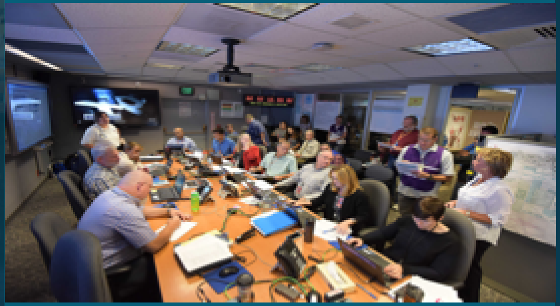
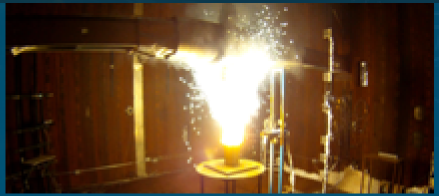
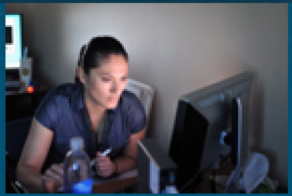
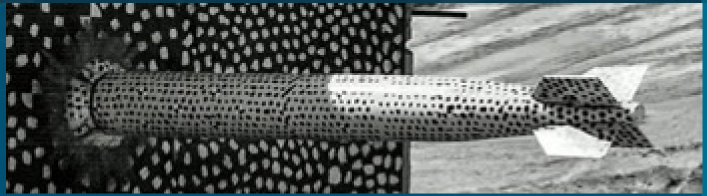
SAND2021-8194PE

SALSA3D









Presented By

Andrea Conley

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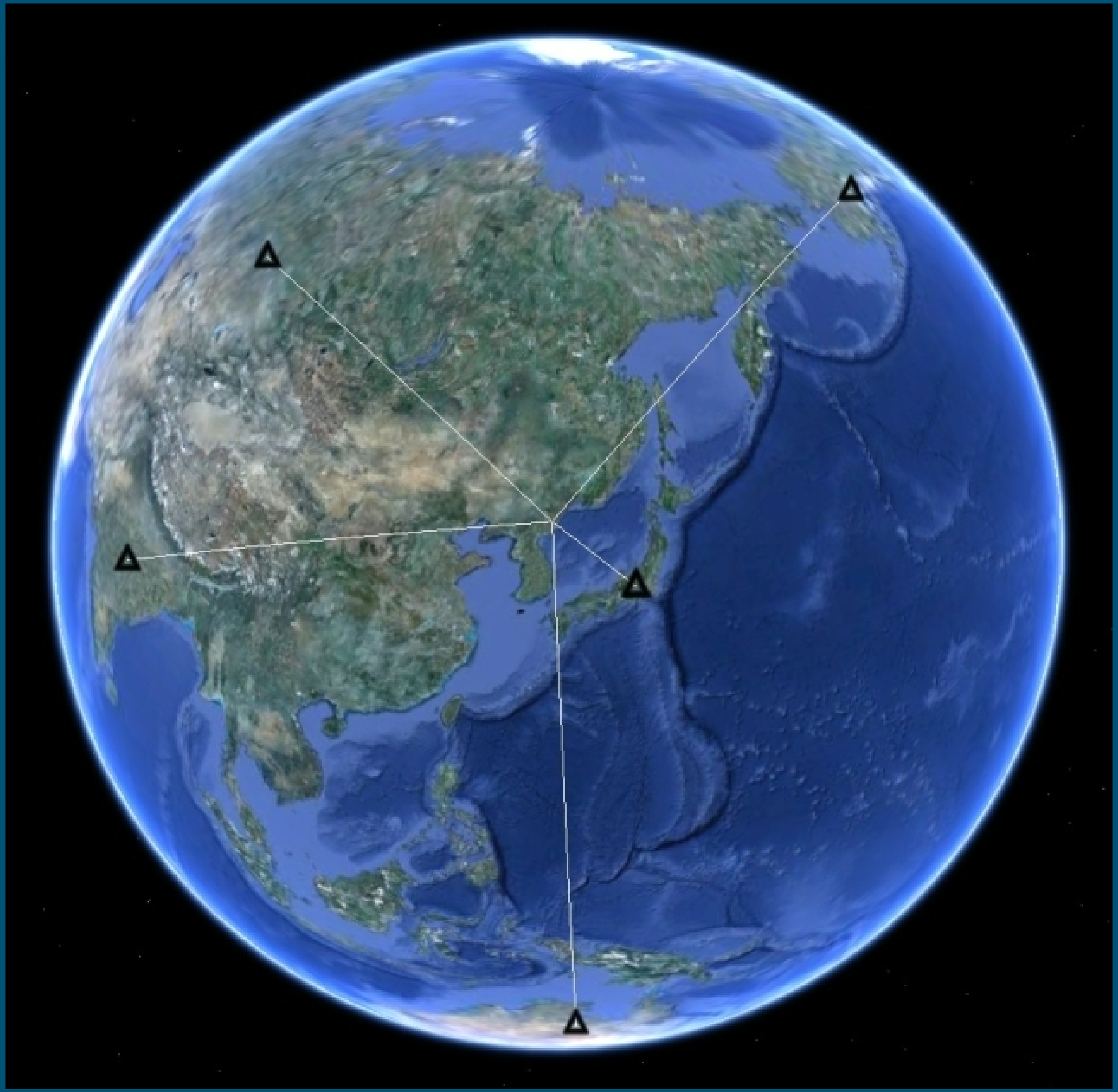
Motivation



- The location of a suspect nuclear event is important because the Comprehensive Nuclear Test Ban Treaty specifies the international community may conduct an onsite inspection in an area of 1000 km^2
- The location of the suspected event should be known to at least this accuracy and precision
- To get accurate event locations, accurate travel-time predictions are required
- **Our primary goal is to make global slowness models that provide the most accurate travel-times and travel-time uncertainties possible**
  - Known geology is used as a sanity check to confirm model is reasonable, but feature identification is not a primary goal

