

# North American Crustal Motion and Glacial Isostatic Adjustment Model Predictions

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# Introduction

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- Our goal is to find a laterally homogeneous GIA model that provides the best fit to observed horizontal and vertical crustal motions across North America. These are the steps that we took:
  - Develop a robust technique to obtain viscoelastic Earth response
  - Generate Earth model responses with many different Earth model parameters and induced surface loads
  - Compare observations to predictions
- The focus is varying the lithospheric thickness and viscosity depth profile to find models with the best fit to crustal motions.
- Residual crustal motions arising from the best fit models may indicate the degree to which lateral heterogeneity of the Earth is important.

# Viscoelastic Earth Response

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- Three methods for finding the viscoelastic response were described by Mitrovica and Peltier, 1992:
  - Full Normal Mode Analysis
  - Collocation Method
  - Mixed Collocation Method
- The full normal mode analysis can fail depending on the viscosity structure.
- The collocation method chooses synthetic inverse decay times, rather than finding the modes directly.
- The mixed collocation method uses the modes found from the normal mode method, but uses least squares to find the amplitudes.

# Full Normal Mode Analysis

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- The full normal mode analysis finds the response amplitude,  $r_j$ , by finding normal modes in the Laplace transform domain by searching negative inverse decay times,  $s$ .
- There is potential for singularities to occur within the viscoelastic moduli,  $\mu(s)$  and  $\lambda(s)$ , depending on the value of the inverse decay time,  $s$ .

$$r_j = \frac{Q(-s_j)R^*(-s_j)B}{[\frac{d}{ds} \det[R(s)]]_{s=-s_j}}$$

$$\mu(s) = \frac{\mu s}{s + \mu/\eta}, \quad \lambda(s) = \frac{s\lambda + \mu K/\eta}{s + \mu/\eta}, \quad K = \lambda + 2\mu/3$$

- $\eta$ : Viscosity,  $K$ : Bulk modules

# Collocation Method

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- The collocation method chooses a set of inverse decay times and finds the amplitudes that will best fit the directly calculated response through least squares methods.
- Singularities don't arise because this method employs positive values of the inverse decay time.
- This method acts more like a curve fitter. It doesn't collect normal modes like the full normal mode analysis.

