Glacial isostatic adjustment - An introduction

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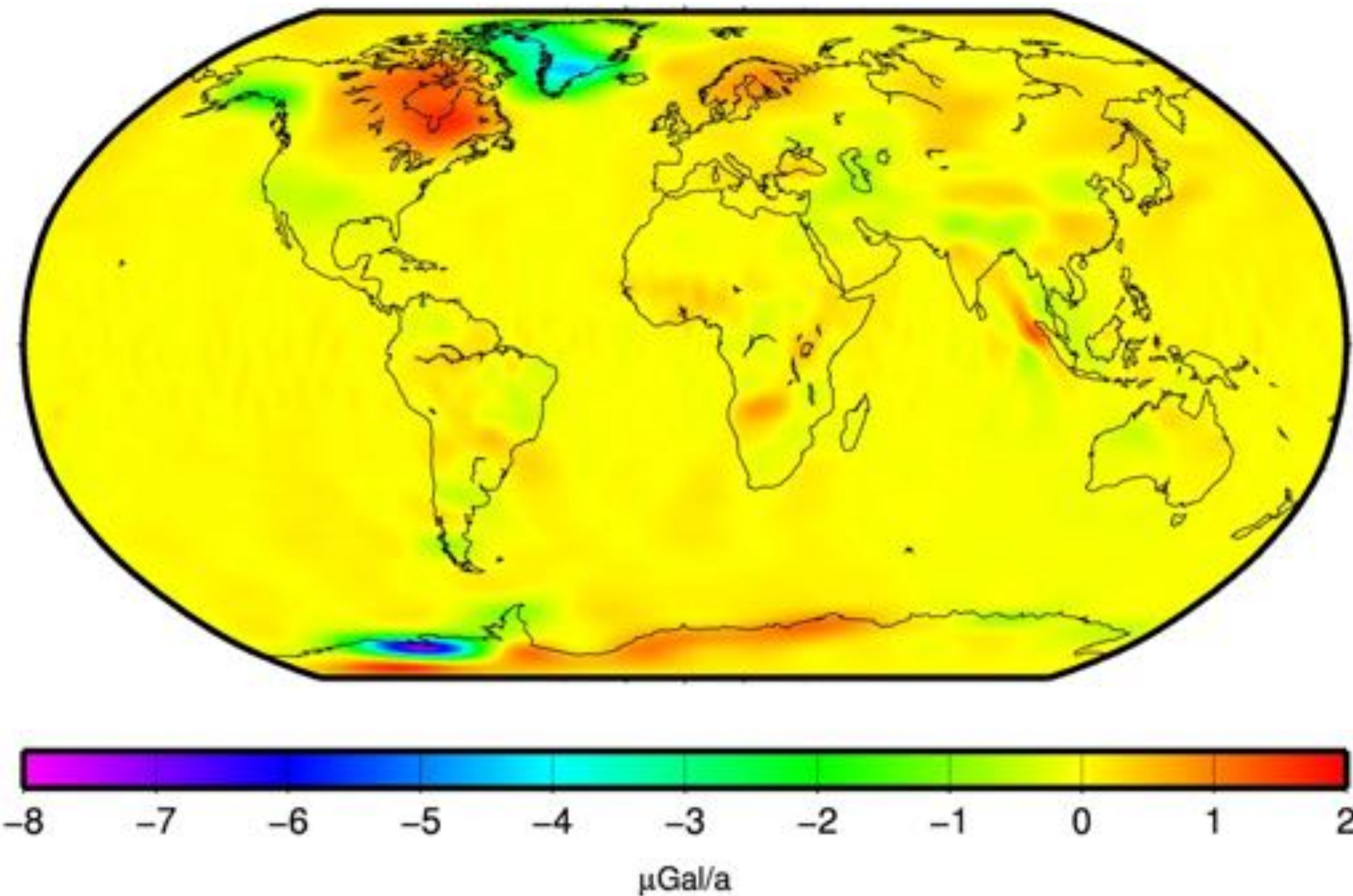
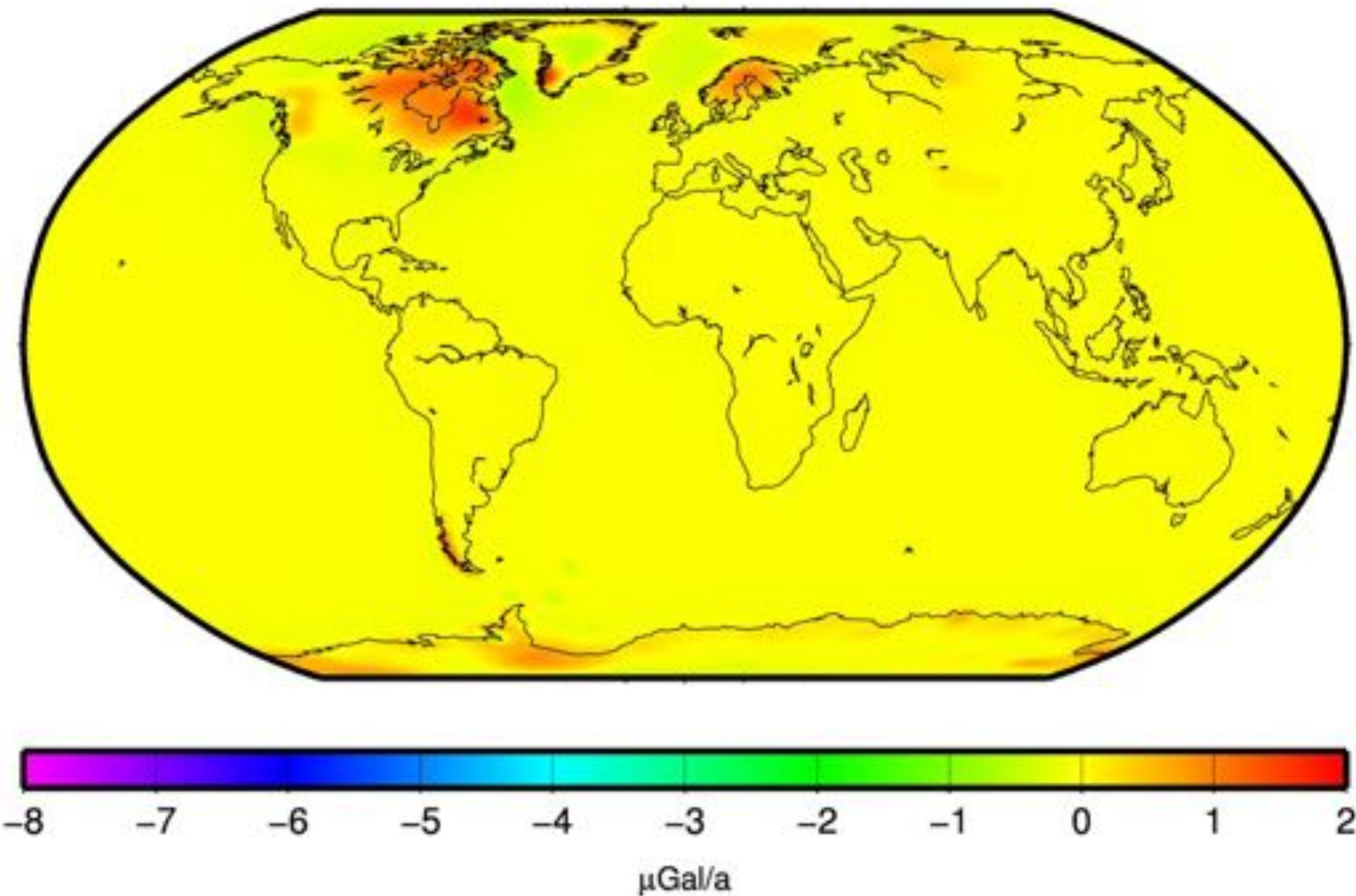
EGSIEM Summer School
Potsdam, Germany
13/09/2017

LANTMÄTERIET

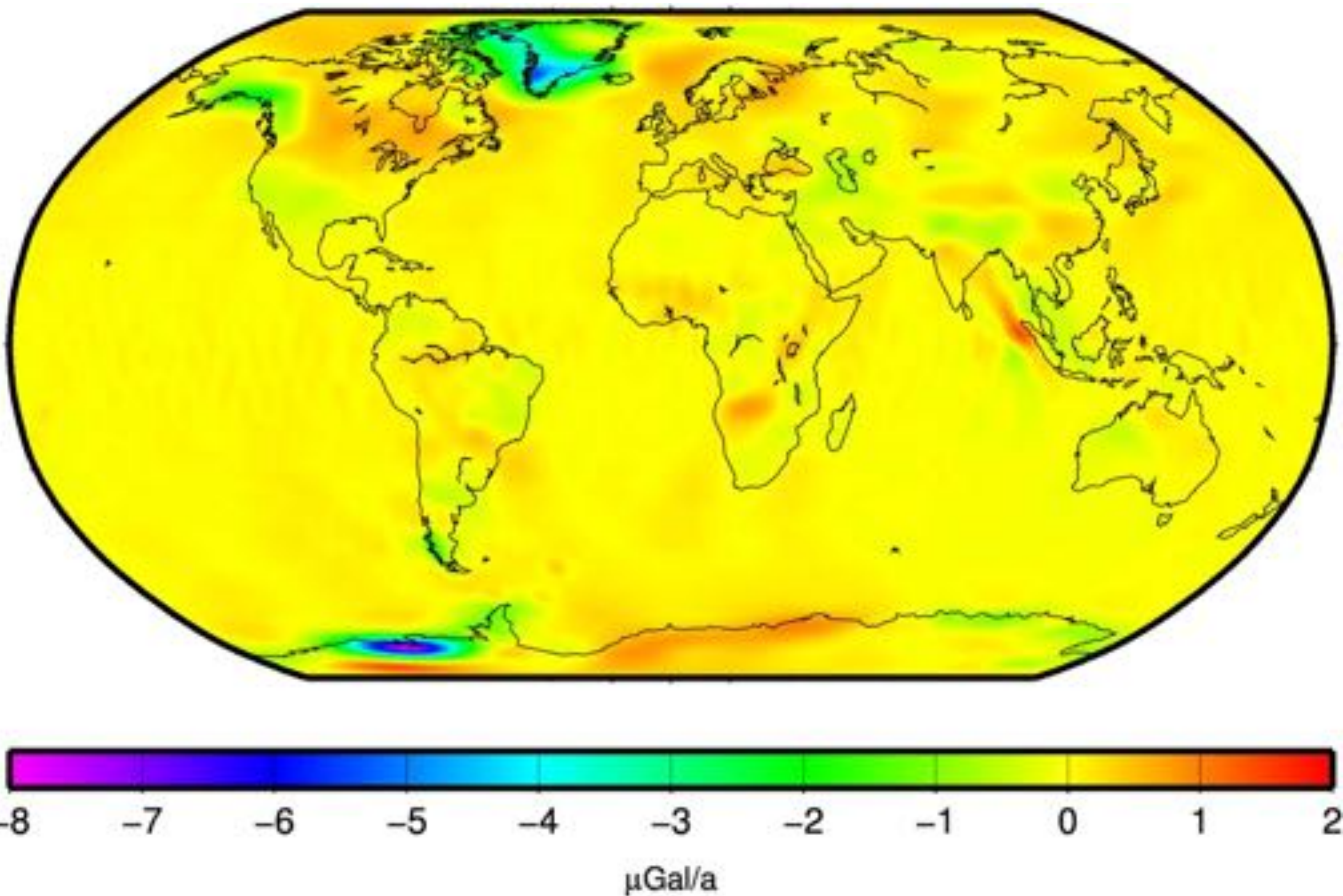
GRACE observation, trend after post-processing



1st EGSIEM GIA correction



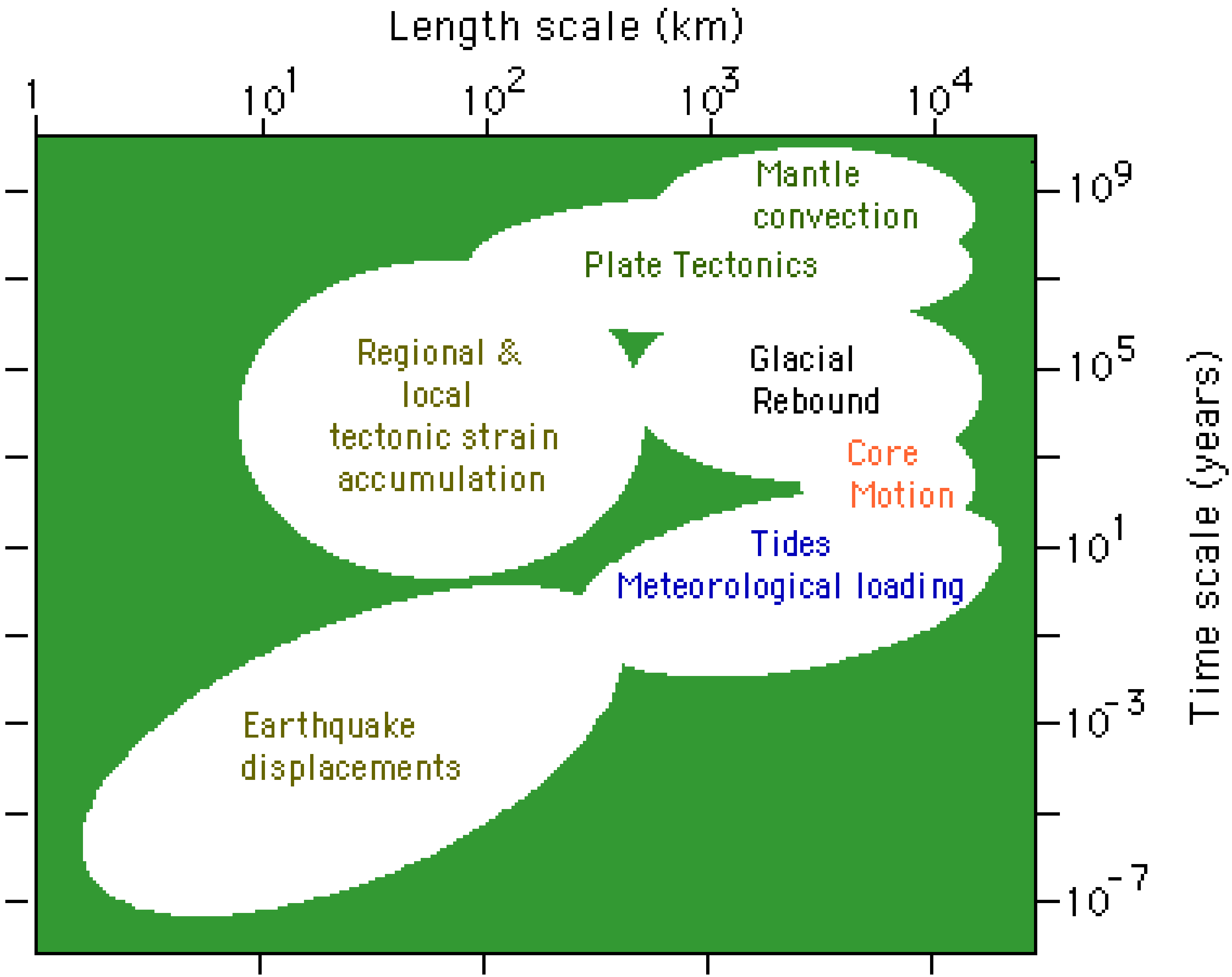
GRACE observation, GIA corrected



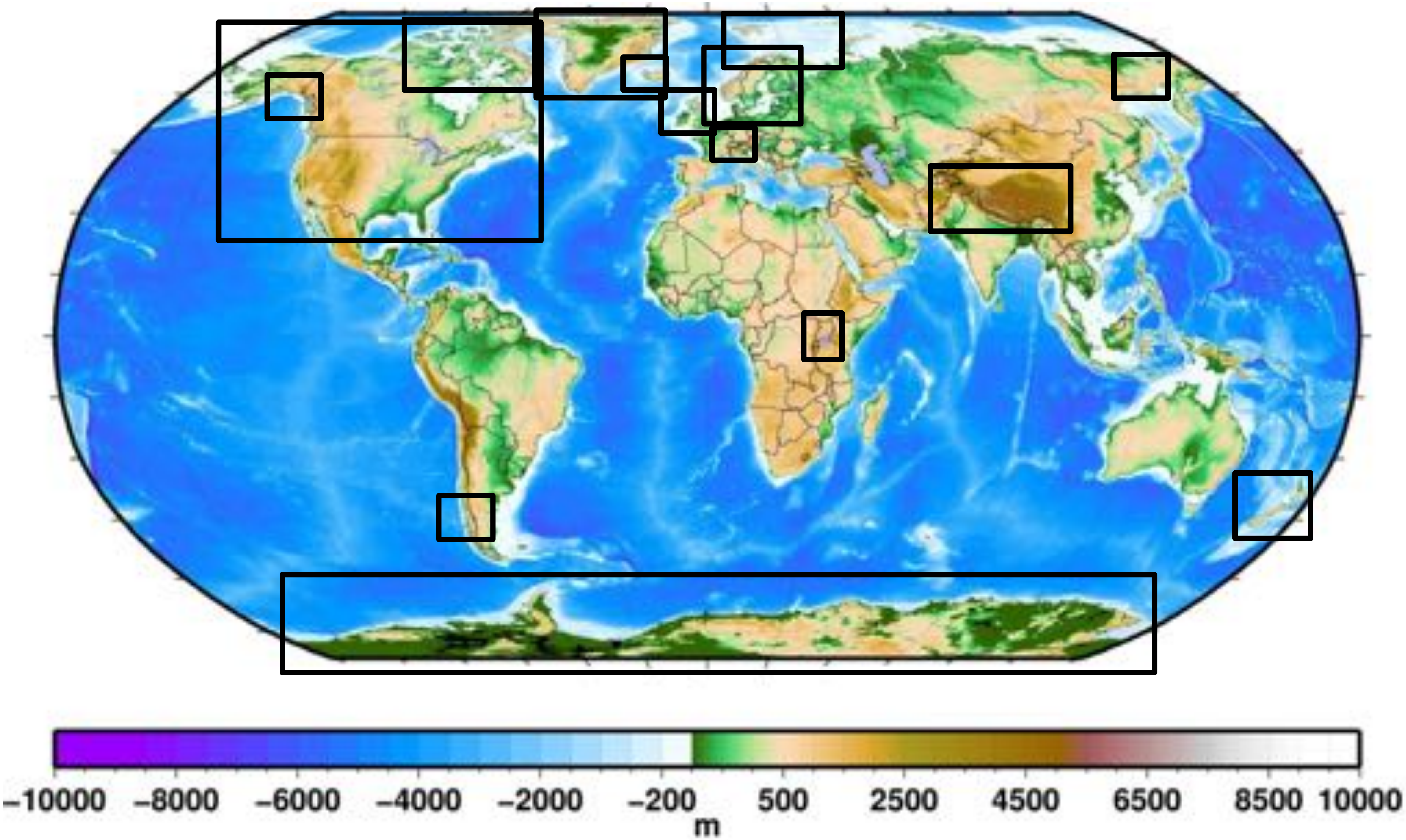
Question: What word or term do you have in mind when you hear "Glacial Isostatic Adjustment"?

FENNOSCANDIA
Equilibrium
LITHOSPHERE
PRESENT-DAY_MASS_CHANGE
Viscosity
Equation_of_motion
GLACIAL_ISOSTATIC_ADJUSTMENT
Laurentia
POSTGLACIAL_FAULTS
SEA-LEVEL_CHANGE
Last_glacial_maximum
POSTGLACIAL_REBOUND
Maxwell_body
Relative_sea_levels
RELAXATION_TIME
ICE_HISTORY
MANTLE
Love_number
BUOYANCY
SEA-LEVEL_EQUATION
Quaternary
HOLOCENE
CRUST
Land_uplift
Ice_sheet
GPS
SUBSIDENCE
Rheology
BIFROST

Time & length scale of some geodynamic processes



GIA vs. the World



Plan

- A bit of “GIA” history
  - Some physics
  - Some applications
- Observations of GIA
  - Some applications
  - GRACE, of course

In case of questions, ask!

Reference for historical development

- Cathles, L.M. (1975) *The viscosity of the Earth's mantle*, Princeton Univ. Press.
- Lliboutry, L. (1998) *The birth and development of the concept of Glacial-Isostasy, and its Modelling up to 1974* in Dynamics of the Ice Age Earth: a modern Perspective, Ed. P.Wu, TTP.
- Ekman, M. (2009) *The Changing Level of the Baltic Sea during 300 Years: A Clue to Understanding the Earth,* Summer Institute for Historical Geophysics, Åland Islands. Open Access Download: http://www.historicalgeophysics.ax/The%20Changing%20Level%20of%20the%20Baltic%20Sea.pdf
- Krüger, T. (2013) *Discovering the Ice Ages. International Reception and Consequences for a Historical Understanding of Climate*. Brill, Leiden.

Northern Europe ca. 1635

(Source: https://upload.wikimedia.org/wikipedia/commons/7/73/Svecia%2C_Dania_et_Norvegia%2C_Regna_Europ%C3%A6_Septentrionalia.jpg)

Luleå city/harbour relocation

Northern Europe ca. 1635

(Source: https://upload.wikimedia.org/wikipedia/commons/7/73/Svecia%2C_Dania_et_Norvegia%2C_Regna_Europ%C3%A6_Septentrionalia.jpg)

(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

Brämön

(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

Athanasius Kircher, Mundus subterraneus (1665)

(Source: Cornell University Library)

Anders Celcius and Johannes Rudman

Anders Celsius
(1701-1744)

?

Johannes Augustini Rudman
(1699-1760)

(Source:https://sv.wikipedia.org/wiki/Anders_Celsius#/media/File:Anders-Celsius-Head.jpg)

Seals rest close to the water surface

(Source:http://www.sll.fi/mita-me-teemme/lajit/saimaannorppa/ringed-seal/leadImage)

Saimaa ringed seal

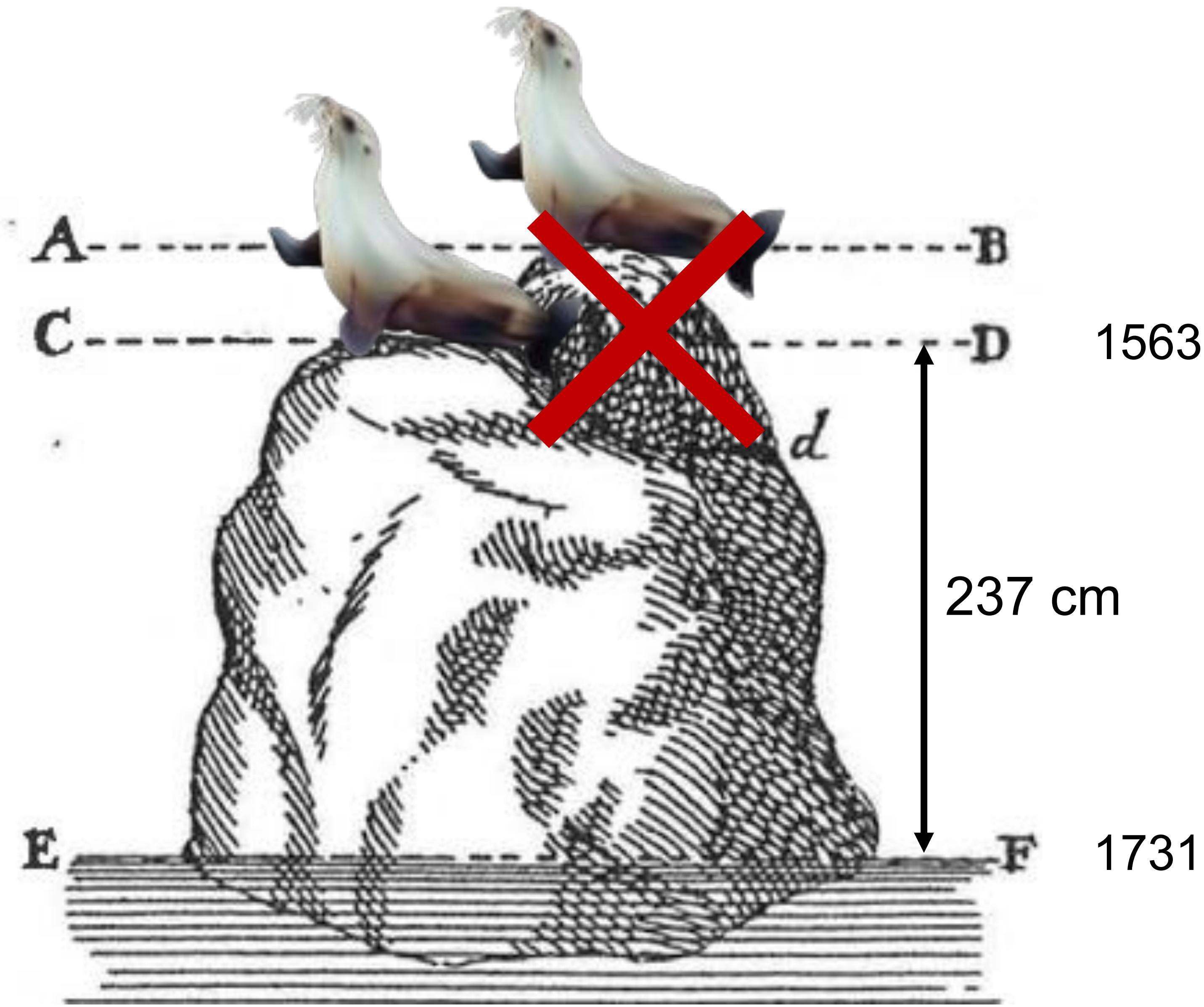
Seal hunting
(Carta Marina)

(Source: http://sydaby.eget.net/ody/opics/maps/saelfangst.jpg)

View to Iggön

(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

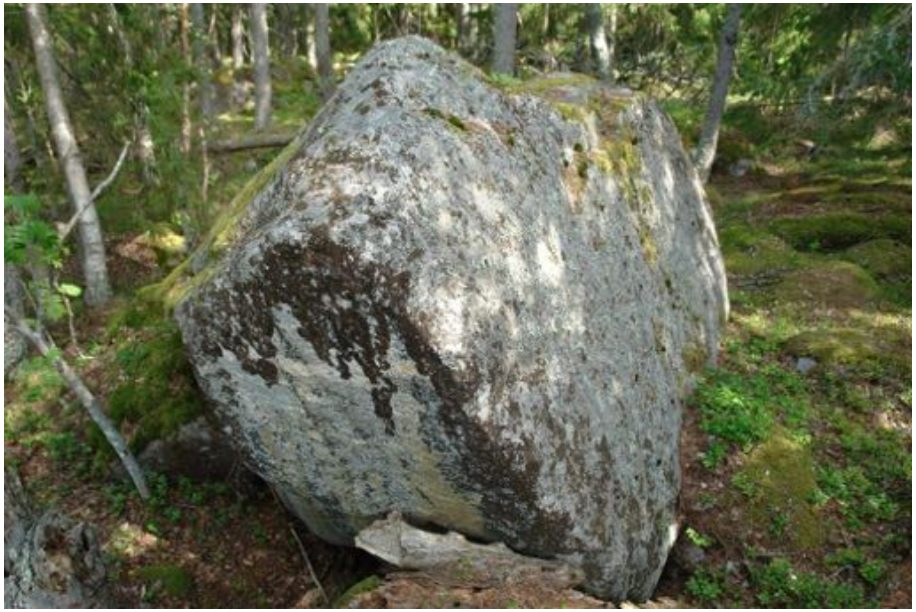
Land uplift complicates seal hunting



(Celsius 1743)

Iggön 2015

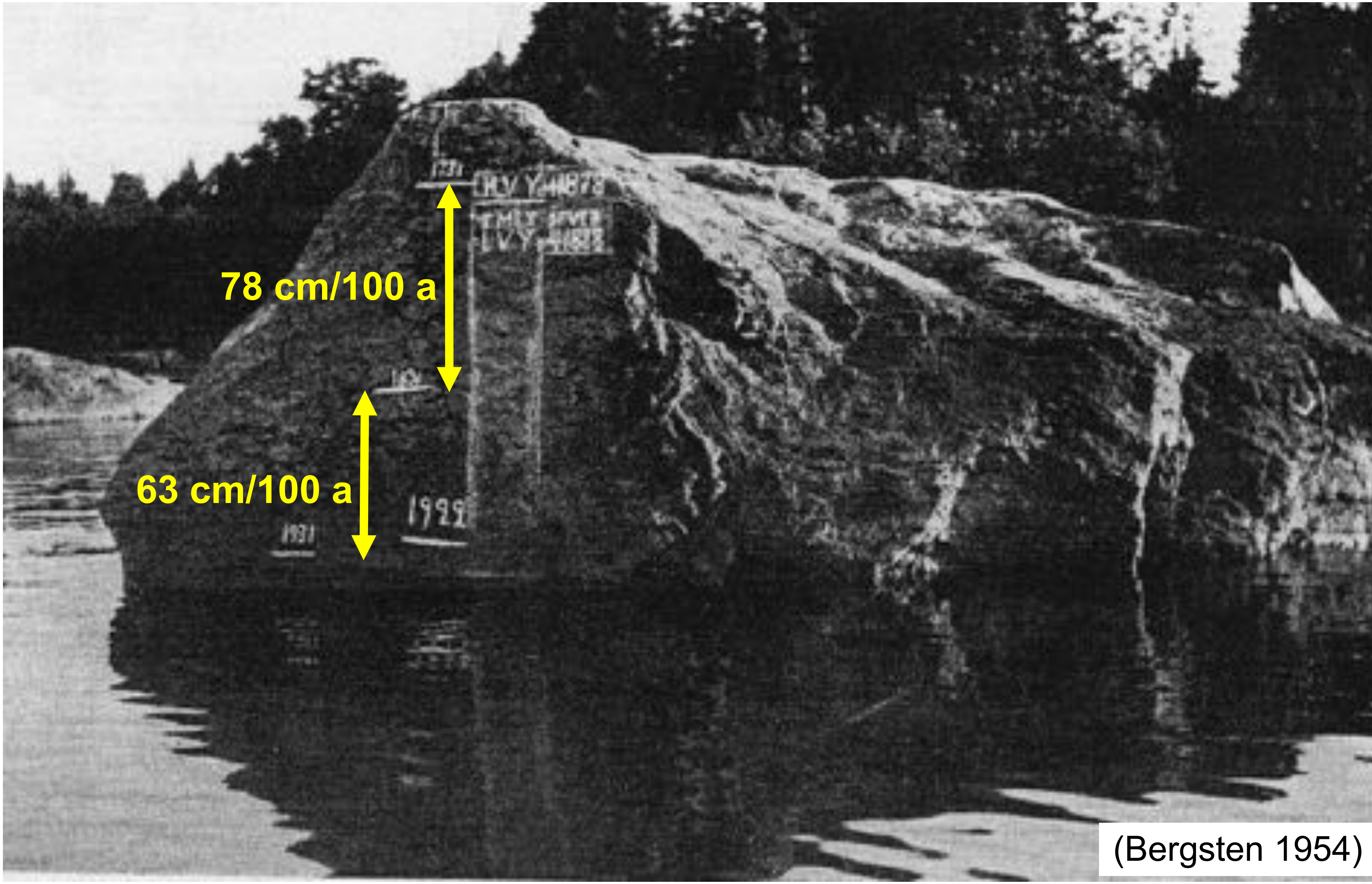
Iggön today



Lövgrund

(Source: https://upload.wikimedia.org/wikipedia/de/0/03/Karte_Gävlefischer.png)

Water marks: example Celsius rock

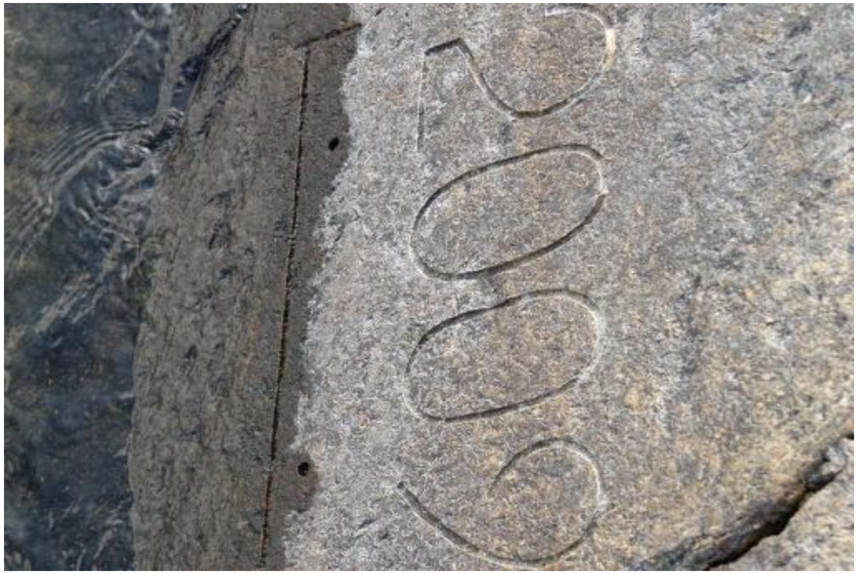


Water marks: example Celsius rock (08/06/2015)

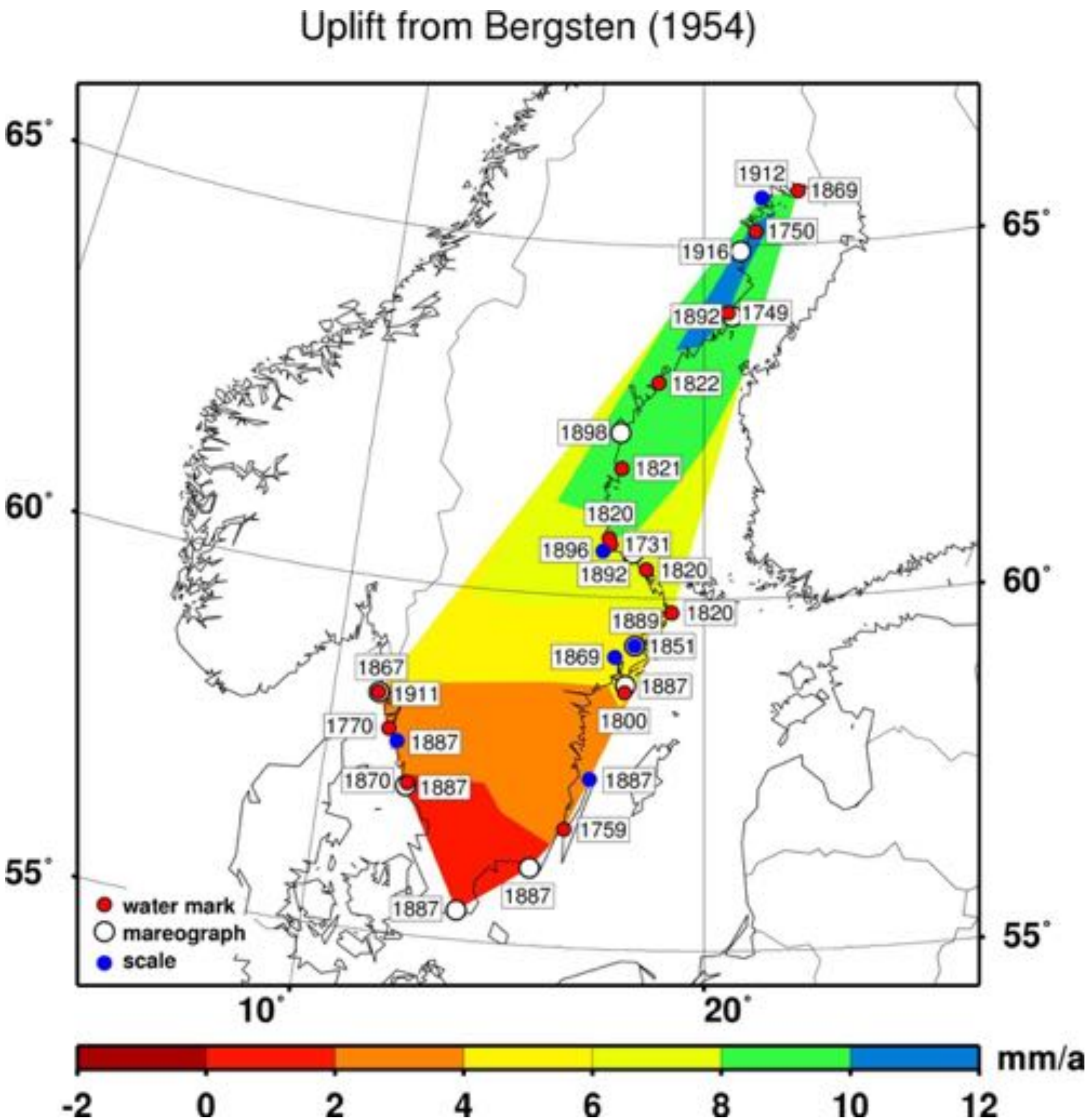
Water marks: example Celsius rock (08/06/2015)

Water marks: example Celsius rock (06/15/2016)

Water marks: example Ledskär/Ratan



Uplift rate from water marks in Fennoscandia



Questions:

- Did sea level fall or did land rise?

  Land uplift

- What is the cause?

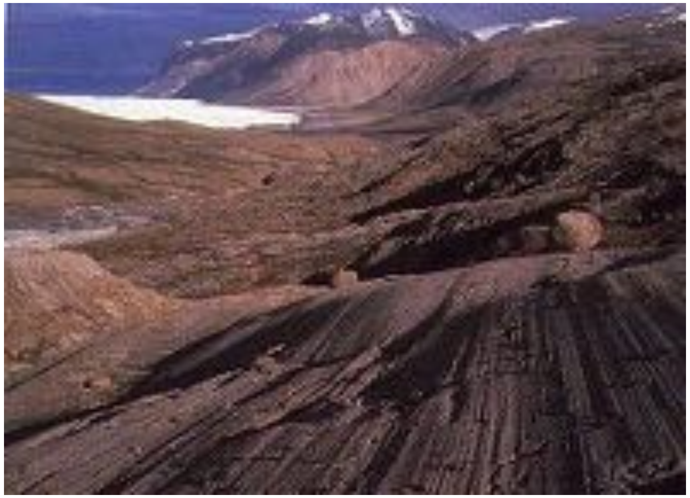
(Steffen and Wu 2011)

A step forward: Explain these structures!

Kettles/Potholes

Drumlin

Striations in bedrock



Erratic boulder

Structures are related to glaciers/glaciations!

- Alp valley inhabitants in the 18th century linked erratics to glaciers
- People knew that glaciers extended much farther before
- Similar knowledge in South America
- Many reported about that, e.g. Pierre Martel (1706–1767) in 1744, James Hutton (1726–1797) in 1795, Jean-Pierre Perraudin (1767–1858) in 1815
- Göran Wahlenberg (1780–1851) published in 1818 theory of a glaciation of the Scandinavian Peninsula, but interpreted as regional phenomenon

Jens Esmark (1763-1839)

https://upload.wikimedia.org/wikipedia/commons/3/37/Jens_Esmark.png

- Investigated glaciers and their traces
- Link erratic boulders and moraines - glacial transportation and deposition
- Introduced 1824 concept that glaciers once covered larger areas (worldwide)
- Several ice ages related to orbital forcings

Ignaz Venetz (1788-1859)

https://upload.wikimedia.org/wikipedia/commons/e/e4/Ignaz_Venetz_1826_-_Wood_2014_p158.jpg

- Investigated glaciers in the Alps
- Suggested in 1821 (but presented in 1829 and published in 1833) that much of Europe had at one point in the past been covered by glaciers

Karl Friedrich Schimper (1803-1867)

https://upload.wikimedia.org/wikipedia/commons/f/fe/Schimper_Karl_Friedrich_1866.jpg

- Ice sheets once covered much of Europe, Asia, and North America
- Talked in 1835/36 about “world winter” and “world summer” – climate changes
- Did not publish much, preferred to give talks
- So his findings were later popularized by…

Louis Agassiz (1807-1873)

https://upload.wikimedia.org/wikipedia/commons/d/df/Louis_Agassiz-2.jpg

- Investigated glaciers and their traces
- Presented 1837 the theory of a past glaciation (”Eiszeit” – ice age) of large parts of Europe in a talk to Swiss scientists
- However, he was not the first (as shown on previous slides), but his numerous subsequent publications advertized this theory, triggered further investigations and eventually lead to acceptence of the ice age theory
- Theory expands in the British Empire & North America

Charles MacLaren (1782-1866)

http://www.edinburghgeolsoc.org/images/z_40_02c.jpg

- Realized in 1841 that sea level must drop when the huge ice sheets formed during the Ice Age
- Estimated to be 800 ft lower (than in 1841)

Now we have two things…

1. Sea-level fall/land uplift in northern Europe
2. Ice age theory

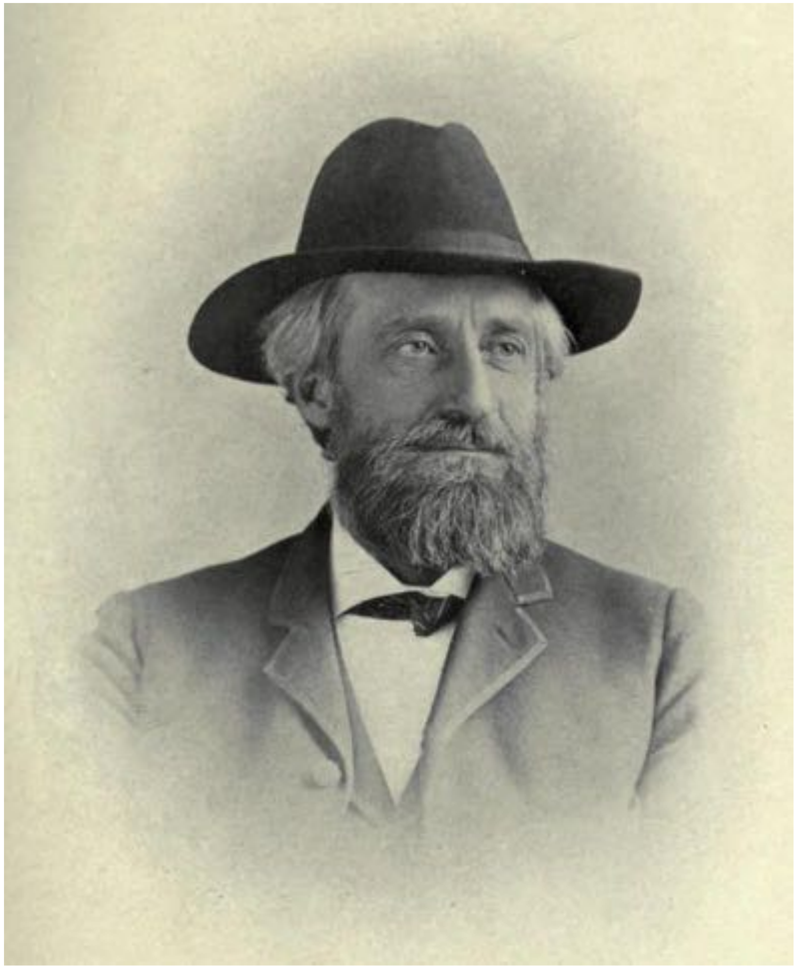
Where is the link (or better, who makes it)?

Thomas Jamieson (1829-1913)

http://www.landforms.eu/ScottishSeaLevels/images/Thomas-Jamieson_small.gif

- Investigated sediments in Scotland and found a sequence of glacial, marine, terrestrial, marine, terrestrial sediments
- Concluded in 1865 that a glacier depressed the area, which was then flooded by the sea and later rose → link ice sheet – land uplift
- Did not use the word ”isostasy”
- Later (1882) found that depression relates to ice thickness

Nathaniel S. Shaler (1841-1906)

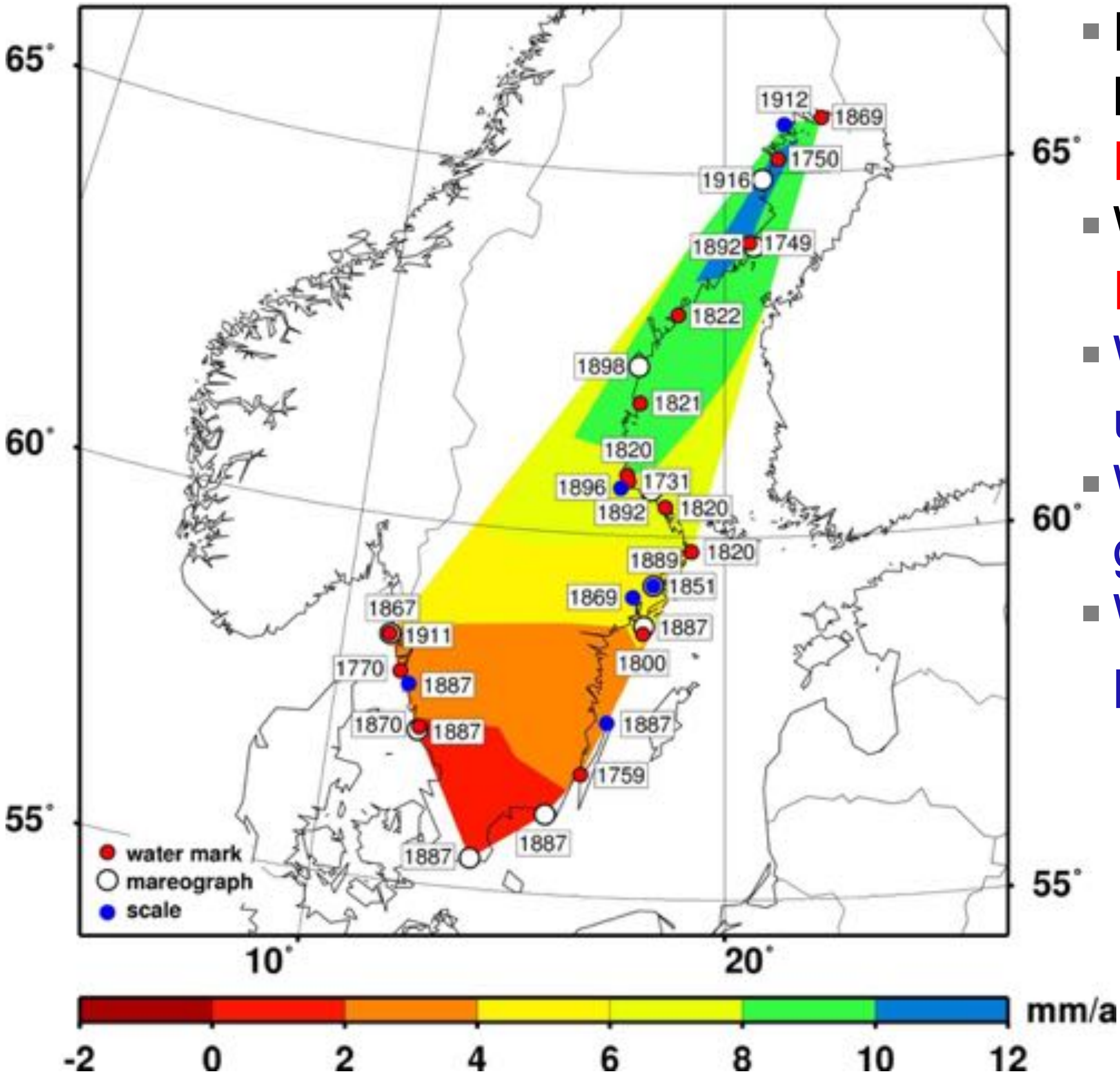


https://upload.wikimedia.org/wikipedia/commons/4/41/Picture_of_Nathaniel_Shaler.jpg

- Reported in 1874 on the changing shoreline of New England
- Made the same suggestion as Thomas Jamieson

Let's go back to this slide

Uplift from Bergsten (1954)

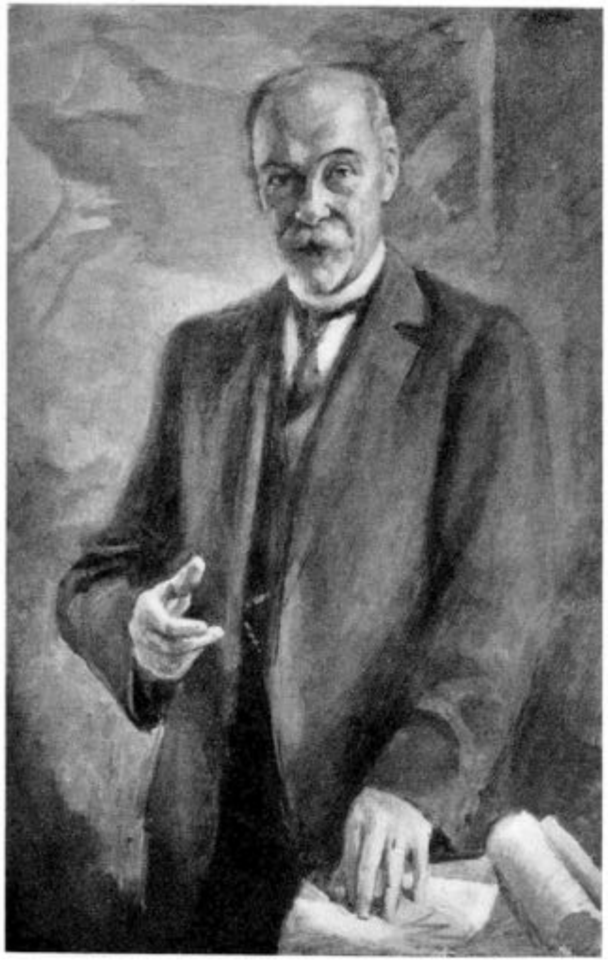


Questions:

- Did sea level fall or did land rise?
  Land uplift!
- What is the cause?
  Former glaciation!
- Where was/is the land uplift?
- When was the glaciation?
- What are the underlying physics?

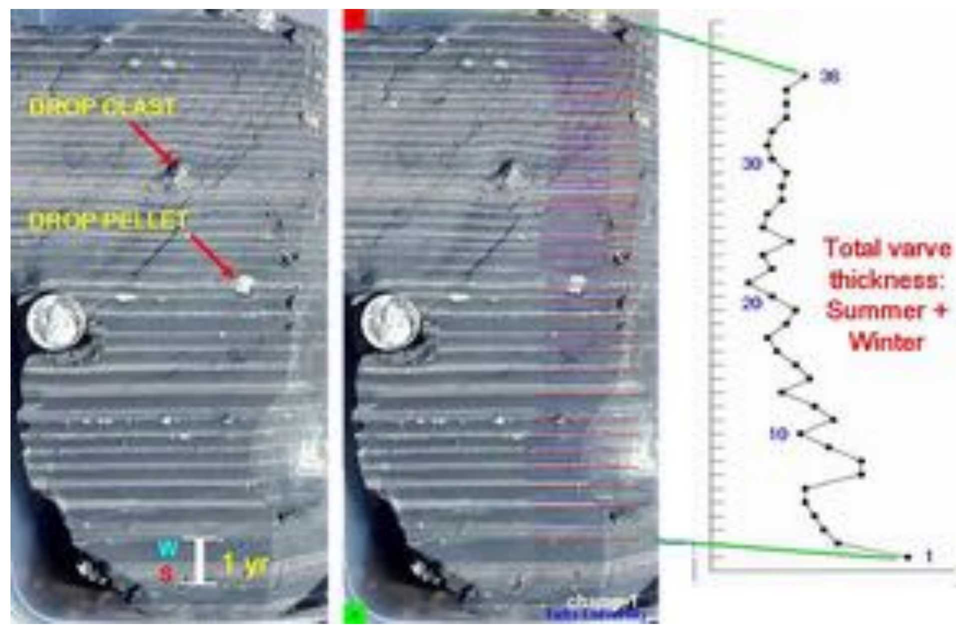
(Steffen and Wu 2011)

Gerard de Geer (1858–1943)



http://sok.riksarkivet.se/sbl/bilder/
17350_7_010_00000553_0.jpg

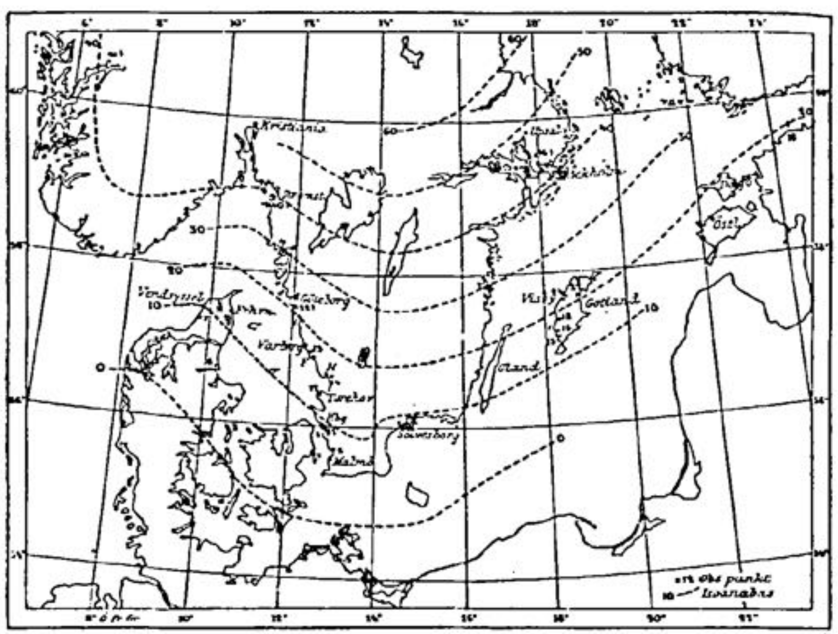
- Varve chronology, the Swedish time scale and glacial features (de Geer moraines)
- Land uplift map in 1888/90
- Last glaciation was not longer than ~9000 years ago



http://eos.tufts.edu/varves/images/varve_chron1.jpg

Postglacial land uplift

Isoanabaser för den postglaciala höjningen.

