Body Wave Tomography

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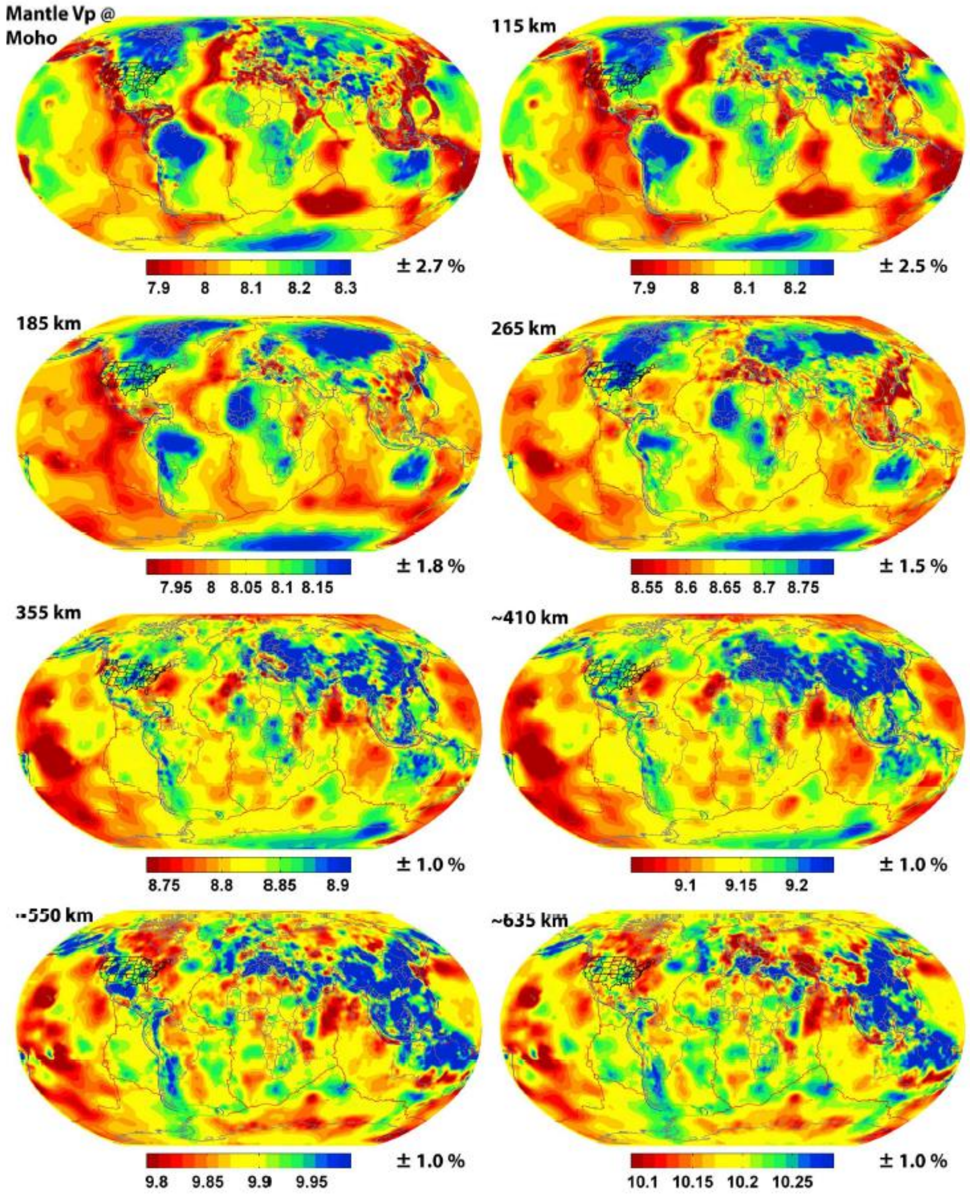
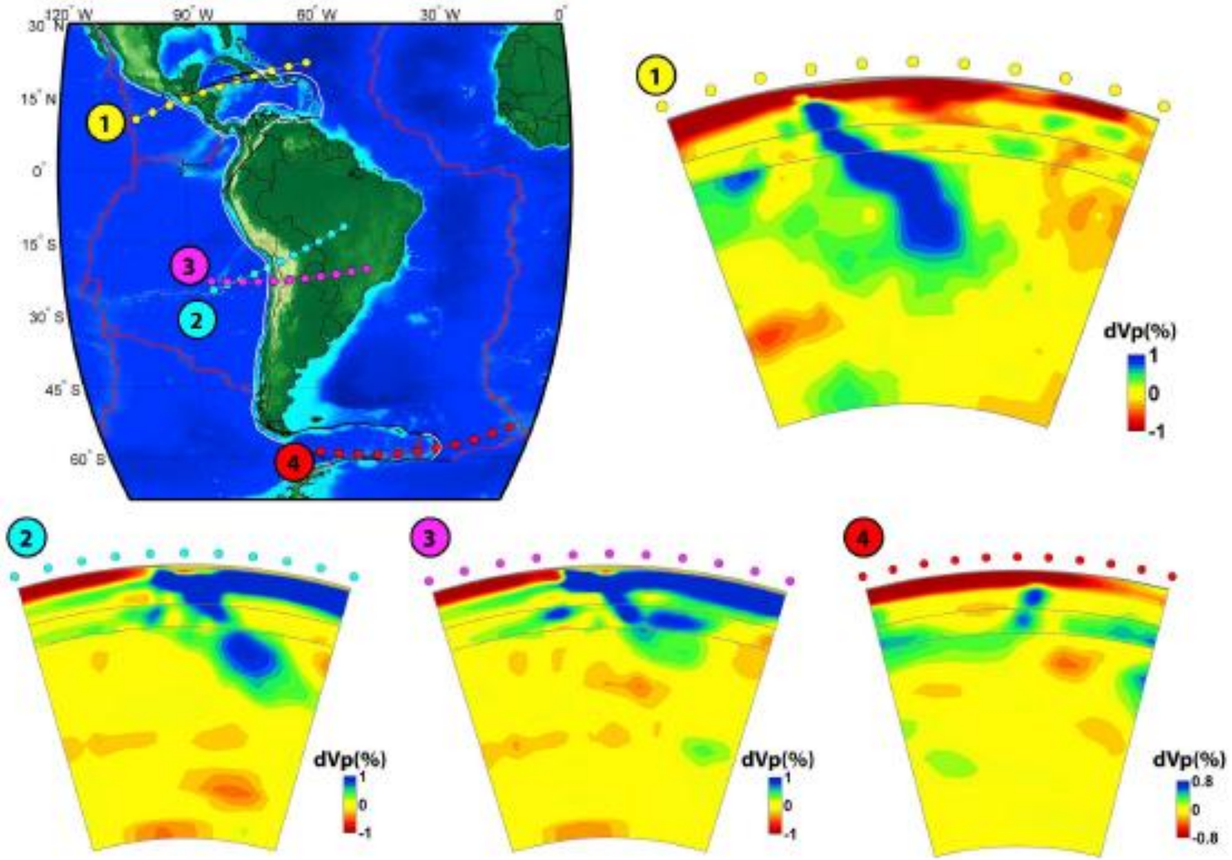


