SAND2011-8737C

SALSA3D - A Global 3D P-Velocity Model of the Earth's Mantle For Improved Event Location in Nuclear Explosion Monitoring

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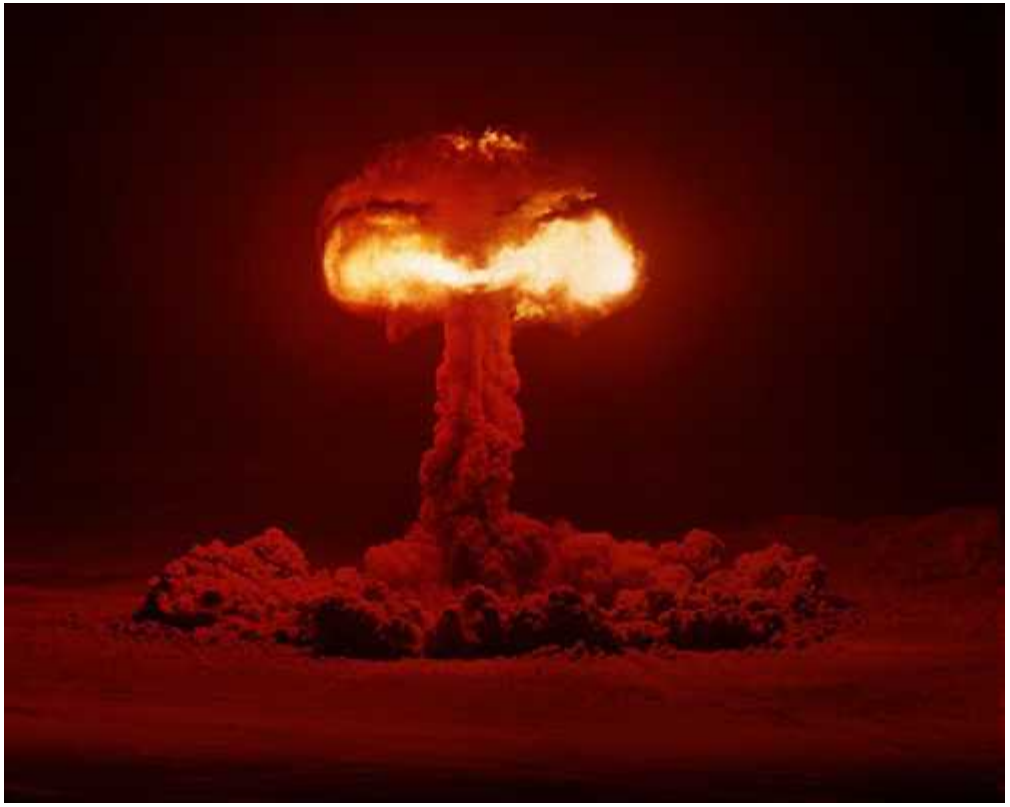
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Monitoring for Nuclear Explosions

Comprehensive Test Ban Treaty (CTBT)
Adopted by UN in 1996, ratified by 155 nations
China, Egypt, Indonesia, Iran, Israel, US have signed, but not ratified
India, North Korea, Pakistan have not signed

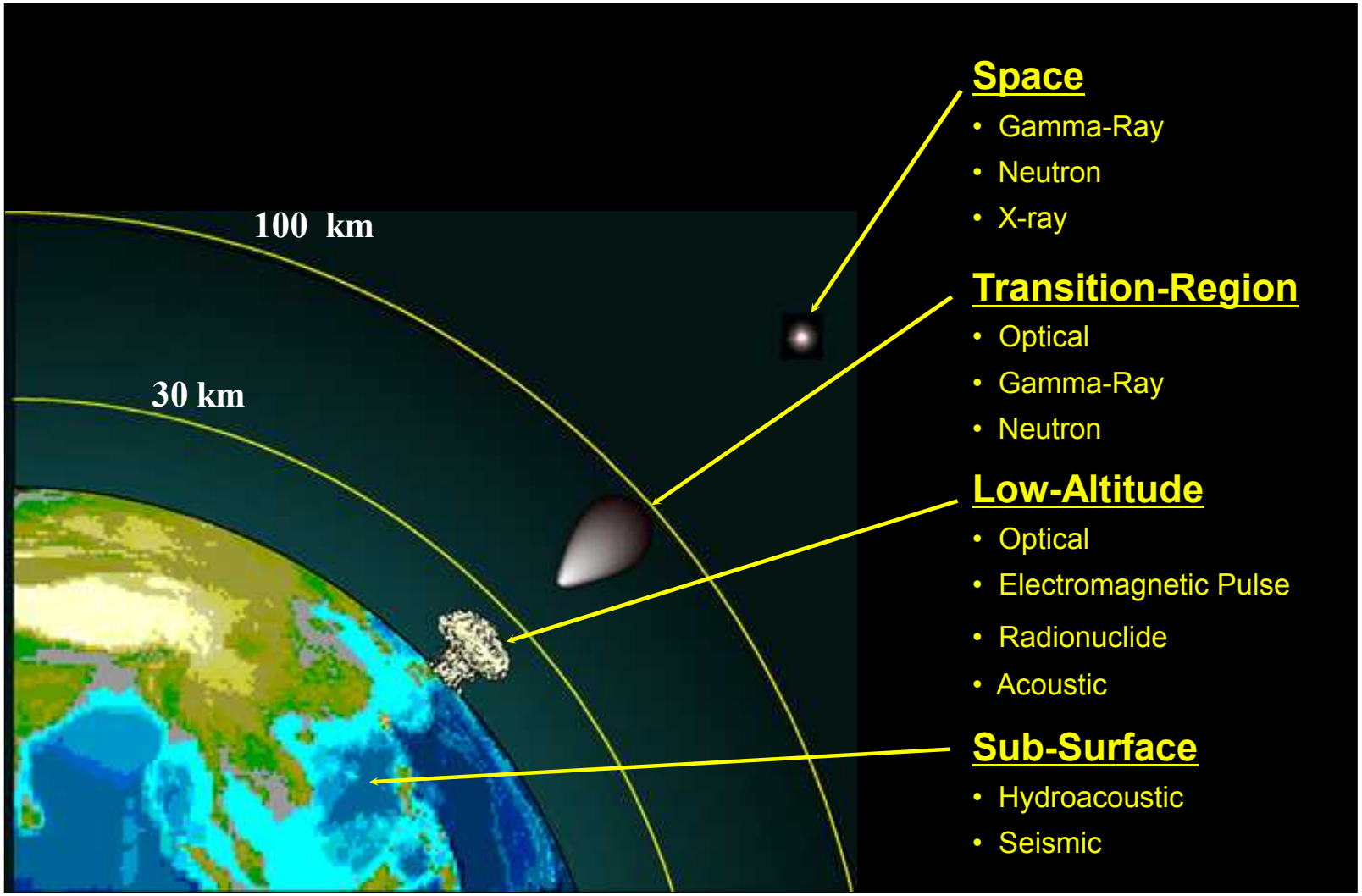


Comprehensive Test Ban Treaty Organization (CTBT)
Vienna, Austria

US National Data Center, AFTAC, Patrick AFB, FL

US Dept. of Energy provides R&D support

Monitoring for Nuclear Explosions



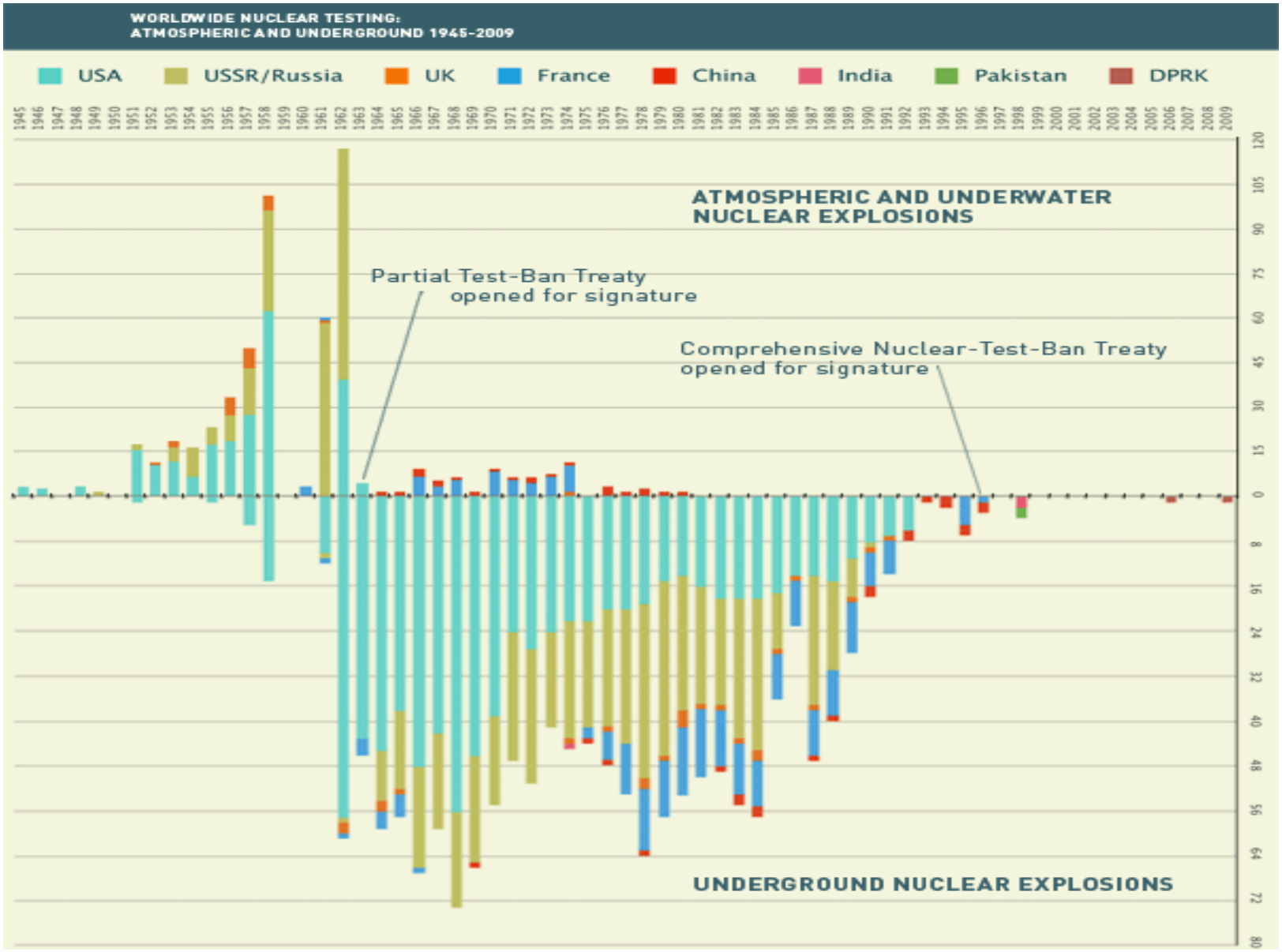
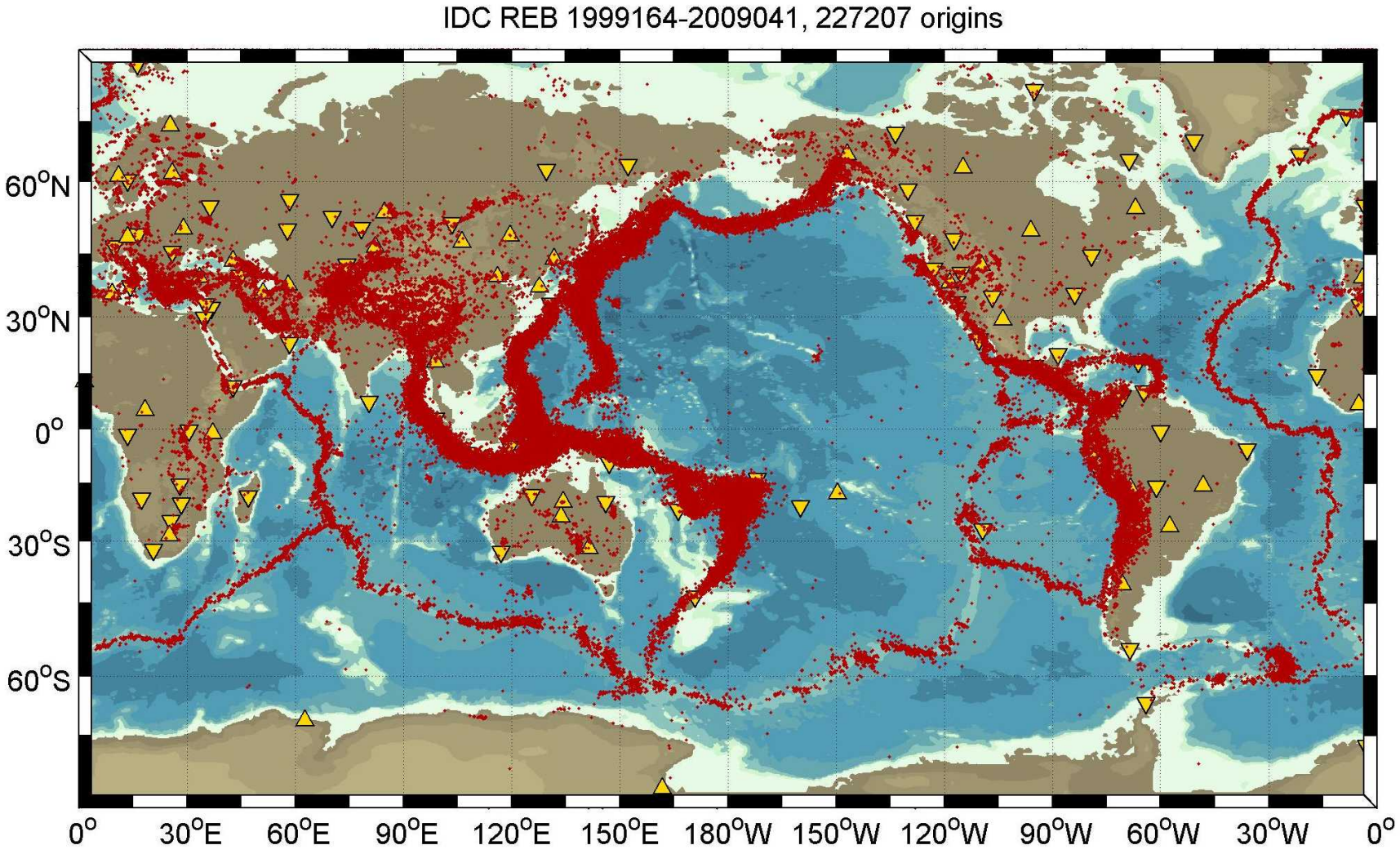
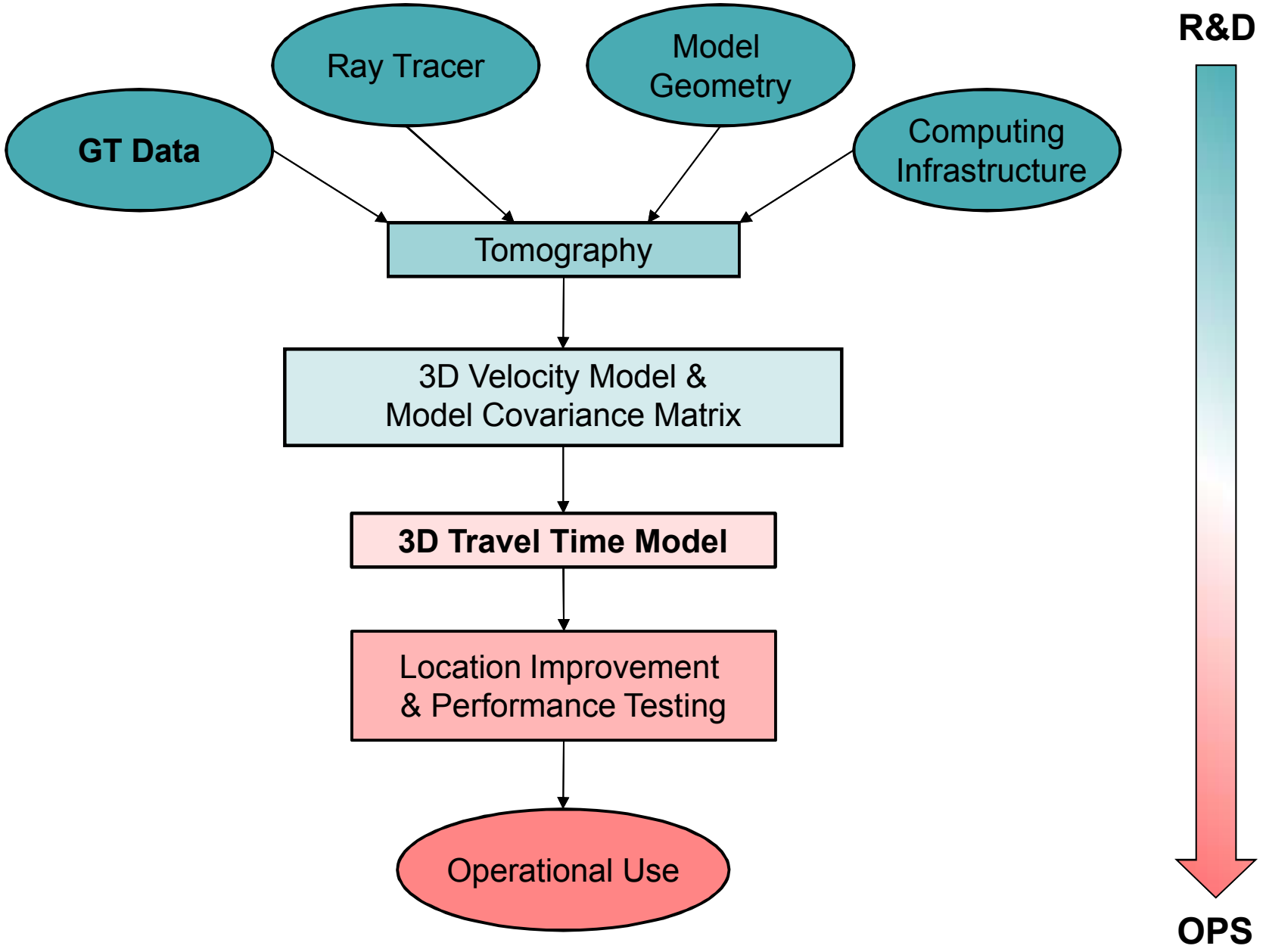