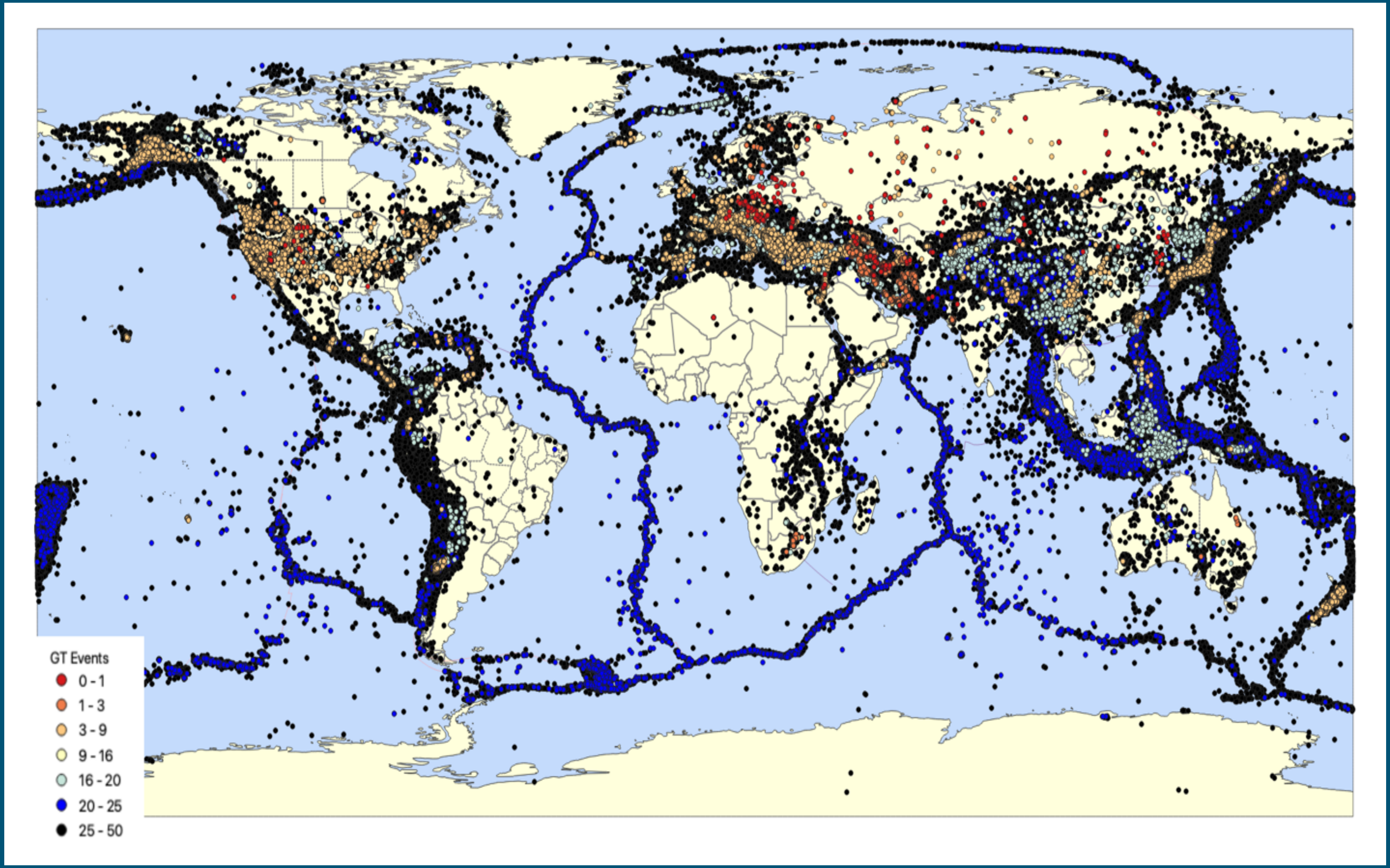
Tomography Data

640K events (523K more than in 2017)

>20K stations (8K more than in 2017)

>2M rays (more will be included in future)

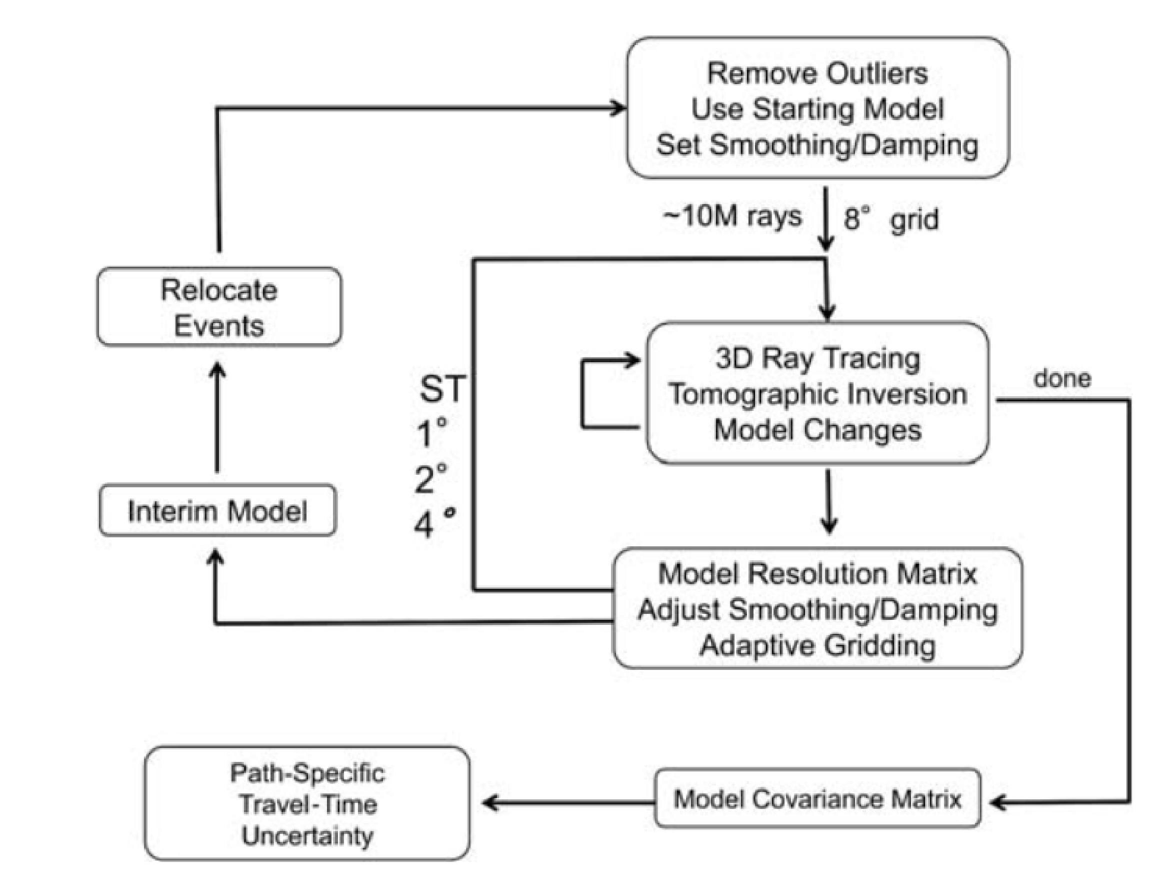
- GT ranges from 0 to 50
- Currently using P and Pn phases
  - Will expand to secondary phases
- Future models will include an S model, a joint P- and S-model, a P model with both mantle and crust inverted for, and a P model with OBS



