LA-UR-19-24897

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

Updates to the Regional Seismic Travel Time (RSTT) Tomography Model

SnT2019

June 26, 2019

Michael Begnaud
Los Alamos National Laboratory

Stephen Myers
Lawrence Livermore National Laboratory

Brian Young
Sandia National Laboratories

Los Alamos NATIONAL LABORATORY EST. 1943

Lawrence Livermore National Laboratory

Sandia National Laboratories

Outline: Status of RSTT

- **The last versioned release of the RSTT model was in 2014 (rstt201404um) www.sandia.gov/rstt**
- **Significant advancements since 2014 include:**
  - Crust and data additions/modifications from RSTT Outreach Workshops – see T5.3-P38, Myers, et al.
    - **Update crust from CRUST2.0 to *CRUST1.0***
    - **New dataset developed using *Bayesloc* (joint relative relocation -- www-gs.llnl.gov/nuclear-threat-reduction/nuclear-explosion-monitoring/bayesloc) to improve event locations and data quality**
  - Developed a method to estimate path-specific (i.e., 2D) travel-time uncertainty based on the decomposition of travel time residuals into uncertainty components
    - **Begun modification of the public version of RSTT travel-time code to include 2D uncertainty**
- **Latest Updates (this presentation):**
  - Overview of tomography methods
  - Update RSTT tomography to use new data set for ALL regional phases (Pn, Pg, Sn, Lg)
  - Overview of travel-time uncertainty methods
  - Calculate error components (model, random, bias) for all phases and demonstrate resulting path-specific travel-time uncertainty calculations
  - Preliminary validation of tomography and uncertainty
    - **Tomography: Travel-time Correction Surfaces (similar to Source-specific Station Corrections (SSSCs))**
    - **Travel-time Uncertainty Surfaces**

Tomography Overview

- **Multi-step: (rstt201404um starting model)**
  - (1) DSS lines, PNE;
  - (2) New Bayesloc data (all phases)
    - **Gradient was set to constant starting 0.001 s^{-1}**
- **LSQR inversion (Paige and Saunders, 1982).**
  - Regularization (optimized for new data)
    - **Smoothing**
    - **Damping to previous iteration**
- **Solving for:**
  - Upper mantle slowness (s)
  - Upper mantle gradient (c^2)
    - **c = g*s + 1/r**
      (g = gradient, r = radius)
    - **Assumption: c*h << 1**
  - Pg/Lg crust (s_c)
    - **(middle crust Pg/Lg)**
  - Crustal stack modifier (of velocities) (α, β)

Mantle Phase

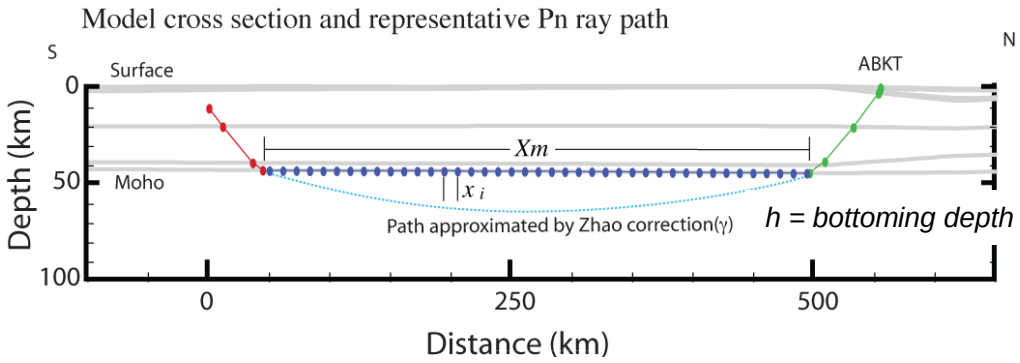
$$TT = \sum_{i=1}^{N} d_i s_i + a + b + g$$

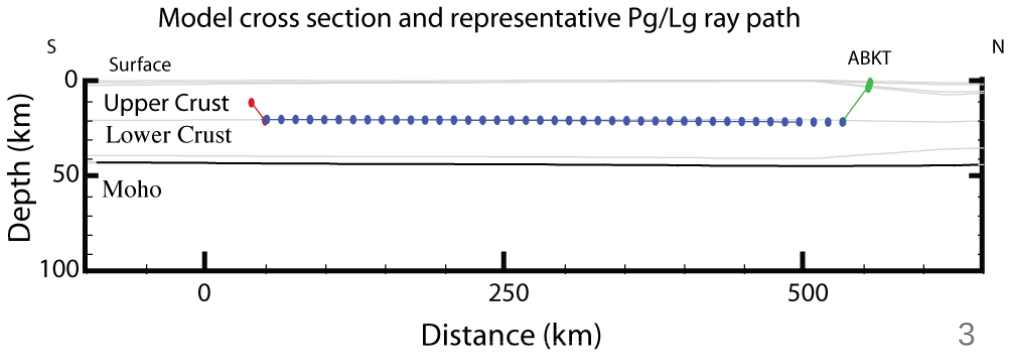
$$T = \sum_{i=1}^{N} x_i s_i + a^u + b^u$$

Crustal Phase

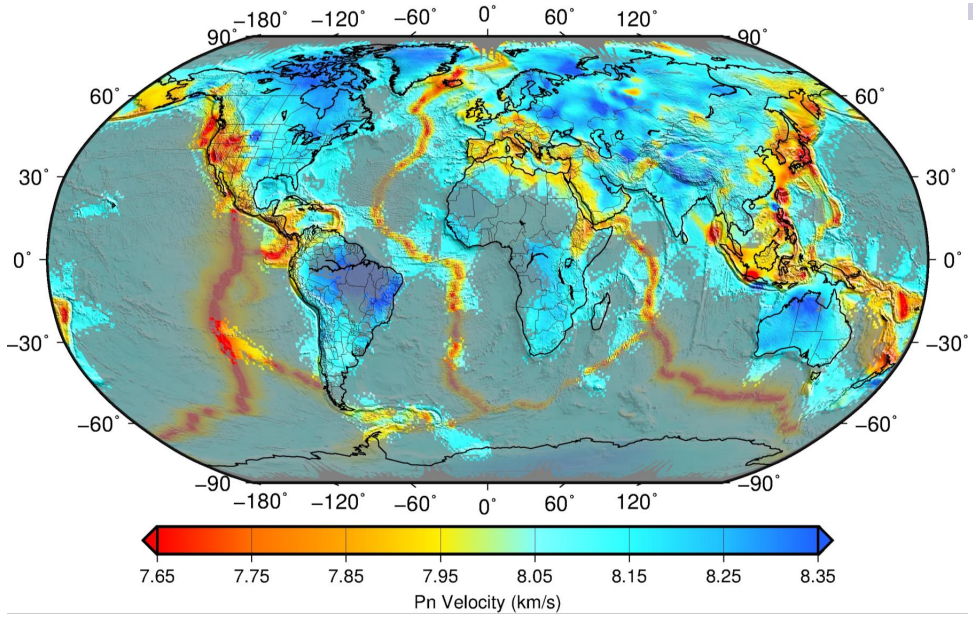
$$g = \frac{c^2 X_m^3}{24 V_0}$$

Gradient Portion



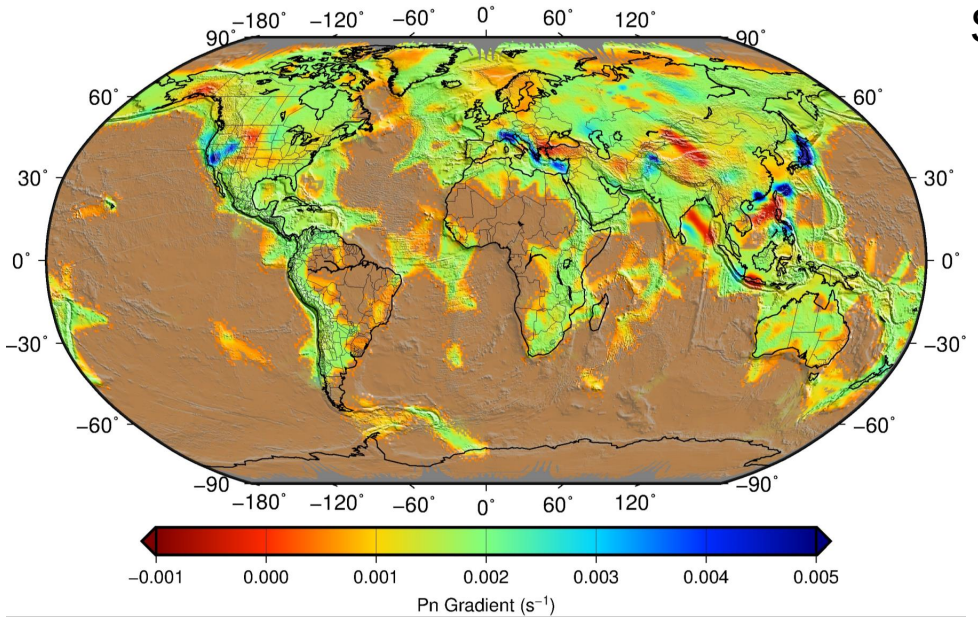


Tomography: Pn, Pg



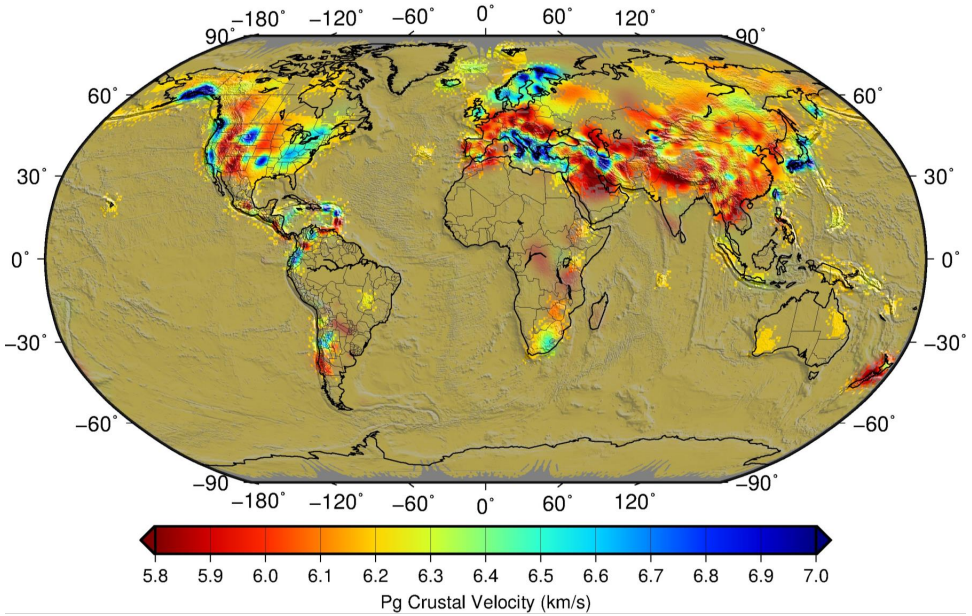
Velocity (km/s)

Pn
Weighted RMS
(by pick error)
1.9 million rays
Start (after DSS fit): 1.42 s
Finish: 1.24 s



Gradient (s^{-1})

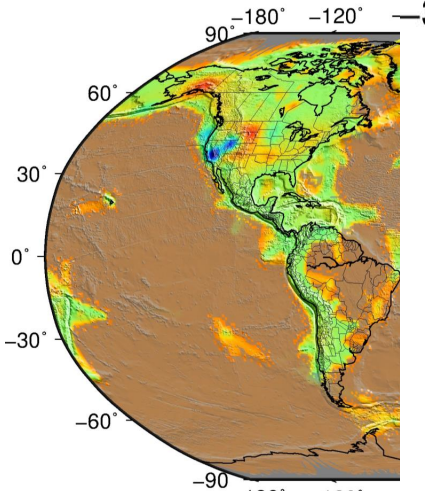
Pg
Weighted RMS
(by pick error)
409K rays
Start (after DSS fit): 1.59 s
Finish: 0.83 s

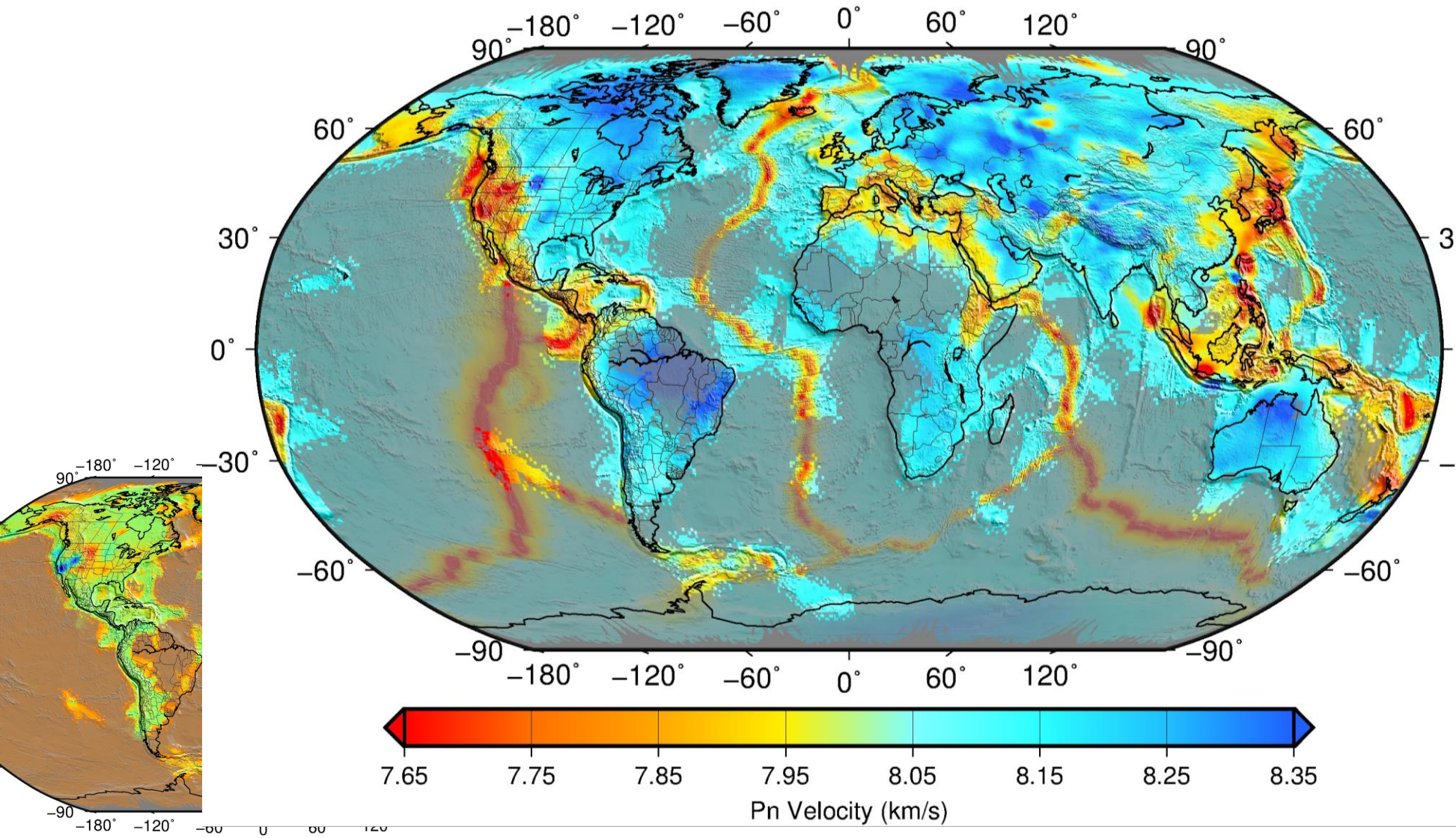


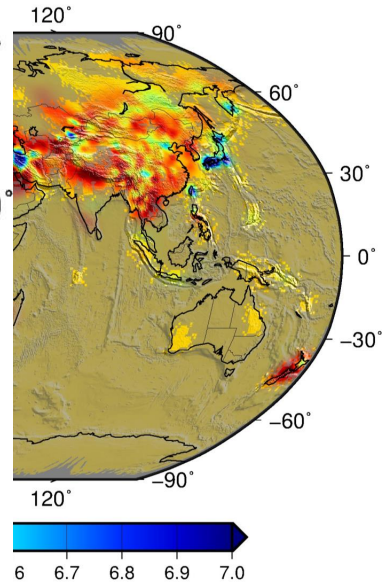
Velocity (km/s)

Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

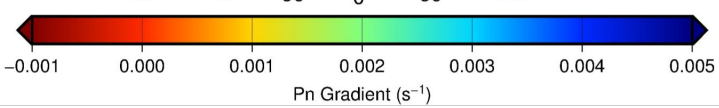
Tomography: Pn, Pg





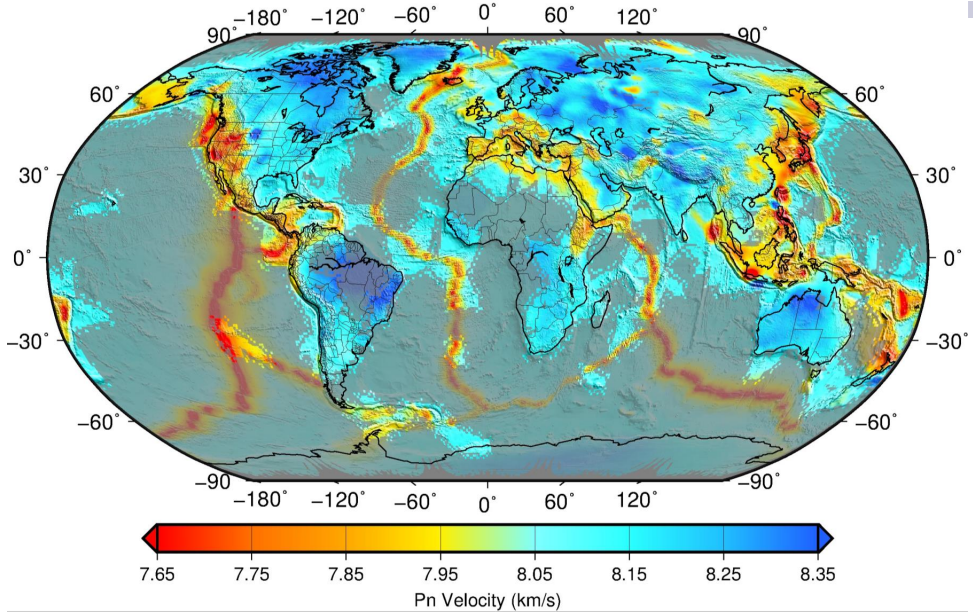


Velocity (km/s)



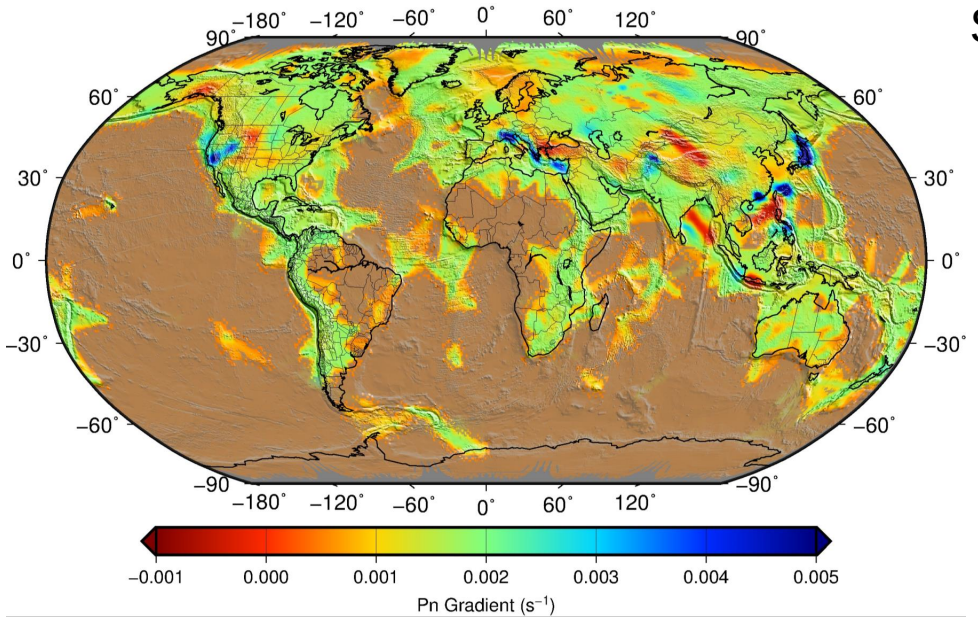
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Pn, Pg



