What Geodynamicists need from Seismologists

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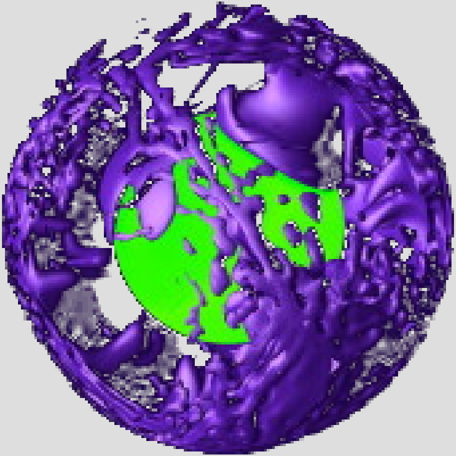
Paleoworlds

Part I: Introduction

Geodynamic Models

- Achievements
  - **many of them**
  - global
  - high resolution
  - comp. efficient
- Challenges
  - link to data



(Tackley)

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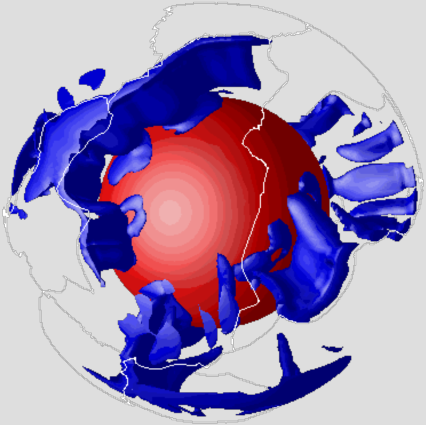

(Zhong)

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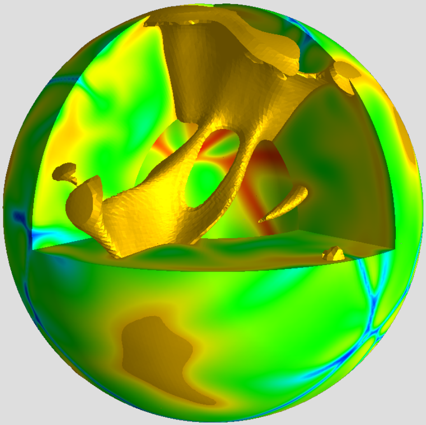

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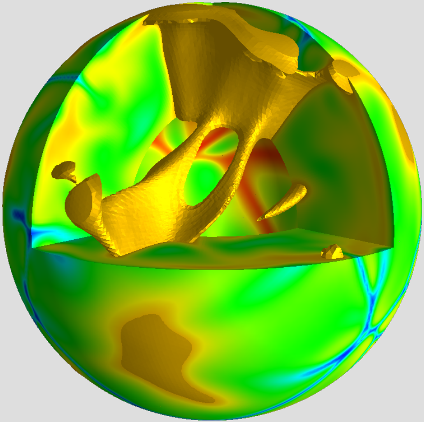

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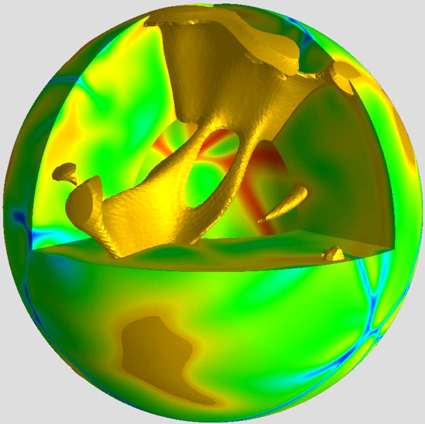

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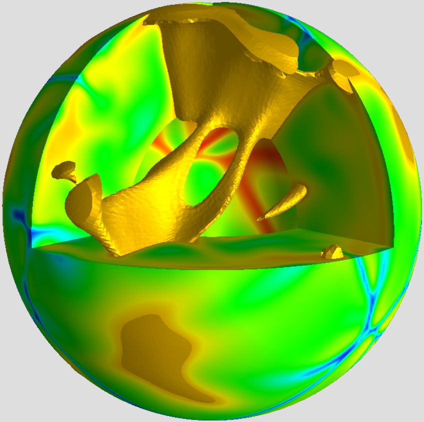

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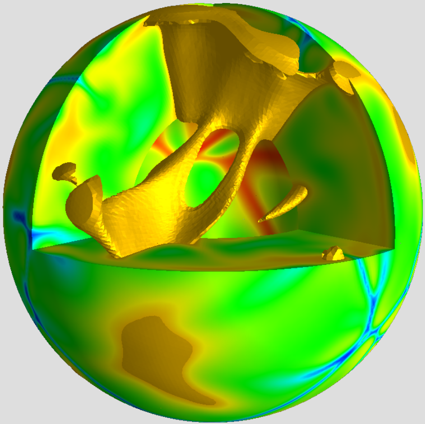
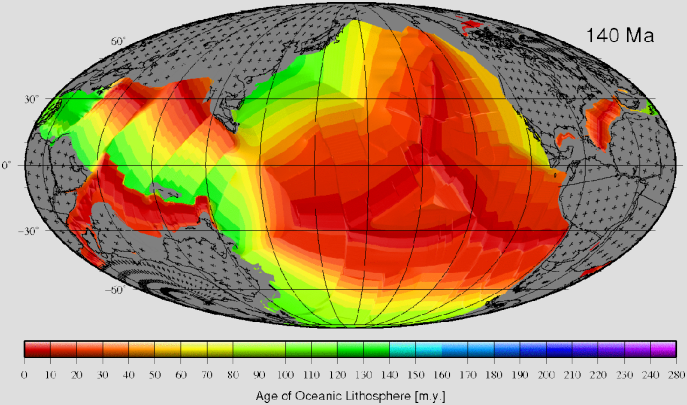