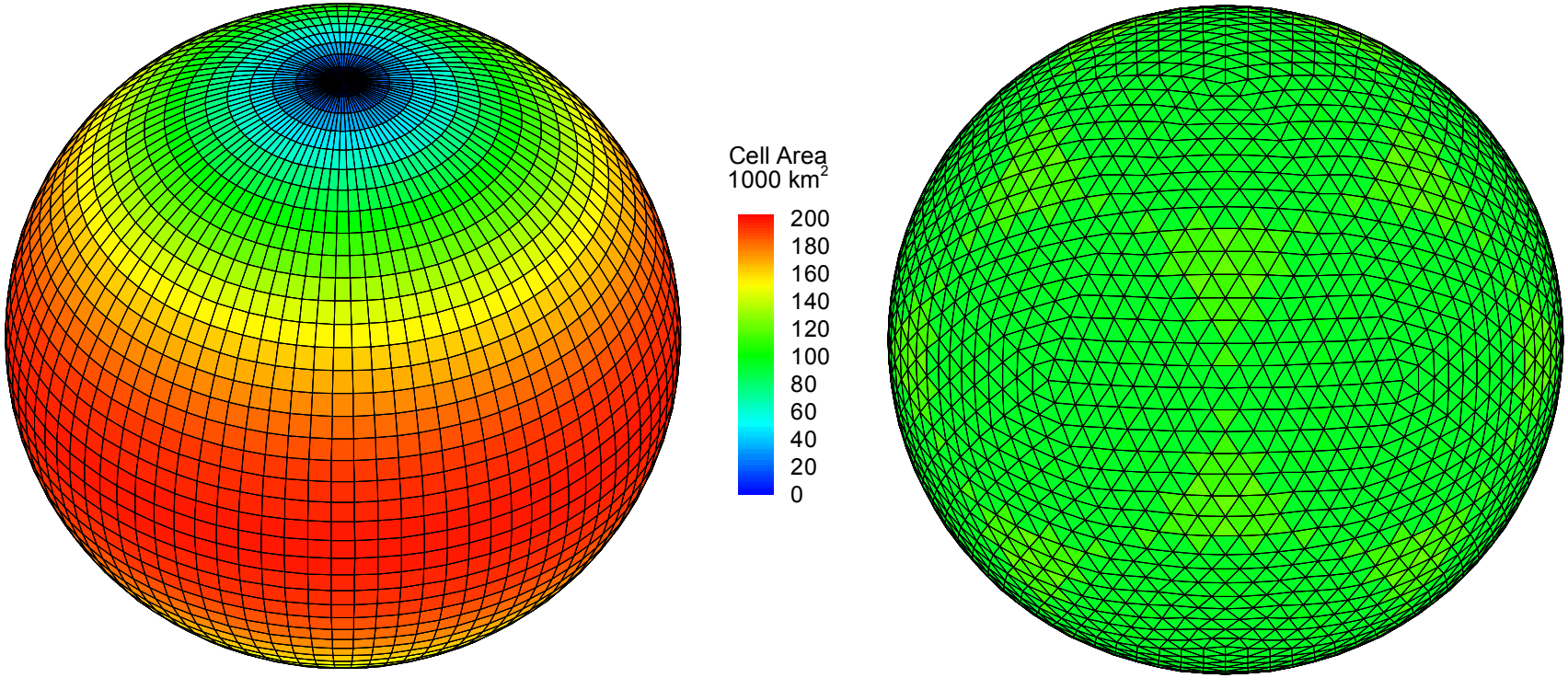
Figure from CTBTO website www.ctbto.org

Improve Accurracy and Precision of Seismic Event Locations




Ray Tracer
Model Geometry
GT Data
Computing Infrastructure
Tomography
3D Velocity Model & Model Covariance Matrix
3D Travel Time Model
Location Improvement & Performance Testing
Operational Use
R&D
OPS

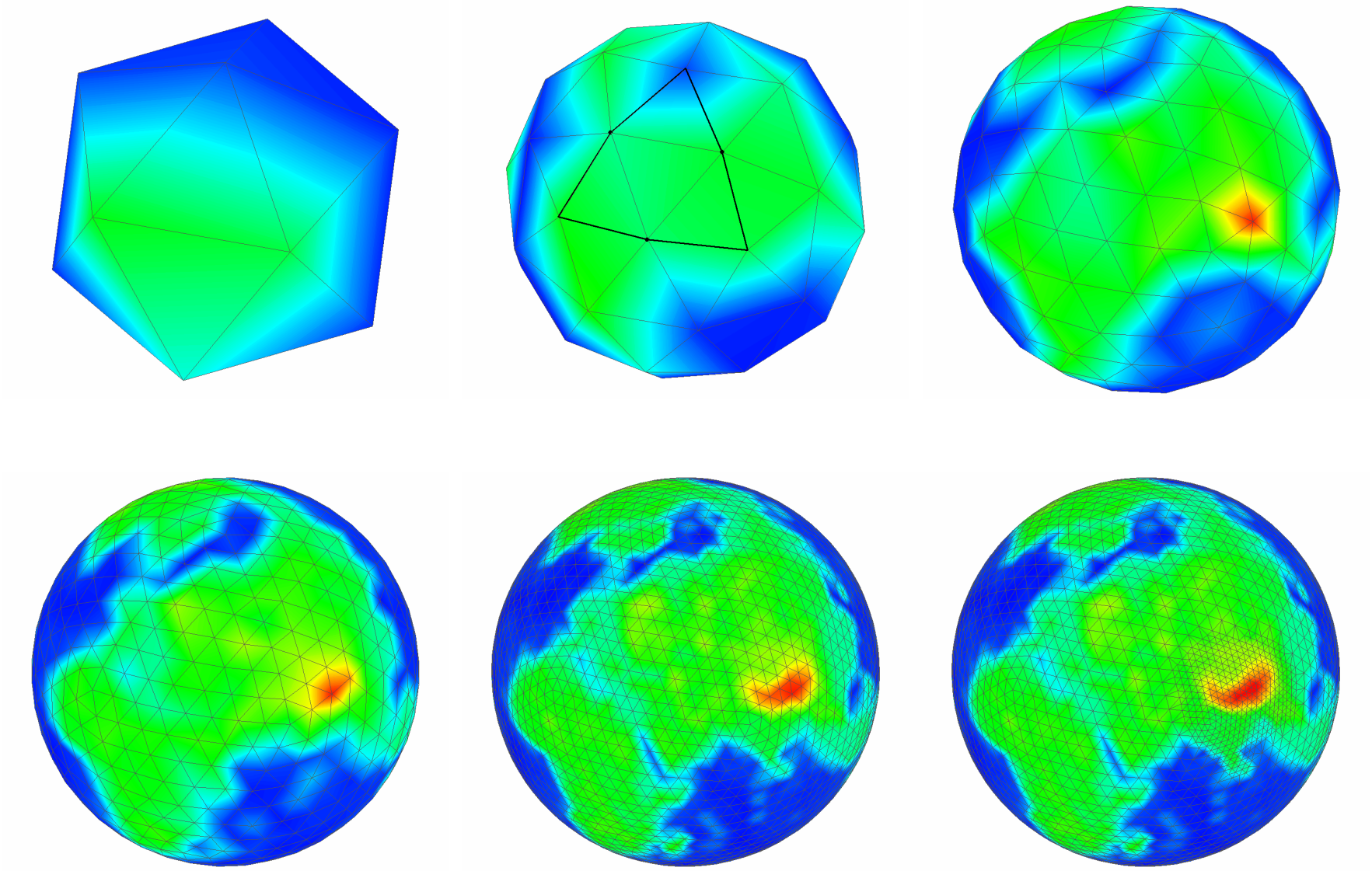
Earth Model Representation



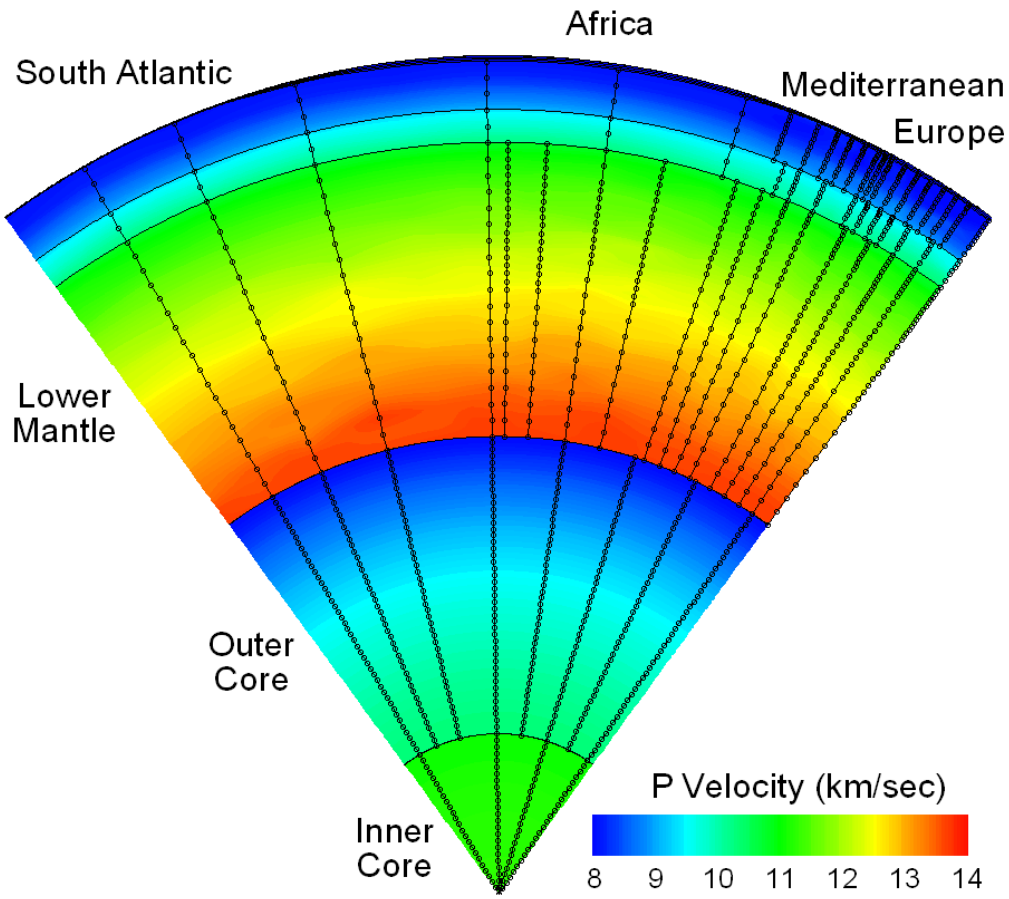
Wang, Z., and F. A. Dahlen (1995), Spherical-Spline Parameterization of Three-Dimensional Earth Models, Geophys. Res. Lett., 22(22), 3099-3102.

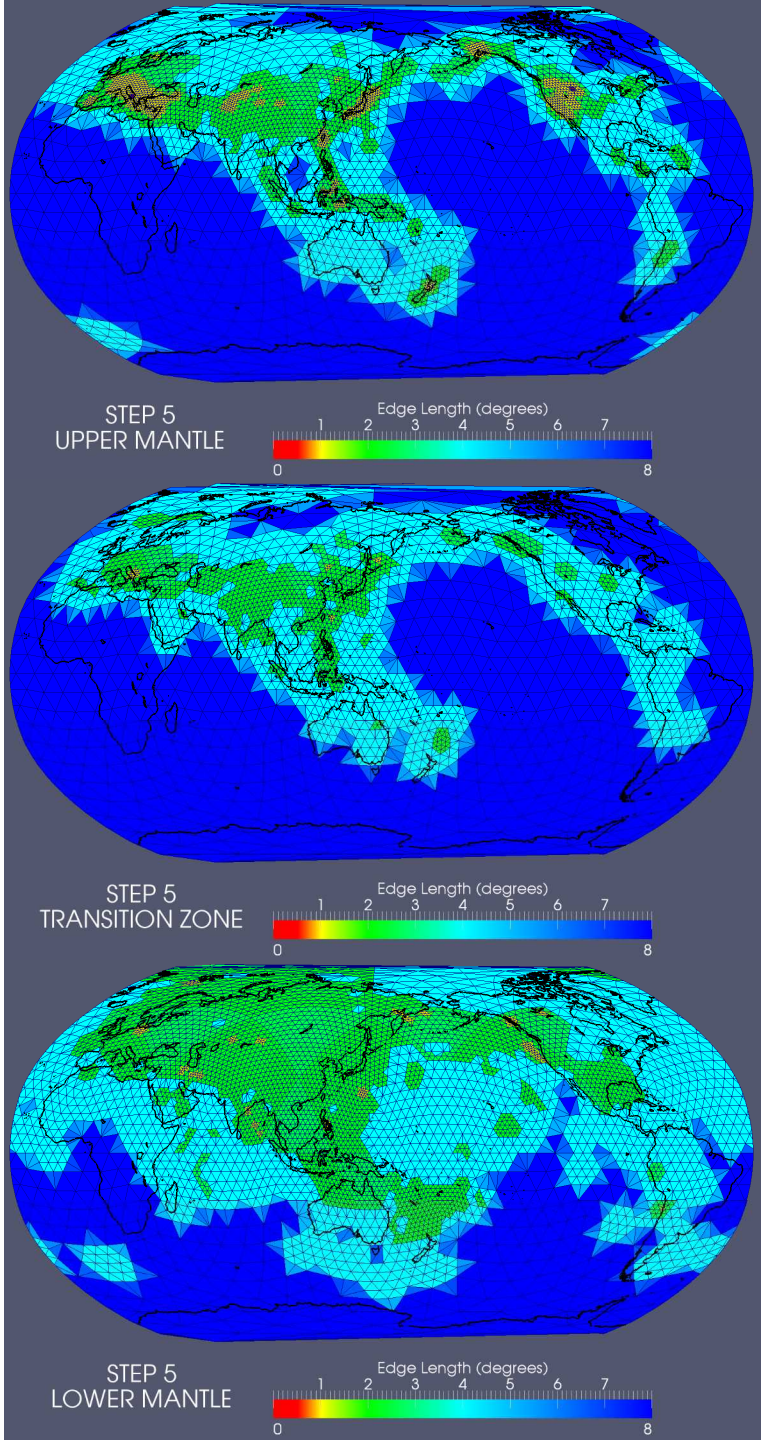
Ballard, S, J. R. Hipp, C. J. Young (2009), Efficient and accurate calculation of ray theory seismic travel time through variable resolution 3D earth models, Seismological Research Letters, 80, 989-999.

Construction of Triangular Tessellation

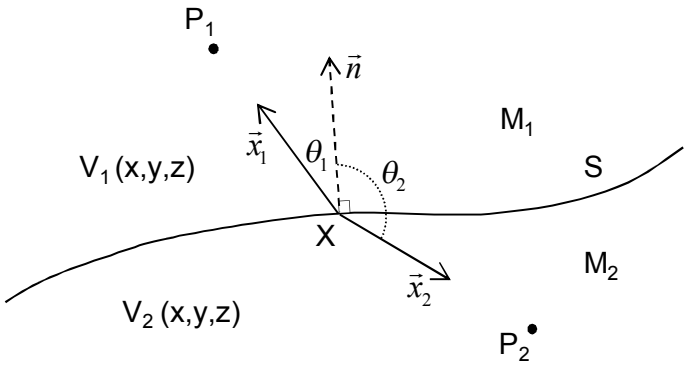


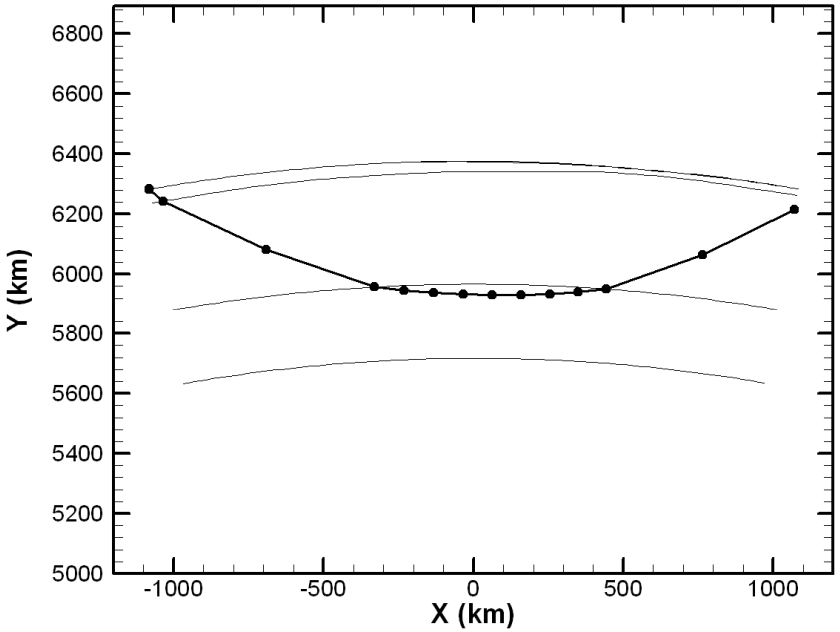
Variable Resolution in Geographic and Radial Dimensions

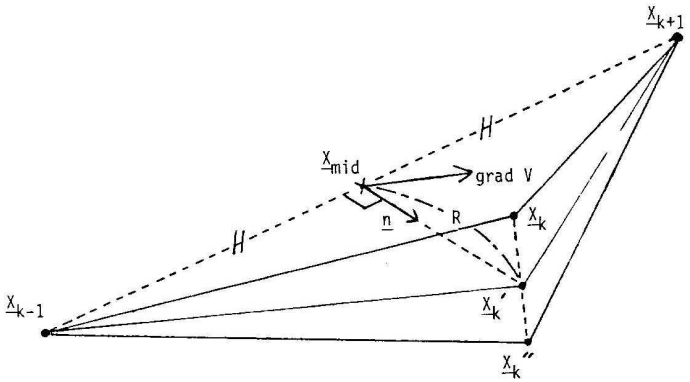




Pseudo Bending





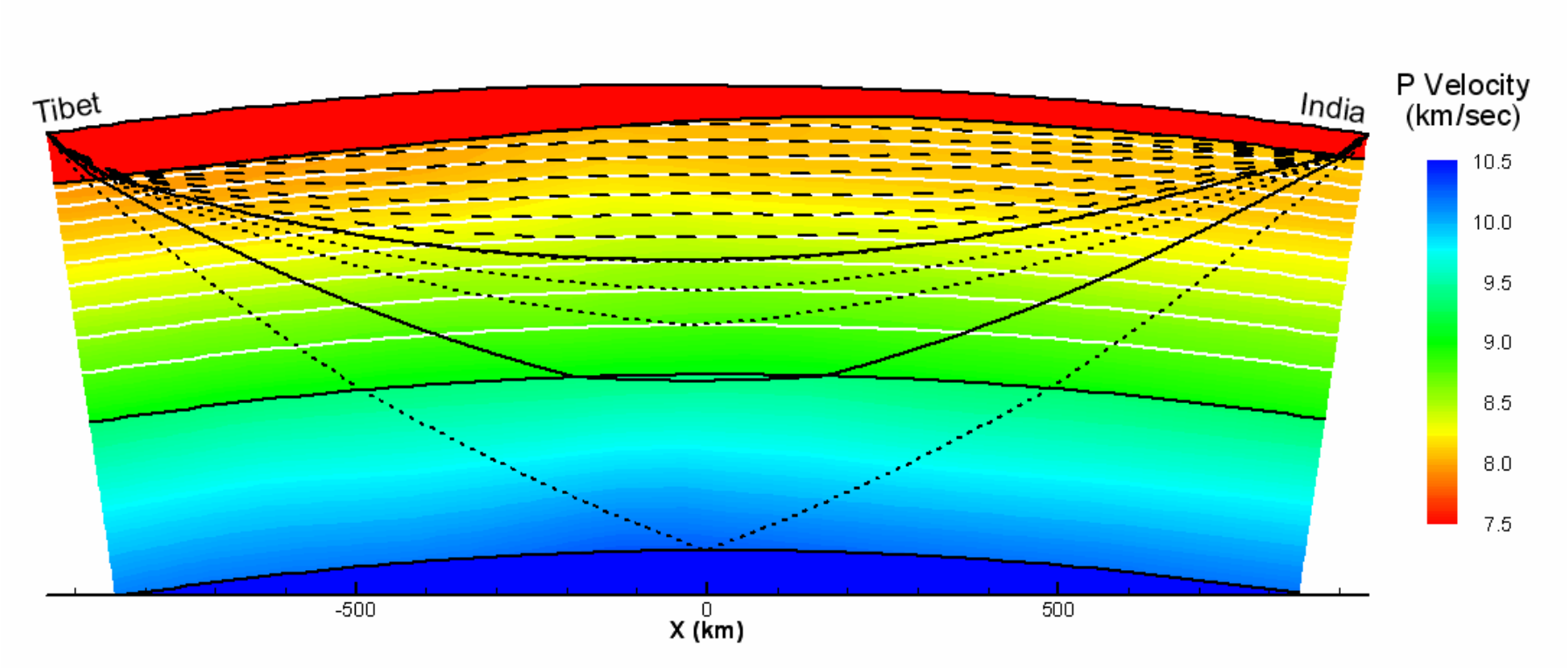


Algorithm:
loop:
    loop:
        enforce Snell's Law
        bend the intermediate points
    until travel time stable
    double nodes
until travel time stable

Um, J. and C. H. Thurber (1987). A fast algorithm for two-point seismic ray tracing, Bull. Seismol. Soc. Am., 77, 972-986.