$$R(s) = \sum_{n=1}^N \frac{r_j}{s + s_j} + R_{el}$$

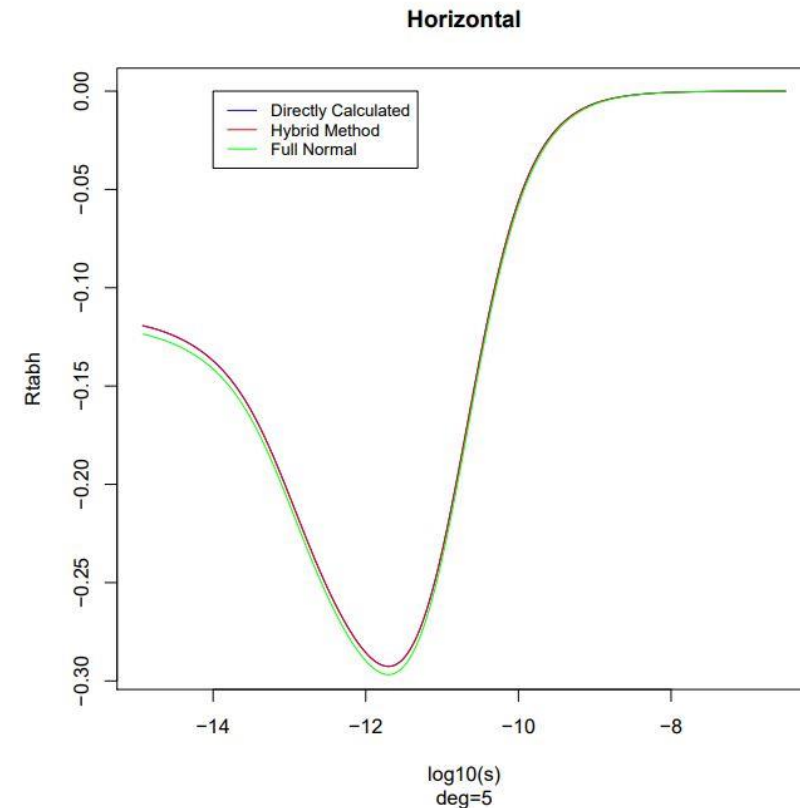
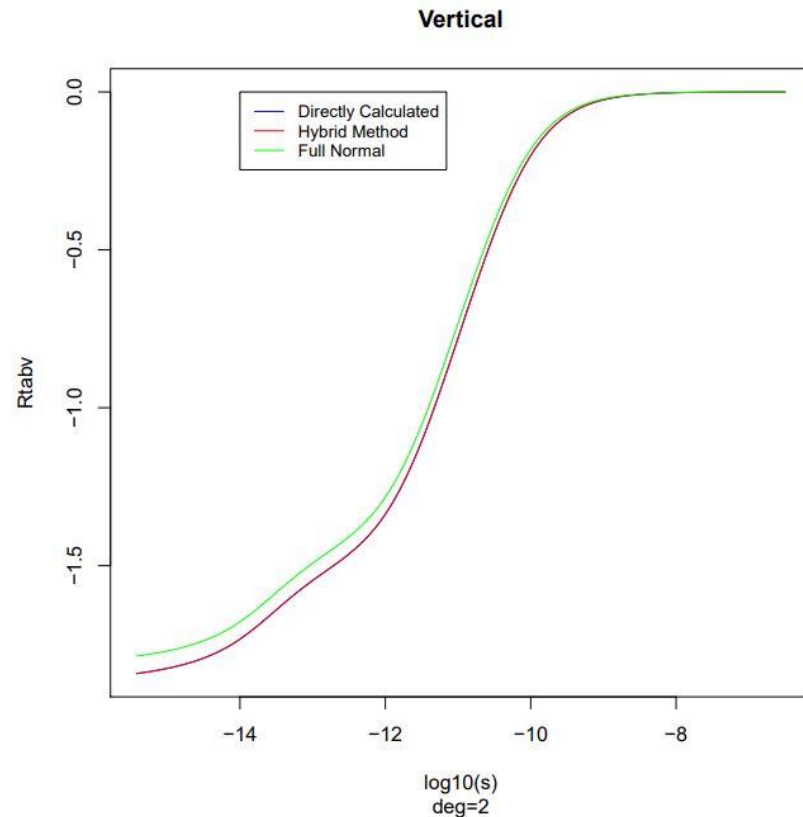
# Hybrid Normal Mode-Collocation(NM-C) Method

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- Steps:
  1. Carry out a full normal mode analysis (FNMA) to find as much of the response as possible.
  2. Employ the collocation method on the residuals between the FNMA results and the directly calculated values to find the remaining response.
- This hybridisation of the two methods employs all of the normal mode response that could be found, while also robustly fitting the directly calculated response.

