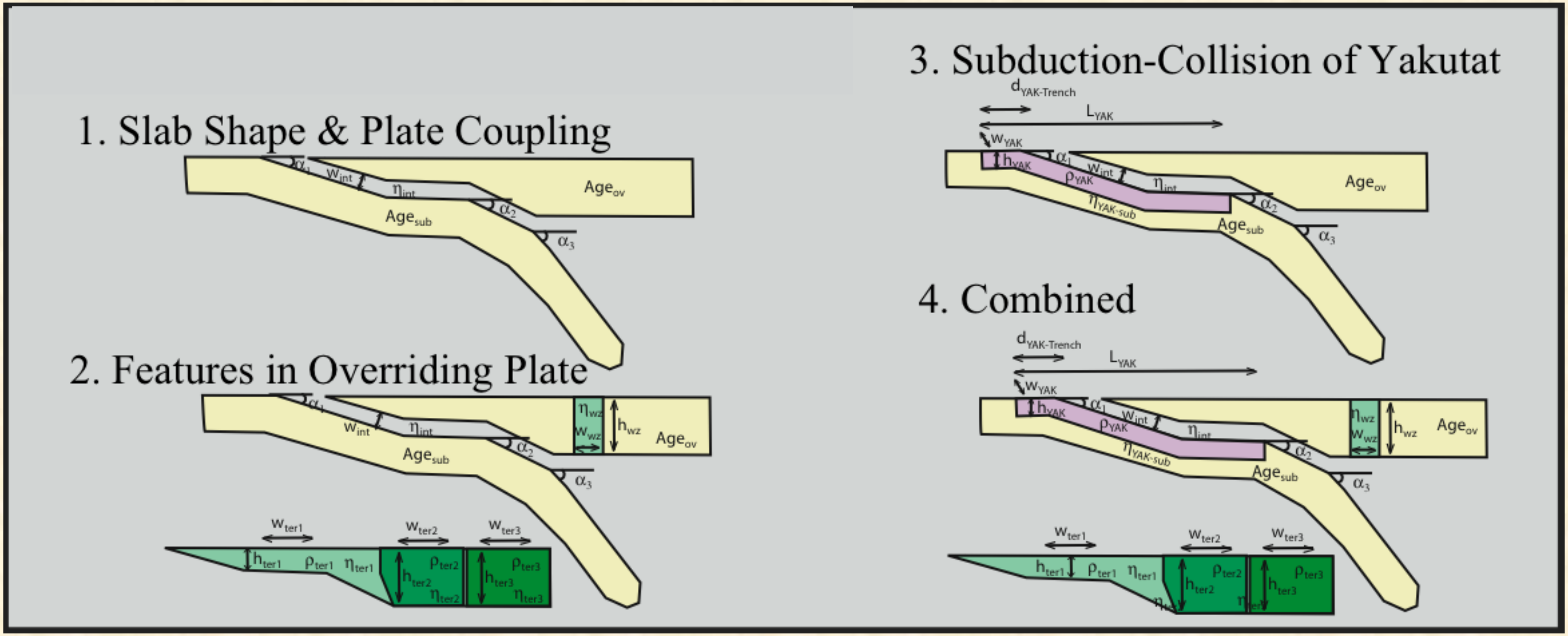


Fitzgerald et al. 1995





Hypotheses for Far-field Deformation in Alaska

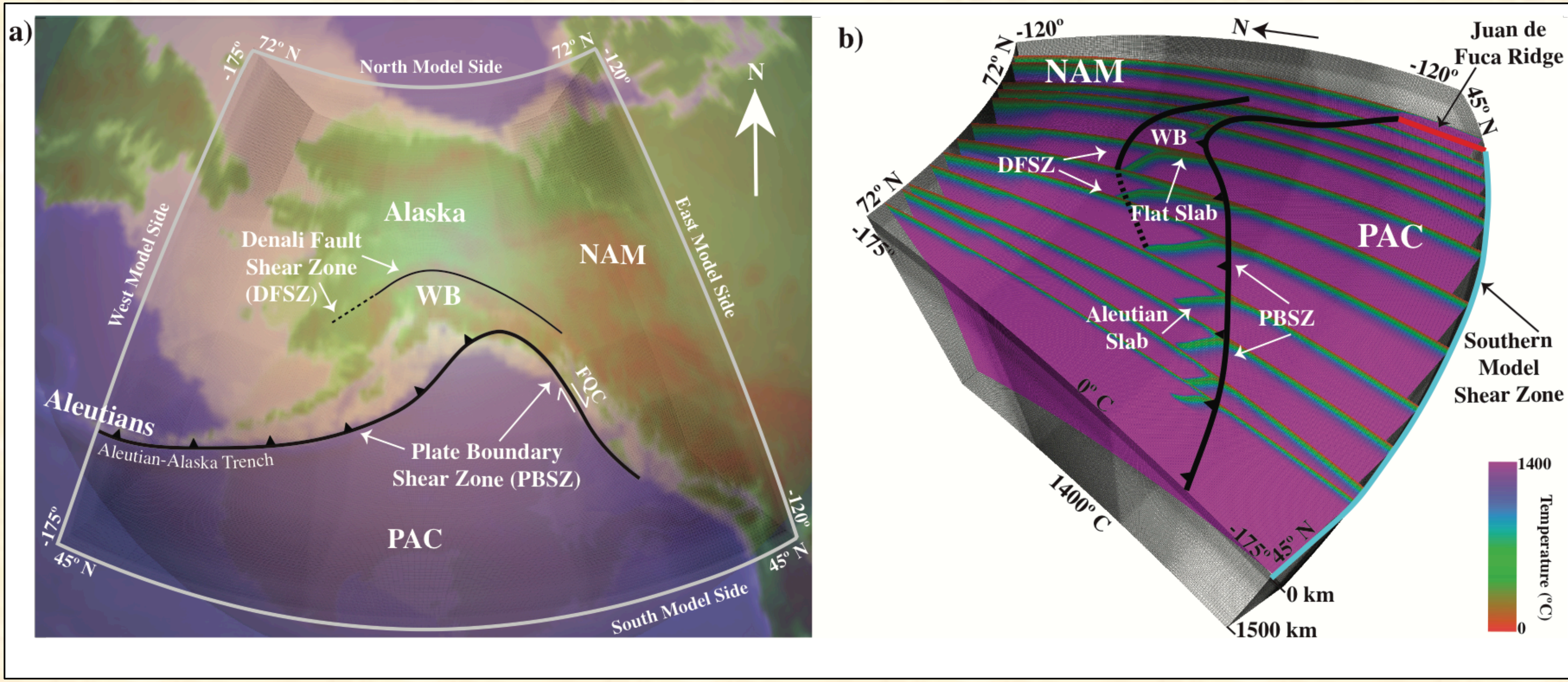


Jadamec, PhD Sketches

Jadamec and Billen, Nature (2010)
Jadamec and Billen, JGR (2012)
Jadamec et al., ACM XSEDE (2012)
Jadamec et al., EPSL (2013)
Jadamec, Journal of Geodynamics (2016)
Haynie and Jadamec, Tectonics (2017)

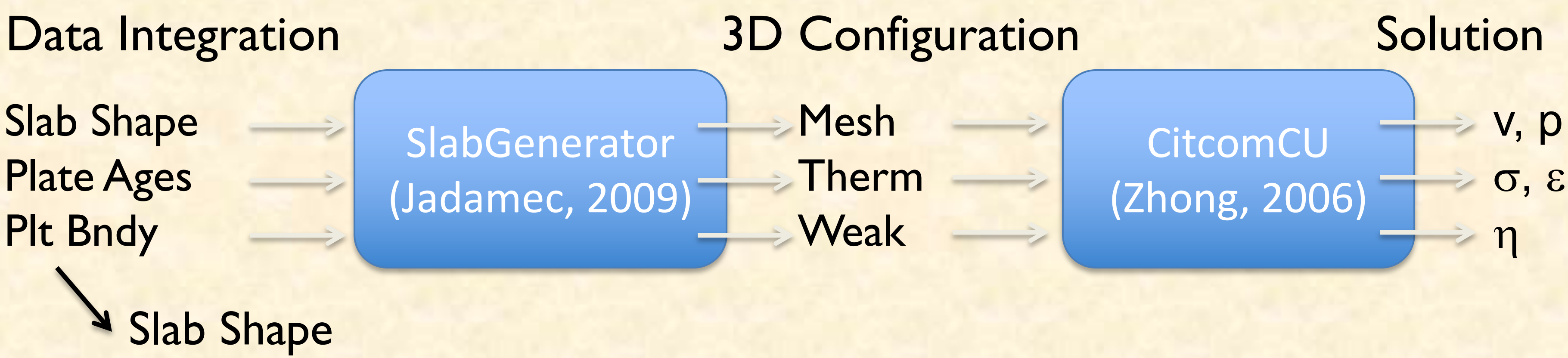
Jadamec et al., In Prep, 2017

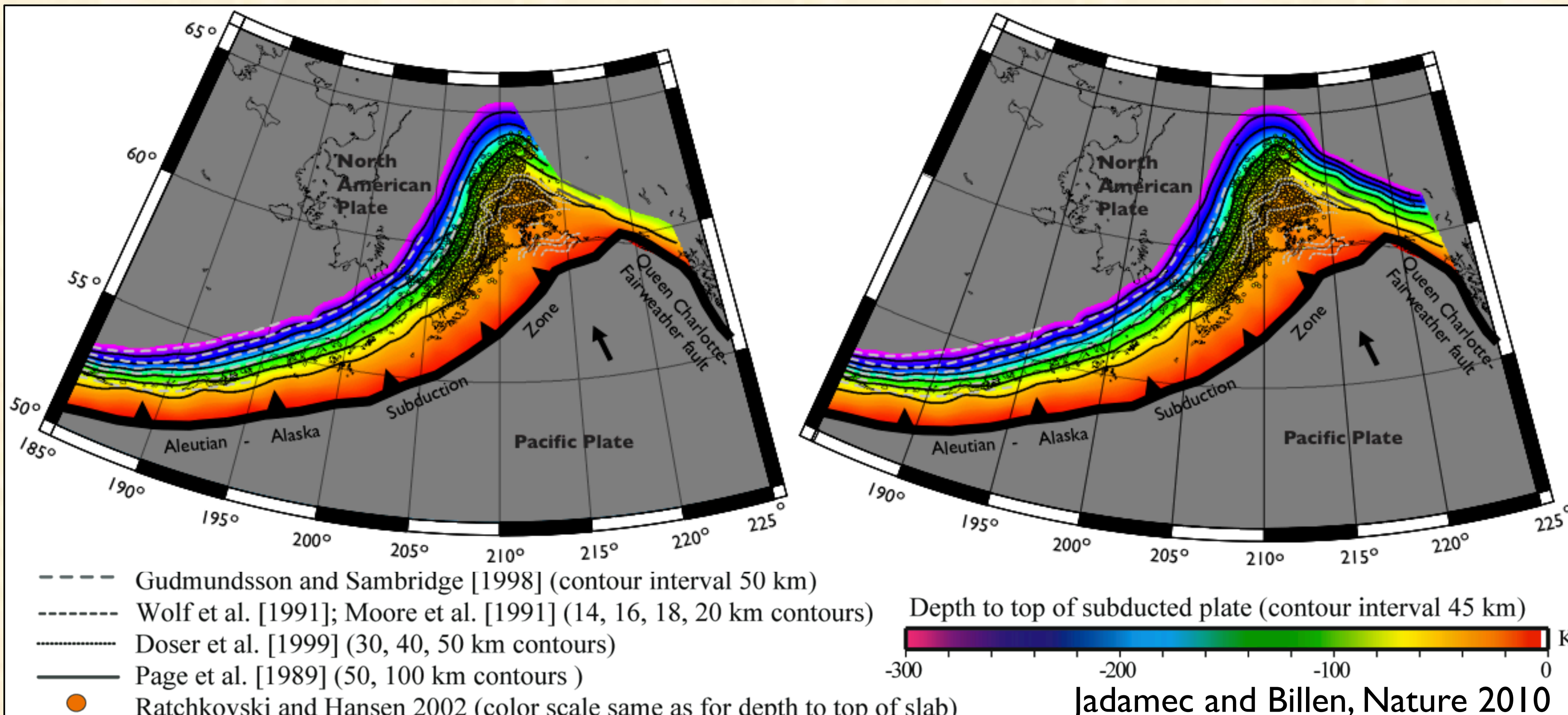
3D Geodynamic Model (AlaskaModel 1.0 - Jadamec)



Jadamec and Billen, 2010, 2012; Jadamec et al., 2013; Haynie and Jadamec, 2017

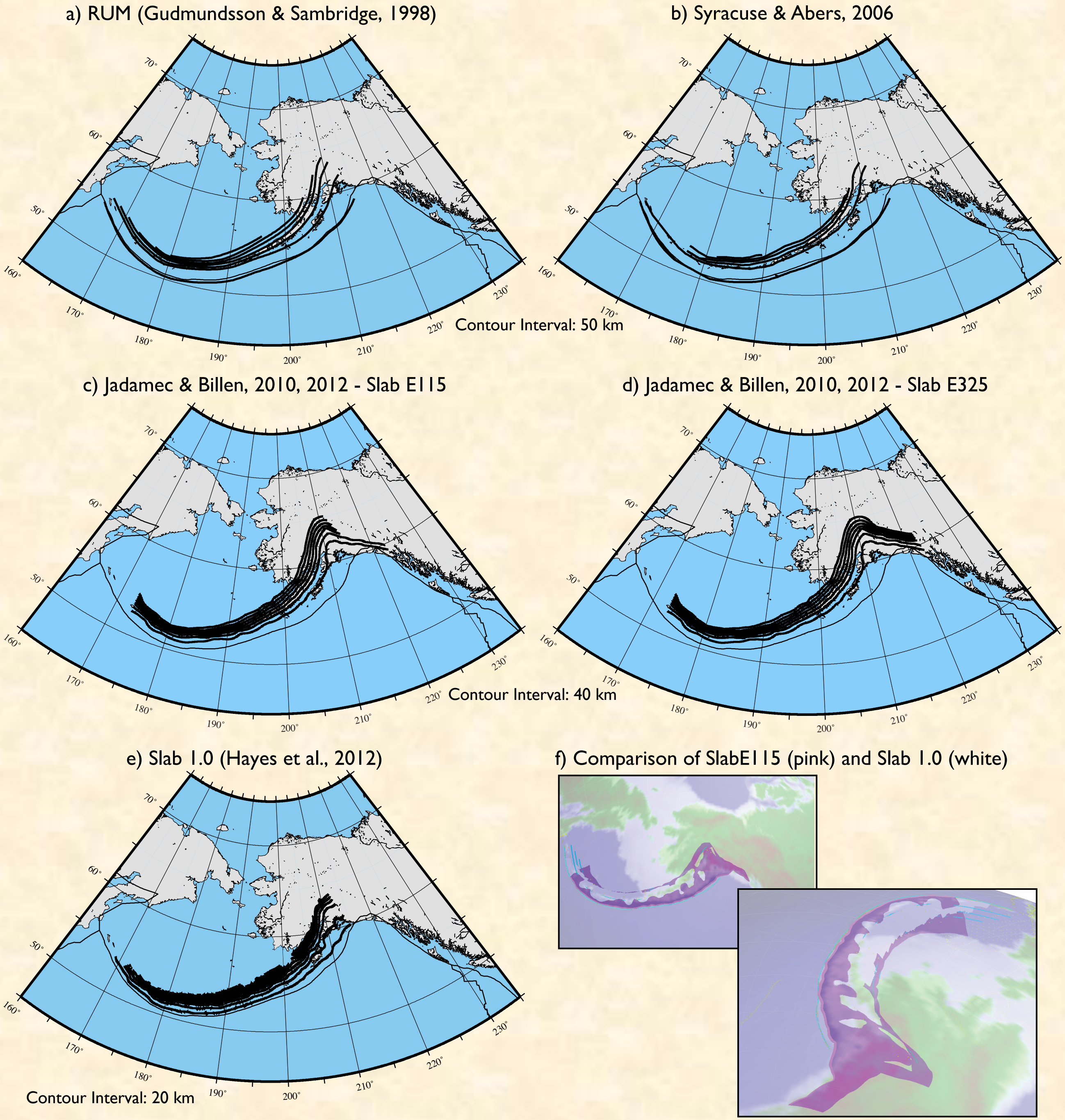
Methods: Definition of 3D Slab Geometry





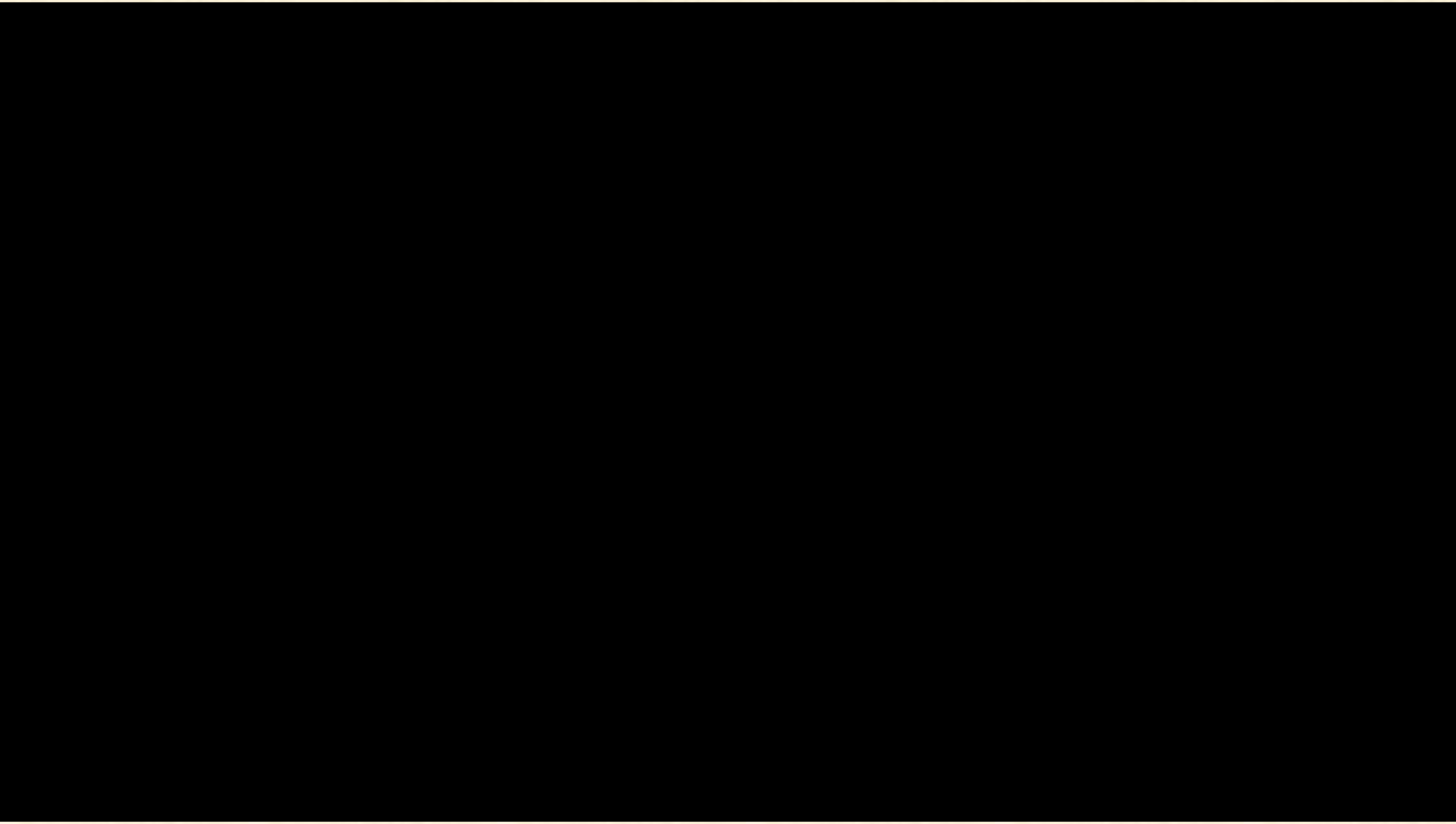
Models of Slab Geometry in Alaska

Models of Subducting Plate Geometry (slab contours)



