Global Seismic Full Waveform Inversion

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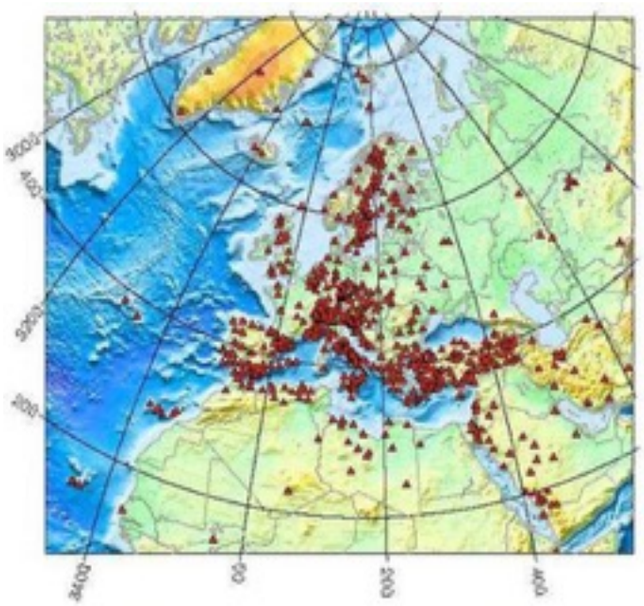
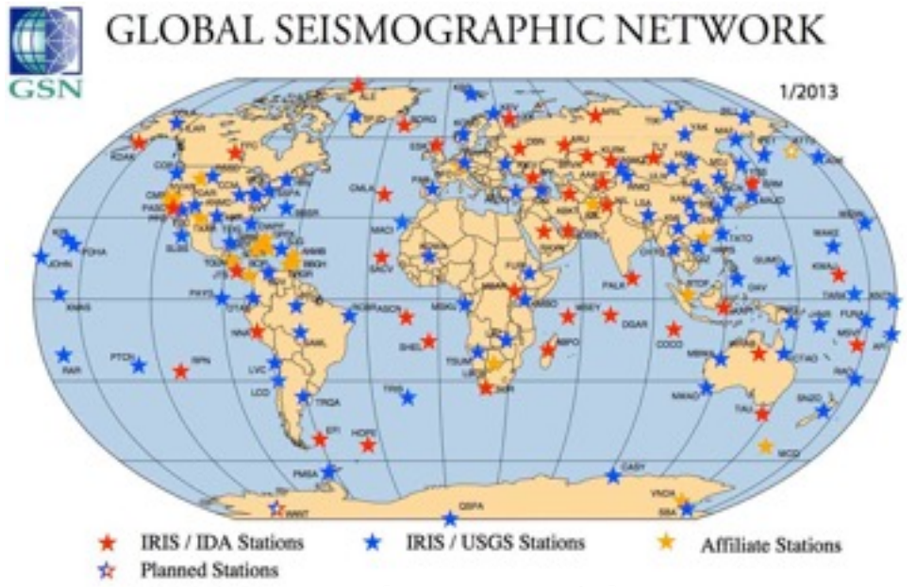
ORNL: Judy Hill, Norbert Podhorszki & David Pugmire

Data Tsunami in Regional & Global Seismology

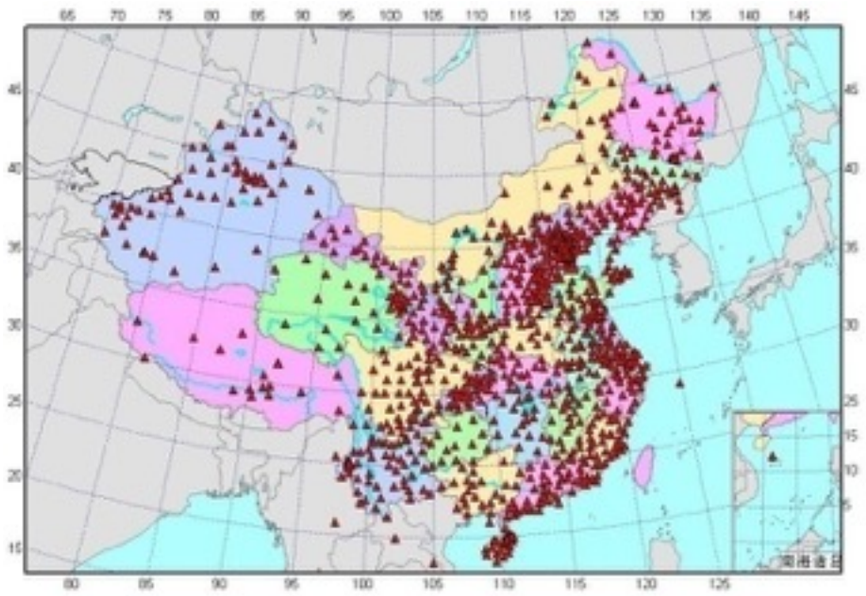


[www.geo.uib.no]

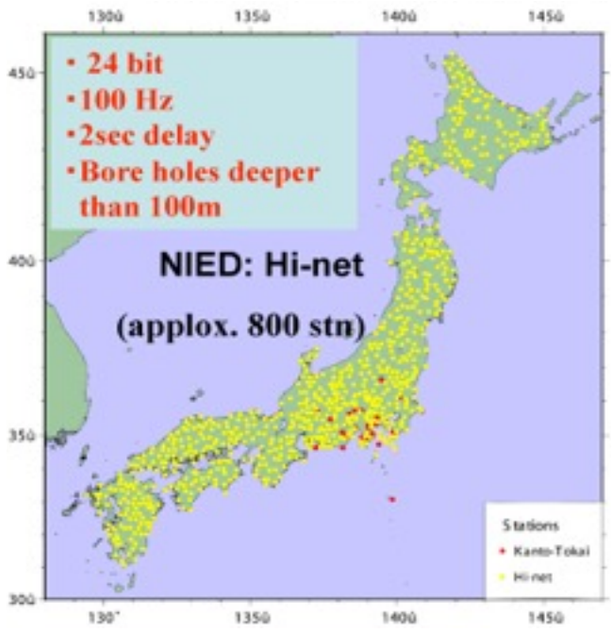


[www.iris.edu]

[web.mst.edu]

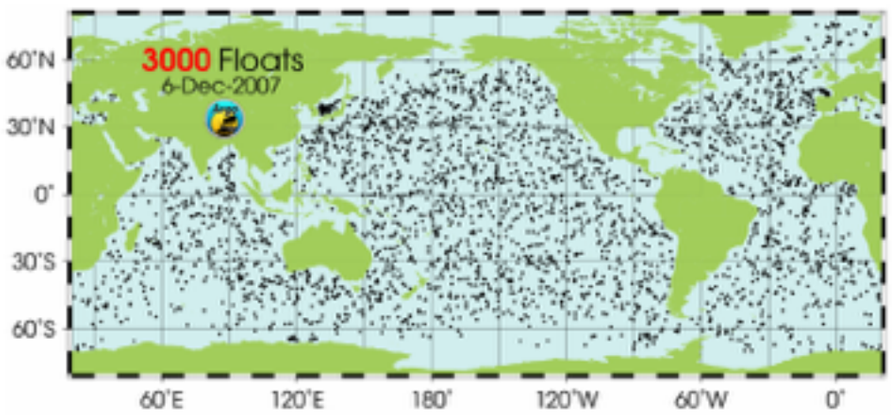


[data.earthquake.cn]



[drh.edm.bosai.go.jp]

MERMAID/MariScope



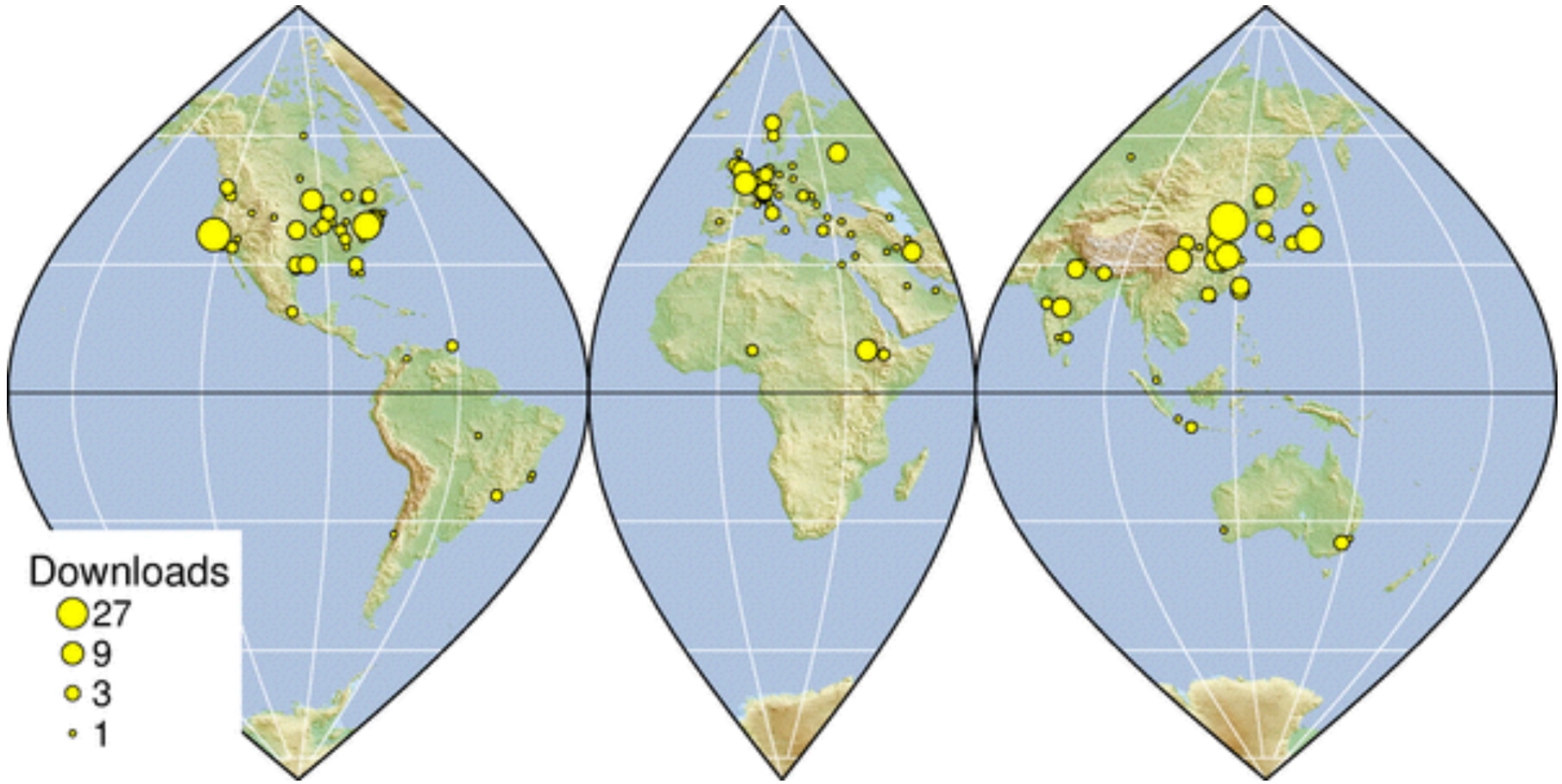
[Simons et al, 2006]

Open Source Forward & Inverse Modeling Software

Spectral-element solvers SPECFEM3D & SPECFEM3D_GLOBE

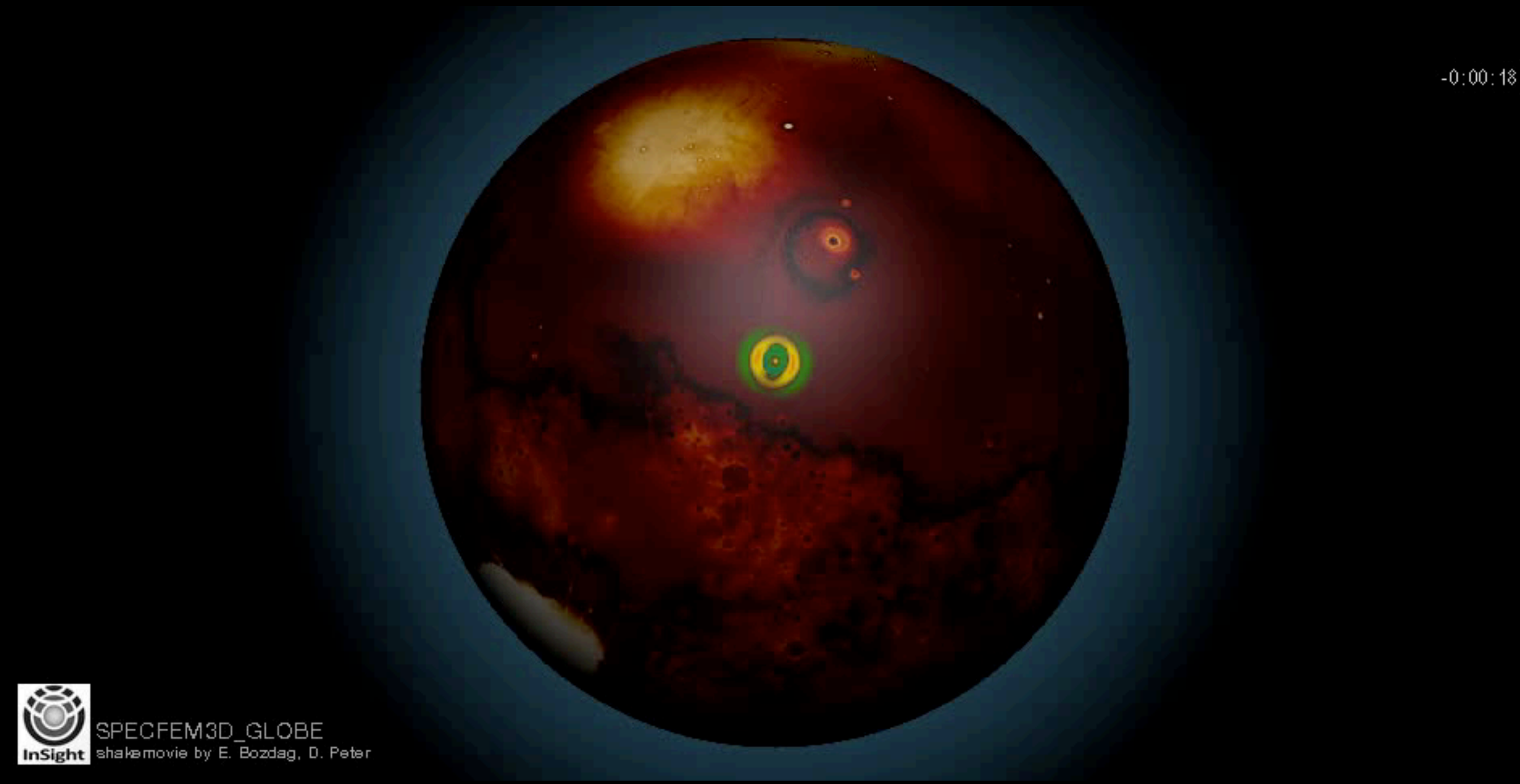
- 3D crust and mantle models
- Topography & Bathymetry
- Rotation
- Ellipticity
- Gravitation
- Anisotropy
- Attenuation
- Adjoint capabilities
- GPU accelerated