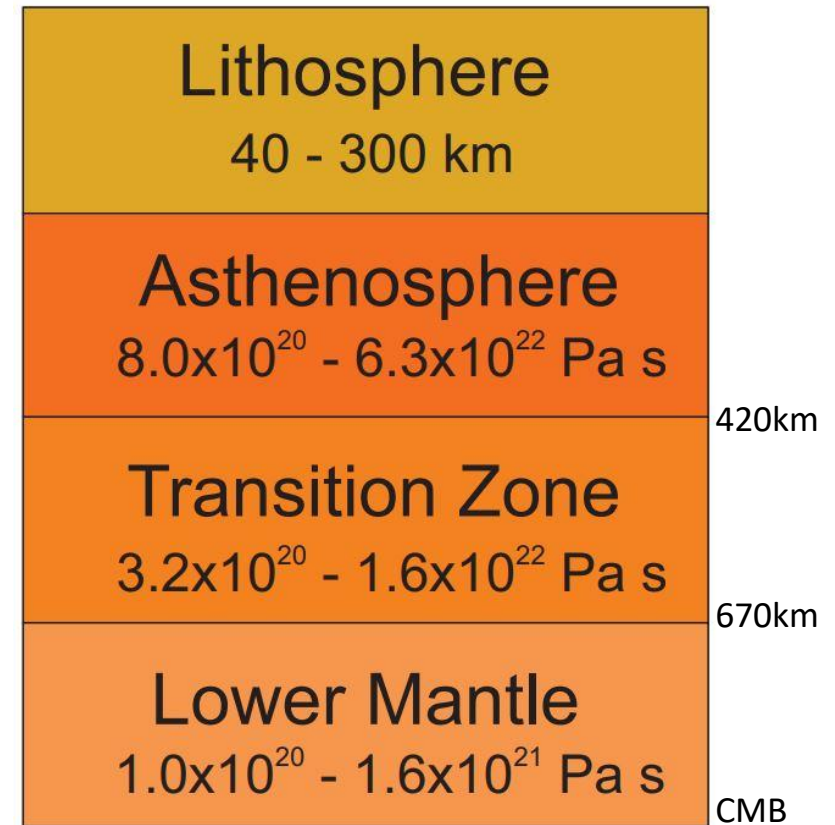
# Hybrid NM-C Method Example

- The response of the FNMA and the hybrid NM-C method is compared to the directly calculated values for the vertical (left panel) and horizontal response (right panel).
- In both examples, the FNMA result varies slightly from the directly calculated values while the hybrid NM-C method agrees well with the directly calculated values.



# Earth Models

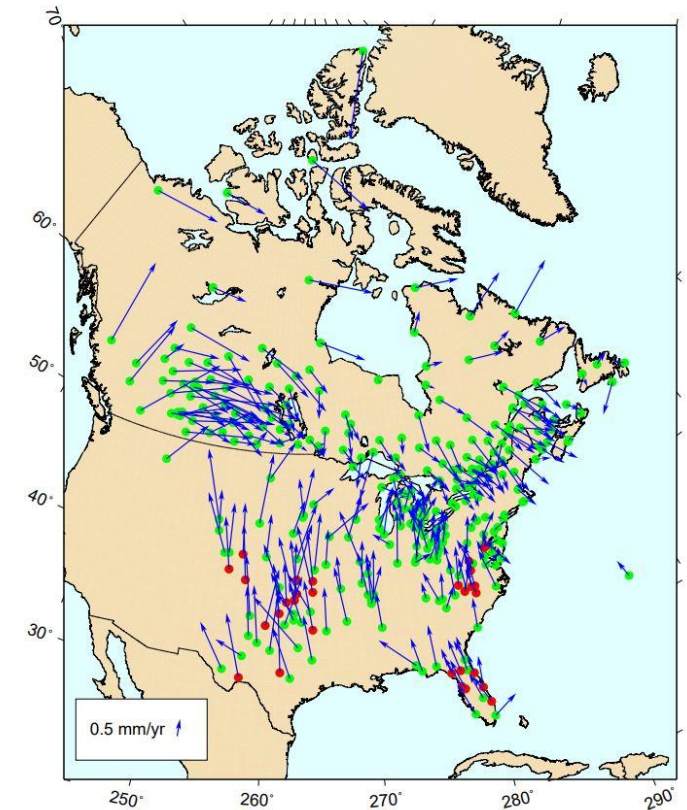
- Use the spherically symmetric Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) for density and elastic parameters.
- Random viscosity profiles were generated with the ranges shown in the figure, as well as:
  - Lower mantle viscosity  $\geq$  transition zone viscosity
  - Transition zone viscosity  $\geq$  upper mantle viscosity
- The same 500 random viscosity profiles were retained for different lithospheric thicknesses.



# IGS14 Observational Data

- IGS14 data set provided by the Nevada Geodetic Laboratory as our comparison for our predictions.  
(<http://geodesy.unr.edu/index.php>; Blewitt et al, 2013)
- While not shown, we did run our analysis with IGS08 and NA12 as well and found little difference in the overall results.
- In order to compare this data set with our predictions, both need to be expressed in the same reference frame.
- Red dots in central United States are used to define a no-net-rotation reference frame by finding and removing an Euler pole of rotation.