Jadamec et al., In Prep

Alaska Slab Geometry

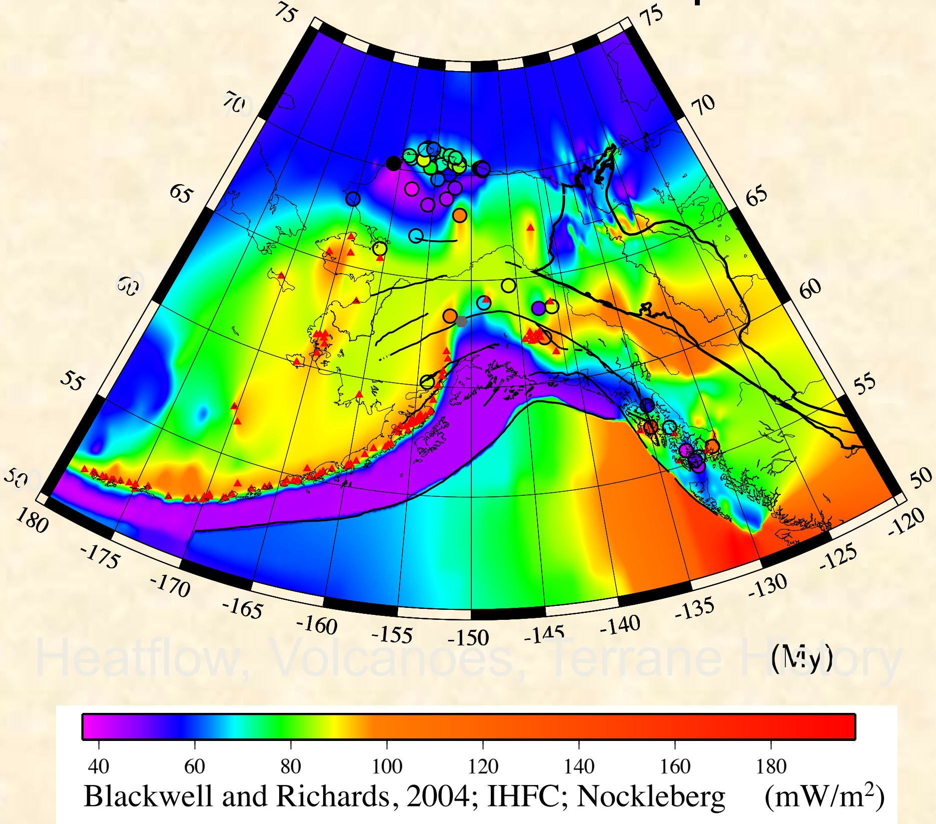


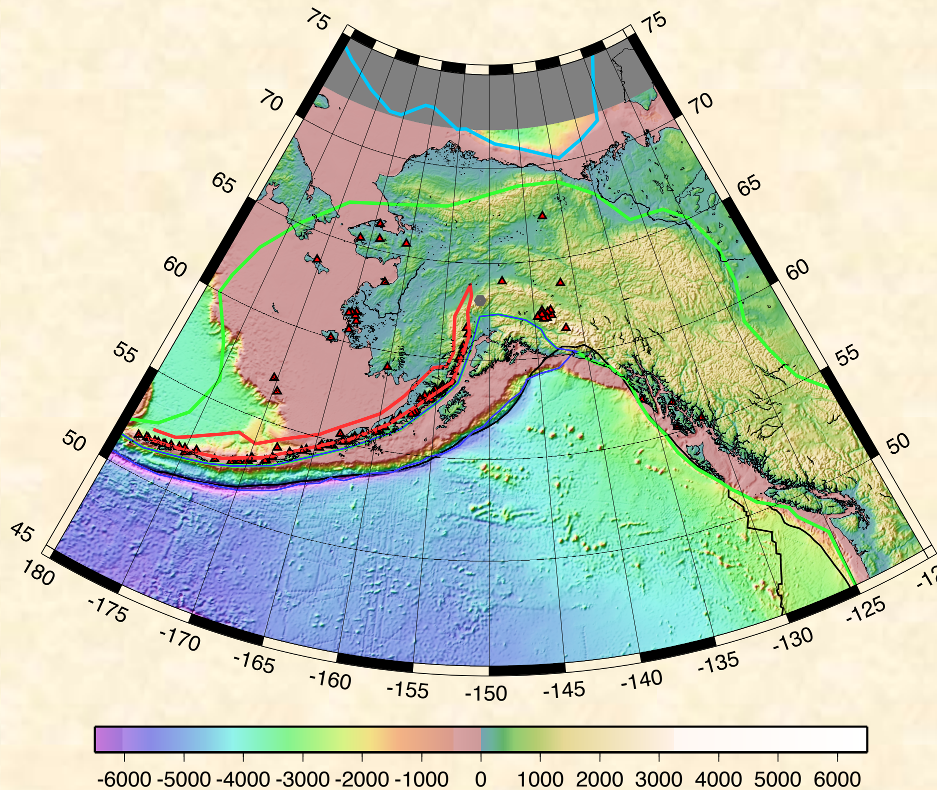
Jadamec & Billen, 2010; Jadamec et al., in Prep.

Methods: Definition of 3D Upper Plate Structure

Data Integration		3D Configuration		Solution
Slab Shape →	SlabGenerator (Jadamec, 2009)	→ Mesh →	CitcomCU (Zhong, 2006)	→ v, p
Plate Ages →		→ Therm →		→ σ, ε
Plt Bndy →		→ Weak →		→ η

↘ Constraints Plate Temperatures





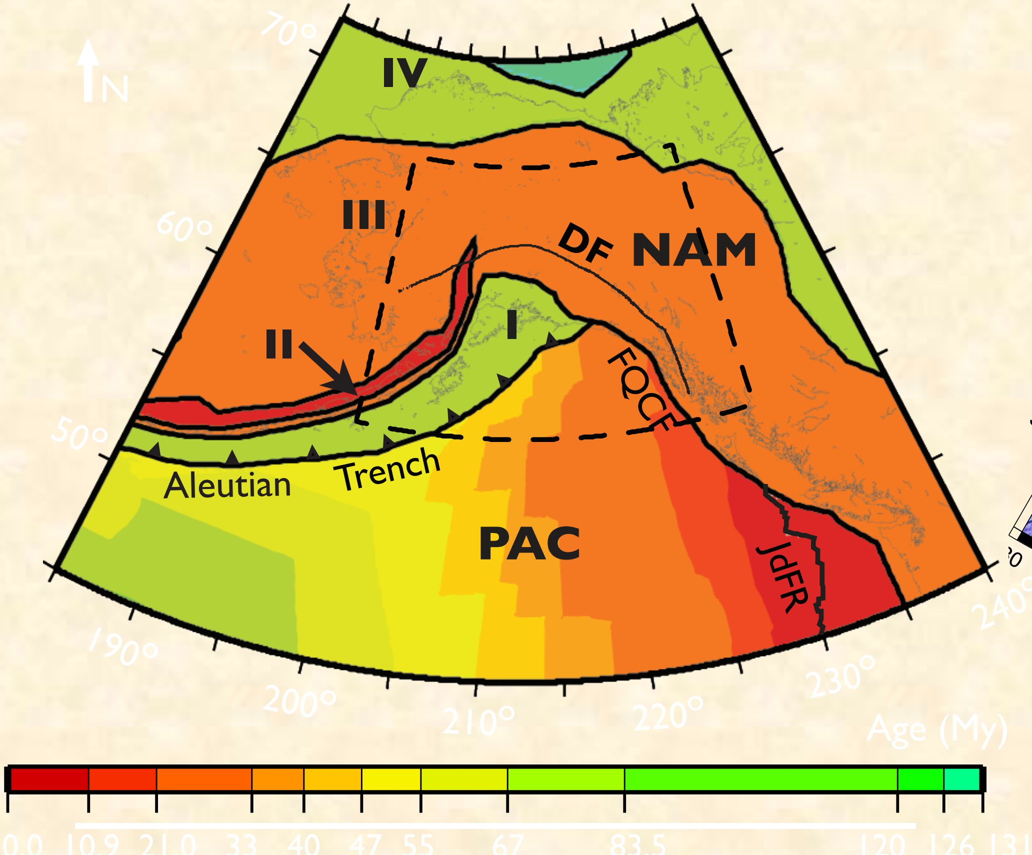
Jadamec et al., EPSL, 2013

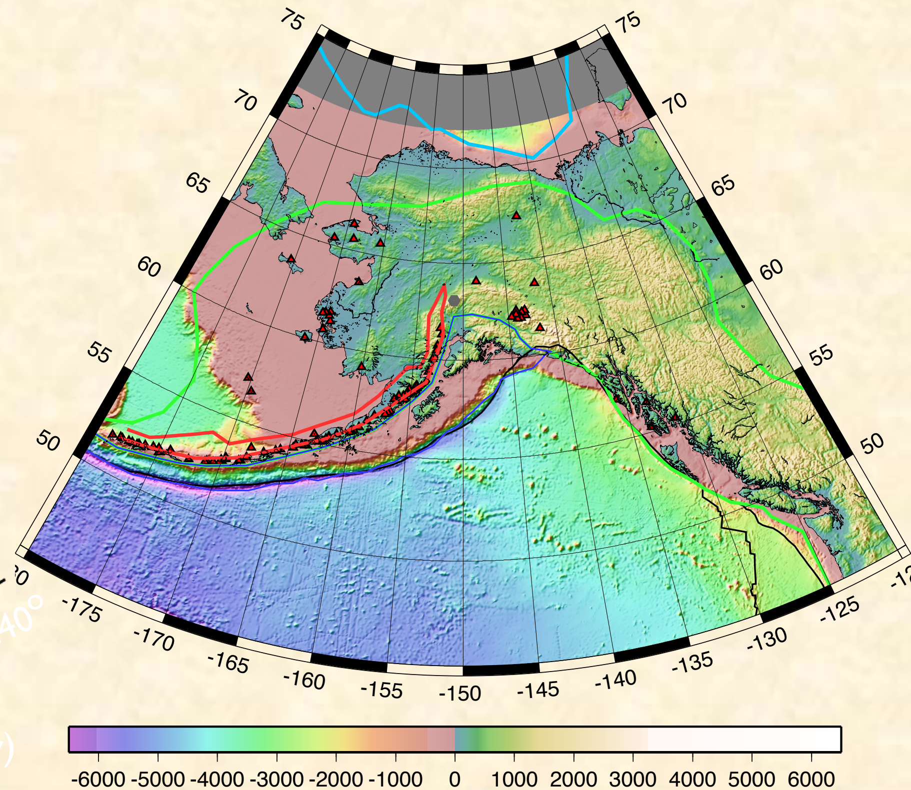
Methods: Definition of 3D Upper Plate Structure