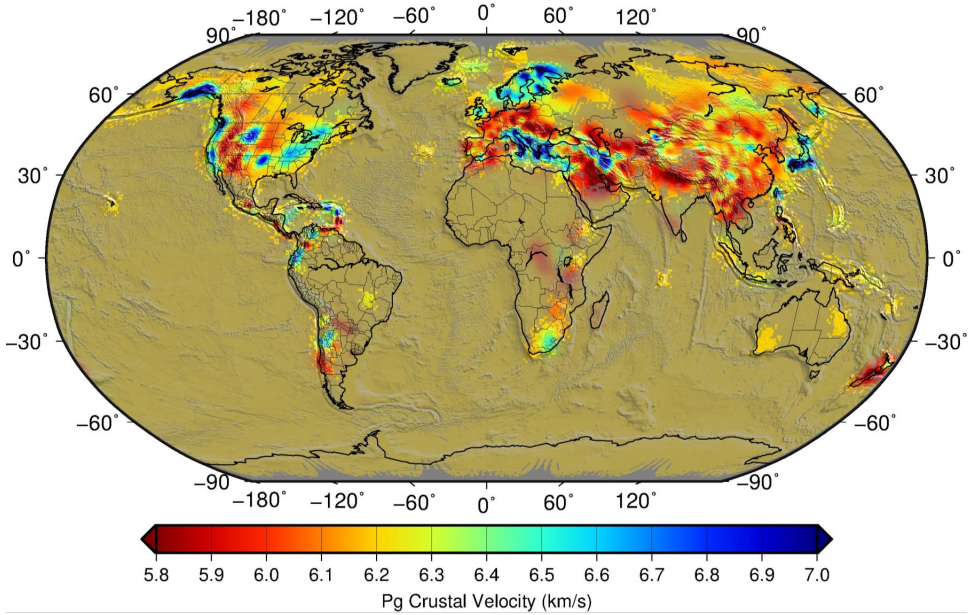
Velocity (km/s)

Pn
Weighted RMS
(by pick error)
1.9 million rays
Start (after DSS fit): 1.42 s
Finish: 1.24 s



Gradient (s^{-1})

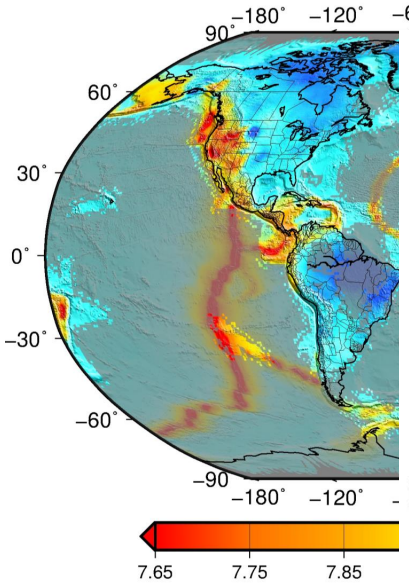
Pg
Weighted RMS
(by pick error)
409K rays
Start (after DSS fit): 1.59 s
Finish: 0.83 s

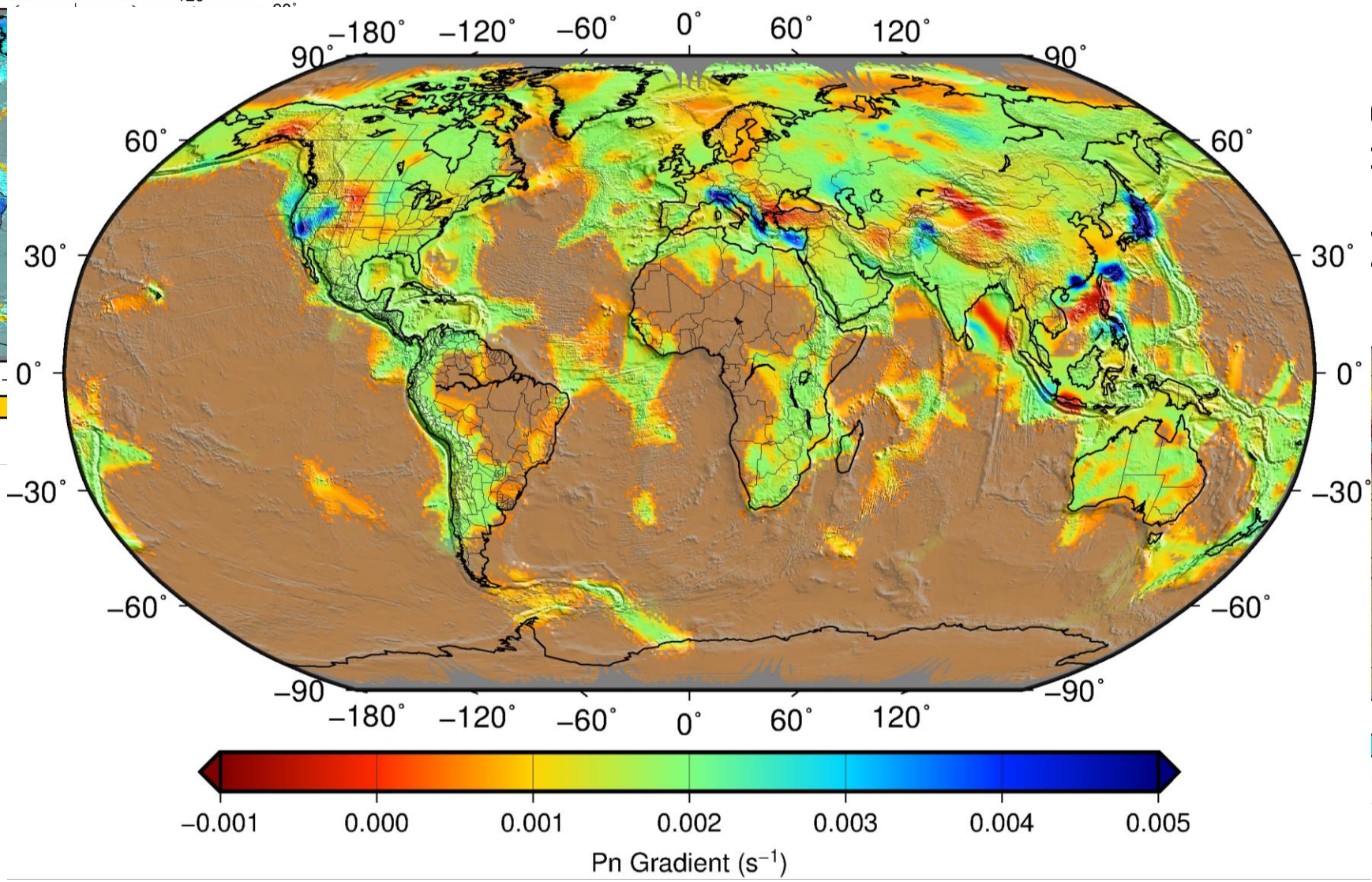


Velocity (km/s)

Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

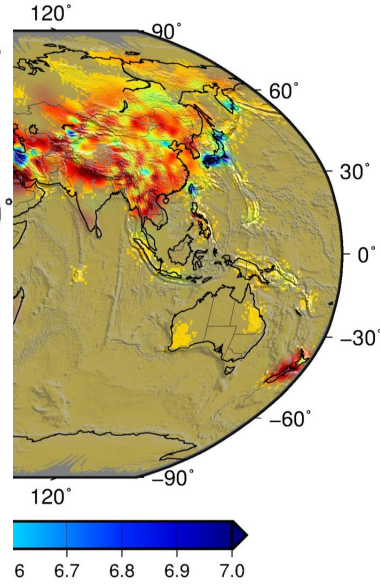
Tomography: Pn, Pg





MS
or)

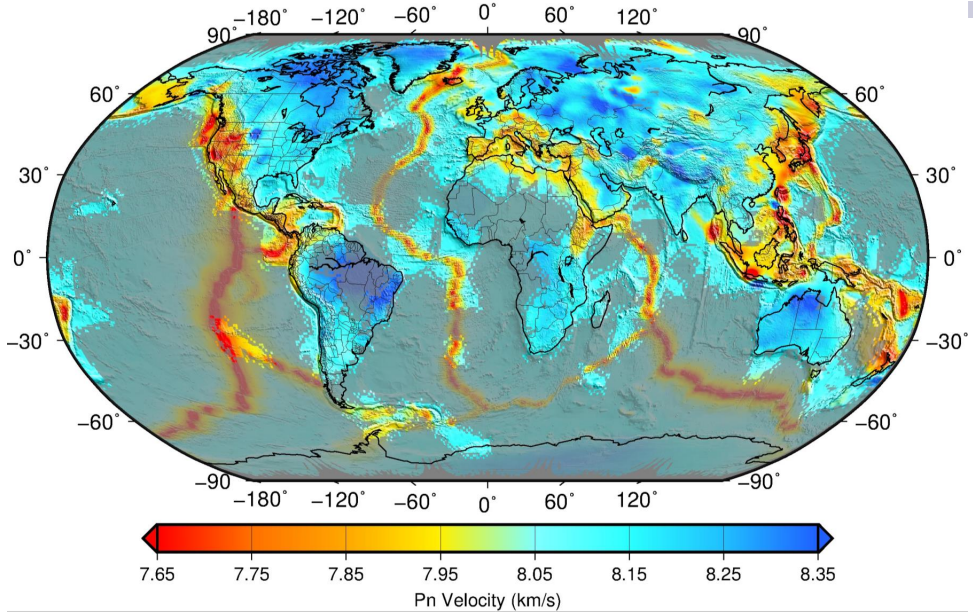
): 1.59 s
s



Velocity (km/s)

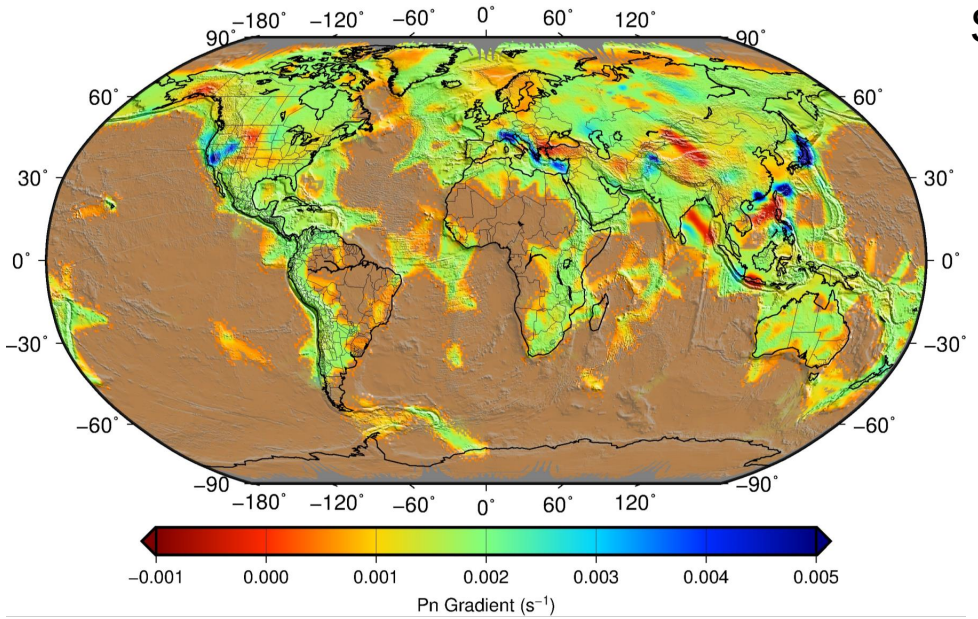
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Pn, Pg



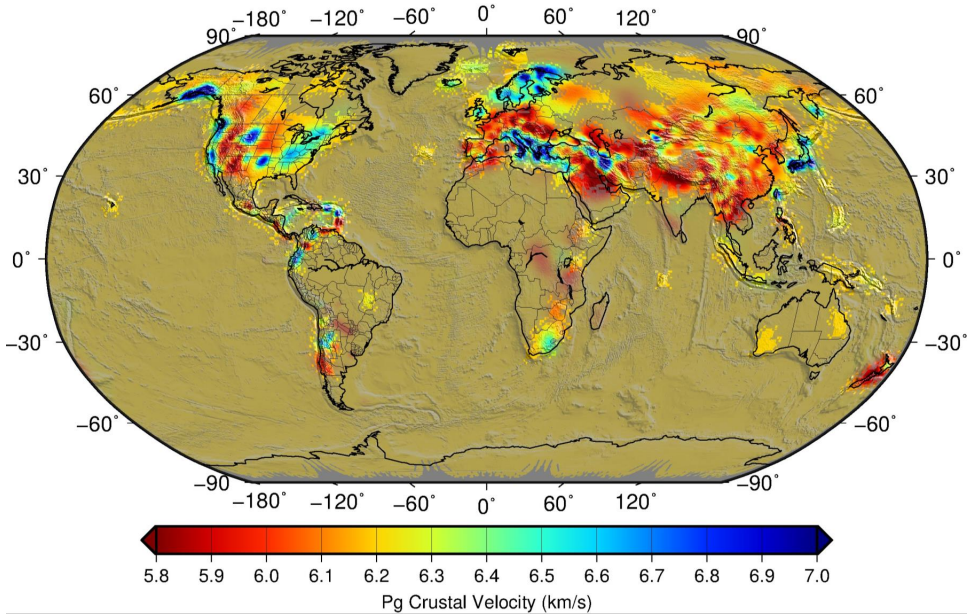
Velocity (km/s)

Pn
Weighted RMS
(by pick error)
1.9 million rays
Start (after DSS fit): 1.42 s
Finish: 1.24 s



Gradient (s^{-1})

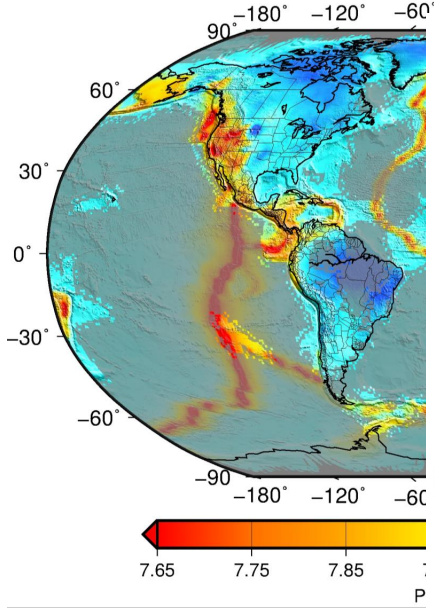
Pg
Weighted RMS
(by pick error)
409K rays
Start (after DSS fit): 1.59 s
Finish: 0.83 s

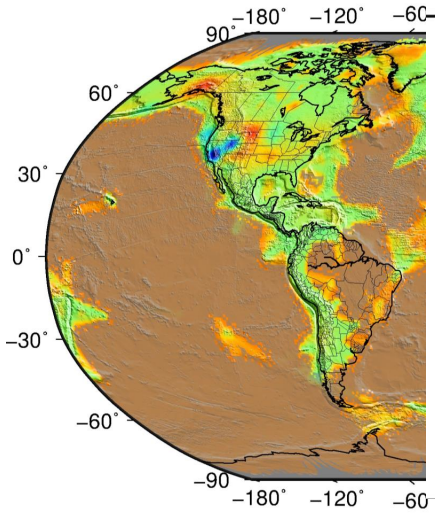


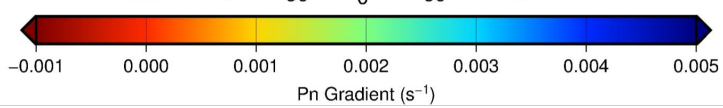
Velocity (km/s)

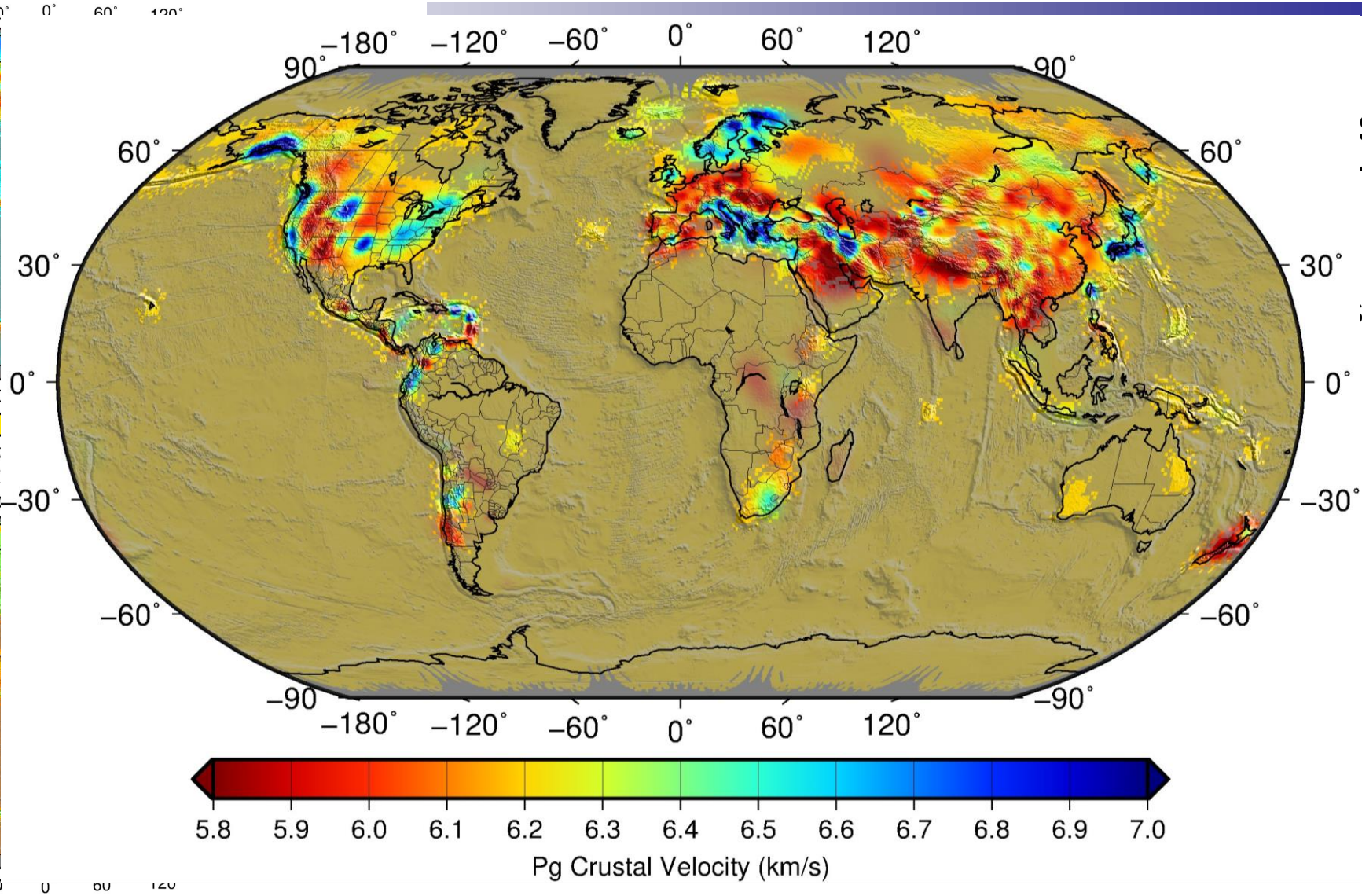
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Pn, Pg









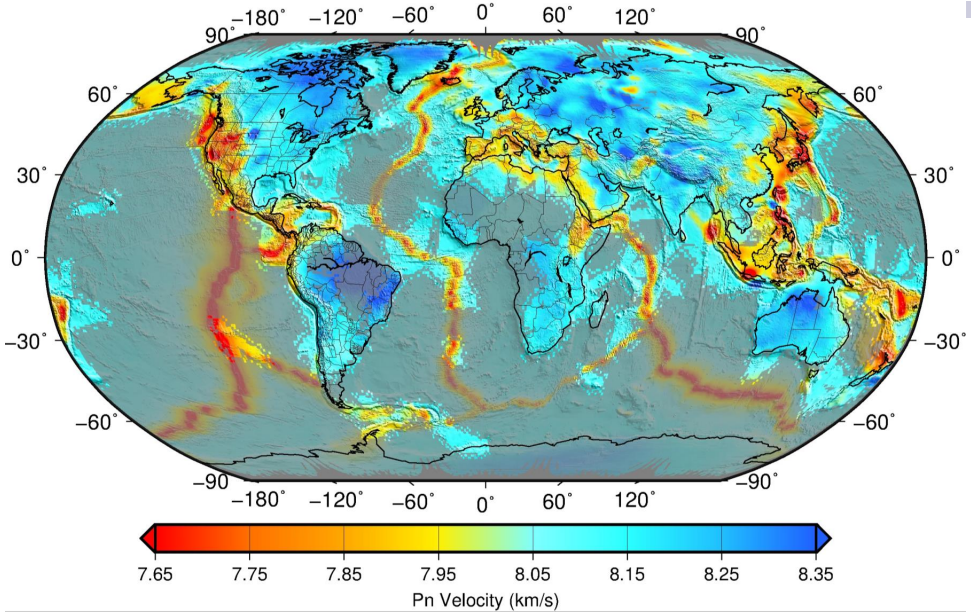
S
)