Zhao, D. and J. Lei (2004), Seismic ray path variations in a 3D global velocity model, Physics of the Earth and Planetary Interiors, 141, 153–166.

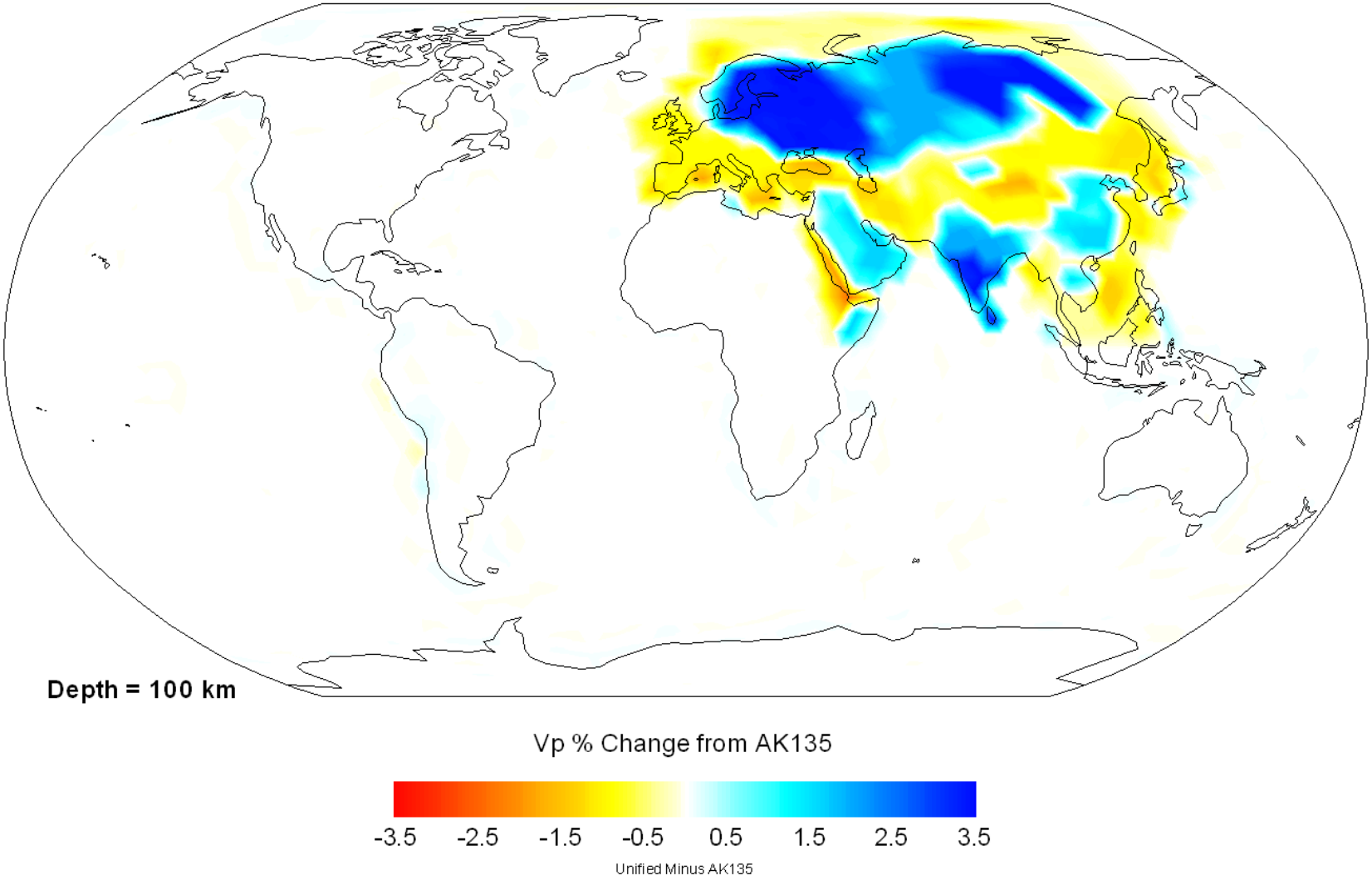
Ray Tracing with Bender



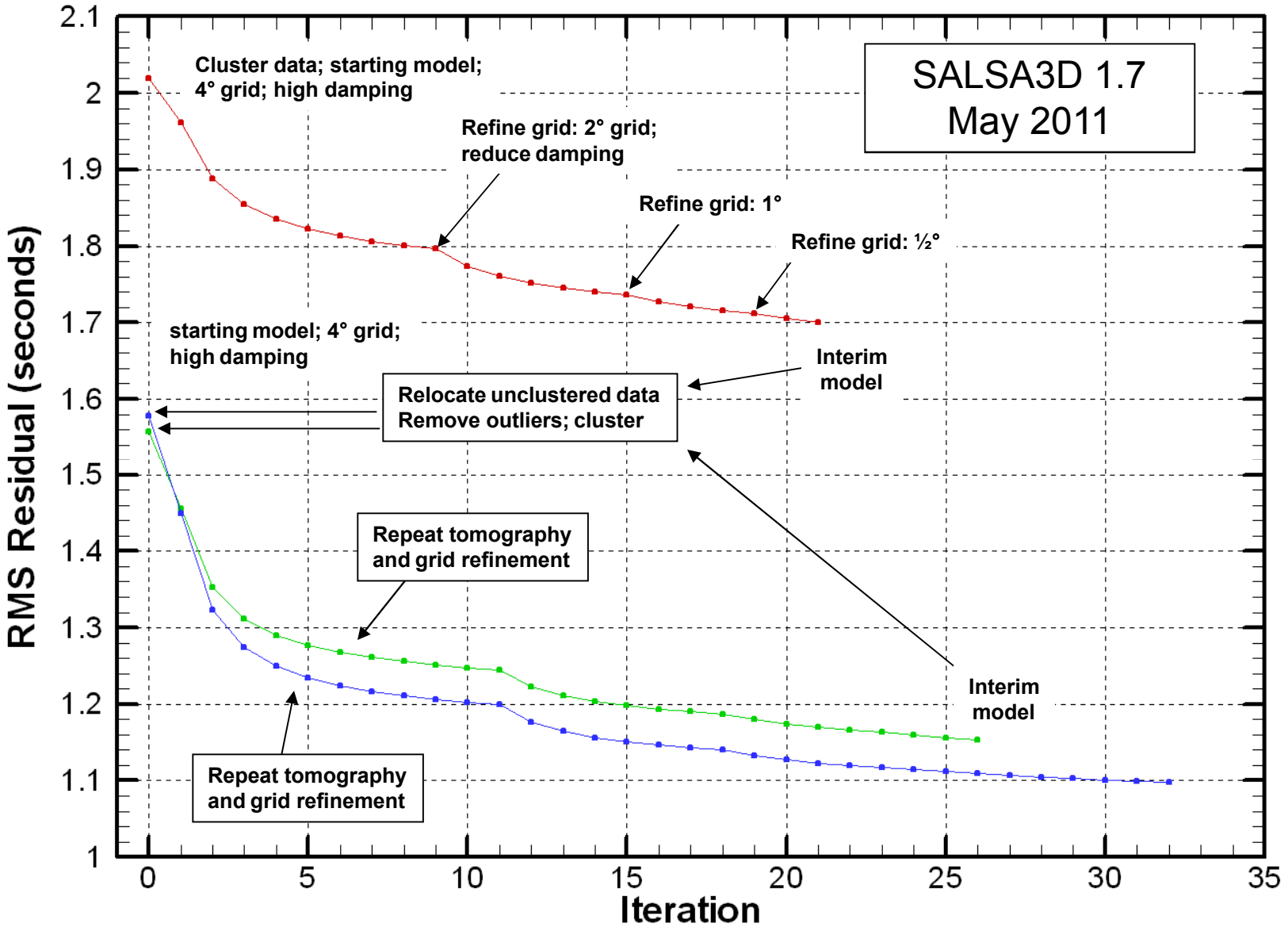
Um, J. and C. H. Thurber (1987). A fast algorithm for two-point seismic ray tracing, Bull. Seismol. Soc. Am., 77, 972-986.

Zhao, D. and J. Lei (2004), Seismic ray path variations in a 3D global velocity model, Physics of the Earth and Planetary Interiors, 141, 153–166.

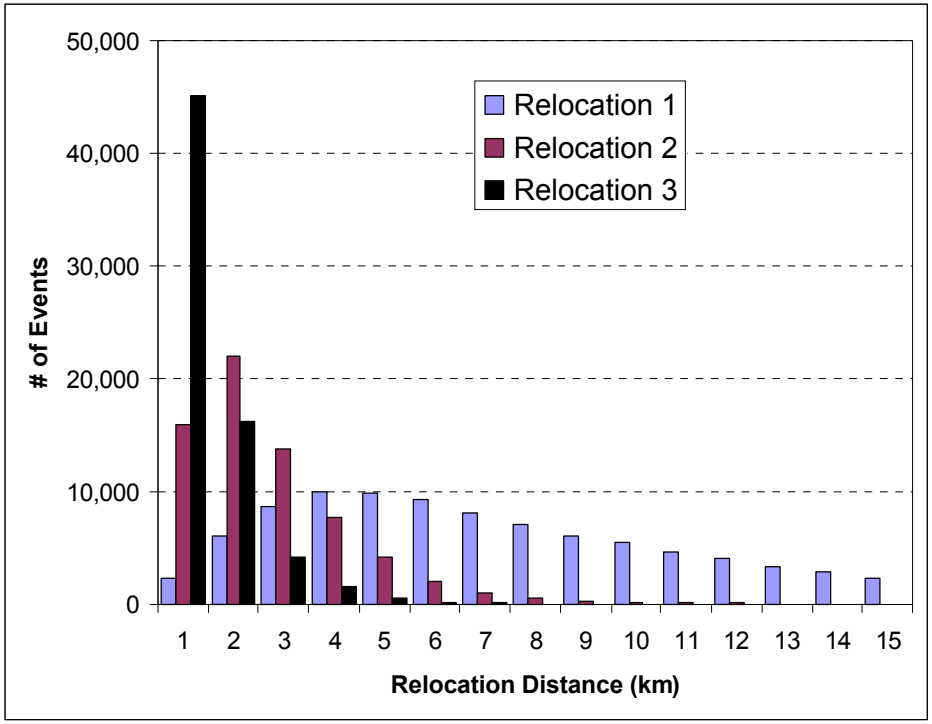
Starting Model

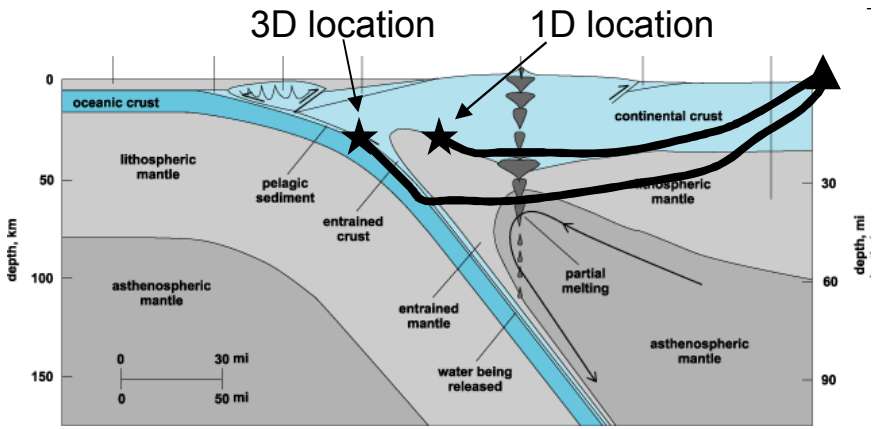


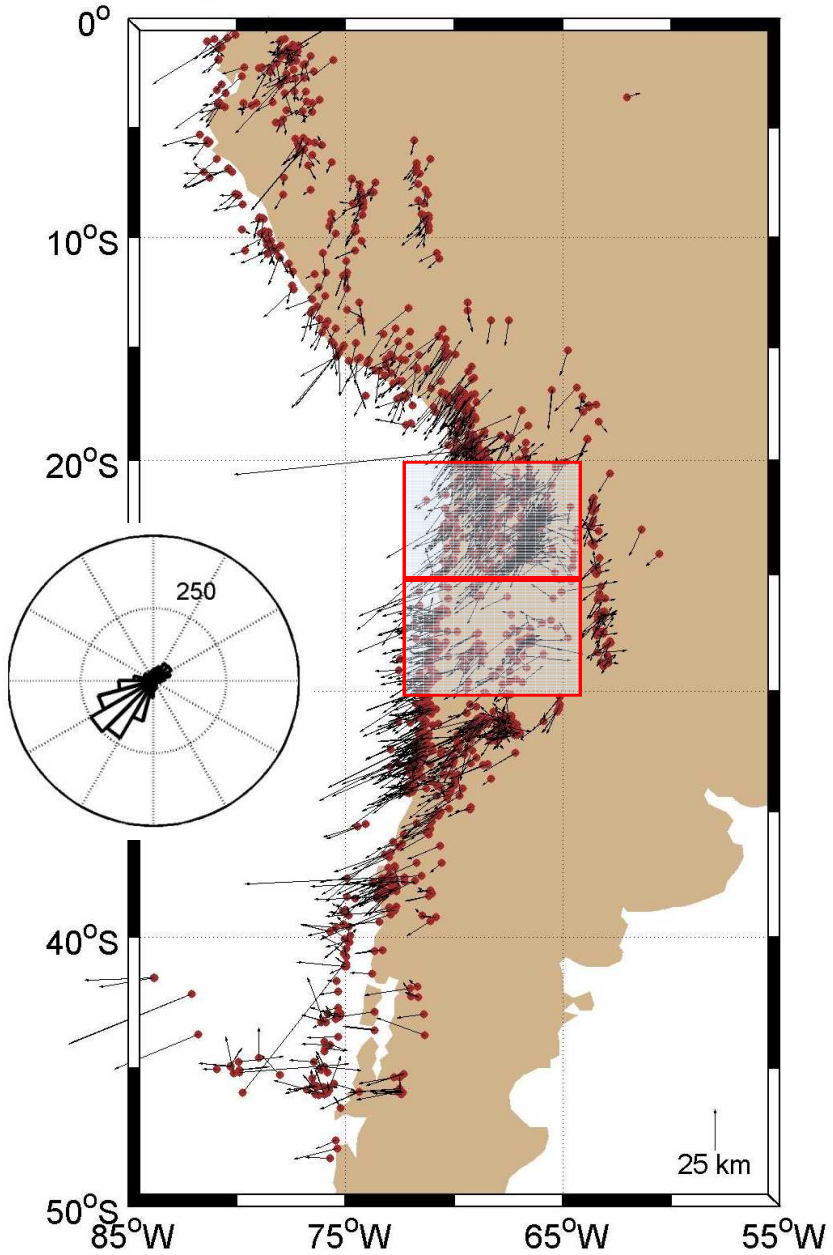
Tomographic Procedure – Event Relocation



Relocation Step







Model Resolution

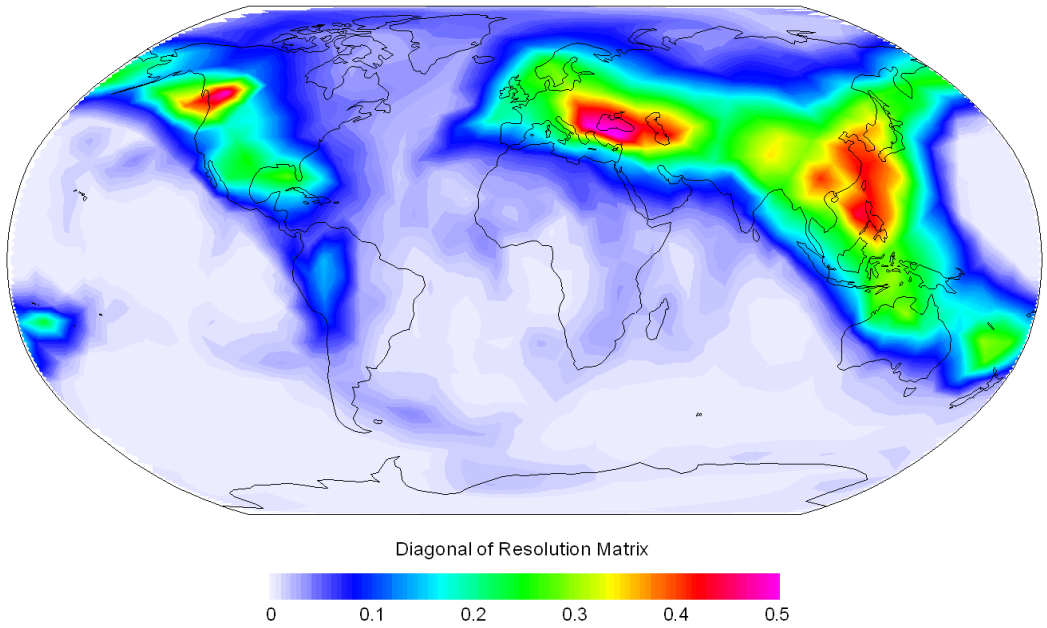
$$\begin{bmatrix} A \\ \alpha L \end{bmatrix} \Delta s = \begin{bmatrix} \Delta d \\ 0 \end{bmatrix}$$