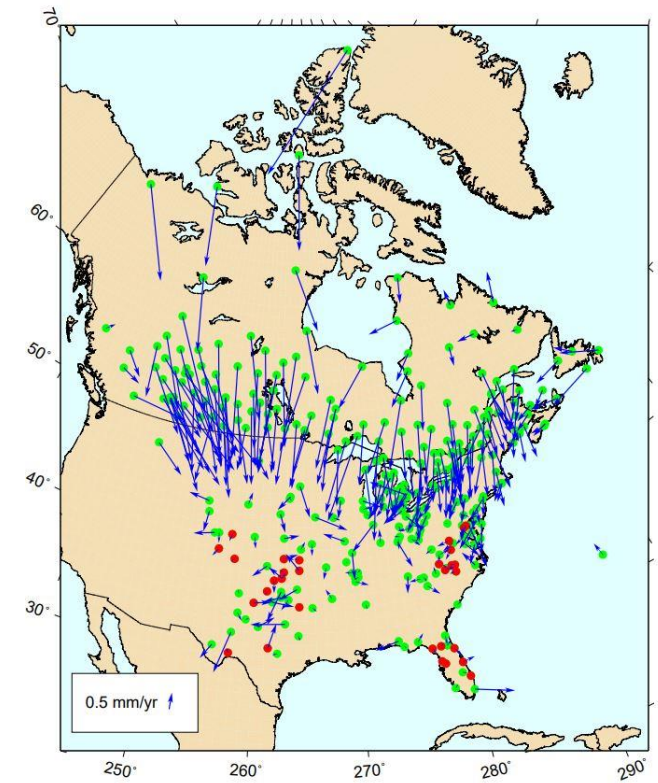
IGS14 Observation



# Observational Data Rotated

- Rotated IGS14 velocities are small in the central United States in the vicinity of the reference sites (red dots).
- Sites located in southern Canada have velocities that are generally directed southwards.

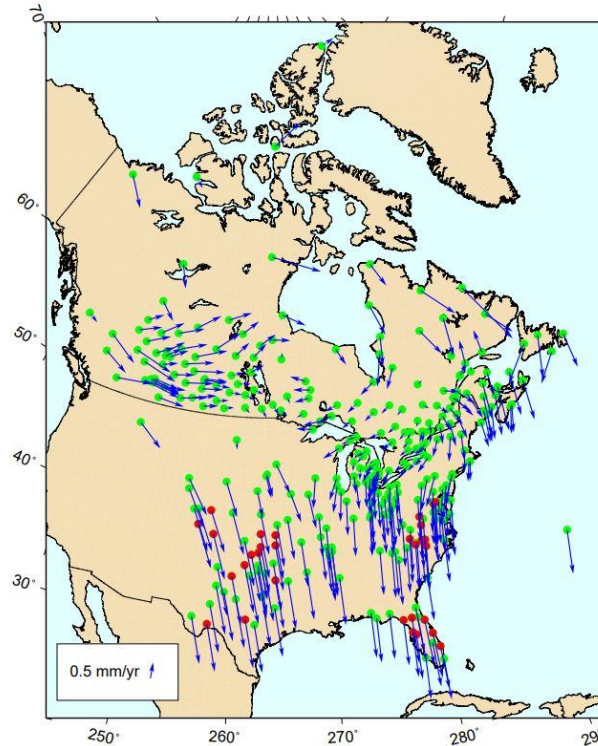
IGS14 Observation Rotated



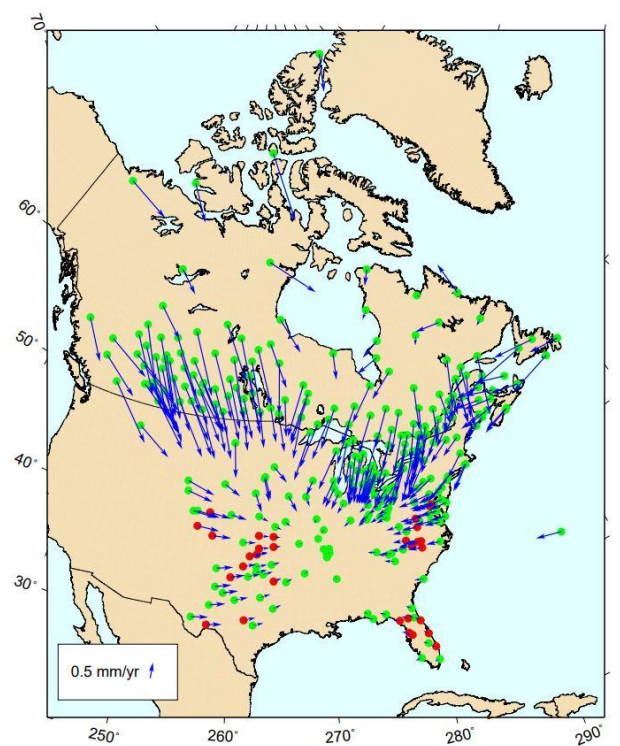
# Prediction Before and After Rotation

- Here is an example of predicted velocities using the same reference sites as the observations.
- Once the predictions and observations are rotated to the same reference frame, the difference can be calculated and summary statistics, such as the root mean square (RMS), can be determined.

