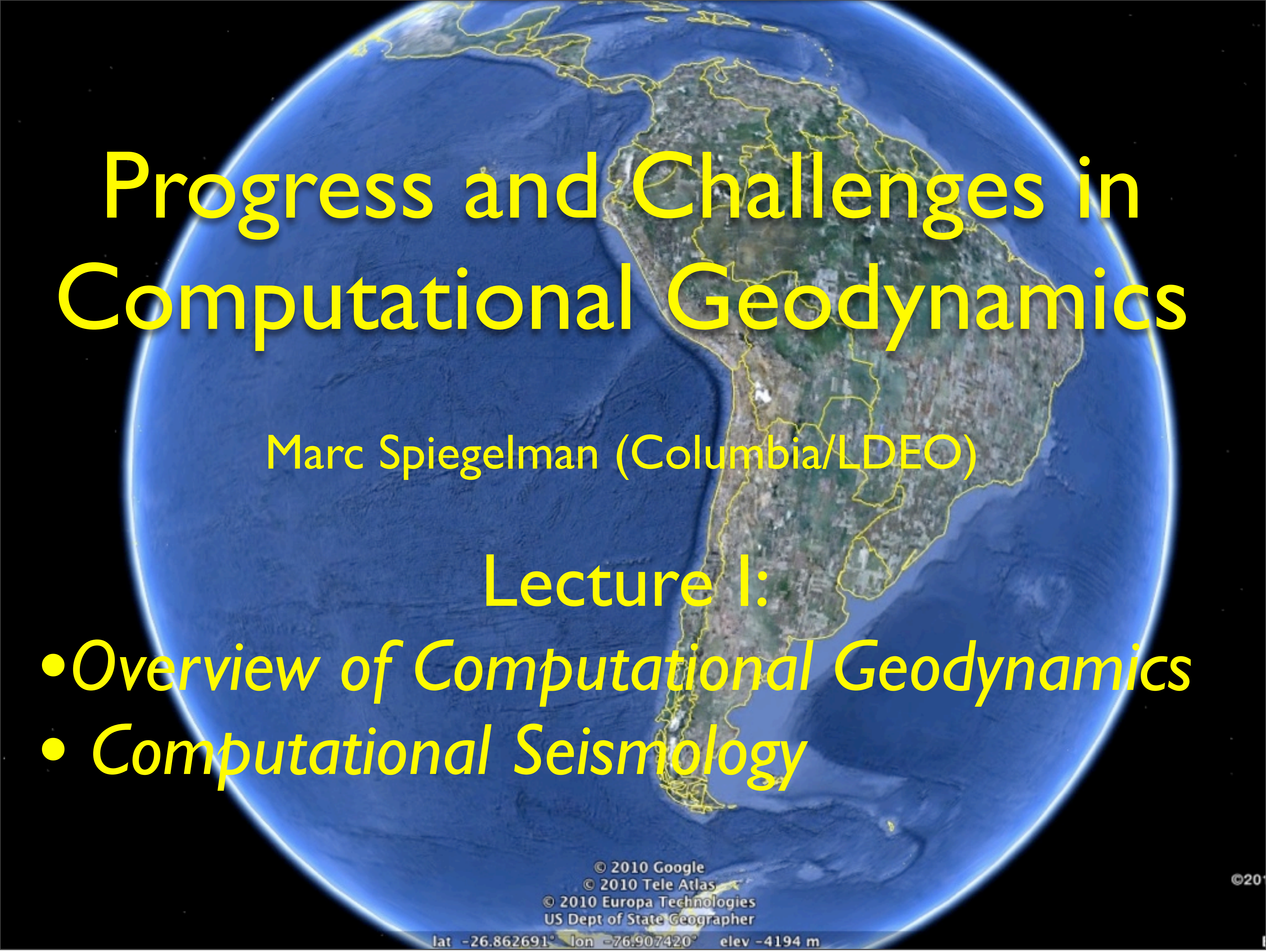


Progress and Challenges in Computational Geodynamics

Marc Spiegelman (Columbia/LDEO)

Lecture I:

- *Overview of Computational Geodynamics*
- *Computational Seismology*

Overview of Lectures

- Lecture I: The Context: Plate Tectonics and Computational Seismology
- Lecture II: Solid Mechanics - Mantle Convection/ Lithospheric Deformation/Earthquake Physics
- Lecture III: Magma Dynamics - coupled fluid-solid problems
- Lecture IV: Putting it all together, toward a consistent computational framework for complex multi-physics problems

Lecture 1

- Introduction to Solid Earth Geoscience:
  - Plate Tectonics 101
  - Overview of Computational Geodynamics
- Computational Seismology
  - The Forward Problem
  - Math, Methods, performance
  - The Inverse Problem
- Available Software: the SPECFem family of HP codes

Plate Tectonics 101

~14 nearly rigid plates in relative motion

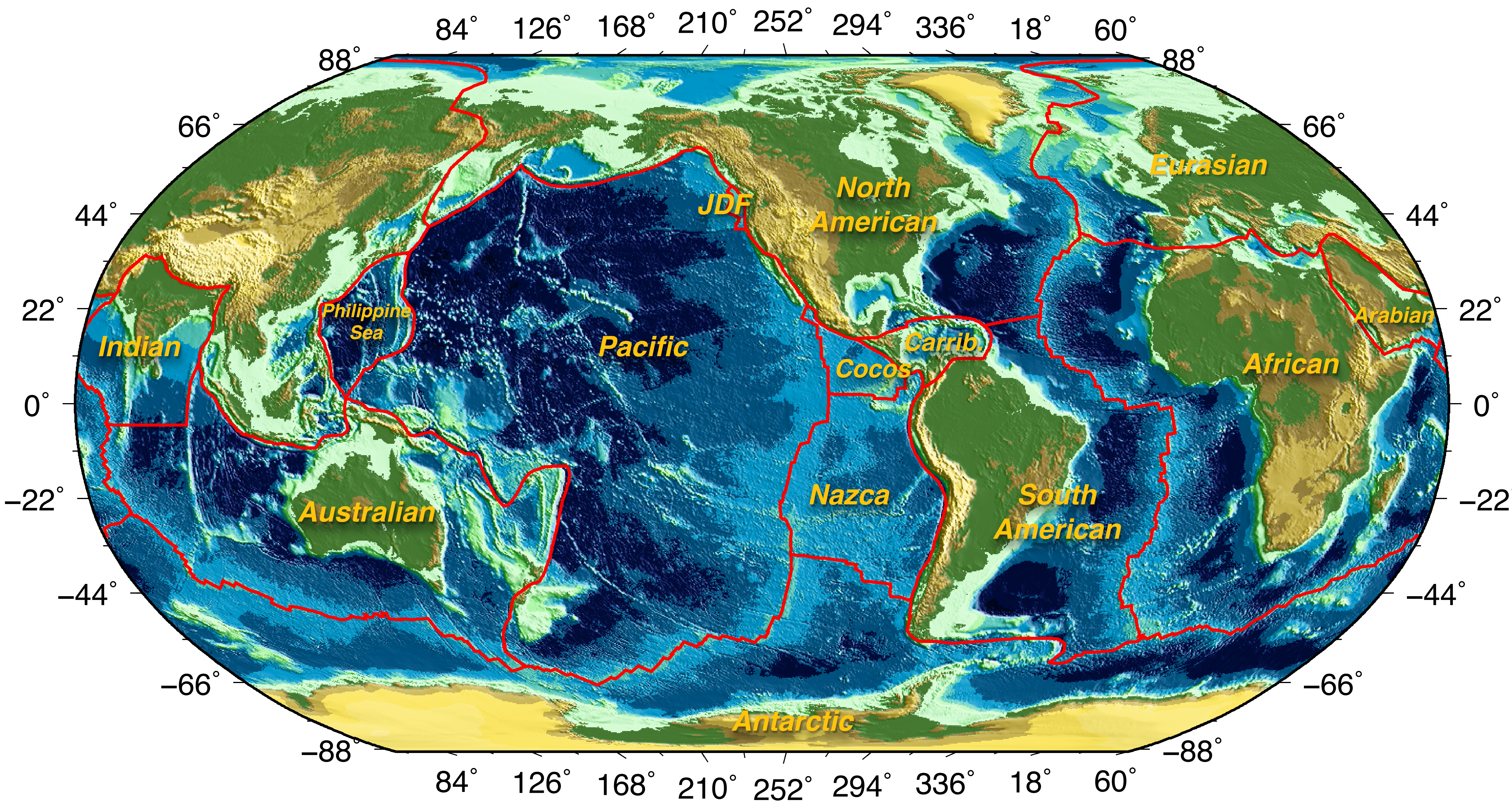


Plate Tectonics 101

Plate Velocities

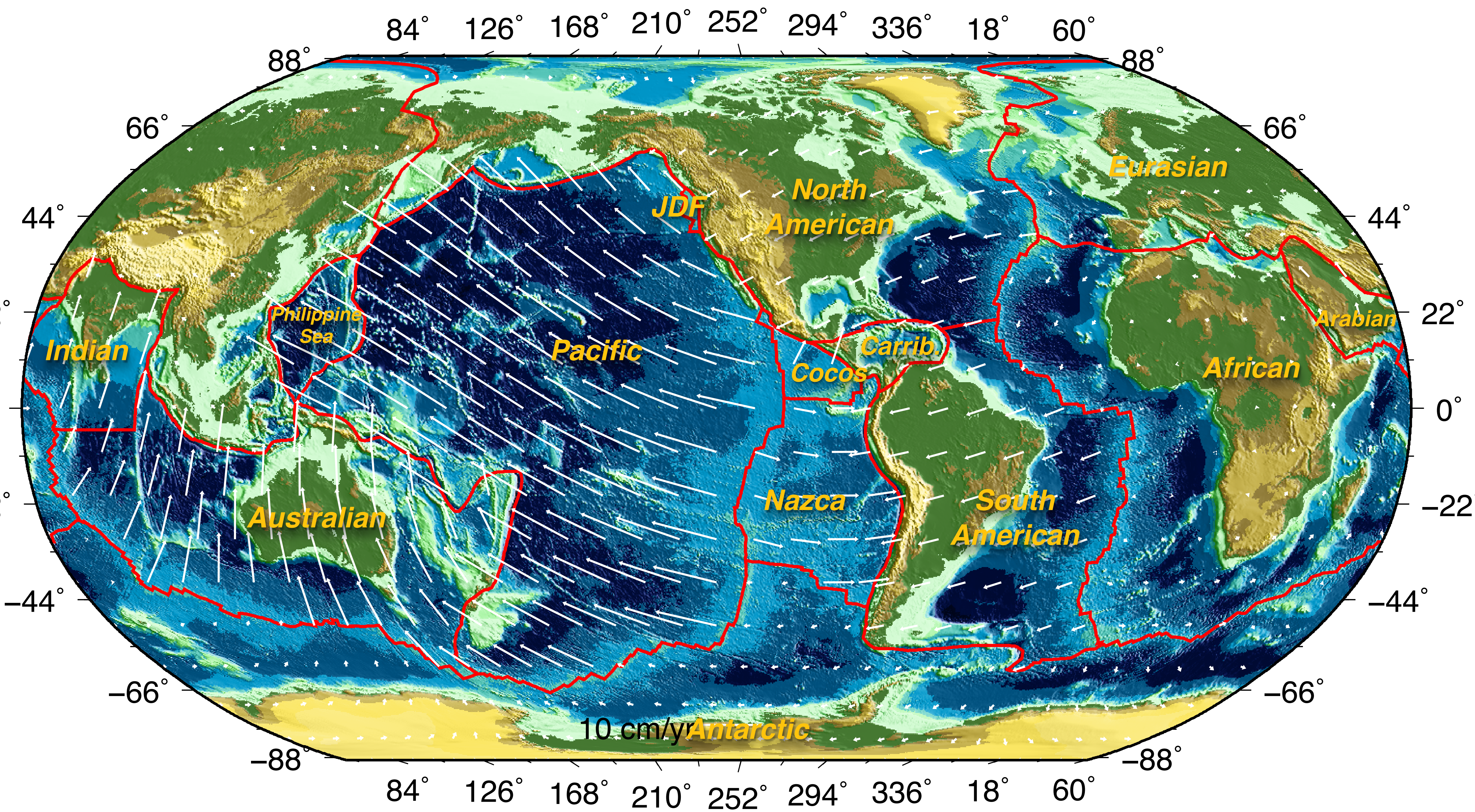
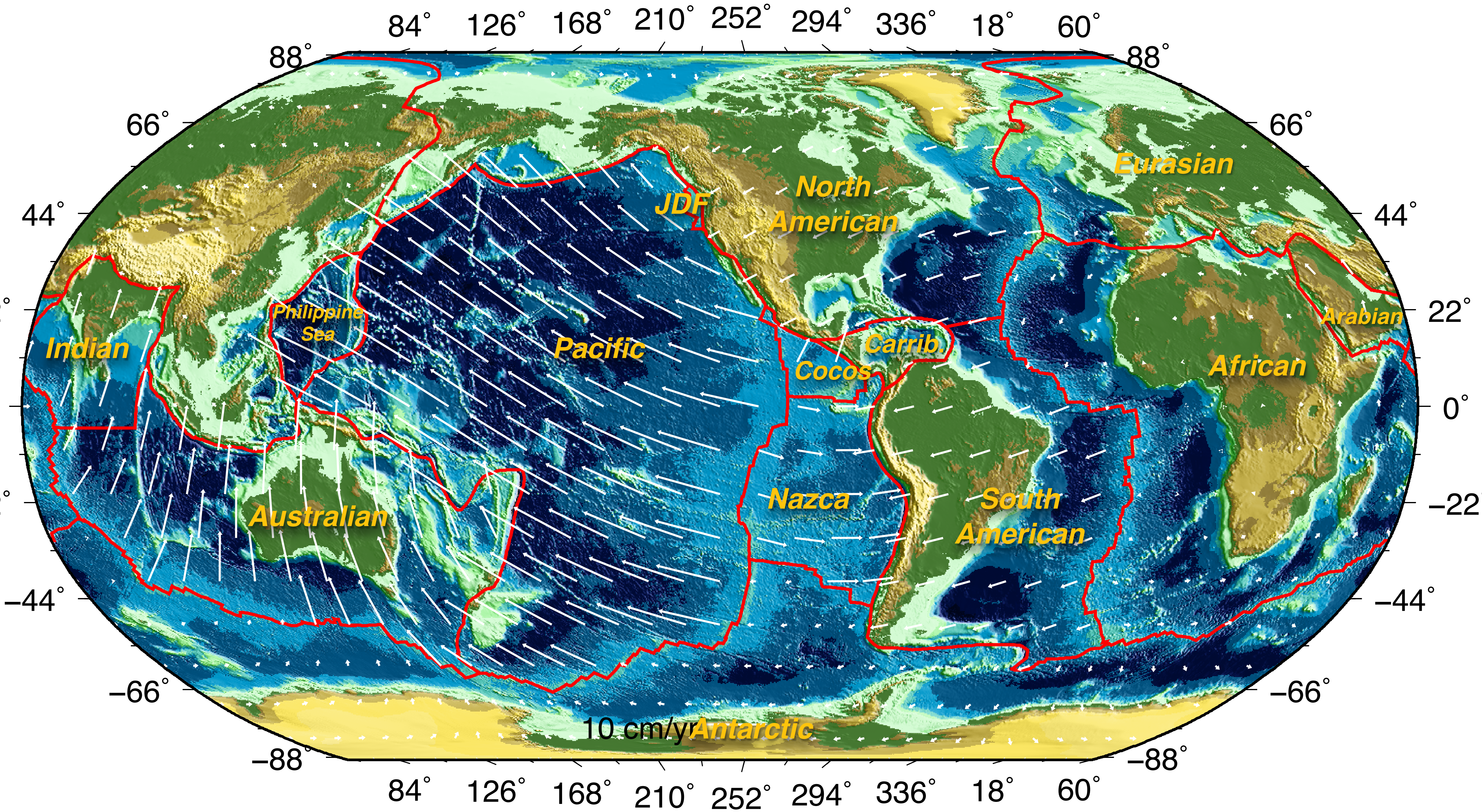


Plate Tectonics 101

Types of Plate Boundary



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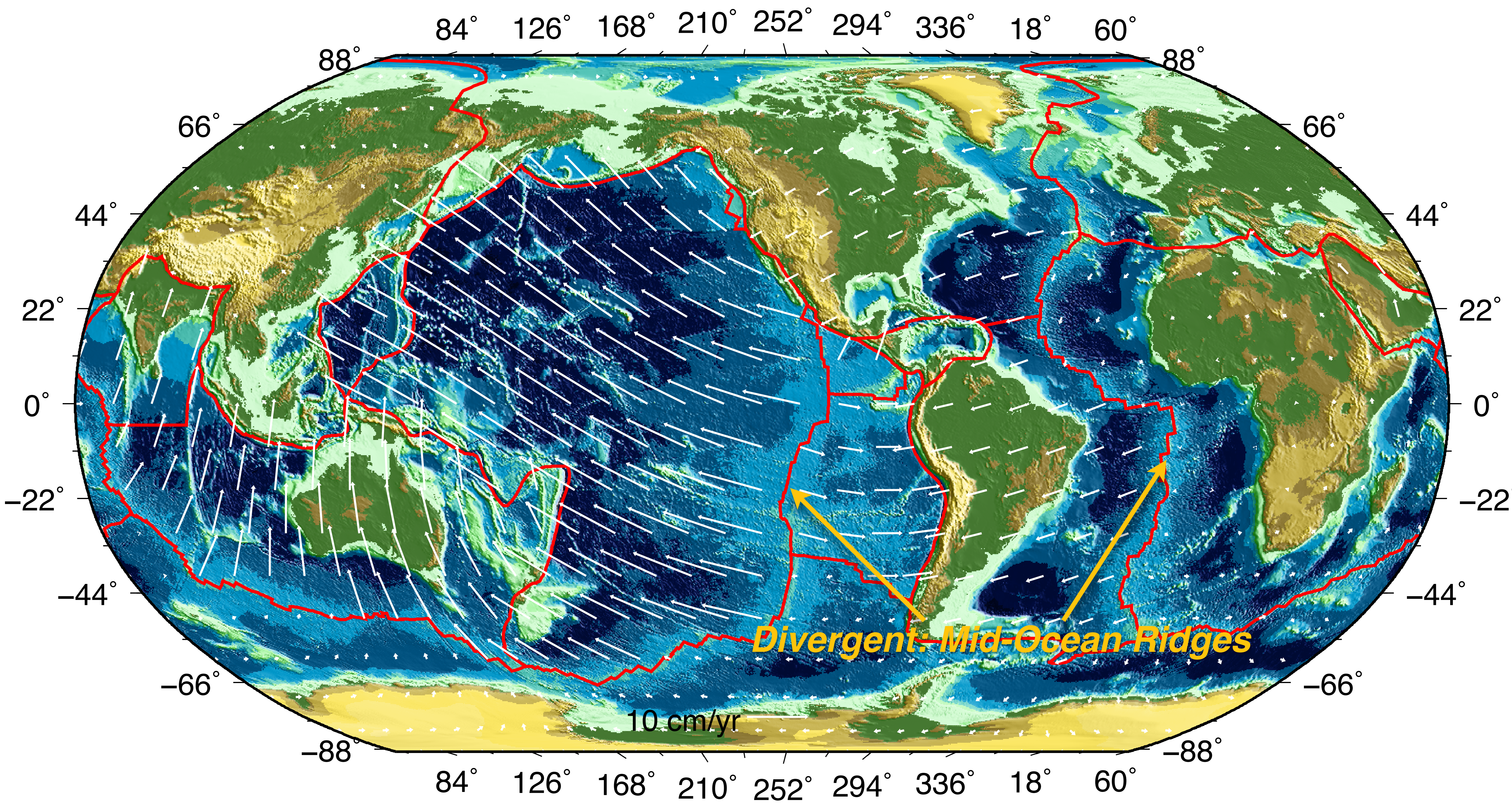