(Bunge)

Recent Earth history (Late Mesozoic/Cenozoic Record):

horizontal motion

plate histories



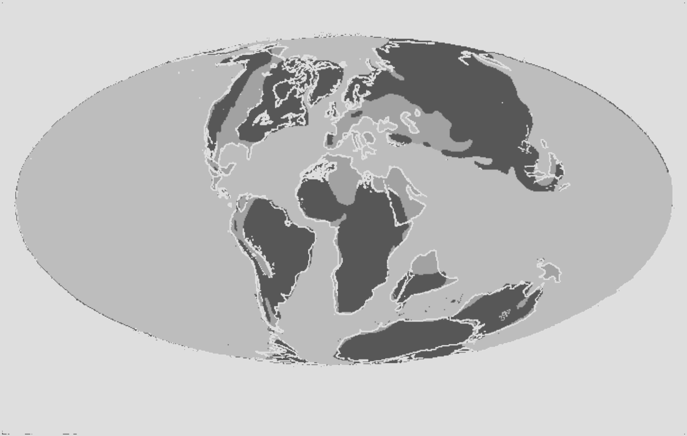
(Dietmar. Mueller, Earthbyte Project University of Sydney, 2011)

Recent Earth history (Late Mesozoic/Cenozoic Record):

vertical motion

epi-orogeny

94 Myr:



(modified after Scotese)

Recent Earth history (Late Mesozoic/Cenozoic Record):

vertical motion

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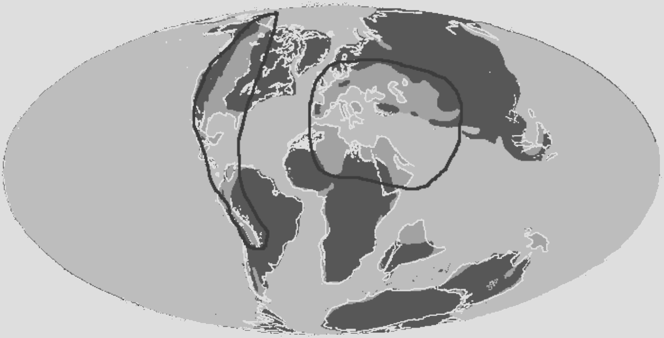
94 Myr: *western interior seaways in the Americas, subsidence in the Tethys realm*



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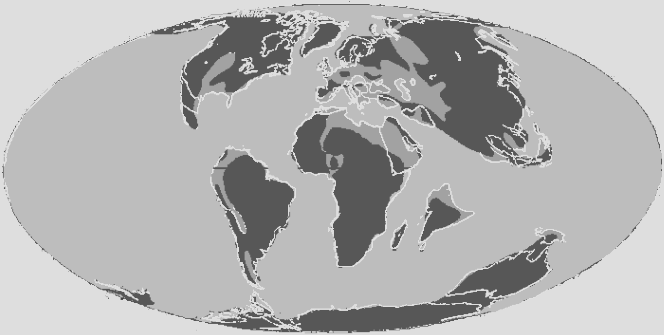

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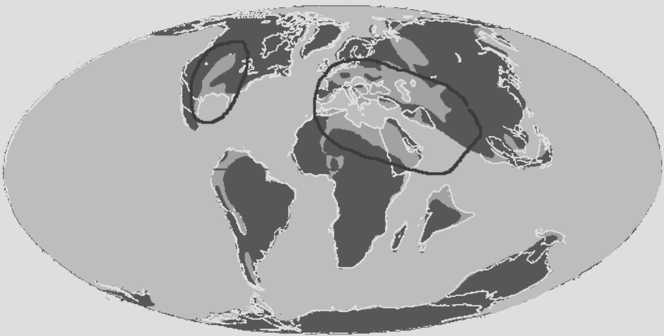
Recent Earth history (Late Mesozoic/Cenozoic Record):

vertical motion

epi-orogeny

66 Myr: *interior seaways, subsidence in the Tethys realm, mid-eastern oil*



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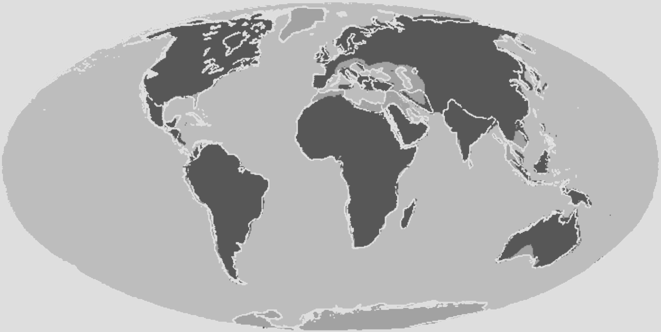