60 km Predictions



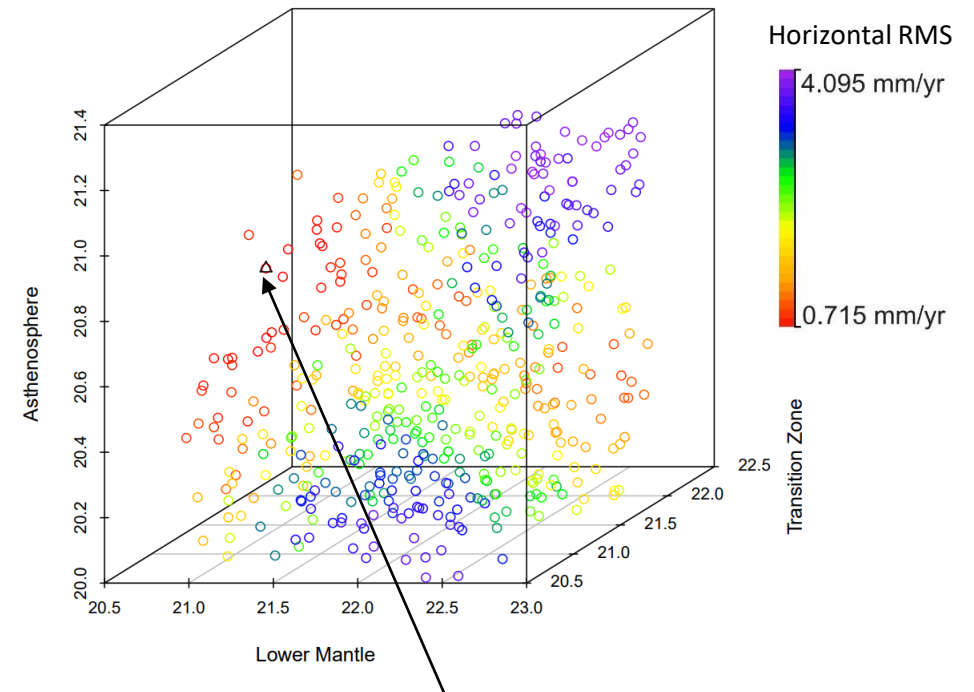
60 km Predictions Rotated



# 3D RMS Scatter Plots

- A 3D scatter plot that represents all of the 500 randomly generated viscosity profiles that were tested for this lithospheric thickness of 60 km.
- Each colored dot represent one viscosity profile.
- For a lithospheric thickness of 60 km, the minimum RMS is located with a viscosity profile around  $1.0 \times 10^{21}$  Pa s for the lower mantle and asthenosphere and  $3.2 \times 10^{21}$  Pa s for the transition zone .

