# Glacial isostasy and plate motion

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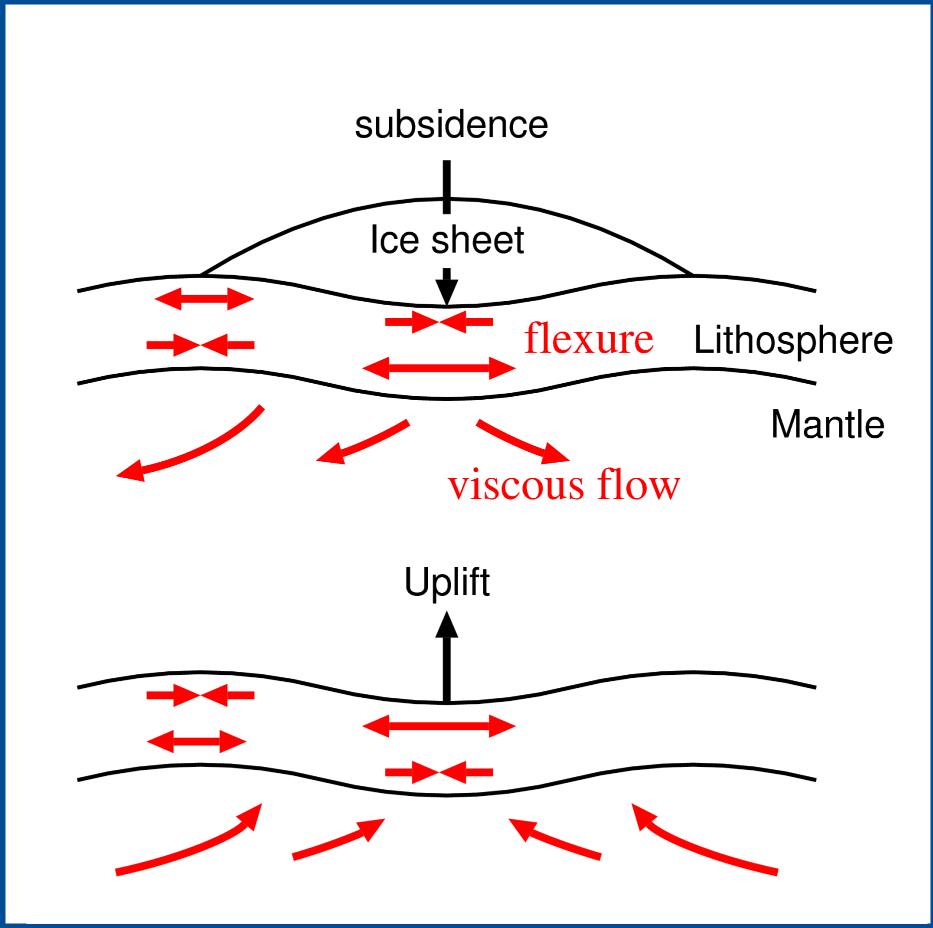
# Overview

- What is GIA?
- Determination of plate motion and relation to GIA
- Physics of GIA induced horizontal motion
- Consequences for observed plate motion
- Excursion to ICE5G
- Summary, conclusions and outlook

# What is GIA?

Glacial isostatic adjustment of the Earth to surface loading

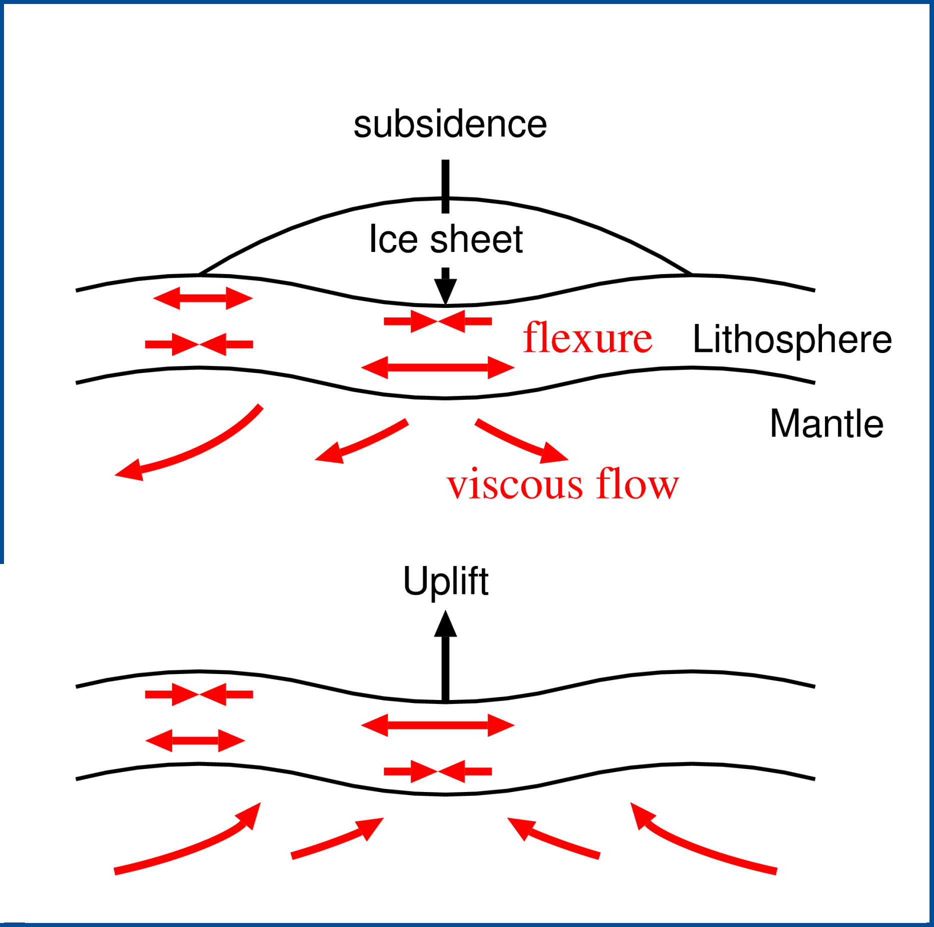
- Glacial loads
  - Extension: *O* (1000 km)
  - Thickness: *O* (1 km)
  - Period: *O* (100,000 yr)
- Last glaciation terminated 8000 yr BP
- Ongoing adjustment of viscoelastic earth