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

Plt Bndy ↘ Constraints Plate Temperatures



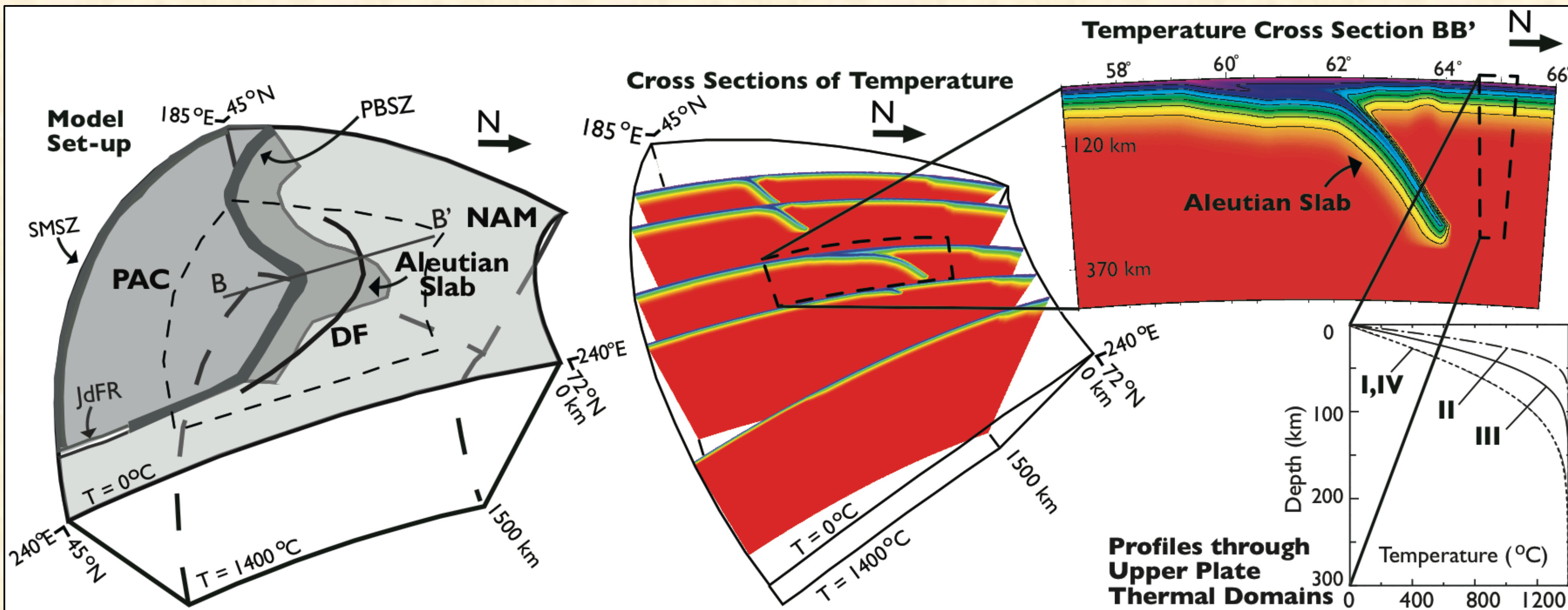


Jadamec et al., EPSL, 2013

Methods: 3D Model Set-Up

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



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

Methods: Definition of Plate Boundary Shear Zone

Data Integration

- Slab Shape
- Plate Ages
- Plt Bndy

→ SlabGenerator (Jadamec, 2009) →

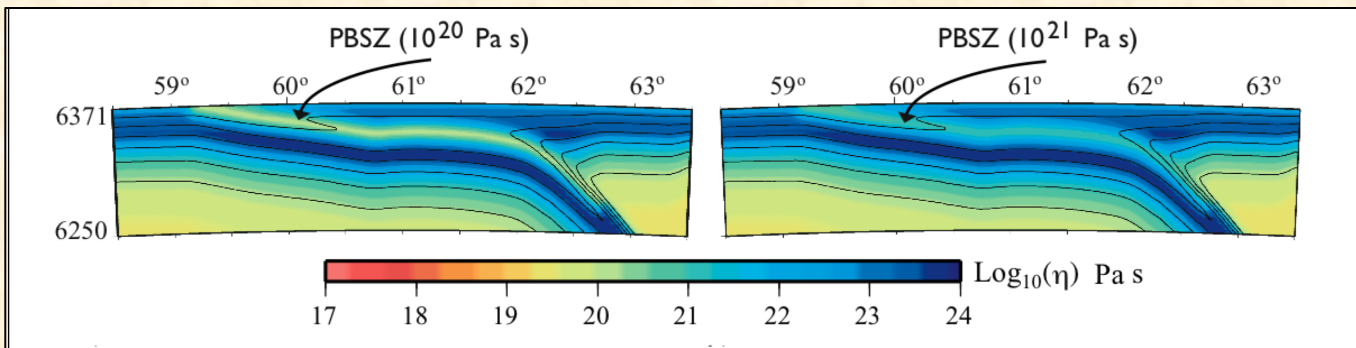
3D Configuration

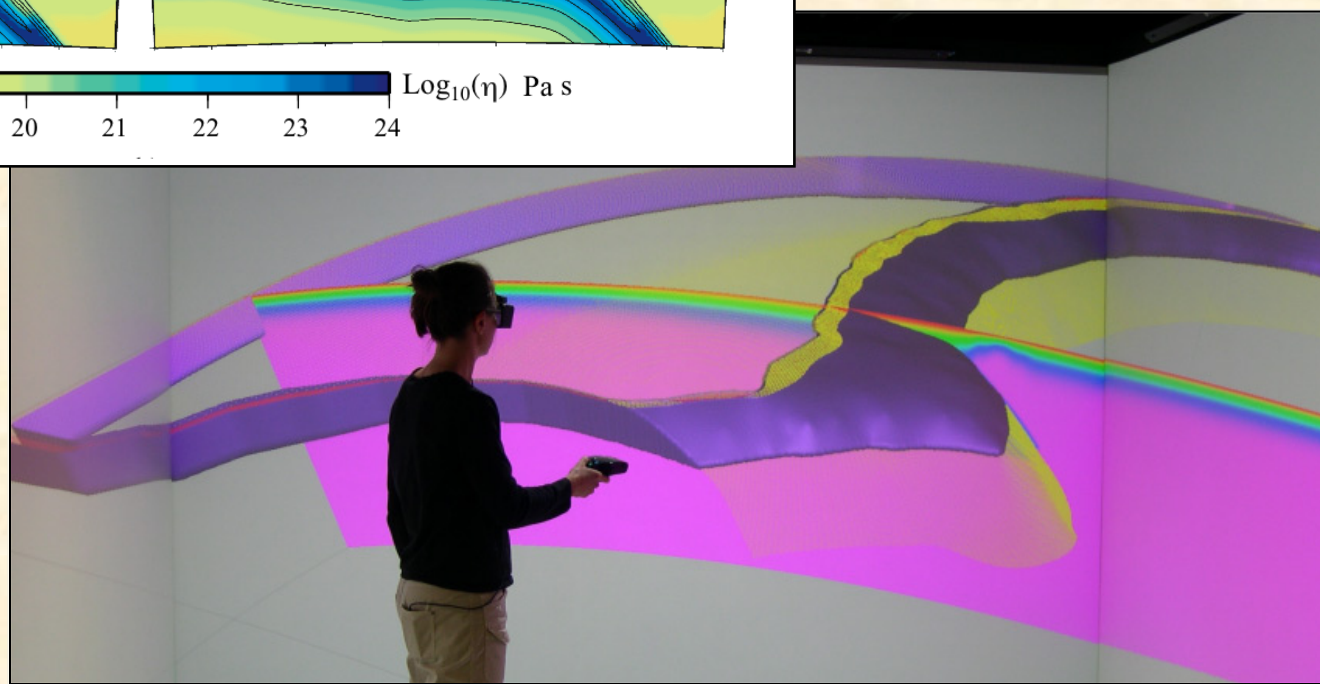
- Mesh
- Therm
- Weak

→ CitcomCU (Zhong, 2006) →

Solution

- v, p
- σ, ε
- η



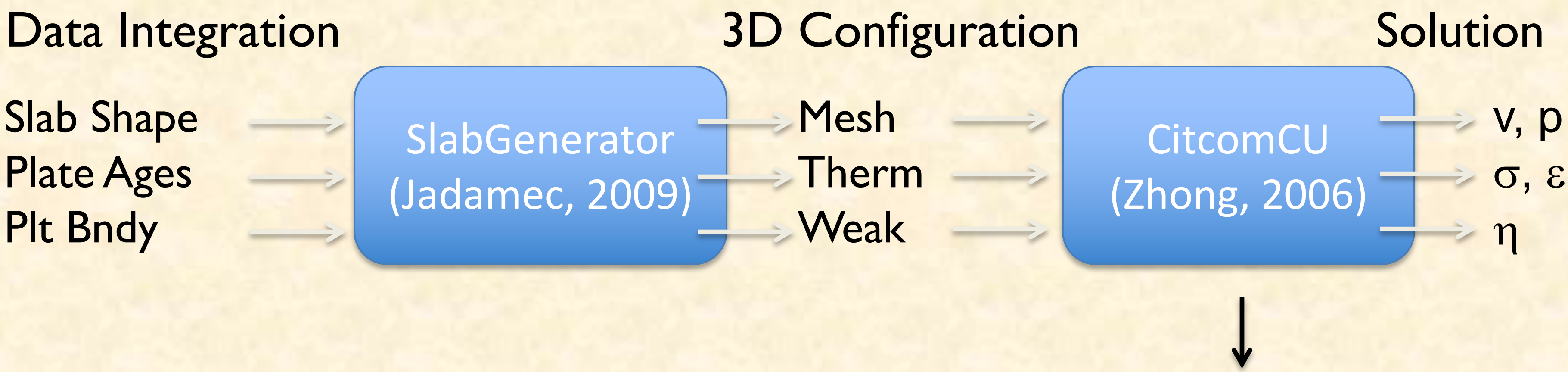


Jadamec and Billen, Nature 2010
Jadamec and Billen, JGR 2012
Jadamec et al. ACM XSEDE12
Jadamec et al., EPSL, 2013

Initial 3D Slab, Mantle, Lithosphere Structure of Alaska (AlaskaModel 1.0)

Jadamec and Billen, 2010, 2012; Jadamec et al., 2013; Haynie and Jadamec, 2017

Methods: Governing Equations in 3D Viscous Flow Model



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

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

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

Model Domain and Bounds

55° x 27° x 1500 km

960 x 648 x 160 elements

2.5 to 25 km resolution

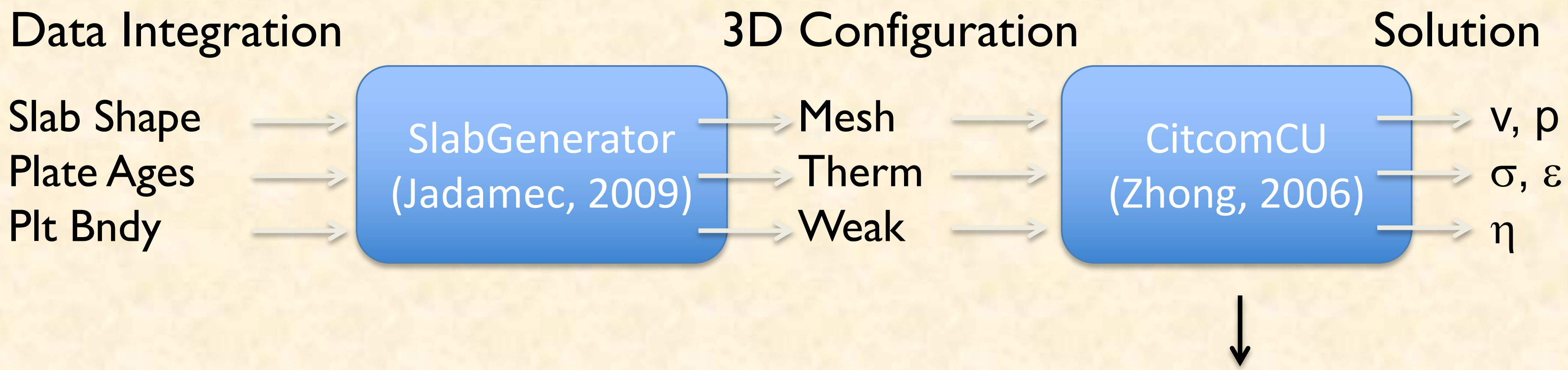
Computing Specifications

Run on XSEDE allocation

360 Cores on Lonestar, TACC

17,280 Compute hours/job

Methods: Viscosity Formulation in 3D Viscous Flow Model



Use Experimentally Derived Flow Law for Viscosity (Hirth and Kohlstedt, 2003)

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

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

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}

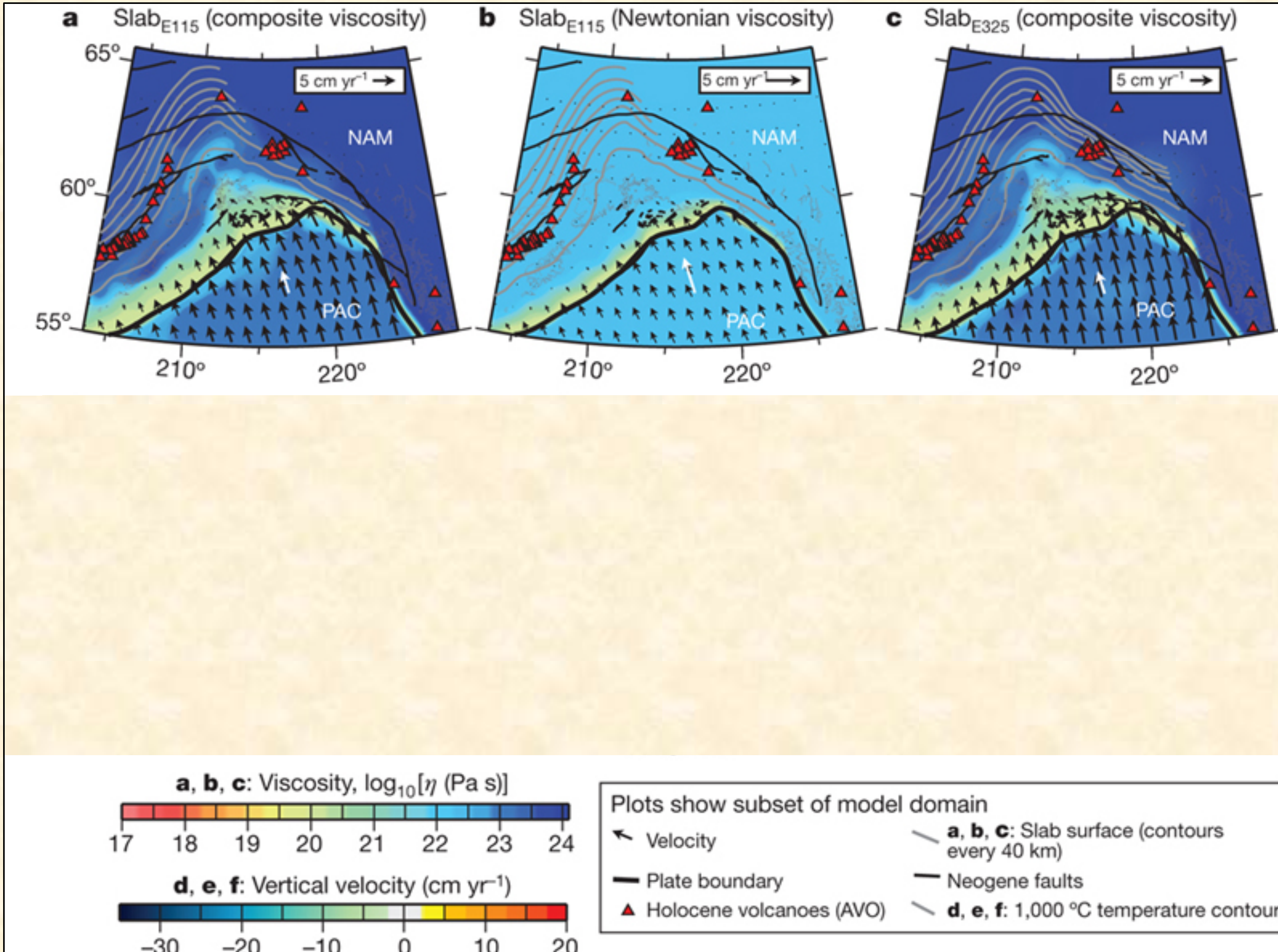
*flow law and parameters for wet olivine (Hirth and Kohlstedt 2003)

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

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

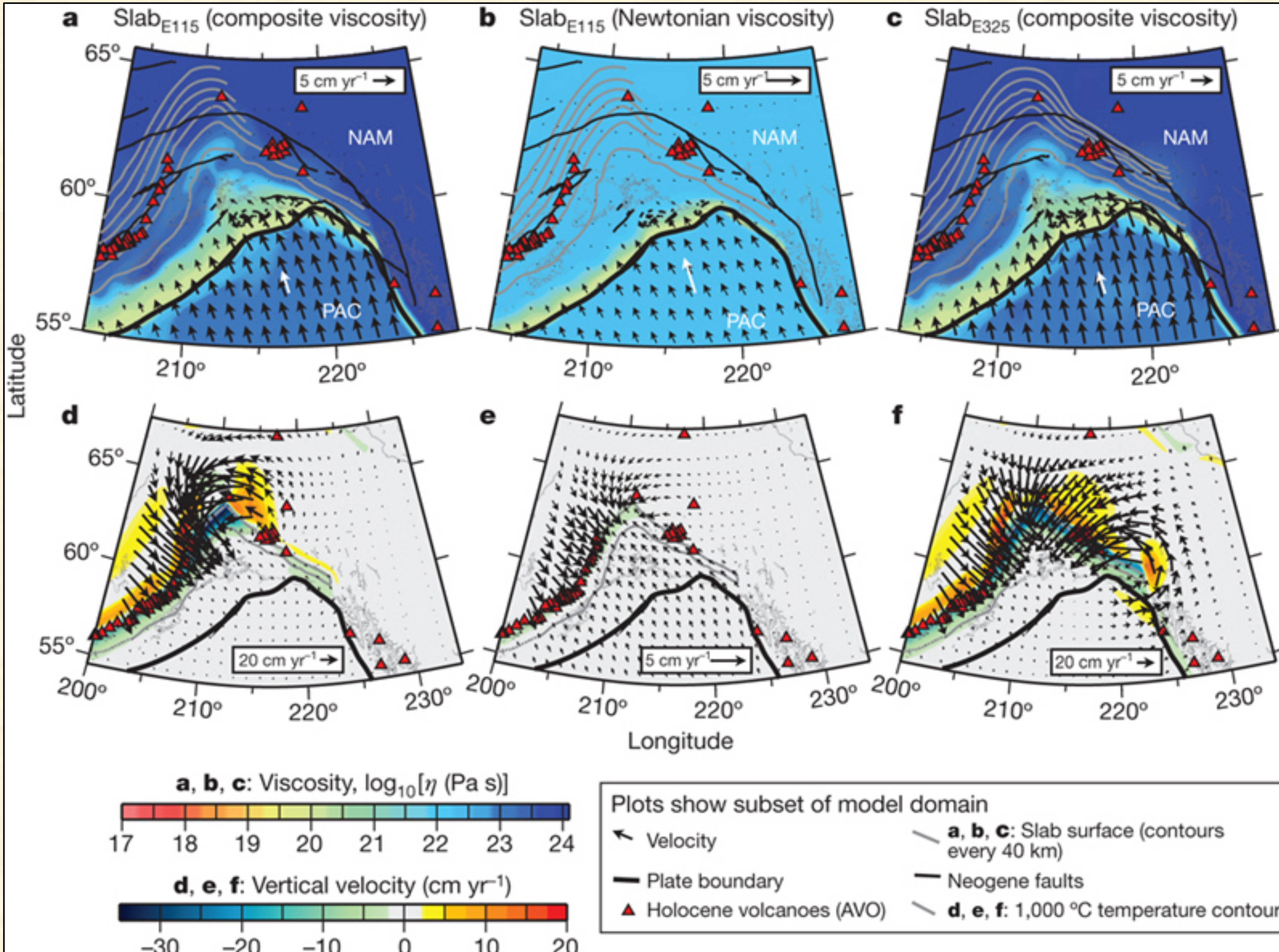
Billen and Hirth, G[3] 2007; Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012

Results: Predicted Velocity at Surface for Pacific Plate



M.A. Jadamec & M.I. Billen *Nature* **465**, 338-341 (2010)

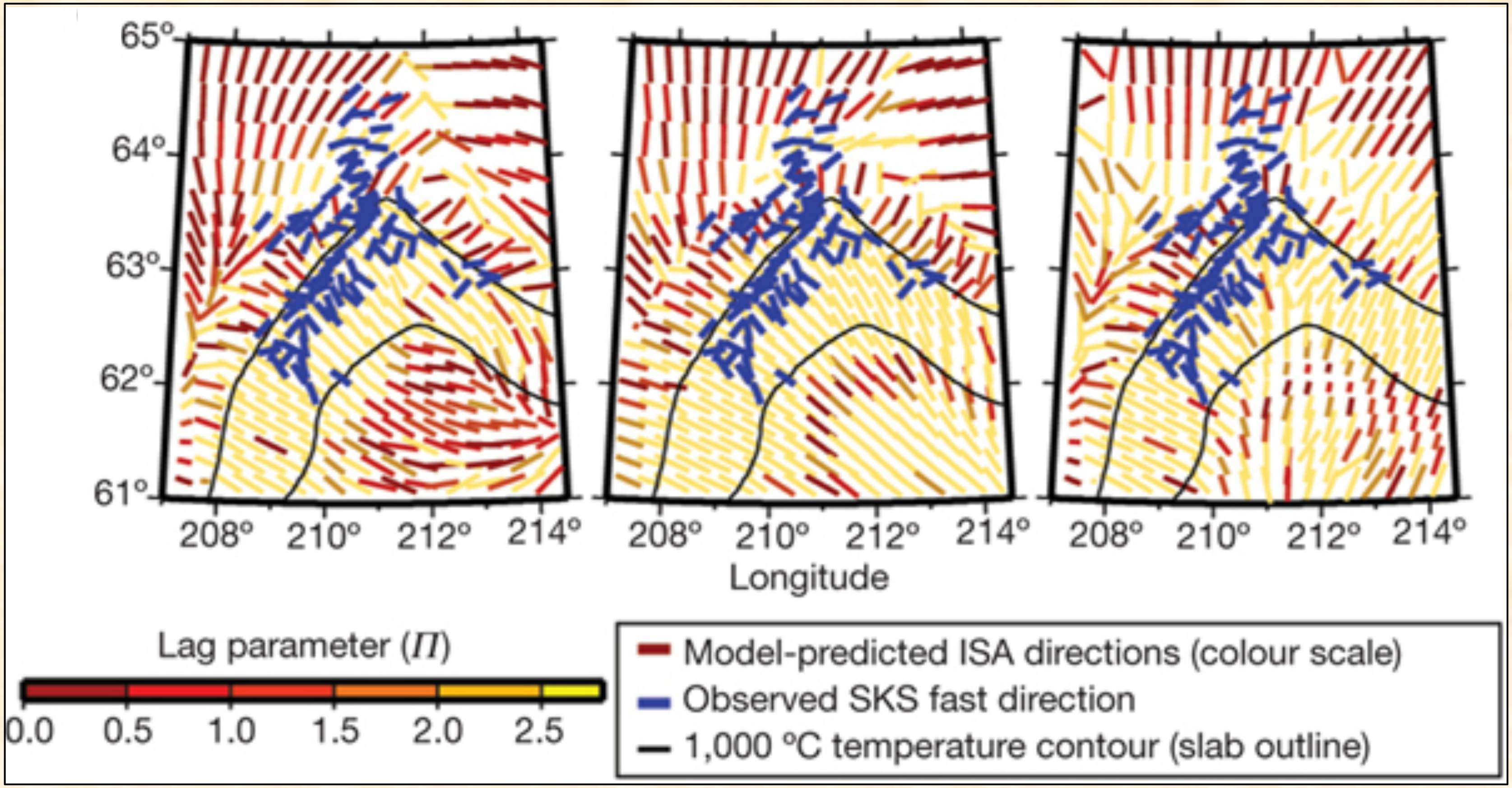
Results: Predicted Velocity at Surface and 100 km Depth



M.A. Jadamec & M.I. Billen *Nature* **465**, 338-341 (2010)