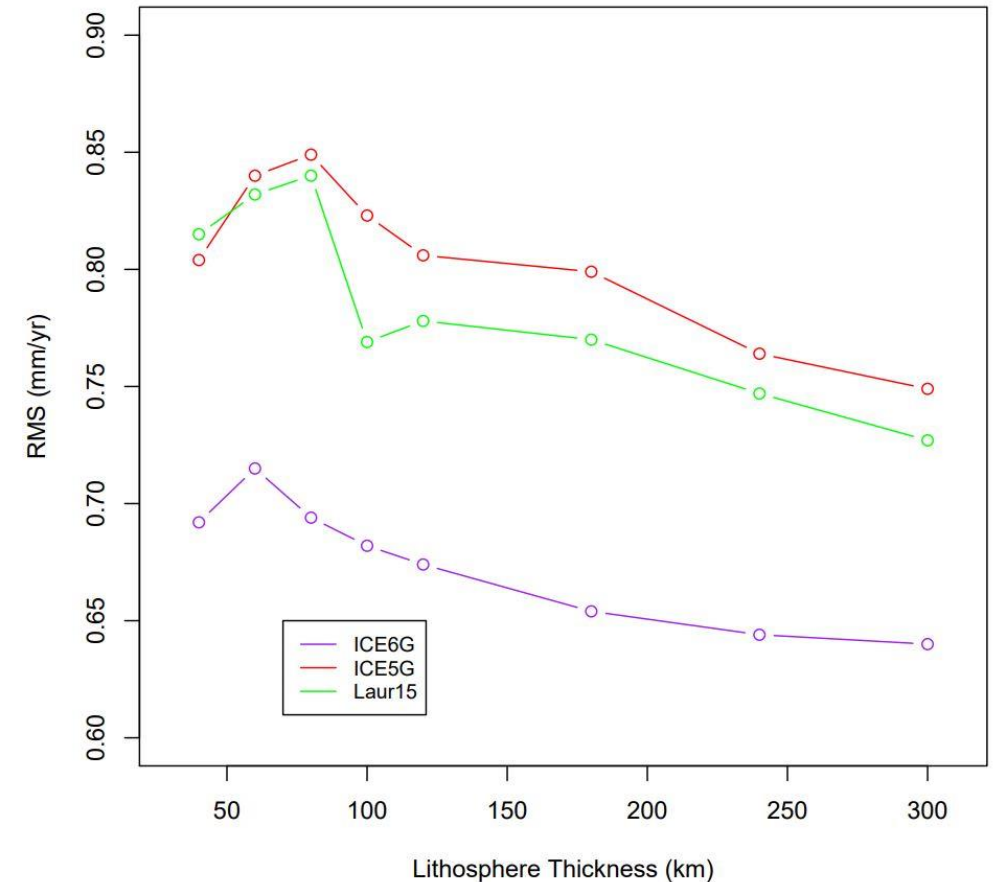
Viscosity Parameter RMS Scatter Plot (60 km)



Smallest Horizontal RMS

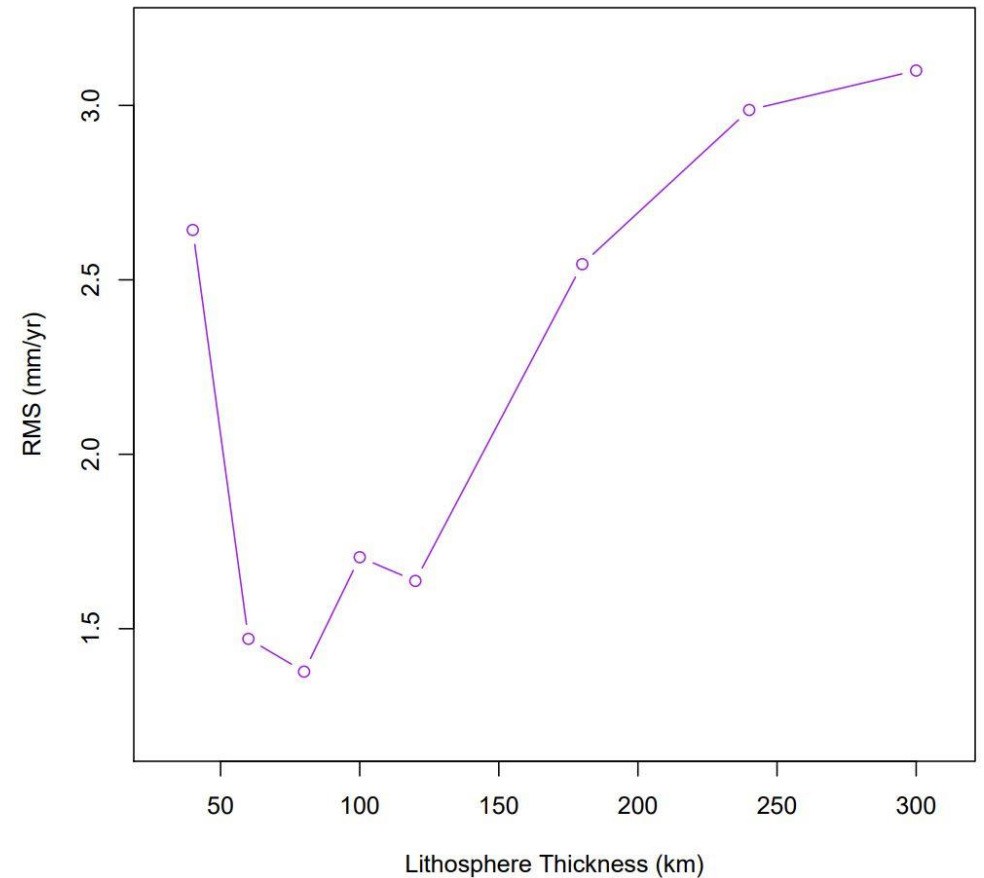
# Horizontal RMS vs Lithospheric Thickness