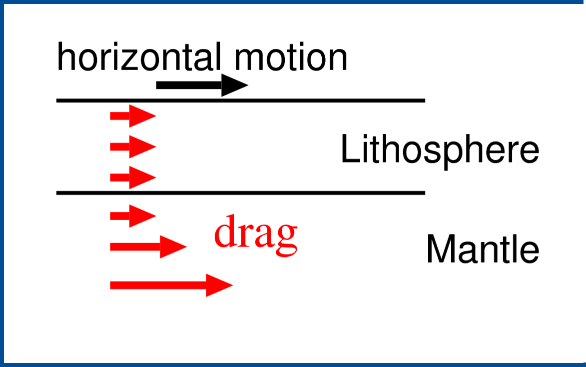


# GIA induced horizontal motions

What happens further away?

- James & Morgan (GRL, 1990):
  - Uplift generates lateral material flow in viscous upper mantle.
  - Flow generates drag of plates.



# Determination of plate velocities

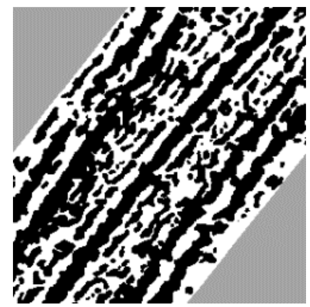
- $T_{char}$ $(V_{MC})$ ~ 10 Myr to 1 Gyr
- ➢ $T_{char}$ $(V_{GIA})$ ~ 1 kyr to 0.1 Myr

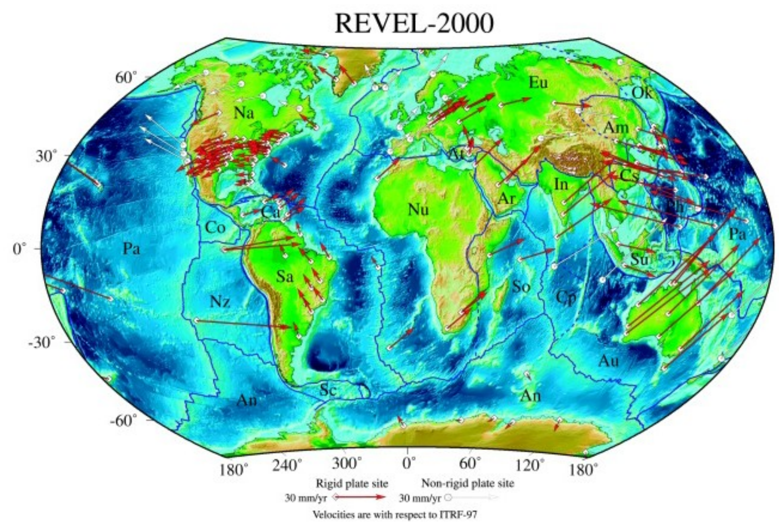
- *Geologically*-based methods (e.g. NUVEL 1A, DeMets et al., GRL, 1994)
  - from geomagnetic reversals

$$< V >_{3.2\ \mathrm{Myr}}$$

- *Geodetically*-based methods (e.g. REVEL, Sella et al., JGR, 2002)
  - from GPS or VLBI data

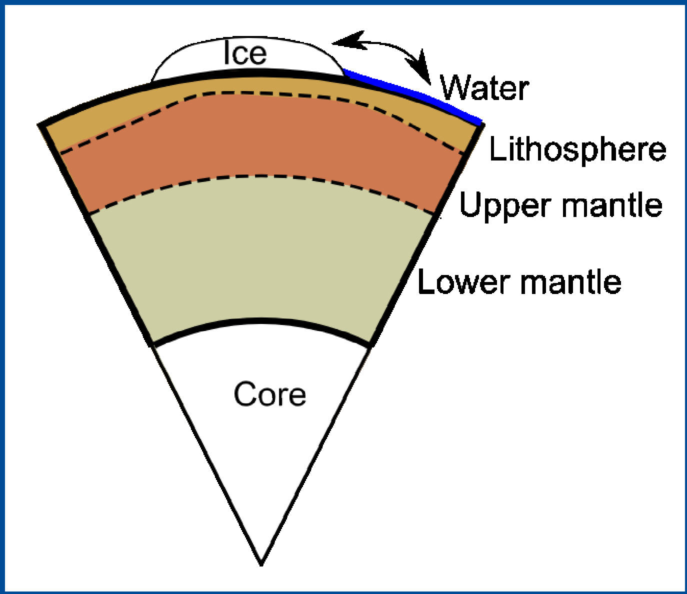
$$< V >_{10\ \mathrm{yr}}$$





# Features of GIA modelling

- PREM structure for shear modulus and density
- Viscosities: $\eta_{UM} = 6 \times 10^{20}$ Pa s,
  $\eta_{LM} = 1 \times 10^{22}$ Pa s
- Elastic lithosphere of variable thickness
  (or 100 km)
- Predefined ice history




- S-FE formulation (Martinec, GJI, 2000)
  - incompressible
  - self-gravitating
  - non-rotating
  - hydrostatically pre-stressed
- Uniqueness conditions
  - centre of mass
  - no surface net-rotation

# Status of numerical code

- Weak formulation
- Spectral parameterization in horizontal direction
- Radial FE for each spectral component
- Explicit time scheme
- Advantages
  - radial dependent quantities are formulated on l.h.s.
  - Spectral FE matrix is only determined once
  - viscous energy and boundary conditions are formulated on r.h.s.
    - Implementation of non-linear rheology is straight forward
    - Easy coupling with dynamic ice/ocean models

$$\delta \mathrm{E}(\mathbf{u}^{i+1}, \phi_1^{i+1}, \Pi^{i+1}, \delta\mathbf{u}, \delta\phi_1, \delta\Pi) = \delta \mathrm{F}^{i+1}(\delta\mathbf{u}, \delta\phi_1)$$

