Probing the Earth

IUGG Plenary Lecture

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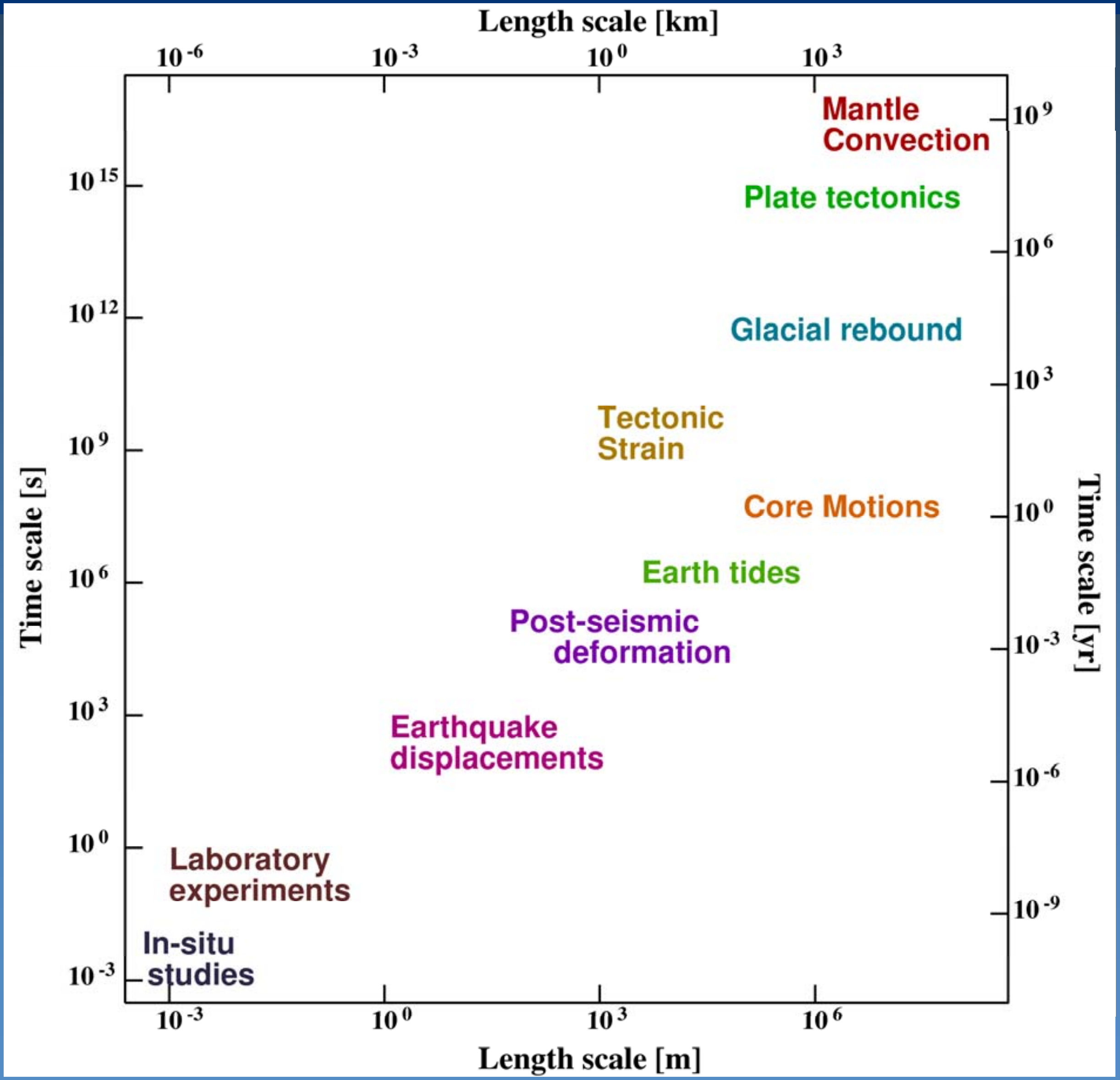
Scales of investigation