Outline

- Background – what is body wave tomography?
- Errors.
- Resolution.
- Interpreting subsurface properties.
- Example.



Tomography

- Tomography, Greek: “Slice picture”.
- Applied in a large number of sciences.
  - Radio astronomy: Used to image remote regions of the universe.
  - Medicine: Map tissue in the human body using computer aided tomography (CAT). Method received Nobel Prize in physiology and medicine (1979).
- Seismic tomography: Technique used to image the subsurface with seismic waves from for instance from earthquakes or explosions.
- Seismic tomography usually resolve for Vp, Vs velocities and Q (quality factor, attenuation).
- Several types of seismic waves can be used to image the subsurface e.g. **body waves**, surface waves, ambient noise.
- Aim: Find a 2D/3D model that image the subsurface. The 2D/3D model can for instance be used to interpret subsurface properties (e.g lithology and fluid saturation) and improve earthquake locations.

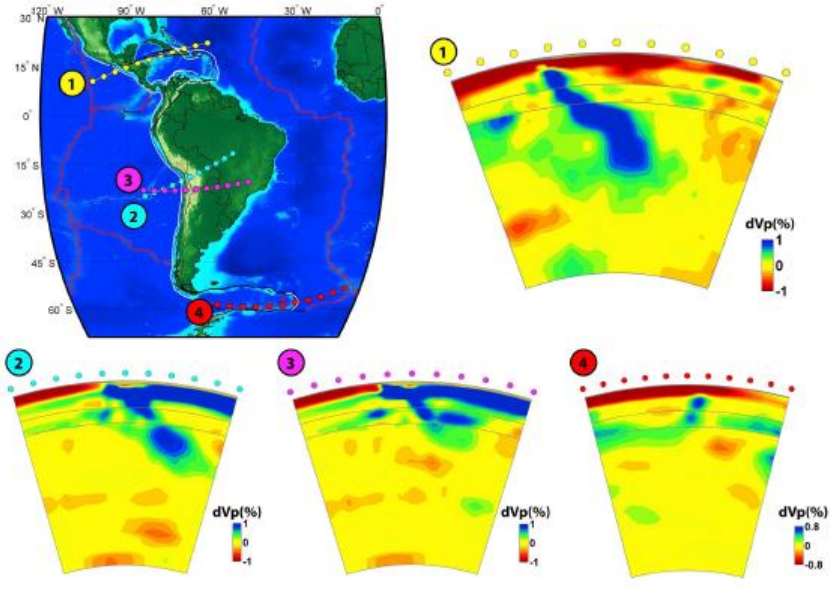
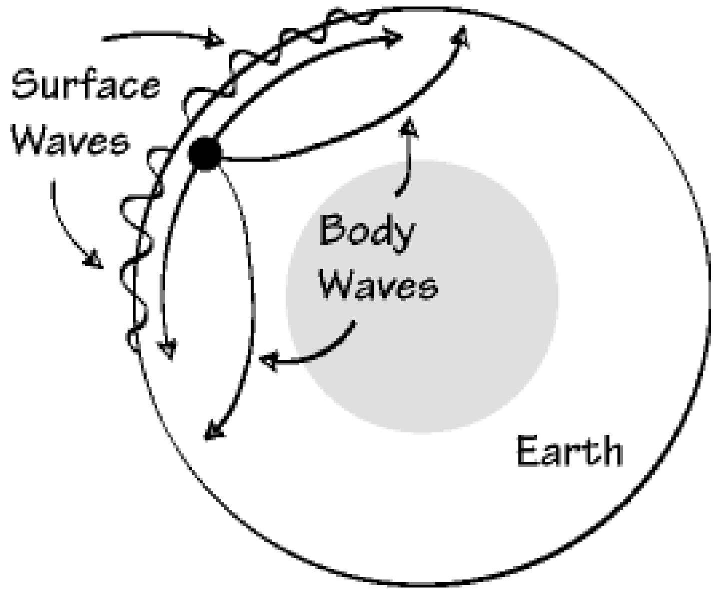


Figure 13. Selected cross sections through the LLNL-G3Dv3 model showing structures beneath South America

Simmons et al. (2012)

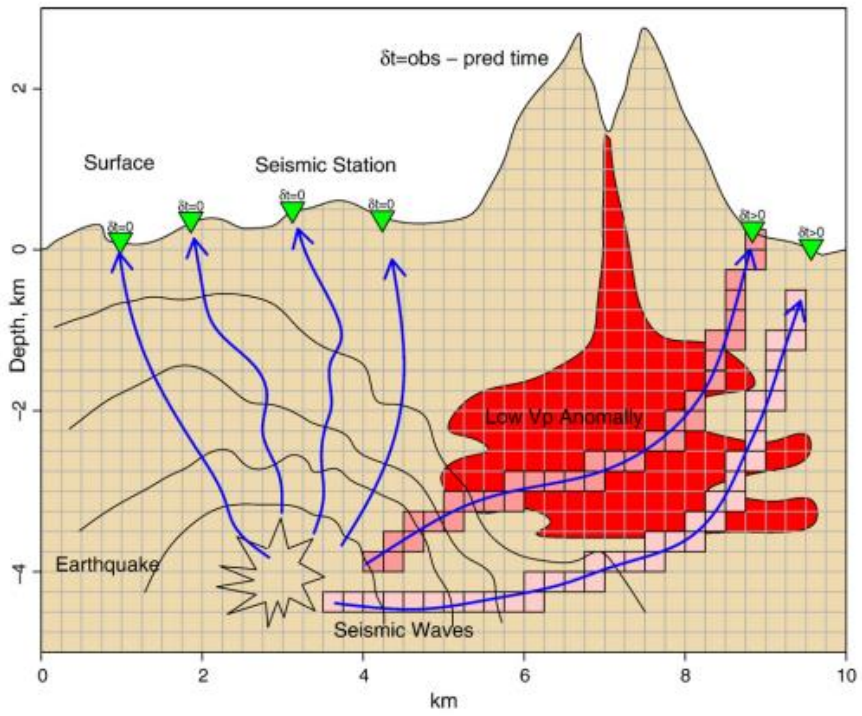
Body wave vs. surface wave tomography

- Body waves travels through the earth's interior, while surface waves travel along the earths surface.
- Surface wave tomography: based on dispersion curves to get S-wave velocity model.
- Body wave tomography: based on arrival times to get P or S-wave velocity model.