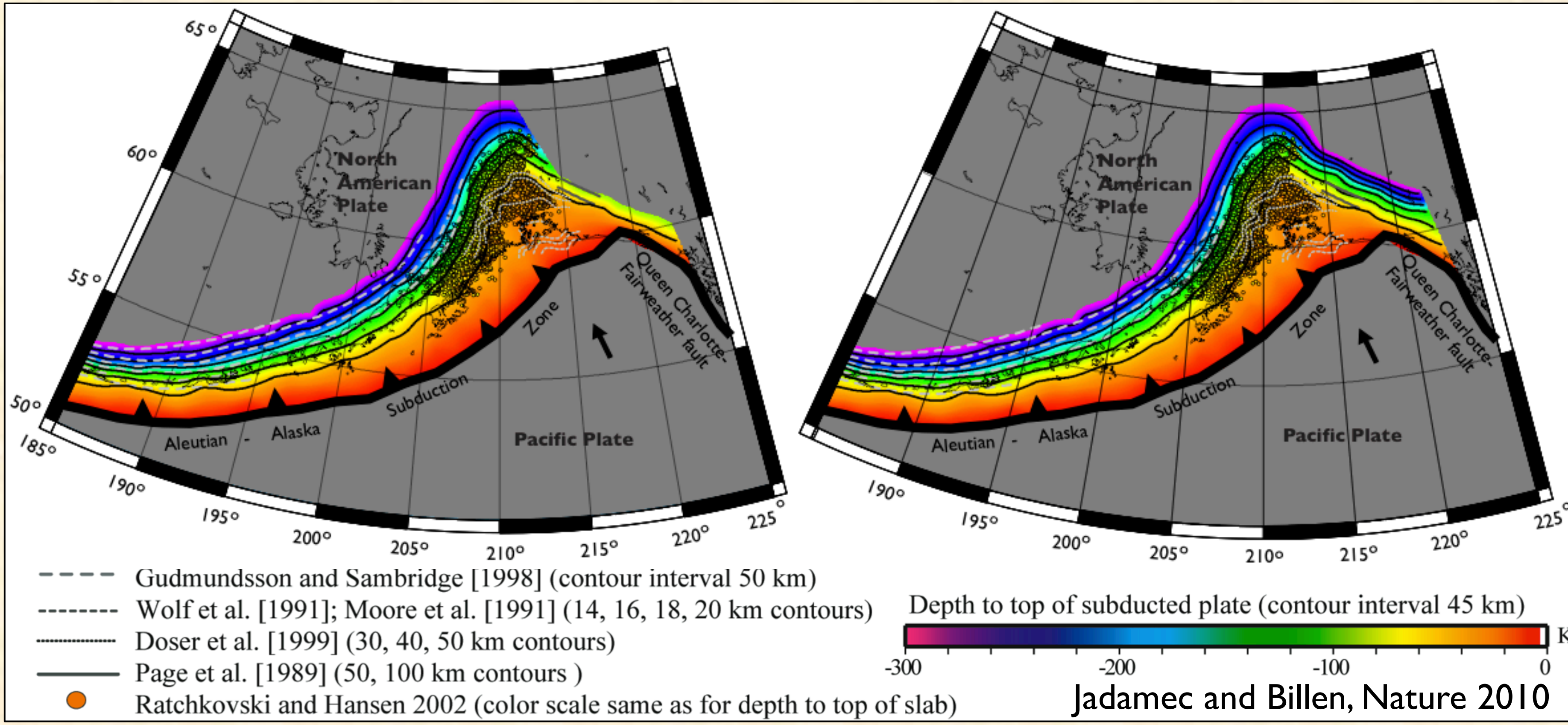
Comparison of Predicted ISA to Observed SKS

Three regions in shear wave splitting observations
SlabE115 and composite rheology best fit obs north of slab nose
Models with composite rheology fit obs to west also in wedge



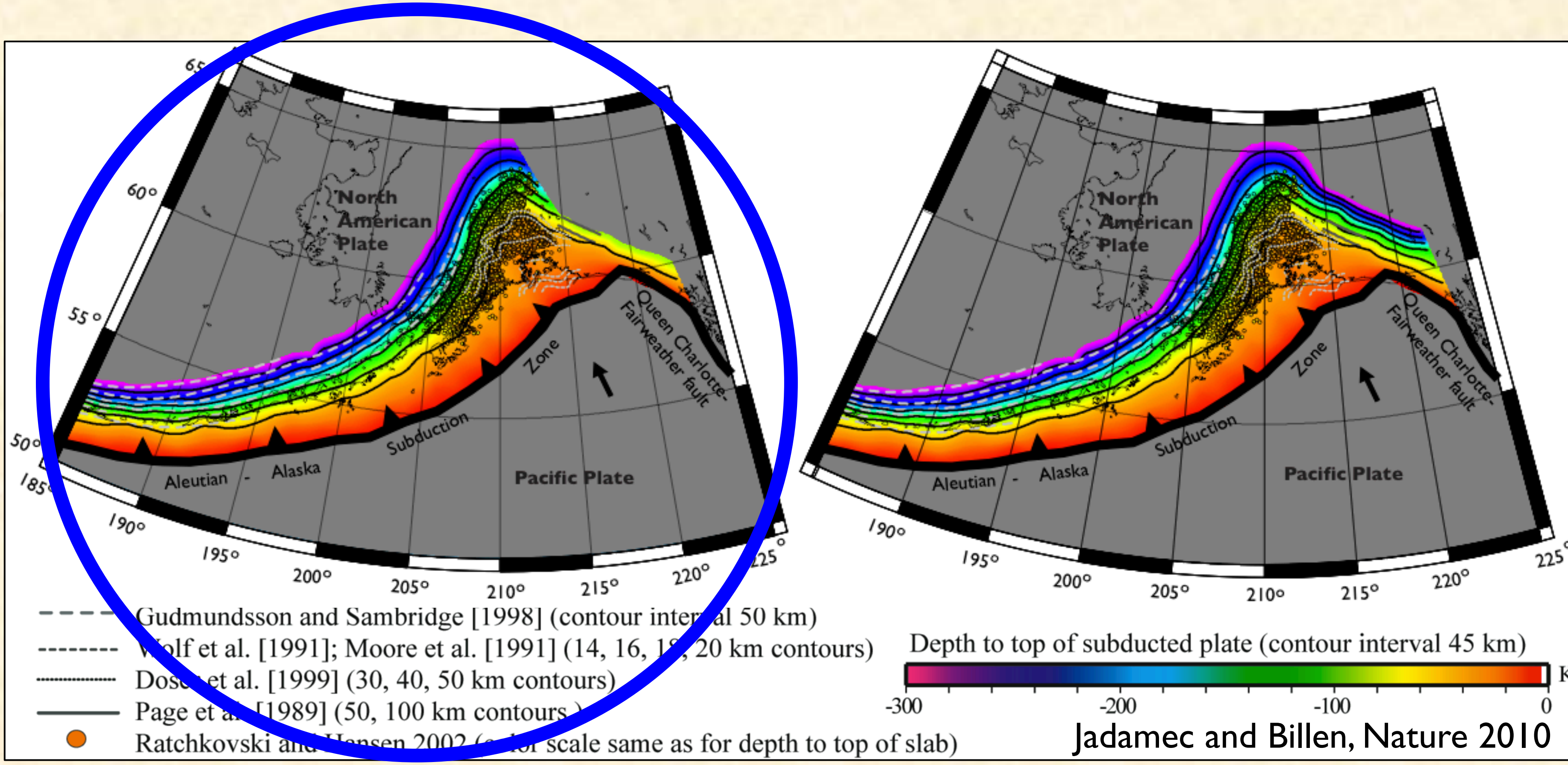
Jadamec and Billen, Nature (2010)
SKS from Christensen and Abers, JGR (2010)

Implications: Two-tiered Slab Geometry Likely for Alaska



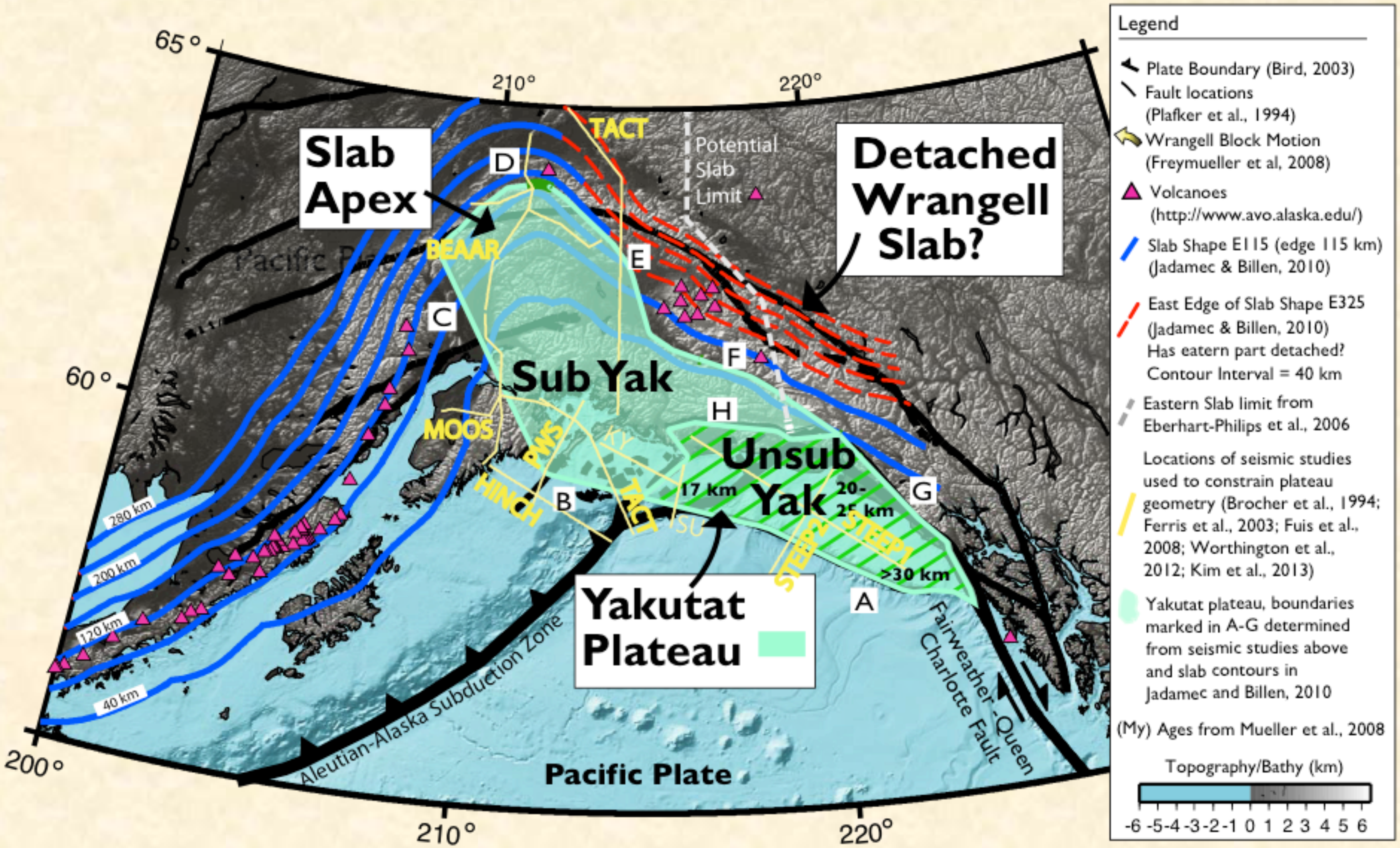
M.A. Jadamec & M.I. Billen *Nature* **465**, 338-341 (2010)

Implications: Two-tiered Slab Geometry Likely for Alaska



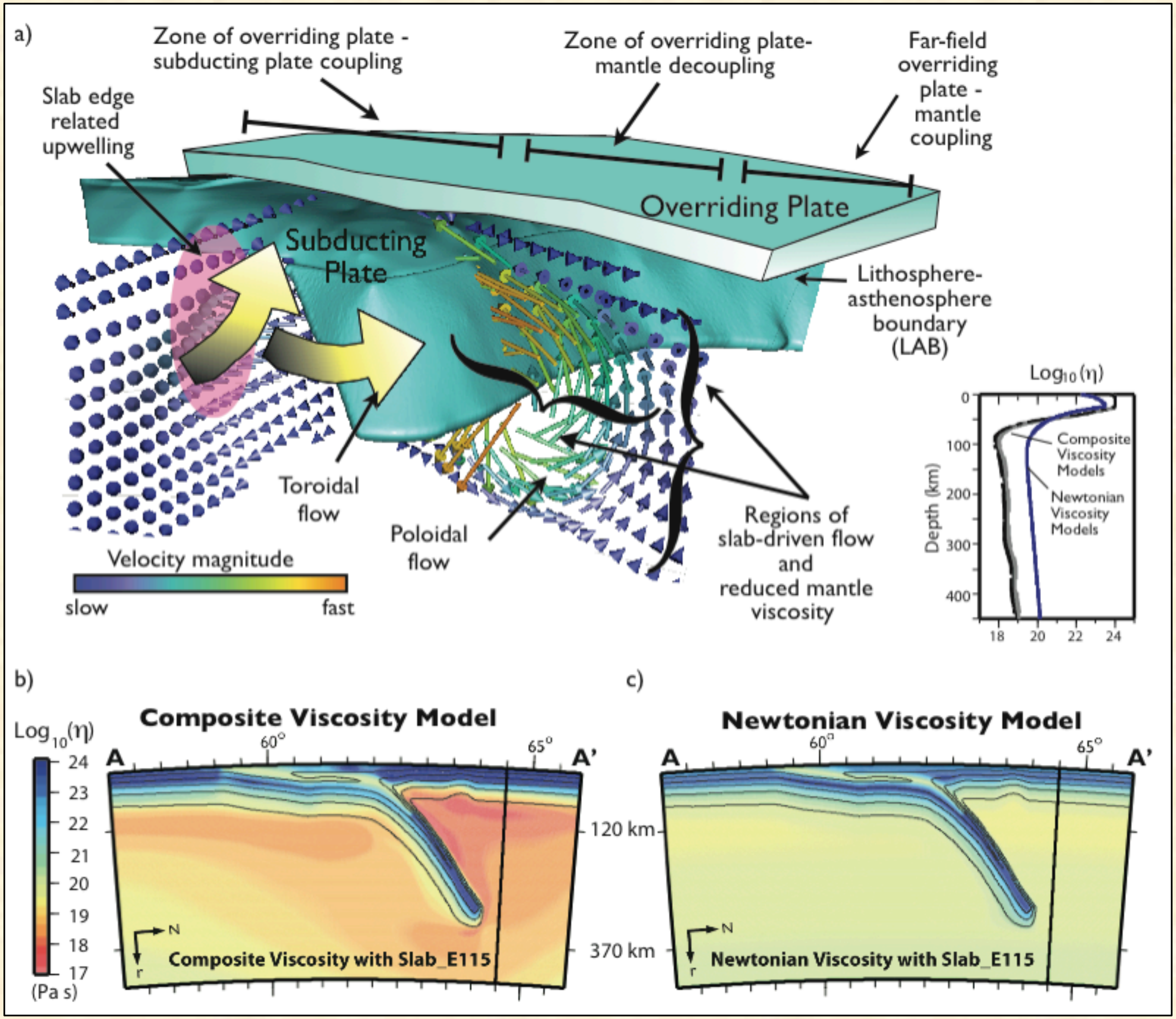
M.A. Jadamec & M.I. Billen *Nature* **465**, 338-341 (2010)

Implications: Where is the rest of the slab?