Time scales:
10^{-8} s – Mineral Physics
10^{9} yr – Mantle Flow

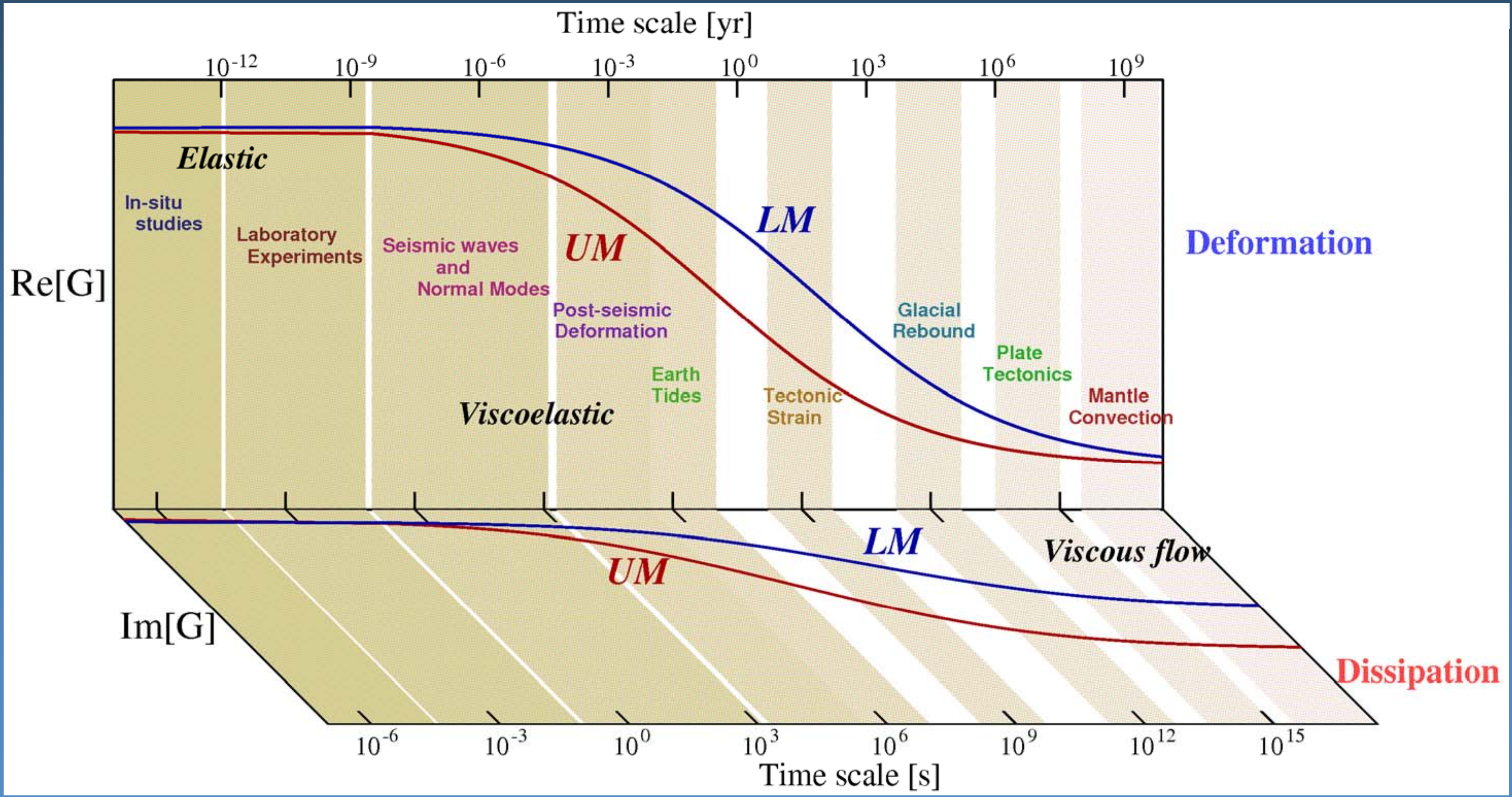
Spatial Scales:
10^{-6} m – Crystal Properties
10^{5} m – Plates

Multi-disciplinary

Overlapping sets of information



Variations of Rheology with scale

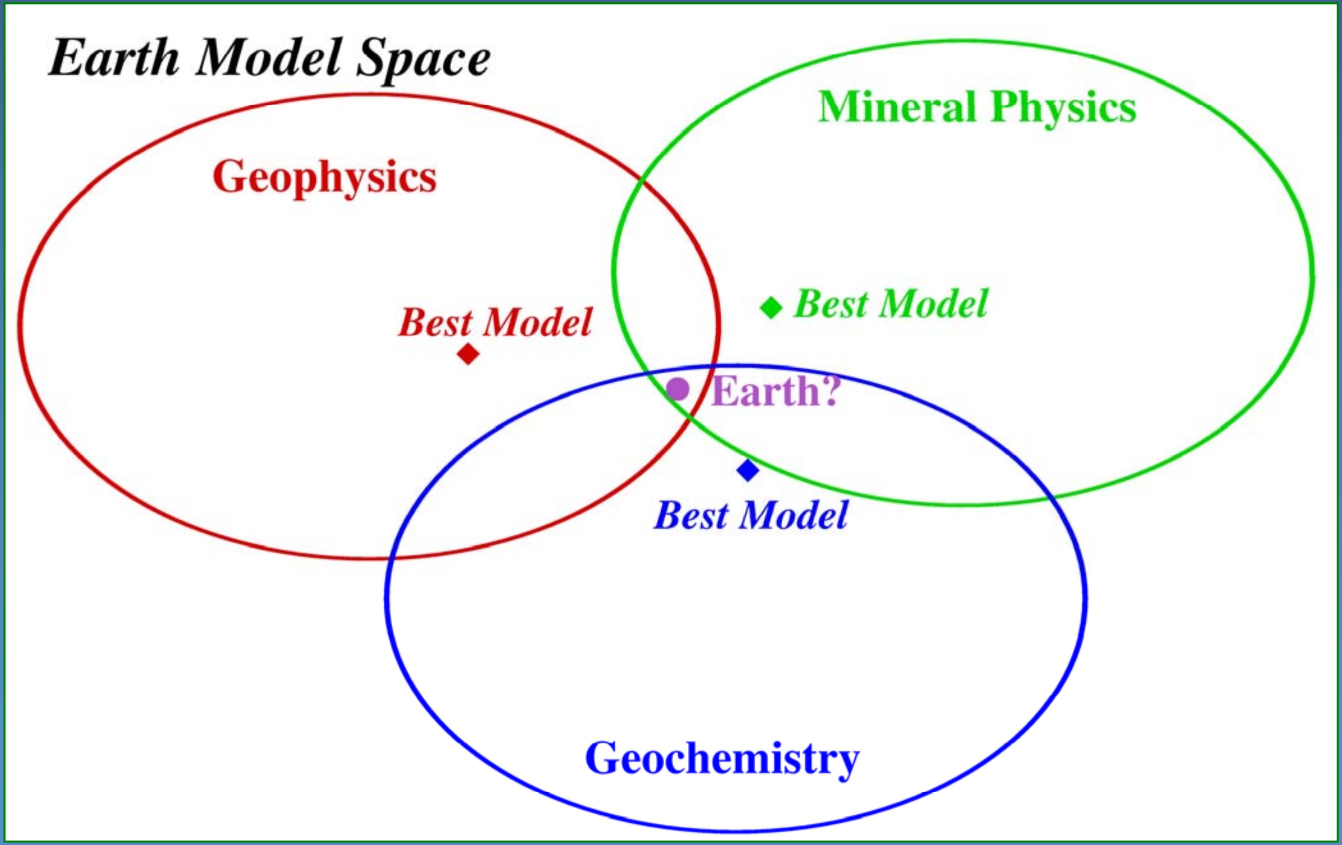


Earth's Mantle

- The Earth's mantle is a complex, dynamic mineral assemblage with both internal heating and heat influx from the core.
- Specific disciplinary tools tend to emphasise those aspects of the system which fit with simple models.
- Frequently there will be a bias due to selective sampling beyond our control e.g. locations of earthquakes
- The true Earth may well not conform to the preferred position derived from individual disciplinary studies – which themselves may indicate inconsistent states.