1.59 s

Velocity (km/s)

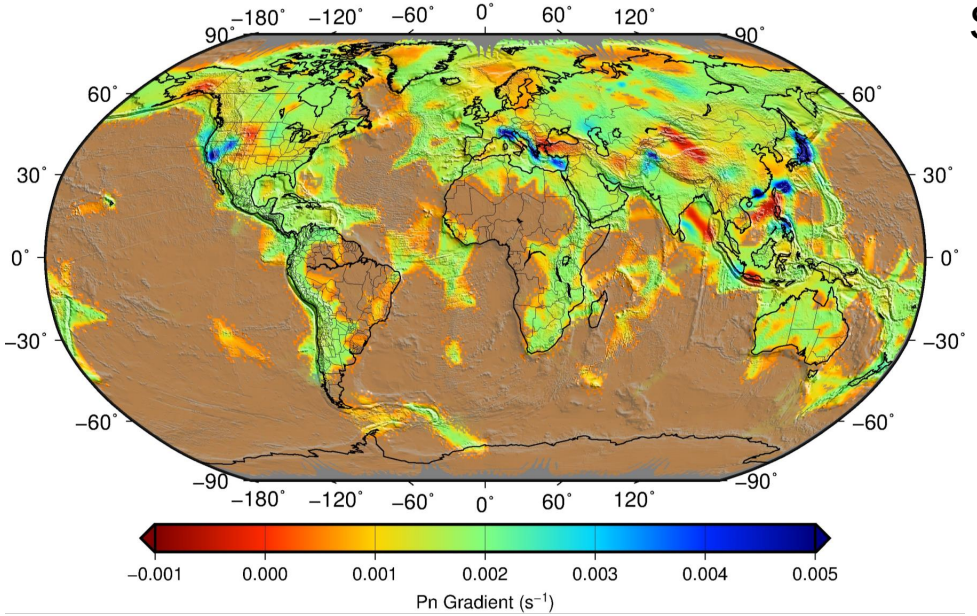
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Pn, Pg



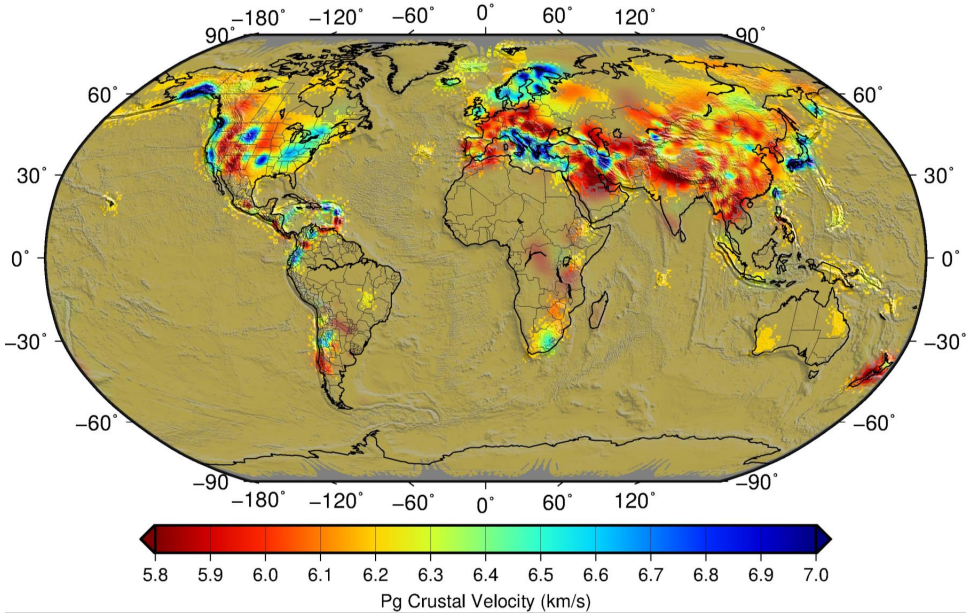
Velocity (km/s)

Pn
Weighted RMS
(by pick error)
1.9 million rays
Start (after DSS fit): 1.42 s
Finish: 1.24 s



Gradient (s^{-1})

Pg
Weighted RMS
(by pick error)
409K rays
Start (after DSS fit): 1.59 s
Finish: 0.83 s



Velocity (km/s)

Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

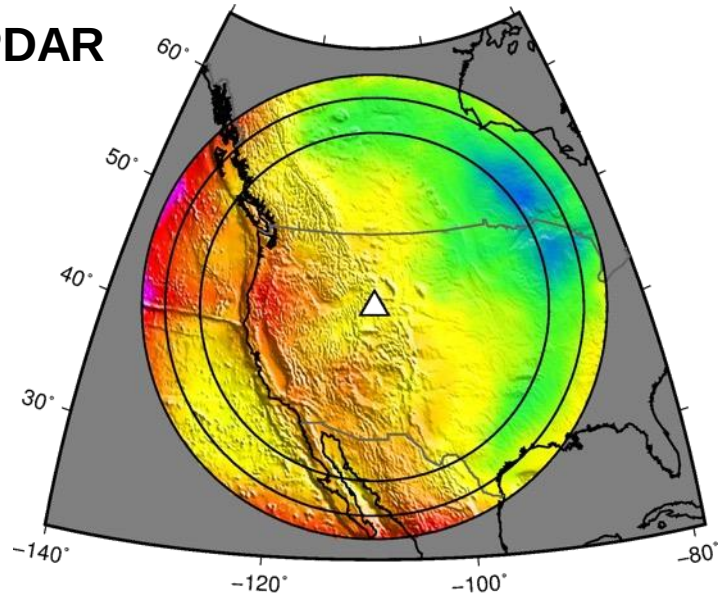
Pn Travel-time Correction Surfaces (s):

10 km Depth

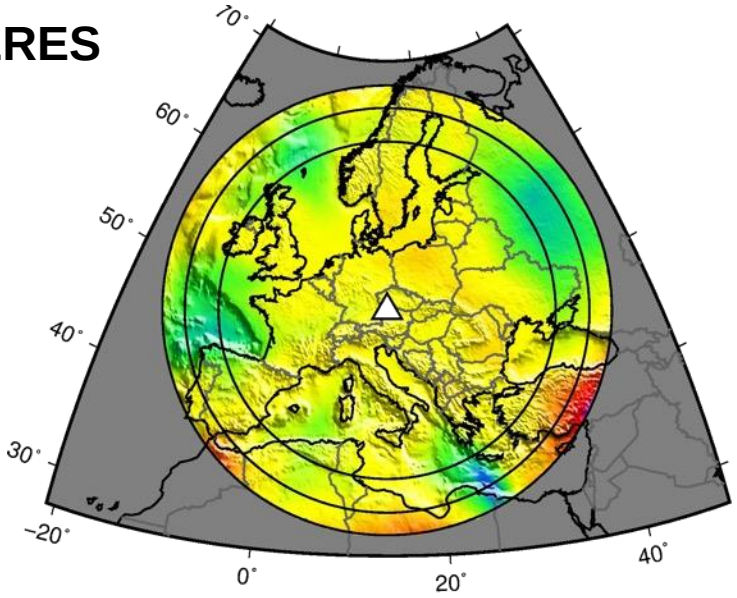
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

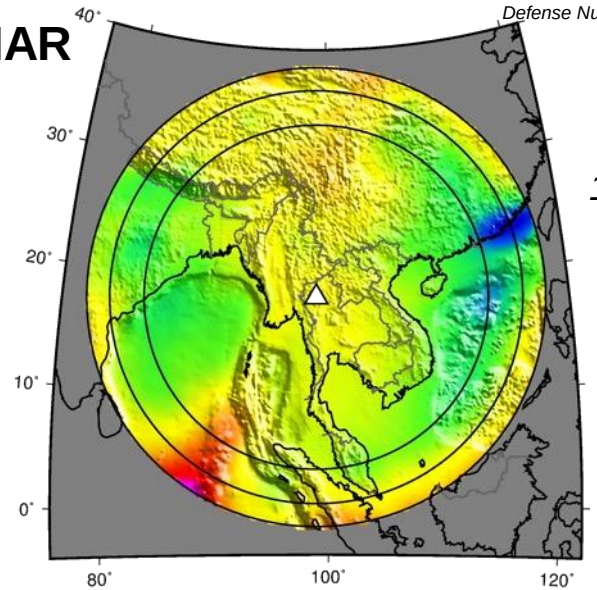
PDAR



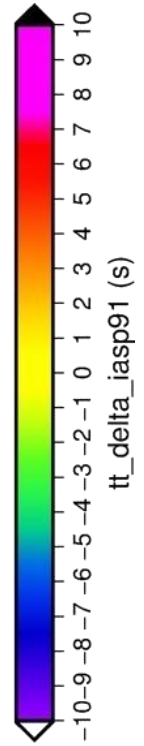
GERES



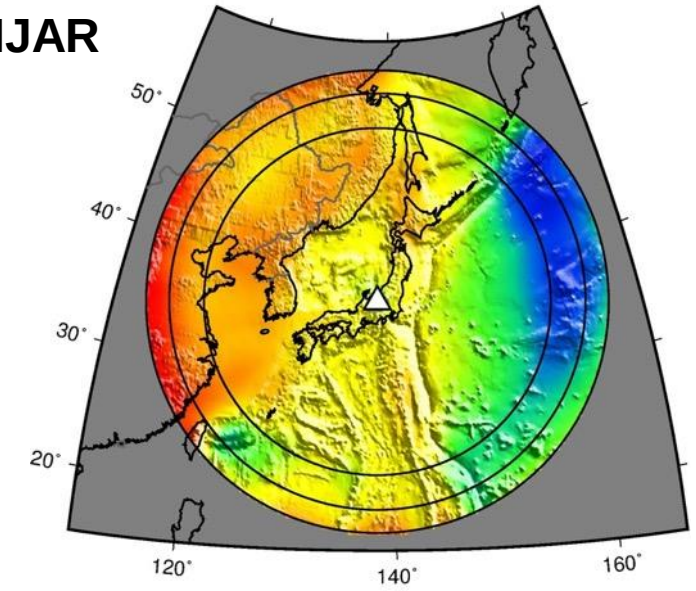
CMAR



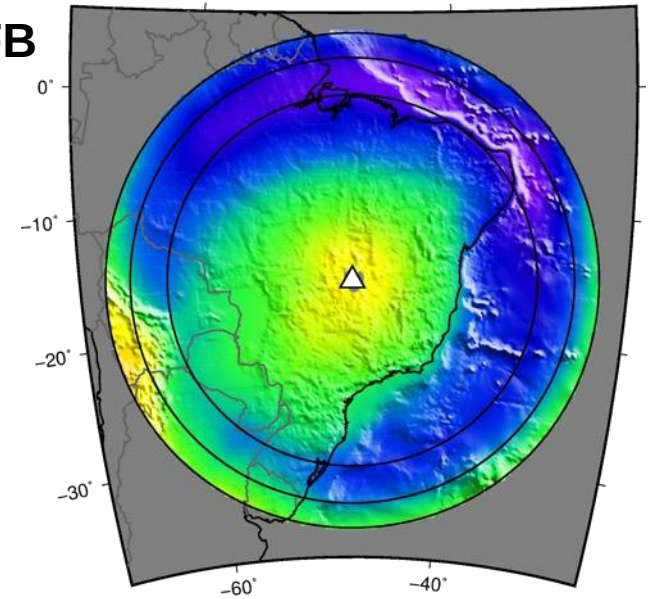
Rings at 15°, 18°, 20°



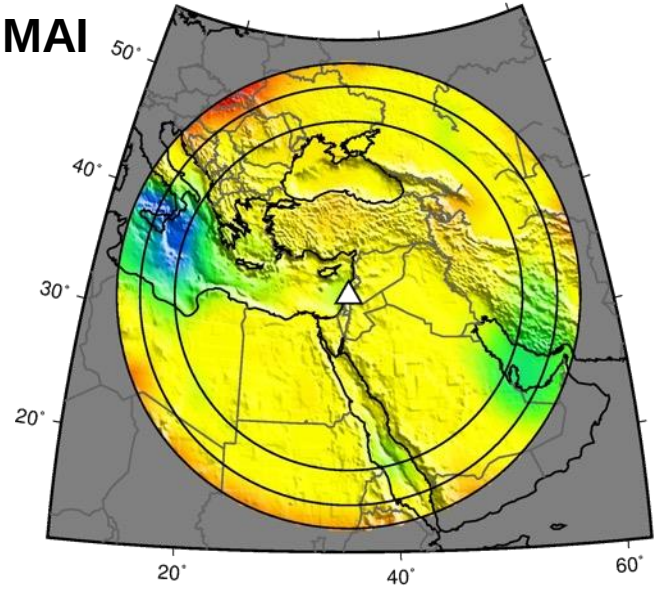
MJAR



BDFB



MMAI



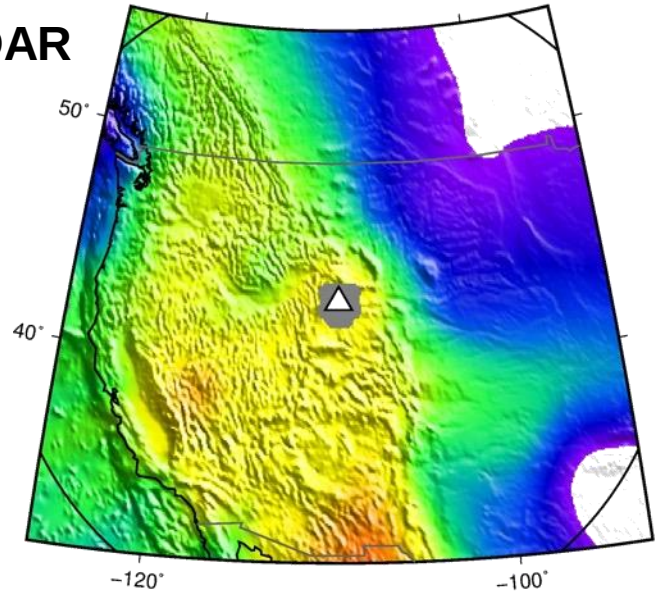
Pg Travel-time Correction Surfaces (s):

10 km Depth

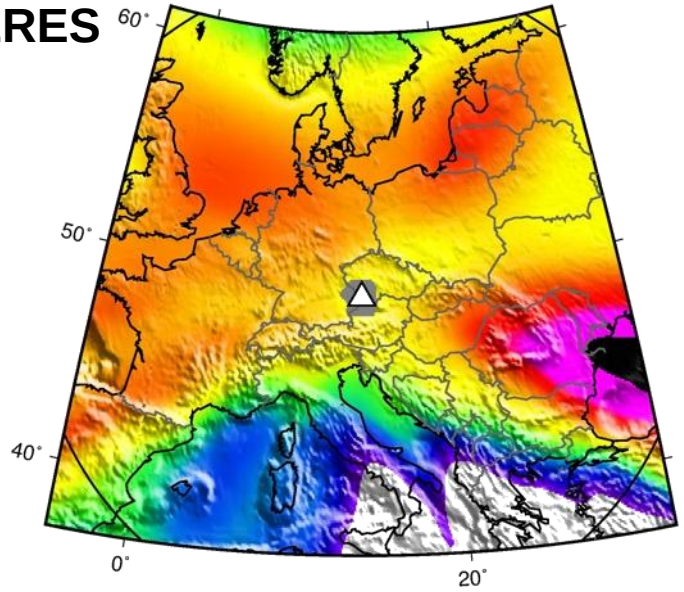
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