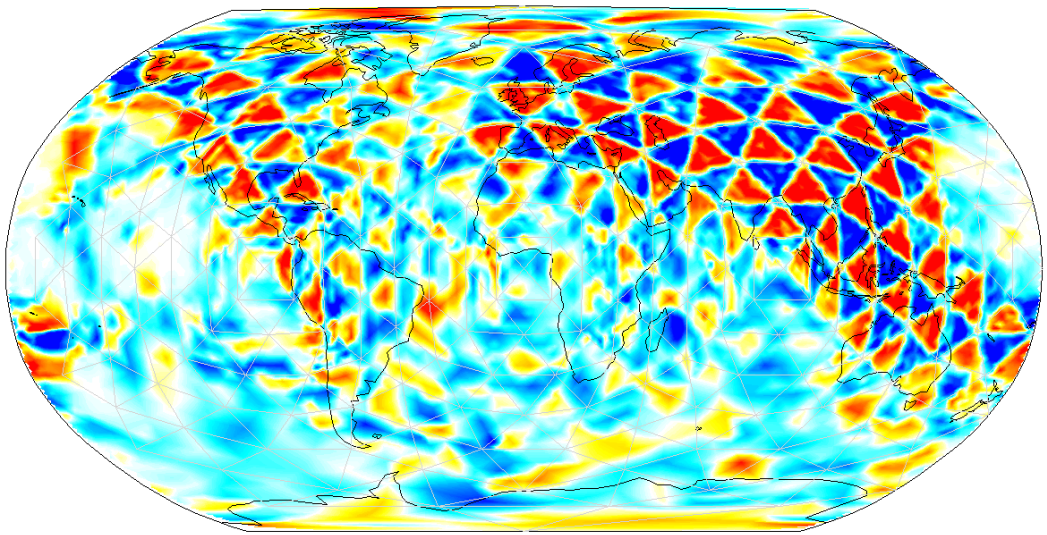
$$G\Delta s = \begin{bmatrix} \Delta d \\ 0 \end{bmatrix}$$

$$\Delta s = \left(G^T G\right)^{-1} A^T \Delta d$$

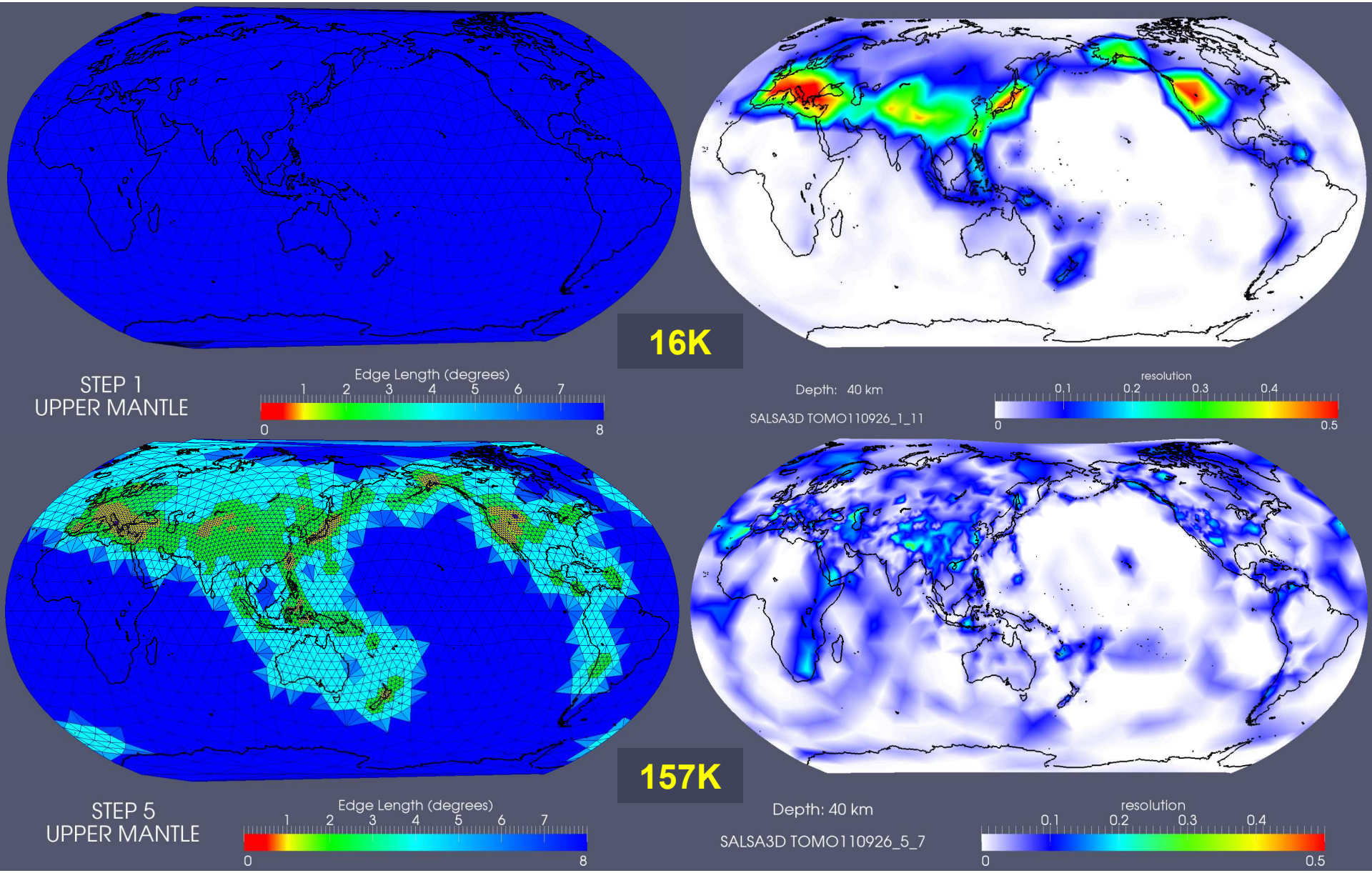
$$\Delta s = \left(G^T G\right)^{-1} A^T A \Delta s_{true}$$

$$R = \left(G^T G\right)^{-1} A^T A$$

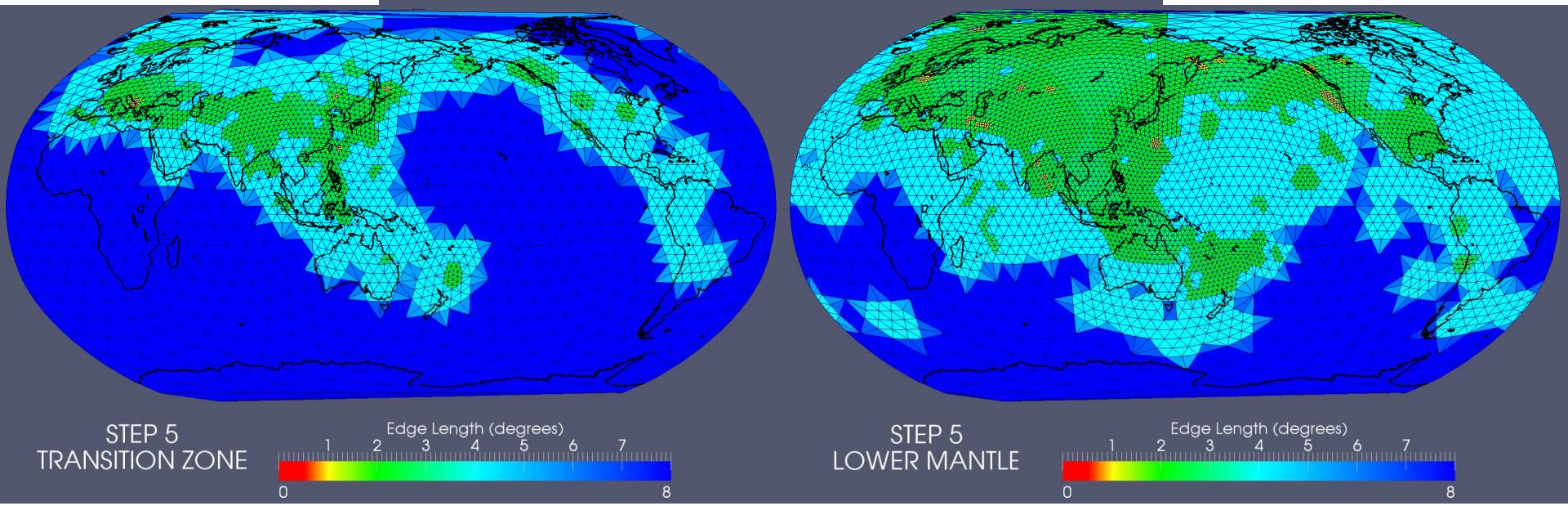




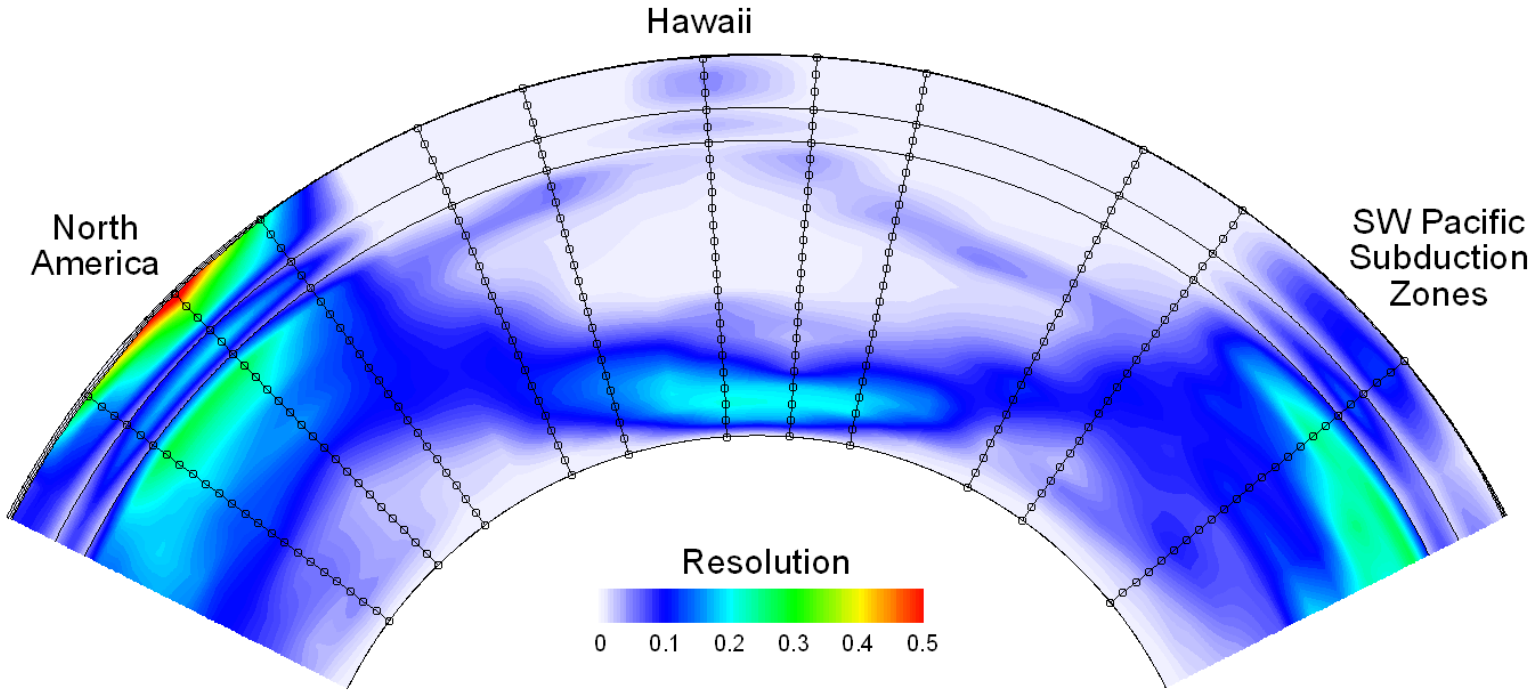
STEPS 1 & 5


16K
STEP 1
UPPER MANTLE
Edge Length (degrees)
1 2 3 4 5 6 7
0
8
Depth: 40 km
SALSA3D TOMO110926_1_11
resolution
0.1 0.2 0.3 0.4
0
0.5
157K
STEP 5
UPPER MANTLE
Edge Length (degrees)
1 2 3 4 5 6 7
0
8
Depth: 40 km
SALSA3D TOMO110926_5_7
resolution
0.1 0.2 0.3 0.4
0
0.5

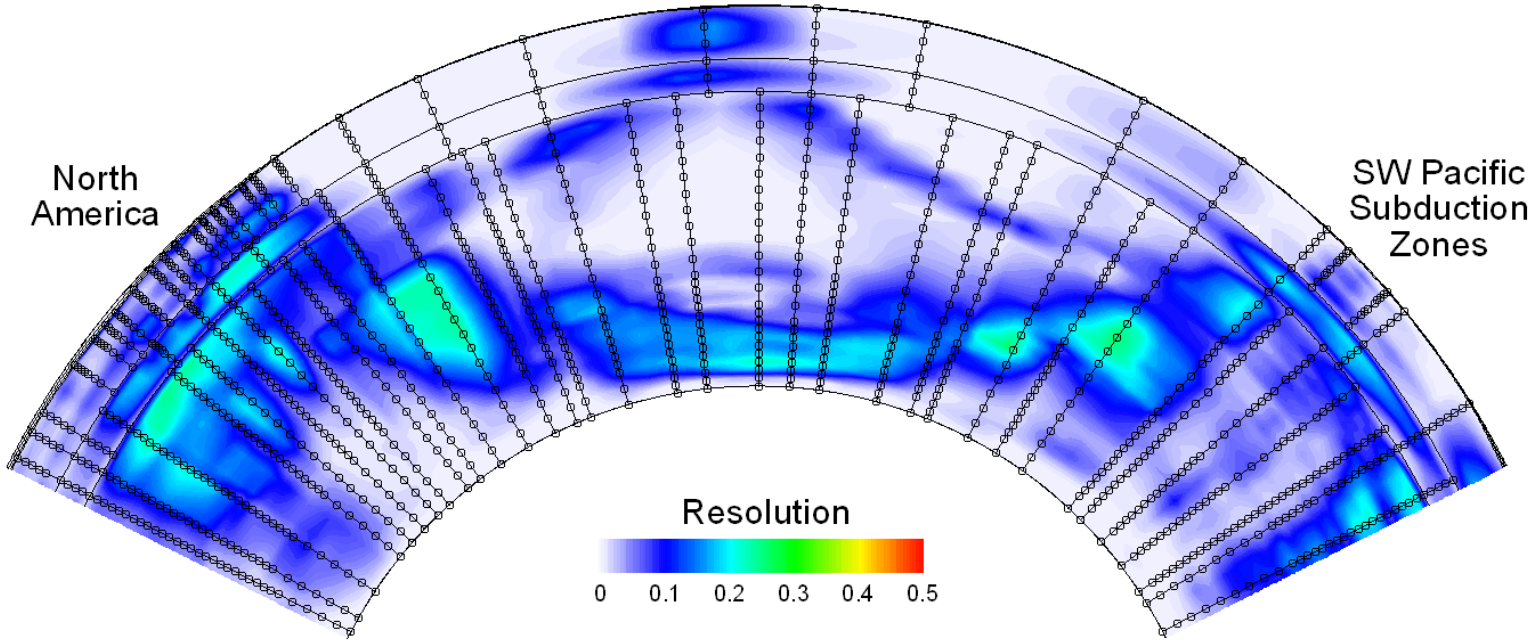
Final Grid


STEP 5
UPPER MANTLE
Edge Length (degrees)
1 2 3 4 5 6 7
0 8
STEP 5
TRANSITION ZONE
Edge Length (degrees)
1 2 3 4 5 6 7
0 8
STEP 5
LOWER MANTLE
Edge Length (degrees)
1 2 3 4 5 6 7
0 8

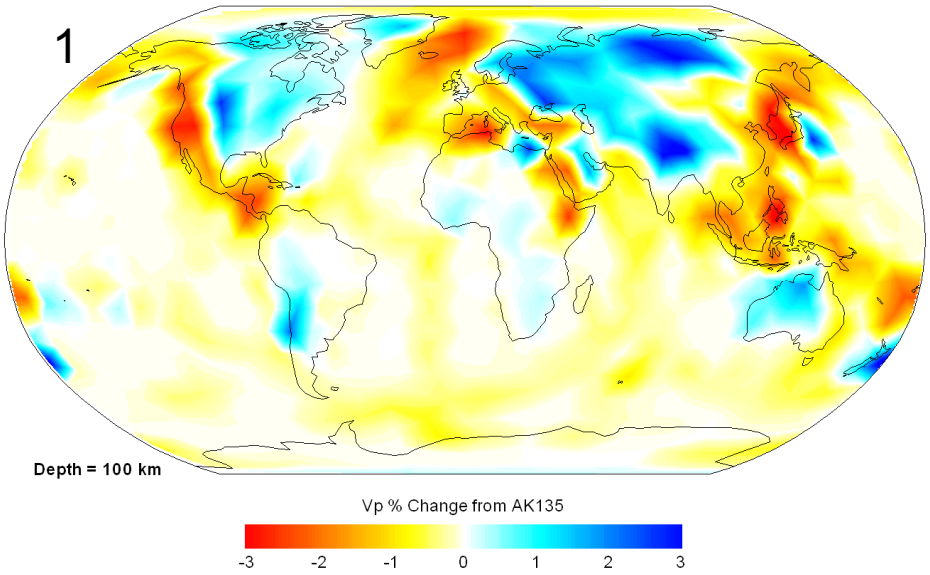
Step 1

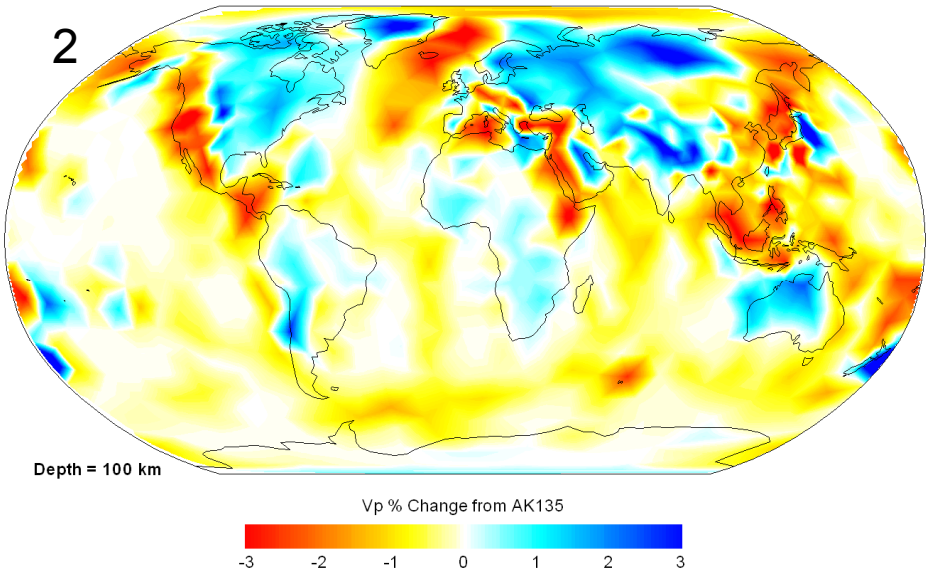

Hawaii
North America
SW Pacific Subduction Zones
Resolution
0 0.1 0.2 0.3 0.4 0.5