Computational Infrastructure for Geodynamics (CIG)
www.geodynamics.org



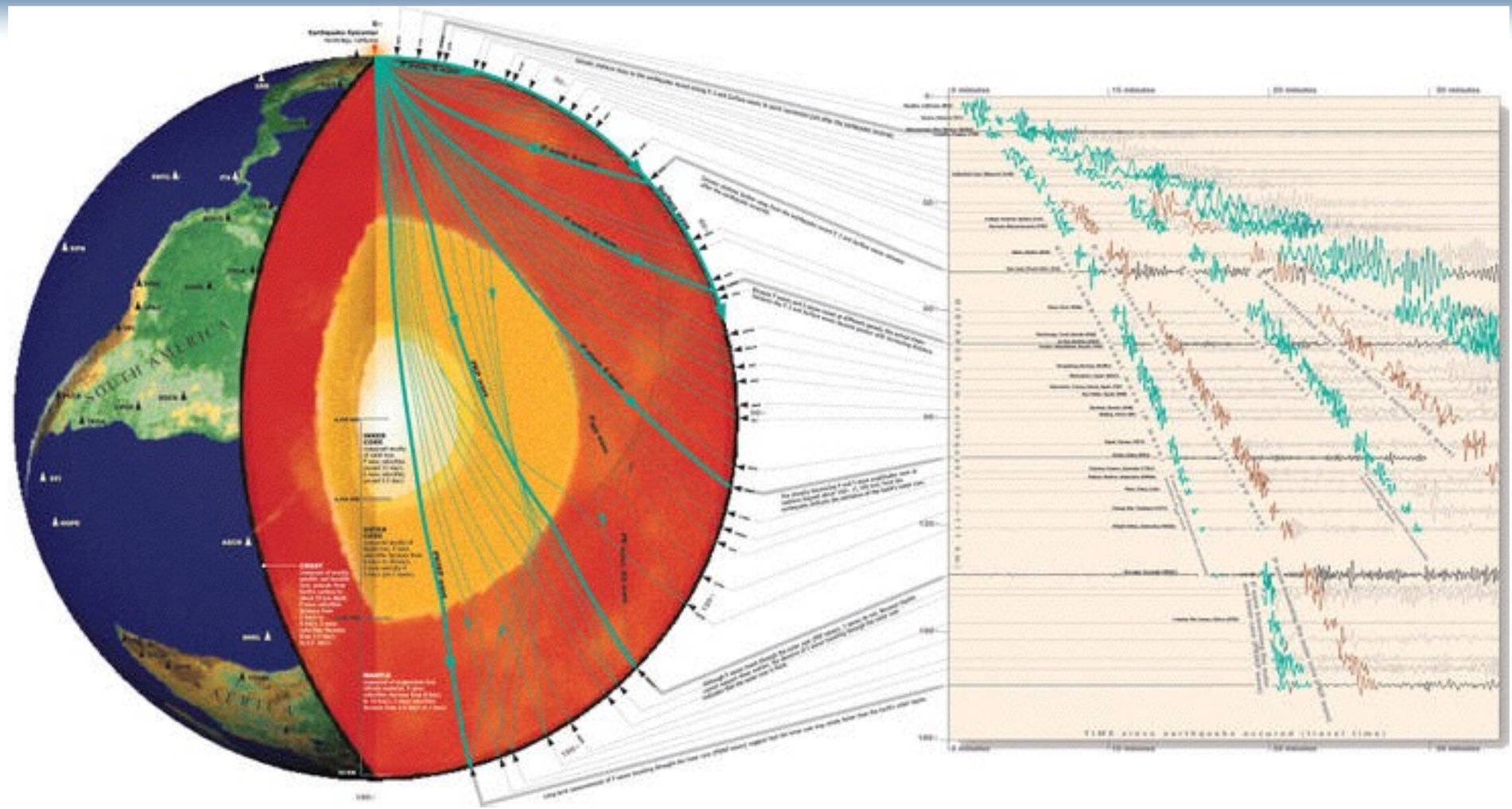
global.shakemovie.princeton.edu (David Luet)

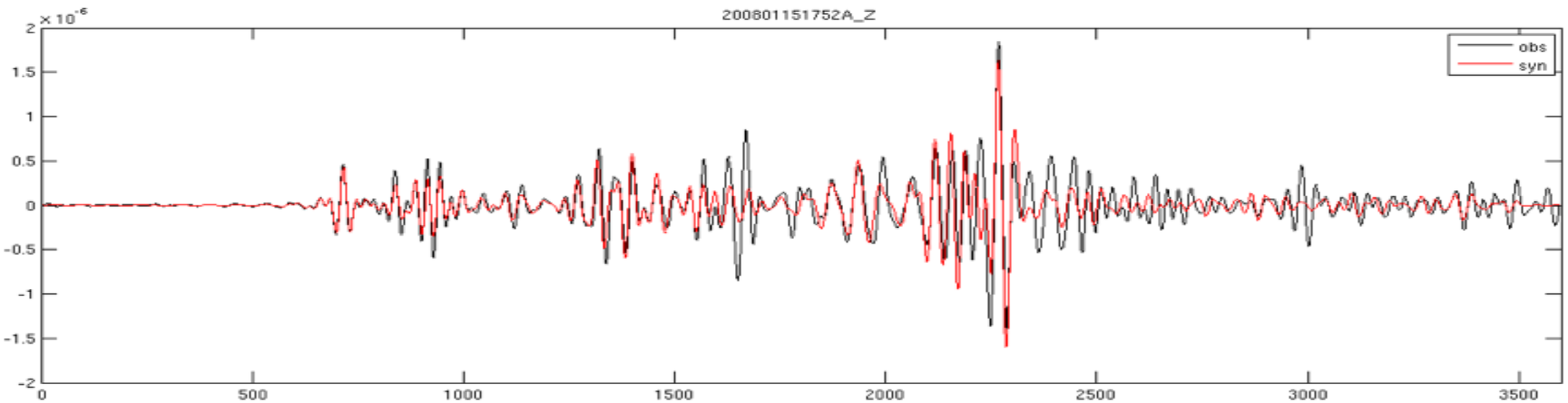
March 29, 2015 M 7.3



Mars ShakeMovie (Daniel Peter)

Goal: Use Complete Seismograms

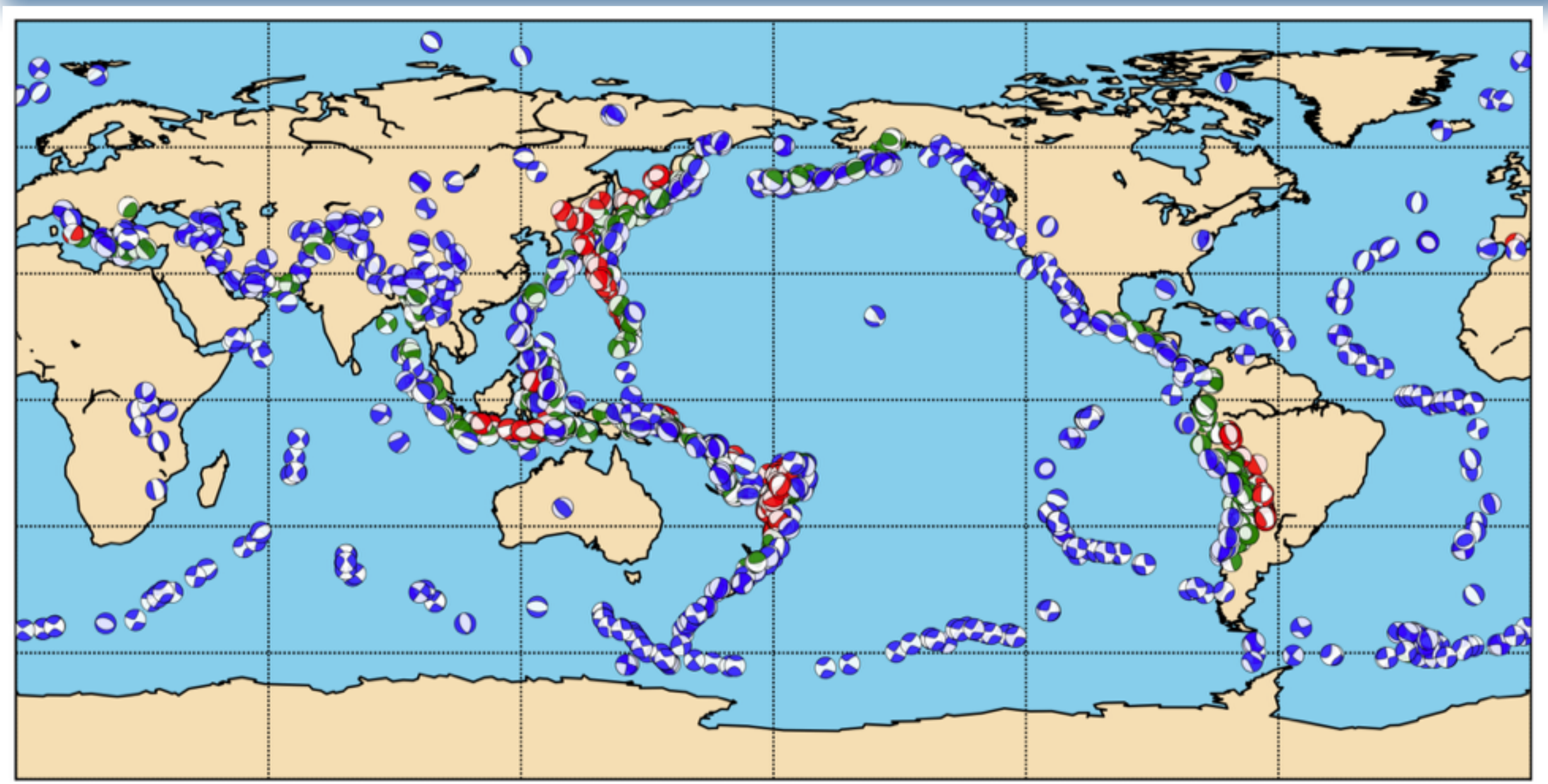




3D Wave Simulations & Full Waveform Inversion

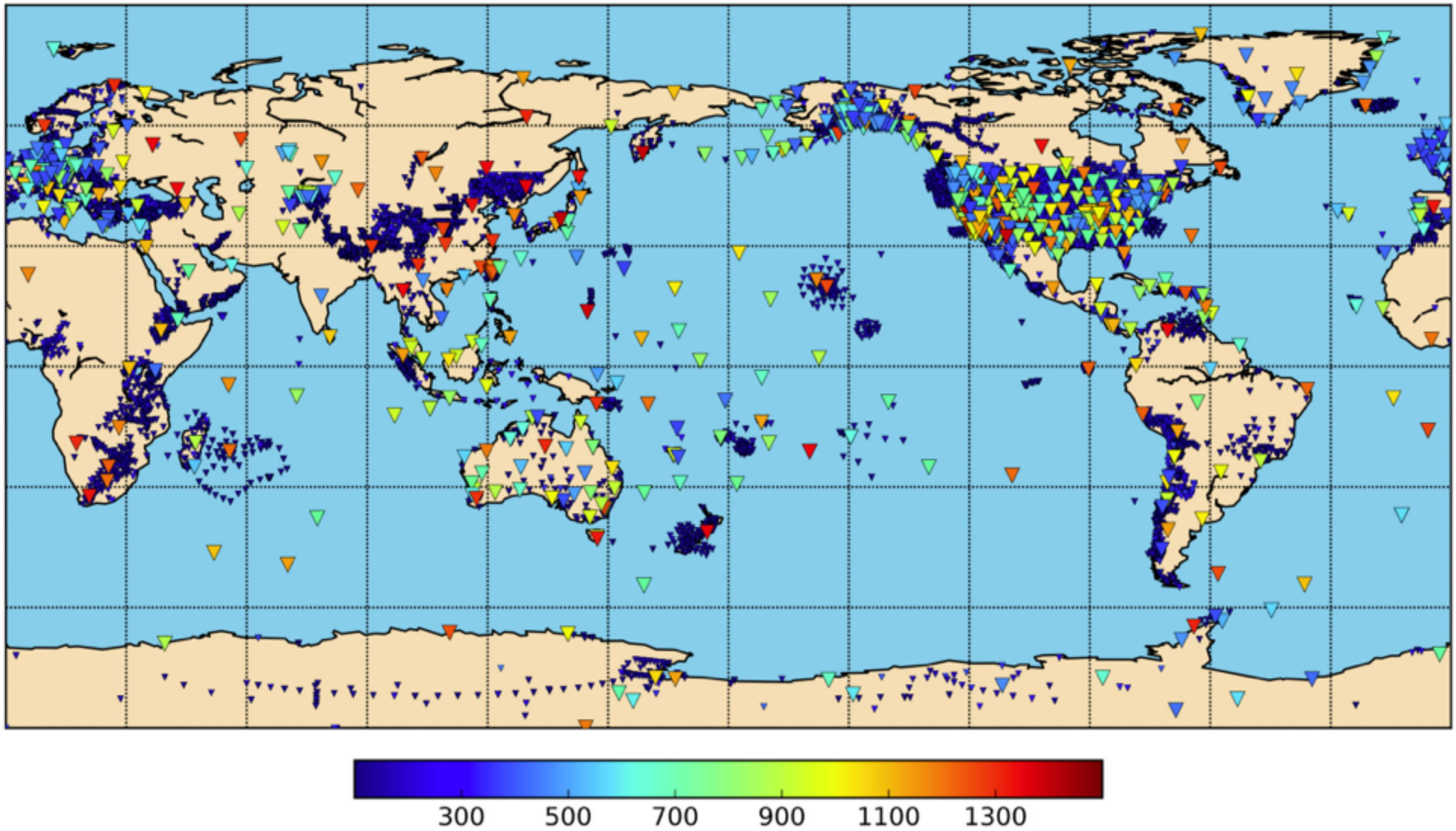
- Forward simulations and Fréchet derivative calculations in realistic 3D Earth models using *spectral-element & adjoint-state methods*
- Use anything and everything in seismograms: Full Waveform Inversion (FWI)
- Inversions for transversely isotropic *P* and *S* wavespeeds
- Invert crust and mantle together, *no crustal corrections*
- Incorporate attenuation in forward & adjoint simulations