- Minimum horizontal RMS plotted against lithospheric thickness for 3 different ice loading models, ICE5G, ICE6G, and Laur15.
- ICE6G results in the smallest horizontal RMS compared to the other ice loading models.
- When we only consider the horizontal motions, thick lithospheres generate the smallest horizontal RMS.
  - ICE5G: (Peltier, 2004)
  - ICE6G: (Peltier et al, 2015)
  - Laur15: (Simon et al., 2015, 2016)



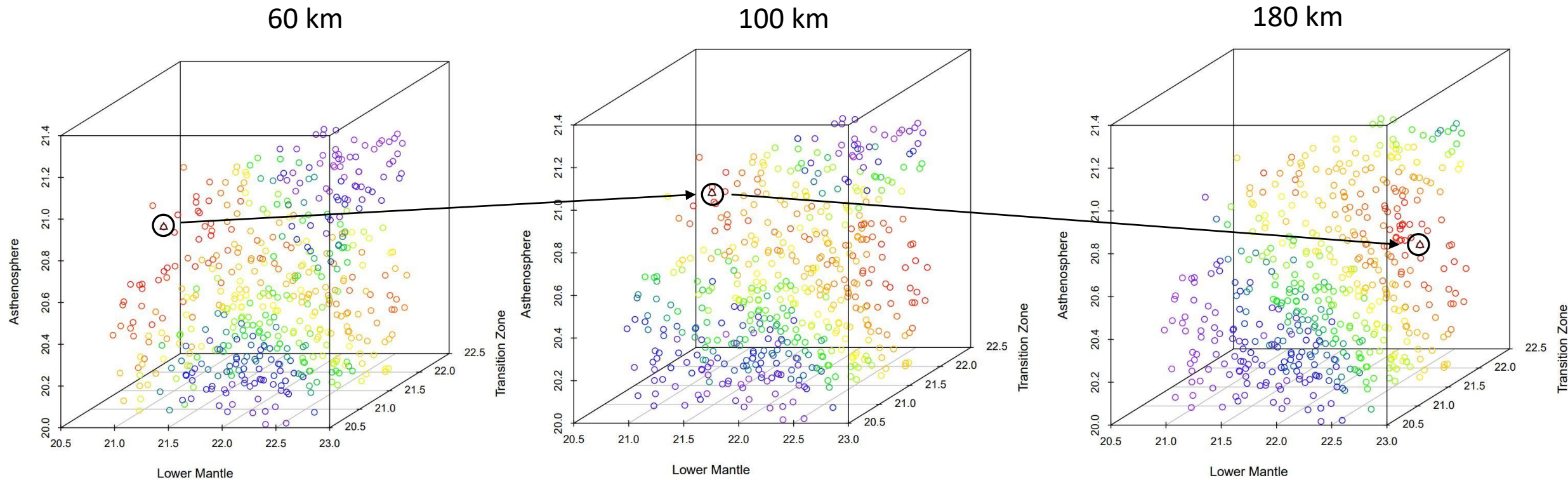
# Vertical RMS vs Lithospheric Thickness

- Vertical RMS from the viscosity profiles that resulted in the smallest horizontal RMS for the ICE6G loading history.
- The vertical RMS is minimized around the 60 to 120 km range with a minimum at 80 km thickness.
- The observations of vertical motion provide a constraint to the lithospheric thickness that is not present in the horizontal motions.



