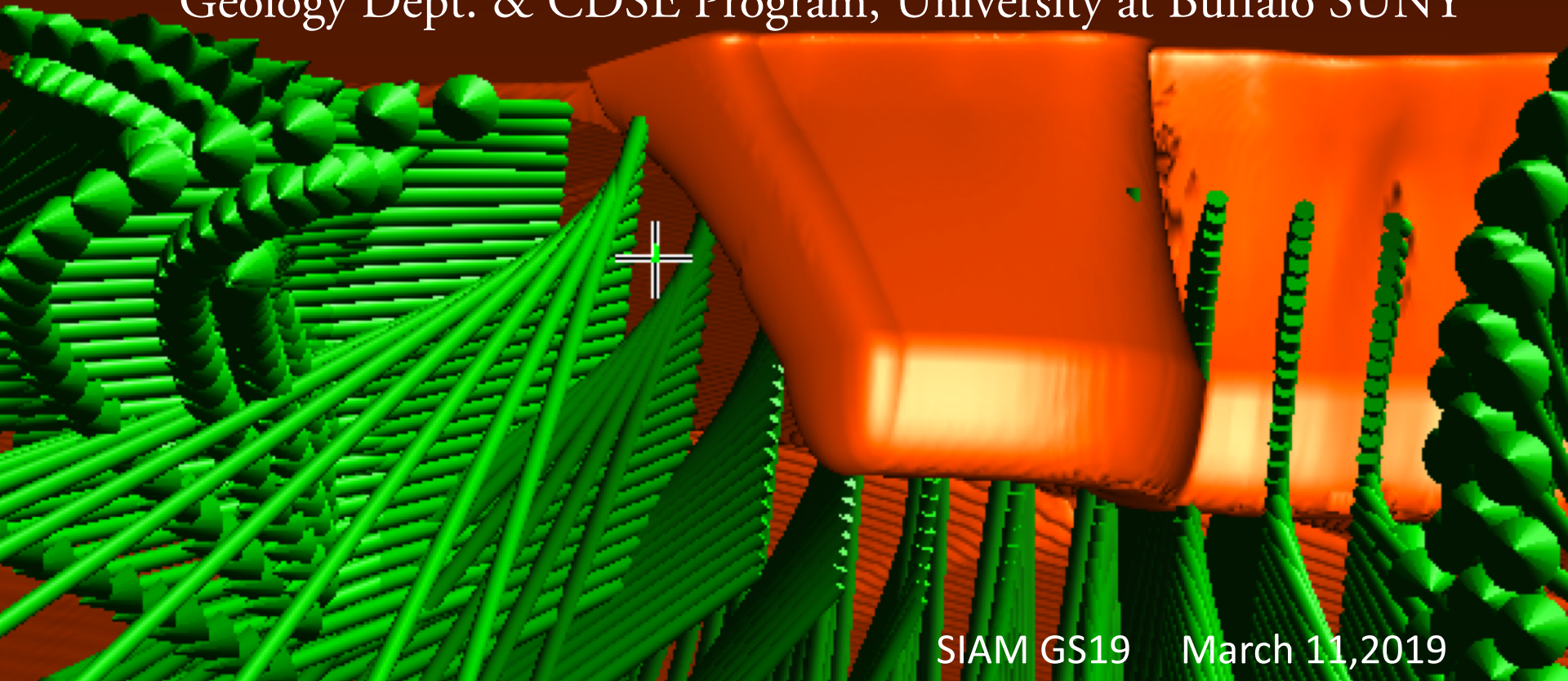
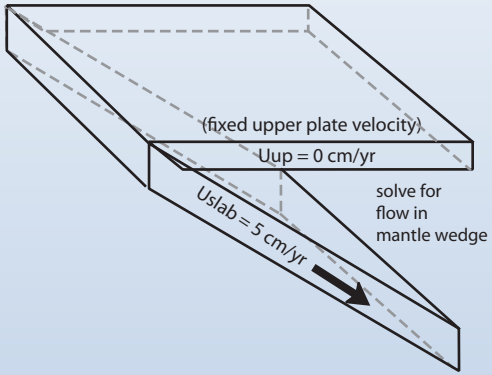
High-resolution Design & Simulation of Nonlinear Flow in Modern Subduction Systems

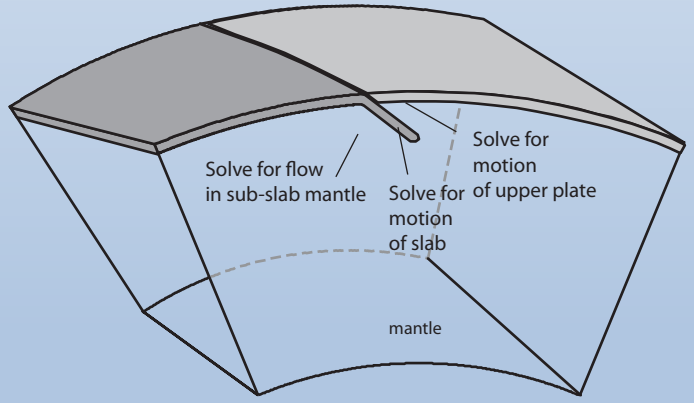
Margarete A. Jadamec
Geology Dept. & CDSE Program, University at Buffalo SUNY

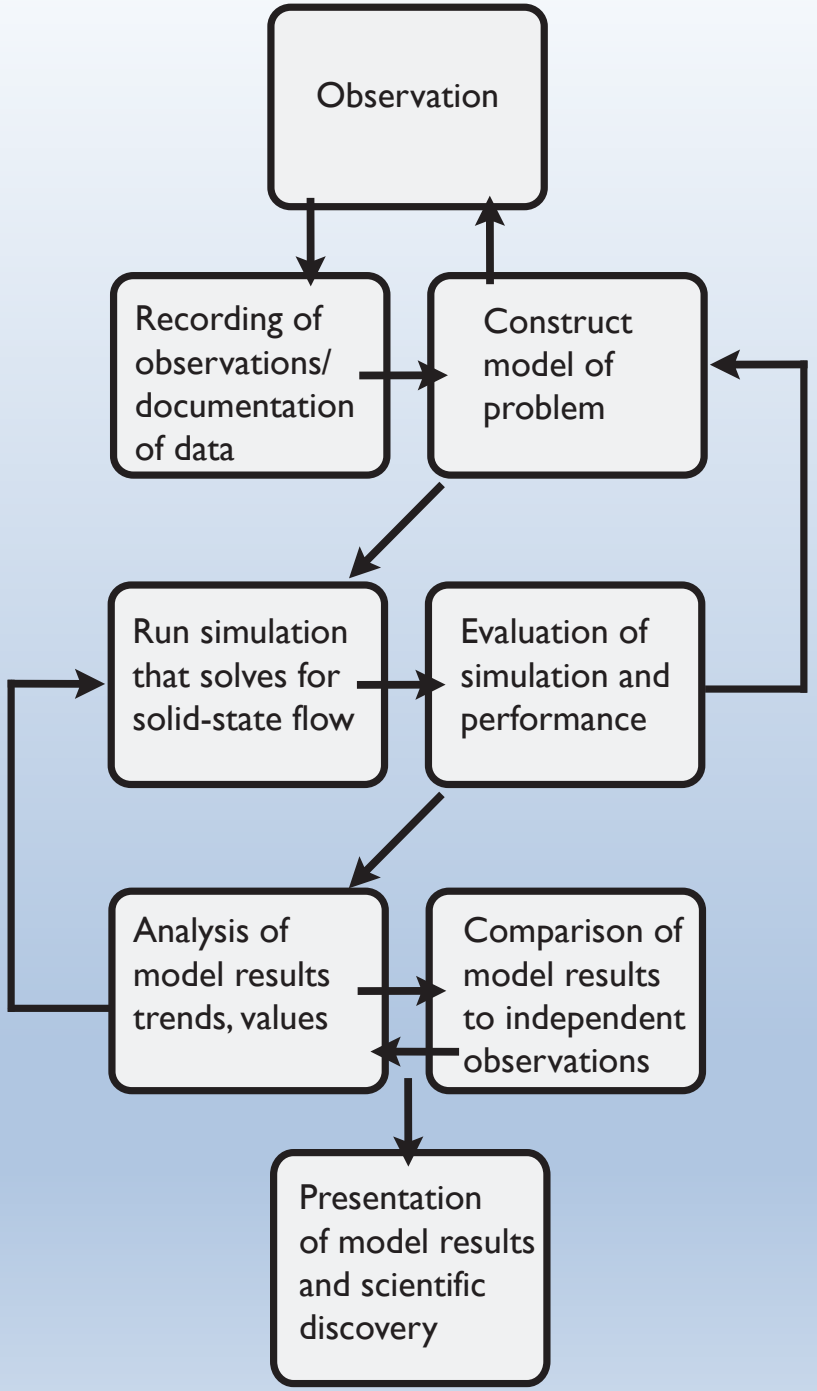


SIAM GS19 March 11,2019

Scientific Discovery in Computational Landscape



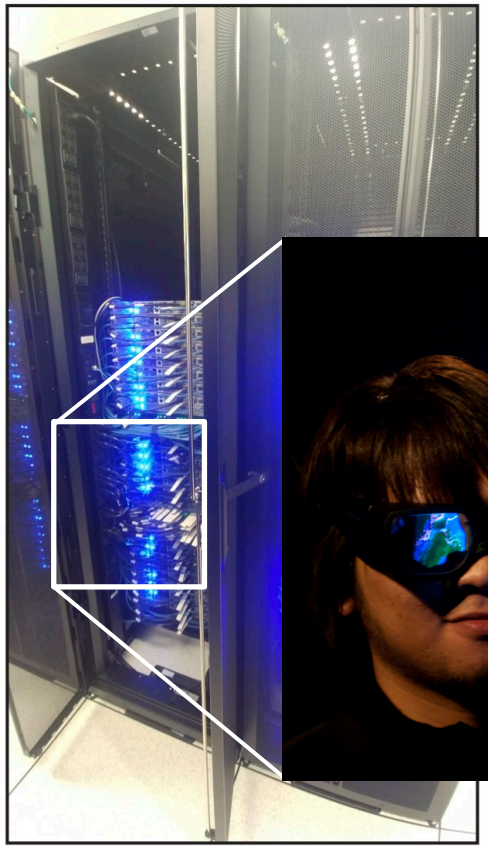




Jadamec, M. A., 2016, Insights on slab-driven mantle flow from advances in three-dimensional modelling. *Journal of Geodynamics*, vol. 100, p. 51-70.

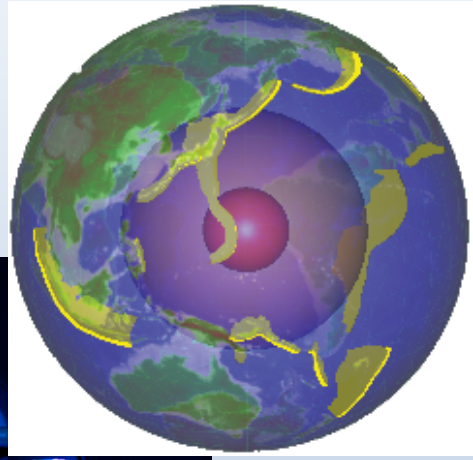
Scientific Discovery Facilitated by HPC + 3D Data Visualization





Geosolver - 1200 core Dell Linux cluster
[100 Intel Xeon Gold 6126 Processors, 2.6 GHz, 19.25 MB L3, 12C]
[9.6 TB RAM - 8GB/core; Intel Omni-Path interconnect]

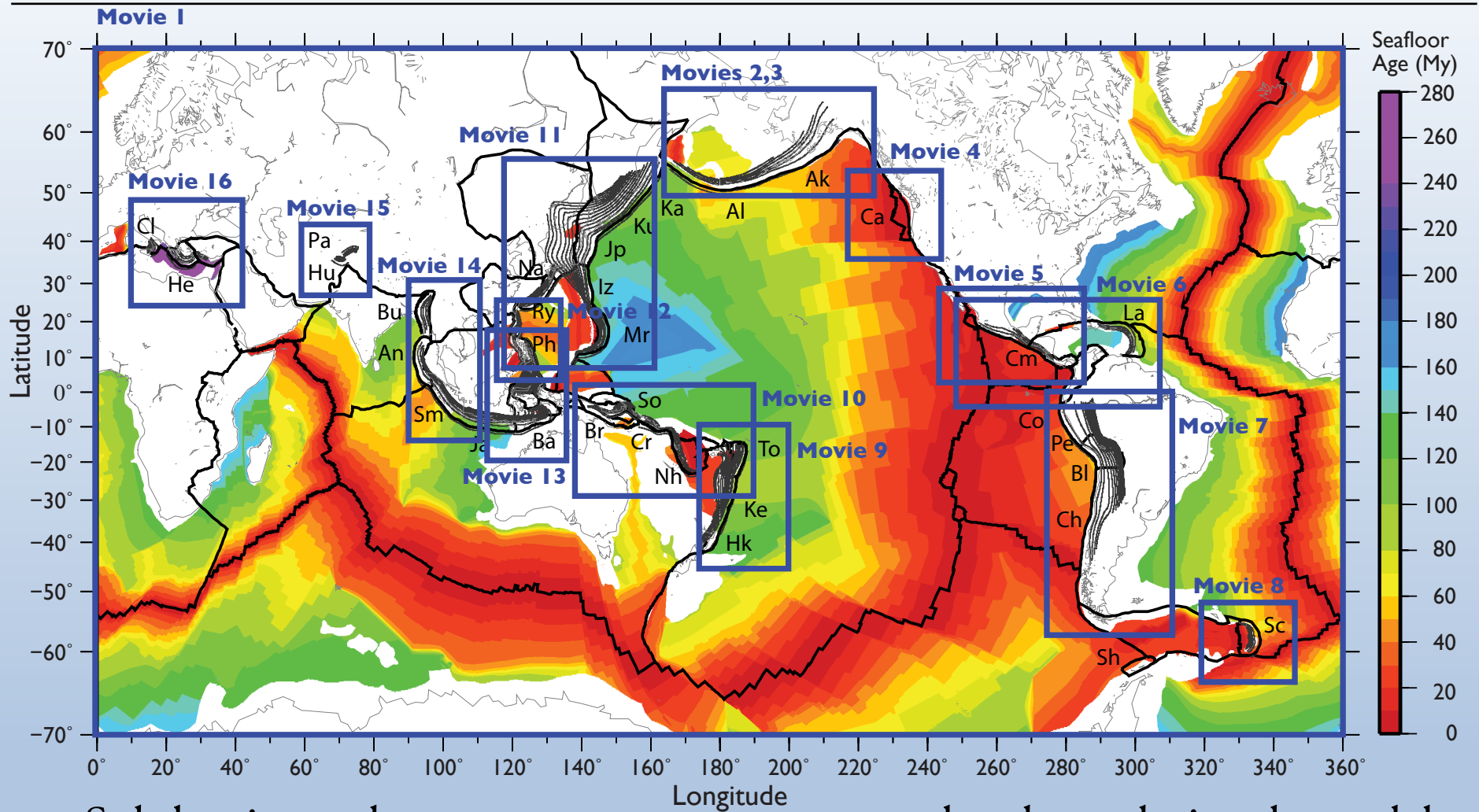
Geosolver (1200-core Dell Skylake partition):
M. Jadamec and M. Knepley Research Groups
Center for Computational Research,
University at Buffalo, SUNY (photo by M. Jones)





3DALIVE at Monash University, Australia (Photo by Louis Moresi)

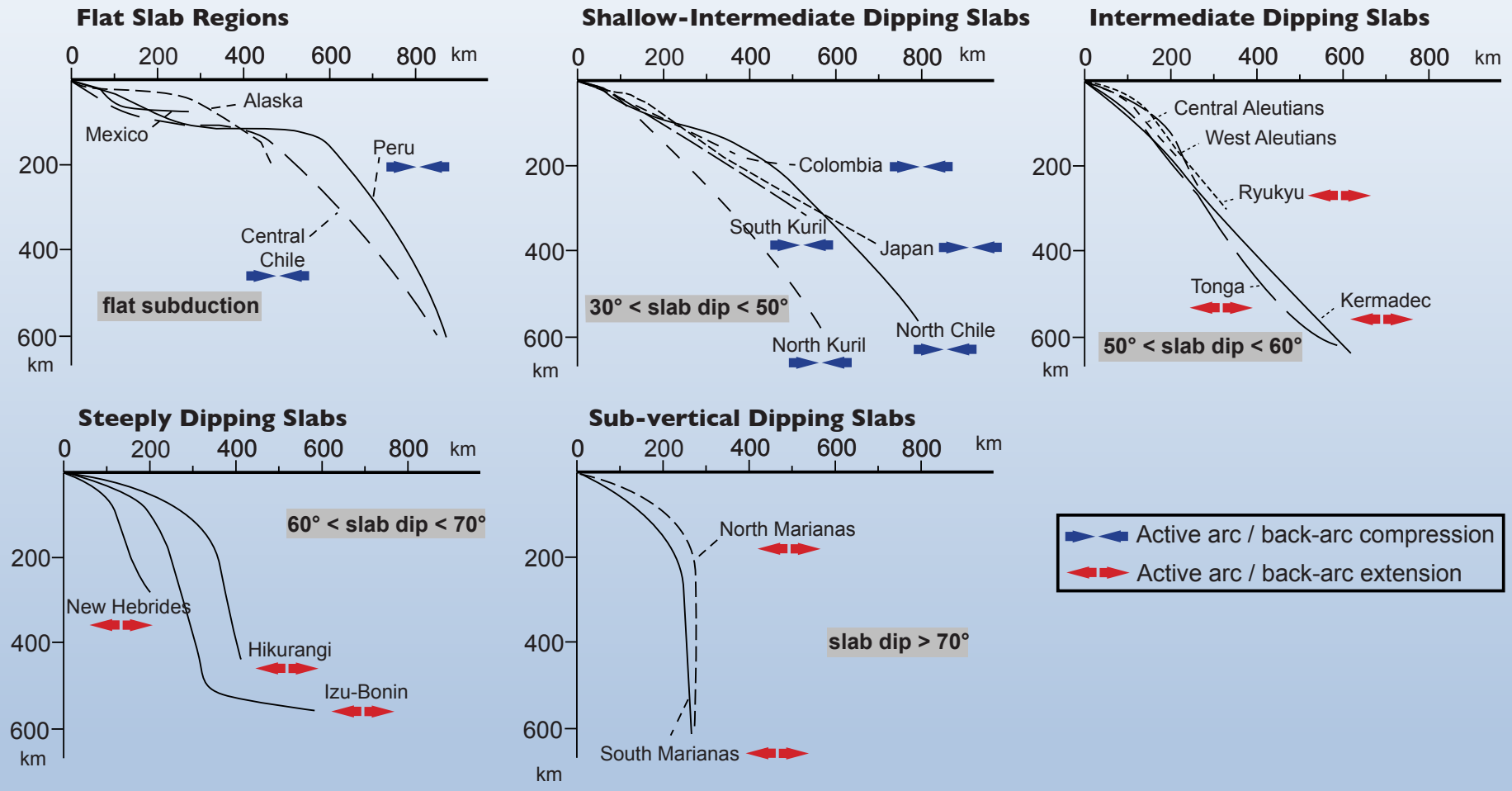
Oceanic & Continental Lithosphere: Denser Layer Sinks



- Subduction volcanoes occur at convergent plate boundaries above slab
- However, observations indicate anomalous volcanoes next to slab edges

Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

What is Geometry of Dense Sinking Oceanic Lithosphere?

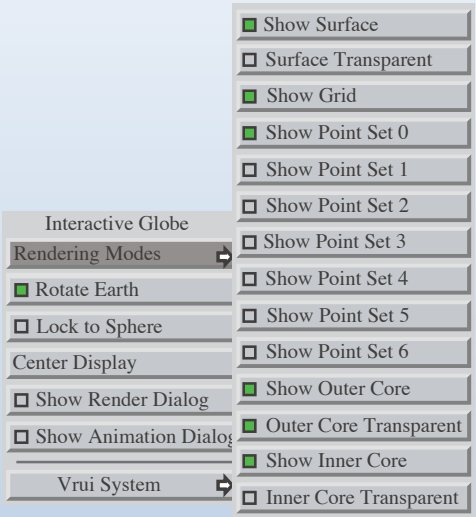


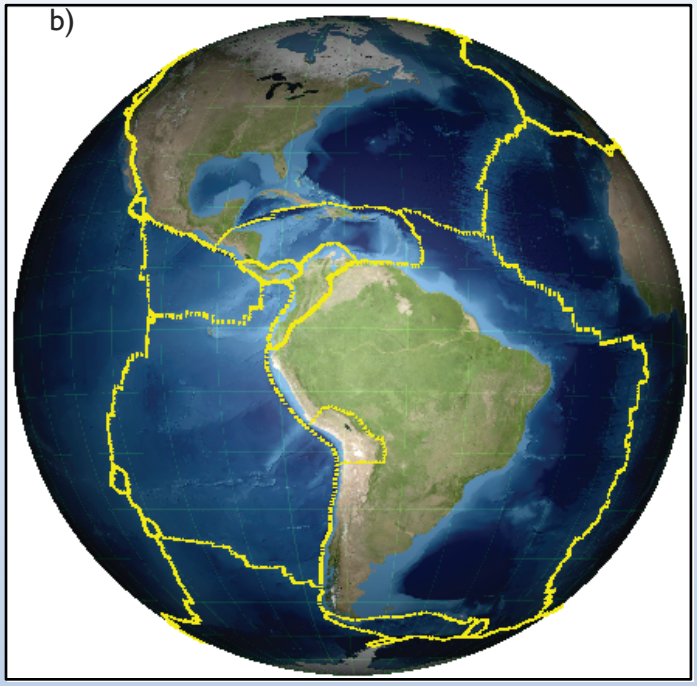
Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

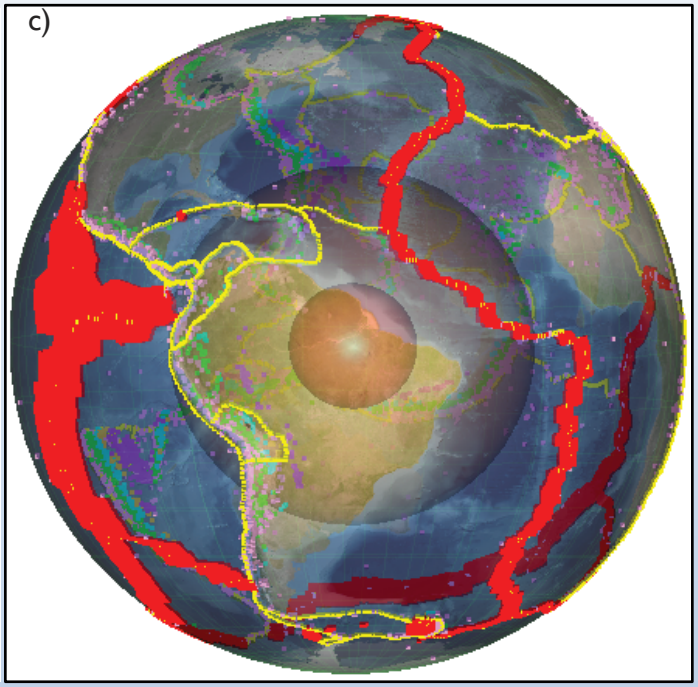
Image courtesy of Serge Lallemand: Lallemand et al., 2005, Geochemistry, Geophysics, Geosystems , 6 (9)

ShowEarthModel Menus and Plate Data Rendering

a)





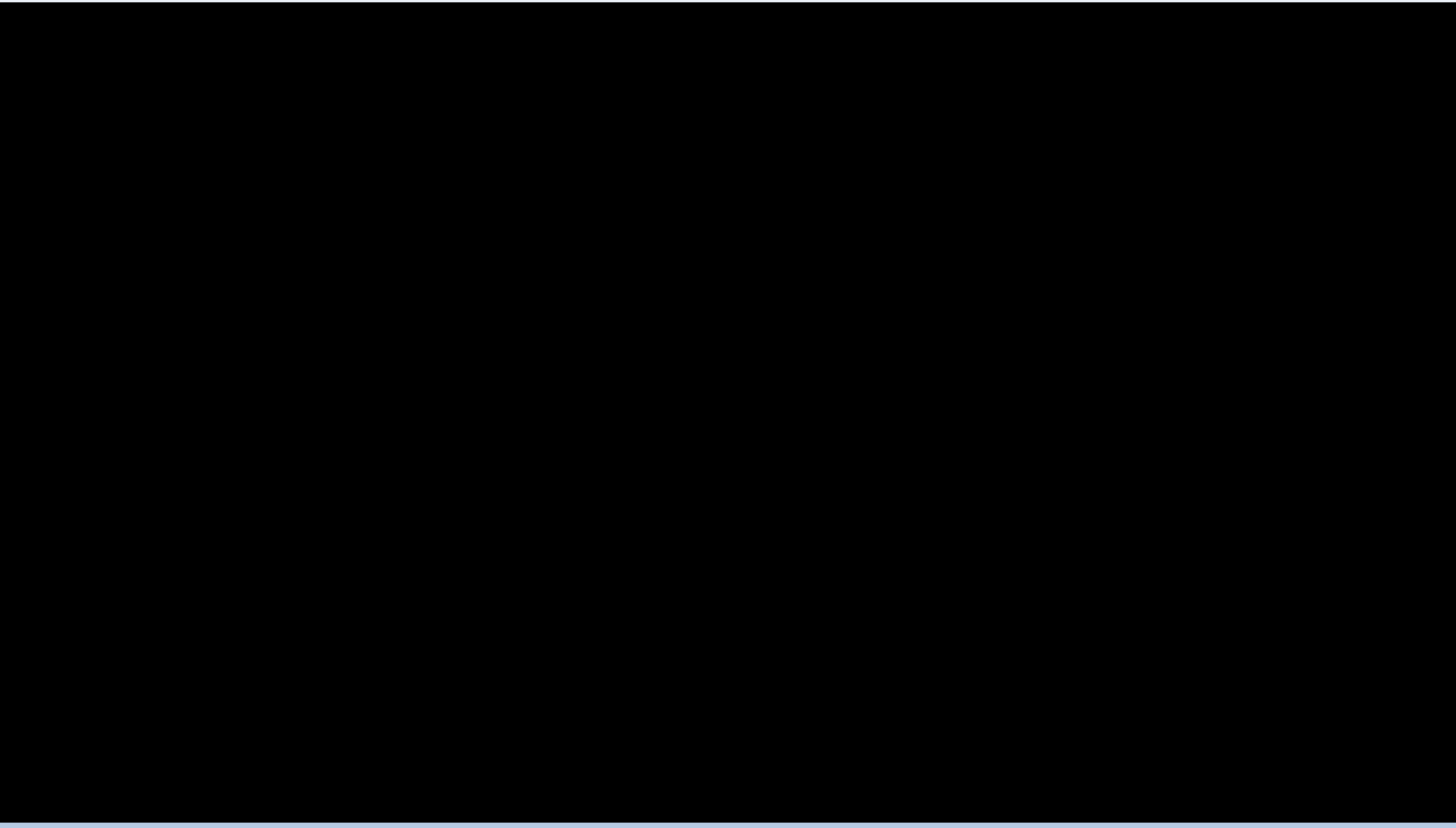


Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

Download Virtual Reality User Interface (Vrui) ToolKit:
http://idav.ucdavis.edu/~okreylos/ResDev/Vrui/index.html

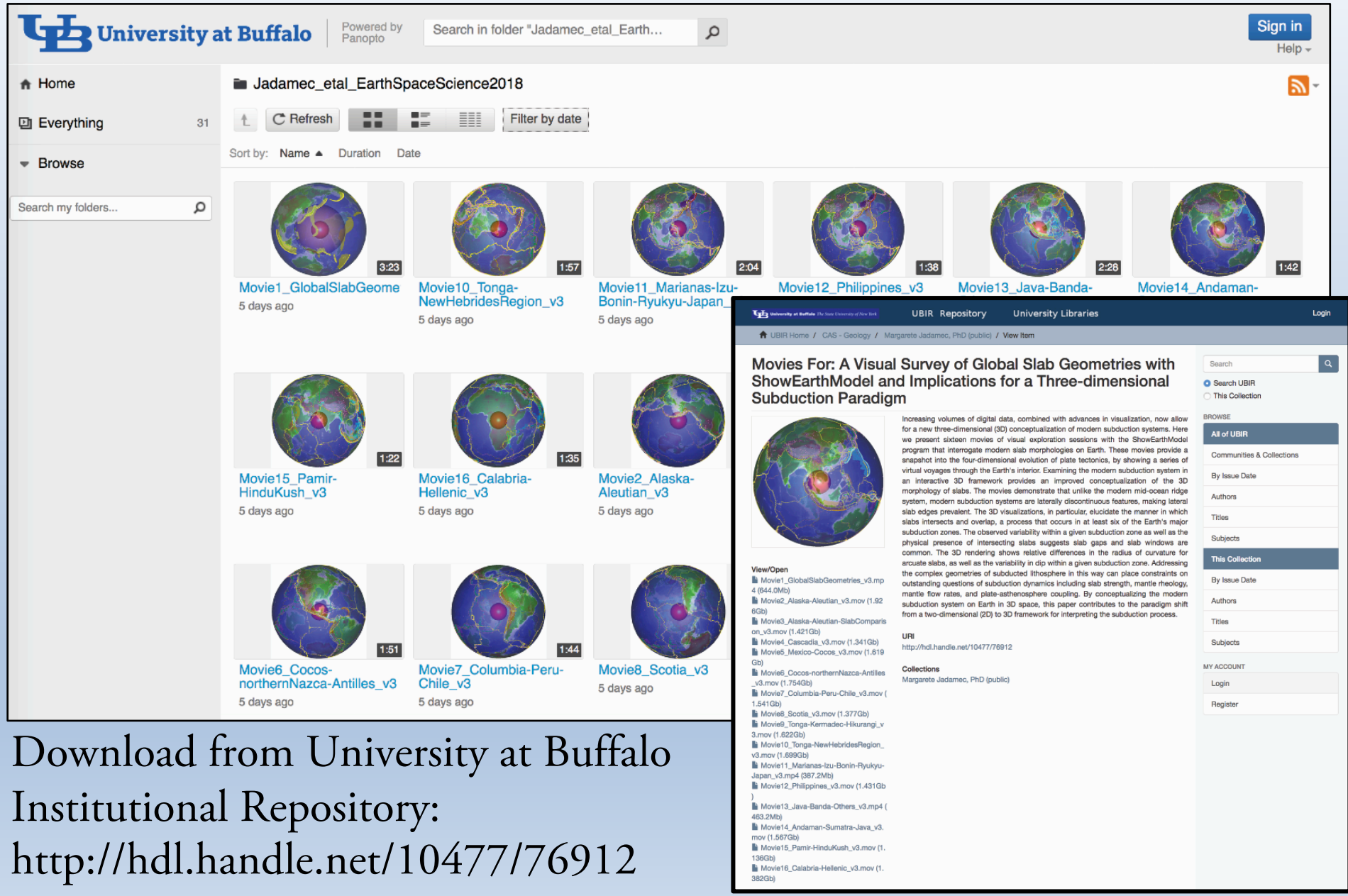
- ShowEarthModel in Example Programs Directory

Movie #1: Global Slab Geometry Comparison



Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

Movies available for Streaming at the University at Buffalo, SUNY Hosted Panopto site: http://goo.gl/Y7PDEX



Download from University at Buffalo Institutional Repository: http://hdl.handle.net/10477/76912

Table 1
List of 16 High-Resolution Visualizations Comparing 3-D Slab Geometries

Movie #	Content	3-D features
Global survey		
Movie 1	Slab geometry comparison[a,b,c,d]	Discontinuous slabs, intersections, edges variable dip
Subduction zones		
Movie 2	Alaska-Aleutian[c,d,e]	Slab edges, variable dip
Movie 3	Alaska-Aleutian Slab Comparison[a,b,c,f]	Slab edges, variable dip
Movie 4	Cascadia[c,d,e]	Slab edges
Movie 5	Mexico-Cocos[c,d,e]	Slab edges, variable dip
Movie 6	Cocos-northern Nazca, Antilles[a,b,c,d,e,g]	Slab window
Movie 7	Columbia-Peru-Chile[c,d,e]	Variable dip, depth
Movie 8	Scotia[c,d,e]	Curved slab, edges
Movie 9	Tonga-Kermadec-Hikurangi[c,d,e]	Variable dip, depth
Movie 10	Tonga, New Hebrides, and North Fiji Basin[c,d,e] (North Fiji Basin region)	Slab edges
Movie 11	Marianas-Izu-Bonin, Ryukyu, Japan, Kamchatka[c,d,e]	Triple junction, slab edges
Movie 12	Philippines (Slabs bounding Philippine Plate)[c,d,e]	Multiple slabs
Movie 13	Java, Banda, and Others[a,c,d,e]	Intersections, curved slabs, edges
Movie 14	Andaman-Sumatra-Java[c,d,e]	Variable dip, depth
Movie 15	Pamir, Hindu Kush[a,c,d,e]	Curved slabs, edges
Movie 16	Calabria and Hellenic[a,c,d,e]	Curved slabs, edges

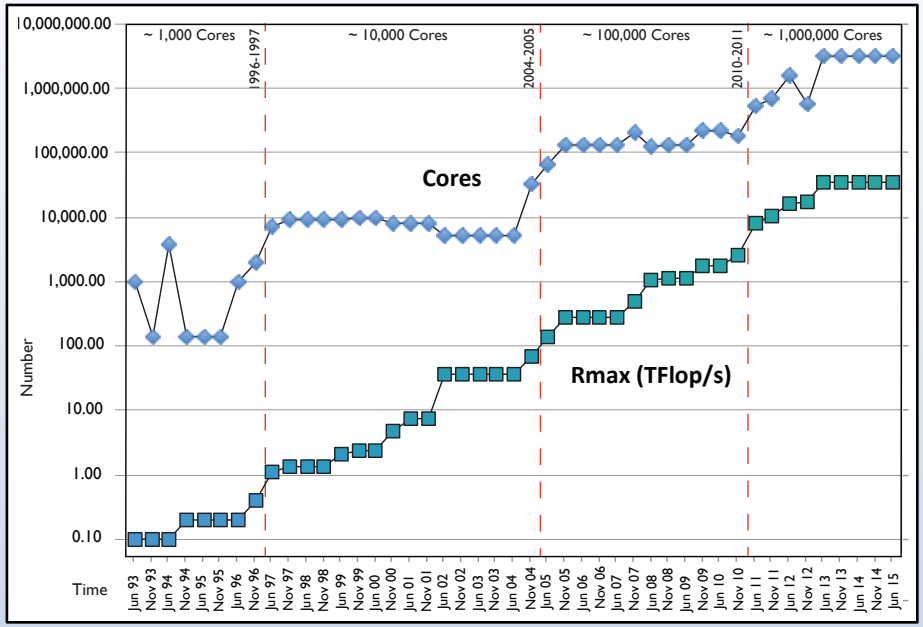
Note. Individual movie files can be downloaded at the SUNY Buffalo Institutional Repository: http://hdl.handle.net/10477/76912 and streamed without needing to be downloaded at the SUNY Buffalo hosted Panopto site: goo.gl/Y7PDEX. Geographic locations of movies are shown in Figures 1 and 4. Data sources:
[a]Gudmundsson and Sambridge (1998) slab contours in 50 km. [b]Syracuse and Abers (2006) slab contours in 50 km. [c]Hayes et al. (2012) slab surfaces. [d]Bird (2003) plate boundaries. [e]Engdahl and Villaseñor (2002) earthquake hypocenters. [f]Jadamec and Billen (2010) slab surface. [g]Jadamec and Fischer (2013) slab surfaces.