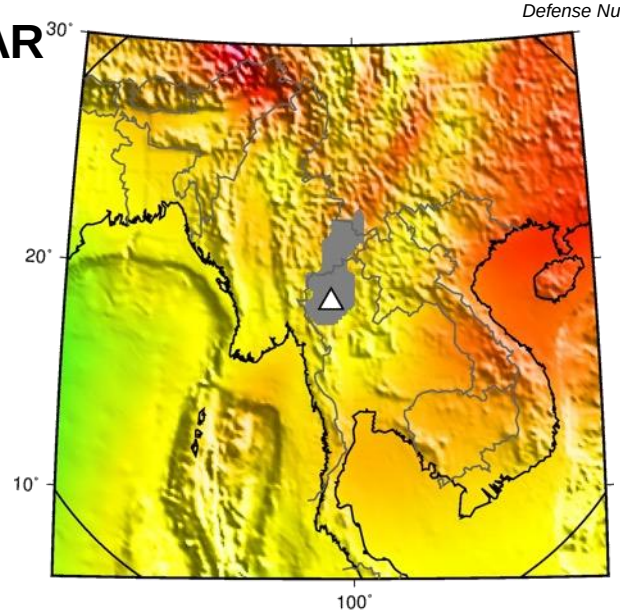
PDAR



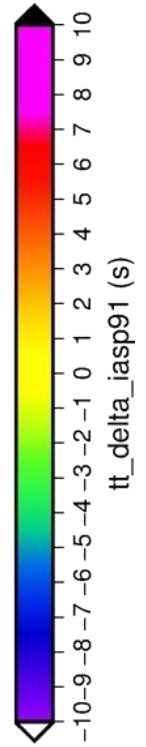
GERES



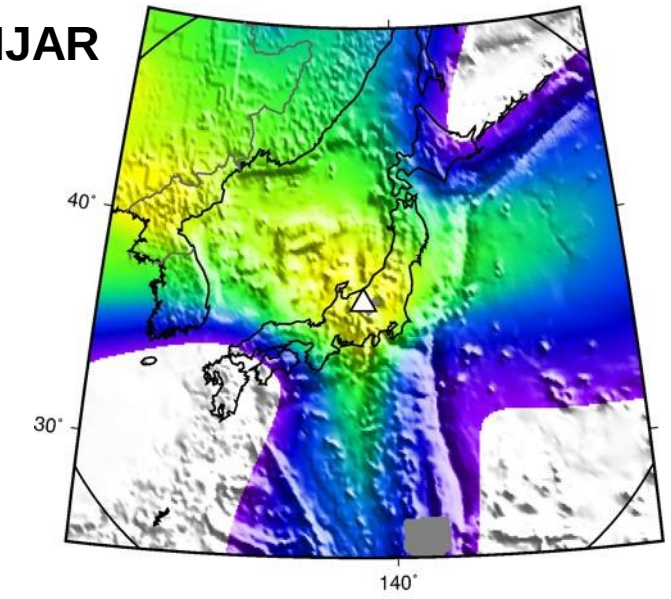
CMAR



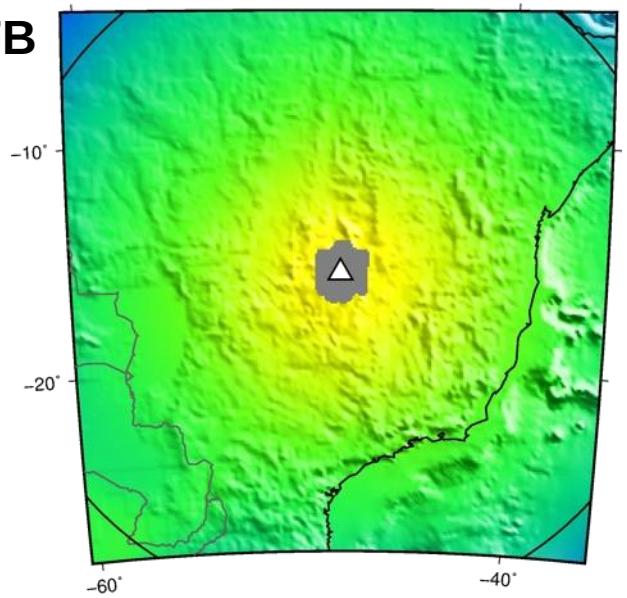
Ring at 15°



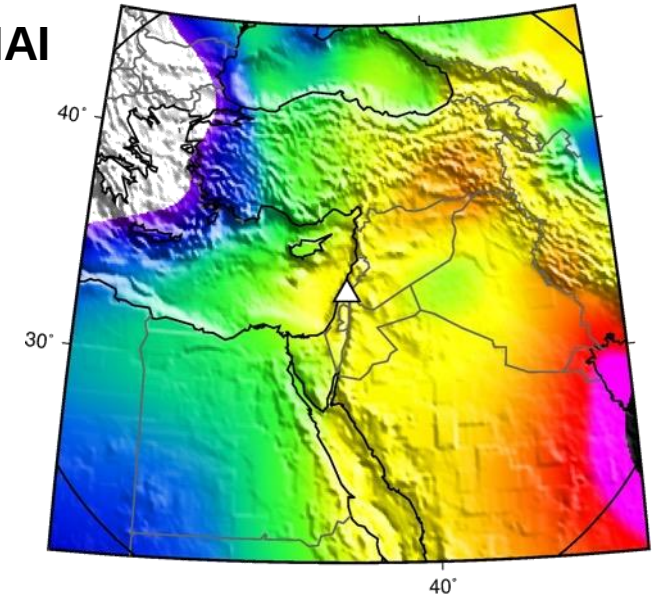
MJAR



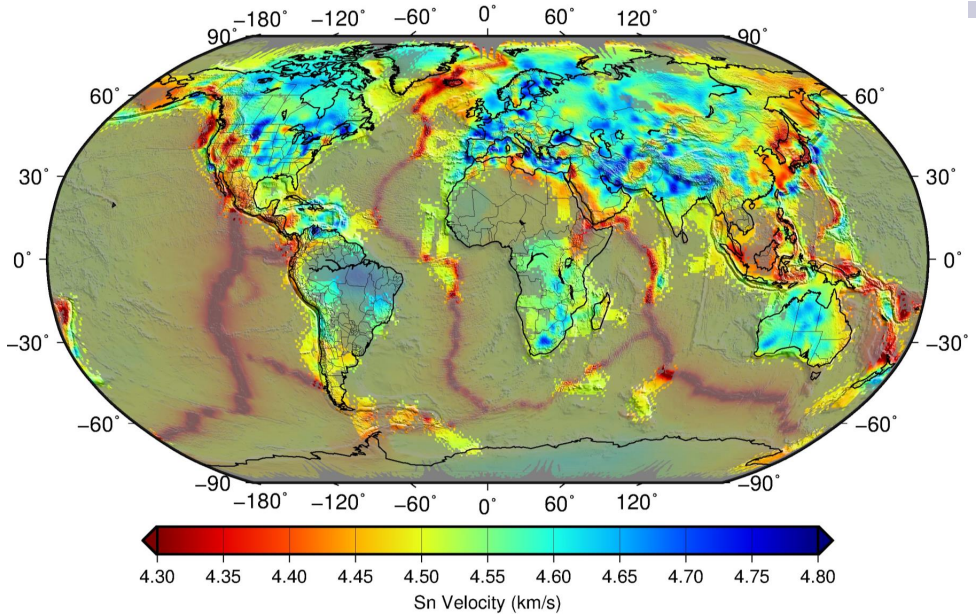
BDFB



MMAI

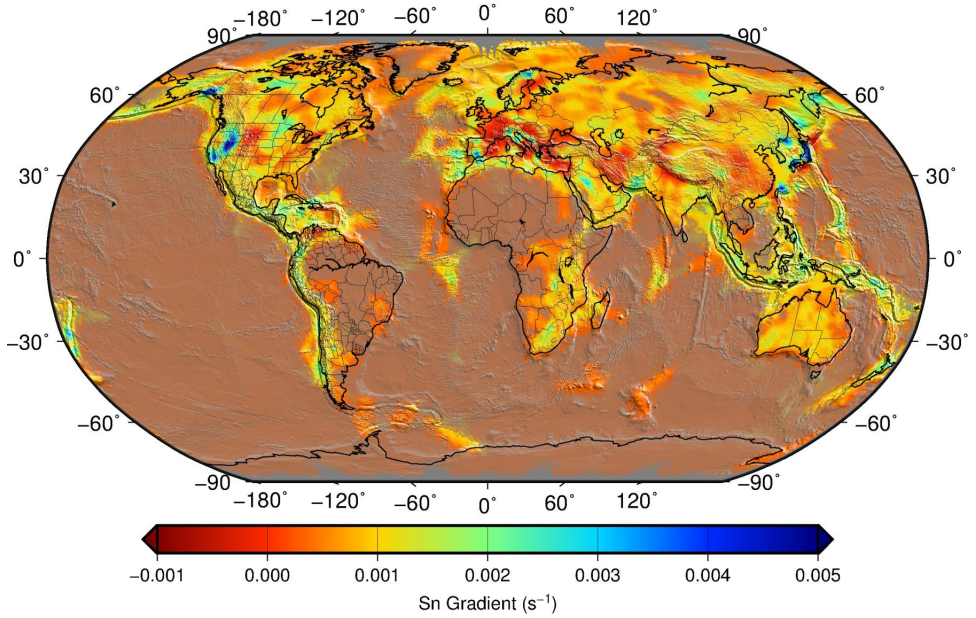


Tomography: Sn, Lg



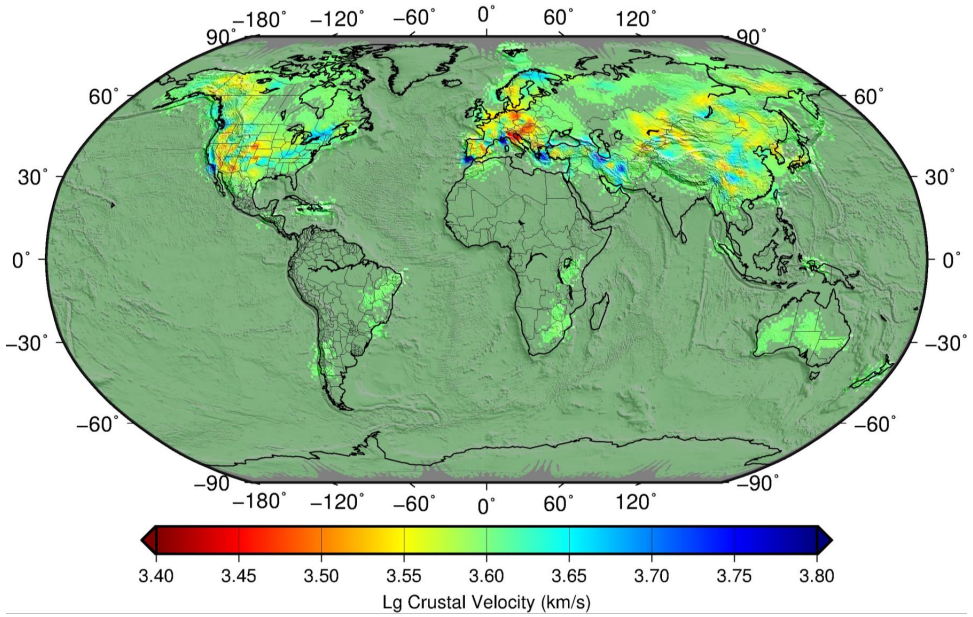
Velocity (km/s)

Sn
Weighted RMS
(by pick error)
262K rays
Start: 4.05 s
Finish: 2.01 s



Gradient (s^{-1})

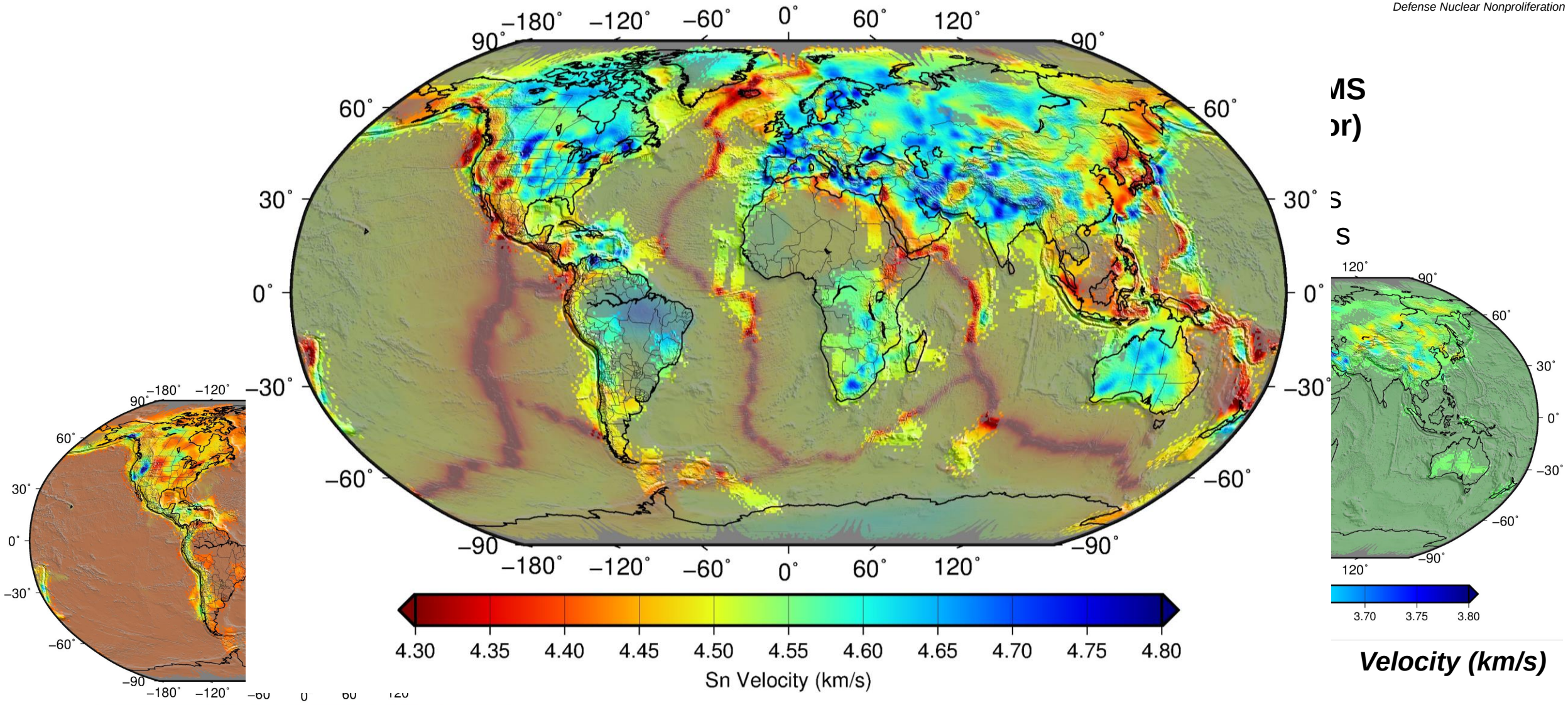
Lg
Weighted RMS
(by pick error)
119K rays
Start: 2.08 s
Finish: 1.71 s



Velocity (km/s)

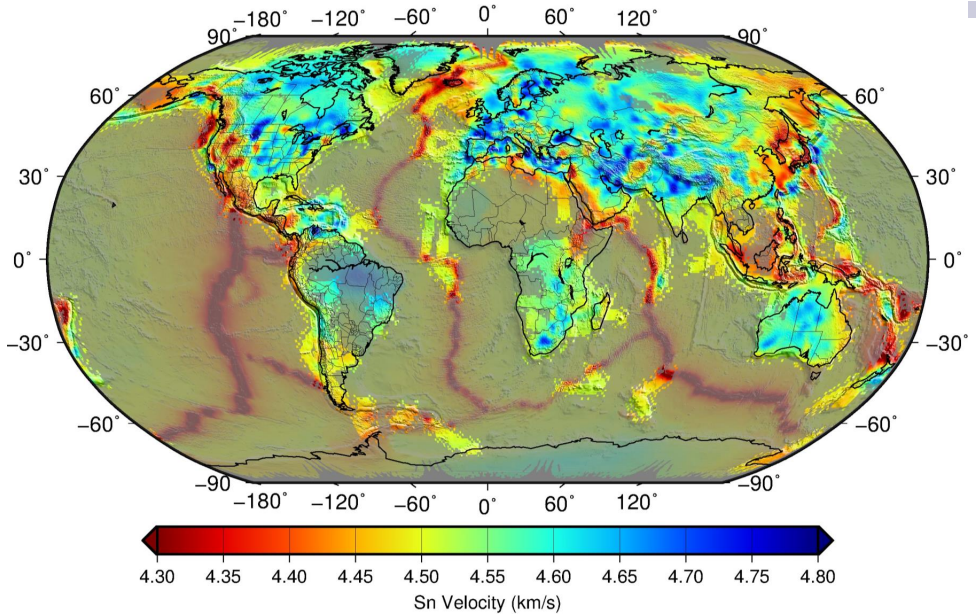
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Sn, Lg



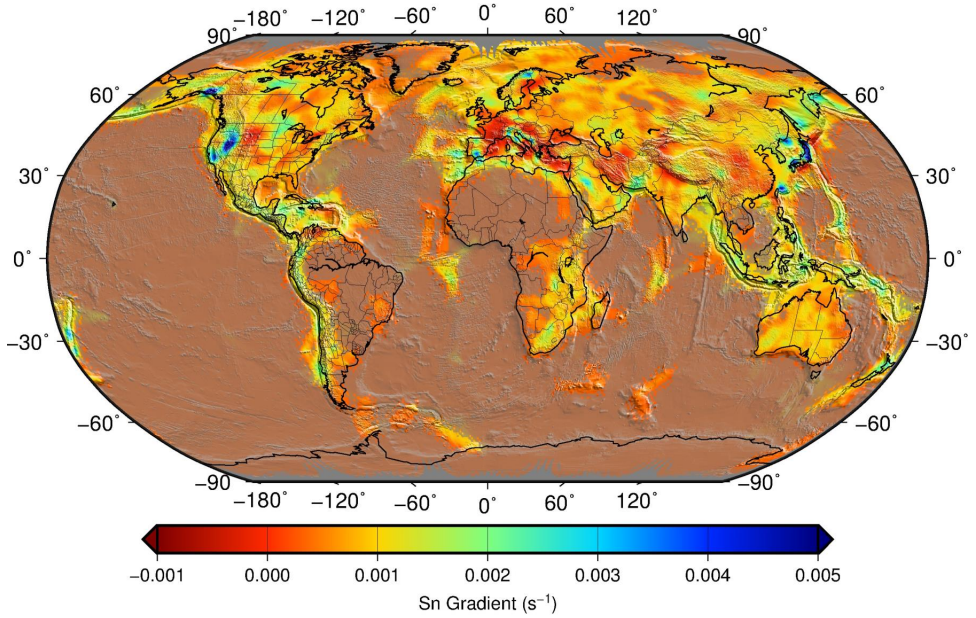
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Sn, Lg



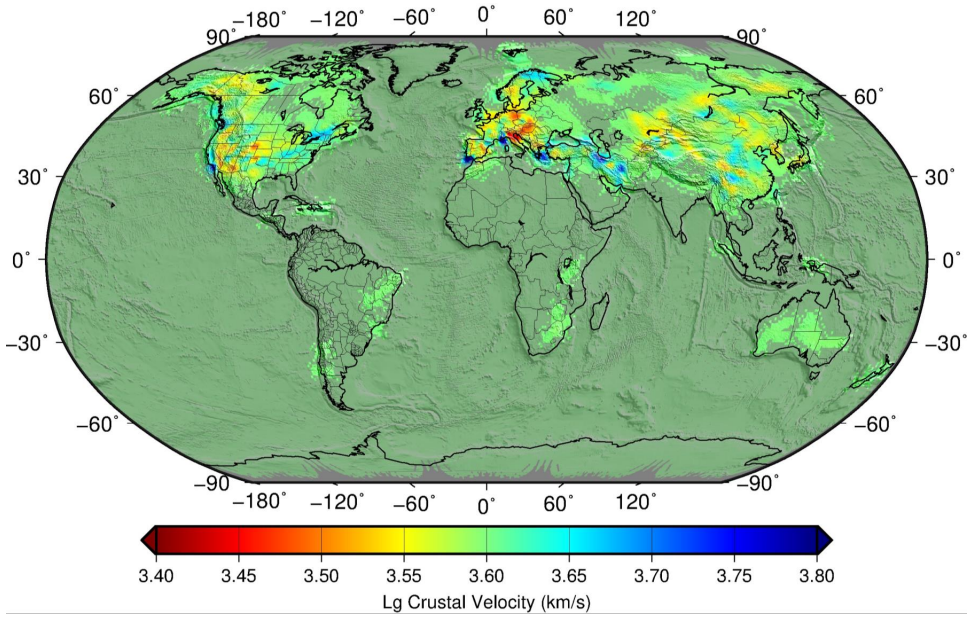
Velocity (km/s)

Sn
Weighted RMS
(by pick error)
262K rays
Start: 4.05 s
Finish: 2.01 s



Gradient (s^{-1})

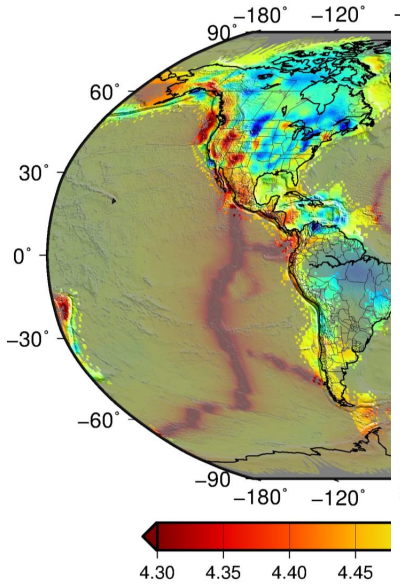
Lg
Weighted RMS
(by pick error)
119K rays
Start: 2.08 s
Finish: 1.71 s

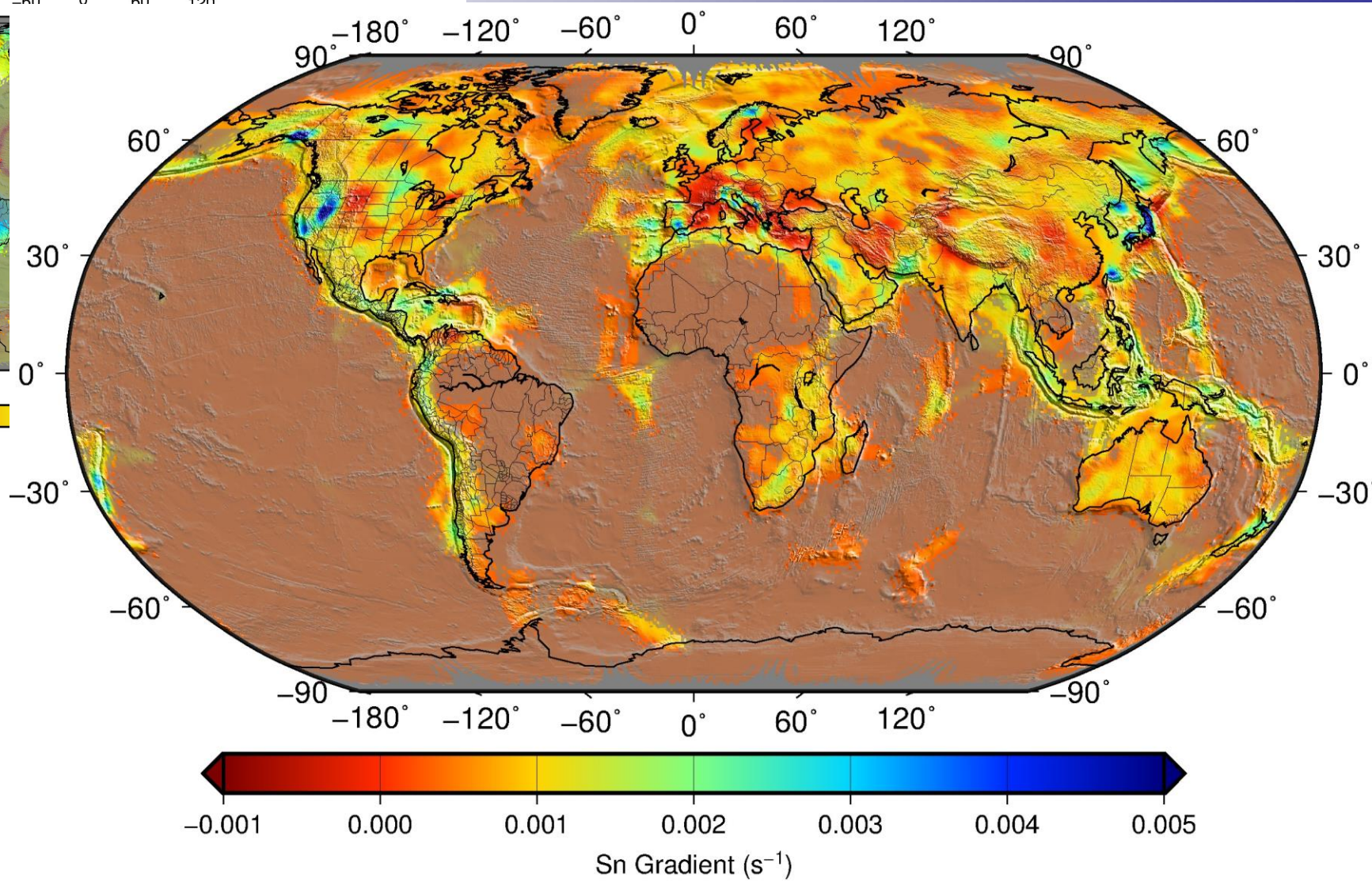


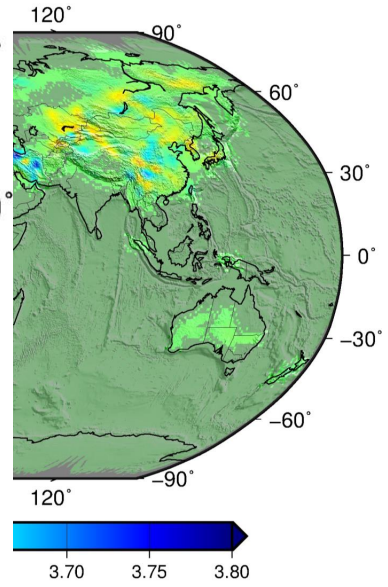
Velocity (km/s)

Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Sn, Lg



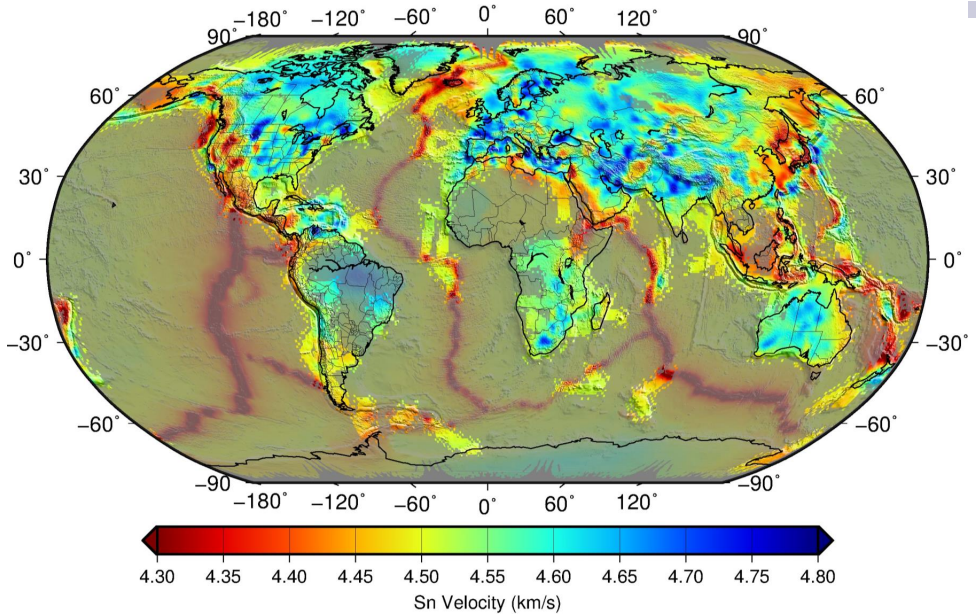




Velocity (km/s)

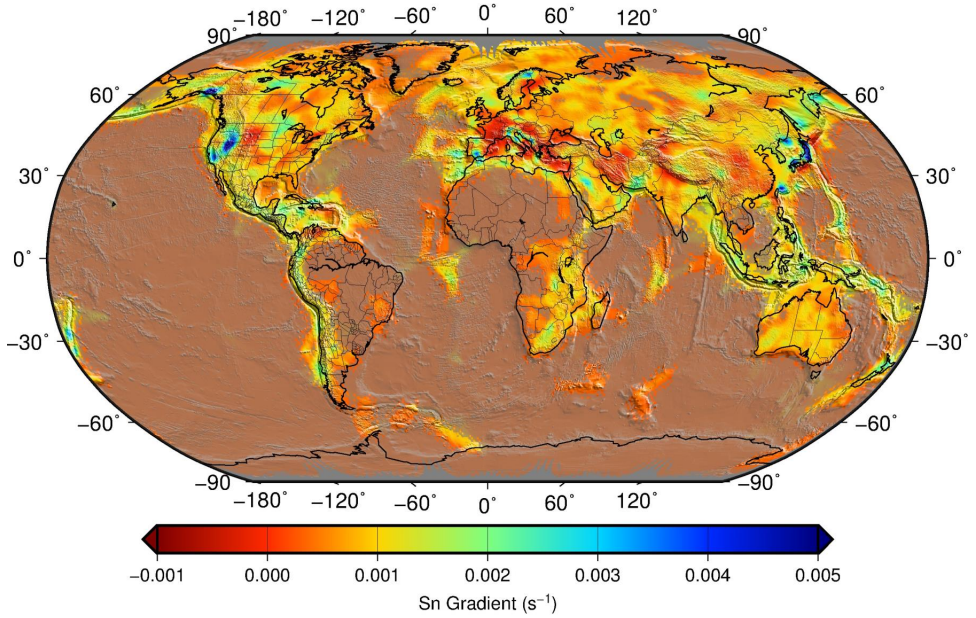
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Sn, Lg



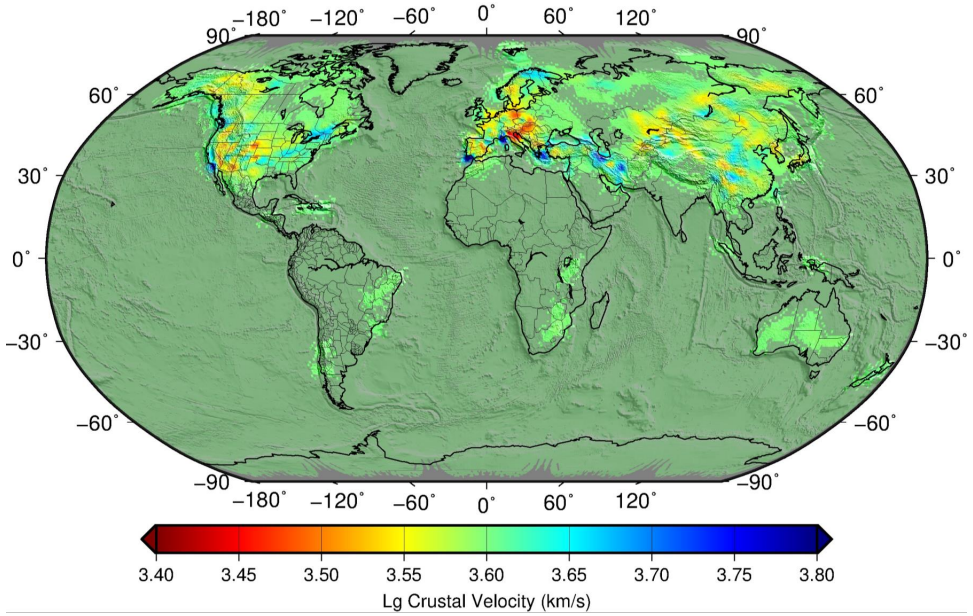
Velocity (km/s)

Sn
Weighted RMS
(by pick error)
262K rays
Start: 4.05 s
Finish: 2.01 s



Gradient (s^{-1})

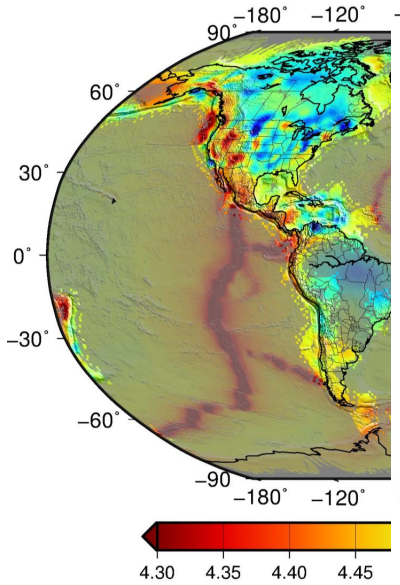
Lg
Weighted RMS
(by pick error)
119K rays
Start: 2.08 s
Finish: 1.71 s

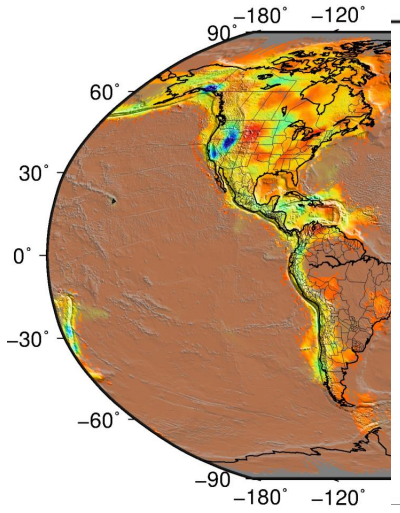


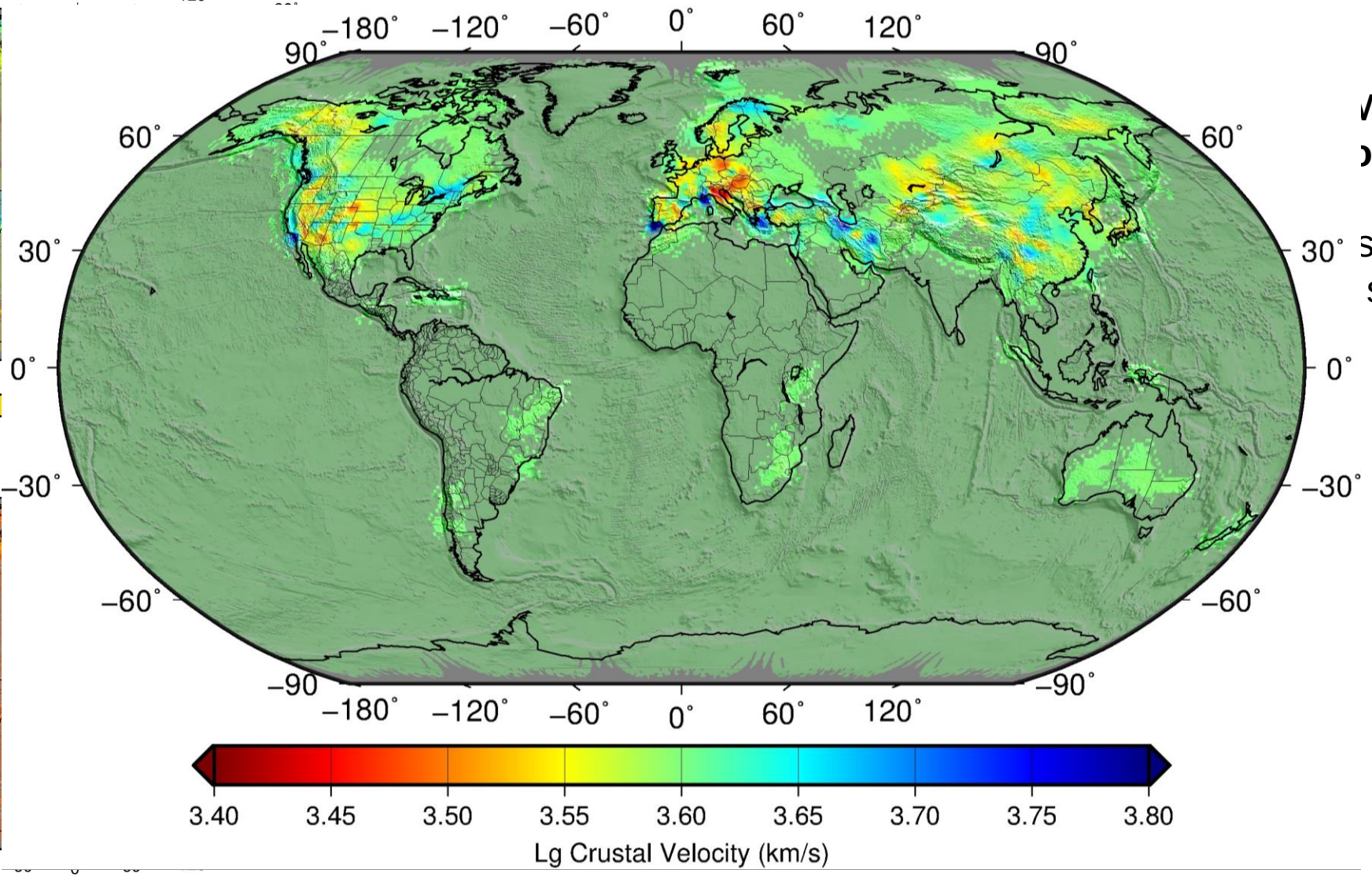
Velocity (km/s)

Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Sn, Lg



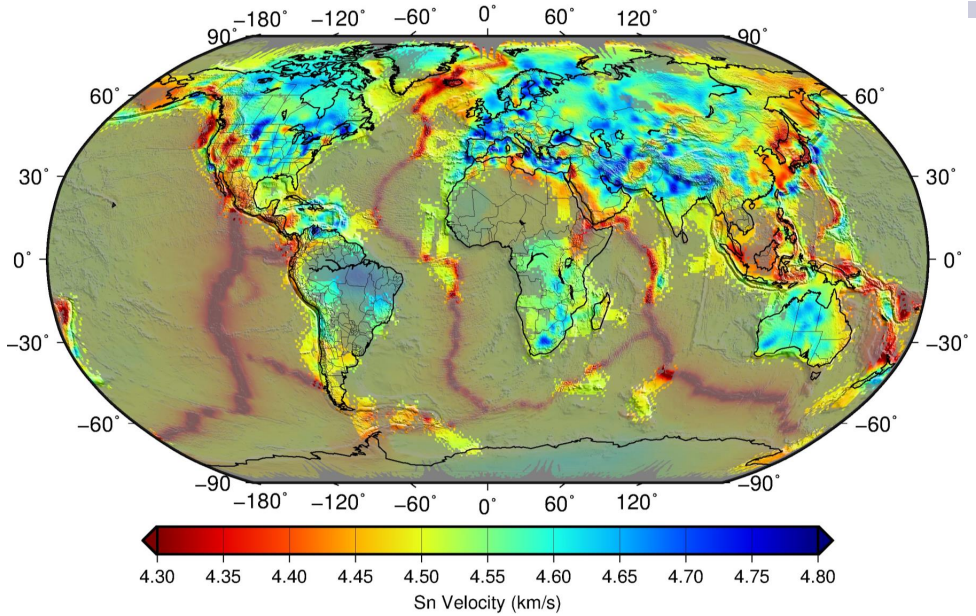




Velocity (km/s)

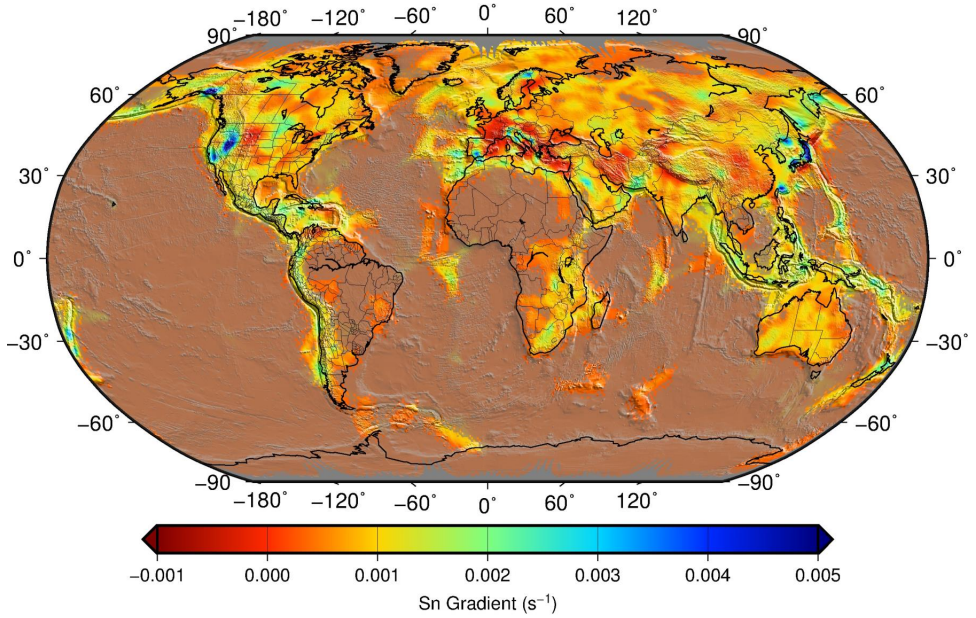
Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

Tomography: Sn, Lg



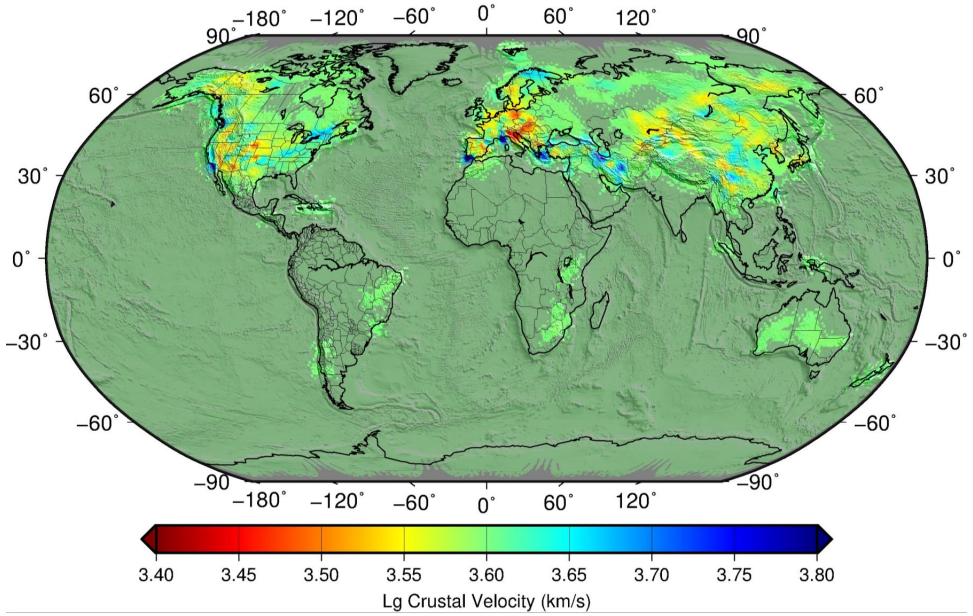
Velocity (km/s)

Sn
Weighted RMS
(by pick error)
262K rays
Start: 4.05 s
Finish: 2.01 s



Gradient (s^{-1})

Lg
Weighted RMS
(by pick error)
119K rays
Start: 2.08 s
Finish: 1.71 s



Velocity (km/s)

Areas with no tomographic resolution are dimmed. Velocities in dimmed areas are unaltered from the starting model

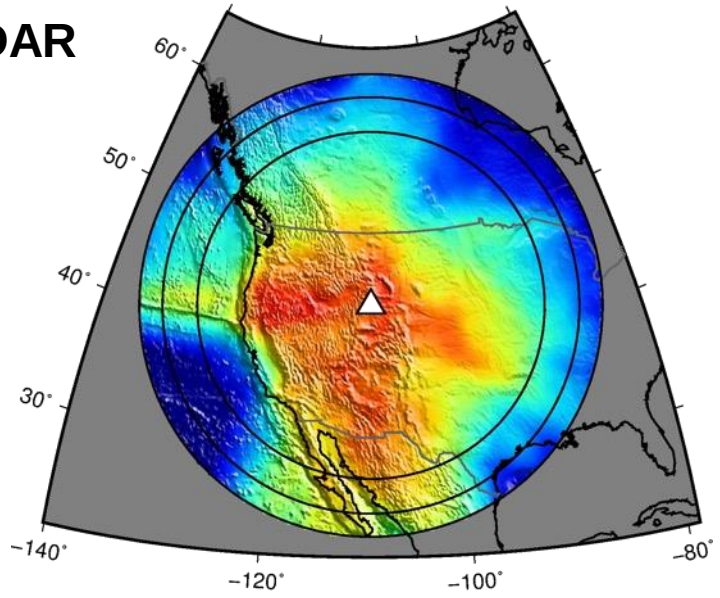
Sn Travel-time Correction Surfaces (s):