Ground Truth (GT) as defined in Bondar et al. (2004), GJI

Tomographic Procedure

Figures from Ballard et al. (2016), BSSA



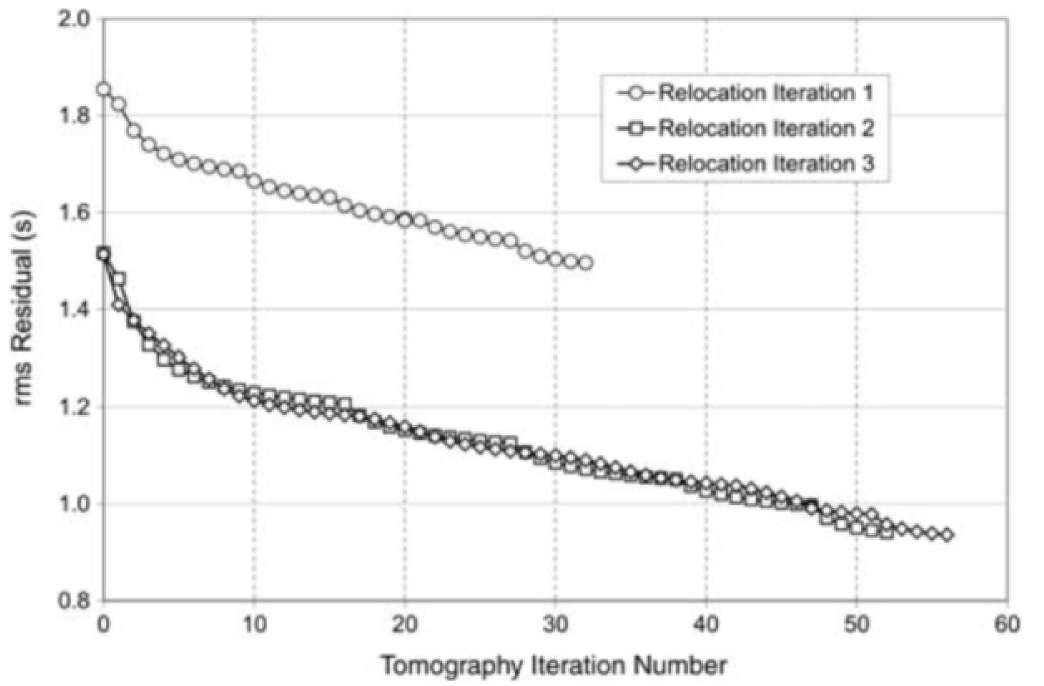


Figure 6. Root mean square (rms) residual versus tomography iteration number. The final rms residual of 0.94 represents a reduction of 50% from the starting model.

- Typically perform ~3-10 iterations of the innermost loop, ~4-5 iterations of the middle loop, and ~2-3 iterations of the outer loop

LSQR algorithm of Paige and Saunders (1982)

Travel Time Prediction Uncertainty

The standard least squares tomography solution seismic slowness, s, is formulated given an $m \times n$ set of non-linear travel time path length weights, $A(s)$; a vector of n associated path residuals, d; an $n \times n$ Bayesian inferred prior model covariance matrix, C_m. The Bayesian prior model parameters are used to constrain the solution in model regions possessing little or no data. This formulation can be written as

$$\begin{bmatrix} C_d^{-1/2} A(s_k) \\ \alpha C_m^{-1/2} \end{bmatrix} \Delta s^{k+1} = \begin{bmatrix} C_d^{-1/2} \left(d - A(s_k) s_k\right) \\ 0 \end{bmatrix} \qquad s^{k+1} = \Delta s^{k+1} + s^k$$

Where C_d are the data variances associated with the travel time path weights, α is a damping parameter applied to ensure solution stability, and the non-linear solution is updated in an iterative manner (k) until convergence is obtained $(\Delta s \approx 0)$. Applying standard solution techniques, the posterior model covariance, $\tilde{C}_m$, and the model resolution, R_m, can be discovered and written as