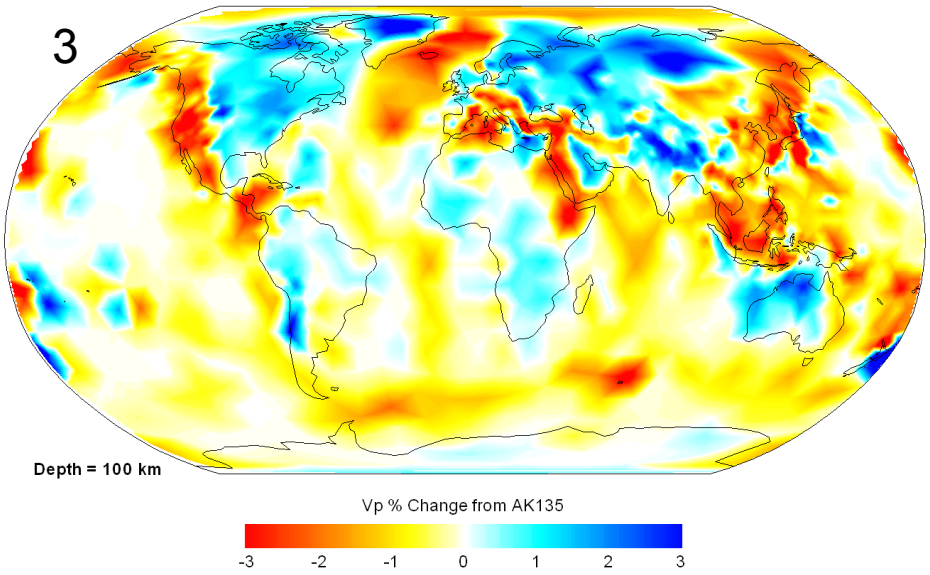
Step 5

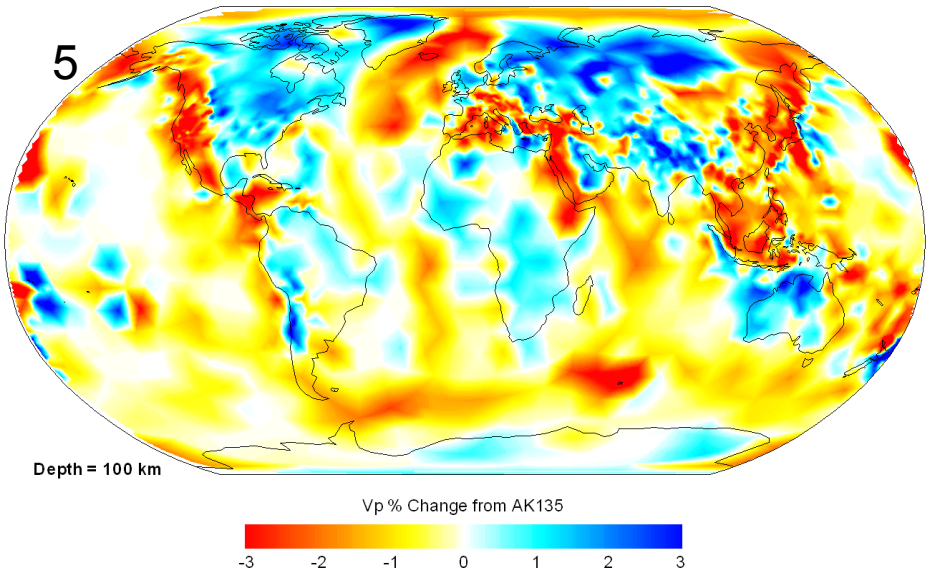

North America
SW Pacific Subduction Zones
Resolution
0 0.1 0.2 0.3 0.4 0.5

SALSA3D

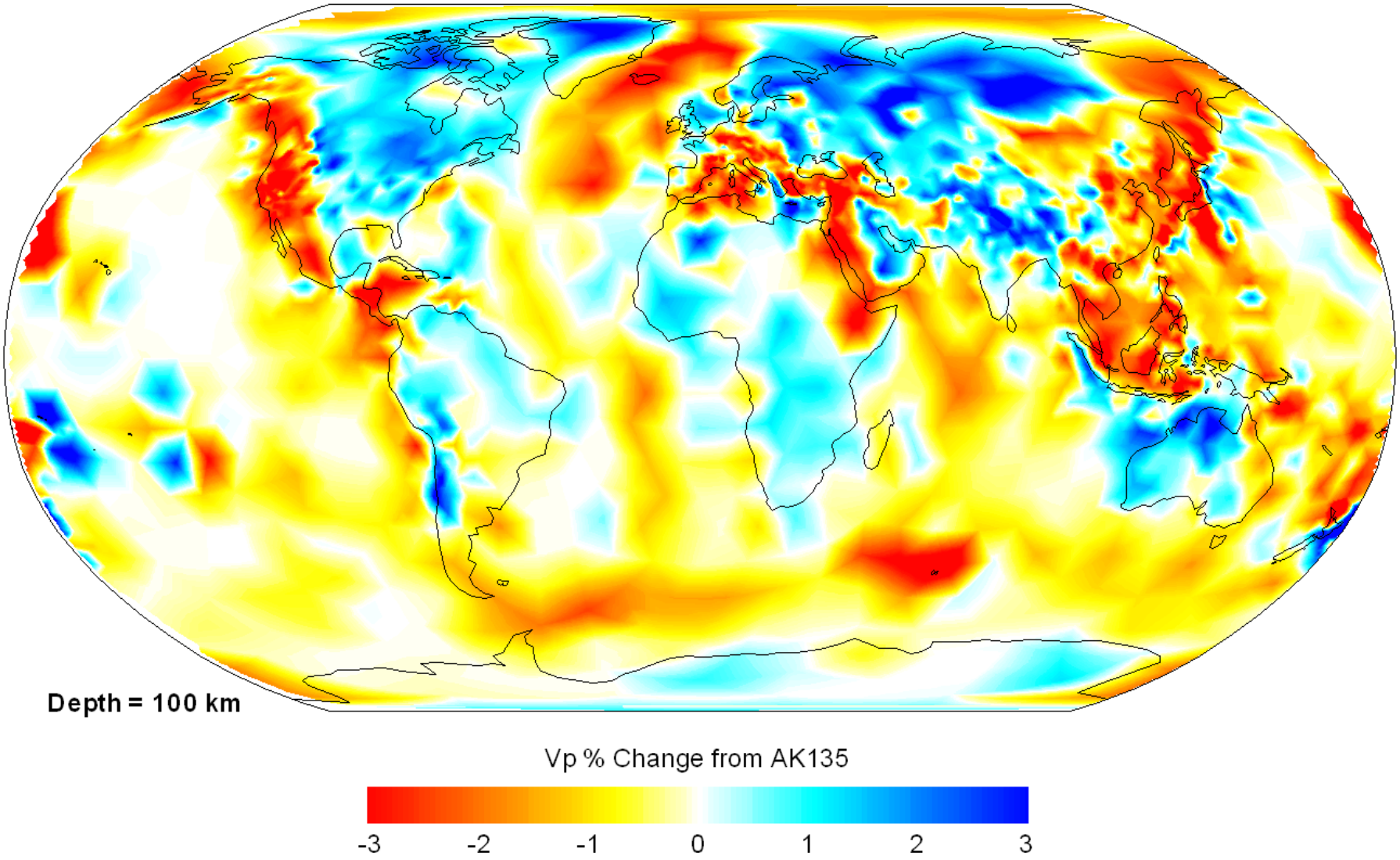

1
Depth = 100 km
Vp % Change from AK135
-3 -2 -1 0 1 2 3


2
Depth = 100 km
Vp % Change from AK135
-3 -2 -1 0 1 2 3

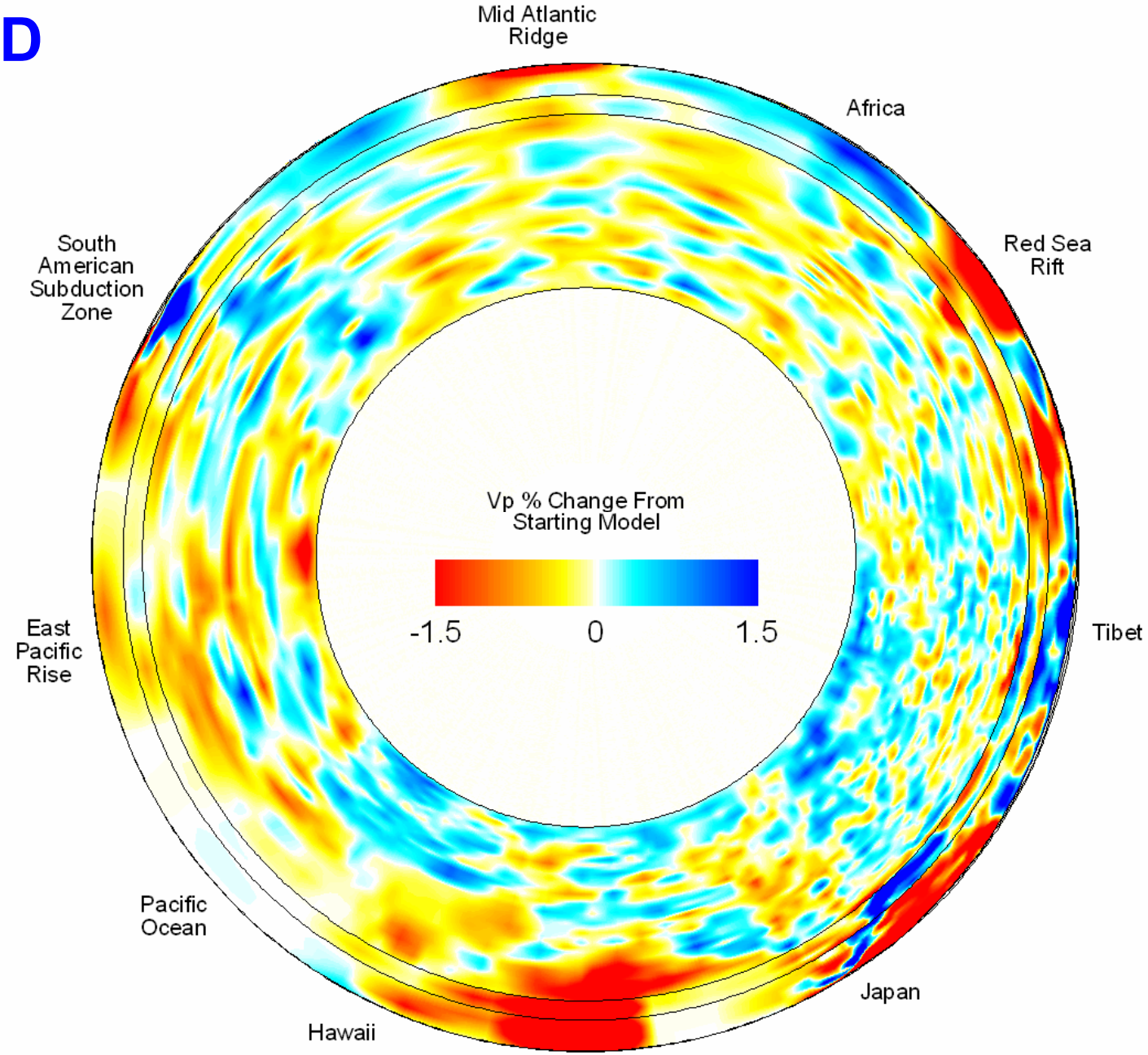

3
Depth = 100 km
Vp % Change from AK135
-3 -2 -1 0 1 2 3


5
Depth = 100 km
Vp % Change from AK135
-3 -2 -1 0 1 2 3

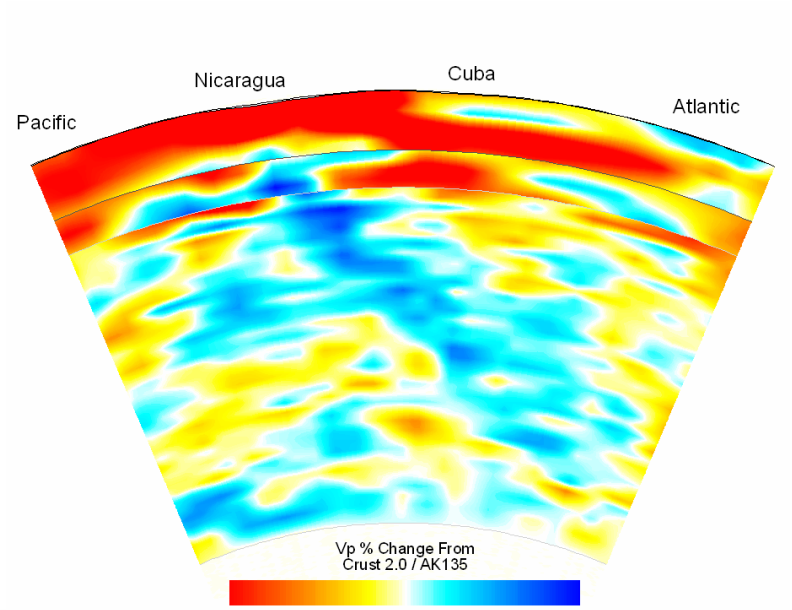
SALSA3D

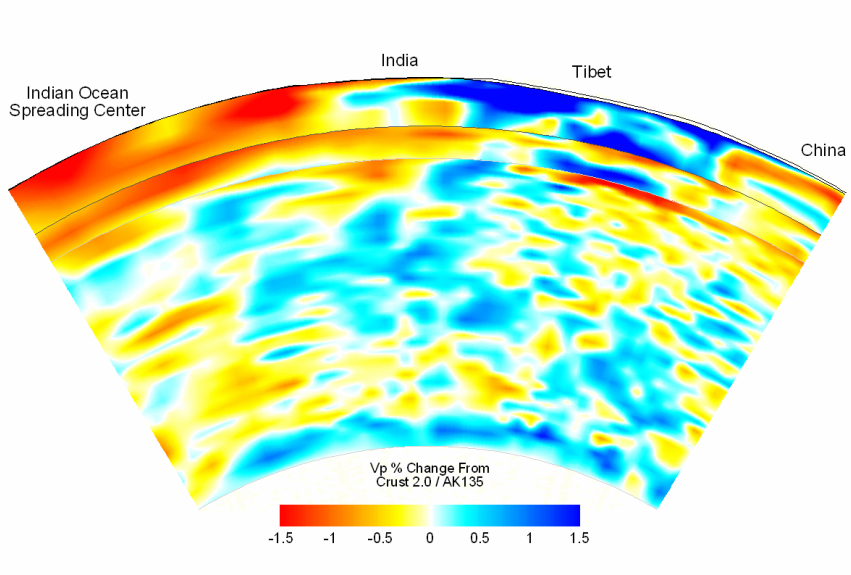


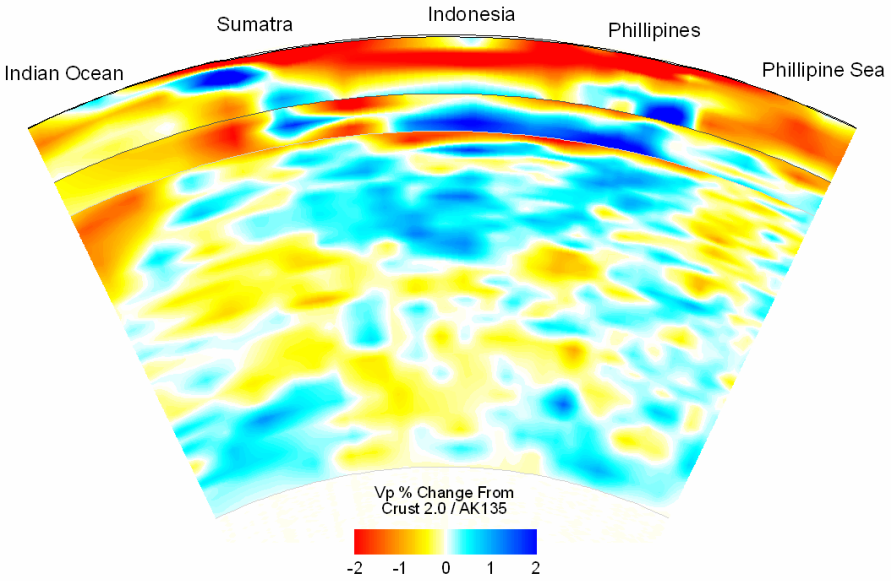
SALSA3D

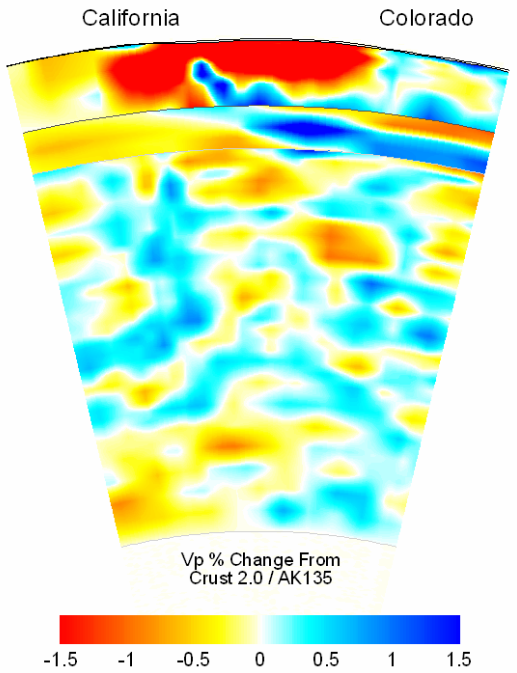

Mid Atlantic Ridge
Africa
Red Sea Rift
Tibet
Japan
Hawaii
Pacific Ocean
East Pacific Rise
South American Subduction Zone
Vp % Change From Starting Model
-1.5
0
1.5