- Define time stepping, spectral resolution, elastic 1D structure, viscous 1D and 3D structure
- Set up of 1D and 3D viscous layers in FE discretization
- l.h.s. of spectral FE system for linear momentum equation
  LU decomposition for Galerkin method of explicit time scheme
- Initialise fields
- itime = 1, number of time steps in history
  - r.h.s. of linear momentum:
    Variation of energy with respect to displacement
    1D layers (solved in spectral domain)
    3D layers (solved in spatial domain)
  - Determine loading for current time steps from current configuration:
    Sea-level equation (solved in spatial domain)
  - Adjust boundary conditions to new loading
  - Satisfy uniqueness condition
  - Solve linear momentum equation:
    Multiply LU decomposed l.h.s with r.h.s. variations
    Back-substitution
  - Initialise fields for next time step
- End of program

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# Induced surface motion

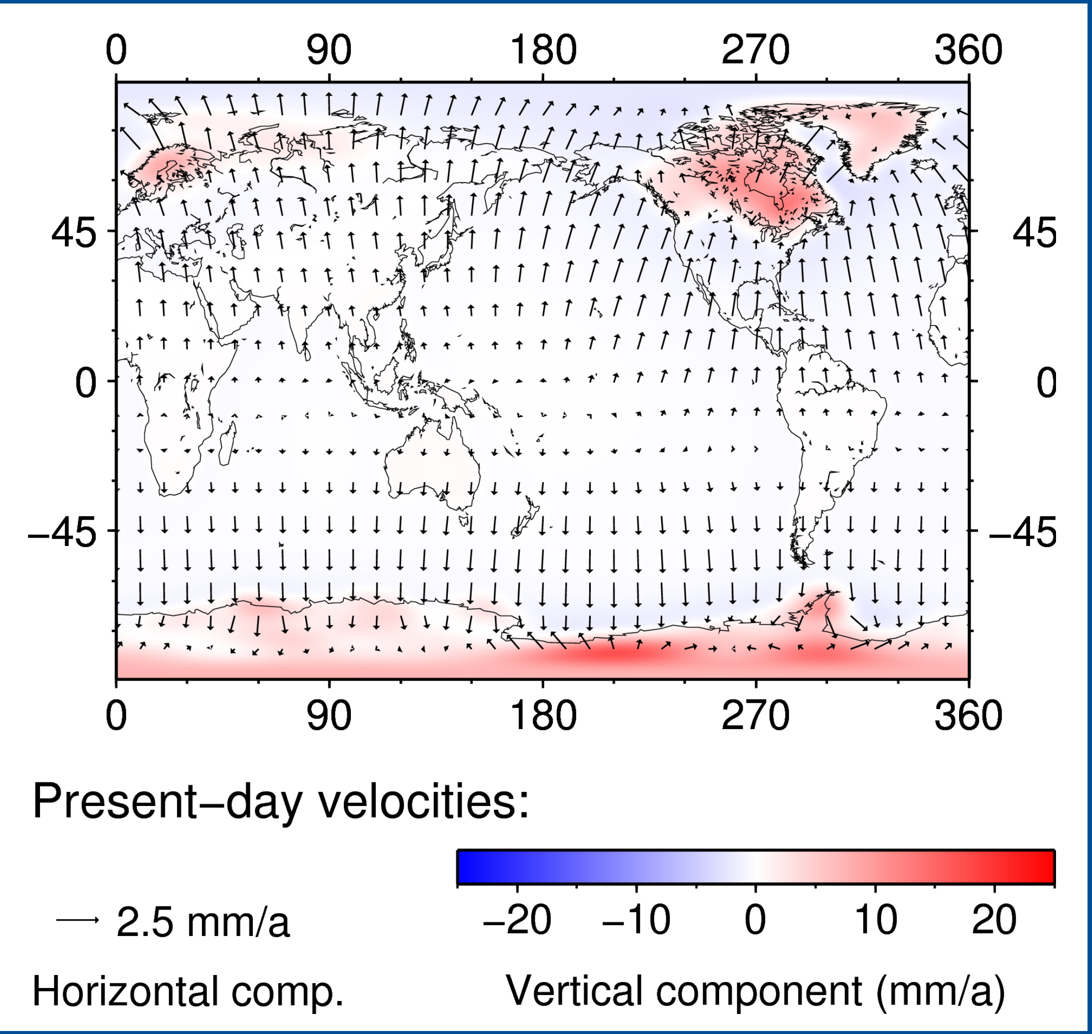
1D earth structure

- standard viscosity model with

  $\eta_{UM} = 6 \times 10^{20}$ s
  $\eta_{LM} = 1 \times 10^{22}$ Pa s

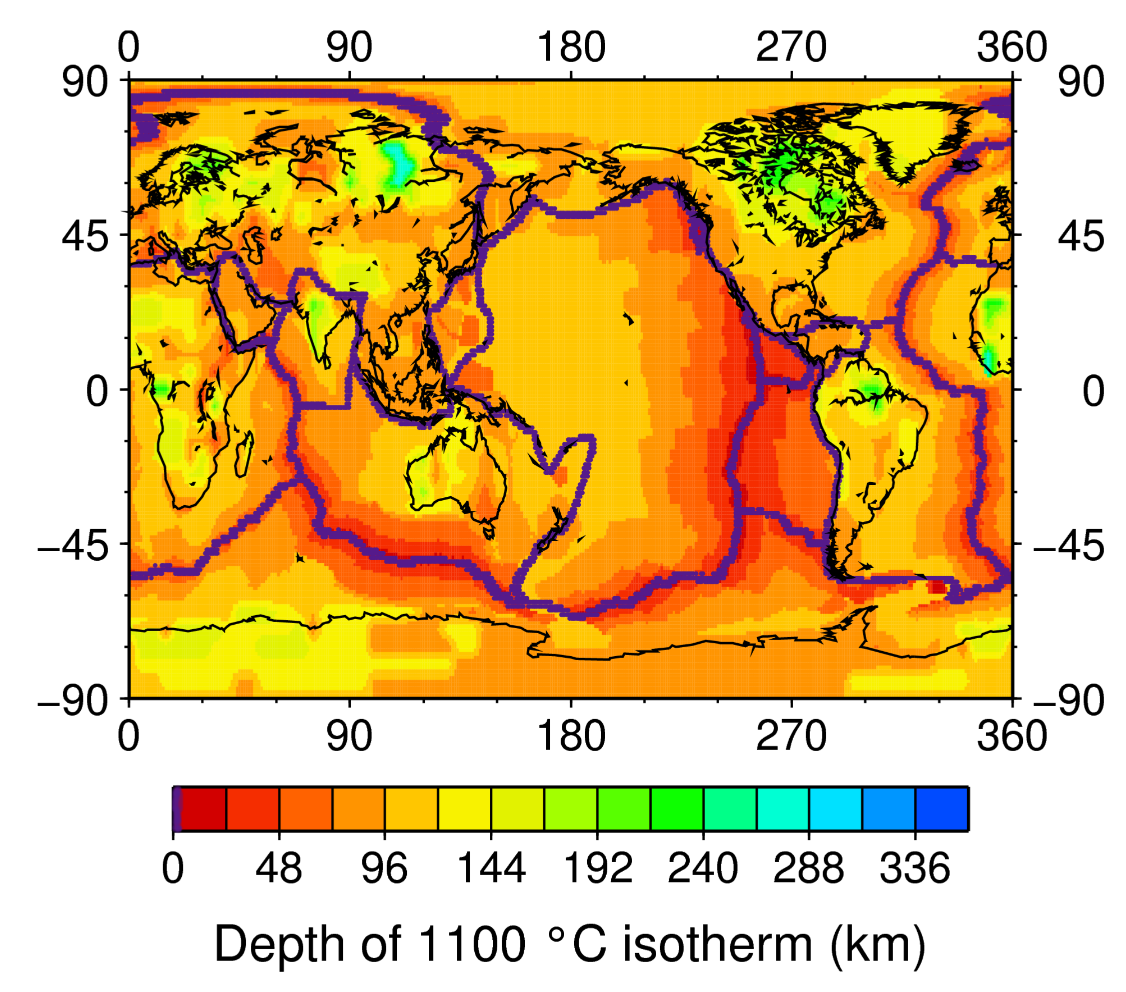
- ICE3G history
- fixed coastlines

Hemispheric motion pattern directed to the polar loading areas



# Thickness of elastic lithosphere

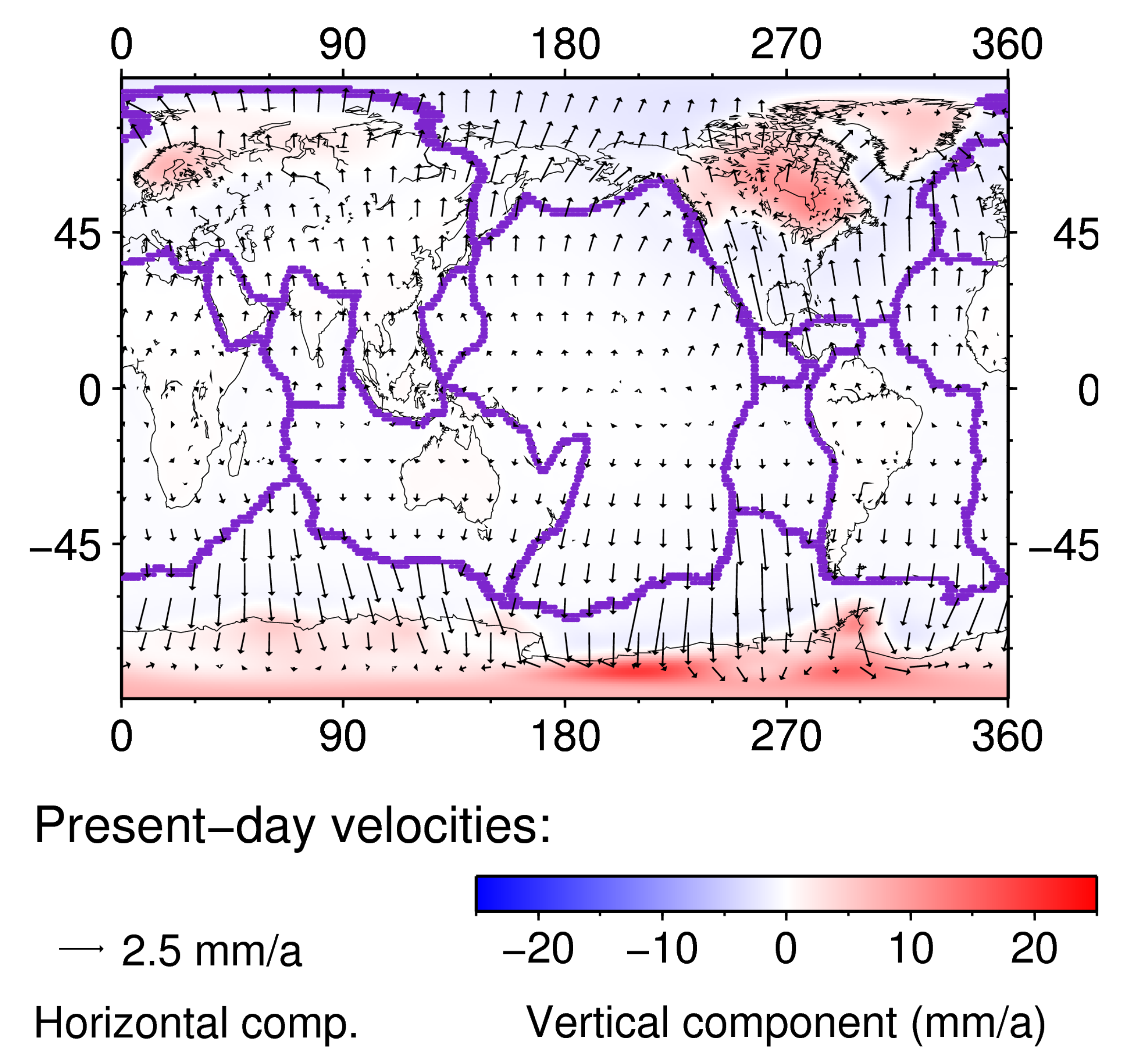
- Depth defined by characteristic isotherm (1100 ºC)
- Mosaic
  - Continental lithosphere from thermal data (Artemieva, Tectonophysics, 2006)
  - Oceanic lithosphere from ocean floor ages (Müller et al., JGR, 1997)
  - Plate boundaries from Bird (G³, 2003)