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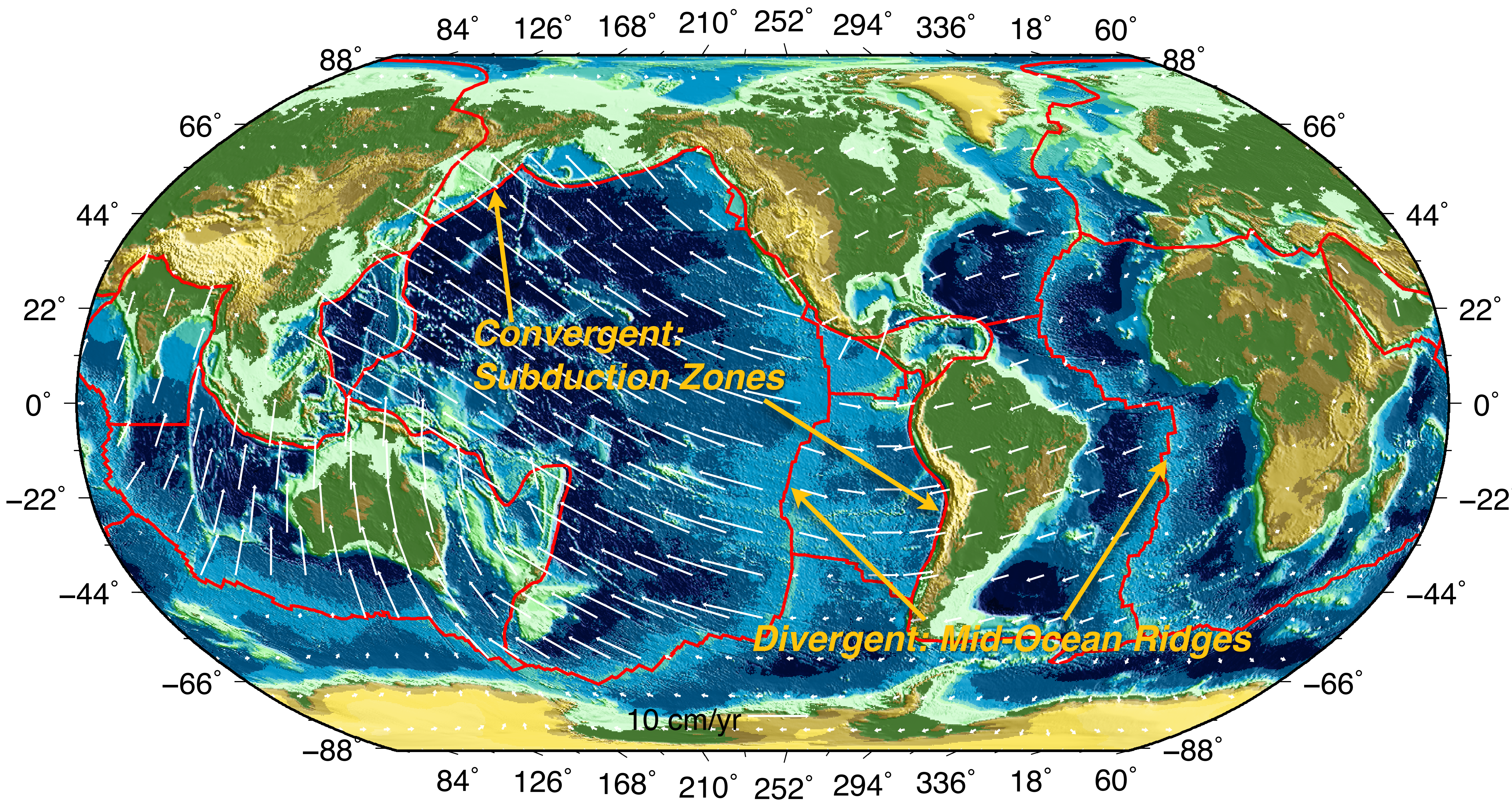

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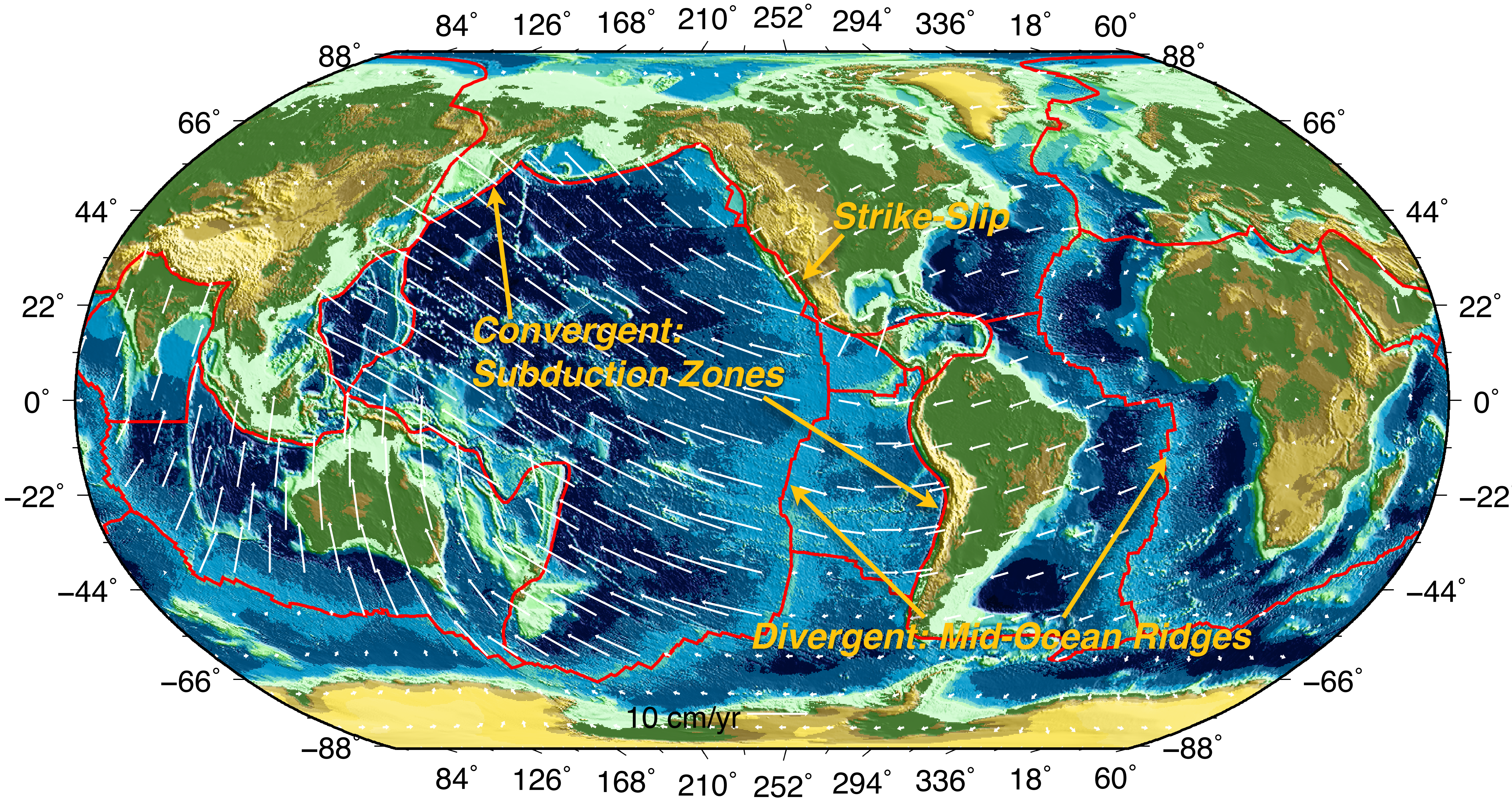

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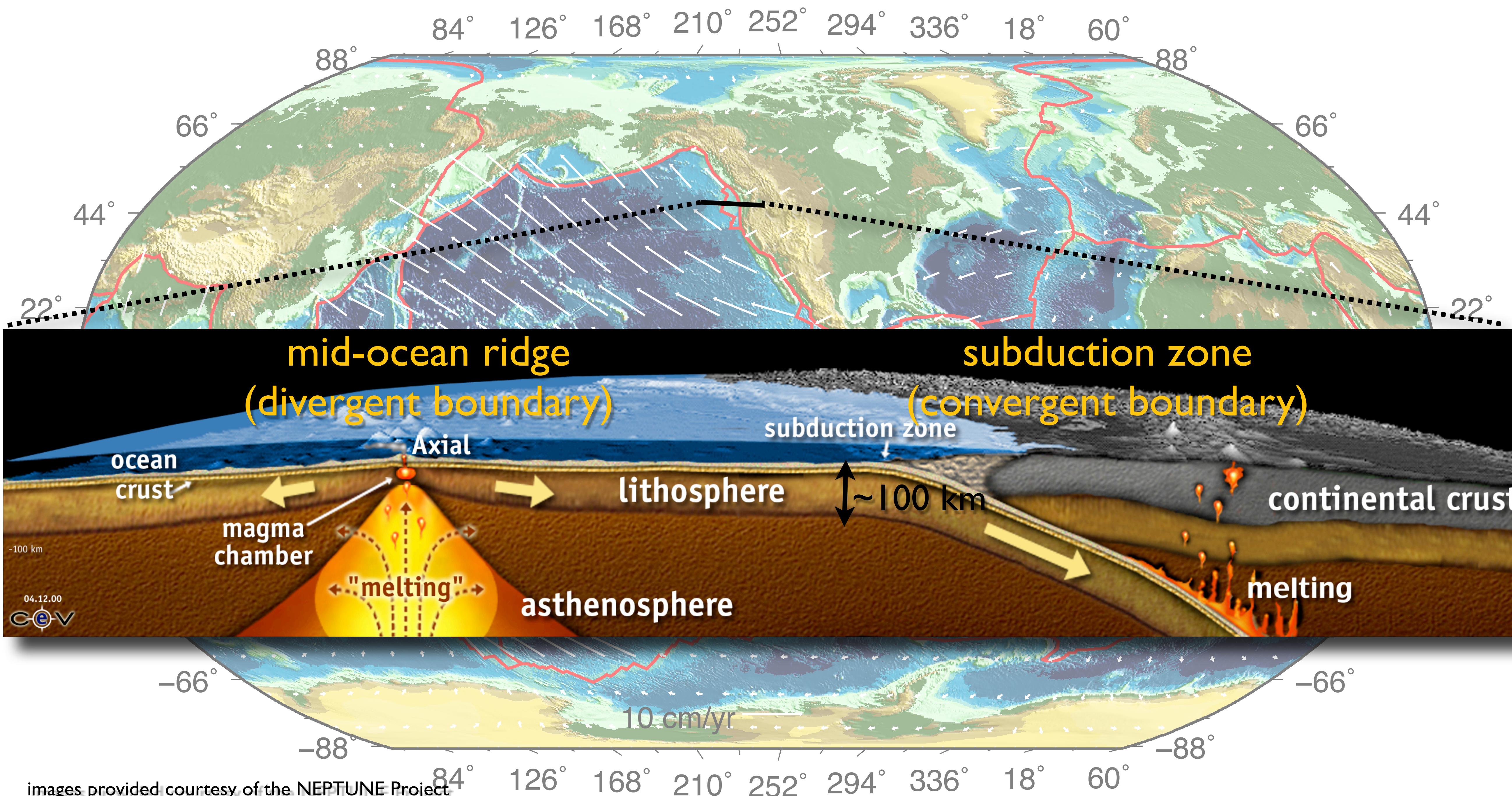

images provided courtesy of the NEPTUNE Project (www.neptune.washington.edu) and CEV

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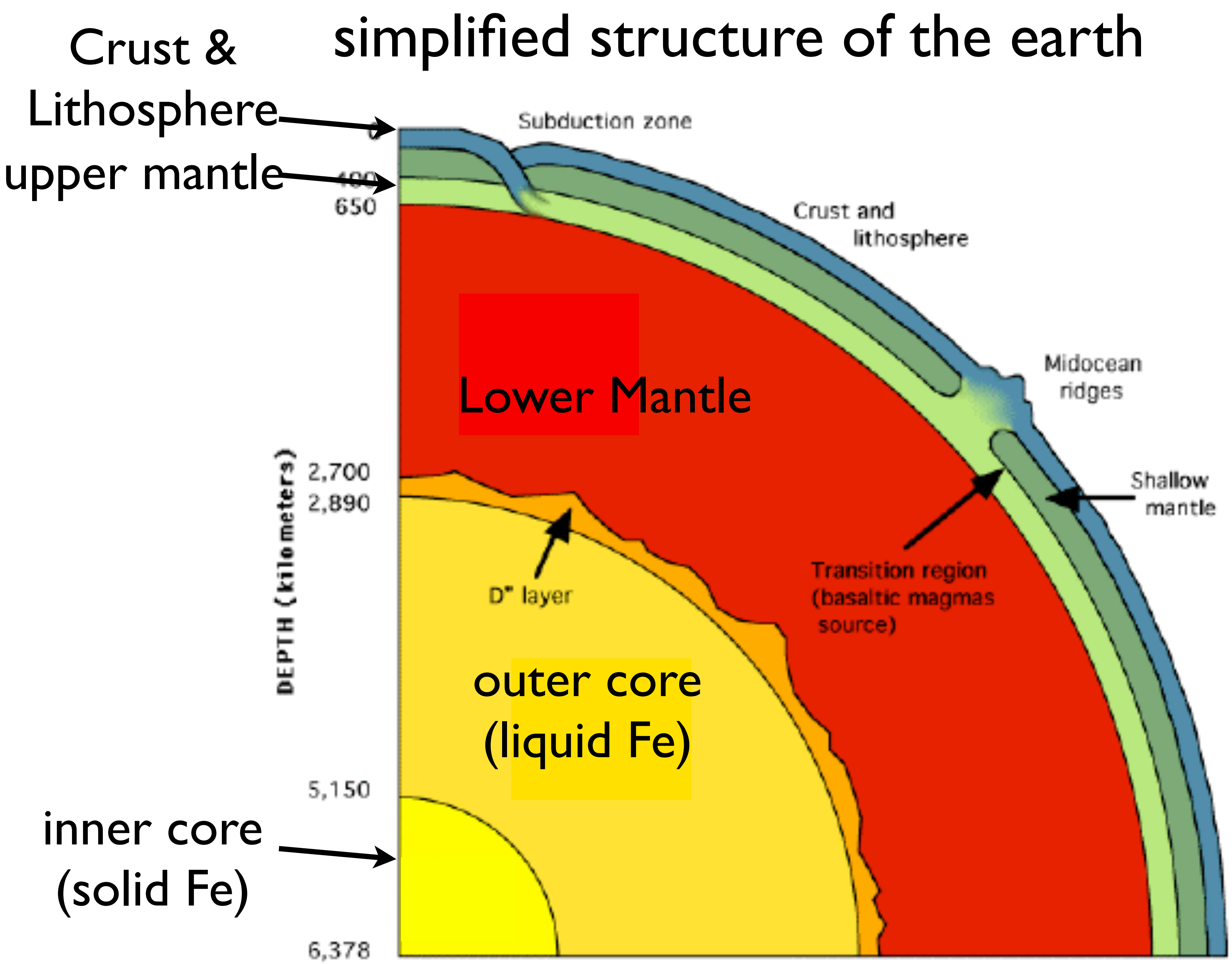

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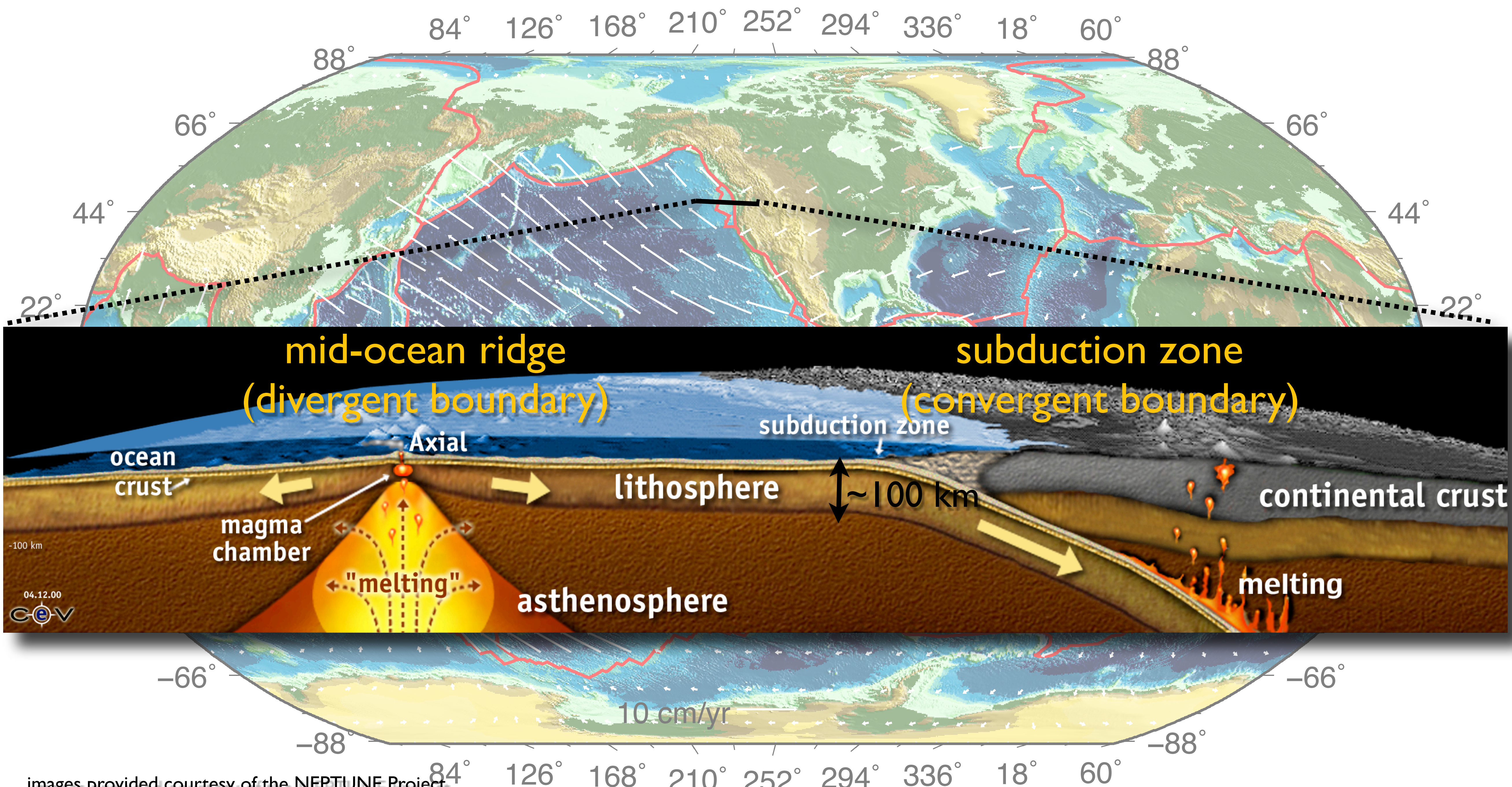


images provided courtesy of the NEPTUNE Project (www.neptune.washington.edu) and CEV