Global Adjoint Tomography: Earthquakes



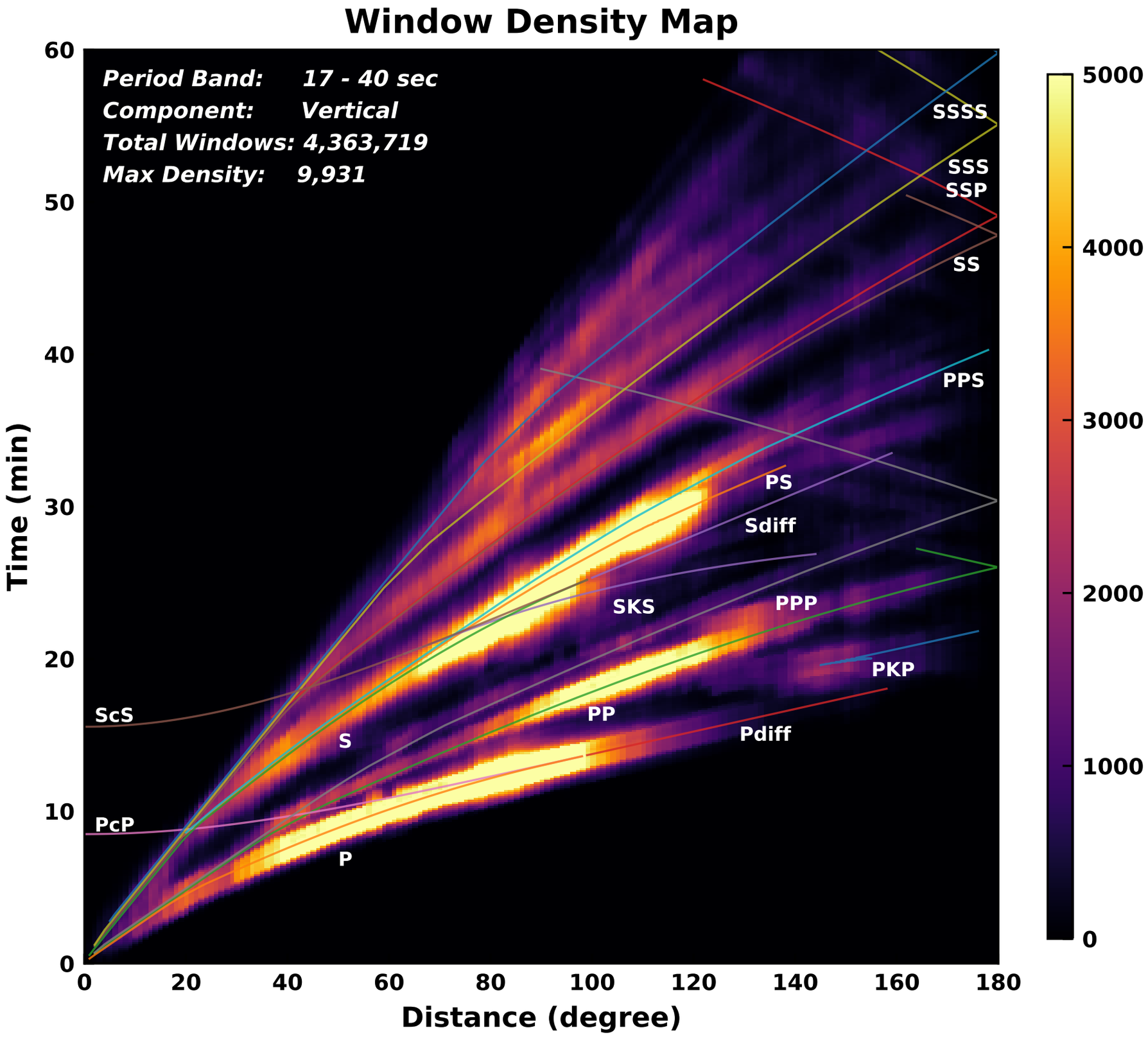
1,480 events

Global Adjoint Tomography: Stations



11,800 permanent and temporary seismographic stations

Window Density Map (Vertical)

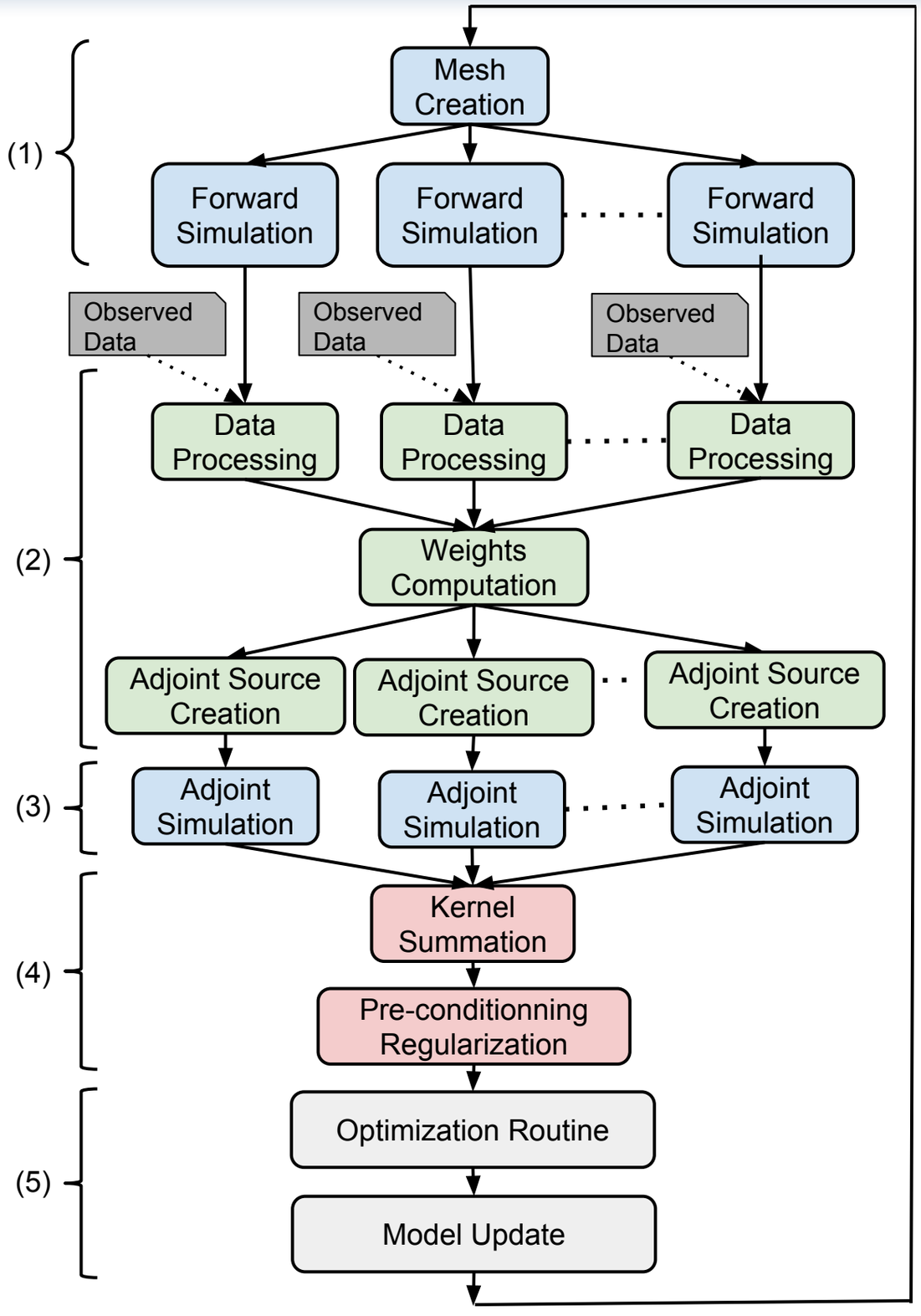


Global Adjoint Tomography Workflow

Challenge#1 Data Volume

8 million 120-min 20 Hz seismograms (6 TB)