Movies Show Slabs are Discontinuous and Edges are Common

Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science*, 5(6), 240-257.

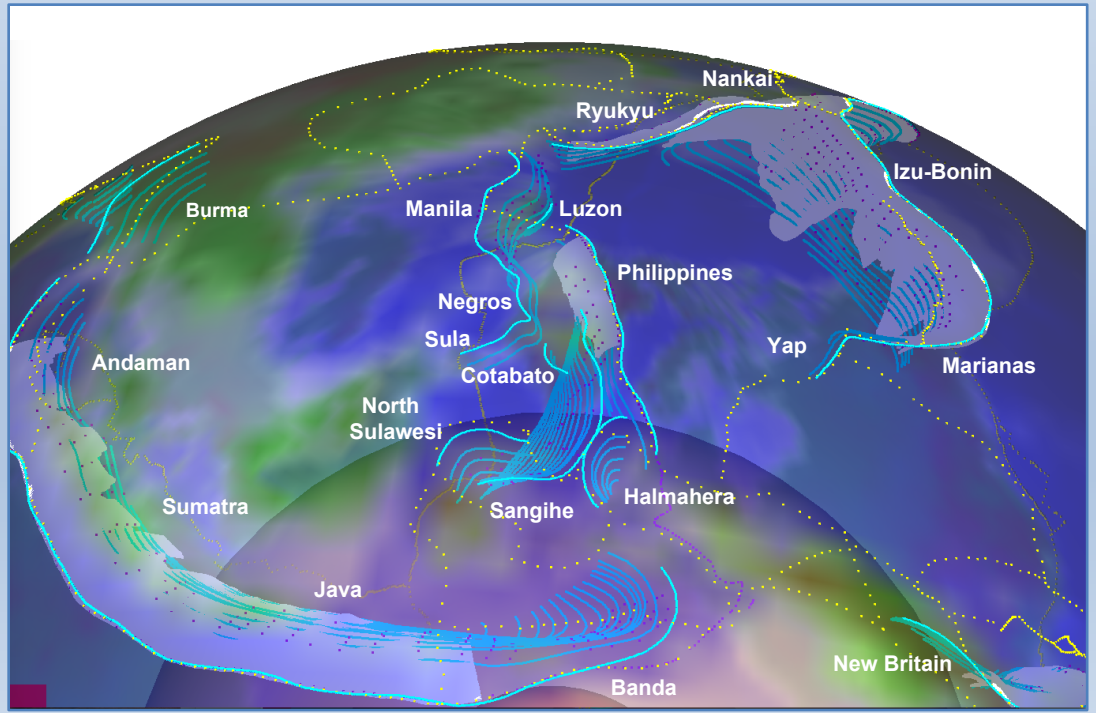
Scientific Discovery in Computational Landscape

HPC Allows For Modeling Complexity:
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



Jadamec, 2016, Journal of Geodynamics

Data Conceptualization:
3D visualization of global slabs
Facilitates 3D model design

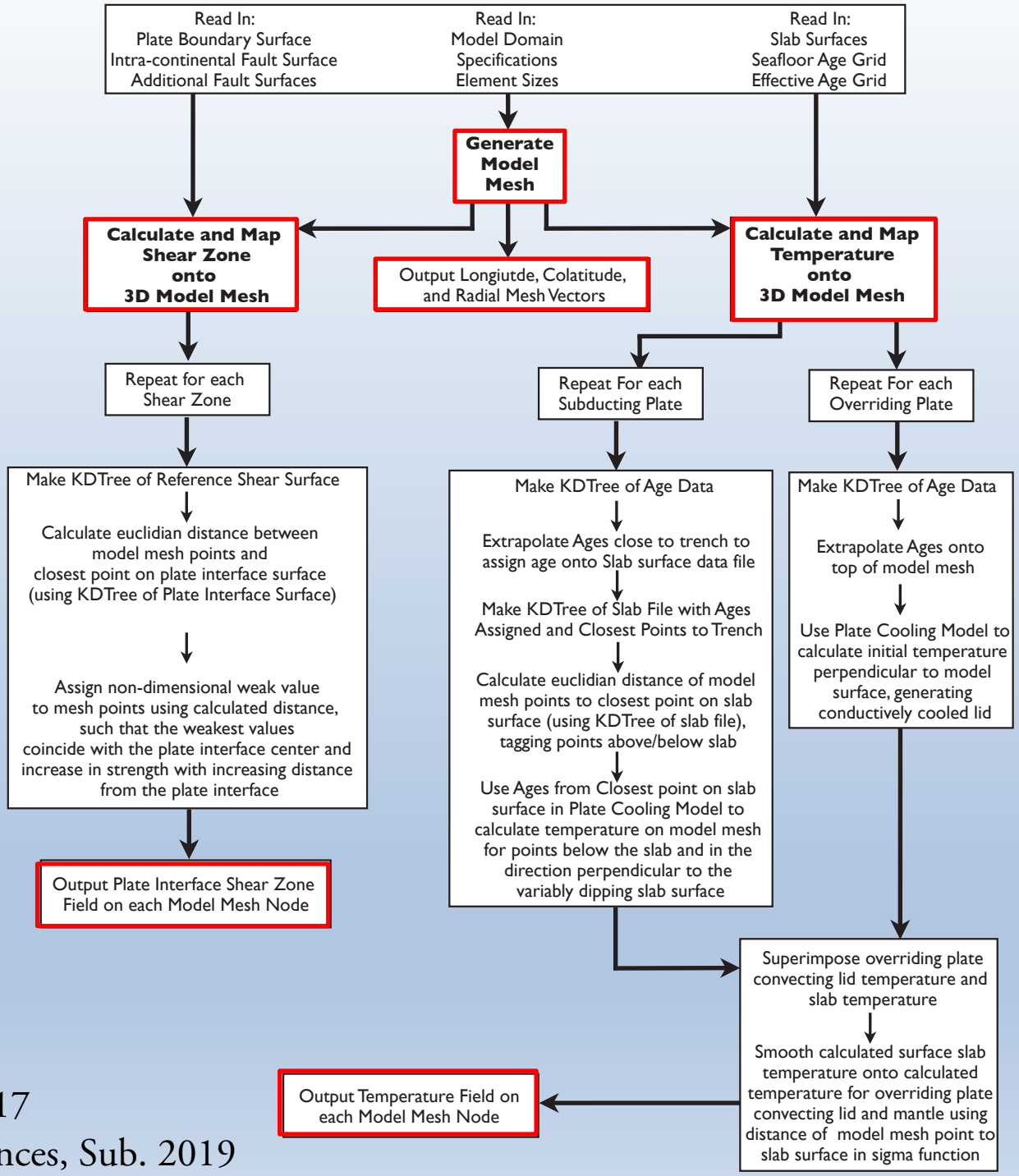


Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

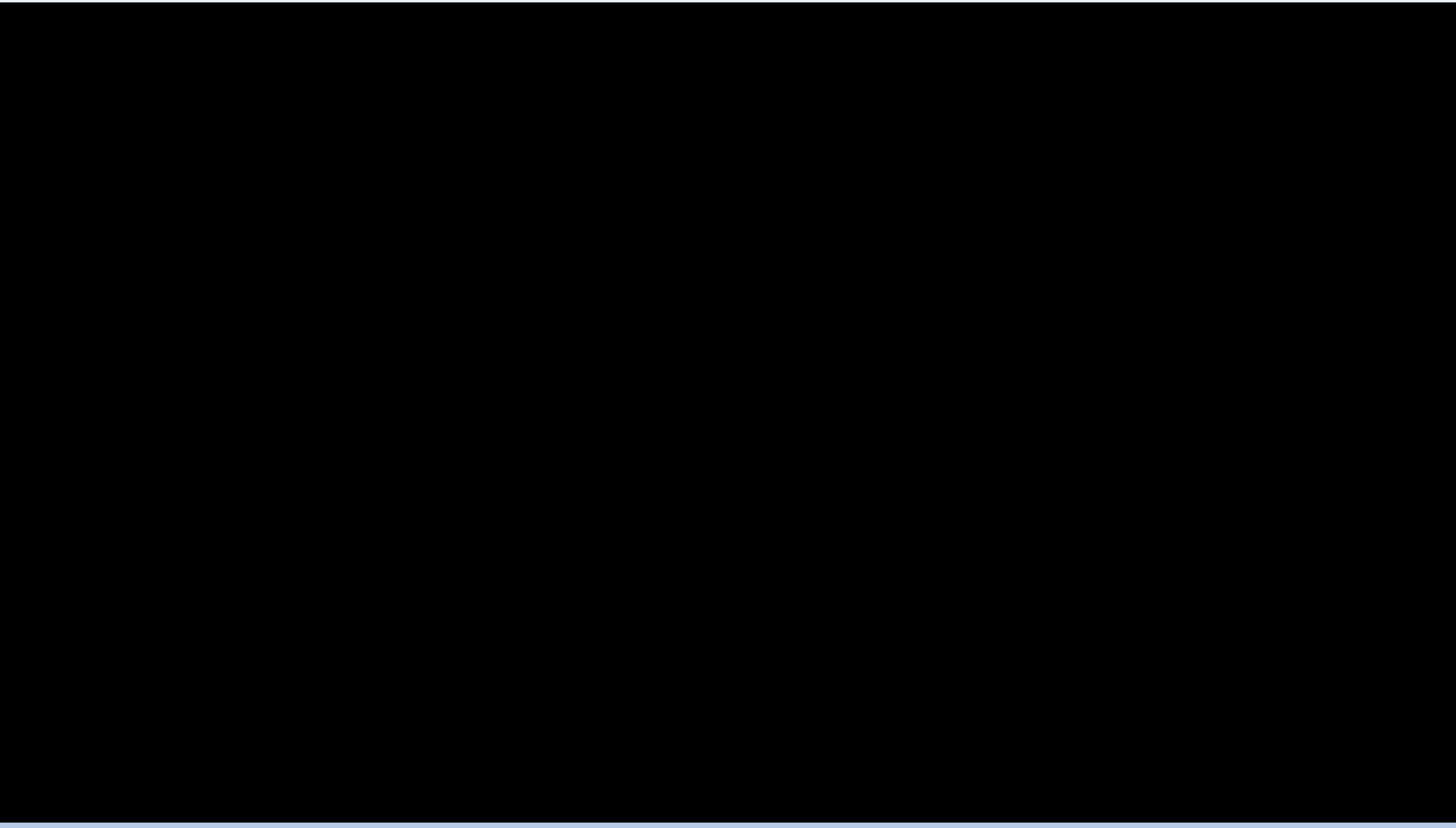
TECT_Mod3D: A TEctonic Construction Tool for Modern 3D Systems

Collaborators:
Oliver Kreylos
Magali Billen
Donald Turcotte
Matt Knepley

Jadamec and Billen, Nature 2010
Jadamec and Billen, JGR 2012
Jadamec et al., XSEDE 2012
Jadamec et al., EPSL 2013
Jadamec, AGU Monograph 2016
Jadamec, J. of Geodynamics 2016
Haynie and Jadamec, Tectonics 2017
Haynie and Jadamec, Science Advances, Sub. 2019

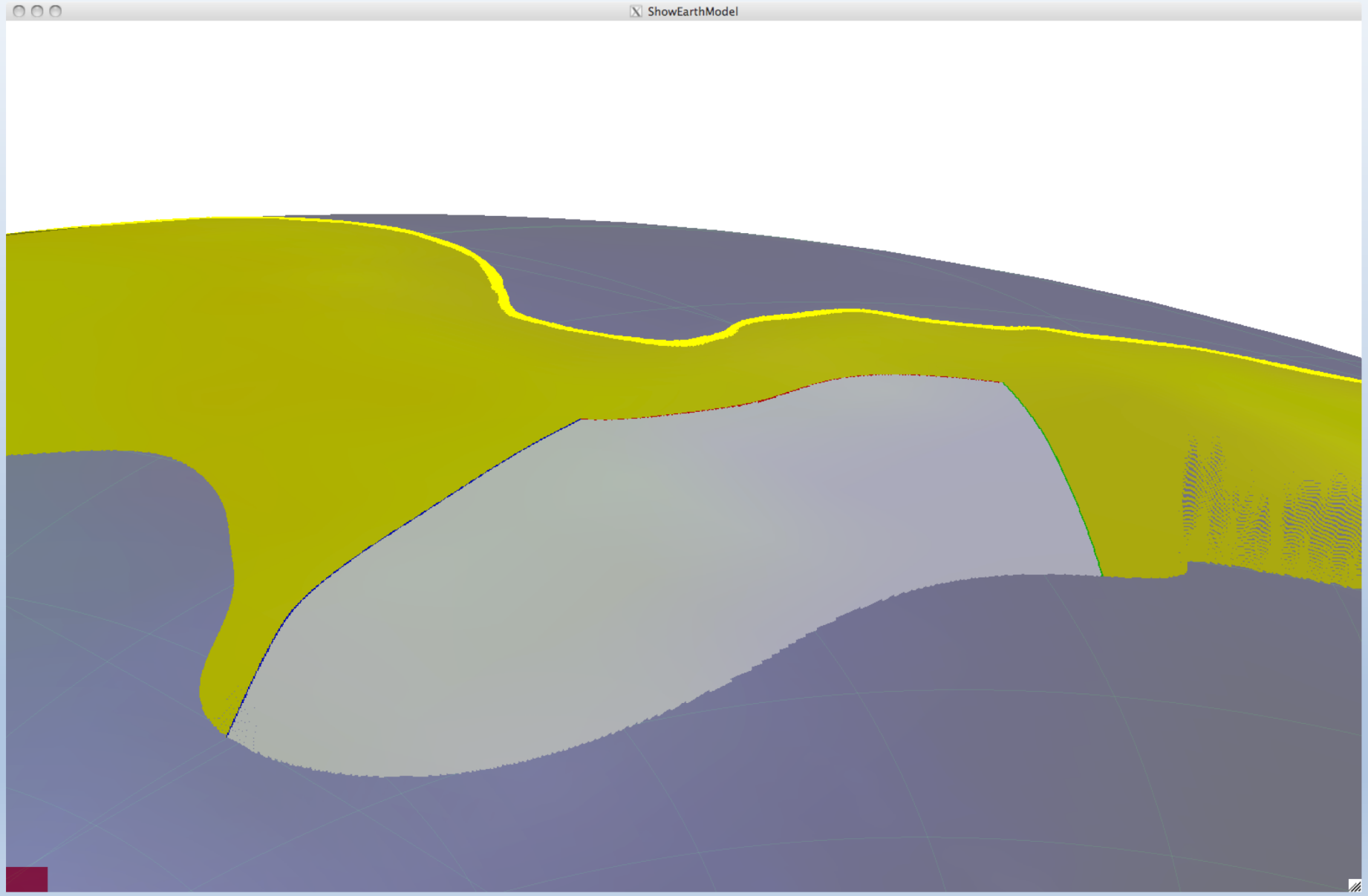


Movie #6: Cocos, Northern Nazca, Antilles Comparisons

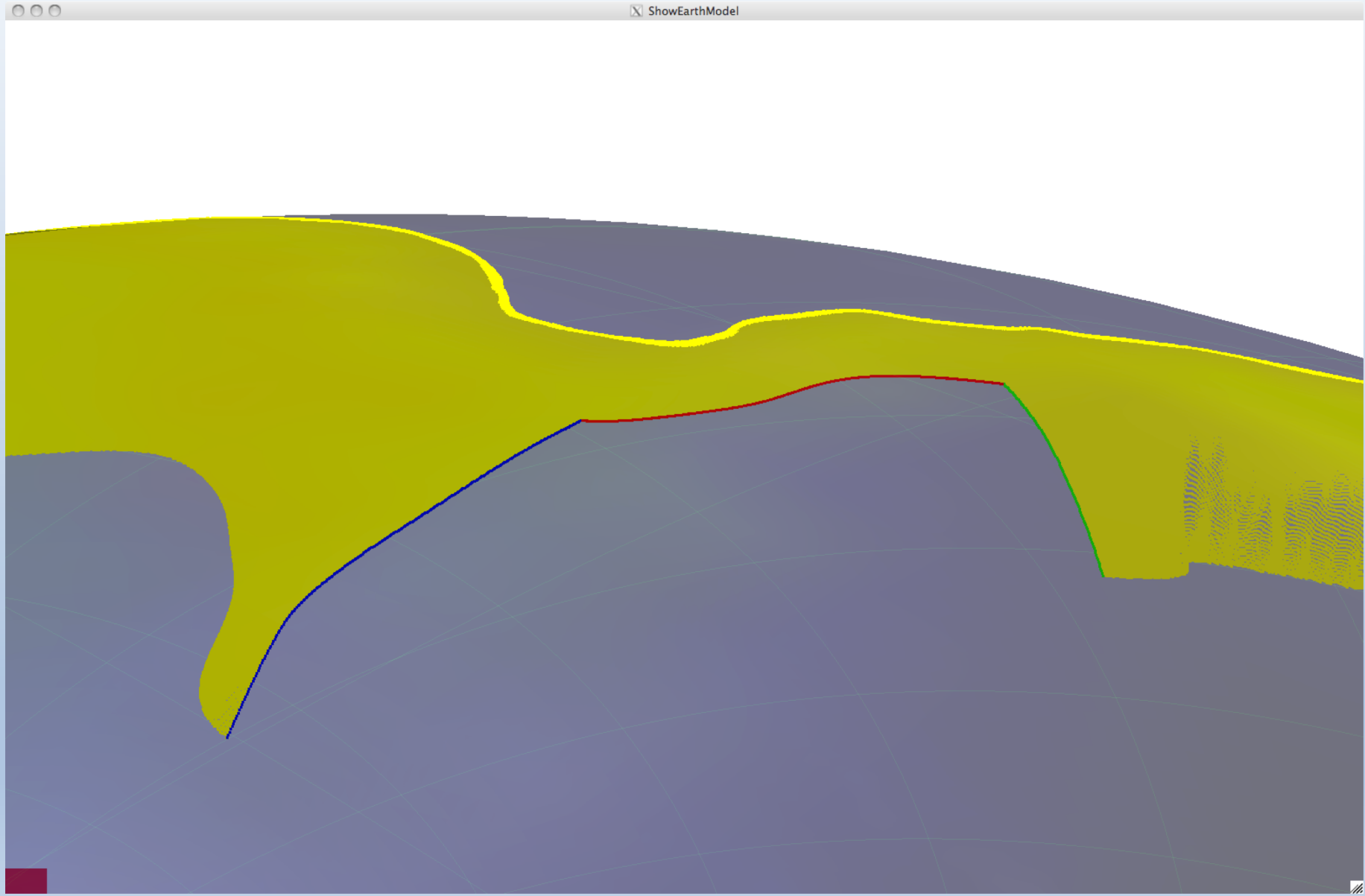


Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

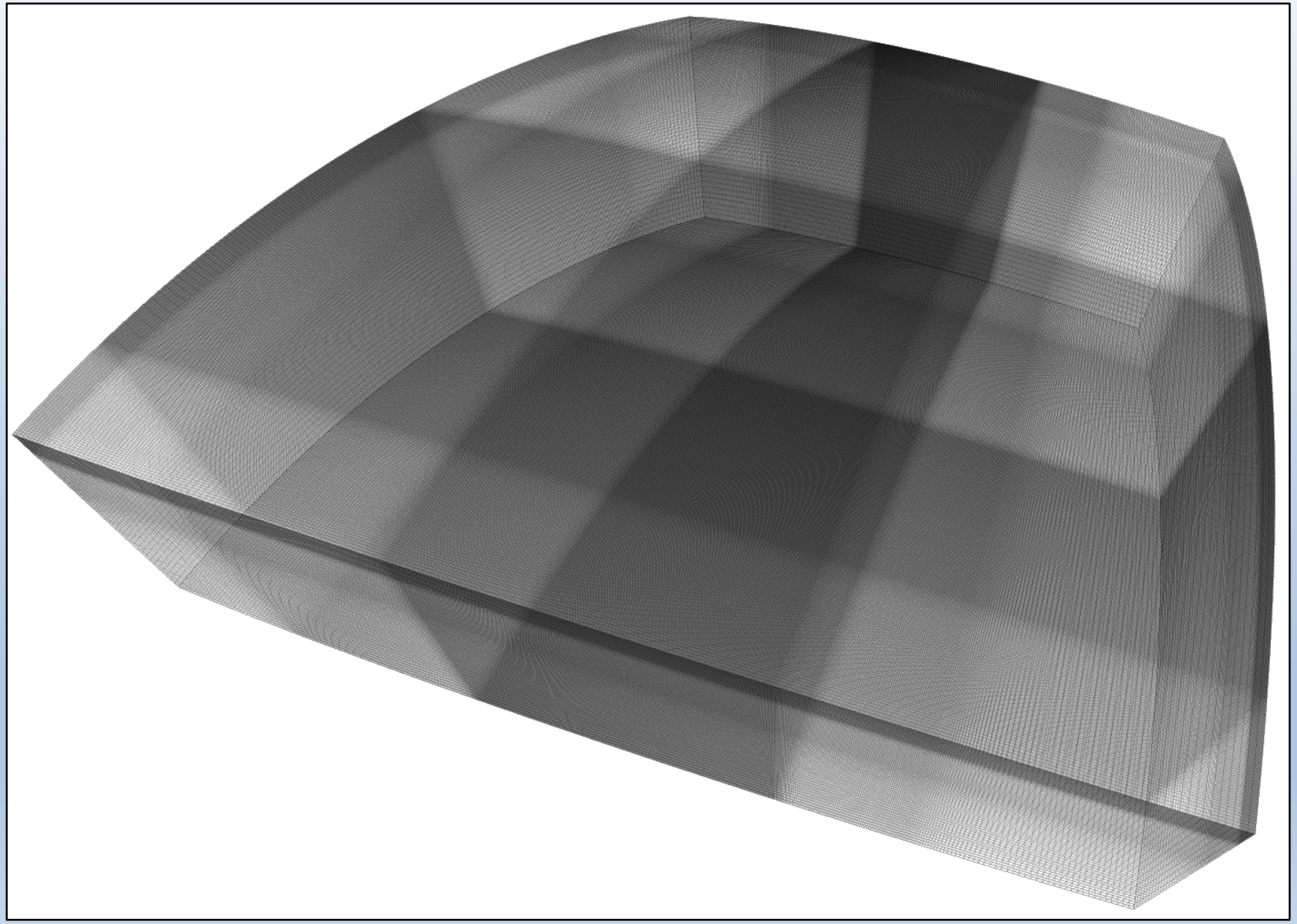
Model Design: Pre-processing Slab Geometry Construction



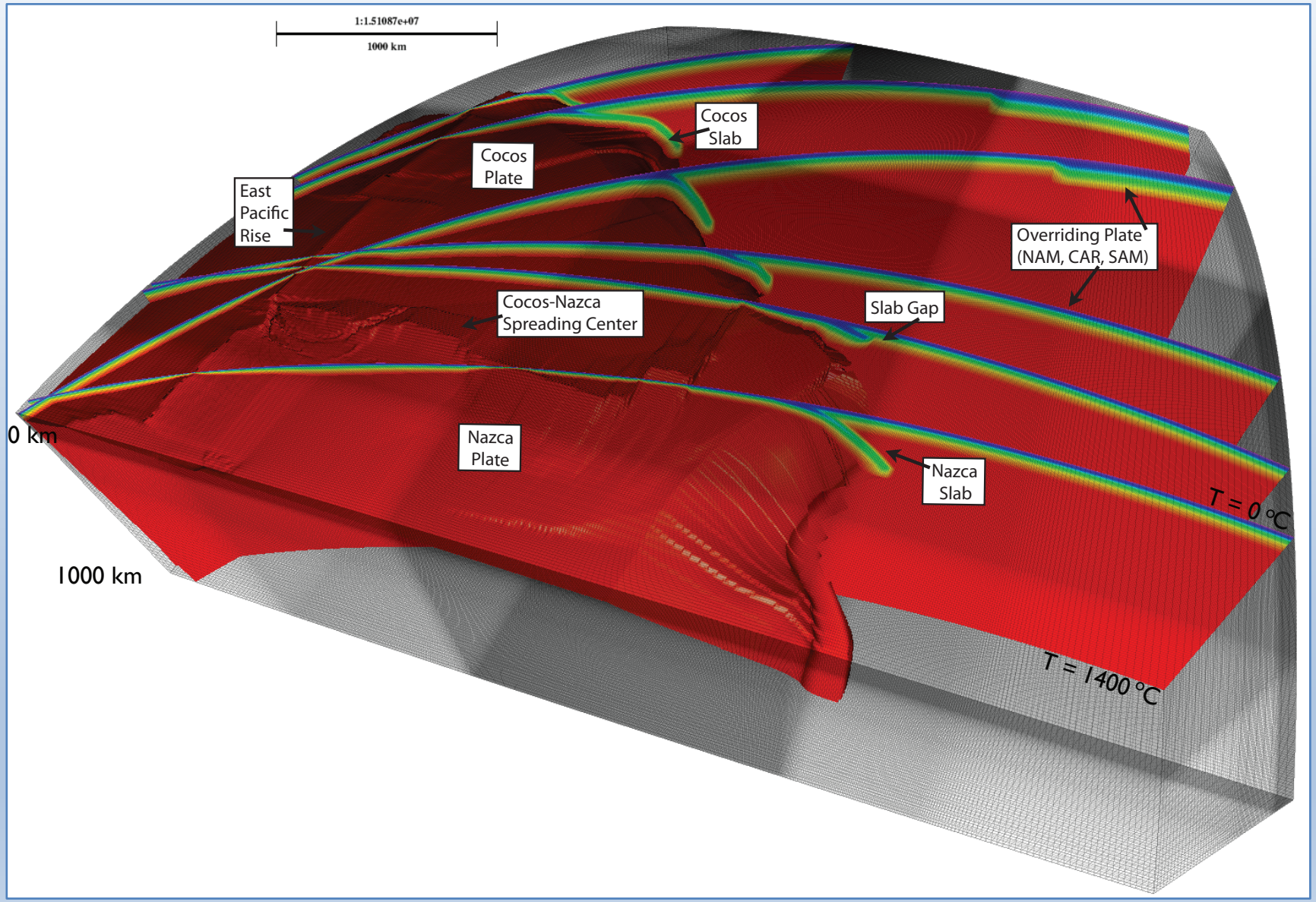
Model Design: Pre-processing Slab Geometry Construction