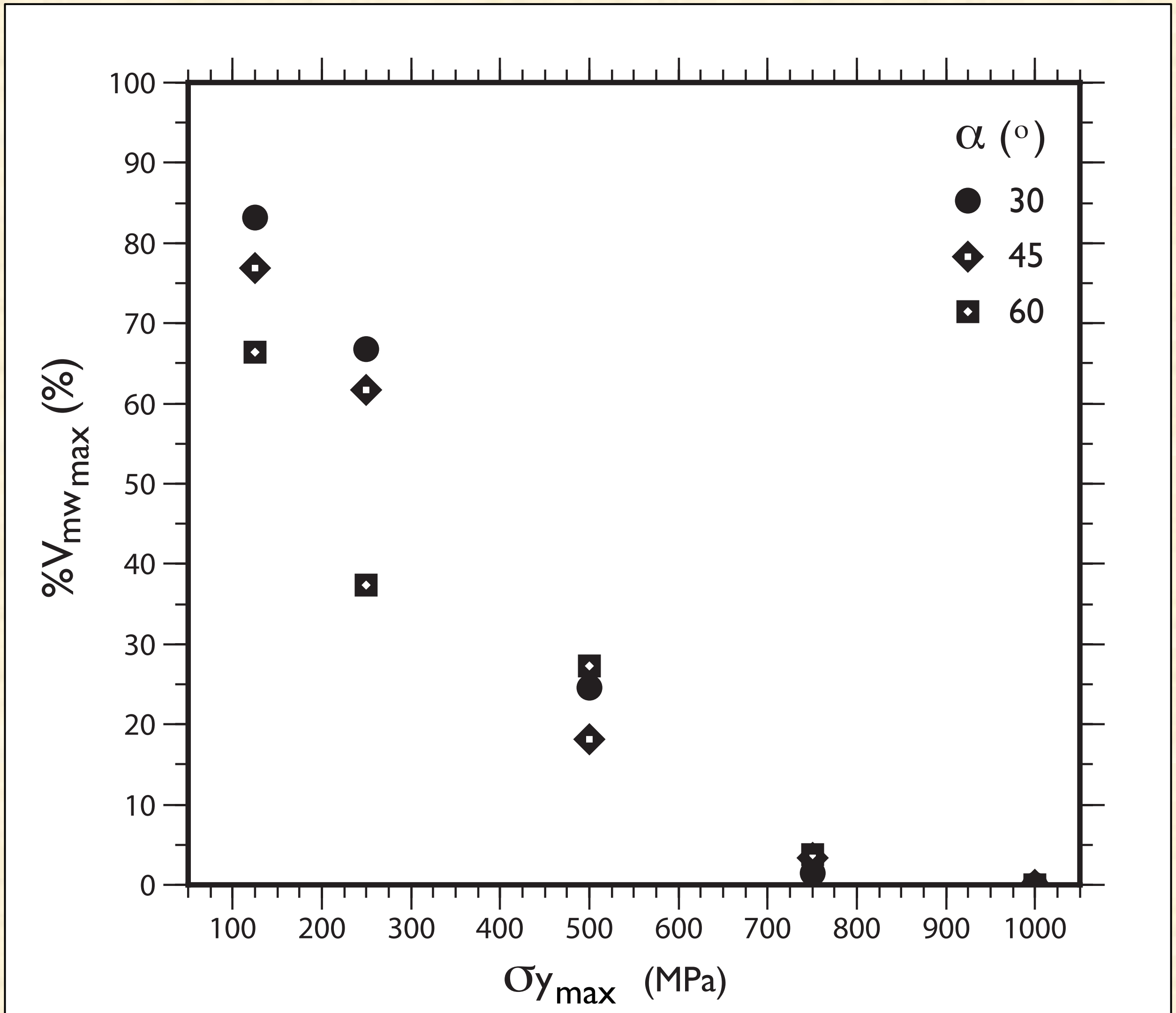
Jadamec et al., In Prep

Implications: 3D Flow & Lateral Variations in Coupling



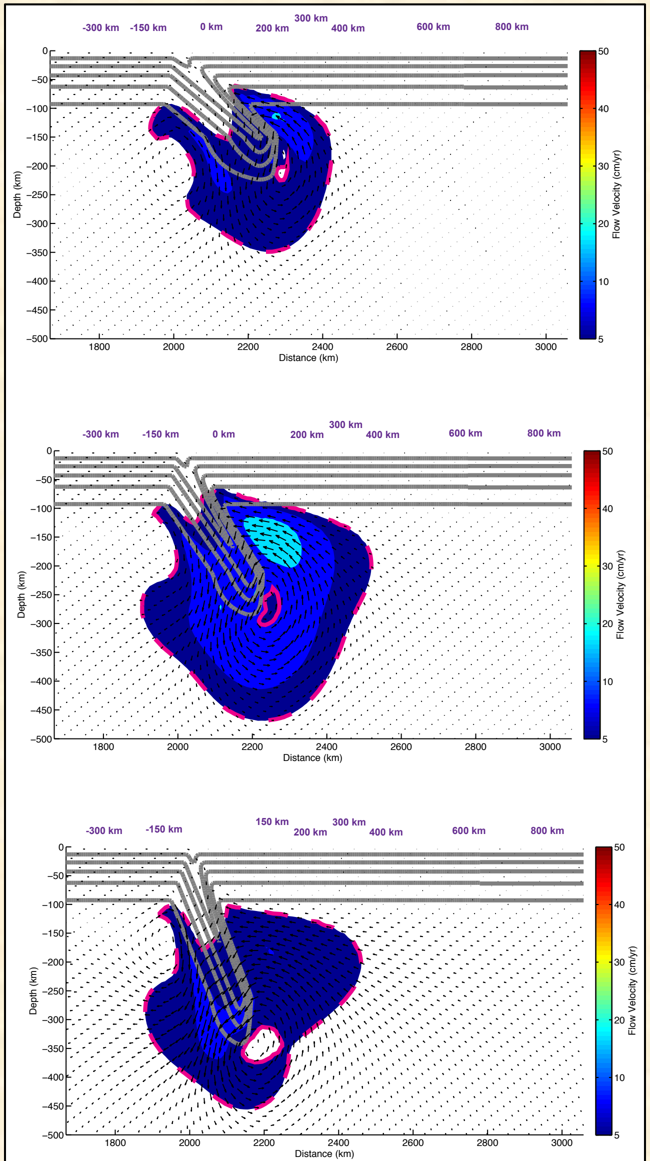
Jadamec, 2016, AGU Monograph, Chpt. 7

Results: Weaker Slabs Induce Faster Flow in Asthenosphere



Jadamec, 2016, AGU Monograph, Chpt. 7

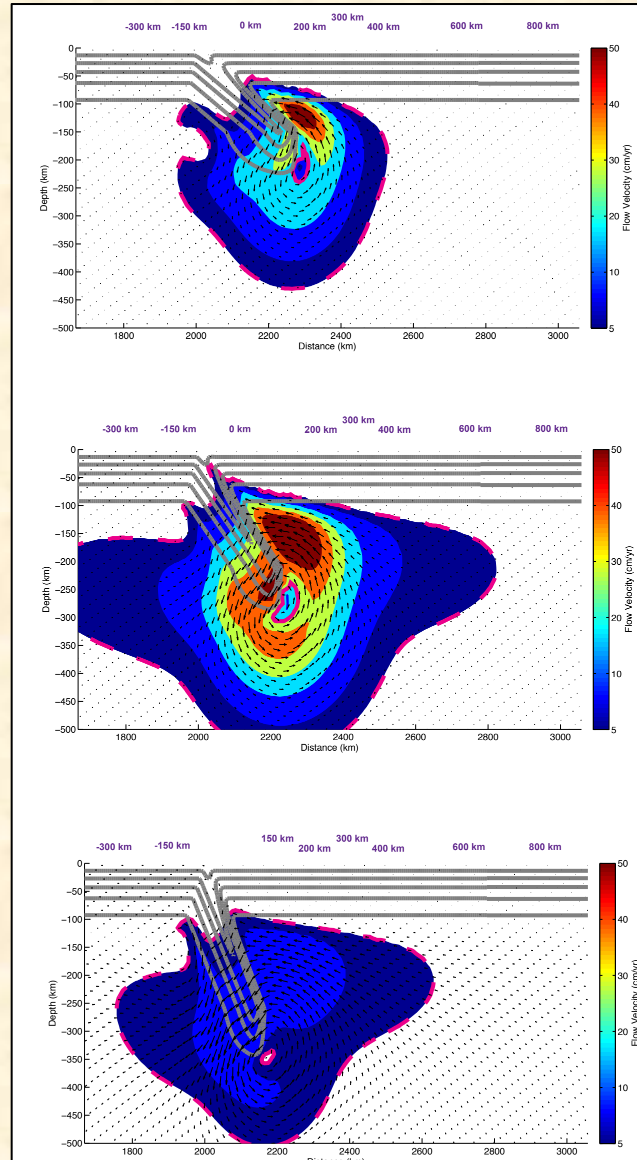
Implications: Slab Driven Mantle Deformation Zones



Dip = 30°
σ_{yMax}=1000 MP

Dip = 45°
σ_{yMax}=1000 MI

Dip = 60°
σ_{yMax}=1000 MI



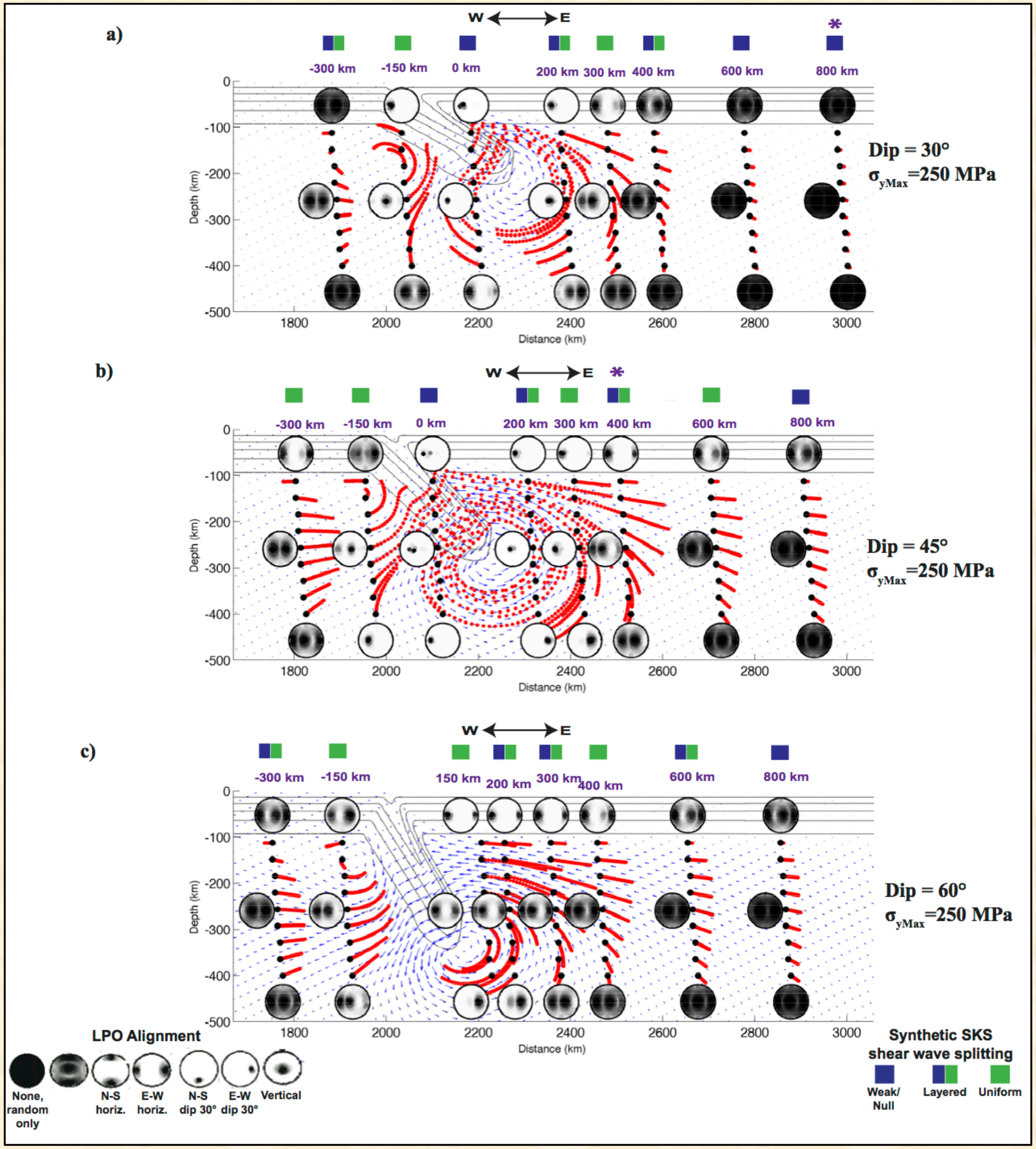
Dip = 30°
σ_{yMax}=250 MPa

Dip = 45°
σ_{yMax}=250 MPa

Dip = 60°
σ_{yMax}=250 MPa

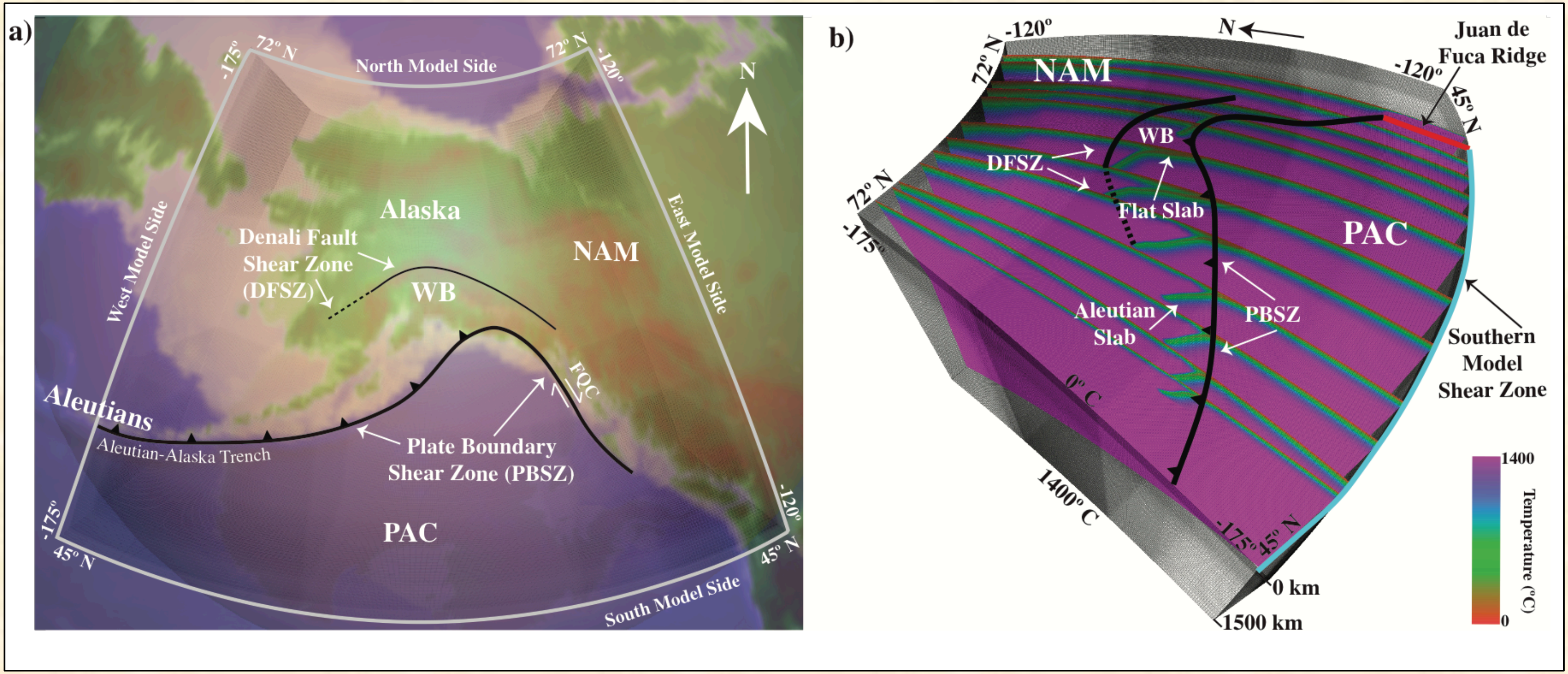
MacDougall, Jadamec, and Fischer, 2017 In Revision, JGR

Implications: Slab Driven Mantle Deformation Zones



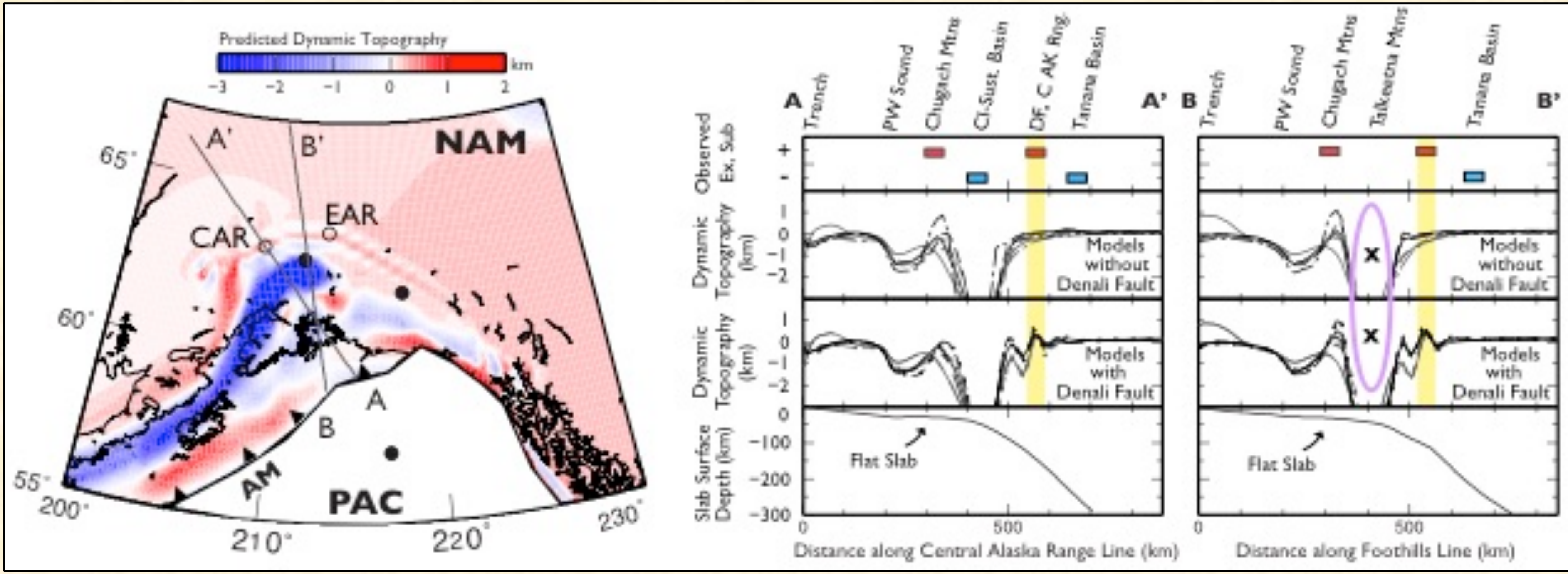
MacDougall, Jadamec, and Fischer, 2017 In Revision, JGR

3D Geodynamic Model (AlaskaModel 1.0 - Jadamec)



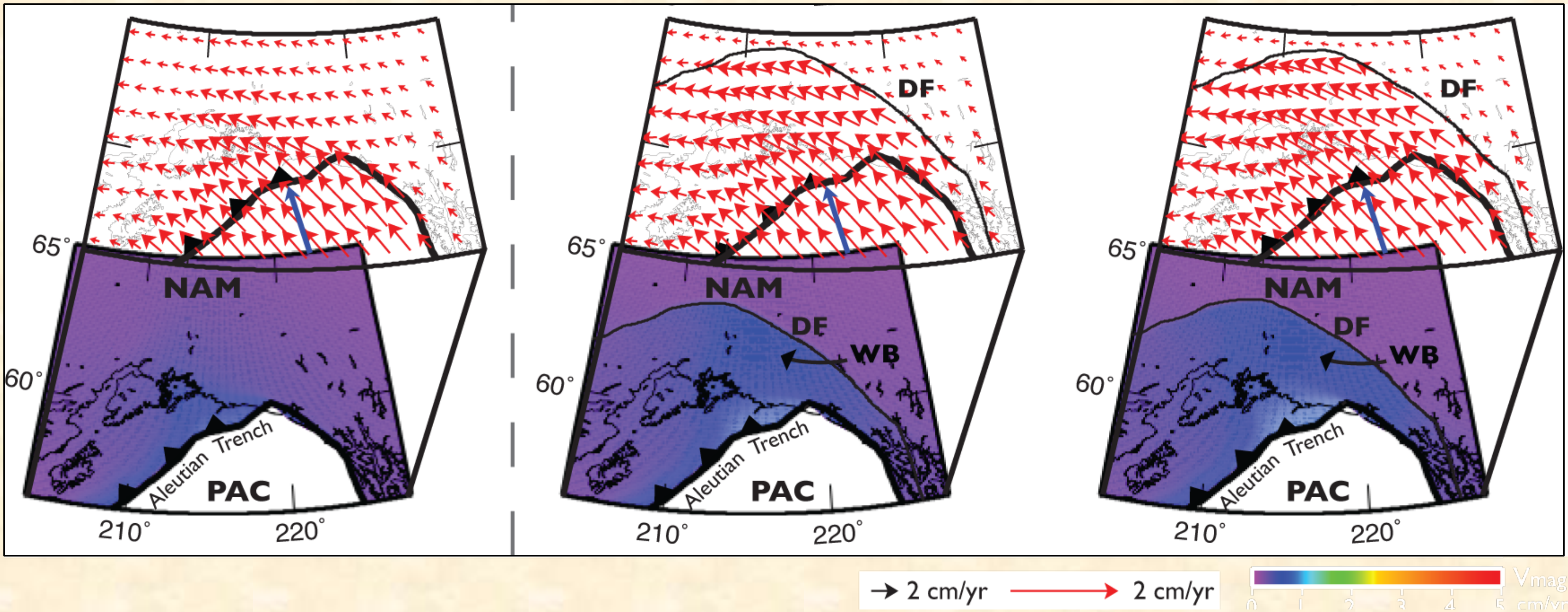
Jadamec and Billen, 2010, 2012; Jadamec et al., 2013; Haynie and Jadamec, 2017