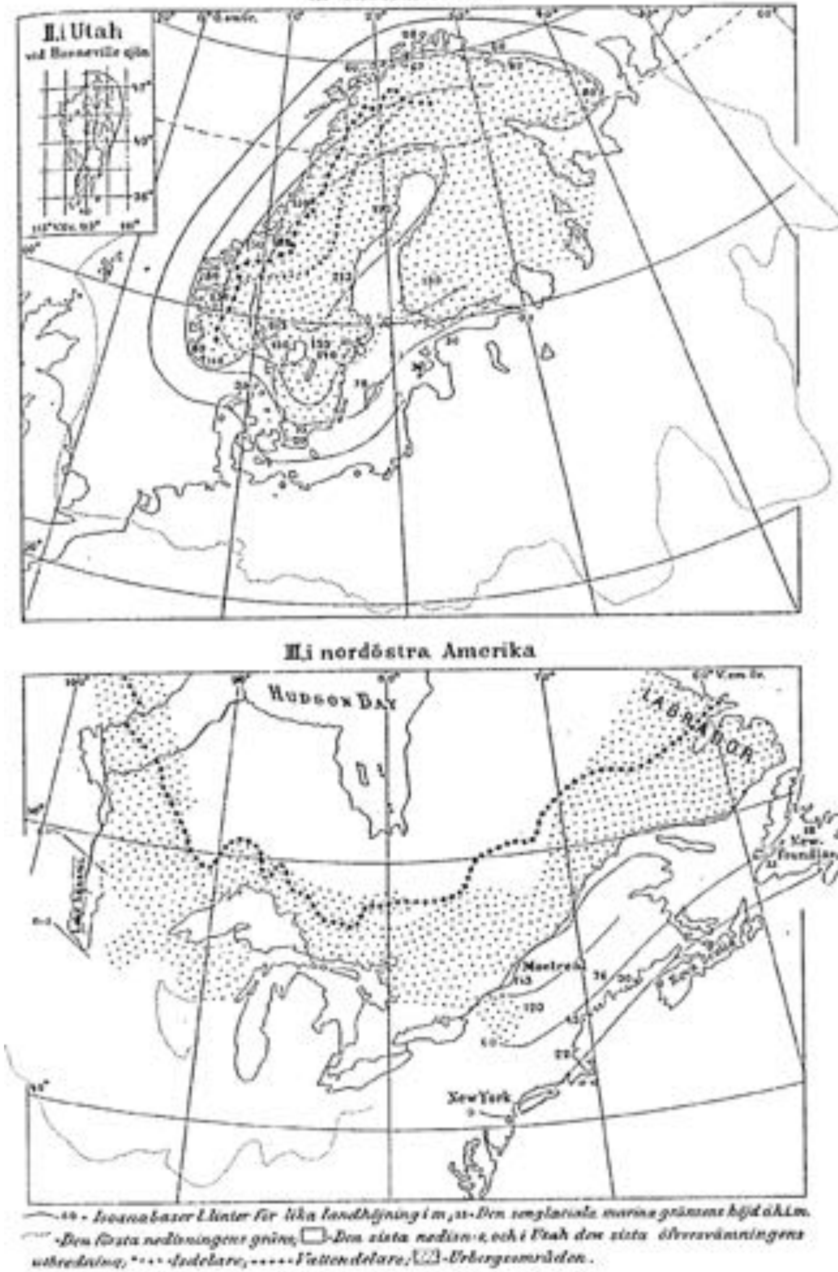


Måtten i meter.

Skala 1 : 11 750 000.

de Geer (1890)

Isoanabaser öfver landhöjningen efter Istiden
I. i Skandinavien

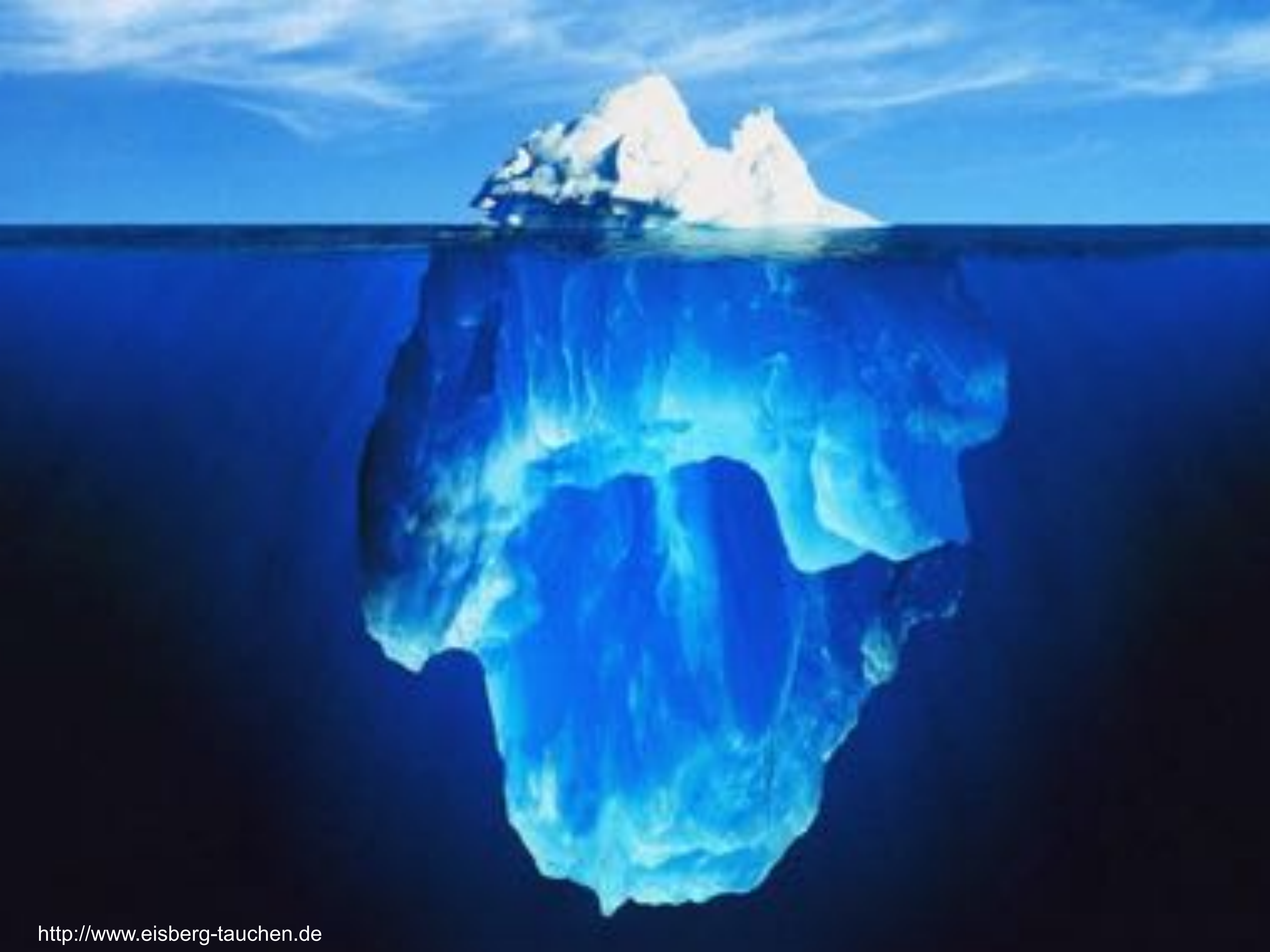


de Geer (1888)

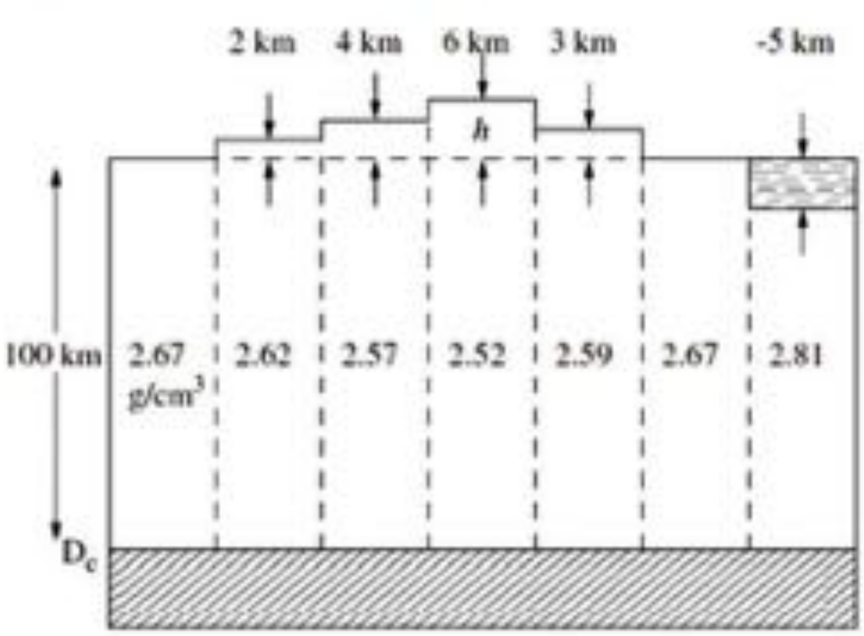
Remaining question (for now)

Questions:

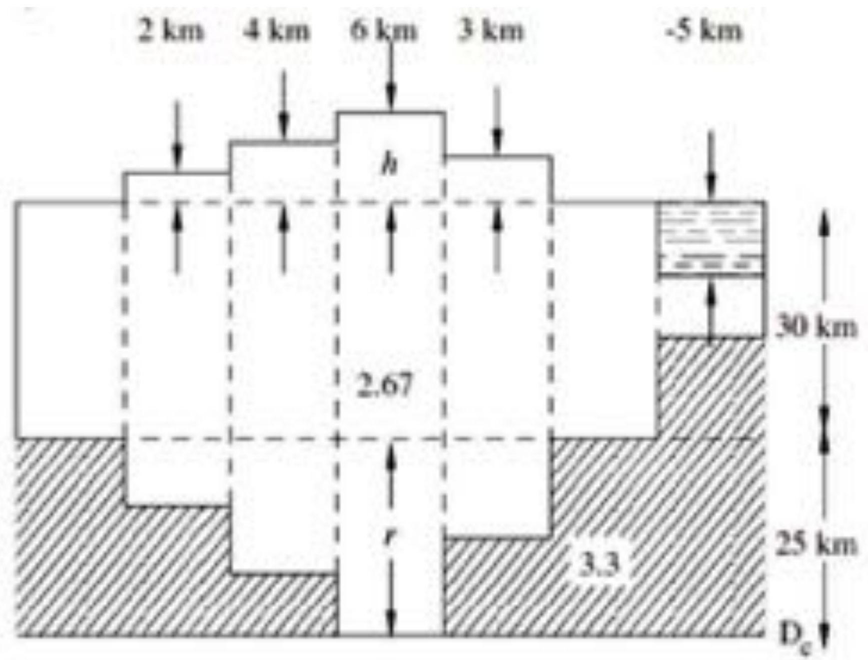
- Did sea level fall or did land rise?
  - Land uplift!
- What is the cause?
  - Former glaciation!
- Where was/is the land uplift?
  - Identified in maps and gravity anomalies
- When was the glaciation?
  - Can be calculated from varves
- What are the underlying physics?


http://www.eisberg-tauchen.de

Isostatic models of Airy & Pratt



Airy-Heiskanen model

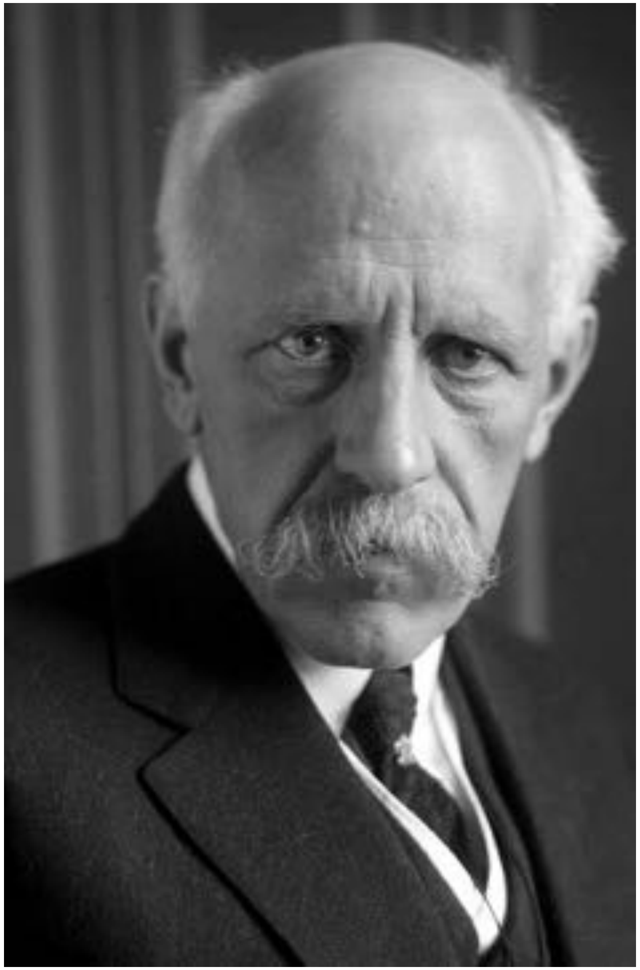


Pratt-Hayford model

Introduced for mountains!

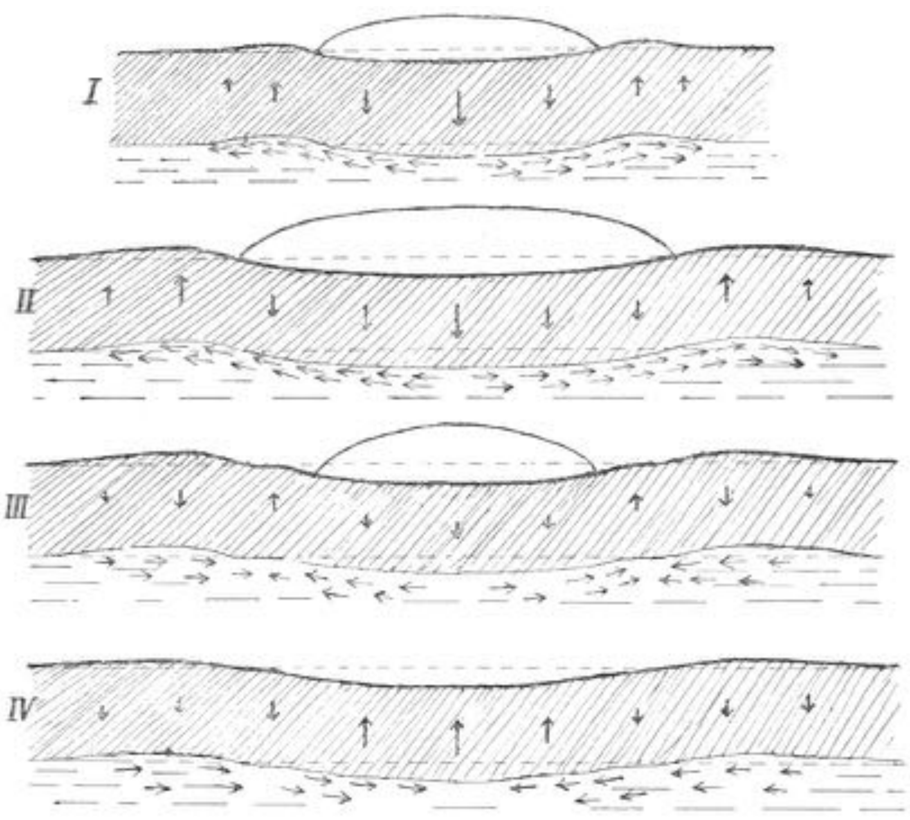
Close (2010)

Fridtjof Nansen (1861–1930)



https://upload.wikimedia.org/wikipedia/en/c/c6/Bundesarchiv_Bild_102-09772%2C_Fridjof_Nansen_%28cropped%29.jpg

- Isostasy as explanation of readjustment
- But why does it take so much time for readjustment (we see it today!)?

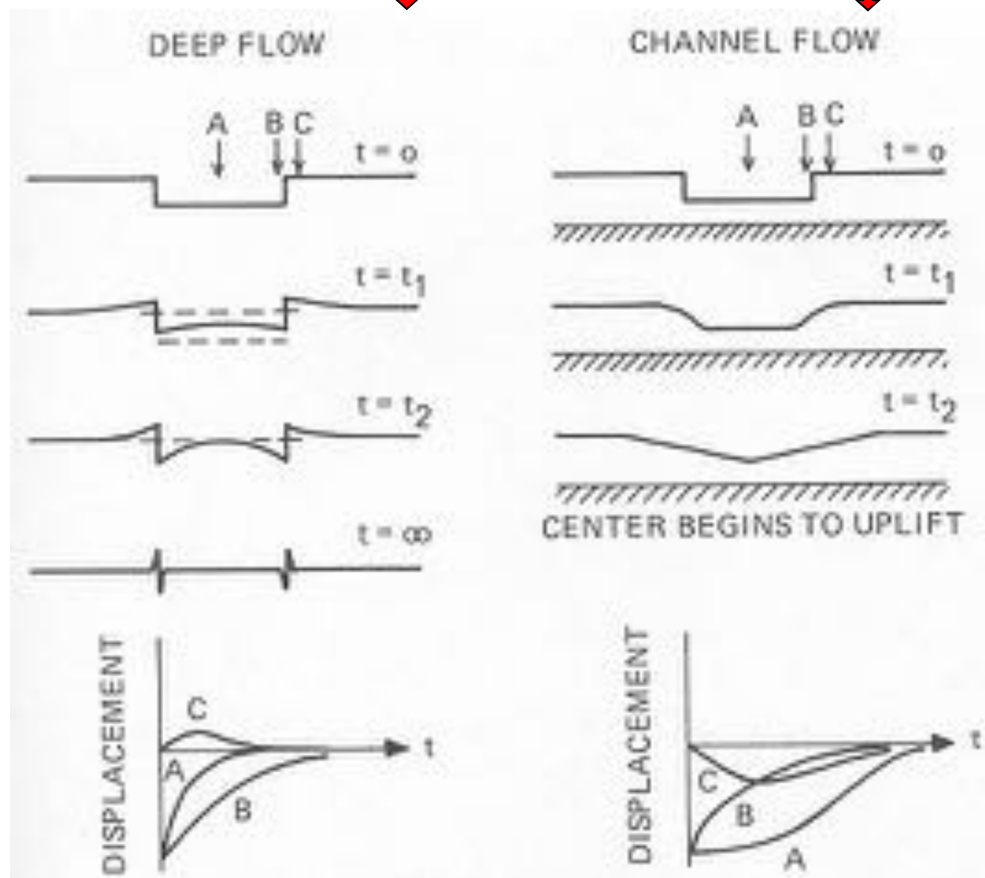


Nansen (1921)

Reginald A. Daly (1871-1957)

https://upload.wikimedia.org/wikipedia/en/0/09/RA_Daly.jpg

- Two rheological earth models, "punching hypothesis" and "bulge hypothesis“



(Cathles 1975)

Rebound modeling and viscosity estimates

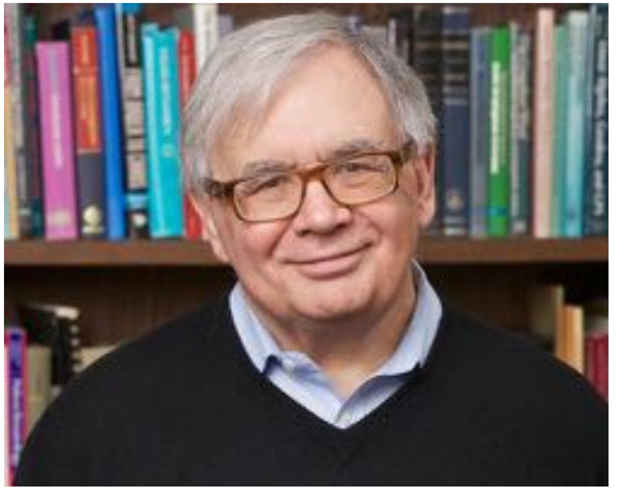
Deep Flow (Punch)	Channel Flow (Bulge) Hi Visc Lower Mantle
Daly (1934)	
Haskell (1935, 1936, 1937) ν ~0.95 x 10^{21} Pa s Predict uplift remaining ~ 20 m*	Van Bemmelen & Berlage (1935) 100 km channel, ν ~1.3 x 10^{20} Pa s Predict uplift remaining ~210 m*
Vening Meinesz (1937) ν ~3 x 10^{21} Pa s	Niskanen (1939) ν ~ 3.6 x 10^{21} Pa s Predict uplift remaining ~200 m*
Gutenberg (1941) ν ~2 x 10^{21} Pa s	Crittenden (1963), McConnell (1968)
Andrews (1968, 1970)	Lliboutry (1971), Artyushkov (1971)
Cathles (1971), Parsons (1972)	Post & Griggs (1973) nonlinear flow
Peltier (1974)	Walcott (1972)

*Fennoscandia!

Development since the 1950s

- Theory of physics → equations
- Computers and increase in computational power
- Dating methods (for fossils, ice cores etc.) → knowledge of past glaciations and sea levels
- Mapping of the oceans → continental drift → convection
- Satellite missions → global gravity models

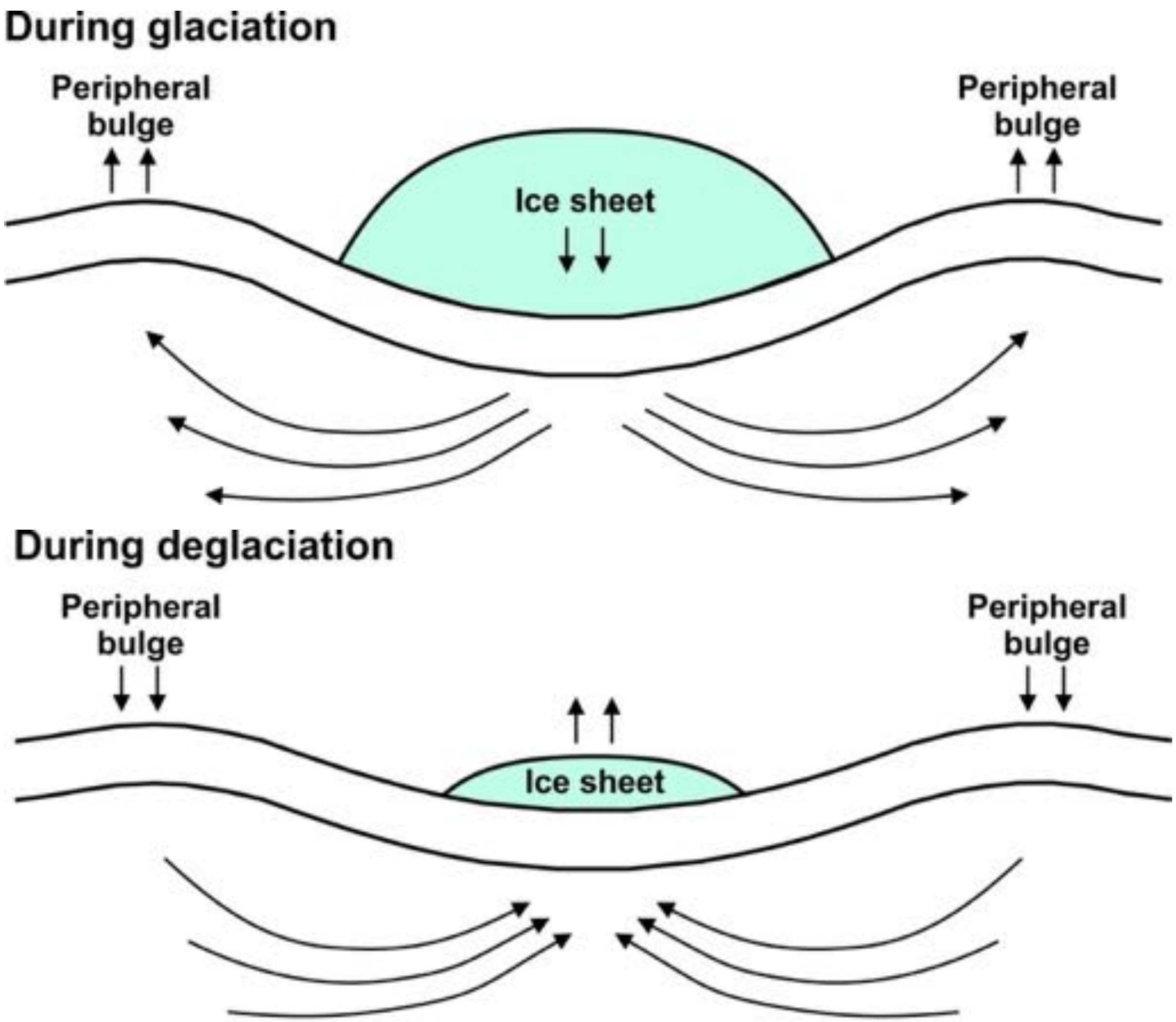
Kurt Lambeck



W. Richard Peltier

(http://www.news.utoronto.ca/sites/default/files/Peltier_12_02-27_0.jpg?1364827862)

Glacial Isostatic Adjustment

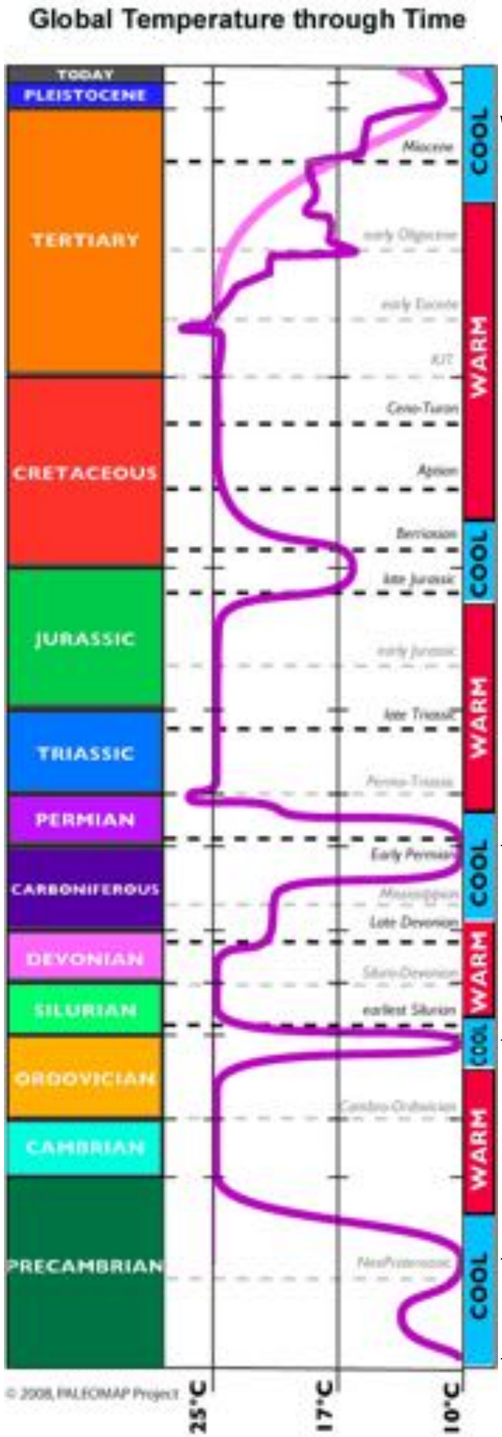


(R. Steffen, 2013)

Ice Ages

How many?

Causes of Ice Age?



Ice Ages through Geologic Time:

Last Ice Age started ~2.6 Ma ago when the Himalayas & Andes were pushed up

Gondwanan Ice Age ~ 300 Ma ago when Pangaea was near the south pole

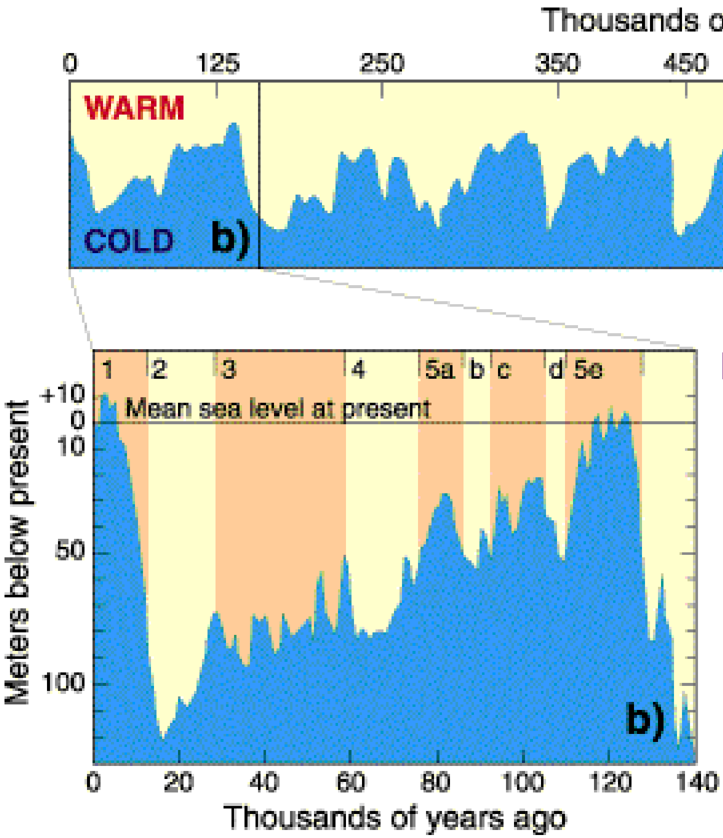
Ordovician Glaciation ~ 450 Ma ago

Neoproterozoic 850 – 630 Ma ago (Snowball Earth?)

Huronian 2700 -2300 Ma ago

Climate and sea-level history

a. Global climate history during the Pleistocene



Interglacial

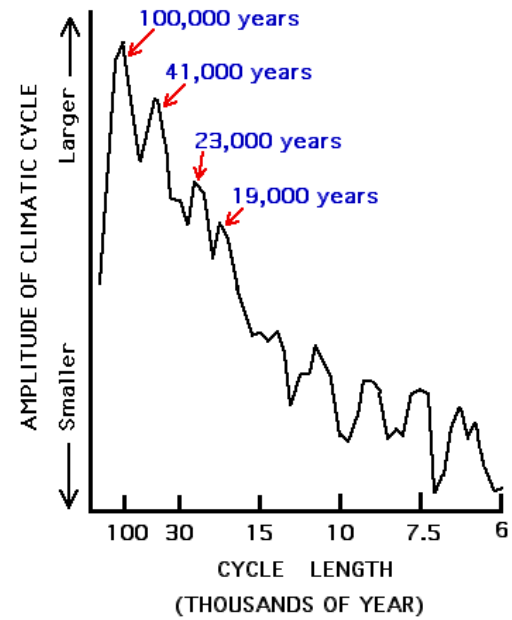
Glacial

b. Late Quaternary sea-level history

Interstadial – minor glacial retreat/warming

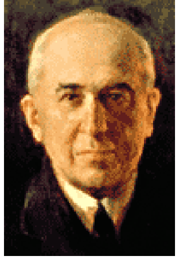
Stadial – minor glacial advance/cooling

Spectrum of climatic variation over the past half million years

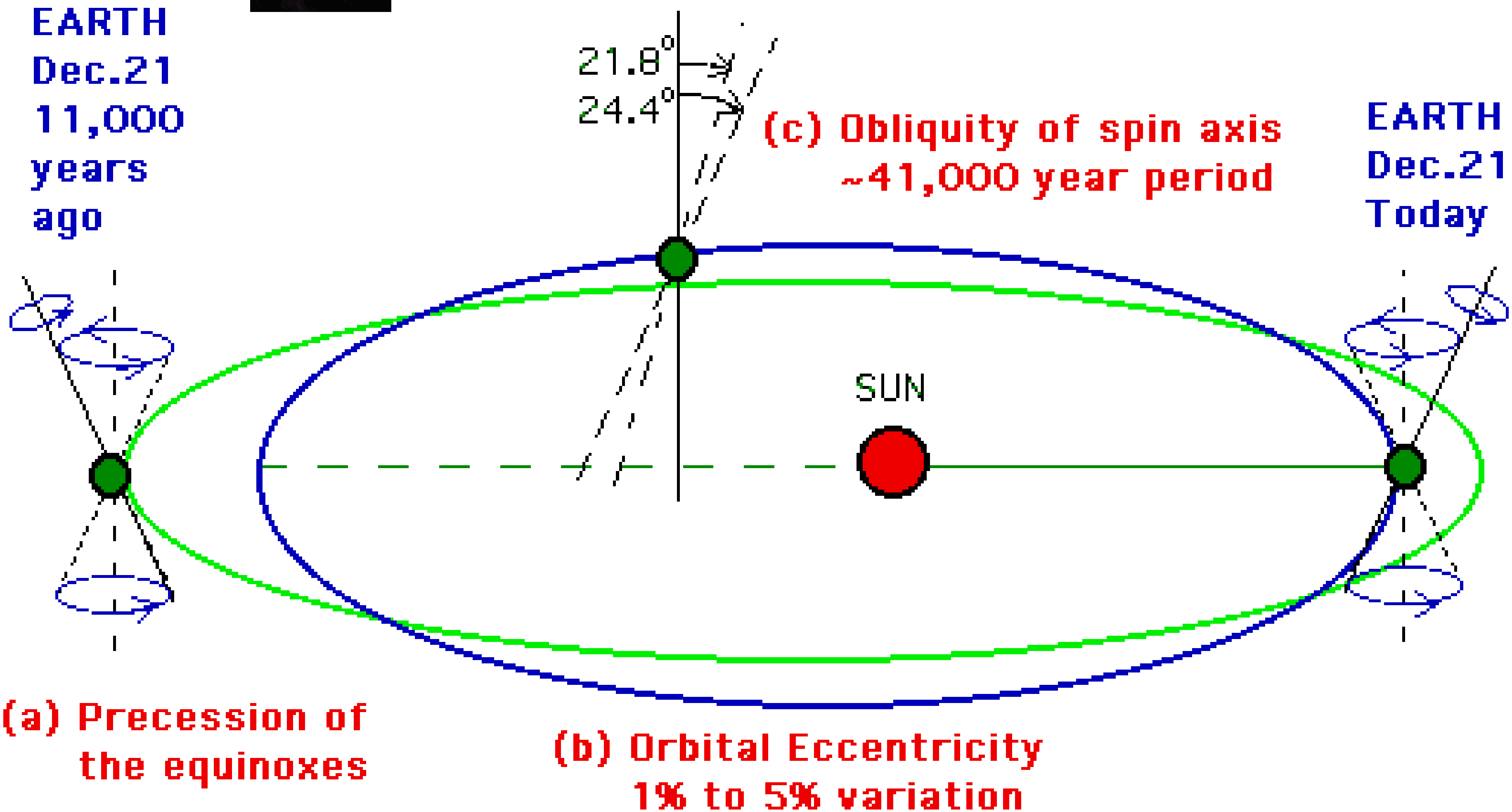


At the height of the last Ice Age 20,000 years ago:

- Large ice sheets with up to 3 km thickness covered North America, Greenland, Northern Europe, parts of Asia, Antarctica
- Total ice mass ~3×10^{19} kg
- Sea level fell by ~120 meters



Milankovitch's orbital theory



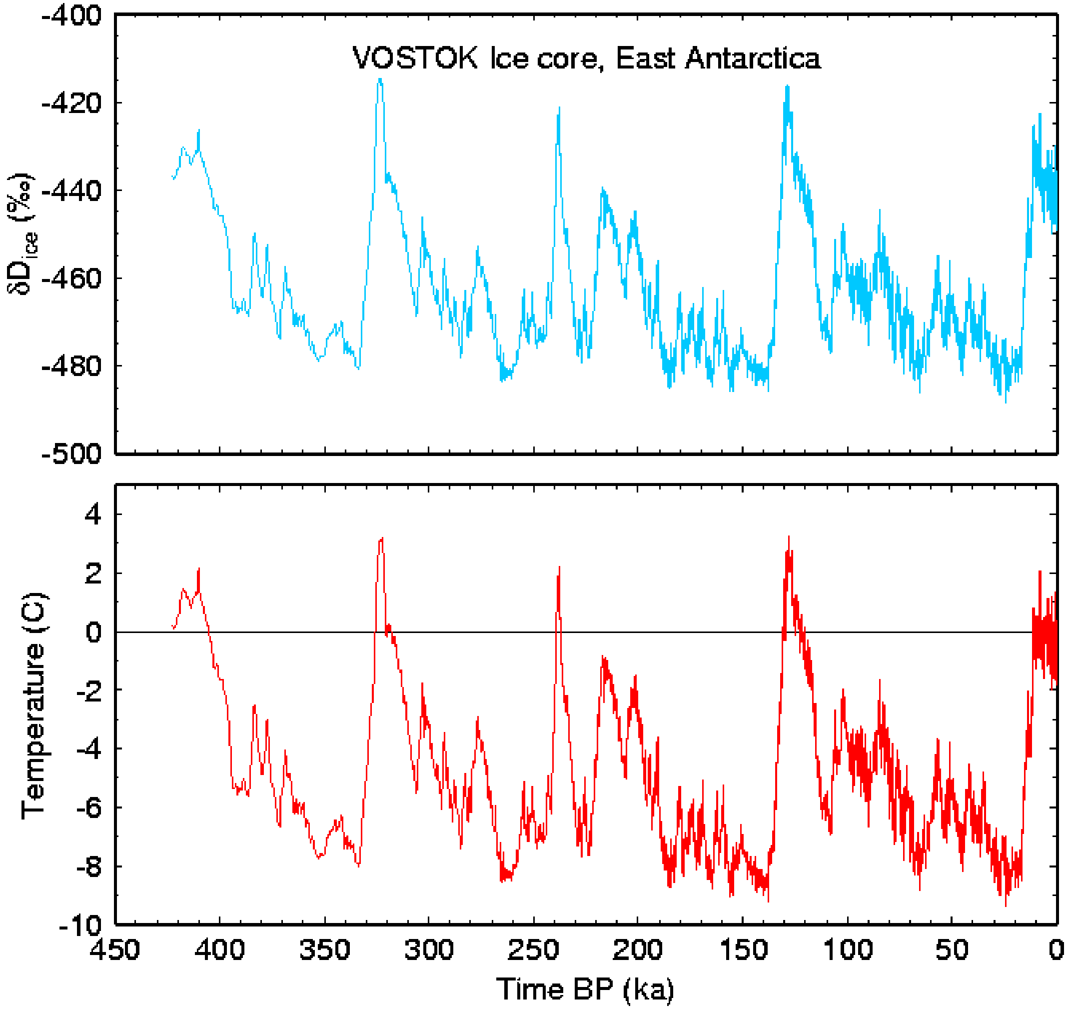
Eccentricity splitting of the precessional singlet
gives 19,000 21,000 and 23,000 year periods

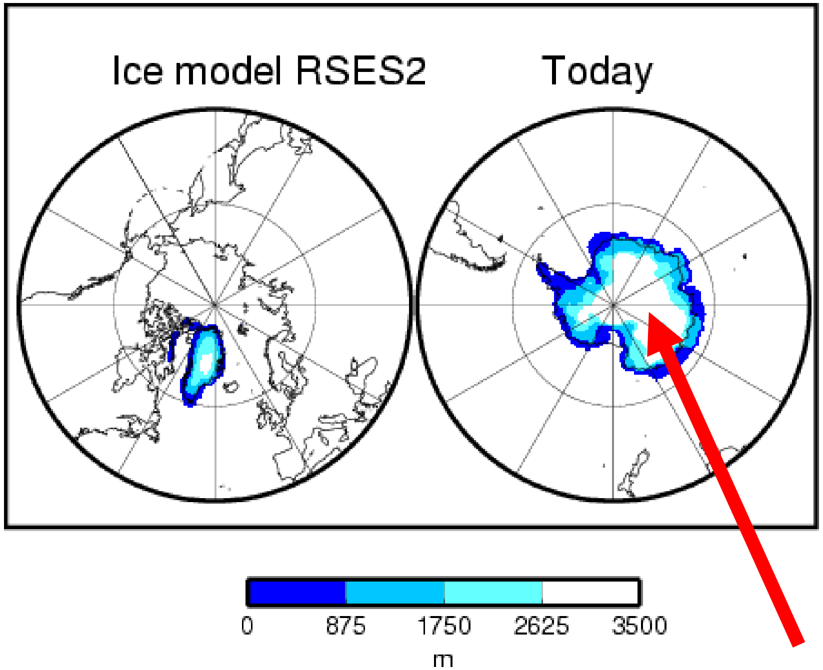
Causes of palaeoclimate change

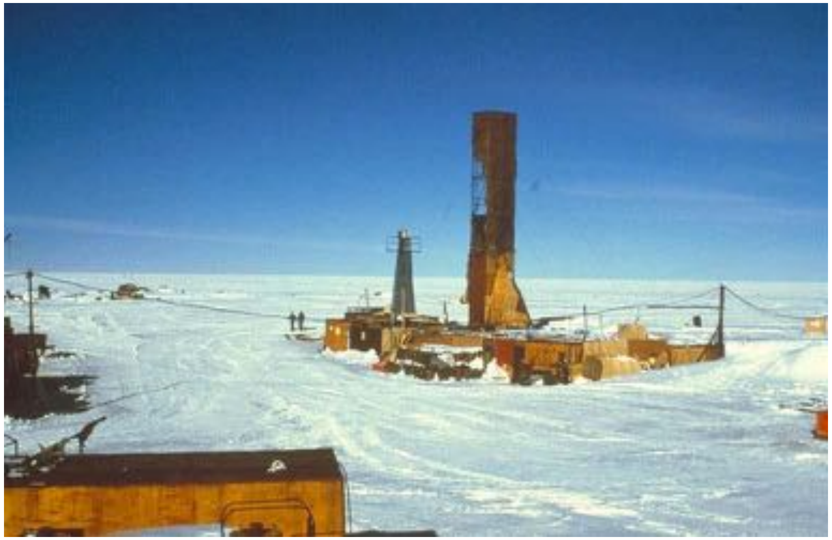
- Changes in Earth's orbit (Milankovitch)
- Changes in solar output (stellar evolution)
- Changes in the location and distribution of continents (plate tectonics) affect wind and ocean currents
- Polar Wander
- Eruption of supervolcanoes, meteorite impact
- Changes in the concentration of greenhouse gases in the atmosphere

Temperature correlates with greenhouse gas concentration

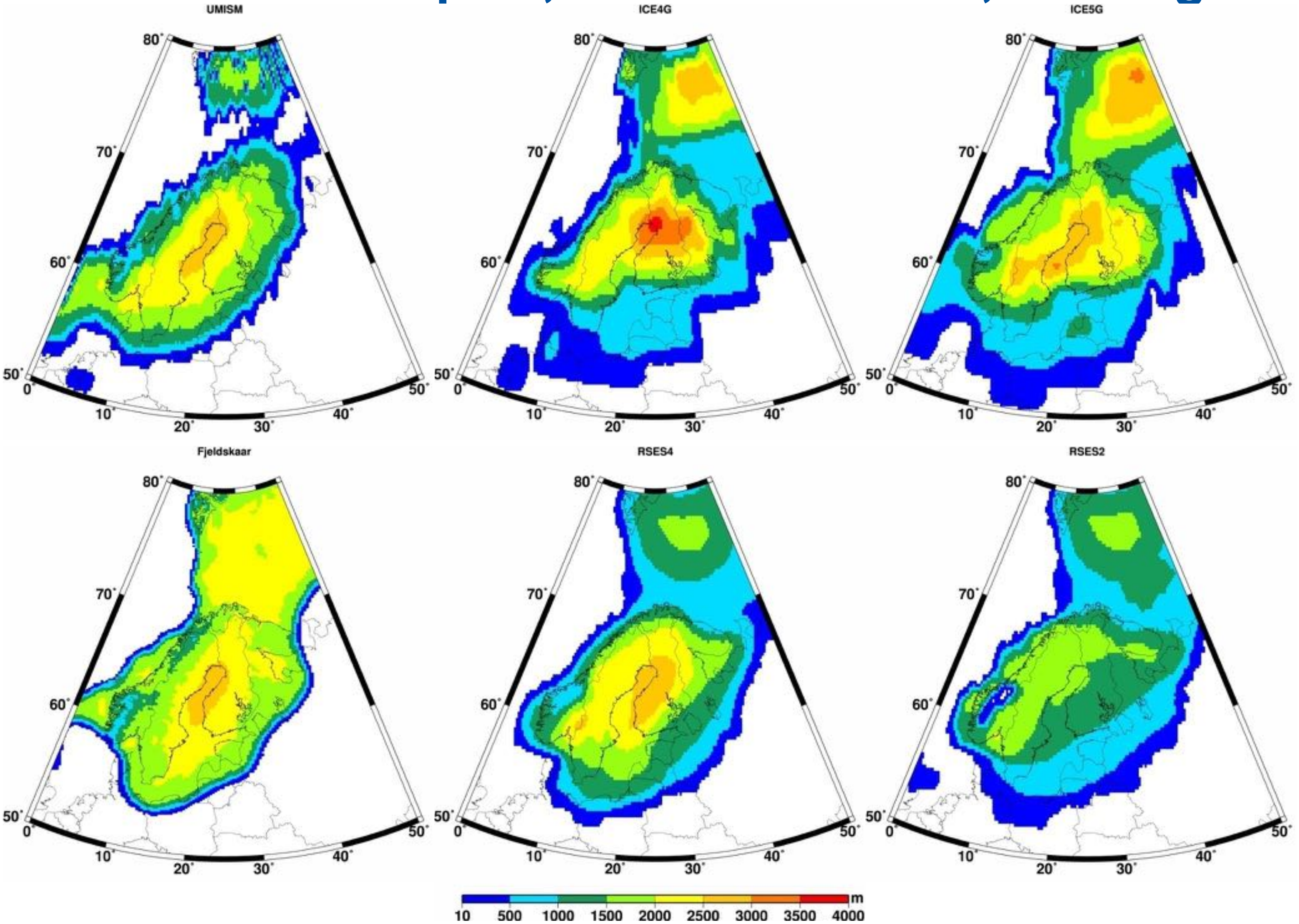
Petit J.R. et al., 1999.
Climate and Atmospheric History of the Past 420,000 years
from the Vostok Ice Core, Antarctica.
Nature, 399, pp.429-436.



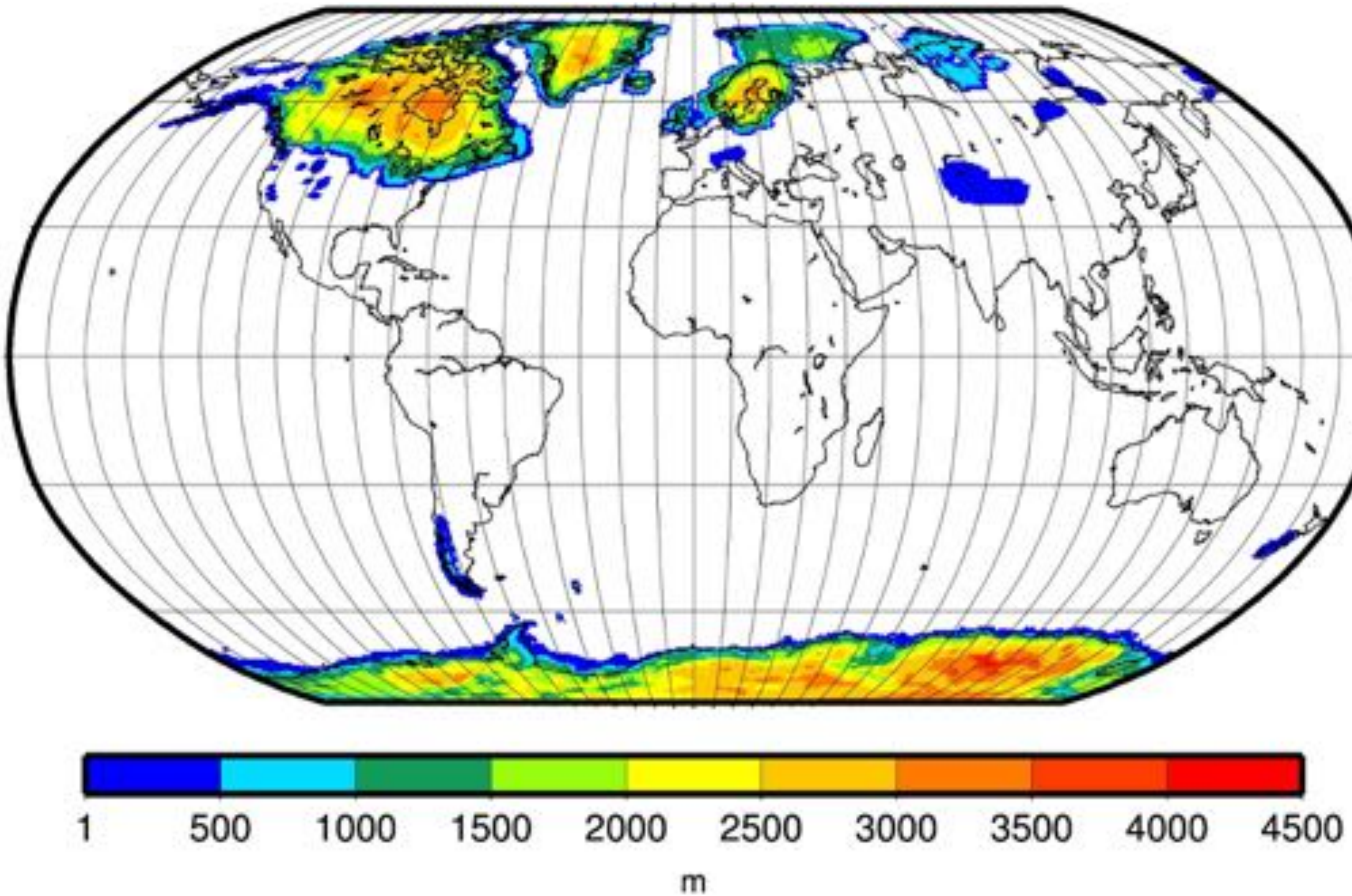




Ice model examples, thickness ca. 18,000 a ago



Ice model for EGSIEM: Ice thickness at 22 ka BP



Physics of GIA

Deformation & stress of a
viscoelastic Maxwell Earth

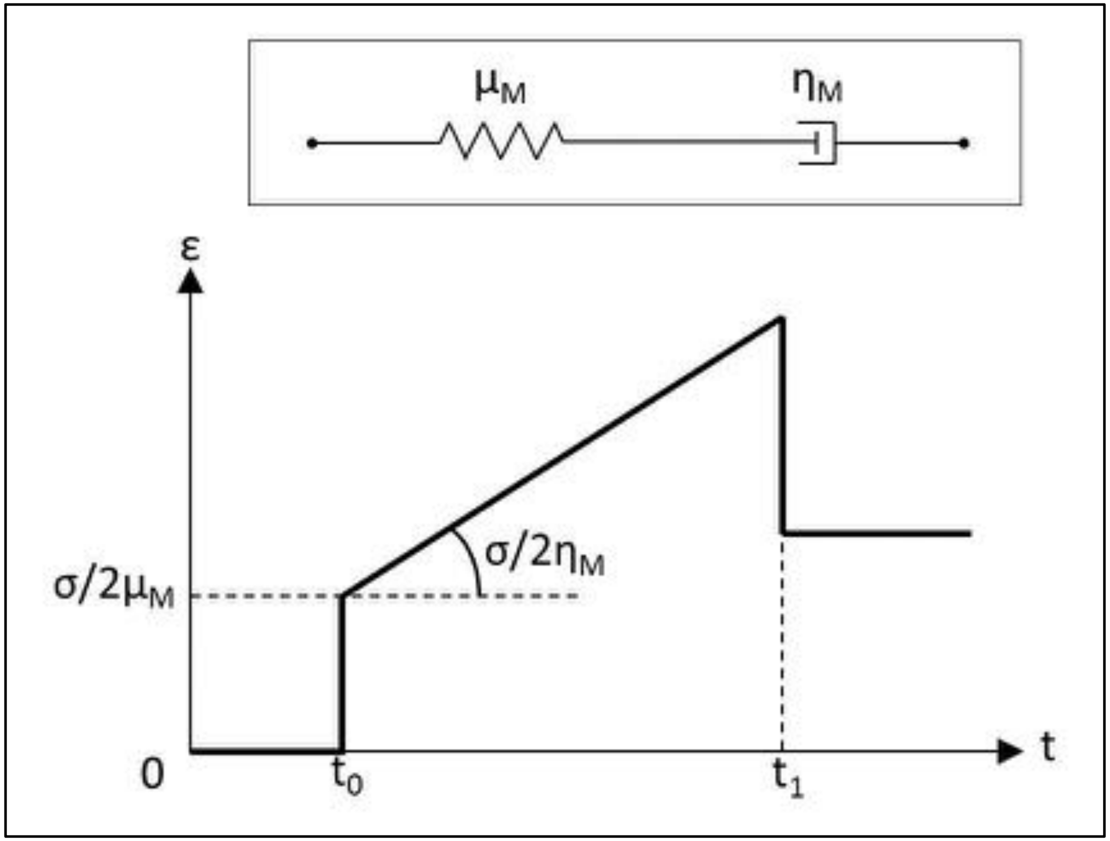
+

Sea-level equation

+

Earth rotation
and feedback to sea levels

Viscoelastic Maxwell Rheology



Elastic component:

$$\varepsilon = \frac{\sigma}{2\mu}$$

where,

ε = strain

Viscous component:

$$\dot{\varepsilon} = \frac{\sigma}{2\eta}$$

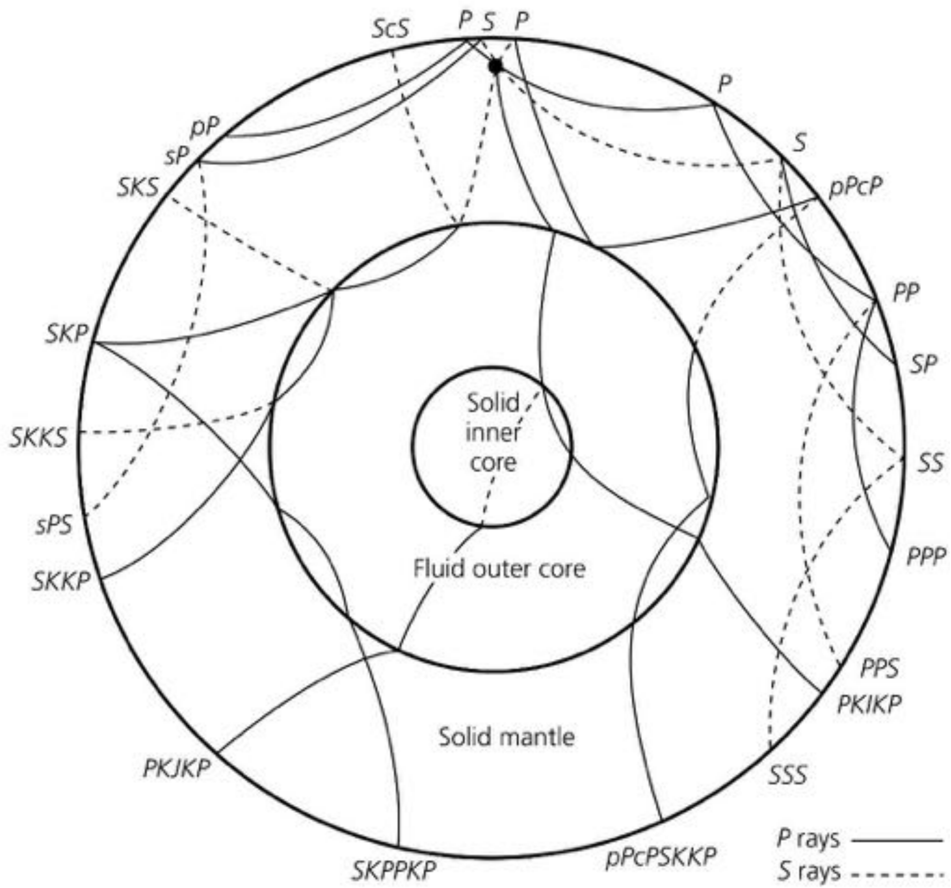
where,

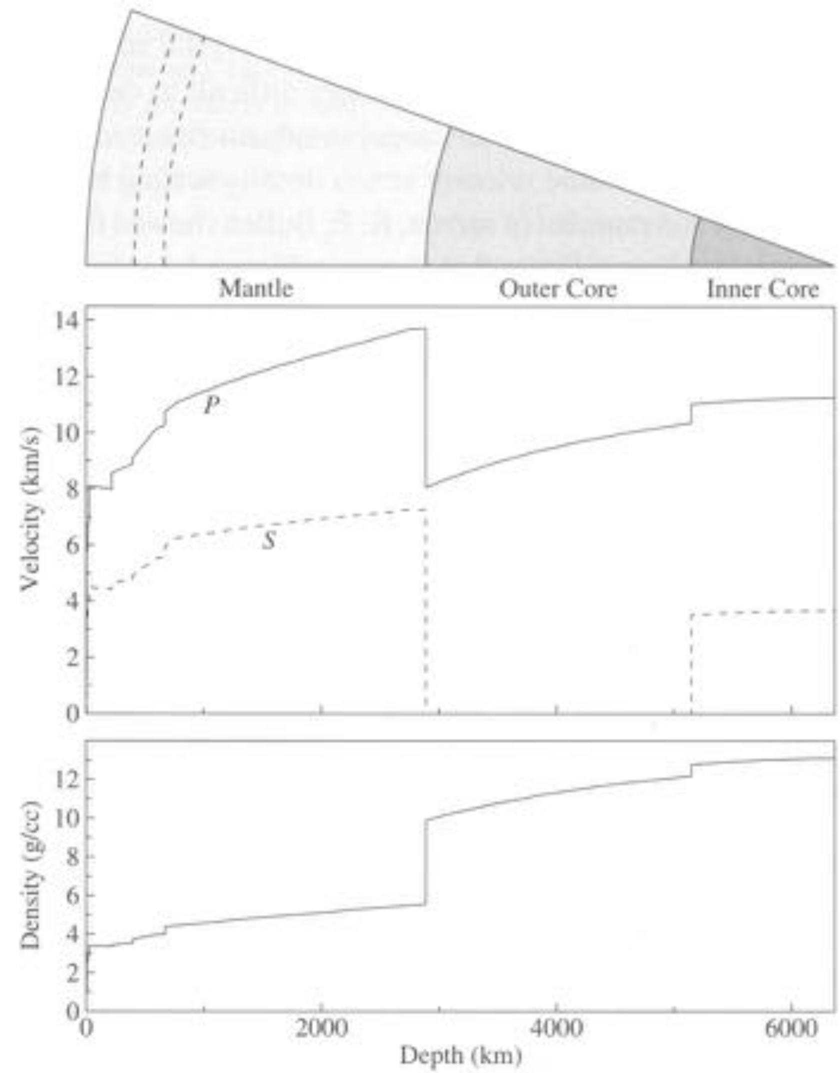
$\dot{\varepsilon}$ = strain rate

after Ranalli (1995)

Determining Earth's Elastic Structure

Figure 3.5-5: Illustration of various body wave phases.