Plate Tectonics 101

Global Distribution of on land Volcanoes

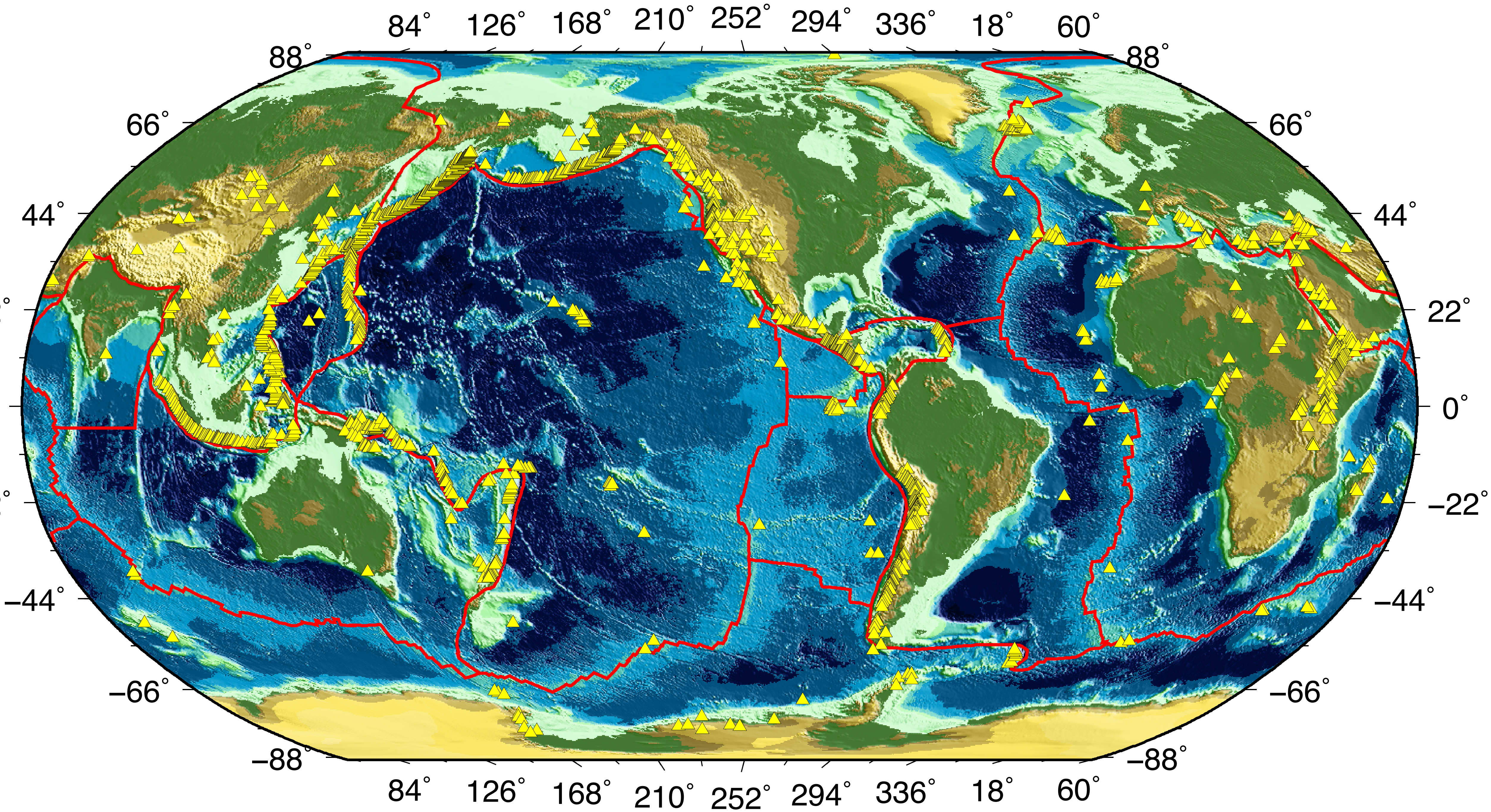


Plate Tectonics 101

Earthquakes > M5

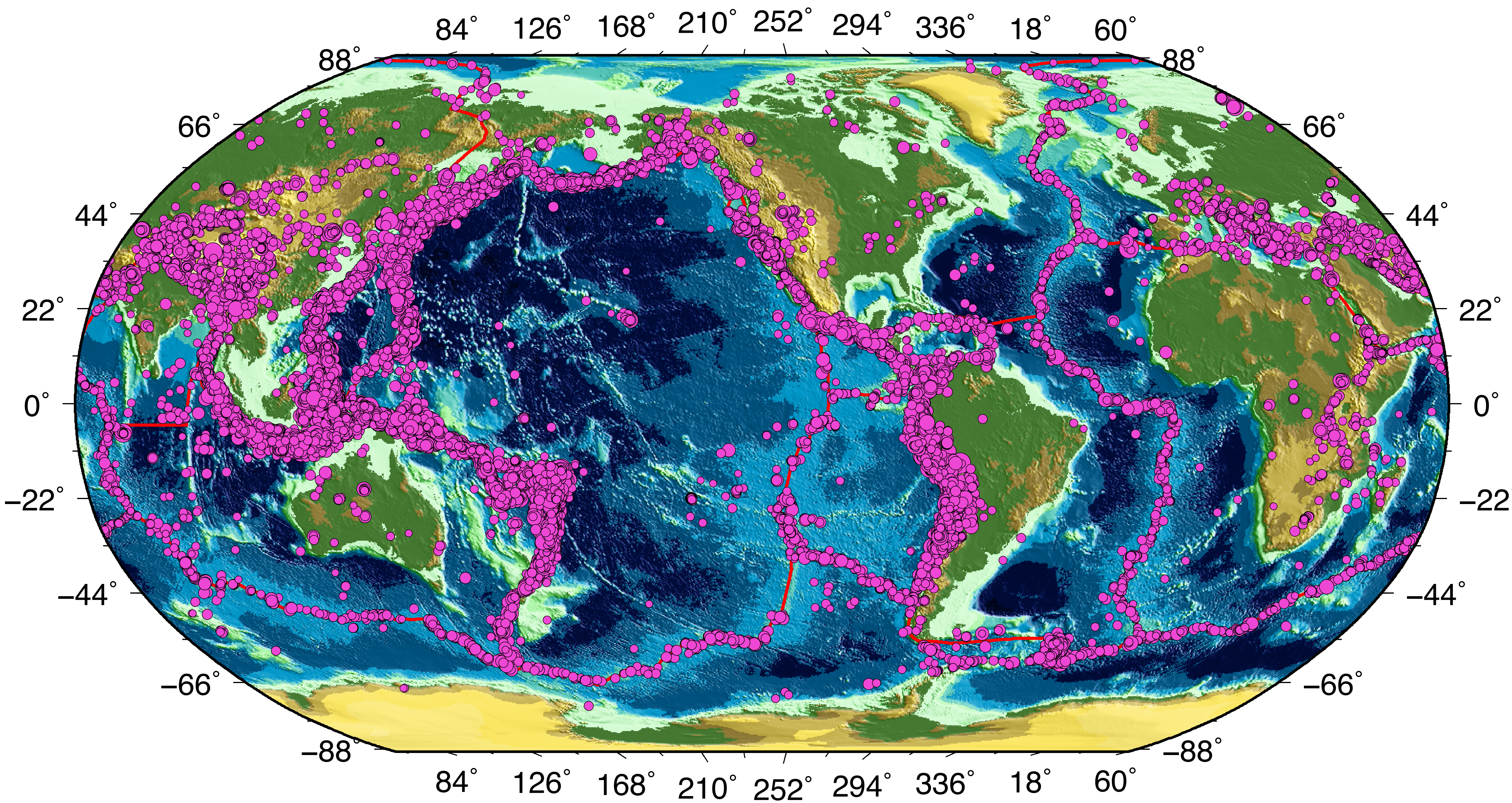
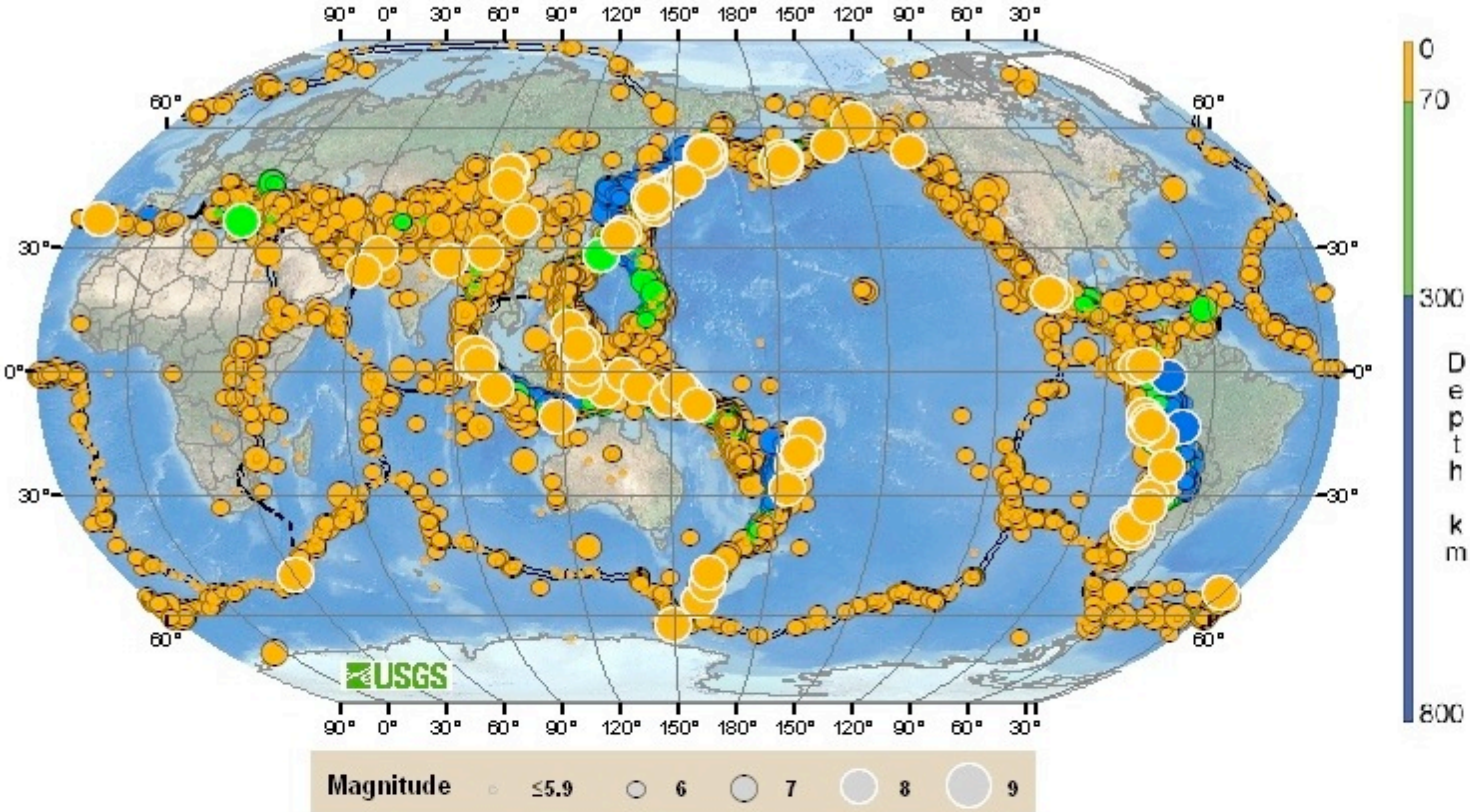


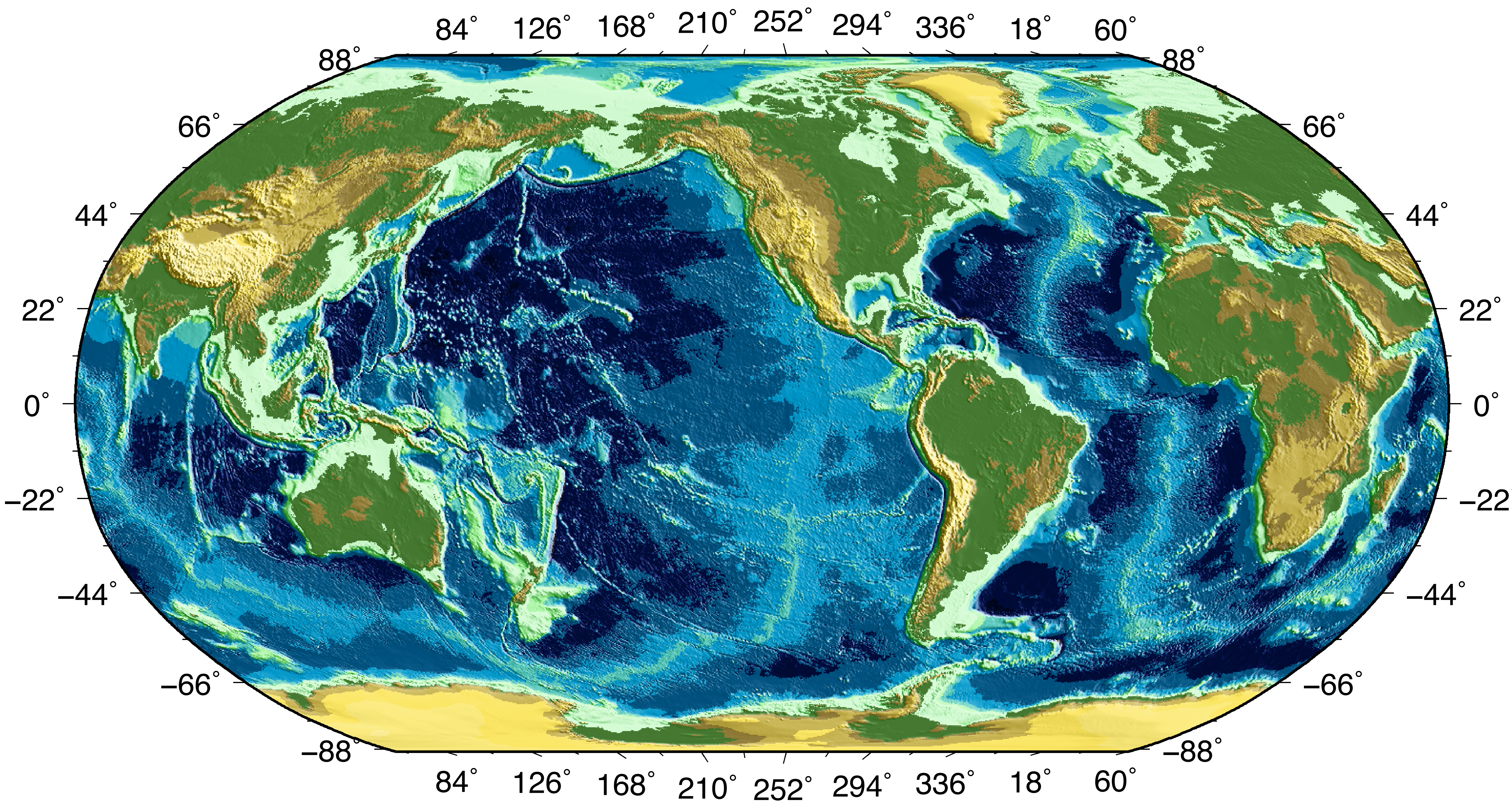
Plate Tectonics 101



http://earthquake.usgs.gov/earthquakes/world/seismicity/index.php

Plate Tectonics 101

Just Topography



What we would like to know

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- ***Structure and Properties*** of Earth's Interior

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- ***Dynamics*** of Plate Tectonics/Global Mantle Convection

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- ***Structure and Properties*** of Earth's Interior
- ***Dynamics*** of Plate Tectonics/Global Mantle Convection
- ***Dynamics*** of Plate Boundaries
  - ***Physics/Predictability*** of Earthquakes and Volcanoes

What we actually know

- Detailed surface plate motions to ~200 Ma
- Geophysical Observations
  - Earthquake locations, Seismograms, Topography, Gravity, Magnetics
- Geochemical Observations
  - composition of earth materials (periodic table plus half the table of isotopes)

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PROXY DATA

The Role of Computational Science in Solid Earth Geodynamics

The Role of Computational Science in Solid Earth Geodynamics

- ***Quantitative Models*** provide the link between what we want to know and what we can actually observe.

The Role of Computational Science in Solid Earth Geodynamics

- ***Quantitative Models*** provide the link between what we want to know and what we can actually observe.
- ***Advanced computation*** has always been an important component of solid earth geoscience because the Earth is
  - too big, too slow and can't build the laboratory experiment (similar to astrophysics)

The Role of Computational Science in Solid Earth Geodynamics

2 of 6 2010 Gordon Bell finalists were in solid earth Geoscience

PRESENTATION	SPEAKER
190 TFlops Astrophysical N-body Simulation on a Cluster of GPUs	Tsuyoshi Hamada, Keigo Nitadori
Extreme-Scale AMR	Carsten Burstedde, Omar Ghattas, Michael Gurnis, Tobin Isaac, Georg Stadler, Tim Warburton, Lucas Wilcox
Scalable Earthquake Simulation on Petascale Supercomputers	Yifeng Cui, Kim B. Olsen, Thomas H. Jordan, Kwangyoon Lee, Jun Zhou, Patrick Small, Daniel Roten, Geoffrey Ely, Dhabaleswar K. Panda, Amit Chourasia, John Levesque, Steven M. Day, Philip Maechling
Multiscale Simulation of Cardiovascular flows on the IBM Bluegene/P: Full Heart-Circulation System at Red-Blood Cell Resolution	Amanda Peters, Simone Melchionna, Massimo Bernaschi, Sauro Succi, Efthimios Kaxiras, Mauro Bisson, Jonas Latt, Joy Sircar
Petascale Direct Numerical Simulation of Blood Flow on 200K Cores and Heterogeneous Architectures	Abtin Rahimian, Ilya Lashuk, Shravan Veerapaneni, Aparna Chandramowlishwaran, Dhairya Malhotra, Logan Moon, Rahul Sampath, Aashay Shringarpure, Jeffrey Vetter, Richard Vuduc, Denis Zorin, George Biros
Toward First Principles Electronic Structure Simulations of Excited	Anton Kozhevnikov, Adolfo G. Eguiluz, Thomas C. Schulthess

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The Role of Computational Science in Solid Earth Geodynamics

SC10 New Orleans, LA The Future of Discovery

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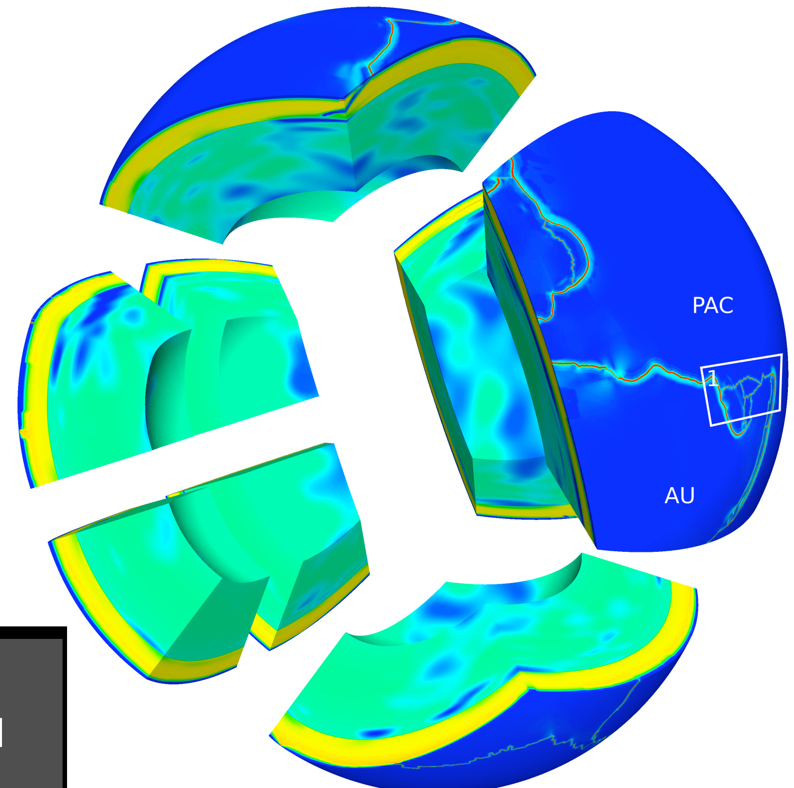

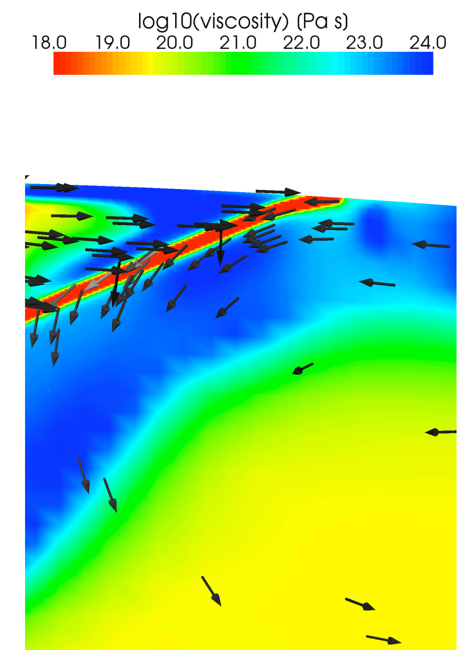

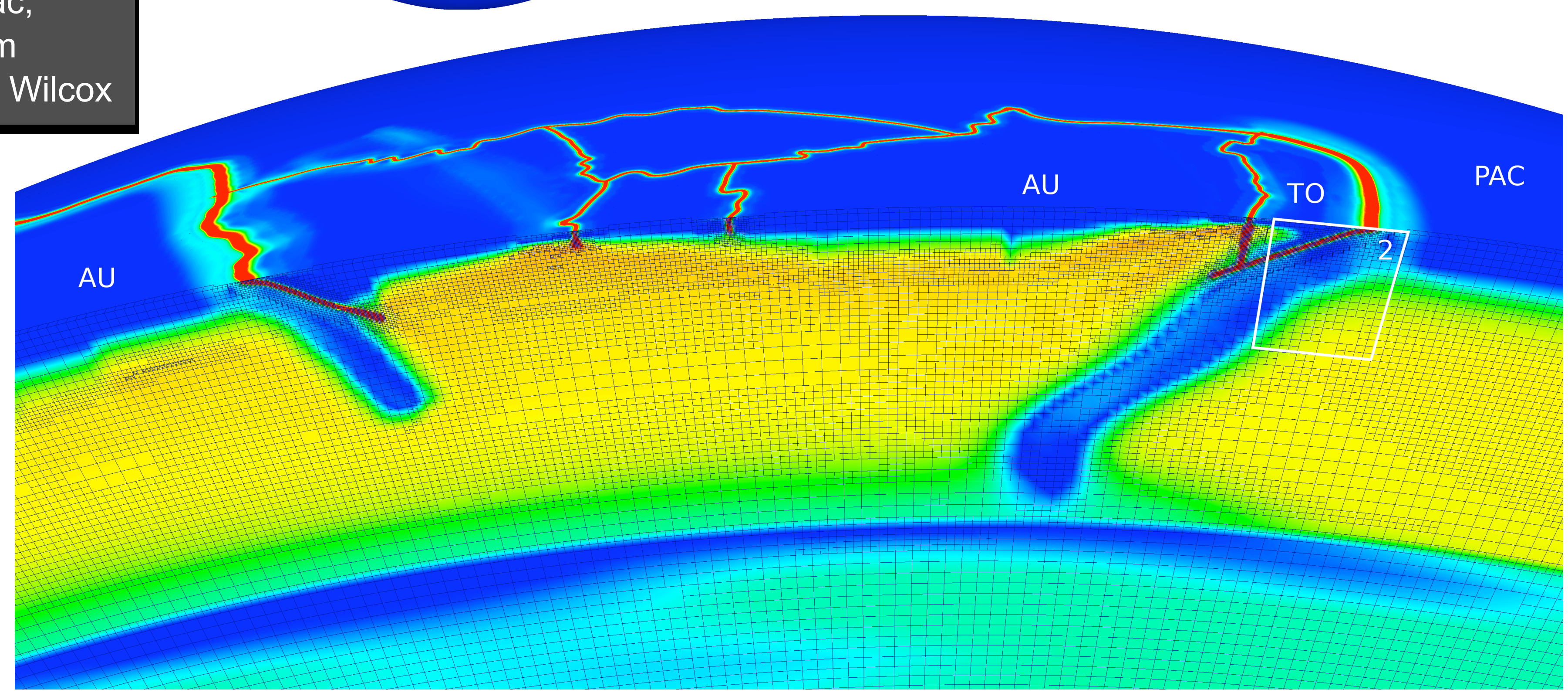

3-D FEM AMR Mantle Convection code

- 150 million Elements
- 55,100 Cores (Jaguar)