Disciplinary Interaction

The most desirable views of the nature of the Earth from the perspective of a number of distinct disciplines are unlikely to be favoured when all results are taken together.

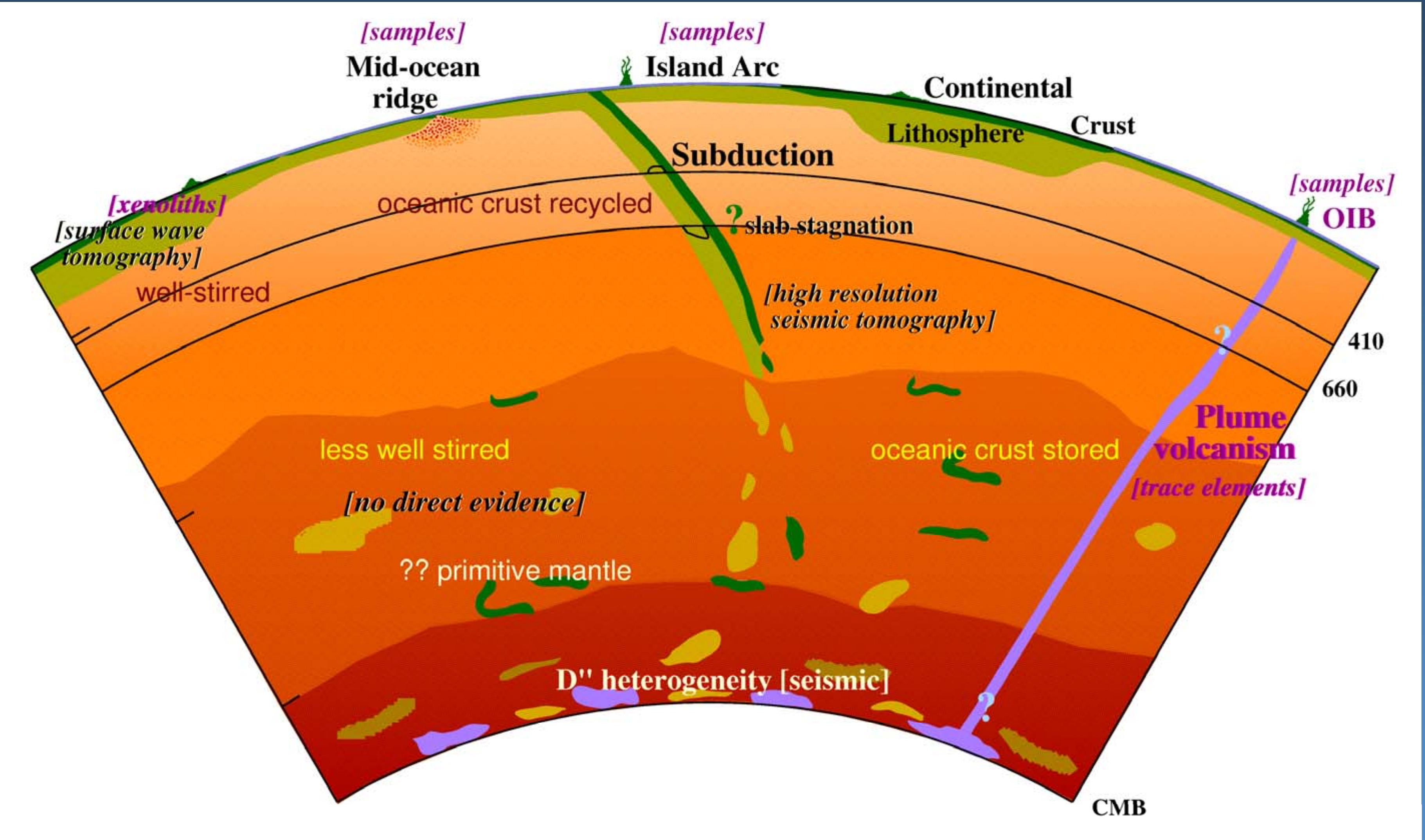


Linking Disciplines

- We have also to recognise that it may not be natural to equate two sensible simplifications
  - e.g. the average structure of the Earth and results from mineral physics based on the influence of pressure and temperature

  even though we would like to use such concepts to enlarge our knowledge.
- In particular geodynamic modelling studies make it clear that the average temperature at some depth will **not** directly correspond to the temperature associated with average properties (though the approximation can be reasonable)

Earth's Mantle – multiple viewpoints



Mantle Heterogeneity Scales

- Much of the patterns of variation in seismic wavespeed will have a strong thermal component e.g. subduction processes, but changes in major element composition may be significant in lower mantle
- Deep mantle features do not all link to recent subduction
- Scattering studies indicate the presence of smaller scale heterogeneity
- Note that there does not have to be a simple relation between geophysically imaged heterogeneity and geochemical reservoirs recognised by trace-element characteristics

