MYRES I:
Heat, Helium & Whole Mantle Convection

Constraints on Mantle Structure from Surface Observables

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The Goal

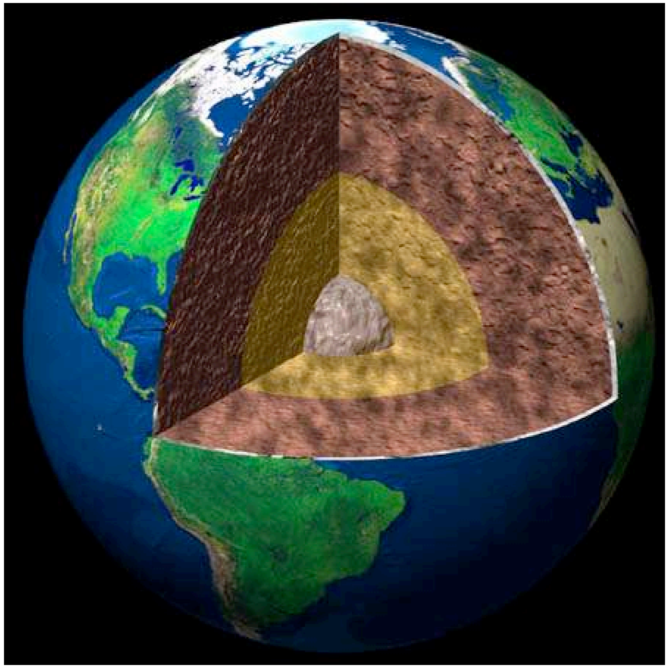
Use observations of surface deformation to determine the density and rheologic structure of the mantle.

Geoid/Free-air gravity

Dynamic topography

Post-glacial rebound

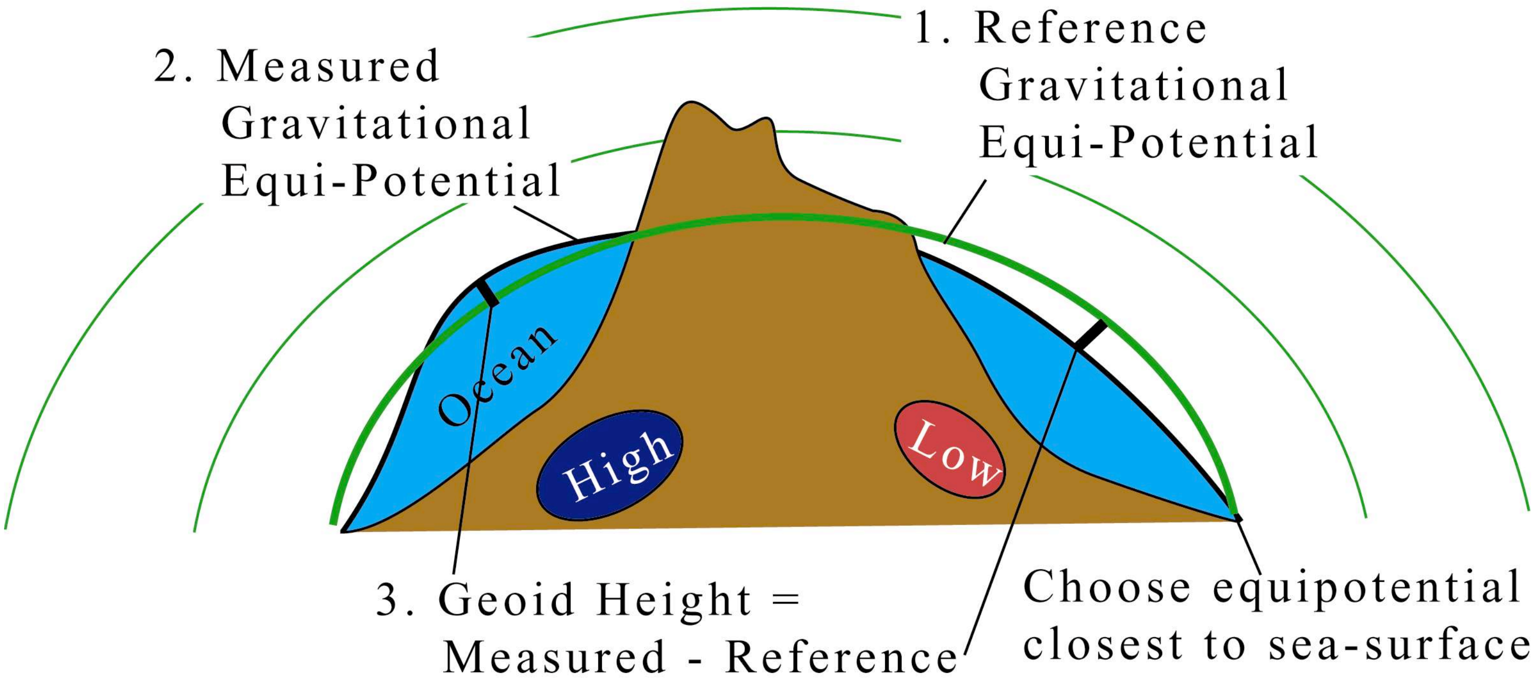
Plate motions



Outline

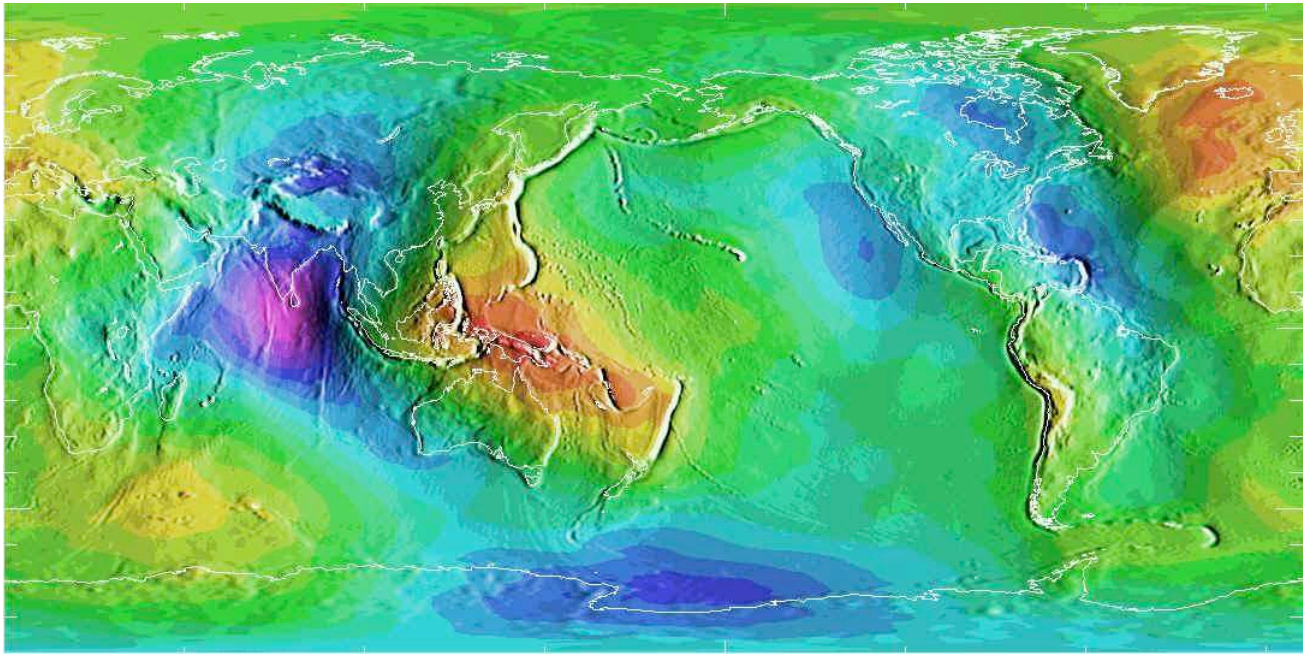
→ The Observations
- The Game (Methods)
- Robust Constraints on Mantle Structure.
- Beyond the Layered Mantle
  - Recent Results
  - Rheology
  - Challenges
- Conclusions

Geoid


2. Measured
Gravitational
Equi-Potential
1. Reference
Gravitational
Equi-Potential
Ocean
High
Low
3. Geoid Height =
Measured - Reference
Choose equipotential
closest to sea-surface

Geoid

- Measured by modelling satellite orbits.
  - Spherical harmonic representation, L=360.