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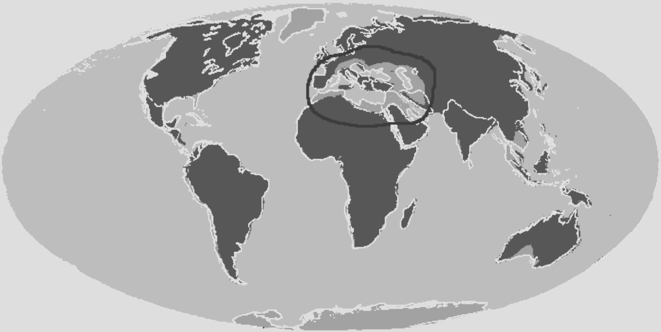
Recent Earth history (Late Mesozoic/Cenozoic Record):

vertical motion

epi-orogeny

14 Myr: *shallow seas in the Tethys and eastern Europe*



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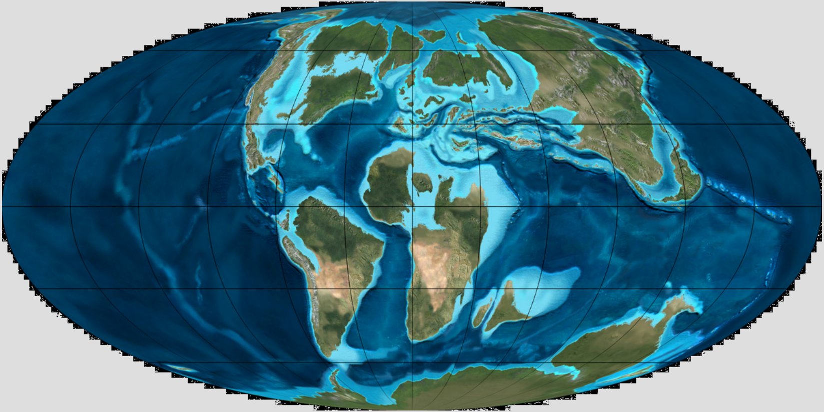
Recent Earth history (Late Mesozoic/Cenozoic Record):

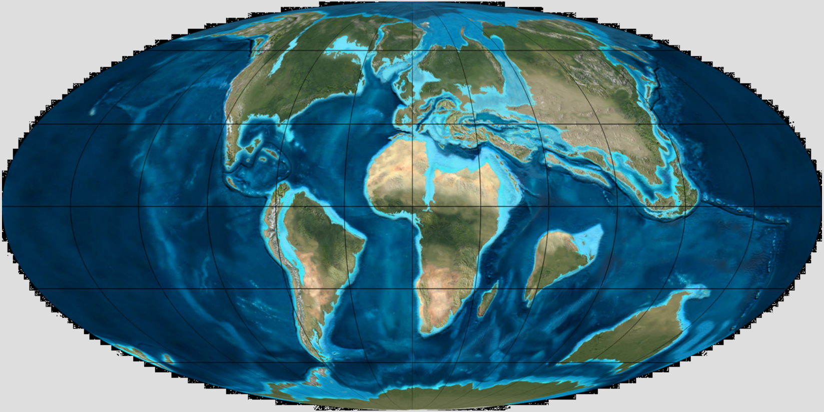
90 Myr



(Blakey, Paleoworlds)

Recent Earth history (Late Mesozoic/Cenozoic Record):

65 Myr



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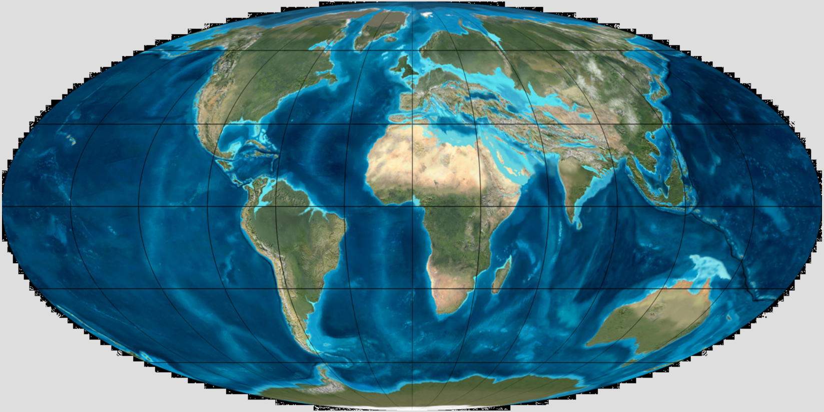
Recent Earth history (Late Mesozoic/Cenozoic Record):

35 Myr



(Blakey, Paleoworlds)

Part II: Equations and Scaling

Conservation of Mass

Focus on longer time scales, and need to suppress acoustic waves. Done through the so called *anelastic approximation* ($\partial \rho / \partial t = 0$), which yields mass conservation in the form:

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

Conservation of Momentum

Focus on highly viscous, so called *stokes flow*.

acceleration = internal friction and driving

$$\overbrace{\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right)}^{\text{inertia}} = \overbrace{\underbrace{-\nabla p}_{\substack{\text{pressure}\\\text{gradient}}} + \underbrace{\eta\nabla^2\mathbf{v}}_{\substack{\text{viscous}\\\text{resistance}}}}^{\nabla\cdot\boldsymbol{\sigma}} + \underbrace{\mathbf{f}}_{\substack{\text{driving}\\\text{forces}}}$$

Simplifications for Stokes Flow

Focus on highly viscous, so called *stokes flow*.

$$\underbrace{\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right)}_{\text{small}} = -\nabla p + \eta\nabla^2\mathbf{v} + \mathbf{f}$$

- Accelerations 20 magnitudes smaller, can be omitted
- Instaneous equilibrium of driving/resisting forces
- Elliptic equation, Boundary conditions are part of global equilibrium
  This is the reason we model global flow.