Results: Dynamic Topography in South Central Alaska



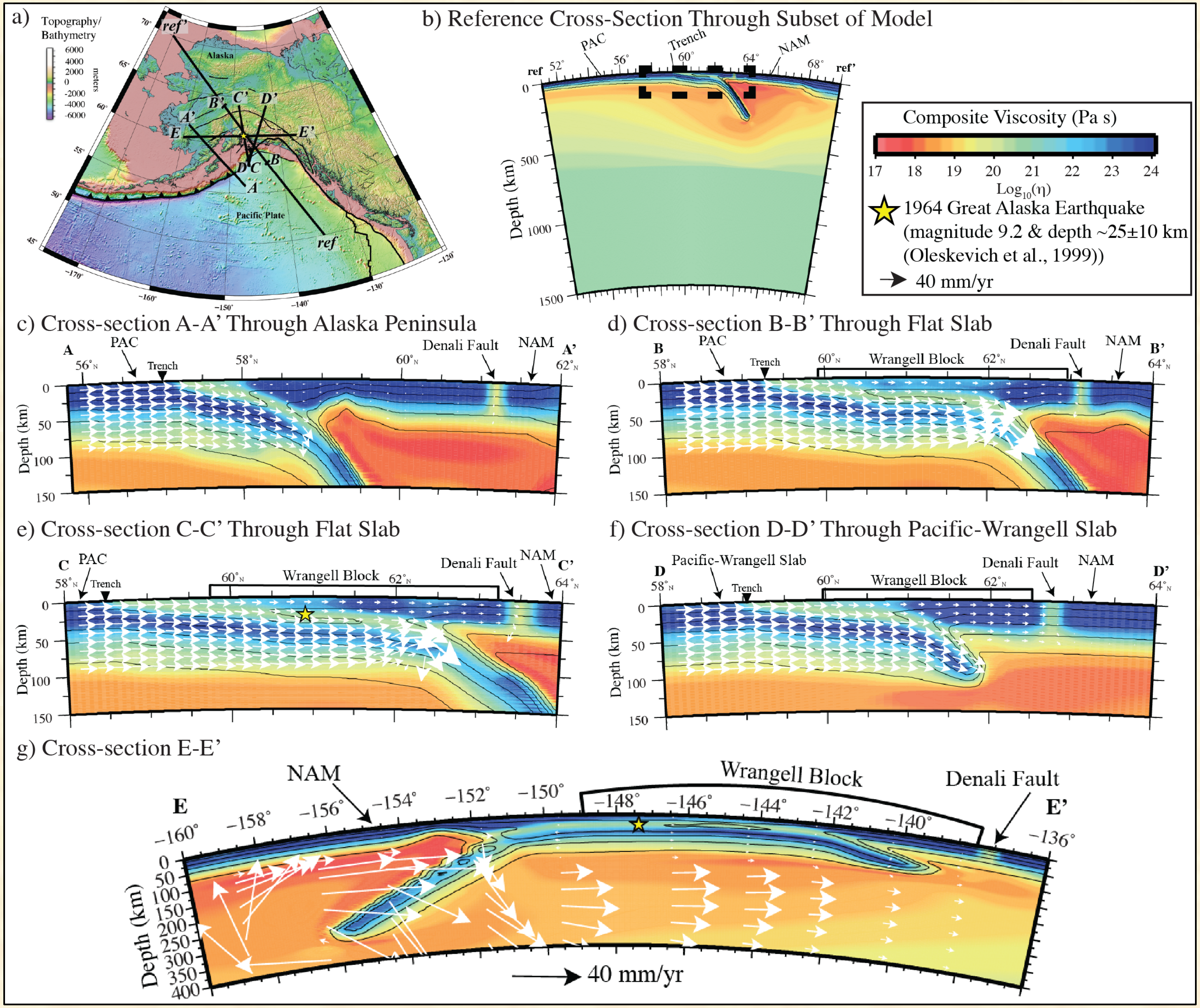
Jadamec et al., 2013, EPSL

Results: Predicted Surface Velocity for Newtonian Models



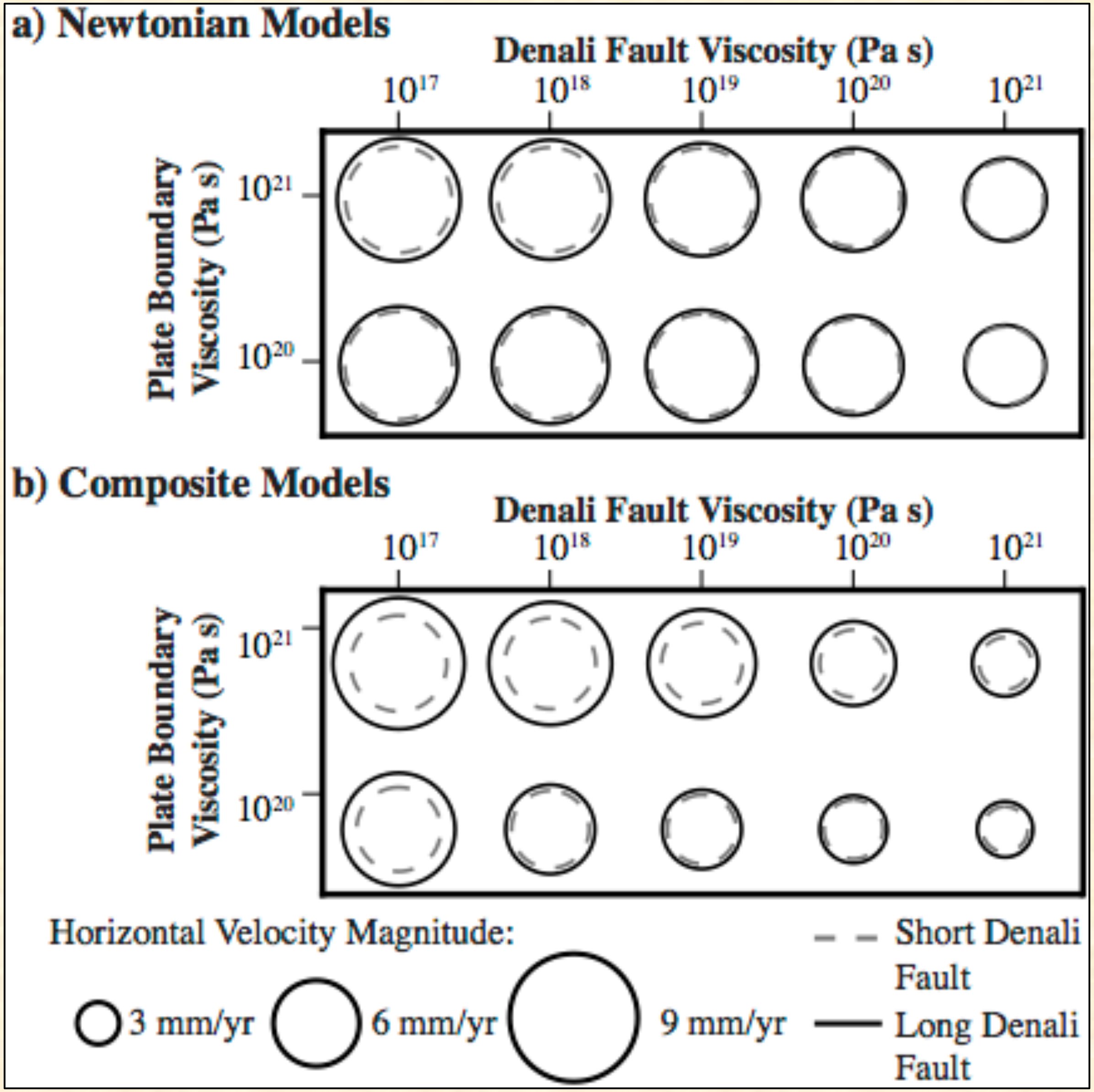
Jadamec et al., 2013, EPSL

Results: Pacific Plate Driver of Wrangell Block Motion & DF



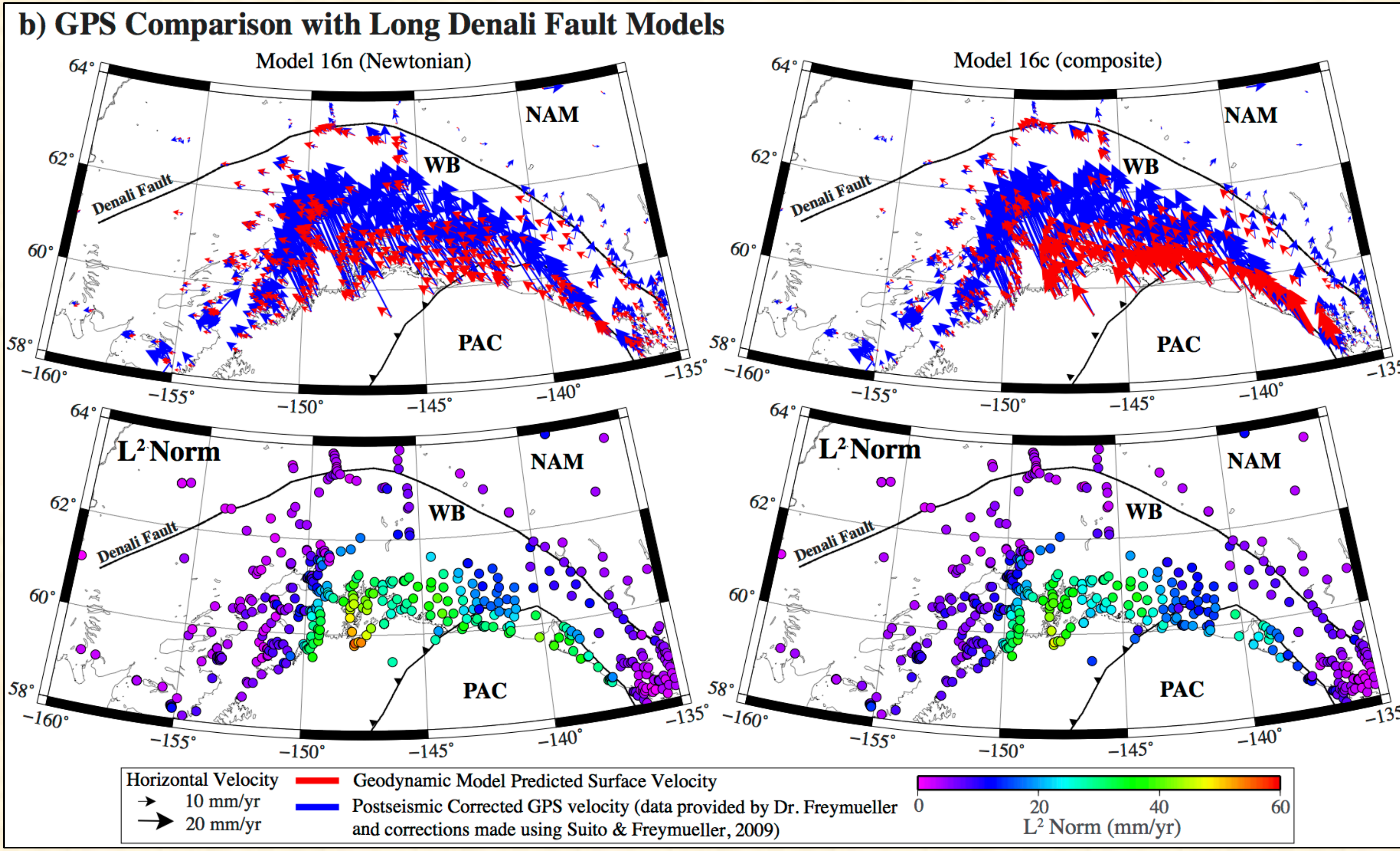
Haynie and Jadamec, Tectonics, 2017

Results: Controls on Wrangell Block Motion



Haynie and Jadamec, Tectonics, 2017

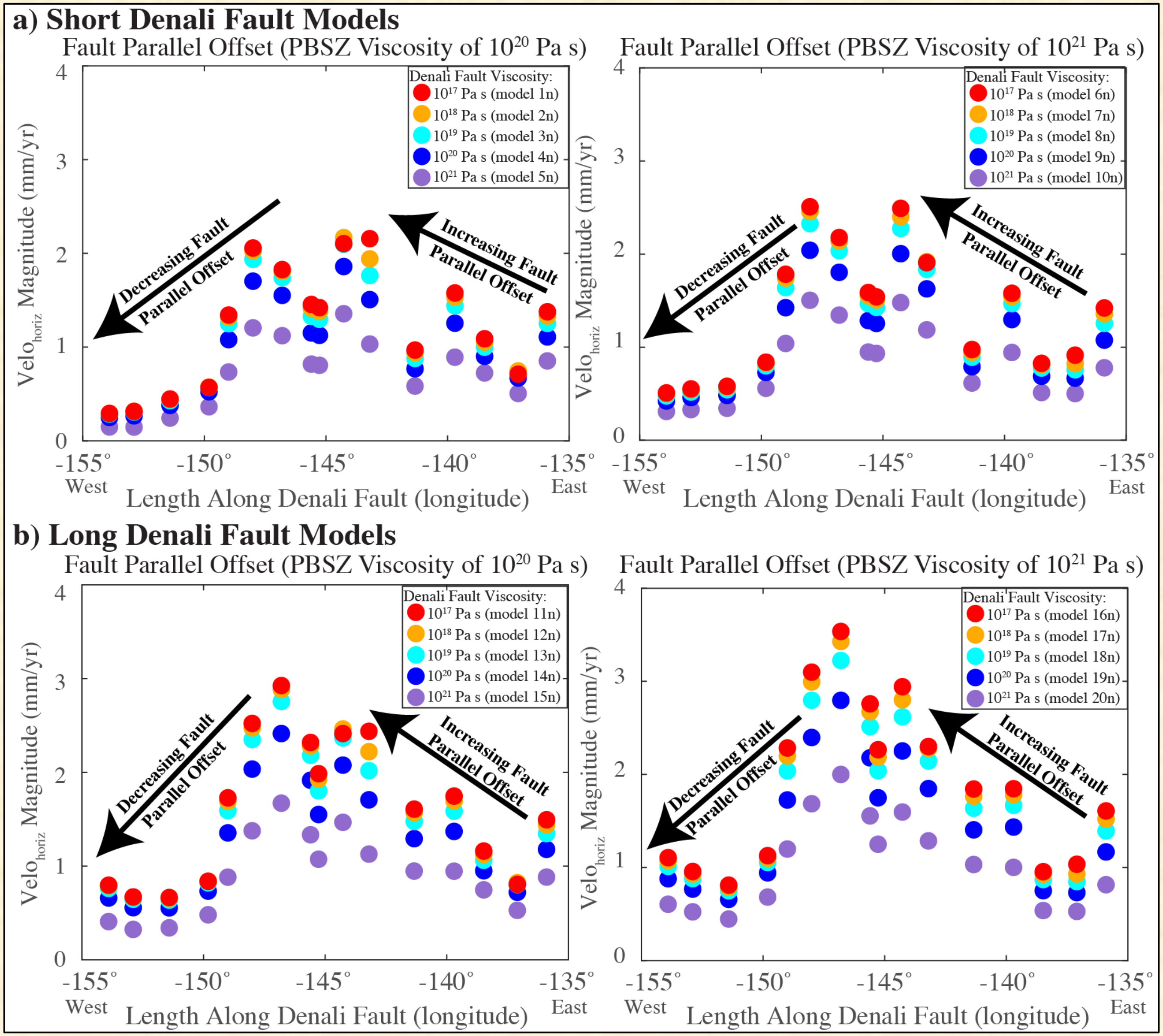
Comparison: Predicted Surface Motion with GPS velocities