The Role of Computational Science in Solid Earth Geodynamics

Scalable Earthquake Simulation on Petascale Supercomputers

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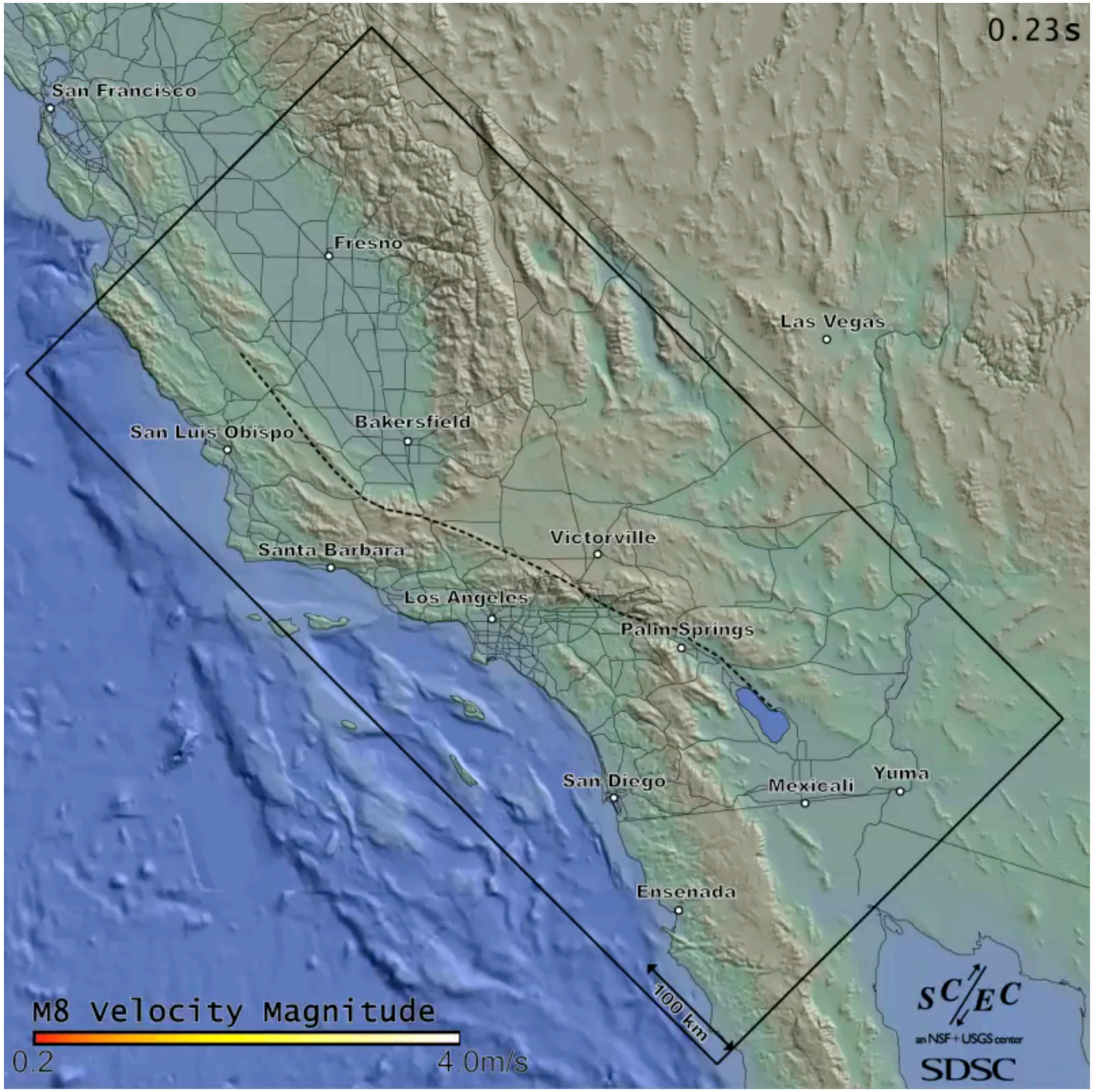
http://visservices.sdsc.edu/projects/scec/m8/1.0/



Domain: 810 x 405 x 100 km
h_min: 40 m
Dofs: 435 Billion
cores: 223,074 (Jaguar)
220 PFlops sustained for 24 hr
highest frequency 2 hz

The Role of Computational Science in Solid Earth Geodynamics

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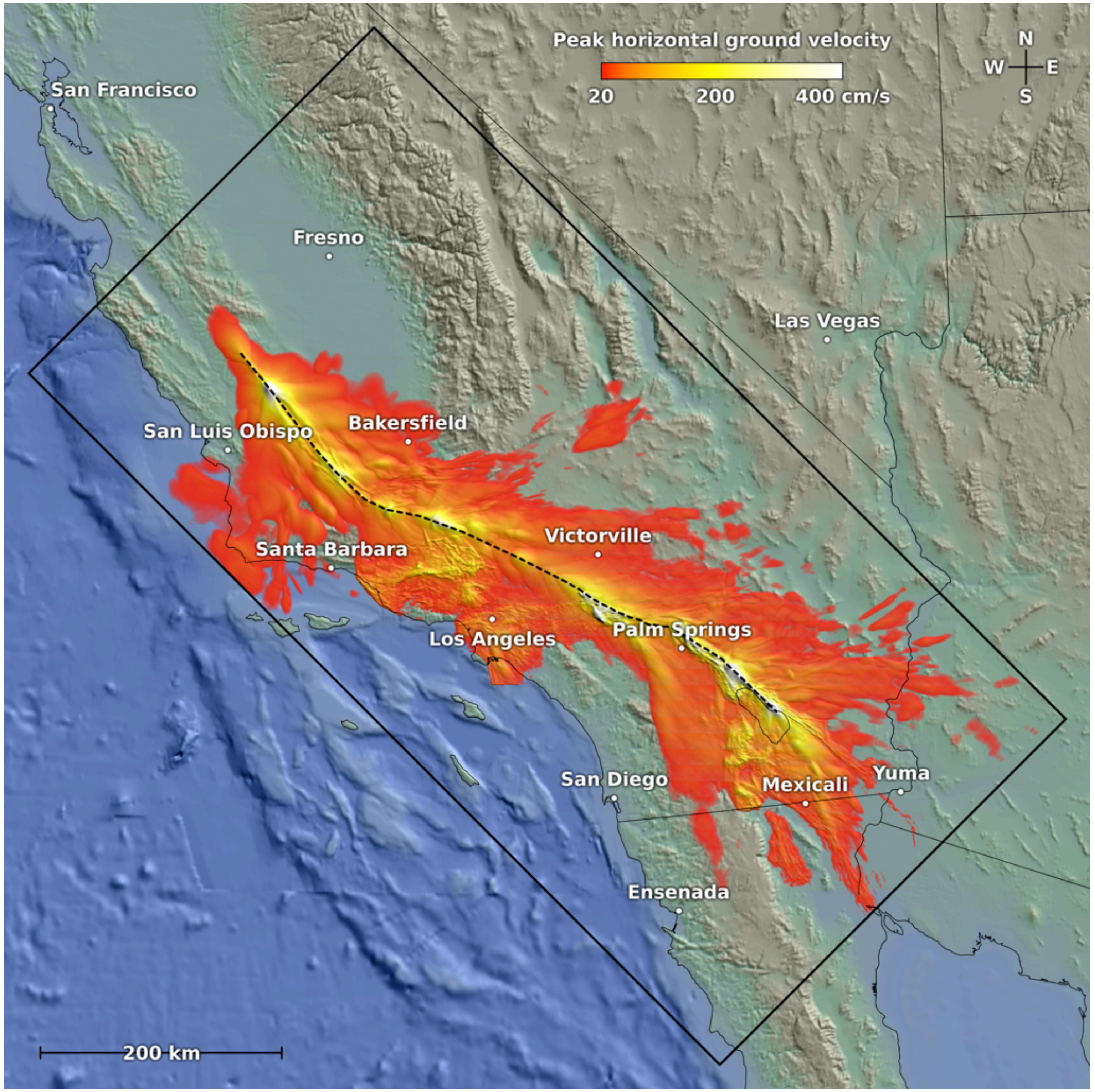

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The Role of Computational Science in Solid Earth Geodynamics

- ***3 Principal Problems in Computational Geodynamics***
  - Computational Seismology
  - Solid Mechanics: Mantle Convection, Continental Deformation, Earthquake Physics
  - Coupled Fluid/Solid Mechanics: Magma dynamics, subsurface flow/oil,water,gas

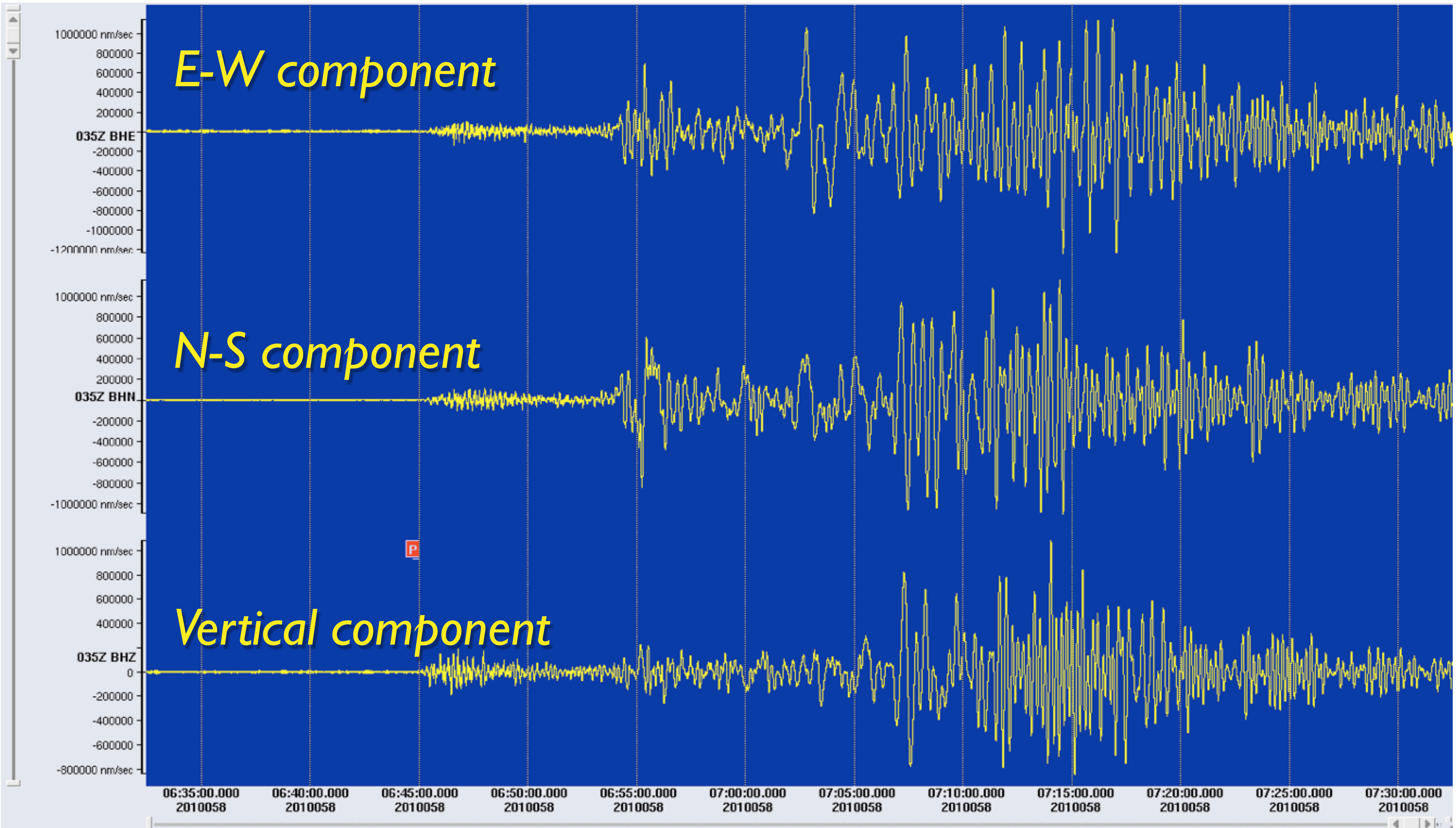
The Challenge

- Putting it all together:
  - Develop Flexible, Interoperable, Open Source, high performance computational tools for exploring a wide range of multi-scale/multi-physics geodynamic models.
  - Use any insight gained to understand both fundamental Earth Science and guide policy/ mitigate against natural hazards.
- This is the goal of the Computational Infrastructure for Geodynamics (CIG) (www.geodynamics.org)

Computational Seismology

Simulation of 2011 January 2, Mw =7.1 Chile Earthquake wavefield using SPECFem3D_Globe.
Red: upward motion Blue: downward motion. http://global.shakemovie.princeton.edu/
Tromp et al, 2010, *GJI* 183, 381-389

Computational Seismology
Data



3 component Broad Band Seismogram of 26 Feb 2010,
8.8 Mb Earthquake offshore Maule, Chile from USArray station 035Z
http://anf.ucsd.edu/spevents/2010/058/a/

Computational Seismology
Sensors

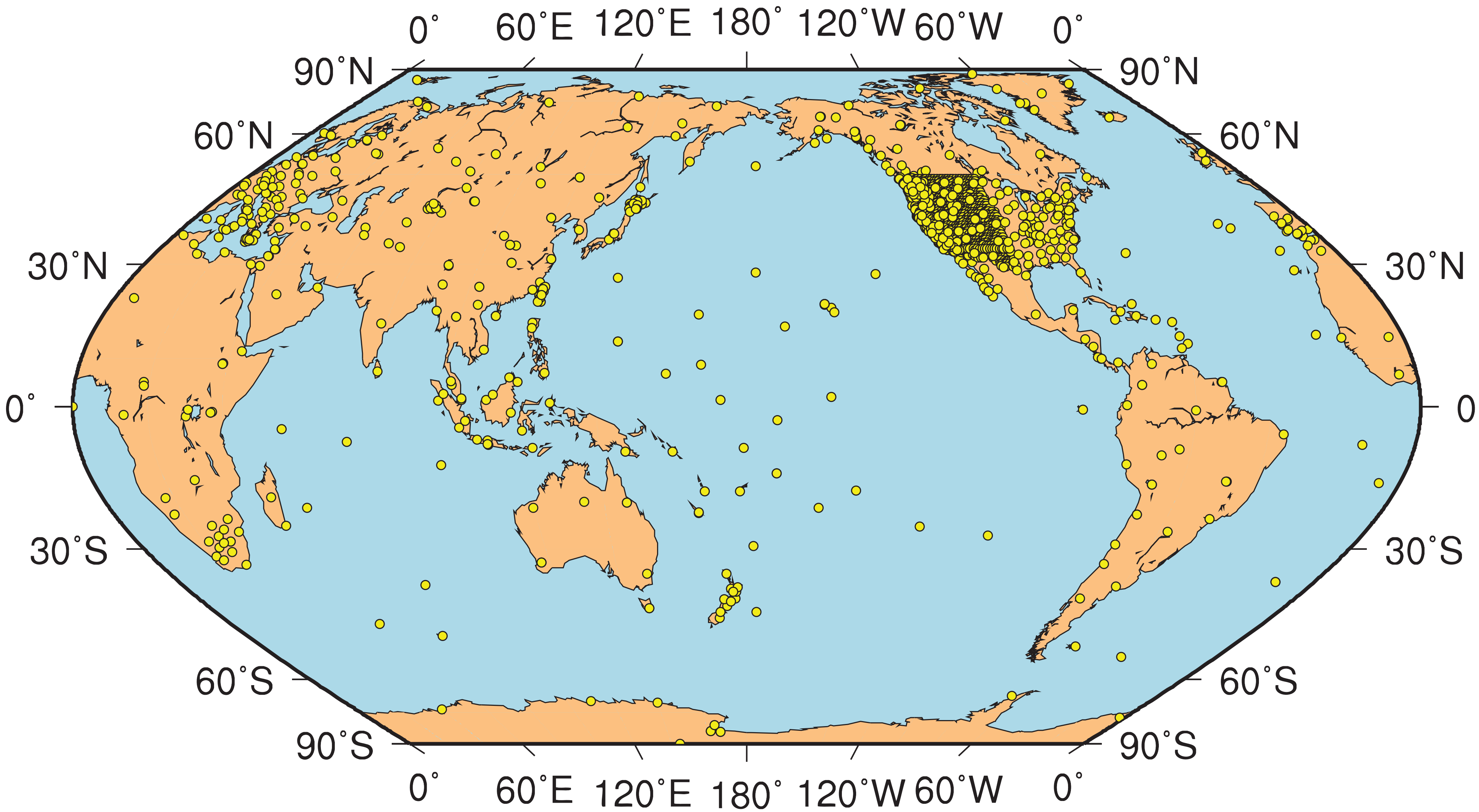


Figure 1. Map showing locations of 1838 seismographic stations supported by members of the FDSN (yellow dots). At each of these locations, the near real-time system provides three-component normal-mode synthetics for the 1-D PREM (Dziewoński & Anderson 1981) and SEM synthetics for 3-D model S362ANI (Kustowski *et al.* 2008) plus Crust2.0 (Bassin *et al.* 2000). The synthetics capture R1 and G1 at all epicentral distances for CMT events with $M_{\mathrm{w}} < 7.5$, and R2 and G2 for CMT events with $M_{\mathrm{w}} \geq 7.5$.