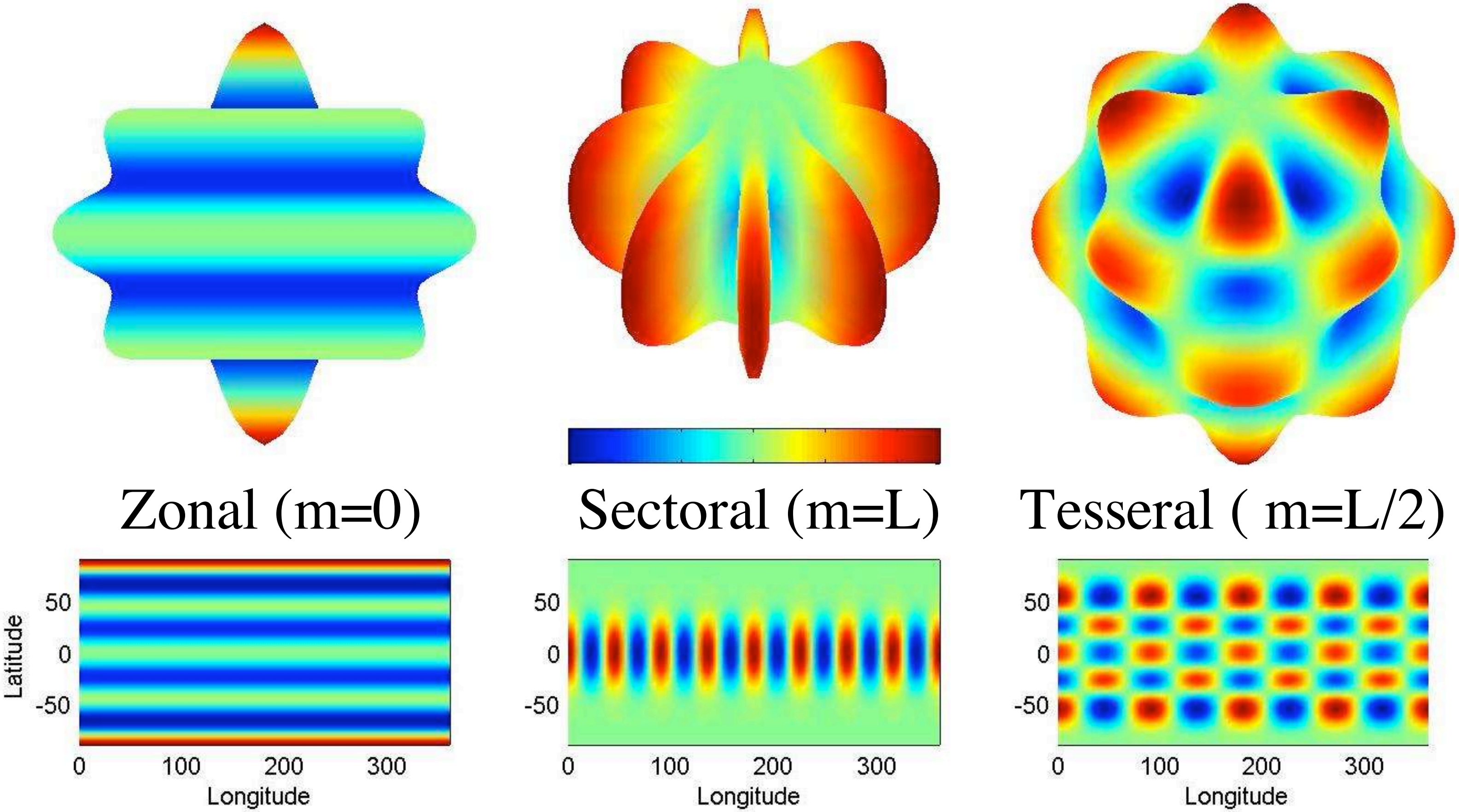


Range +/- 120 meters

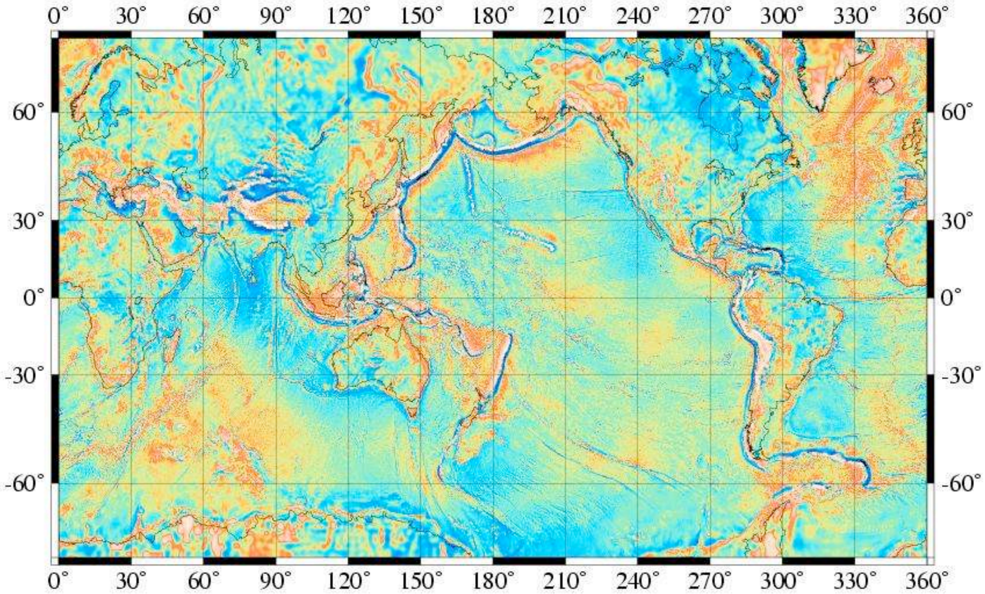
From, http://www.vuw.ac.nz/scps-students/phys209/modules/mod8.htm

Spherical Harmonics

Example Components for Degree (L) = 8



Free-Air Gravity

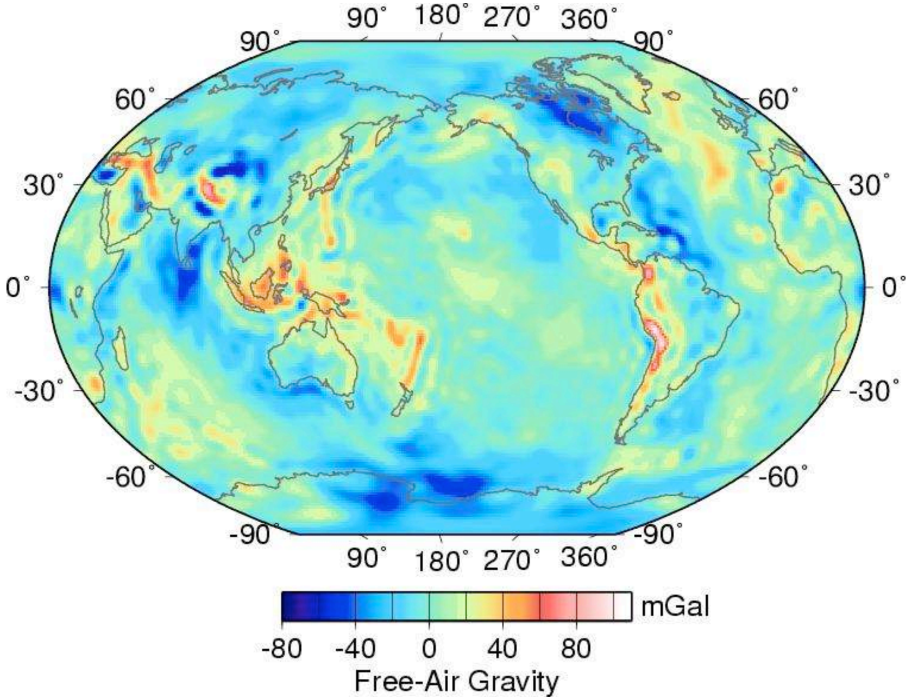


- Derivative of geoid (continents)
- Measured over the oceans using satellite altimetry (higher resolution).

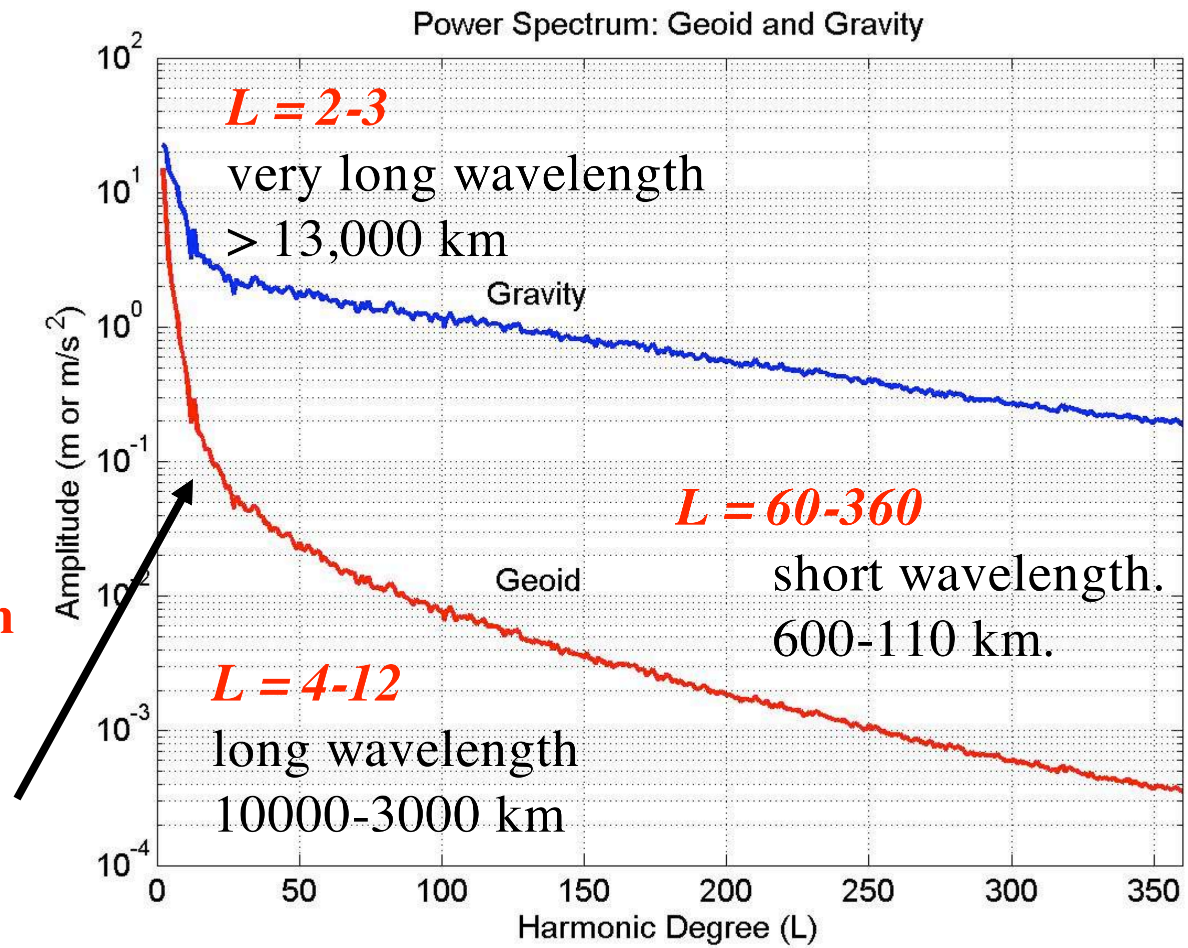
Free-Air Gravity

- Most sensitive to ***shallow crustal structure*** at short wavelengths (< 100 km).

- Shallow density structure may ***mask or obscure*** deeper structures.