Earth's Mantle – multidisciplinary

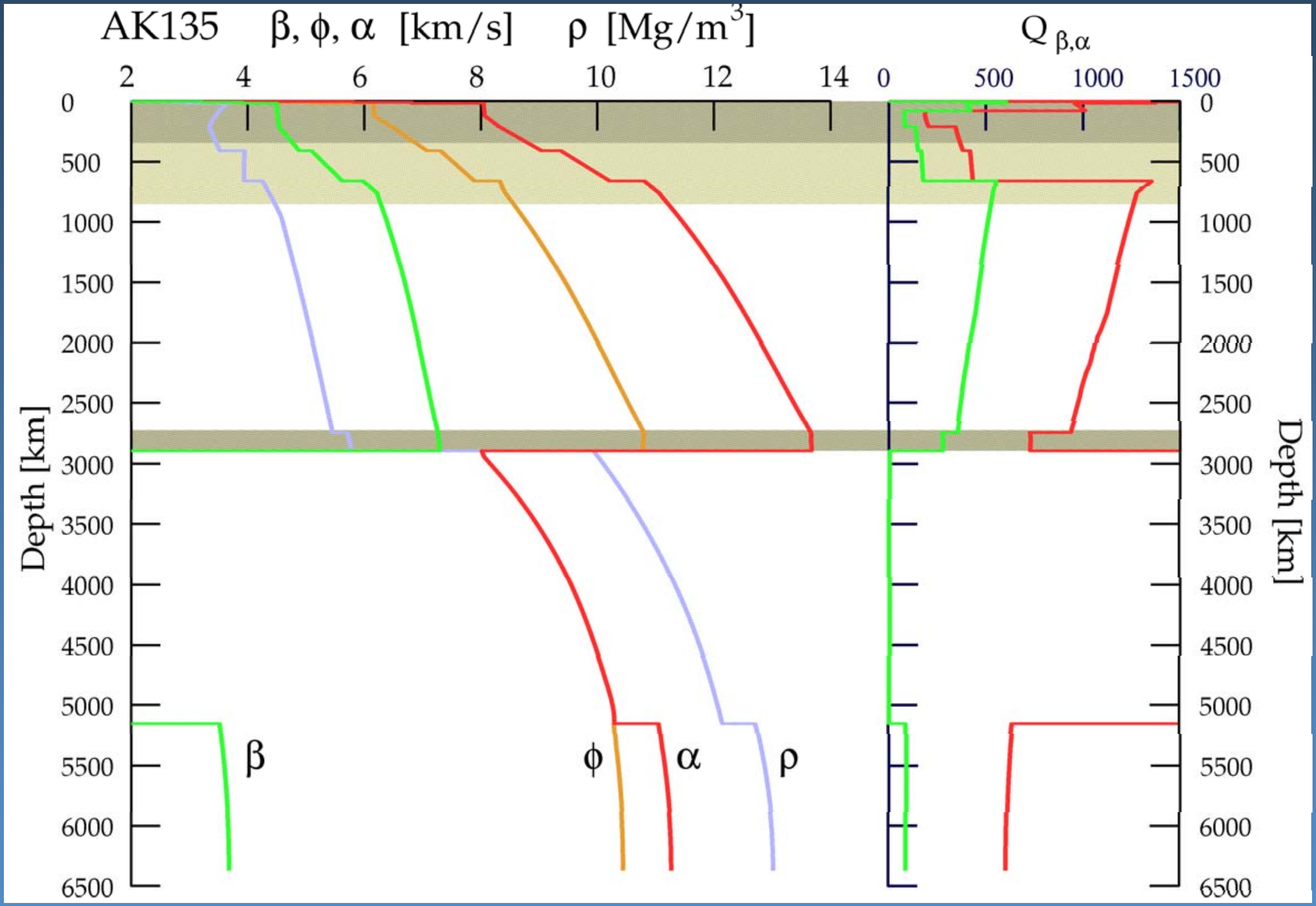
- It is most important to take a holistic viewpoint, and to work with multidisciplinary input
- This requires recognition of the capabilities and the limitations of the different probes into the Earth
  - Where are the weaknesses?
  - How can they be rectified?

- Geophysical probes are immediate, geochemical information has a dimension of time
  - With residence times of 500 Ma – 1 Ga is the geochemical information for the same mantle as the present day?

Deep Earth properties

- The most common approach to understanding the properties of the deep Earth has been via the construction of seismological models and their subsequent interpretation through matching of results from mineral physics.
- Most effort has been expended on the dominant radial structure, but the nature of 3-D variations is of major importance in understanding geodynamic processes.
- In the middle part of the lower mantle the level of heterogeneity is such that the radial gradients should be reliable.

Seismological models



The shaded zones indicate the strongest 3-D variations where a 1-D model will inevitably have major limitations

“Average Models”

What is the relevance of the average model?

- How do we average?
  - radial (resolution issues – averaging lengths)
  - spherical shells (comparisons of different styles of irregular sampling)
- What do we average?
  - V(<T>) .ne. <V(T)>
    but might be close (cf numerical simulations)

What questions should we be asking?

Nature of heterogeneity spectrum as a guide to dynamic processes

Mineral seismic models

- In recent years efforts have been made to use mineral physics models to make direct predictions for seismological information to be compared to observation.
- Such a process requires a very high level of reliability for the mineral physics models
  - for individual minerals including effects such as spin transitions in Fe
  - for the composite properties associated with the appropriate phase assemblage
- It also requires a very keen appreciation of the class of seismic information to be used and its dependency on earth structure.