# Induced surface motion

3D earth structure

- plate boundaries defined as 200 km wide low-viscosity intervals
- variable thickness of elastic lithosphere
- 1D mantle
- ICE3G history
- fixed coastlines

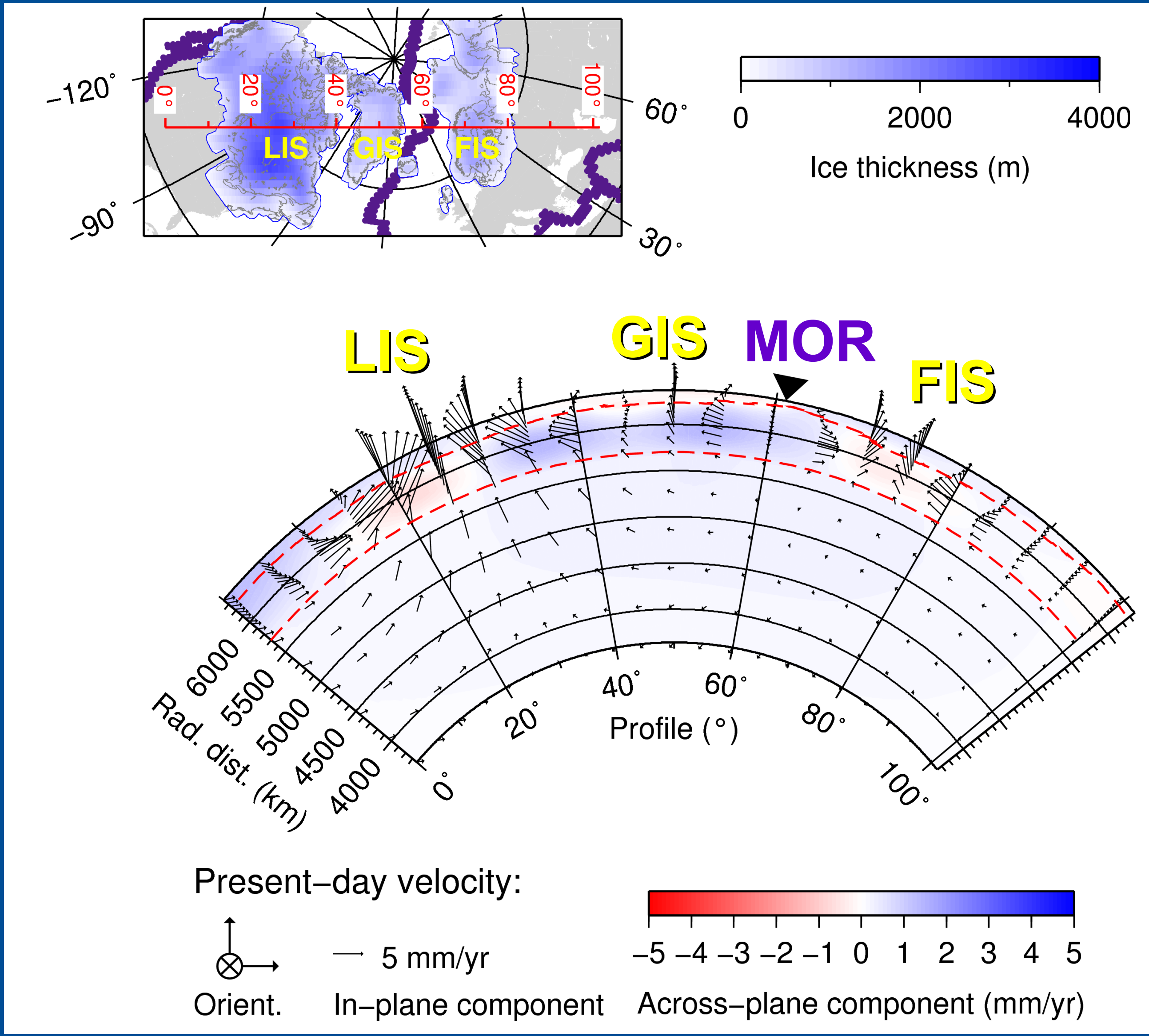


# Cross section I

Mid Ocean Ridge (**MOR**)

## Ice sheets:

Laurentide (LIS)
Greenland (GIS)
Fennoscandia (FIS)