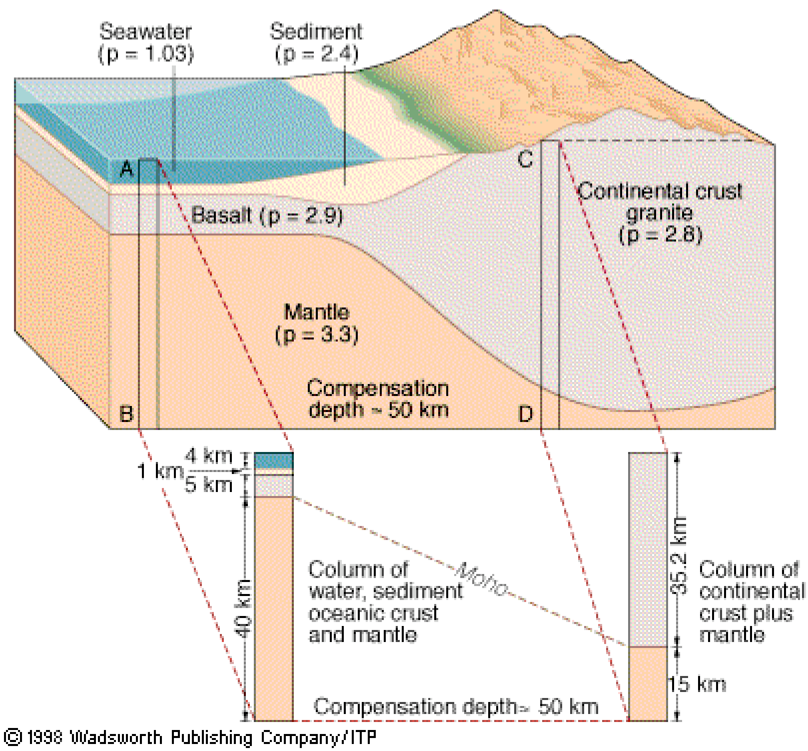
Geoid/Free-air Gravity Spectra



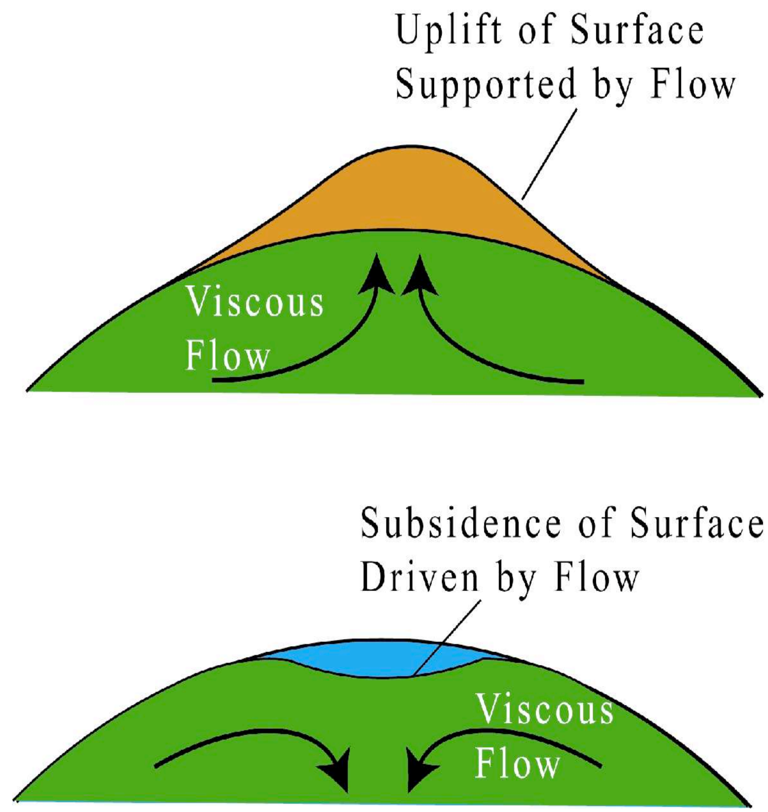
Red Spectrum

Dominated by signal at long wavelengths

Dynamic Topography

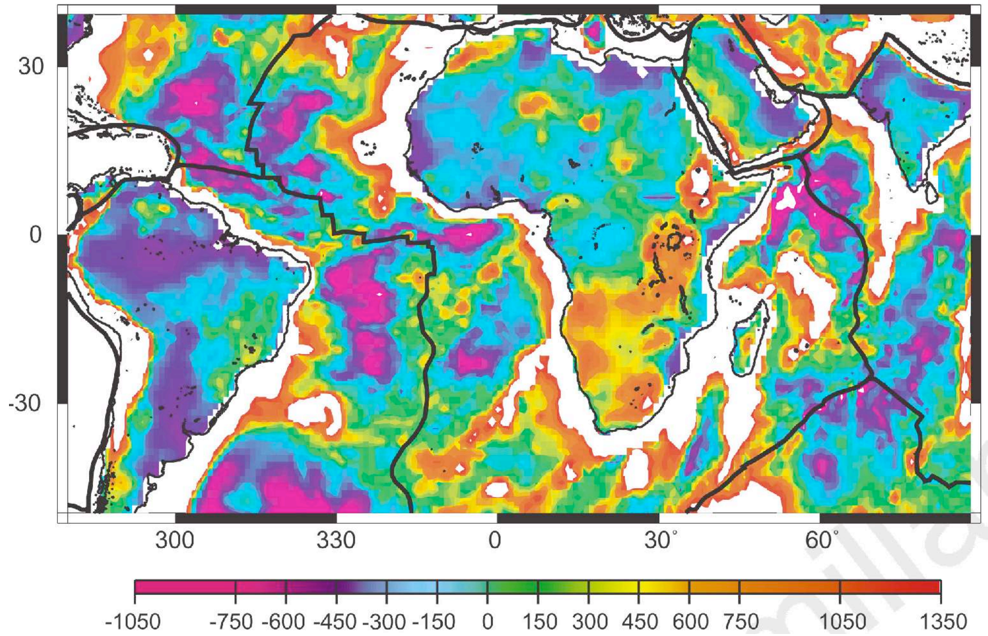


Isostatically Compensated



Dynamically Supported

Dynamic Topography



From : Lithgow-Bertelloni & Silver, Nature 1998 (fig 1)

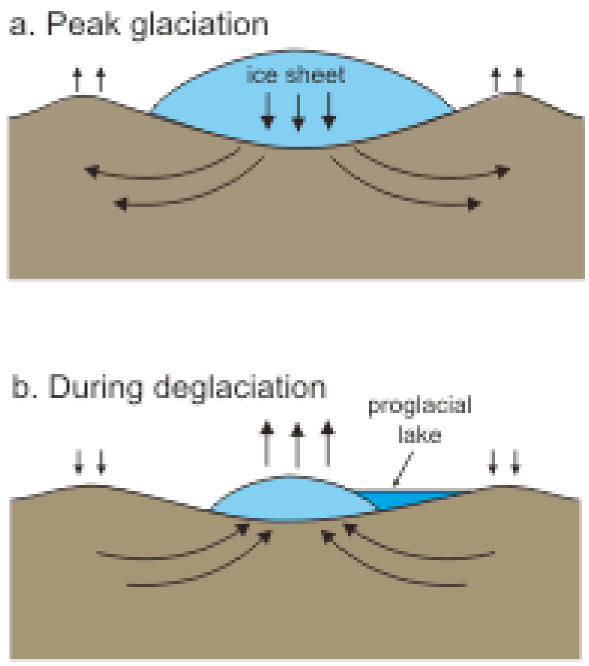
– Corrections for lithosphere age, sediment loading…

– Difficult to measure, poorly known.

– Use ***magnitude as constraint (+/- 900 meters).***

Post-Glacial Rebound (PGR)

- Glacial Isostatic Adjustment (GIA).
  - ***returning to isostatic equilibrium***.
  - Unloading of the surface as ice melts (rapidly).



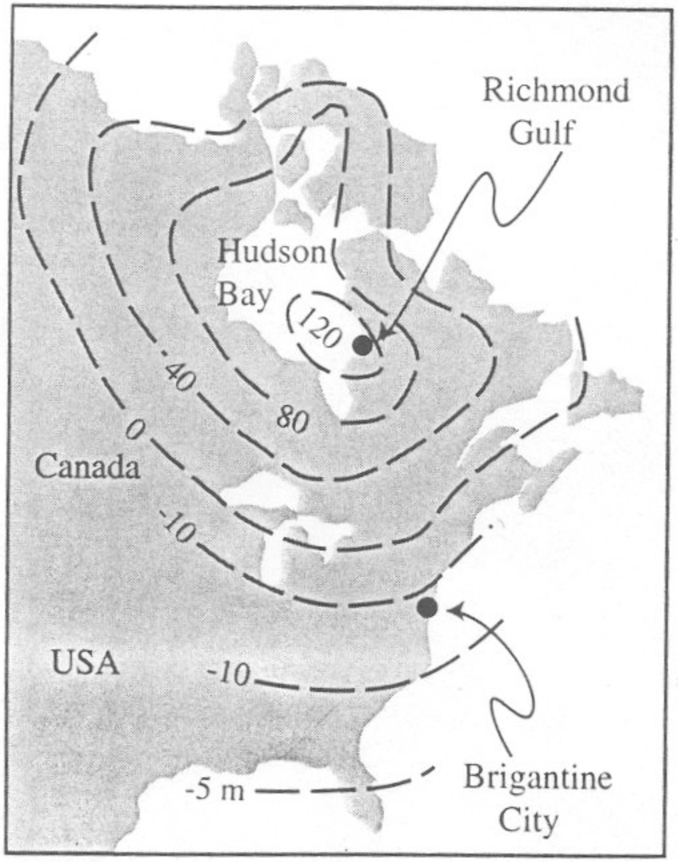
From :

http://www.pgc.nrcan.gc.ca/geodyn/docs/rebound/glacial.html

Post-Glacial Rebound (PGR)

- Drop in apparent sea-level, caused by uplift of the land.
- 100' s of meters in < 18,000 years.
- Very well constrained in a few locations.
- Moderate quality in lots of locations.

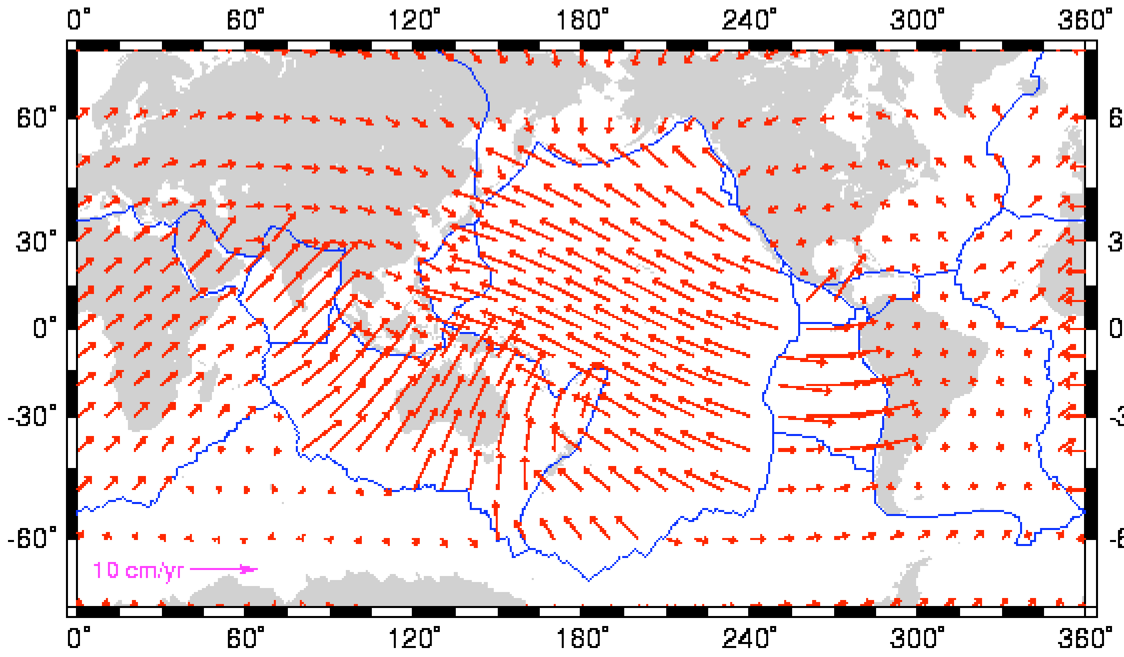
Uplift/Subsidence (meters)



From http://www2.umt.edu/geology/faculty/sheriff/

Plate Motion

- Well-known for the present time.
- Accuracy degrades for times further in the past.