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$$0 = -\nabla p + \eta \nabla^2 \mathbf{v} + \mathbf{f}$$

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Simplifications for Stokes Flow

Focus on highly viscous, so called *stokes flow*.

$$\underbrace{\eta \nabla^2 \mathbf{v}}_{\text{resisting}} = \underbrace{\nabla p - \mathbf{f}}_{\text{driving}}$$

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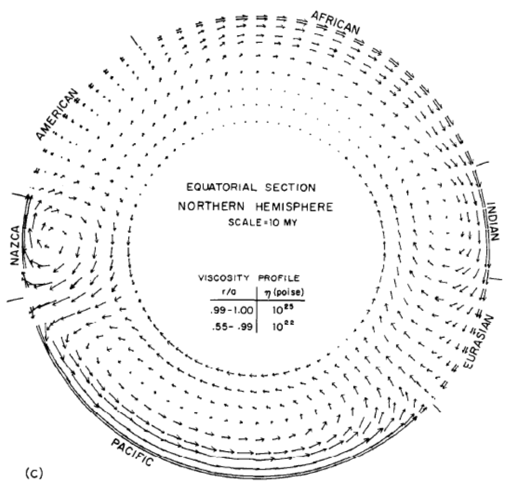
Example: Hager and O'Connells classic instaneous flow models

- Boundary condition:
  - **current plate motion**
- Output:
  - present-day flow
- Lesson:
  - no simple flow geometry
  - no stable piles



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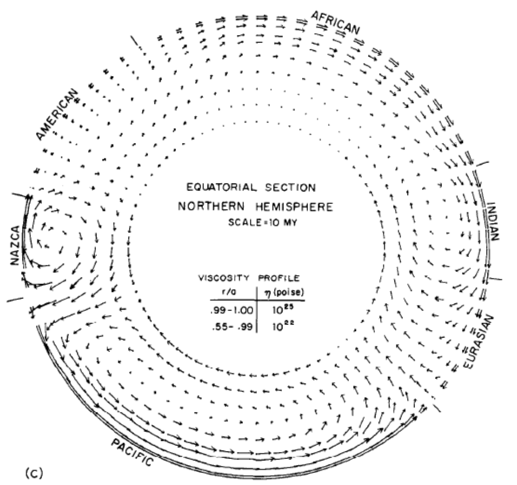

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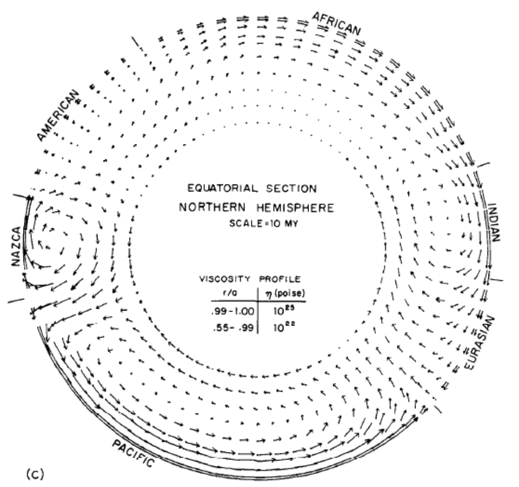

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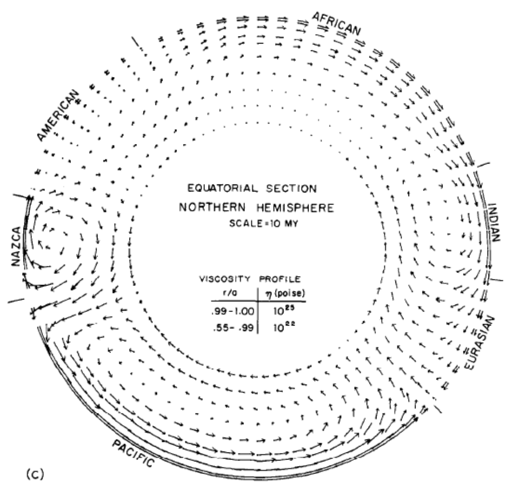
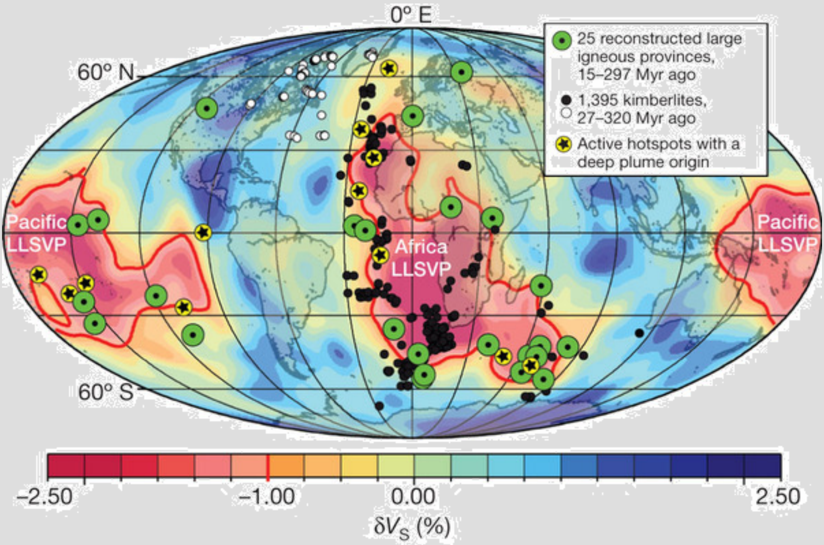
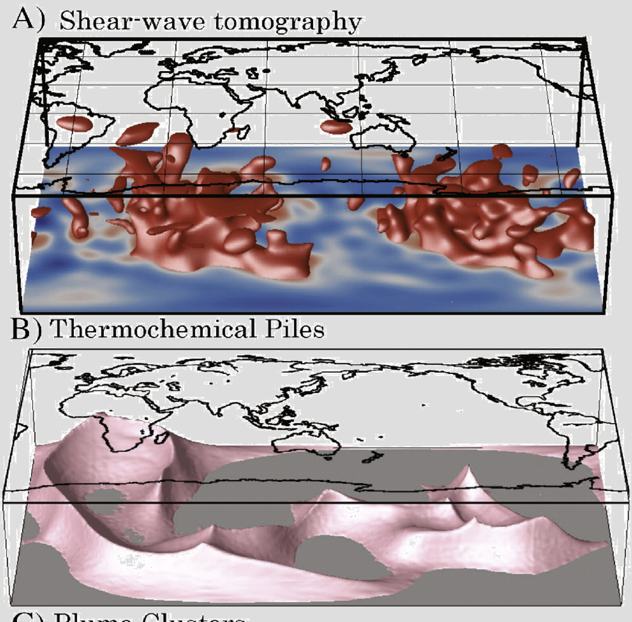