Computational Seismology Fundamental Questions

Given heterogeneous distribution of sources (plate boundaries) and sparse set of receivers, can we

- Accurately locate Earthquakes?
- Infer dynamics of earthquake rupture? (Eq. Seismology)
- Develop high resolution image of earth's interior? (Structural Seismology)

- To do all of this requires modeling and extracting information from seismograms

Computational Seismology
The Forward Problem

Strong Form: Elastic Wave propagation

$$\rho \mathbf{u}_{tt} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{f}$$

$$\boldsymbol{\sigma} \cdot \mathbf{n} = \mathbf{0} \quad \text{on} \quad \partial\Omega$$

$$\mathbf{u} = \mathbf{0}, \quad \mathbf{u}_t = \mathbf{0} \quad \text{at} \quad \mathrm{t} = 0$$

where

elastic displacement field:	$\mathbf{u}(\mathbf{x}, t)$
stress tensor:	$\boldsymbol{\sigma} = \mathbf{C} : \varepsilon$
strainrate tensor:	$\varepsilon = 1/2(\nabla \mathbf{u} + \nabla \mathbf{u}^T)$
Earthquake Moment tensor Source:	$\mathbf{f} = -\mathbf{M}\delta(\mathbf{x} - \mathbf{x}_s)$

For isotropic Elastic media

$$\rho \mathbf{u}_{tt} = \nabla \cdot \mu(\nabla \mathbf{u} + \nabla \mathbf{u}^T) + \nabla(k - 2\mu/3)\nabla \cdot \mathbf{u} + \mathbf{f}$$

Computational Seismology
The Forward Problem

Weak Form

Choose test-functions $\mathbf{w}$ and trial functions $\mathbf{u} \in \mathcal{V}$ s.t.

$$\int_{\Omega} \rho \mathbf{w} \cdot \mathbf{u}_{tt} dV = \int_{\Omega} \nabla \mathbf{w} : \sigma dV + \mathbf{M} : \nabla \mathbf{w}(\mathbf{x}_s) \mathbf{S}(\mathbf{t})$$

$$\mathbf{u} = \mathbf{0}, \quad \mathbf{u}_t = \mathbf{0} \quad \text{at} \quad \mathrm{t} = 0$$

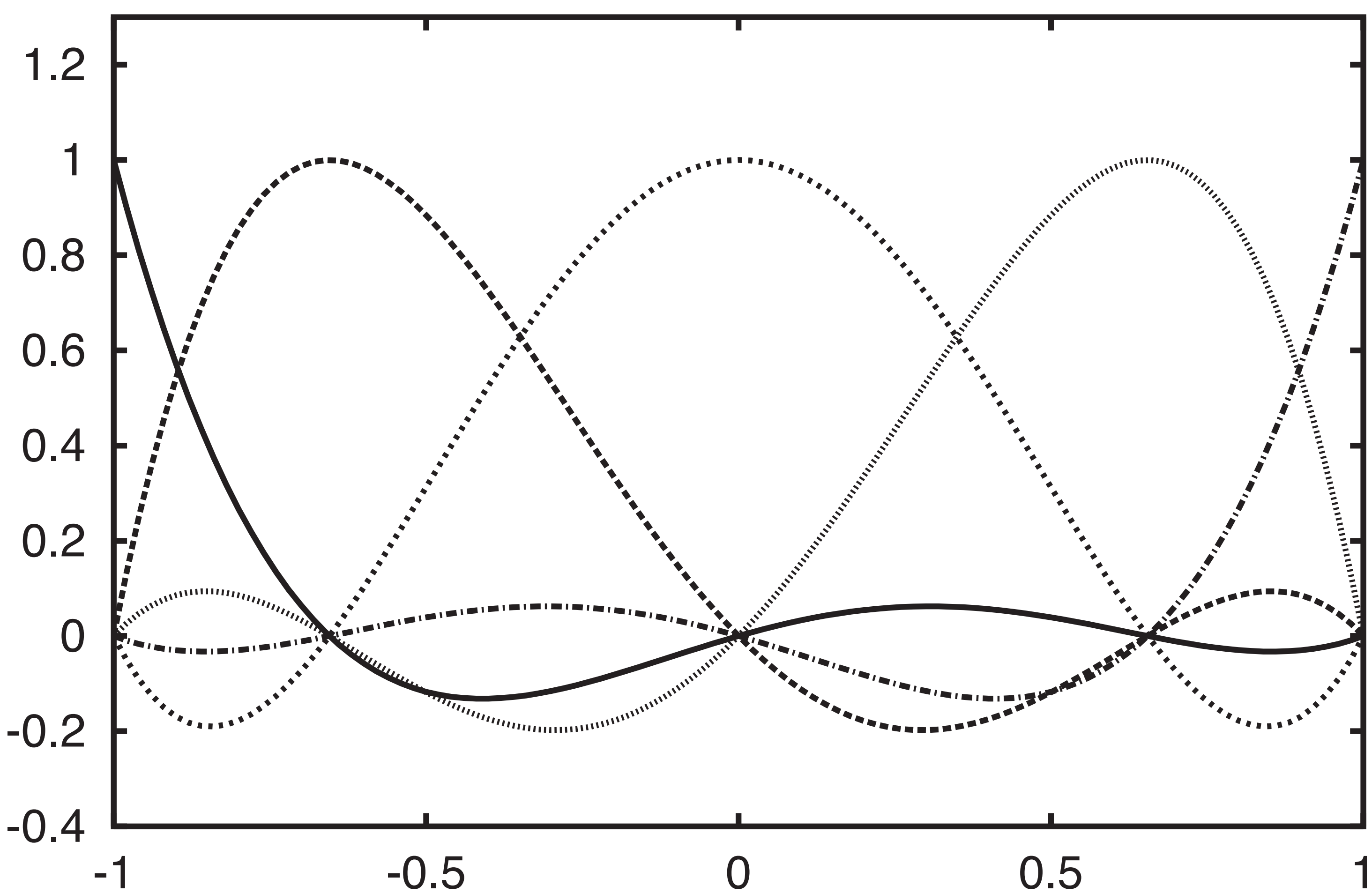
- Note: Free stress Boundary conditions $\sigma \cdot \mathbf{n} = \mathbf{0}$ are automatically included as natural boundary conditions.
- Issue is simply choice of discrete function space $\mathcal{V}$ for test functions $\mathbf{w}$ and $\mathbf{u}$.
- Once chosen, the problem assembles into simple discrete wave equation

$$M\ddot{\mathbf{d}} + K\mathbf{d} = \mathbf{f}$$

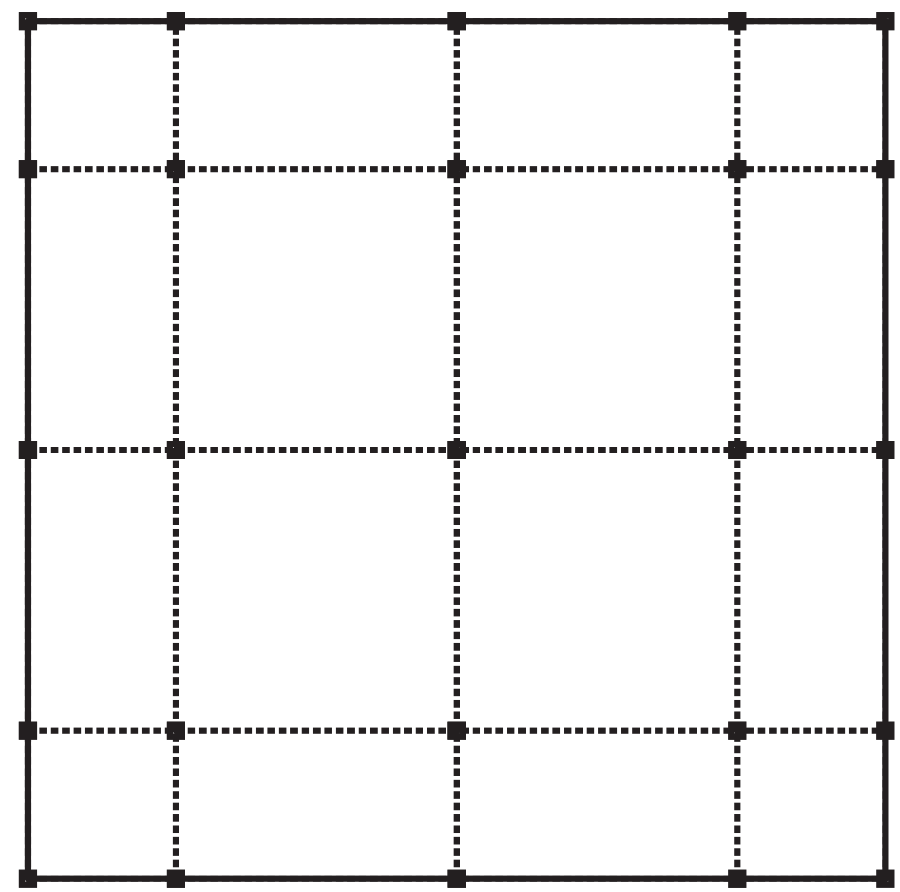
for displacements $\mathbf{d}$.

Computational Seismology
Spectral Element methods

J. Tromp, D. Komatitsch and Q. Liu / Commun. Comput. Phys., **3** (2008), pp. 1-32



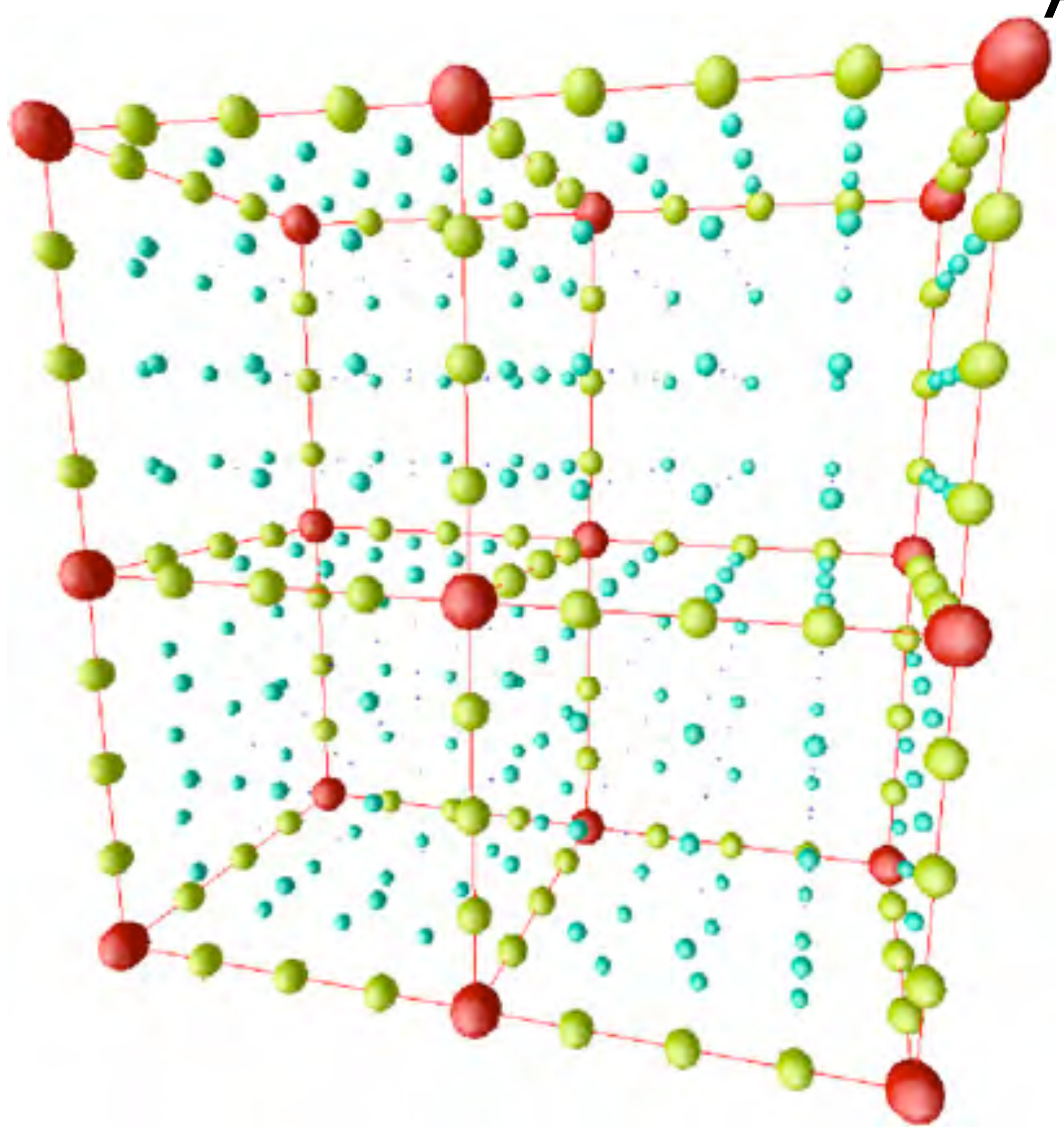
4th order Spectral Lagrange element using Gauss-Legendre-Lobatto Quadrature



2-D hexahedral reference element: tensor product element

Computational Seismology
Spectral Element methods

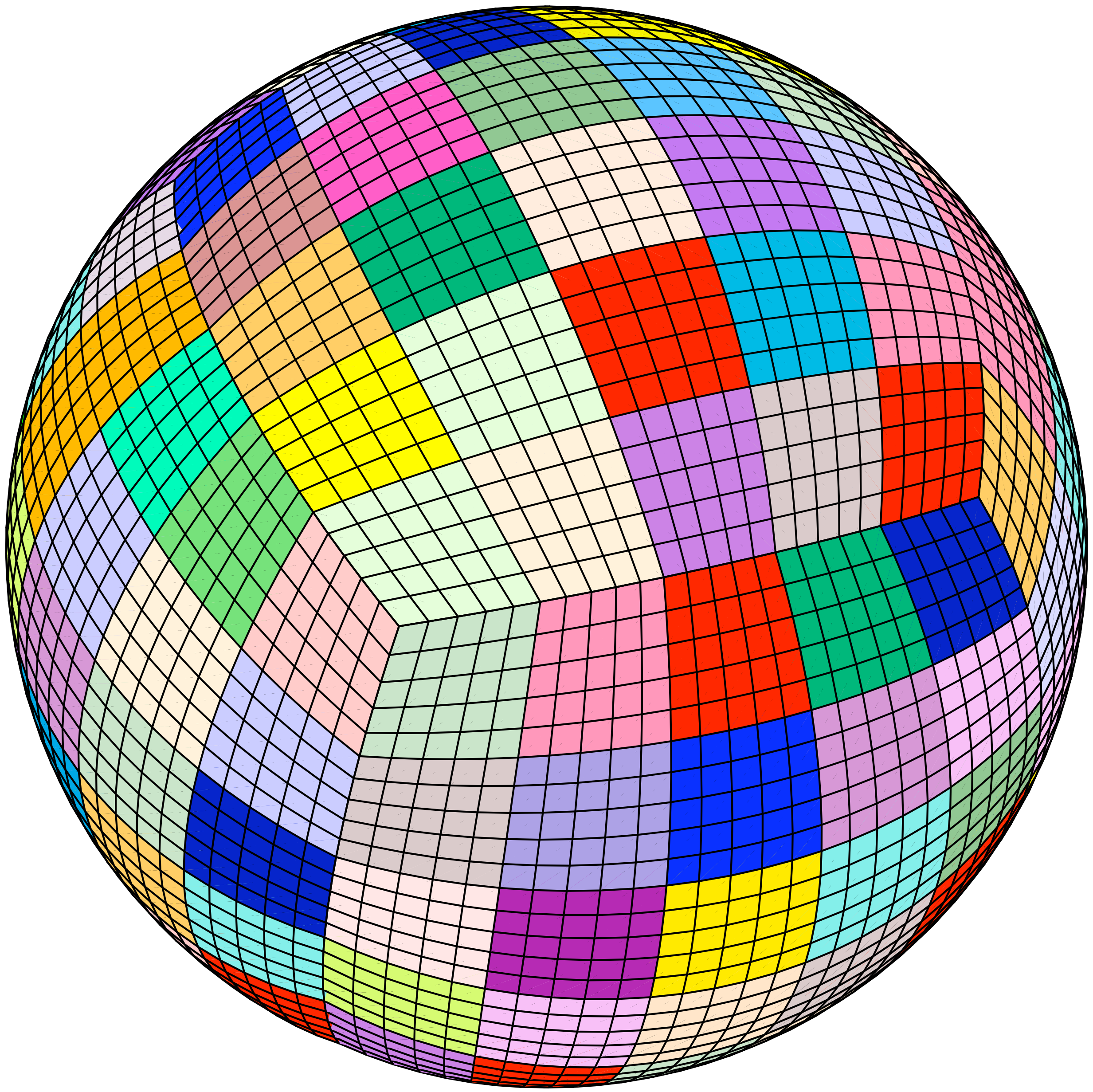
A few nice Computational Features



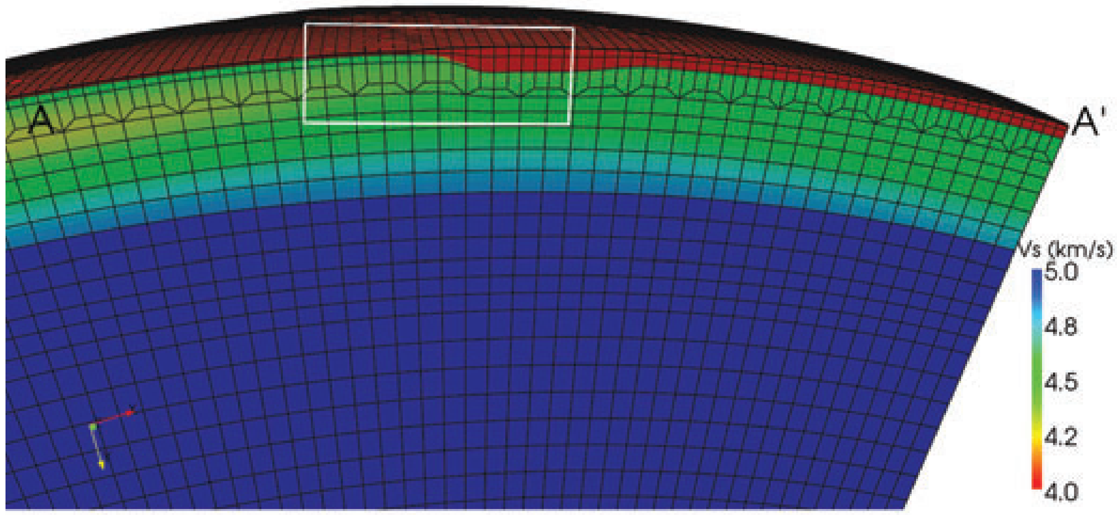
4, 3-D hexahedral reference elements
showing 5^3 dofs/element (4th order)

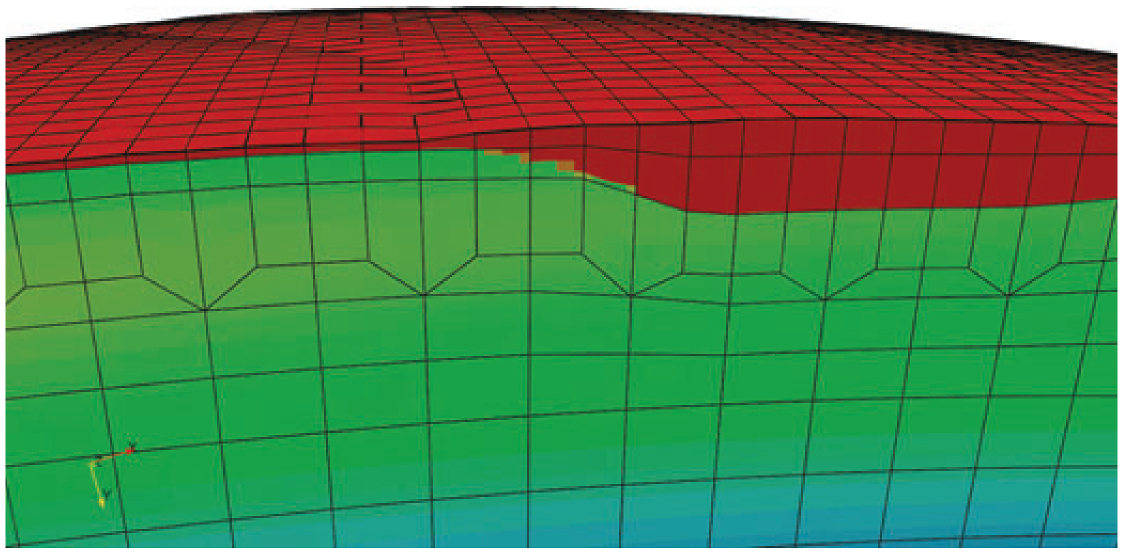
- Diagonal Mass Matrix: Lagrange Polynomials are "orthogonal" under GLL quadrature rules
- Assembly parallelizes/vectorizes very well

Computational Seismology
Spectral Element methods



Global Hexahedral mesh
“cubed sphere”





Vertical structure showing
crustal model and doubling layers

Computational Seismology
The Forward Problem

Discrete Form

$$M\ddot{\mathbf{d}} + K\mathbf{d} = \mathbf{f}$$

where M is a diagonal mass matrix, $K(C)$ is the stiffness matrix, $\mathbf{d}$ is discrete vector of displacements.