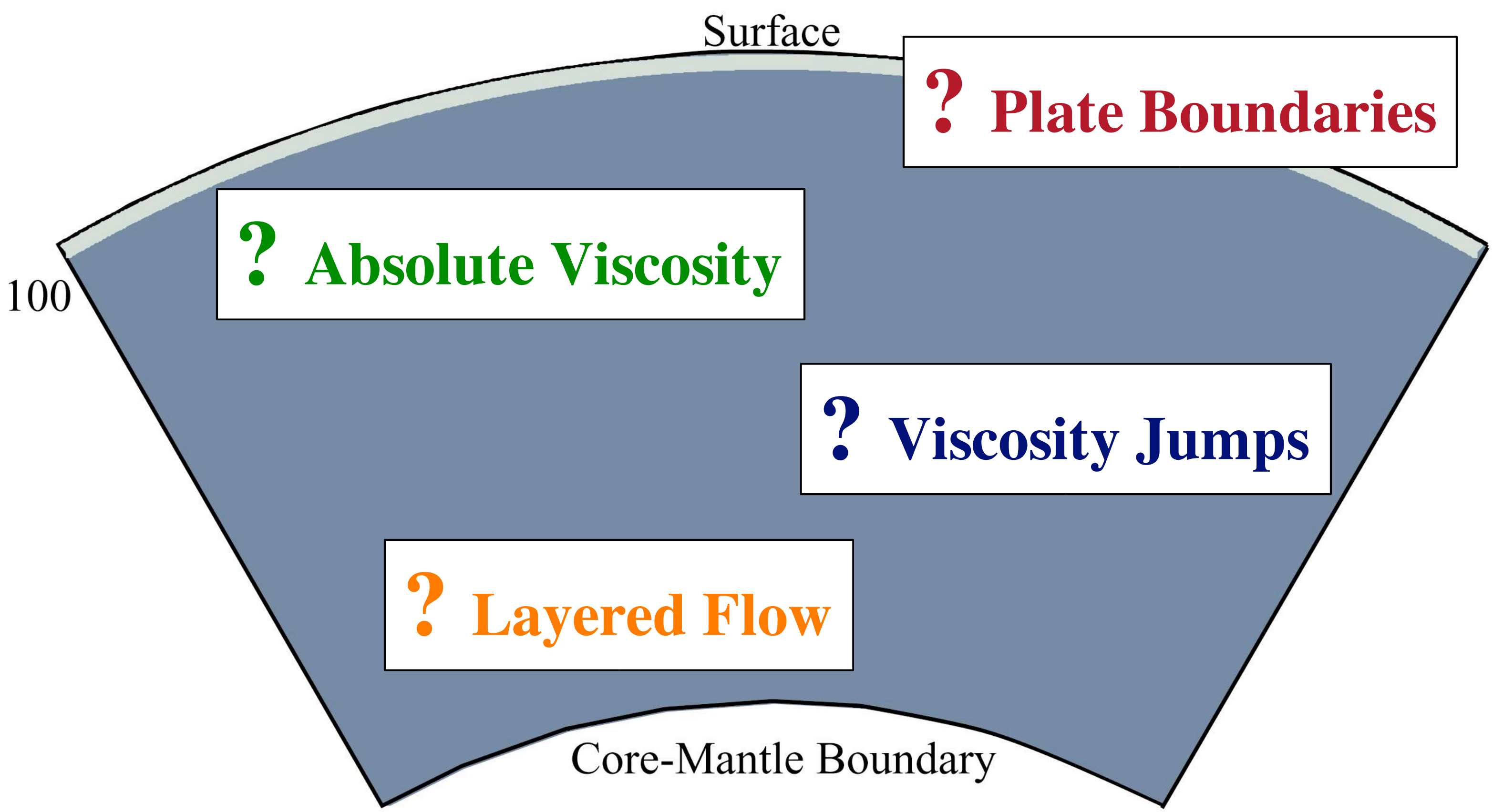


Data: Argus & Gordon 1991 (NUVEL-NNR), Figure: T. Becker

Summary of Surface Observations

Observation	**Quality**
Post Glacial Rebound	variable (center)
Plate Motion	good (recent)
Dynamic Topography	
- surface/670 km/CMB	poor (magnitude)
Geoid	good (<100 km)
Free-air Gravity	good (shallow)

Building the Mantle Structure



Methods - 1

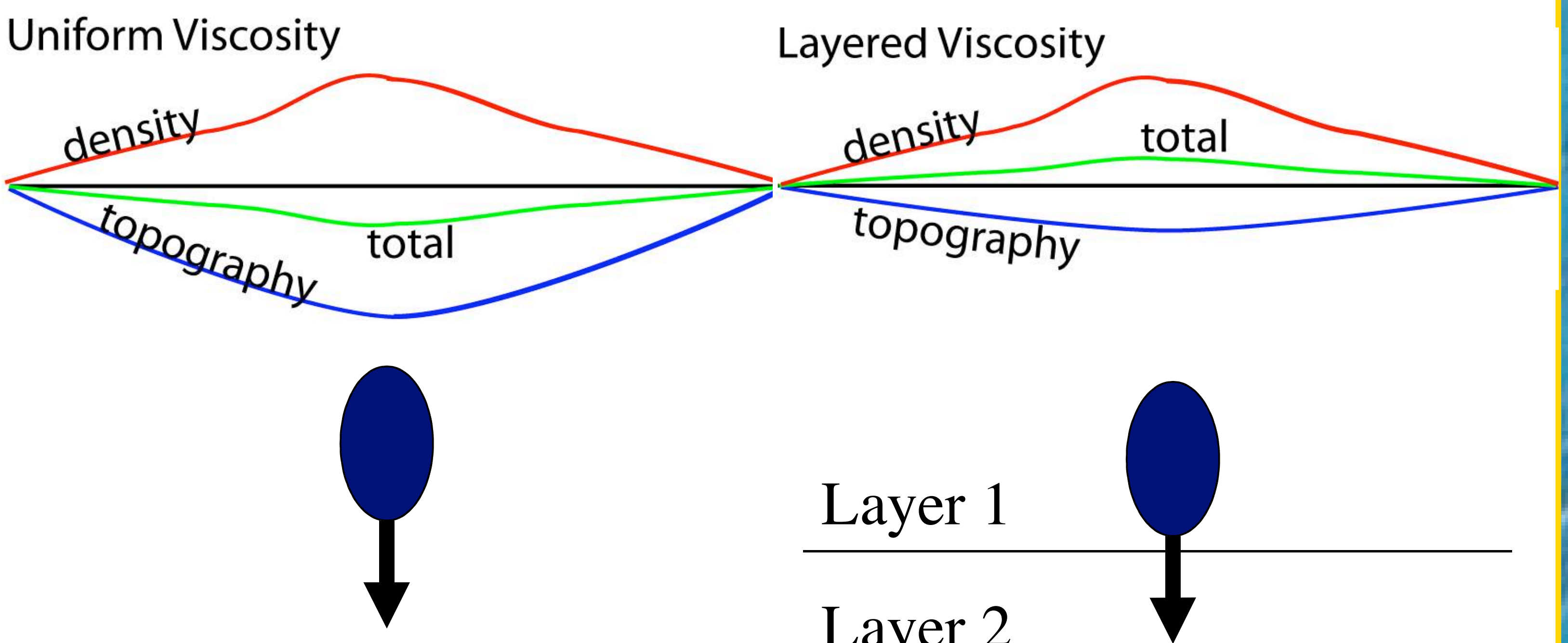
- Solve coupled flow & gravitational potential equations for:
  - ***instantaneous*** deformation (flow, surface deformation, geoid) ***relative*** viscosity variations.
  - ***time-dependent*** deformation (relative sea-level curves, plate motions) for ***absolute*** viscosity and variations.
- Internal density structure (except PGR):
  - seismic tomography, slab seismicity, history of subduction.
  - ***scaling to density.***

Methods - 2

- ***Analytic*** Methods
  - Radial/1-D or limited lateral structure.
  - Forward and inverse models.
    - How many layers (unknowns) can be determined?
    - Predict multiple observations.
- ***Numerical*** Models
  - Radial & strong lateral viscosity variations.
  - Forward models (too costly for inversions?).
  - Global and/or regional studies.

Geoid

Sensitive to ***radial*** and ***lateral*** viscosity structure.



"Robust" Constraints on Viscosity Structure (1)

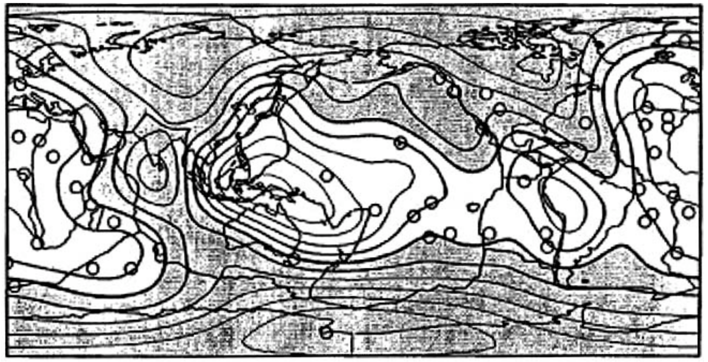
- Geoid:
  - *Very long wavelength* structure explained by lower mantle structure.
  - *Jump or increase* in viscosity from upper to lower mantle.

From :

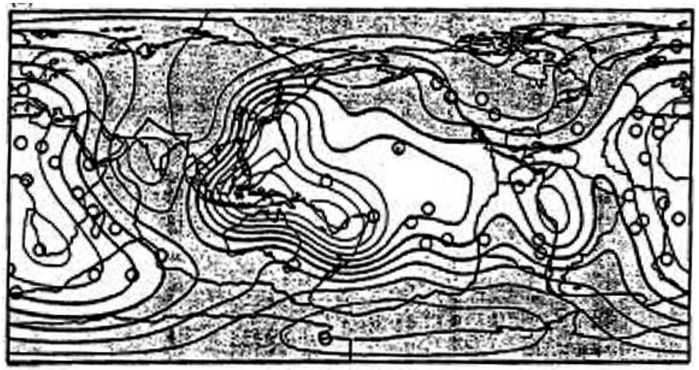
Hager & Richards,

phil trans 1989, (fig 1, 5a)

Observed

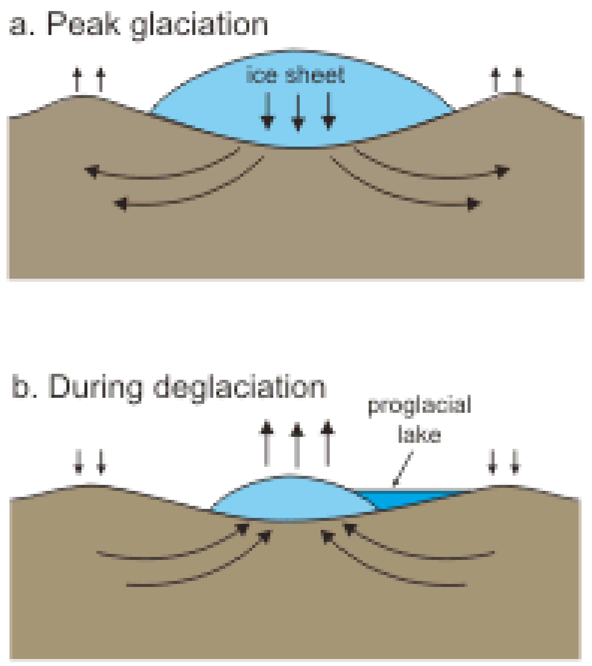


Predicted



Post-Glacial Rebound (PGR)

- Rate of rebound:
  - sensitive to ***absolute viscosity***.
- Depends on:
  - ice-load size/shape, sea-level measurements & unloading history.
  - lateral variations in elastic plate properties.