Body wave tomography - concept

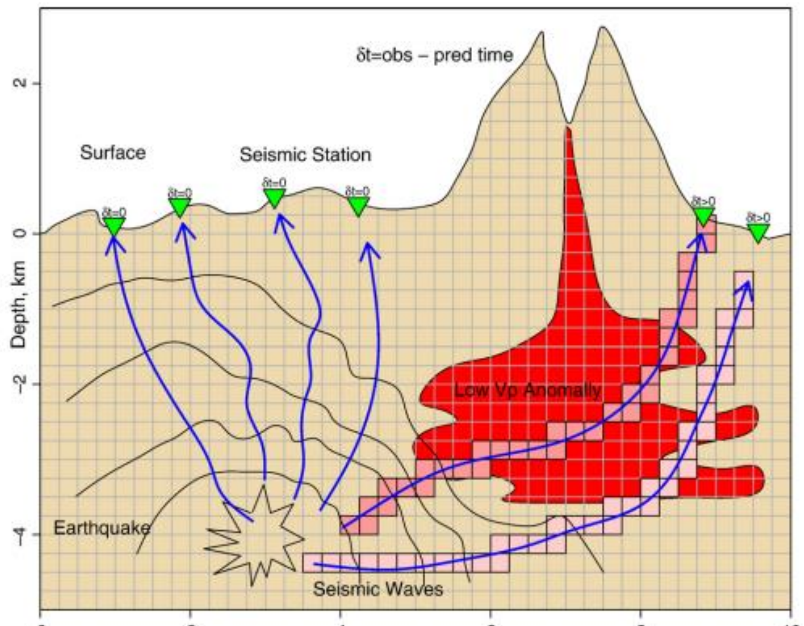
- Seismic energy travels from earthquake/source to stations at the surface.
- Assume an initial model, often a 1D-velocity model is used.
- Travel time residual: Difference between observed and predicted travel time (δt).
- If the initial 1D model is close to correct the travel time residuals at the stations are small.
- If the waves pass through an anomalous structure, the travel time residuals increase.
- The anomaly can be reconstructed using overlapping rays travelling from different angles.



Lees, 2007

Tomography – How is it done?

- Model is parametrized into cells or any other type of basis function.
- Travel time can be estimated (assume rays): $$\Delta T = \int_{\text{ray}} \frac{1}{V(\text{ray})} \text{dl} = \int_{\text{ray}} S(\text{ray}) \text{dl}$$
- Assume a simple model, most often a 1D model.
- Use model for locating earthquakes.
- Ray paths are calculated from the earthquake locations to the stations at the surface.
- Weighting estimated for each ray. In block models, this represents the penetration length for the ray in each cell. The weighting and ray paths are collected in a large matrix (G).
- Model equation: **d = Gm**, travel time residuals = (ray path and weighting) x (perturbations relative to reference model).
- Iteration to solve the inverse problem. Ray paths and earthquake locations depend on velocity model, non-linear solution.



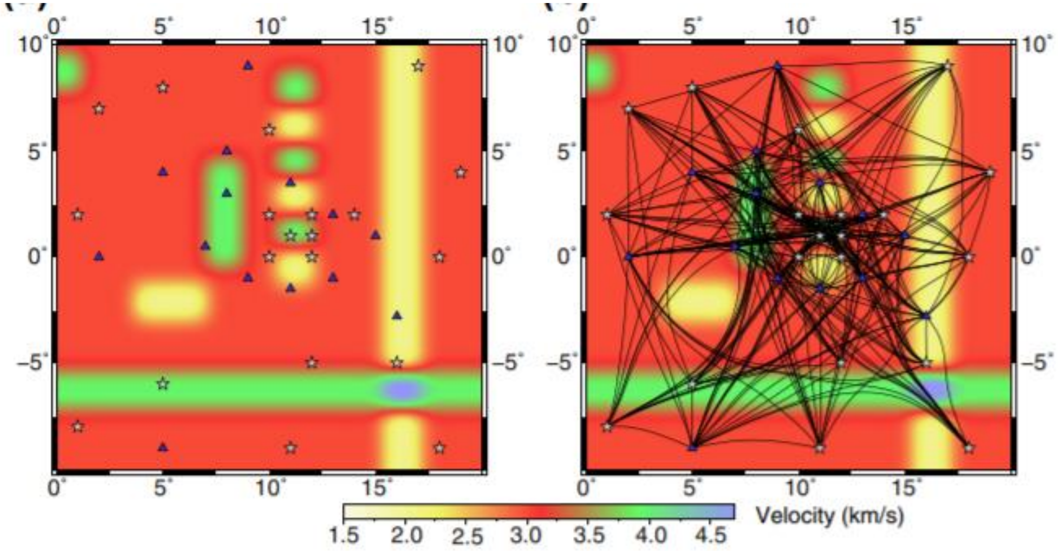
Lees, 2007

Error

- Important to address the issues related to errors and resolution in tomographic models.
- Apply approximate methods to find error and resolution since the inversion matrices involved are so large.
- Noise and uncertain phase picks. Introduce uncertainties in geophysical models.
- Waves from almost same source location may produce different travel time residuals at the same station. Can cause fluctuation.
- Damping and filtering:
  - To avoid large fluctuations the models are damped or filtered (“regularization”).
  - Regularization: mathematical method for controlling effects of errors.
  - Exclude sharp boundaries within the model.
  - Put limits on on perturbation strength.
  - Tomographic models smoother than real life situations.
  - Tomographic model is seen as the minimum strength of the perturbations.