Explicit Time Marching Scheme (Newmark)

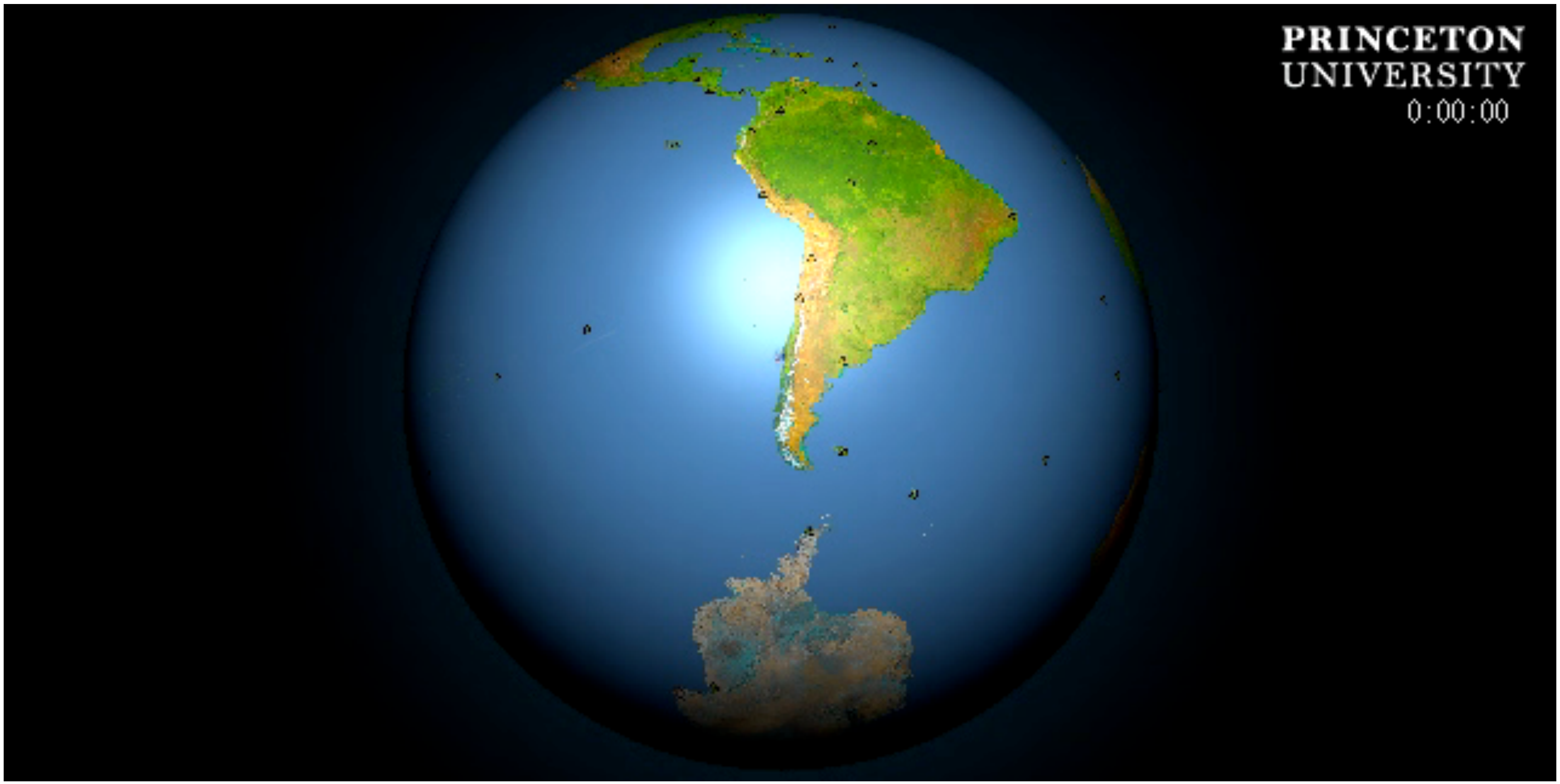
Define Acceleration: $\mathbf{a}_k = \ddot{\mathbf{d}}_k = M^{-1}[-K\mathbf{d}_k + \mathbf{f}_k]$
Define Velocity: $\mathbf{v}_k = \dot{\mathbf{d}}_k$
Initialize : $\mathbf{d}_0 = \mathbf{v}_0 = \mathbf{0}$, $\mathbf{a}_0 = M^{-1}\mathbf{f}_0$
for $n = 1, 2, \ldots$ **do** {loop until $t = T$}
$\quad \mathbf{d}_n = \mathbf{d}_{n-1} + \Delta t \mathbf{v}_{n-1} + \frac{\Delta t^2}{2}\mathbf{a}_{n-1}$
$\quad \mathbf{v}_n = \mathbf{v}_{n-1} + \frac{\Delta t}{2}[\mathbf{a}_{n-1} + \mathbf{a}_n]$
end for

- CFL Stability Criteria: $\Delta t \leq \alpha(\Delta x / c_p)_{min}$. ($\alpha \sim 0.5$)

Computational Seismology
Full wavefield propagation

Computational Seismology
Full wavefield propagation

7.1 Mw Jan 02, 2011 Chile Earthquake



Computational Seismology
Synthetic Seismograms

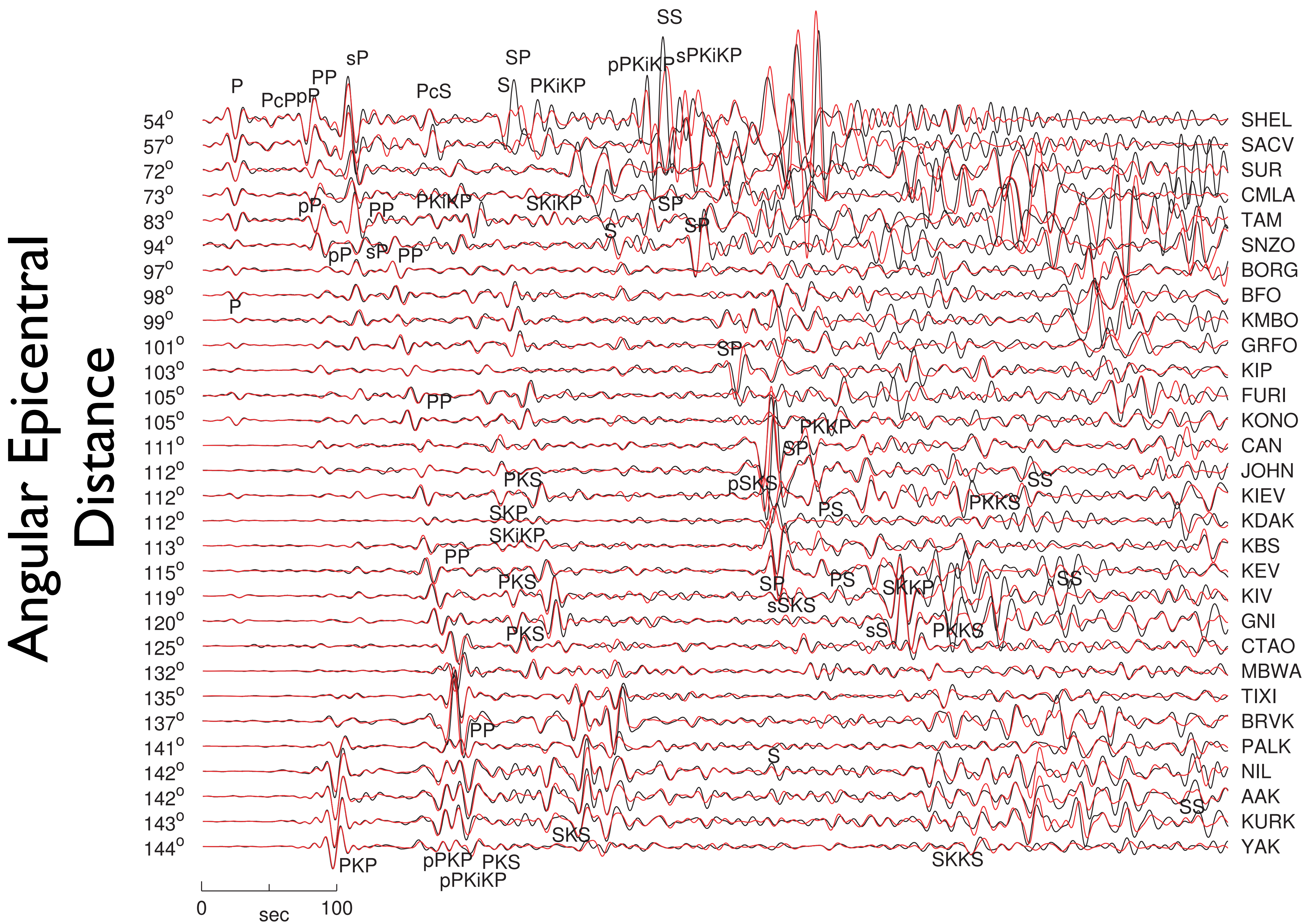
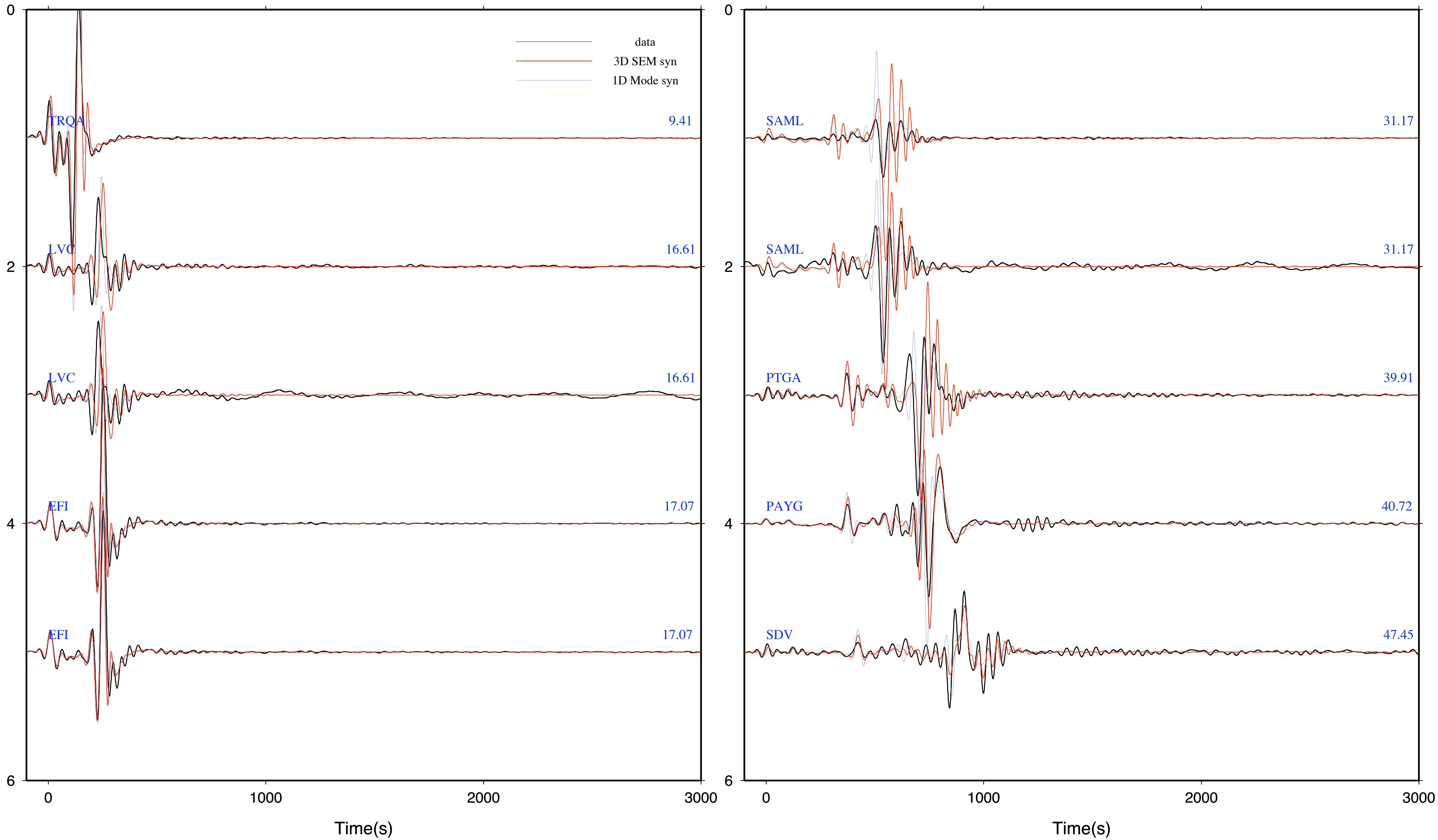


Figure 7. Vertical component record section comparing data (black) and SEM synthetics (red) for the 2008 September 3, $M_w = 6.3$ Santiago del Estero, Argentina earthquake, which occurred at a depth of 571 km. The records are aligned on the *P* wave, plotted as a function of epicentral distance, and bandpass filtered between 17 and 60 s. Major seismological body wave arrivals are labelled. Epicentral distance is plotted to the left of each set of traces, and FDSN station identification codes are plotted to the right.

Computational Seismology
Synthetic Seismograms

7.1 Mw Jan 02, 2011 Chile Earthquake



Computational Seismology

Computational Cost/Performance

Basic Scaling

- Resolution depends on highest frequency wave we want to propagate accurately.
- Let $\tau = 2\pi/\omega$ be the period of a wave with frequency ω
- Wavelength $\lambda = \tau c$ depends on period and wavespeed
- Resolution $h \propto \lambda \propto \tau_{min}$
- Time step limited by cfl condition $\Delta t \propto h \propto \tau_{min}$
- Number of elements $N_{el} \propto V/h^3 \propto \omega^3$
- Number of time steps $N_t = T/\Delta t \propto \omega$
- Total ops $O(\omega^4)$

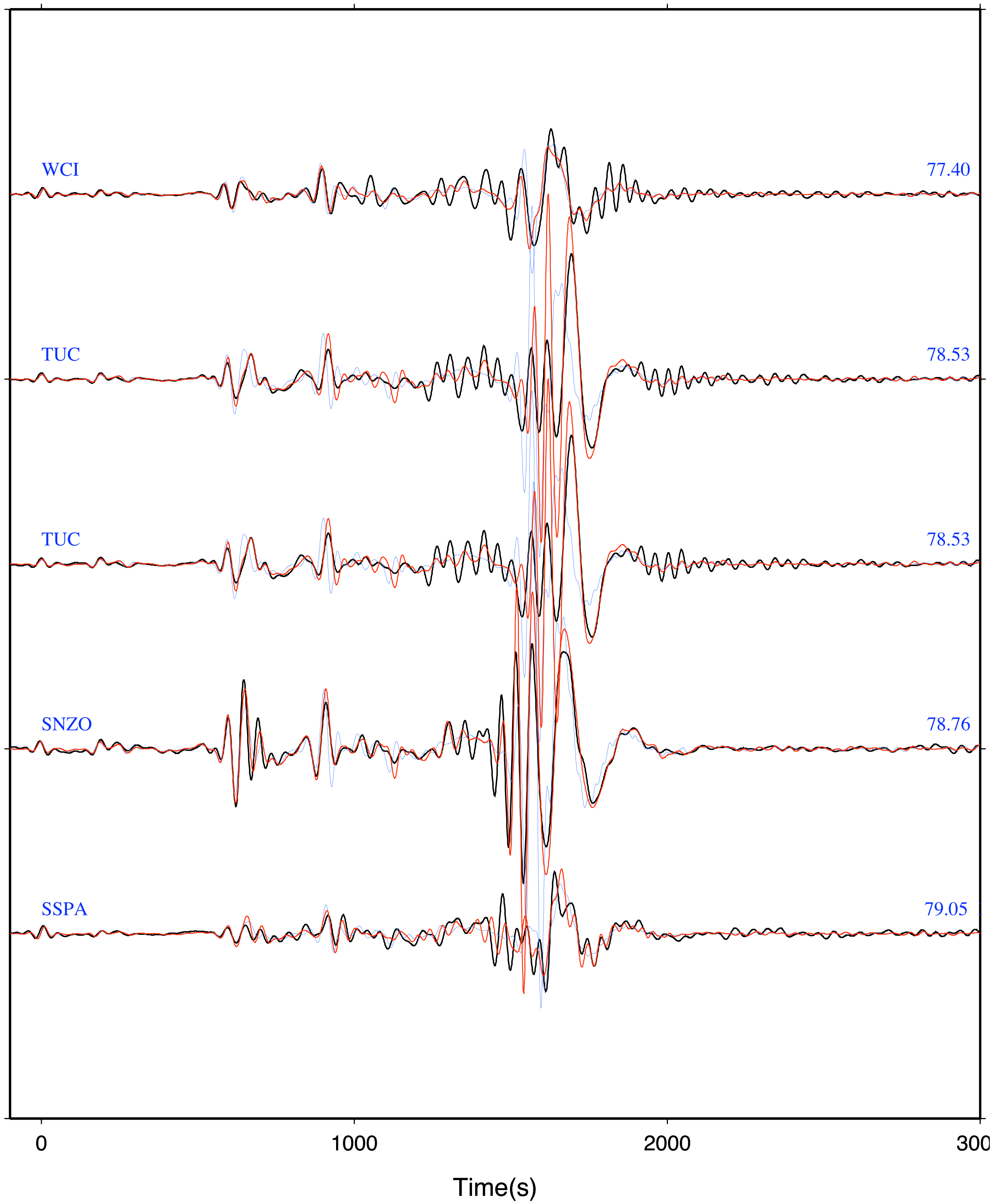
Computational Seismology
Computational Cost/Performance

- Routine Global Long period simulation (17 s)
  ~400 CPU cores in ~ 4 hours

- 2003 Gordon Bell Prize (Komatisch et. al, 2003)
  5 s minimum period (h~2.9 km)
  14.6 Billion dofs
  1944 Vector processors on Earth Simulator
  30% peak on 38% of the machine 5Tflop sustained

- M8 (SCEC simulation 2010 GB Finalist)
  2 hz maximum frequency (1/2 s period)
  regional mesh with 435 Billion dofs
  223K opteron cores of Jaguar
  220 Pflops

Computational Seismology
The Inverse Problem



- The Forward Problem: Given an earth model calculate synthetic seismograms at n locations.
- The Inverse Problem: given mismatch between data and synthetic seismograms, refine the Earth model to minimize the misfit.
- The Inverse Problem can be cast as a "PDE Constrained Optimization" problem solvable by adjoint methods

Computational Seismology
PDE Constrained Optimization
(the short course)

PDE Constrained Optimization: the generic problem

minimize $\quad J[u] = \frac{1}{2}\int_{\Omega}(u-d)^2 dV$

subject to $\quad \mathcal{L}(p)u = f$, + BC's and IC's (PDE constraint)

with

- u: solution field
- d: data
- $\mathcal{L}(p)$: Linear operator with parameters p

Computational Seismology
PDE Constrained Optimization

Define Lagrangian

$$L[\lambda, u, p] = \frac{1}{2}\int_\Omega (u-d)^2 dV + \int_\Omega \lambda\left[\mathcal{L}(p)u - f\right] dV$$

- $\lambda(x,t)$ is a Lagrange multiplier
- Lagrangian provides weighted misfit between solution, data and PDE constraint.

Computational Seismology
PDE Constrained Optimization

Optimality conditions

Calculate the first variation and set to zero

$$\delta L = \delta L_\lambda + \delta L_u + \delta L_p = 0$$

where

$$\begin{aligned}
\delta L_\lambda &= \int_\Omega [\mathcal{L}(p)u - f]\, \delta\lambda dV = 0 \\
\delta L_u &= \int_\Omega \left[(u-d) + \mathcal{L}^\dagger(p)\lambda\right] \delta u dV = 0 \\
\delta L_p &= \int_\Omega [\lambda G(p) u]\, \delta p dV = 0
\end{aligned}$$

- $\mathcal{L}^\dagger$ is the adjoint operator defined by $\int_\Omega \lambda \mathcal{L} u dV = \int_\Omega u \mathcal{L}^\dagger \lambda dV$
- Note: linear elastic wave propagation is *self-adjoint* s.t. $\mathcal{L}^\dagger = \mathcal{L}$

Computational Seismology
PDE Constrained Optimization

Implications

- $\delta L_\lambda = 0$ implies that u satisfies the original PDE with forcing f
- $\delta L_u = 0$ implies that the Lagrange multiplier satisfies the adjoint PDE

  $$\mathcal{L}^\dagger(p)\lambda = -(u - d)$$

  with forcing driven by the mismatch between data and synthetics
- if u and λ satisfy their respective PDE's, then the gradient δL reduces to just model sensitivity which can be written in terms of a *sensitivity Kernel*

  $$\delta L = \int K(u, \lambda, p)\delta p dV$$

  where

  $$K(u, \lambda, p) = \lambda G(p) u$$

Computational Seismology
PDE Constrained Optimization

Example: Waveform Tomography

- Given model p (e.g. ρ, C or v_p, v_s), solve the forward problem

$$\int_{\Omega} \rho \mathbf{w} \cdot \mathbf{u}_{tt} dV = \int_{\Omega} \nabla \mathbf{w} : \sigma(\mathbf{u}) + \mathbf{M} : \nabla \mathbf{w}(\mathbf{x}_s) S(t)$$

  with $\mathbf{u}(\mathbf{x}, 0) = \mathbf{u}_t(\mathbf{x}, 0) = \mathbf{0}$

- Solve the adjoint problem in reverse time (using the same code)

$$\int_{\Omega} \rho \mathbf{w} \cdot \hat{\mathbf{u}}_{tt} dV = \int_{\Omega} \nabla \mathbf{w} : \sigma(\hat{\mathbf{u}}) + \sum_r \int_0^T (u_r - d_r) dt$$

  with $\lambda(\mathbf{x}, t) = \hat{\mathbf{u}}(\mathbf{x}, T - t)$ and “IC's” $\hat{\mathbf{u}}(\mathbf{x}, 0) = \hat{\mathbf{u}}_t(\mathbf{x}, 0) = \mathbf{0}$

- Calculate Sensitivity Kernels and optimize to minimize δL (e.g. CG, Newton, etc).