Seismological representations I

- Seismological models are normally specified in terms of wavespeed, because this reduces the influence of the poorly known density distribution – that is not needed for the times of passage of seismic waves

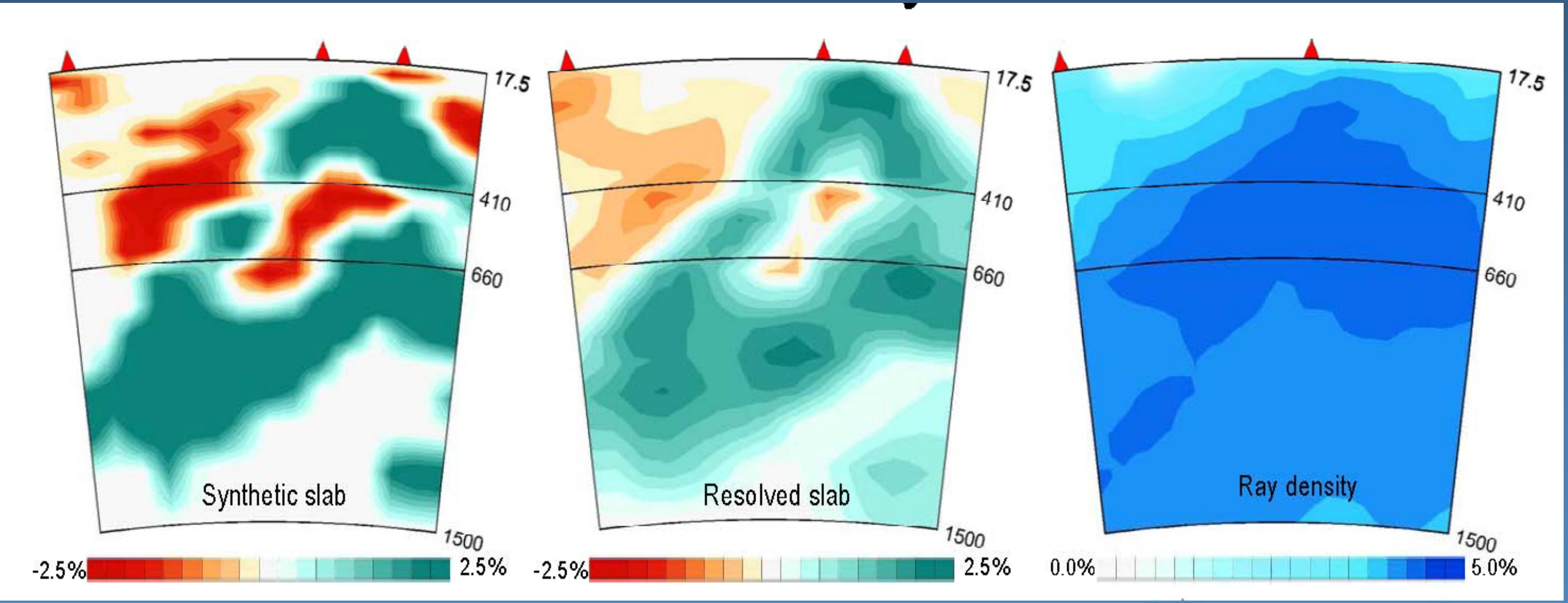
  shear wavespeed $\beta = (\mu/\rho)^{1/2}$

  bulk-sound speed $\phi = (\kappa/\rho)^{1/2} = (\alpha^2 - \frac{4}{3}\beta^2)^{1/2}$

- Where parametric models are employed greater flexibility can be achieved by working directly with moduli and density
- Such a representation is then closer linked to mineral physics information
- Nevertheless much seismic tomographic information is likely to be represented through wavespeed variation

Seismological representations II

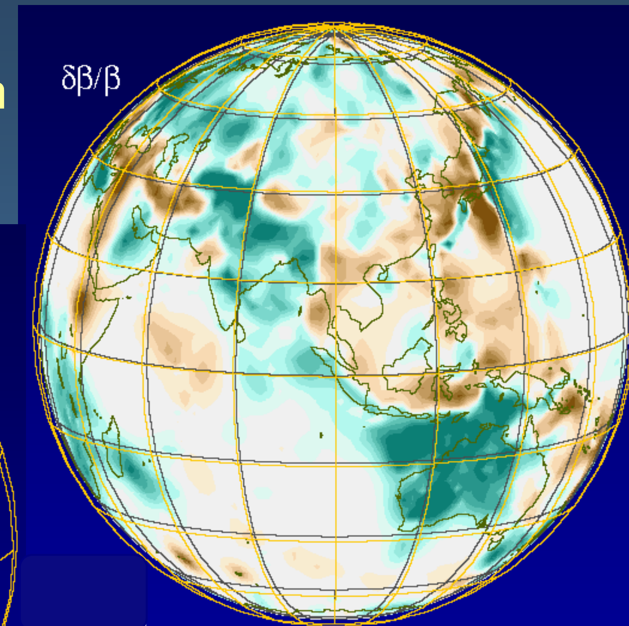
- The dependencies on available sources and receivers mean that most tomographic images represent a muted version of actual variation.



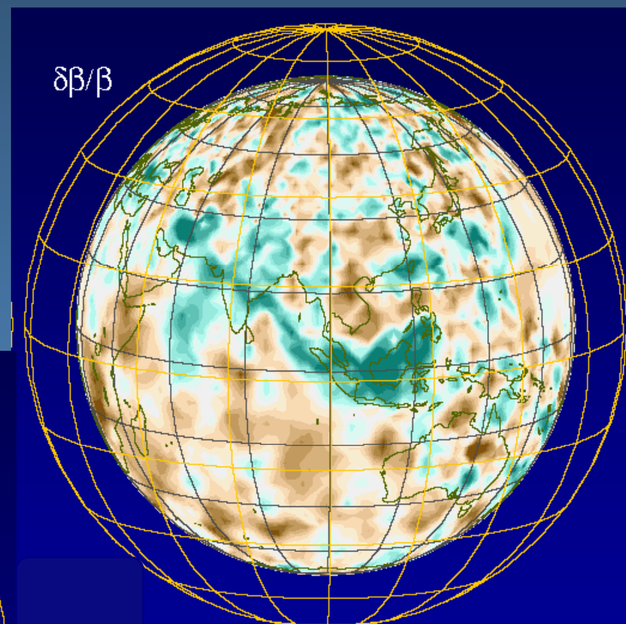
- Nevertheless ratios of wavespeeds, e.g., bulk-sound and shear wavespeed for common source receiver pairs can be reliable.