Resolution

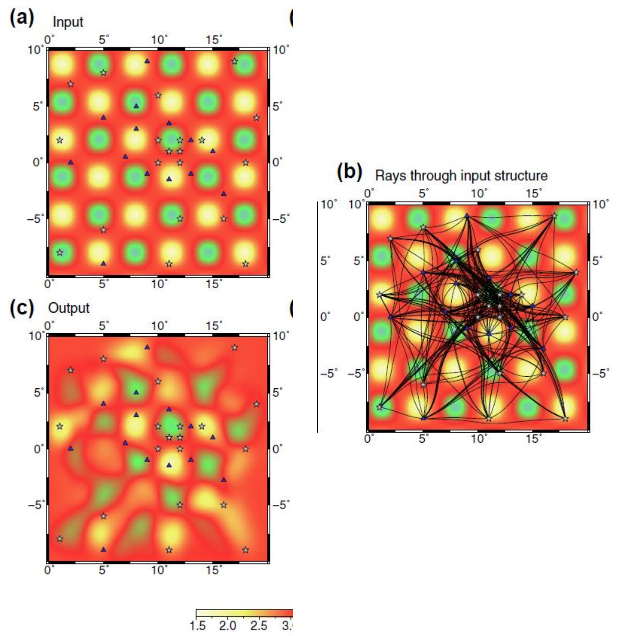
- Resolution depend on frequency and ray coverage.
- Frequency: higher frequencies sample smaller structures.
- Ray coverage:
    - Station distribution, e.g. more stations onshore than offshore.
    - Earthquakes not evenly distributed in the subsurface, often occur in clusters.
    - May oversample some regions and exclude other regions. This may cause bias in the models.
    - Largely solved by down-weighting paths in the model.
    - Rays often follow regions with higher velocity, can result in shadow zones in the model.
- Checker board tests can be used to test resolution of tomography models.



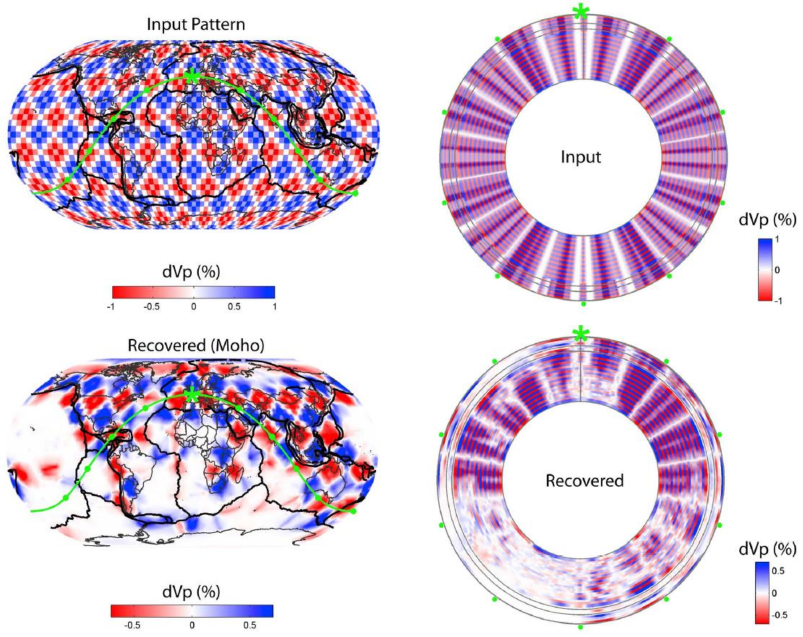
Rawlinson et al. (2014)

Resolution – checker board test

- Checker board tests can be used for resolution/sensitivity analysis.
- Check how well features are resolved in the tomographic model.
- Idea:
  - Use a synthetic test model, often a grid of perturbations (“checker board”). Generate an artificial data set using the same station configurations, sources and phase types as in the original tomographic model.
  - Inversion that aim at reconstructing the checker board.
  - Check how well the grid of perturbations are resolved.
  - This gives an idea of model sensitivity and how well the model resolves geological structures.
- Limitations:
  - Do not take into account real noise.
  - Using the same parametrization and assumptions as in the original inversion, shows an ideal image of resolution.
  - Results depend on which synthetic test model is used.