Stein & Wysession (2003)

Shearer (1999) based on PREM (Dziewonski & Anderson 1981)

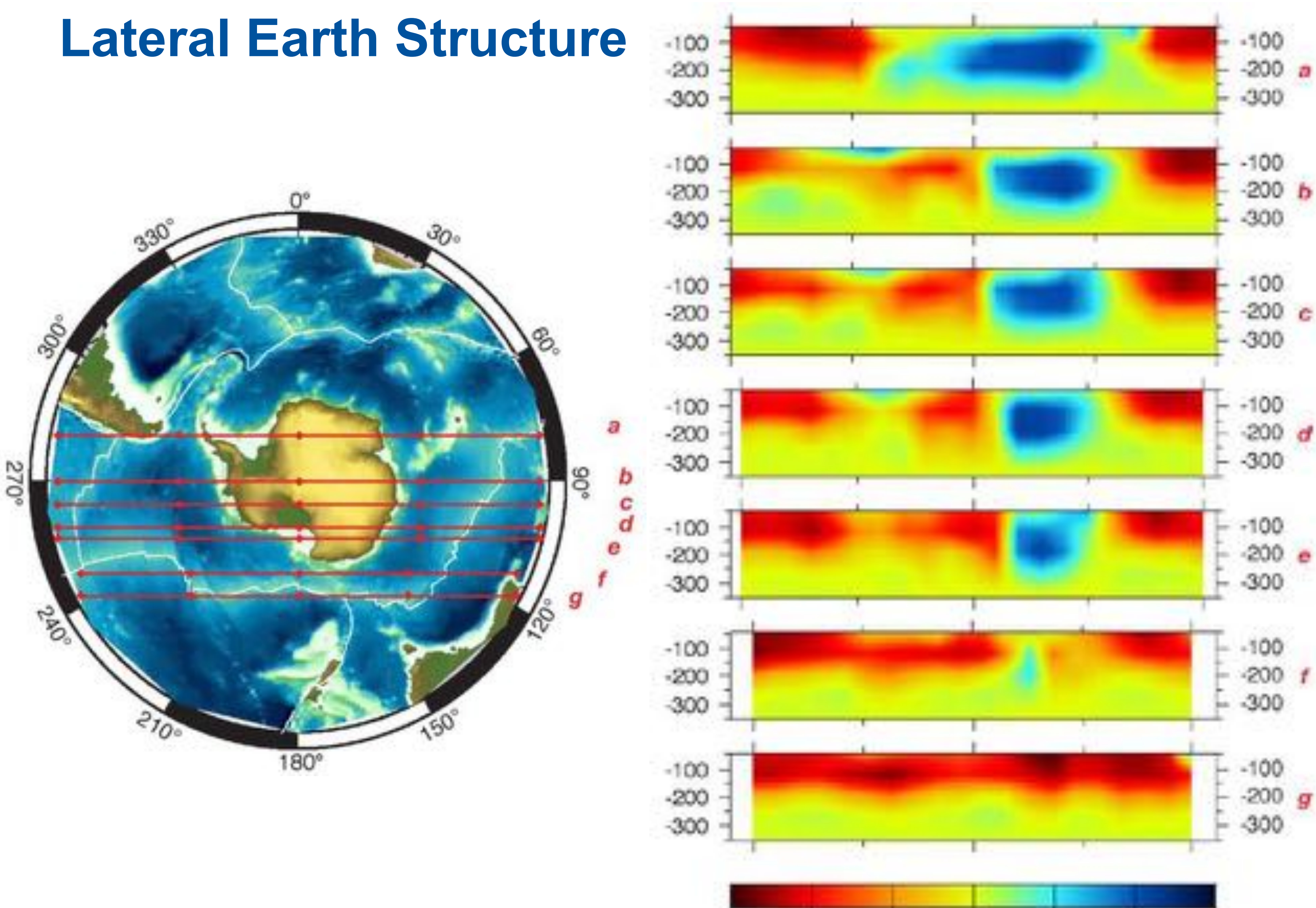
Determining Earth's Viscosity Structure

Two most common approaches:

1. Laboratory deformation experiments on Earth materials at high temperatures and pressures. Primary limitations are simulating realistic strain rates and finding suitable samples for the deep mantle

2. Geophysical modelling of surface observables related to isostatic adjustment and mantle flow. Primary limitations are resolving power of data and limitations of models

Lateral Earth Structure



Morelli and Danesi (2004)

Equations to model Earth deformation

Newton's Law: $$\vec{\nabla}\cdot\overline{\overline{\tau}}-\vec{\nabla}\left(\vec{u}\cdot\rho_o g_o\hat{r}\right)-\rho_1 g_o\hat{r}-\rho_o\vec{\nabla}\phi_1=0$$

Div of stress

Advection of Prestress

Internal buoyancy

Incremental gravity

Mass Conservation $$\rho_1=-\rho_0\vec{\nabla}\cdot\vec{u}-\vec{u}\cdot\left(\partial_r\rho_0\right)\hat{r}$$

Perturbed density

Volume change

Density stratification

Self Gravitation $$\nabla^2\phi_1=4\pi G\rho_1$$

Perturbed Grav. Potential generated by perturbed density

Visco-elastic Maxwell $$\partial_t\overline{\overline{\tau}}=\partial_t\overline{\overline{\tau}}^{0}-\frac{\mu}{\nu}\left(\overline{\overline{\tau}}-\Pi\overline{\overline{I}}\right)\qquad \overline{\overline{\tau}}^{0}=\lambda\theta\overline{\overline{I}}+2\mu\overline{\overline{\varepsilon}}$$

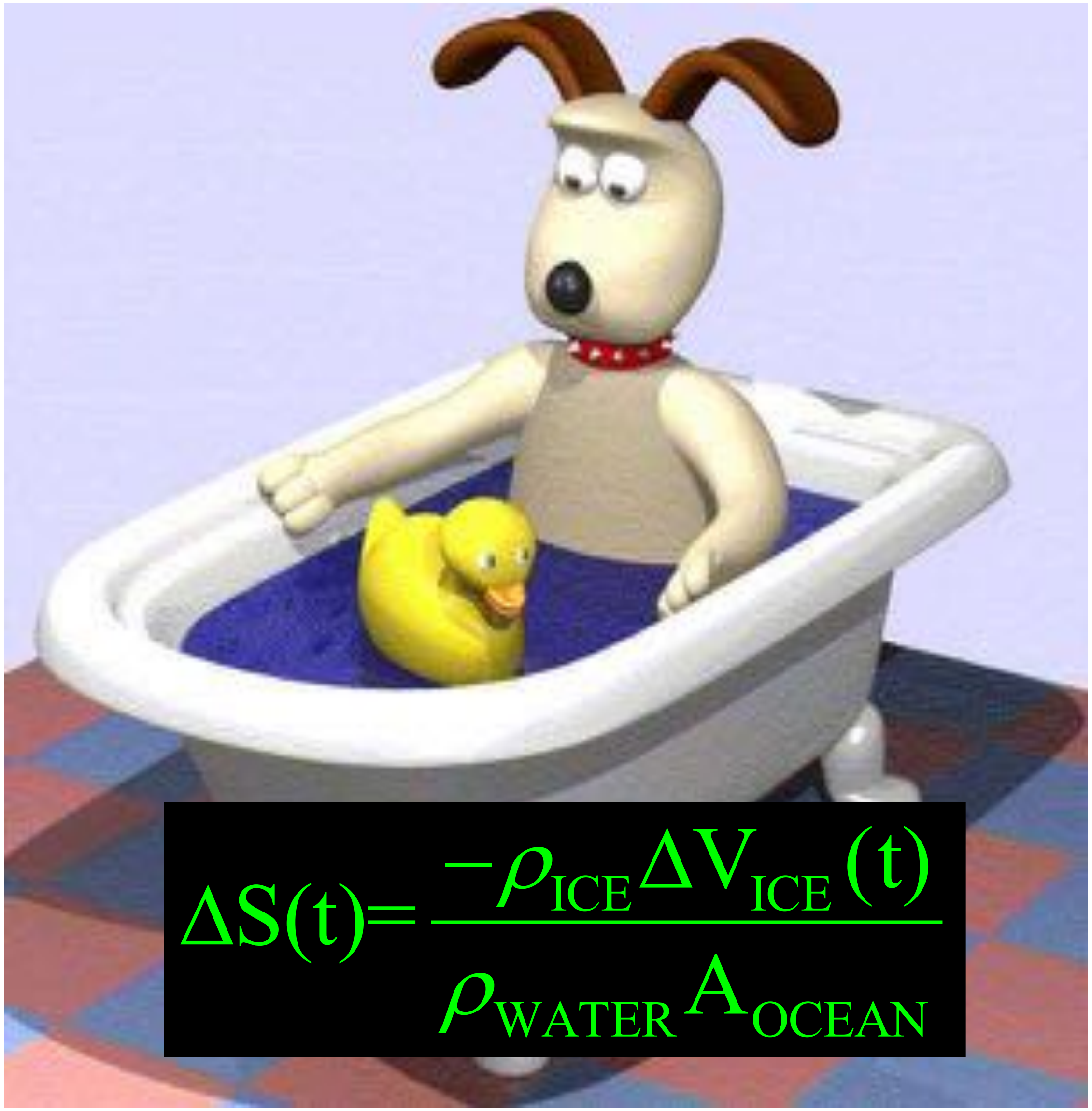
Elastic & Viscous contribution

The Sea-Level Equation

After deglaciation,
where in the oceans will
the melted ice-water go?

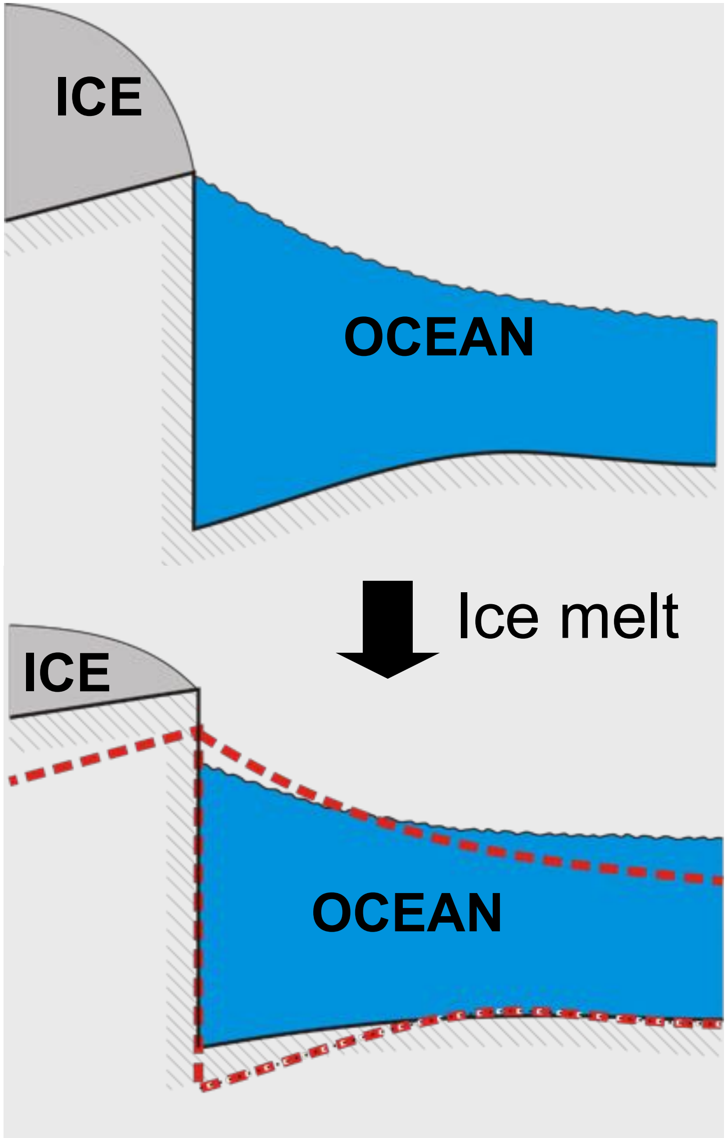
Answer: melted ice water will NOT be uniformly distributed in the oceans!

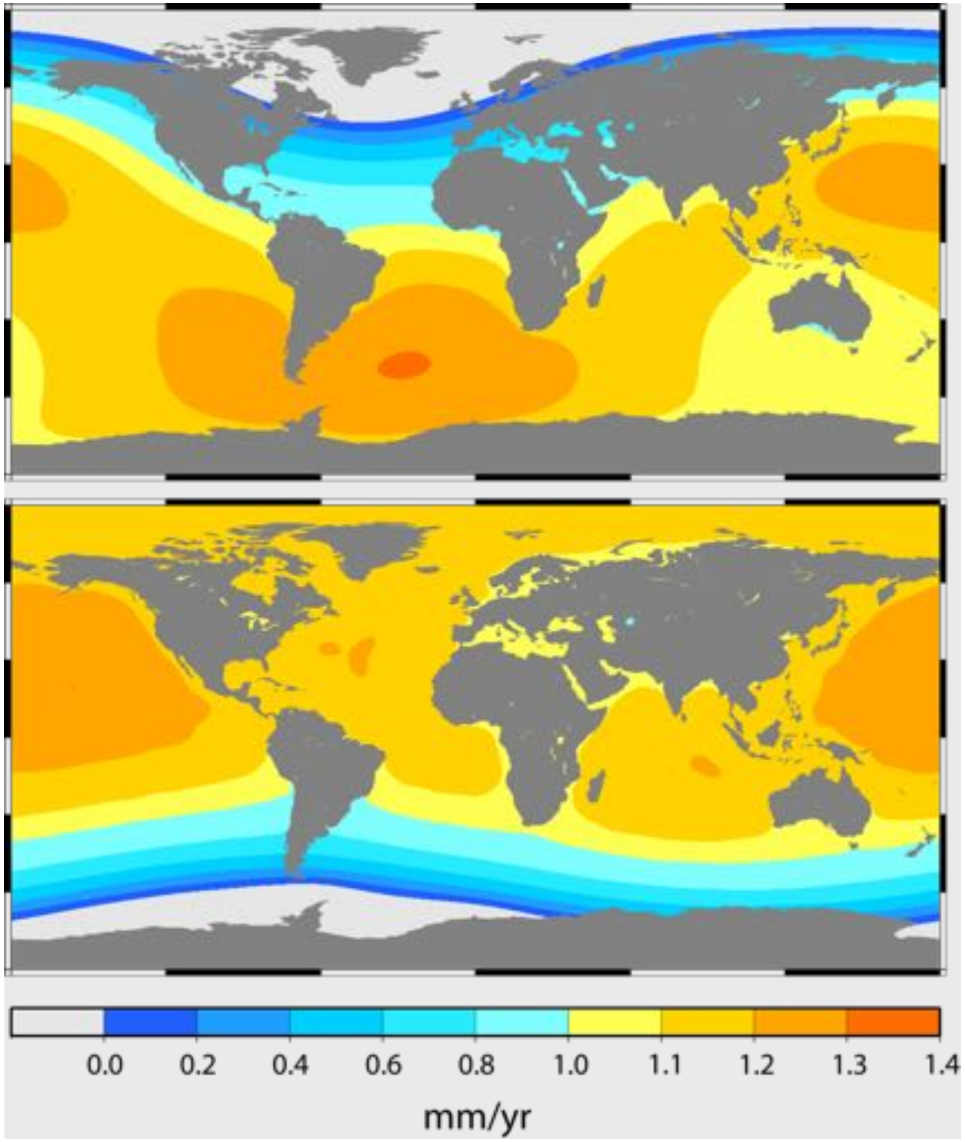
Glacio-Eustasy



$$\Delta S(t) = \frac{-\rho_{ICE} \Delta V_{ICE}(t)}{\rho_{WATER} A_{OCEAN}}$$

Perturbations to ocean floor and surface

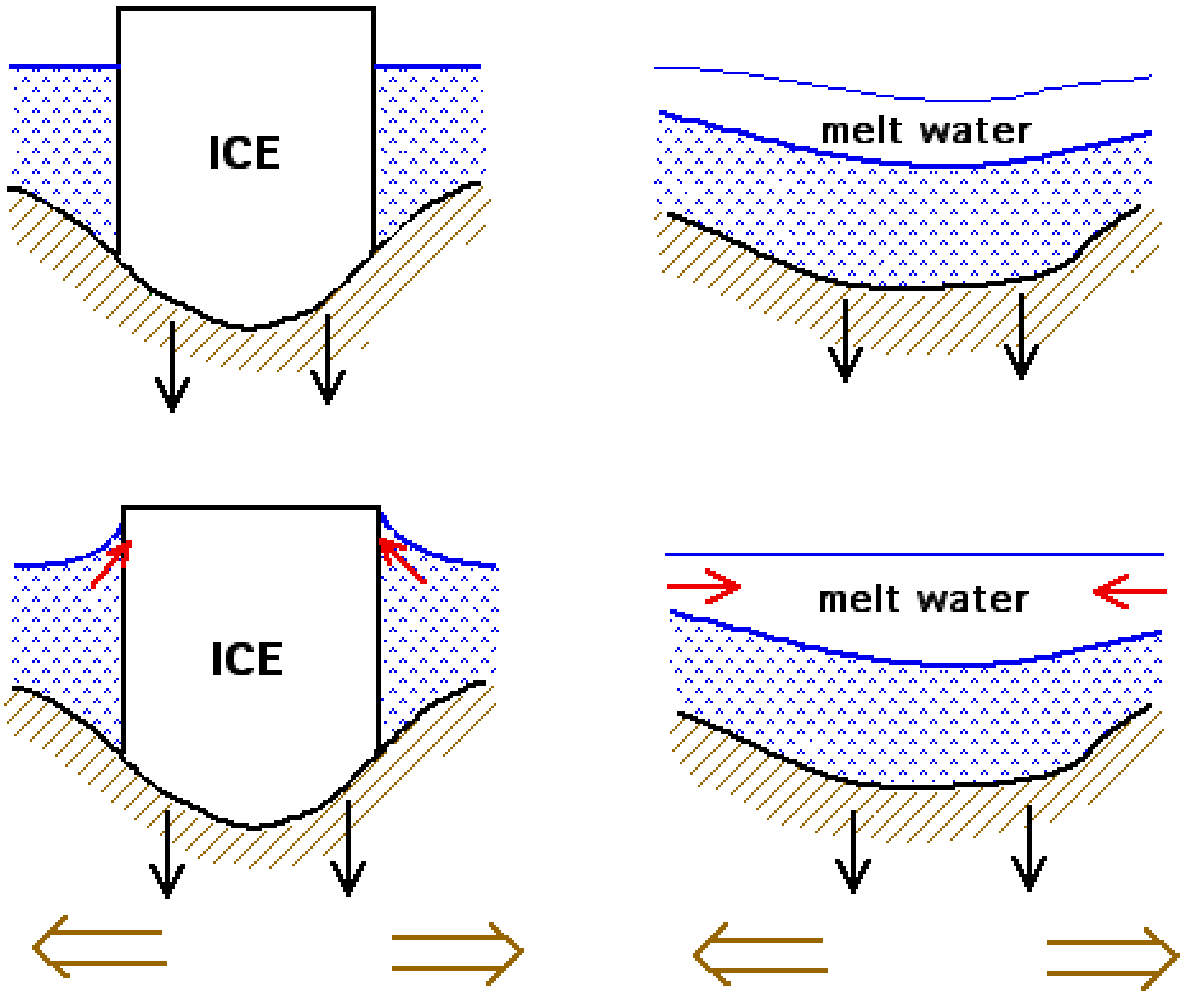




Tamisiea et al. (2003)

Sea-level equation

$$S = \frac{-M_i(t)}{\rho_w A_0} + \frac{\phi}{g} - U + \frac{-1}{A_0} \left\langle \frac{\phi}{g} - U \right\rangle$$



“mean” sea level is an equipotential surface

Sea-level equation with rotational feedback

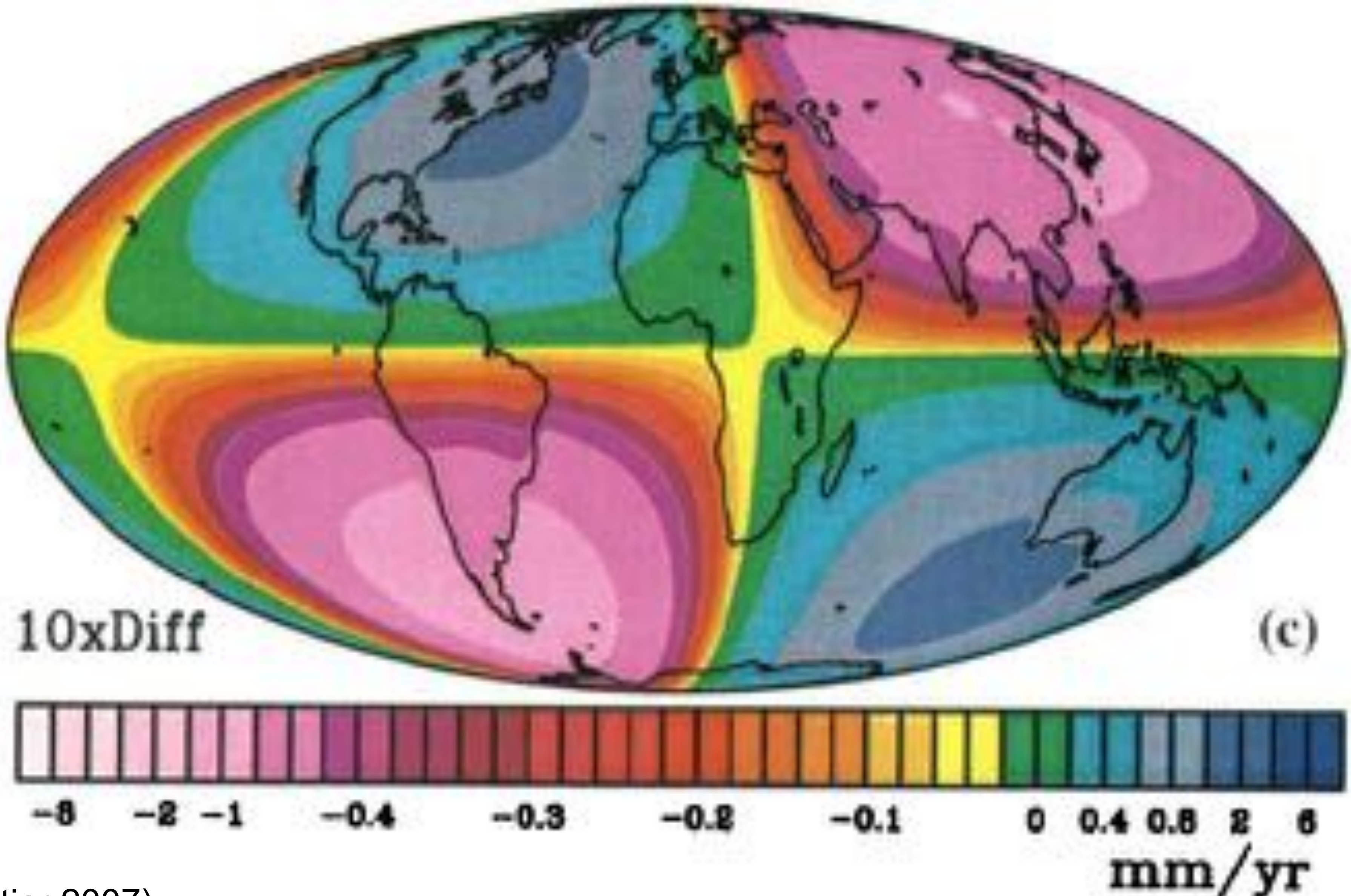
$$S(\theta,\psi,t)=\left\lfloor \frac{\phi(\theta,\psi,t)}{g}-U(\theta,\psi,t)-\frac{M_I(t)}{\rho_w A_o}-\frac{1}{A_o}\left\langle \frac{\phi(\theta,\psi,t)}{g}-U(\theta,\psi,t)\right\rangle_o \right\rfloor O(\theta,\psi,t)$$

Perturbed Potential: $\phi(\theta,\psi,t)=\phi^L(\theta,\psi,t)+\phi^R(\theta,\psi,t)$

Surface loading (ϕ^L, U^L) — Earth Rotation (ϕ^R, U^R)

Radial Displacement: $U(\theta,\psi,t)=U^L(\theta,\psi,t)+U^R(\theta,\psi,t)$

Effect of rotation on sea-level rate



(Peltier 2007)

Key elements of a GIA model

Earth Forcing

Rotational potential

- Euler equations

Surface loading

Ice Model

- Multidisciplinary approach

Ocean Model

- Sea-level equation

Earth Model

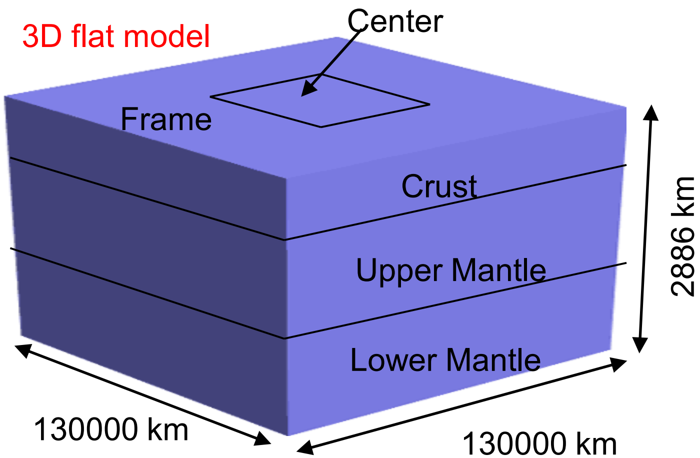
Geometry

- Spherical/Flat
- Internal structure: 1D & 3D

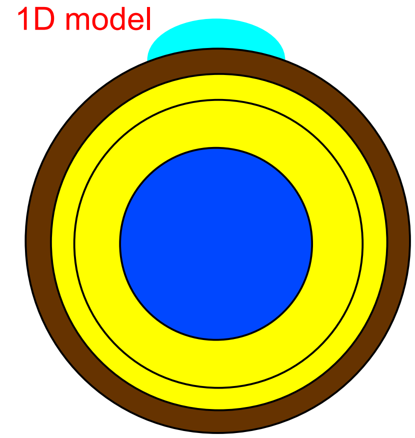
Rheology

- Viscoelastic
- Linear and non-linear viscous deformation

Earth models

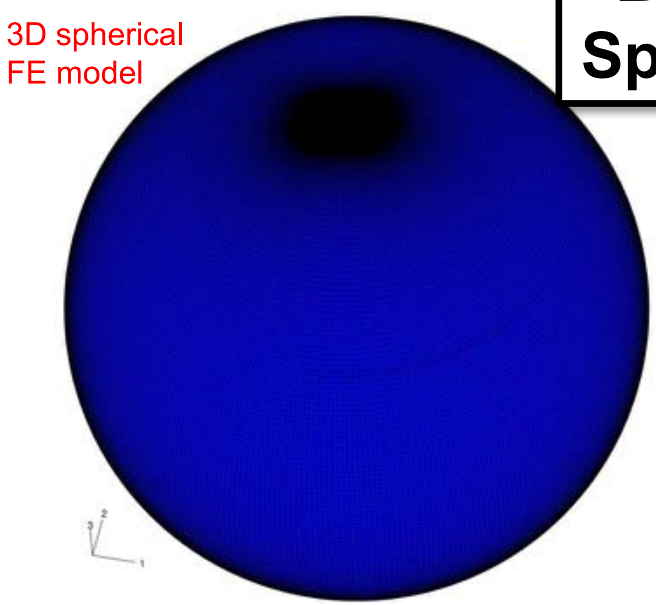


(Wu 2004, GJI)

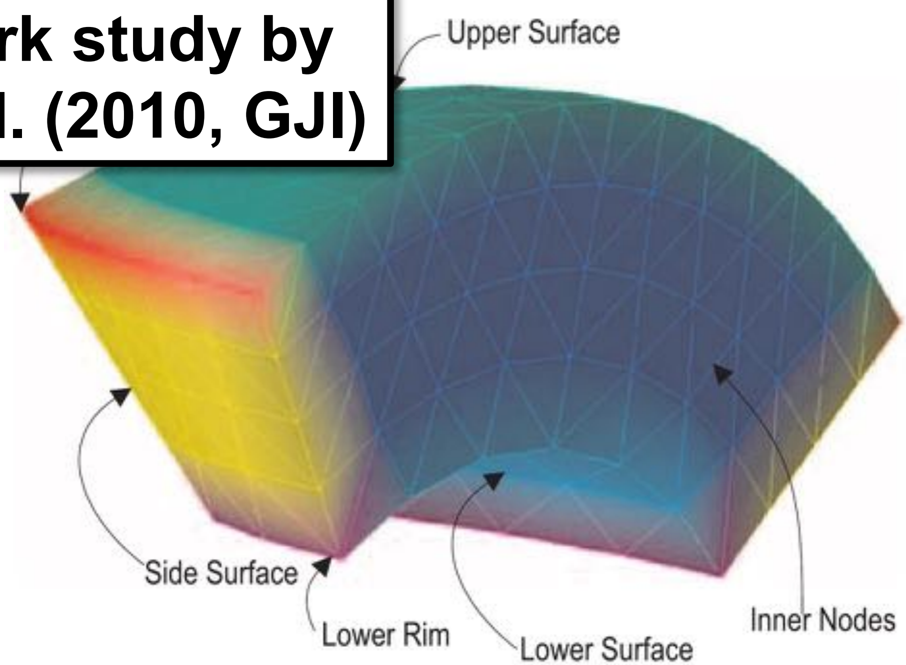


(Munk & MacDonald 1960;
Farrell and Clark 1976;
Mitrovica et al. 1994, JGR;
Mitrovica and Milne 1998;
Kaufmann et al. 2002, JGR
Spada et al. 2007)

Benchmark study by Spada et al. (2010, GJI)



(Wu 2004, GJI)



(Latychev et al. 2005, GJI)

Study of Glacial Isostatic Adjustment is multi-disciplinary!

- Geomorphology
- Glaciology
- Oceanography
- Climatology
- Rock Physics
- Geodynamics
- Geodesy
- Aerospace Engineering
- Astronomy
- Archeology

Recent applications:

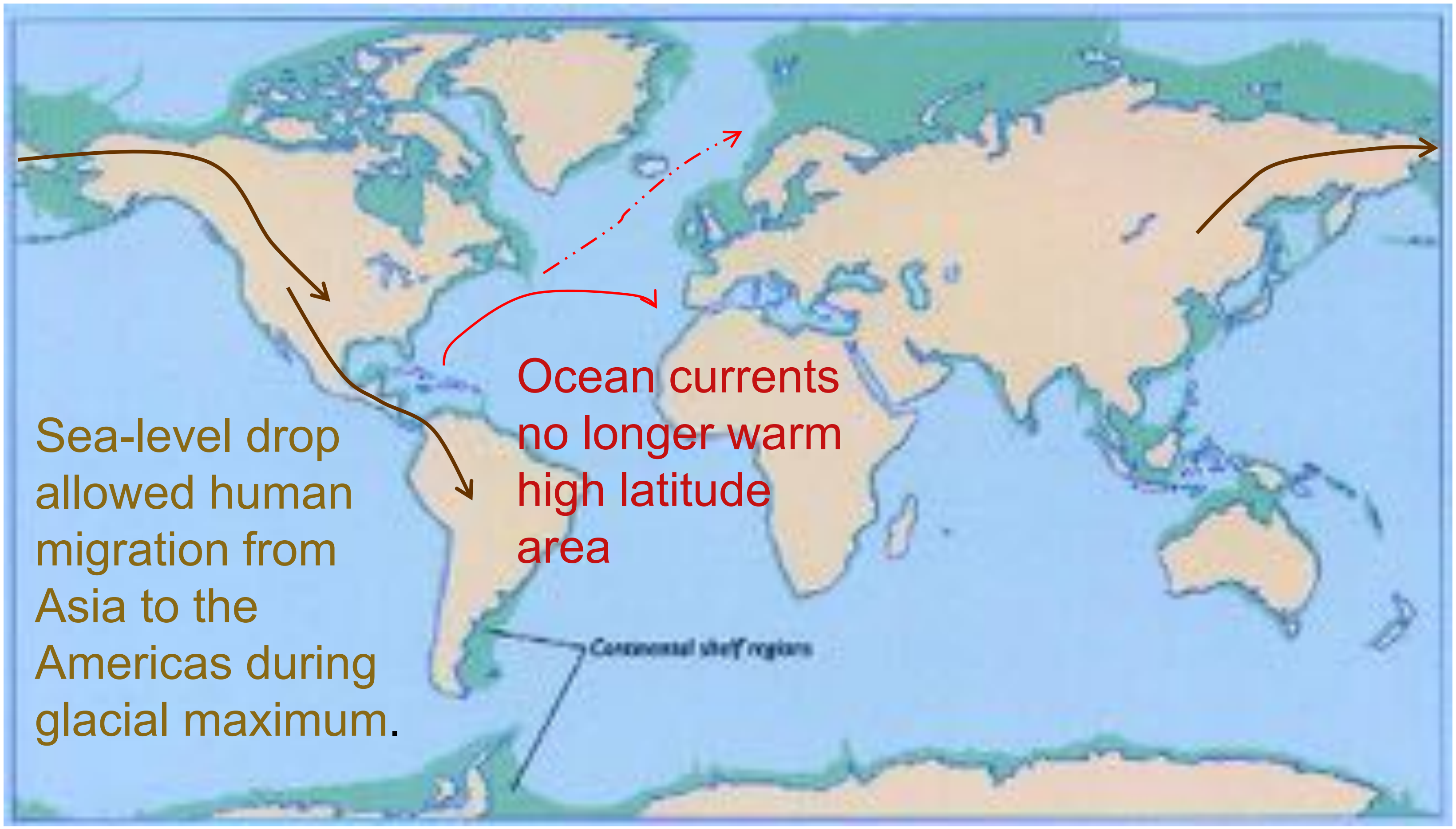
- Mantle rheology & viscosity profile
- Ice thickness & topography model
- Geodetic Reference Frame definition
- Earth rotation (polar wander, length of day, J-dot)
- Monitor Global Warming & Climate Change
- Archeology & land boundaries
- Geomorphology of the past & future of Water Resources
- GIA-induced earthquakes & Nuclear Waste Management
- Cause of seismic tomography & lateral heterogeneity
- Sensitivity kernel and design of geodetic observation networks

Geomorphology of the past & future

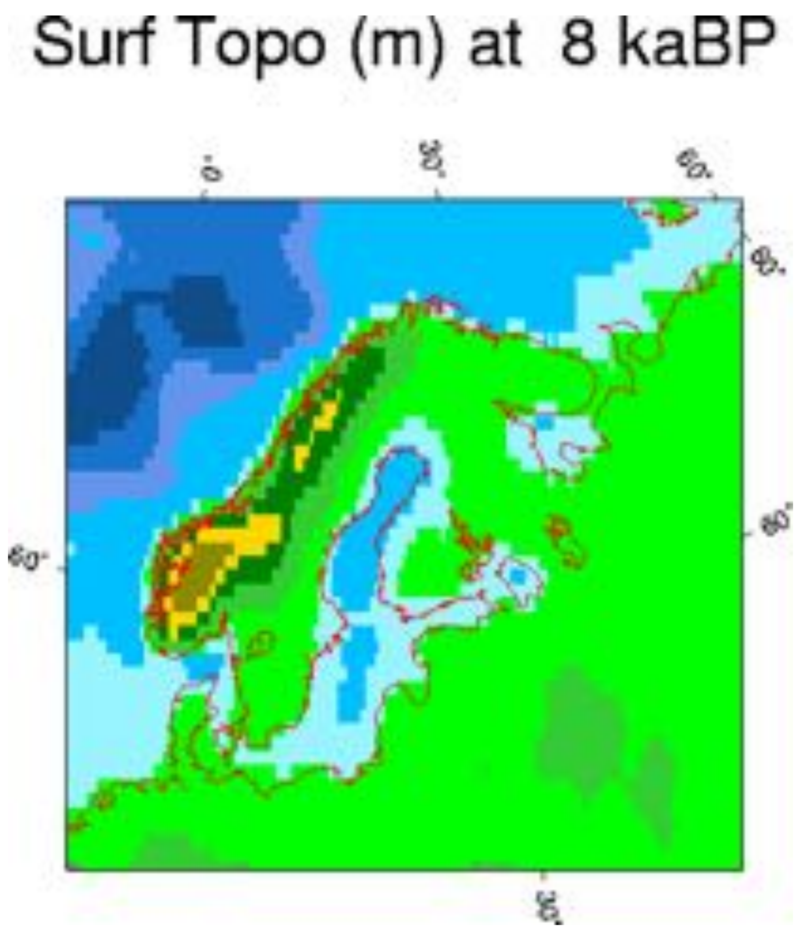
Application: water resources, land claim, archaeology, human history

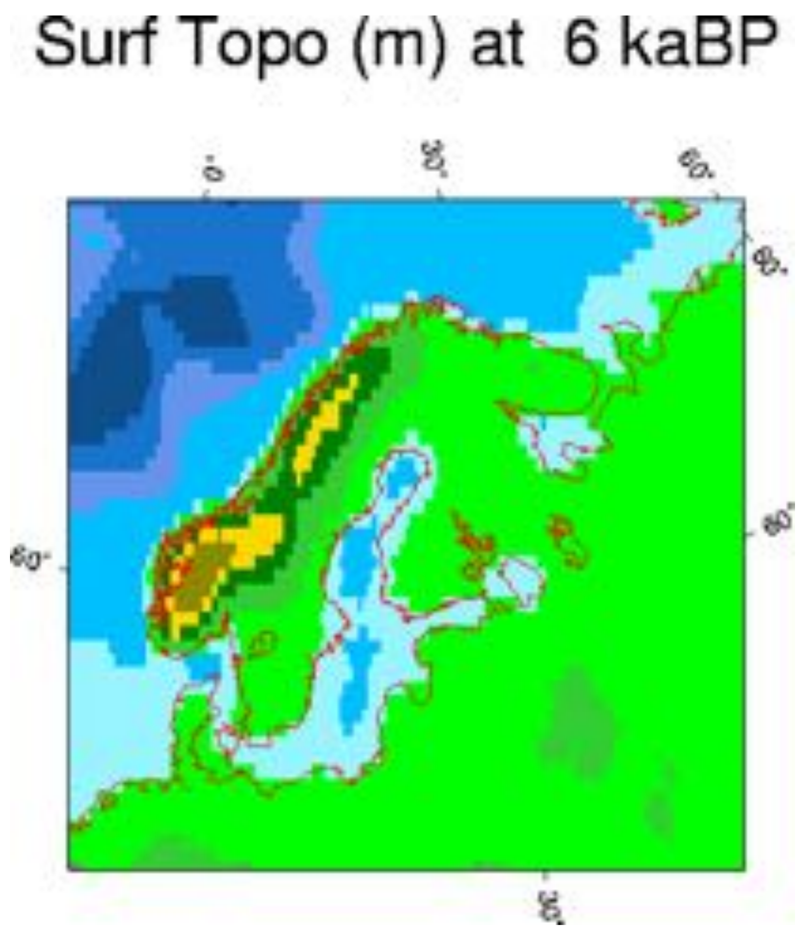
Effects of LGM

During the last glacial maximum, global sea level dropped by ~120 m, exposing continental shelves & forming land bridges.



Topographic changes





RF3b ICE-4G

Freshwater seals – trapped after an ice age

Baikal seal

(Source:https://upload.wikimedia.org/wikipedia/commons/a/a7/Baikal-seal_4747-pho.jpg)

Caspian seal

(Source:https://upload.wikimedia.org/wikipedia/commons/d/db/Caspian_Seal.jpg)

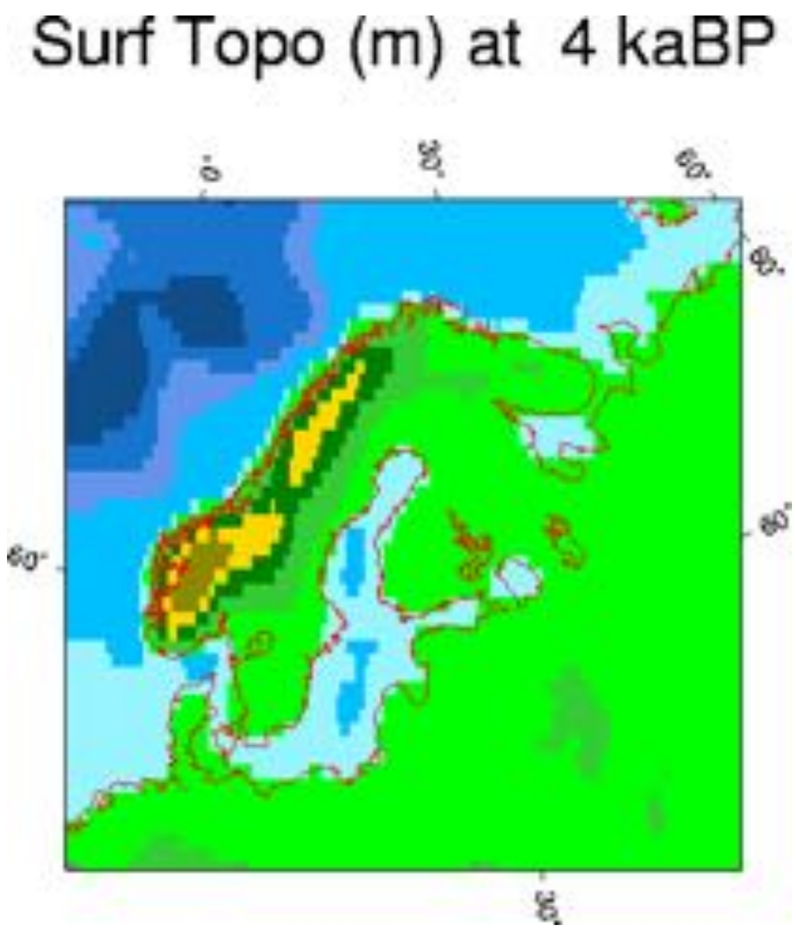
Saimaa ringed seal

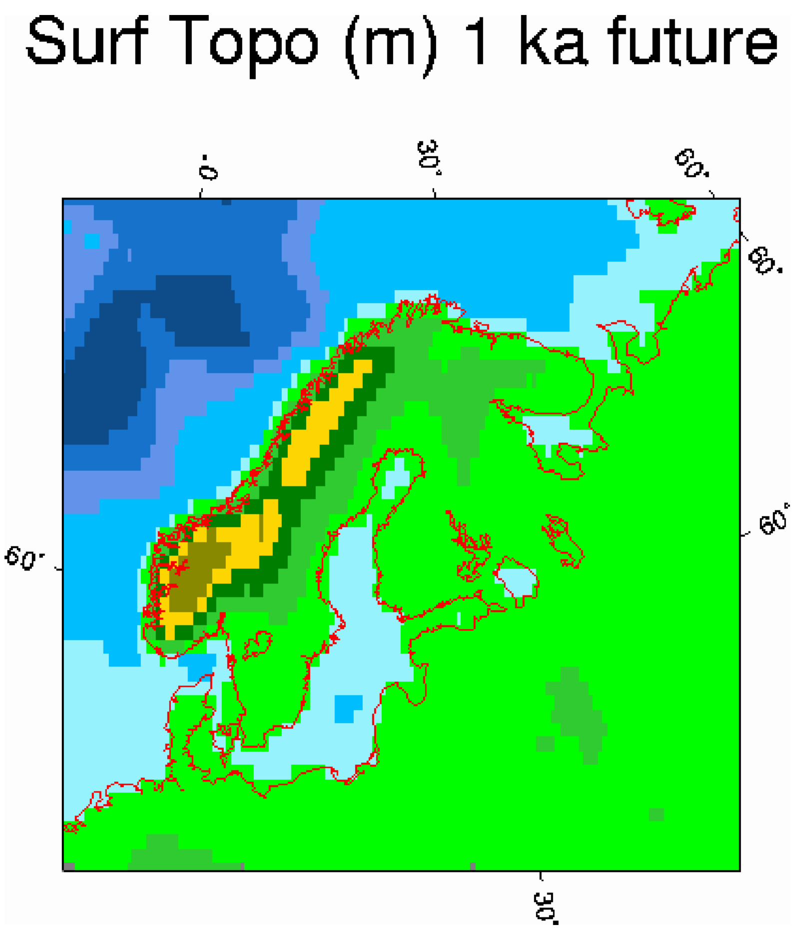
(Source:http://www.sll.fi/mita-me-teemme/lajit/saimaannorppa/ringed-seal/leadImage)

Ladoga seal

(Source:https://upload.wikimedia.org/wikipedia/commons/b/b3/The_freshwater_ringed_seals._lake_Ladoga.jpg)

Topographic changes





No global warming assumed

RF3b ICE-4G

Glacial isostatic adjustment Part 2 - Observations

Holger Steffen

With input from Martin Lidberg, Rebekka Steffen, Wouter van der Wal, Pippa Whitehouse and Patrick Wu

EGSIEM Summer School
Potsdam, Germany
13/09/2017

LANTMÄTERIET

GIA Observations

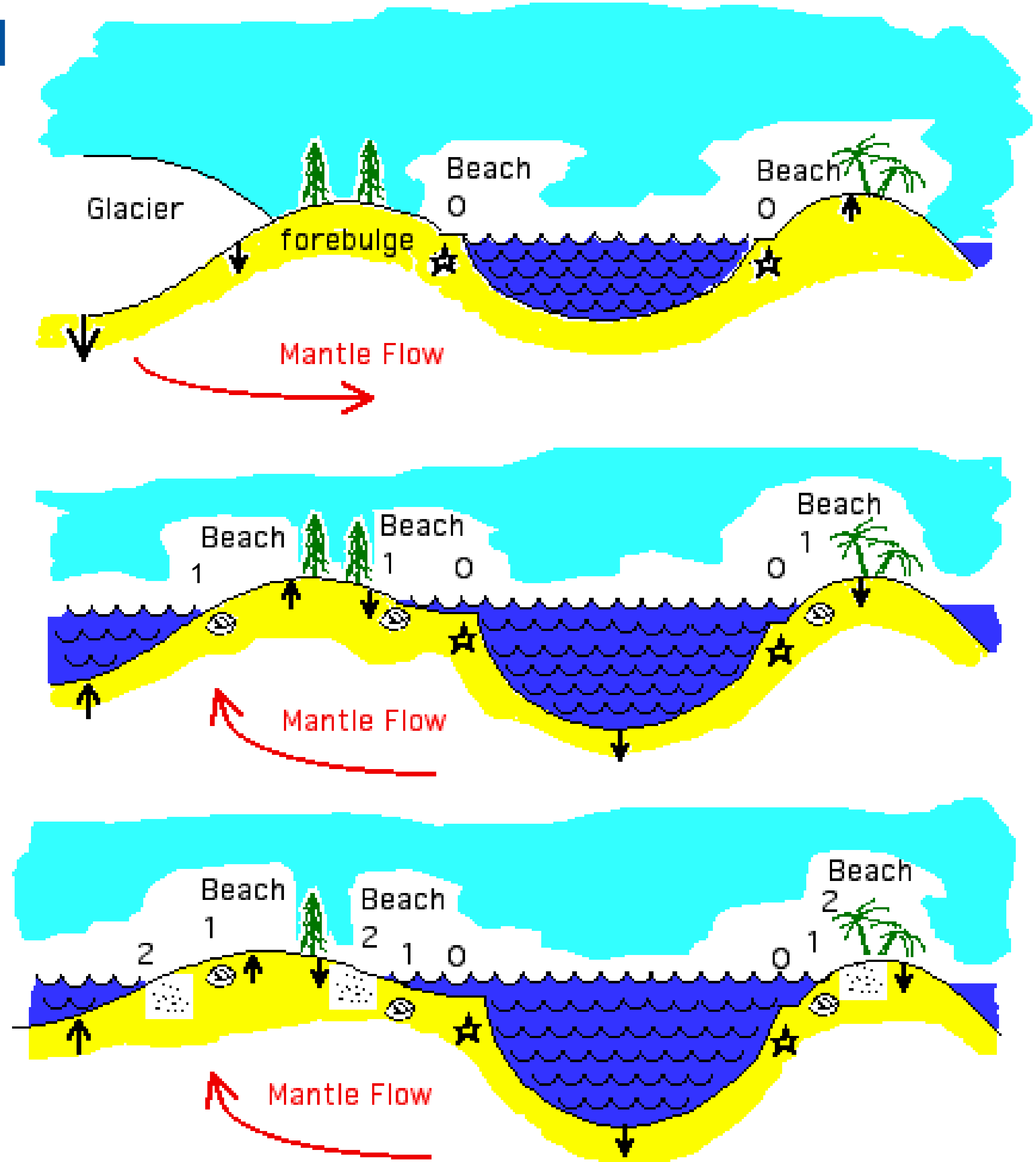
What type?

Which time period is covered?