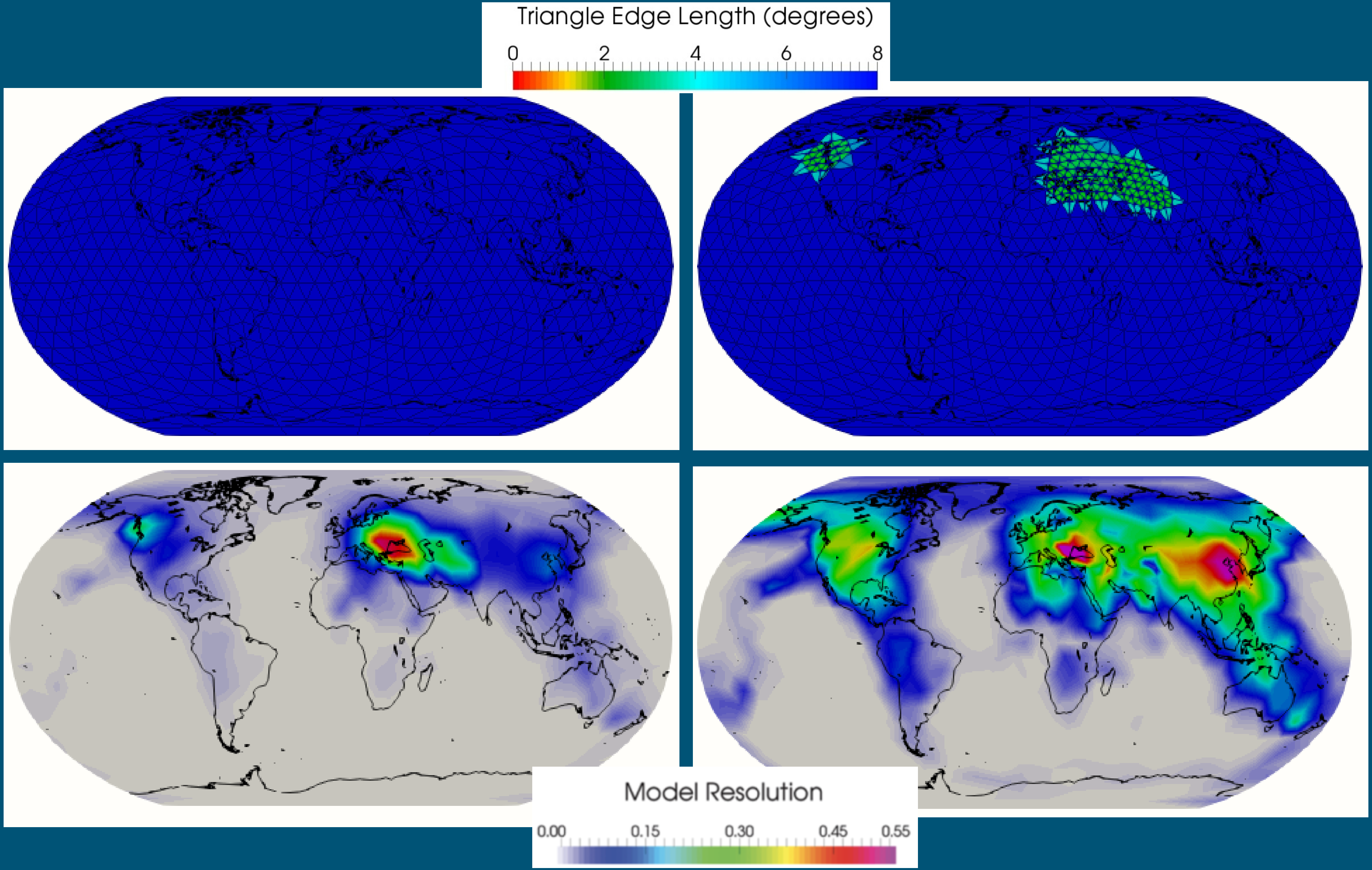
$$\tilde{C}_m = \left[A^T C_d^{-1} A + C_m^{-1}\right]^{-1} \qquad R_m = \tilde{C}_m A^T C_d^{-1} A = I - \tilde{C}_m C_m^{-1}$$

Given these definitions we can formulate the travel time and associated uncertainty of an arbitrary ray path, p, given its grid node vector of path length weights ($W_p = \langle w_{pj} \rangle$) as

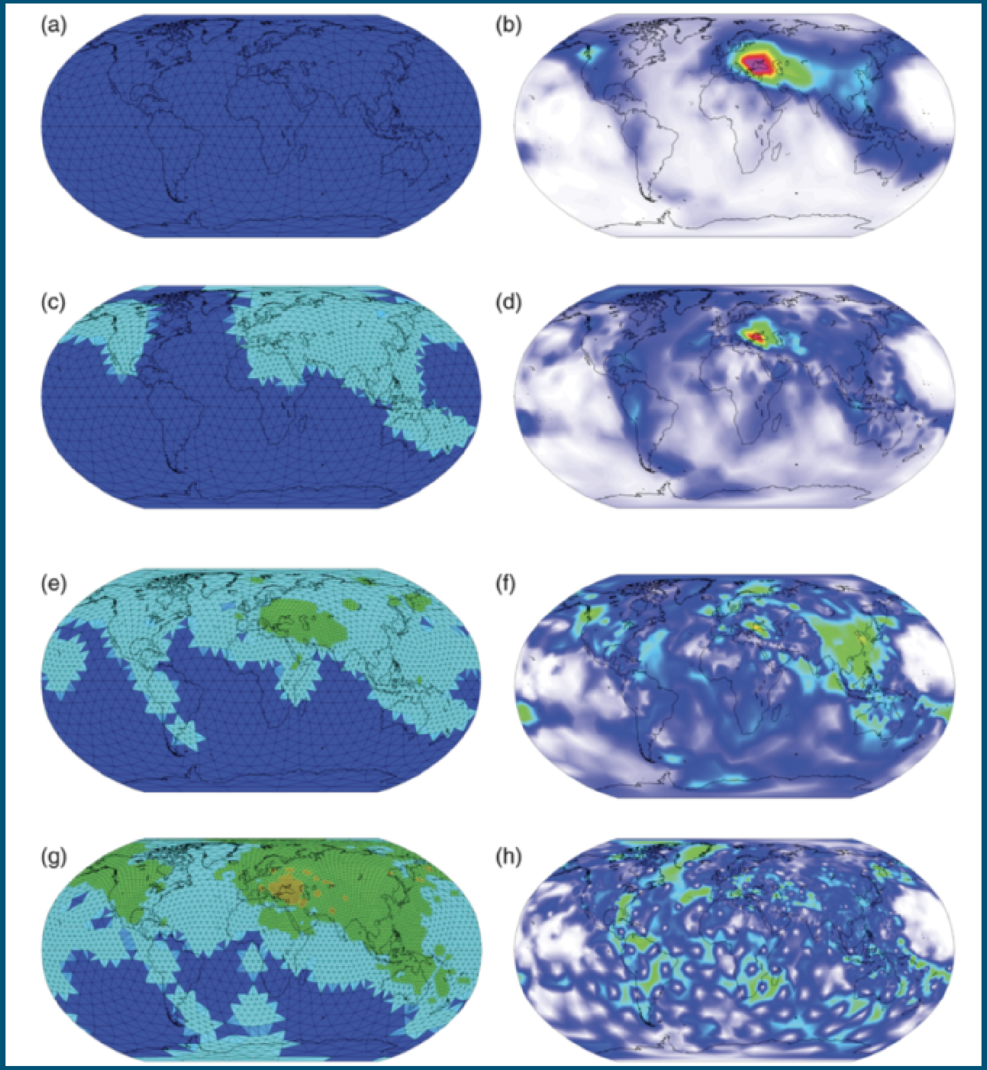
$$\tilde{t}_p = \sum_{j=0} w_{pj} \tilde{s}_j \pm \tilde{\sigma}_p \qquad \tilde{\sigma}_p = \sqrt{W(\tilde{s}_m)\tilde{C}_m W^T(\tilde{s}_m) + W(s_m) C_m W^T(s_m)}$$