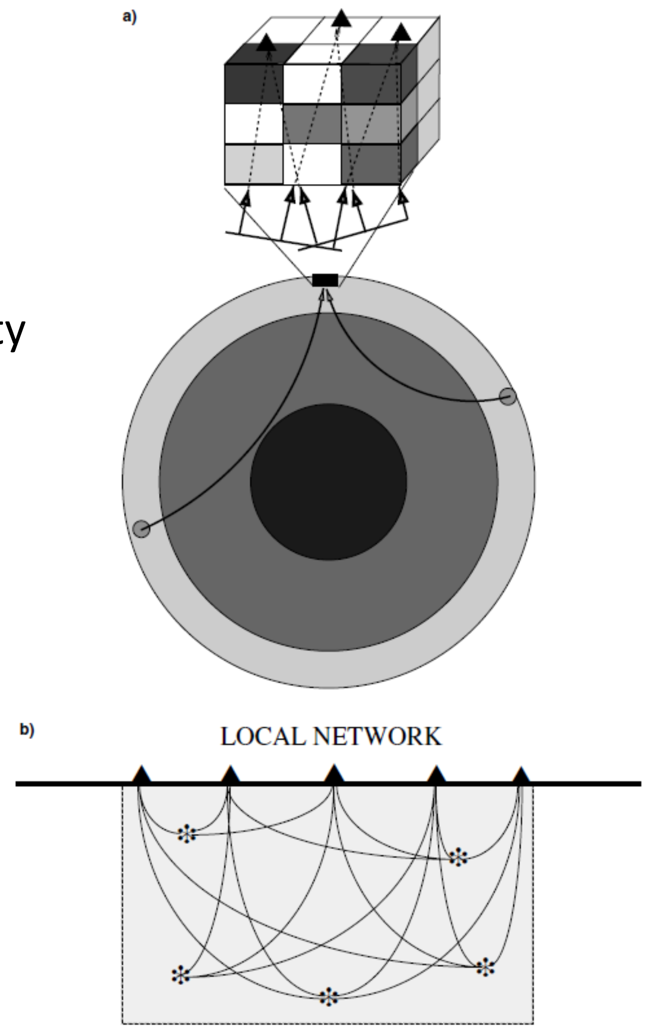
Rawlinson et al. (2014)



Simmons et al. (2012)

Local and teleseismic body wave tomography

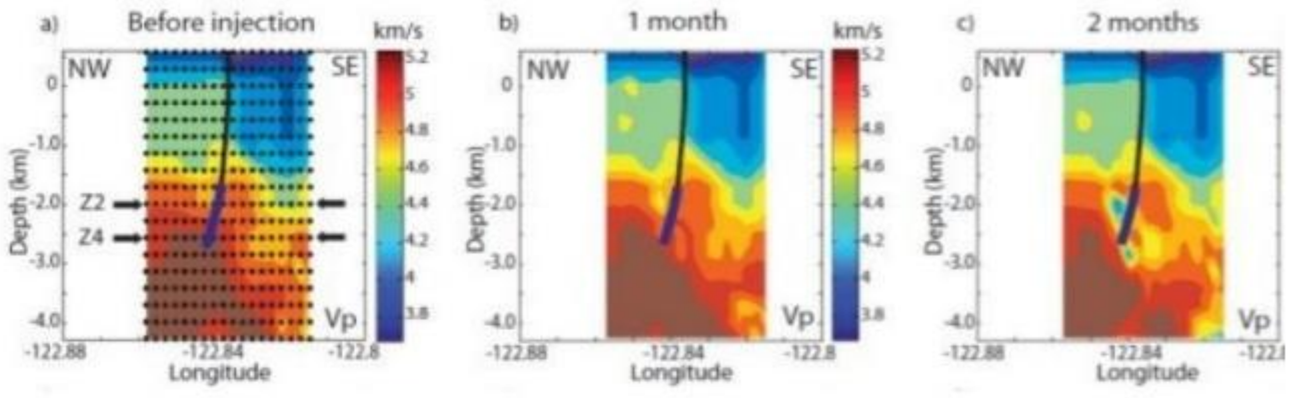
- Both type local and teleseismic body waves can be used to interpret a velocity structure.
- Teleseismic: Only the structures beneath the stations that contribute to travel time perturbations - plane wave assumption.
- Local: Whole ray path contribute to arrival time perturbations.