Observations of GIA

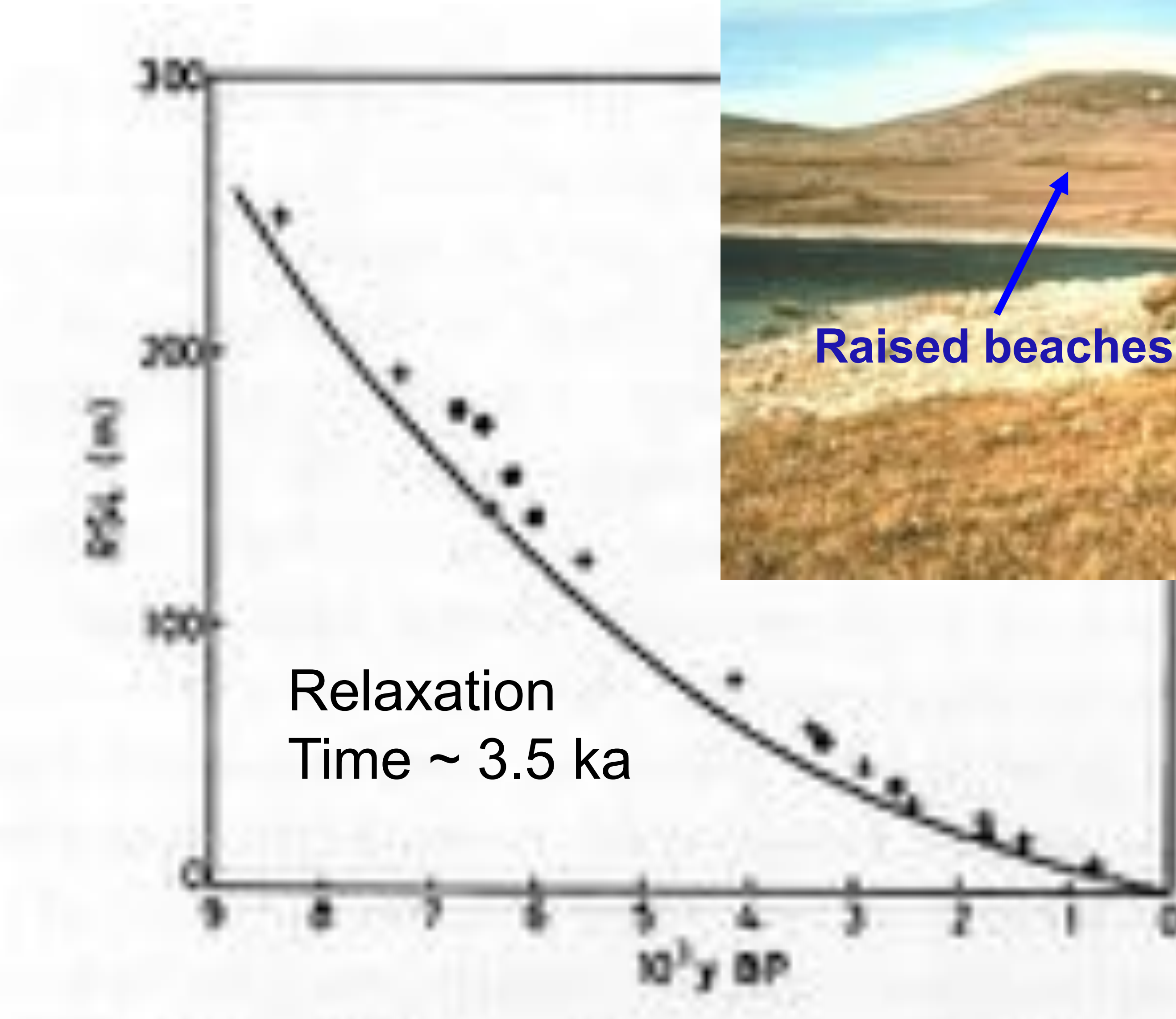
- Vertical motion
  - Relative sea levels (geologic, palaeontological and archaeological evidence)
  - Present-day rate of uplift – Levelling, GNSS, tide gauges, altimetry
- Horizontal motion - GNSS, VLBI, DORIS
- Gravity change due to redistribution of mass – terrestrial (gravimeter) and space-geodetic techniques (GRACE, hlSST)
- Changes in the state of stress - earthquakes
- Change in Moments of Inertia
  - Polar wander
  - Non-tidal acceleration (Length Of Day)

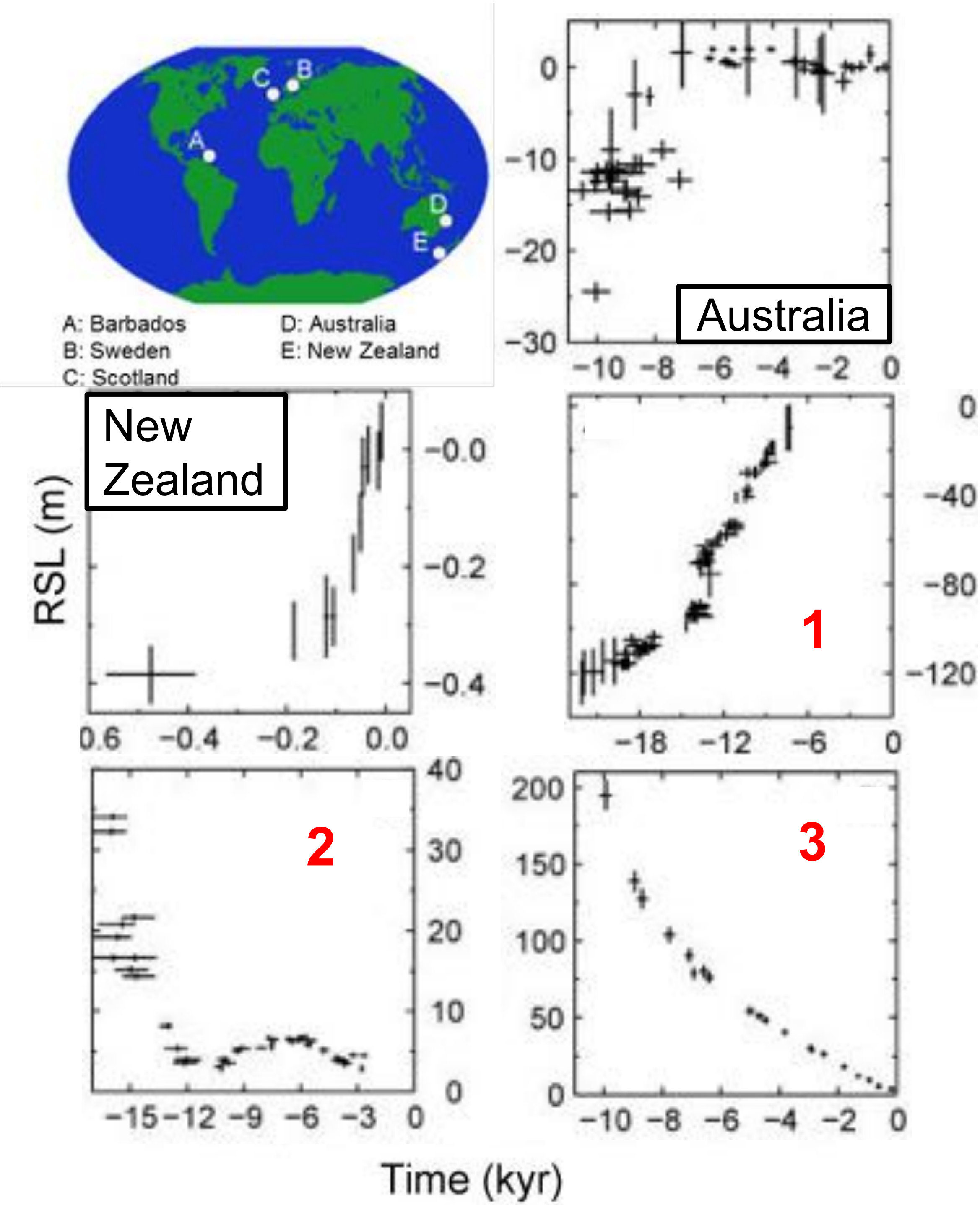
Glacial Rebound



NW Latvia

Relative sea levels in Hudson Bay

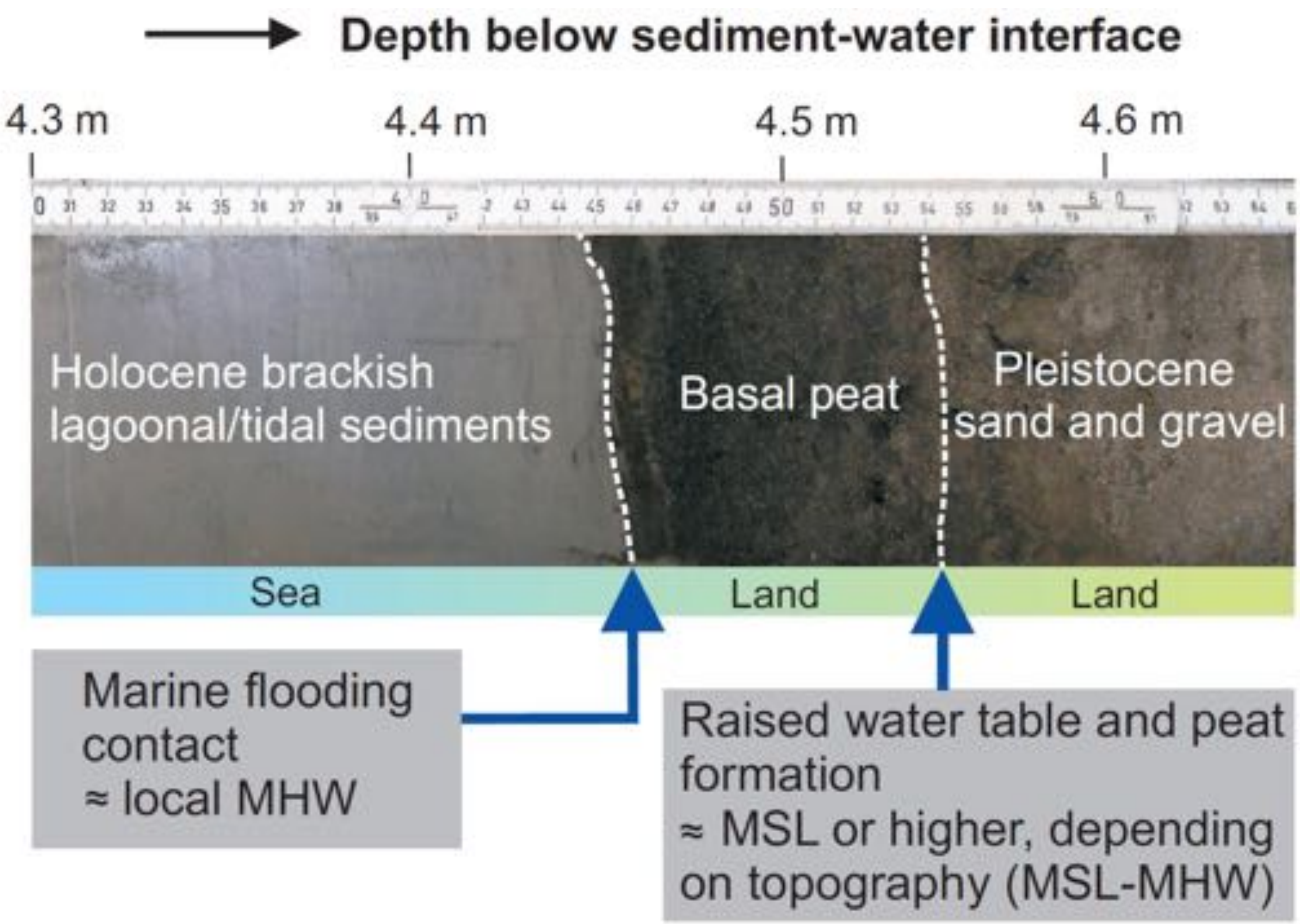




- Observed sea-level response to past ice change reflects contributions
- These processes will govern the sea-level response to future ice mass change

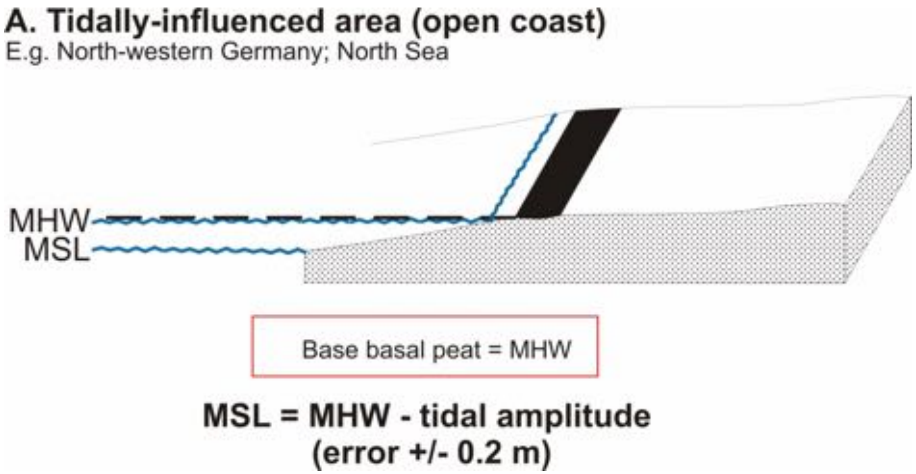
Milne et al. (2009)

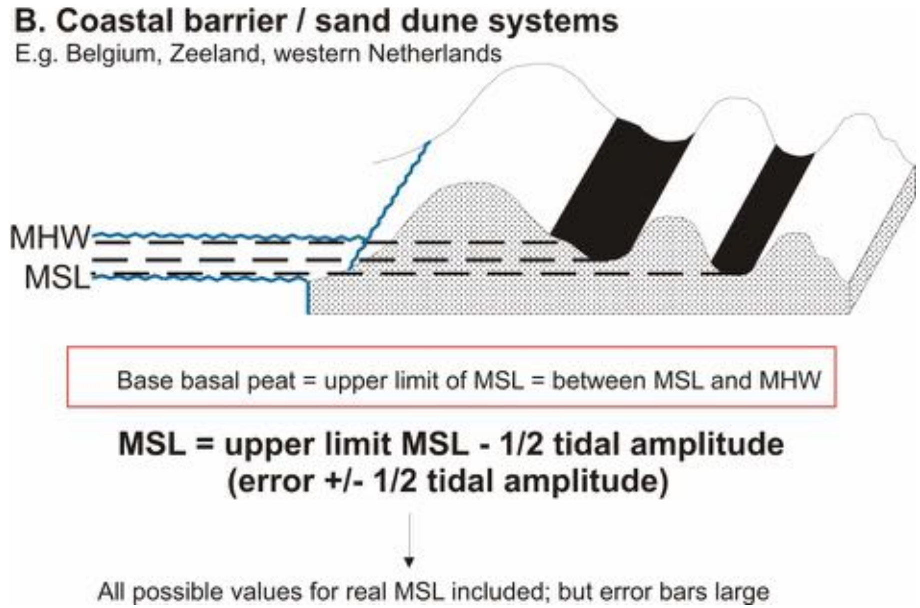
Basal peat as sea-level indicator



Vink et al. (2013)

Sea level indicator vs. type of coast





MSL… mean sea level
MHW…mean high water

(slides courtesy of Annemiek Vink)

Mesolithic find spot in Poel (southern Baltic Sea)

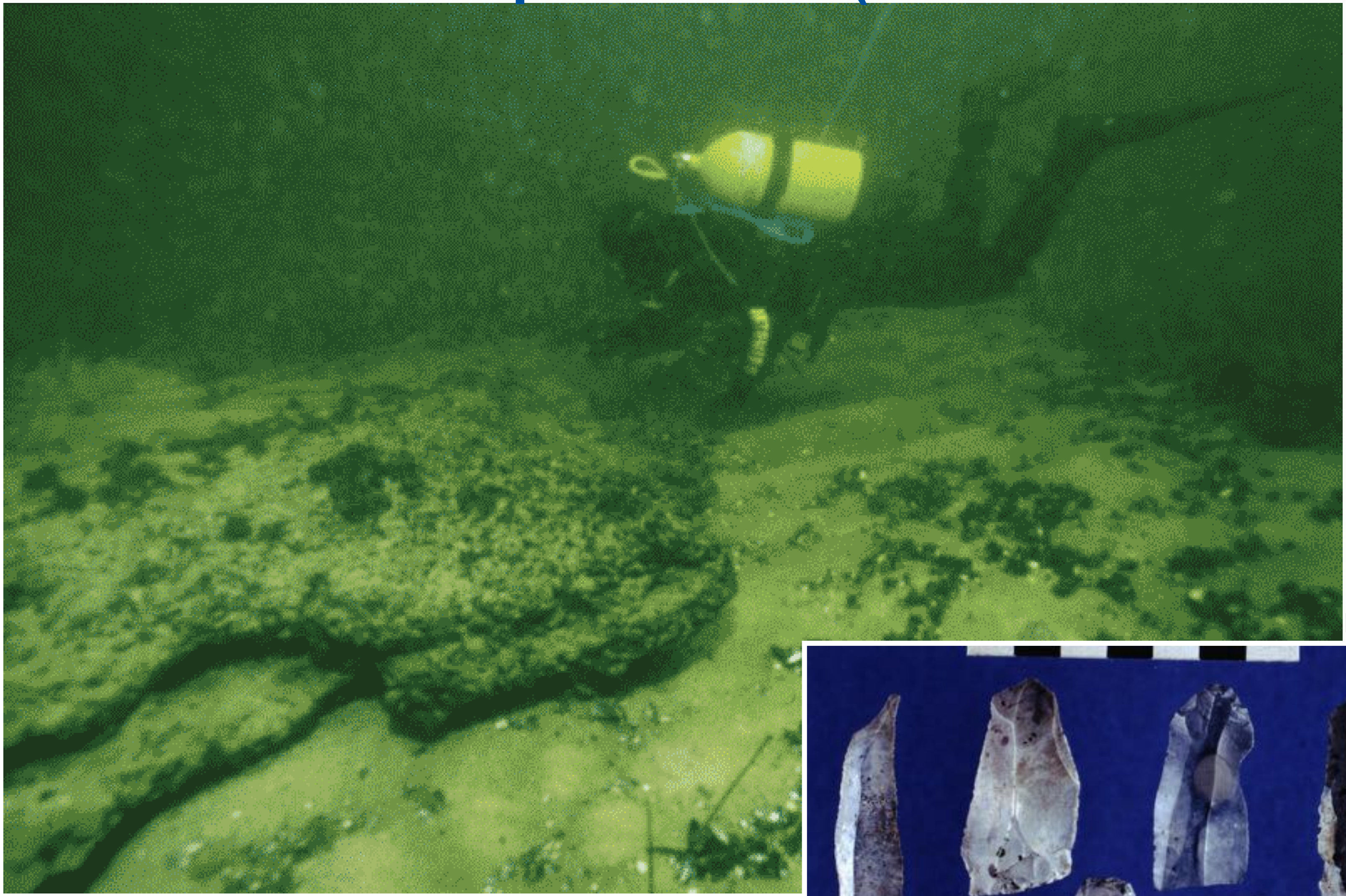


Photo: H.Lübke

In 7 m water depth

Mesolithic find spot in Timmendorf (Poel)

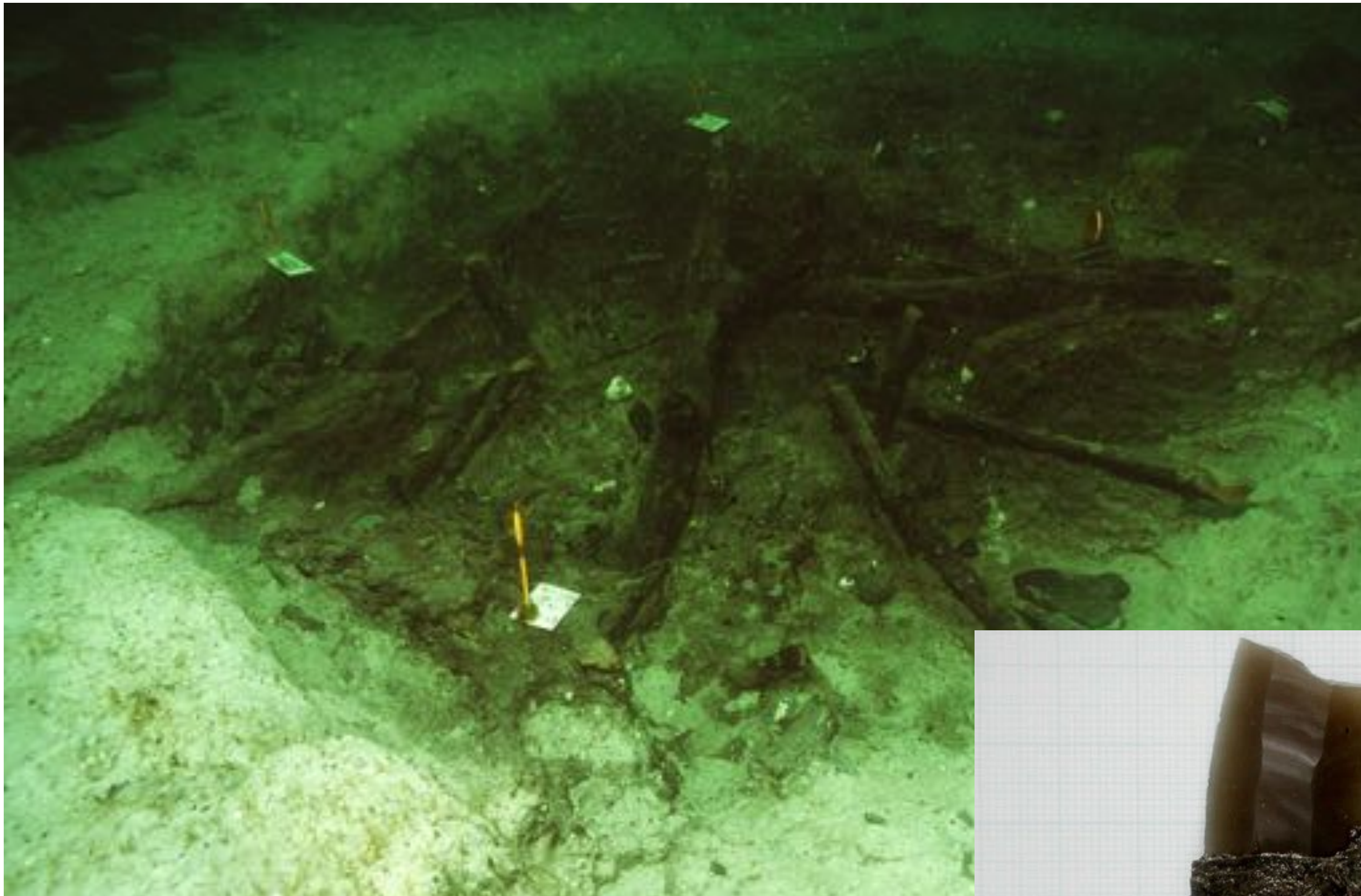
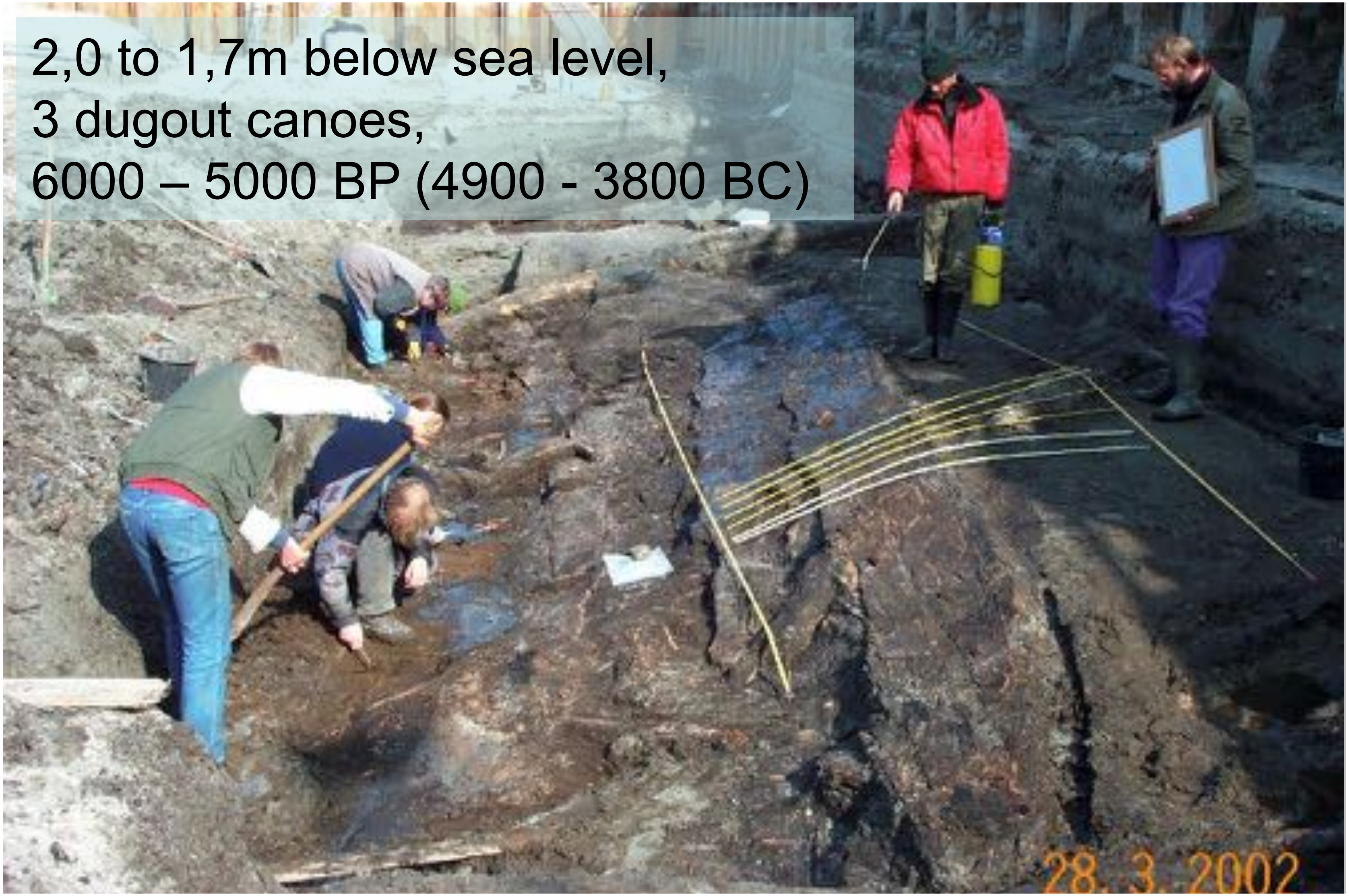


Photo: H.Lübke

In 3 m water depth

Find spot 225 in Stralsund



(Picture courtesy of R. Lampe)

Recent midwater

Oak stump in
Greifswalder Bodden
-0,75m HN,
1190 ± 45 BP
(840 ± 60 AD)

(Photo courtesy of R. Lampe)

Whale bones in SW Sweden

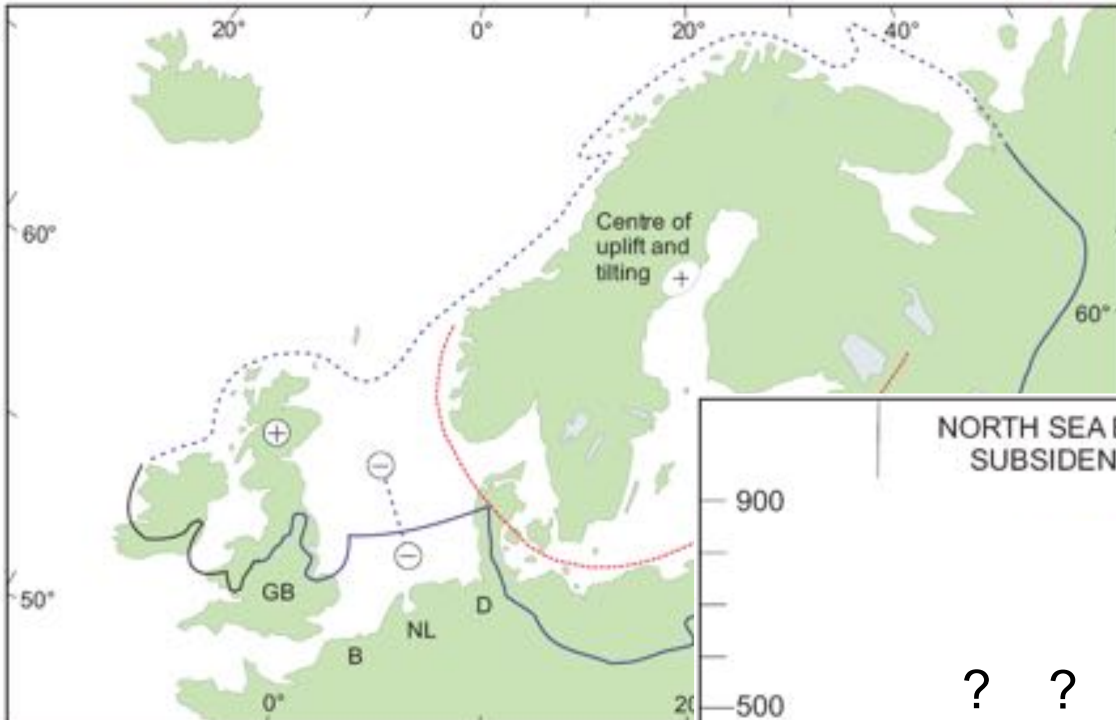
(Anderung et al. 2013)

Example:
RSL application in Europe

Southern North Sea coast – forebulge

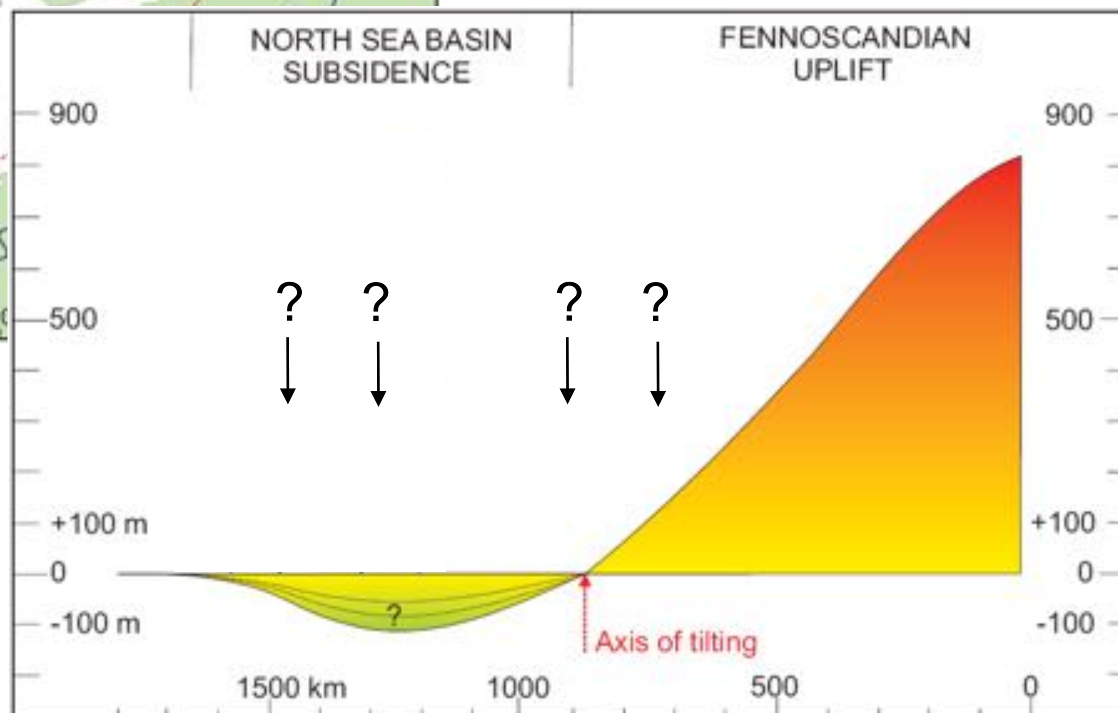
West Swedish coast - archeology

Coastal change at the German North Sea coast



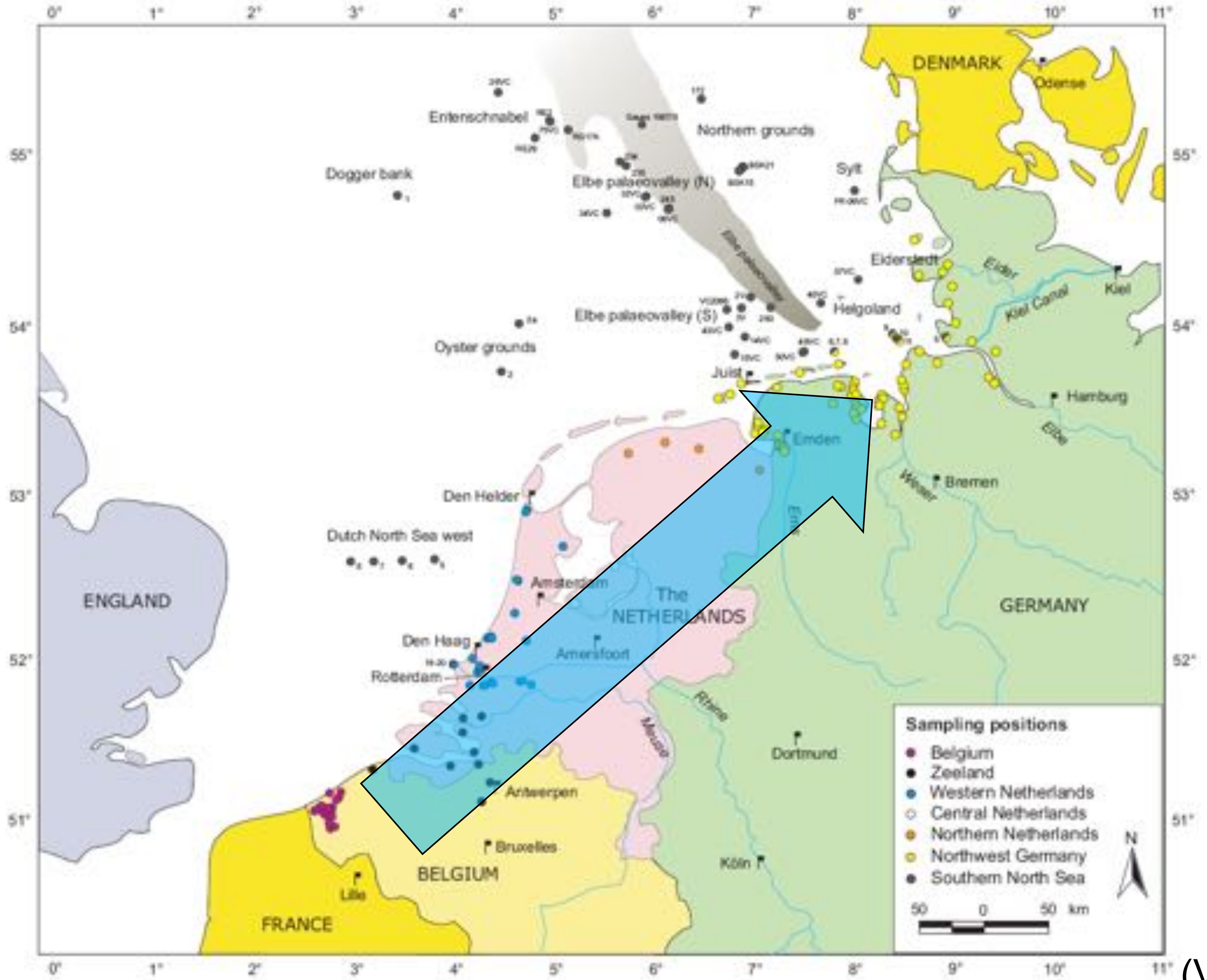
- Affected by subsidence due to GIA

Postglacial crustal movement



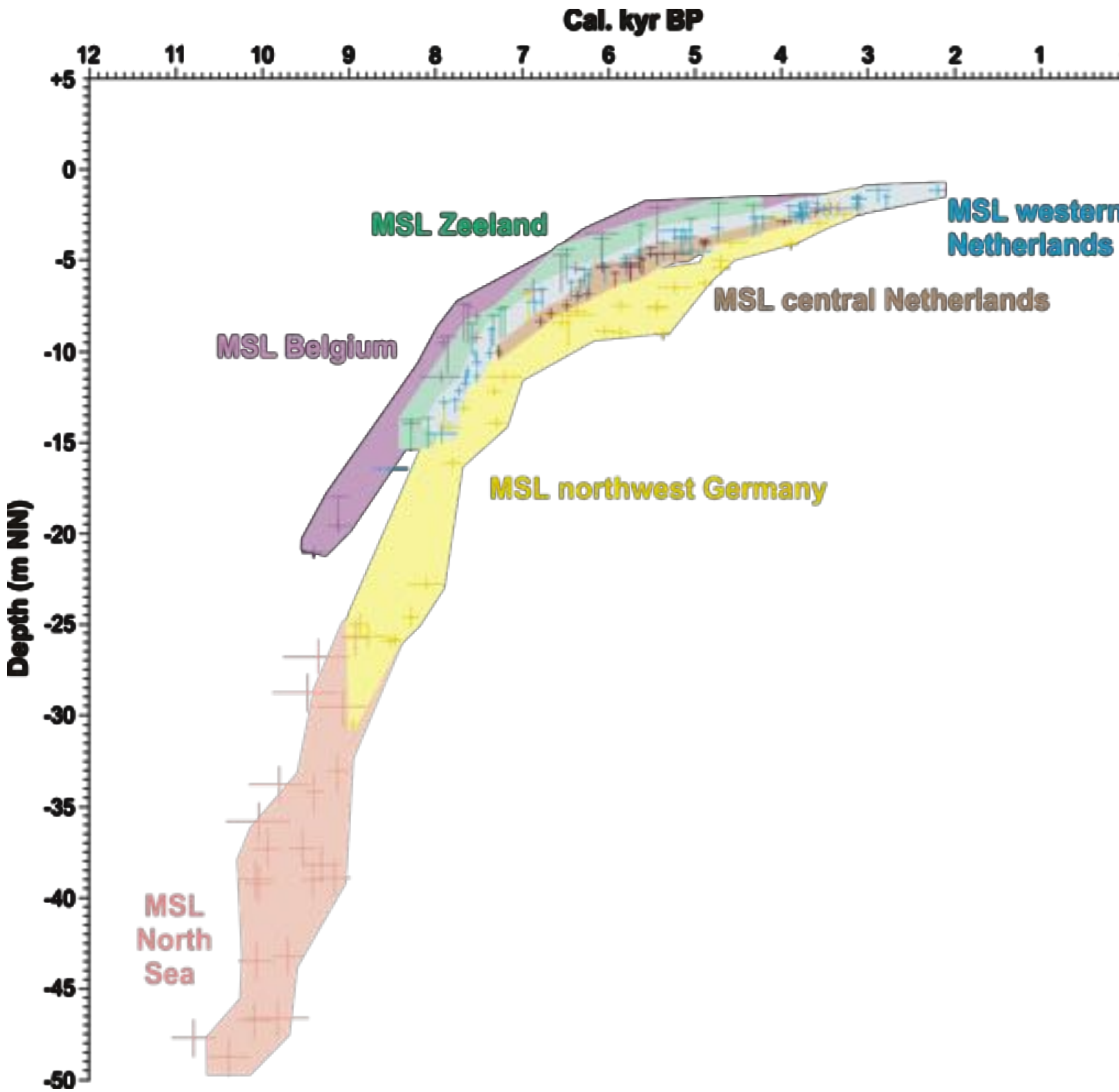
(Vink et al., in prep. after Mörner 1980)

Relative sea-level data



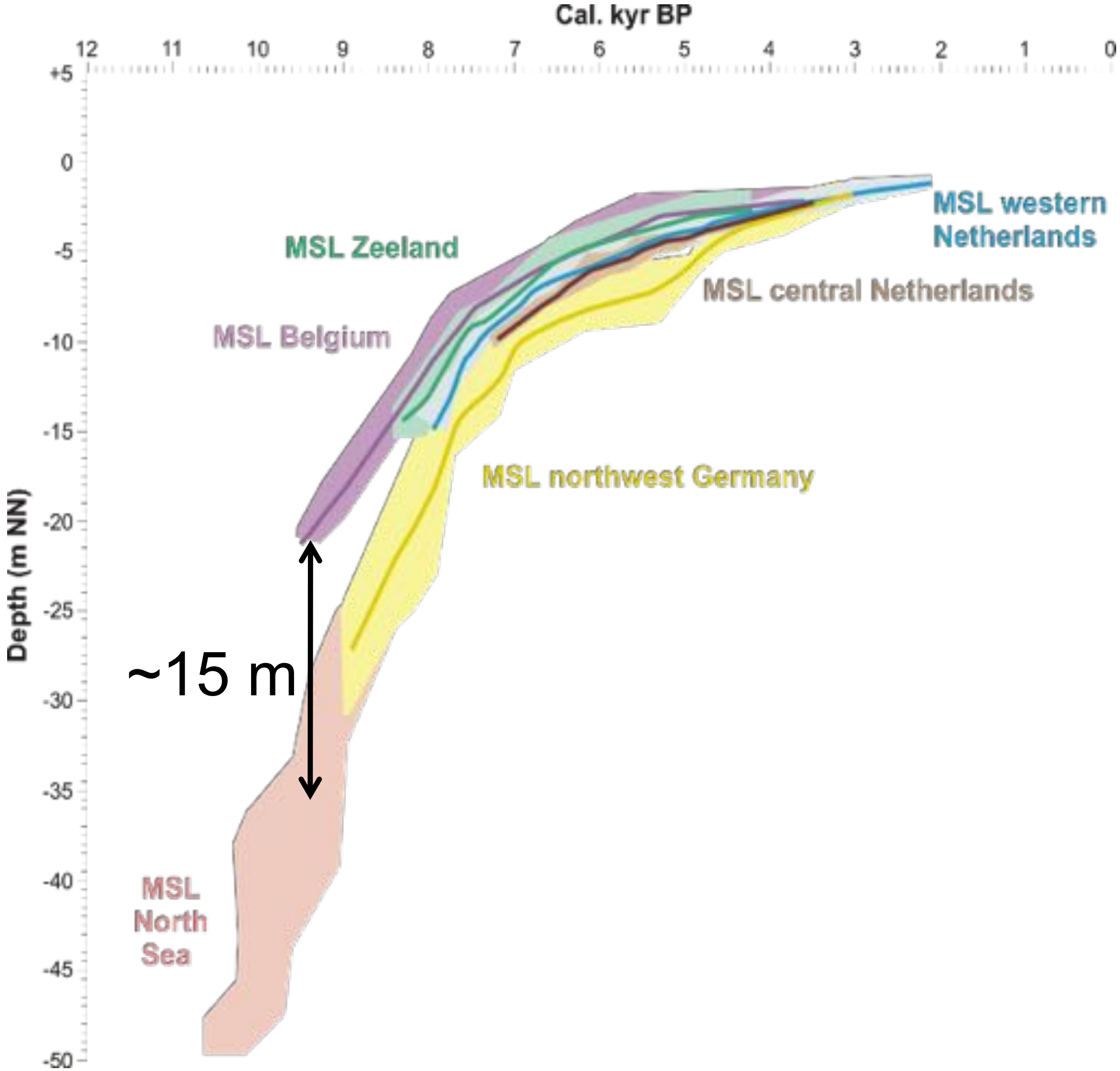
(Vink et al., in prep.)

Comparison of sea-level curves



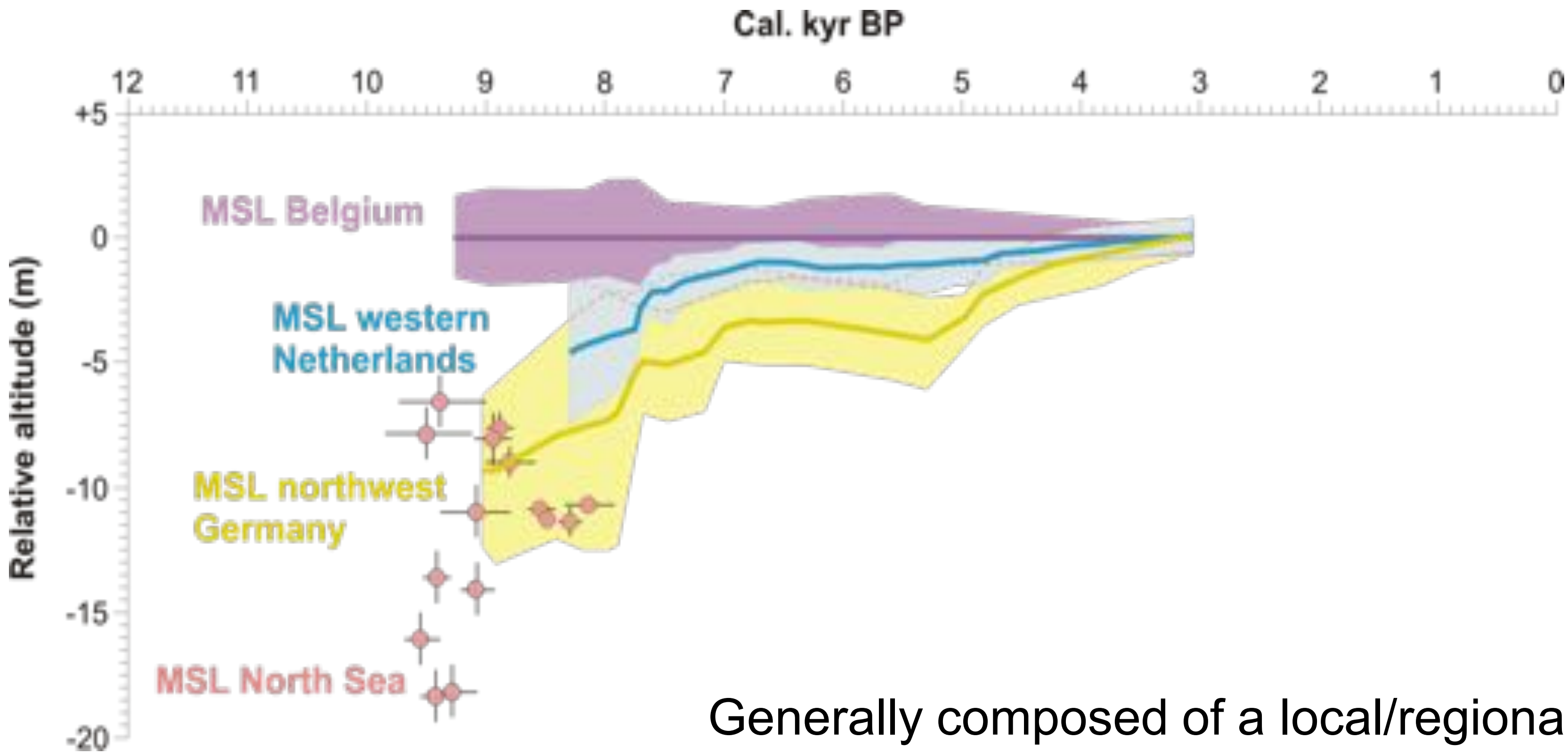
(Vink et al. 2007, QSR)

Comparison of sea-level curves



(Vink et al. 2007, QSR)

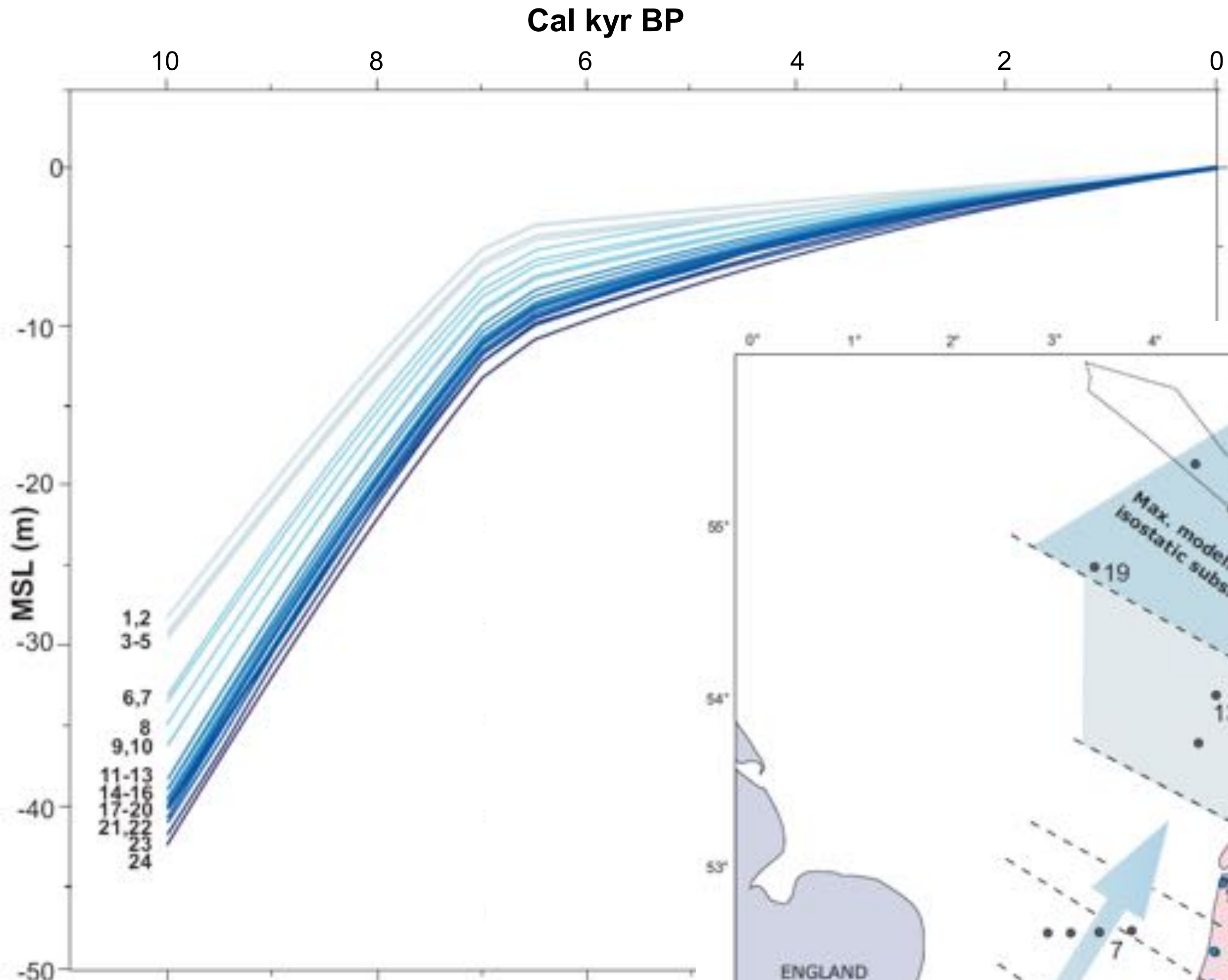
Relative crustal movements

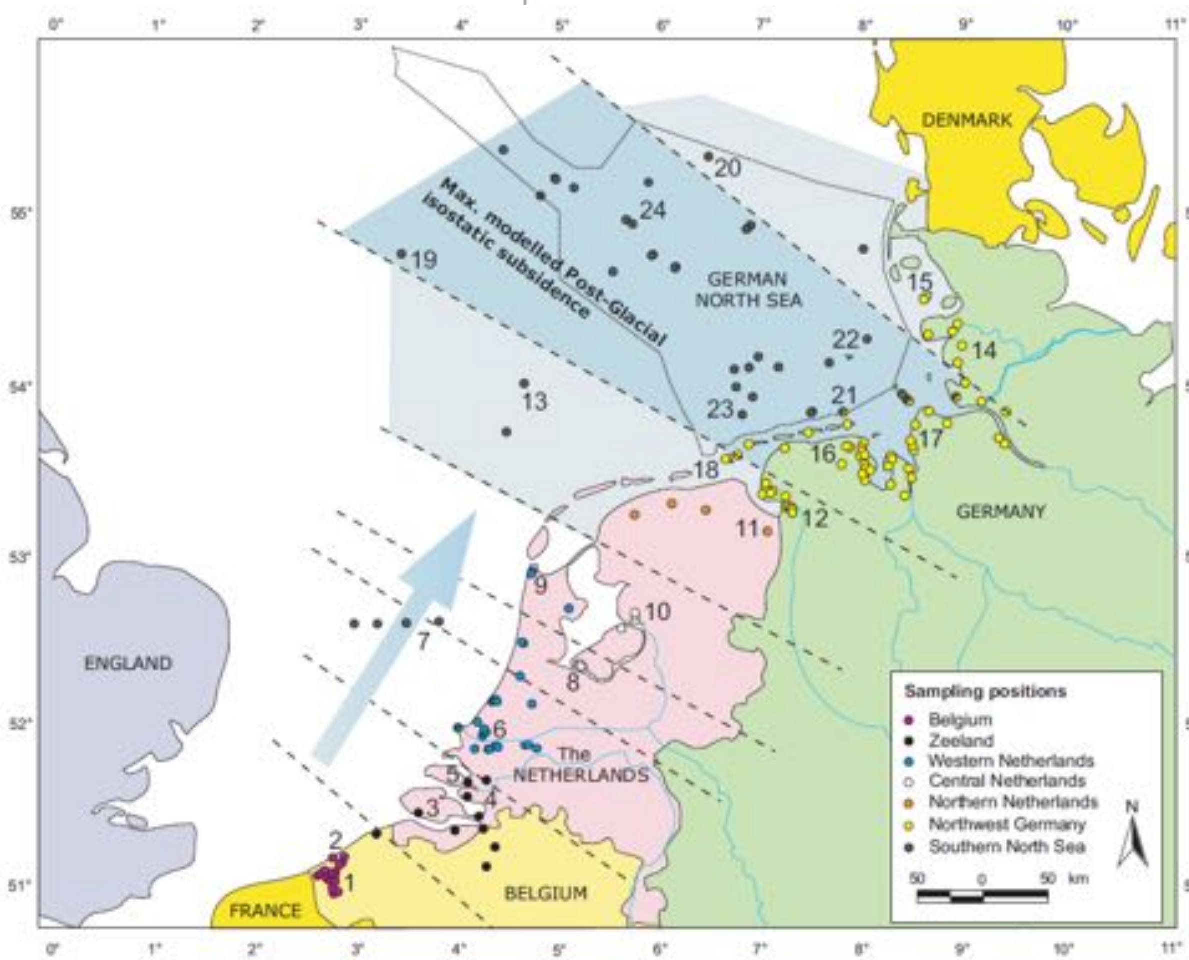


Generally composed of a local/regional (linear) tectonic component and an (non-linear) isostatic component.