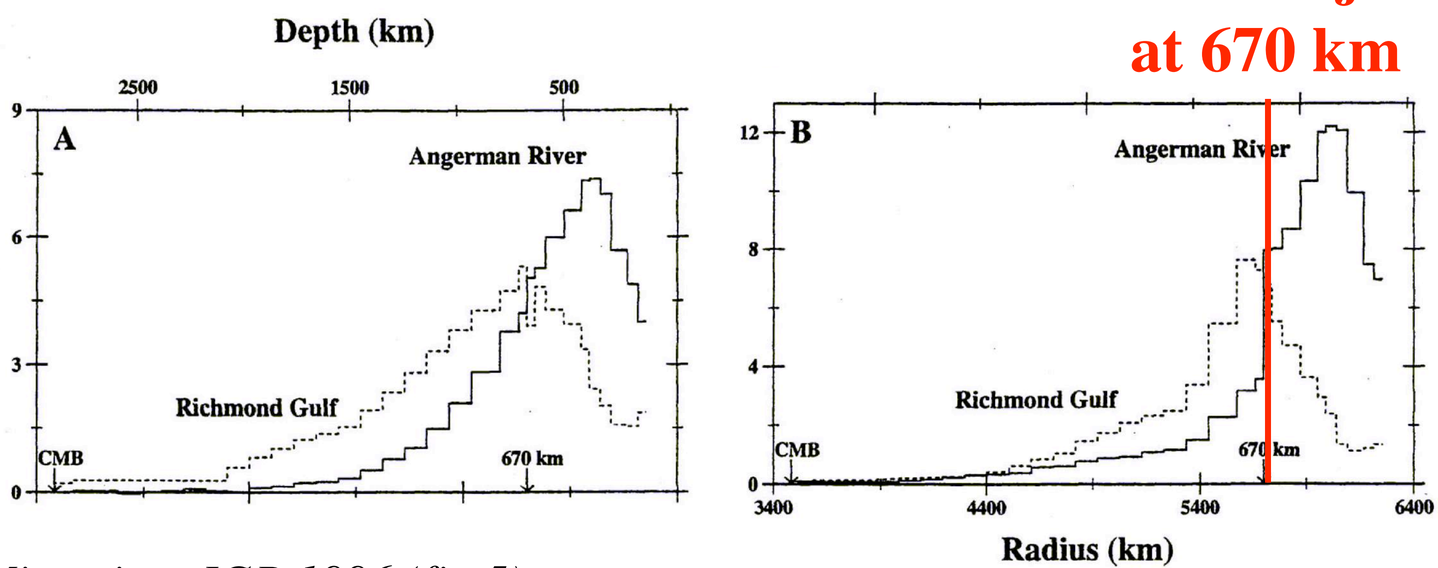
From :

http://www.pgc.nrcan.gc.ca/geodyn/docs/rebound/glacial.html

"Robust" Constraints on Viscosity Structure (2)

- Post-glacial rebound:
  - Average ***upper*** **(<1400 km)** mantle viscosity.
  - Haskell value, $\eta = 10^{21}$ **Pa s.**

Start with jump at 670 km



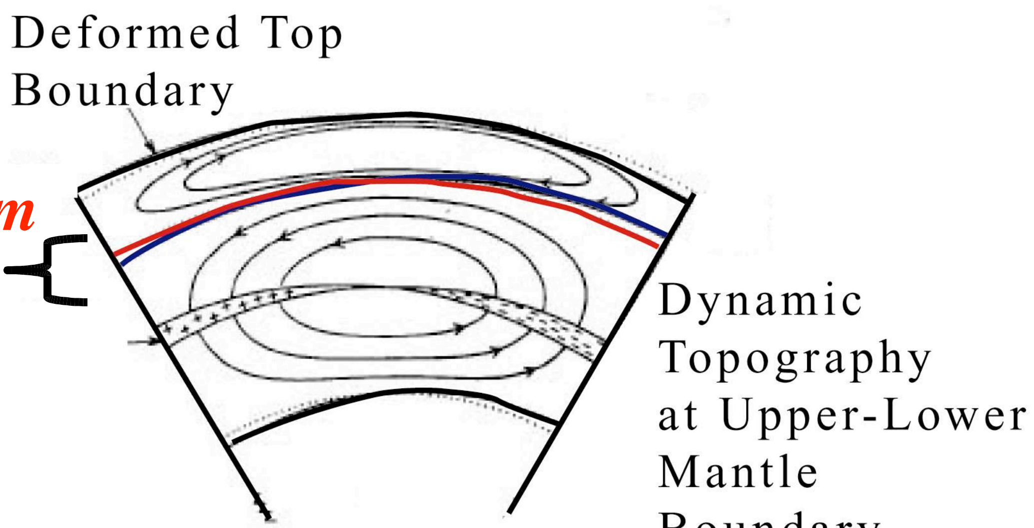
Mitrovica, JGR 1996 (fig 5)

Frechet Kernels (depth sensitivity)

"Robust" Constraints on Viscosity Structure (3)

- Chemical boundary to flow at ***670 km inconsistent*** with small (~10 km) observed dynamic topography.

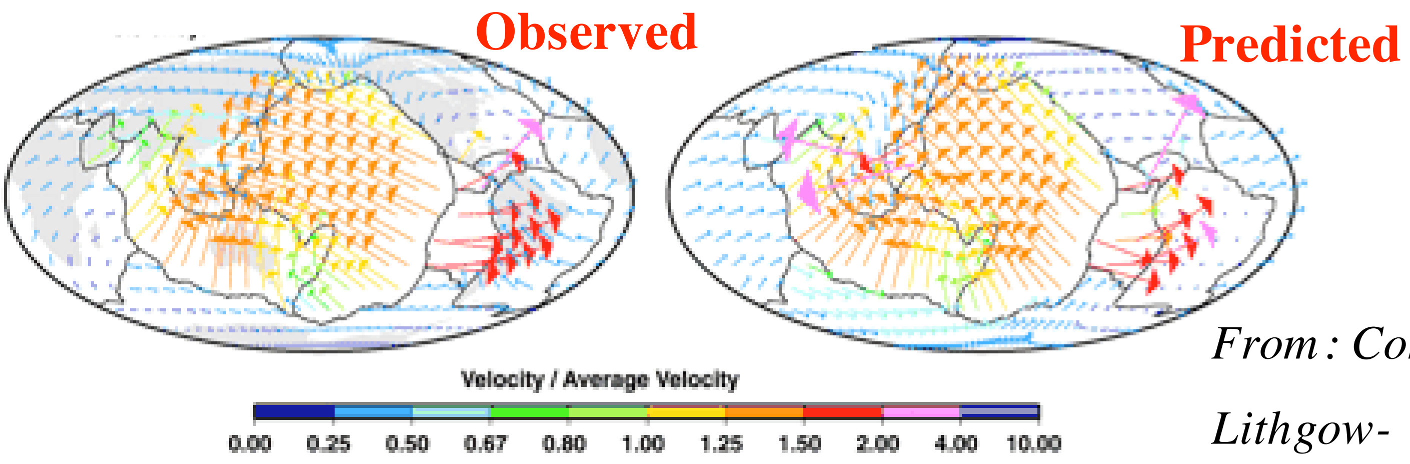
Predicts ~ 100 km topography



Richards & Hager, Physics of the Planets, 1988 (fig 5)

Plate motions

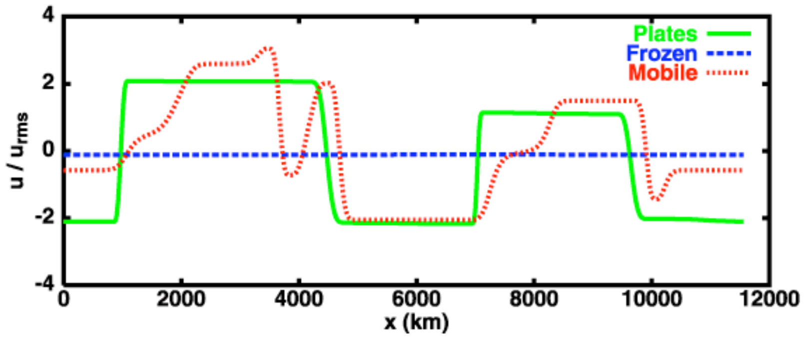
- Purely radial viscosity structure
  - ***poloidal motion*** (divergence/ convergence) .
- How to use in modelling?
  - Impose as boundary conditions.
  - Predict from model (defined plate regions).



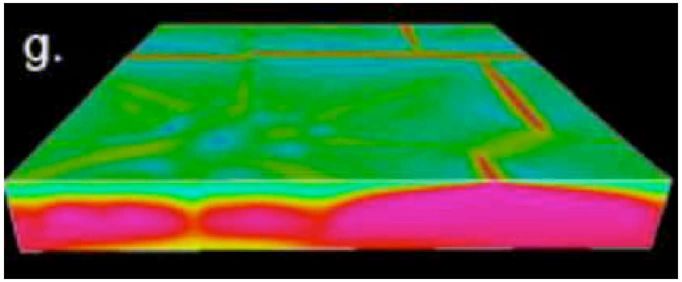
From: Conrad & Lithgow-Bertelloni,

"Robust" Constraints on Viscosity Structure (4)

- ***Weak asthenosphere*** stabilizes plate motion.
- Lateral variation in strength (fault/shear zone)
  - ***rigid*** plates & ***toroidal motion*** (strike-slip).



Richards et al, Gcubed, 2001 (fig. 3)

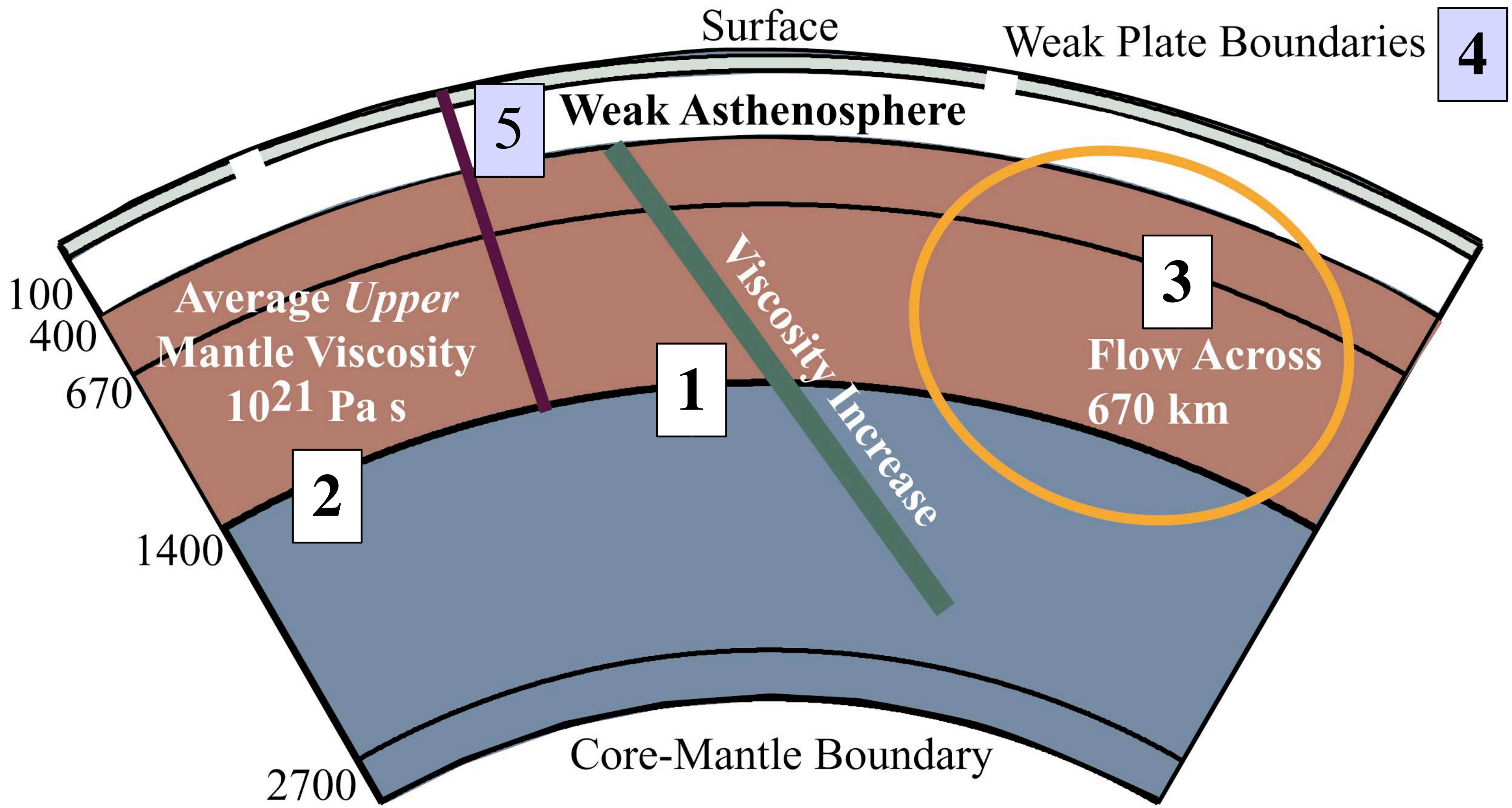


Tackley G3, 2000a (fig. 8)

Summary of Surface Observations

Observation	Resolution
Absolute	
•	
Post Glacial Rebound	*Note: Absolute viscosity trades-off with assumed density*
Plate Motions	
	margins & asthenosphere.
Relative	
Dynamic Topography	No boundary to flow.
Geoid	Deep, long wavelength.
Free-air Gravity	Shallow, intermediate-long wavelengths

“Robust” Mantle Structure



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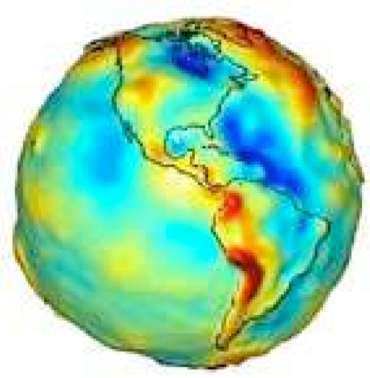
  - Rheology
  - Challenges
- Conclusions



Can we go further?