10 TB kernels

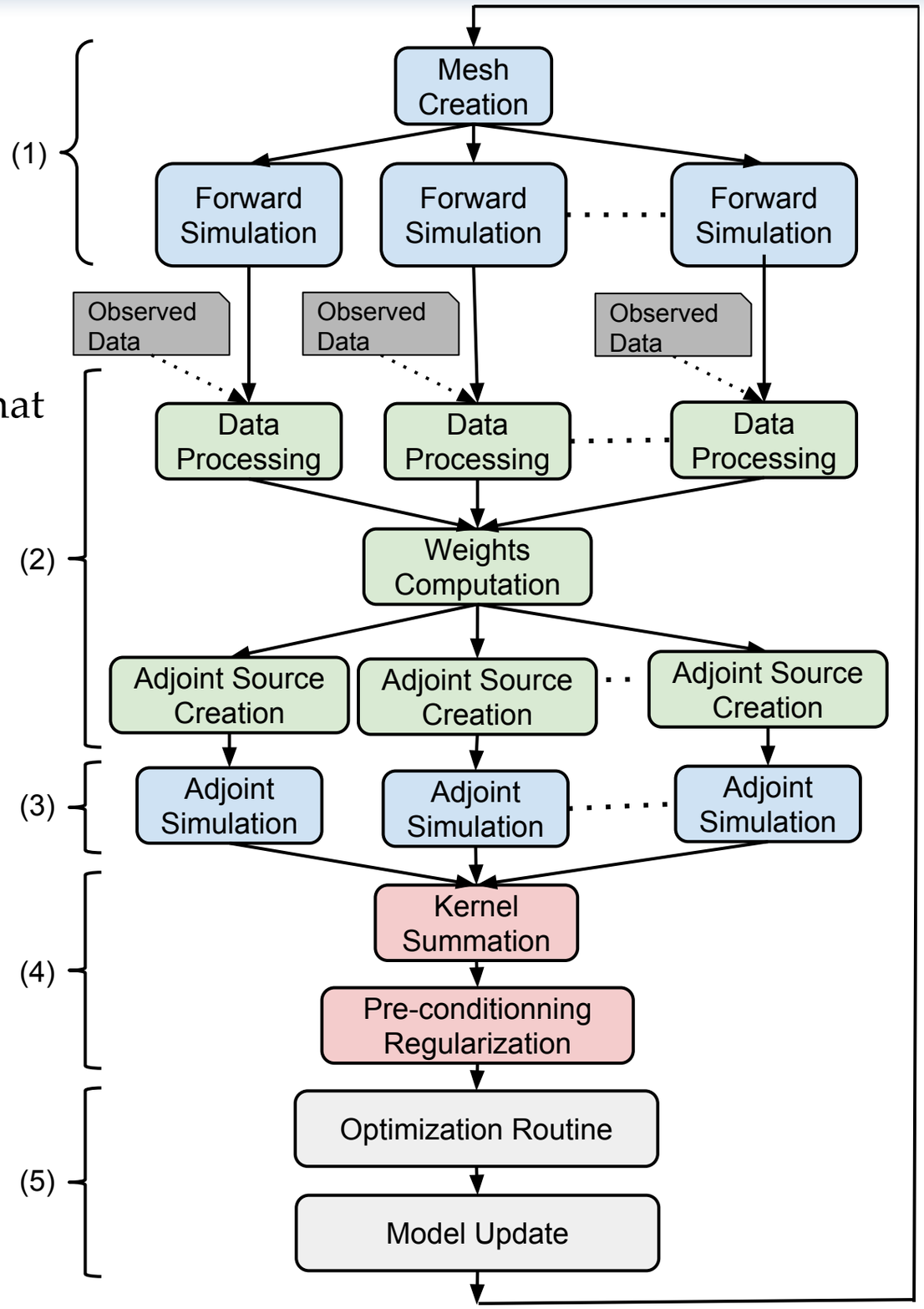


1 PB wavefield files

Global Adjoint Tomography Workflow

Challenge#1 Data Volume

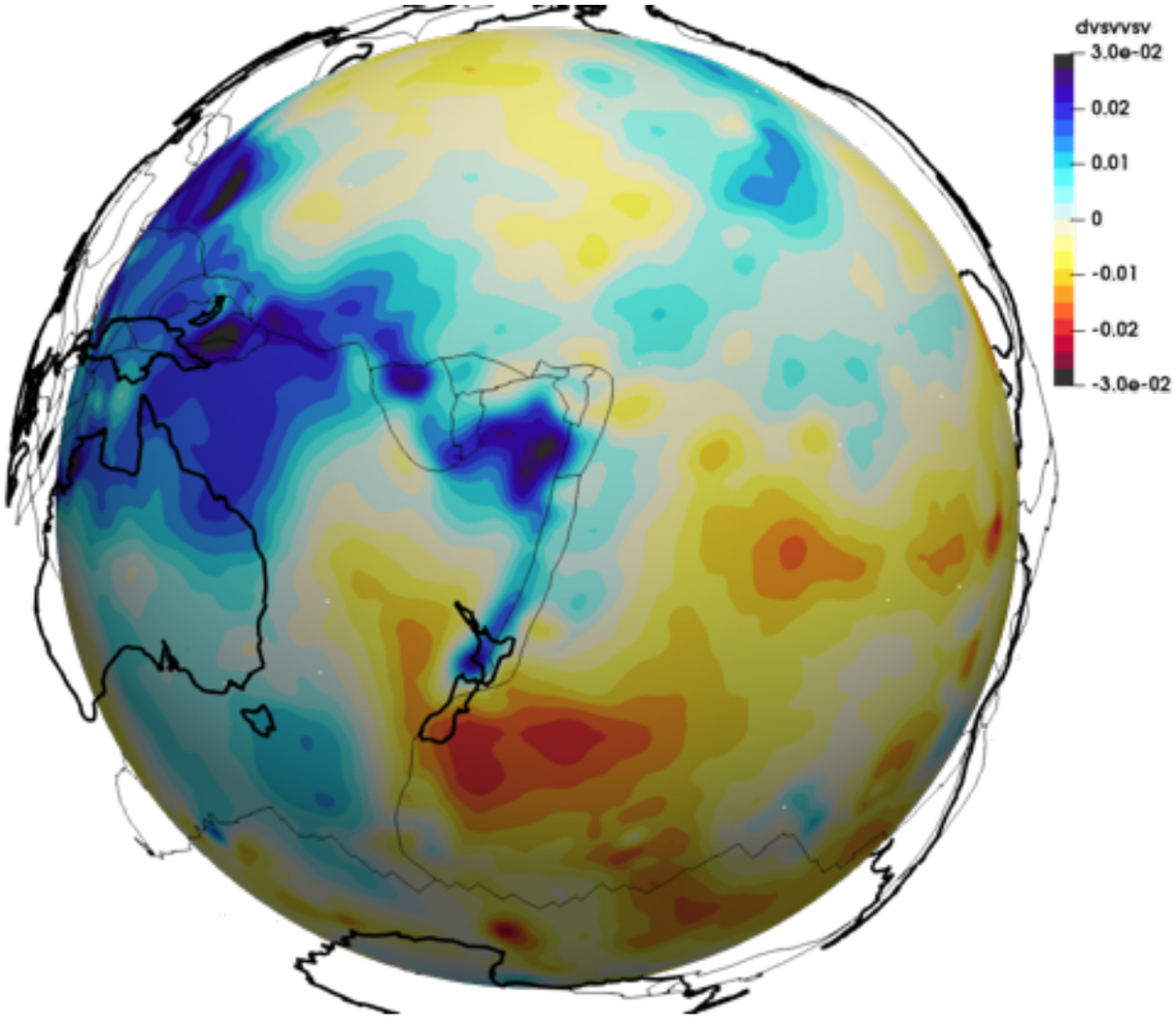
Adaptable Seismic Data Format
ASDF (Krischer et al. 2016)

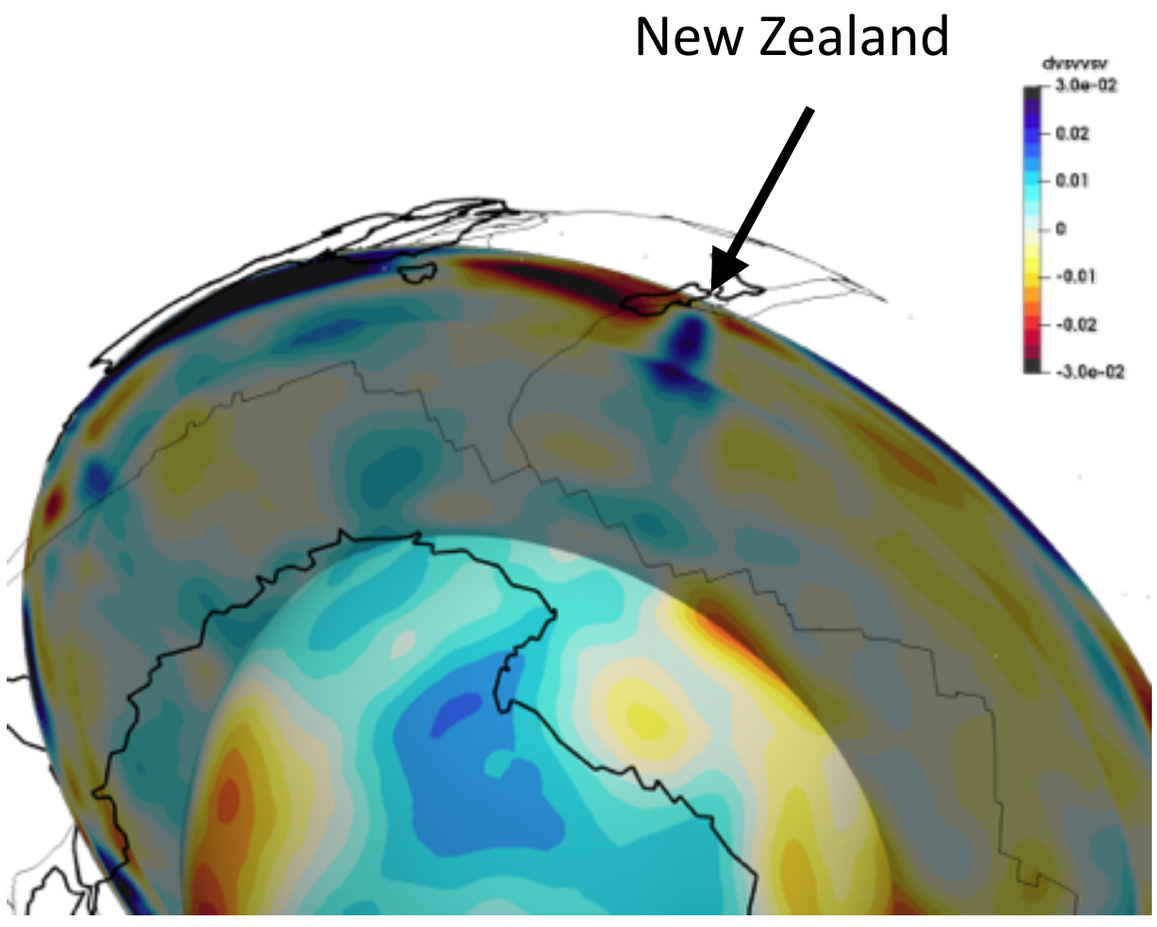


Adaptable I/O System
ADIOS (Liu et al. 2014)

Model GLAD-M25

Fiji Subduction 440 km





Subduction Zones

GLAD-M25 South America

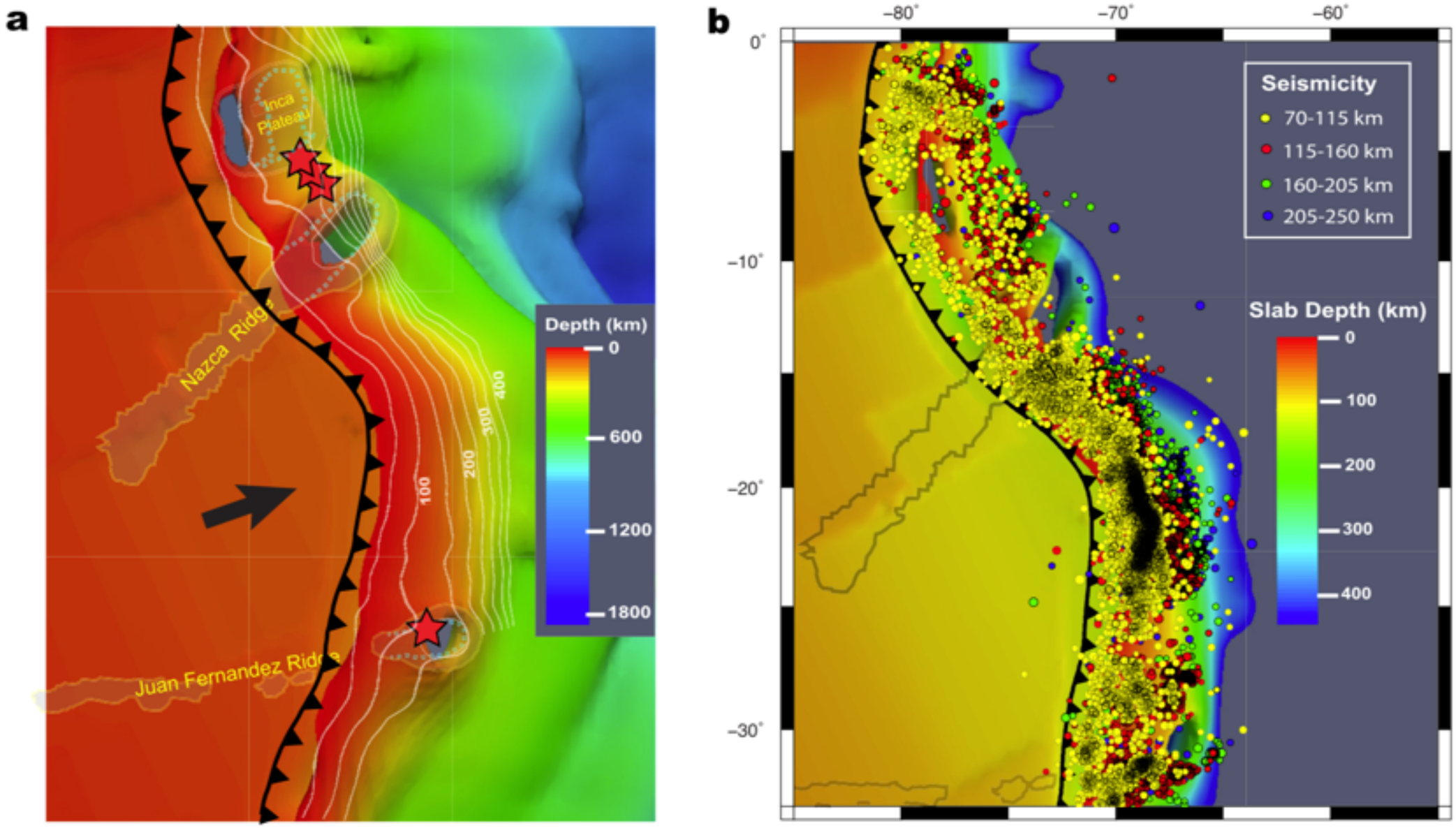
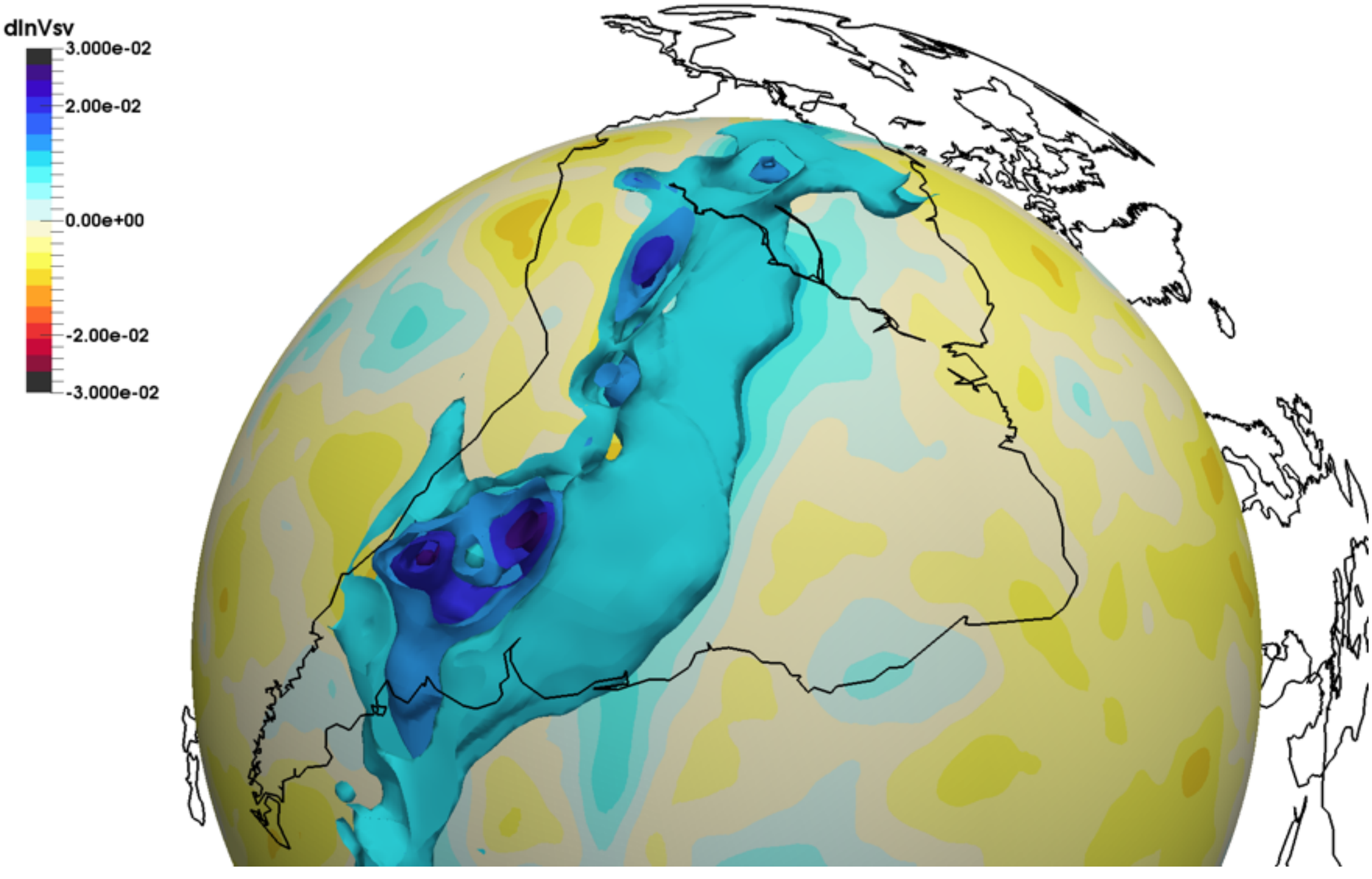