Model Design with **TECT_Mod3D**: Mesh Construction

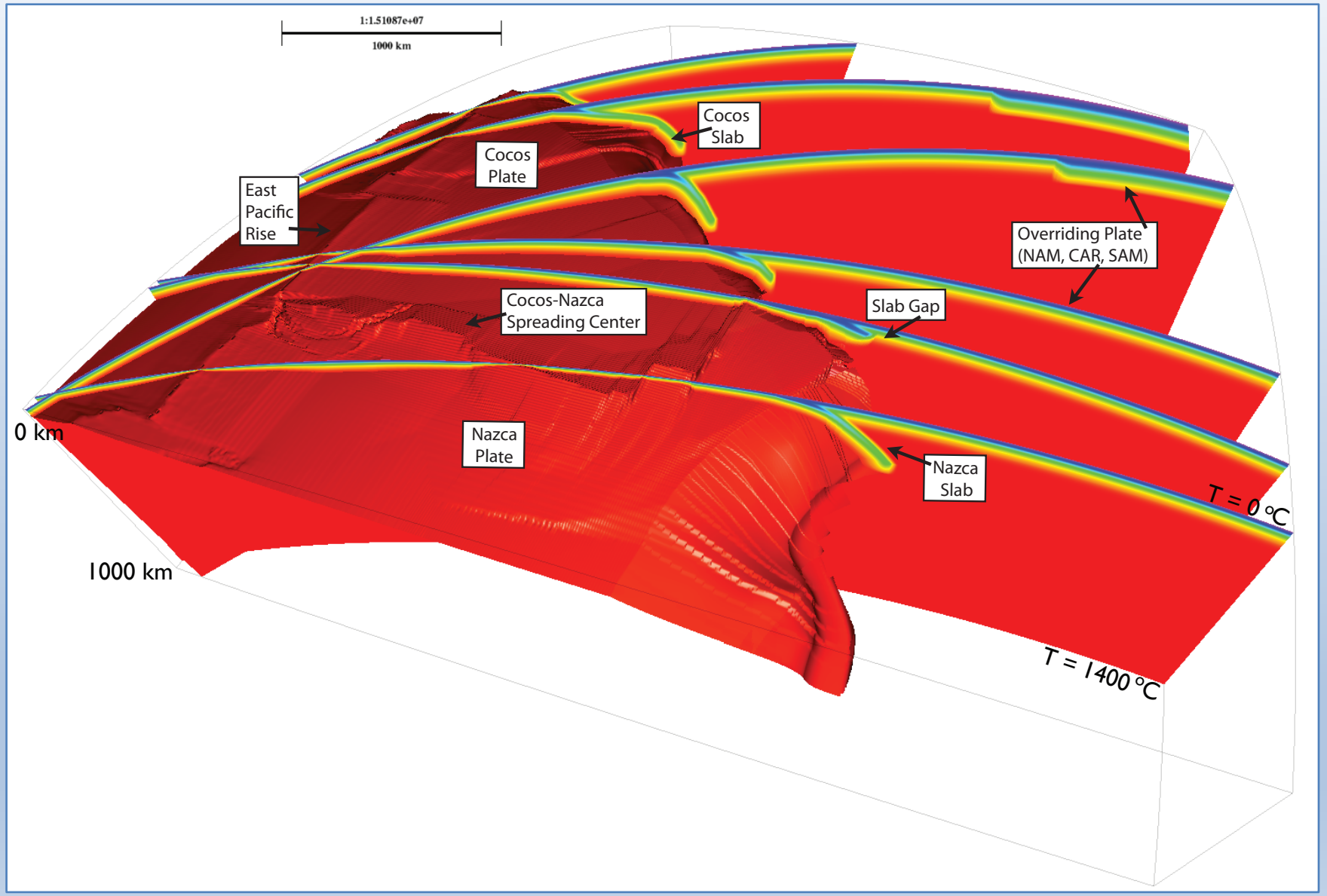


TECT_Mod3D: Mapping Thermal Structure onto Mesh



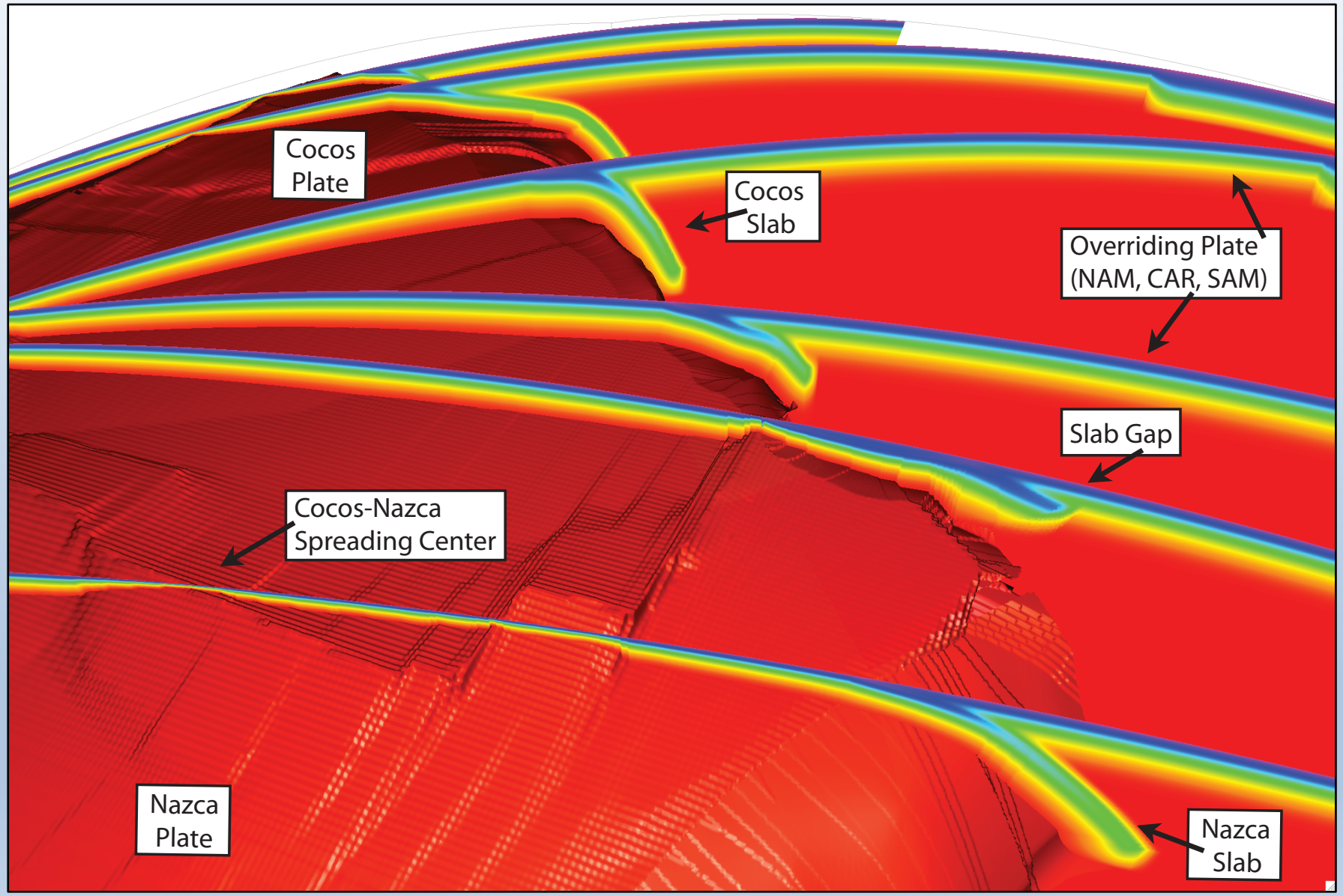
Visualization Software used: 3DVisualizer by Oliver Kreylos (Kreylos et al., VRCIA 2006)

Model Design with **TECT_Mod3D**: 3D Thermal Structure



Visualization Software used: 3DVisualizer by Oliver Kreylos (Kreylos et al., VRCIA 2006)

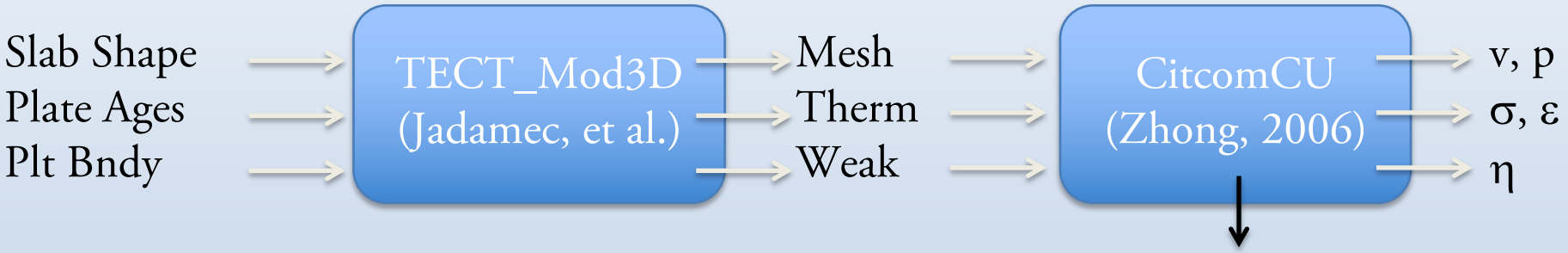
Model Design with **TECT_Mod3D**: 3D Thermal Structure



Visualization Software used: 3DVisualizer by Oliver Kreylos (Kreylos et al., VRCIA 2006)

Simulations: Solve Stokes Equations for Incompressible Flow

Data Assimilation (Obs., Big Data) | 3D Model Design | High Performance Computing



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

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

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

Model Problem Sizes

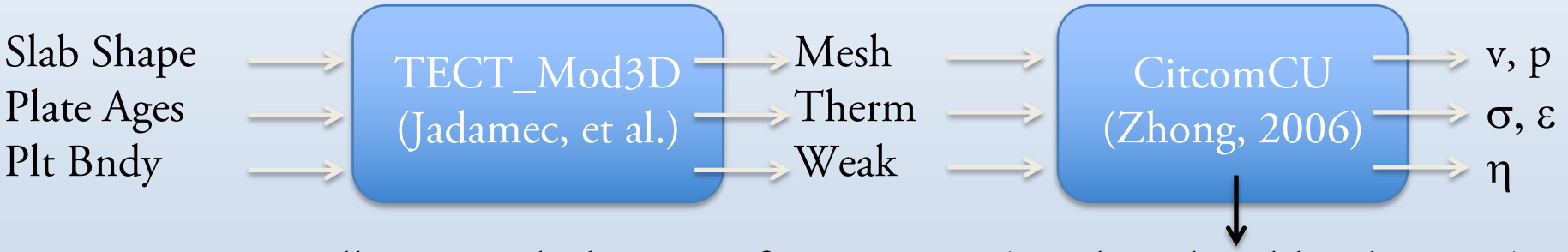
55° x 27° x 1500 km (AK)
960 x 648 x 160 elements (AK)
896 x 864 x 112 (CocNaz)
~2.5 to 25 km resolution

Typical Computing Specifications

360-720 Cores on Lonestar, TACC, Geodynamics Cluster, Univ. Houston Geosolver, CCR, UB
~10,000 – 20,000 Compute hours/job

Simulations: Solve Stokes Equations with Non-linear Viscosity

Data Assimilation (Obs., Big Data) | 3D Model Design | High Performance Computing



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

Composite Rheology

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

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

where the flow law for wet olivine* is

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

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)

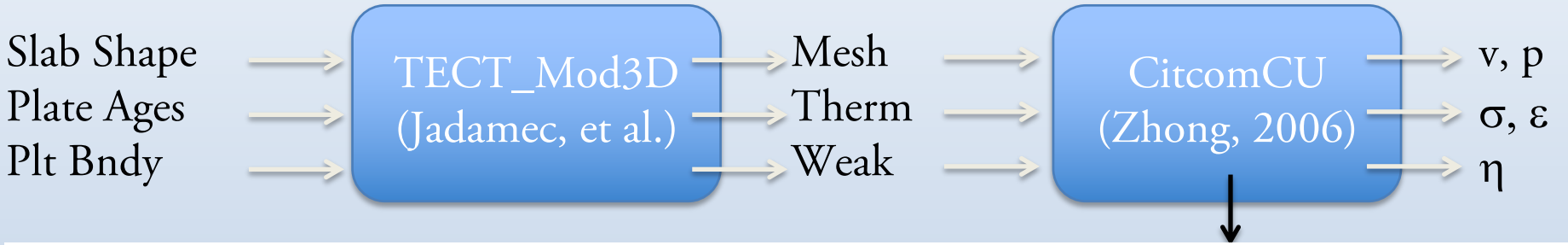
and a depth-dependent yield stress is applied such that if

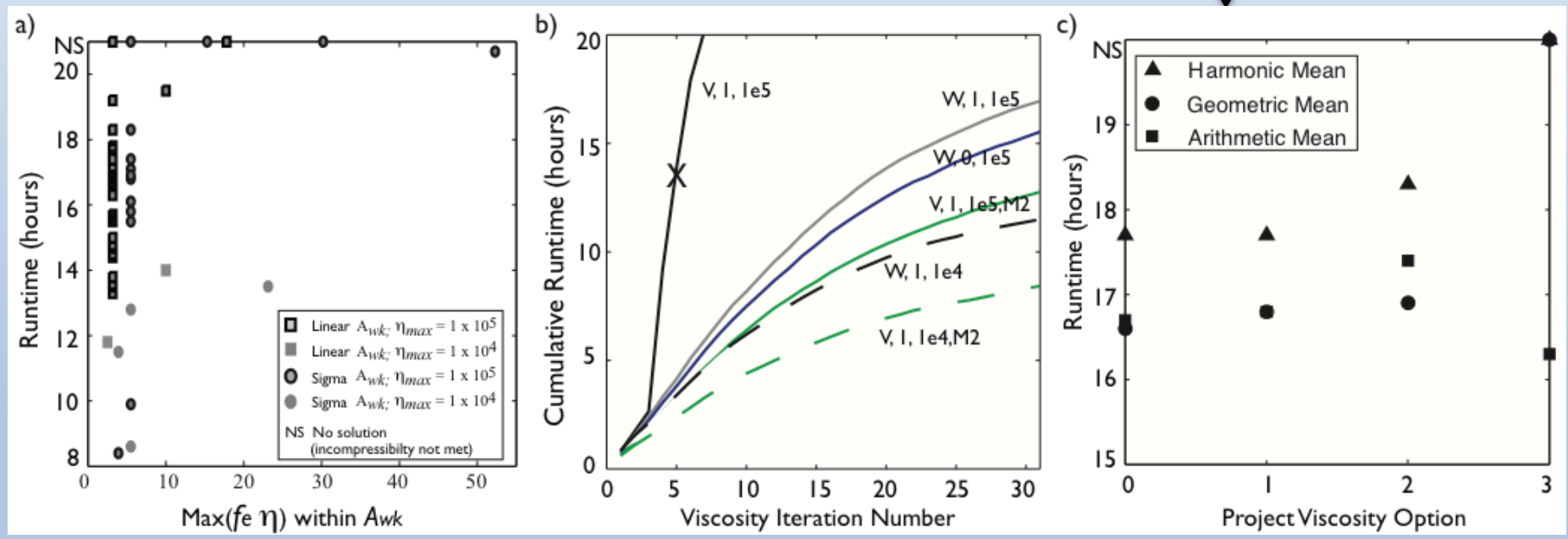
$$\sigma > \sigma_y, \eta_{eff} = \frac{\sigma_y}{\dot{\varepsilon}_{II}}, \text{ and if } \sigma < \sigma_y, \eta_{eff} = \eta_{com}$$

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

Simulations: Solve Stokes Equations with Non-linear Viscosity

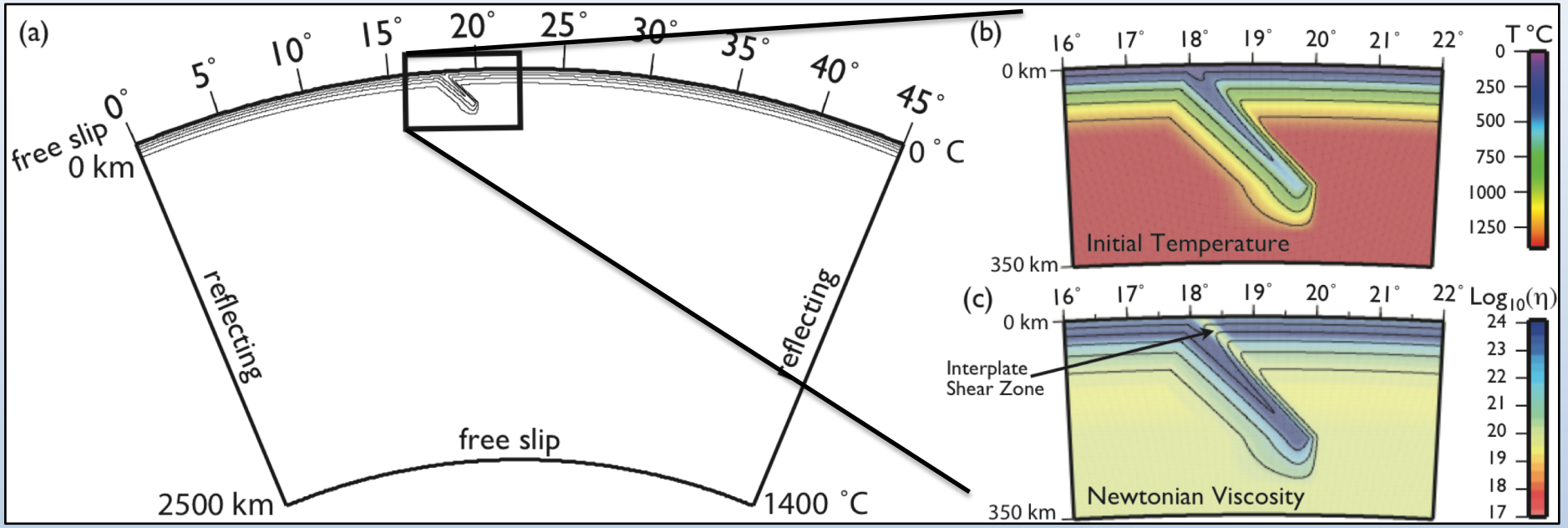
Data Assimilation (Obs., Big Data) | 3D Model Design | High Performance Computing





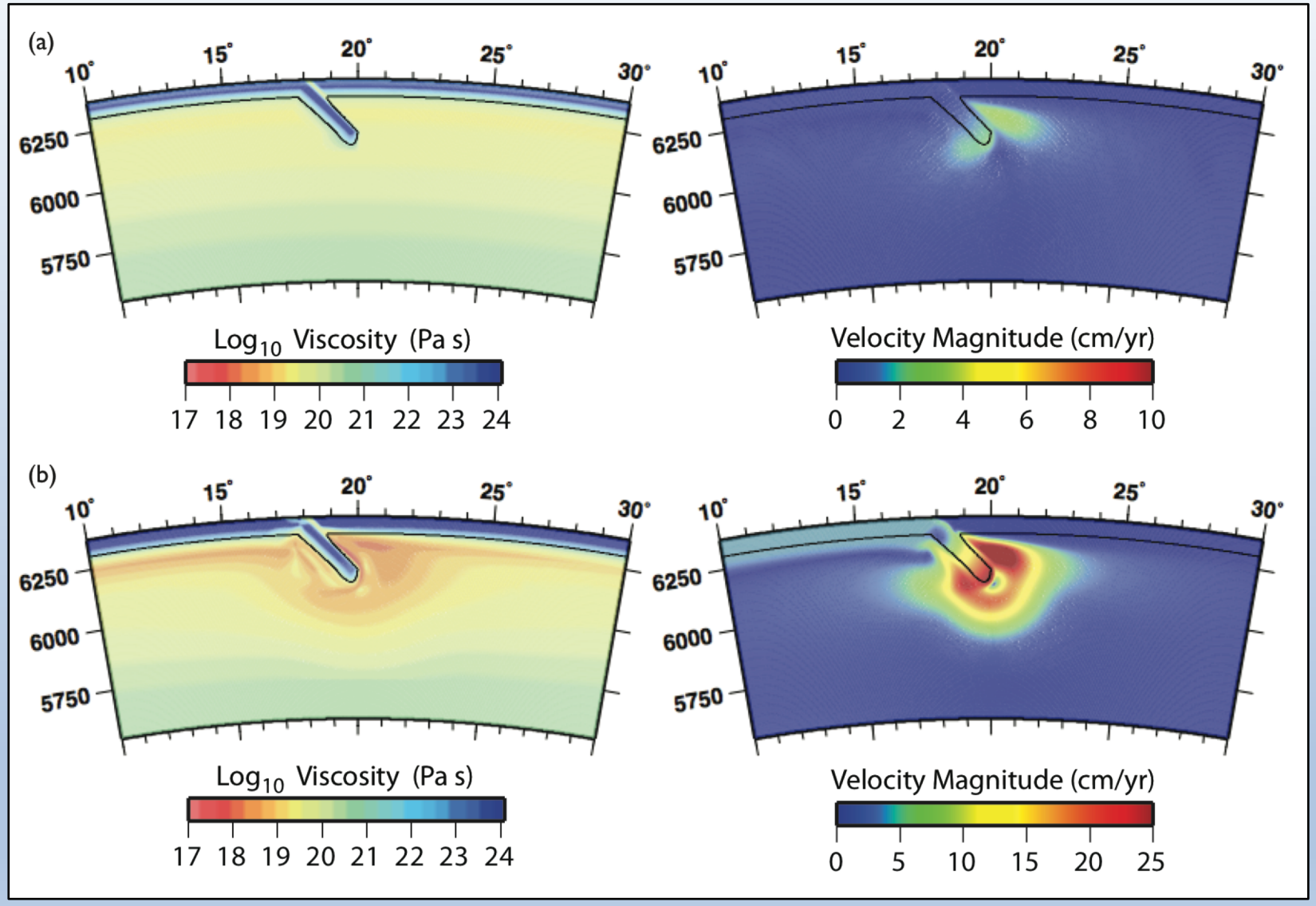
Jadamec, M. A., Billen, M. I., and Kreylos, O., 2012, Three-dimensional simulations of geometrically complex subduction with large viscosity variations. 8 pp. In: *ACM Proceedings of the 2012 Conference on eXtreme Science and Engineering Discovery Environment.*

2D Model Set-up: Buoyancy driven flow at Subduction Zones



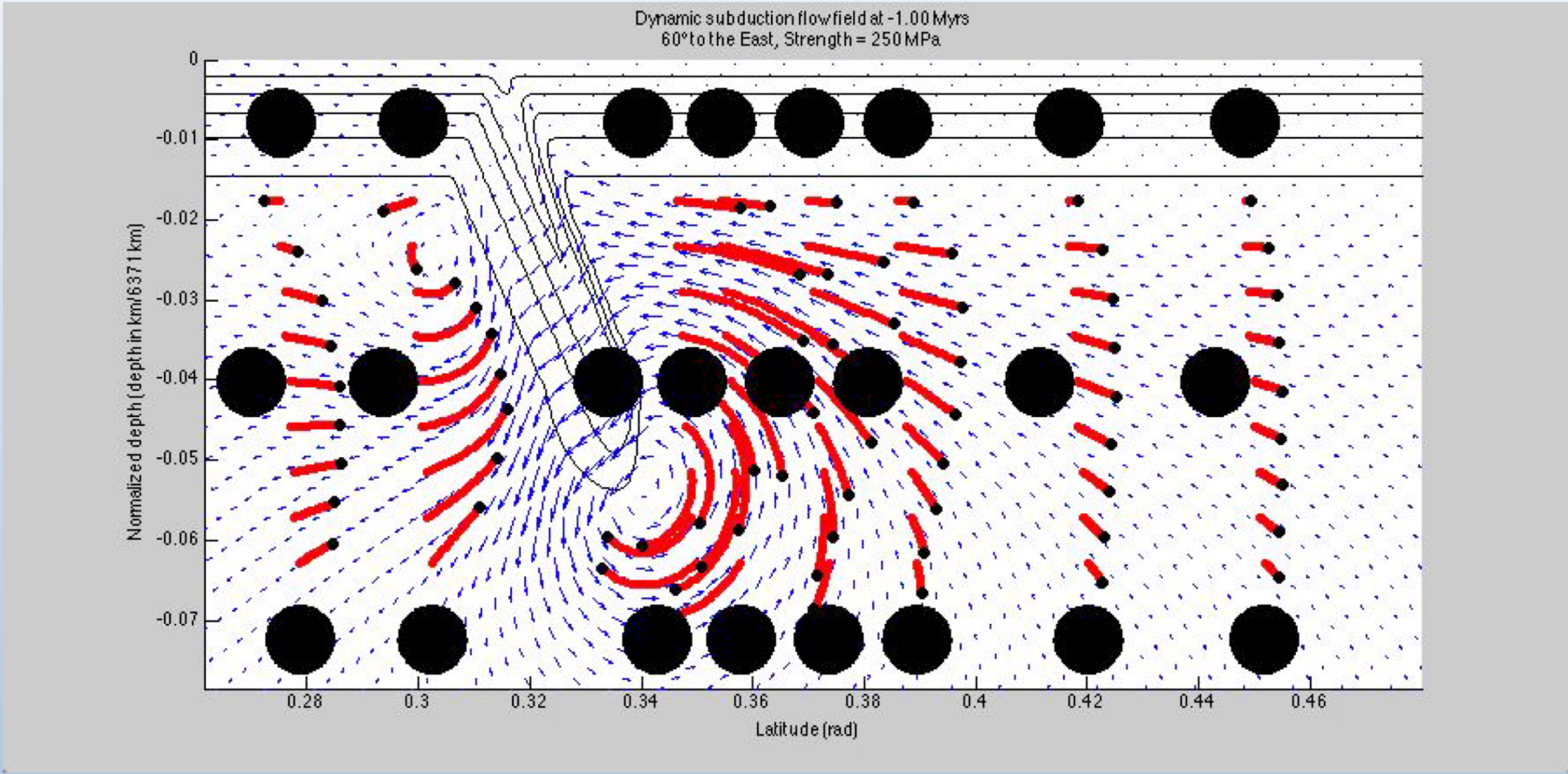
Jadamec, M. A. (2016) Slab driven mantle weakening and rapid mantle flow, p. 135-155.. *In:* G. Morra, D. A. Yuen, S-M. Lee, S. Stein (Eds.), *Subduction Dynamics: From Mantle Flow to Mega Disasters*. Geophysical Monograph Series, vol 211. John Wiley & Sons.

Results: Dynamic Mantle Weakening (~3 orders magnitude)



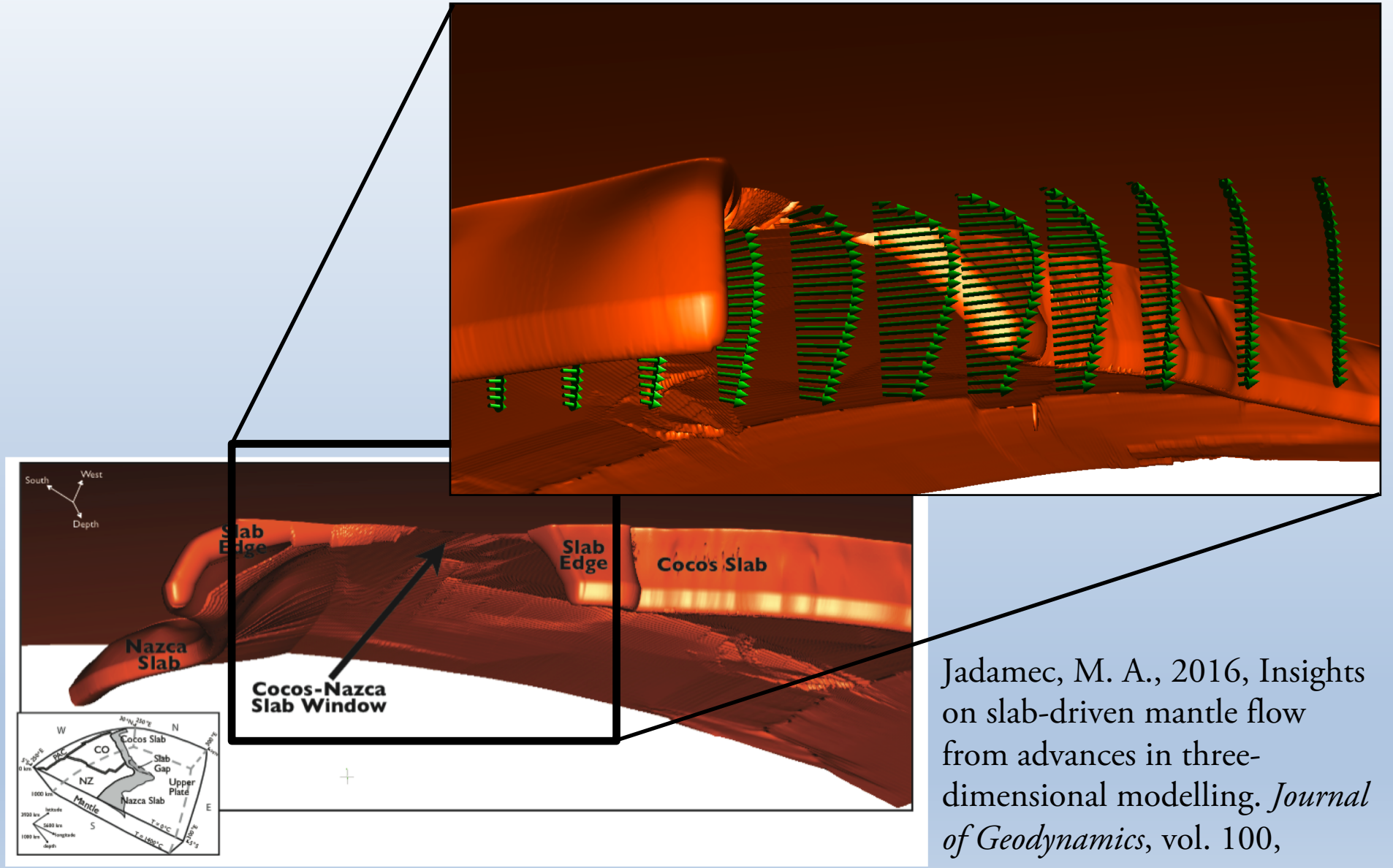
Jadamec, M. A. (2016) Slab driven mantle weakening and rapid mantle flow, p. 135-155.. *In:* G. Morra, D. A. Yuen, S-M. Lee, S. Stein (Eds.), *Subduction Dynamics: From Mantle Flow to Mega Disasters*. Geophysical Monograph Series, vol 211. John Wiley & Sons.