(Torsvik, 2010)

Lassak et al., 2009



Conservation of Energy

Temp changes = advection, conduction and heat sources

$$\underbrace{\frac{\partial T}{\partial t}}_{\text{Temp changes}} = \underbrace{-\mathbf{v} \cdot \nabla T}_{\text{advection}} + \underbrace{\kappa \nabla^2 T}_{\substack{\text{thermal}\\ \text{diffusion}}} + \underbrace{\mathbf{H}}_{\text{heat sources}}$$

Conservation of Energy

Advection dominates diffusion because the mantle is a good insulator.

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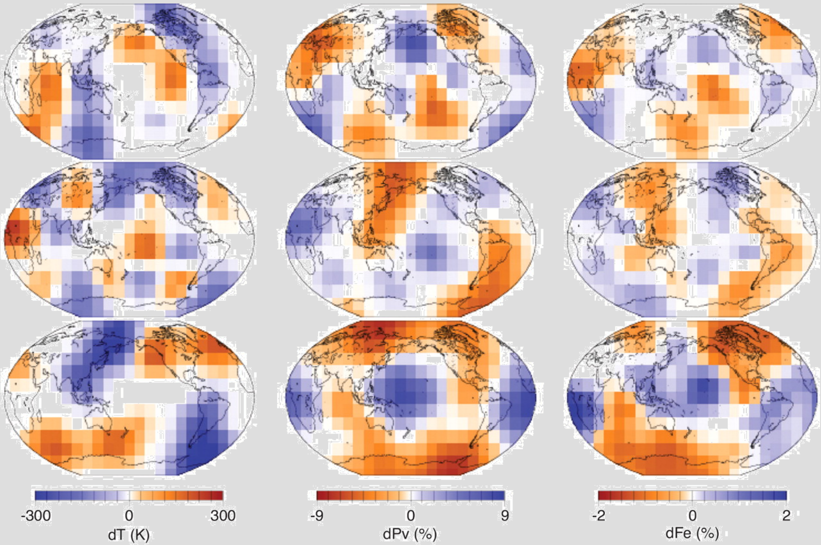
The Peclet Number

$$Pe = \frac{UL}{\kappa}.$$

An estimate of the advection dominance in the mantle is given through the Peclet number, which is of order $\mathbf{10}^4$. This indicates that advective processes in the mantle dominate thermal diffusion by four orders of magnitude, outside of thermal boundary layers.

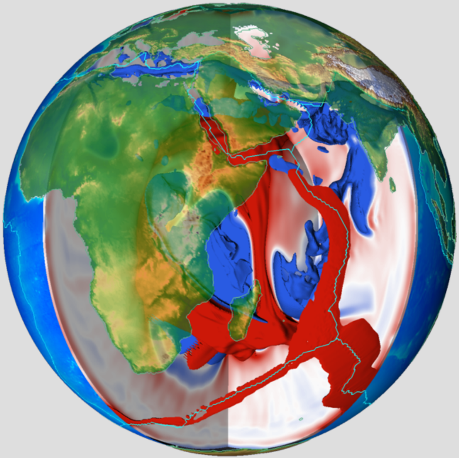
Consequence: Thermal gradients are sharp, thermal boundary layers accommodate large temperature changes, and hence the lateral temperature variations arising from the boundary layers are high.
(one needs to cool the core.)