10 km Depth

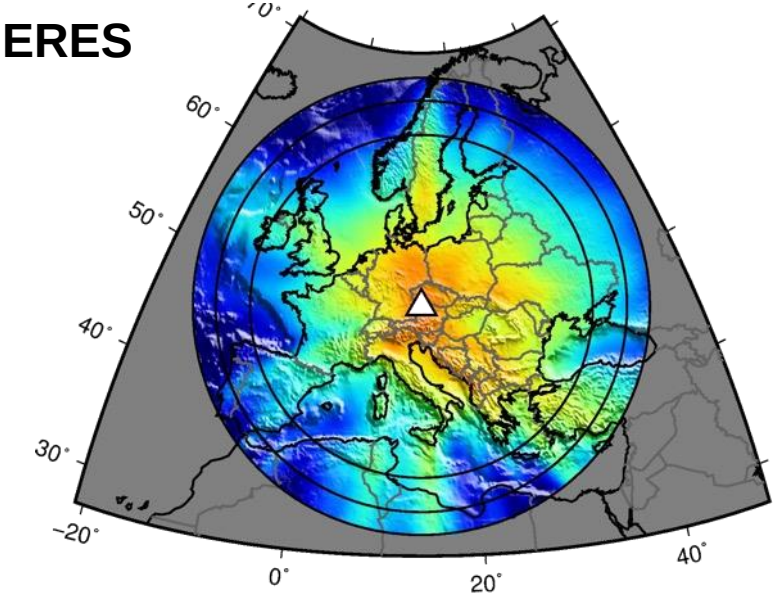
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

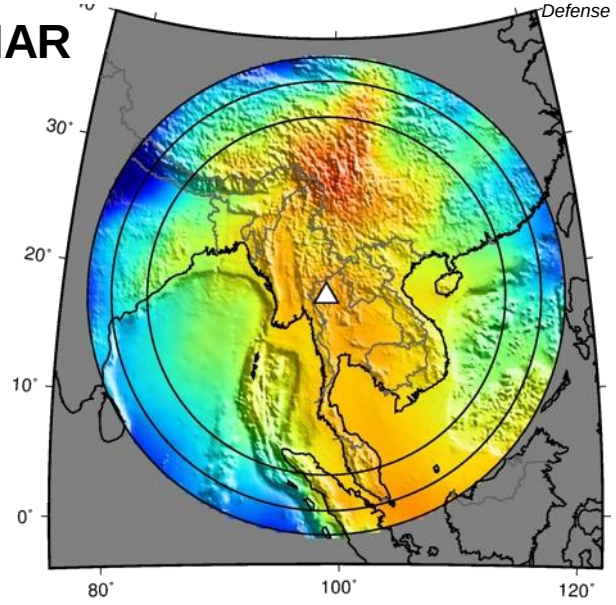
PDAR



GERES

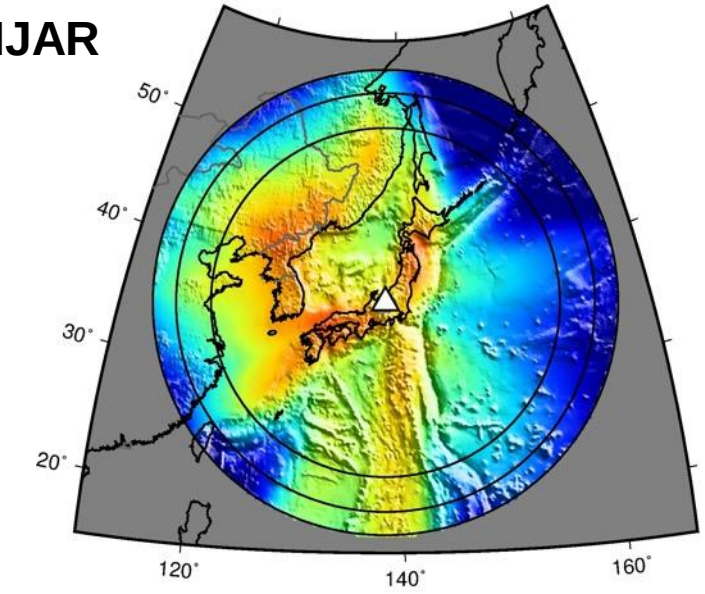


CMAR

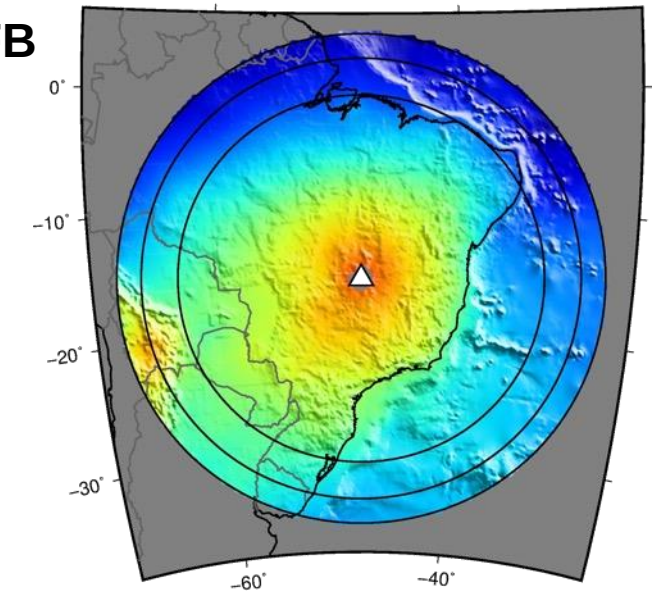


Rings at 15°, 18°, 20°

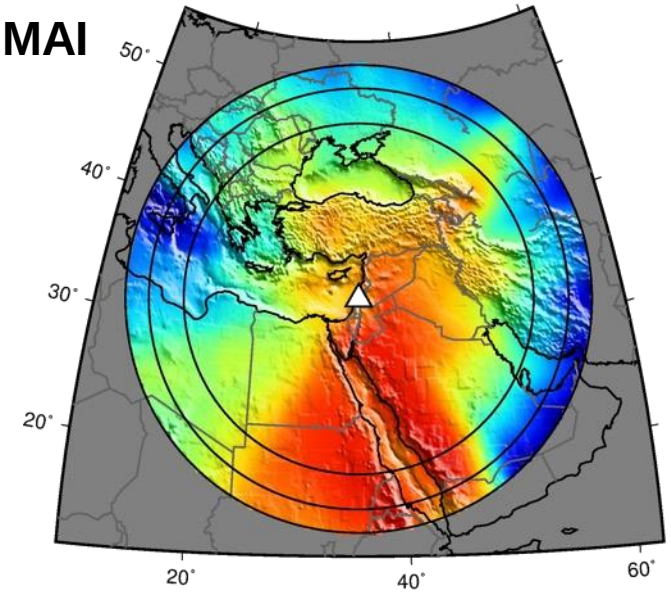
MJAR

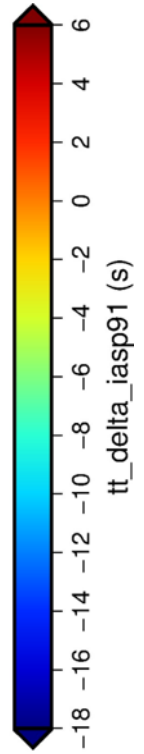


BDFB



MMAI





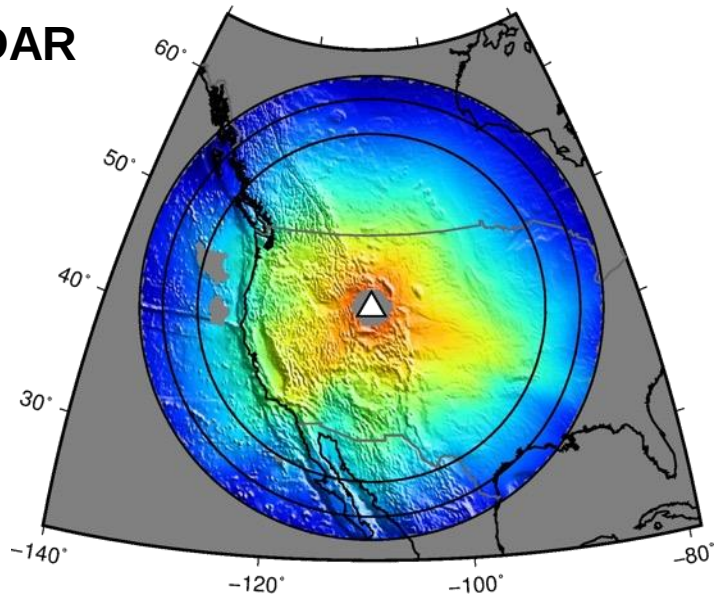
Lg Travel-time Correction Surfaces (s):

10 km Depth

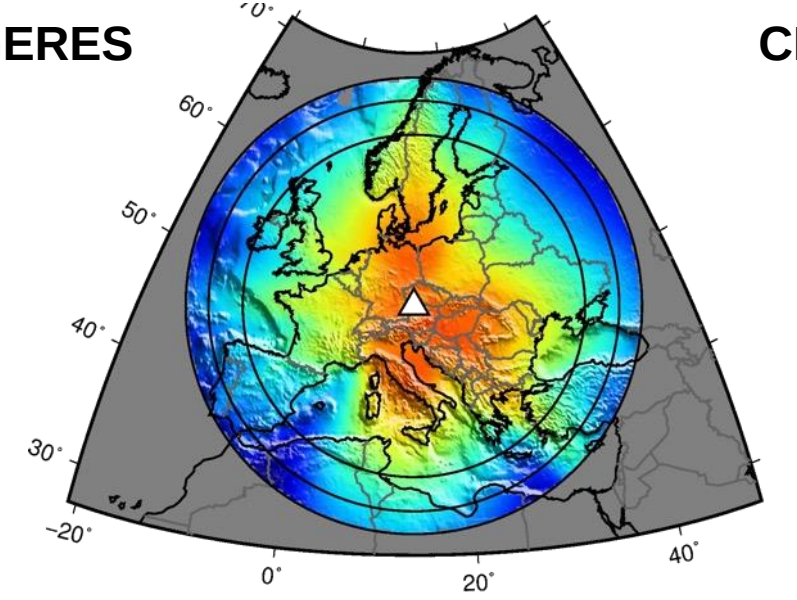
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

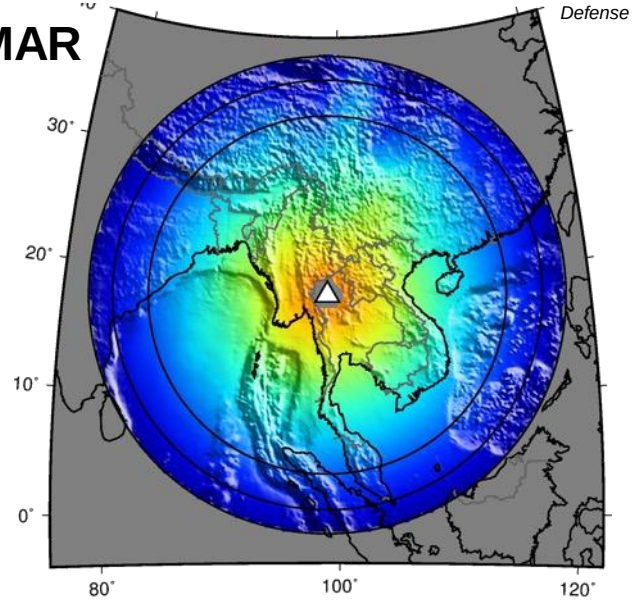
PDAR



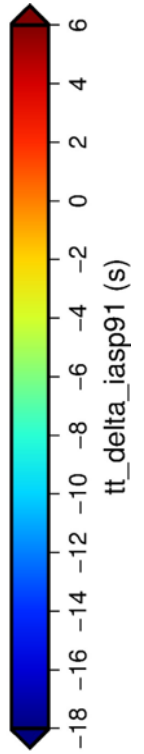
GERES



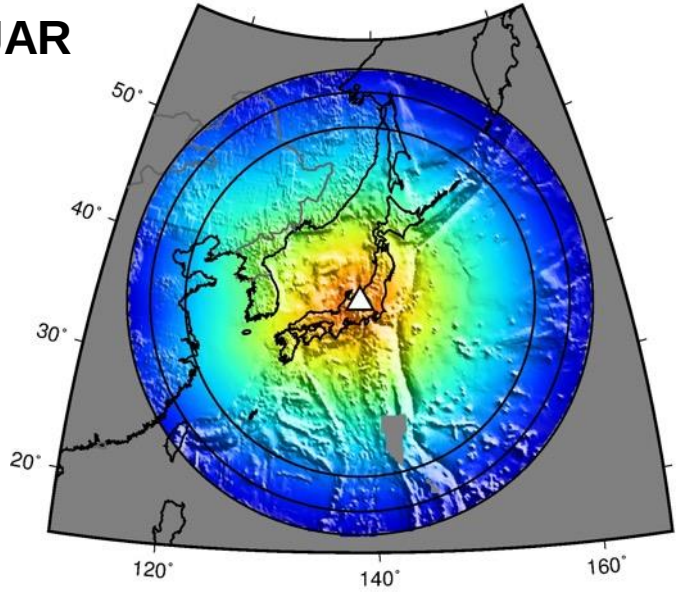
CMAR



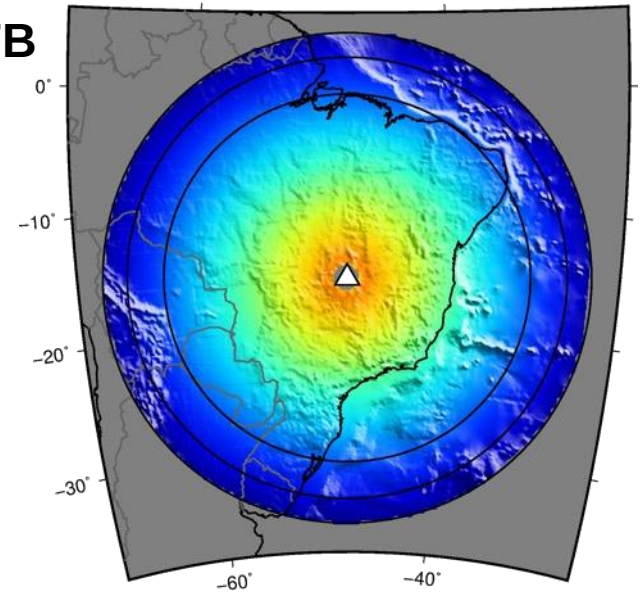
Rings at 15°, 18°, 20°



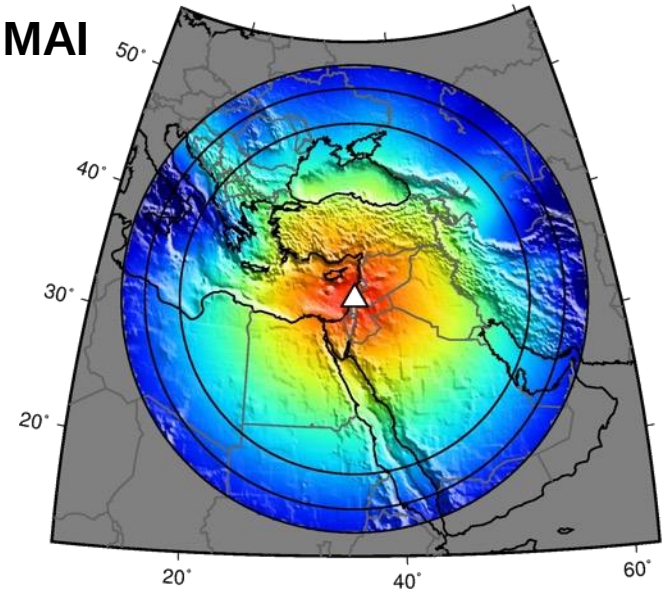
MJAR



BDFB



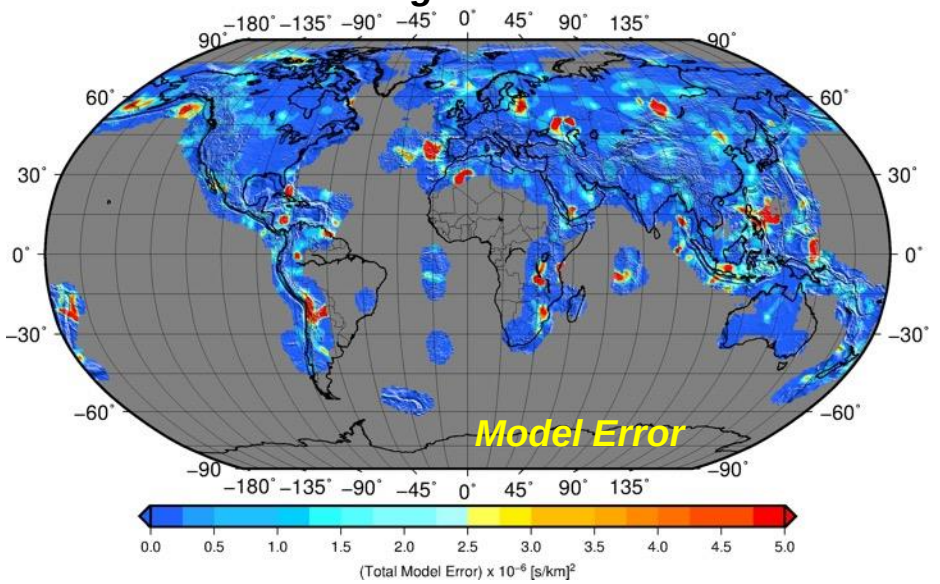
MMAI



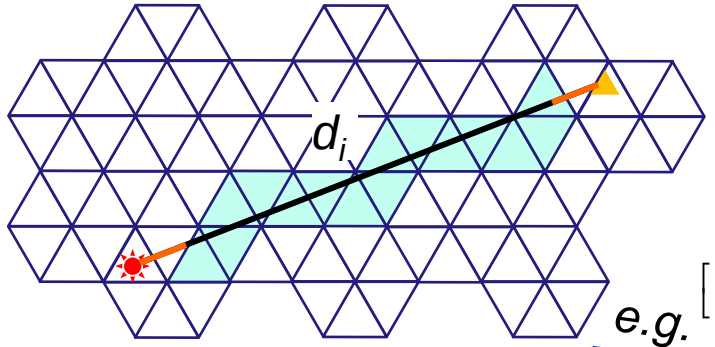
Path-dependent Uncertainty Overview

- **The goal for RSTT is to have the general user be able to estimate a path-dependent travel time prediction uncertainty on-the-fly (e.g., NDC in a box).**
- **Variations in apparent slowness residuals among model nodes allow for separation into "model", "random/pick", and "bias" error components using a Random Effects Model.**
  - See Waveform Experts Group presentations: WGB48, WGB50, WGB51, WGB52
  - For areas with no ray coverage, background values for model, random, and bias based on each distance bin (2-16° with 2° bins): *Mean + 2*std*
  - Crustal Error [s/km]^2 = 18% of weighted average slowness (by layer thickness)
- **Calculate Travel Time Uncertainty for a Specific Path with Touched Nodes M**
  - Form a covariance matrix (M x M) of Model and Bias error values (Random error is optional) [s/km]^2
  - **Total TT Uncertainty [s^2] = Path Weights [km^2] * Covariance: [1 x M][M x M][M x 1] + Crustal Path Weights [km^2] * Crustal Error**

Pn: 6 deg Distance Bin



"Touched" Nodes (n)



Path i: Observed Apparent Slowness (s_i), Calculated App. Slowness (S_i)

$$s_i = \frac{(t_i - t_o) - (T_{oi,s} + T_{oi,r} + T_{oi,g})}{d_i} \qquad S_i = \frac{T_{oi,h}}{d_i}$$