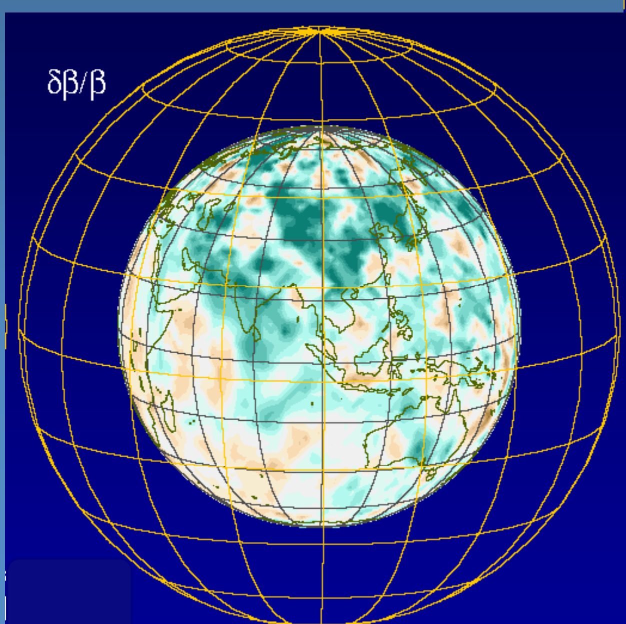
Tomography in a sphere

150-200 km depth



1100-1300 km depth





-1.5 0.0 1.5

Reference model ak135

2700-2800 km depth

Mineral Physics representations

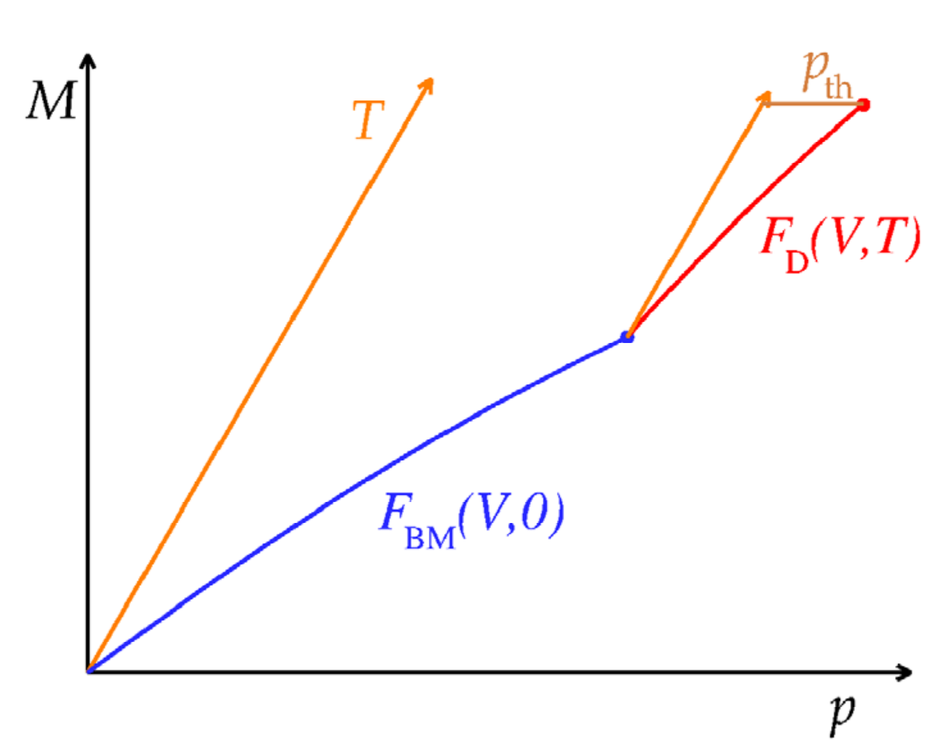
- For individual mineral systems we can set up self-consistent equations of state (EOS) that include both strain and thermal components
- The nature of the EOS depends on a variety of choices, including the specific experimental data employed as constraints.
- The limitations of experimentation mean that lower mantle conditions are well removed from available experimental conditions.
- The problems of unconstrained extrapolation can be curbed if very high pressure constraints can be introduced, e.g. from shock wave or *ab initio* studies.

Mineral Physics EOS

Based on representation of Helmholtz Free Energy for each component $F(V,T) = F_{BM}(V,0) + F_D(V,T)$

combines a "cold" part $F_{BM}(V,0)$ and a "warm" part $F_D(V,T)$

The contributions to the *elastic moduli* can be thought of in terms of trajectories in an M, T, p space



Use Gibbs Free energy minimisation to determine phase proportions in mantle systems under appropriate T, p conditions

Equation of State – Limitations

- For isotropic pressure can use a variety of suitable EOS forms
- Anisotropic approach needed for full representation of elasticity, currently effective but depends on B-M form that is just suitable for Earth's mantle
- Experiments are difficult on tiny specimens and are of necessity at much higher frequencies that in seismology
- In the seismic band – viscoelastic effects important
  - Hence need for attenuation corrections to lab values, more important for S waves than P waves