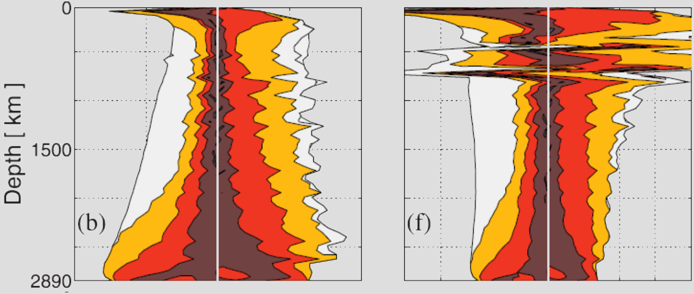
(Trampert, 2004)

Geodynamic Forward Models

- Schuberth et al., 2008a,b
- Schaber et al., 2009
- Goal:
  - quantitative comparisson with seismic models by going through the convection process and mapping to elastic variation
  - testing compositional mantle models with dynamically plausible temperatures



Histogram Geodynamic Forward Model

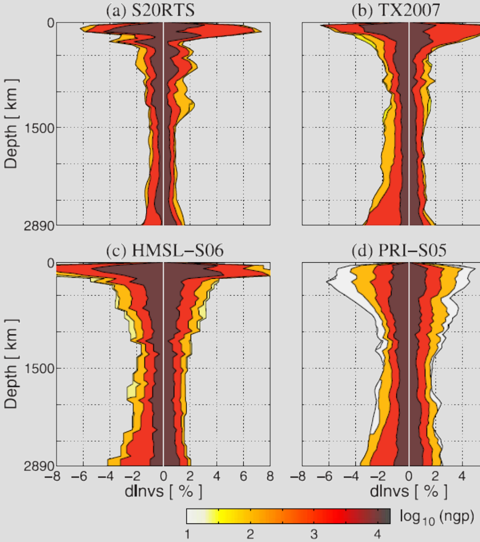


Model M2

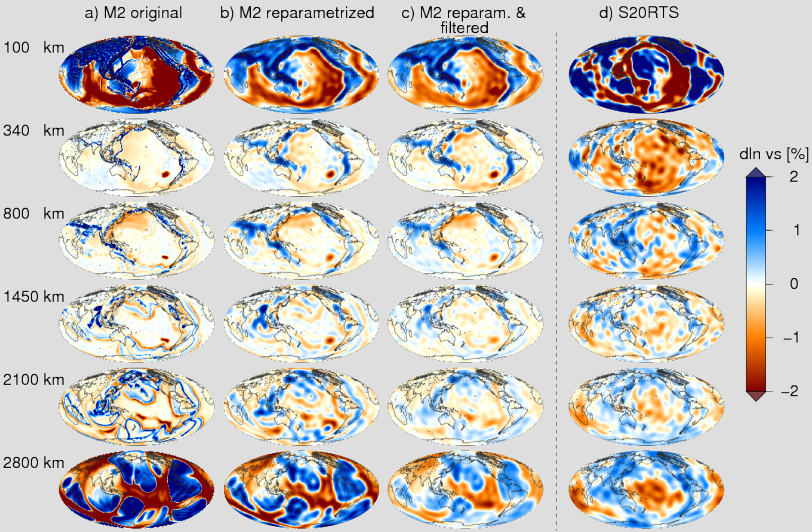
Visc. 100/1/100

Q_{CMB} 35%

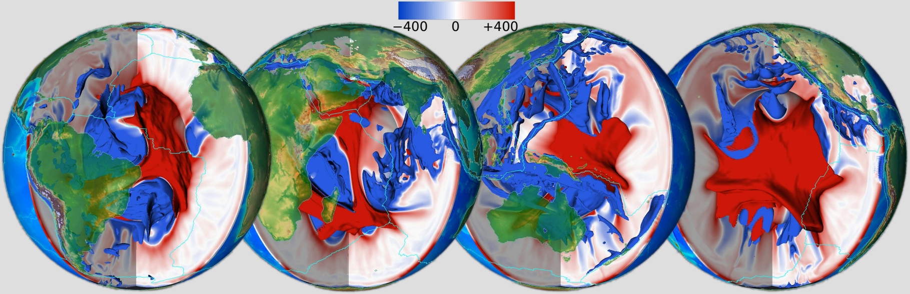
Histograms Tomographic Models



Seismic Filtering



Gedankenstütze



- High resolution (of order $\mathbf{10}^9$ grid points) geodynamic forward models of mantle heterogeneity can be constructed for comparisson to seismic models

Part III: Geodynamic Inversions

The Adjoint equations of mantle convection

$$\nabla \cdot \phi = 0$$

$$\nabla \cdot (\eta \nabla \phi) + \tau \nabla \theta = \nabla \chi$$

$$-\frac{\partial \tau}{\partial t} - \nabla \cdot (\tau \mathbf{v}) + R \hat{\mathbf{e}}_r \cdot \phi = \nabla^2 \tau + \delta(\mathbf{x}, t - t_1)[\theta(\mathbf{x}, t_0) - \theta_I(\mathbf{x})]$$

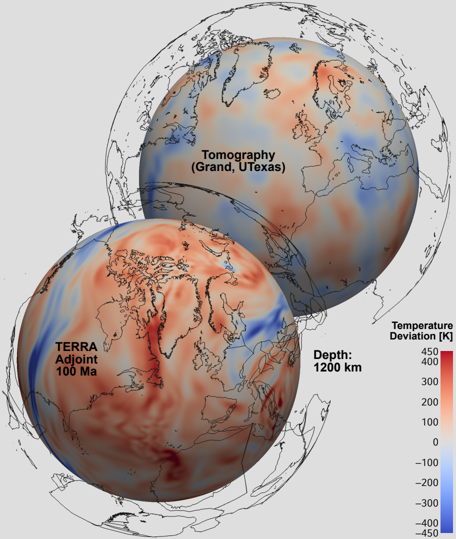
Solve a set of unintuitive *adjoint* equations

- terminal condition on temperature
- adjoint diffusion operator stable vs. time-reversal
- iterative procedure: computationally expensive, but now feasible
  ⇒ optimise for suitable flow histories (backwards in time)

An example of our estimate for sub-icelandic mantle, **100 Myrs** ago.