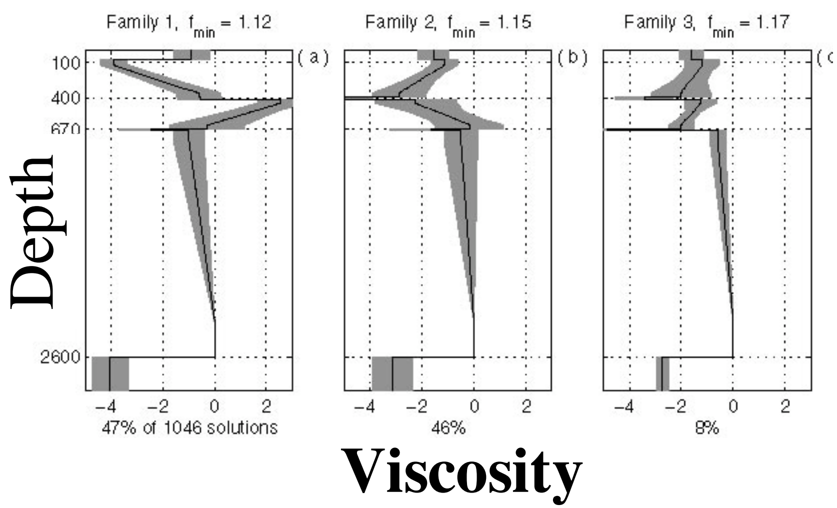
- What is the ***resolving power*** of the observations?
  - How many layers?
  - What range of viscosity?
  - Are model results ***unique***?
  - How are models affected by ***a priori assumptions***?

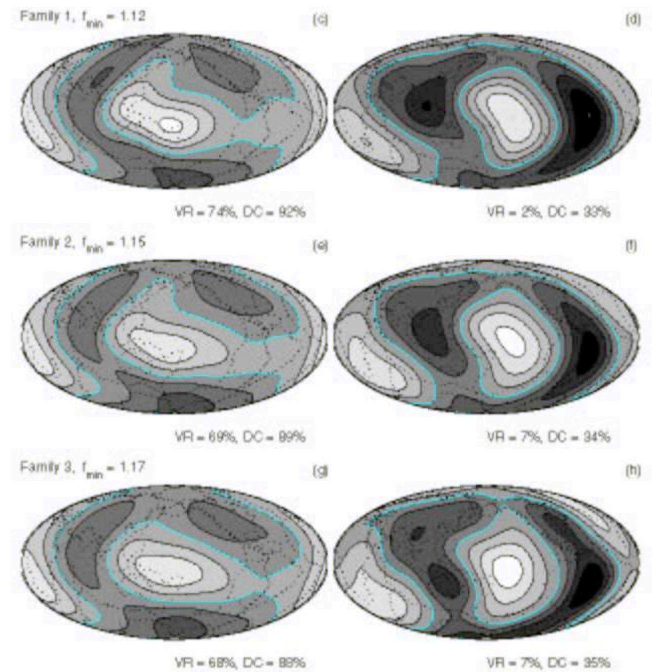
Challenges

- **1) Get to know the data:**
  - need observations that are ***sensitive*** to variations in mantle structure.

Current Mantle Structure Models - Radial

- Predict Geoid & Dynamic Topography
- Variance reduction (L=2-6): **74%**
  - *All three families work*



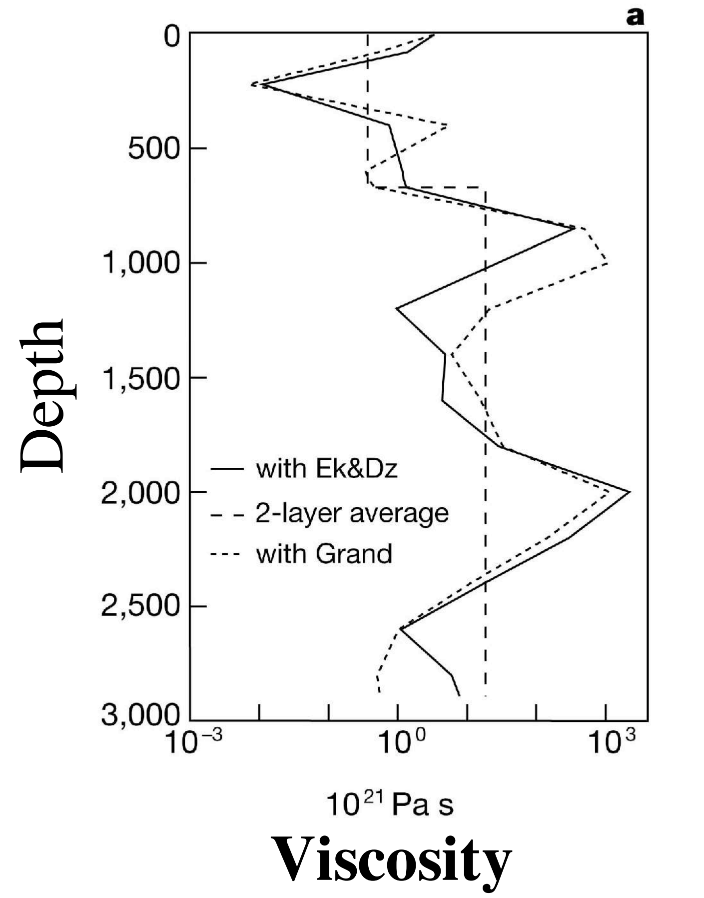


Geoid **Dyn. Topo.**

Panasyuk & Hager, GJI 2000 (fig 5 & 6).

Current Mantle Structure Models - Radial

- Observations:
  - free-air gravity/geoid,
  - plate divergence,
  - excess CMB ellipticity
- Irregular radial profile
  - L=2-20 geoid
  - Variance reduction **77%**
  - Compared to **65%** for two layer model.
- ***Is this result unique?***



Forte & Mitrovica Nature 2001 (fig 2)

Challenges

- **1) Sensitive observations.**
- **2) Limitations of methods:**
  - **Analytic** methods
    - ***Radial viscosity*** structure.
    - Linear (***Newtonian***) rheology.

Viscous Rheology

- Experimental data:
  - Viscosity is strongly dependent on pressure temperature, stress (strain-rate), grain size, water, melt, & mineralogy …

Flow Law:

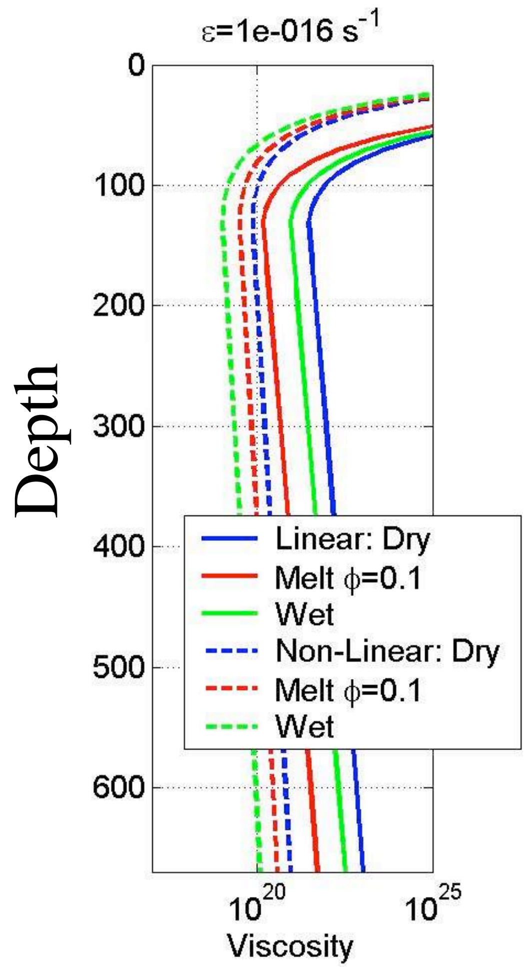
$$\dot{\epsilon} = A\sigma^n d^{-p} C_{OH}^r e^{-\alpha\phi} \exp\left[-\frac{E+PV}{RT}\right]$$

Viscosity:

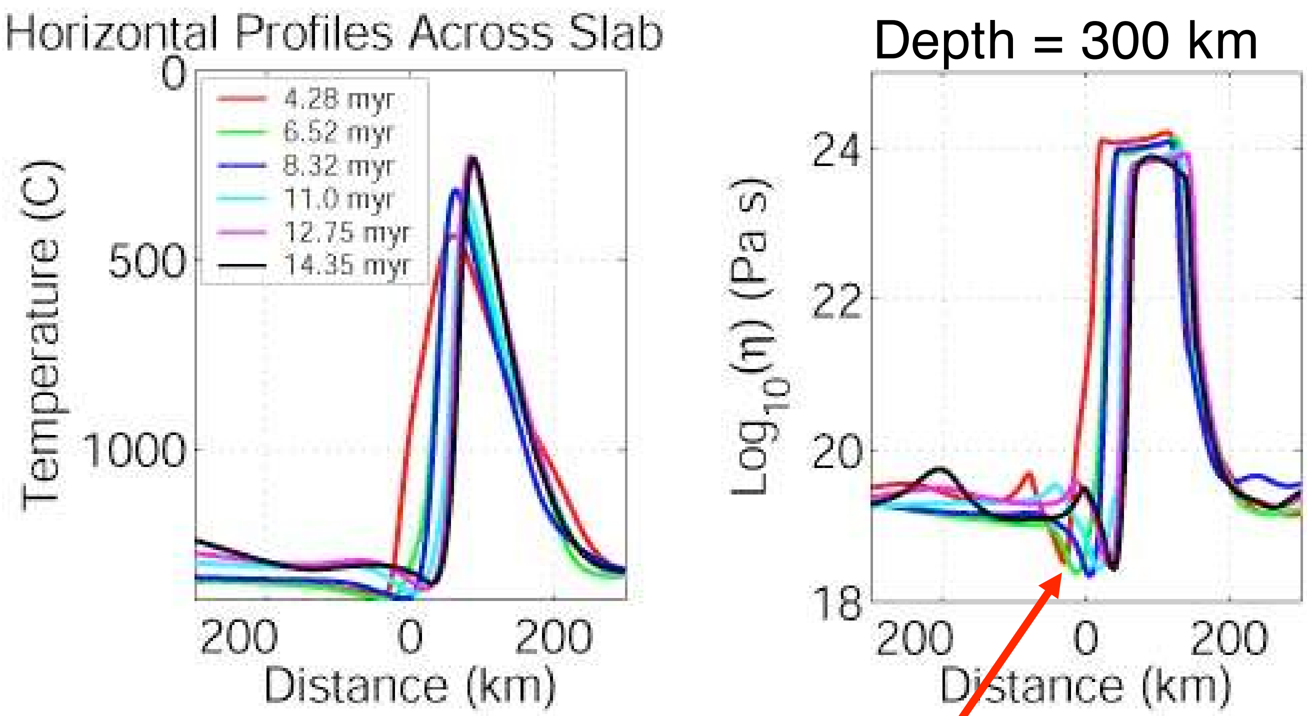
$$\eta = \frac{\sigma}{\dot{\epsilon}}$$

Viscous Rheology

- ***Olivine***: well-constrained.
  - peridotite ≠ olivine.
- ***Deep-earth mineralogy***
  - Need better constraints
  - e.g. perovskite - theoretical.
- Educated guesses:
  - grain size,
  - water & melt concentrations.