SALSA3D

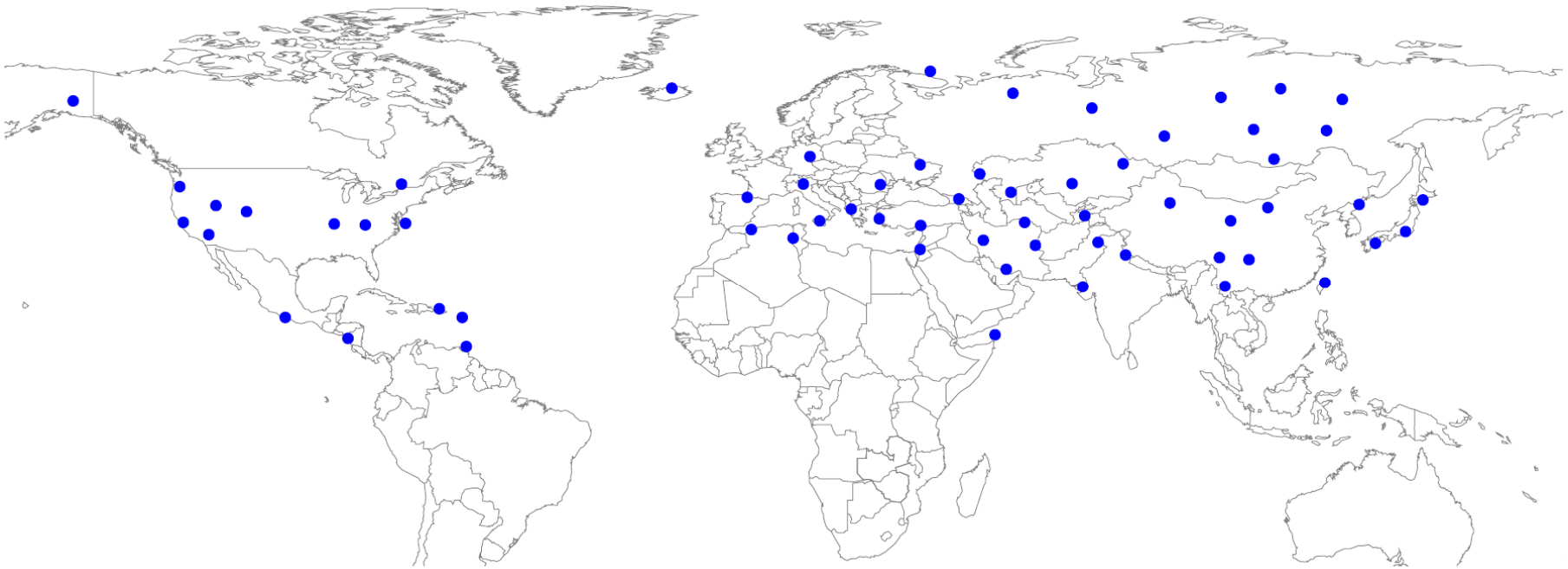

Nicaragua
Cuba
Pacific
Atlantic
Vp % Change From
Crust 2.0 / AK135


India
Tibet
Indian Ocean
Spreading Center
China
Vp % Change From
Crust 2.0 / AK135
-1.5 -1 -0.5 0 0.5 1 1.5

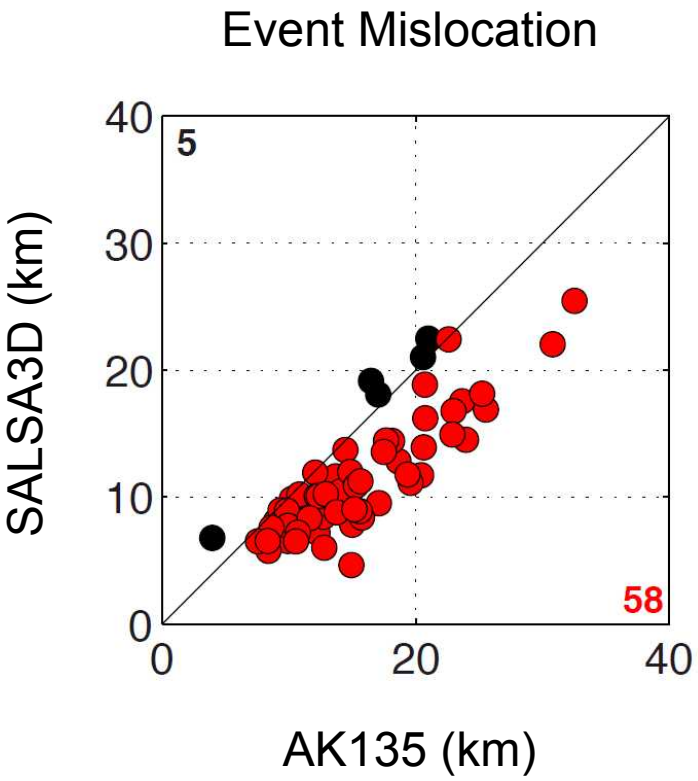

Sumatra
Indonesia
Phillipines
Indian Ocean
Phillipine Sea
Vp % Change From
Crust 2.0 / AK135
-2 -1 0 1 2

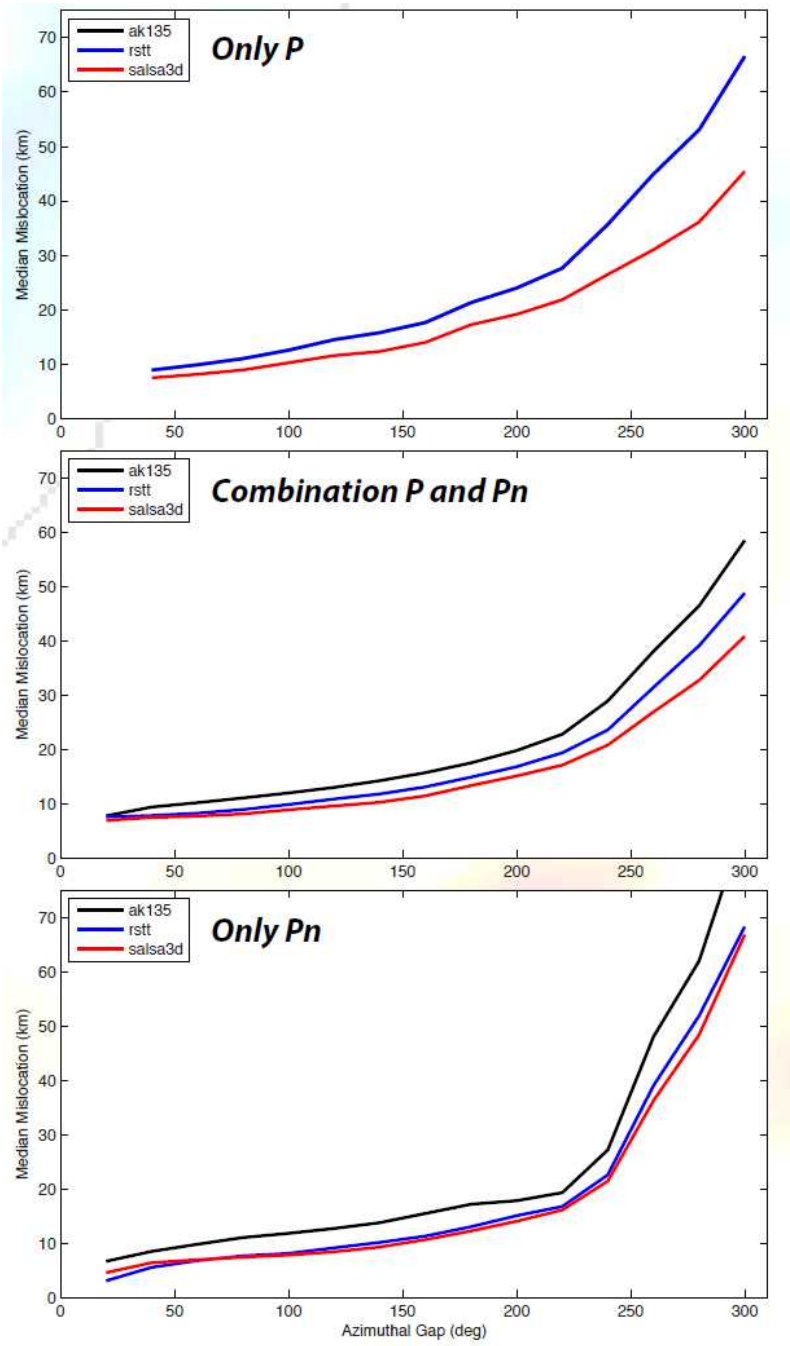

California
Colorado
Vp % Change From
Crust 2.0 / AK135
-1.5 -1 -0.5 0 0.5 1 1.5

Validation Events – Left out of tomography

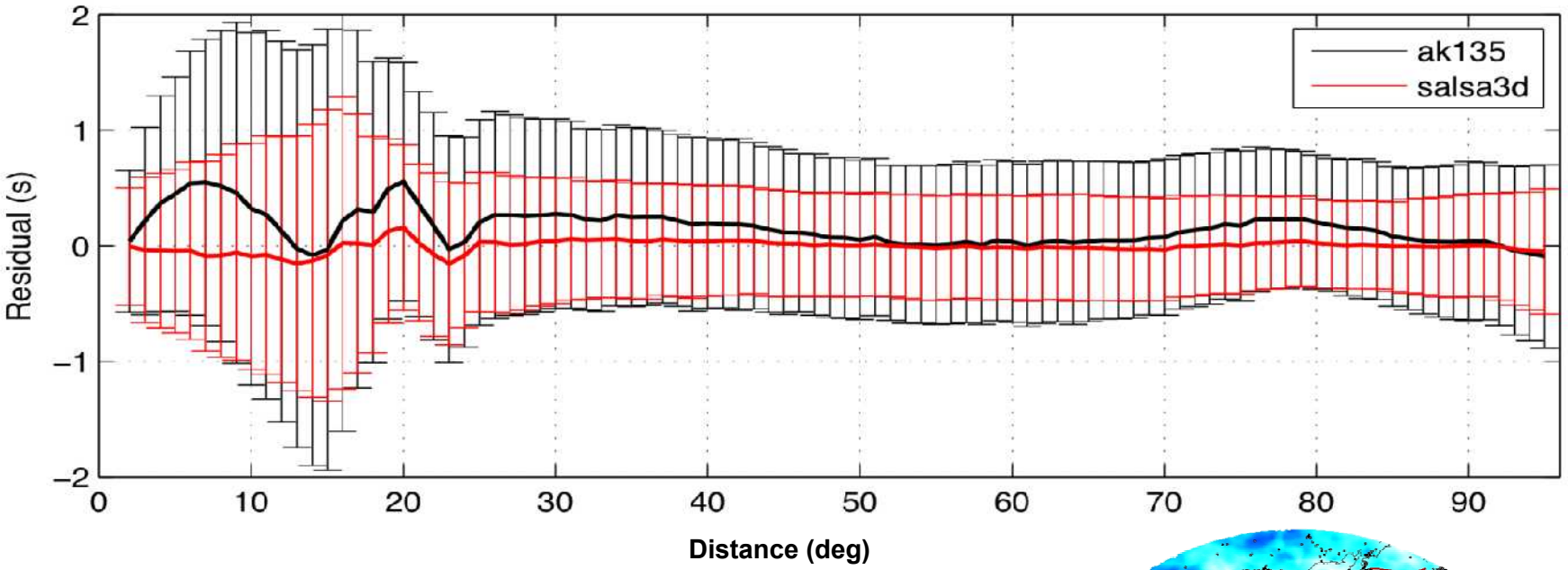


Seismic Event Location Improvement



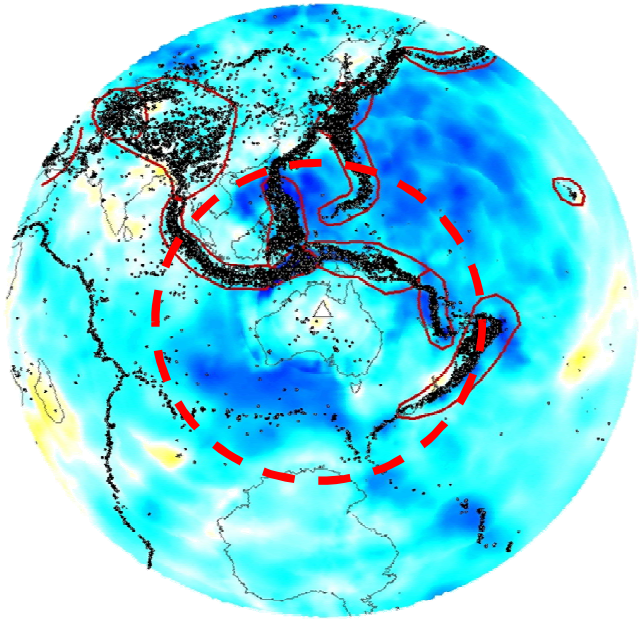


Travel Time Uncertainty – Traditional Approach

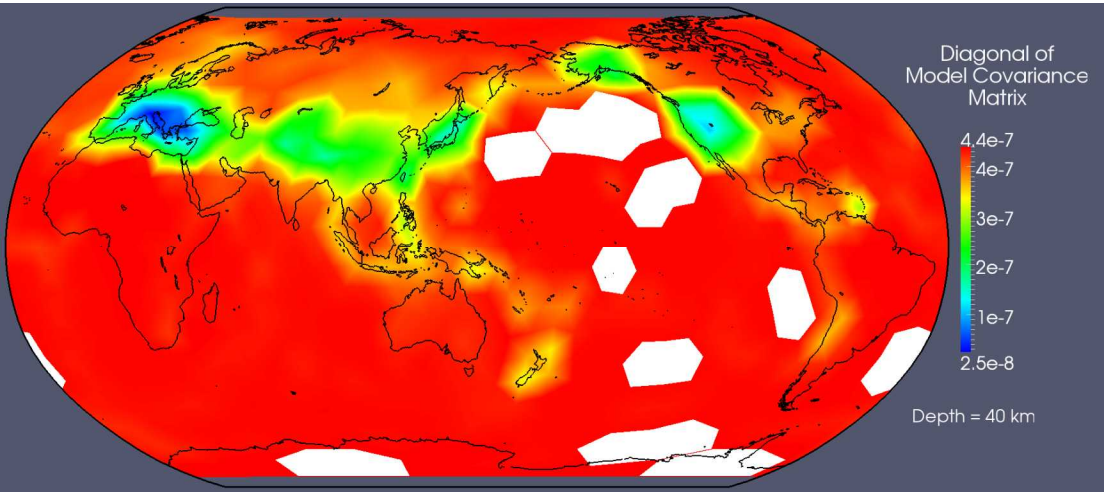


- Uncertainty a function only of distance
- Independent of station, azimuth

- Must account for pick uncertainty



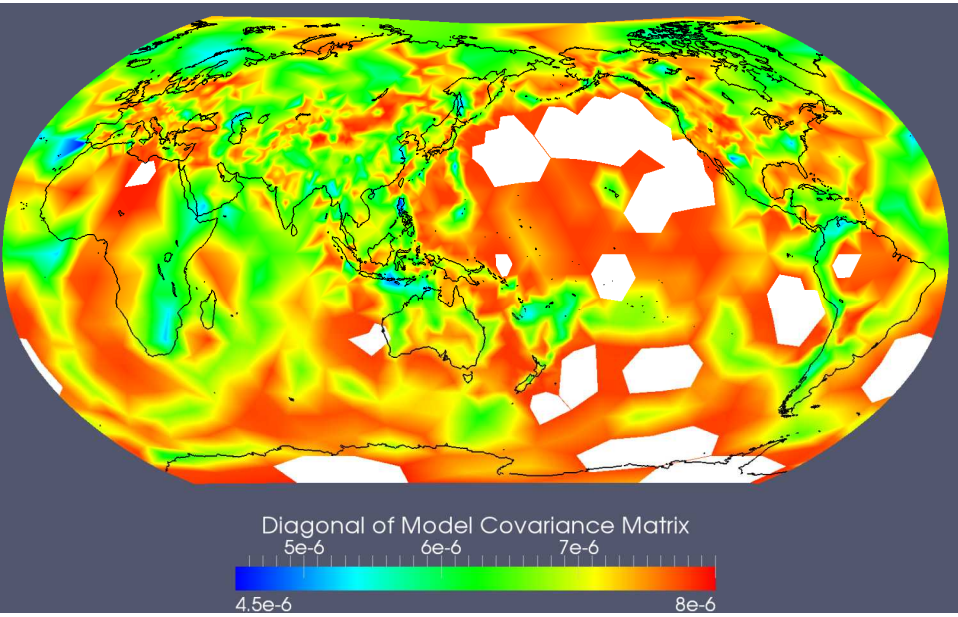
Model Covariance Matrix

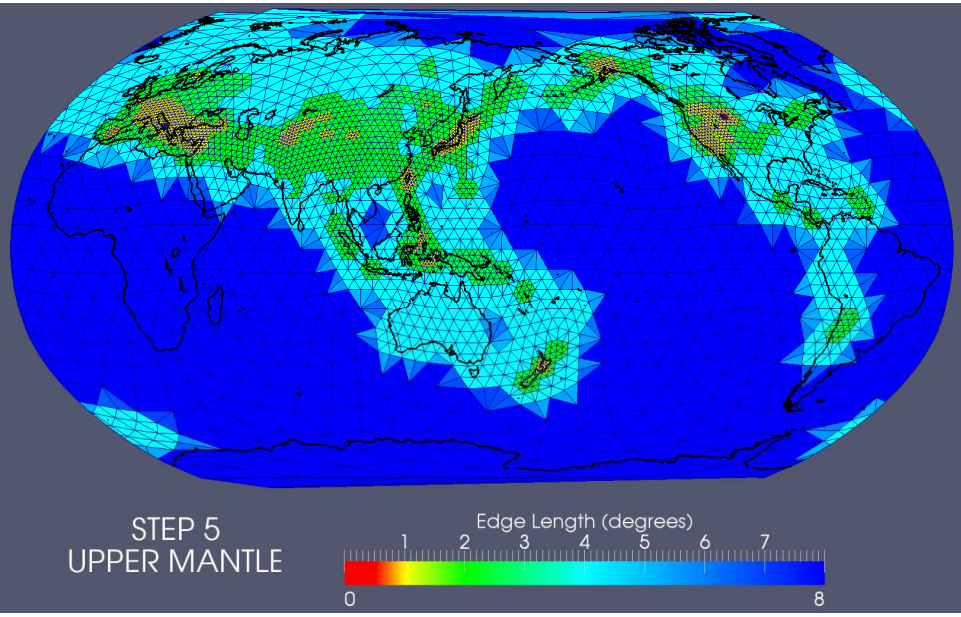


$$C_M = \left(G^T G\right)^{-1} G^T \begin{bmatrix} C_{\Delta d} & 0 \\ 0 & C_{\Delta s} \end{bmatrix} G \left(G^T G\right)^{-1}$$