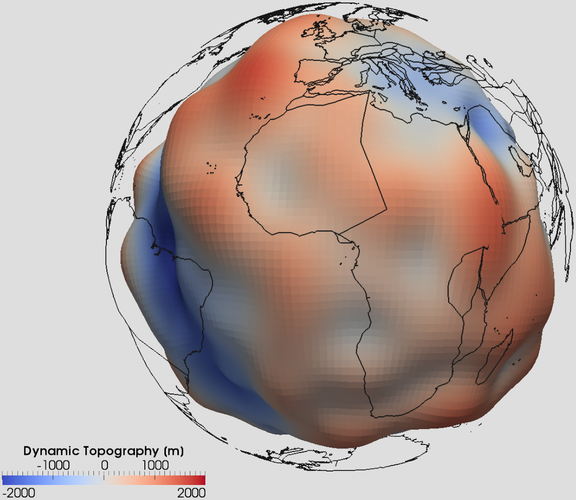
- Forward simulation:
  - $T \xrightarrow{\text{mineral physics}} v$
  - residual forward model vs. tomography (from Grand)

- Adjoint simulation:
  - terminal condition $T \xleftarrow{\text{mineral physics}} v$
  - model update for time 100 Myrs ago



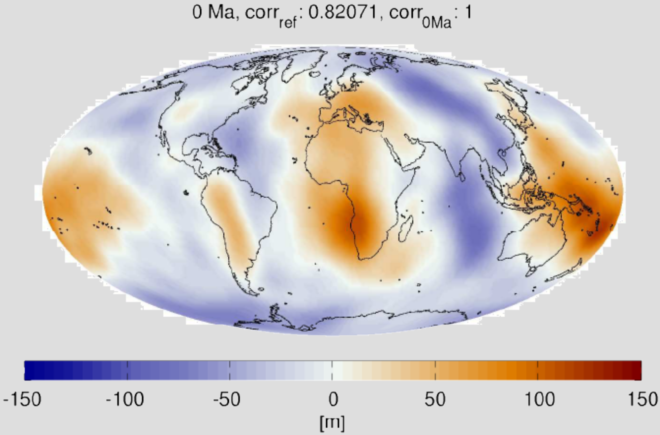
Dynamically supported global topography 40 Myrs ago

- Low lying Tethys and Farallon regions associated with active subduction at the time. (Topography is 500 times exagerated.)



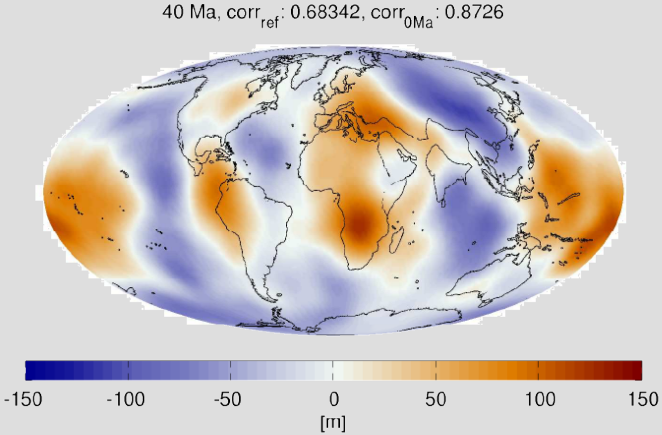
Large temporal Geoid variations implied by our inversions

today



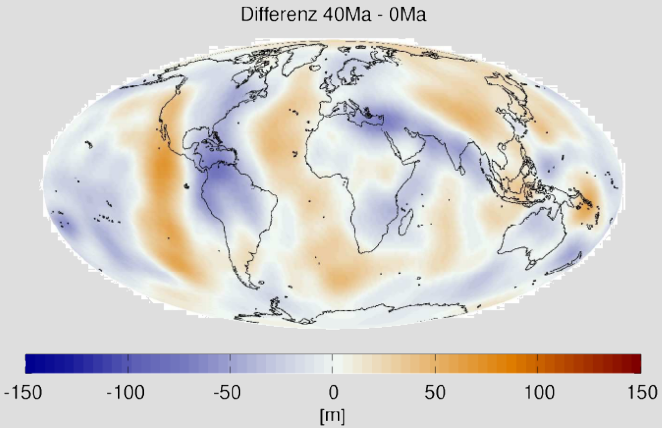
Large temporal Geoid variations implied by our inversions

40Myr



Large temporal Geoid variations implied by our inversions

difference



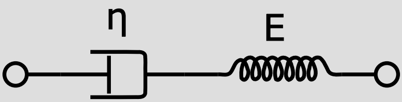
Conclusion

- Geophysicists from seismology, mineral physics, and geodynamics together should start exploring time-dependent earth models.
- Large challenges (e.g., seismic resolution, composition, uncertainties in geologic interpretations) are ahead.
- Large payoff in terms of understanding the dynamics of our planet waits in return.

(Special thanks to: B. Schuberth, C. Moder, J. Oeser, M. Mohr, A. Horbach, L. Colli, T. Chust and everyone from the Munich group!)

Thank you!

Continuum: Elastic or Viscous?