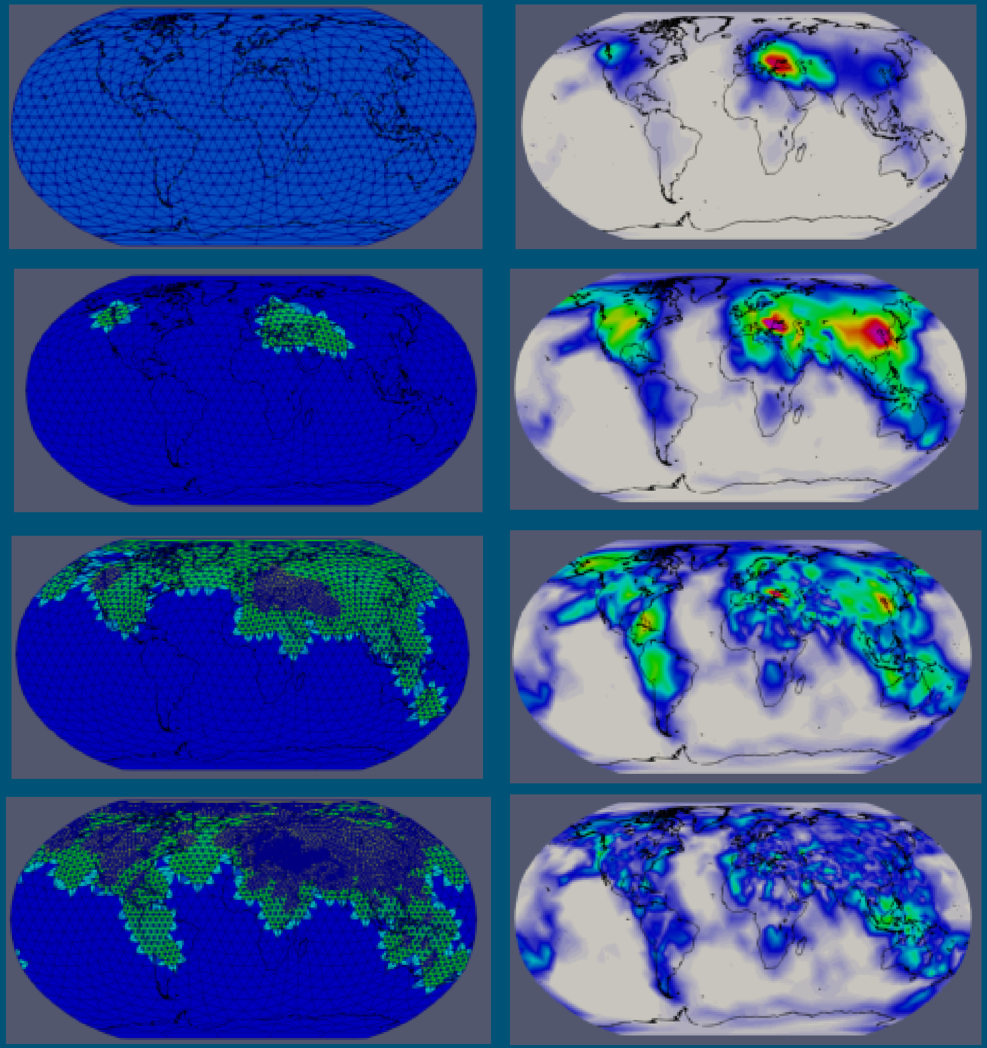
Here $W(\tilde{s}_m)$ imply weights for nodes along the path p that lie in regions of the posterior model (the mantle), while $W(s_m)$ define weights for nodes along the path that lie in prior model regions for which slowness updates were not computed (the crust).