(Vink et al. 2007, QSR)

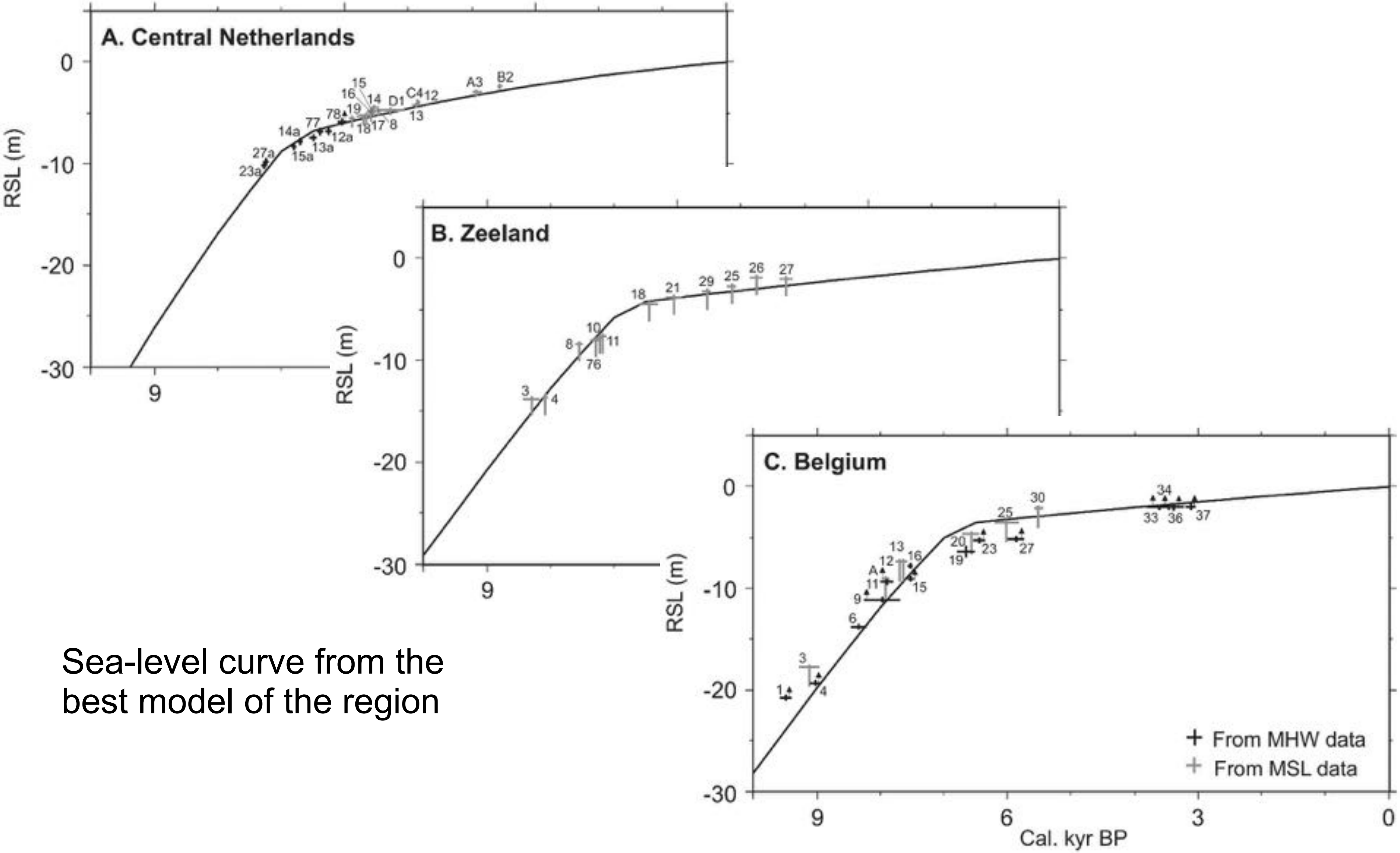
Modelled sea-level curves





(Vink et al., in prep.)

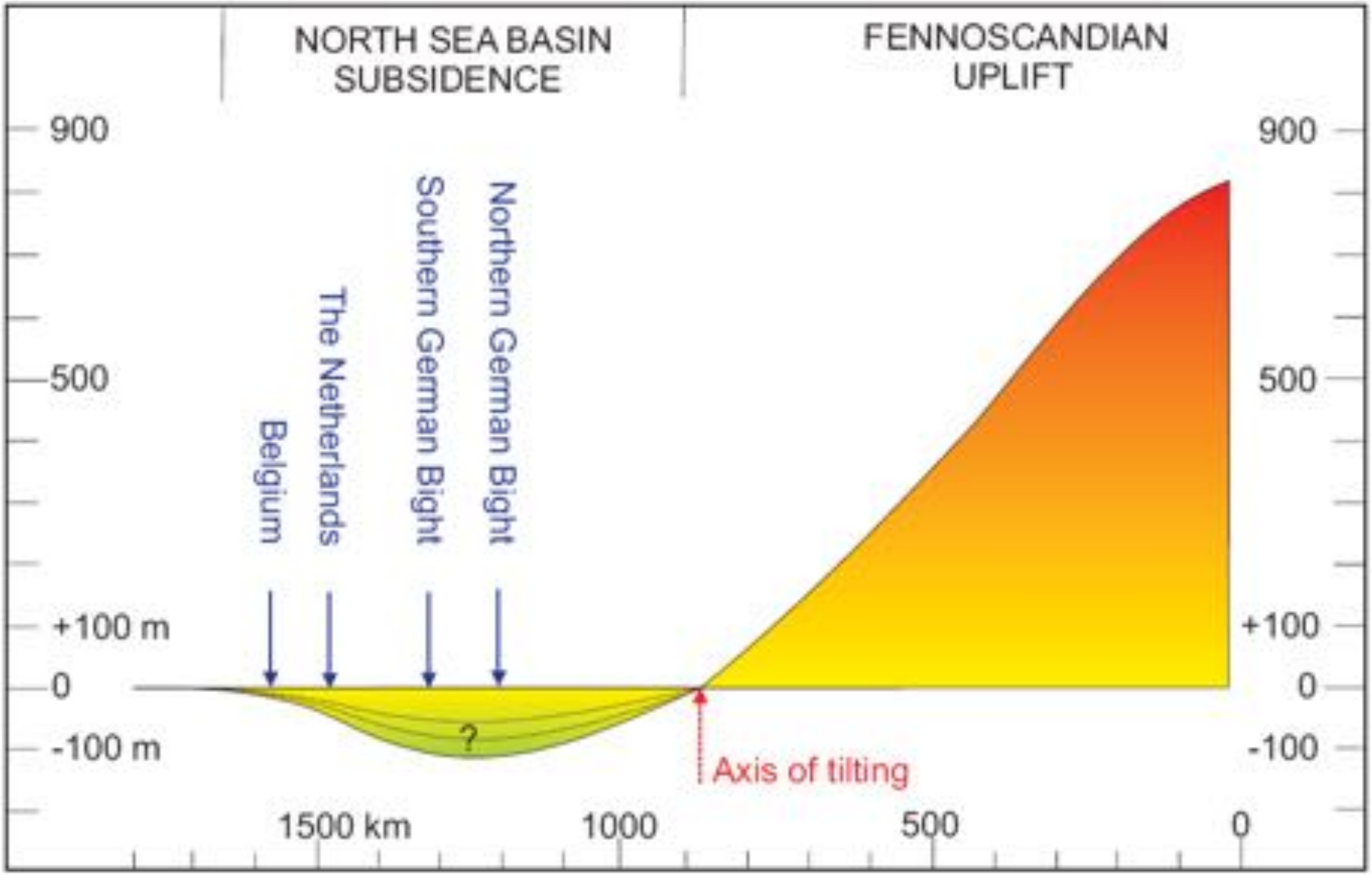
Modelled curves vs. sea-level data



Sea-level curve from the best model of the region

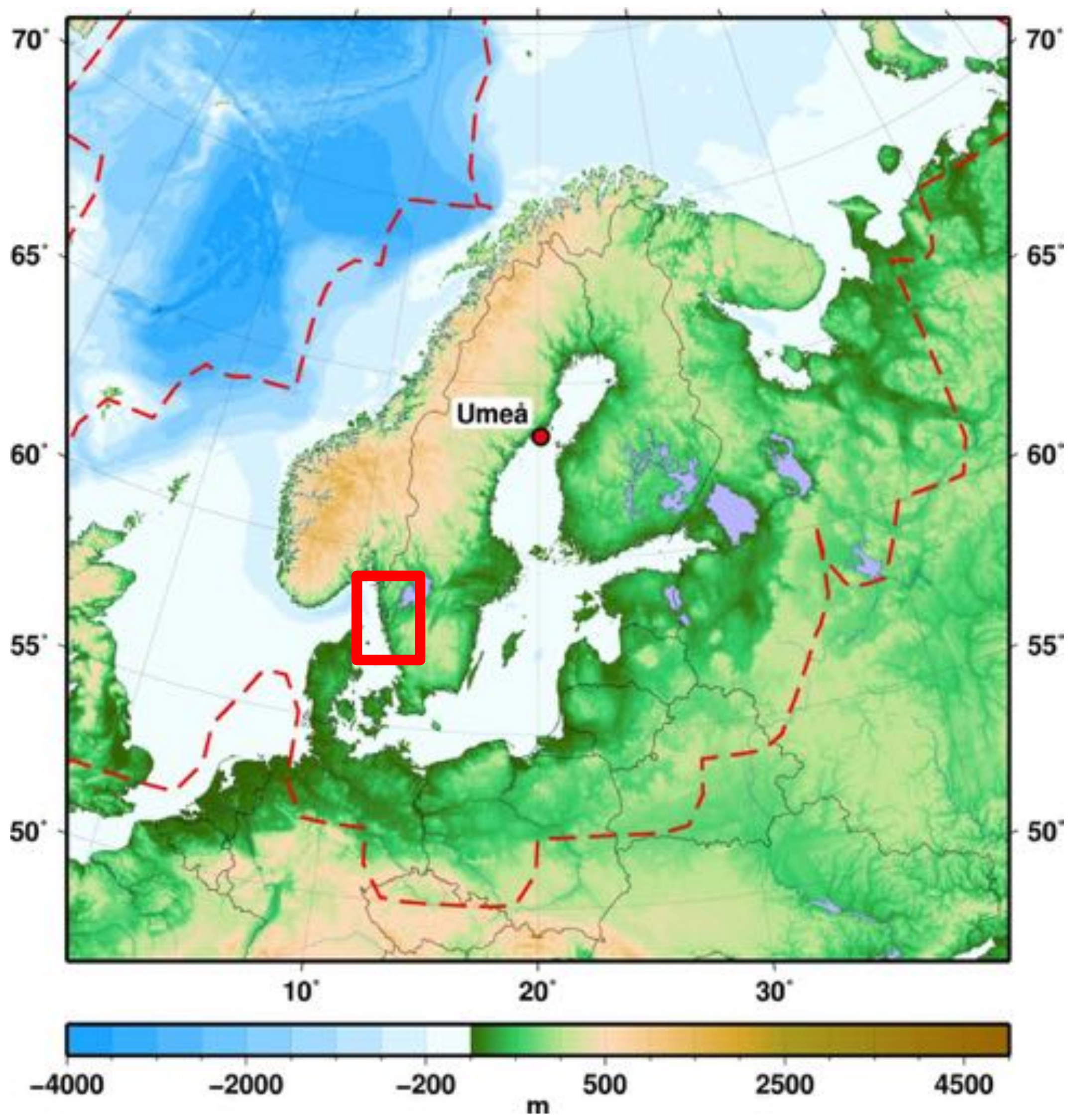
(Vink et al. 2007, QSR)

Coastal change at the German North Sea coast

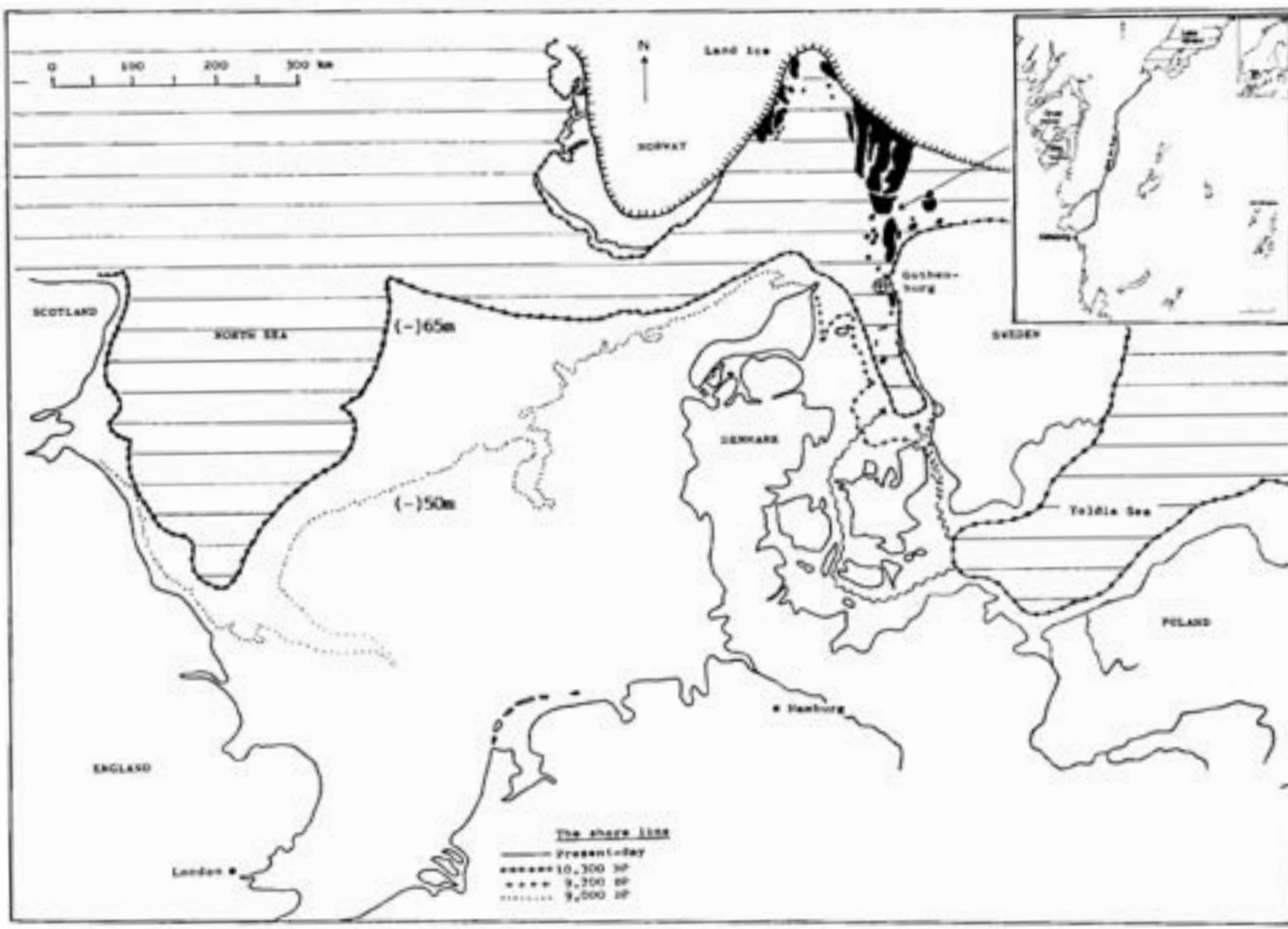


(Vink et al., in prep., after Mörner 1980)

Archeology: The first Swedes



Palaeotopography of the North Sea



(Schmitt 1994, OJOA)


Norwegen
Oslo
Stockholm
Hensbacka
Bromme
Ahrensburg culture
Hamburg
Image NASA
© 2008 Tele Atlas
© 2008 Europa Technologies

Nösund

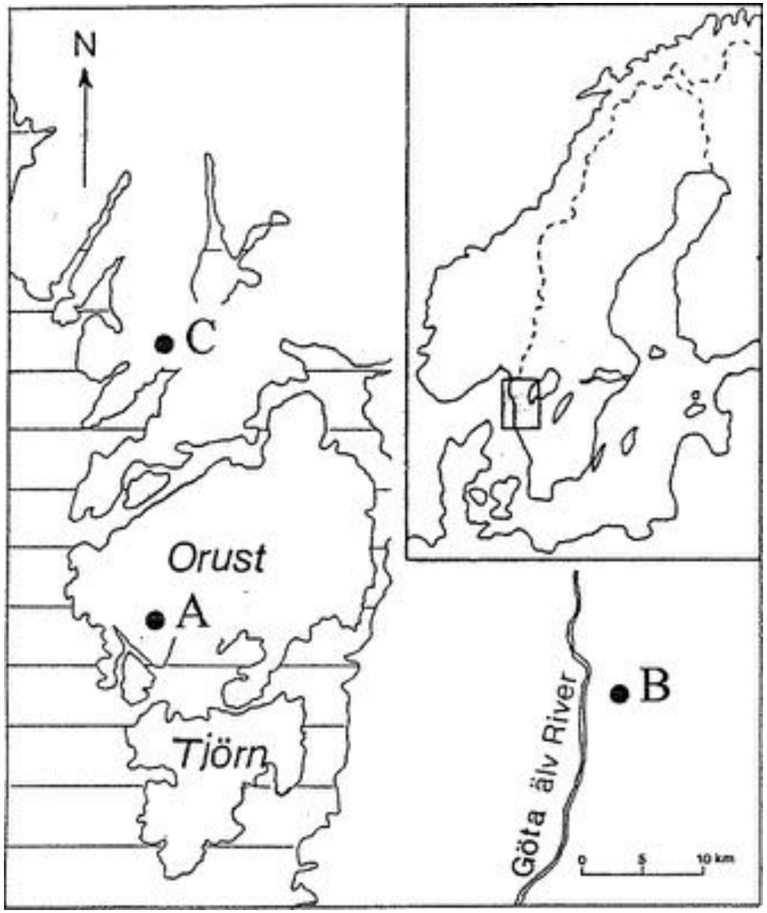
Swedish coast near Smögen

Hensbacka sites

A Nösund

B Kolamossen

C Gullmarsskogen



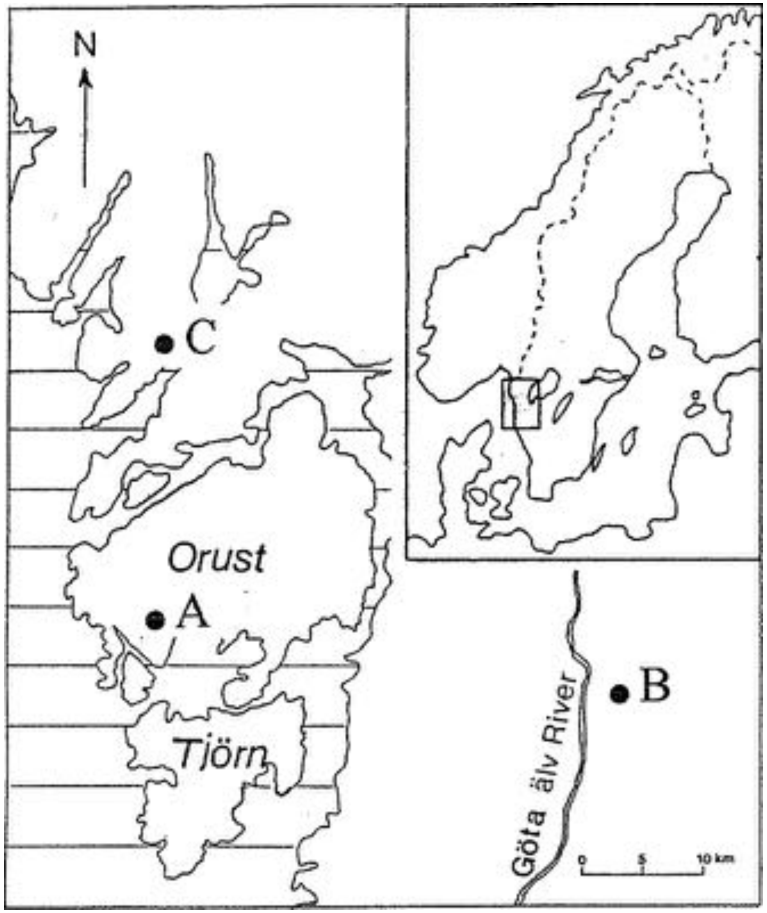
(Schmitt et al. 2009, OJOA)

Hensbacka sites

A Nösund
10280±100 a BP
56 - 57 m a.s.l.

B Kolamossen
10260±120 a BP
50 m a.s.l.

(Svedhage 1985a,b;
Svedhage & Schmitt 1995)



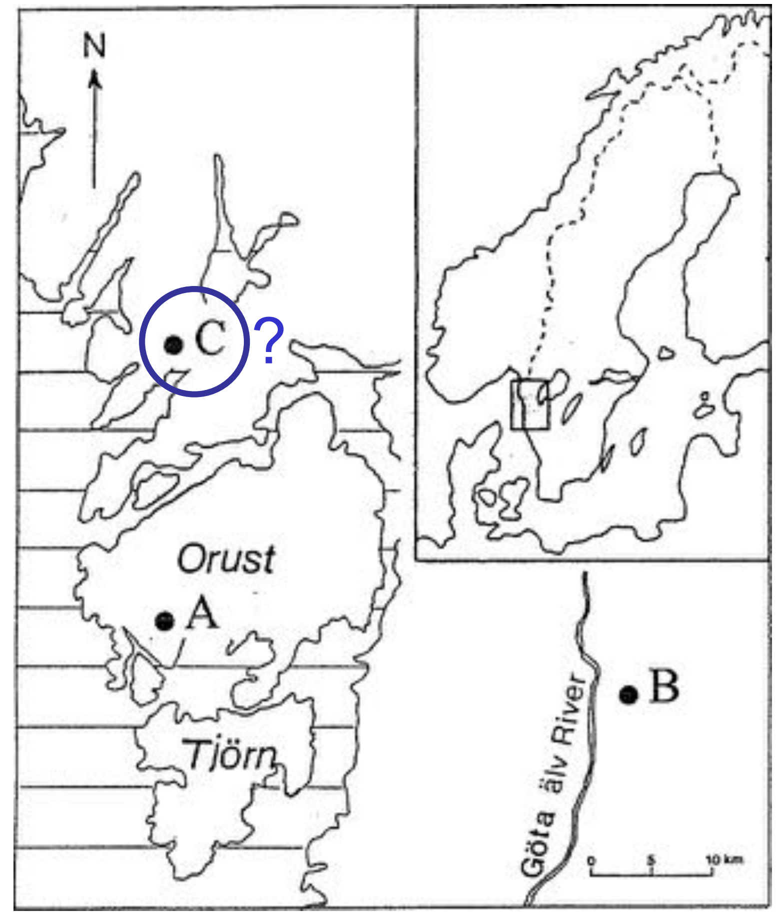
(Schmitt et al. 2009, OJOA)

Hensbacka sites

A Nösund
10280±100 a BP
56 - 57 m a.s.l.

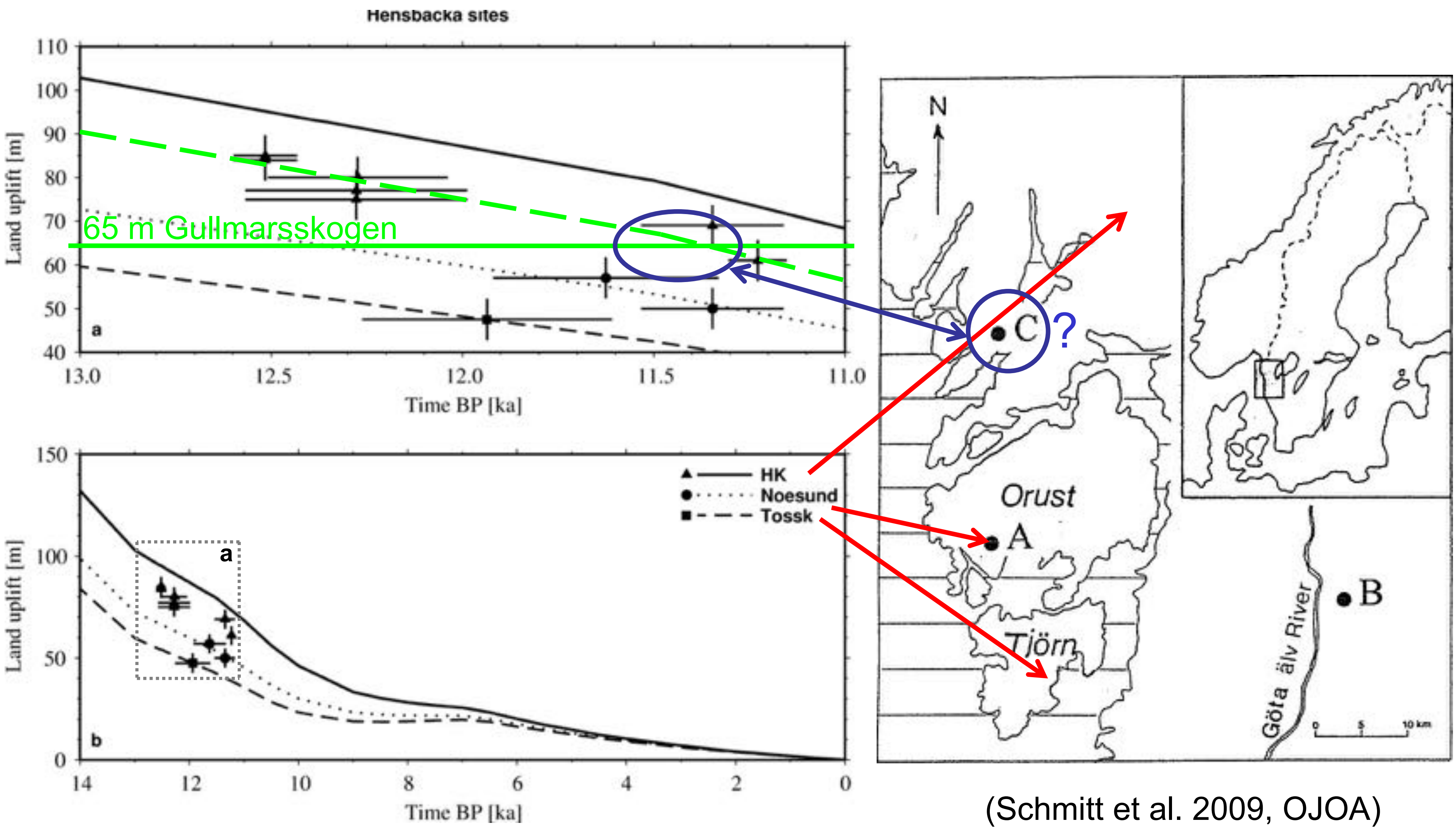
B Kolamossen
10260±120 a BP
50 m a.s.l.

C Gullmarsskogen
??? a BP
65 m a.s.l.



(Schmitt et al. 2009, OJOA)

Results



(Schmitt et al. 2009, OJOA)

Geodetic techniques

Levelling
GNSS
VLBI
Tide gauges
Satellite altimetry

(Repeated) Levelling

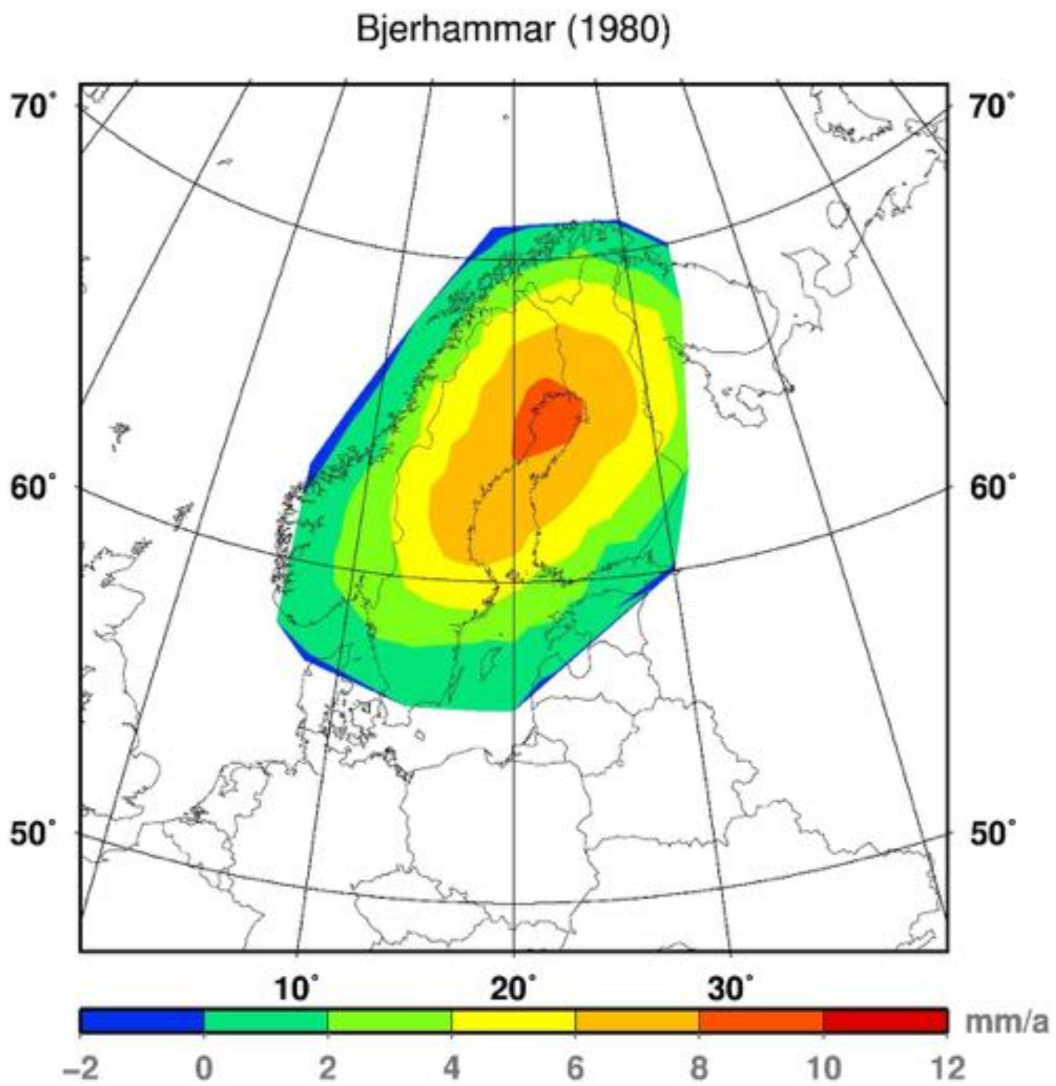
(Somewhere near
the Arctic circle)

Motorized levelling (introduced by Lantmäteriet in the 70s)

(Source:http://www.fig.net/organisation/comm/5/activities/reports/gavle/Image14.gif)

(Source:http://www.fig.net/organisation/comm/5/activities/reports/gavle/Image11.gif)

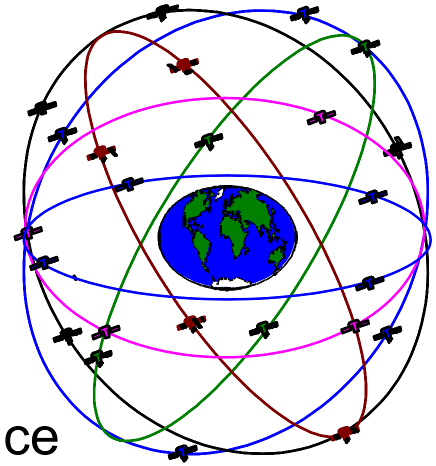
Uplift rate mainly from levelling

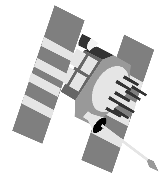


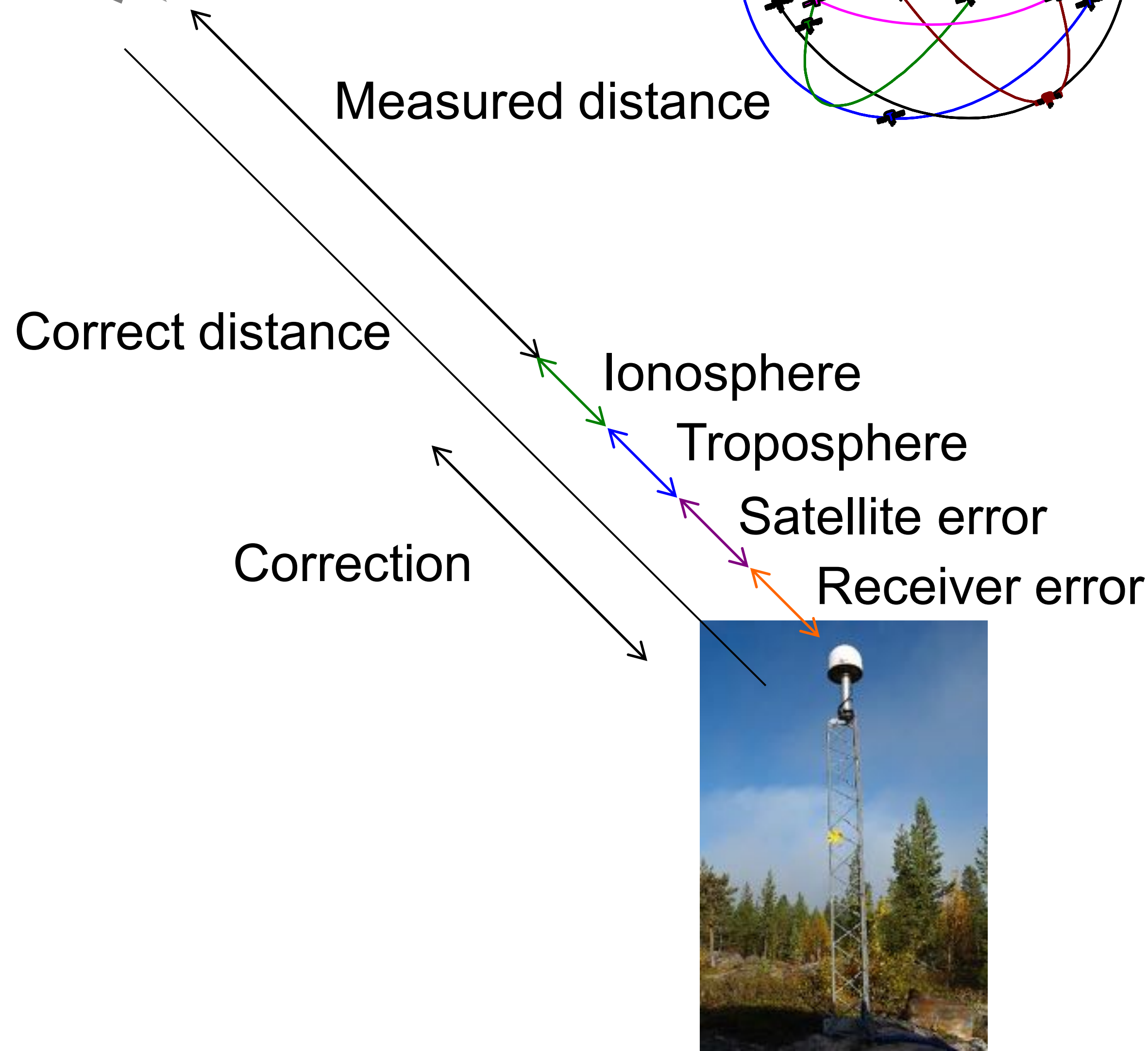
(after Steffen and Wu 2011)

- Apparent uplift!
- One of the few maps covering whole northern Europe
- More maps/models mainly focus on a certain country

Global Navigation Satellite System

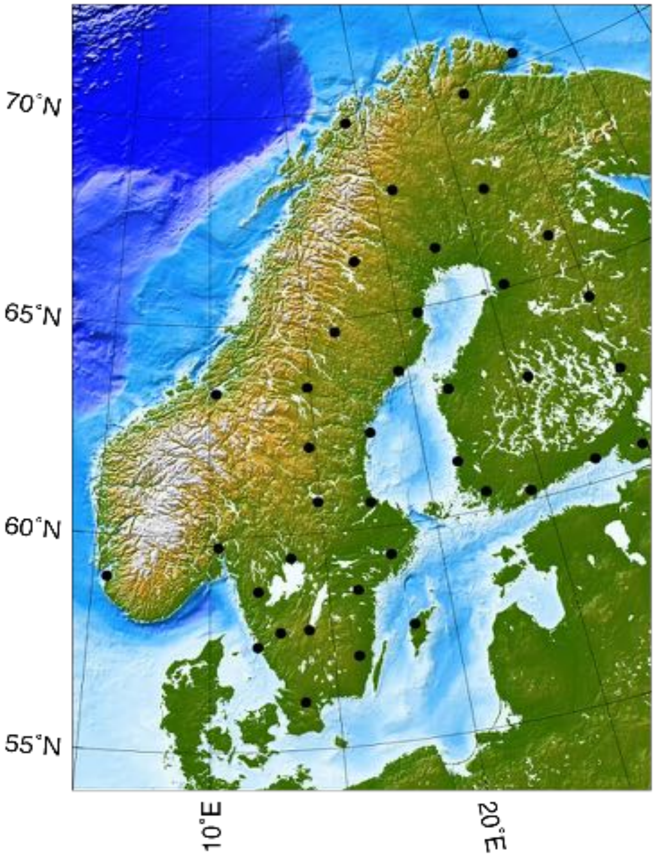






BIFROST Project - GNSS

- Permanent GPS systems across Norway, Sweden, and Finland
- First observations 1993
- Started with 16 sites, quickly increased to about 40 sites, ~100–200 km spacing
- First 3-D map of GIA (anywhere) produced 2001



Published velocity results:

2002 Johansson et al., JGR

GIPSY, Aug 1993 - May 2000

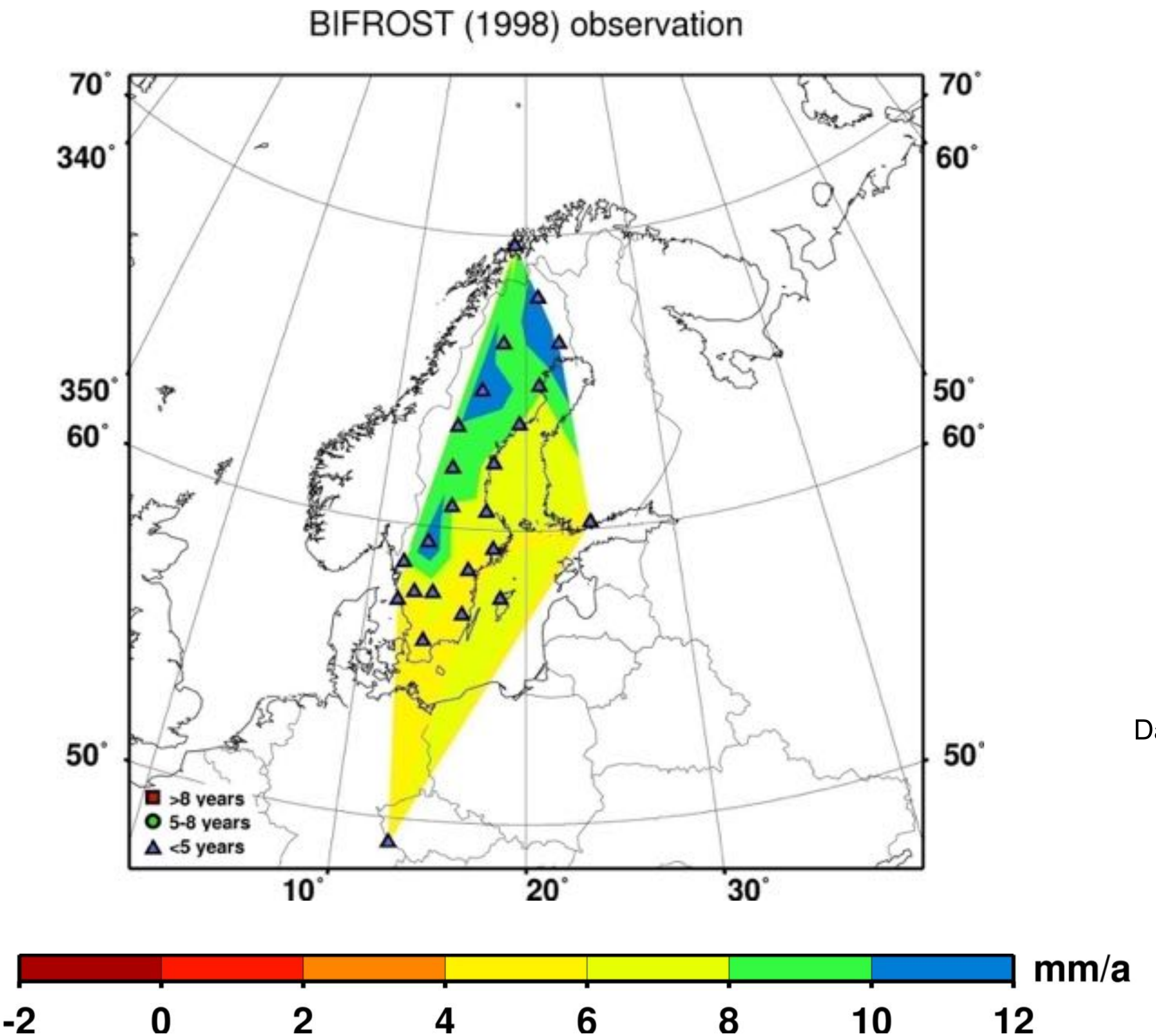
2007 Lidberg et al., J Geodesy

GAMIT, 1996 - June 2004

2010 Lidberg et al., J Geodynamics

GAMIT, 1996 - fall 2006

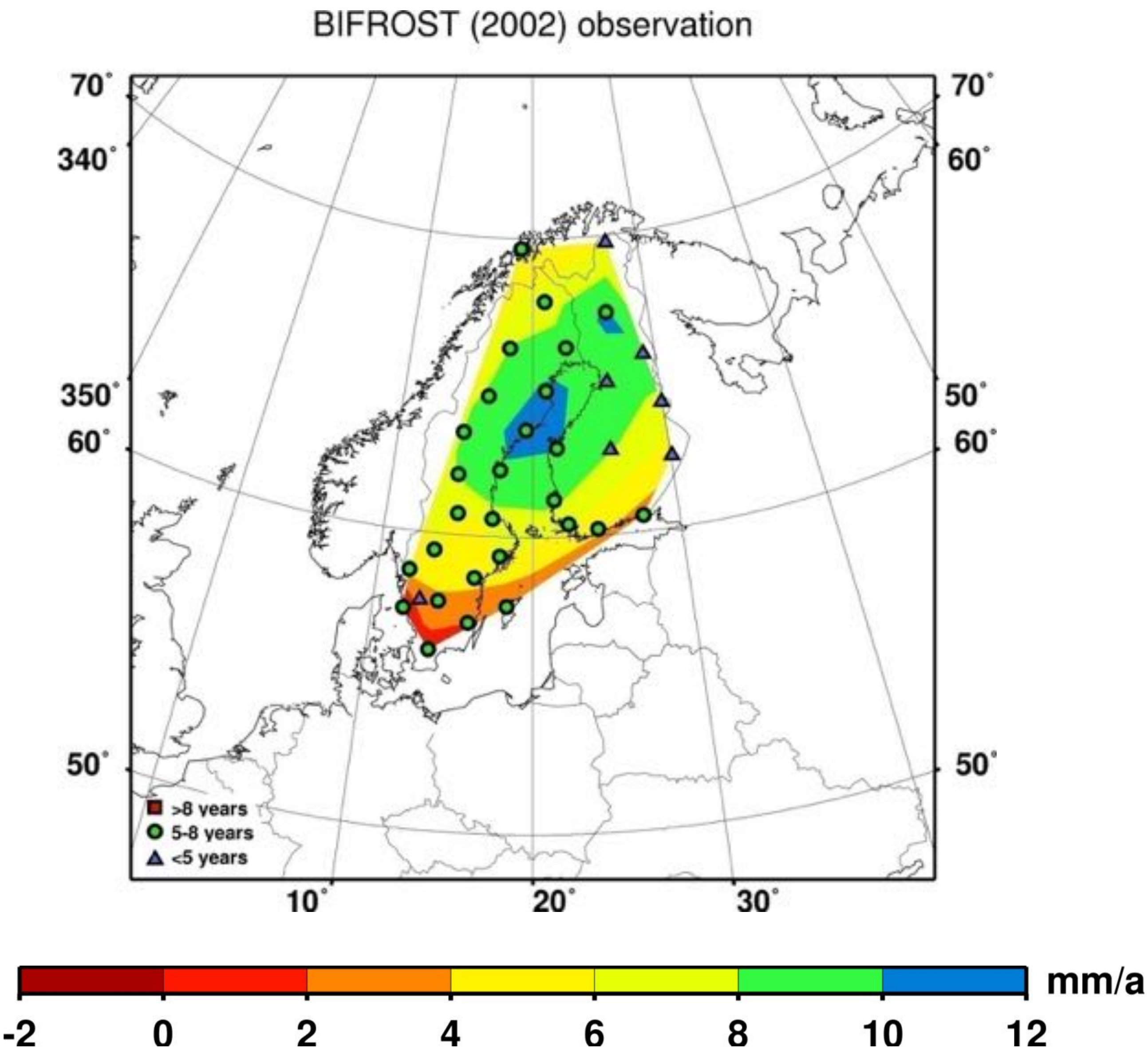
GPS determined uplift rate in Fennoscandia



Data from Scherneck et al. (1998)

(Steffen and Wu 2011)

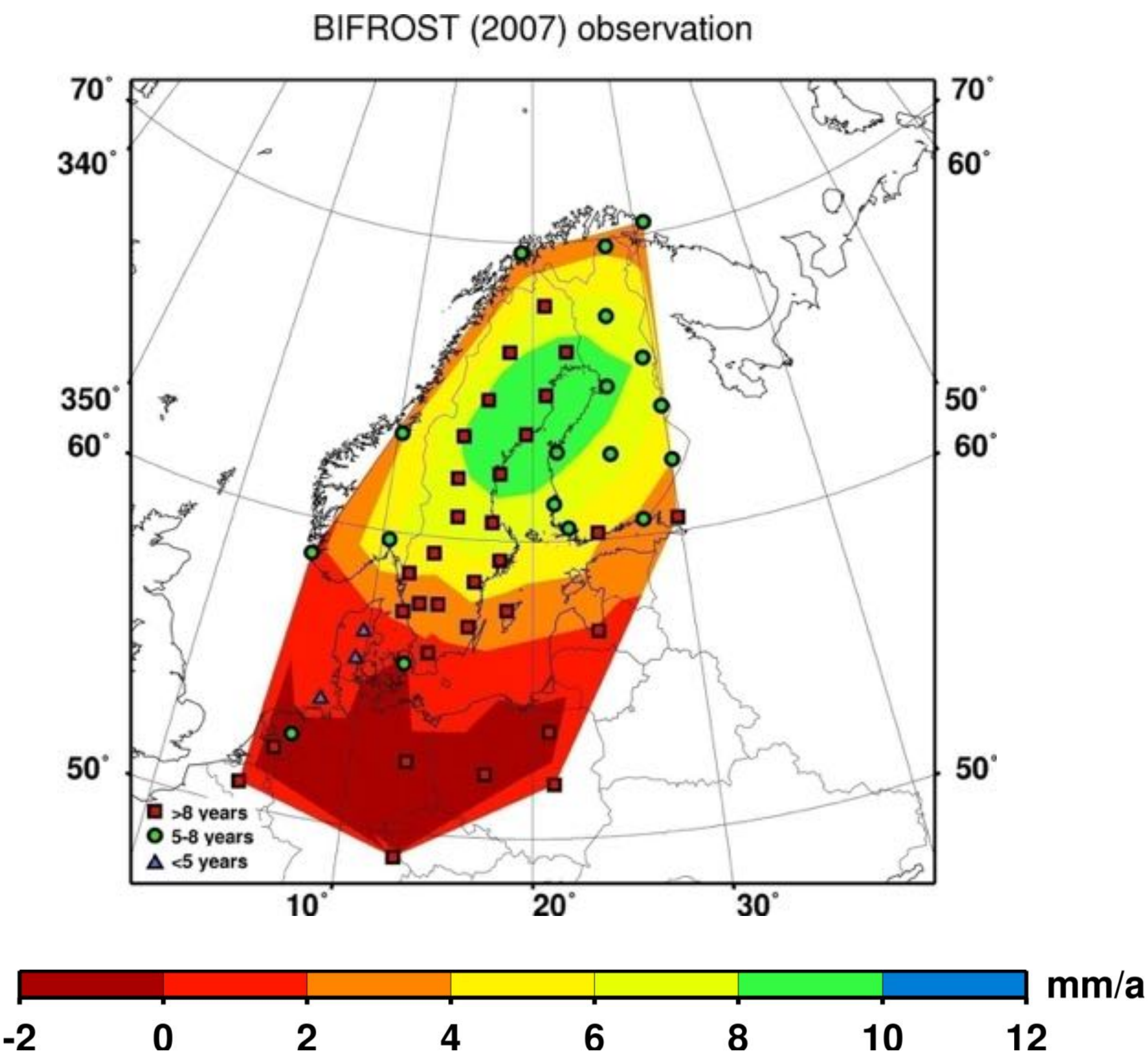
GPS determined uplift rate in Fennoscandia



Data from Johansson et al. (2002)

(Steffen and Wu 2011)

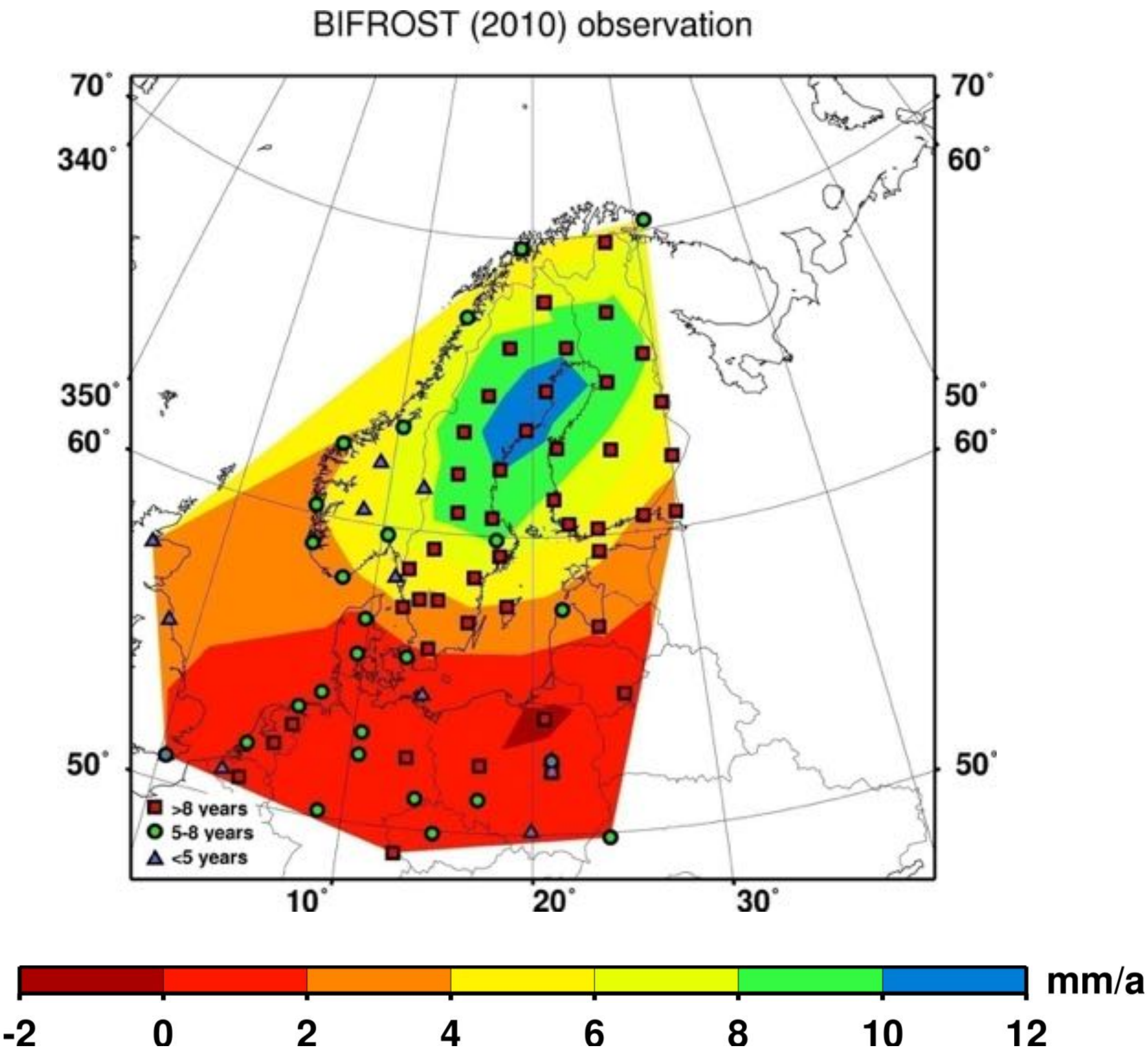
GPS determined uplift rate in Fennoscandia



Data from Lidberg et al. (2007)

(Steffen and Wu 2011)

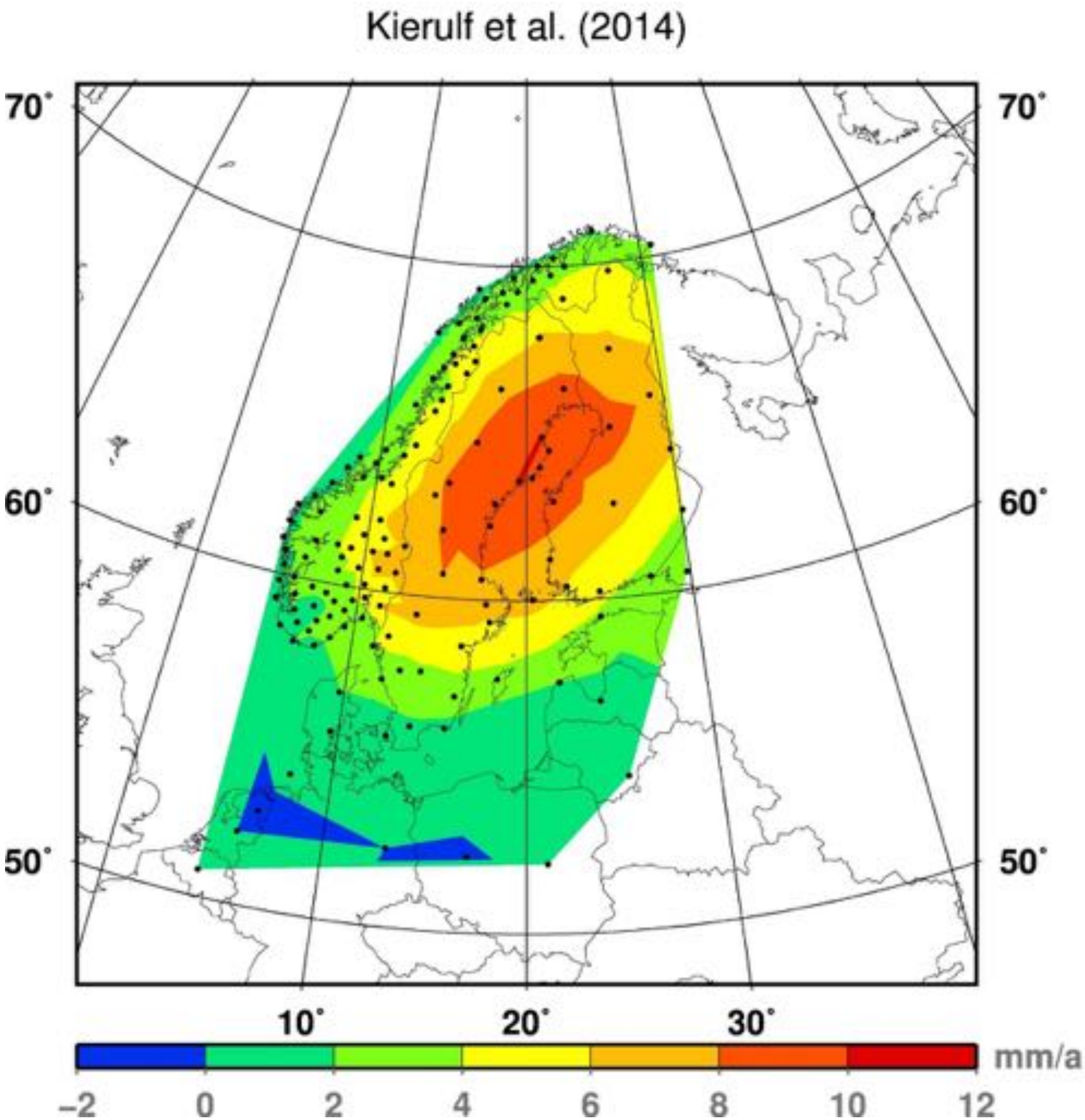
GPS determined uplift rate in Fennoscandia