Earth is viscoelastic:

- elastic over short times (earthquake waves!)
- viscous over long times (plate tectonics!)

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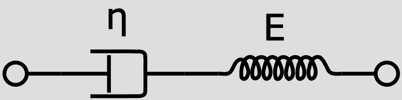

Earth is viscoelastic:

- elastic over short times (earthquake waves!)
- viscous over long times (plate tectonics!)

Maxwell time = viscous relaxation to $1/e$:

$$\tau_M = \frac{\eta}{G}$$

$\Rightarrow$ Lithosphere ($\tau_M = 10,000$ yr) = viscous fluid

Viscous Behavior: Creep

Mechanisms:

- Nabarro-Herring creep
  (bulk diffusion)
- Coble creep
  (grain boundaries)
- Dislocation creep

Viscous Behavior: Creep

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- Dislocation creep

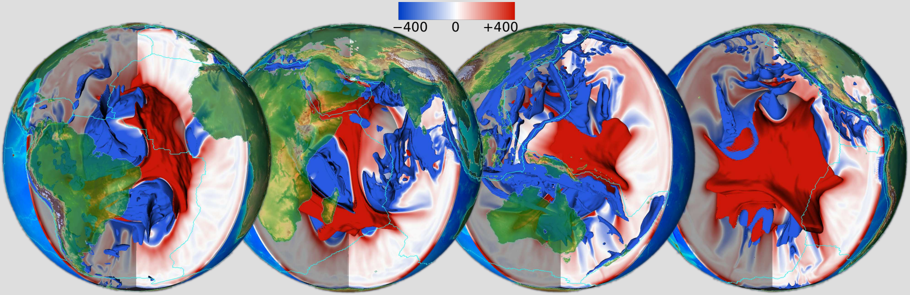
Empirical Arrhenius-type equations:

$$k = A\,e^{-Q_{creep}/(R\,T)}$$

(R: gas constant; Q_{creep}: activation energy)

- T in exponent: sensitive
- strongest = cold
- dominant: dislocation creep

Mantle Circulation Models



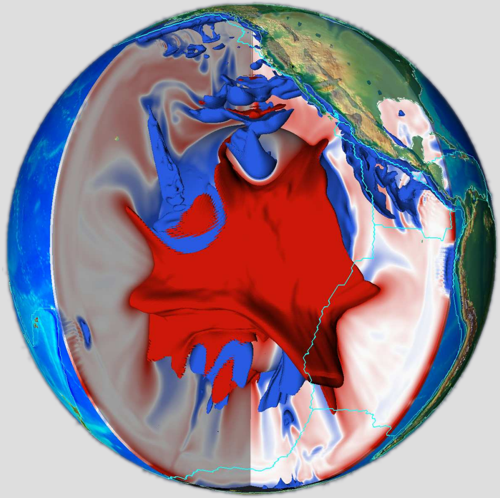
- Mantle convection: basics well understood
- Needed: comparison with observations (tomography!)
- Problem: unknown initial conditions

  ⇒ assimilation of surface velocities or backwards in time

Prev. TERRA MCMs: Plates from Lithgow-Bertelloni

- Coarse time stepping (10–20 Ma: artifacts like "jumping" slabs)
- Too short timespan ($<$ convective time scale)
- Errors (Tethys!)

$\Rightarrow$ Need for better plate boundaries + new software



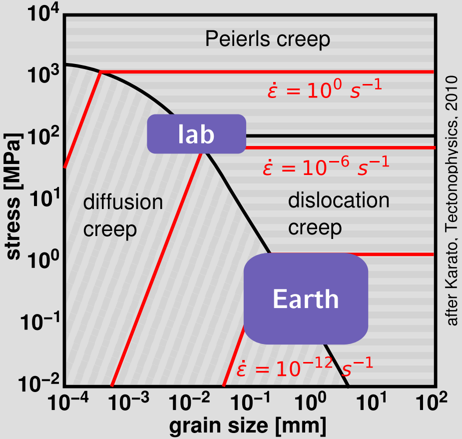
Thank you!

Laboratory Experiments?

- Fast deformation

  ⇒ other creep mechanisms
- Small samples

  ⇒ thermal equilibrium



Assumptions

- Spherical Earth, constant gravity: small error, only vertical direction
- Constant density: error less than 1% + in vertical direction
- Incompressible: $K \ll p$ in lithosphere $\Rightarrow$ volume change $< 0.5\%$
- Anelastic rheology: elasticity small + unknown over geologic times
- Isostatic equilibrium: $\tau_M \ll$ age of the Earth $\Rightarrow$ equilibrated
- Constant thermal properties, mineralogy: correction via grid (heat)
- Newtonian rheology: approximation, true rheology not known

SHELLS: Only Momentum Equation

Temporal development of faults:

- Behavior of lithosphere depends on its past
- Initial conditions unknown $\Rightarrow$ cannot create present-day state
- Future state unknown $\Rightarrow$ from present-day to future is meaningless

Fault geometry from current forces: continuum deformation and fault formation is highly nonlinear $\Rightarrow$ chaotic

$\Rightarrow$ Fault geometry as input, no energy equation needed

Comparison with GPS data

- Problem:
  - GPS signal includes elastic deformation
  - SHELLS omits elasticity
- Modifications to the model:
  - Brittle part of fault = locked
  - Slip in brittle part = compensated by elastic deformation
  - Comparison of elastic deformation with GPS data

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Icosahedral Grid