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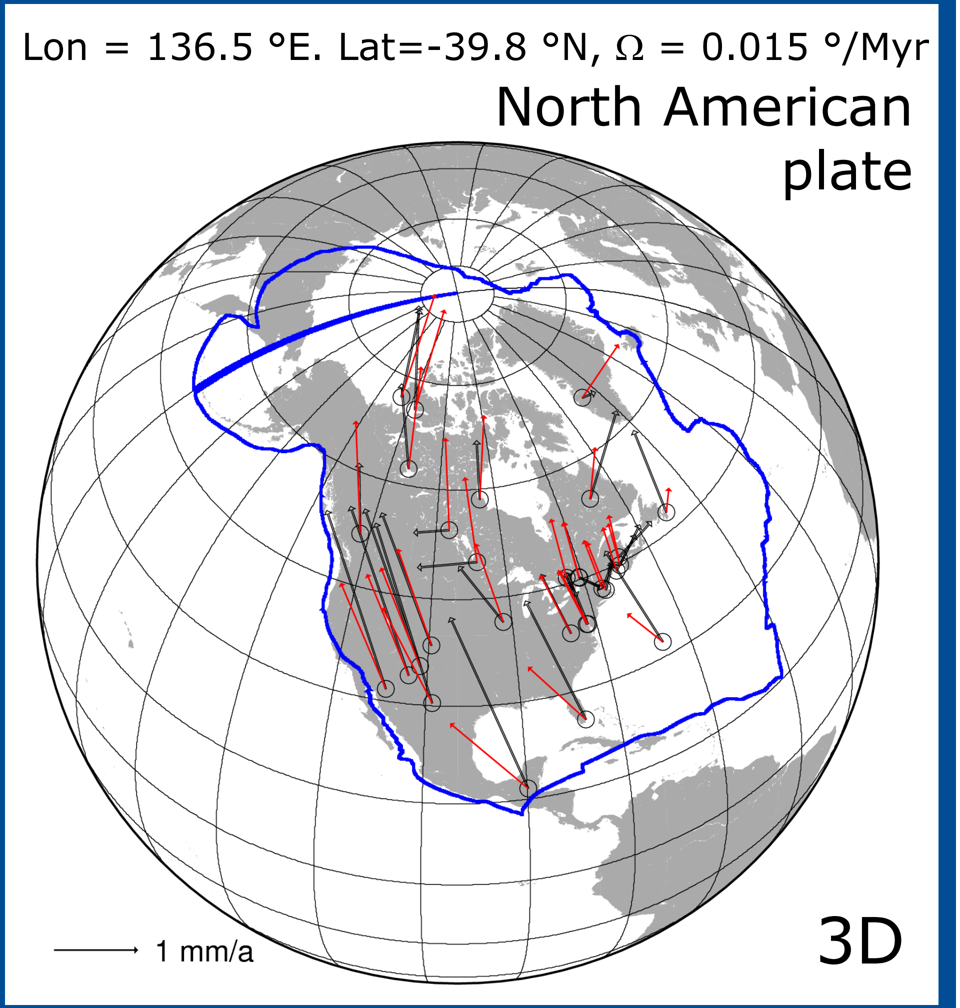
# GIA induced plate motion

Motion of NA plate determined from ITRF 2005 (Altamimi et al., JGR, 2007) and corrections due to GIA

| Model | Lon.(ºE) | Lat. (ºN) | Ω (º/Myr) |
|---|---|---|---|
| ITRF-2005 | −87.4 ±0.6 | −4.3 ±0.9 | 0.192 ±0.002 |
| 1-D | +1.1 | −0.0 | +0.002 |
| 3-D | +2.4 | +3.6 | +0.008 |

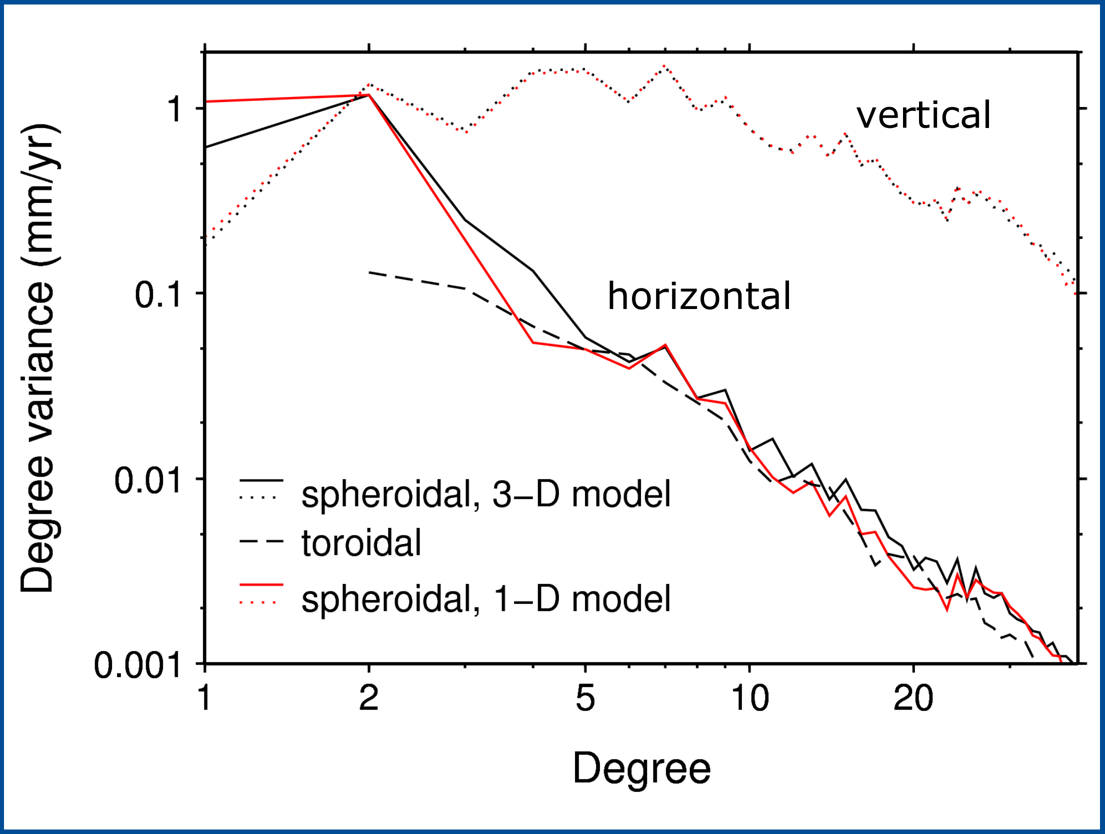
- GIA induced motion
  - < 10 % of observed plate motion
  - above accuracy of determined plate motion