Thurber, 2003

Interpreting subsurface properties from tomographic models

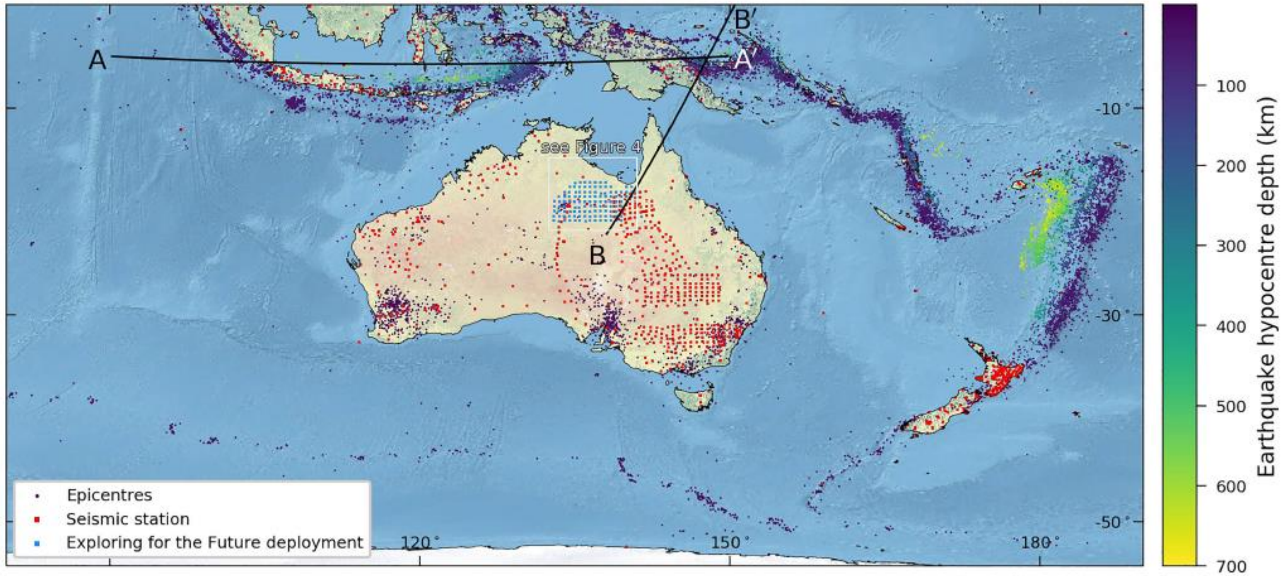
- Indirect measurements.
- An example of how properties can be interpreted from seismic images:
  - Higher temperatures, lower Vp, Vs velocities.
- Challenging as various properties may give rise to the same seismic image.
- Need some “a prior” information from for instance laboratory experiments.
- Labs represent different conditions and scales than real life.
- Properties of the subsurface can be better resolved combining body wave tomography with other methods.



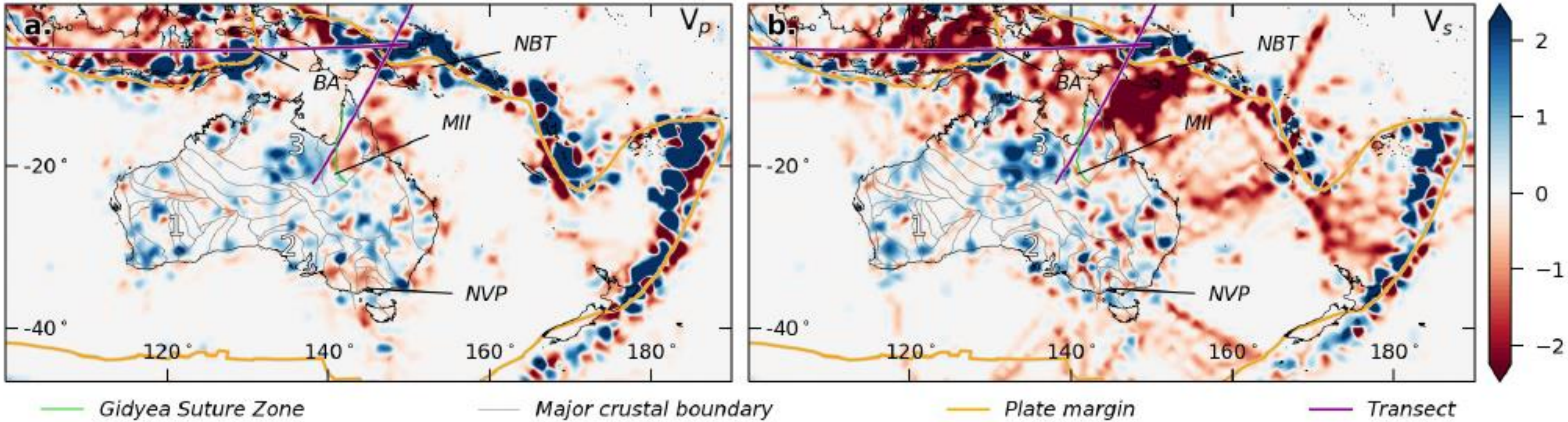
Example: injection test performed at the Geysers geothermal field in California.