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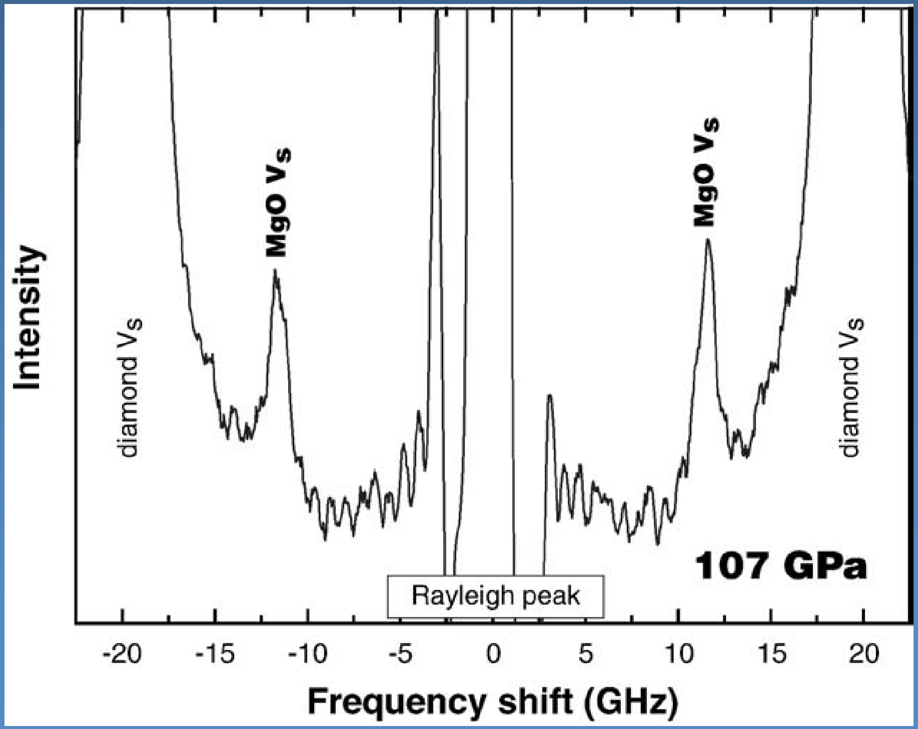
Measurements at high p, T

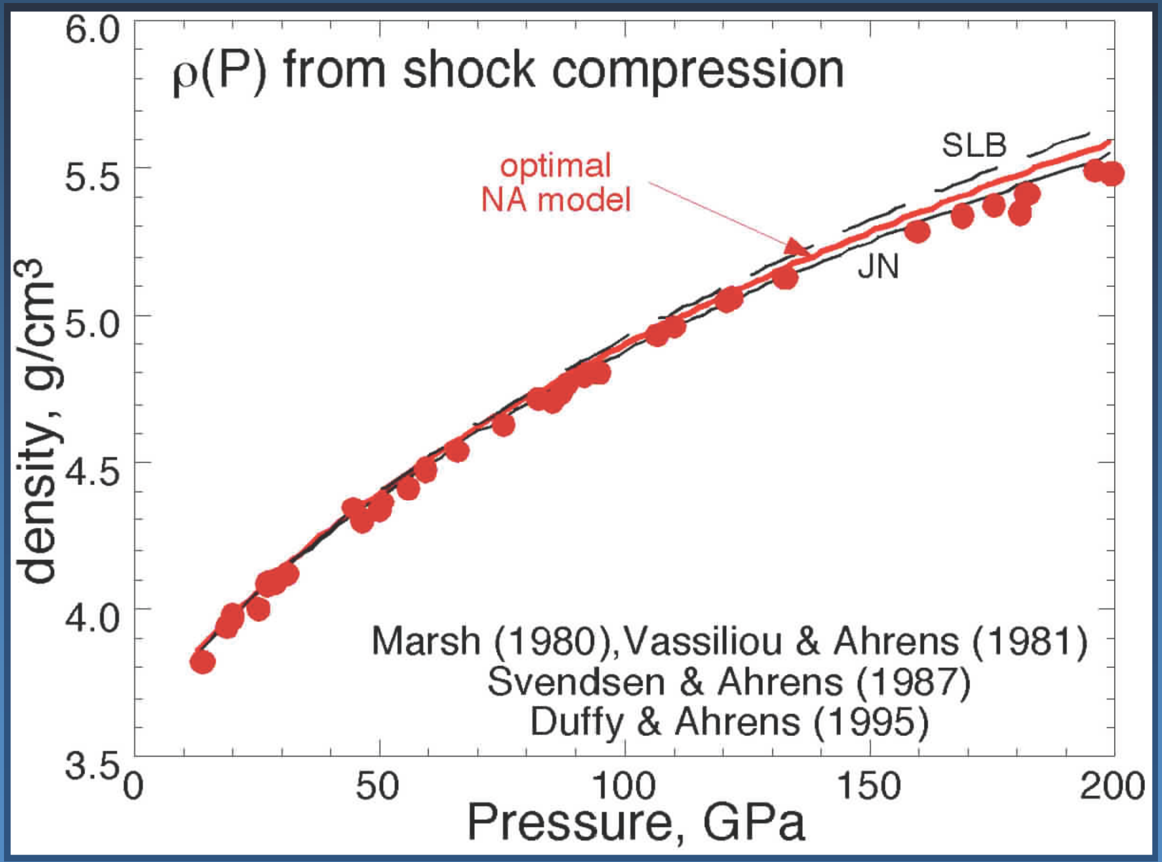
- Mineral Physics Equations of State are based on development of capacity for laboratory studies at high pressures and temperatures (including synchrotron studies)



Shear peaks detected in diamond cell at high pressure and temperature but P peaks shielded by properties of diamond cell
[Murakami EPSL 2009]

EOS variability for MgO

- Even for a well characterised material such as MgO significant differences arise at high pressure in EOS fits



- Such differences can have significant influence on the interpretation of e.g. seismological results

Use of Mineral Physics representations

- We have begun to realise the potential significance of features such as spin transitions in Fe on mineral physics properties.
- We will always push as far as we can in interpretation but must carry a clear appreciation of the limitations of the methods from all the disciplines involved.
- Thus we have to ensure that comparisons with, e.g., seismological results are carried out in an appropriate way with an understanding of the limitations of indirect inference forced on us by the nature of observations.