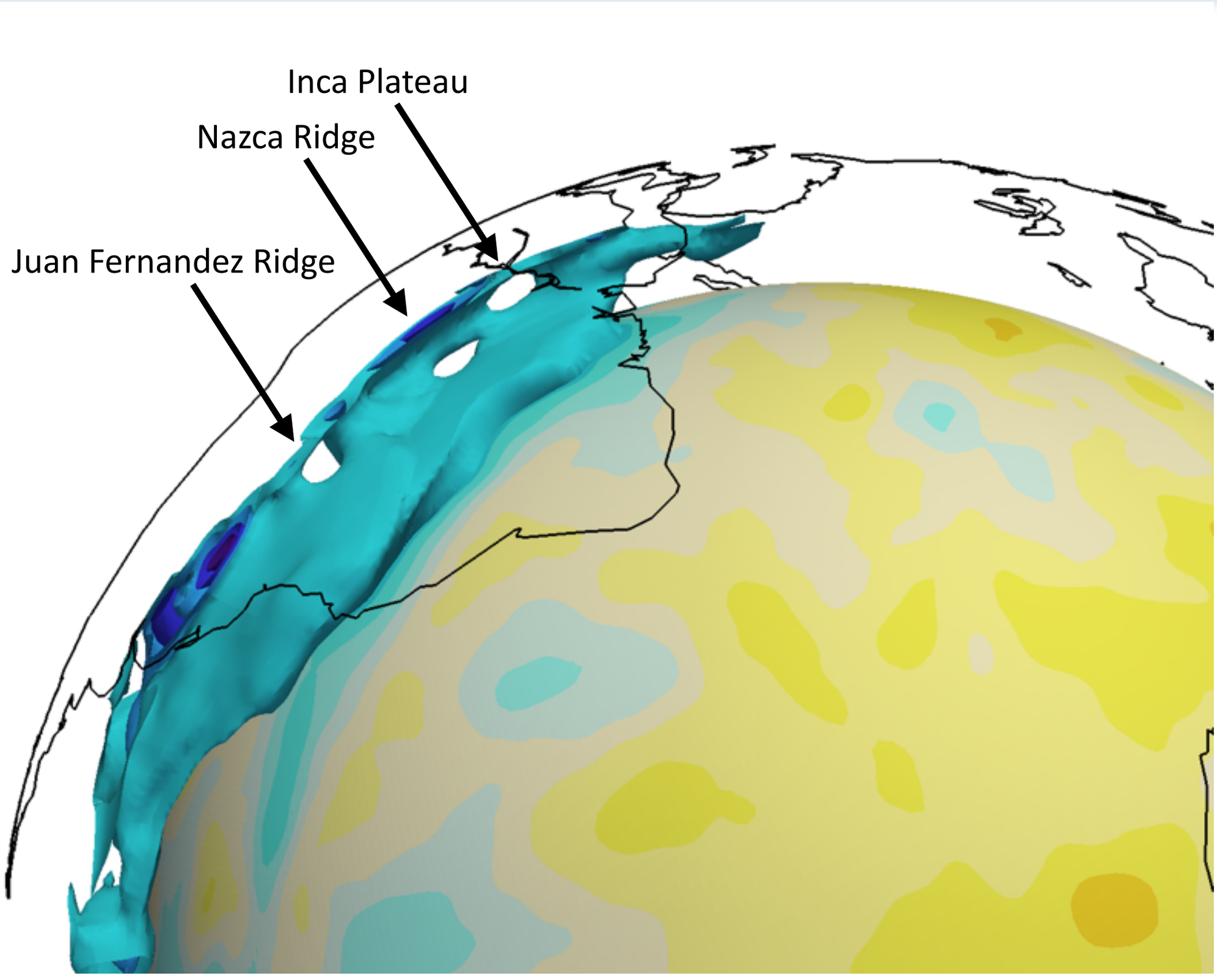
Fig. 5. 3-D geometry of the predicted present-day slab beneath South America and that of the Nazca Plate west of the trench (outlined using an isotherm of 300 °C cooler than the ambient mantle). a) 3D aerial view of the subducting Nazca Plate (temperature isosurface), with colors representing the depth of the slab's upper surface on the right side of the trench and depth of the plate's lower surface on the left side. The slab tears are illustrated with both the isosurface of temperature and the evolution of buoyancy features (translucent gray areas). Thin white lines are the interpolated Benioff zones from Hayes et al. (2012). Dashed lines within the subducting buoyancy features outline their original intact geometry. Red stars indicate the locations of adakitic eruptions. b) Map-view comparison of the slab geometry with the distribution of intermediate-depth seismicity ($M_b > 3.0$ from ISC seismic catalog). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Liu et al, 2016