Computational Seismology

Example Sensitivity Kernel

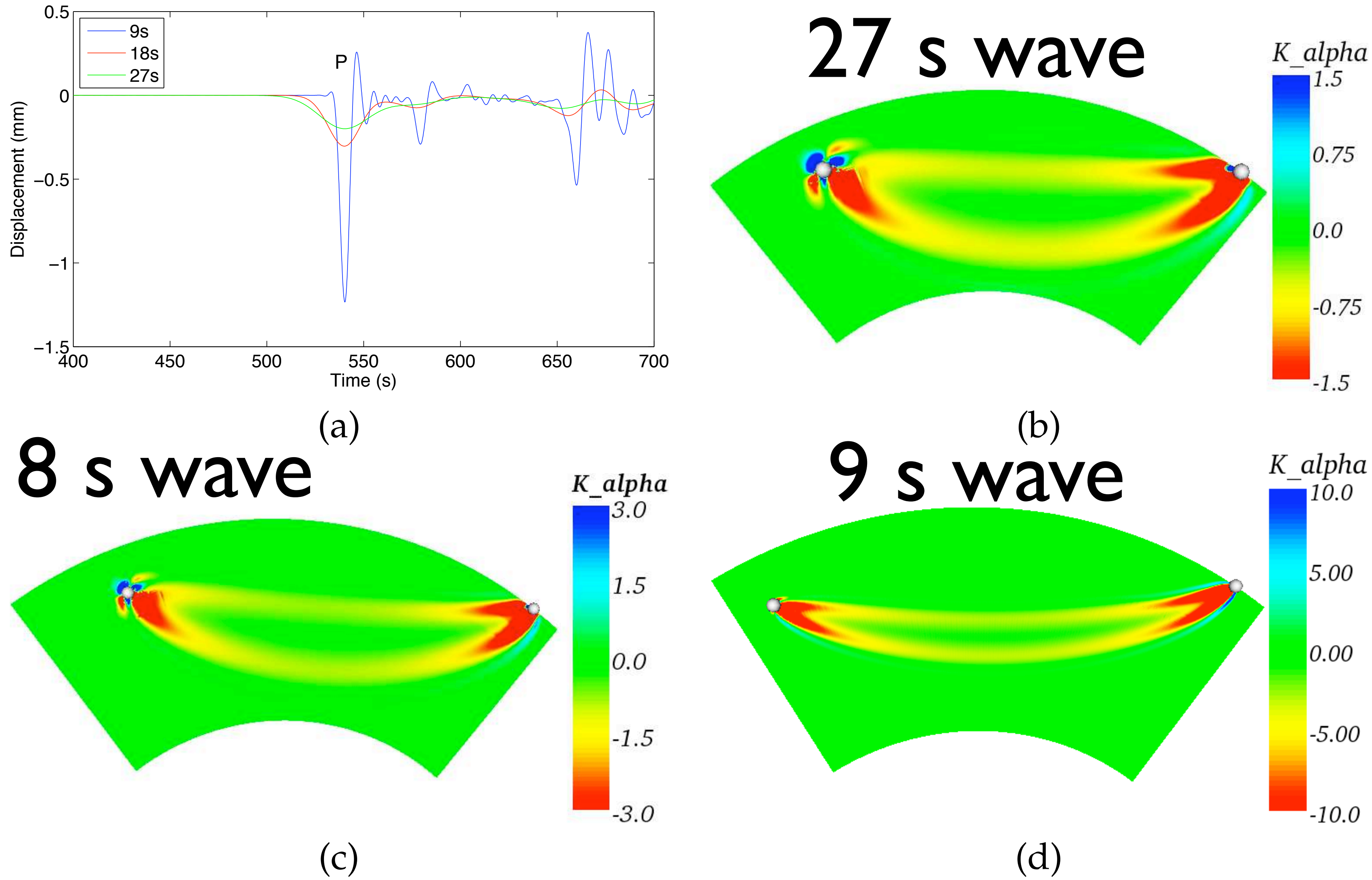


Figure 10: (a) Vertical component synthetic velocity seismograms recorded at an epicentral distance of 60 for simulations accurate down to periods of 27 s (green), 18 s (red) and 9 s (blue), respectively. (b) Source-receiver cross-section of the K_α kernel, defined by (4.27), for a 27 s P wave recorded at a station at an epicentral distance of 60°. The source and receiver locations are denoted with two small white circles. The unit of the sensitivity kernels is $10^7 \mathrm{s/km}^3$ throughout this paper. (c) K_α kernel for an 18 s P wave recorded at a station at an epicentral distance of 60°. (d) K_α kernel for a 9 s P wave recorded at a station at an epicentral distance of 60°. *Courtesy of [40].*

Computational Seismology

Example 3-D Regional Waveform Tomography

Geophysical Journal International

Geophys. J. Int. (2010) **180,** 433–462 doi: 10.1111/j.1365-246X.2009.04429.x

Seismic tomography of the southern California crust based on spectral-element and adjoint methods

Carl Tape,[1*] Qinya Liu,[2] Alessia Maggi[3] and Jeroen Tromp[4]

[1]*Seismological Laboratory, California Institute of Technology, Pasadena, CA* 91125, *USA. E-mail: carltape@gps.caltech.edu*
[2]*Department of Physics, University of Toronto, ON, Canada*
[3]*Institut de Physique du Globe, Université de Strasbourg, Strasbourg, France*
[4]*Department of Geosciences and Program in Applied & Computational Mathematics, Princeton University, Princeton, NJ, USA*

Full problem:

16 Iterations

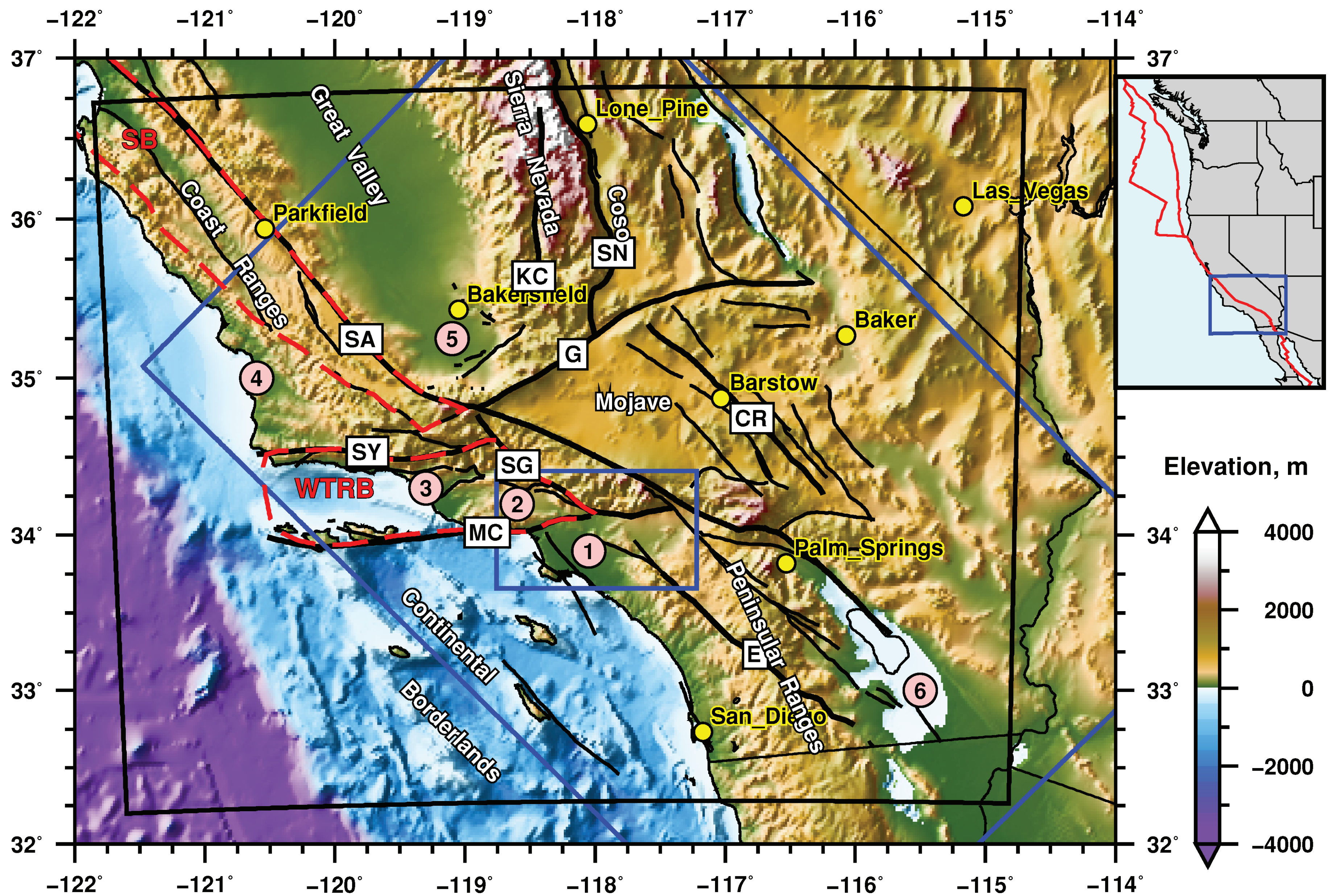
6800 wavefield simulations

800,000 total cpu hours (178 cores)

Computational Seismology

Example 3-D Regional Waveform Tomography

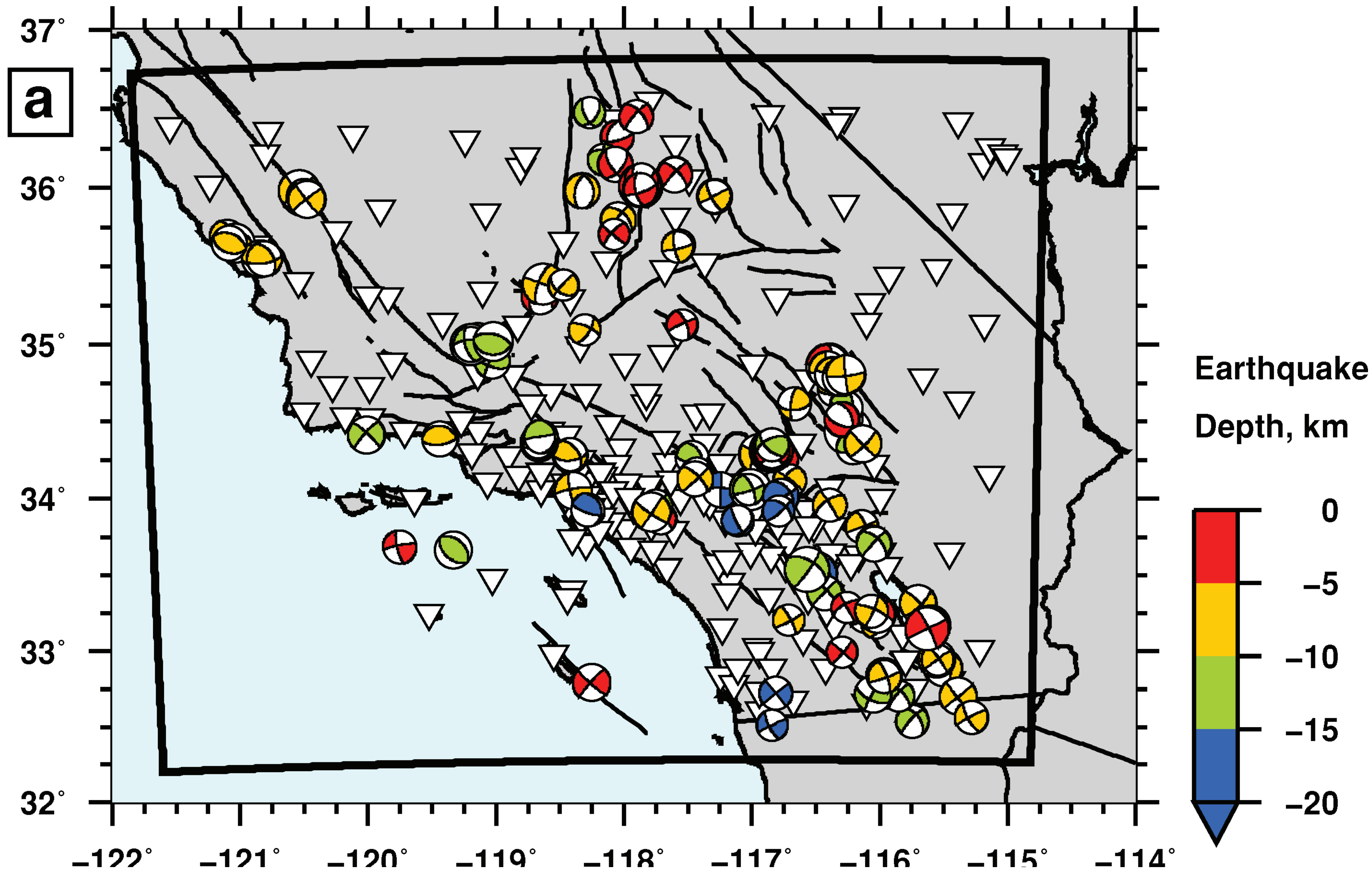
Seismic tomography of the southern California crust



- Regional Models are critical for Earthquake hazard assessment (shaking)

Computational Seismology

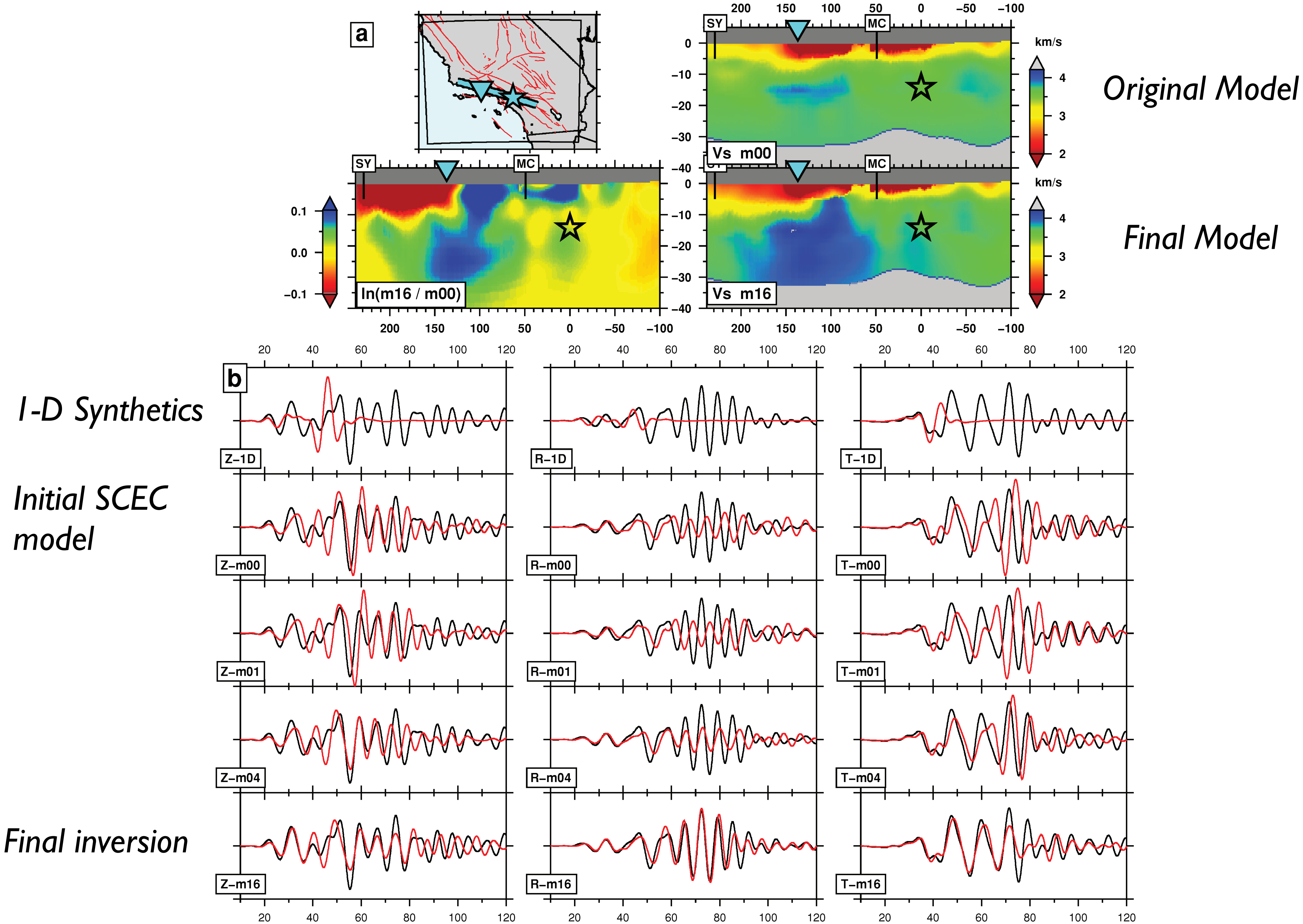
Example 3-D Regional Waveform Tomography



- 143 Earthquakes (beach balls)
- 203 stations (triangles) used in inversion
- 91 Additional earthquakes used for validation.

Computational Seismology

Example 3-D Regional Waveform Tomography



- Model improvement in waveform misfit

Computational Seismology

Example 3-D Regional Waveform Tomography

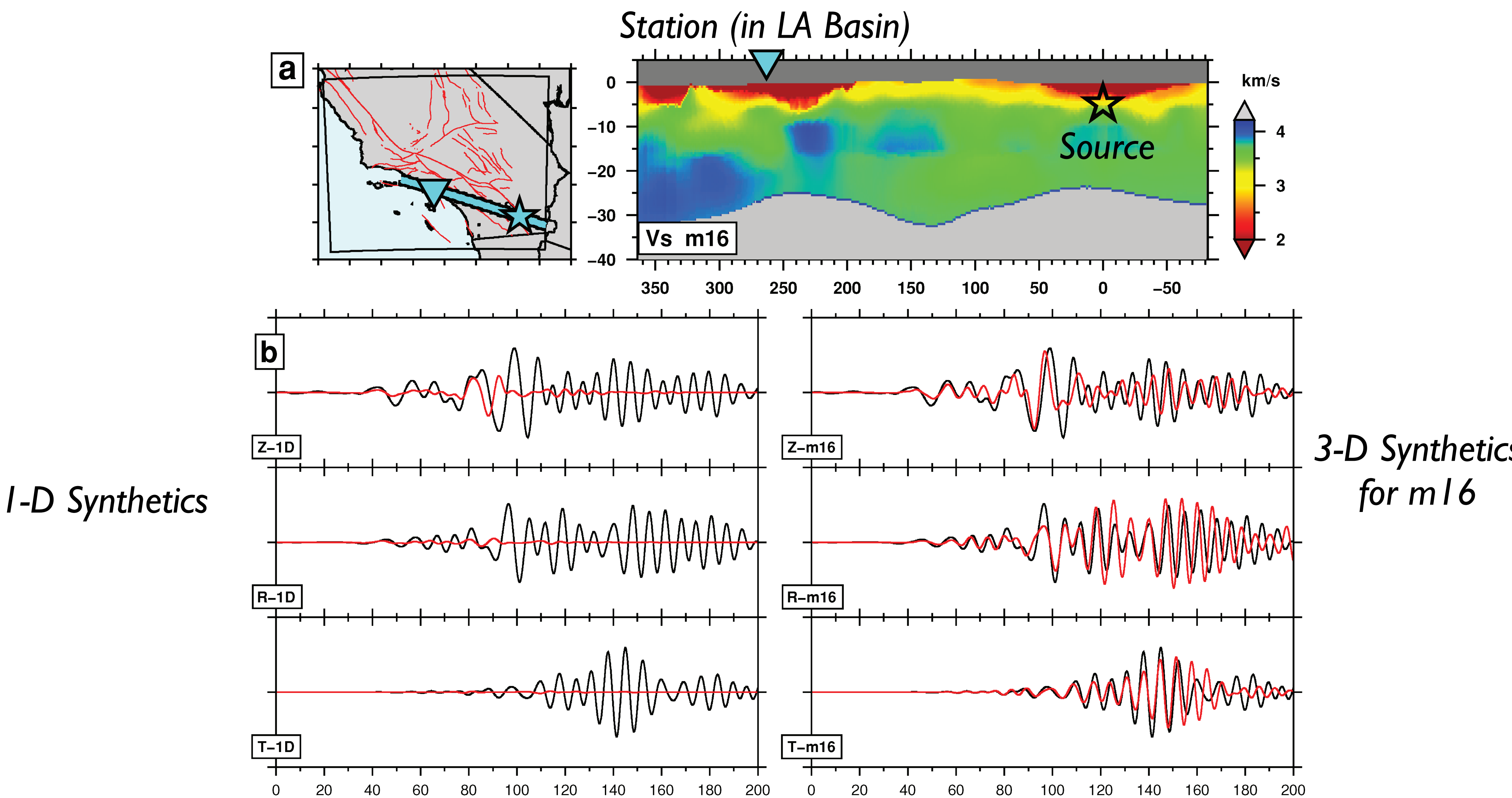
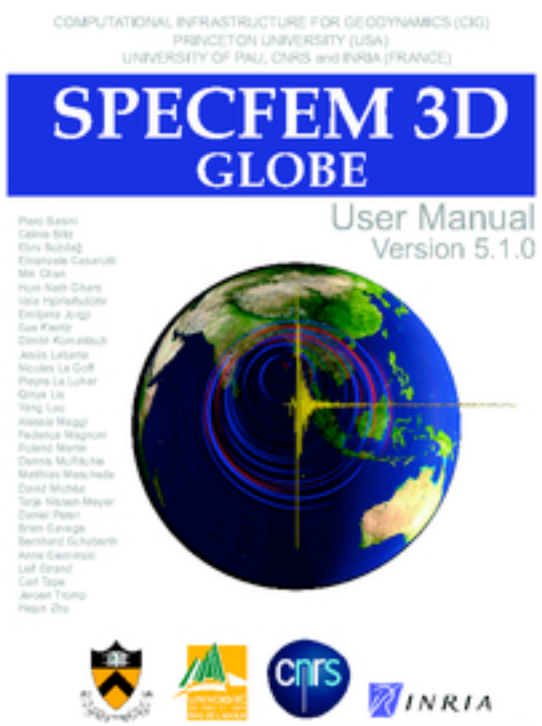


Figure 5. The influence of sedimentary basins on the seismic wavefield. (a) Cross-section of the final V_S crustal model $\mathbf{m}_{16}$, containing the path from event 14179736 (⋆; M_w 5.0, depth 4.9 km), beneath the Salton trough, to station LAF.CI (∇; distance 263.5 km), within the Los Angeles basin. (b, left column) Data (black) and 1-D synthetics (red). (b, right column) Data (black) and 3-D synthetics for model $\mathbf{m}_{16}$ (red). The seismograms are bandpass filtered over the period range 6–30 s. Z, vertical component, R, radial component, T, transverse component.