# Degree variances of surface motion

Influence of plates

- Equipartitioning of spheroidal and toroidal component of GIA induced surface deformations for $j > 3$
- Equipartitioning appears in plate motions driven by convective flow (e.g. Čadek & Ricard, EPSL, 1992)
- Toroidal motion vanishes for $j = 1$ due to uniqueness condition of no surface net-rotation



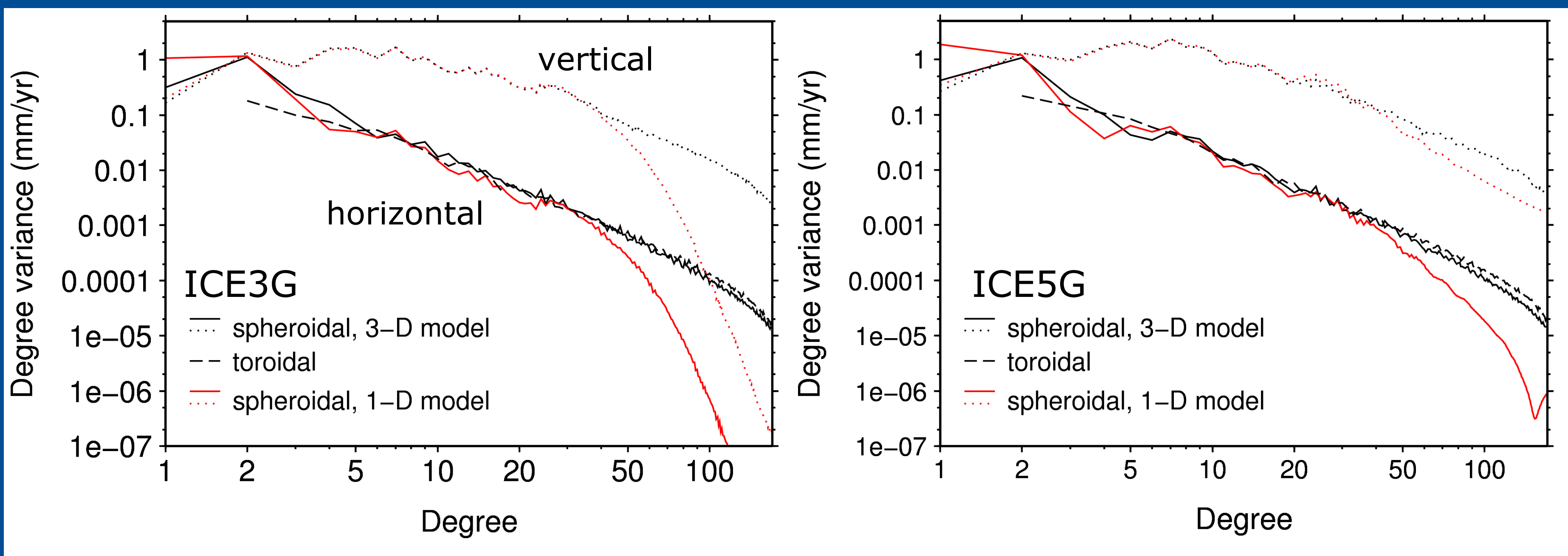
# Excursion to ICE5G

- Comparison of ICE3G (without SLE) and ICE5G (with SLE)
- Consequences of the much larger Laurentian ice dome in ICE5G
  - ICE5G is optimized for VM2 (small lower mantle viscosities)
- Consequences of VM2 and ICE5G in spectrum of surface velocities

# Degree variances of surface velocities

Comparison of ICE3G without SLE (left) and ICE5G with SLE (right)

- Left: For j>50, reduction due to flexural rigidity (1D)
- Right: With SLE equation amplitudes for larger j only slightly reduced for 1D model

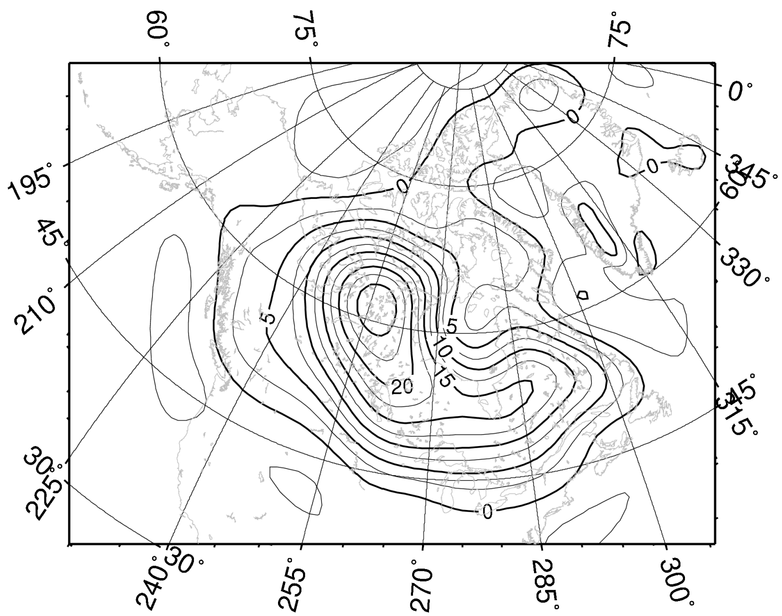


# Uplift rates of ICE5G

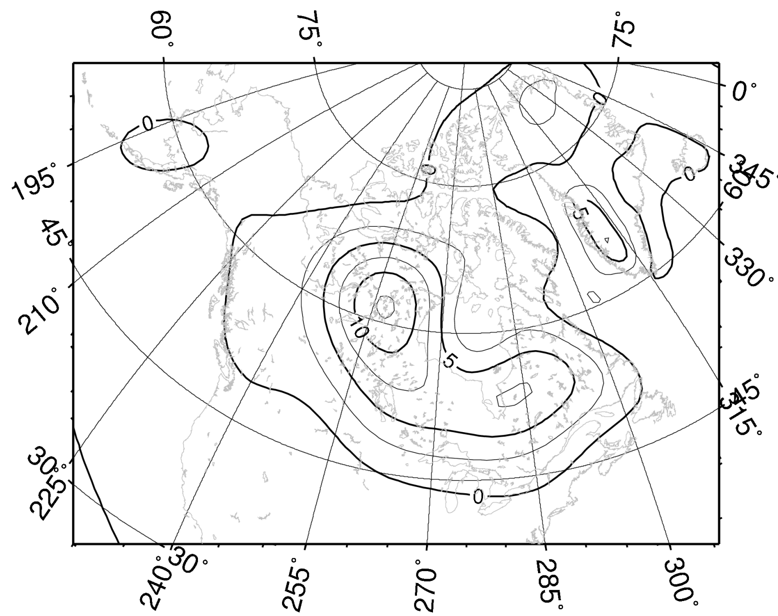
Comparison of different earth models loaded by ICE5G