Nature of mantle heterogeneity

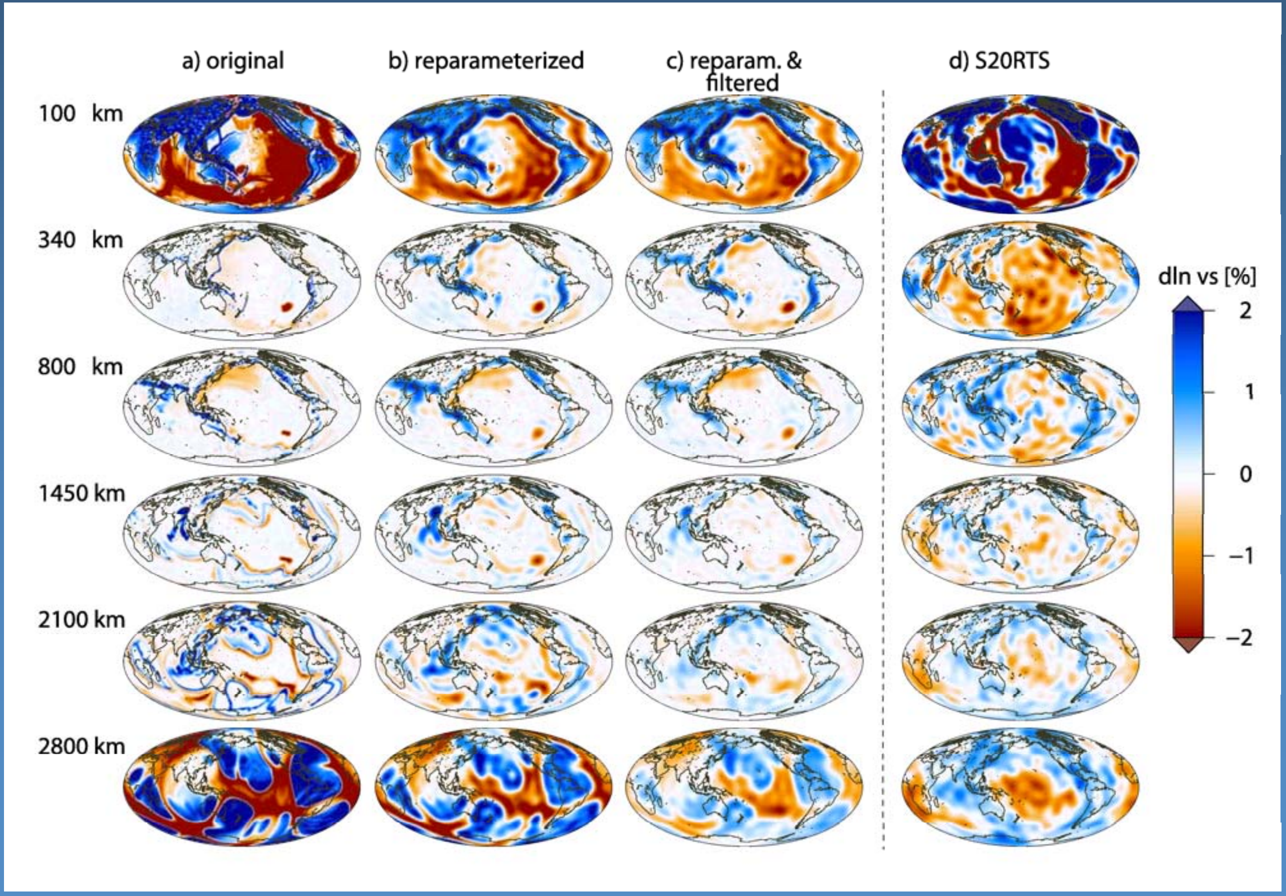
- Former melt fraction/restite mixture (hence mixture modelling rather than equilibrium) – pyrolite as average of a mixture of components
- Anisotropy of mineral and fractional components
- Influence of temperature (differential thermal expansion)
- Relation to seismic heterogeneity
- Chemical vs thermal influences

Wavespeeds and derivatives

- The styles of variability displayed in isochemcial convection models lie well beyond what can be explained using first-order perturbations from a single adiabat or reference model.
- We need to recognise the non-linearity in temperature dependence of wavespeed derivatives – changes occur more rapidly at elevated temperature.
- We also need to be wary of the influences of background models in the display and interpretation of 3-D seismic variations.
- Perturbations in wavespeed do not have to equate to departures from a mineral physics reference state.

Geodynamic testing

- Geodynamic modelling capabilities approach Earth conditions and so begin to provide test beds for understanding the limitations of our representations



Modelling at Earth-like conditions with allowance for filtering effect of tomographic recovery

Schuberth et al., G3, 2009

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Next steps?

- Integrate geochemical understanding into dynamic models in a systematic way

- Systematic Testing of 3-D structural recovery:
- Undertake tomographic inversions for Earth-like geodynamic models with known assumptions about mineral physics characteristics.
  - This requires 3-D seismic calculations and a fully nonlinear inversion scheme.
- Compare the tomographic models with the original state and use the discrepancies to calibrate understanding!