Results: Slab-driven Asthenospheric Flow Generates Fabric



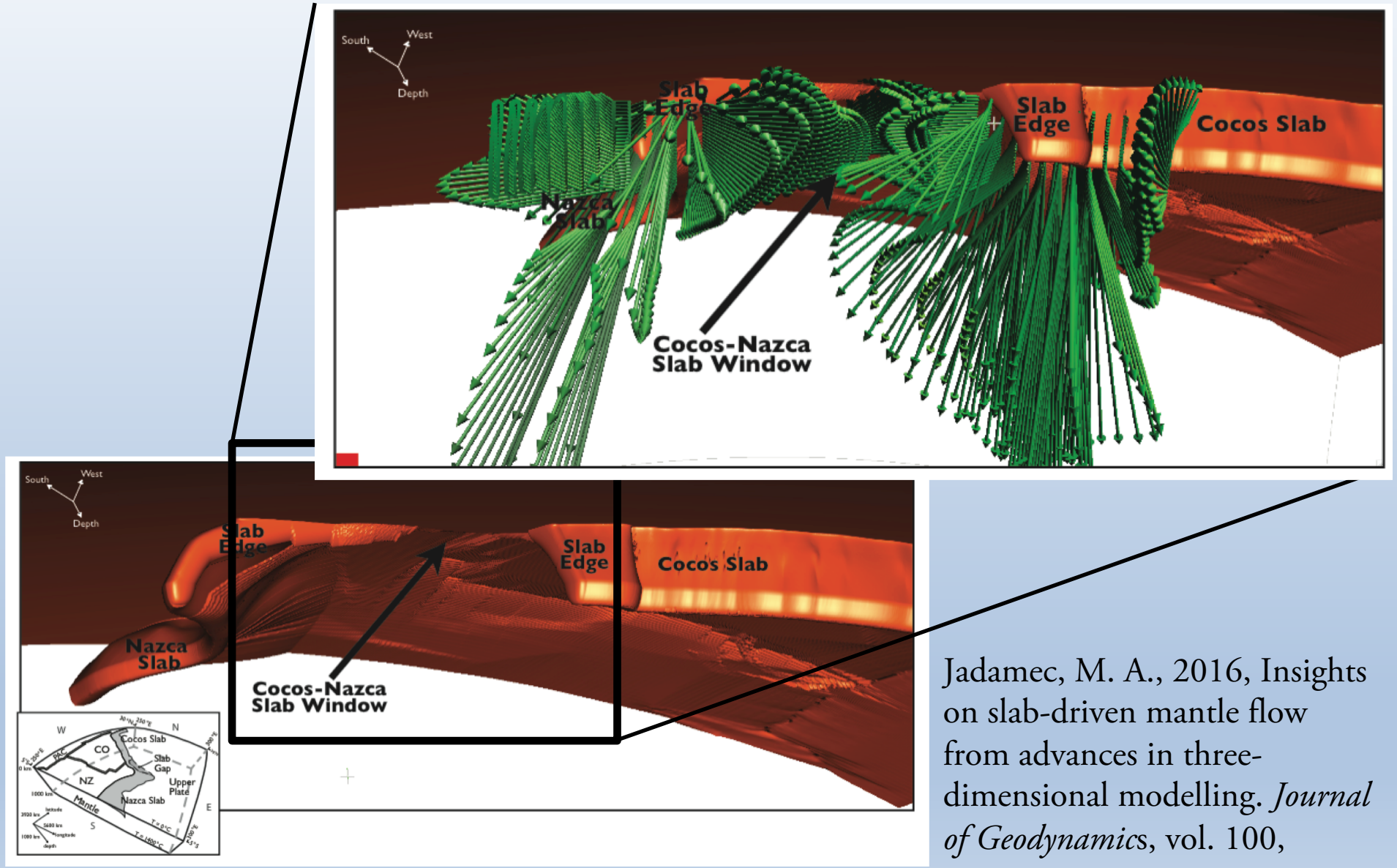
MacDougall, J., Jadamec, M. A., and Fischer K. M. (2017) The zone of influence of the subducting slab in the asthenospheric mantle . *Journal of Geophysical Research,* vol. 122, 26 pp.

Results: Dynamically Driven Flow Through Slab Discontinuity



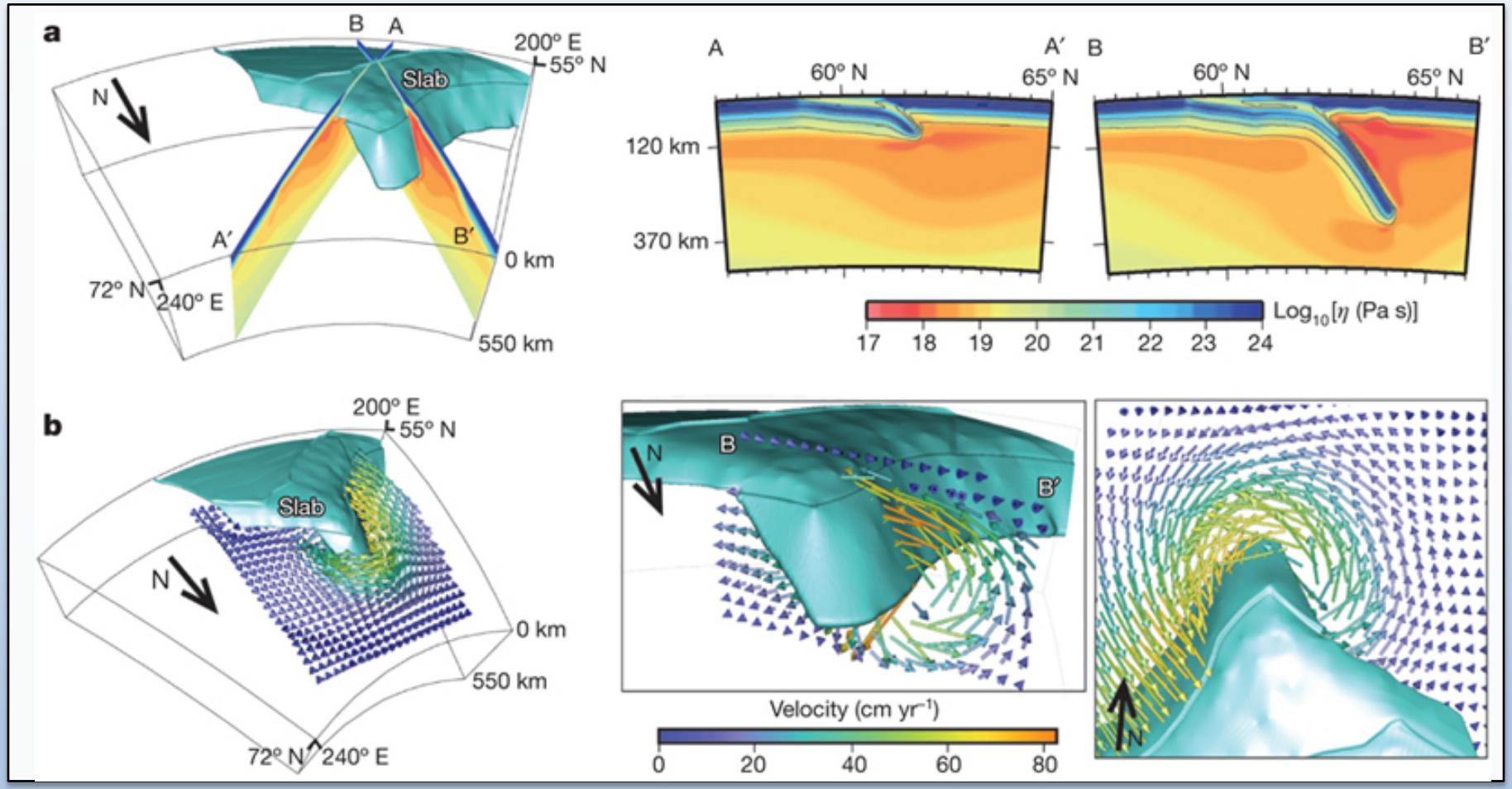
Jadamec, M. A., 2016, Insights on slab-driven mantle flow from advances in three-dimensional modelling. *Journal of Geodynamics*, vol. 100, p. 51-70.

Results: Toroidal Flow Around Each Slab Edge, with upwelling



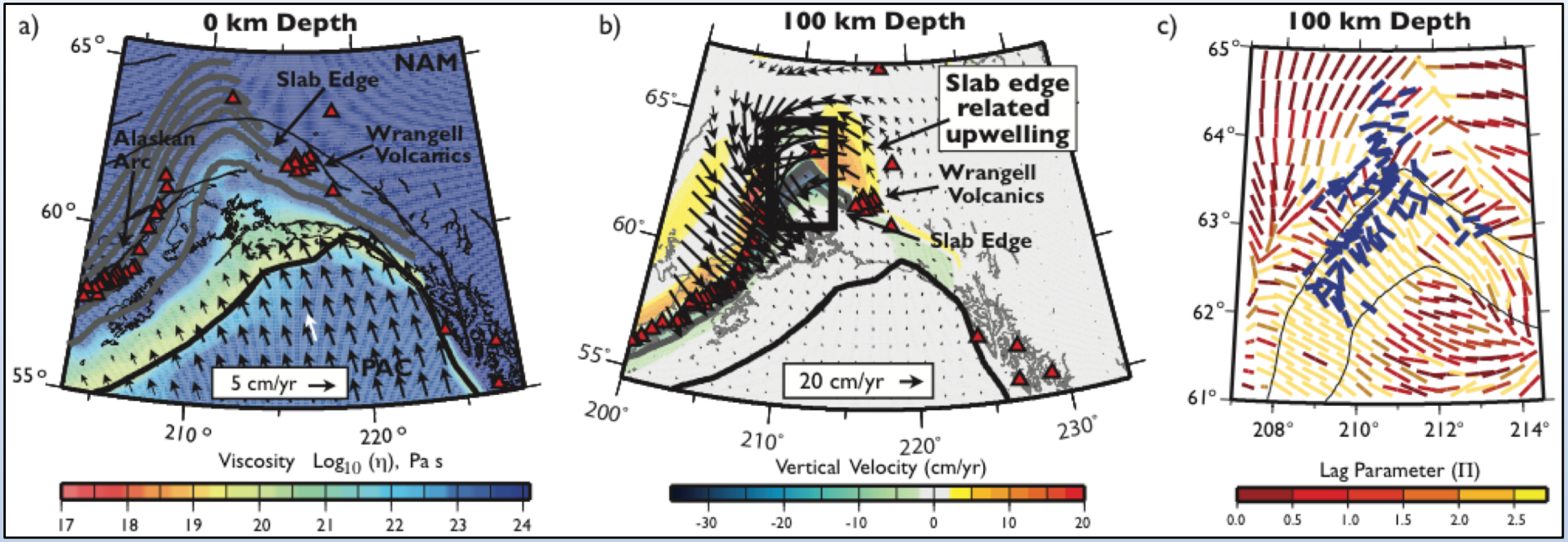
Jadamec, M. A., 2016, Insights on slab-driven mantle flow from advances in three-dimensional modelling. *Journal of Geodynamics*, vol. 100, p. 51-70.

Results: Dynamic Weakening and Toroidal Flow for Alaska



Jadamec, M. A. and Billen, M. I. (2010) Reconciling surface plate motions with rapid three-dimensional flow around a slab edge. *Nature*, vol. 465, p. 338-341.

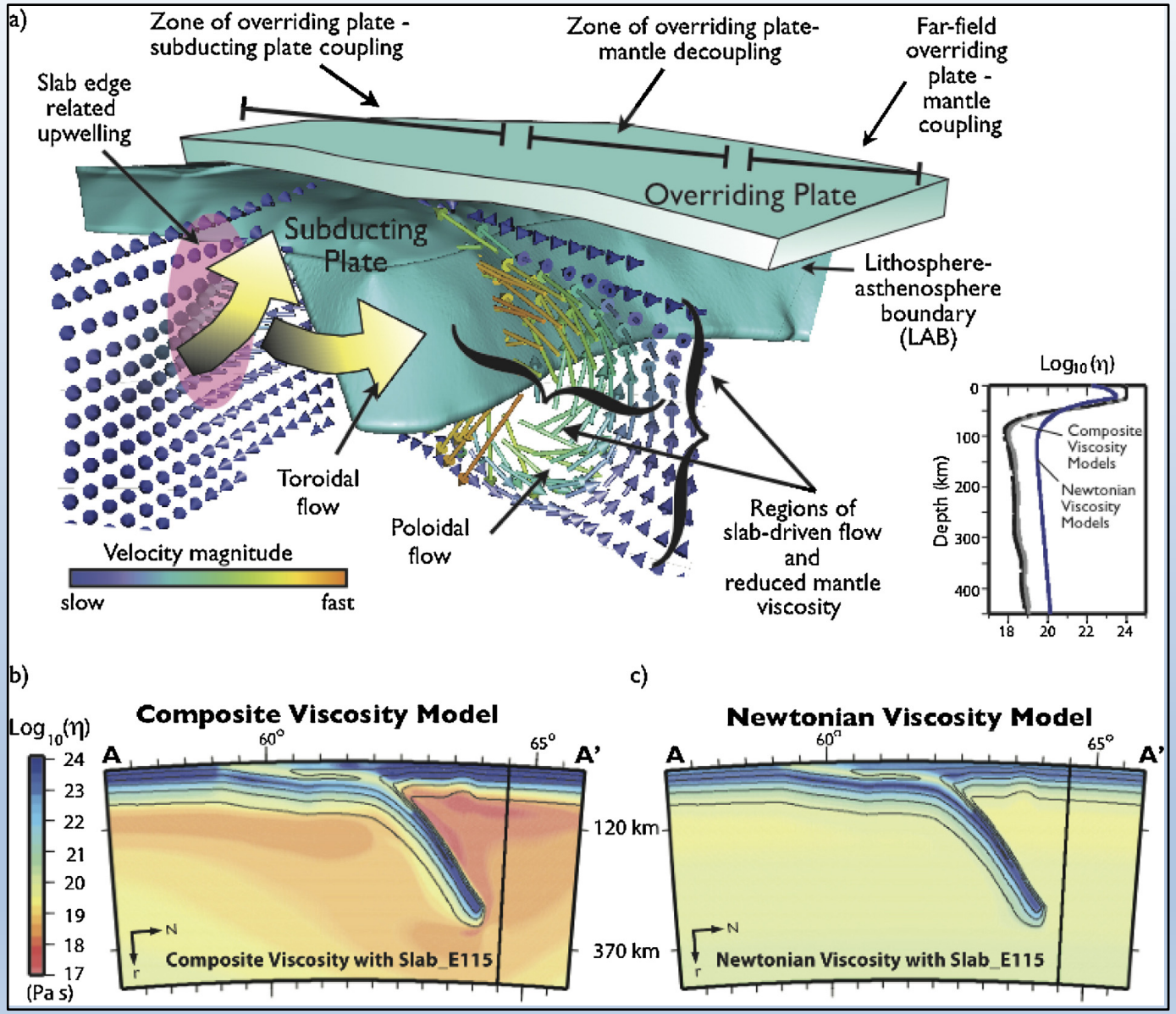
Results: Toroidal flow and Slab-driven Mantle Upwelling



Jadamec, M. A. and Billen, M. I. (2010) Reconciling surface plate motions with rapid three-dimensional flow around a slab edge. *Nature*, vol. 465, p. 338-341.

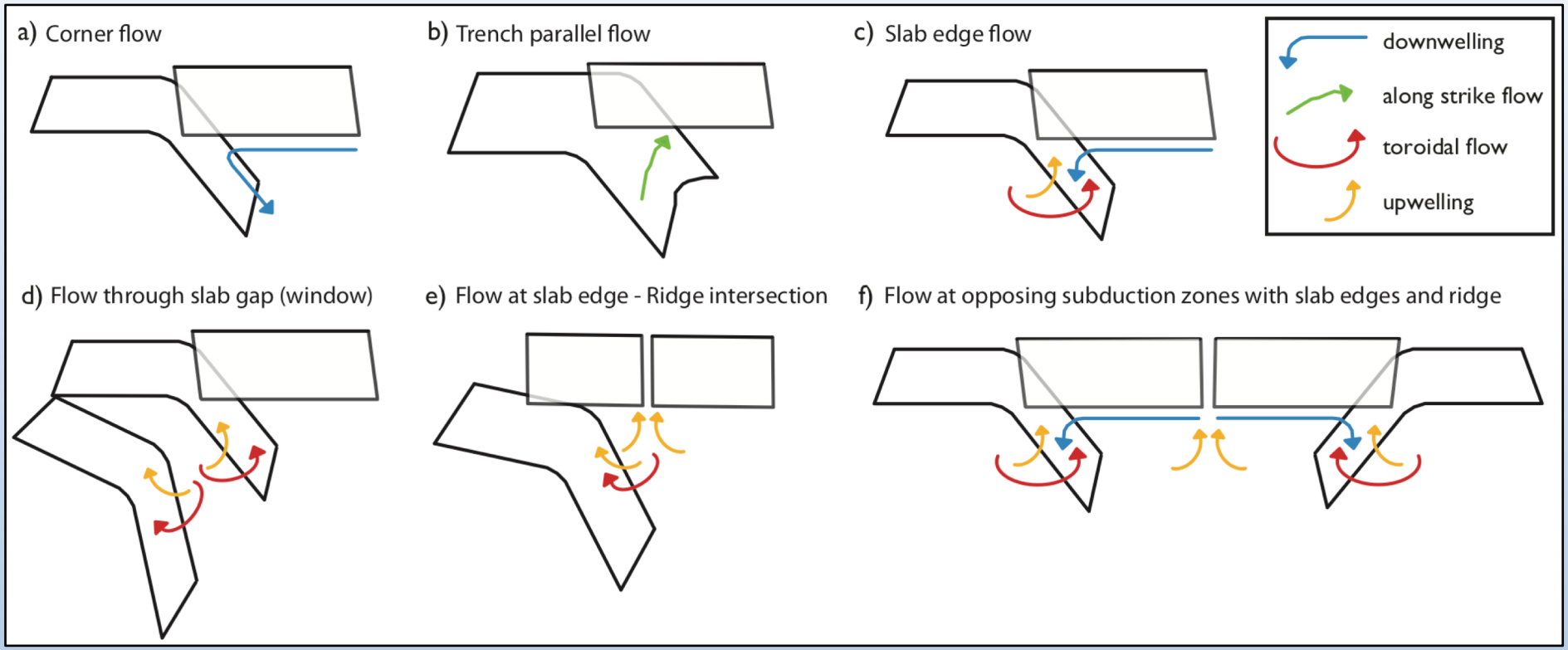
Jadamec, M. A. and Billen, M. I. (2012) The role of rheology and slab shape on rapid mantle flow: Three-dimensional numerical models of the Alaska slab edge. *Journal of Geophysical Research*, vol. 117, B02304, 20 pp.

Conceptual Model: 3D Framework, Locally Decoupled Zone



Jadamec, M. A. (2016) Insights on slab-driven mantle flow from advances in three-dimensional modelling. *Journal of Geodynamics*, vol. 100, p. 51-70.

Conceptual Diagrams of Types of Slab-driven Flow

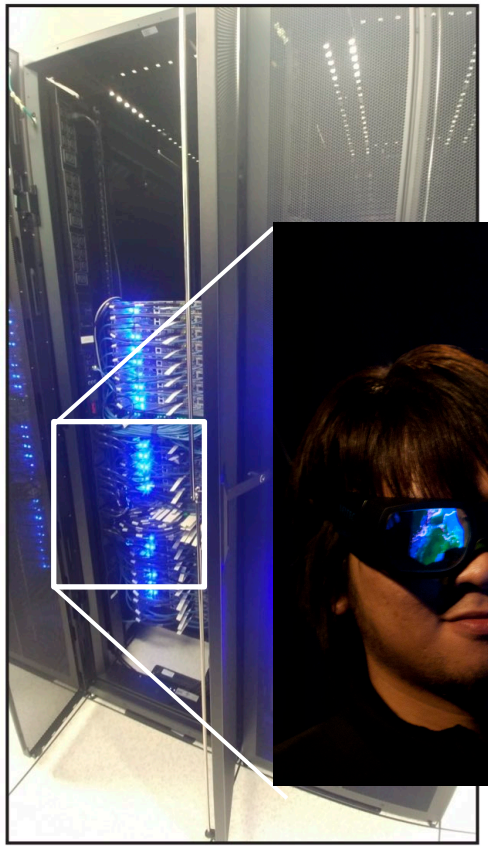


Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

Jadamec, M. A., 2016, Insights on slab-driven mantle flow from advances in three dimensional modelling. *Journal of Geodynamics*, vol. 100, p. 51-70.

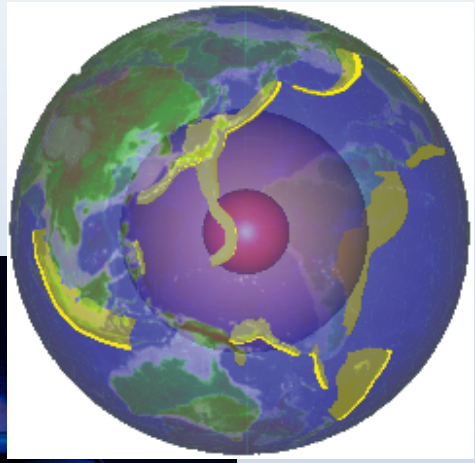
Thank You!





Geosolver - 1200 core Dell Linux cluster
[100 Intel Xeon Gold 6126 Processors, 2.6 GHz, 19.25 MB L3, 12C]
[9.6 TB RAM - 8GB/core; Intel Omni-Path interconnect]

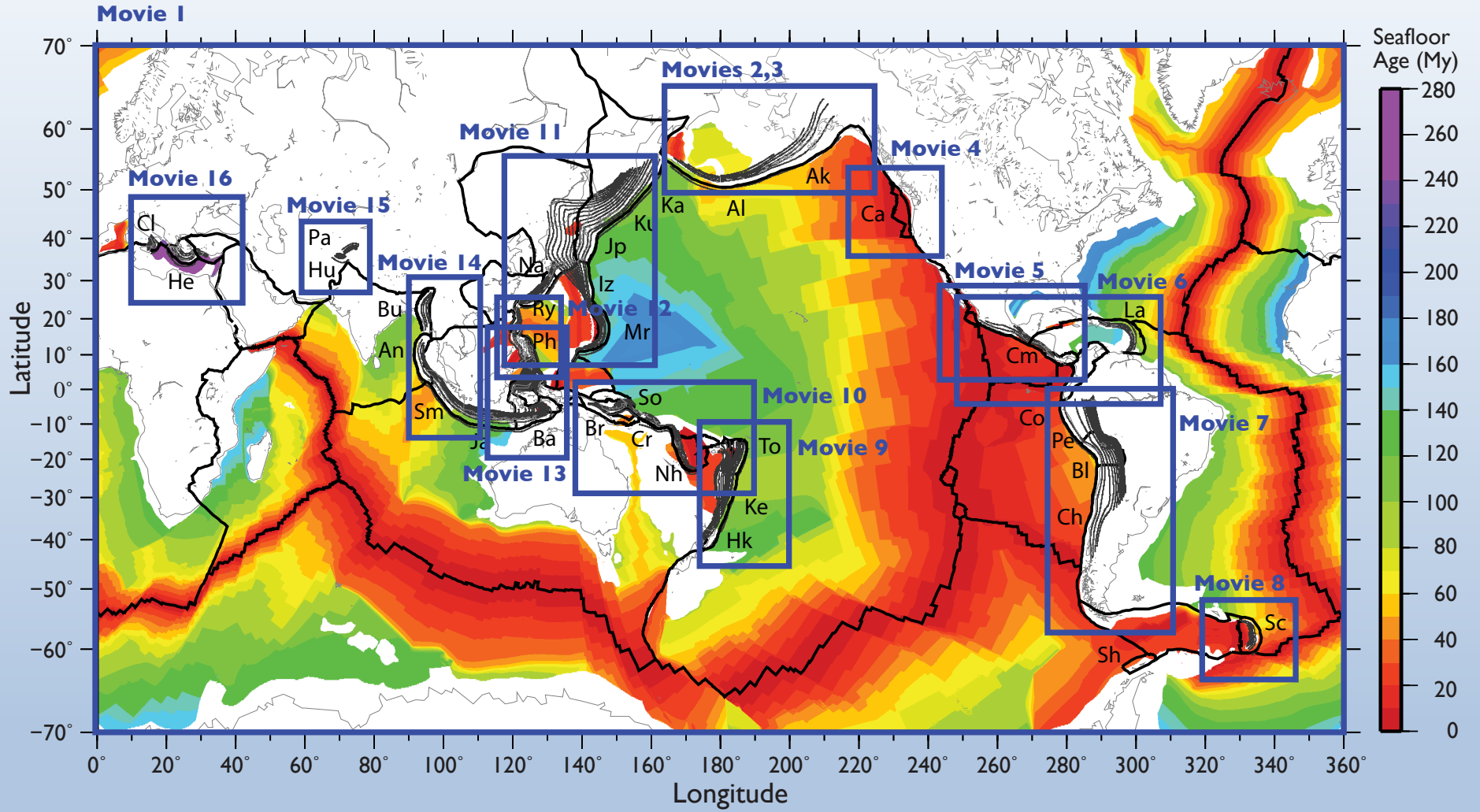




3DALIVE at Monash University, Australia (Photo by Louis Moresi)

Margarete Jadamec
mjadamec@buffalo.edu www.acsu.buffalo.edu/~mjadamec

Case Study of (a) Central America and (b) Alaska Region



- Subduction volcanoes occur at convergent plate boundaries above slab

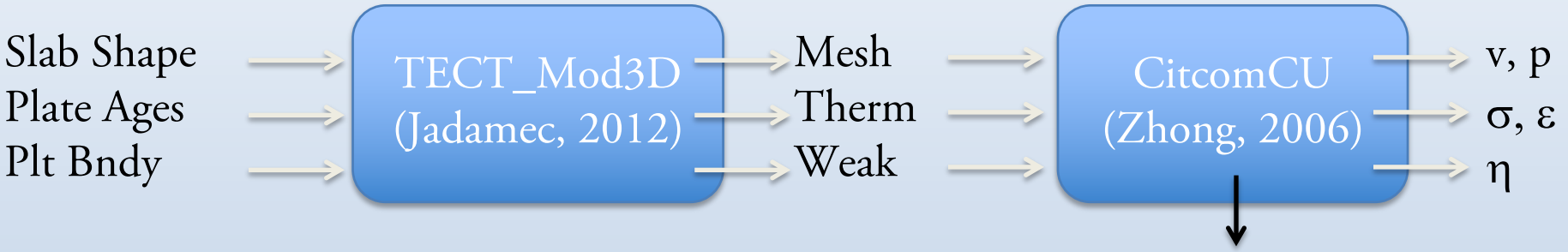
Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

Simulations: Solve Stokes Equations with Non-linear Viscosity

Data Assimilation (Obs., Big Data)

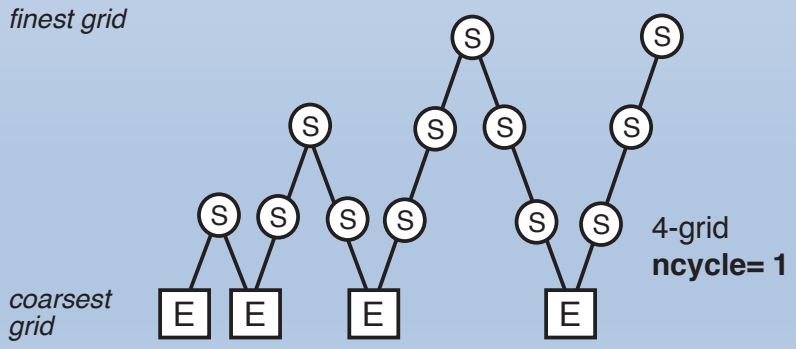
3D Model Design

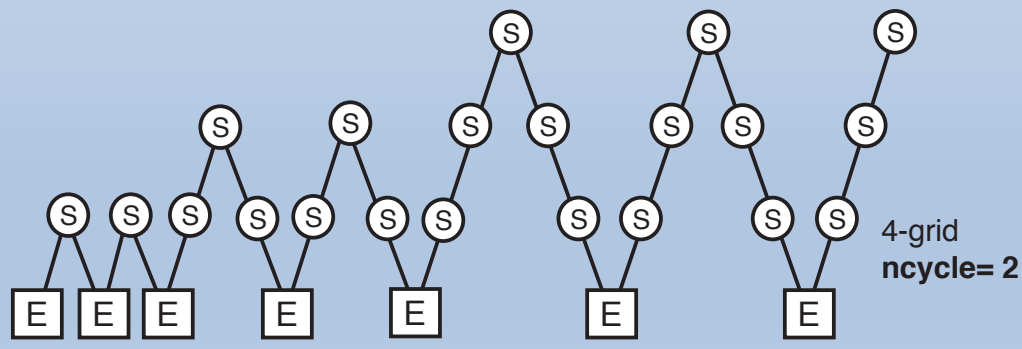
High Performance Computing



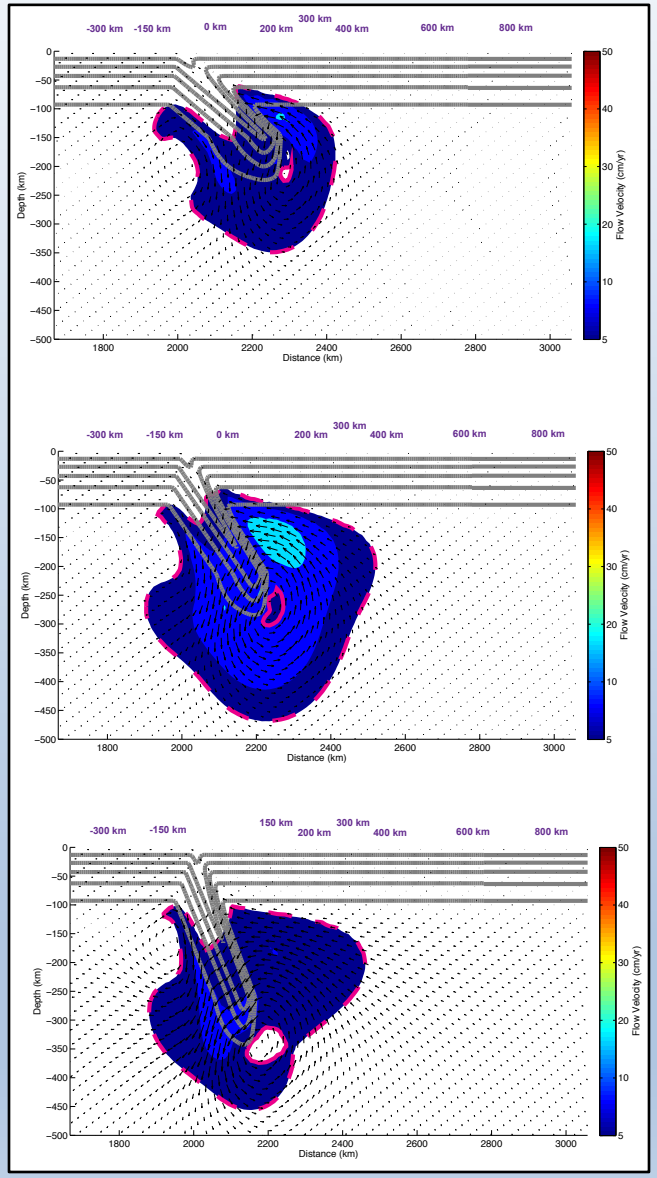
Solves conservation equations (1,2) for viscous flow (Moresi et al. 96; Zhong, 06)

- CitcomCU uses Full Multigrid (FMG) reduce the residual, expedite convergence
- FMG useful for problems with large viscosity variations (~ 7 orders magnitude)