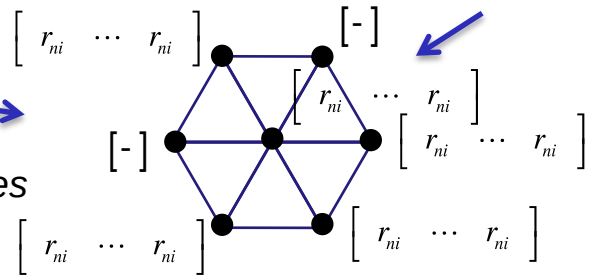
Apparent Slowness Residual

$$r_{ni} = s_i - S_i$$

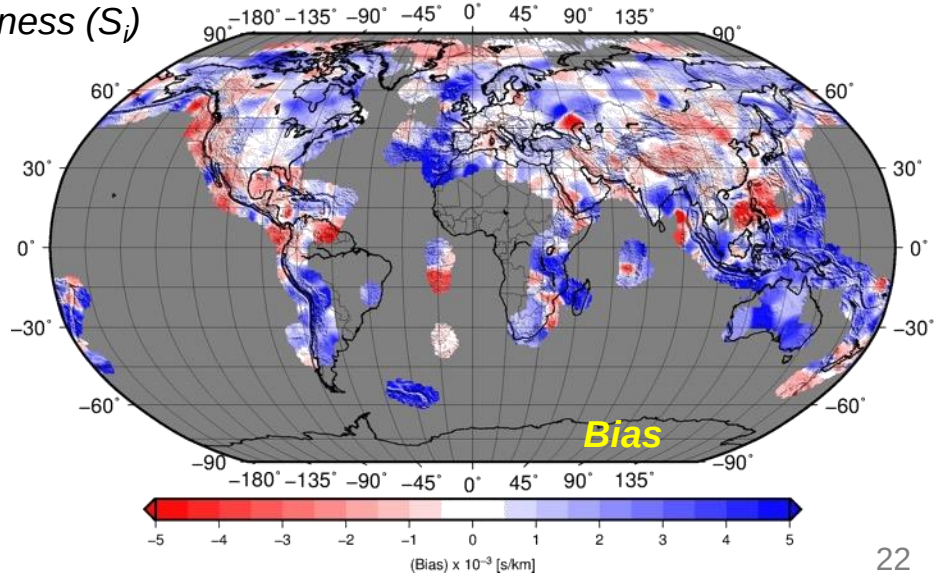
(for path i along touched nodes n)

e.g.

$$\begin{bmatrix} r_{ni} & \cdots & r_{ni} \end{bmatrix}$$



Collect Residuals for all paths at Nodes to Run Random Effects Model



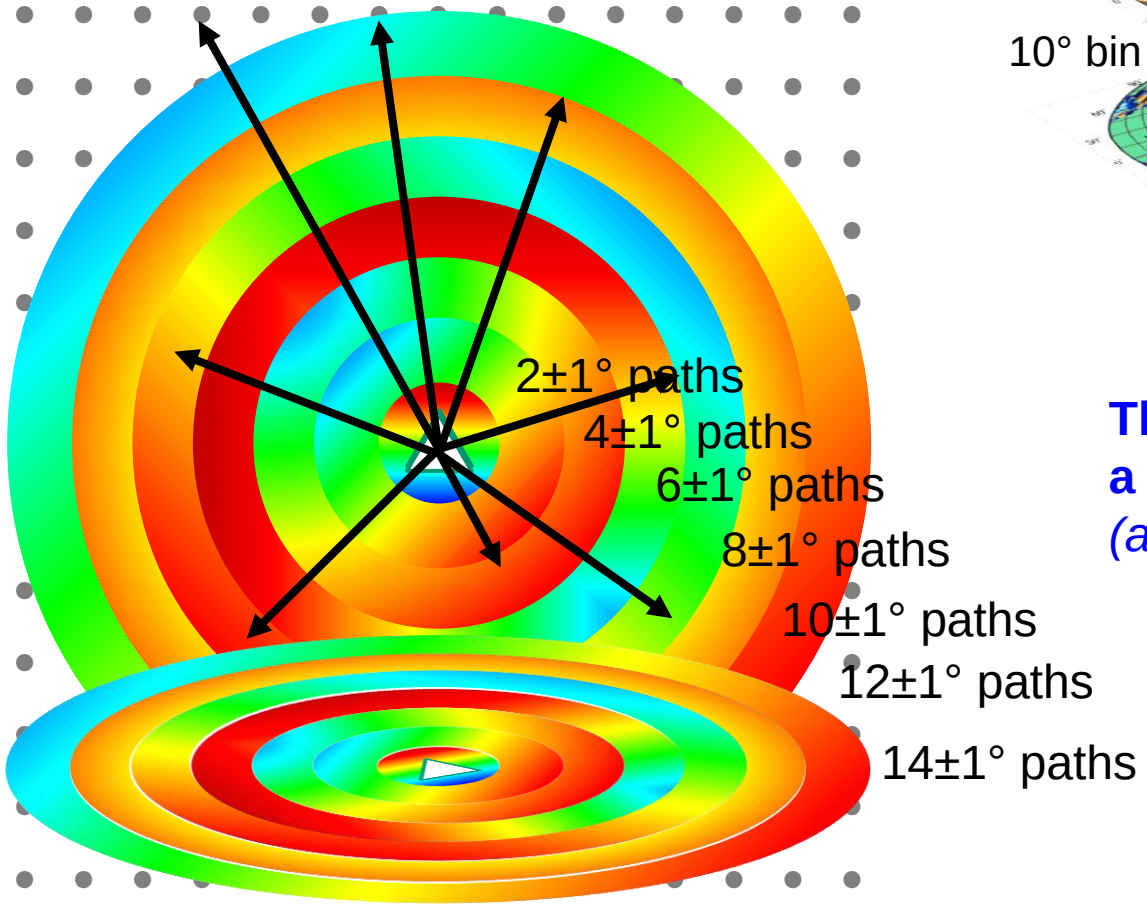
Building a Travel-time Uncertainty Surface for a Station/Phase

U.S. DEPARTMENT OF ENERGY

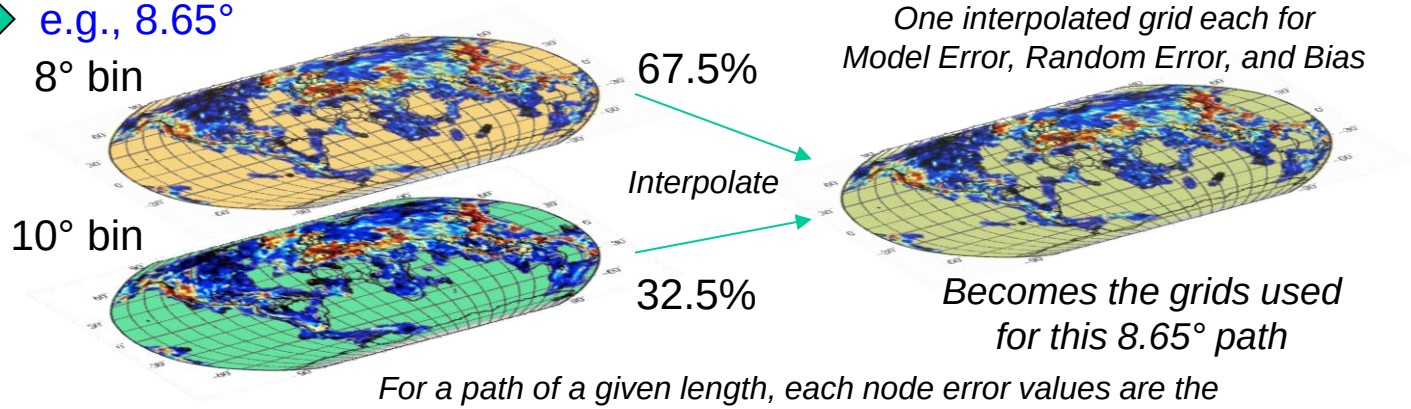
National Nuclear Security Administration
Defense Nuclear Nonproliferation

Trace rays in a grid or specified points

- Determine distance
- Build specific distance error grids by interpolating between distance bins
- Calculate travel time uncertainty along path



Determine a Grid for Each Error Type Based on Distance



For a path of a given length, each node error values are the weighted average of the values in bracketing distance bins

The resulting travel-time uncertainty surface represents a series of values for specific interpolated distance bins
(actual surfaces are smooth between bins from interpolation)

- Error values $(s/km)^2$ and weights (km) are used to integrate uncertainty along the path
- Results in one travel-time uncertainty value (s) for that path

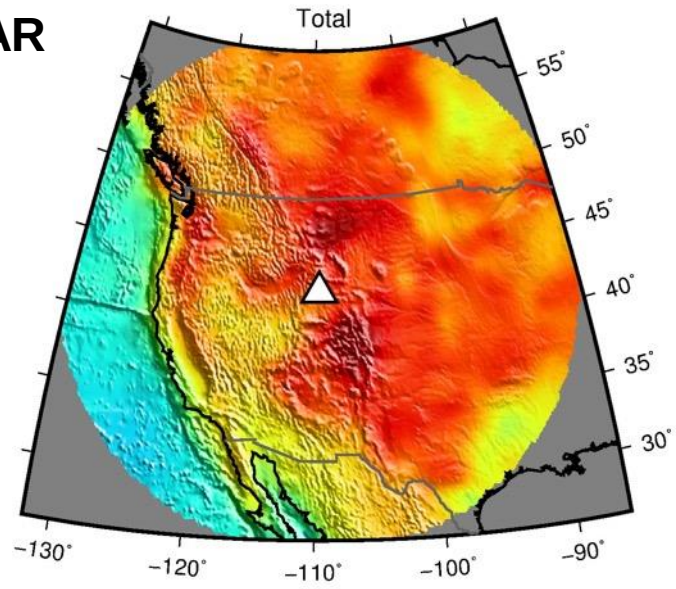
Pn Travel-time Uncertainty Surfaces (s):

0 km Depth

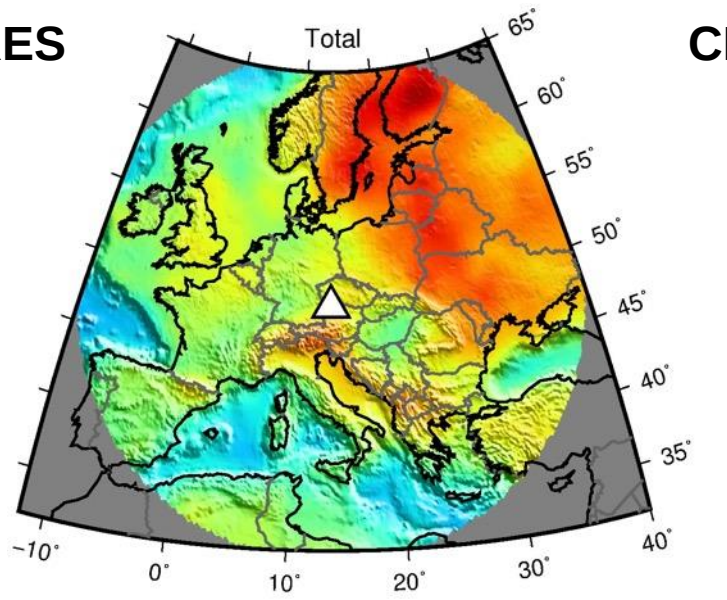
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

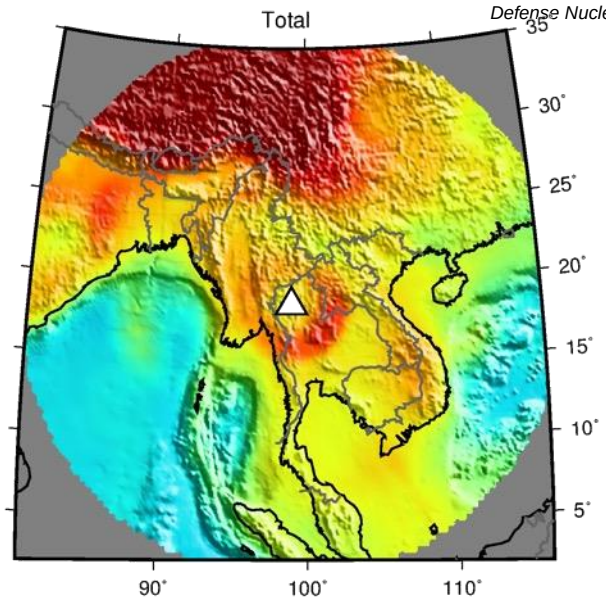
PDAR

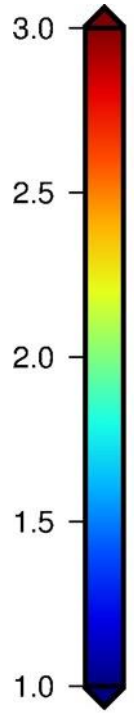


GERES

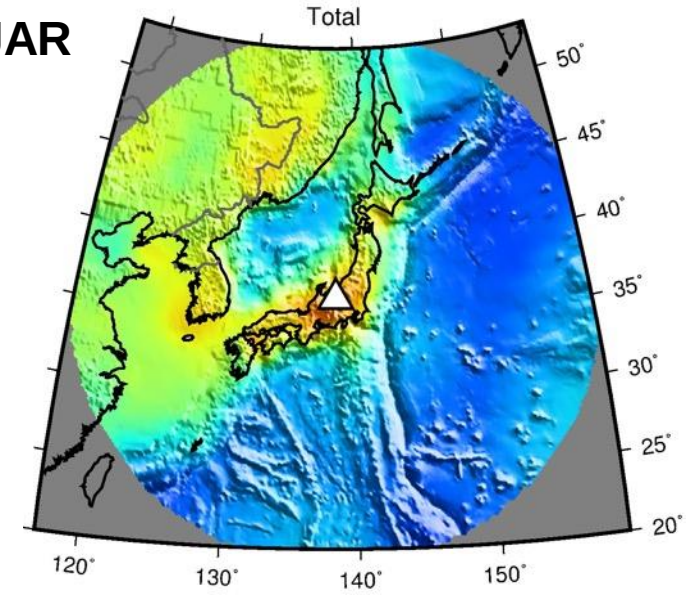


CMAR

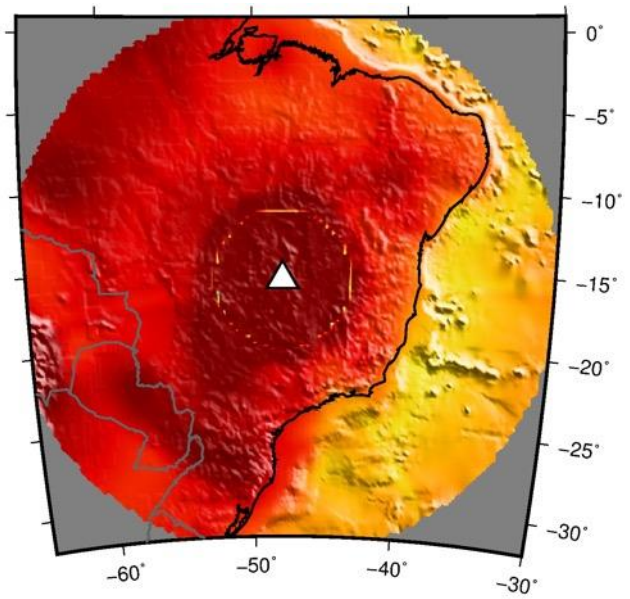




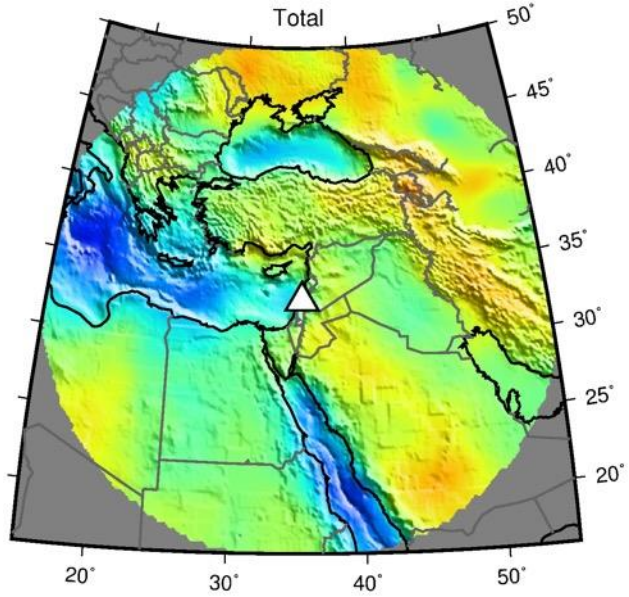
MJAR



BDFB



MMAI



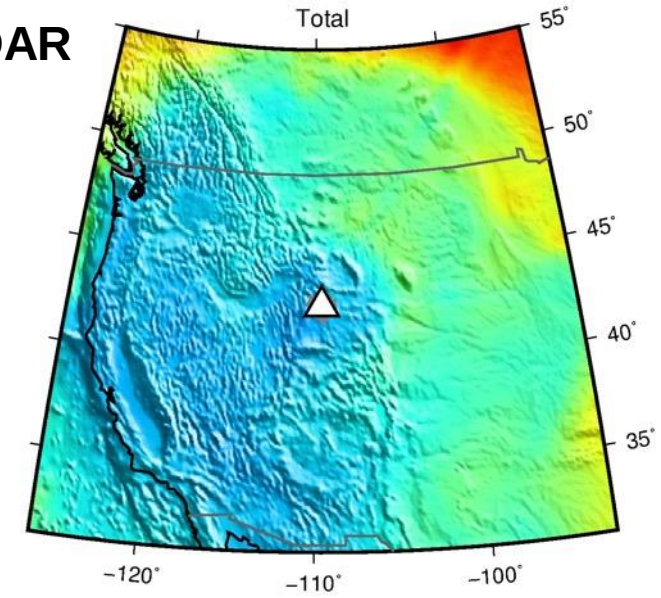
Pg Travel-time Uncertainty Surfaces (s):

0 km Depth

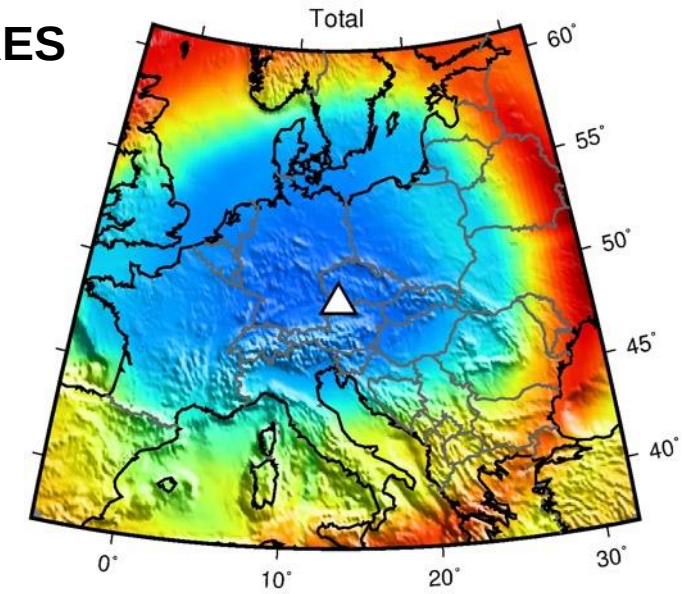
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