Viscous Rheology



Note low viscosity regions at slab boundary

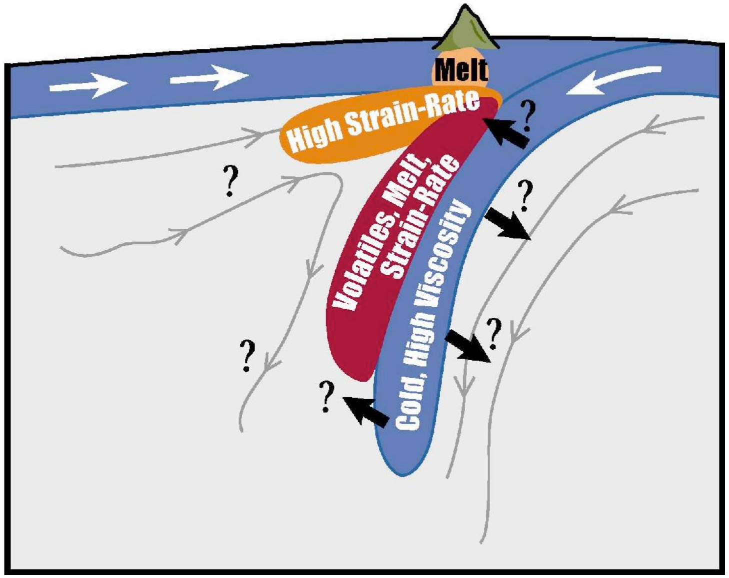
Should we go further?

- Experimental data

  ➜ strong viscosity variations.

- 3-D dynamics
  - ***slab penetration*** into strong lower mantle,
  - ***mixing*** of geochemical signatures,
  - origin of ***plate tectonics***.

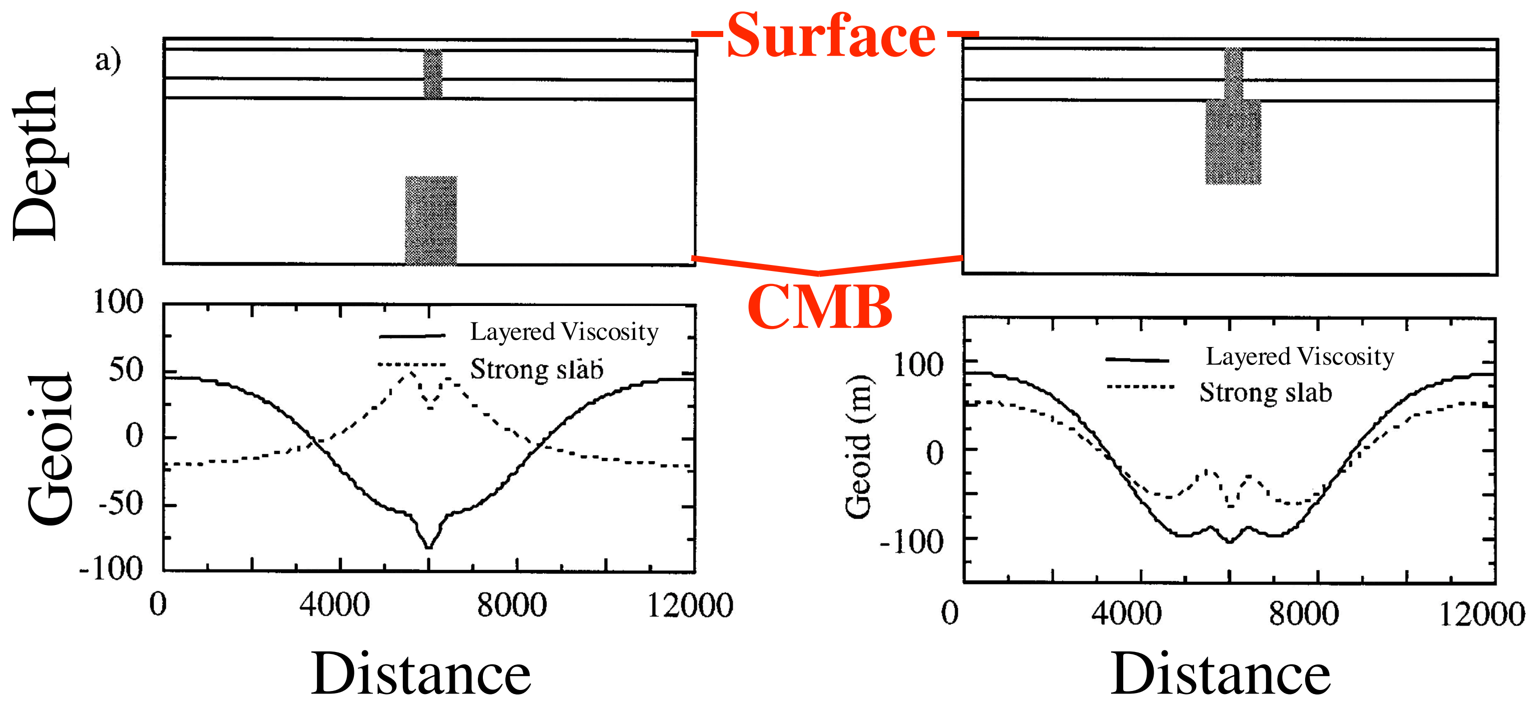
- Yes ➜new challenges.



Challenges

- **1) Sensitive observations.**
- **2) Limitations of methods:**
  - **Analytic** methods
    - ***Radial viscosity*** structure.
    - Linear (***Newtonian***) rheology.
  - Realistic rheology is **numerically** expensive ***memory/time/cpus***.

Illustrative Example (1)



- Stiff slab in the mid-mantle vs the lower mantle: ***reverses sign of the geoid***

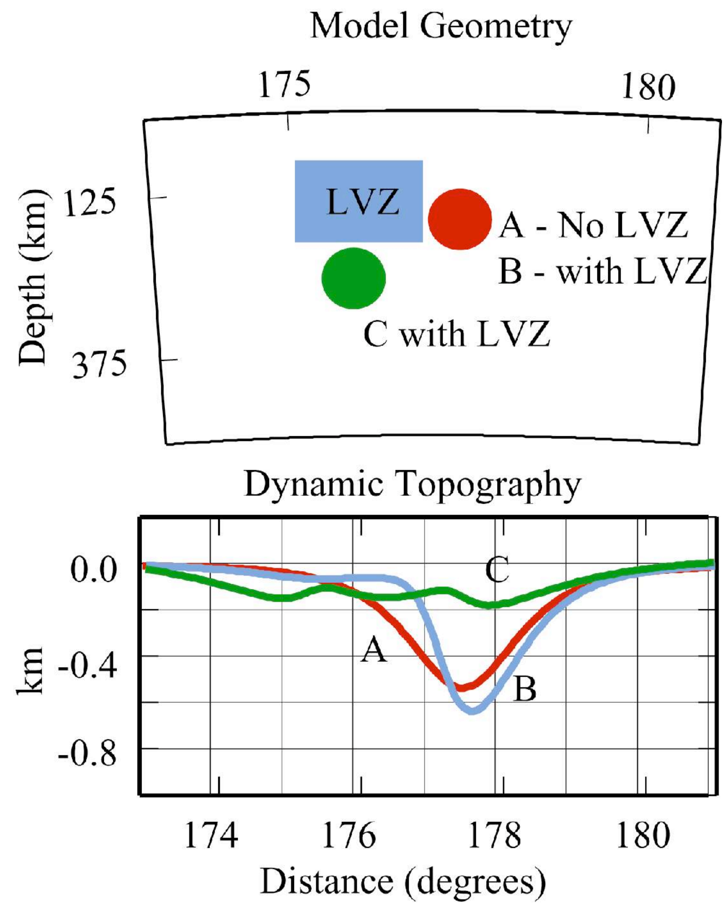
Zhong & Davies EPSL 1999 (fig 5)

Illustrative Example (2)

- Dense sinker
- Low Viscosity Zone

- ***LVZ modifies dynamic topography***

Billen, Appendix, Thesis Caltech 2001.



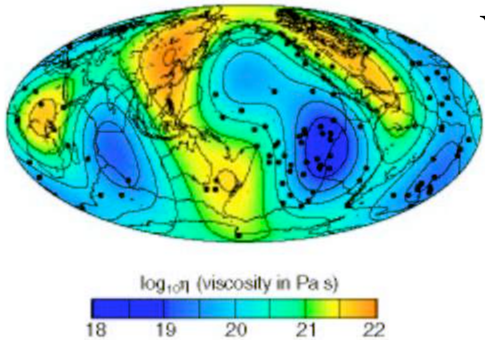
Two Illustrative Examples

- What is the magnitude of LVVs in
  - upper mantle (weak regions & strong slabs)?
  - lower mantle (strong slabs)?
- May be right for the wrong reasons?
  - Lateral viscosity variations can ***reverse*** the sign of the geoid.

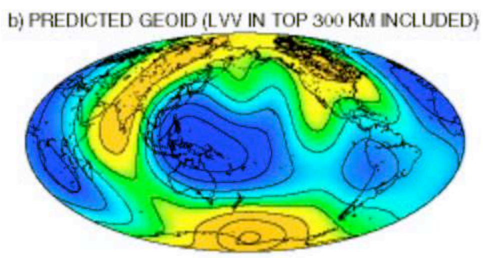
Is a radial viscosity structure still a useful parameterization?