Data from Lidberg et al. (2010)

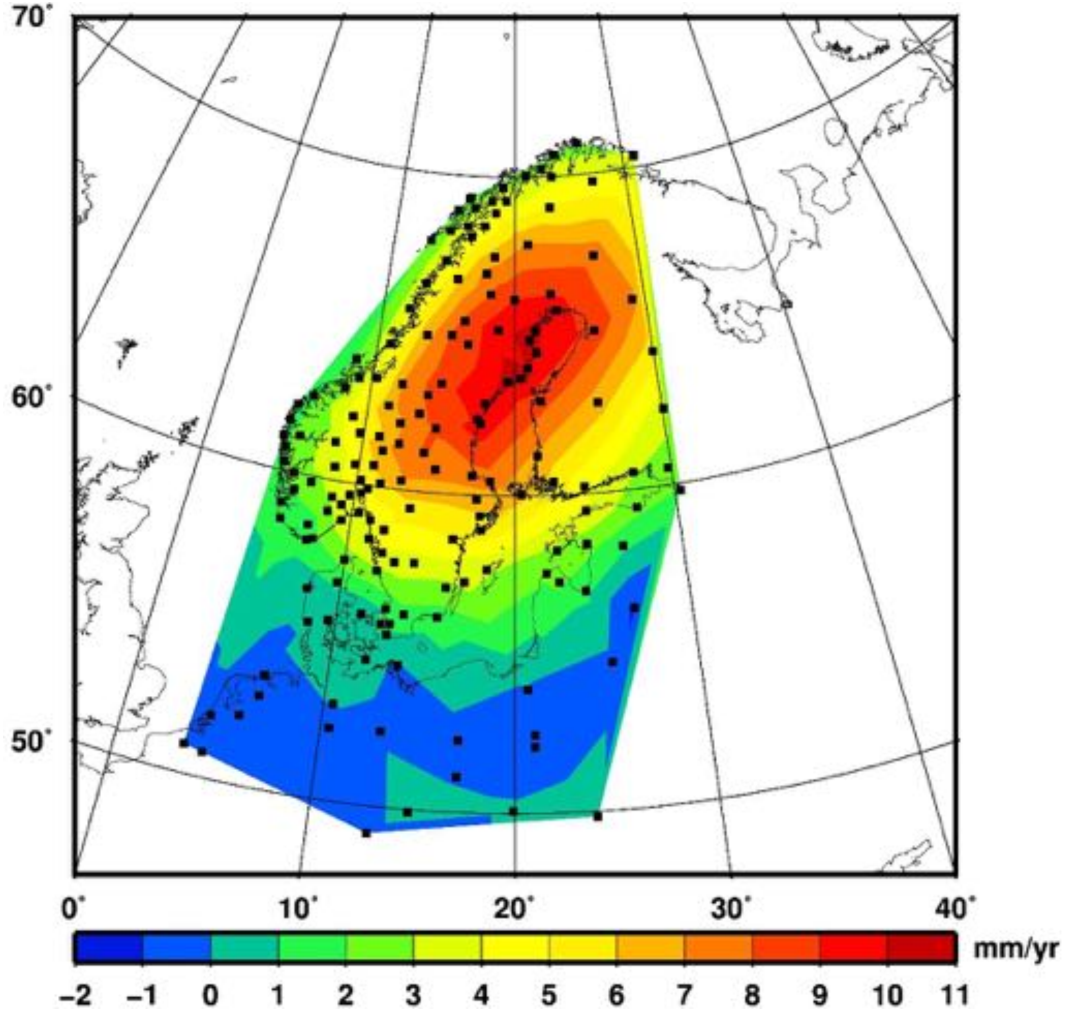
(Steffen and Wu 2011)

GPS determined uplift rate in Fennoscandia



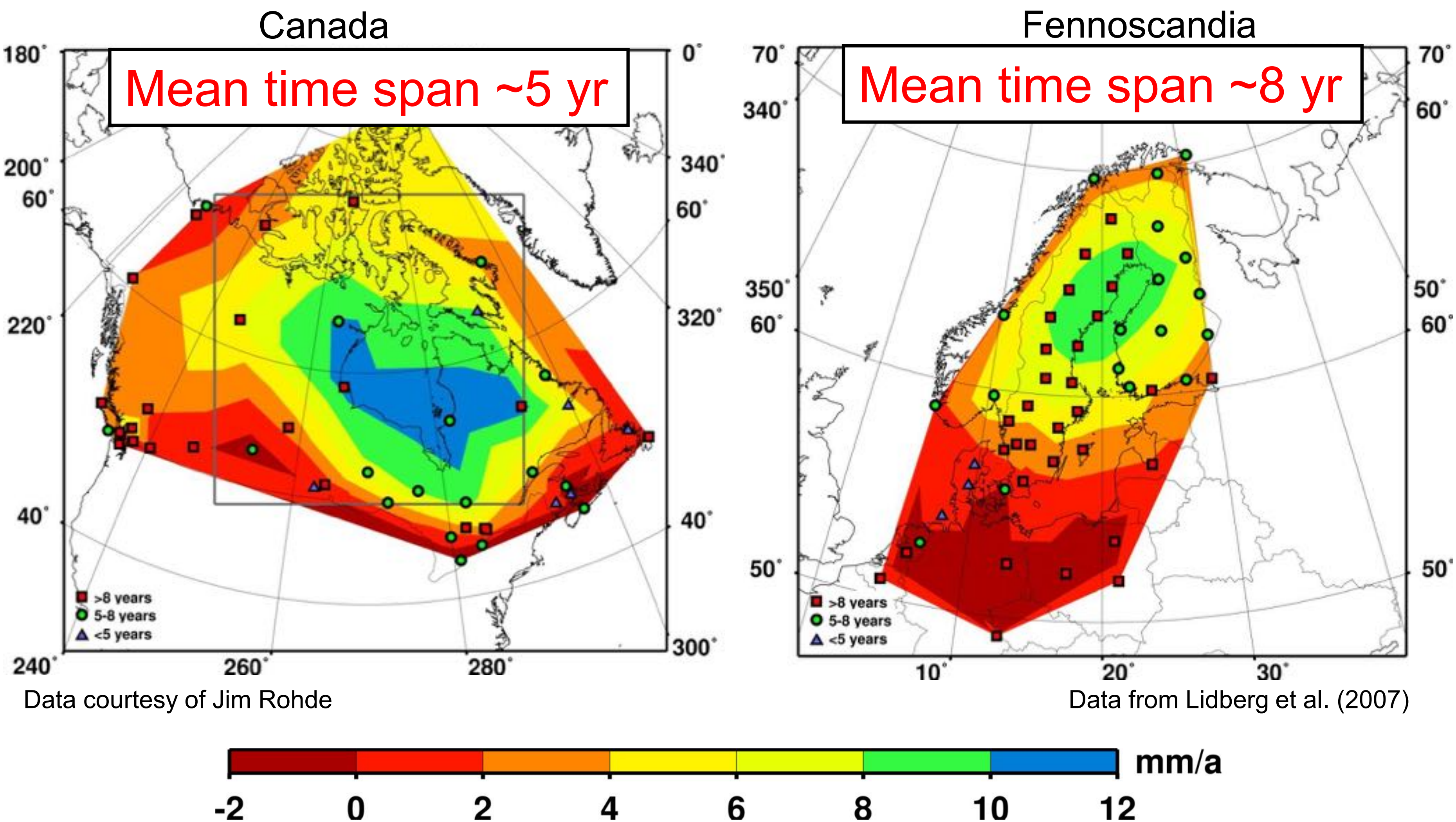
Two antennas in Arjeplog

Observations: BIFROST GNSS data



(Kierulf et al., in prep.)

GPS stations and determined uplift velocity in Canada and northern Europe

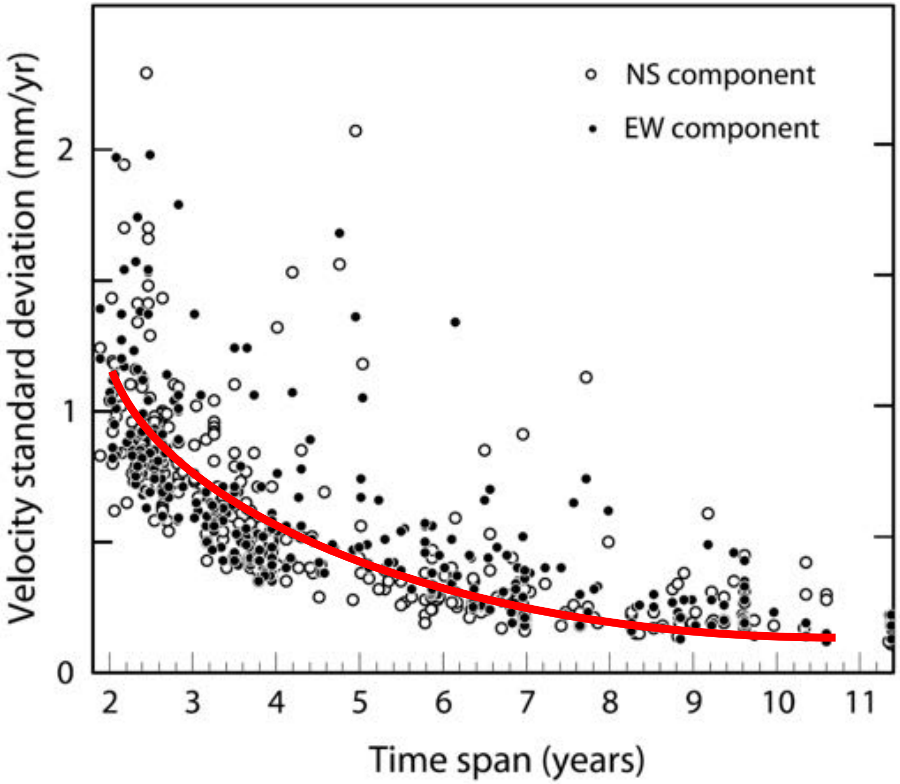


(Wu et al. 2010, GJI)

Accuracy of GPS observations

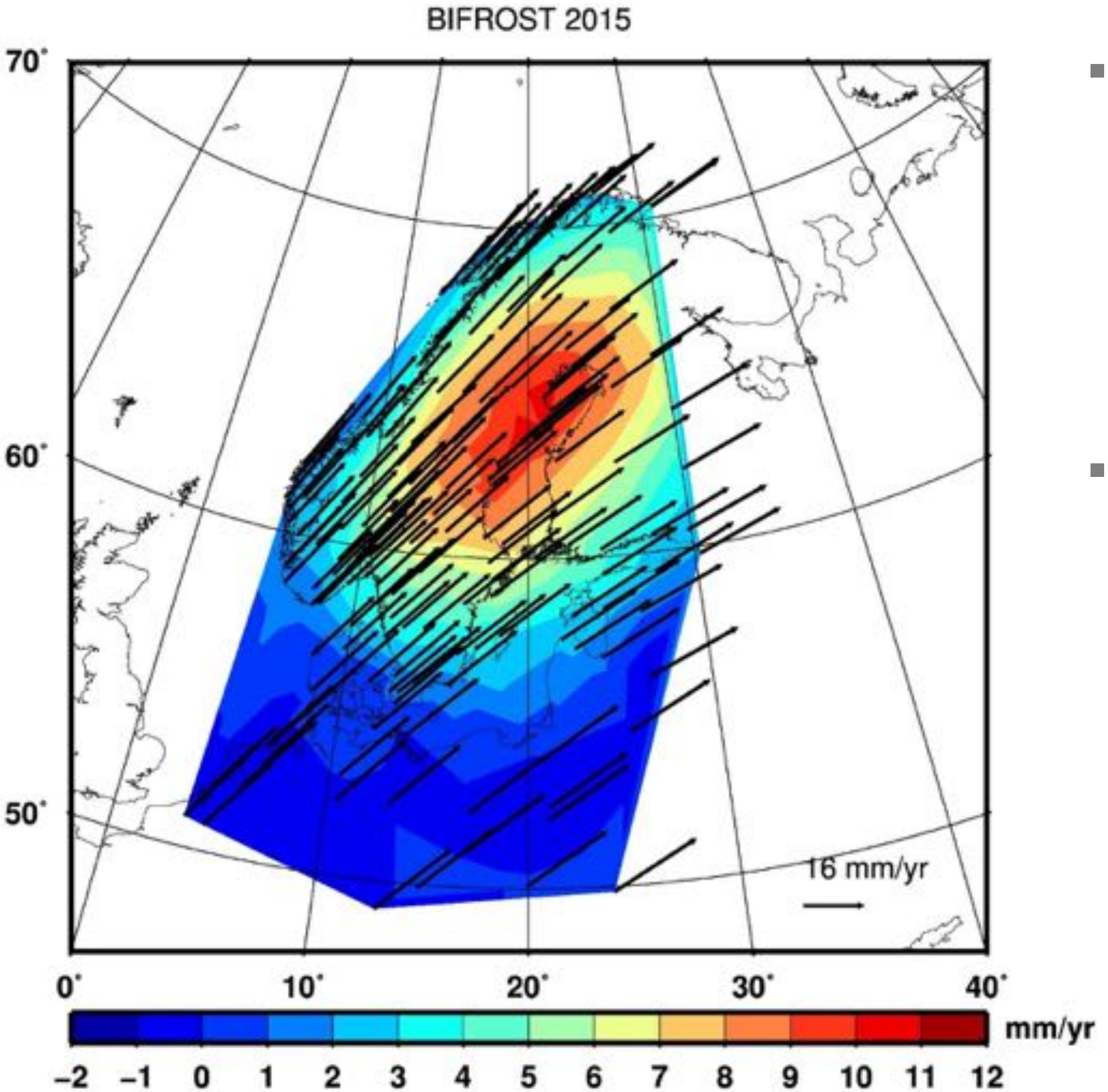
- Accuracy depends on the time span of all instruments in a network,
- A longer time span generally decreases the errors.

Calais et al. (2006)



- 5 years: 0.6 mm/a for tangential velocities
  2.0 mm/a for vertical velocities
  (Calais et al. 2006),
- 8 years: 0.2 mm/a for tangential velocities
  0.5 mm/a for vertical velocities
  (Calais et al. 2006, Lidberg et al. 2007).

Velocity field from the most recent BIFROST calculation

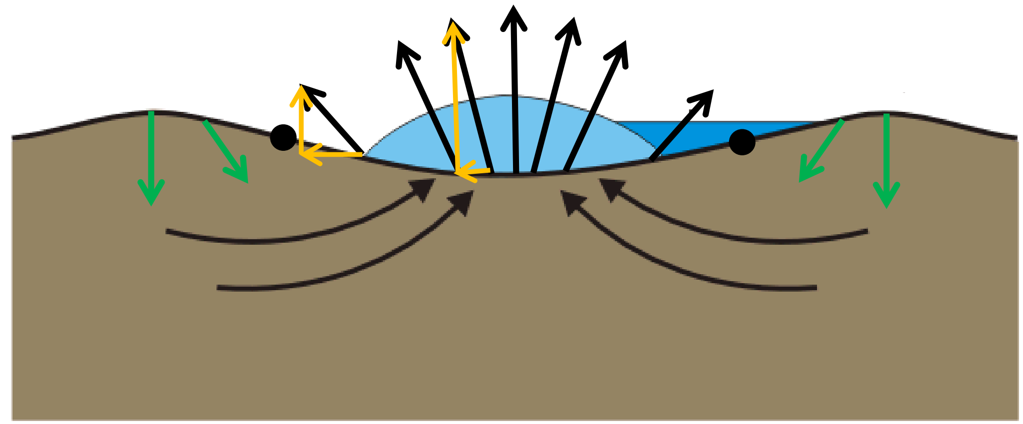


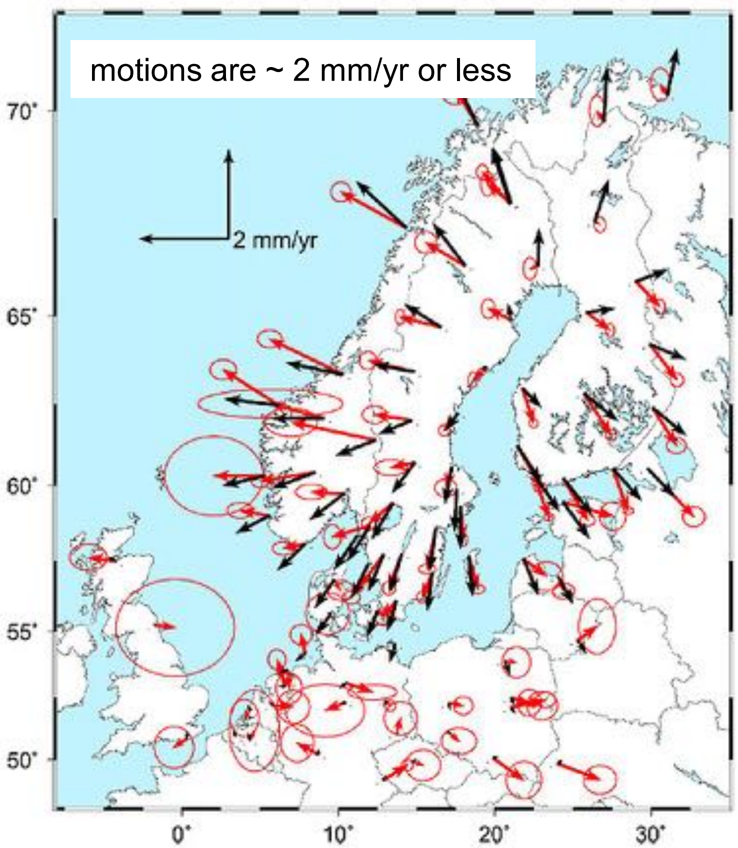
- Uplift > 1cm/a in the centre (somewhere between the cities of Umeå and Skellefteå), forebulge with 1-2 mm/a in northern Germany and Poland
- Horizontal motion generally 2-3 cm/a northeastward

Horizontal deformation due to GIA

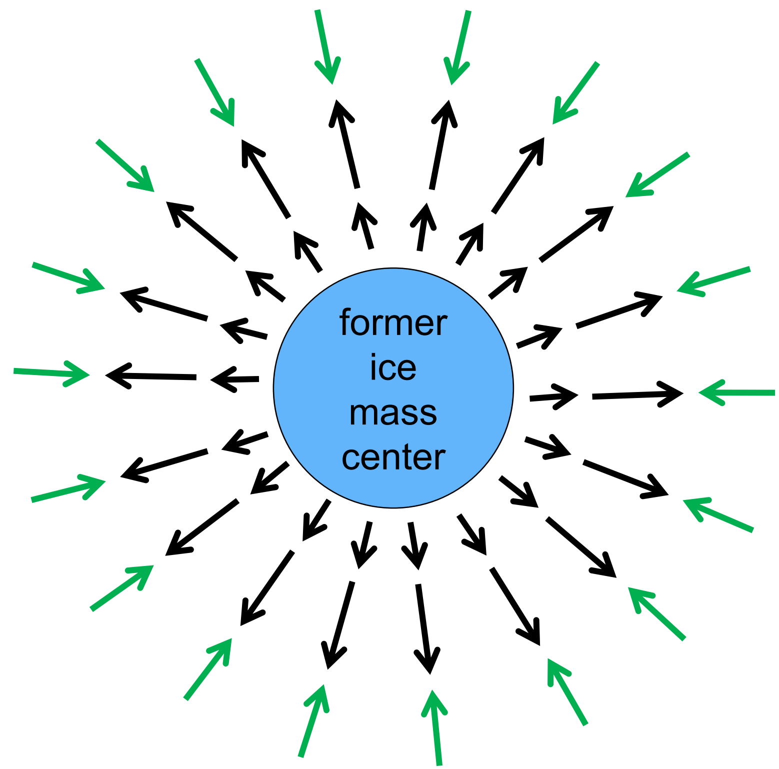
During deglaciation, crustal horizontal motions are radially away from the former ice mass center, and increase in magnitude away from the load.

In the forebulge region, motions are towards the former ice mass center.



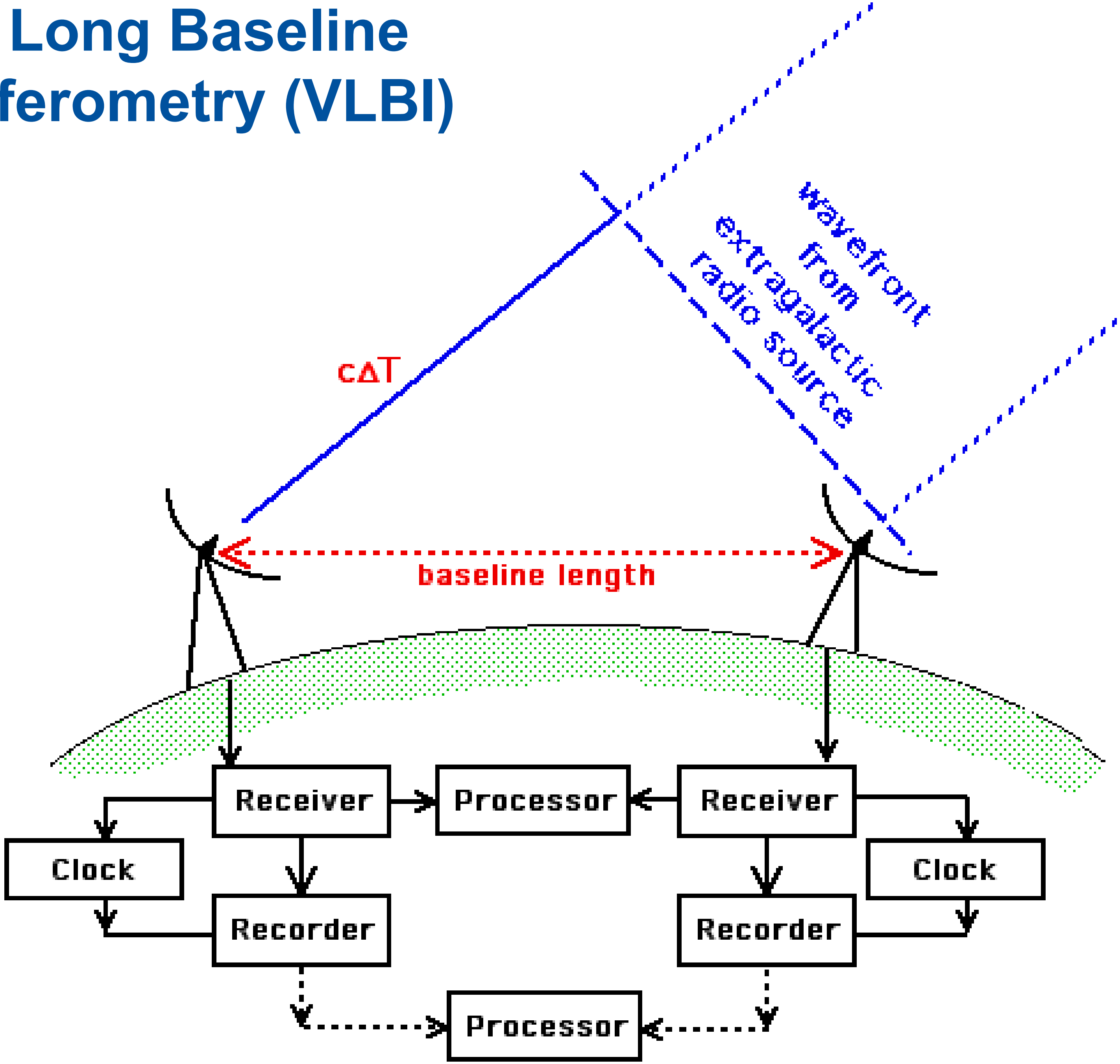


Fennoscandia BIFROST [Lidberg et al. (2010)]

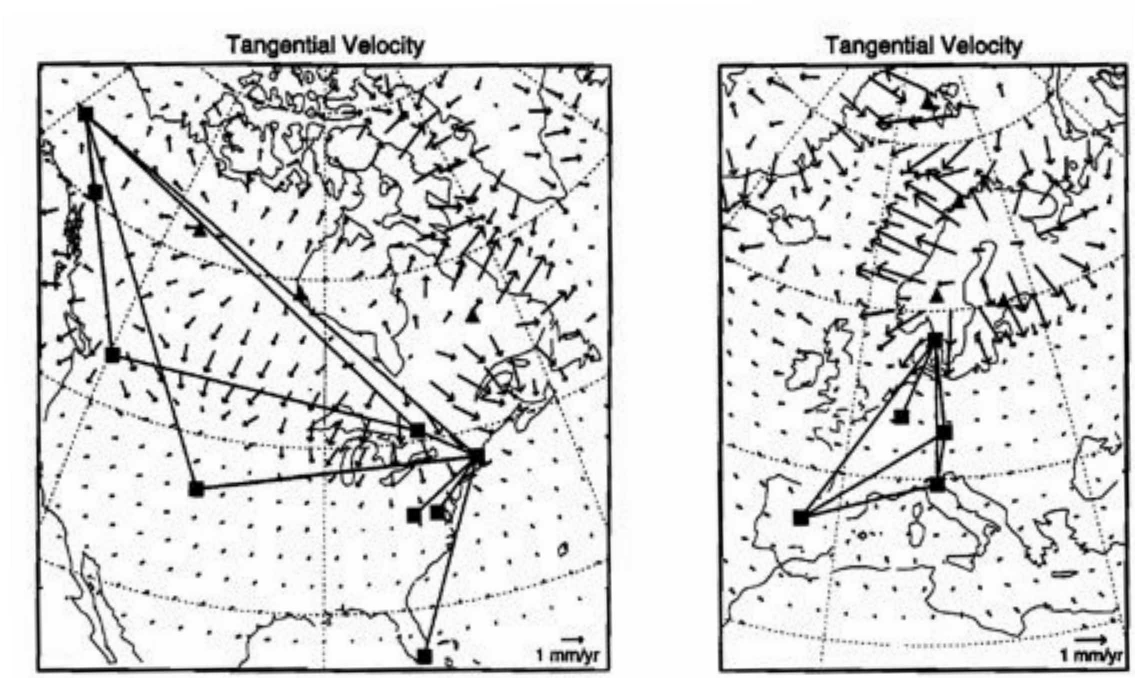


Very Long Baseline Interferometry (VLBI)

Very Long Baseline Interferometry (VLBI)



Very Long Baseline Interferometry (VLBI)



GIA model predictions of horizontal velocities

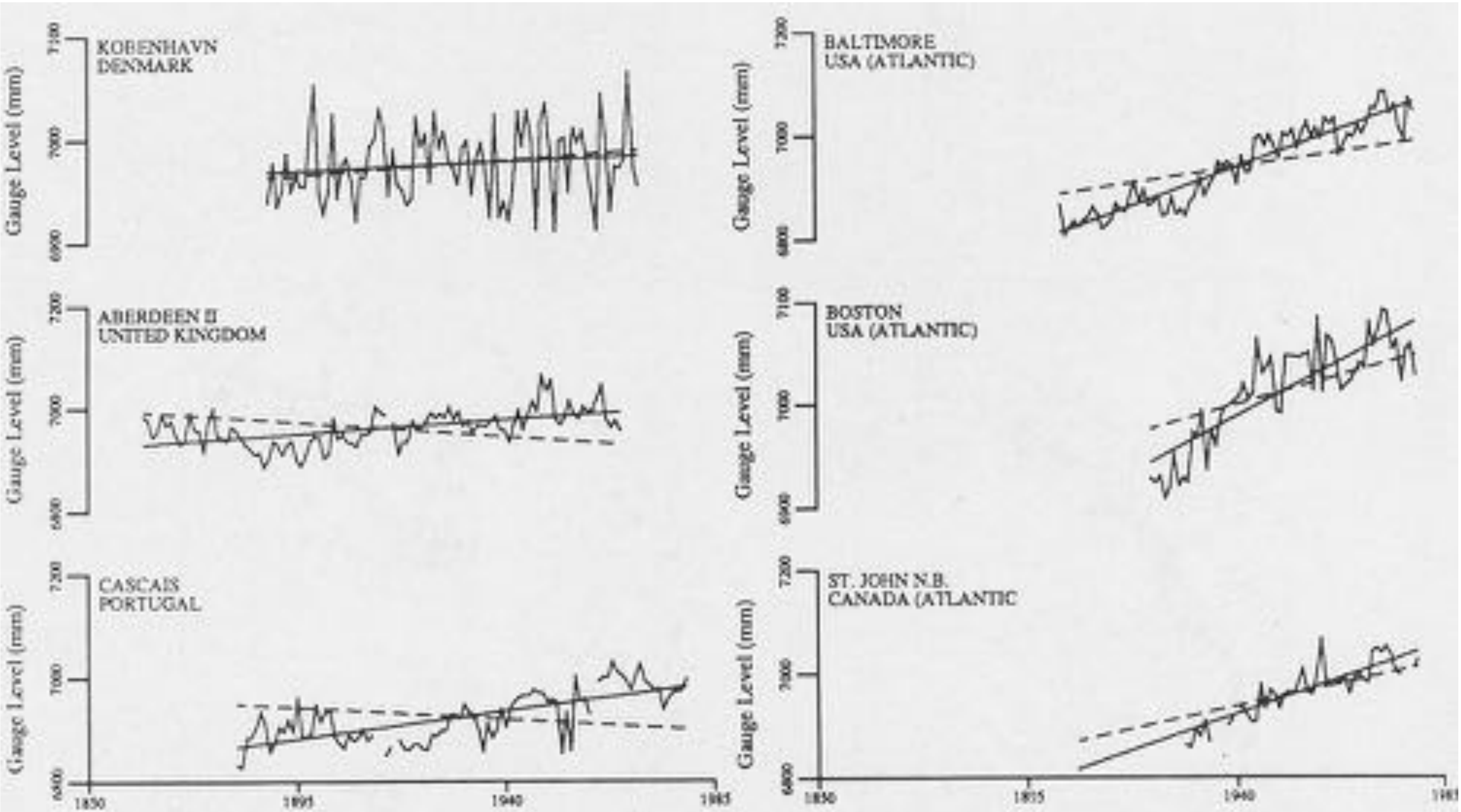
Table 2. Comparison between Observed and Predicted Rates of VLBI Baseline Length Change (mm/yr)

Baseline	Duration	GLB754 Obs. ± 2σ	ICE-3G Prediction
ALGO-GILC	1984.5-1991	3.6 ± 2.0	1.8
ONSA-WETT	1984-1991	–0.6 ± 0.6	-1.0
RICH-WEST	1984-1991	0.1 ± 0.4	-0.6

(James & Lambert 1993)

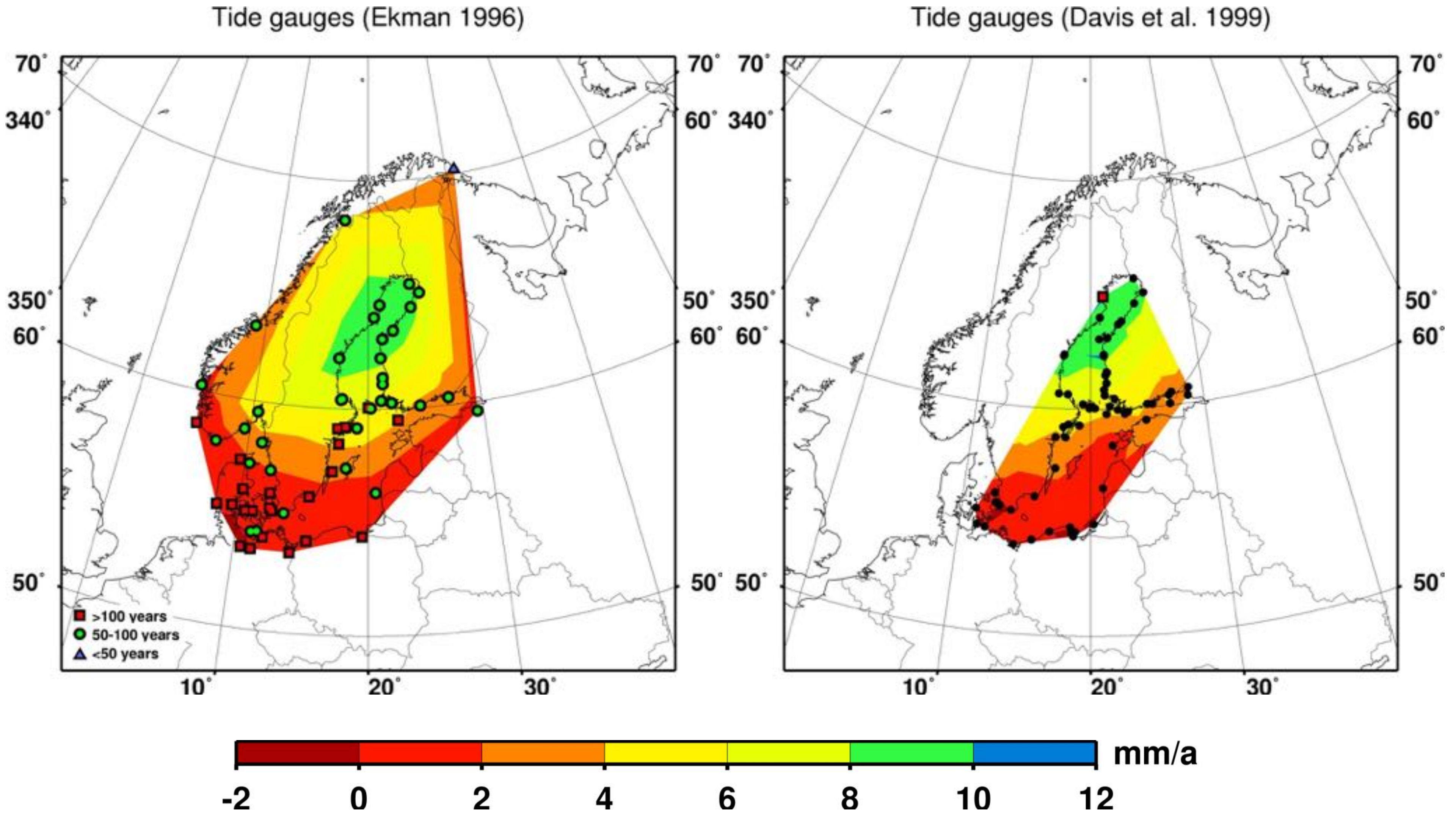
Annually averaged tide gauge record

(solid lines - best fits to data, dashed lines- due to GIA only)



(Peltier & Tushingham 1989)

Tide gauge & uplift rate



(Steffen and Wu 2011)

Tide gauge & uplift rate

$$\dot{S}_{tg} = -\dot{U} + \dot{T} + \dot{D} + \dot{S}_{var} + \dot{S}_{res}$$

$\dot{S}_{tg}$ = error-free tide-gauge rate

$\dot{U}$ = land-uplift rate from GPS (due to GIA & tectonics)

$\dot{T}$ = contribution due to thermal expansion

$\dot{D}$ = contribution due to recent deglaciation

$\dot{S}_{var}$ = annual & interannual variability

$\dot{S}_{res}$ = residual sea-level change

Satellite altimetry

Satellite altimetry & uplift rate

$$\dot{S}_{alt} = \dot{T} + \dot{D} + \dot{S}_{\mathrm{var}} + \dot{S}_{res} + \dot{S}_{drift}$$

$\dot{S}_{alt}$ = error free altimetry rate

$\dot{S}_{drift}$ = altimetry error

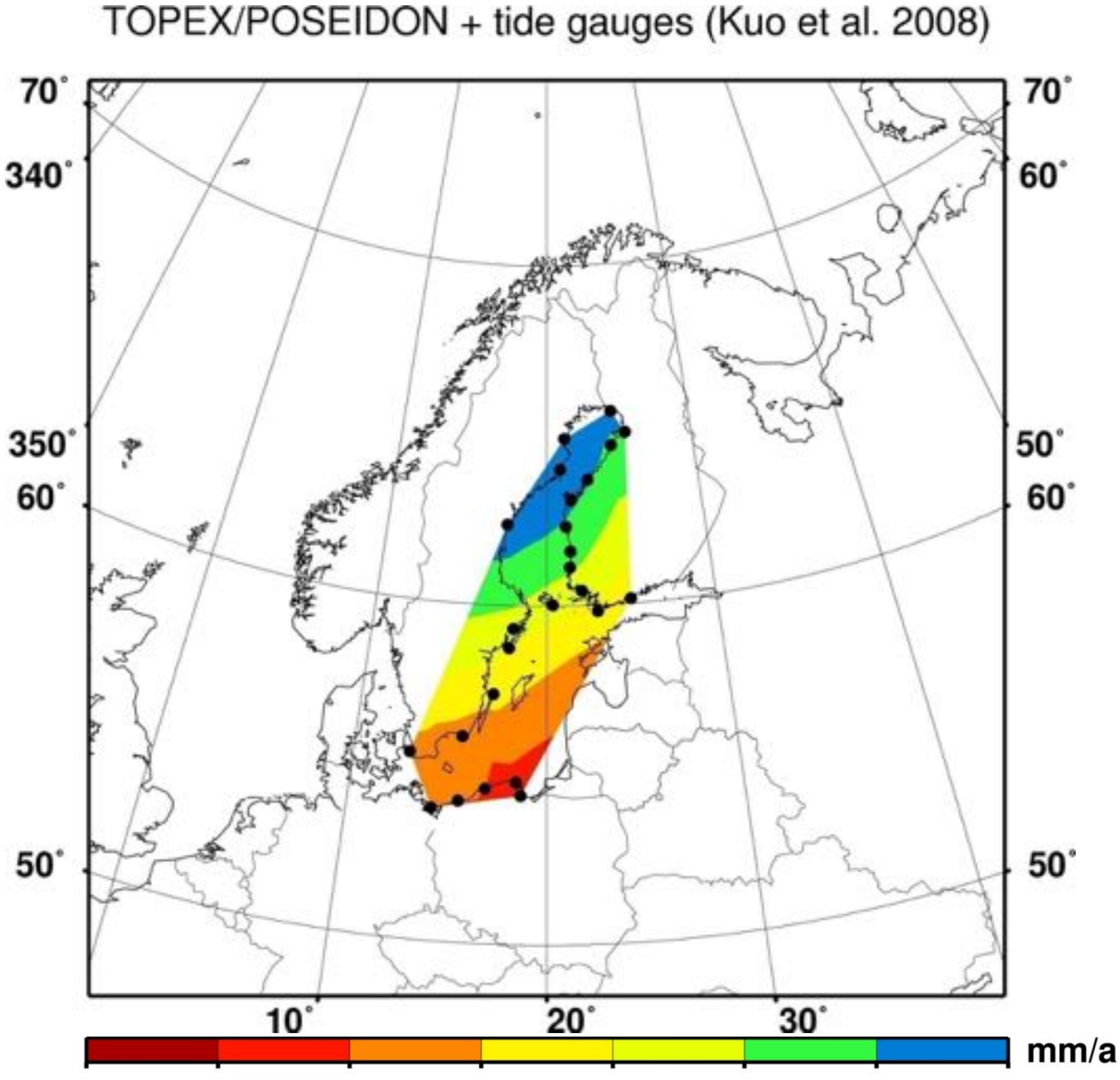
Combining altimetry & tide-gauge measurements:

$$\dot{S}_{tg} = -\dot{U} + \dot{T} + \dot{D} + \dot{S}_{var} + \dot{S}_{res}$$

land uplift rate can be obtained :

$$-\dot{U} = \dot{S}_{tg} - \dot{S}_{alt} + \dot{S}_{drift}$$

Satellite altimetry & uplift rate

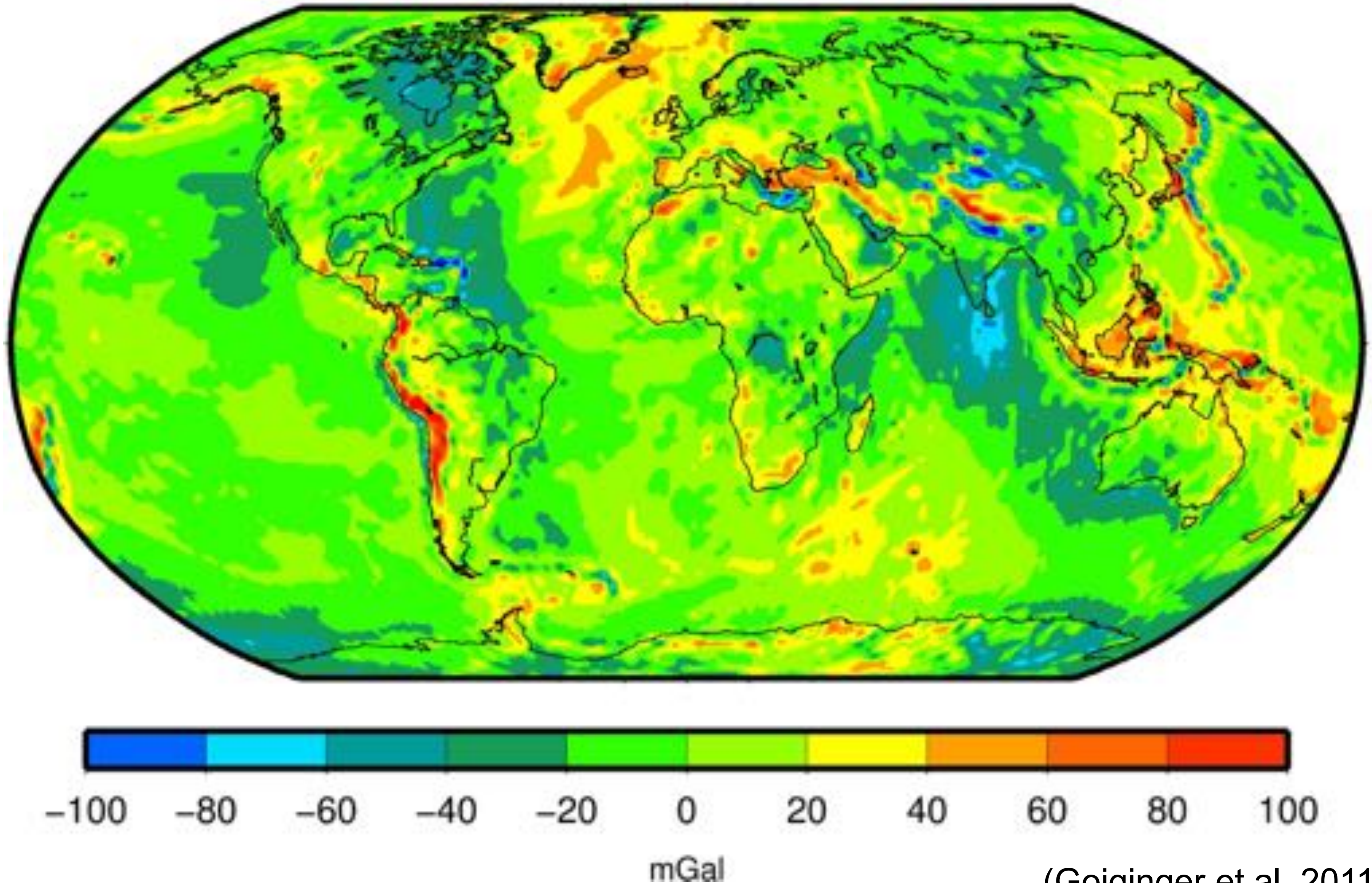


(Steffen and Wu 2011)

Gravimetry

Static
Time-variable
Relative, absolute, super-conducting

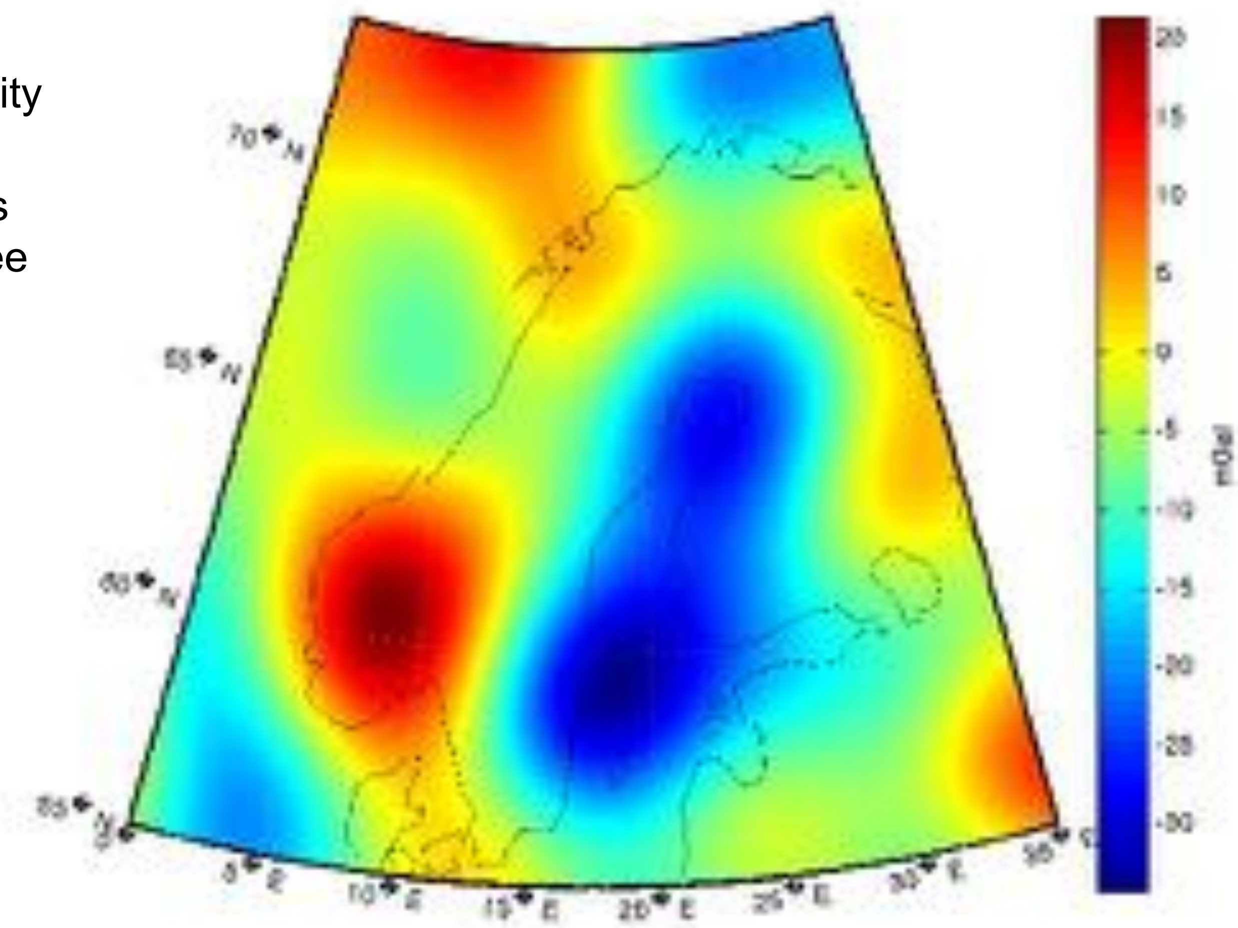
GOCO02S gravity field anomalies



(Goiginger et al. 2011)

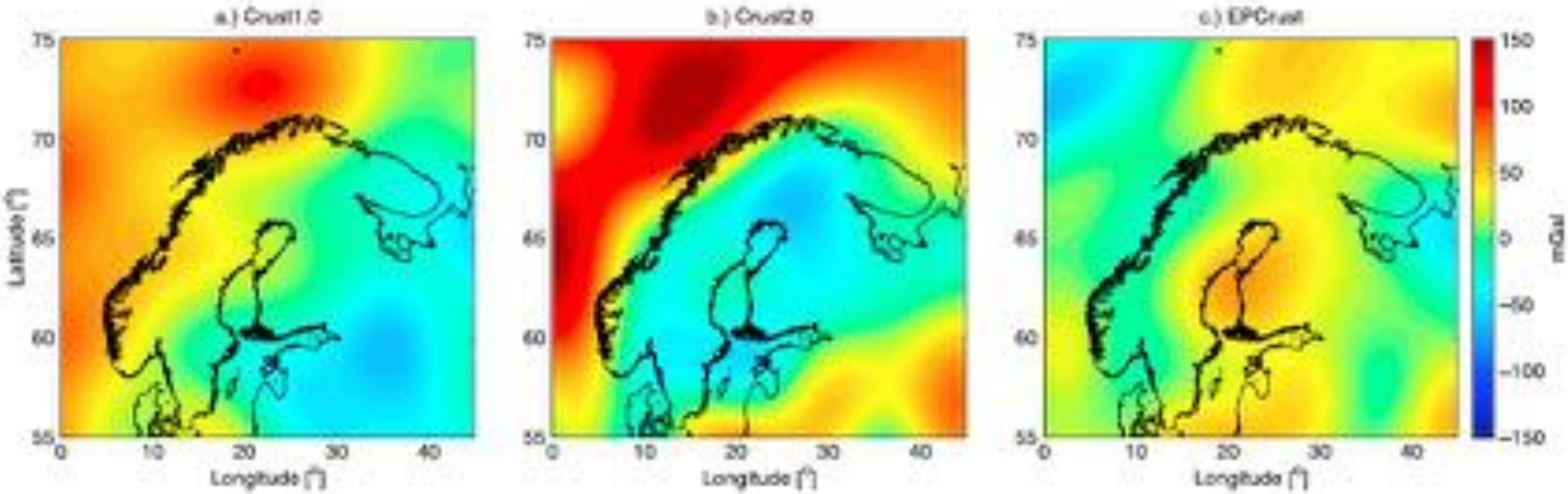
GIA in the static gravity field

- Satellite-based gravity field EIGEN-GL04C
- Spherical harmonics domain 10-60 degree (300-3000km)



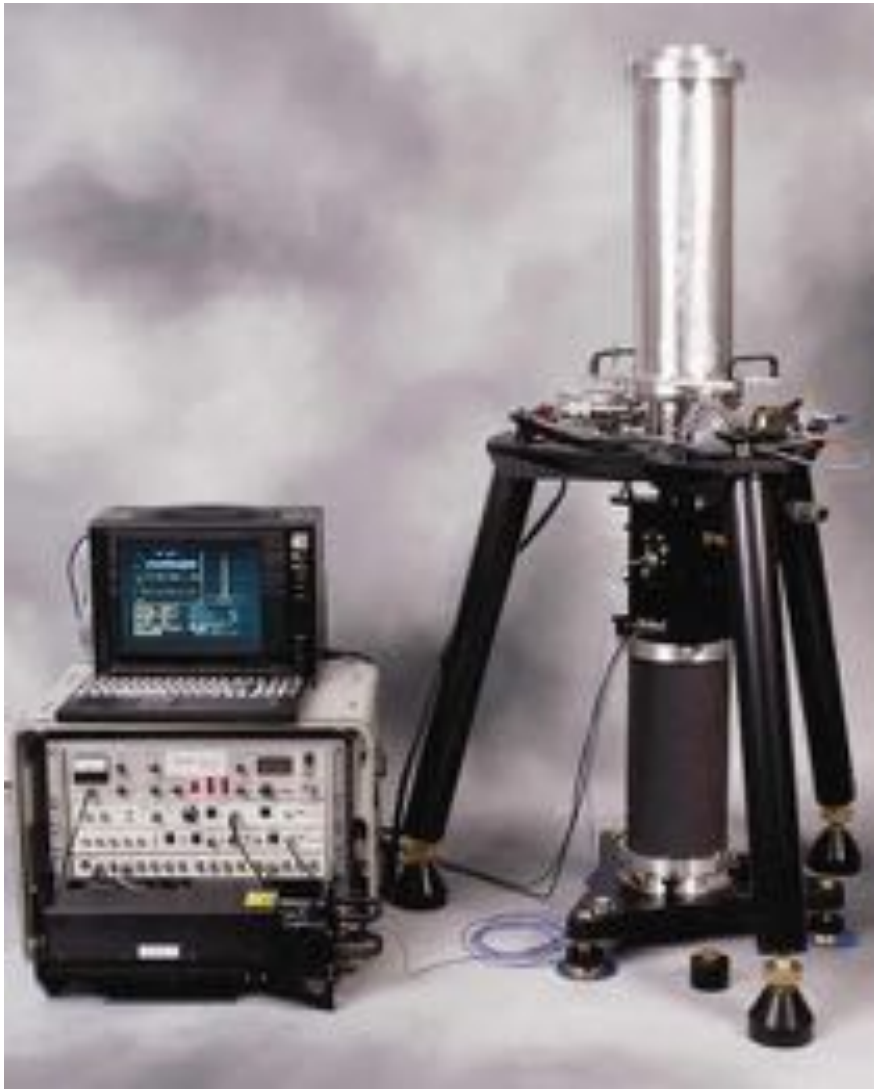
(Figure courtesy of Wouter van der Wal)