Strong Plate Boundary & Weak Fault Produce Fastest Motions South of Denali Fault

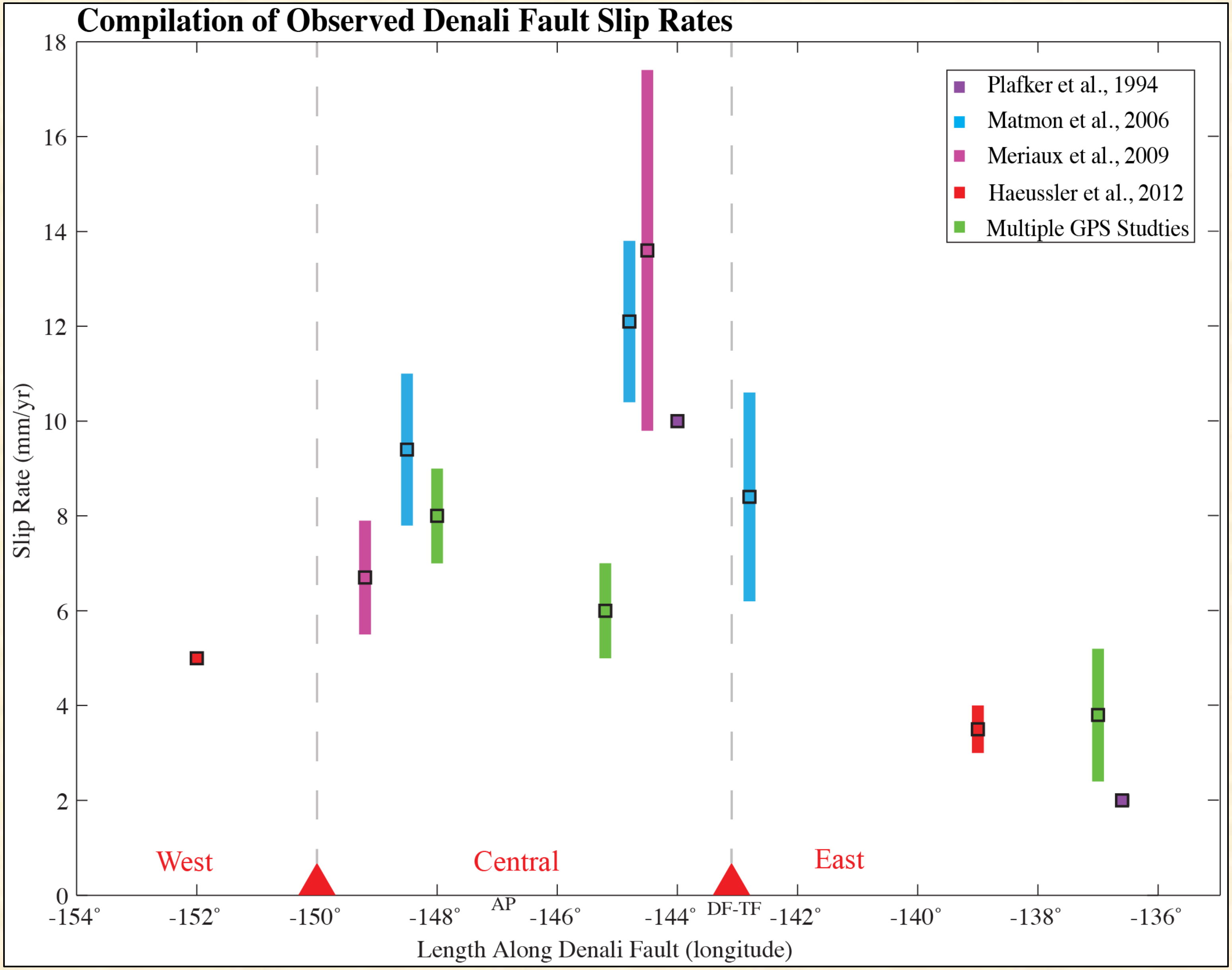
Haynie and Jadamec, Tectonics, 2017

Results: Along Strike Variation in Denali Fault Motion



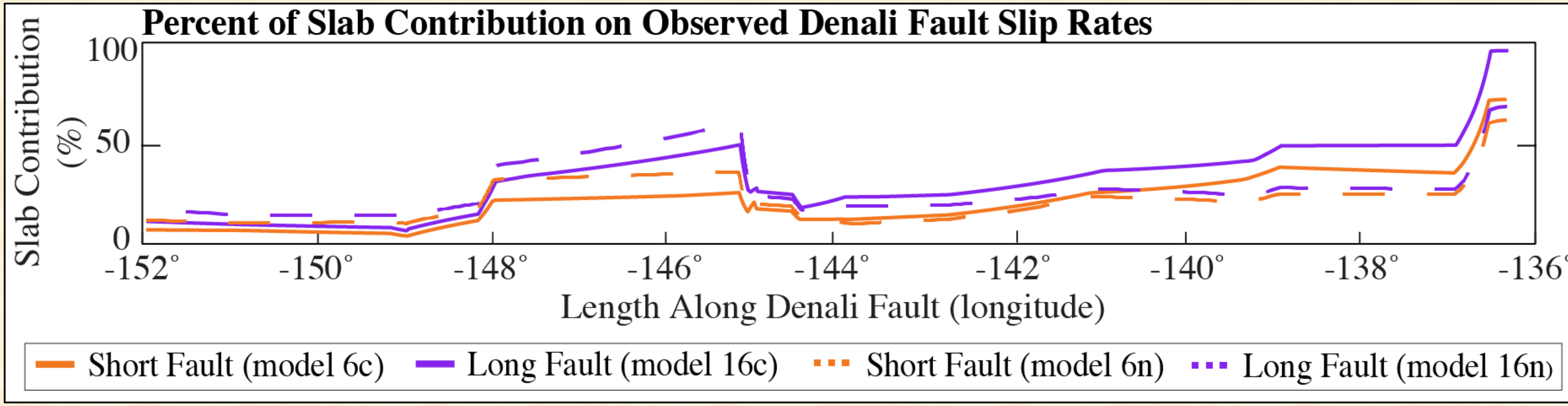
Haynie and Jadamec, Tectonics, 2017

Discussion: Observations Predict Along Strike Variation



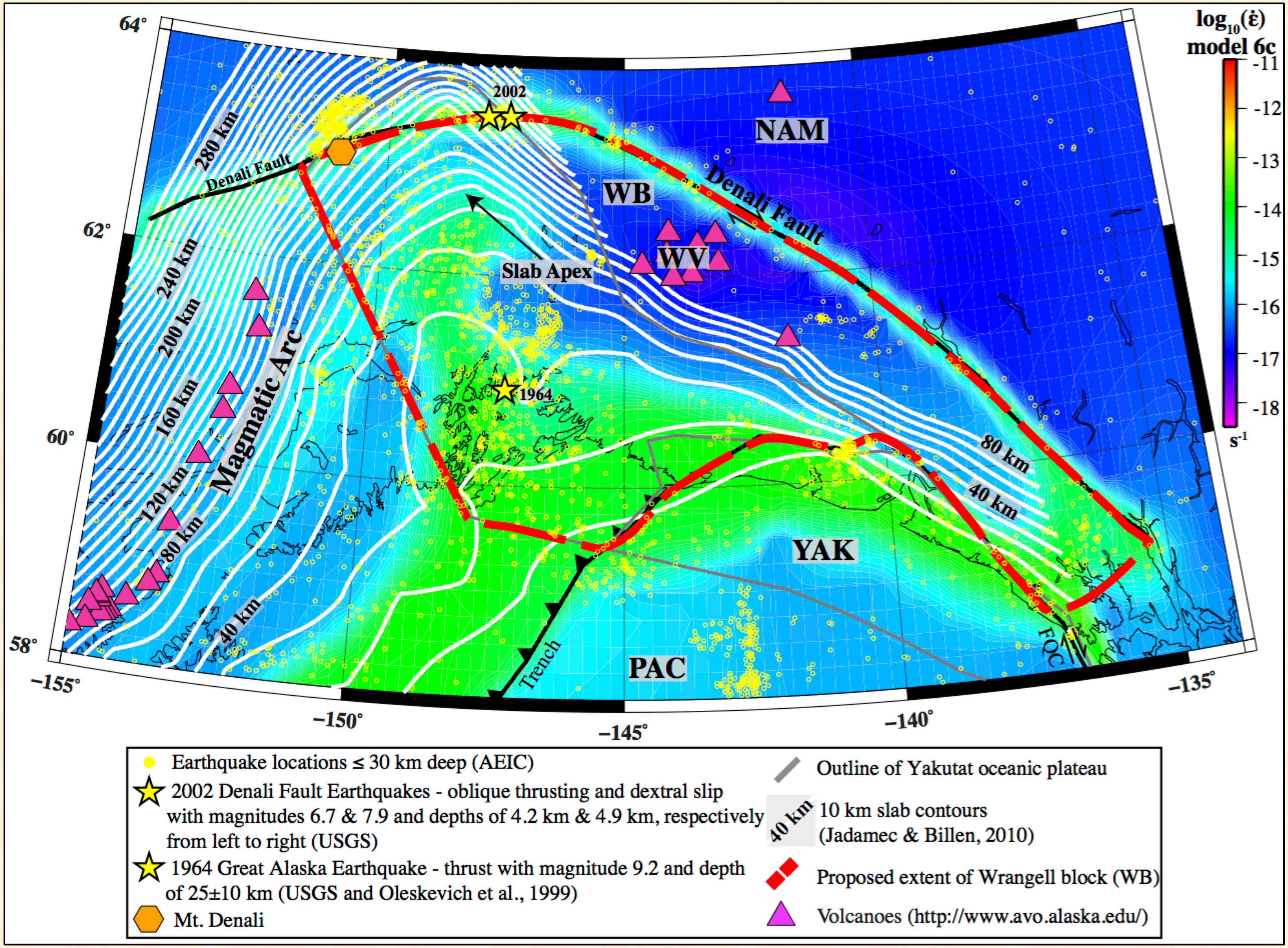
Haynie and Jadamec, Tectonics, 2017

Implications: Slab Controls ~ 25% Motion on Denali Fault



Haynie and Jadamec, Tectonics, 2017

Implications: New Framework Great 1964 AK Earthquake

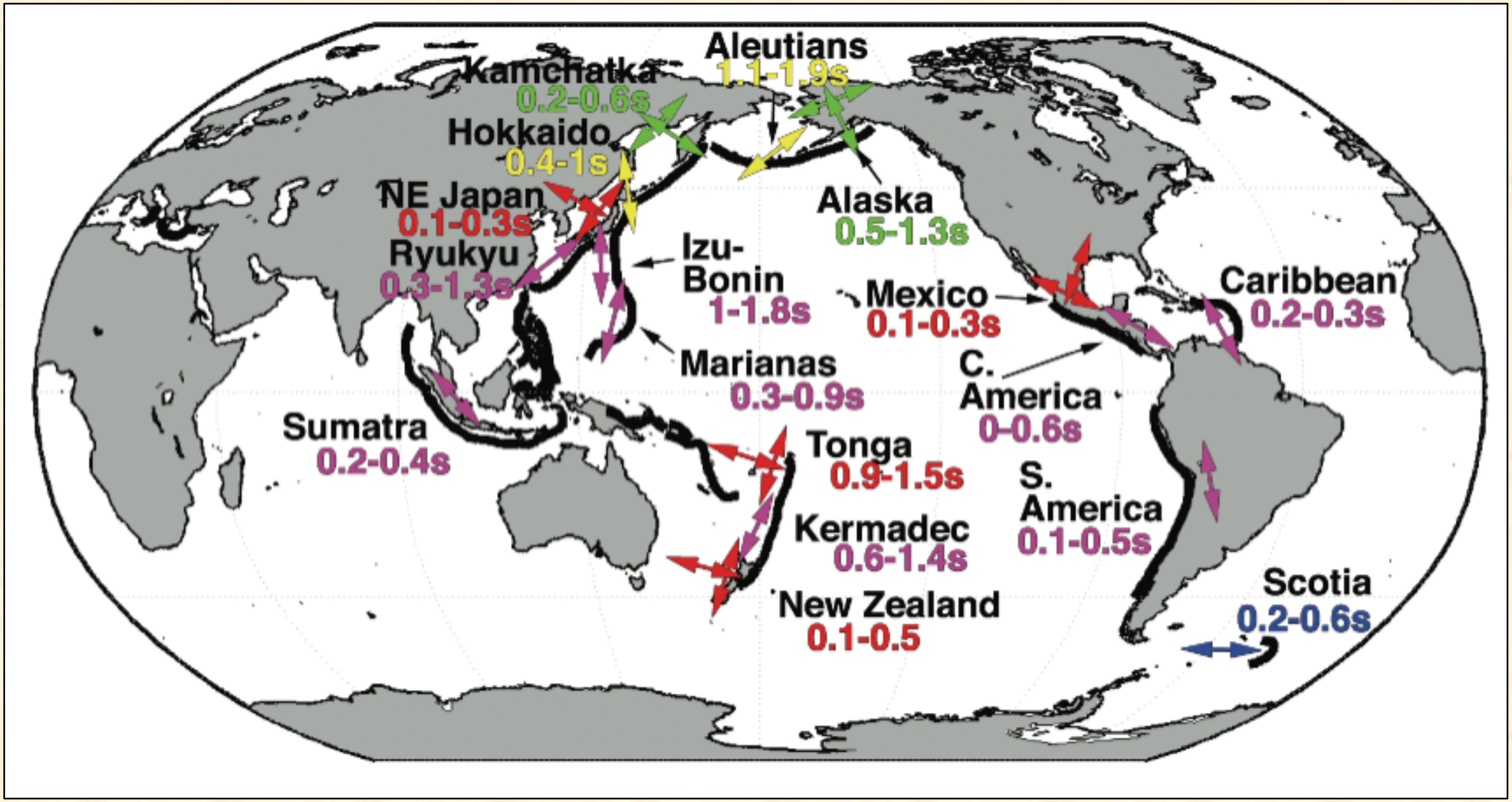


Haynie and Jadamec, Tectonics, 2017; Jadamec et al., In Prep.

Use High-resolution 3D Model of Specific Regions to Constrain Process: Alaska Specific Questions

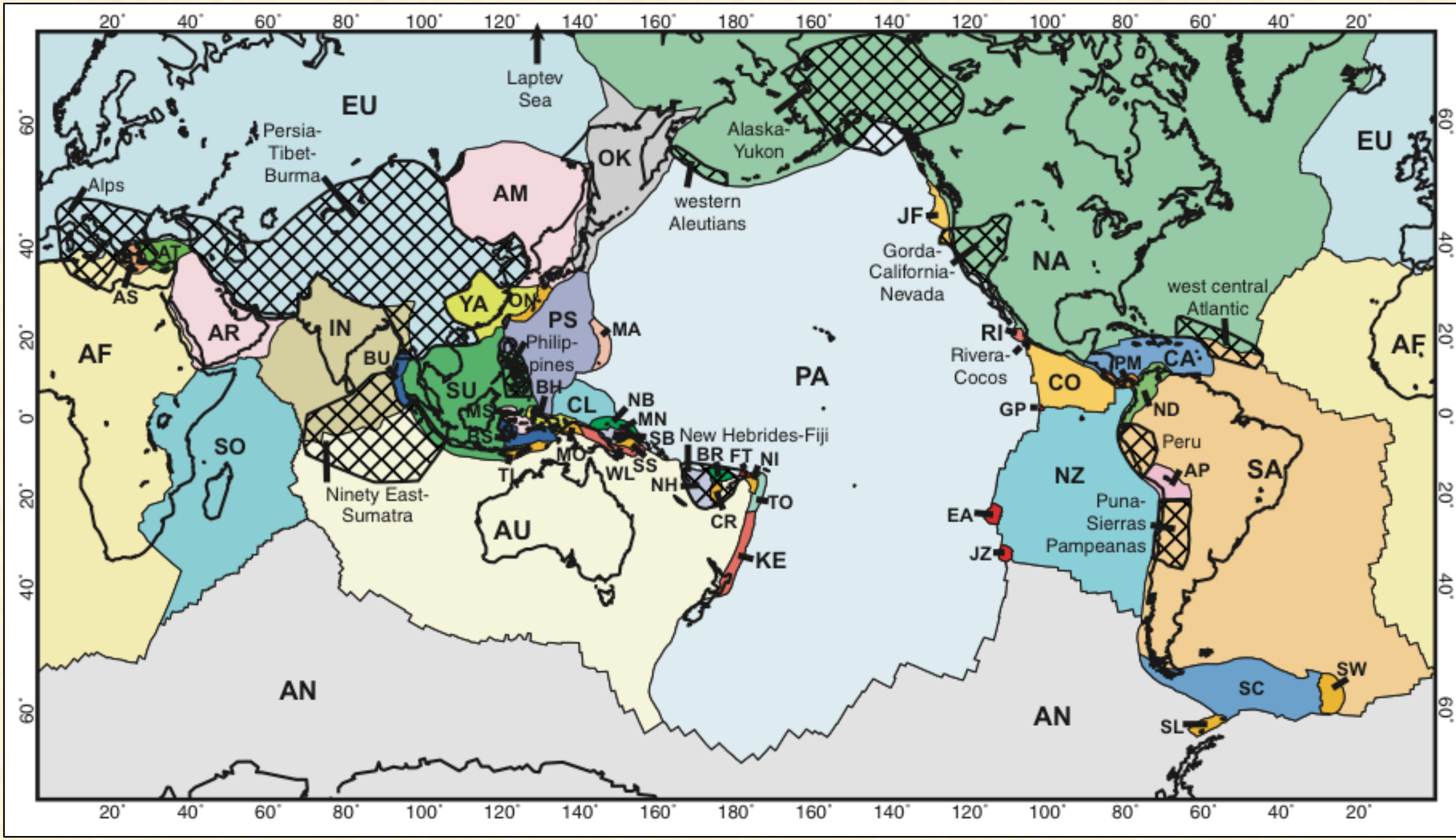
- Initial 3D Slab, Mantle, Lithosphere Structure of Alaska (AlaskaModel 1.0) – Synthesis next step AlaskaModel 2.0
- What is the slab geometry in Alaska? 2-tiered slab shape likely
- What is the mantle flow field in southern Alaska? Toroidal & Poloidal Flow & Localized Upwelling
- Why is there localized mountain building in Central Alaska Range over 500 km from the plate boundary? Flat slab + Denali fault
- What controls Wrangell Block (fore-arc sliver) motion in Alaska? Driving forces of Flat slab + Resisting forces along Denali fault
- What are implications of slab structure on hazards in Alaska? 1964

Mantle Deformation Zones May Surrounding Slabs Globally



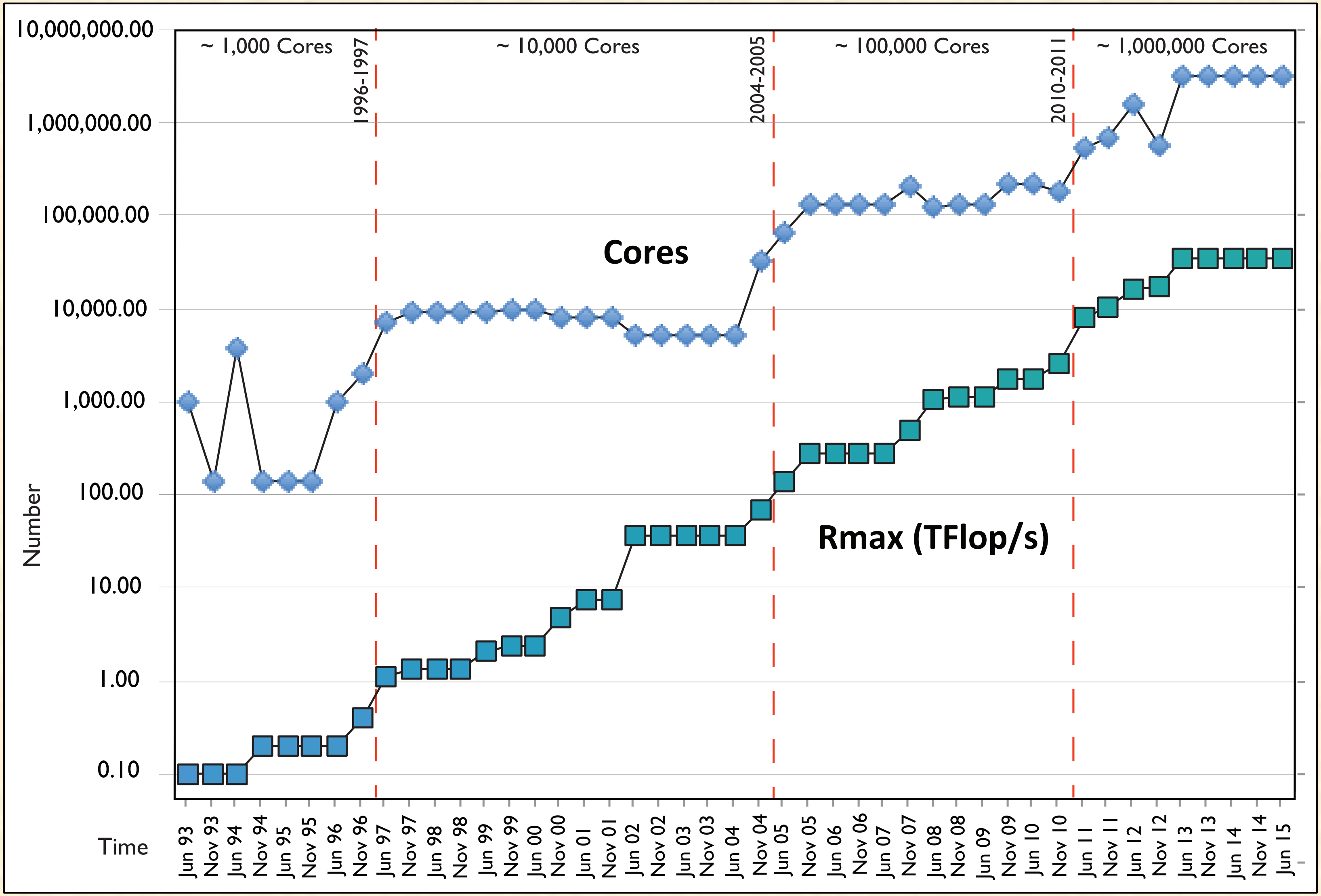
Long and Wirth (2013)

Slab Contribution Broad Zones of Lithosphere Deformation



Bird, G³ 2003

Scientific Discovery Advanced by High Performance Comp.