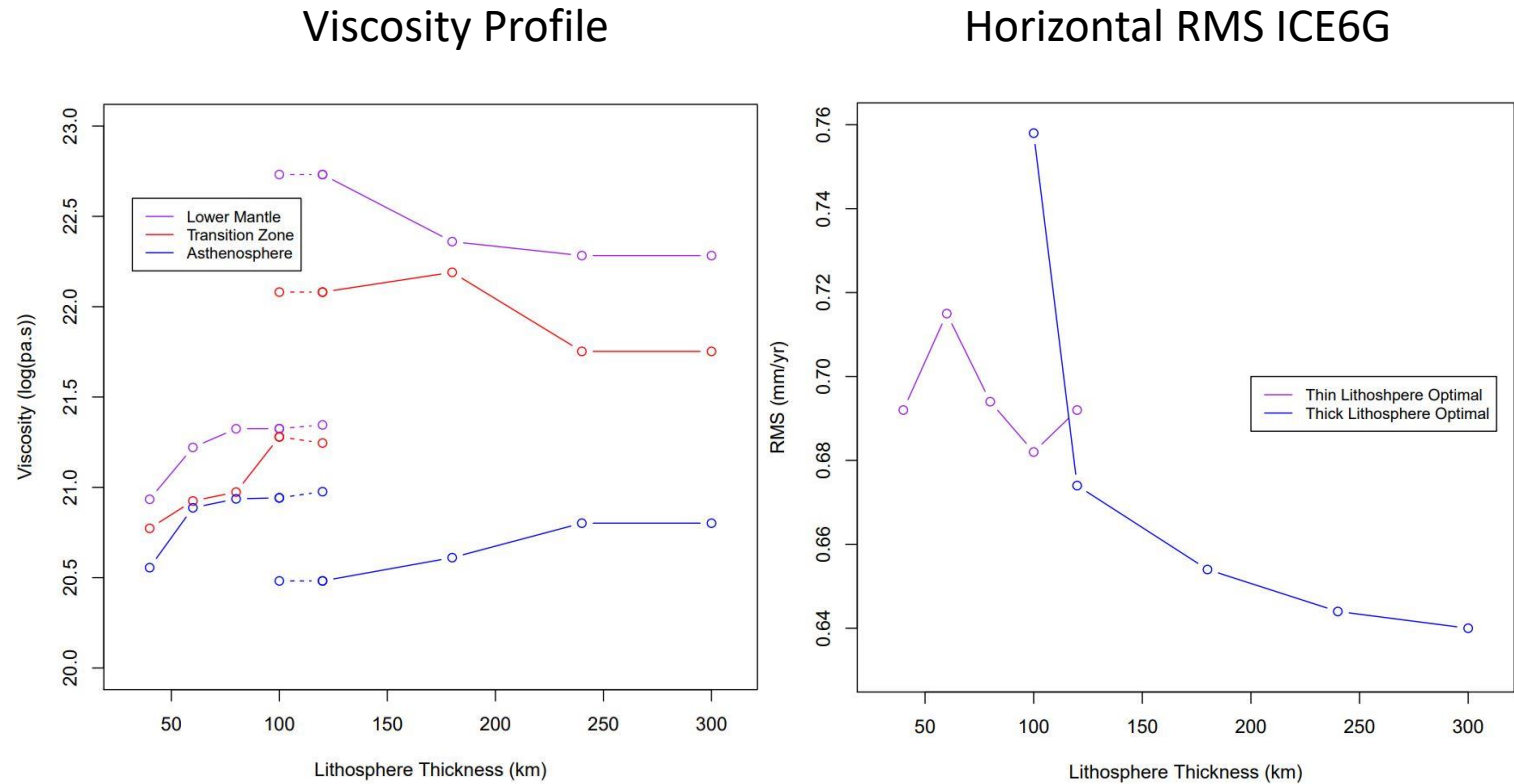
# Optimal Viscosity Profile

- As the lithospheric thickness increases, the optimal viscosity profile migrates.



# Viscosity Profile vs Lithospheric Thickness

- Optimal viscosity values migrate as lithosphere thickens (left panel).
- At thinner lithospheres, the optimal viscosity profile is similar to common viscosity profiles such as VM1.
- At thicker lithospheres, the lower mantle and transition zone viscosities increase substantially, while the asthenospheric viscosity lowers.
- The viscosity transition occurs sharply between 100 to 120 km (right panel).



# Summary

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- Generated a large number of random viscosity profiles over a large range of lithospheric thicknesses to find the best fit to observed crustal motion in North America.
- The horizontal component shows a weak preference to very thick lithospheres, while the vertical showed a strong preference towards the 60 to 120 km thickness with a best fit at 80 km.
- Two local minimum viscosity profiles that are dependent on lithospheric thickness were found. The transition occurs between 100 to 120 km.
- For the best fit vertical RMS at 80 km thickness, the RMS of the residual horizontal velocities is about 0.7 mm/yr indicating substantial unexplained signal. It is possible that lateral heterogeneity in the Earth model is required to explain the remaining signal. (Latychev, 2005)