GIA in the static gravity field

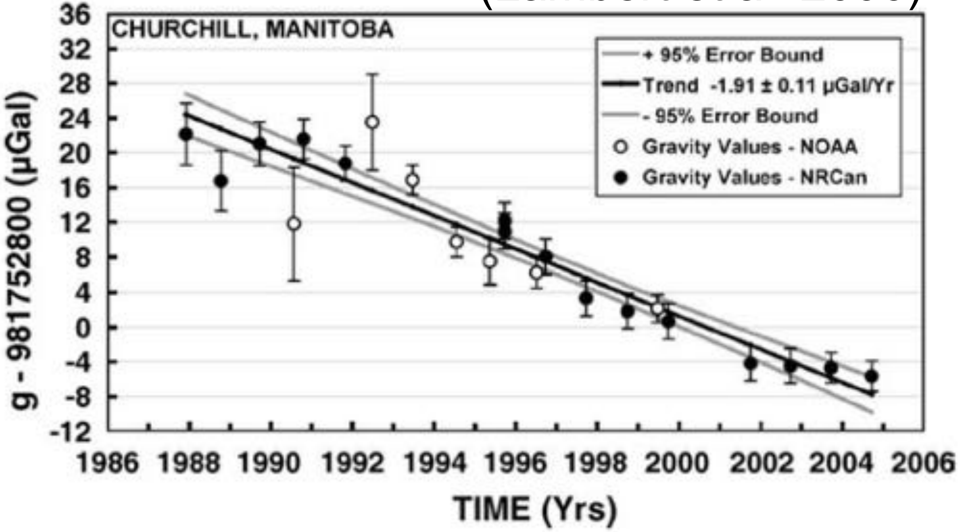


(Root et al., 2015)

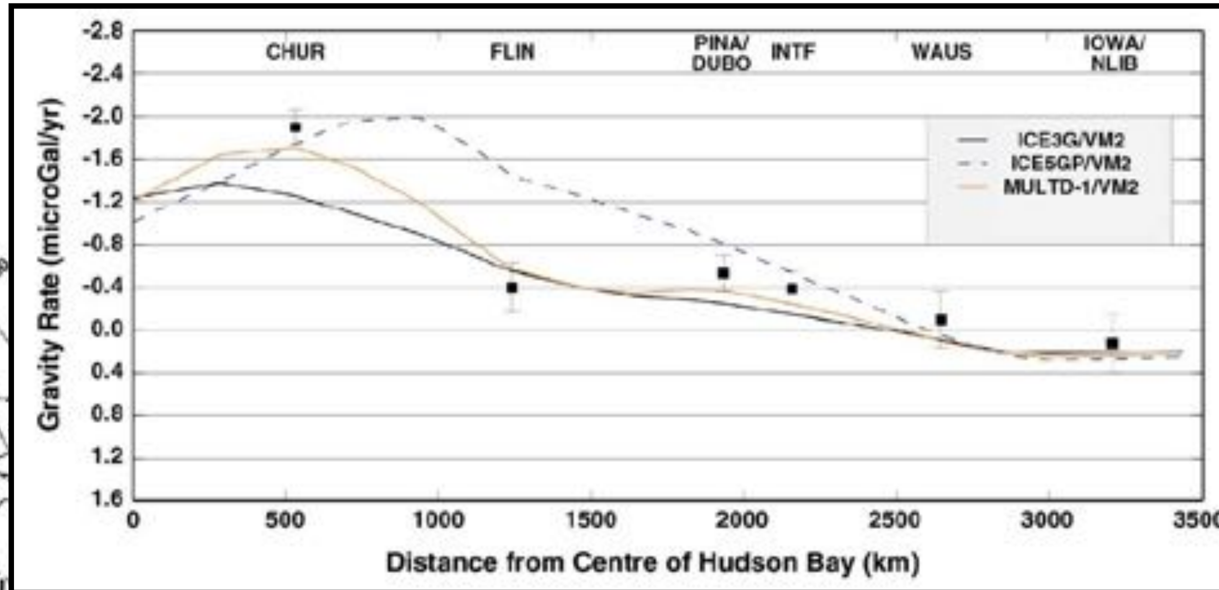
Absolute Gravimeter FG5 & measured rates of change in gravity

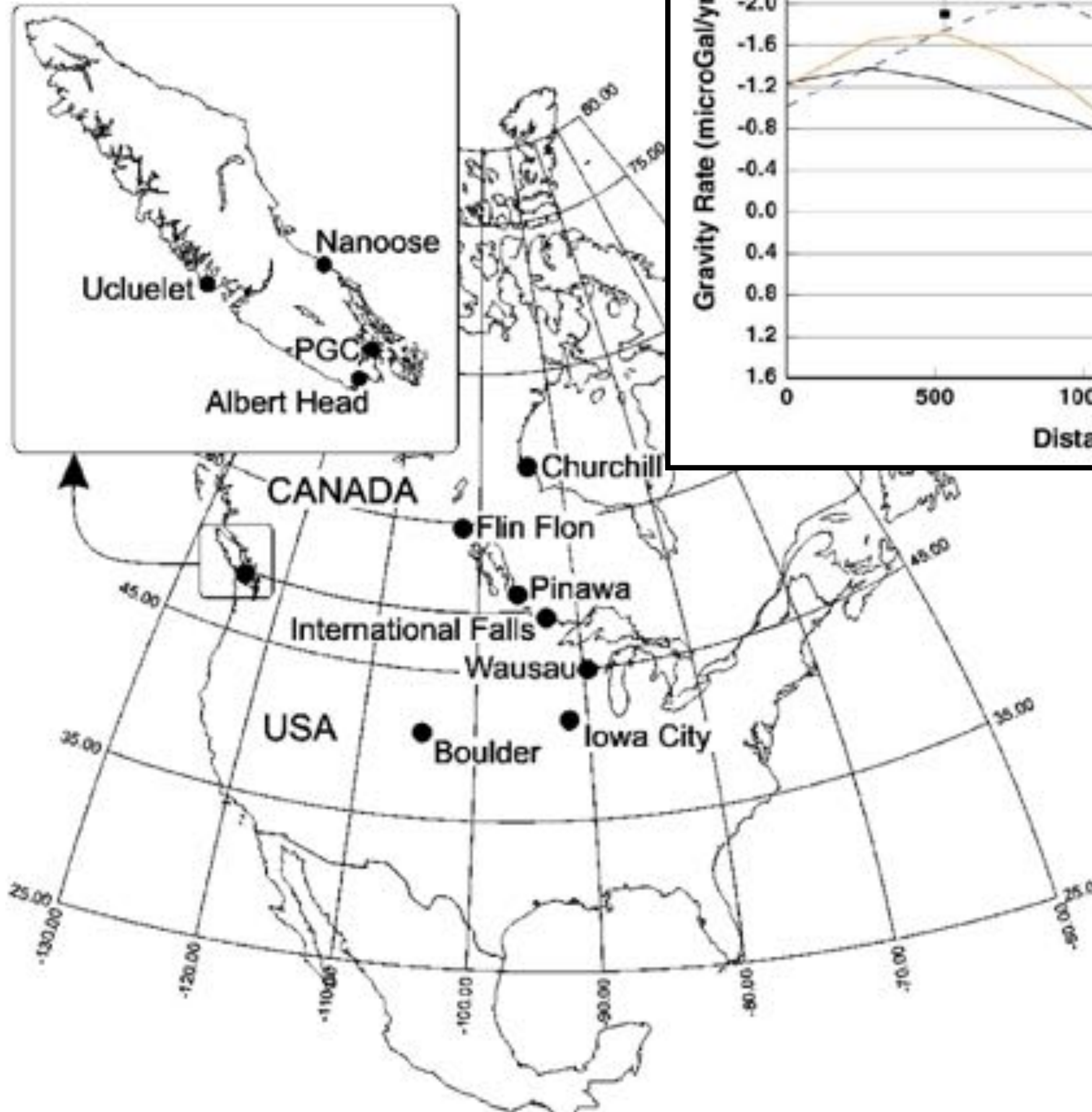


(Lambert et al. 2006)



Measured rates of change in gravity

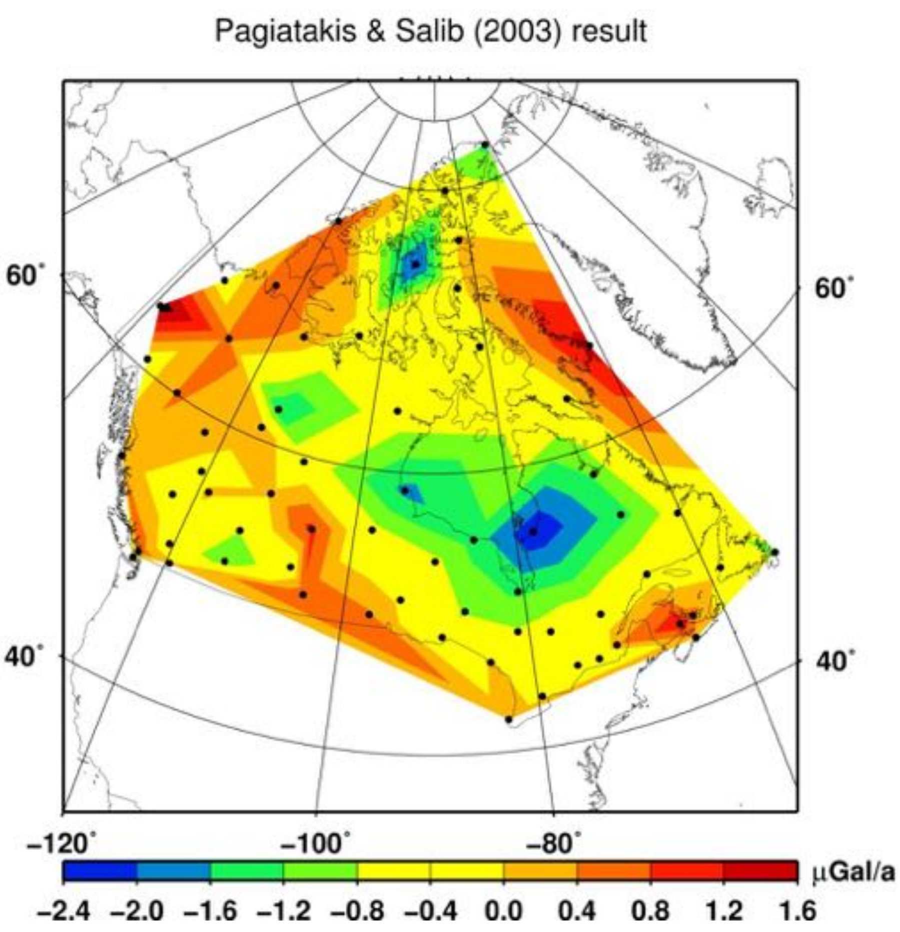




(Lambert et al. 2006)

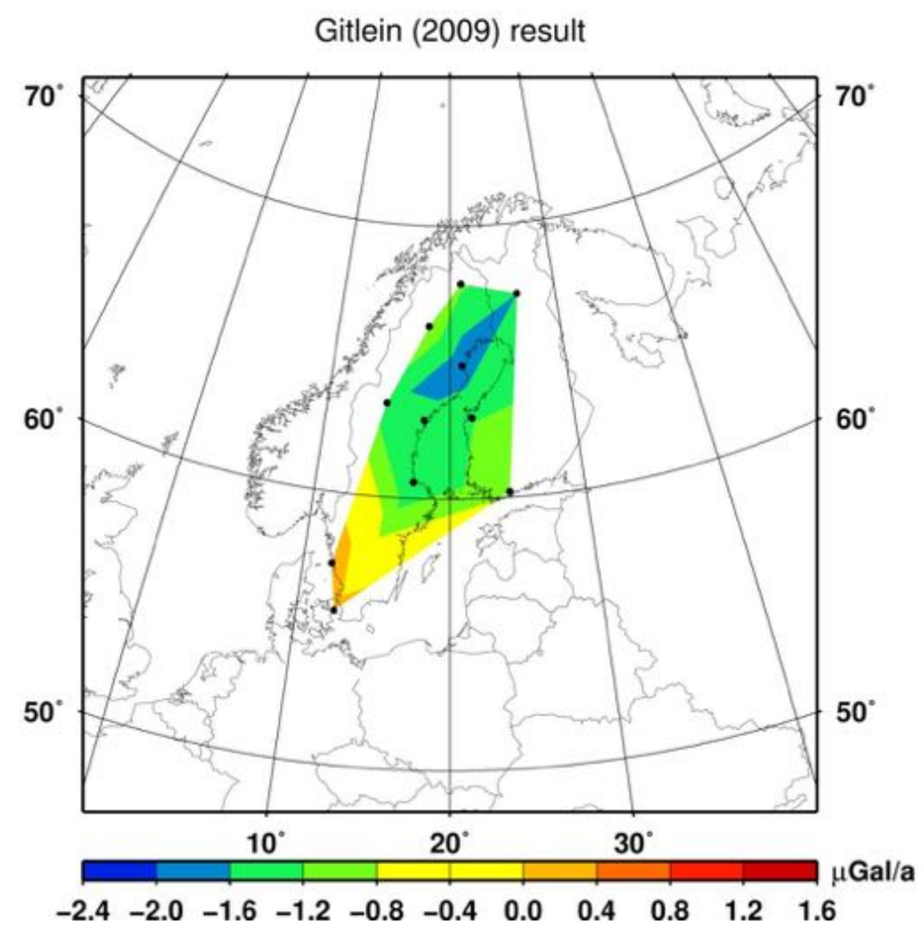
Vertical gravity rate from gravity measurements in Canada and Fennoscandia

Canada



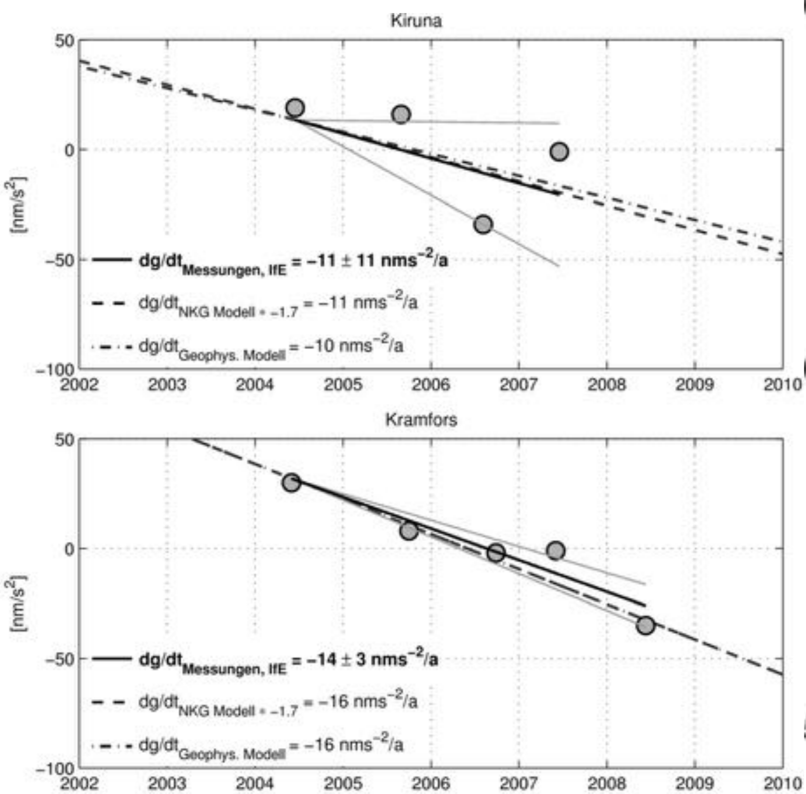
Absolute and relative gravimetry

Fennoscandia

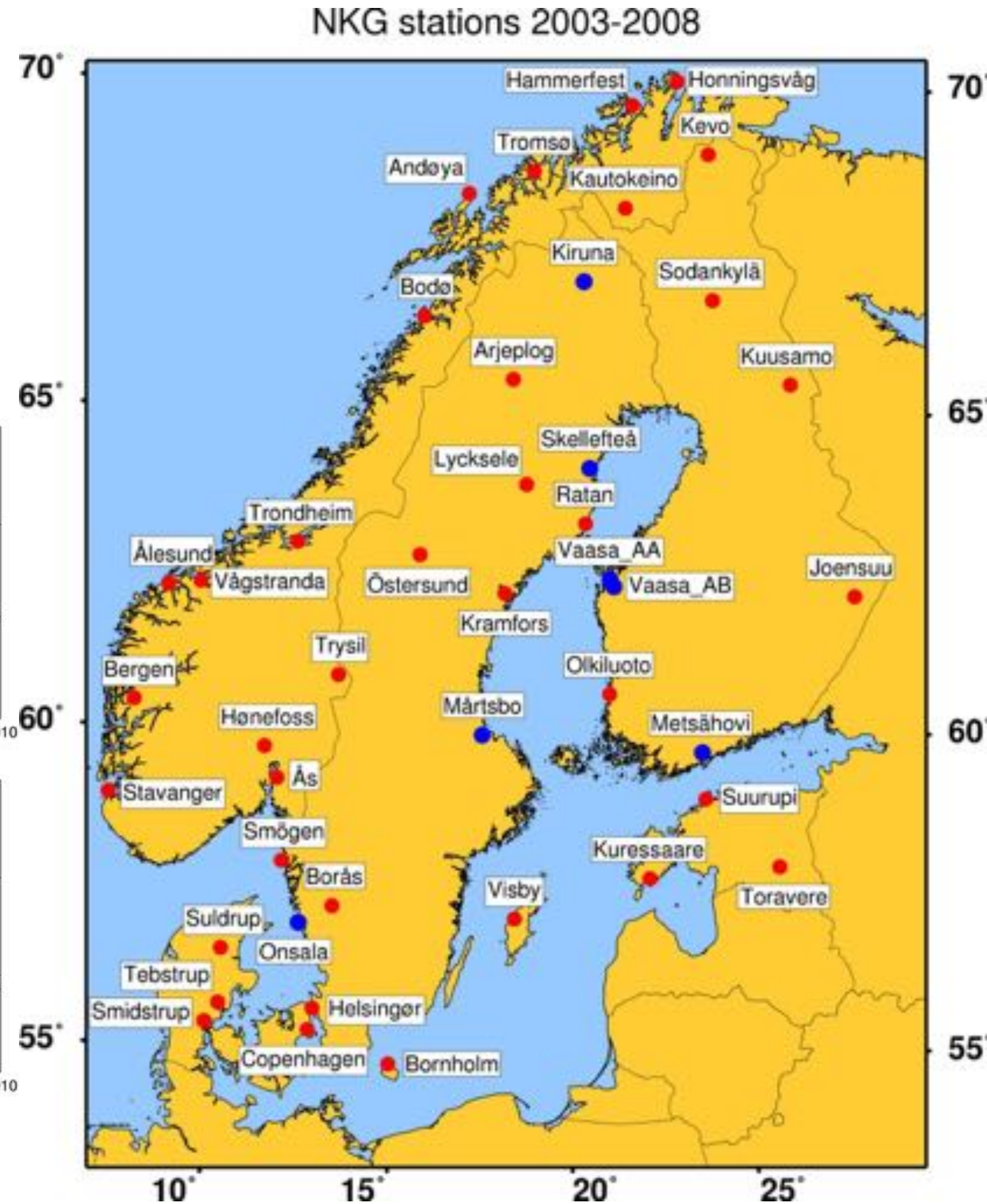


Absolute gravimetry

Absolute gravity stations in Fennoscandia

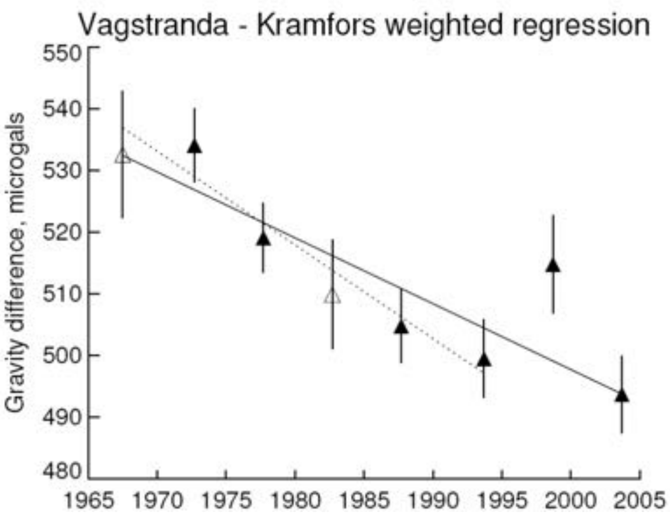


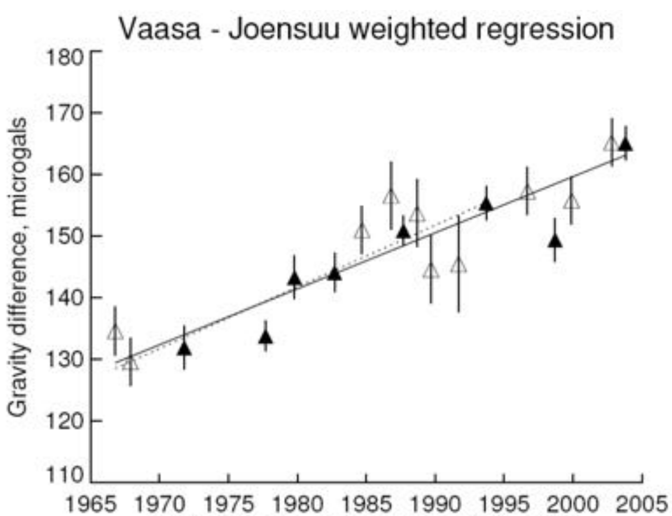
(Gitlein 2009)



(Steffen and Wu 2011)

Relative gravity measurements in Fennoscandia

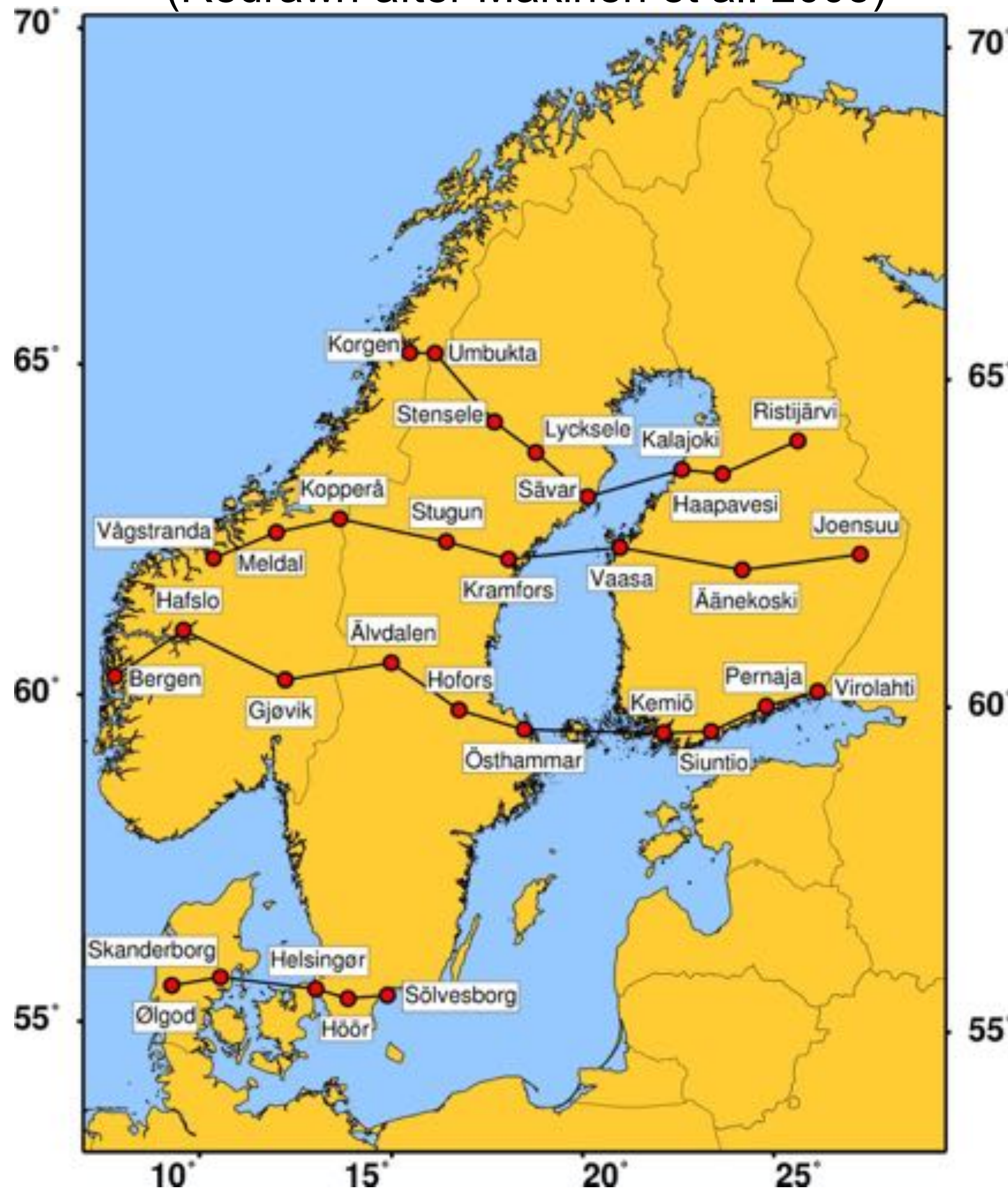




Solid symbols = five or more gravimeters
Dotted line = last published

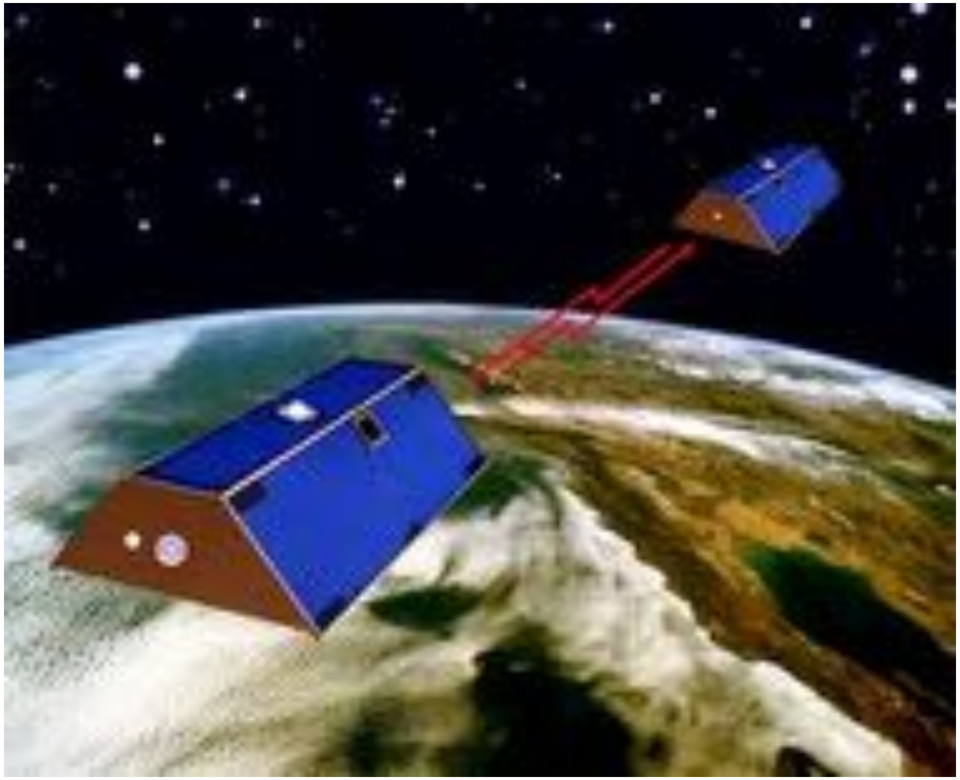
(Mäkinen et al. 2005)

(Redrawn after Mäkinen et al. 2005)



(Steffen and Wu 2011)

GRACE:
Gravity Recovery And Climate Experiment

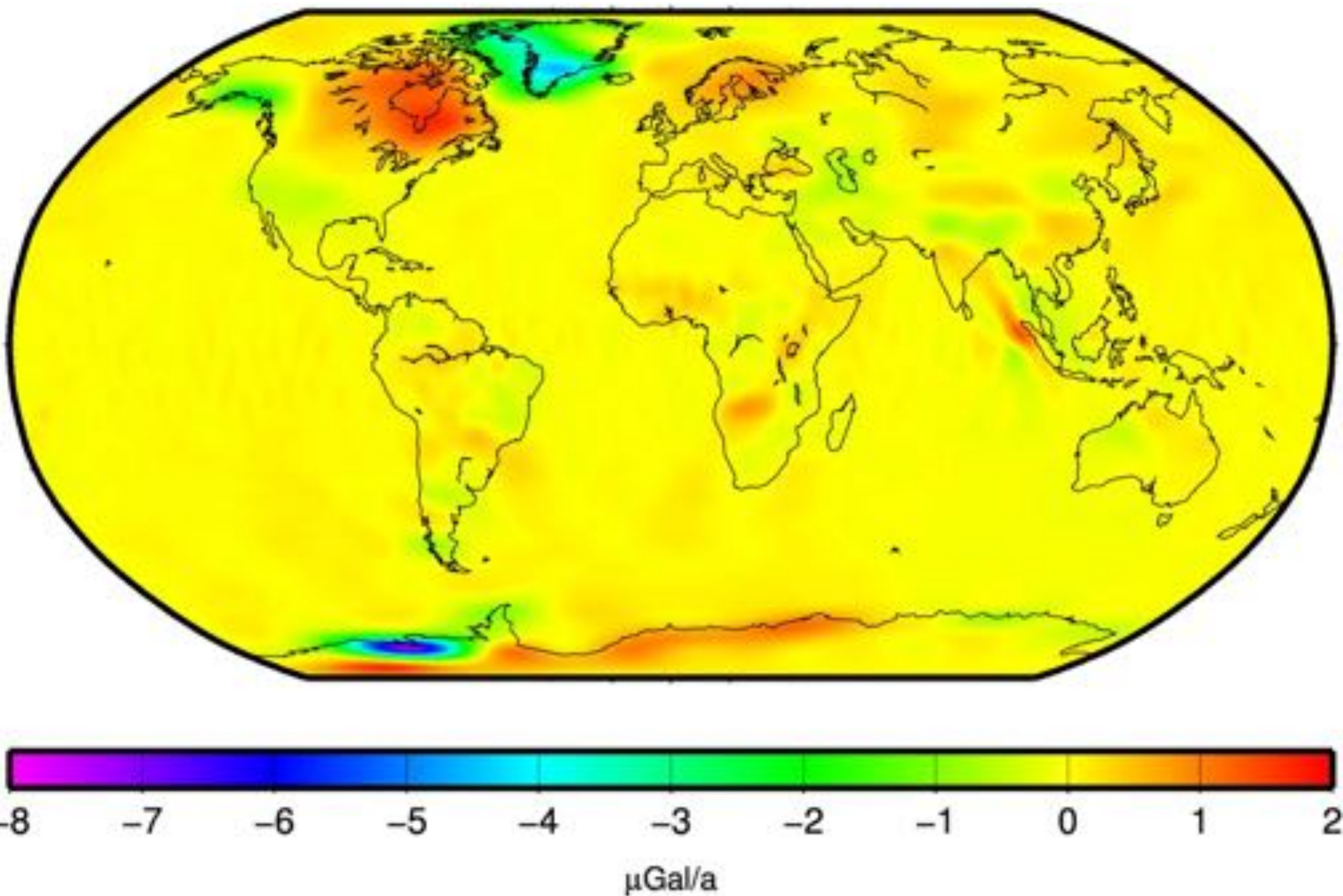


Two identical space crafts flying about 220 kilometers apart in a polar orbit 500 kilometers above the Earth

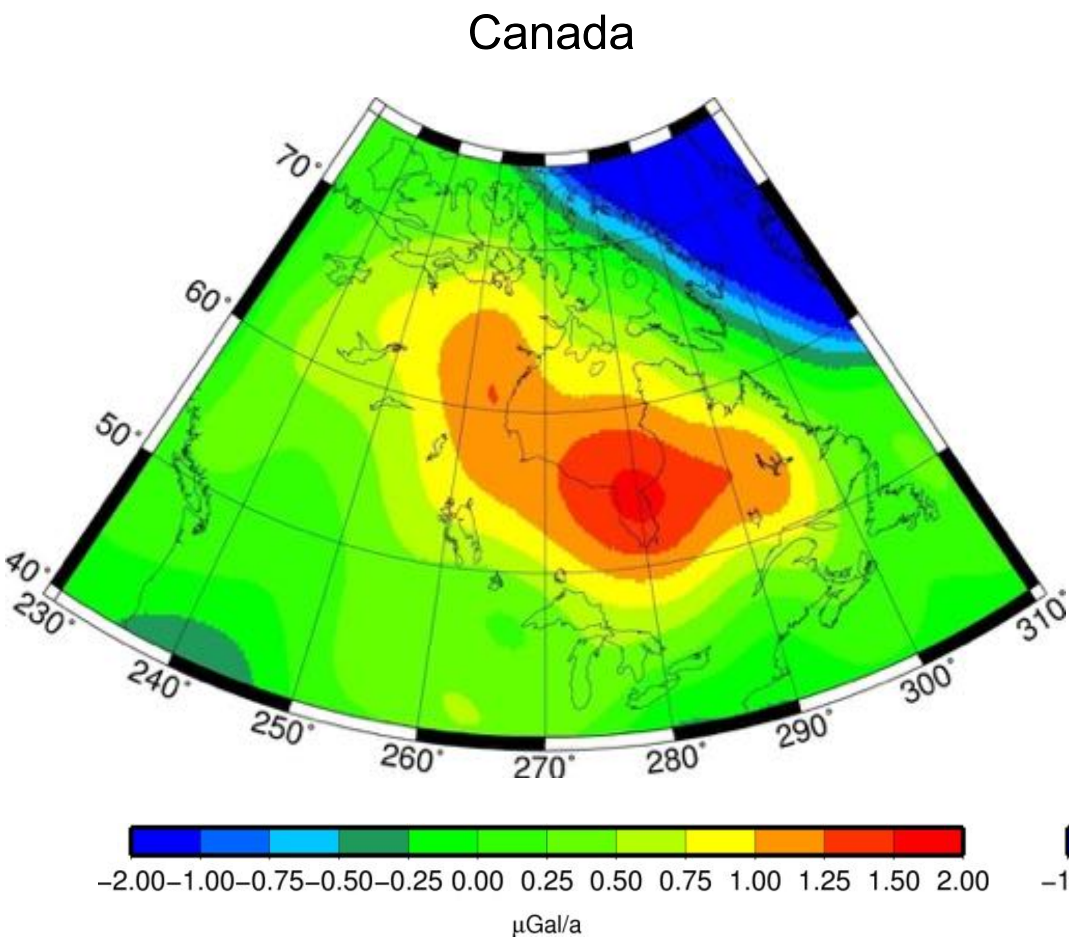
Map the Earth's gravity fields by using GPS and microwave ranging system

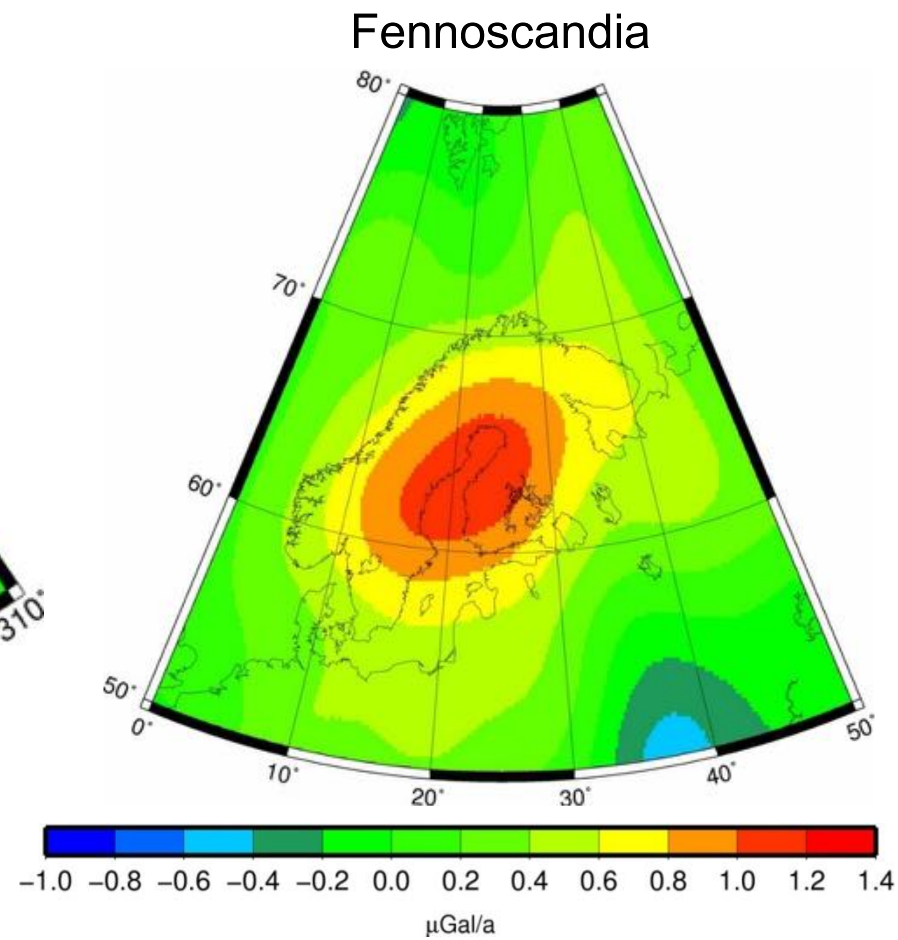
Study gravity variations due to distribution & flow of mass within the Earth & surrounding

GRACE observation, trend after post-processing



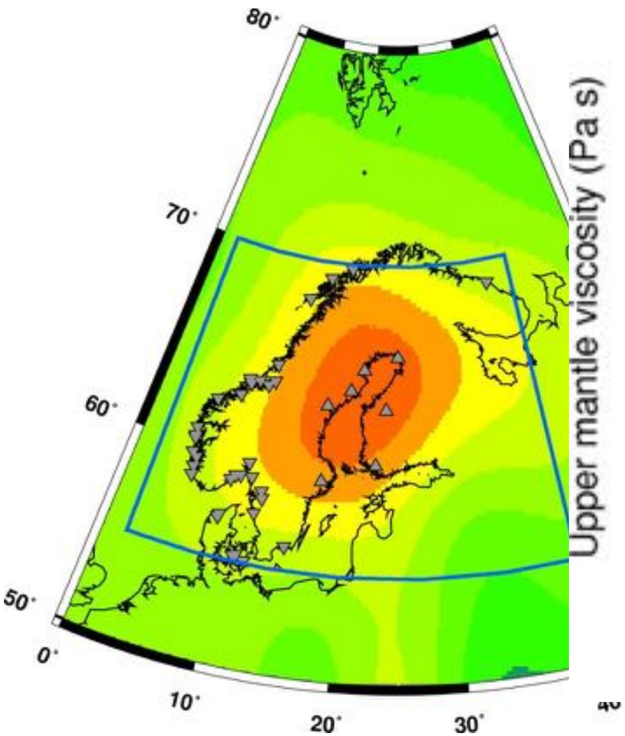
Vertical gravity rate from GRACE in Canada and northern Europe

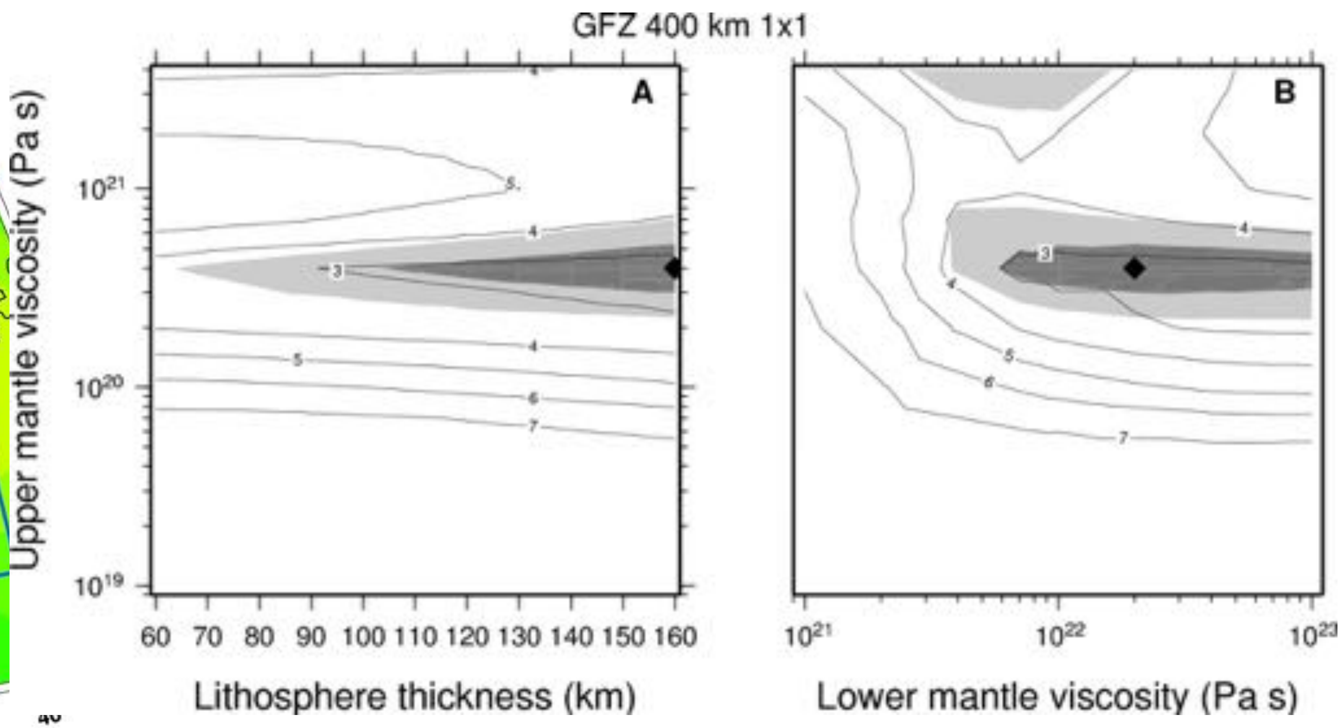




GFZ RL05, 335 km Gaussian, d/o 60, 01/2003-02/2013

Determination of 1D Earth structure



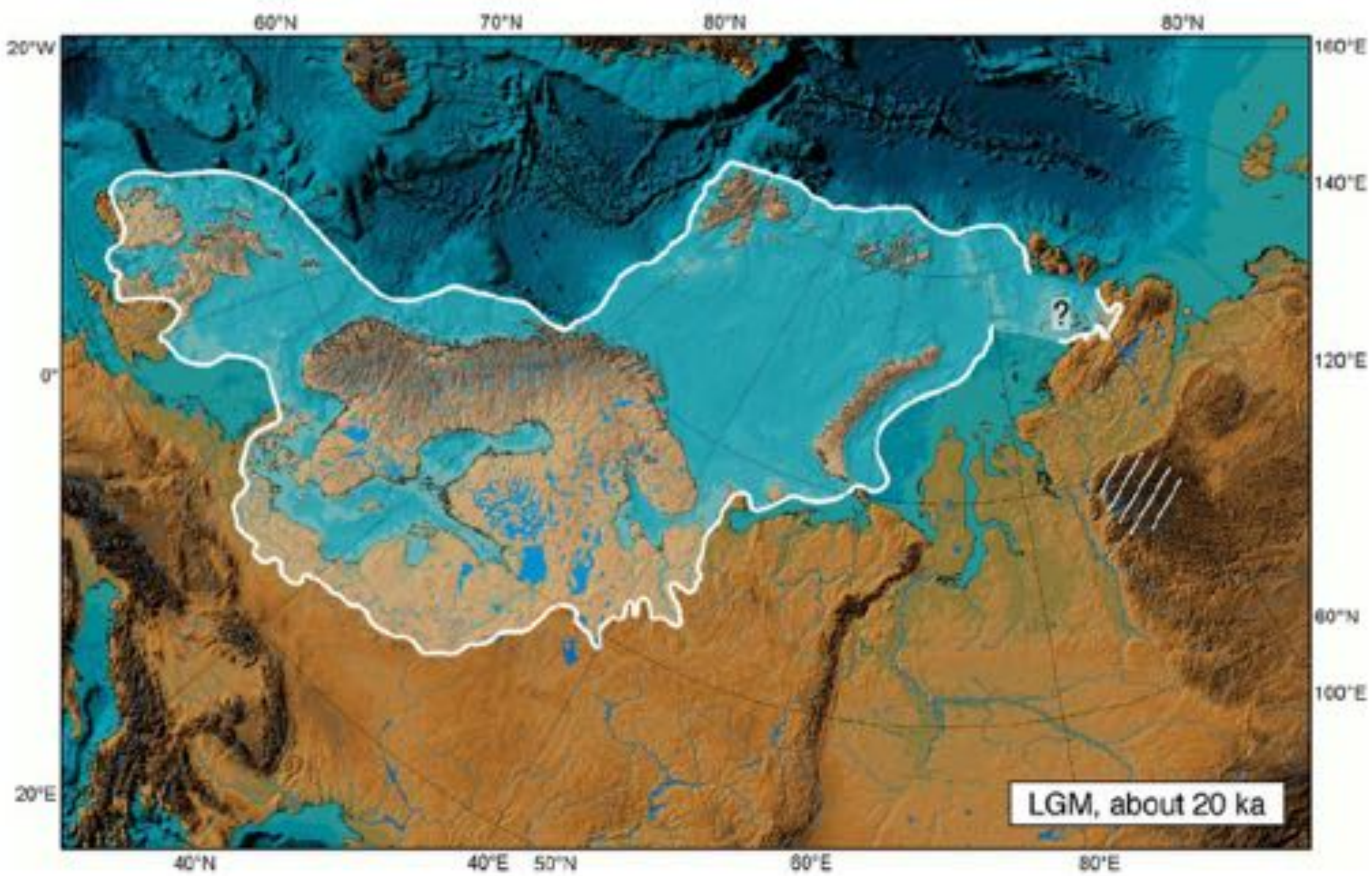


Diamond: best model; Dark gray: σ_1; Light gray: σ_2

GRACE:
1D Model parameters
(Steffen et al. 2010, GJI):
h_{lith} = 160 km
v_{UM} = 4 x 10^{20} Pas
v_{LM} = 2 x 10^{22} Pas

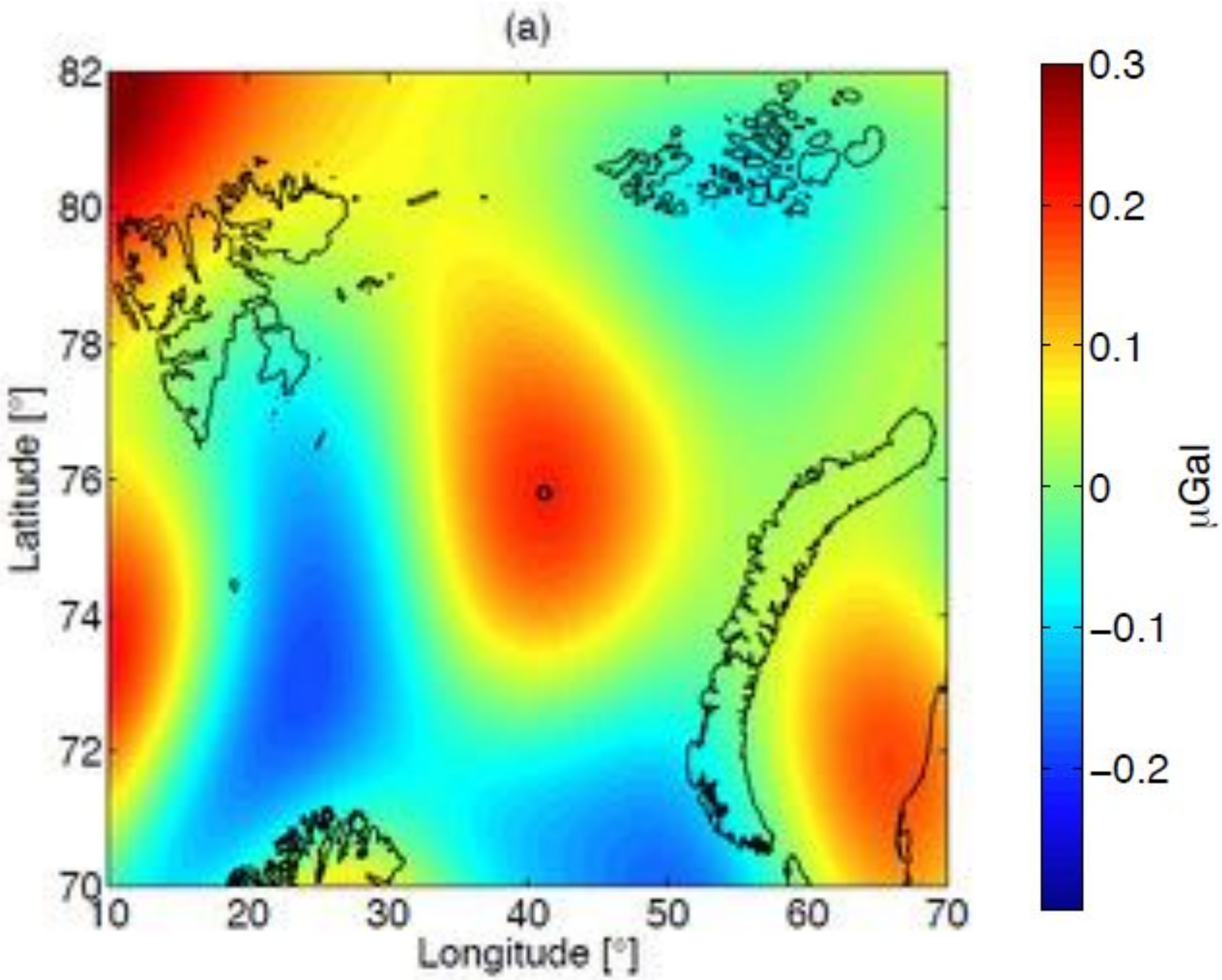
Sea-level data:
1D Model parameters
(Steffen and Kaufmann 2005, GJI):
h_{lith} = 120 km
v_{UM} = 4 x 10^{20} Pas
v_{LM} = 10^{23} Pas

GRACE observes GIA in the Barents Sea



Svendsen (2004)

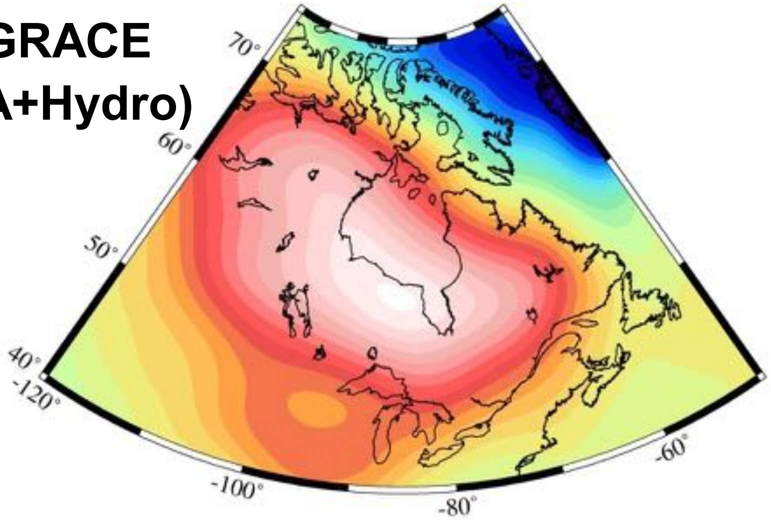
GRACE observes GIA in the Barents Sea



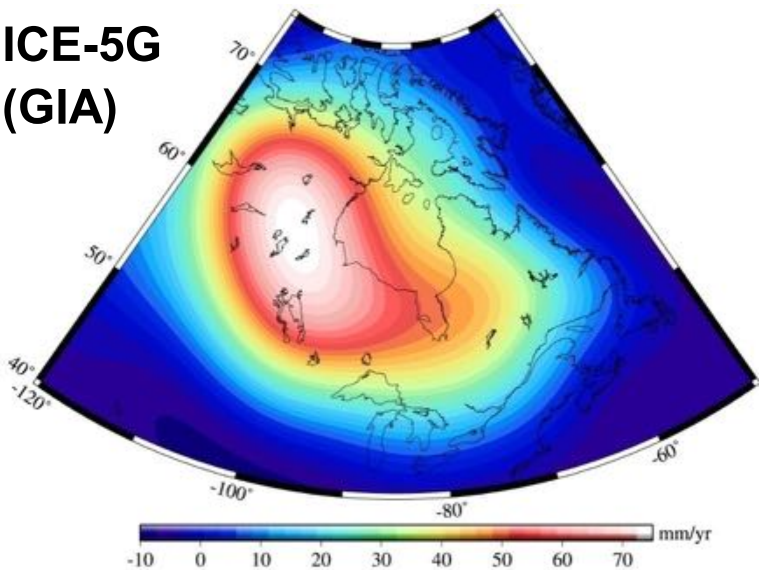
Root et al. (GRL, 2015)

Background: water storage from GRACE

GRACE (GIA+Hydro)

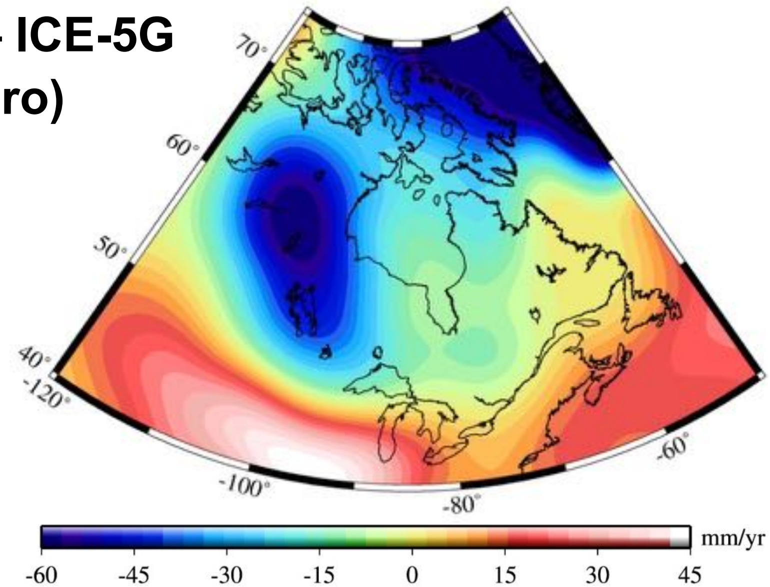


ICE-5G (GIA)



Common GIA correction using ICE-5G

GRACE – ICE-5G (Hydro)

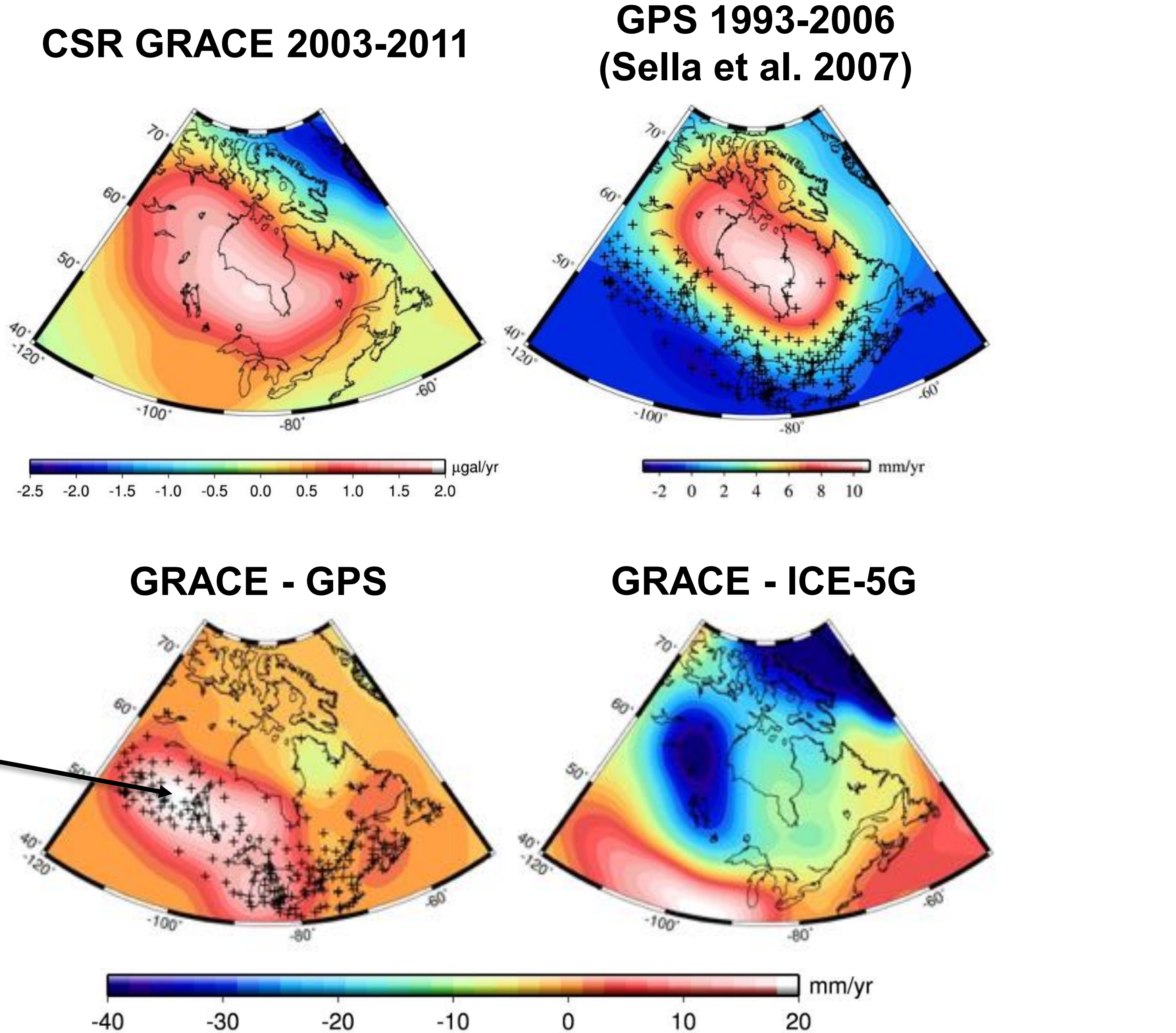


(Wang et al. 2013, Nature Geosci.)