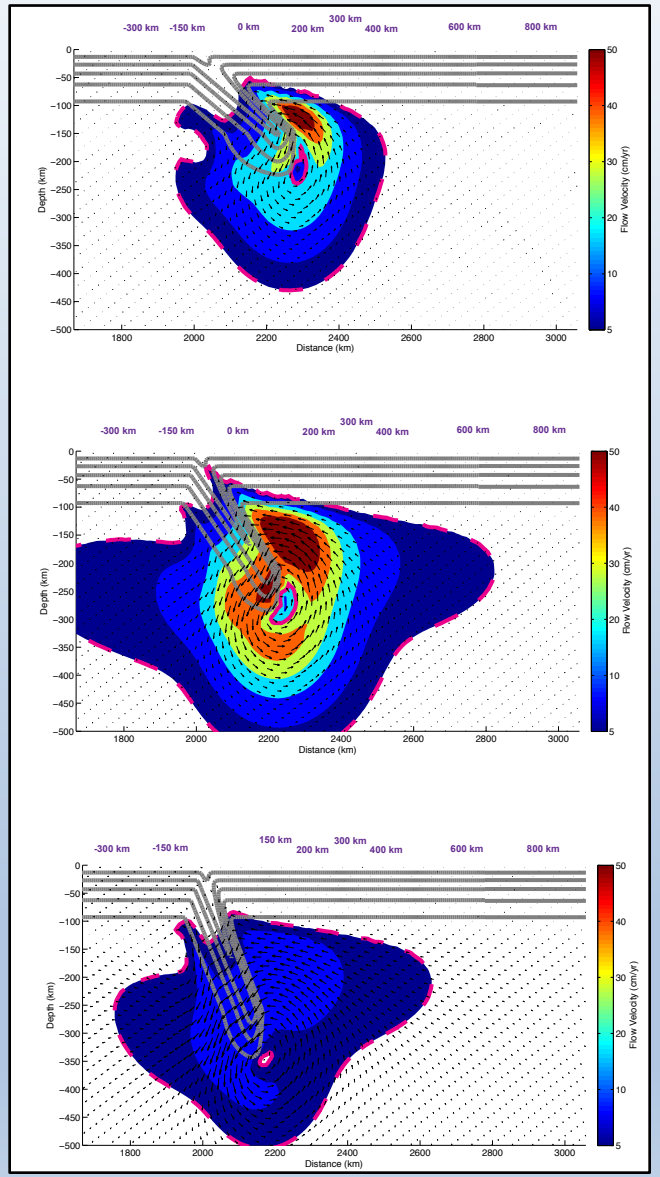
Results: Zone of Influence of the Slab in the Mantle



Dip = 30°
σ_{yMax}=1000 MP

Dip = 45°
σ_{yMax}=1000 MP

Dip = 60°
σ_{yMax}=1000 MP



Dip = 30°
σ_{yMax}=250 MPa

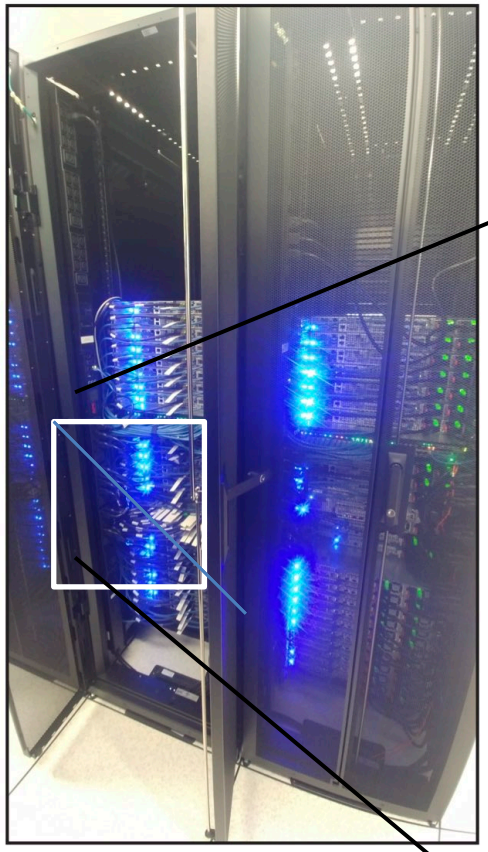
Dip = 45°
σ_{yMax}=250 MPa

Dip = 60°
σ_{yMax}=250 MPa

MacDougall, Jadamec, and Fischer, 2017, JGR

High Performance Computing for Complex Problems



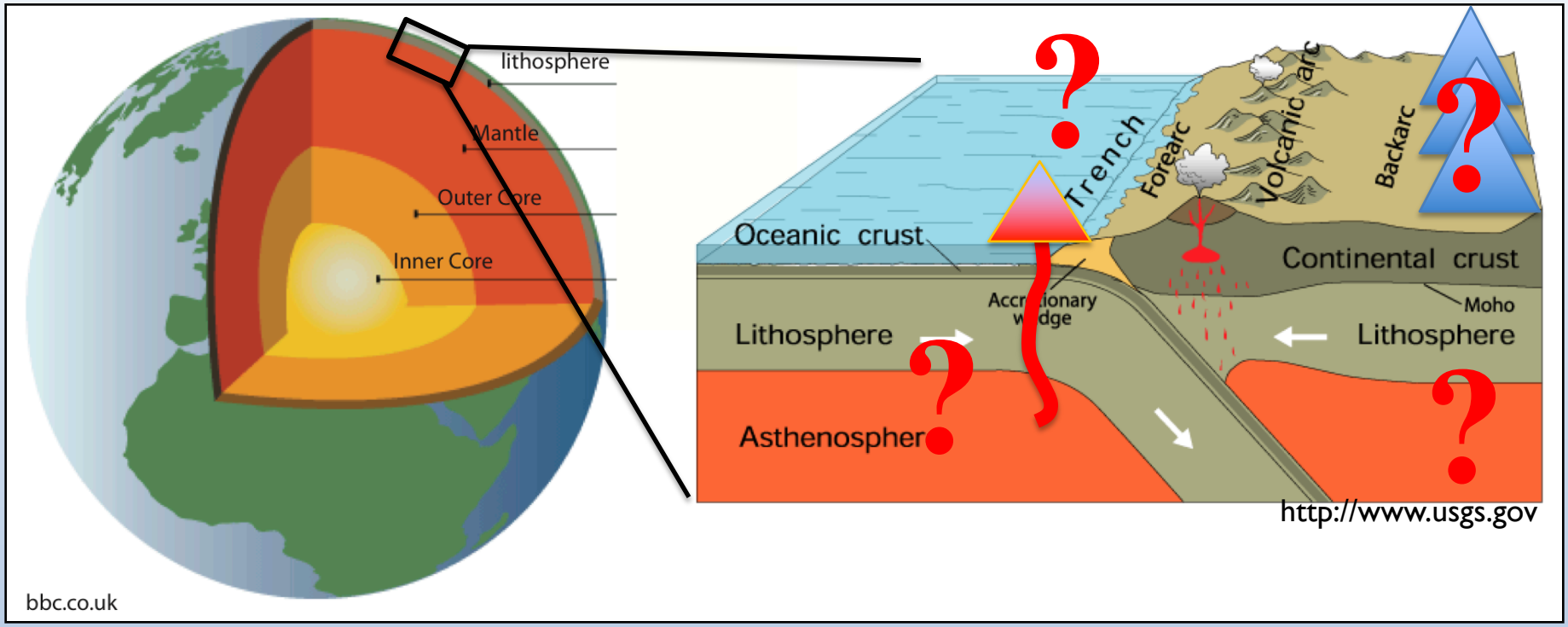




Geosolver - 1200 core Dell Linux cluster
[100 Intel Xeon Gold 6126 Processors, 2.6 GHz, 19.25 MB L3, 12C]
[9.6 TB RAM - 8GB/core; Intel Omni-Path interconnect]

geosolver: Jadamec and Knepley Groups, UB CCR

Use 3D VR & HPC for Scientific Discovery in Geodynamics



Data Assimilation (Obs., Big Data)

Model Design (3D Visualization)

High Performance Computing

Slab Shape
Plate Ages
Plt Bndy

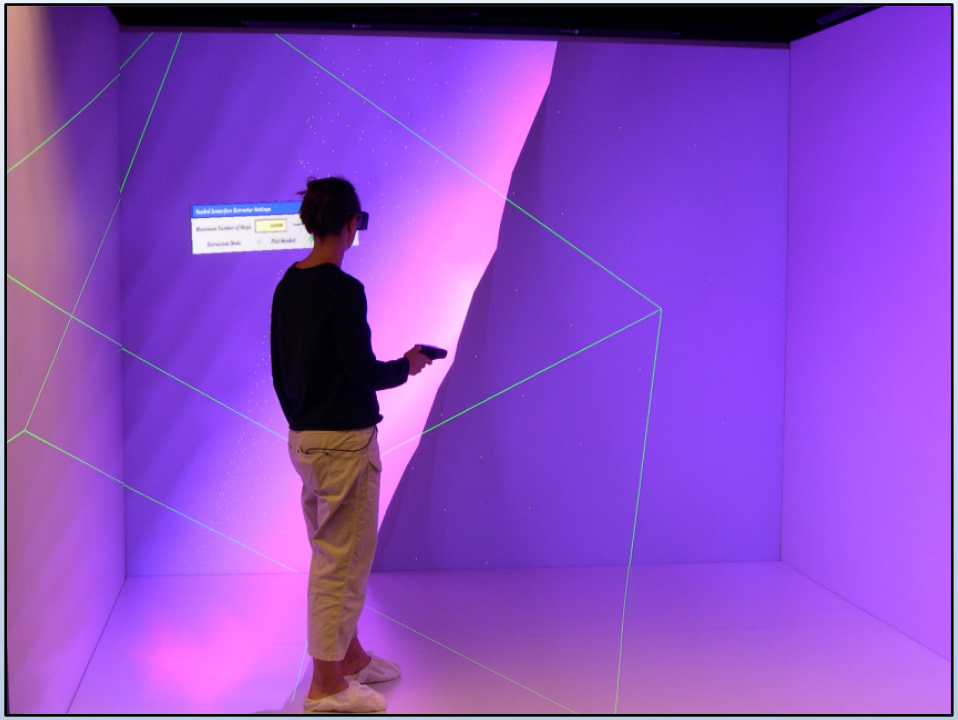
→ TECT_Mod3D (Jadamec, 2009) →

Mesh
Temp
Weak

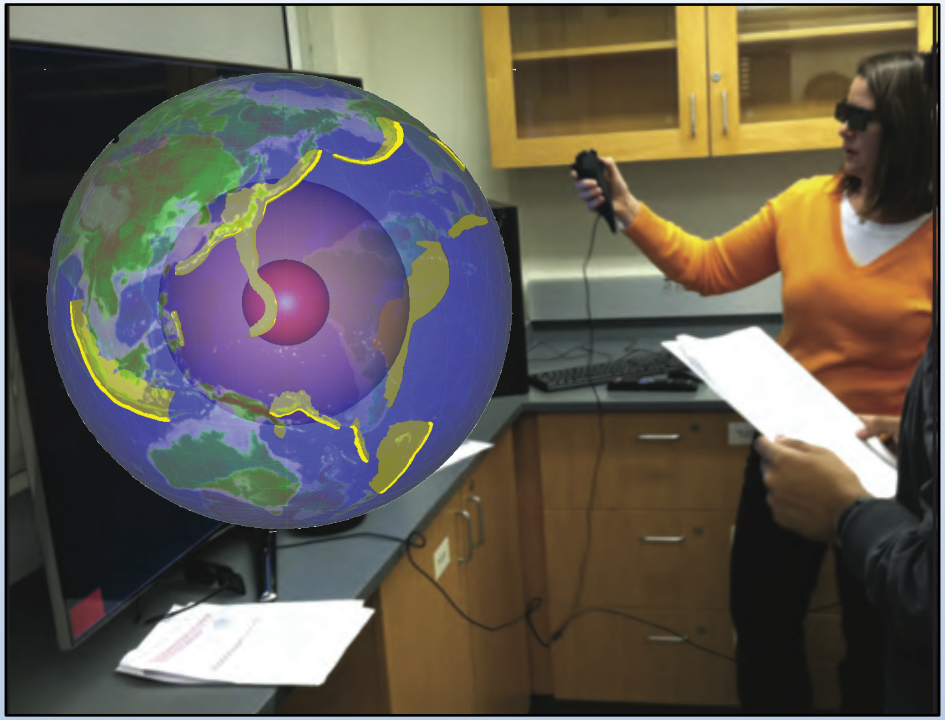
→ CitcomCU (Zhong, 2006) →

v, p
σ, ε
η

3D VR: Conceptualize, Explore, and Query



UC Davis KeckCAVES



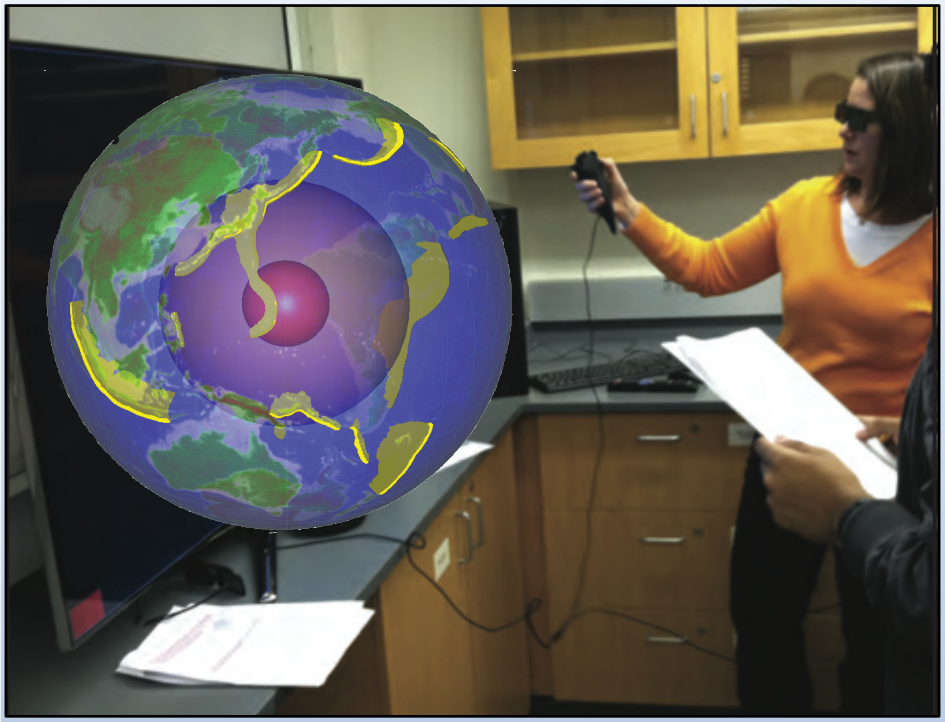
Brown University

Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

3D VR: Lower Budget Systems (3DTV, HTC Vive)



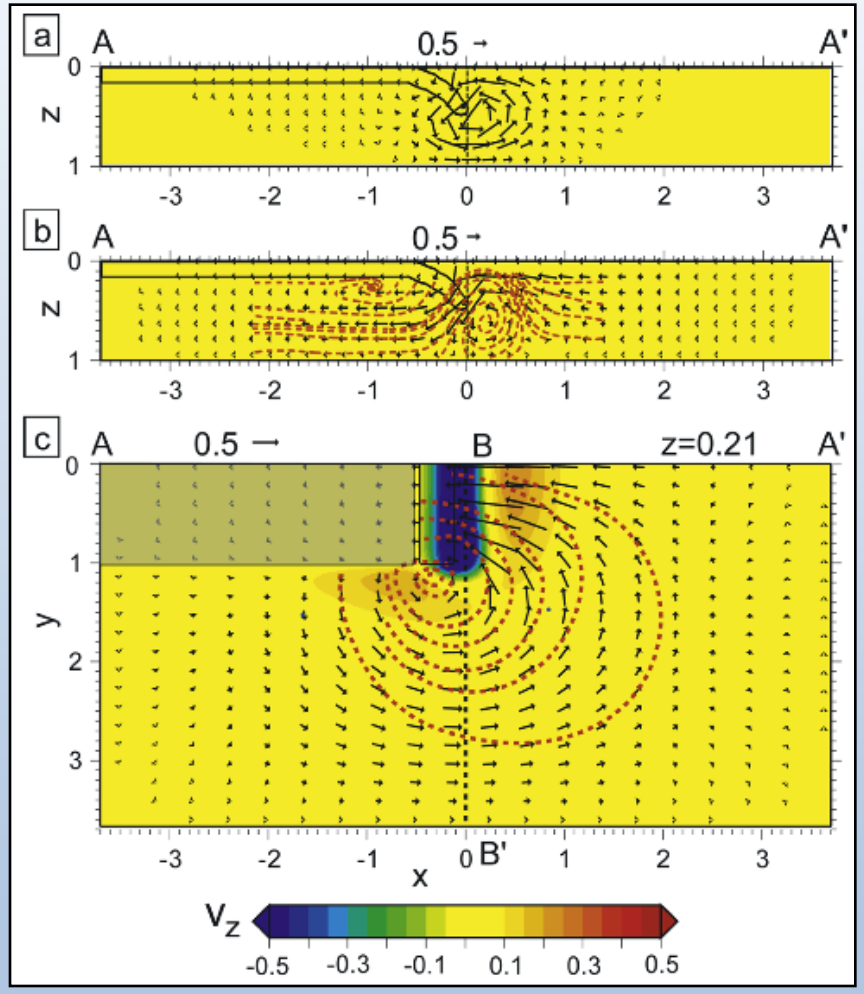
UB Geodynamics Research and Visualization Lab



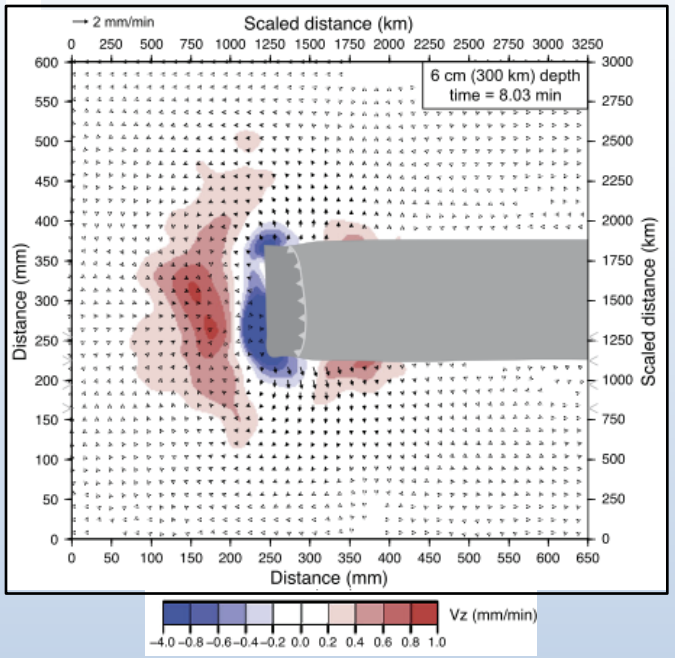
Brown University

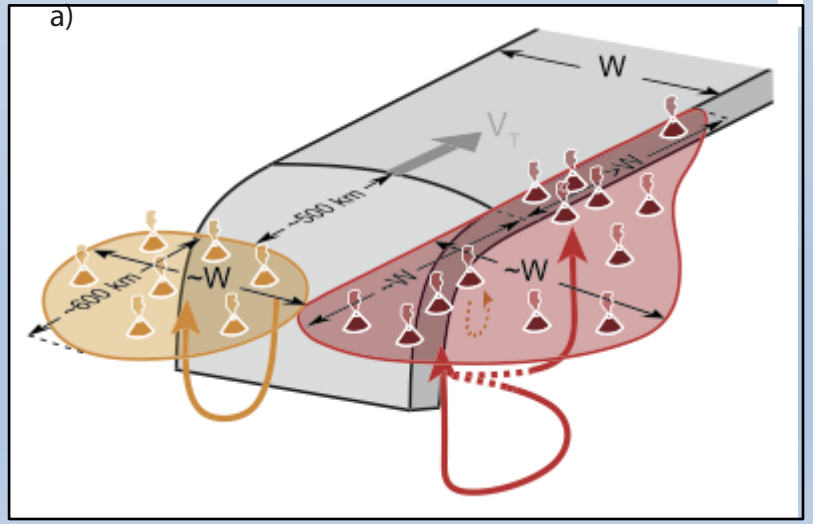
Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

Implications: See This in Generalized 3D Models



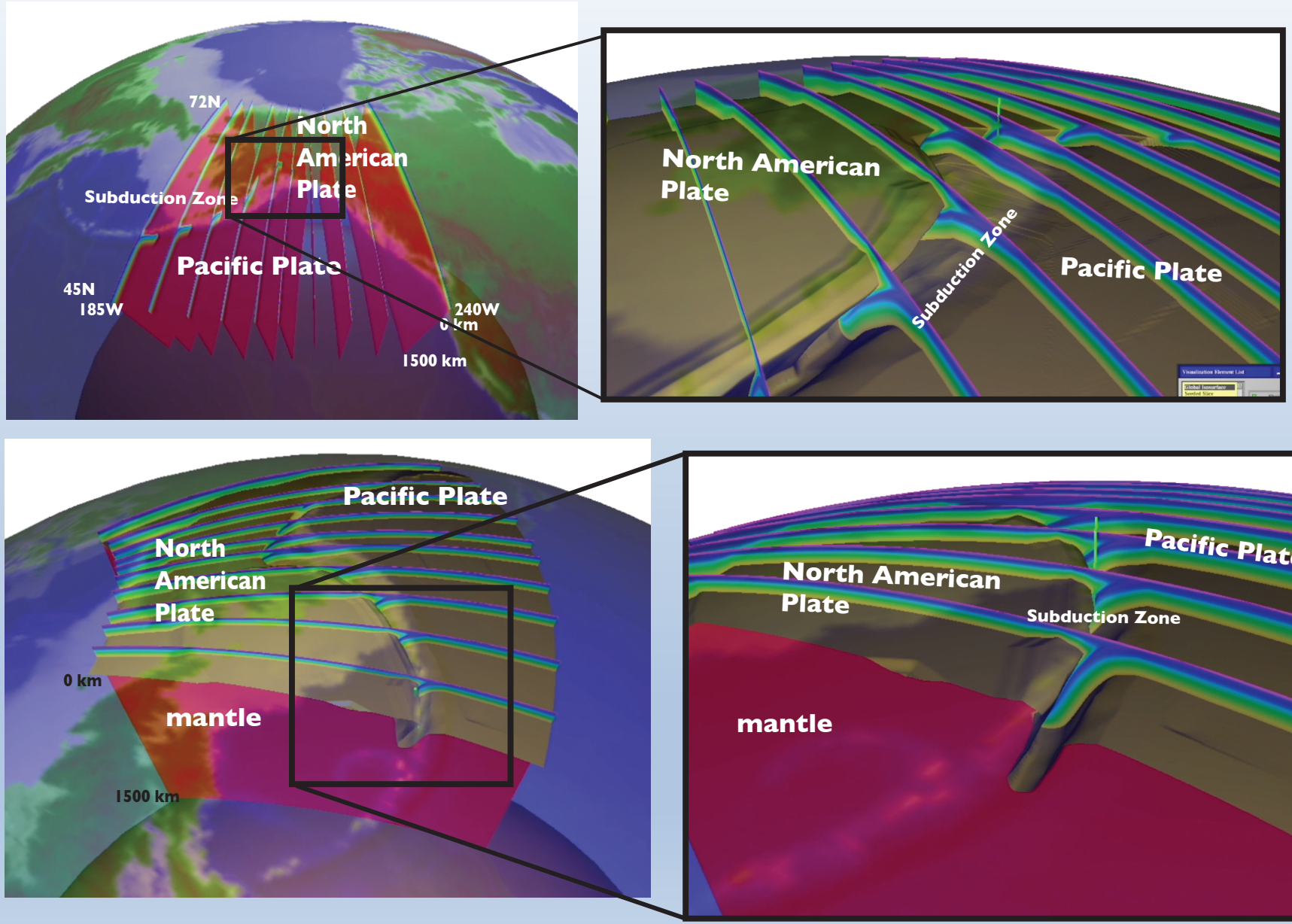
Piromallo et al., GRL 2006





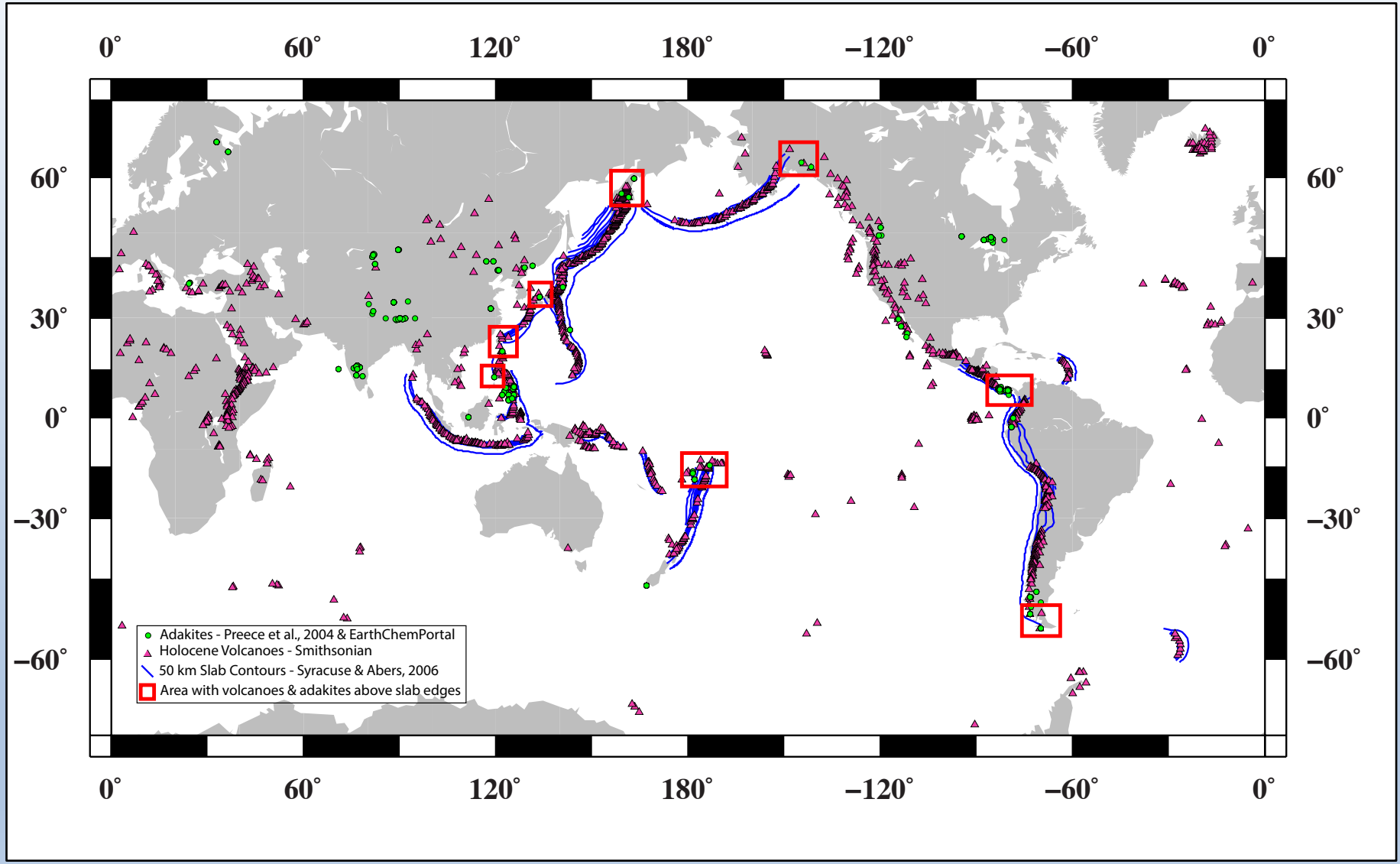
Strak and Schellart, 2014

Tect_Mod3D: Build Framework & Thermal Structure for AK



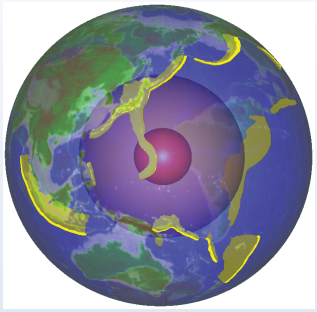
Haynie and Jadamec, 2017, Tectonics; Jadamec et al., in prep.