Grid and Model Resolution

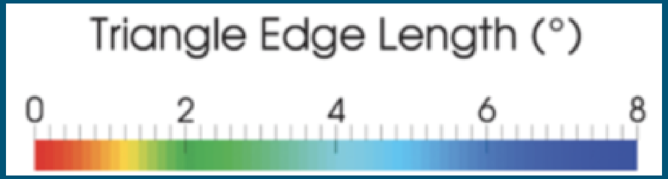


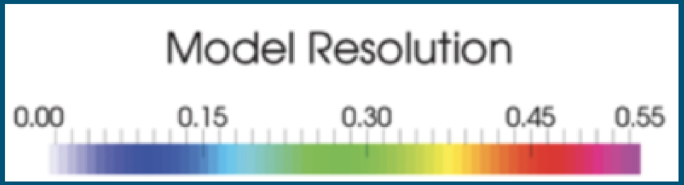
Grid and Model Resolution





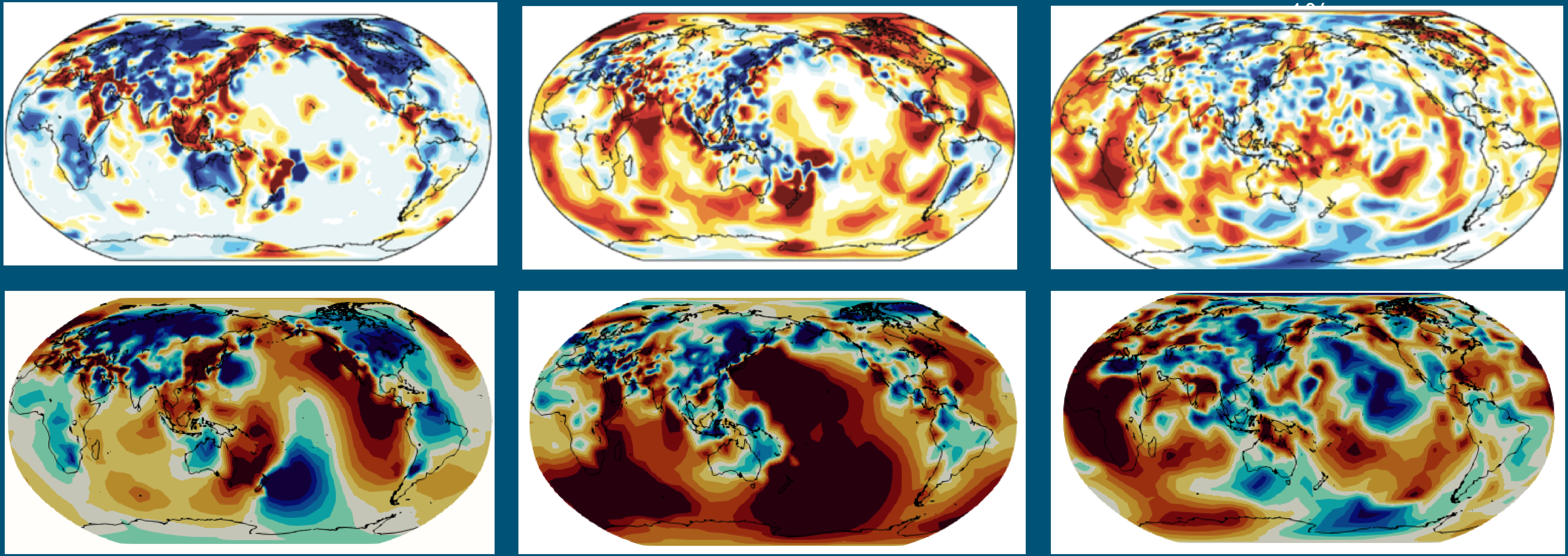
Ballard et al. (2016), BSSA





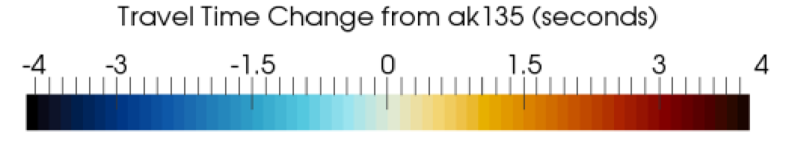
Mantle Slowness at 800 km depth

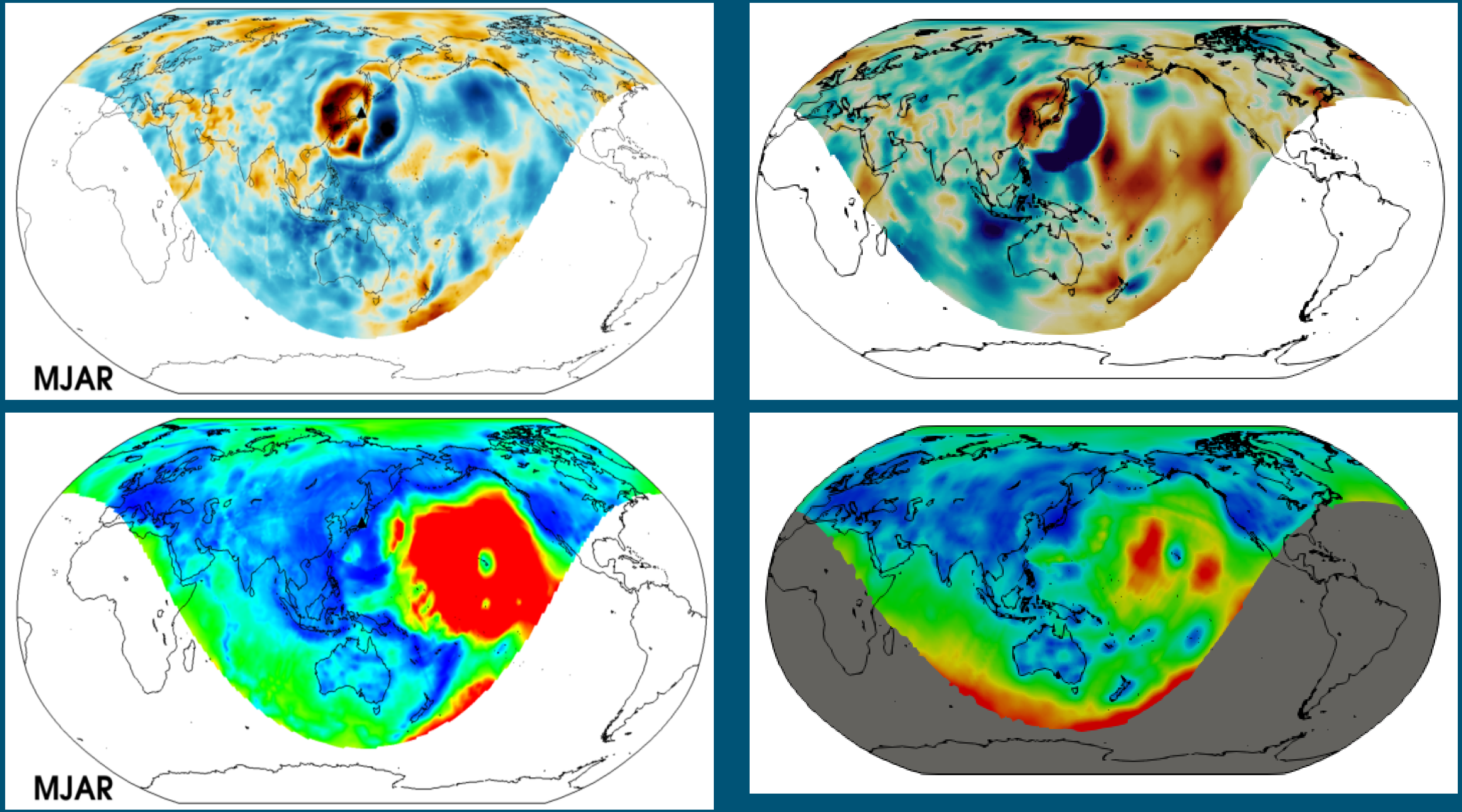
100 km ± 3% | 500 km ± 2% | 2500 km



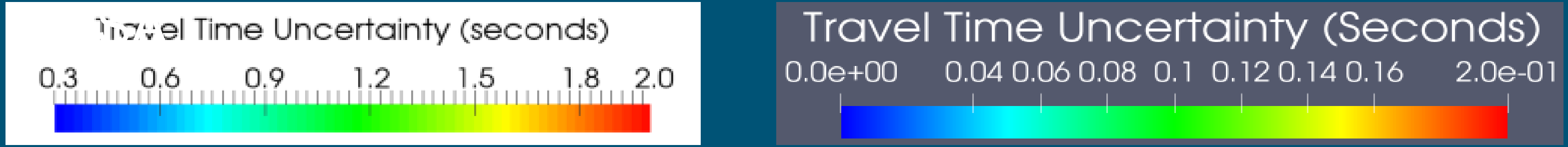