Jadamec, 2016, Journal of Geodynamics

Data: Strohmaier et al. (2015),
Total cores and Rmax value for supercomputers worldwide ranked Number 1, from 1993-2015, according to TOP500 list ranked by performance on LINPACK Benchmark

Thank You

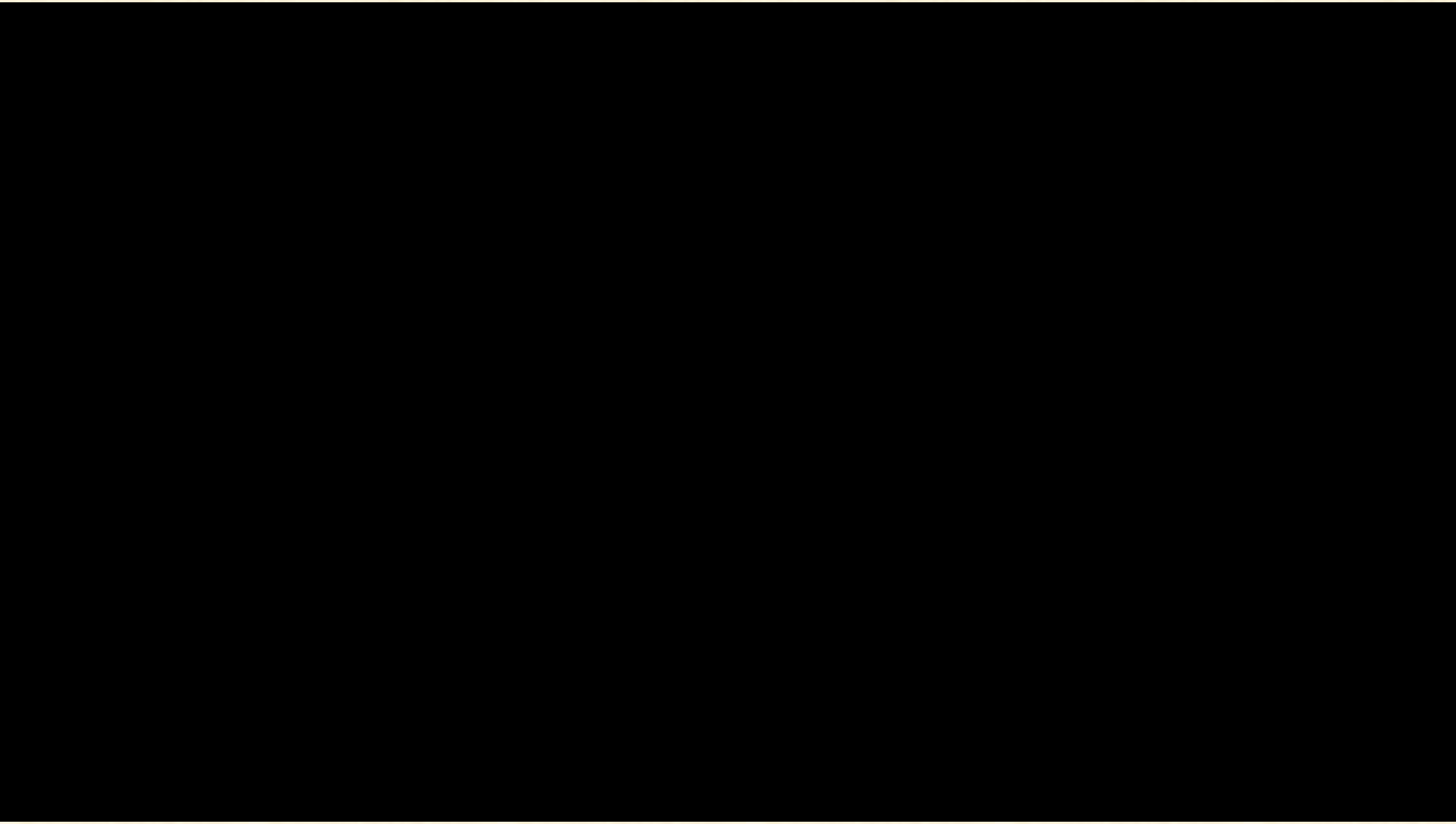
Wesley K. Wallace

Upcoming Elsevier Volume:

Alaska: A window to Tectonic Process

Editors: M. Jadamec and J. Freymueller

Slabs are Inherently 3D Objects with Complex Geometries

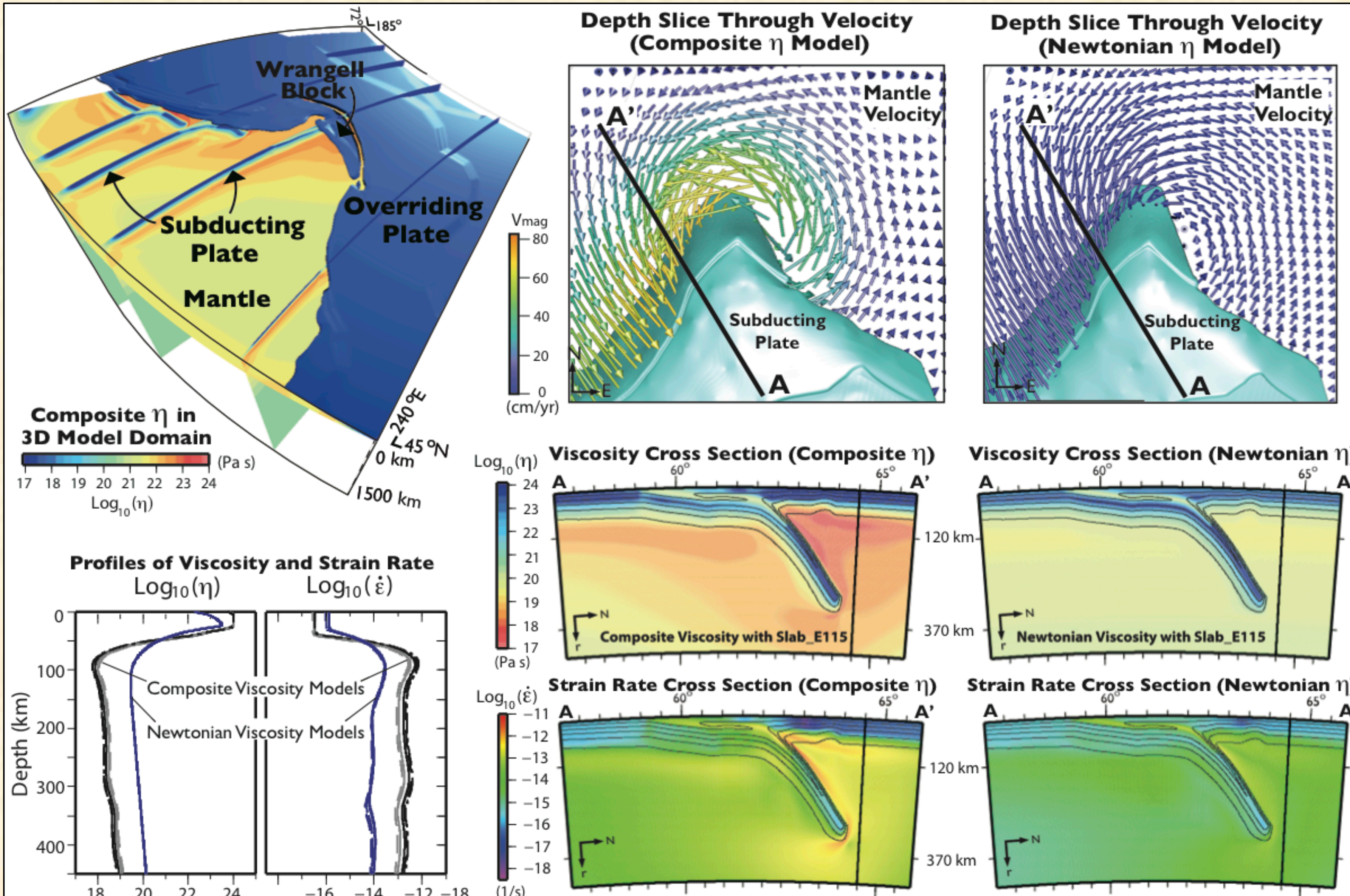


Jadamec et al., in Prep.

Use High-resolution 3D Model of Specific Regions to Constrain Process

- Slabs are Inherently 3D – Implications Slab Strength
- 3D Structure Important for Plate & Mantle Deformation
- Mantle Deformation Zones May Surrounding Slabs Globally
- Scientific Discovery Advanced by High Performance Computing
- Geodynamic Modeling as a Tool for Synthesis and Data Assimilation

Results: Rapid Slab Driven Mantle Flow Close to SZ



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

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

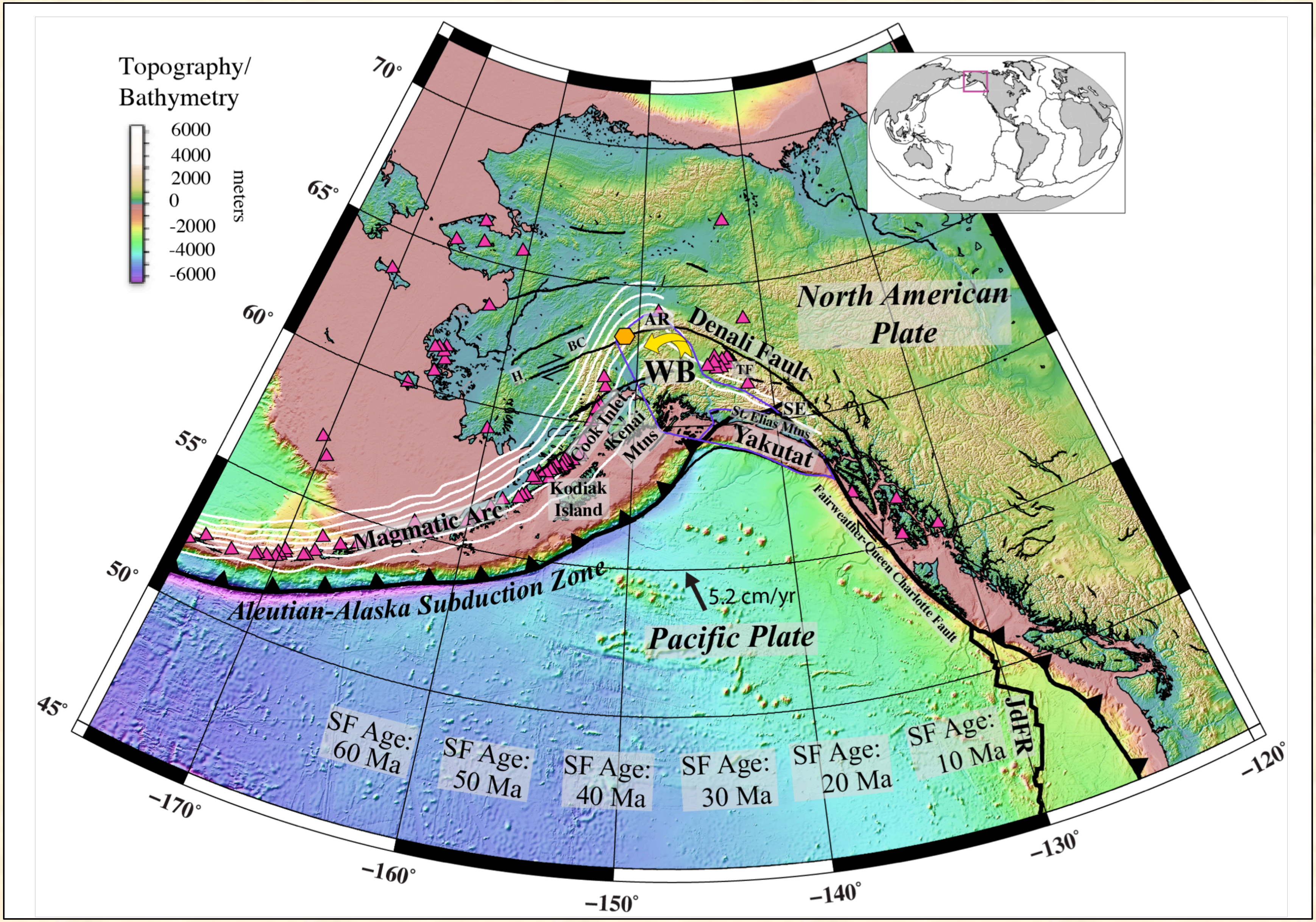
Filmed by Oliver Kreylos in the KeckCAVES

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.

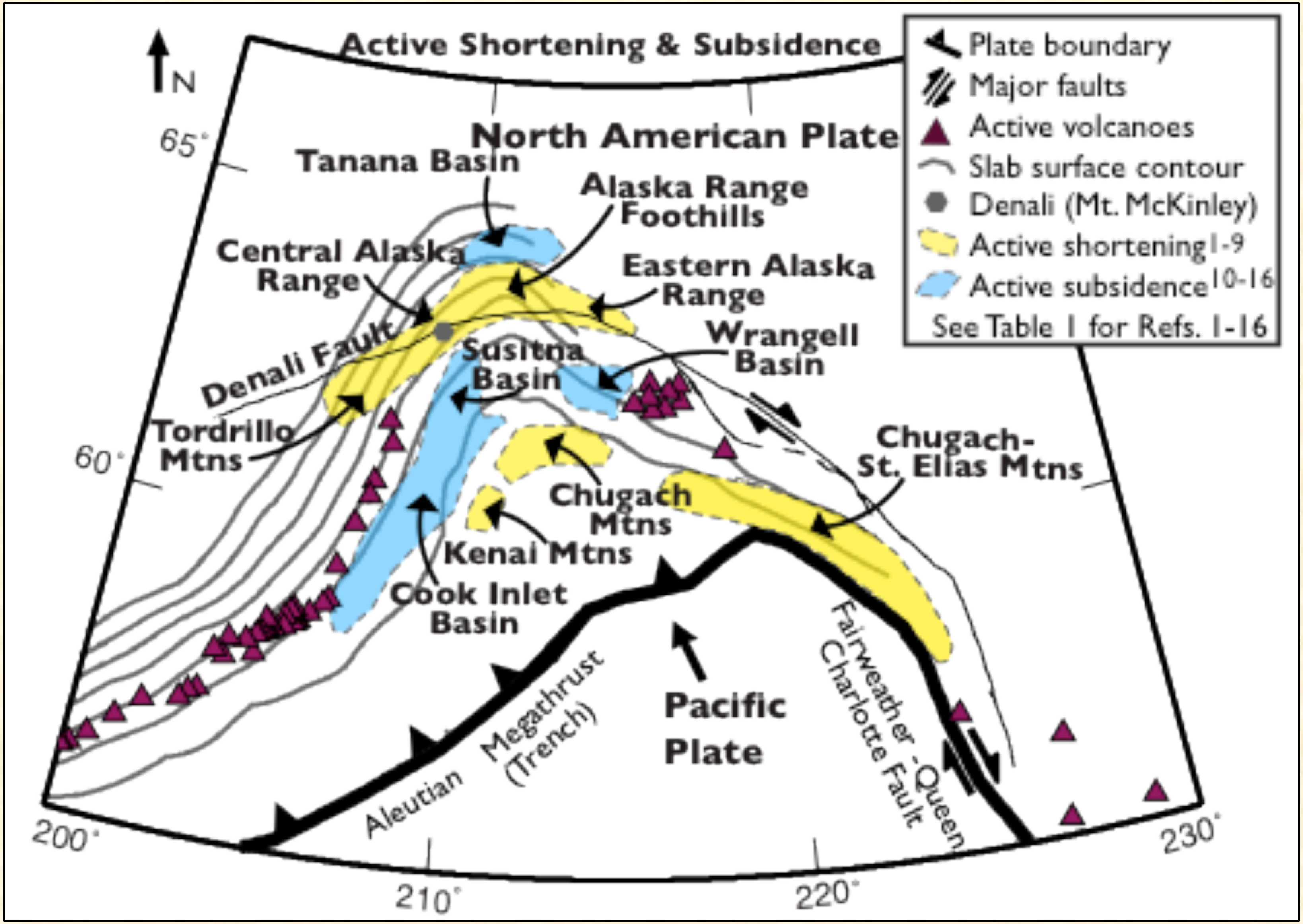
Jadamec et al., EPSL, 2013

Pacific-North America Plate Boundary in Alaska



Haynie and Jadamec, Tectonics, 2017

Active Shortening and Subsidence in South Central Alaska



Jadamec et al., 2013, EPSL