- Influence of local structure (sedimentary basins) on shaking

Computational Seismology
Available Software

- Source (F90): at CIG (www.geodynamics.org)

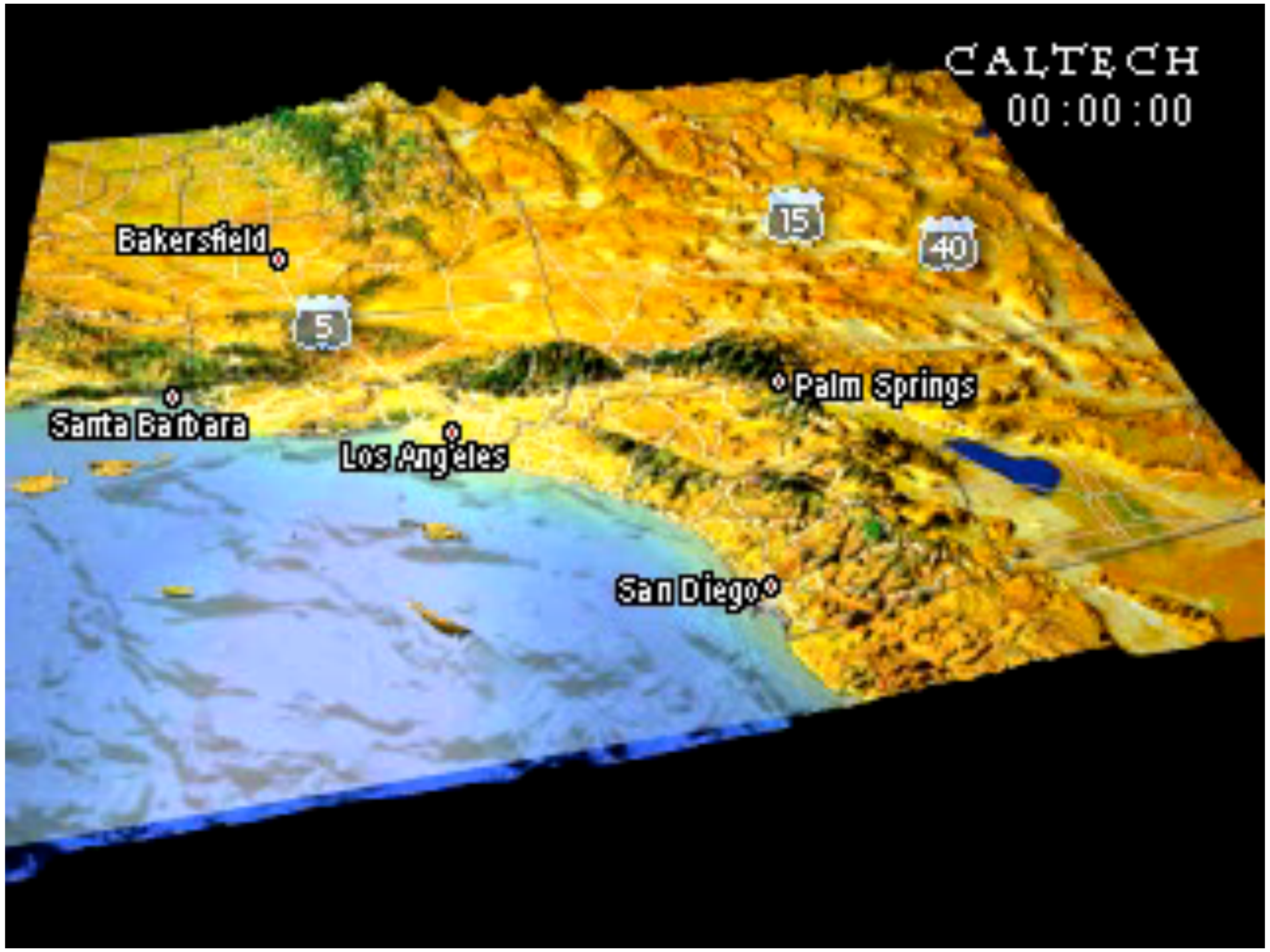


3-D Global Model
v5.1.0 Cubed Sphere
Both forward and adjoint models
Open Source: GPL license

3-D Regional model
v2.0.0 "Sesame"
accepts arbitrary hexahedral meshes,
Well interfaced with CUBIT (Sandia).
Forward and Adjoint models, absorbing boundaries
Open Source: GPL license

- Pre-Computed Synthetics:
  - 3-D Global: http:/global.shakemovie.princeton.edu/
  - Regional SC: http://shakemovie.caltech.edu/

Computational Seismology



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Computational Seismology
GPU implementations

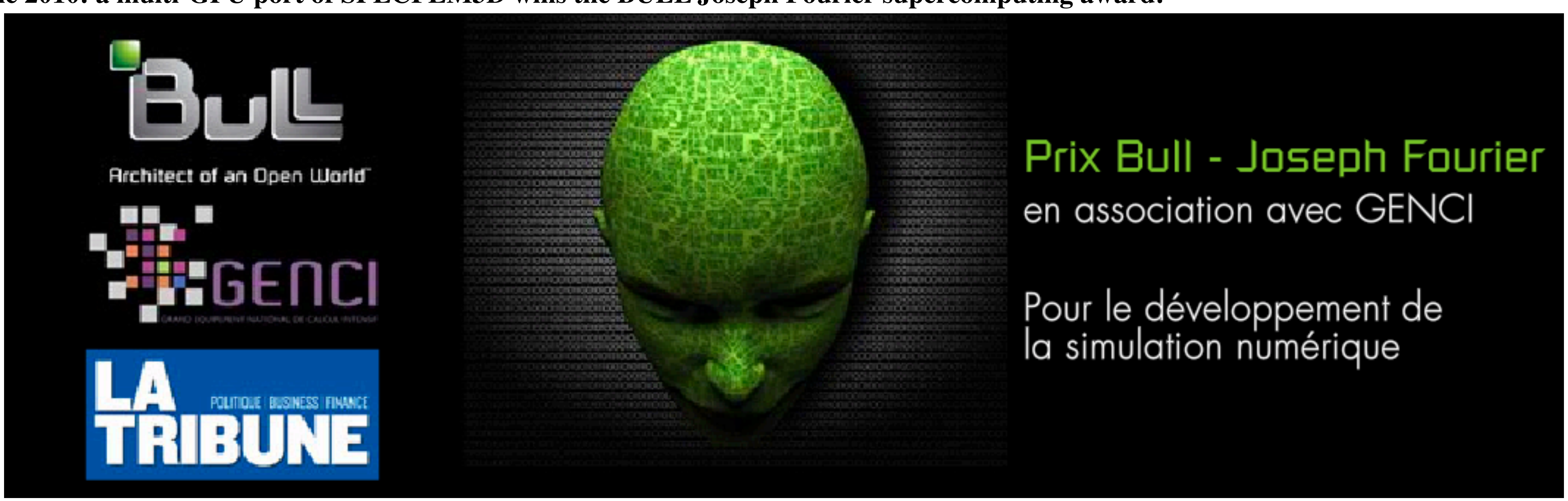
Dmitri Komatisch (U. Pau):

Dimitri Komatitsch, Fluid-solid coupling on a cluster of GPU graphics cards for seismic wave propagation, *Comptes Rendus de l'Académie des Sciences – Mécanique*, doi: 10.1016/j.crme.2010.11.007, in press (2011). PDF reprint BibTeX

Dimitri Komatitsch, Gordon Erlebacher, Dominik Göddeke and David Michéa, High-order finite-element seismic wave propagation modeling with MPI on a large GPU cluster, *Journal of Computational Physics*, vol. 229(20), p. 7692-7714, doi: 10.1016/j.jcp.2010.06.024 (2010). PDF reprint BibTeX

David Michéa and **Dimitri Komatitsch**, Accelerating a 3D finite-difference wave propagation code using GPU graphics cards, *Geophysical Journal International*, vol. 182(1), p. 389-402, doi: 10.1111/j.1365-246X.2010.04616.x (2010). PDF reprint BibTeX

June 2010: a multi-GPU port of SPECFEM3D wins the BULL Joseph Fourier supercomputing award:



Computational Seismology
GPU Cluster Configuration

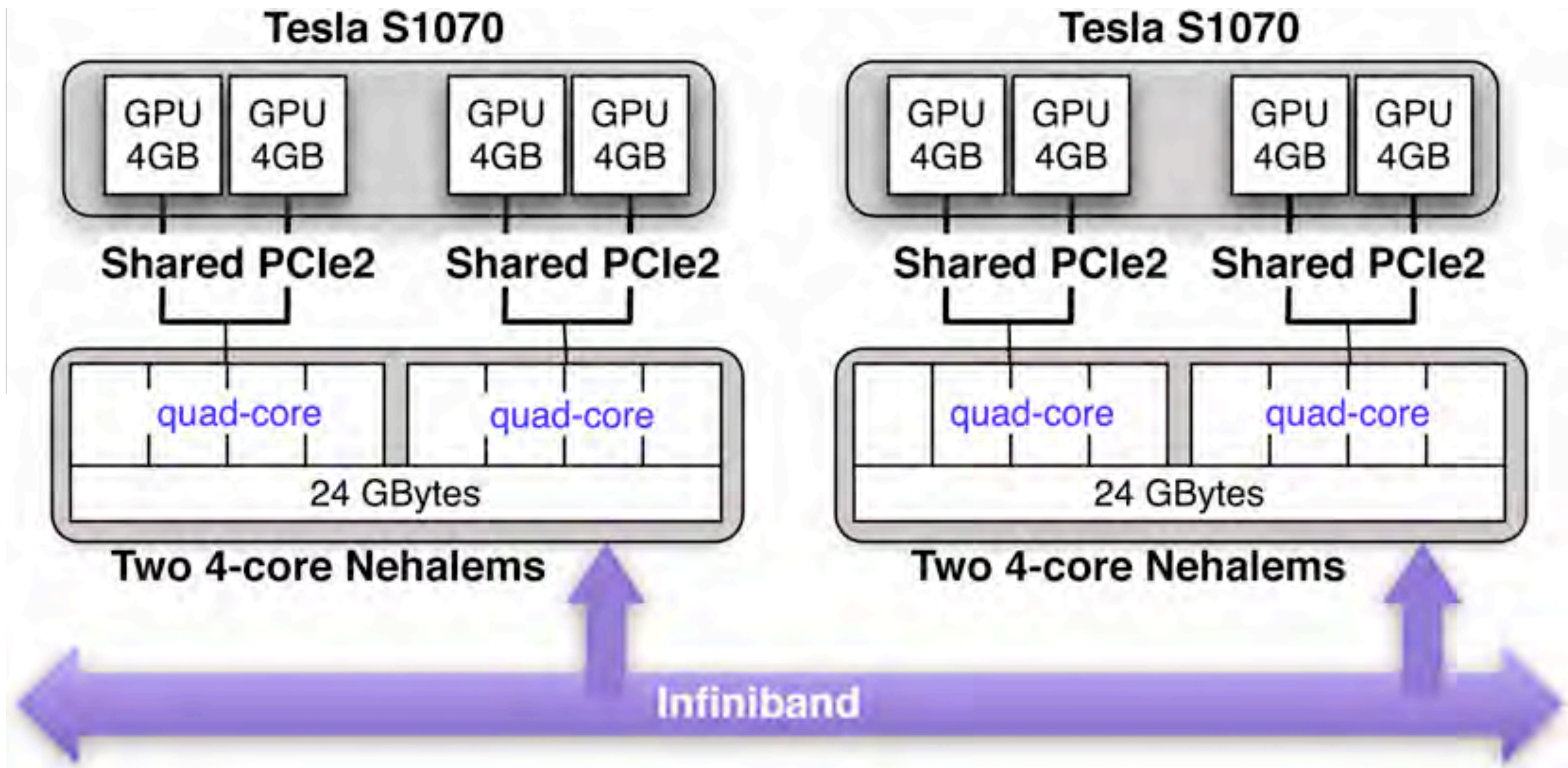


Fig. 9. Description of the cluster of 48 Teslas S1070 used in this study. Each Tesla S1070 has four GT200 GPUs and two PCI Express-2 buses (i.e., two GPUs share a PCI Express-2 bus). The GT200 cards have 4 GB of memory, and the memory bandwidth is 102 GB/s with a memory bus width of 512 bit. The Teslas are connected to BULL Novascale R422 E1 nodes with two quad-core Intel Xeon X5570 Nehalem processors operating at 2.93 GHz. Each node has 24 GB of RAM. The network is a non-blocking, symmetric, full duplex Voltaire InfiniBand double data rate (DDR) organized as a fat tree.

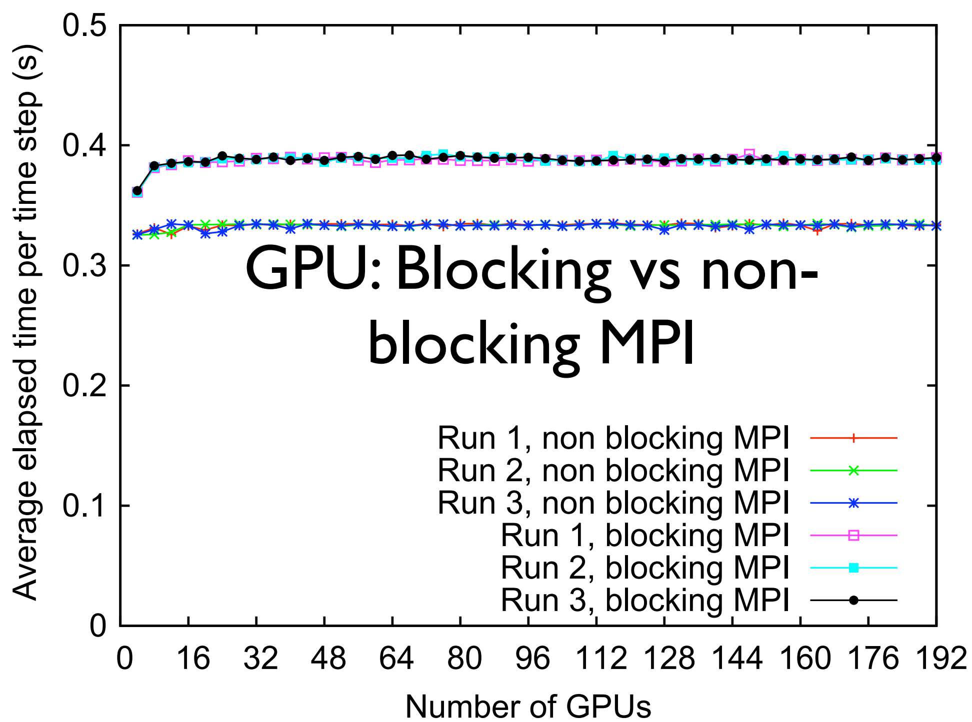
- 48 Nodes: each with
  - 1 S1070 (4 GT200 GPUs)
  - 2 quad-core 2.93GHz Nehalems
- Infiniband connect between nodes
- Total: 192 GPUs + 384 CPU cores

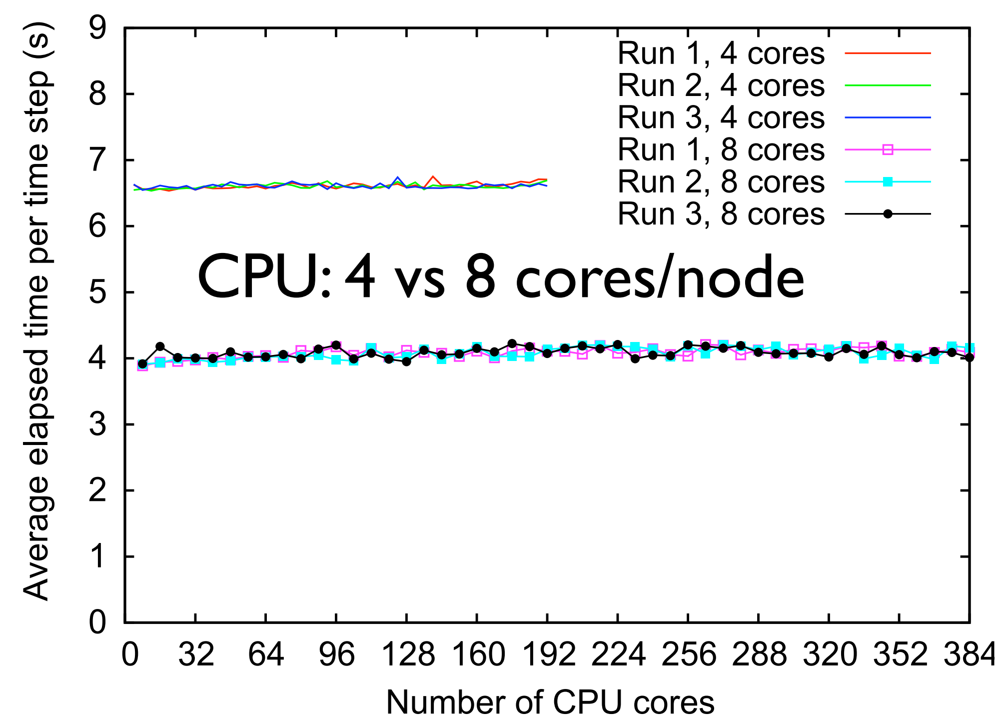
Computational Seismology

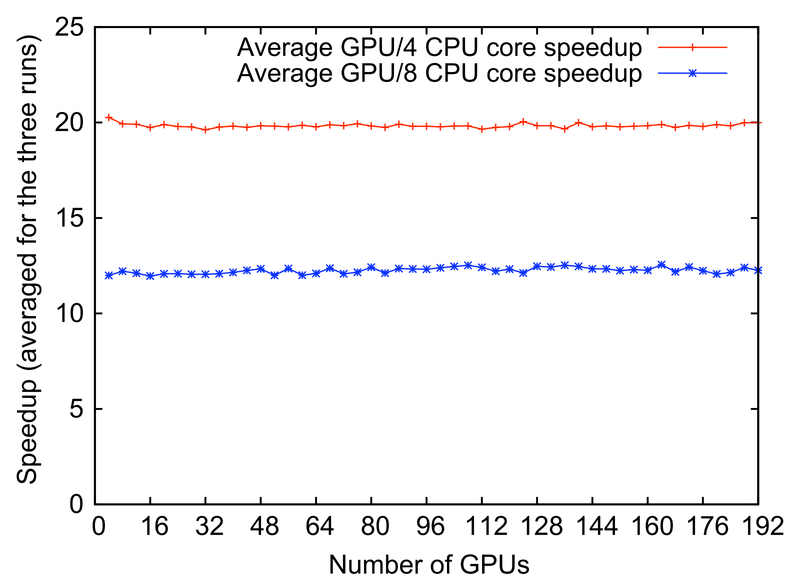
CPU vs. GPU Performance

Dimitri Komatitsch, Gordon Erlebacher, Dominik Göddeke and David Michéa, High-order finite-element seismic wave propagation modeling with MPI on a large GPU cluster, *Journal of Computational Physics*, vol. 229(20), p. 7692-7714, doi: 10.1016/j.jcp.2010.06.024 (2010). [PDF reprint] [BibTeX]

Weak Scaling Results







Speedup GPU/CPU
~12x or 20x
(depending on how you count)

Computational Seismology

Summary

Computational Seismology

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- Computational Seismology is a beautiful computational problem
  - Well Posed Forward problem
  - Explicit, single physics & Linear
  - Highly Parallel (Multicore, Vector and GPU)

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    - Complexity is maneagable and 10x GPU speedup will translate directly to inverse problem

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  - Complexity is maneagable and 10x GPU speedup will translate directly to inverse problem
- Near State of the art codes publically available through CIG (Open Source GPL)

Computational Seismology

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- Extremely important for imaging current Earth structure and estimating Seismic Hazard
- But doesn’t yield Earth Dynamics.
    - That’s a much harder problem (to be continued...)