- Top Row: Ballard et al. (2016), BSSA (2 relocation iterations)
- Bottom Row: Current model after 5 adaption iterations

Travel Time Prediction and Uncertainty

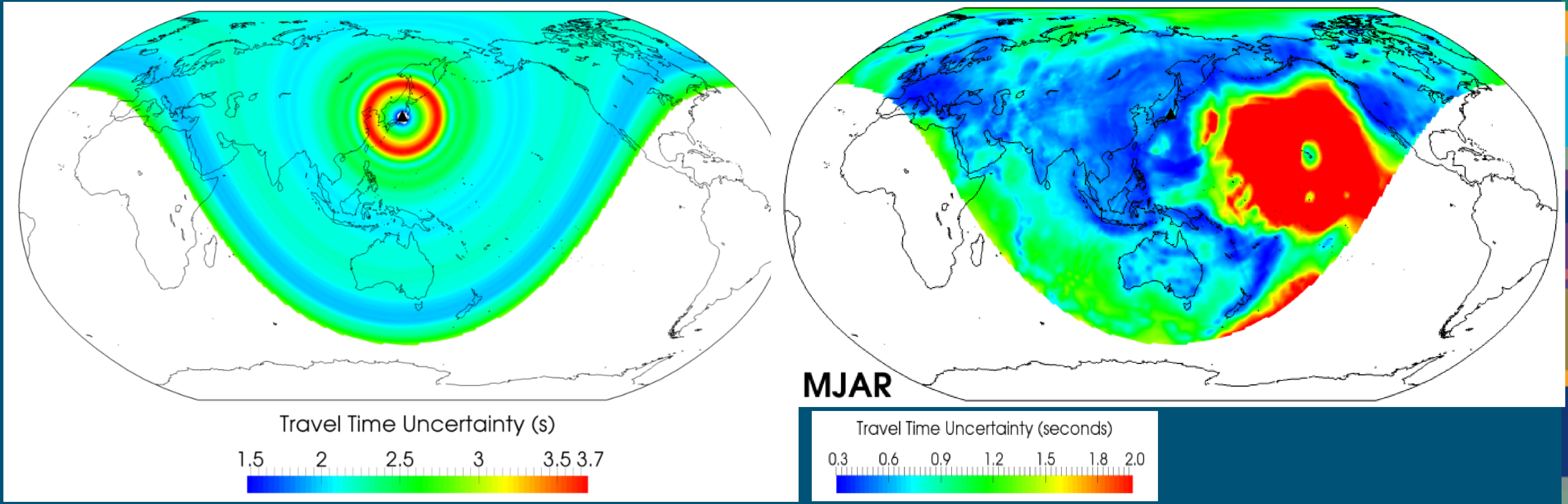




Ballard et al. (2016),



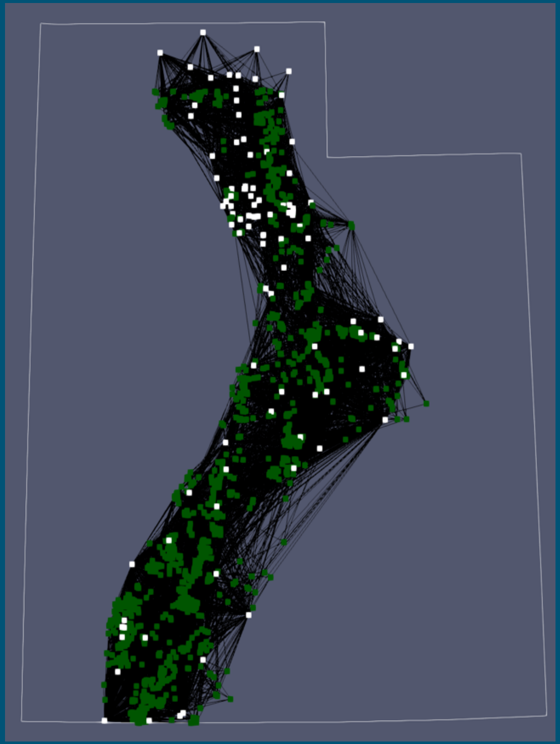
Comparison with Standard Uncertainty

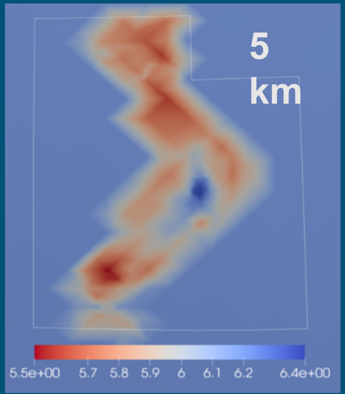


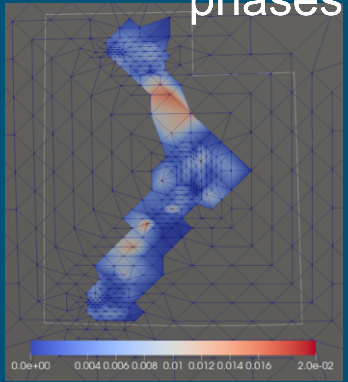
Figures from Ballard et al. (2016), BSSA