15 petaflops to compute
180GB of RAM to store
computed in distributed mode

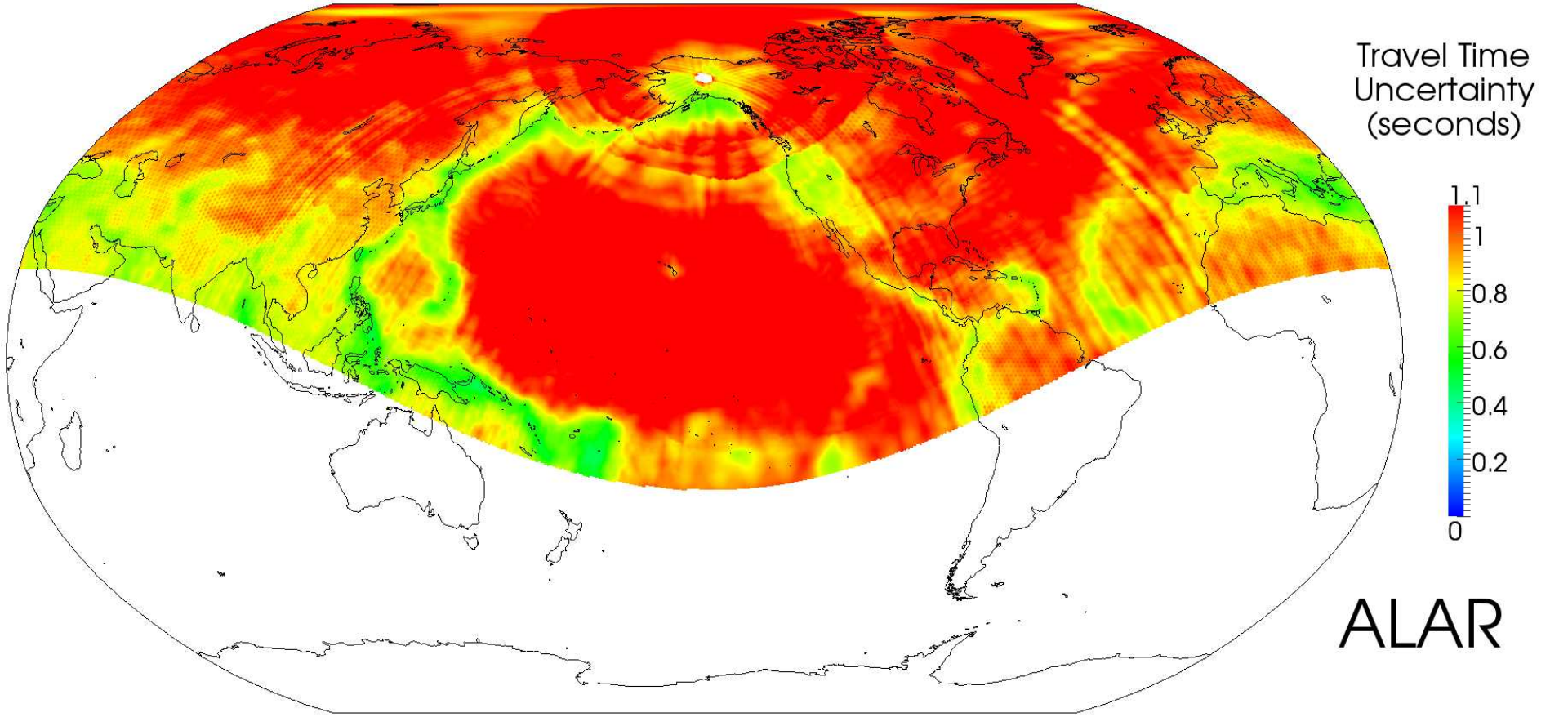
$$\sigma_T^2 = W \begin{bmatrix} C_M & 0 \\ 0 & C_{NR} \end{bmatrix} W^T$$



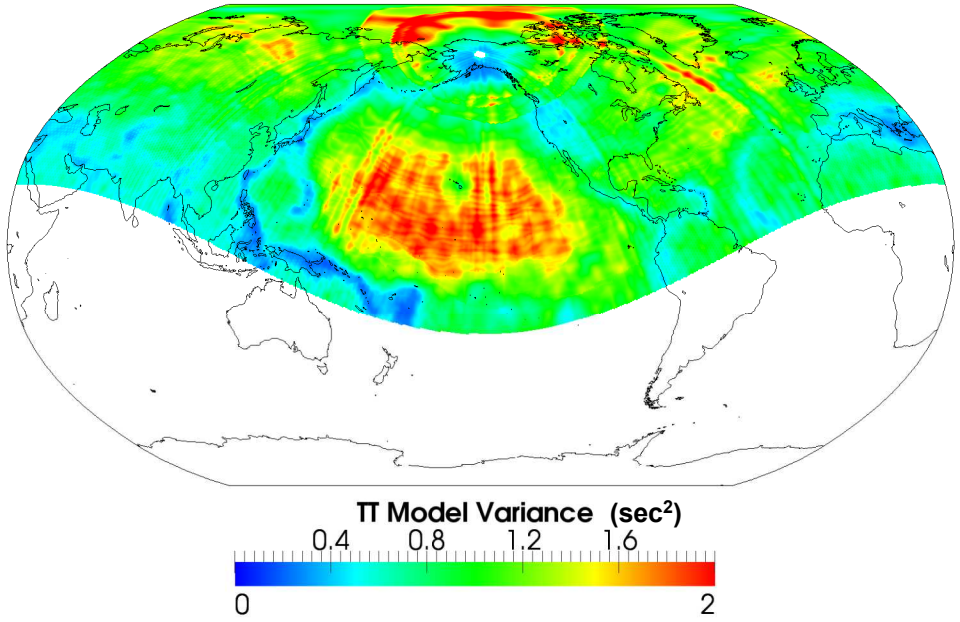


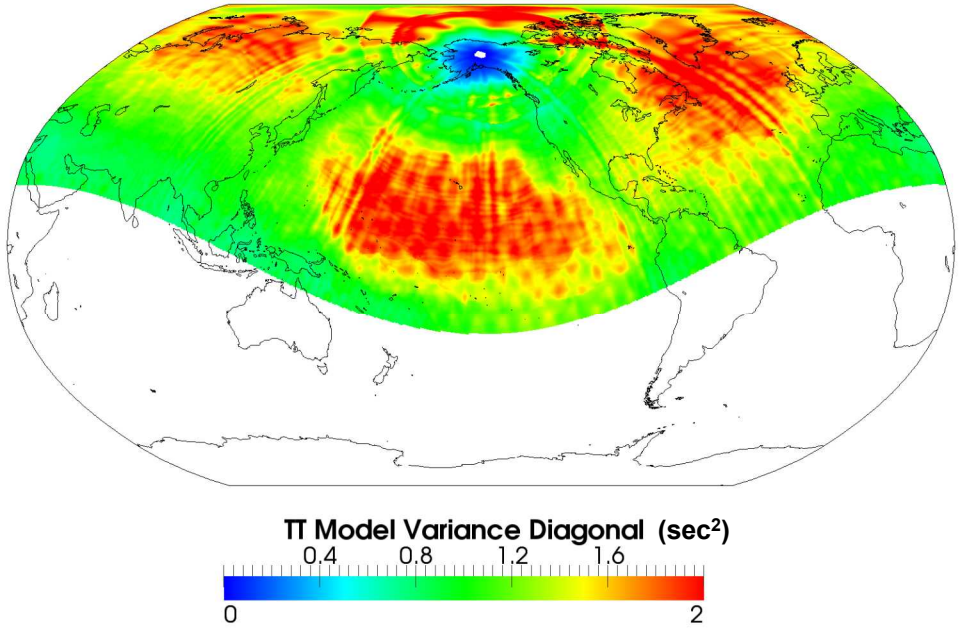
Travel Time Uncertainty

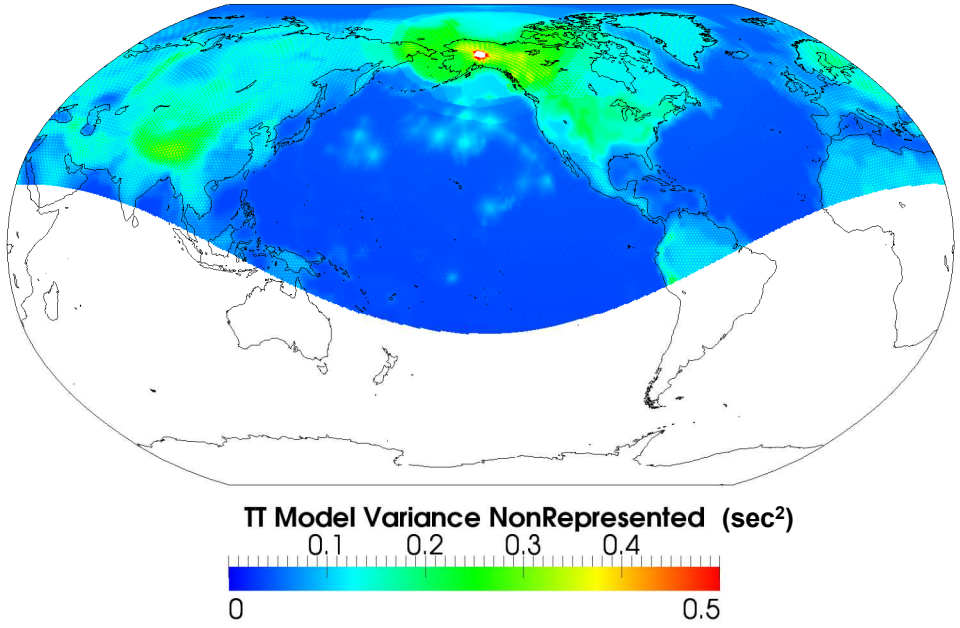
$$C_M = \left(G^T G\right)^{-1} G^T \begin{bmatrix} C_{\Delta d} & 0 \\ 0 & C_{\Delta s} \end{bmatrix} G\left(G^T G\right)^{-1} \qquad \sigma_T^2 = W \begin{bmatrix} C_M & 0 \\ 0 & C_{NR} \end{bmatrix} W^T$$