Hutchings et al., (2014)

AusArray project, Imaging the lithospheric mantle using body-wave tomography



Haynes et al. (2020)



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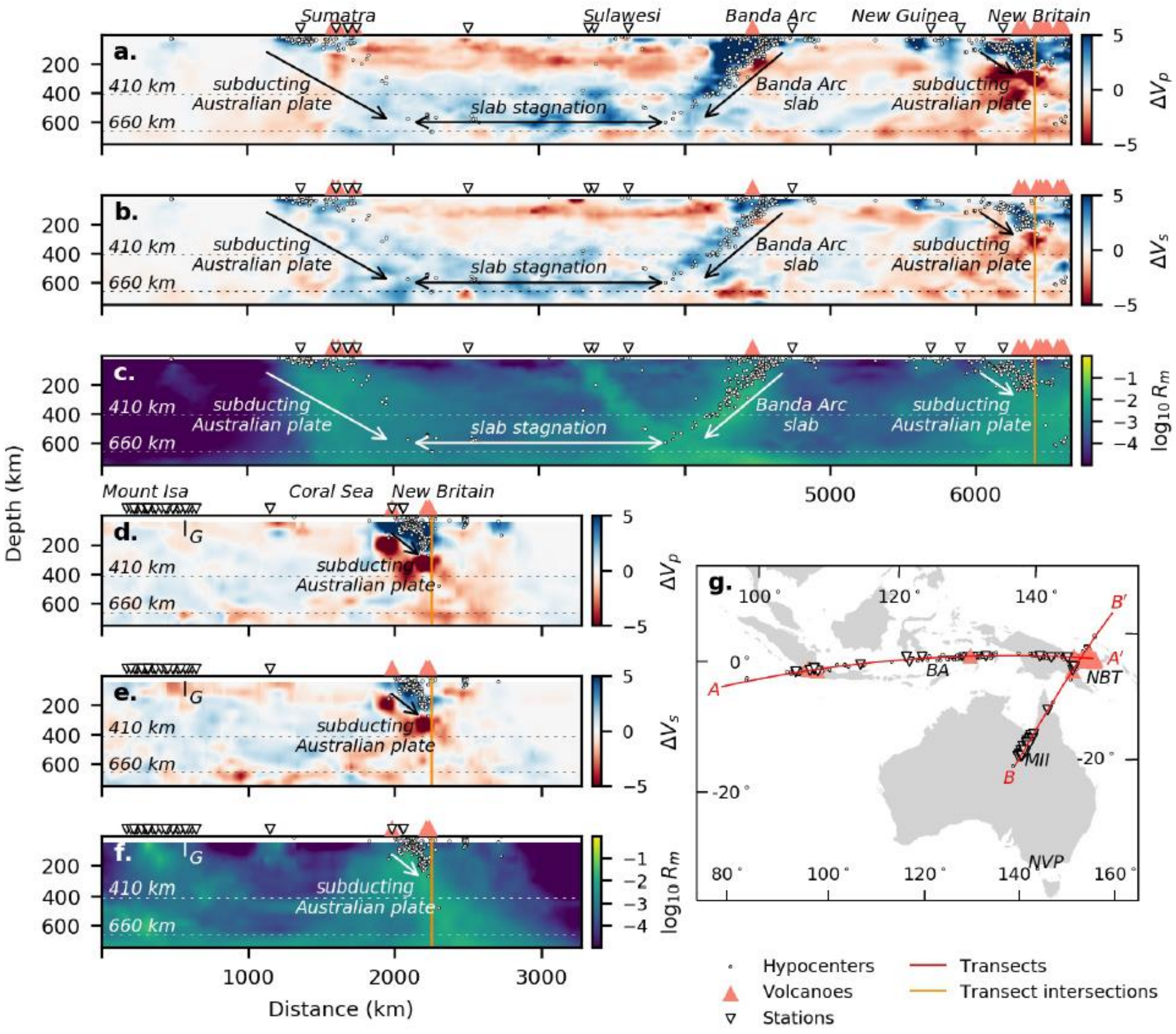

Ray density plot

Summary

- Body wave tomography is used to image the subsurface.
- There are some limitations to the method:
  - Regularization applied to avoid large fluctuations. Limits perturbation strength and excludes sharp boundaries.
  - Ray coverage.
  - Non-linearity and non-unique solutions.
- Provides an indirect measure of subsurface properties.
- Can be combined with other methods to improve our understanding of subsurface properties and geological conditions.

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