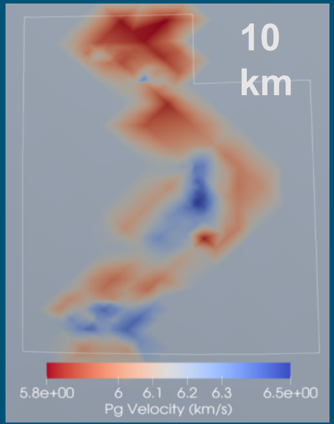
Utah Model

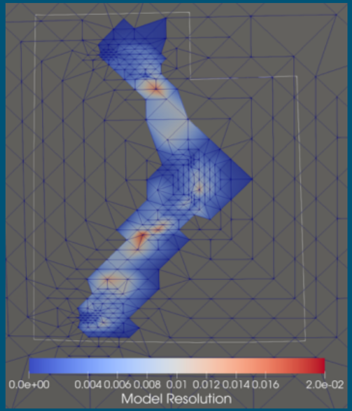
- We want to extend the SALSA3D model to include the crust as well as the mantle in our inversions
- As an initial step towards this goal, we created a local crustal Pg velocity model along the Wasatch Front, Utah using arrivals provided by the UUSS to assess the applicability of our tomography approach to crustal tomography.
- We successfully generated a model that resulted in feasible event relocations using analyst-picked and ground-truth mining events.
- Having established feasibility, we are now conducting crustal waveform modeling to understand and accurately implement crustal phases in our algorithm.

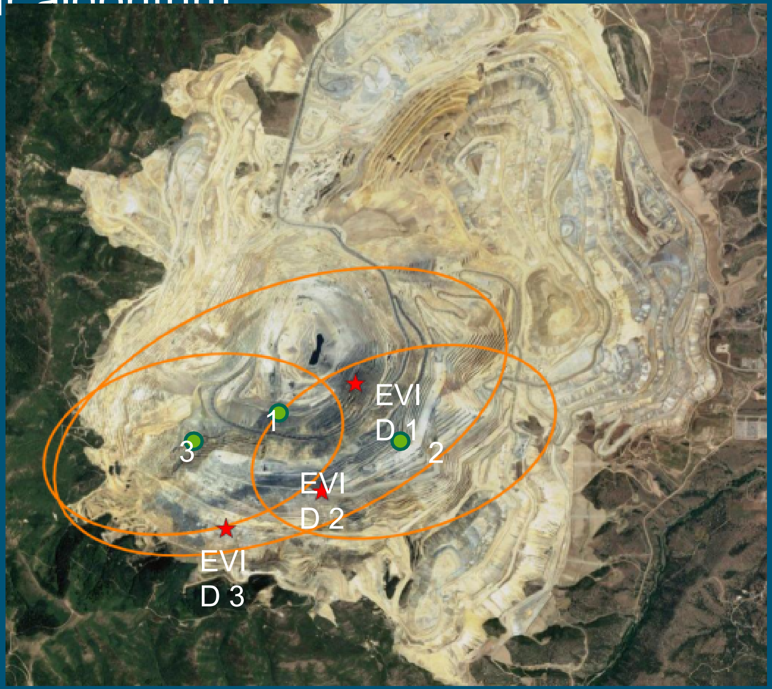












Event relocations of 3 GT events at Bingham Mine with 95% coverage ellipses.

Summary and Future Work

- We are in the process of generating our first new SALSA3D model since 2017.
  - The new model will use data from up to 523K more events and 20K more sites than in 2017.
  - Generating an updated P model allows new staff to learn how to create SALSA3D models while simultaneously improving upon past models.
  - The new model will include secondary phases, which will be added in one-by-one to assess the effects of each phase.
- We successfully computed a model covariance matrix for our model which allows us to calculate path-dependent travel time uncertainty estimates.
- The new model appears similar to older models on the continents after just one relocation iteration.
  - More work needs to be done to correct artifacts in the oceans, which likely result in part from the inclusion of a water layer.
- As a first step toward inverting the crustal model for SALSA3D, we verified that our tomography approach is feasible by creating a reasonable local crustal velocity model in Utah.
  - We are now performing crustal waveform modeling to improve our understanding of how regional phases can be used in our inversions.
- We will eventually include OBS data provided by LANL to investigate mantle velocities beneath the oceans.
- We have begun work to implement a joint inversion capability for SALSA3D. We will begin with joint P- and S-wave inversions and extend to surface waves and gravity in the future.
- Similar to SALSA3D, we intend to develop a 3D velocity model for *S*-wave travel time prediction.

SALSA3D - References

Ballard, S., J. R. Hipp, M. L. Begnaud, C. J. Young, A. V. Encarnacao, E. P. Chael, W. S. Phillips (2016) SALSA3D – A Tomographic Model of Compressional Wave Slowness in the Earth's Mantle For Improved Travel Time Prediction and Travel Time Prediction Uncertainty, Bulletin of the Seismological Society of America, Vol. 106, No. 6, pp. 2900-2916, December 2016, doi: 10.1785/0120150271.

Ballard, S., J. Hipp, B. Kraus, A. Encarnacao, and C. Young (2016). GeoTess: A generalized Earth model software utility, Seismol. Res. Lett. 87, no. 3, doi: 10.1785/0220150222.

Ballard, S., J. R. Hipp and C. J. Young (2009). Efficient and Accurate Calculation of Ray Theory Seismic Travel Time through Variable Resolution 3D Earth Models, Seismological Research Letters v 80, 6 doi: 10.1785/gssrl.80.6.989.