Slab Edge Volcanoes Not Explained by 2D Convergence

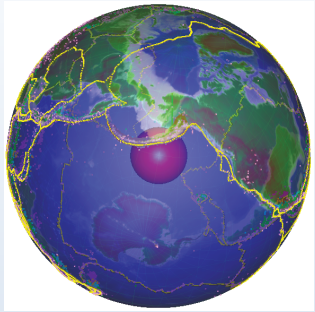


Pham et al., 2016; Jadamec et al. in prep

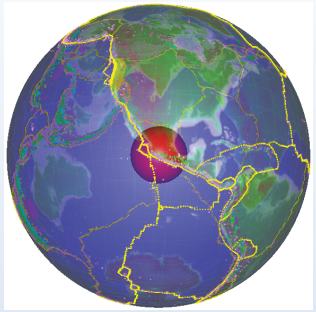
a) Movie 1: Global Slab Model Comparison



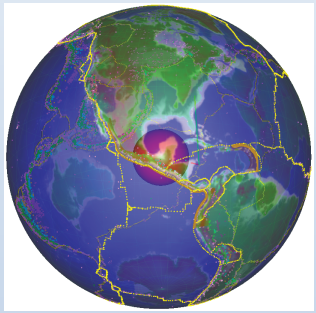
b) Movies 2,3: Alaska-Aleutian Subduction Zone



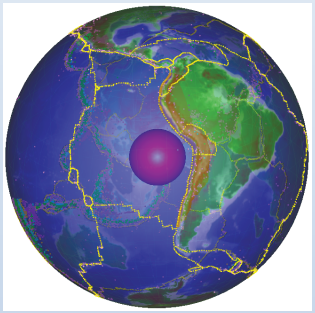
c) Movie 4: Cascadia Subduction Zone



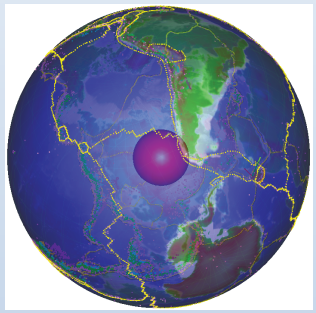
d) Movies 5,6: Caribbean Plate Systems



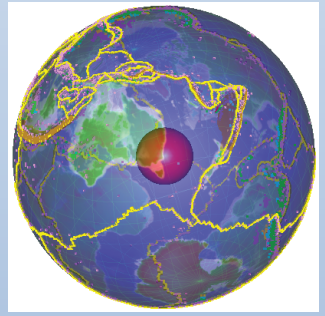
e) Movie 7: Columbia-Peru-Chile



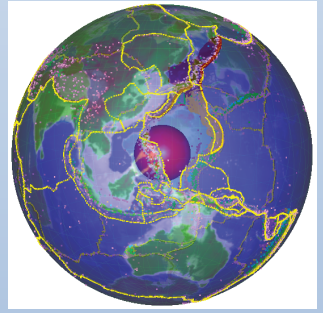
f) Movie 8: Scotia Subduction Zone



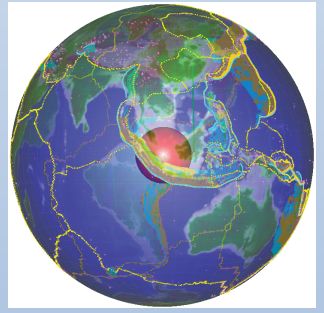
g) Movies 9,10: Tonga-Kermadec-Hikurangi and New Hebrides (North Fiji Basin Region)



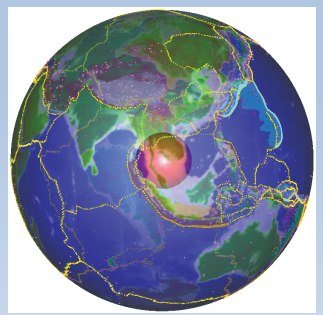
h) Movies 11, 12: Marianas-Izu-Bonin-Ryukyu-Japan (Triple junction region) and Philippines



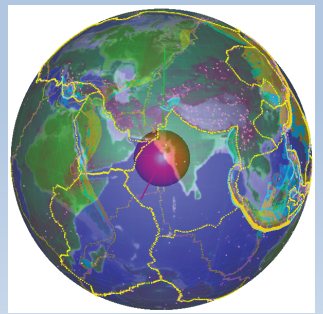
i) Movie 13: Java, Banda, and Others (multiple short and intersecting slabs)



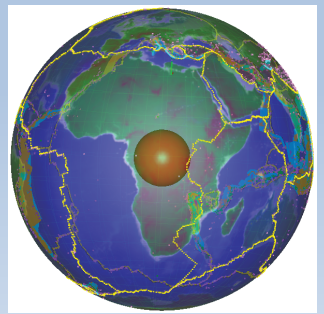
j) Movie 14: Andaman-Sumatra-Java



k) Movie 15: Pamir and Hindu Kush



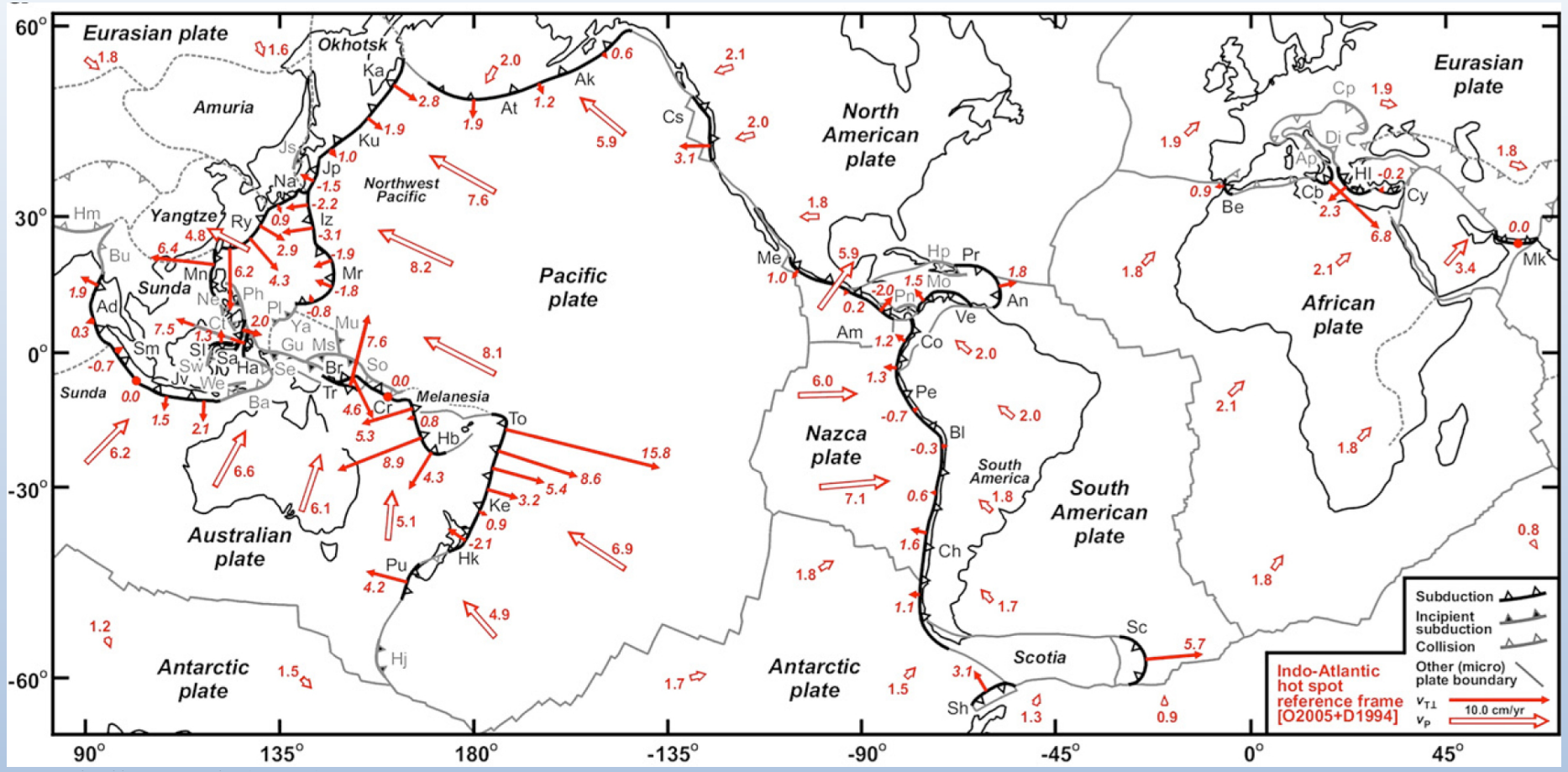
l) Movie 16: Calabria and Hellenic slabs



ShowEarthModel Globe Renderings Showing Location of Movies 1-16: Virtual Tours Through Global Slab Geometries in Earth's Interior

Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.

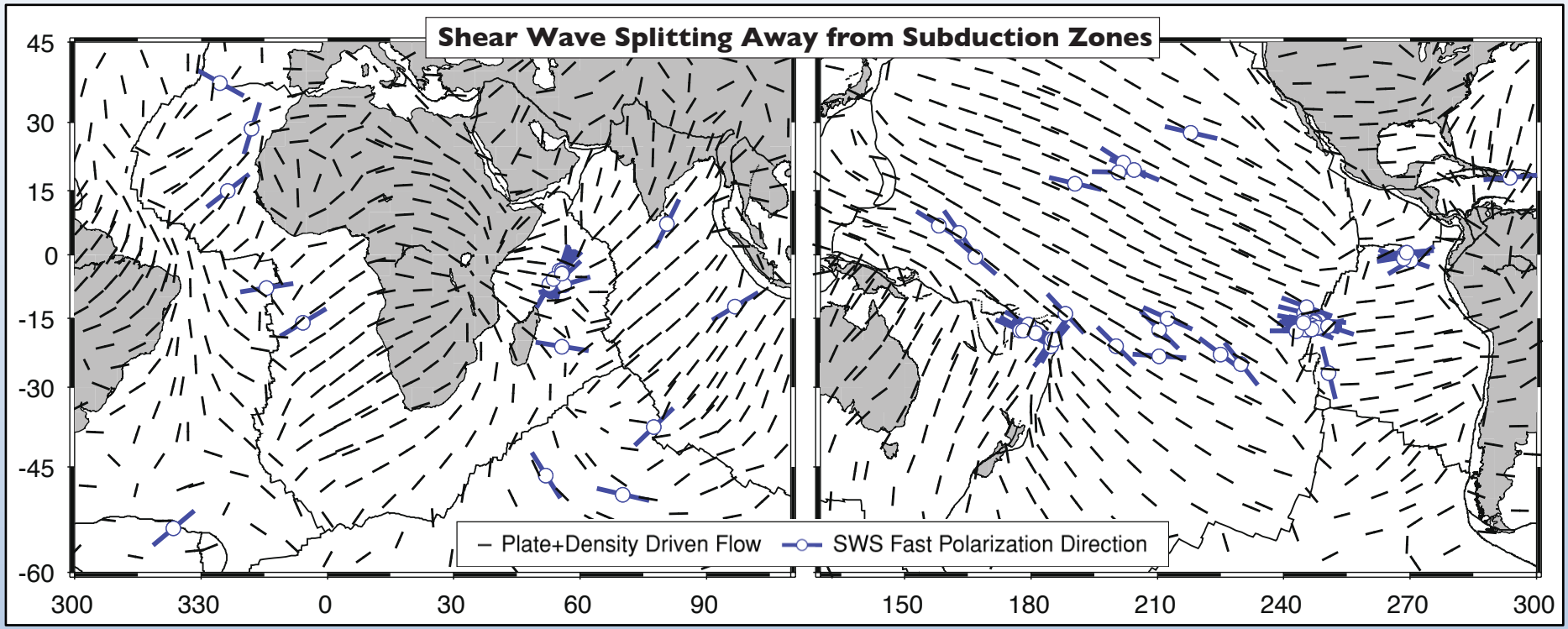
Surface Plate Motion: Convergent, Divergent, Transform



Schellart et al., Earth-Science Reviews (2008)

- Earth behaves as viscous fluid on timescales of millions of years
- Outer thermal boundary layer ~15 Plates (0-250 km thick)
- Subduction zones occur at convergent plate boundaries

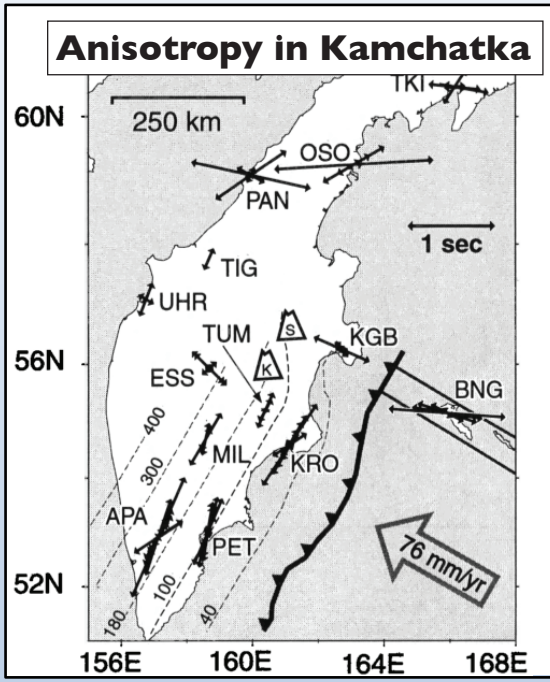
What About the Mantle Underneath the Plates?



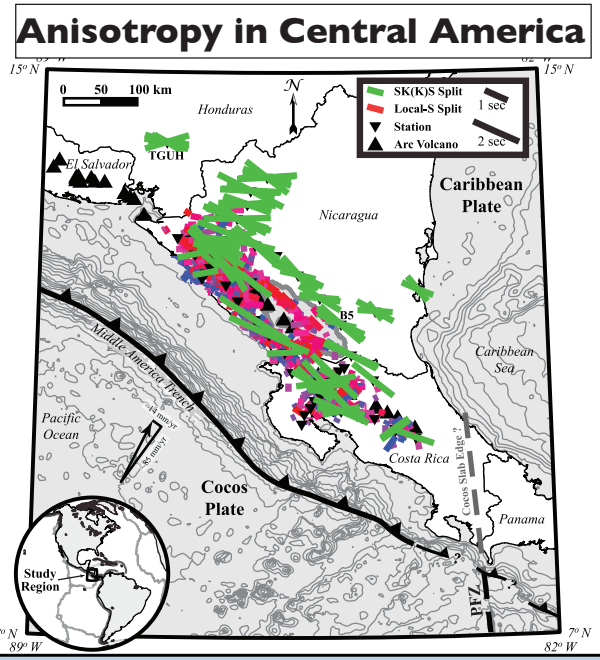
Conrad et al., JGR 2007; Long and Silver, Surv. Geophys. 2009

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)

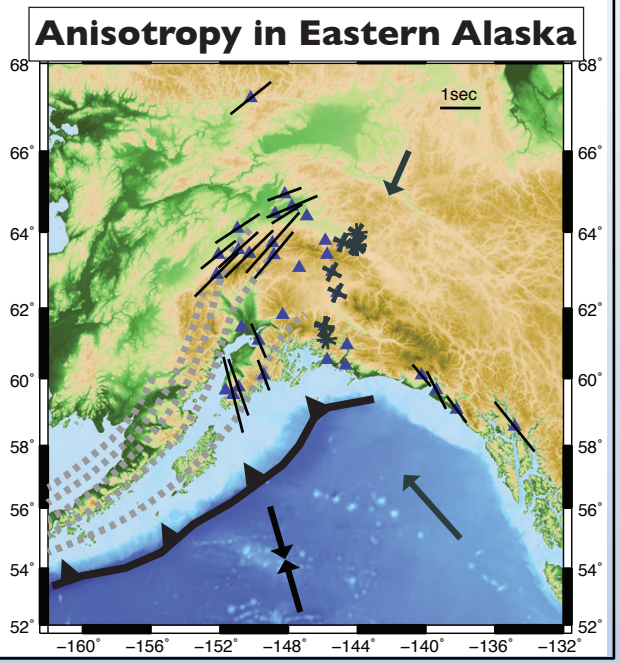
Plate Mantle-(de)coupling & Is Complex Flow Common?



Peyton et al., GRL 2001



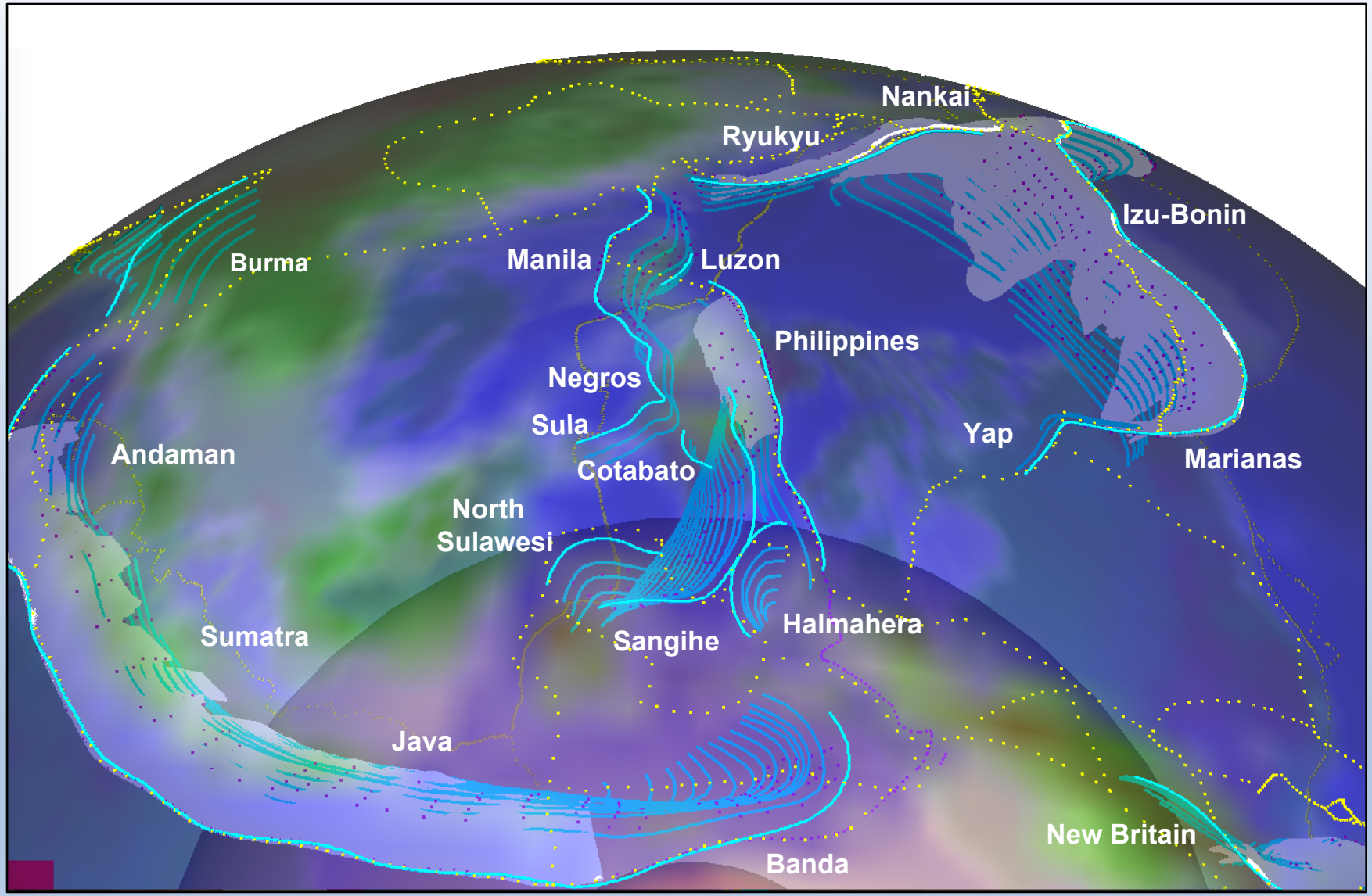
Abt et al., JGR 2010



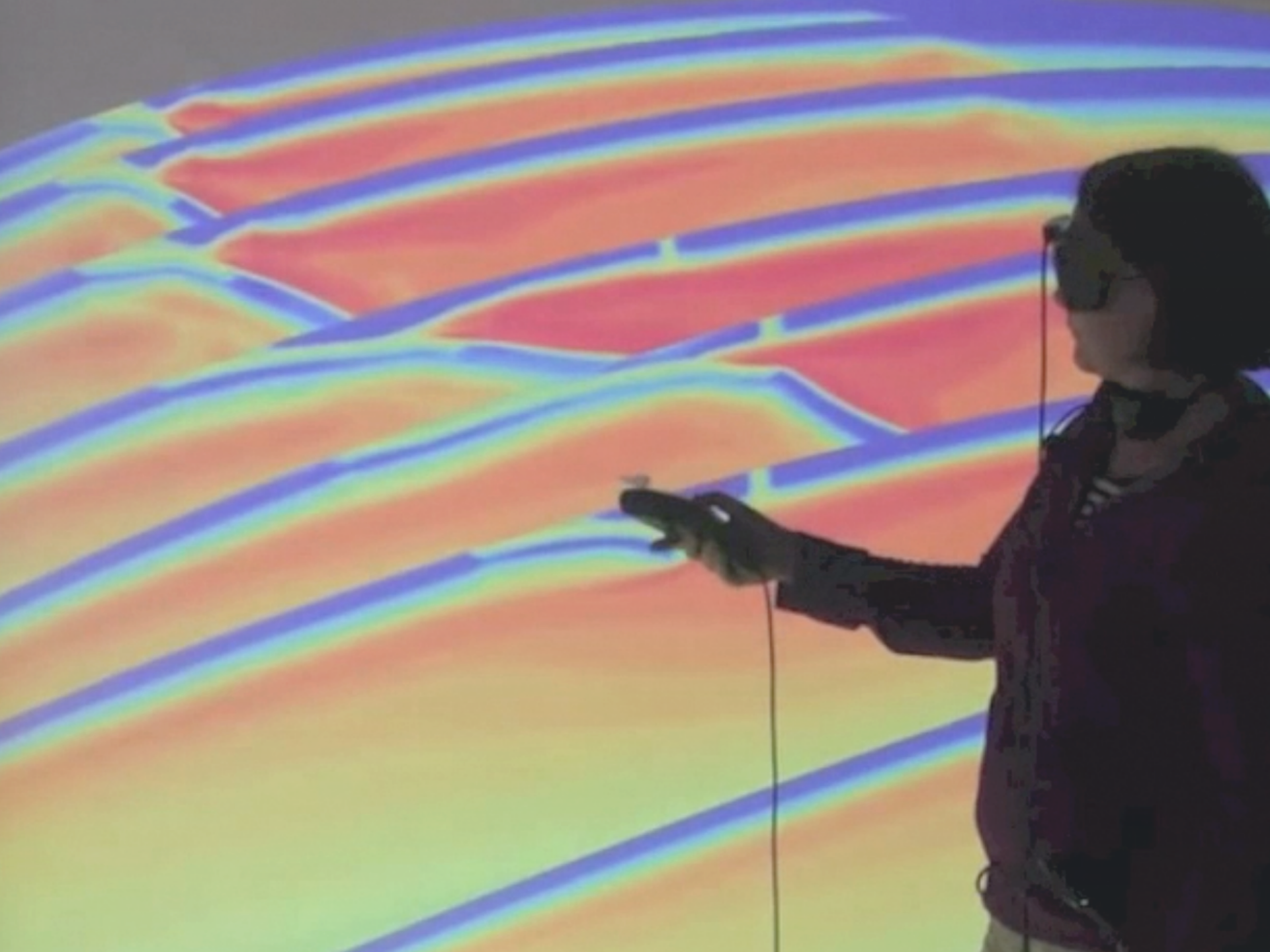
Hanna and Long, Tect. 2012

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)

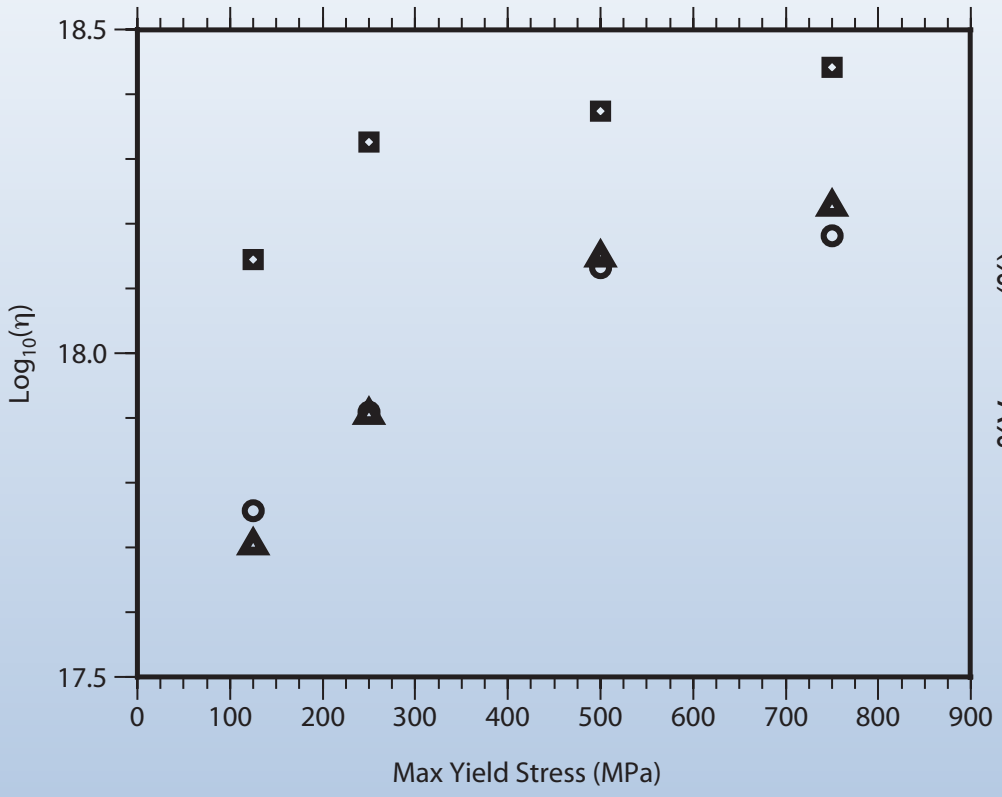
Intersecting Slab Geometries in Philippine-Indonesia Region

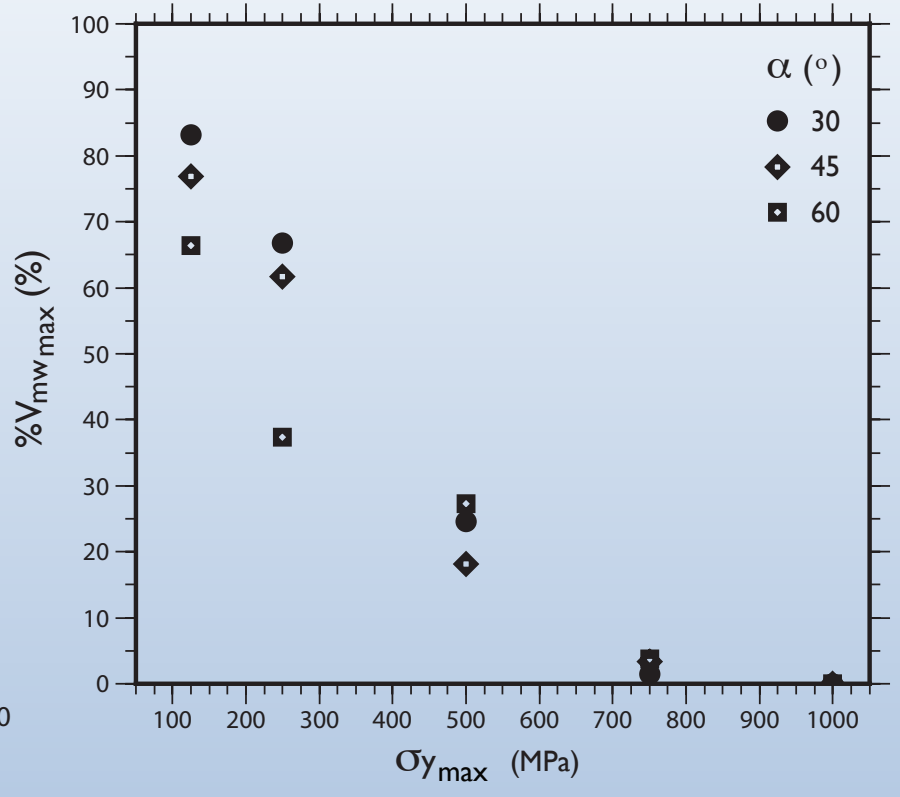


Jadamec, M. A., Kreylos, O., Chang, B., Fischer K. M., and Yikilmaz, M. B. (2018). A Visual Survey of Global Slab Geometries With ShowEarthModel and Implications for a Three-Dimensional Subduction Paradigm. *Earth and Space Science,* 5(6), 240-257.



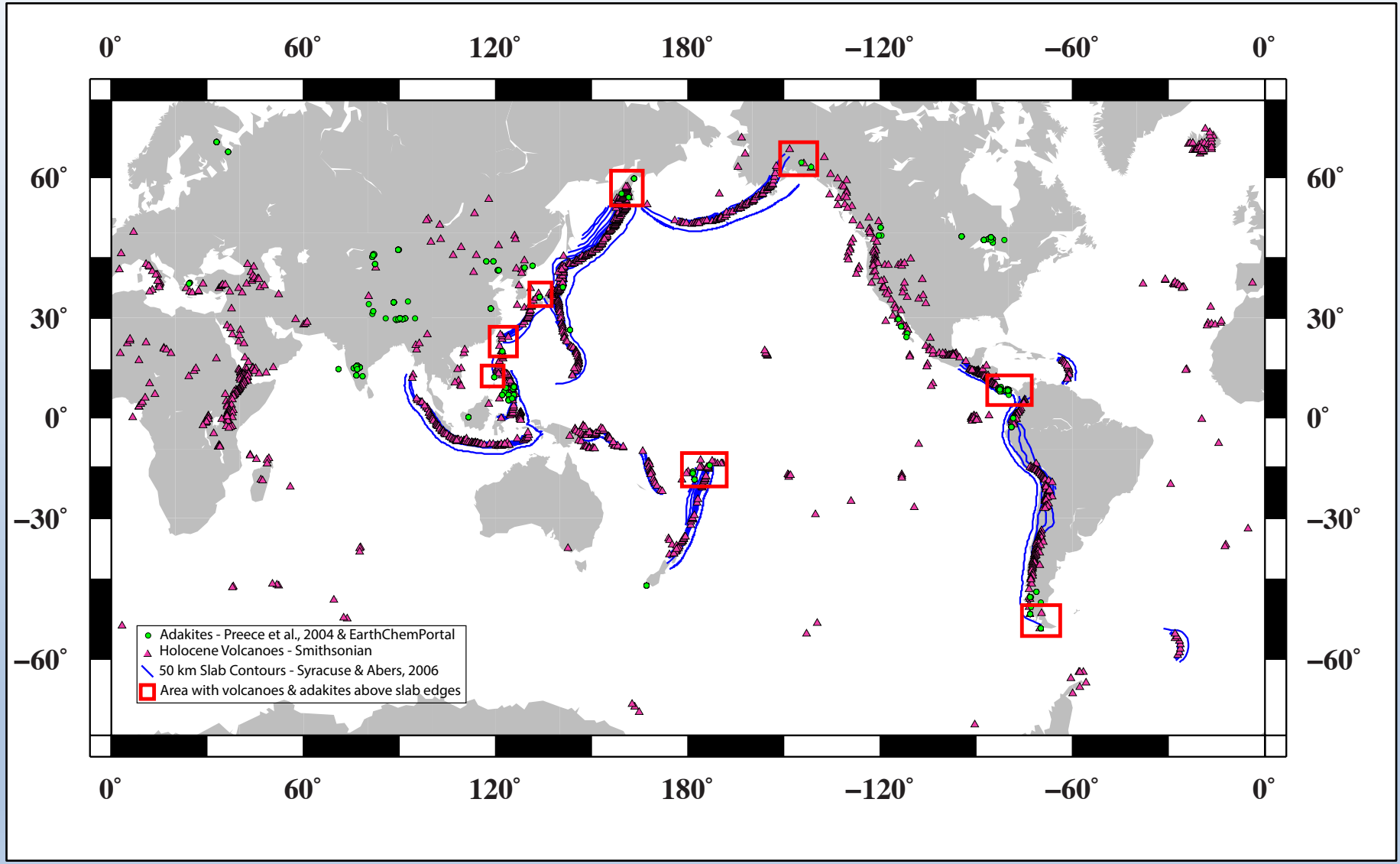
Results: Mantle Flow Order of Magnitude Faster Plate Motions





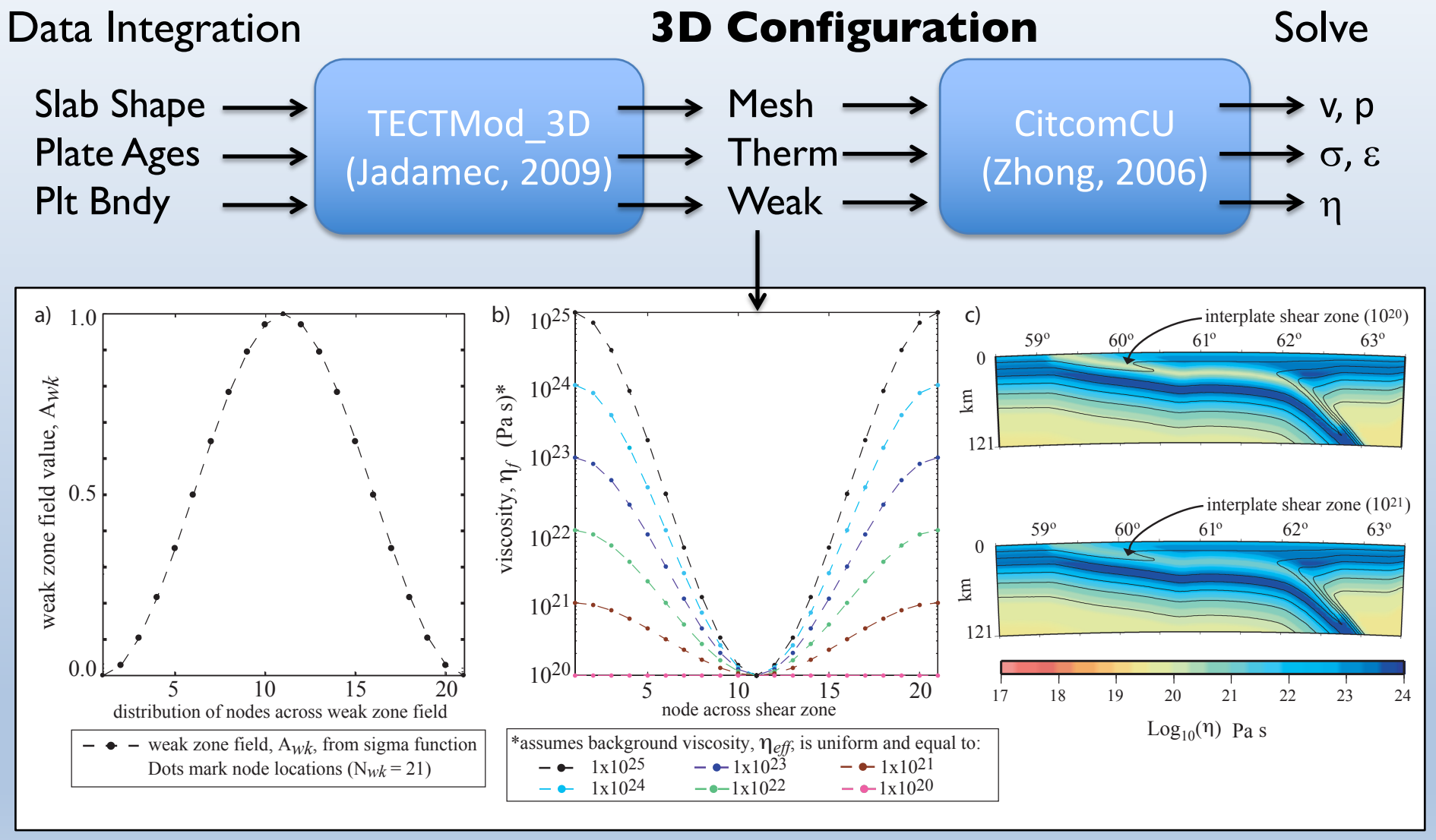
Jadamec, M. A. (2016) Slab driven mantle weakening and rapid mantle flow, p. 135-155.. *In:* G. Morra, D. A. Yuen, S-M. Lee, S. Stein (Eds.), *Subduction Dynamics: From Mantle Flow to Mega Disasters*. Geophysical Monograph Series, vol 211. John Wiley & Sons.