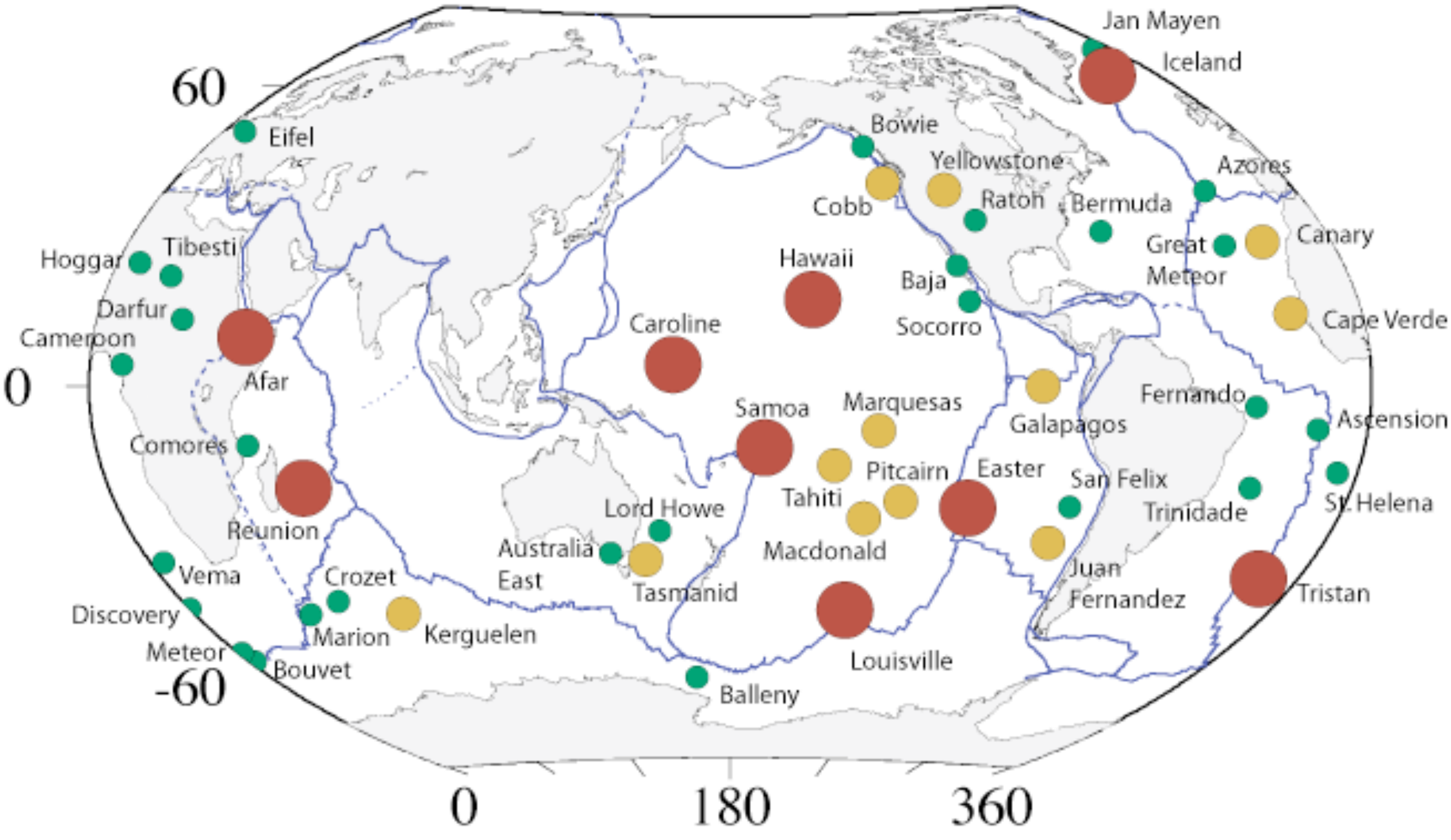
Model GLAD-M25



Model GLAD-M25

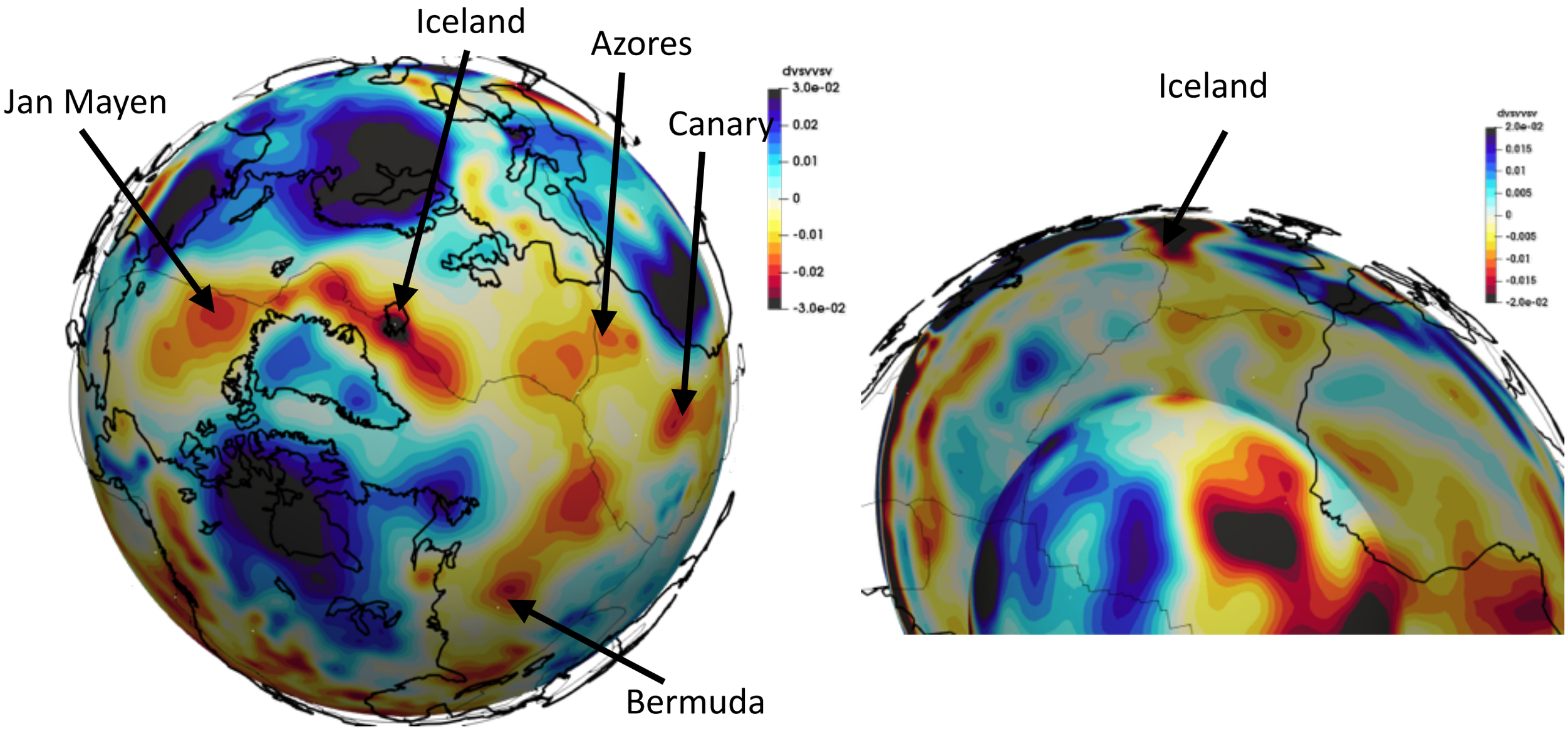


Hotspots & Mantle Plumes



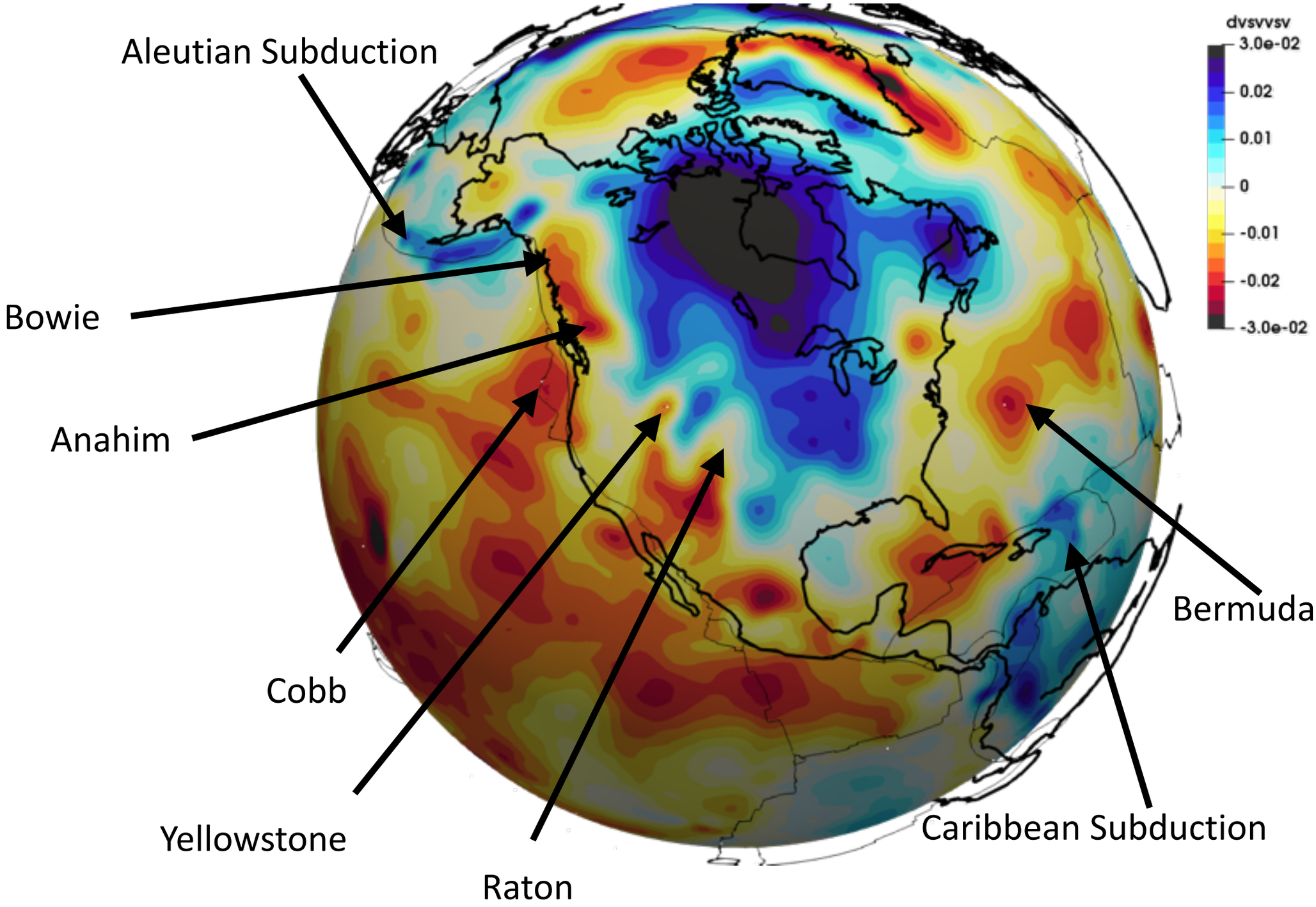
Model GLAD-M25

Iceland Hotspot 250 km



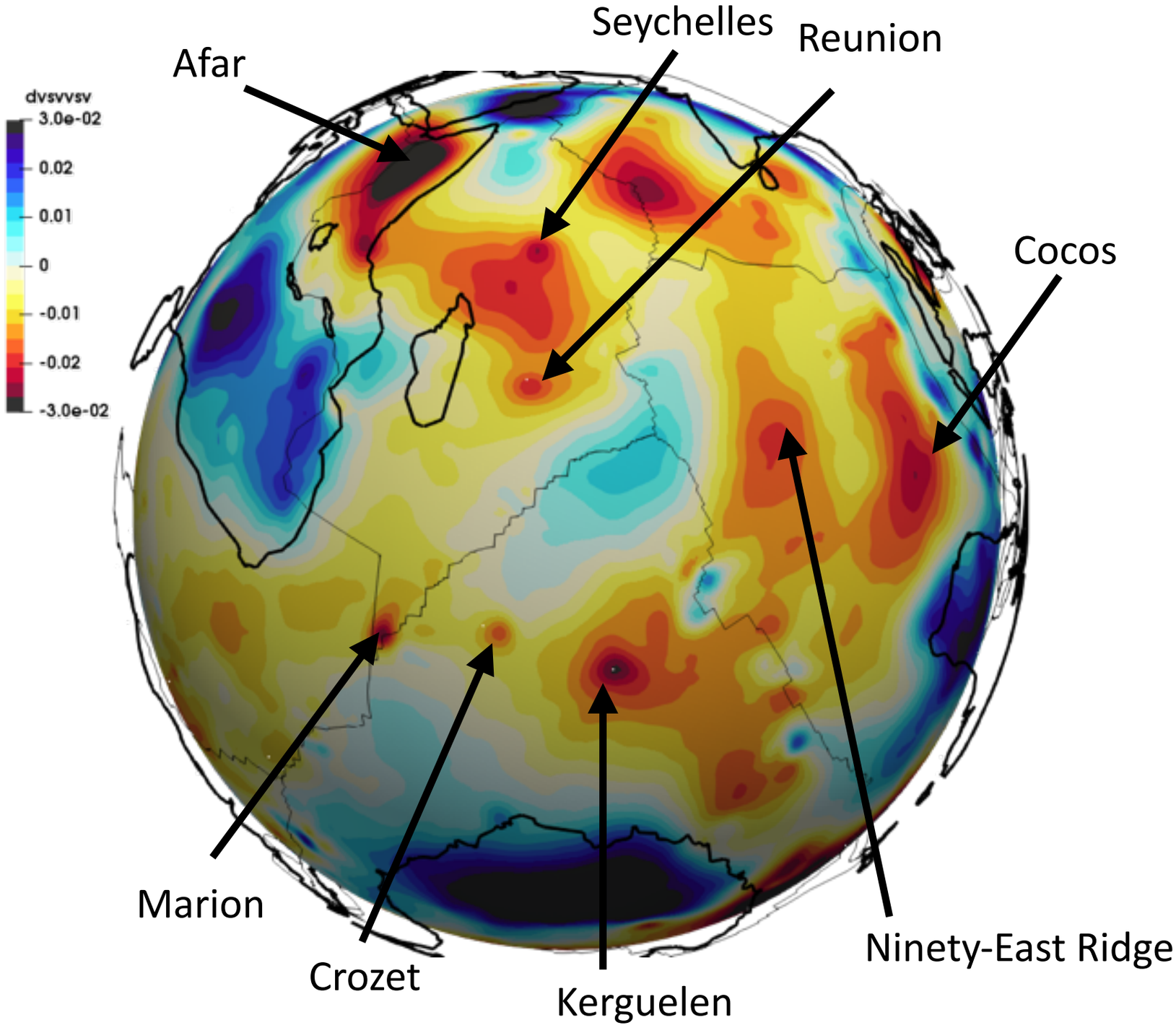
Model GLAD-M25

North America at 250 km



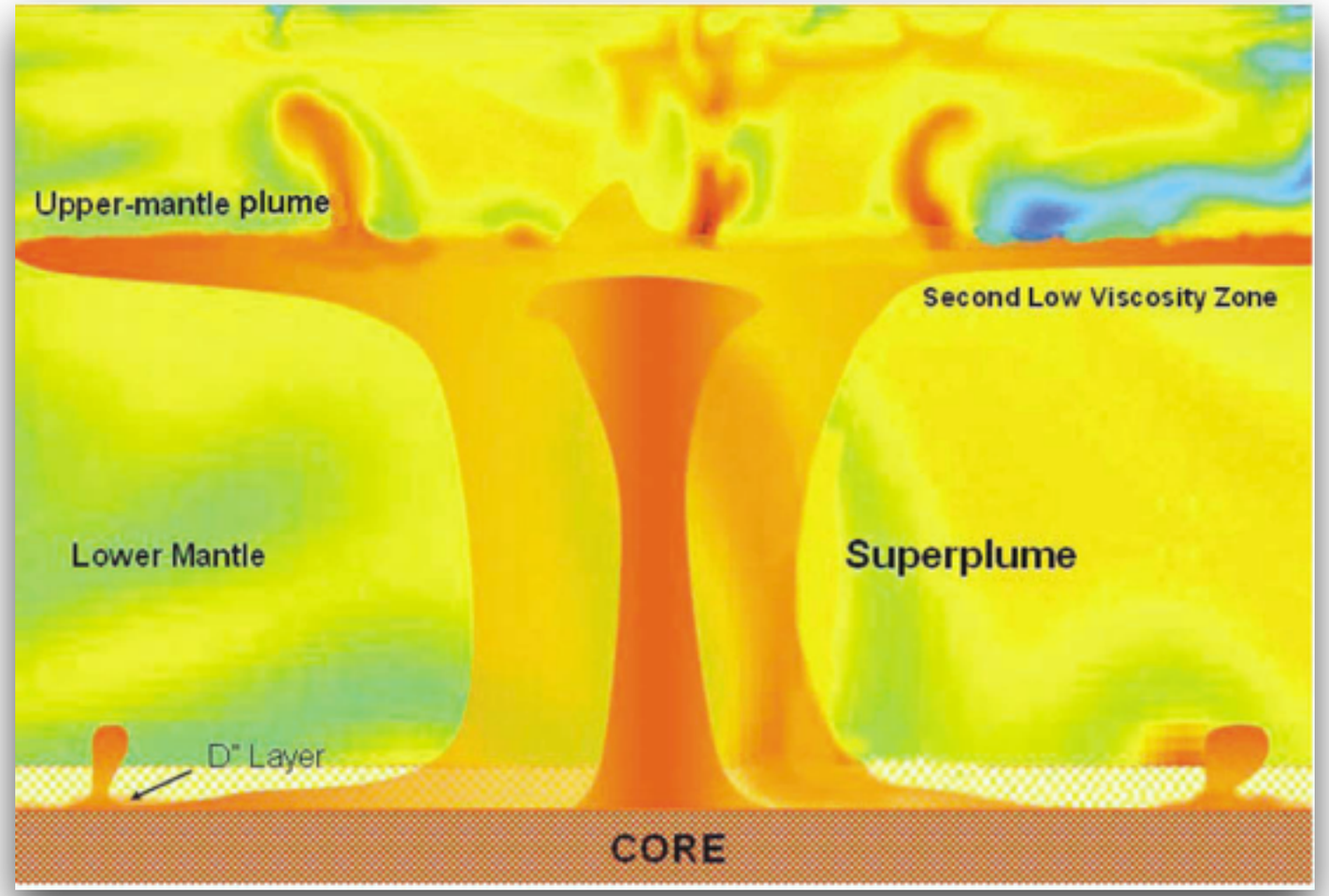
Model GLAD-M25

Indian Ocean at 250 Km



Multi-Scale Mantle Plumes

Stable lower-mantle plumes followed by small upper-mantle plumes: primary & secondary plumes

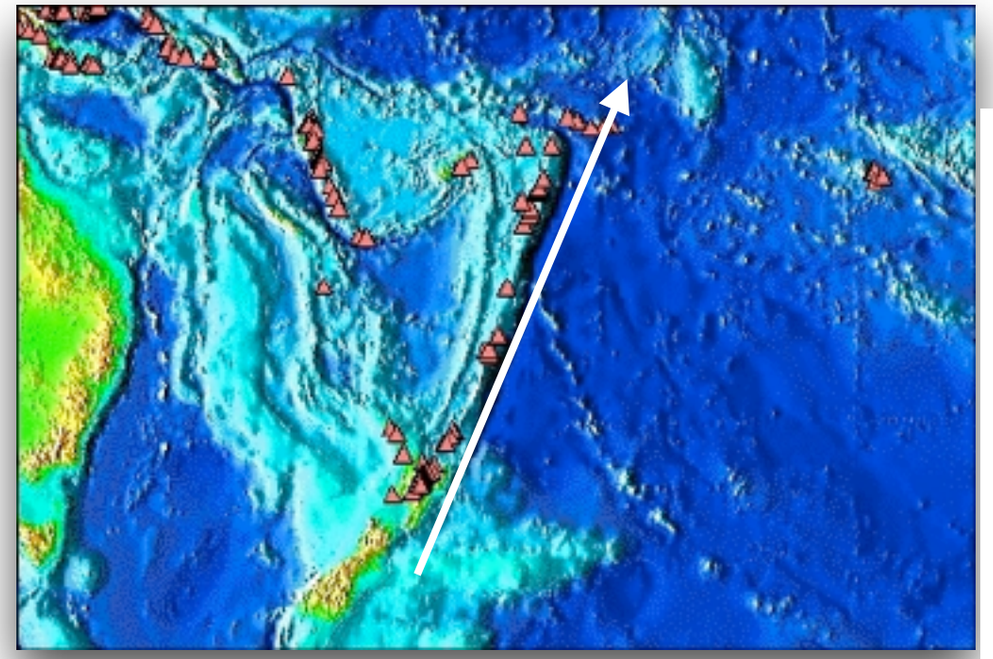


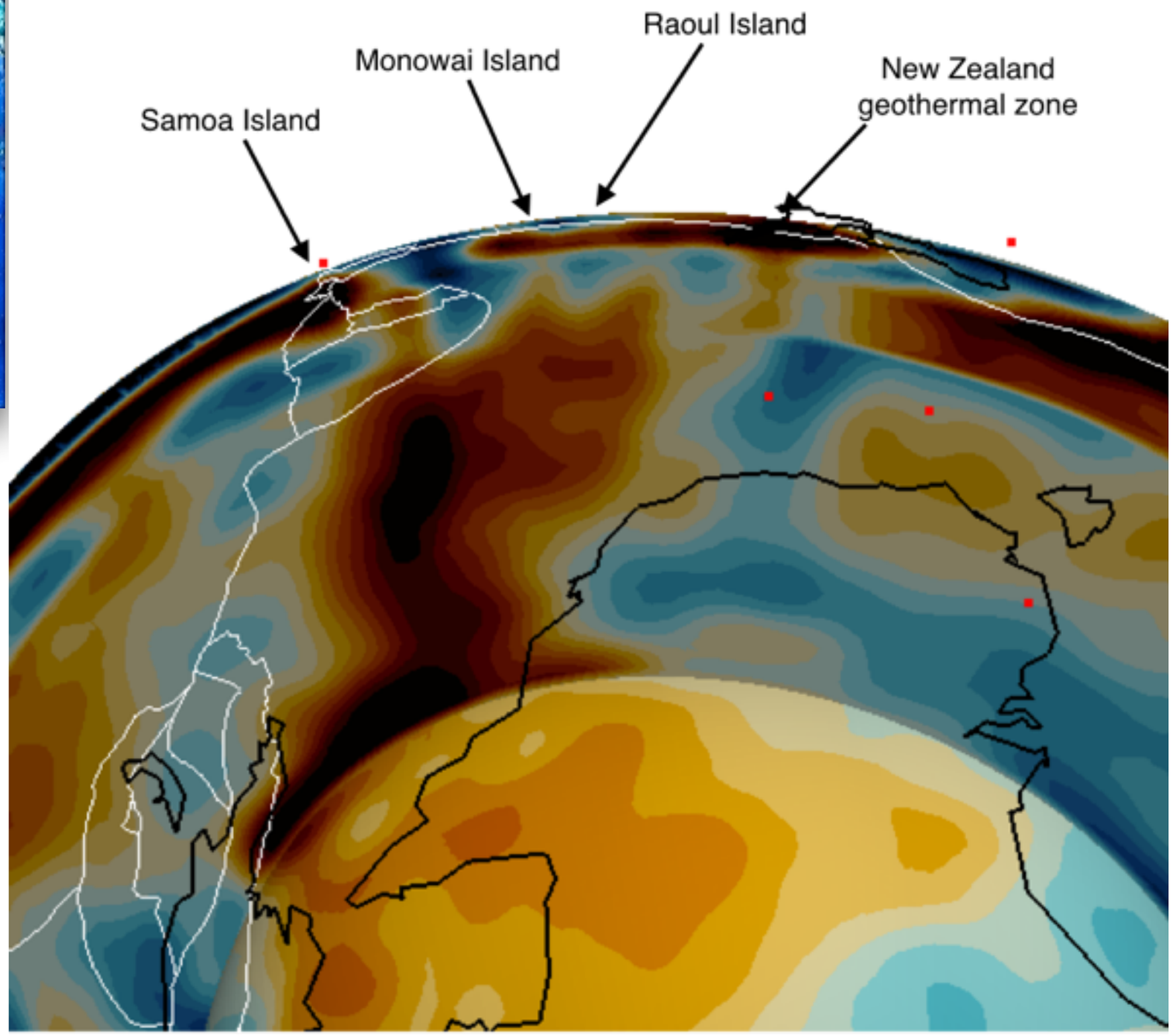
Controlled by:

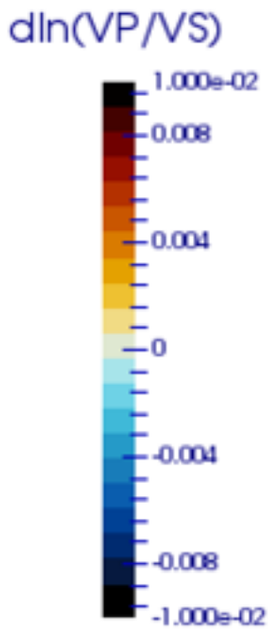
- mantle viscosity
- thermal conductivity
- thermal expansivity
- phase transitions

Matyska & Yuen, 2007

Model GLAD-M25





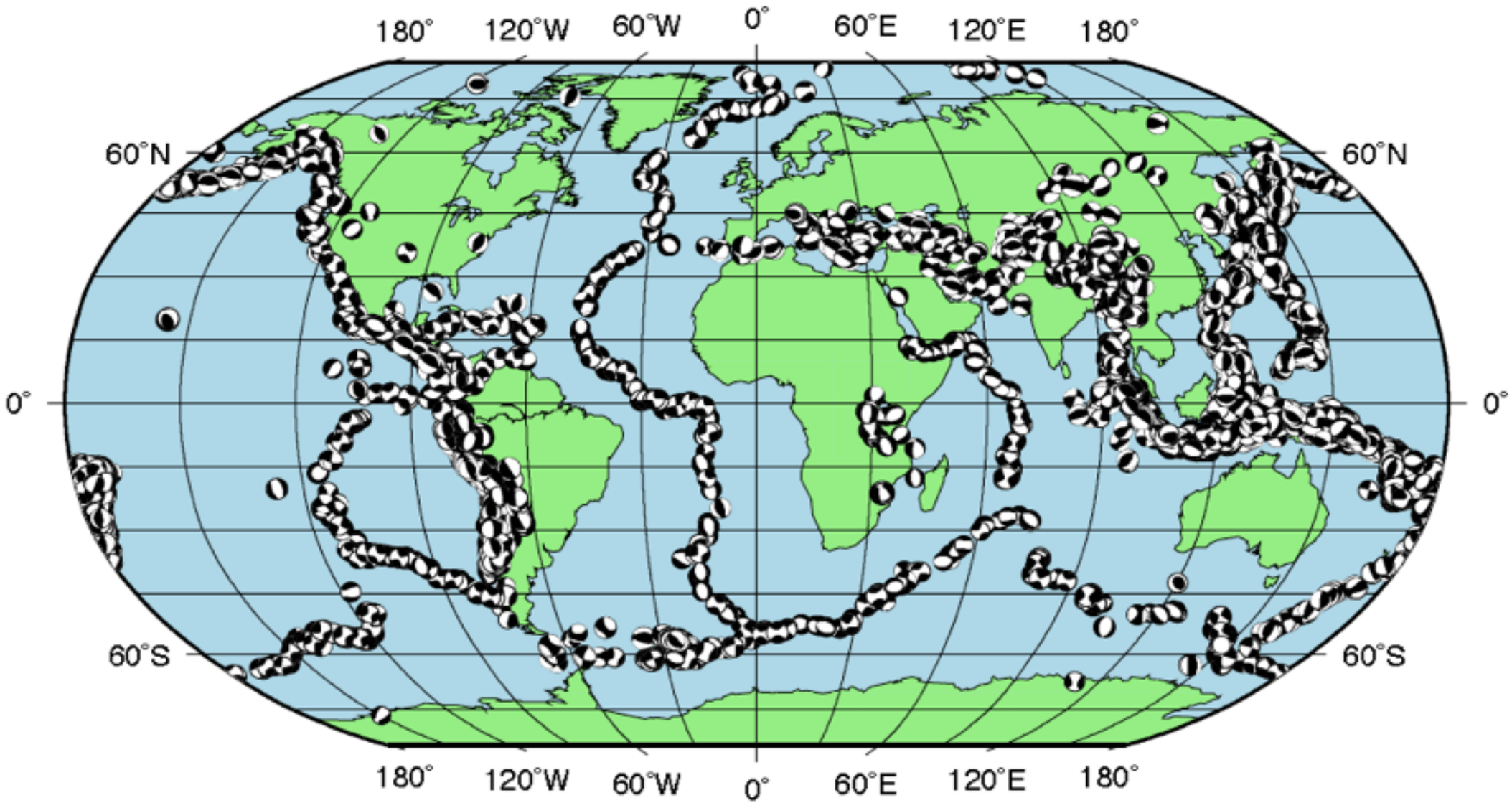


Pillars of the Mantle II

Imaging Earth's Interior with Adjoint Tomography

David Pugmire & Ebru Bozdağ

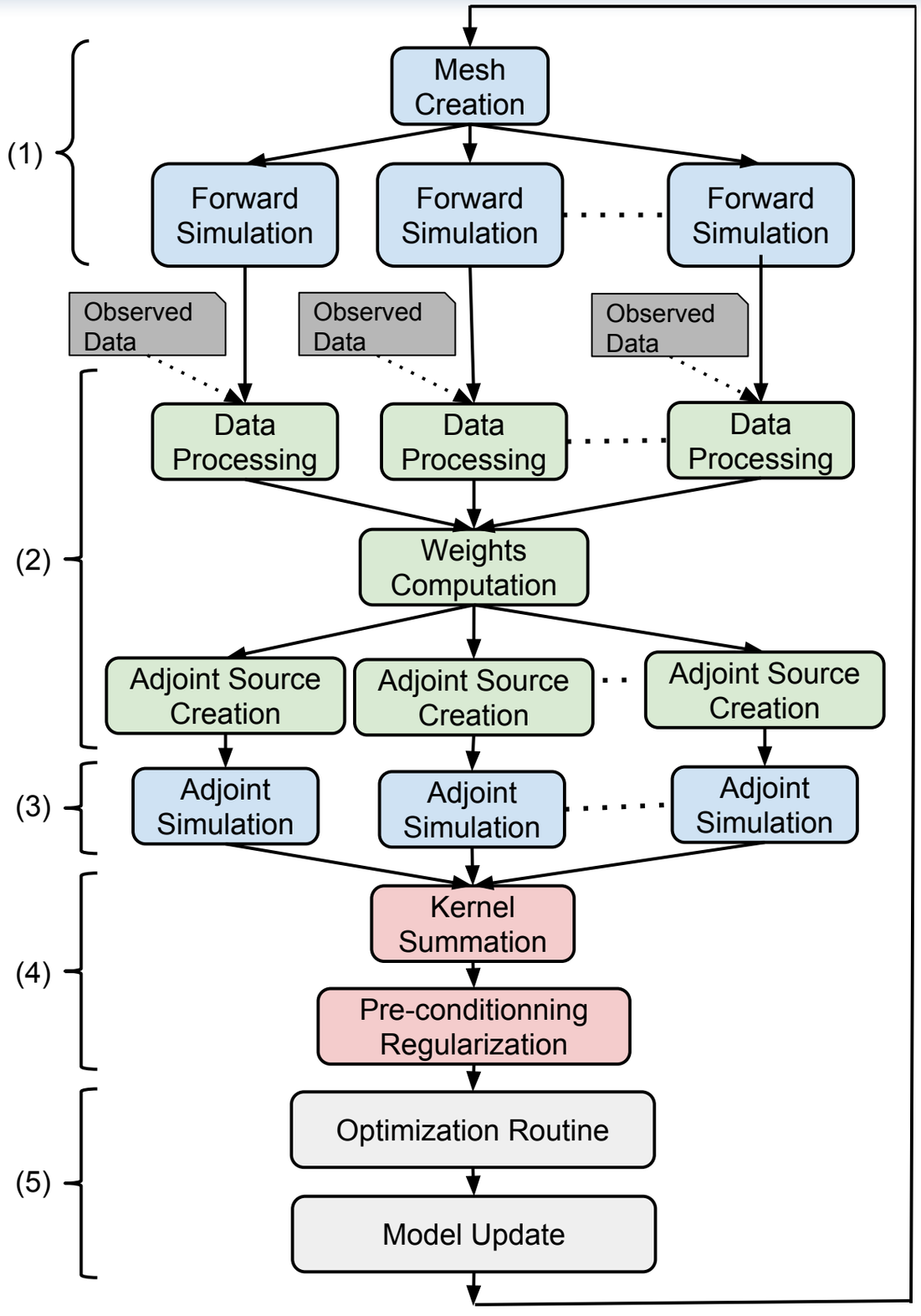
Exascale Goal: Use All Available Data



More than 6,000 earthquakes ($5.5 \leq Mw \leq 7.0$) since 1999

Global Adjoint Tomography Workflow

Challenge #2
Expensive Simulations
&
Complex Workflow



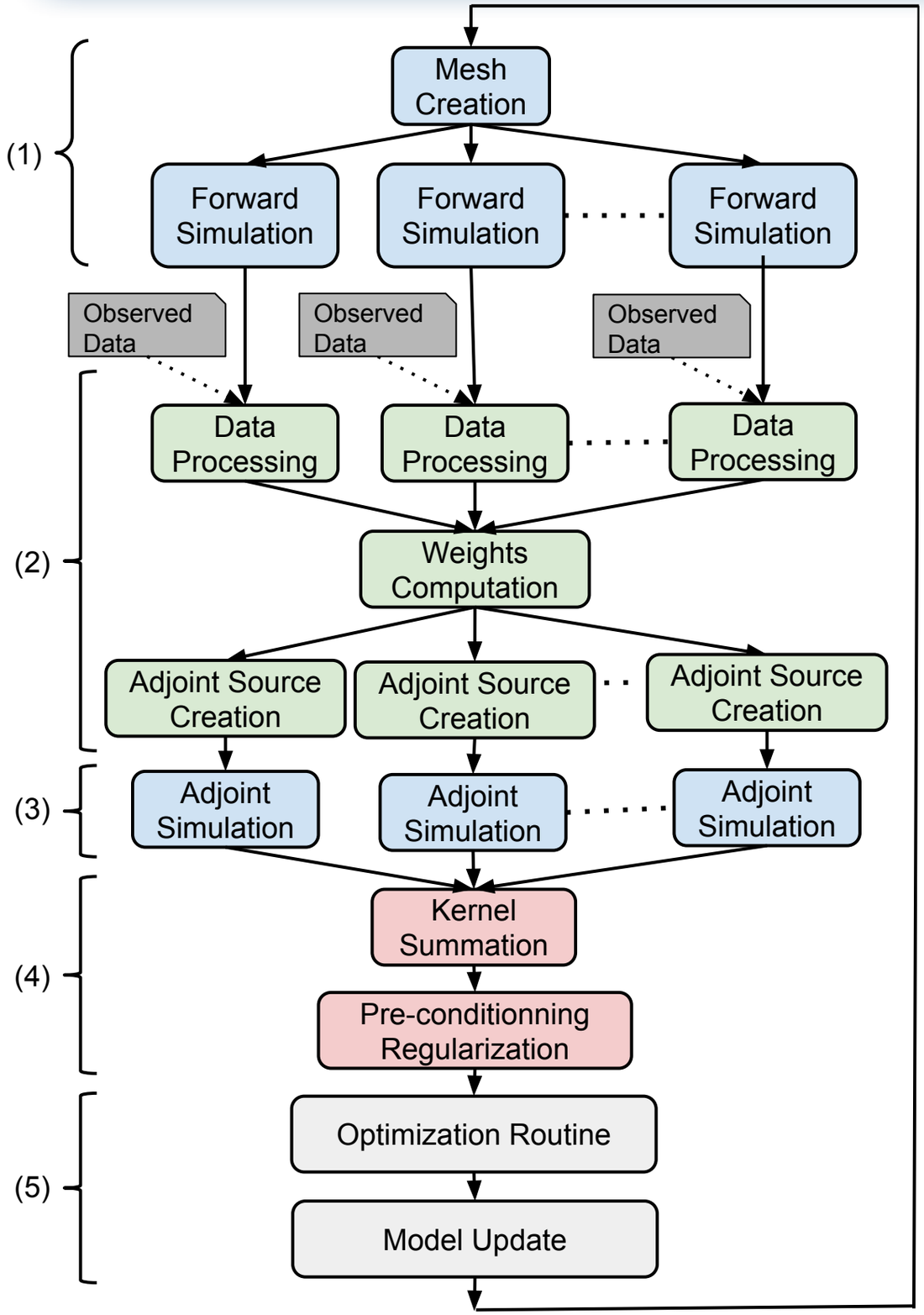
0.1 million core hours for data processing