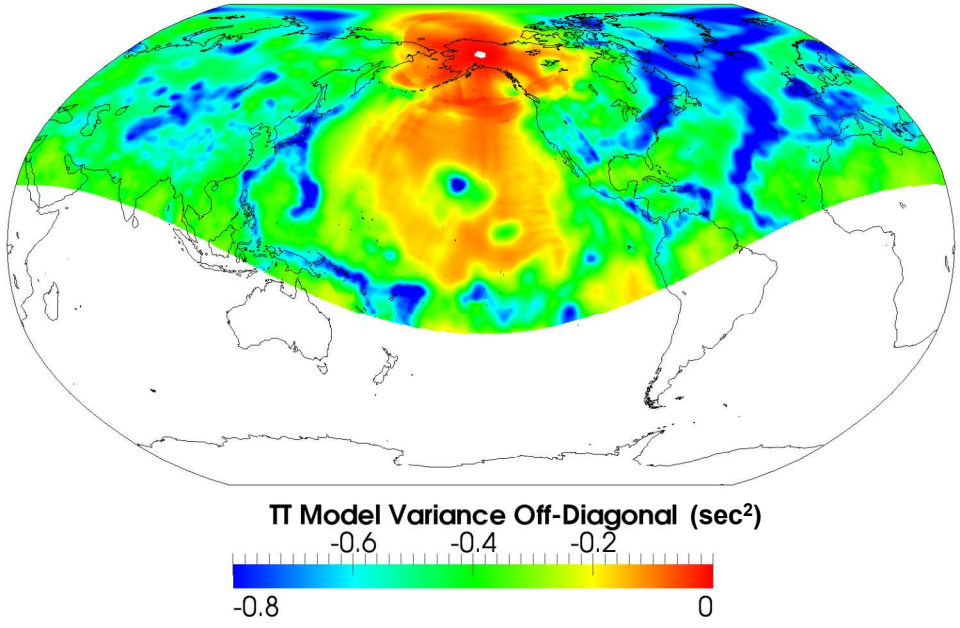


Model Covariance Matrix Decomposition

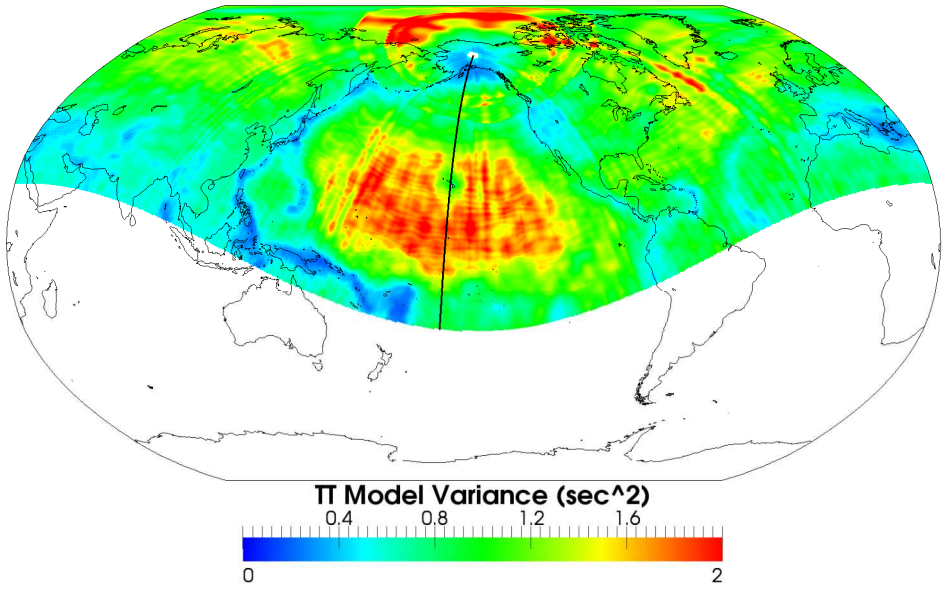


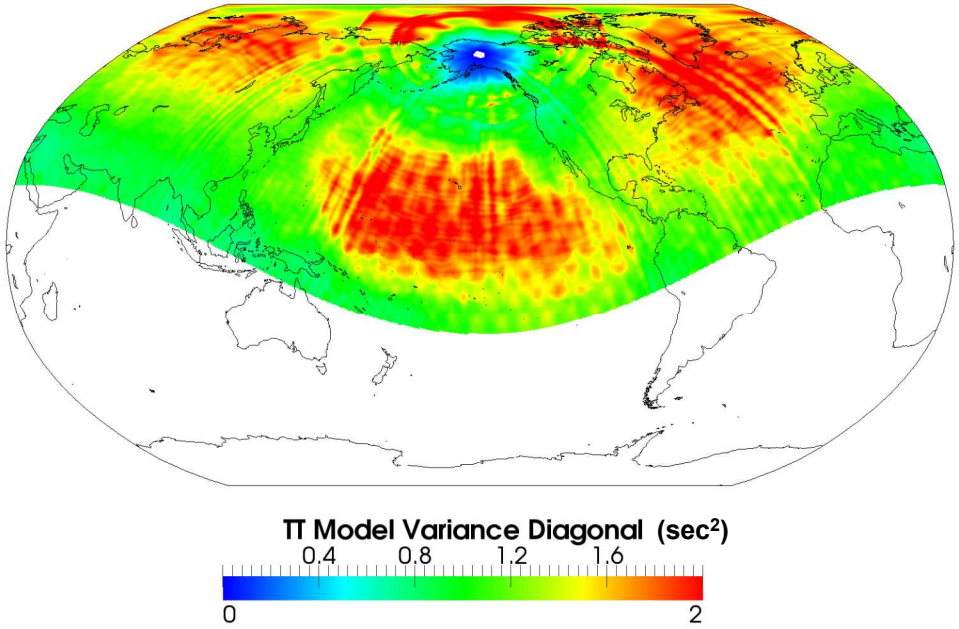


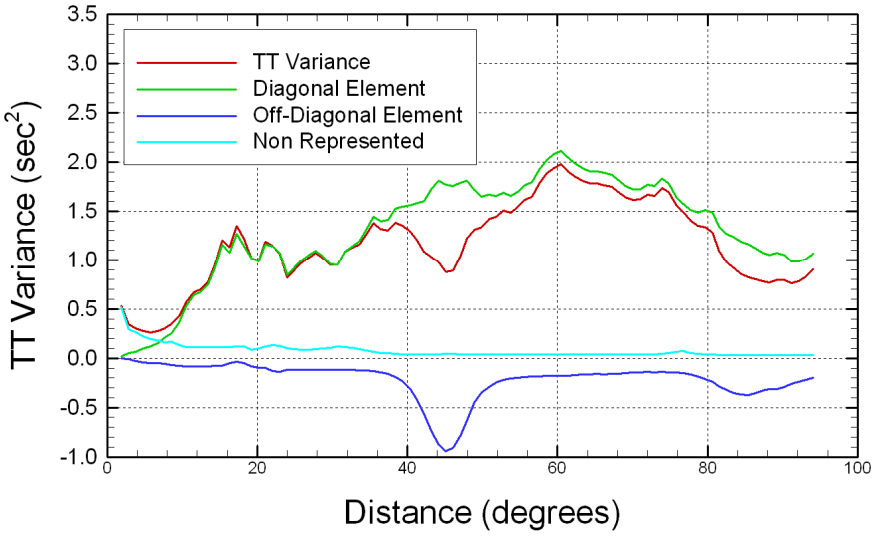


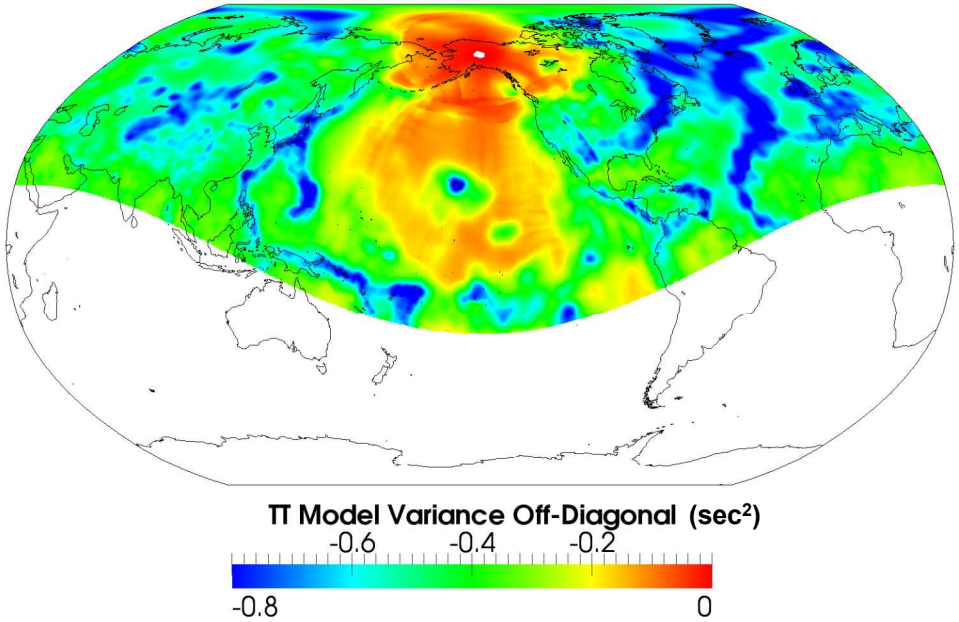


Model Covariance Matrix Decomposition



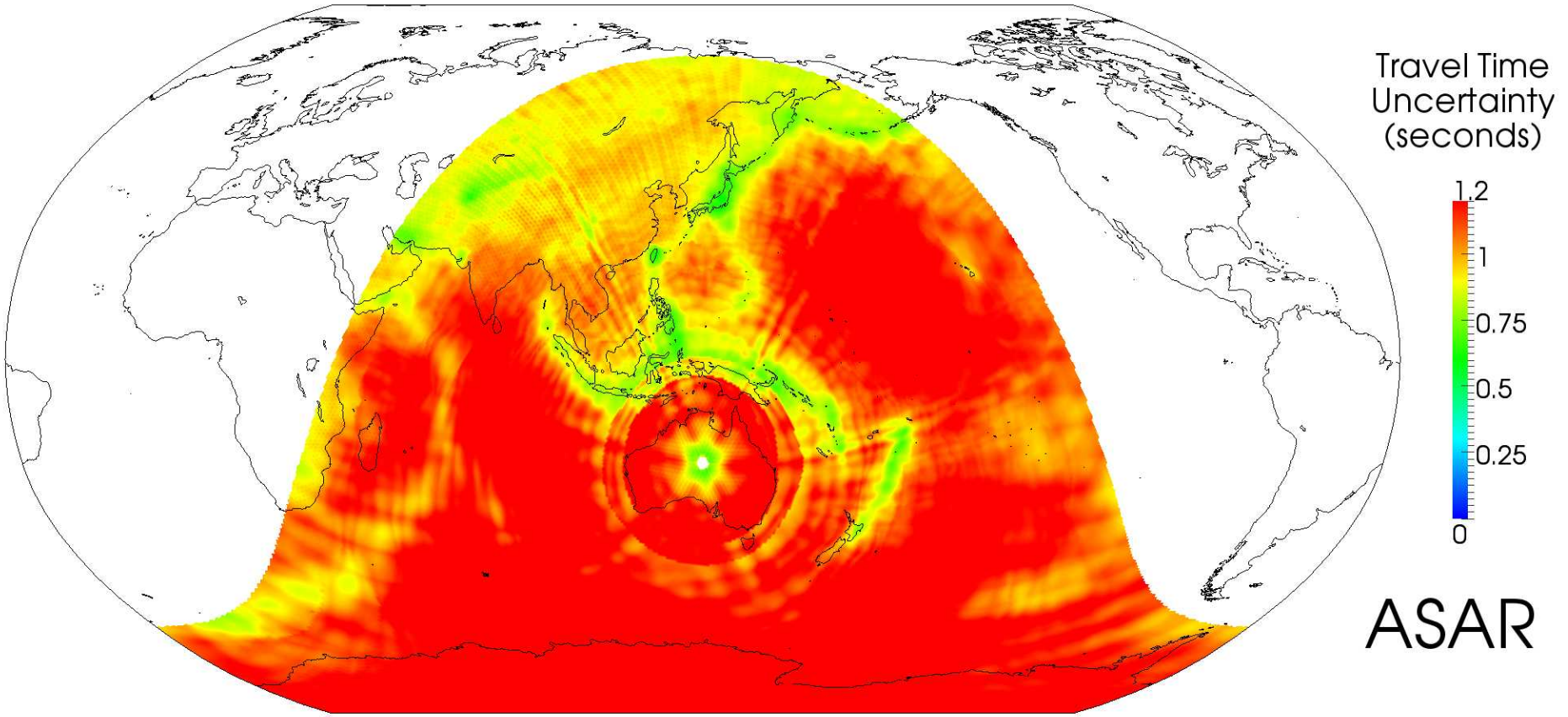






Travel Time Uncertainty

$$C_M = \left(G^T G\right)^{-1} G^T \begin{bmatrix} C_{\Delta d} & 0 \\ 0 & C_{\Delta s} \end{bmatrix} G\left(G^T G\right)^{-1} \qquad \sigma_T^2 = W \begin{bmatrix} C_M & 0 \\ 0 & C_{NR} \end{bmatrix} W^T$$



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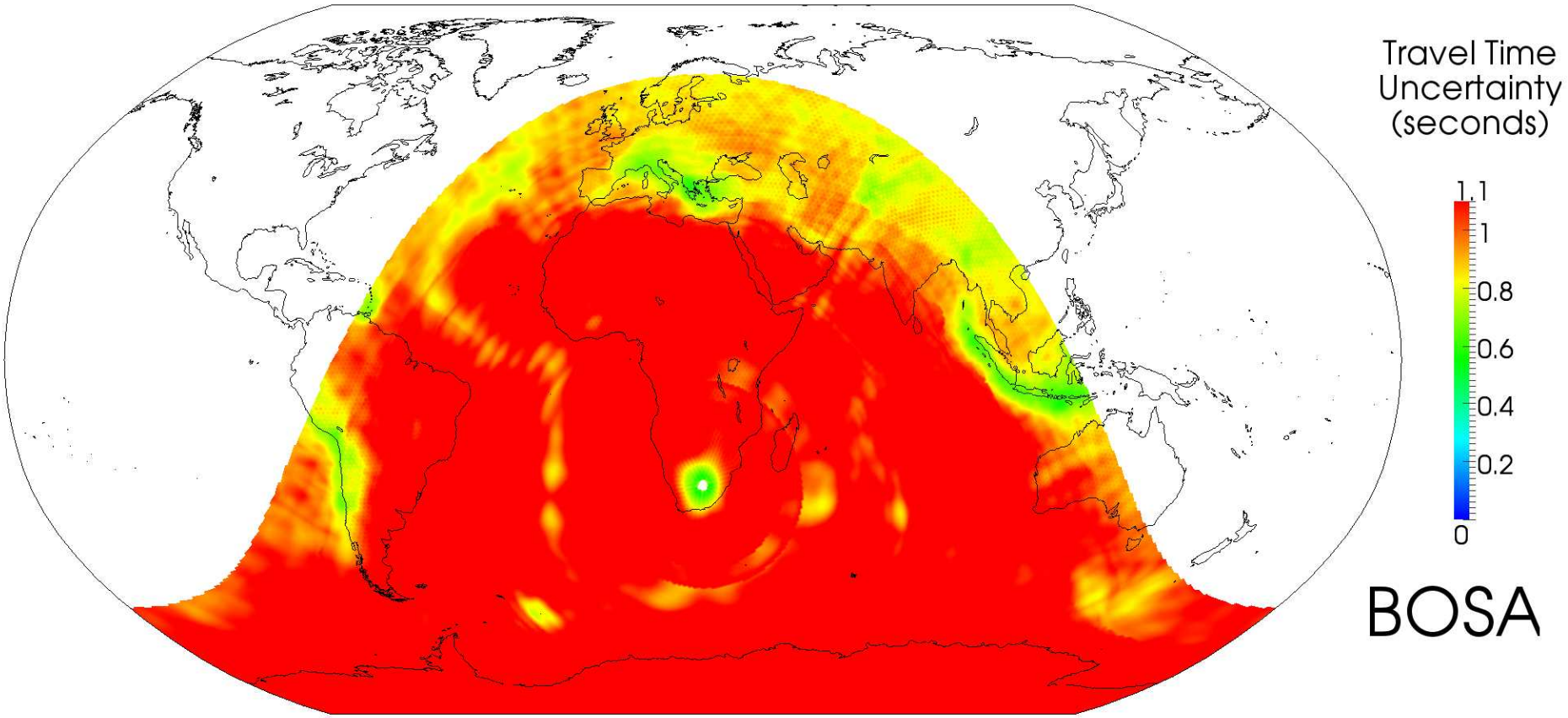

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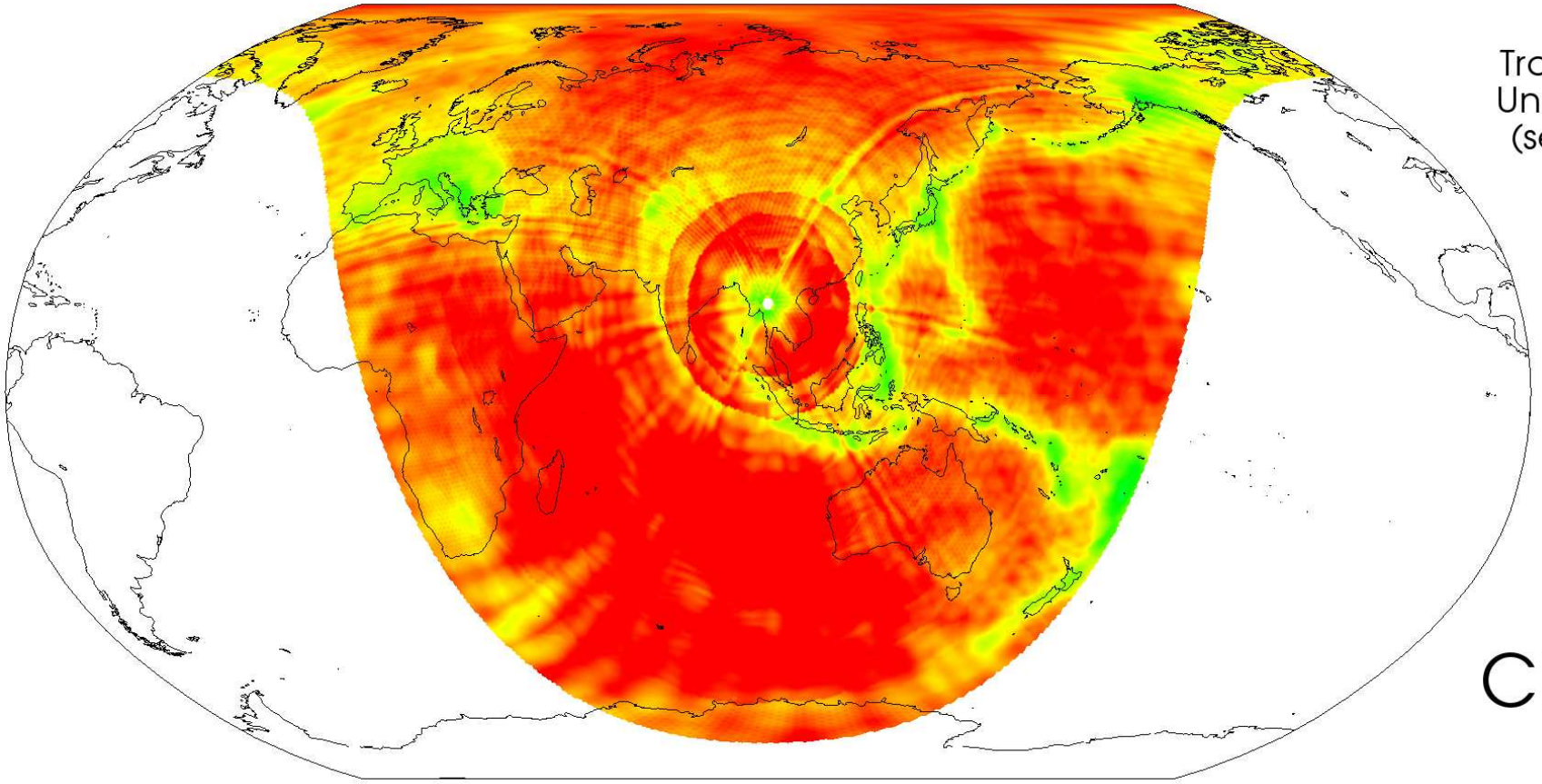
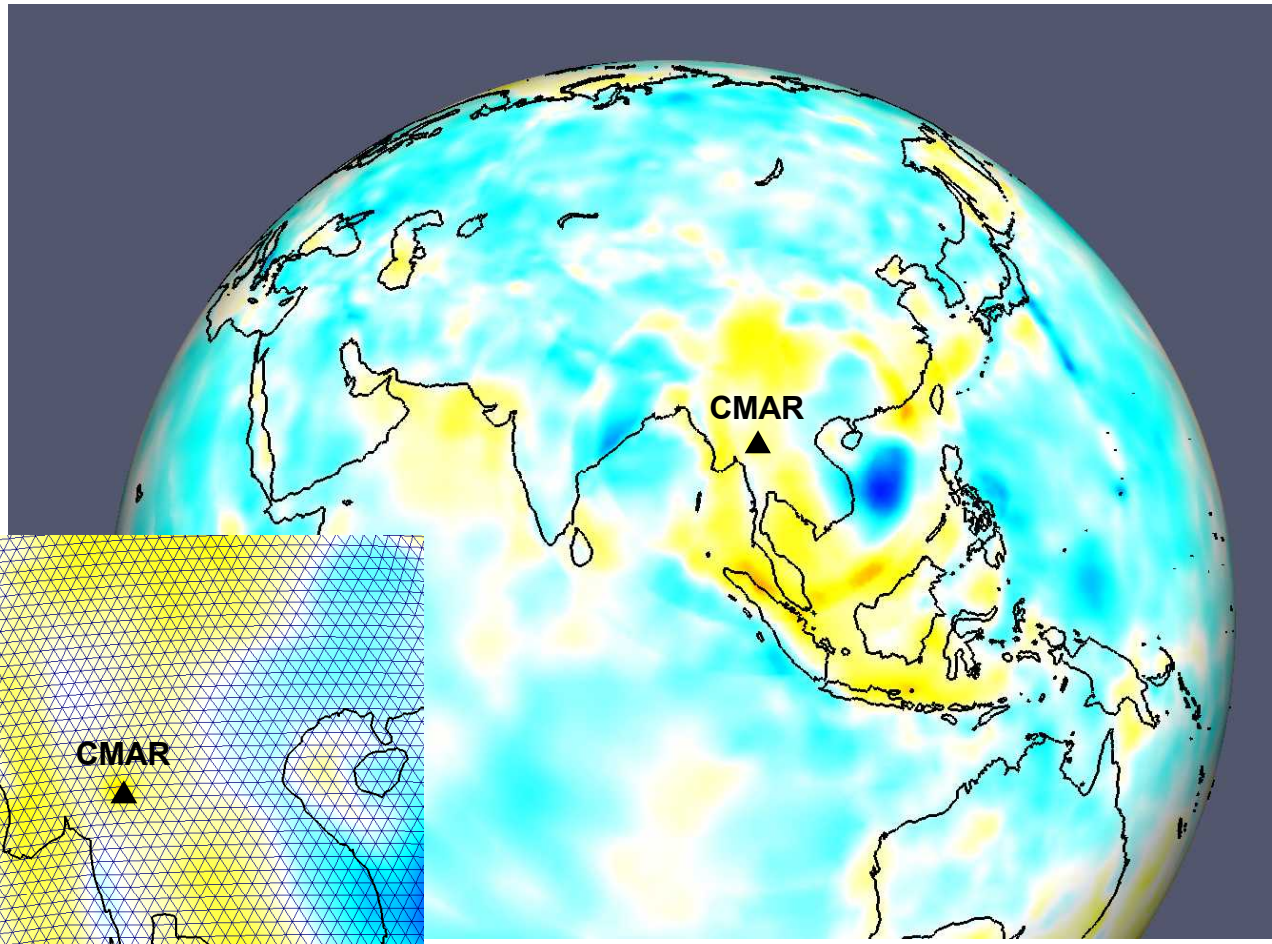
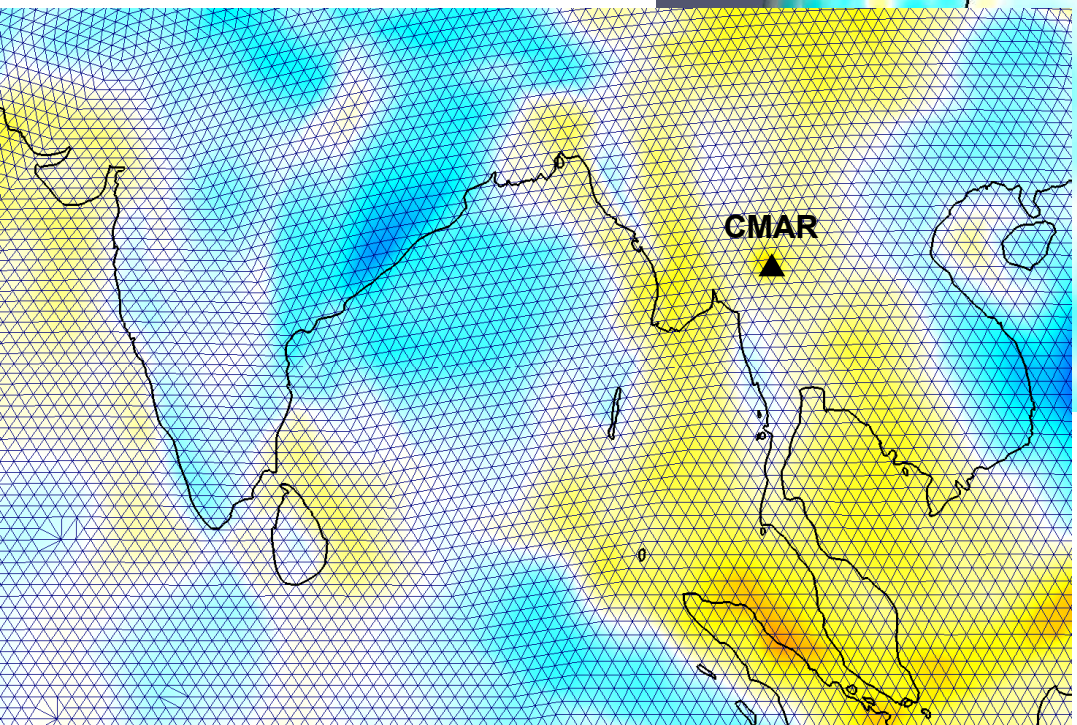
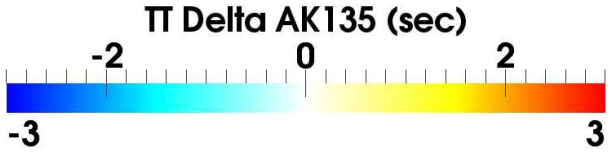


3D Travel Time Lookup Tables

- TT relative to AK135:
  - 3D model
  - Empirical correction
- TT Uncertainty
- Derivatives







Summary

- **The SALSA3D model is designed for improving travel time prediction.**
- **Data come from a dedicated location database produced from collecting existing GT events and mining the database for additional.**
  - Final observations are produced from clustering arrivals based on ray similarity.
- **Full Tomographic Procedure:**
  - Ray tracing before each iteration of LSQR,
  - Adaptive grid refinement using the model resolution matrix,
  - Relocation of original data using interim model,
  - Clustering and outlier removal,
  - Repeat of process from the beginning using the starting model
- **Travel time uncertainty calculated using the full model covariance matrix.**
  - Path dependent uncertainty

Future Work

- **Further data quality control**
- **New phases: pP, PKP, S**
- **Simultaneous inversion: gravity, surface waves, etc.**
- **Calibration of travel time uncertainty**
- **Operationalization: Lookup tables**
  - Travel time, uncertainty, empirical corrections, derivatives