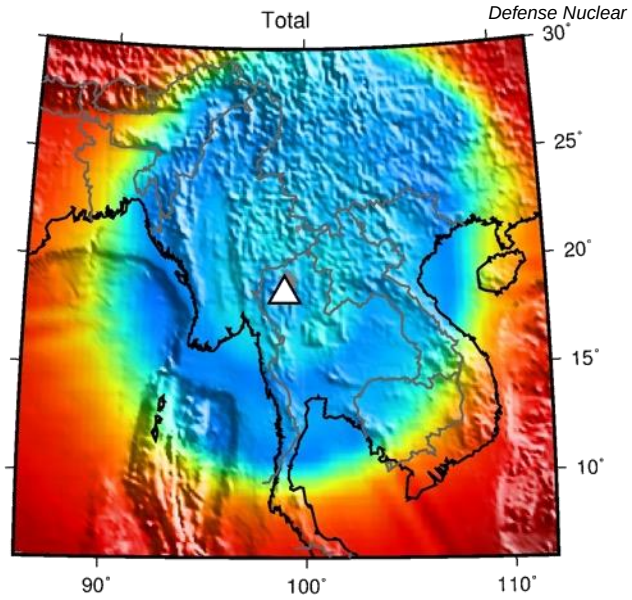
PDAR



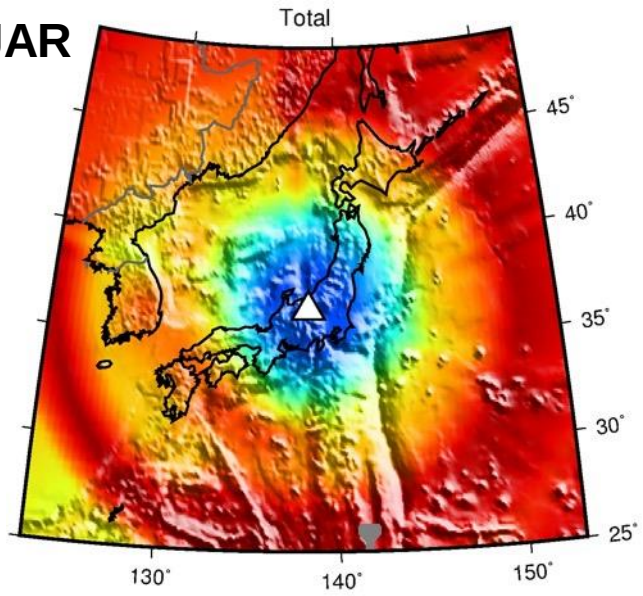
GERES



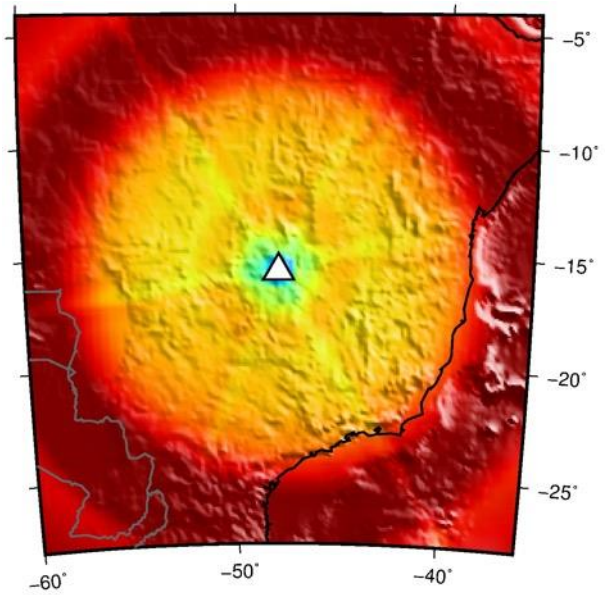
CMAR



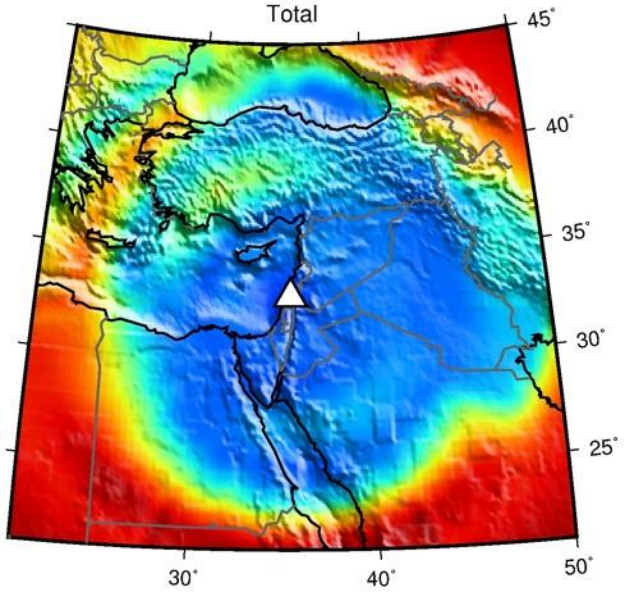
MJAR

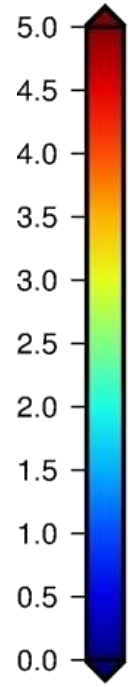


BDFB



MMAI





Sn Travel-time Uncertainty Surfaces (s):

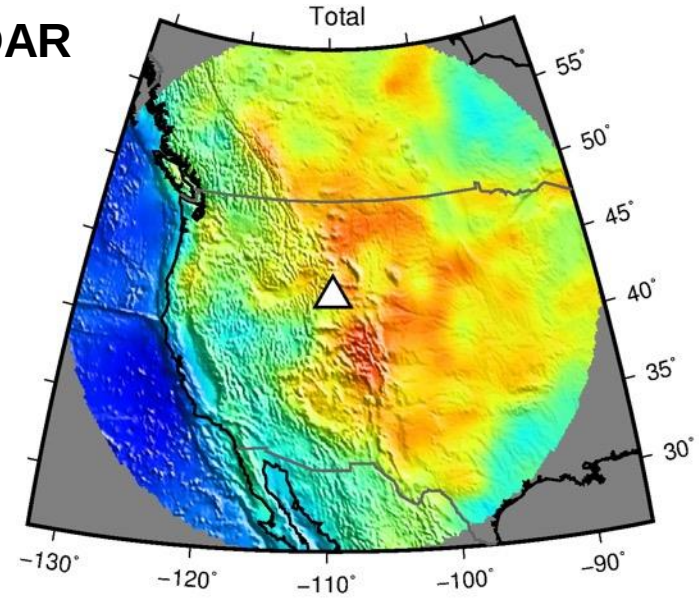
0 km Depth

U.S. DEPARTMENT OF ENERGY

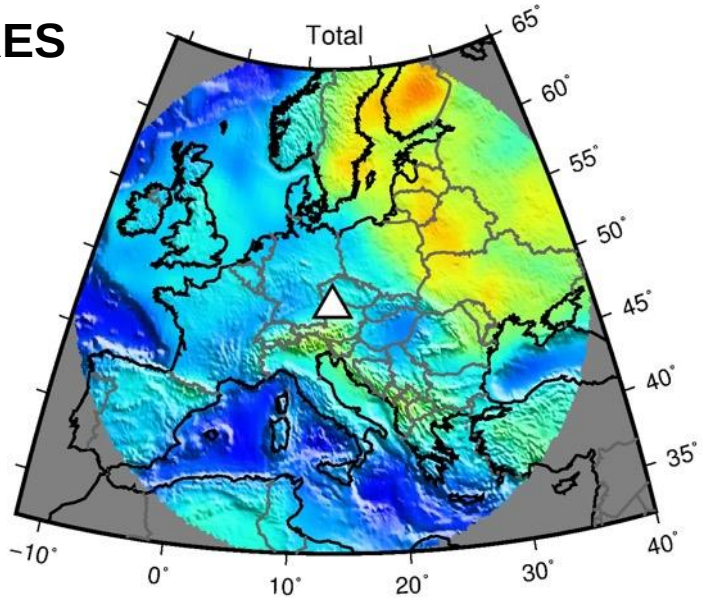
National Nuclear Security Administration

Nuclear Nonproliferation

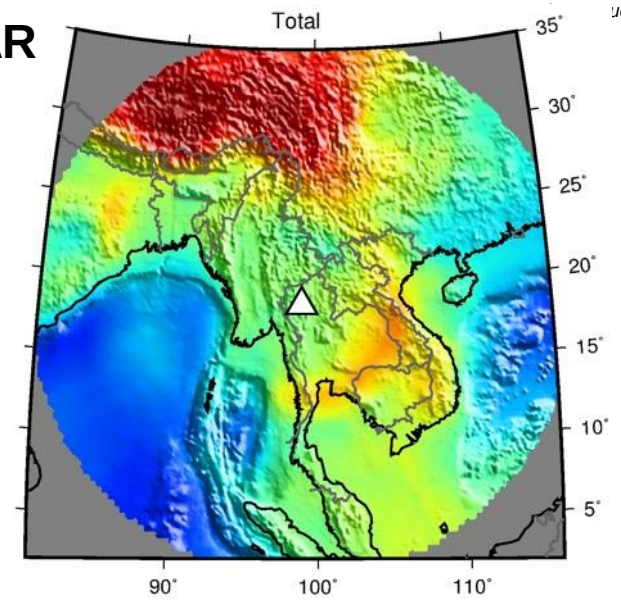
PDAR



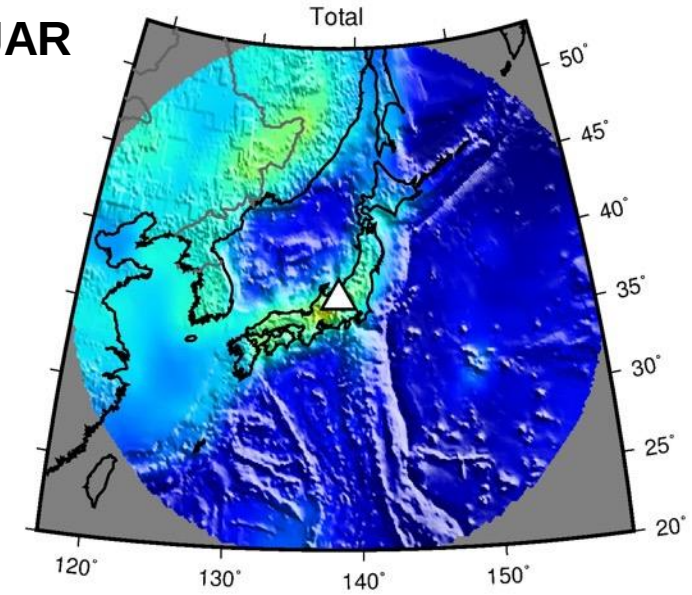
GERES



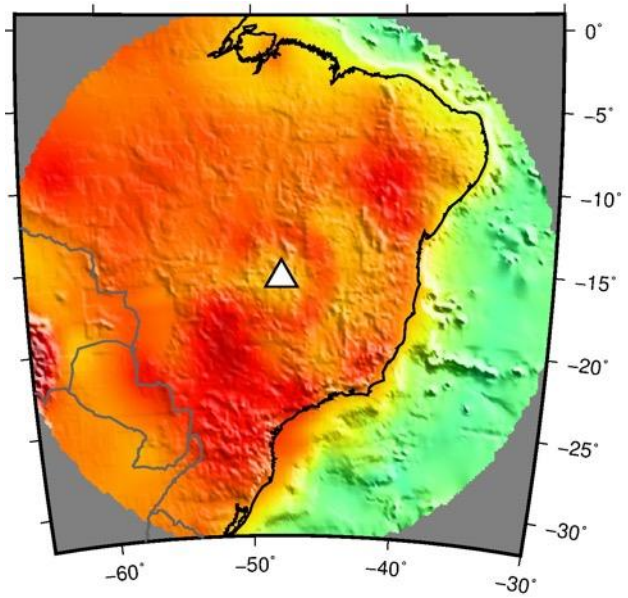
CMAR



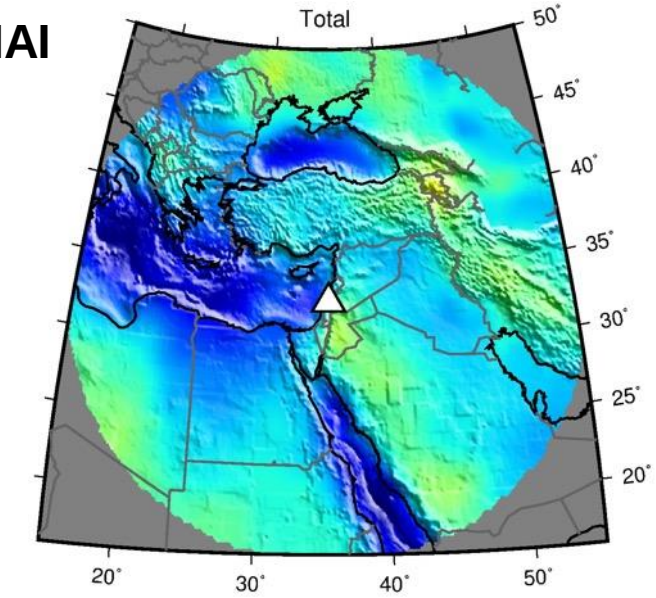
MJAR

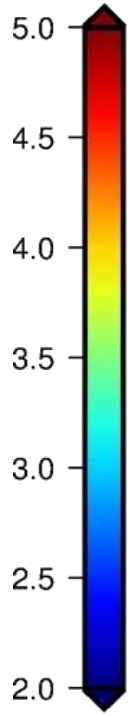


BDFB



MMAI





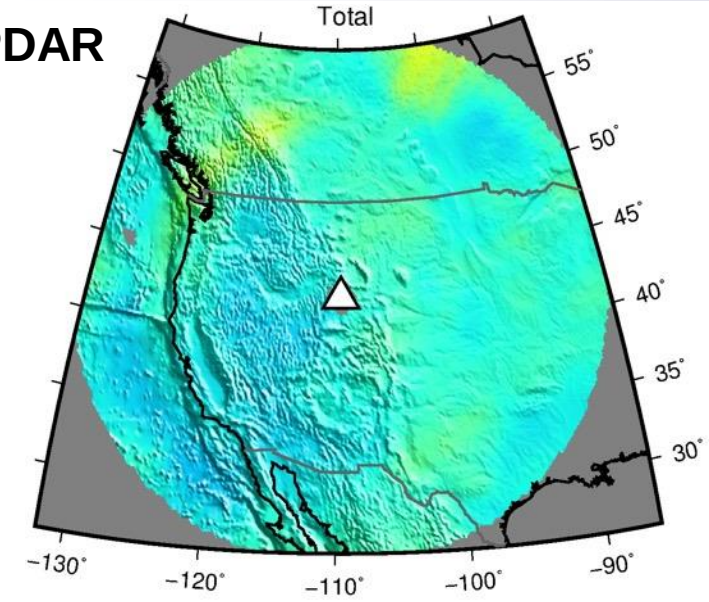
Lg Travel-time Uncertainty Surfaces (s):

0 km Depth

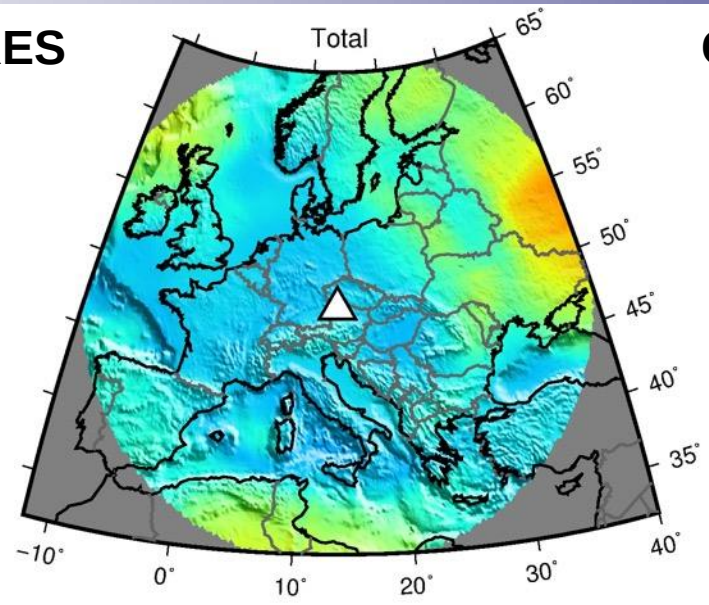
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration
Defense Nuclear Nonproliferation

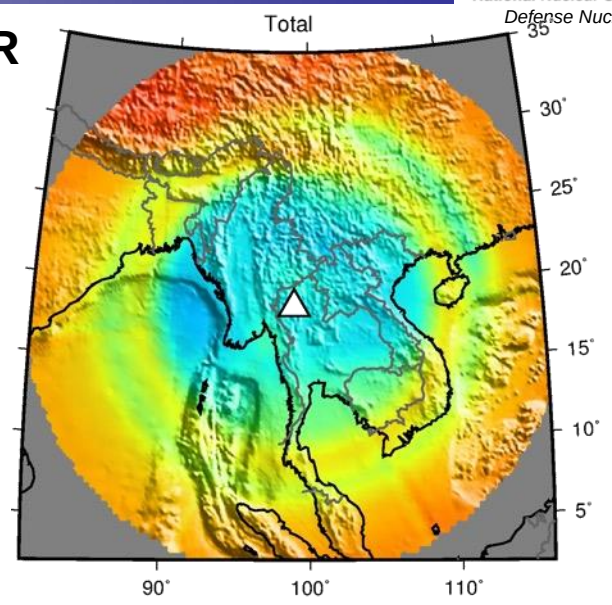
PDAR



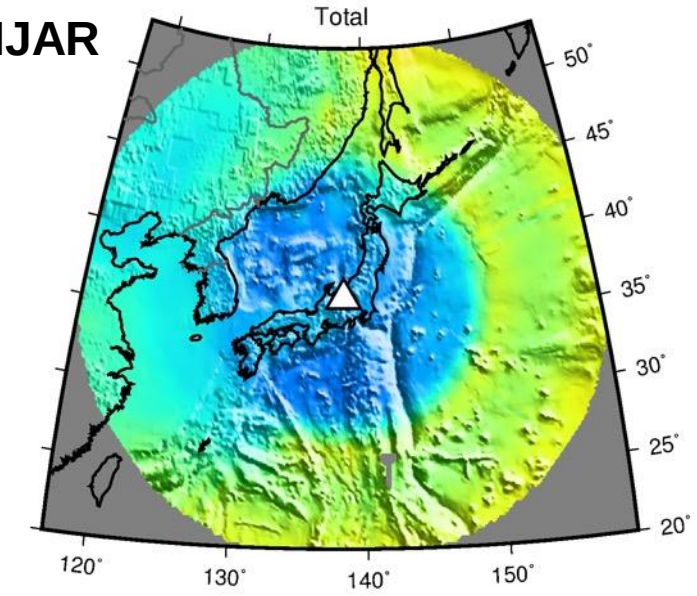
GERES



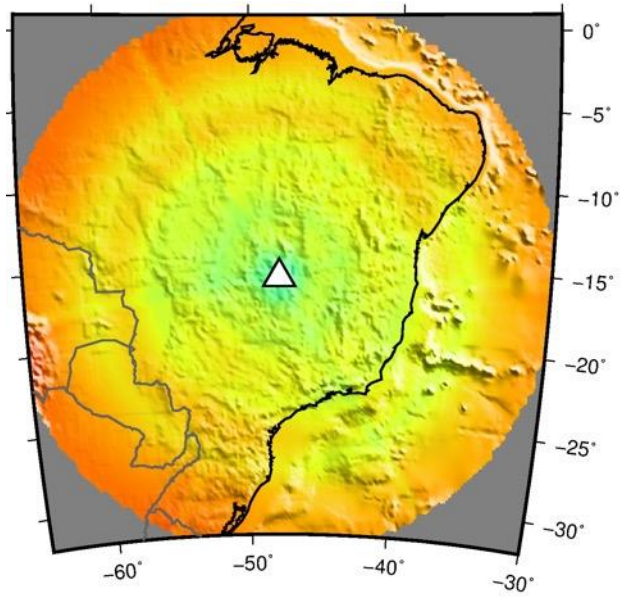
CMAR



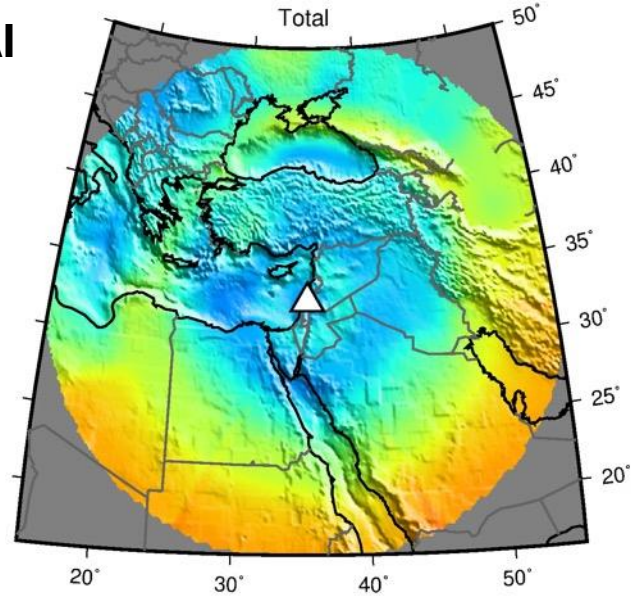
MJAR

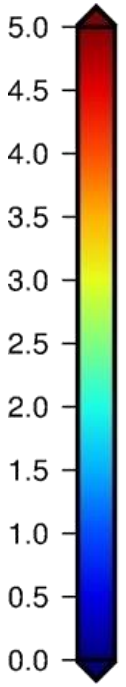


BDFB



MMAI





Conclusions and Future Work

- **Completed a full model update for all regional phases (Pn, Pg, Sn, Lg) using new Bayesloc-processed global data set**
  - Preliminary validation of tomography model for select stations by producing travel-time correction surfaces
- **Calculated error components for each phase using a random effects model and created model error, random error, and bias grids at distinct distance bins (2-16° with 2° bins)**
  - Background values for each distance bin determined using the values for that bin
  - *Mean + 2*std*
  - Preliminary validation of estimates of travel time uncertainty for select stations
- **Working with SNL on updates to RSTT code to handle 2D uncertainty**
- **Future Work:**
  - Full validation of all IMS primary and auxiliary stations for travel time difference (to iasp91)
  - Validation of model + uncertainty using GT5 or better events + REB arrivals
  - Assist creation of Source Specific Station Corrections (SSSCs) for all regional phases