- Uplift reaches 30 mm/a for lower-mantle viscosity, $\eta_{LM}$ = $10^{22}$ Pa s.
- Rates are comparable to ICE3G for VM2 ($\eta_{LM}$ = $1.8 \times 10^{21}$ Pa s).

ICE5G and high-viscous lower mantle (LM+)



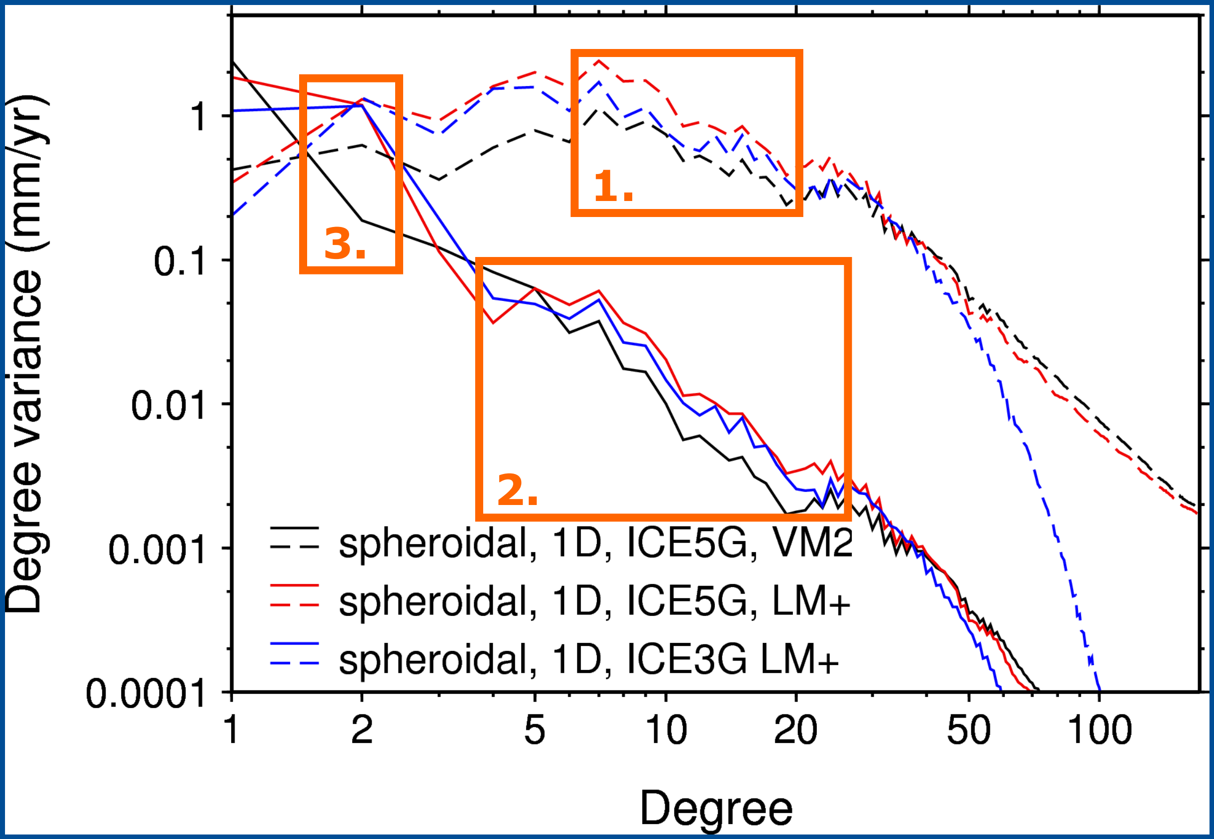

ICE5G and low-viscous lower mantle (VM2)



# Degree variances

Comparison of ice and earth models

1. VM2 reduces vertical velocities to range of ICE3G, LM+ for j=7-20
2. Horizontal velocities are governed by lower mantle viscosity
3. Polar motion (j=2) is governed by $\eta_{LM}$ and too low for VM2



# Summary

- A lithospere-strength model was constructed based on thermal data for continental lithosphere and ocean floor ages for oceanic lithosphere.
- We applied a spectral FE code
  - for the response to GIA loading
  - in a spherical geometry
  - allowing for lateral variations in lithosphere thickness
- We discussed
  - horizontal motions induced by GIA,
  - influence of lithosphere structure on surface motion,
  - consequences for motion of tectonic plates and GPS corrections
  - influence of ICE5 on the modelling strategy

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# Conclusions and outlook

- GIA induced horizontal motions
  - are globally distributed and
  - significantly influenced by consideration of plate boundaries
  - and by 1D lower mantle viscosity
- We observe an equipartitioning of horizontal spheroidal and toroidal motion in degree variances.
- The GIA-induced plate motions are comparable or above the present accuracy when determined by space-geodetic methods.
- If the tectonic plate motions are geodynamically interpreted the influence of GIA has to be considered.
- ICE5G has to be considered with prespecified viscosity model VM2

- Consideration of lateral viscosity variations in the mantle
- A more realistic parameterisation of the plate boundaries
- Extension of code for non-linear rheologies, compressibility
- Application to gravity, sea-level and intra-plate deformation
- Inversion for a consistent viscosity/ice model