Current Mantle Structure Models - Lateral

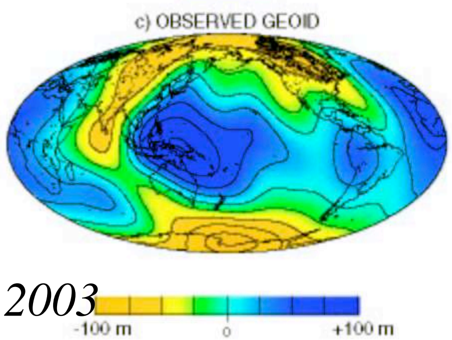
Viscosity



Geoid: Predicted



Observed



Cadek & Fleitout, GJI, 2003 (fig 10, 11)

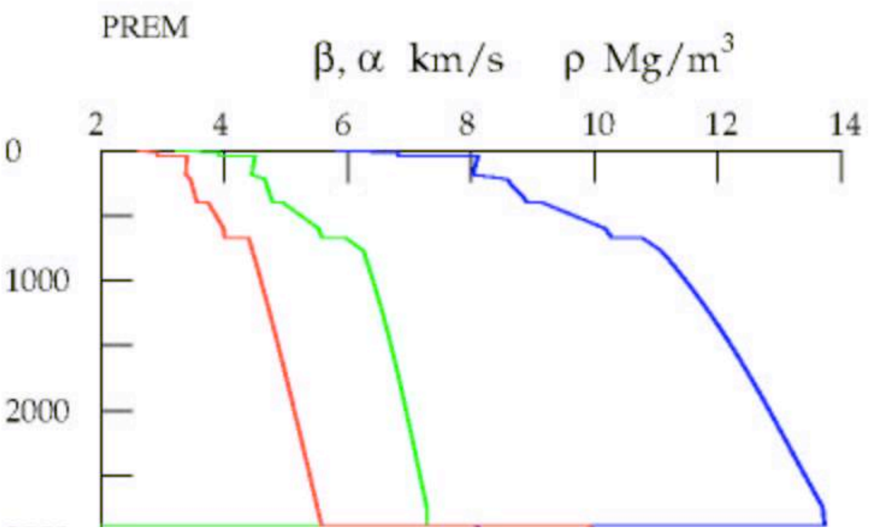
- Observations
  - Geoid.
  - Dynamic Topography.
- Inversion for LVV in top 300 km.
  - Up to L=4.
  - ***Inhibited flow at 670.***
  - Maximum variance reduction ***92%***
  - As good as 5 layer radial model

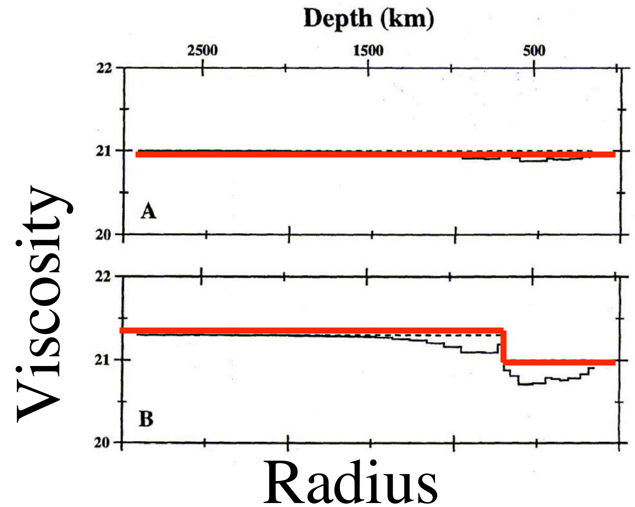
Challenges

- **1) Sensitive observations.**
- **2) Limitations of methods.**
- **3) A priori assumptions:**
  - Simple relationships between ***viscosity & seismic velocity*** boundaries.

Viscosity & Seismic Structure

- Are seismic discontinuities, viscosity discontinuities?
- Inversions can depend on starting structure.



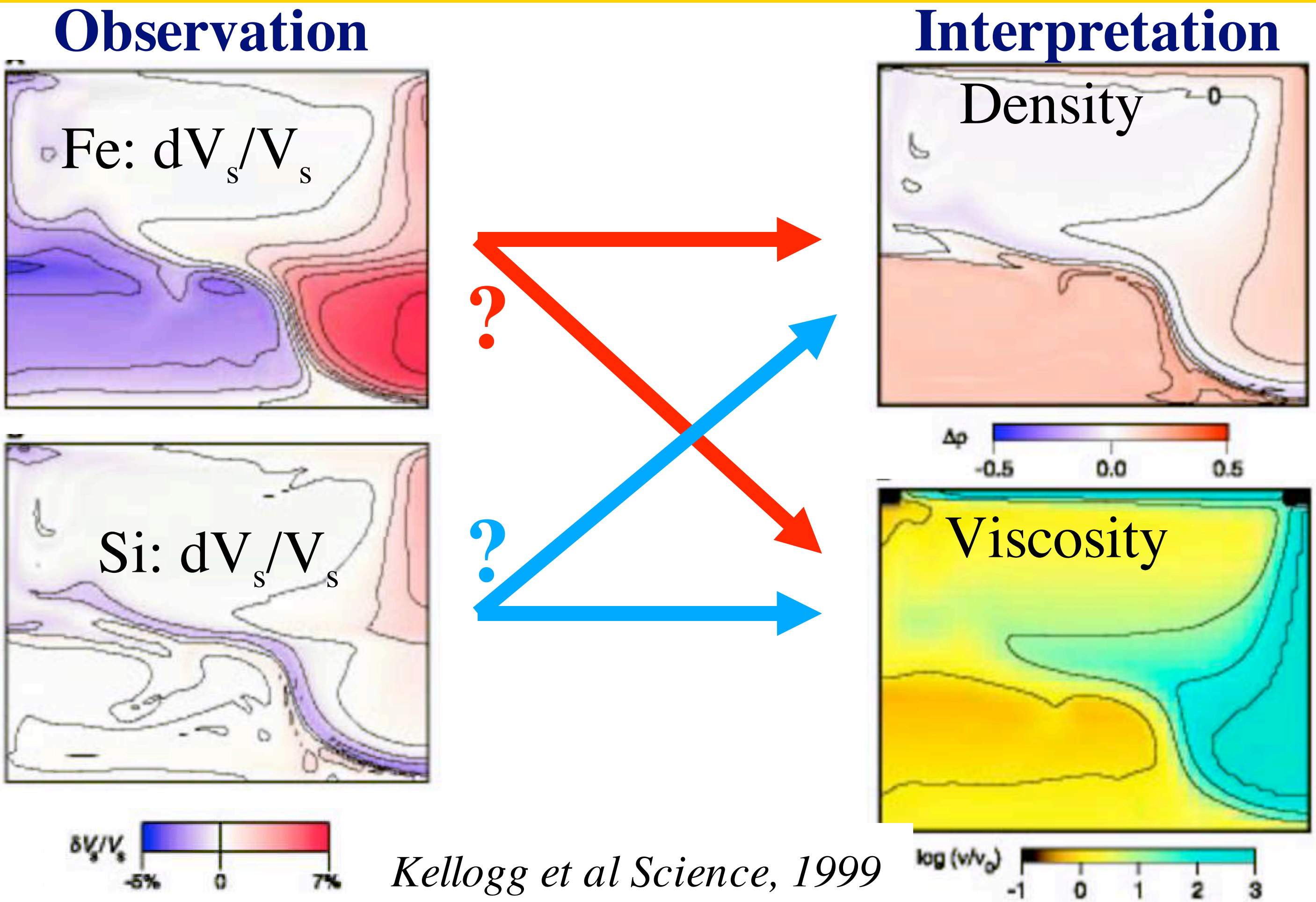


Mitrovica, JGR 1996, (fig 6)

Challenges

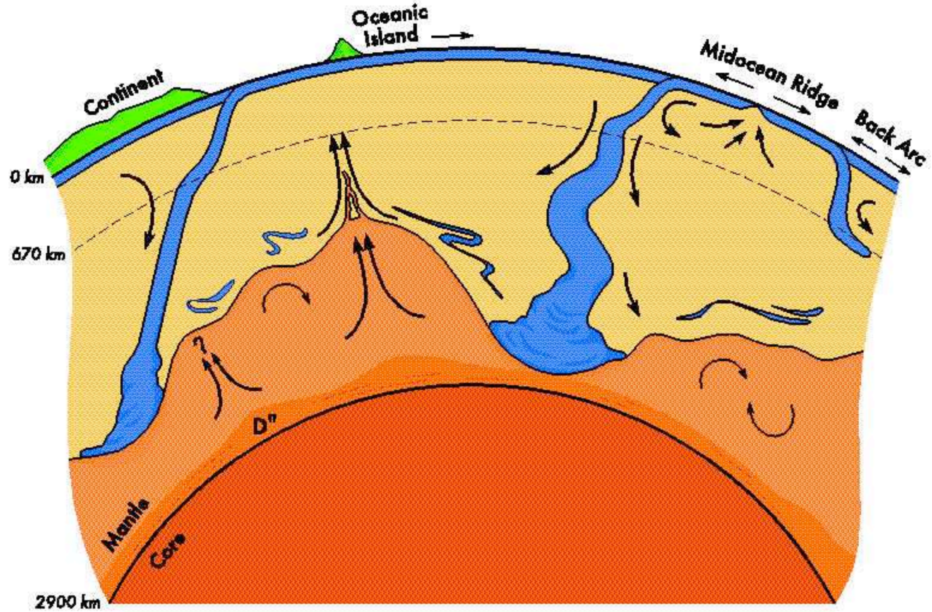
- **1) Sensitive observations.**
- **2) Limitations of methods.**
- **3) A priori assumptions:**
- **4) Poorly known observables:**
  - Seismic velocity-to-density scaling:
    - *Temperature and compositional buoyancy*
  - Dynamic topography on the surface and CMB:
    - ***not well known, but also contributes to the geoid***
  - Post-glacial rebound (***assumes ice-load***).

Seismic, Density & Viscosity Structure



Kellogg et al Science, 1999

Viscosity & Seismic Structure



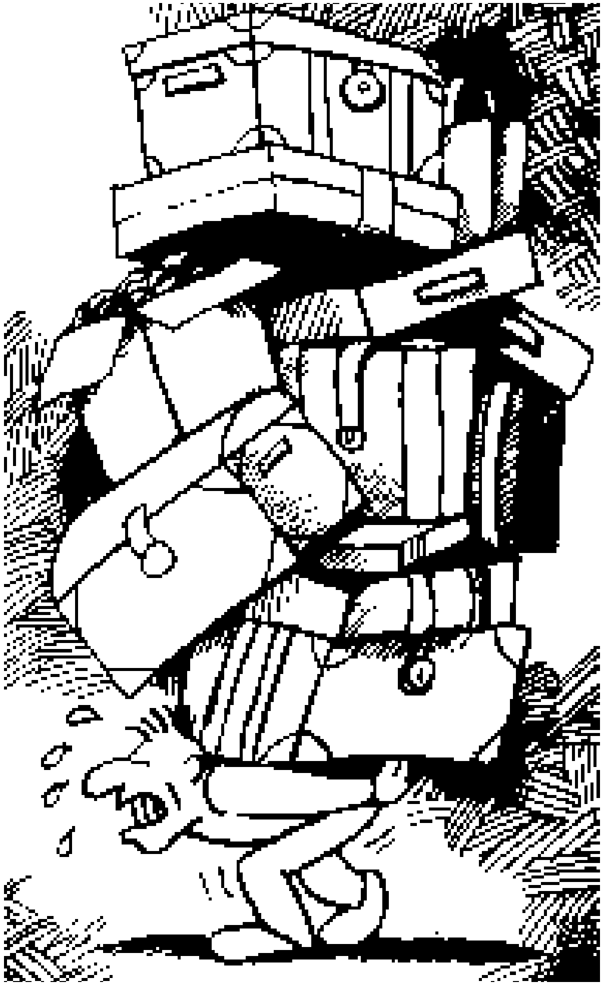
Kellogg et al

Science, 1999

How can we use surface observations to detect or rule-out this kind of structure?

Conclusions

- ***Unnecessary Baggage??***
  - Radial viscosity structure.
  - Linear (Newtonian) viscosity.
  - Seismic boundaries = viscosity boundaries.
- ***Inversions*** - how can these be extended? Unique?
- Use ***forward*** models to explore how complexities affect dynamics.



Conclusions

- Surface observables are ***not enough***.
- Better constraints on ***connections to seismic & mineralogical*** observations.
- Combine with ***observations that are sensitive to the subsurface*** behavior:
  - Seismic anisotropy.
  - Geochemical/petrologic constraints.
  - More experimental constraints on mineral physics and rheology.