3 million core hours for forward simulation

6 million core hours for adjoint simulation

1 million core hours for line search

Global Adjoint Tomography Workflow Management



Main sources of trouble:

- Hardware failures
- Human errors

We are implementing the RADICAL EnTK workflow management toolkit:

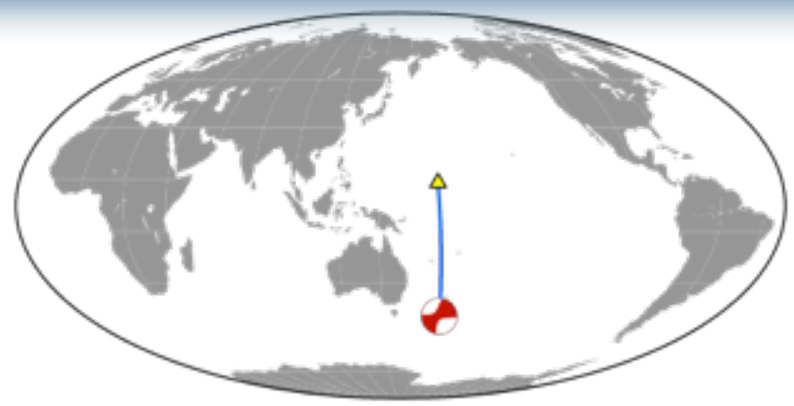
- ***Automation***: save time & human effort for repeated tasks
- ***Efficiency***: acceleration, taking full advantage of HPC systems
- ***Fault tolerance***: automated job failure detection & recovery

Shantenu Jha (Rutgers)

Exascale Goal: Higher-Frequency Body Waves

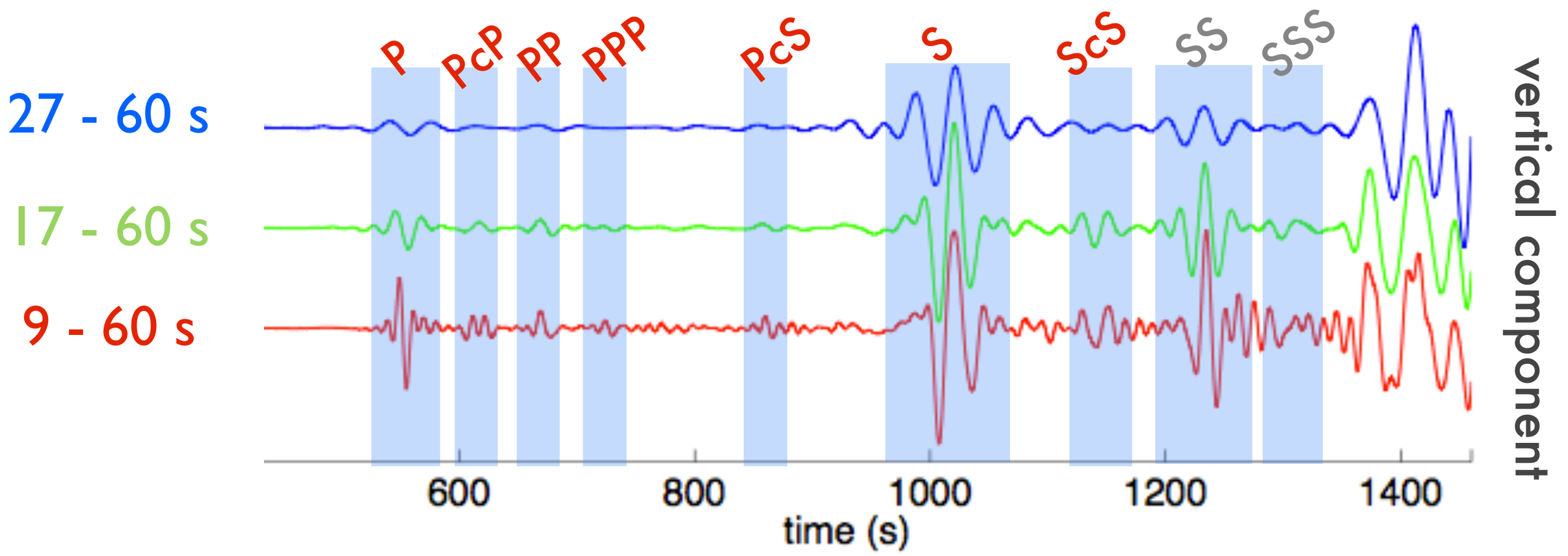
Short term goal (2018): 9 s (“Summit”)

Long term goal (2021): 1 s (exascale)



Station: KWAJ

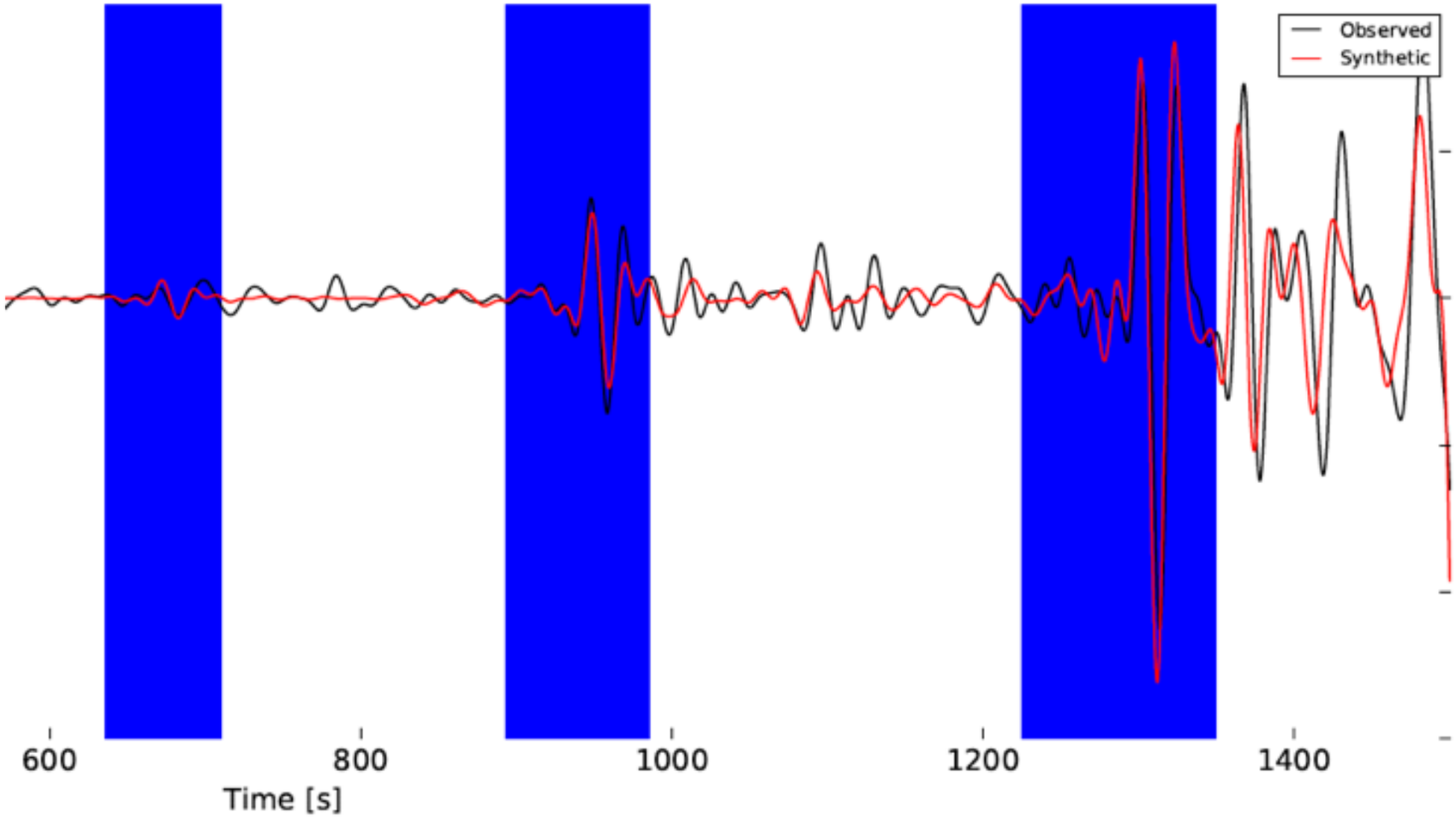
Δ= 52°



Ebru Bozdağ

Machine Learning for Data Assimilation

Use of Machine Learning for automated window selection



Center for Accelerated Application Readiness (CAAR) project in preparation for ORNL's next machine "Summit"

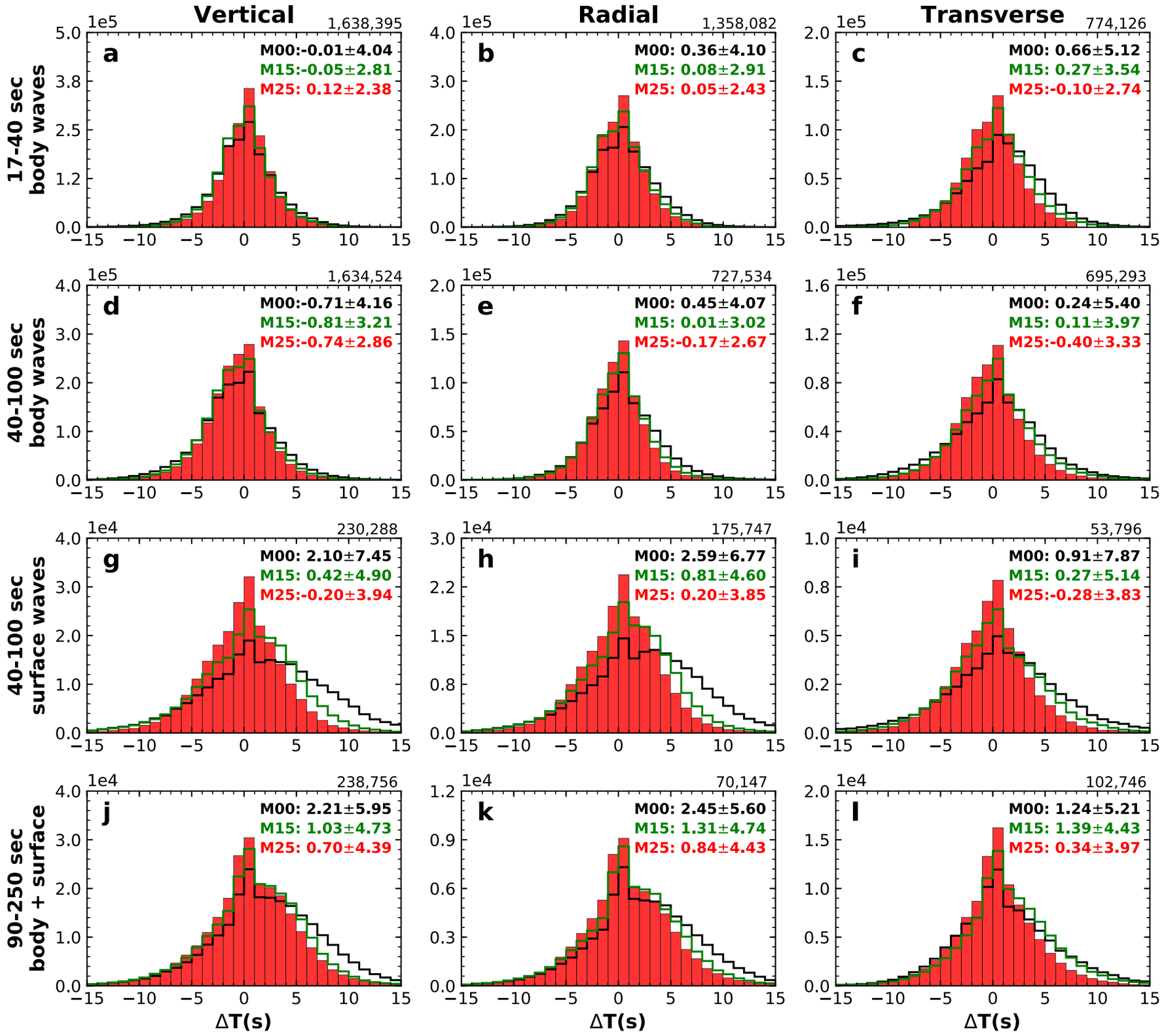
Partnership with IBM, NVIDIA & Mellanox

Yangkang Chen

Summit Seismology Science Goals

- Use data with a shortest period of ~1 Hz
- Use all available events with magnitudes greater than ~ 5.5
- Use entire 200 minutes long, three-component seismograms
- Workflow stabilization & management
- Allow for transverse isotropy with a random symmetry axis
- Allow for variations in attenuation
- Facilitate uncertainty quantification
- Source encoding to reduce the cost of the gradient calculation
- Opportunities for ML/AI in data selection & assimilation
- Data mining, feature extraction & visualization

Held-Out Dataset



Held-Out Dataset

	Vertical (%)	Radial (%)	Transverse (%)
17–40 s	11.8 (29.2)	14.1 (33.7)	21.5 (43.4)
40–100 s body waves	14.5 (26.2)	12.9 (32.2)	16.9 (39.0)
40–100 s surface waves	29.3 (49.1)	28.1 (49.4)	23.7 (51.2)
90–250 s	10.9 (30.9)	14.3 (34.8)	24.0 (34.9)

Table 2: Changes in fit for 360 earthquakes not used in the inversion in the twelve measurement categories between the new model, GLAD-M25, and its starting model, GLAD-M15, and, in parentheses, between GLAD-M25 and model S362ANI combined with CRUST2.0, which was the starting model for the GLAD-M15 inversion.