Slab Edge Volcanoes Driven by 3D Non-linear Flow Upwellings



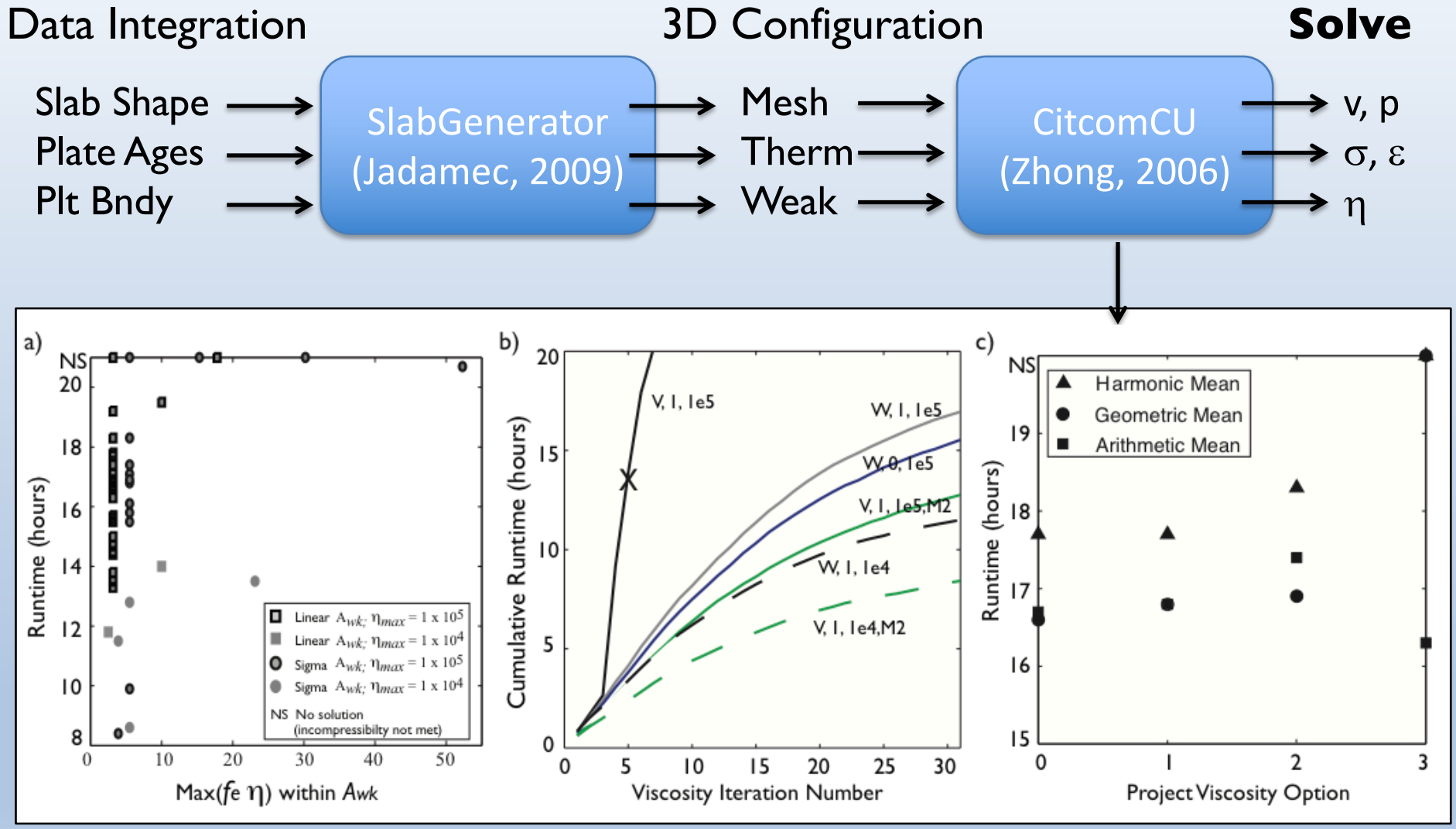
Pham et al., 2016; Jadamec et al. in prep

Observationally Based 3D Modeling Workflow



Jadamec, M. A., Billen, M. I., and Kreylos, O., 2012, Three-dimensional simulations of geometrically complex subduction with large viscosity variations. 8 pp. In: *ACM Proceedings of the 2012 Conference on eXtreme Science and Engineering Discovery Environment.*

Observationally Based 3D Modeling Workflow



Jadamec, M. A., Billen, M. I., and Kreylos, O., 2012, Three-dimensional simulations of geometrically complex subduction with large viscosity variations. 8 pp. In: *ACM Proceedings of the 2012 Conference on eXtreme Science and Engineering Discovery Environment.*

Need High Fidelity Tools to Analyze and Interpret Output

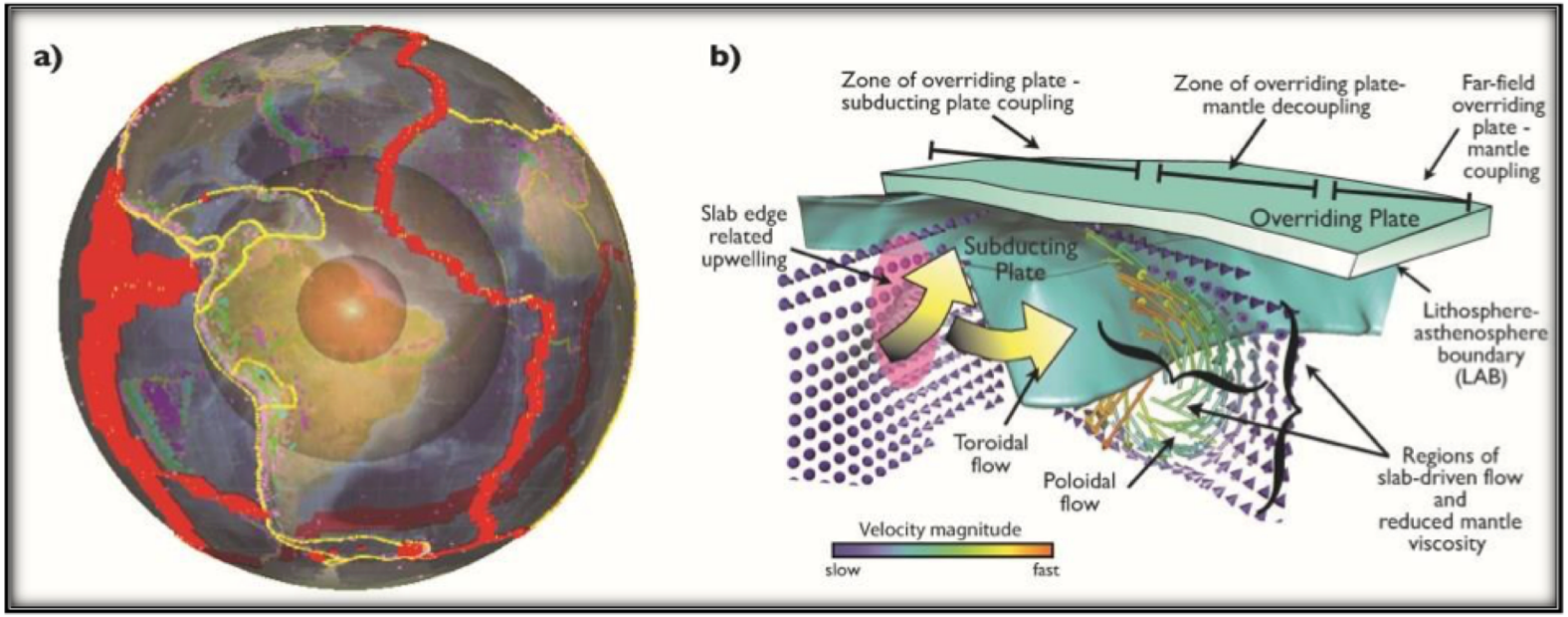
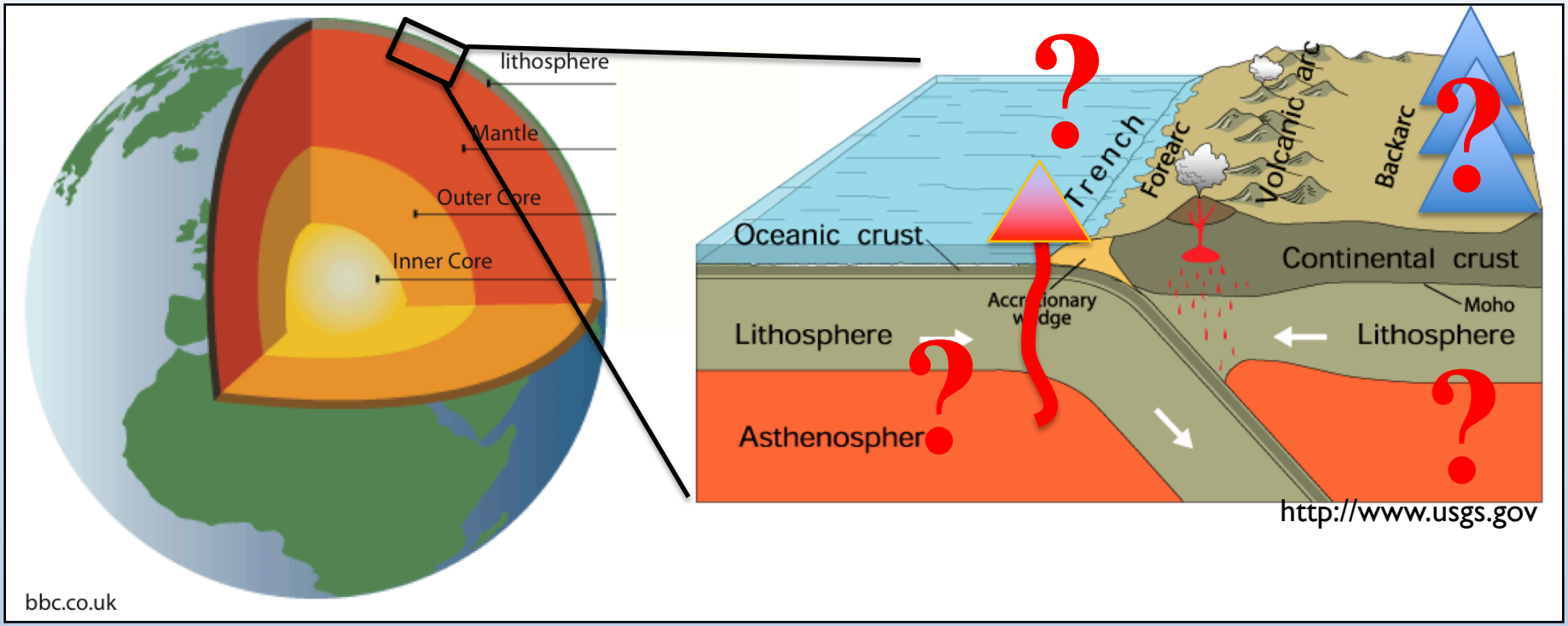
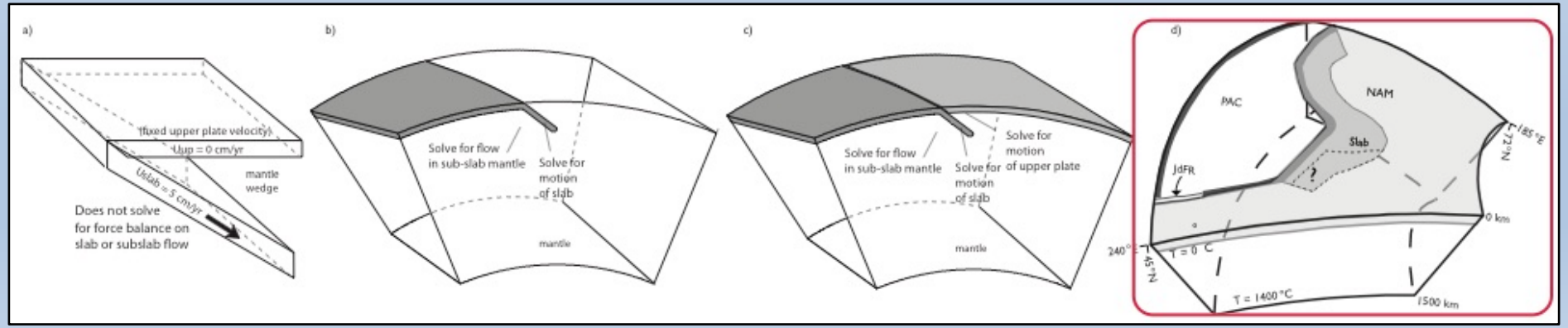


Figure 2. Multiscale global and regional tectonics. *Large-scale computational resources will allow geophysicists to model and simulate plate tectonics at higher-resolutions and increased physical accuracy. (a) Observational constraints on the nature of tectonic plates, overlain on the major structural boundaries within the Earth. (b) Results from a high-resolution 3D regional model of a single plate boundary show small-scale convection. Convection on Earth contains small-scale, highly non-linear processes shown in (b) embedded within the larger-scale, whole mantle convection that occurs in (a). Image courtesy of M. A. Jadamec (University of Houston); modified from Jadamec, J. Geodynamics v. 100:51-70, 2016.*

NIH-DOE-NSF Report on ExaScale Computing, 2017

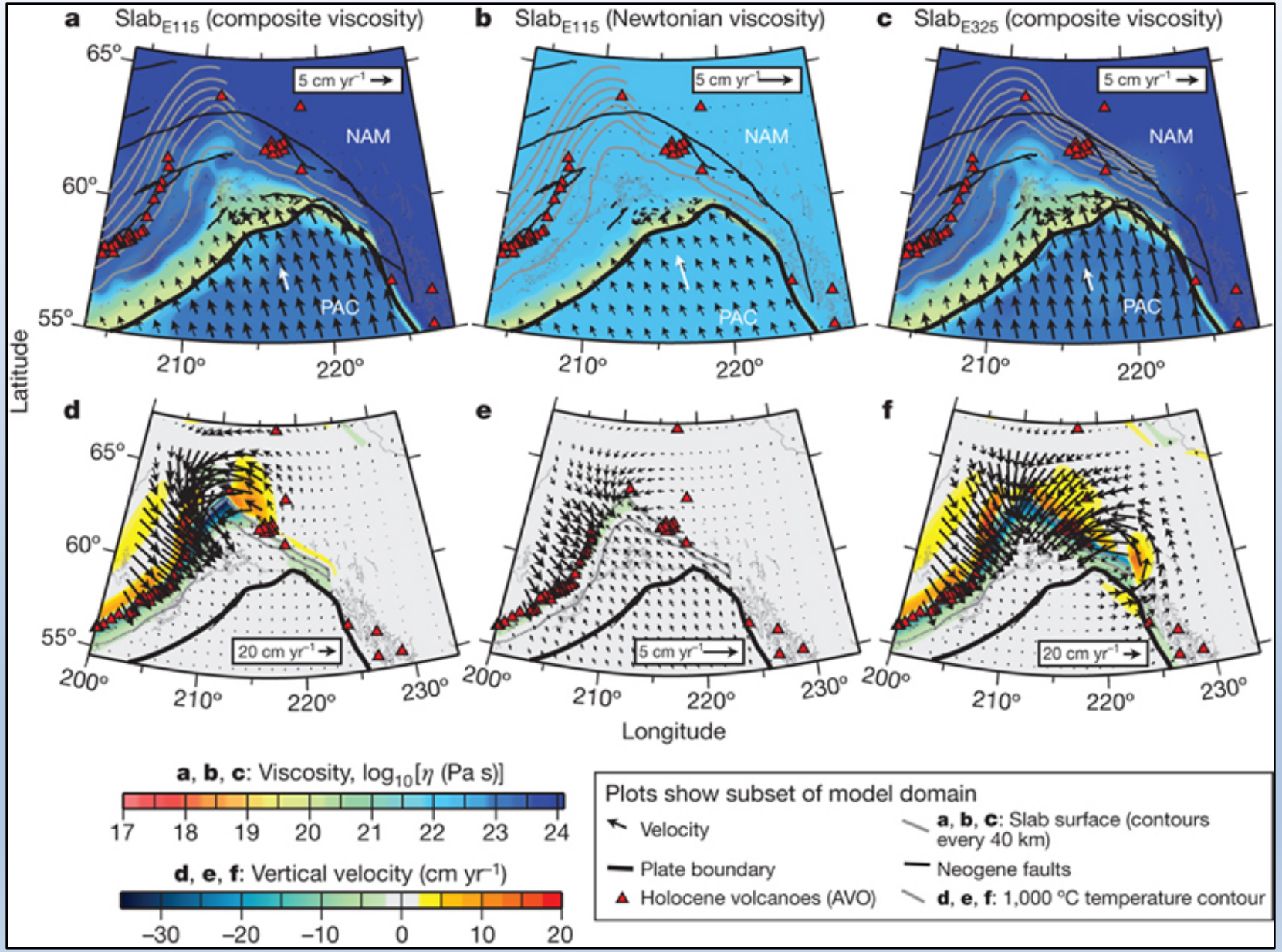
Representing the Subduction Zones in a Model





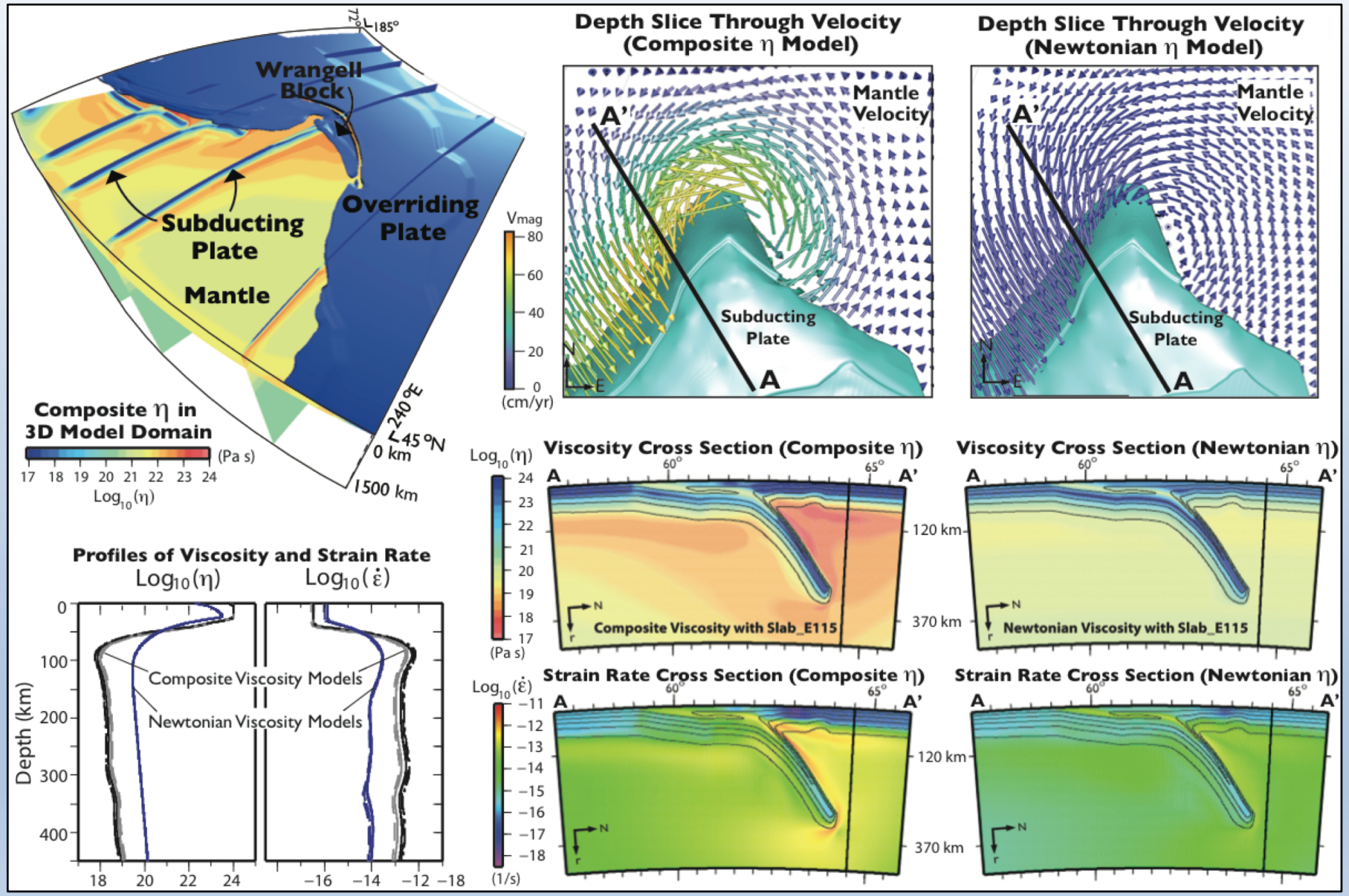
Jadamec, 2016, Journal of Geodynamics

Results: Predicted Velocity at Surface and 100 km Depth



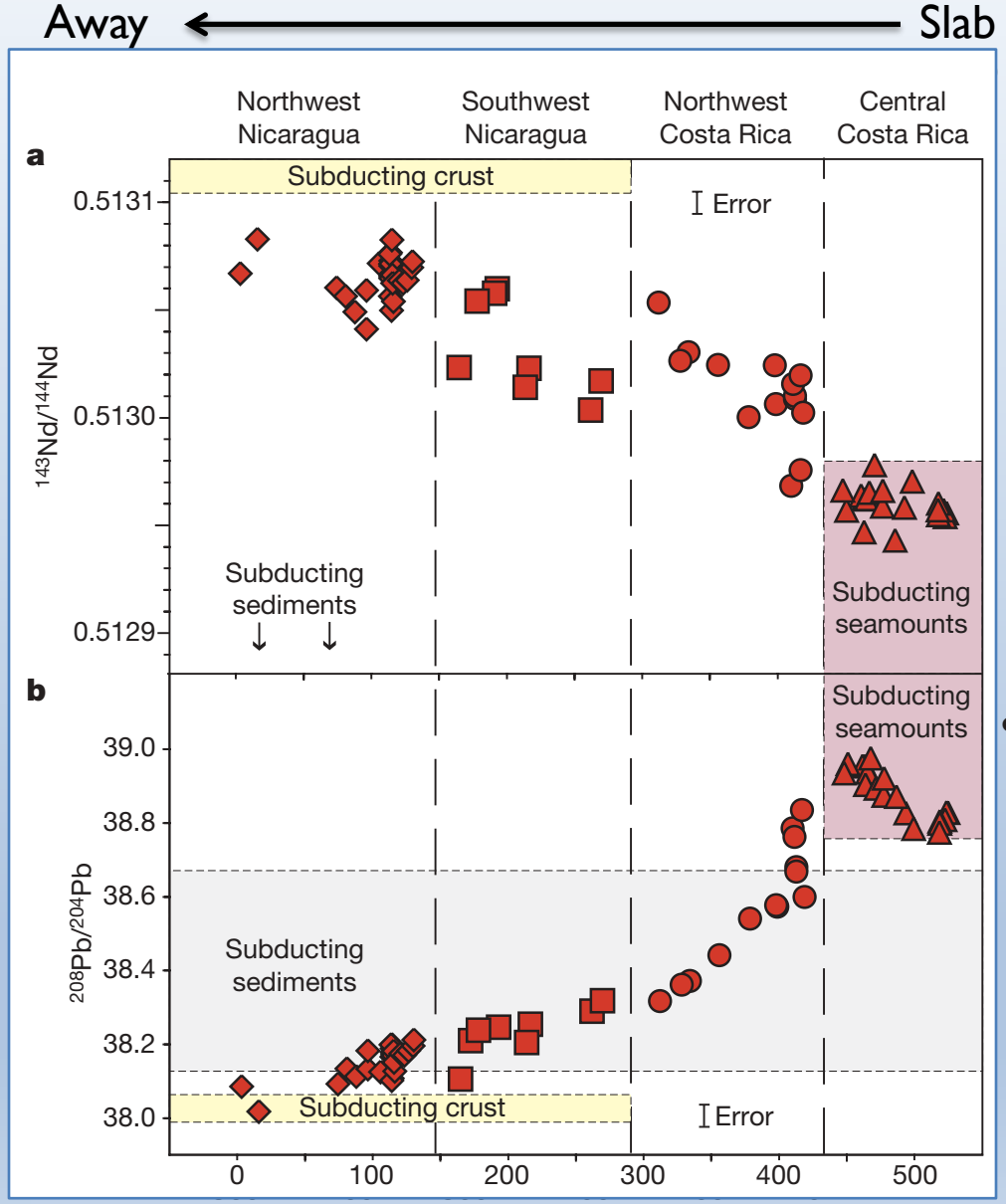
M.A. Jadamec & M.I. Billen *Nature* 465, 338-341 (2010)

Results: Toroidal flow around around slab edge in Alaska

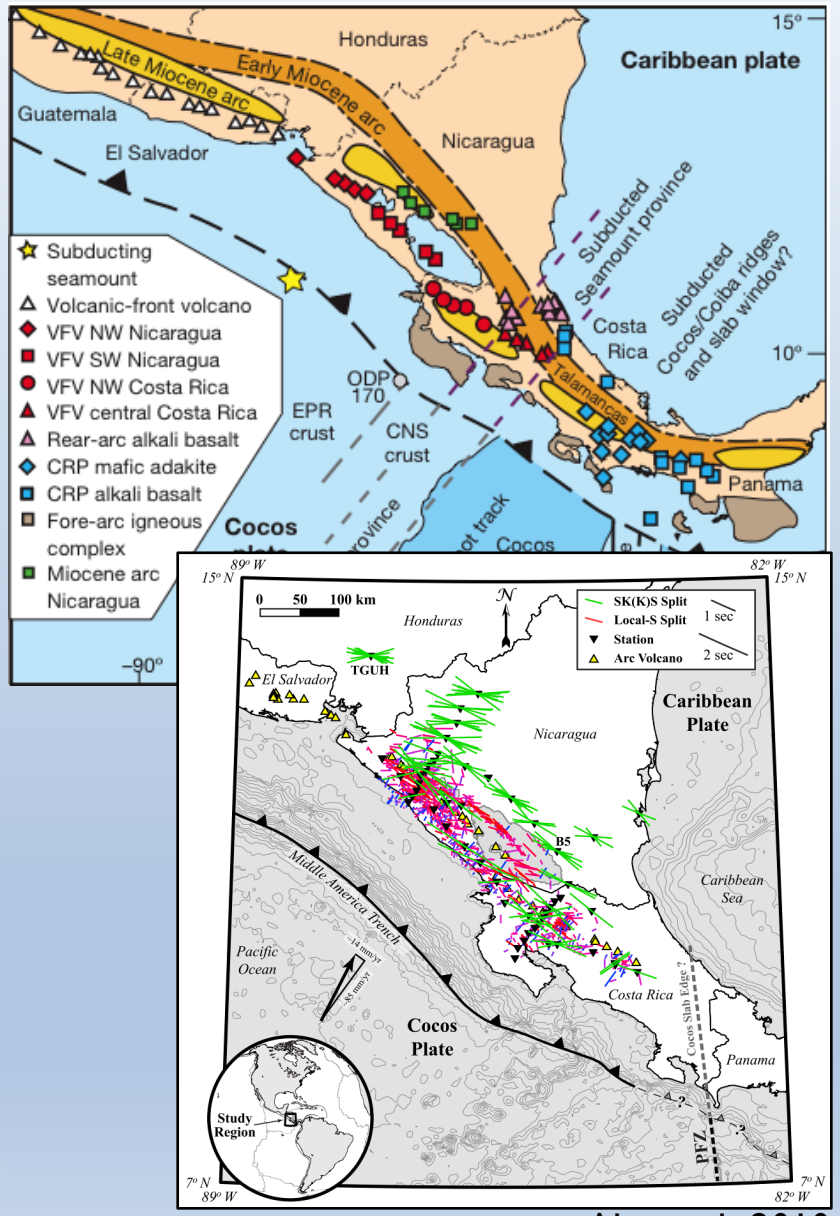


Jadamec and Billen, Nature 2010; Jadamec and Billen, JGR 2012; Jadamec et al., EPSL 2013

Implications: Northwest Directed Mantle Wedge Flow



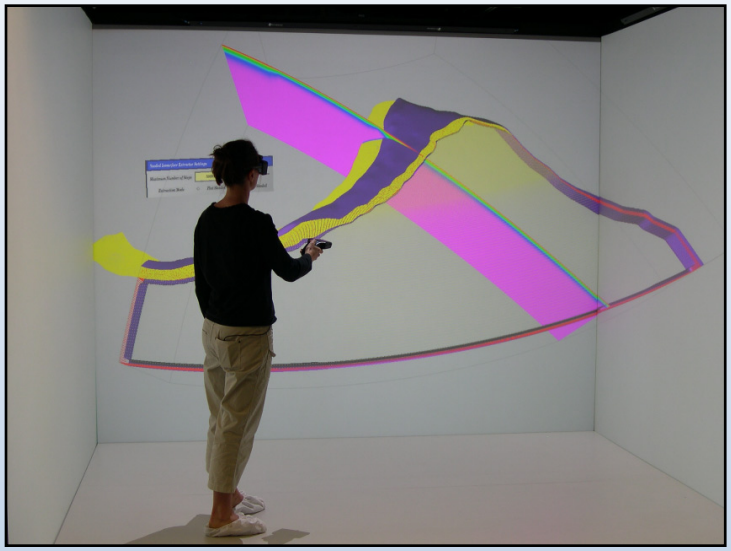
Hoernle et al., Nature 2008



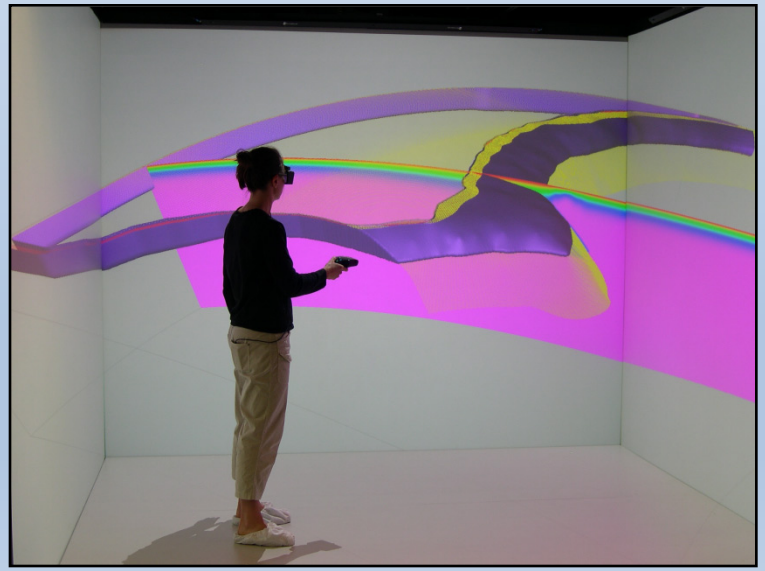
Abt et al., 2010

3D VR in CAVE: To Conceptualize, Explore, and Query





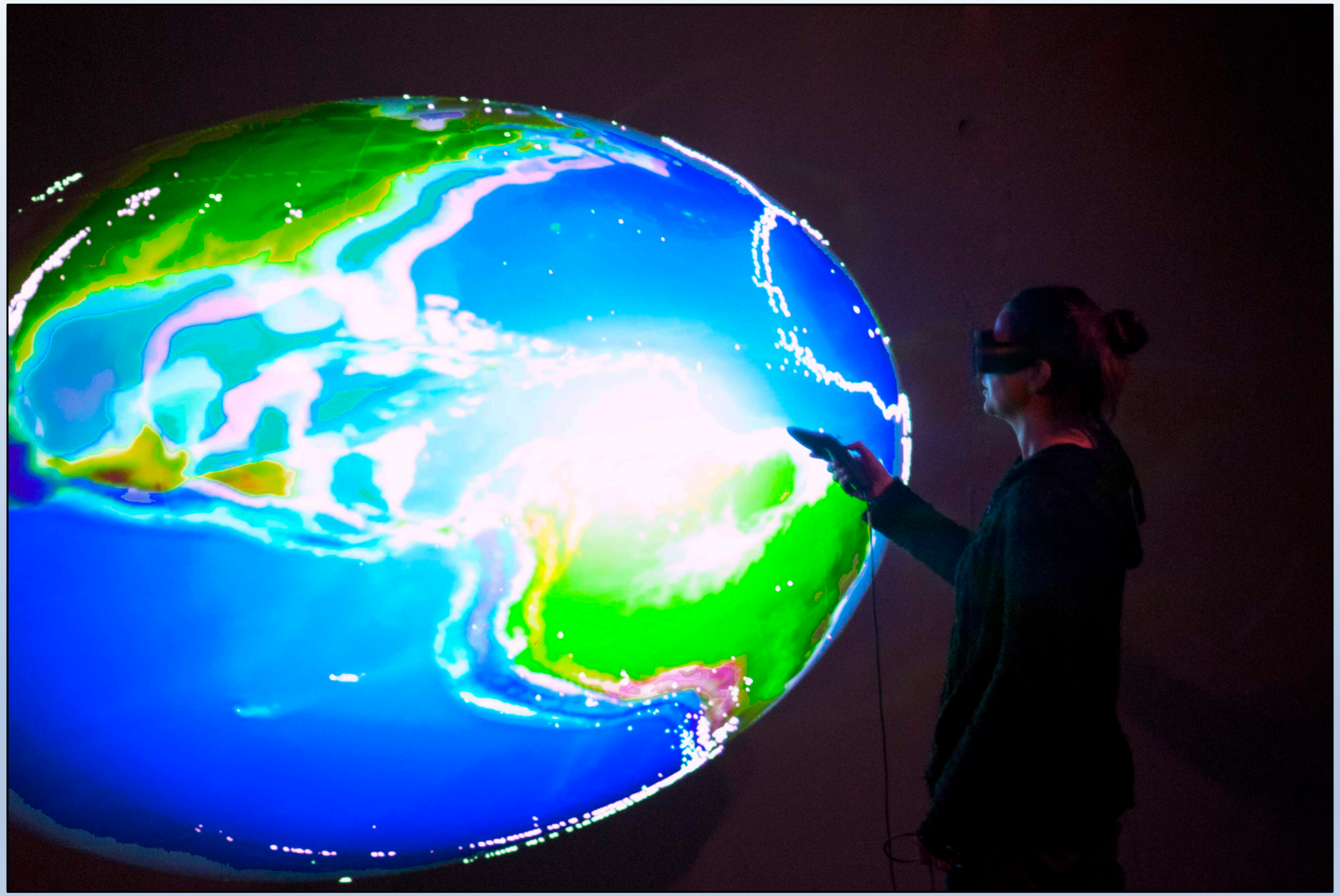




Kellogg et al. (2008) Pure and Applied Geophysics, 165 (3-4), p. 621-633

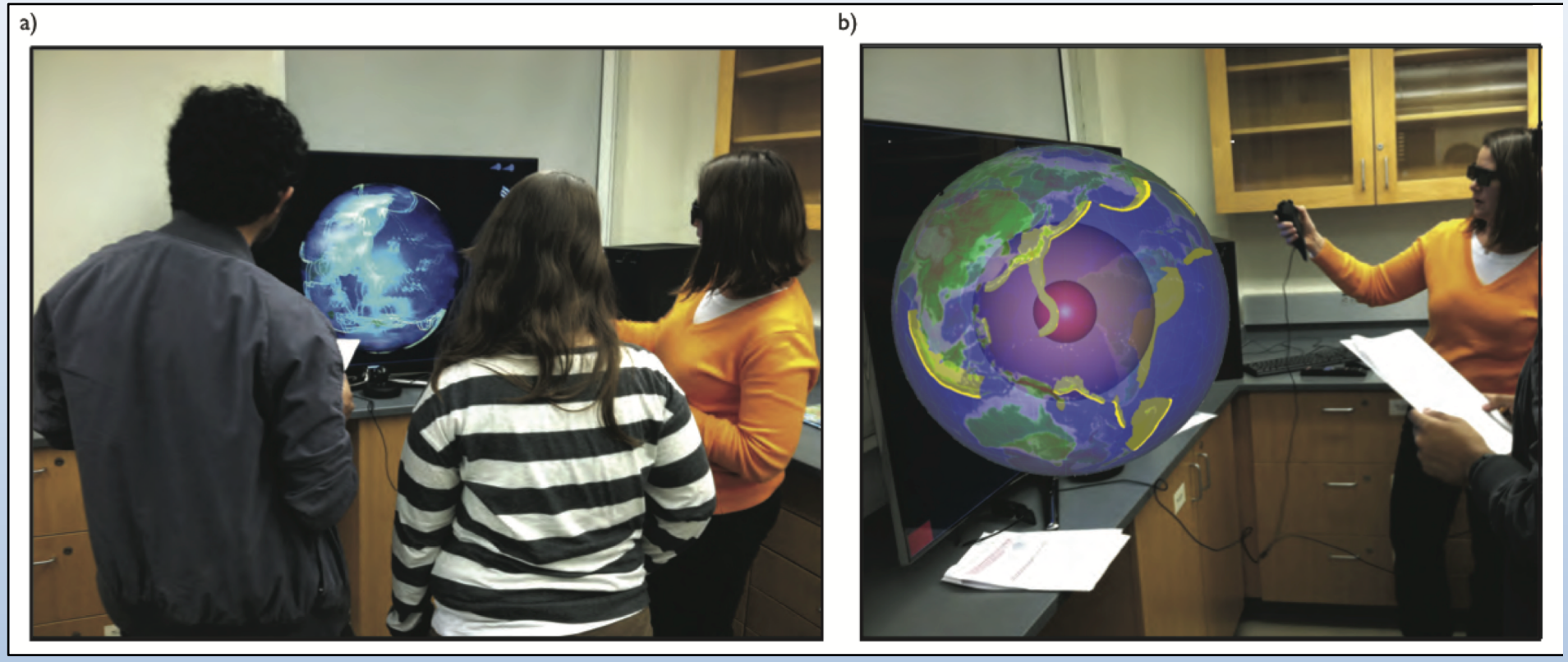
http://graphics.cs.ucdavis.edu/~okreylos/ResDev/KeckCAVES/Pictures.html

Immersion: To Conceptualize, Explore, and Query (HT Wall)



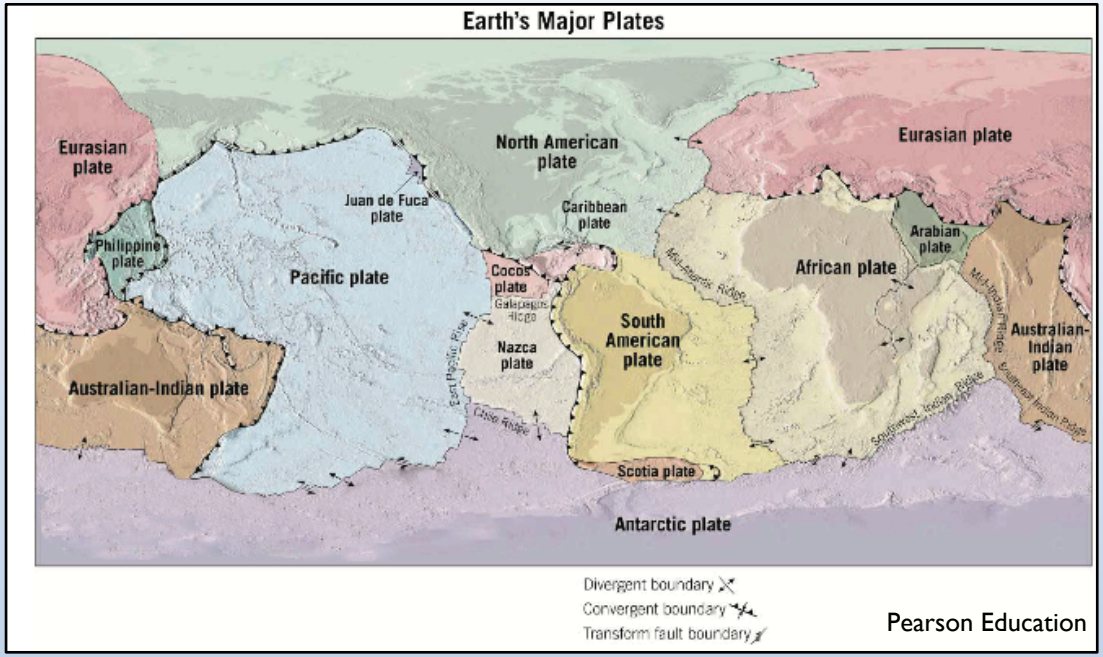
3DALIVE, Monash University, Australia

3D Interactive: To Conceptualize, Explore, and Query (3DTV)

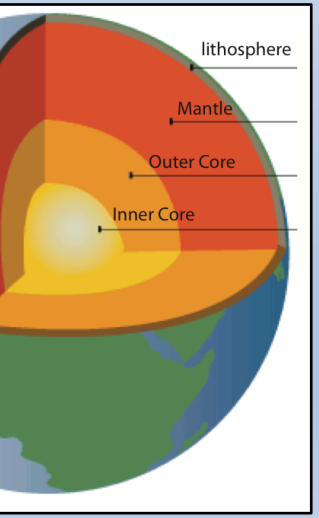


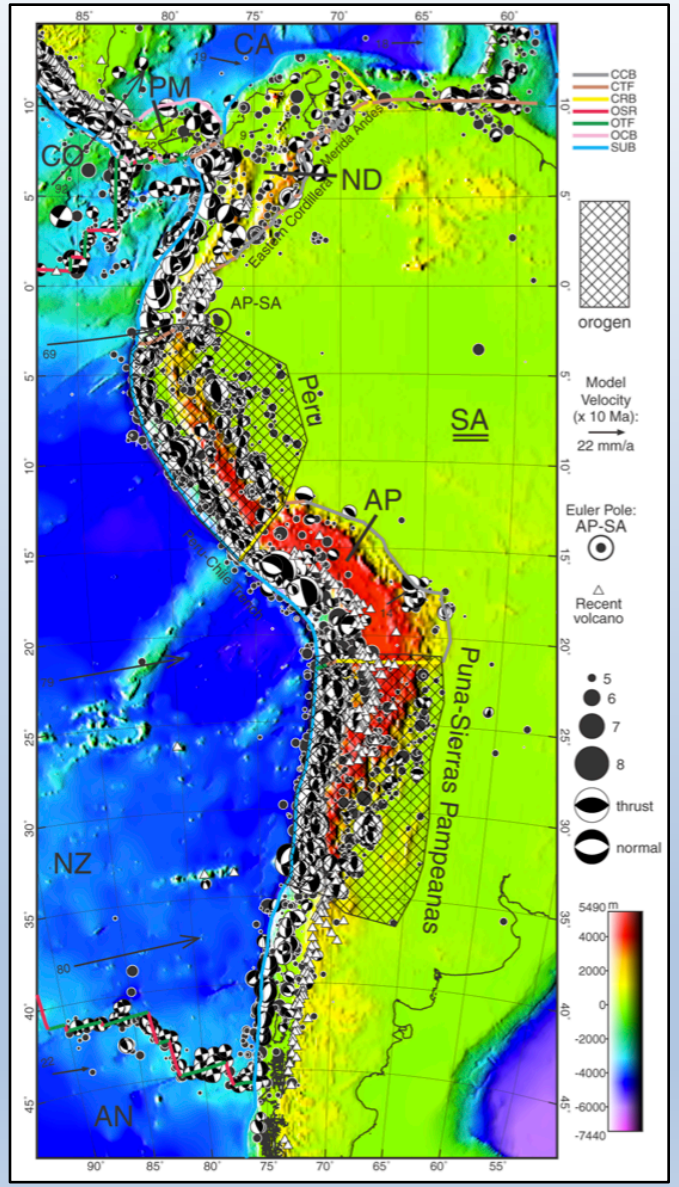
Interactive 3D System, Brown University & UB Geodynamics Research and Visualization Lab, Cooke Hall

Plate Tectonics and Deformation at Plate Boundaries



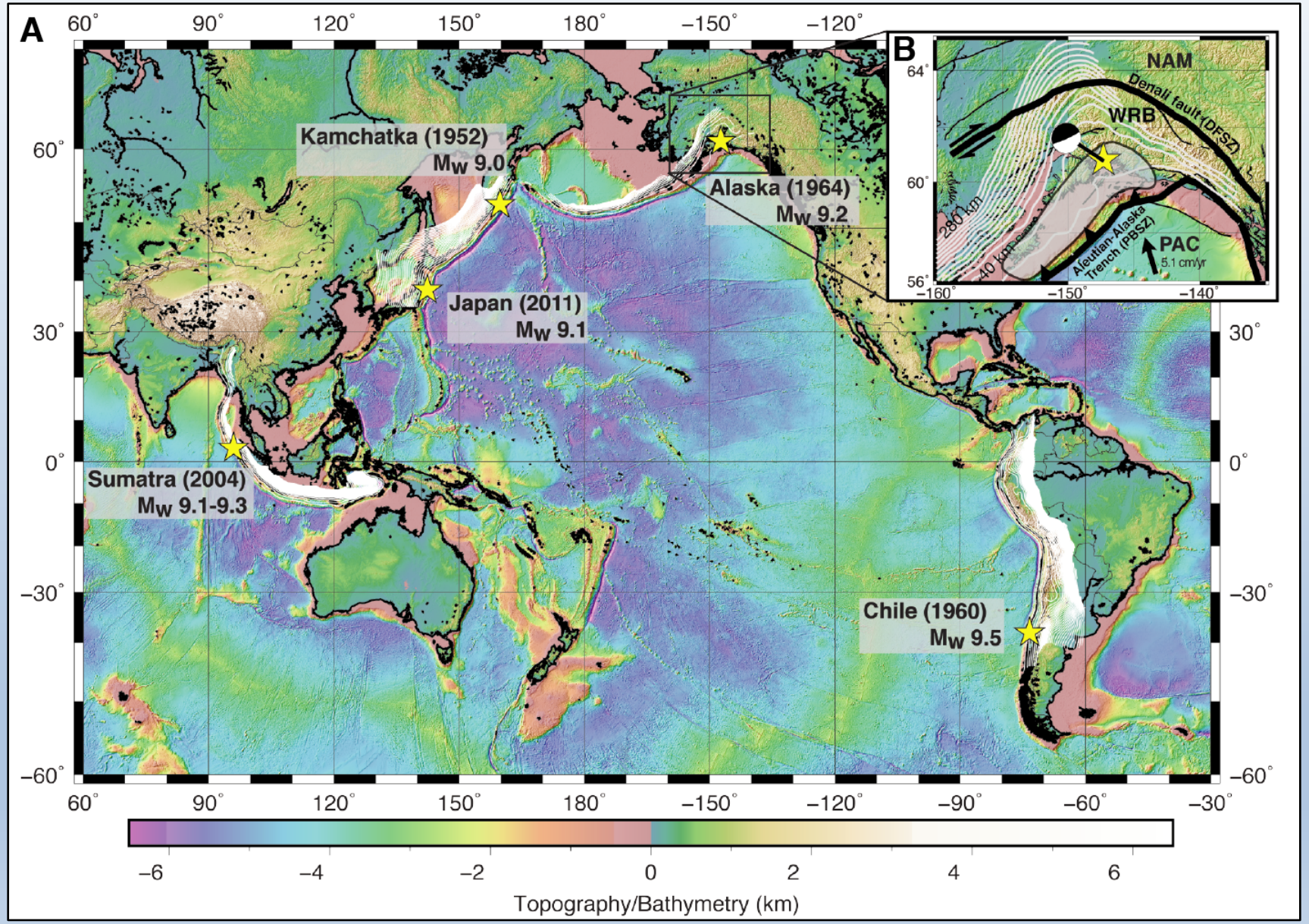
Rohr & Furlong, 95
Zhong & Gurnis, 96
Hall et al., 00
Billen et al., 03
Syracuse & Abers, 06
Kneller & van Keken, 07
Schellart et al., 07
Ammon et al., 08
Jadamec & Billen, 10





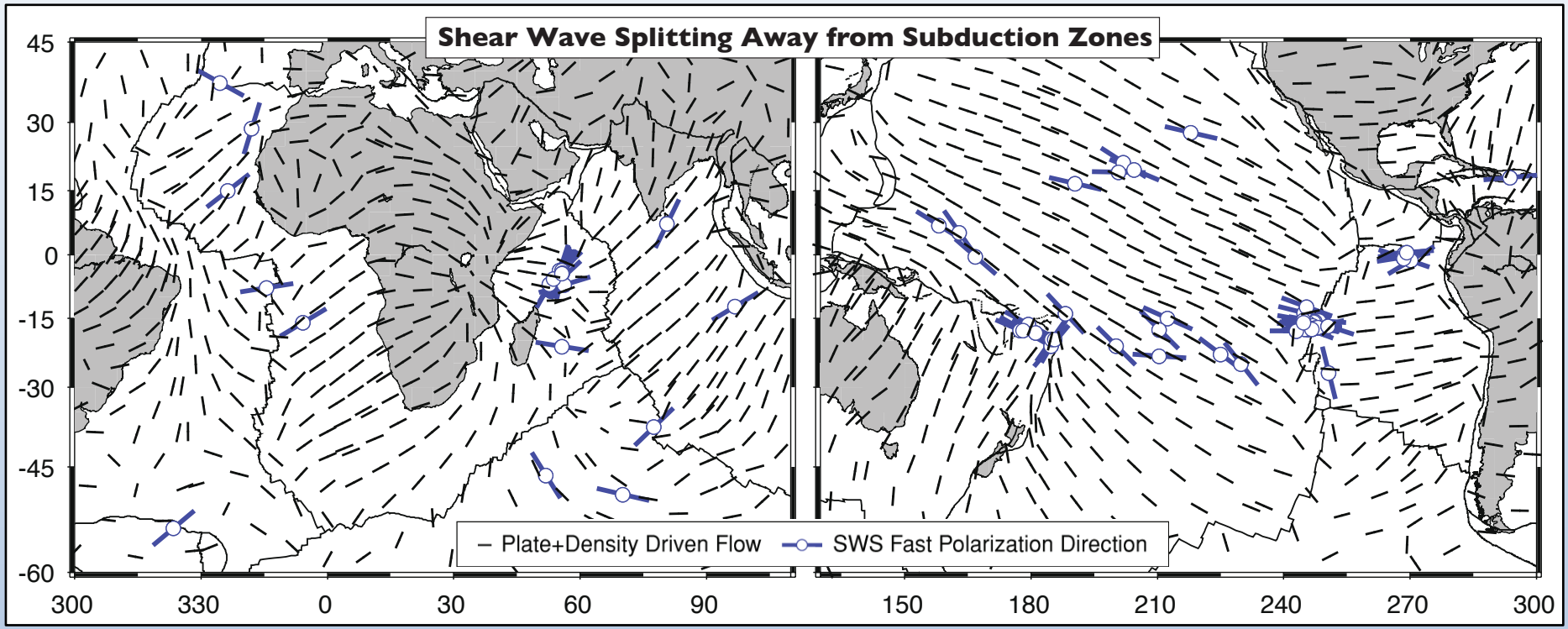
Bird 2003

Plate Tectonics and Locations of Great Earthquakes



Haynie and Jadamec, 2019, To be Submitted Science

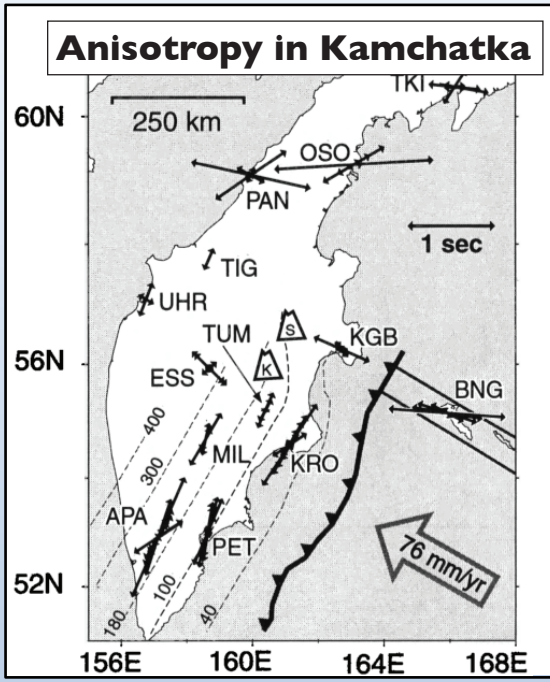
What About the Mantle Underneath the Plates?



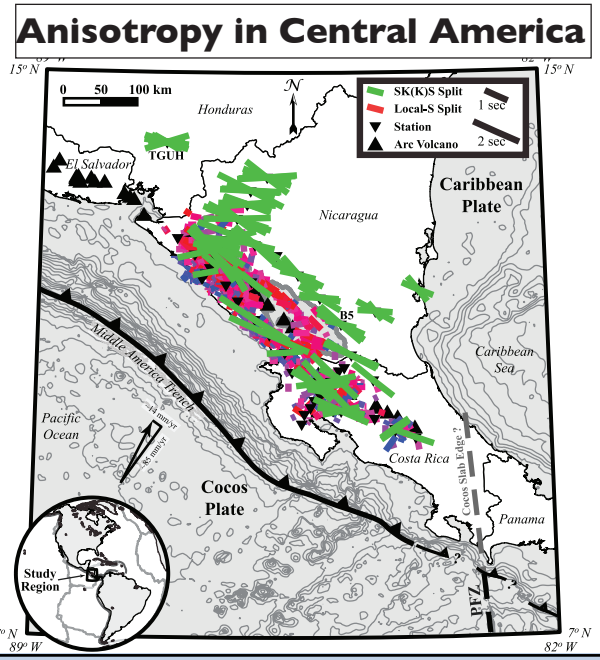
Conrad et al., JGR 2007; Long and Silver, Surv. Geophys. 2009

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)

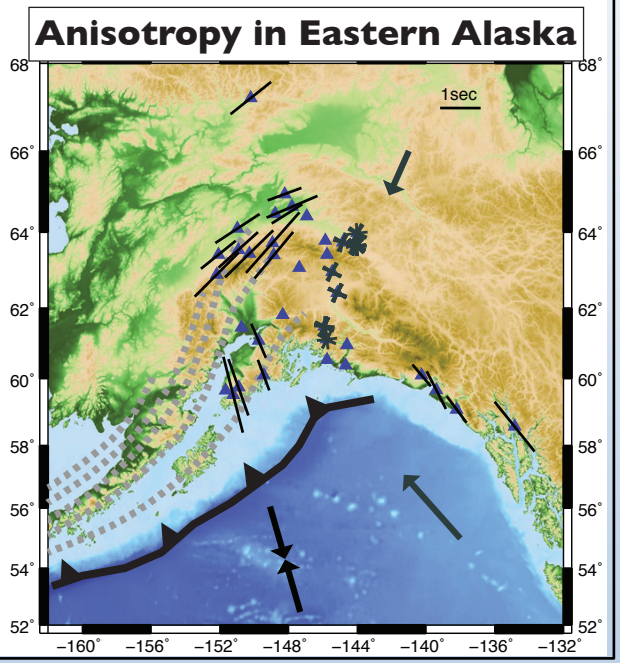
Plate Mantle-(de)coupling & Is Complex Flow Common?



Peyton et al., GRL 2001



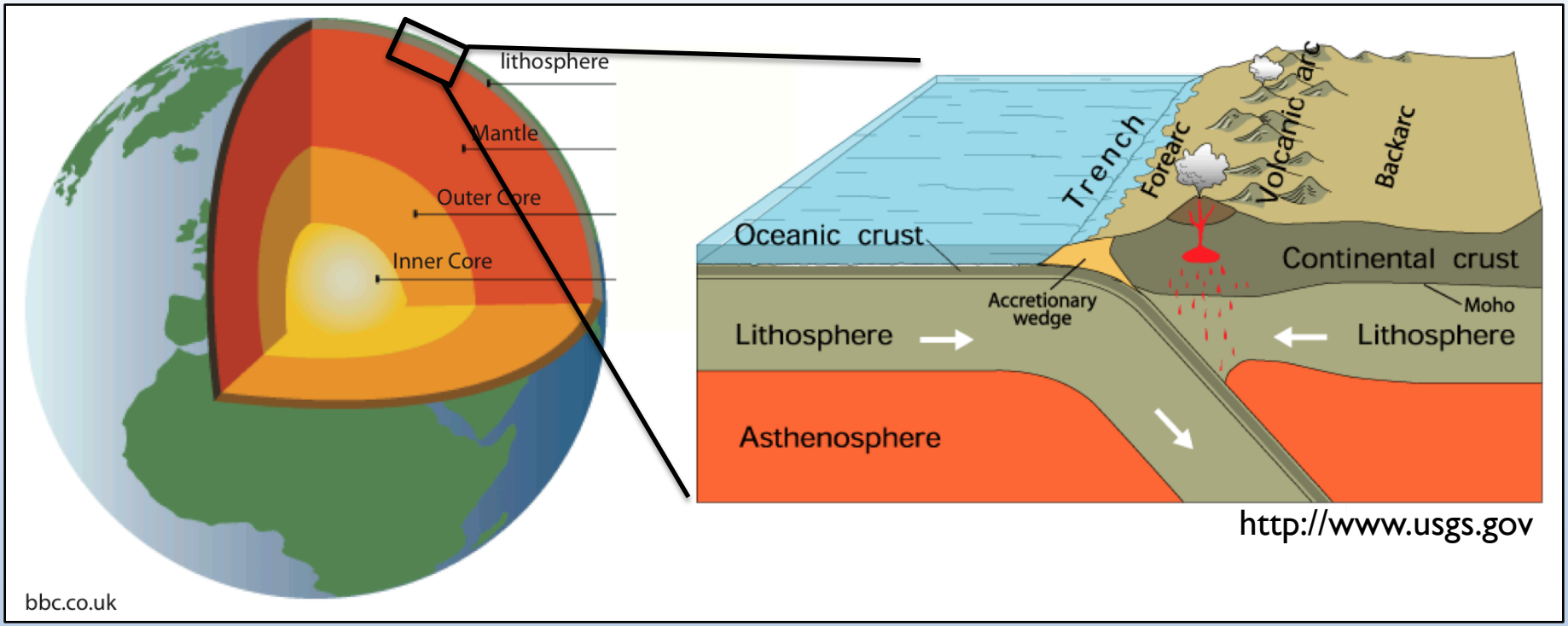
Abt et al., JGR 2010



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)

Plate Tectonics: Subduction at Convergent Boundary



- Outer layer of Earth composed of ~ 15 plates (~150 km thick)
- Plates in motion with respect to one another
- Approximate long-term def. Earth as highly viscous fluid (~10^{20} Pa s)
- Subduction zones occur at convergent plate margins where one plate descends beneath another plate into the viscous mantle
- *Deformation concentrated at the plate boundaries*