Hydrological trend in North America

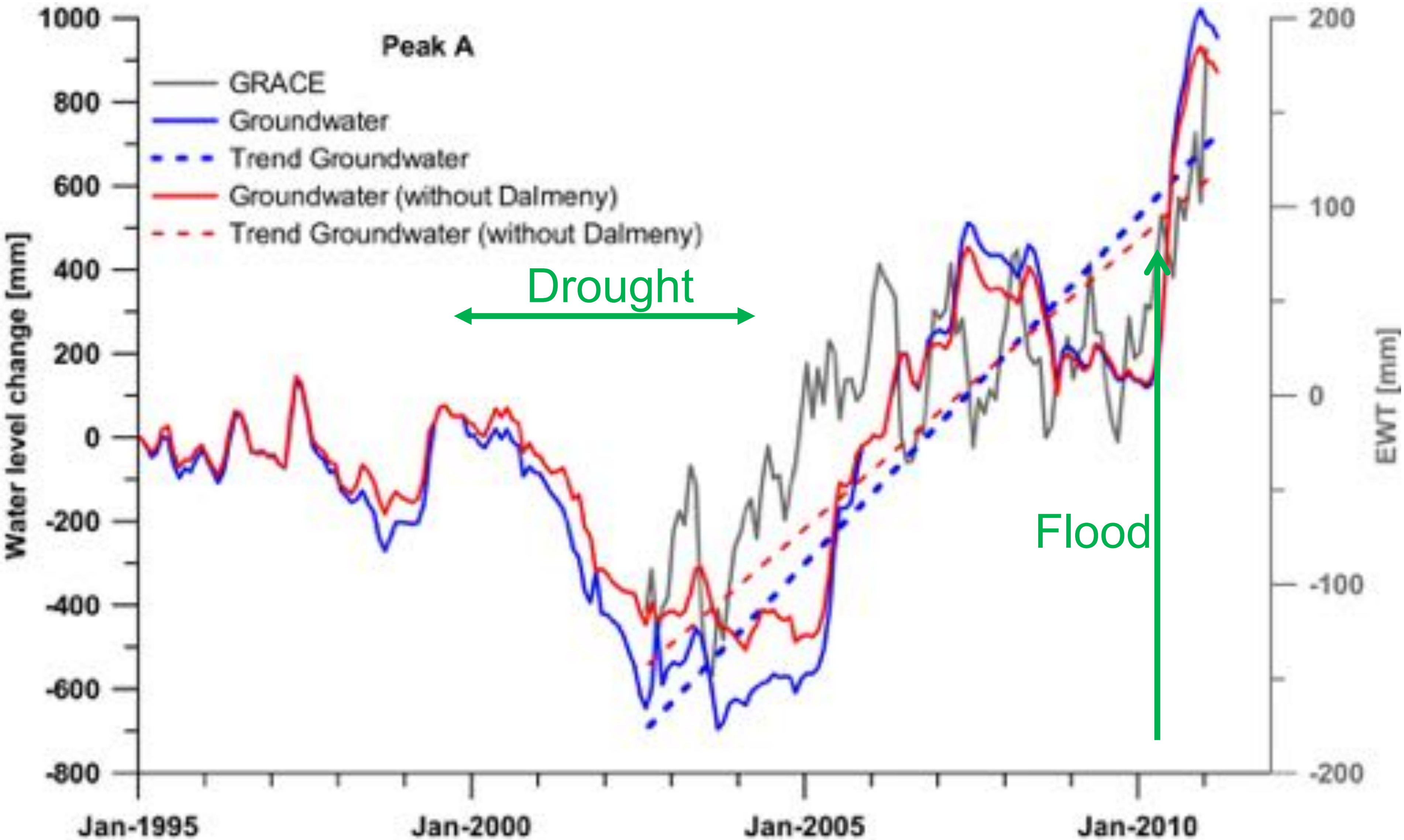
GIA correction using GPS-observed GIA

Peak A



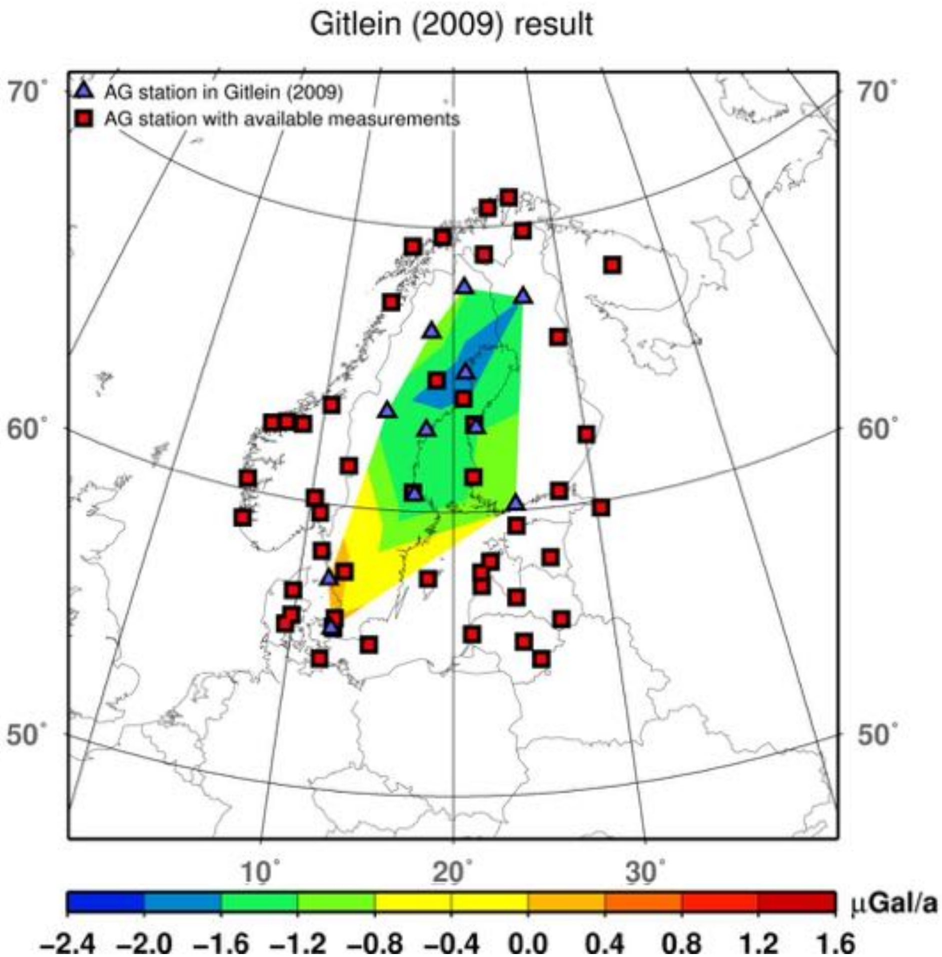
(Wang et al. 2013, Nature Geosci.)

Averaged groundwater vs. GRACE

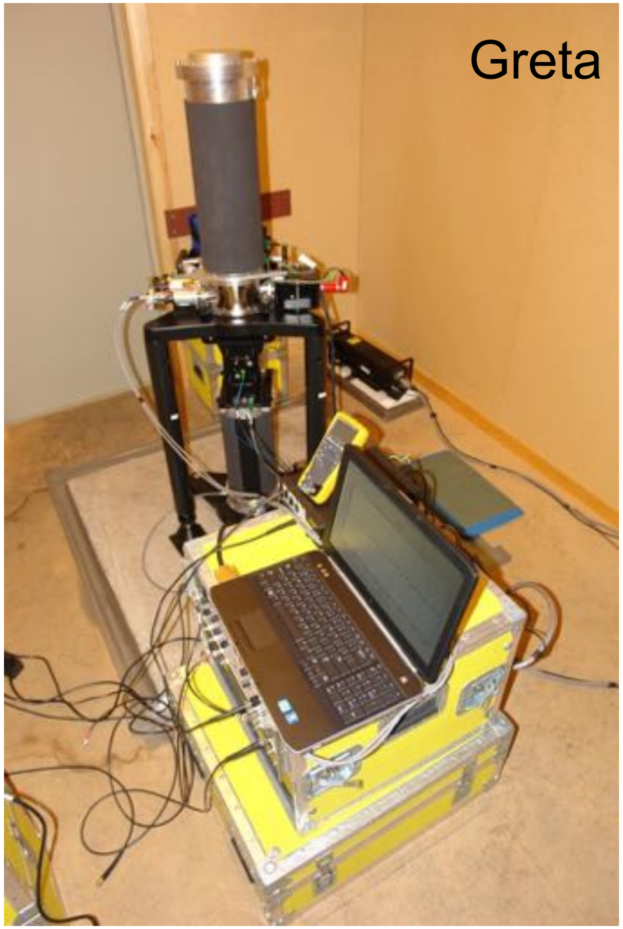


(Wang et al. 2013, Nature Geosci.)

Absolute gravity stations in Fennoscandia



(Steffen et al. 2012, GJI)



FG5-233 from Lantmäteriet

(Photo: Steffen)

Absolute gravity network

FG5-220 from IfE (Photo: Gitlein)

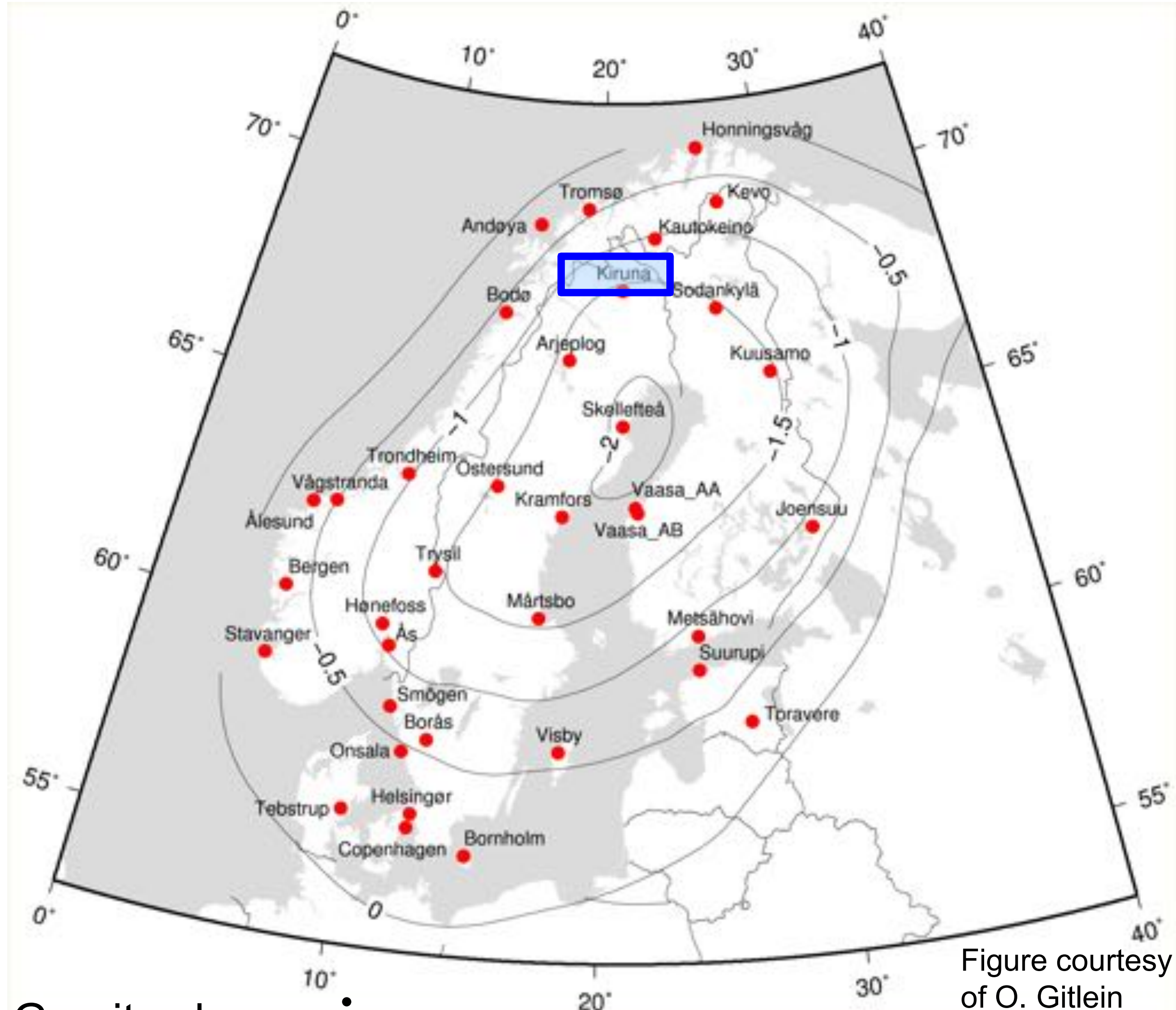
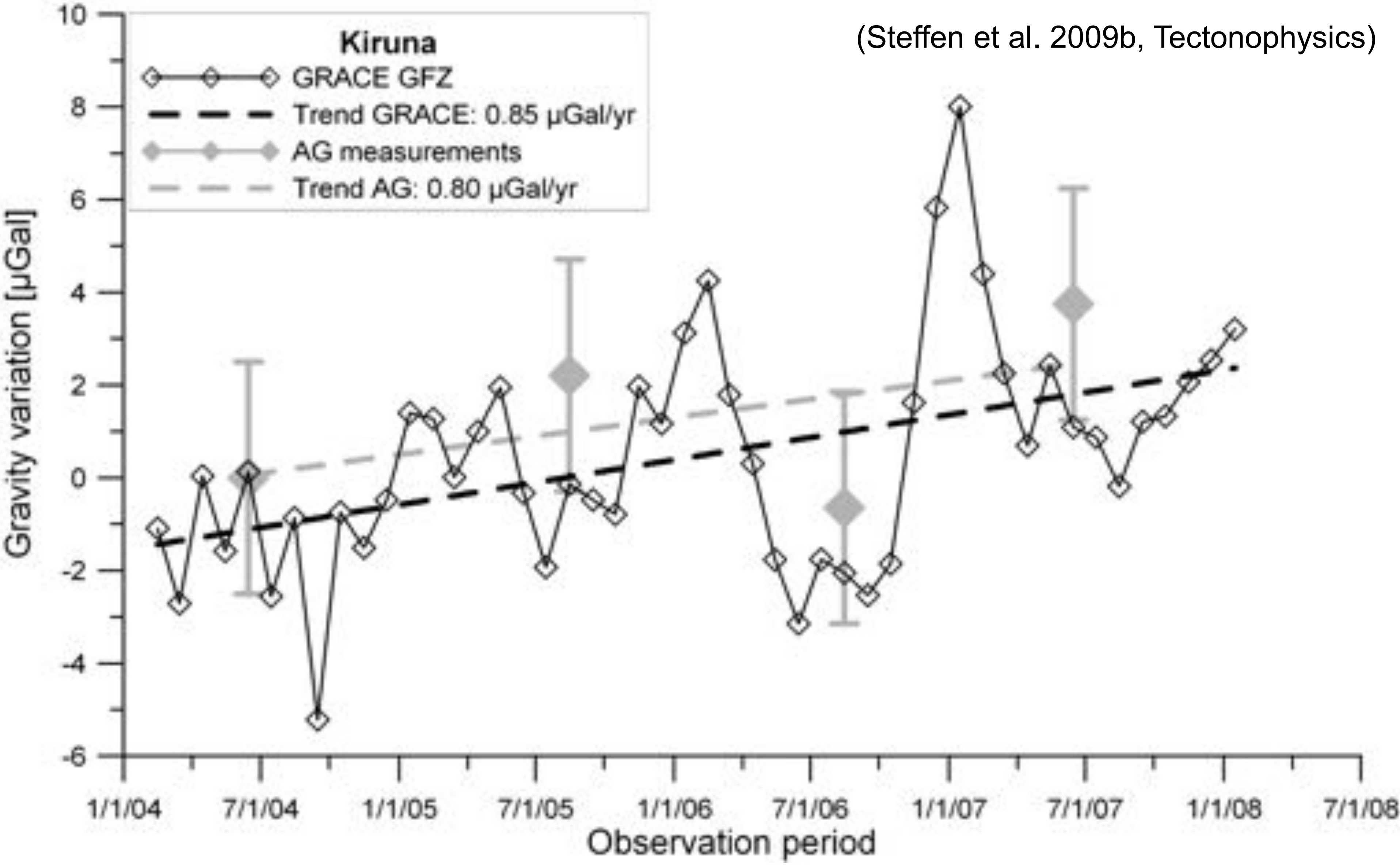


Figure courtesy of O. Gitlein

Gravity change $\dot{g}$
after Ekman and Mäkinen (1996)

Comparison to absolute gravity

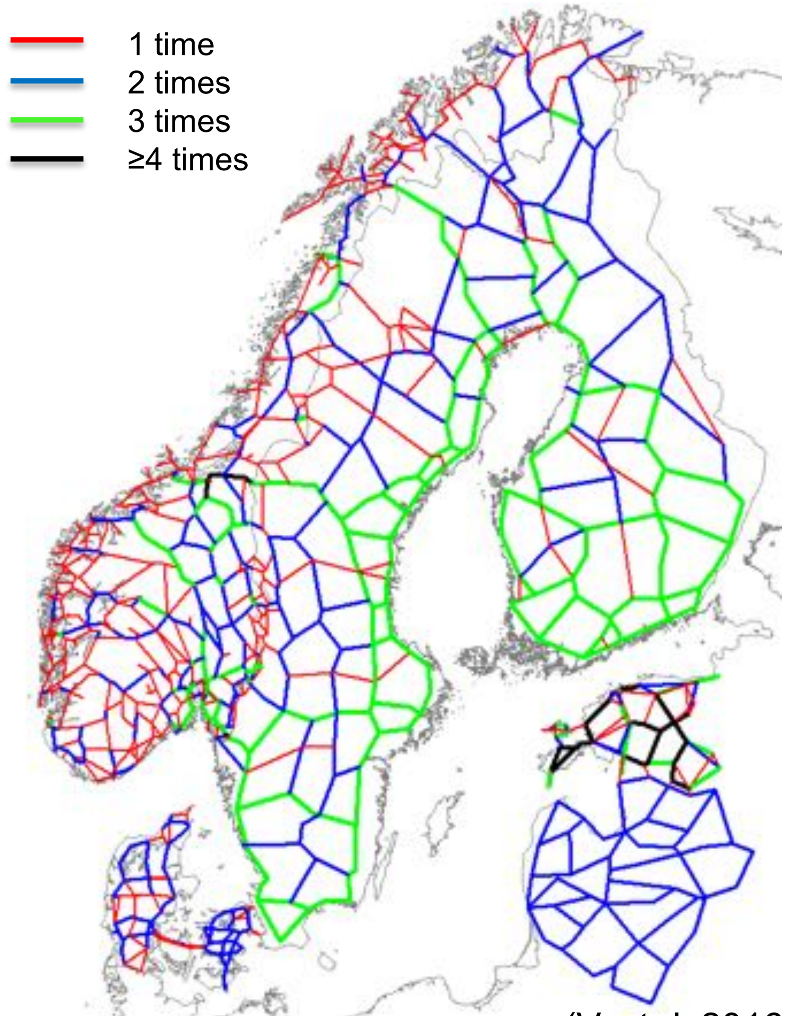
(Steffen et al. 2009b, Tectonophysics)



Combinations

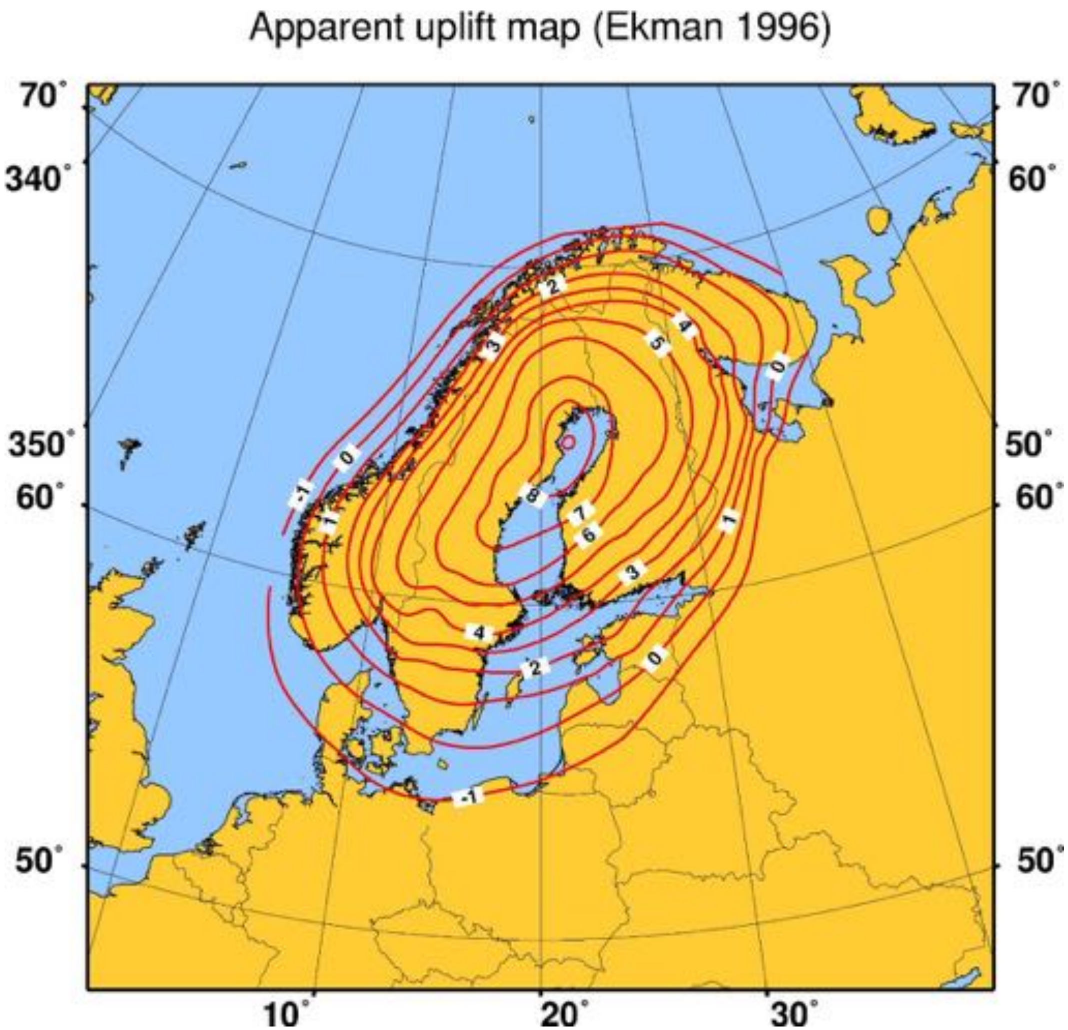
Why do we need models of land uplift?

- **Connection to NAP**: In Sweden, for example, national height system RH2000 is a realization of the European Vertical Reference System (EVRS) using the Normaal Amsterdams Peil (NAP) as zero level
- **Common reference epoch**: for all levelling observations
- **Today's position**: due to land uplift, position as of today is different to the one in the reference system (different epoch)



(Vestøl, 2016)

Land-uplift map from combined observations

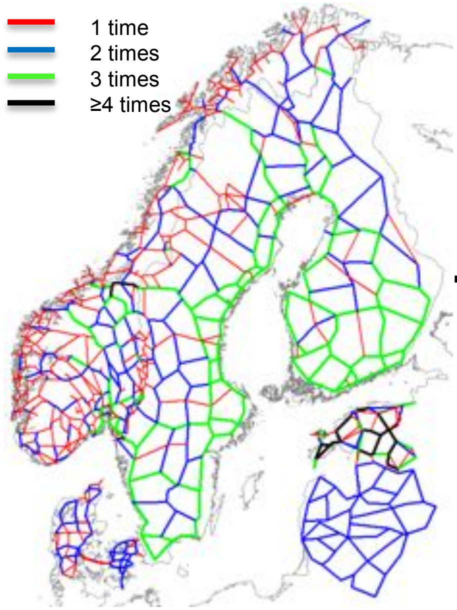


- Apparent uplift!
- Combined from repeated levelling, tide gauges and lake levels
- Widely accepted within the Nordic community

(Steffen and Wu 2011)

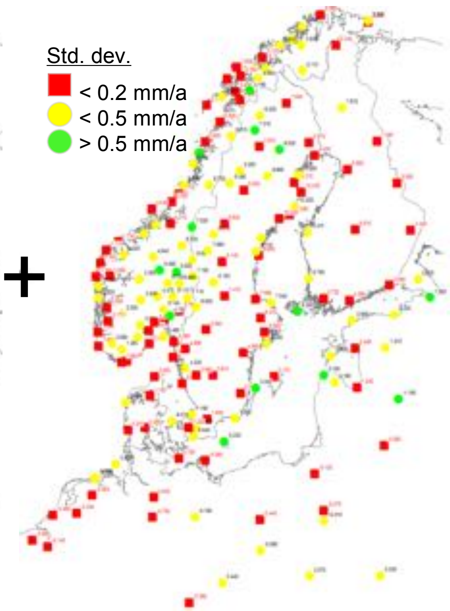
Basic concepts for an empirical model

Levelling



+

GNSS



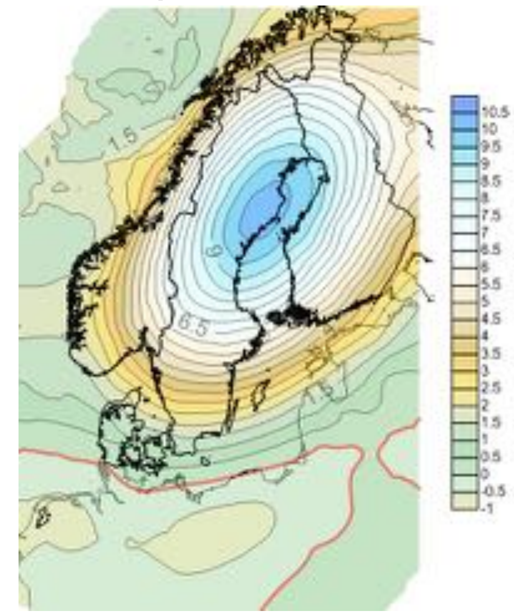
+

Some math

Least-squares collocation with unknown parameters to estimate the absolute uplift in the observation points

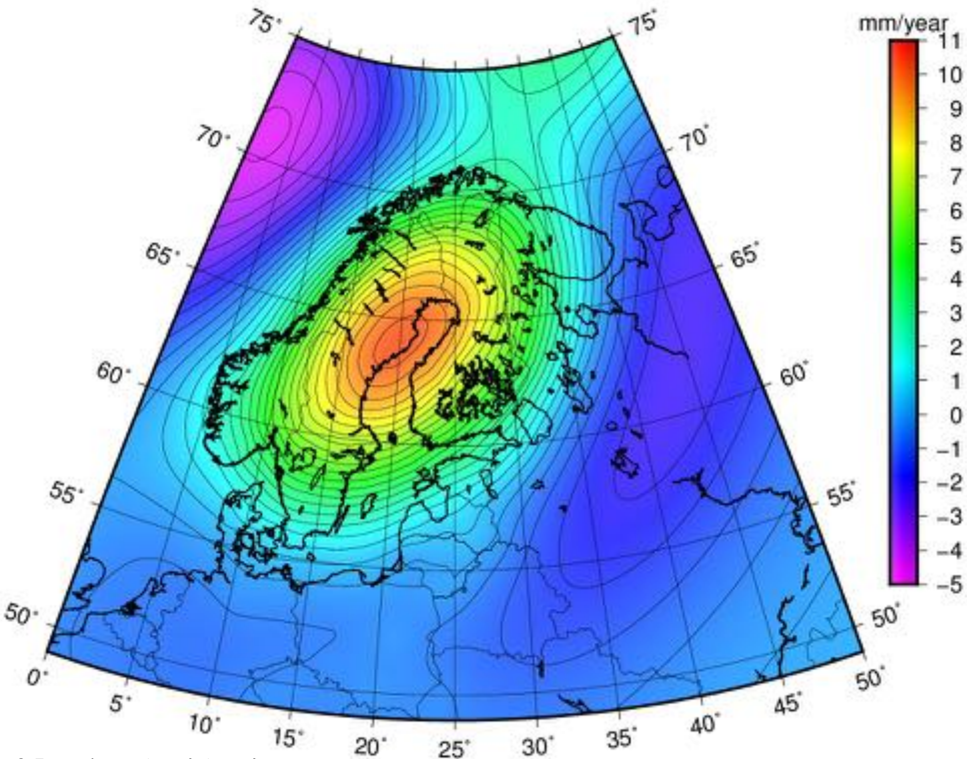
=

Empirical model



- Geodetic observations alone are used to calculate the absolute land uplift in ITRF2008
- Example NKG2016LU: Trend surface consisting of a 5th degree polynomial; least-squares collocation to estimate an additional signal (=difference from trend surface); a first order Gauss-Markov covariance function with halved correlation after 40 km and variance $(3 \text{ cm/a})^2$ selected for this latter part of the solution

NKG2016LU_abs



0.5 mm/a contour interval

- Absolute land uplift in ITRF2008 (relative to the centre of mass)
- Statistics:

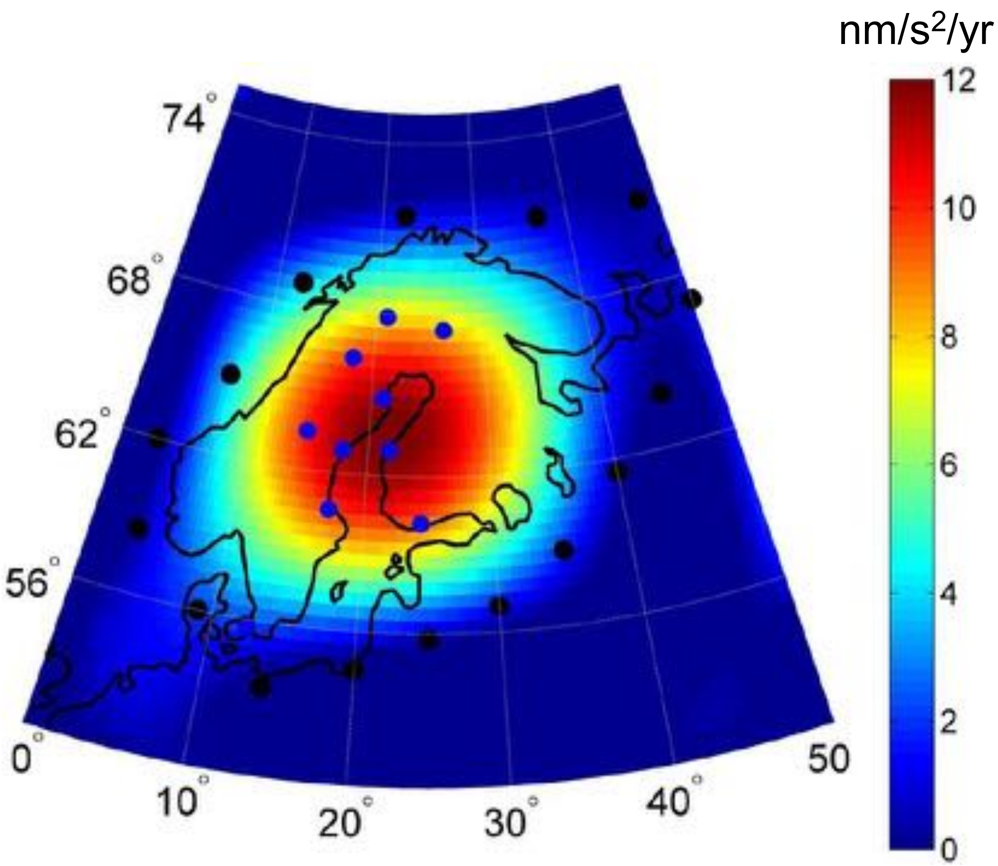
#	313 x 301
Min	-4.61
Max	10.29
Mean	0.90
StdDev	3.14

- Should be used for the correction of GNSS or other space geodetic techniques

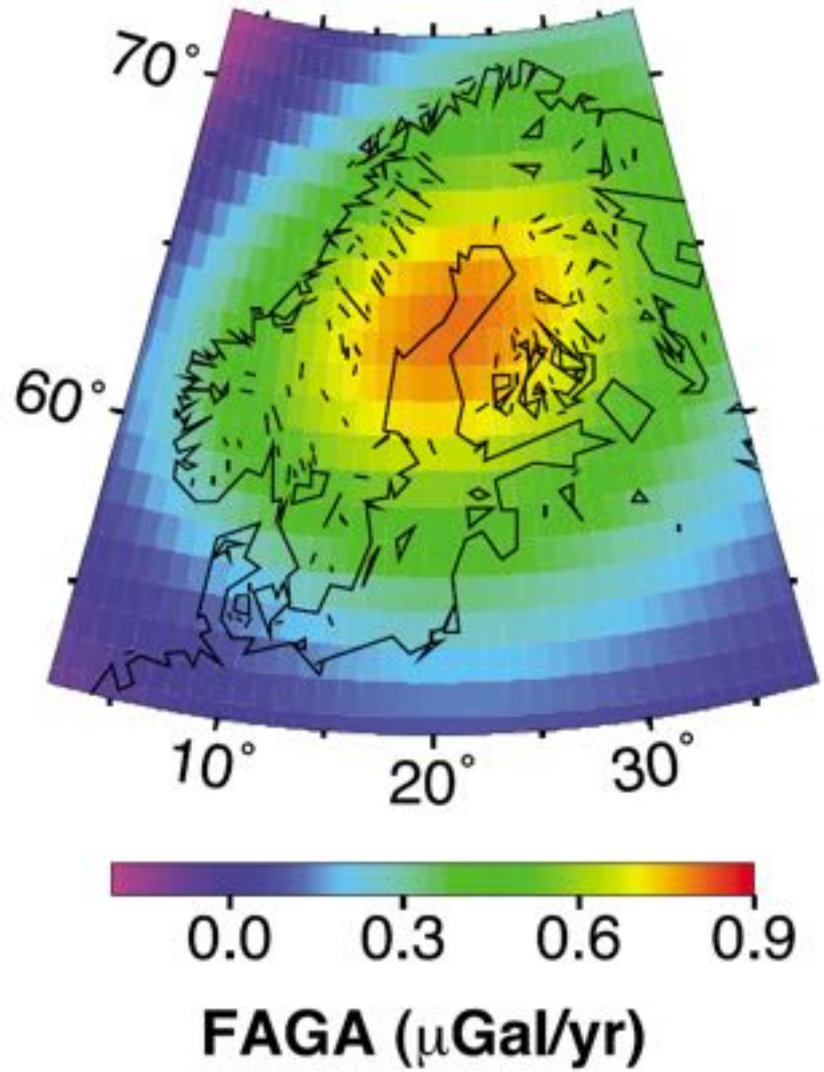
$$\dot{h}^{\text{grid}}_{\text{NKG2016LU\_abs}} = \dot{h}^{\text{grid}}_{\text{NKG2016GIA\_prel0306}} + \overbrace{LSC\left\{\dot{h}^{\text{obs. points}}_{\text{empirical\_abs}} - \dot{h}^{\text{obs. points}}_{\text{NKG2016GIA\_prel0306}}\right\}}^{\text{Residual surface (grid)}}$$

Further data combination model examples

GRACE + AG (+ GPS) + geophysical model



GRACE + GPS + tide gauges



(Müller et al. 2011, PCE)

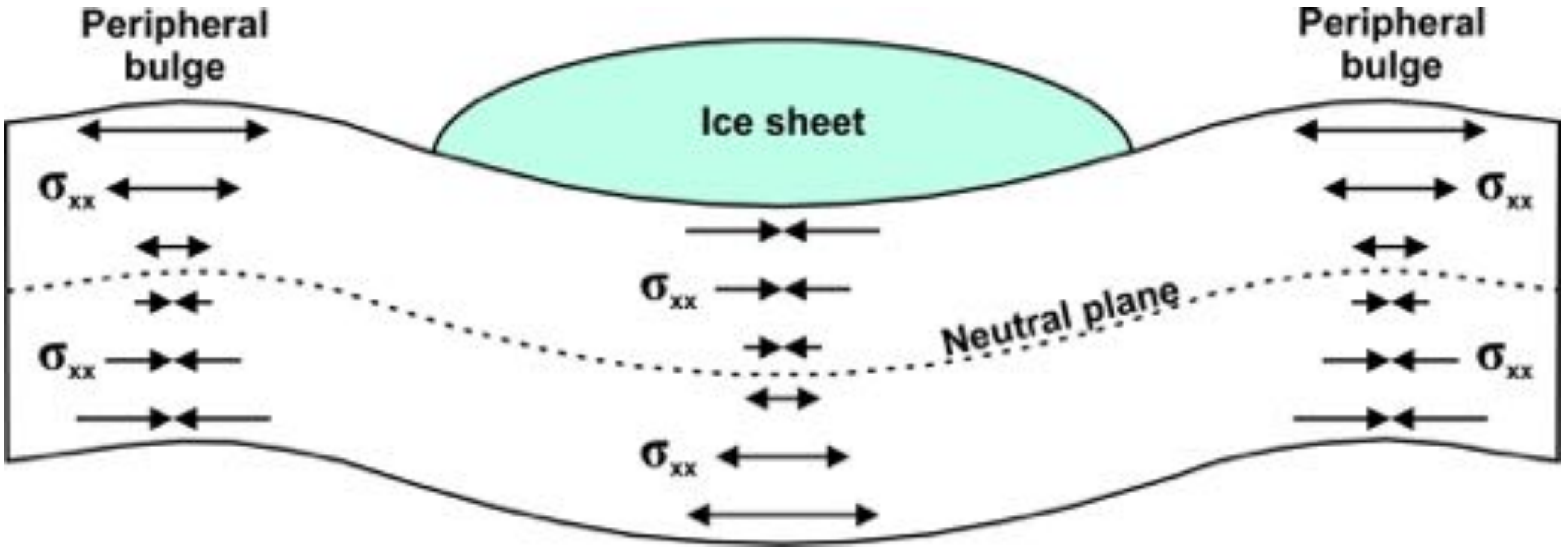
(Hill et al. 2011, JGR)

Intraplate Earthquakes and glacially induced faults

Application:

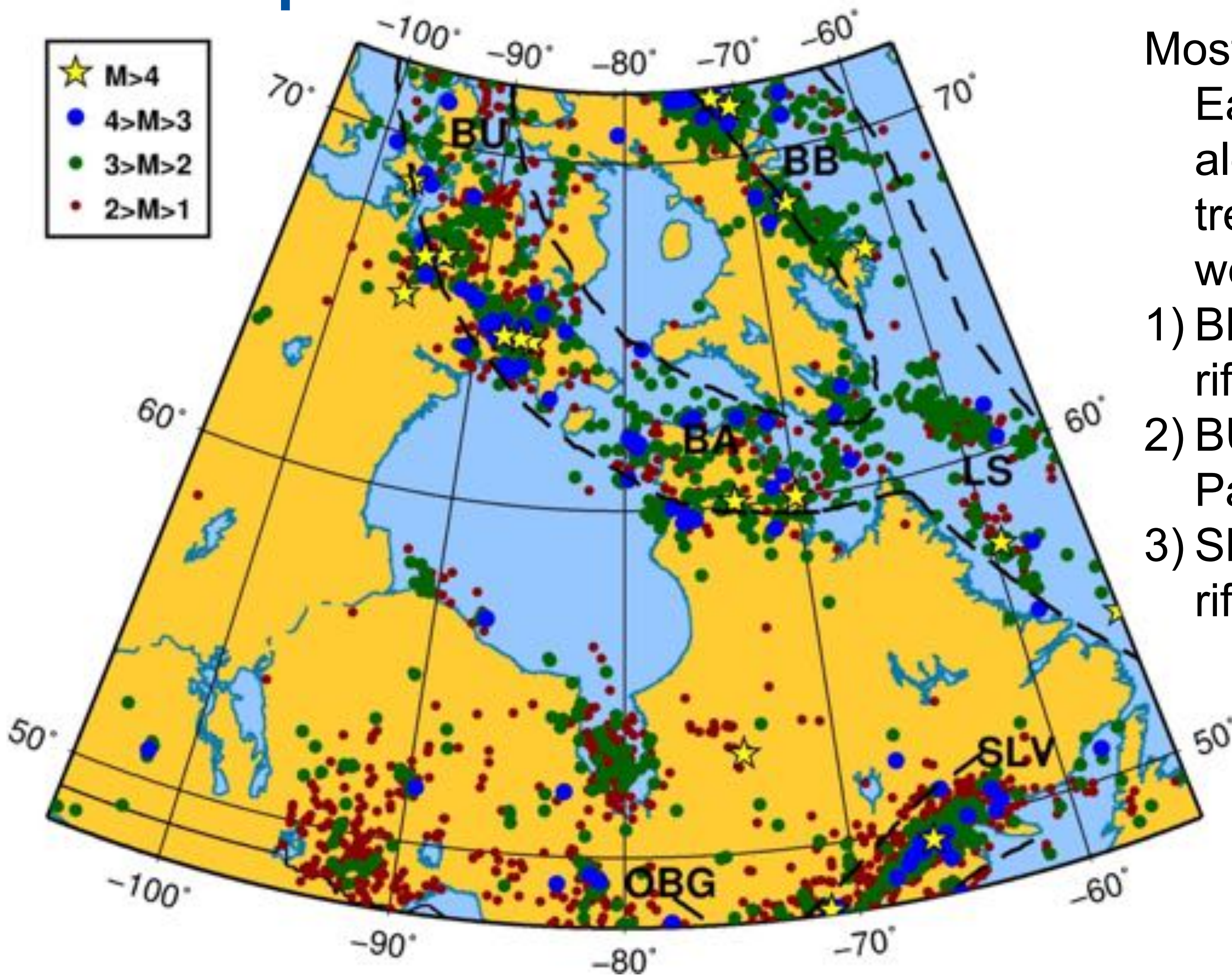
Nuclear Waste Management

Stress due to GIA



(R. Steffen 2013)

Earthquakes in Eastern Canada



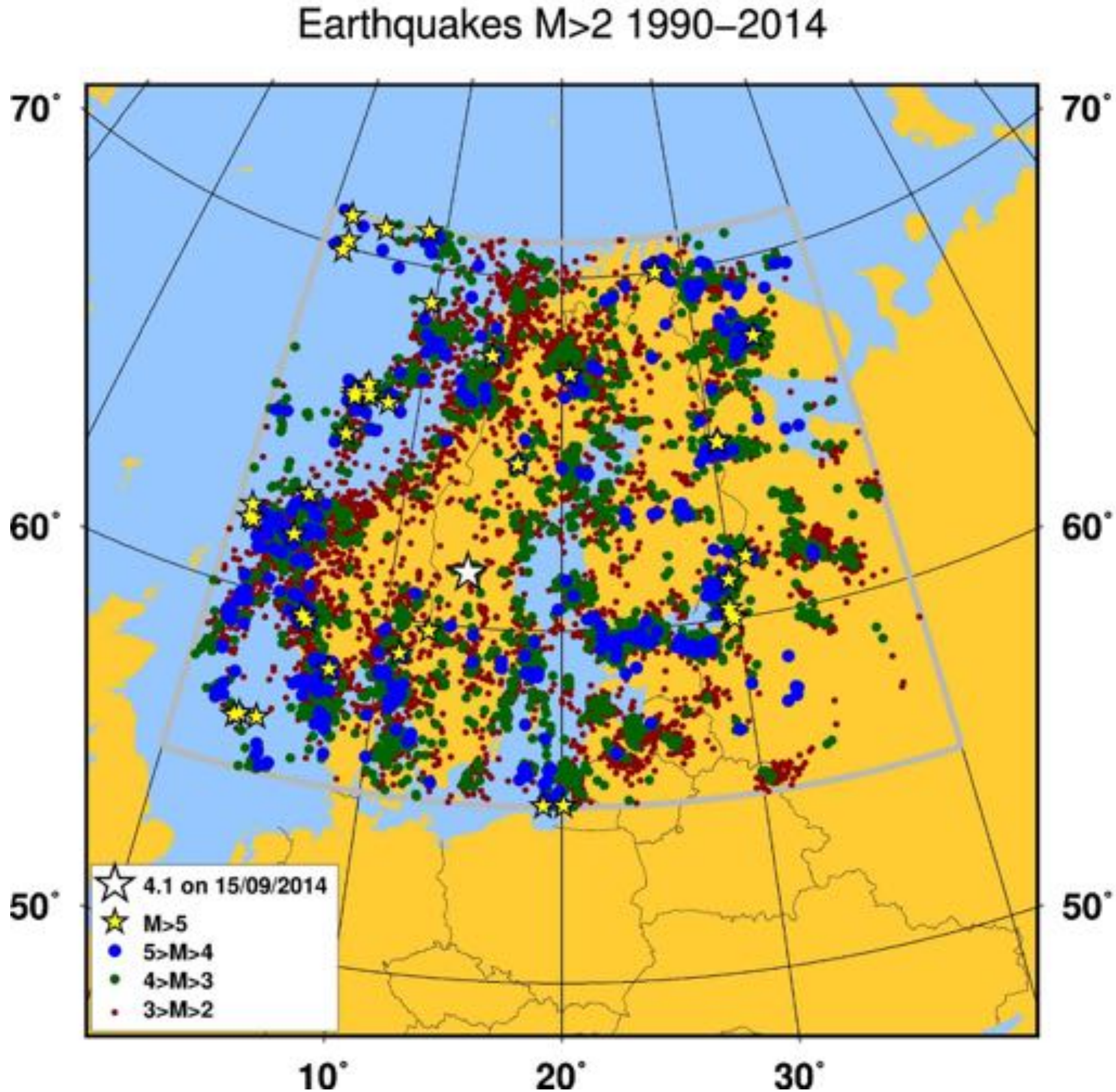
BA - Bell Arch; BB - Baffin Bay; BU - Boothia Uplift; GB - Grand Banks; LS - Labrador Sea; OBG - Ottawa Bonnechere Graben. SLV - St. Lawrence Valley;

Most seismic activity in Eastern Canada along the 3 tectonic trends or pre-weakened zones:

1) BB-LS-GB Mesozoic rift margin
2) BU-BA reactivated Paleozoic structures
3) SLV-OBG Paleozoic rifts

(R. Steffen et al. 2012)

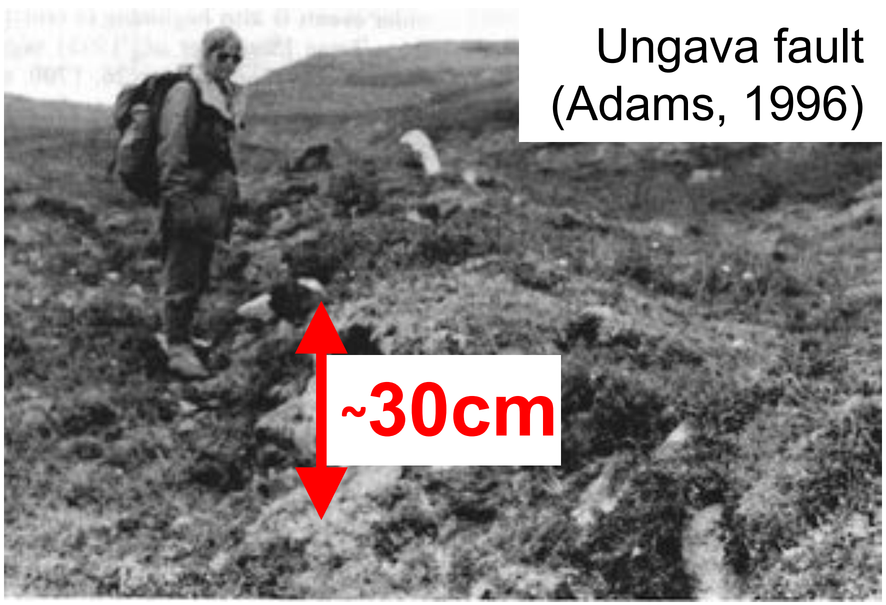
Earthquakes in Northern Europe



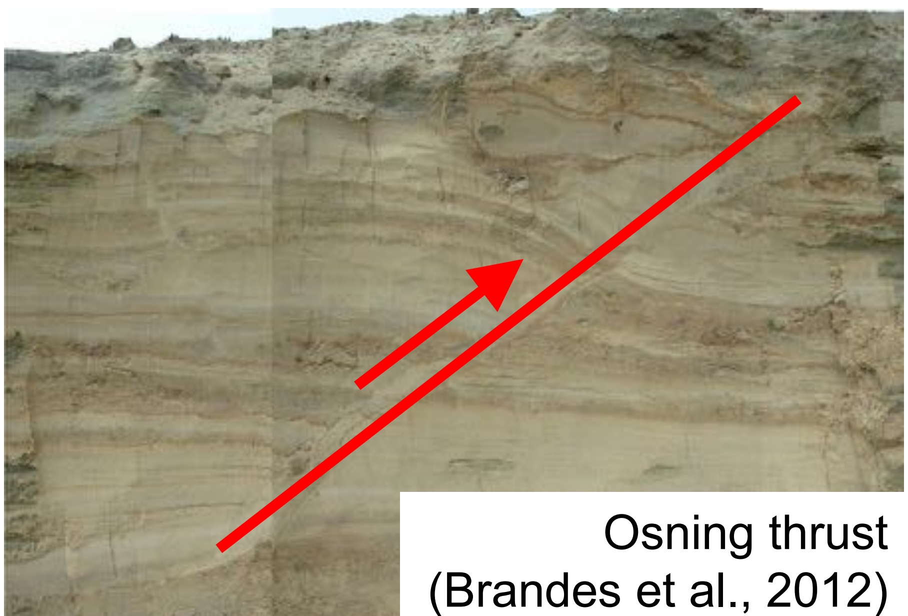
Most seismic activity offshore Norway and Bothnian Gulf (oil and ore extraction)

(update from Steffen & Wu 2011, J. Geodyn.)

Glacially induced faults



Ungava fault
(Adams, 1996)



Osning thrust
(Brandes et al., 2012)

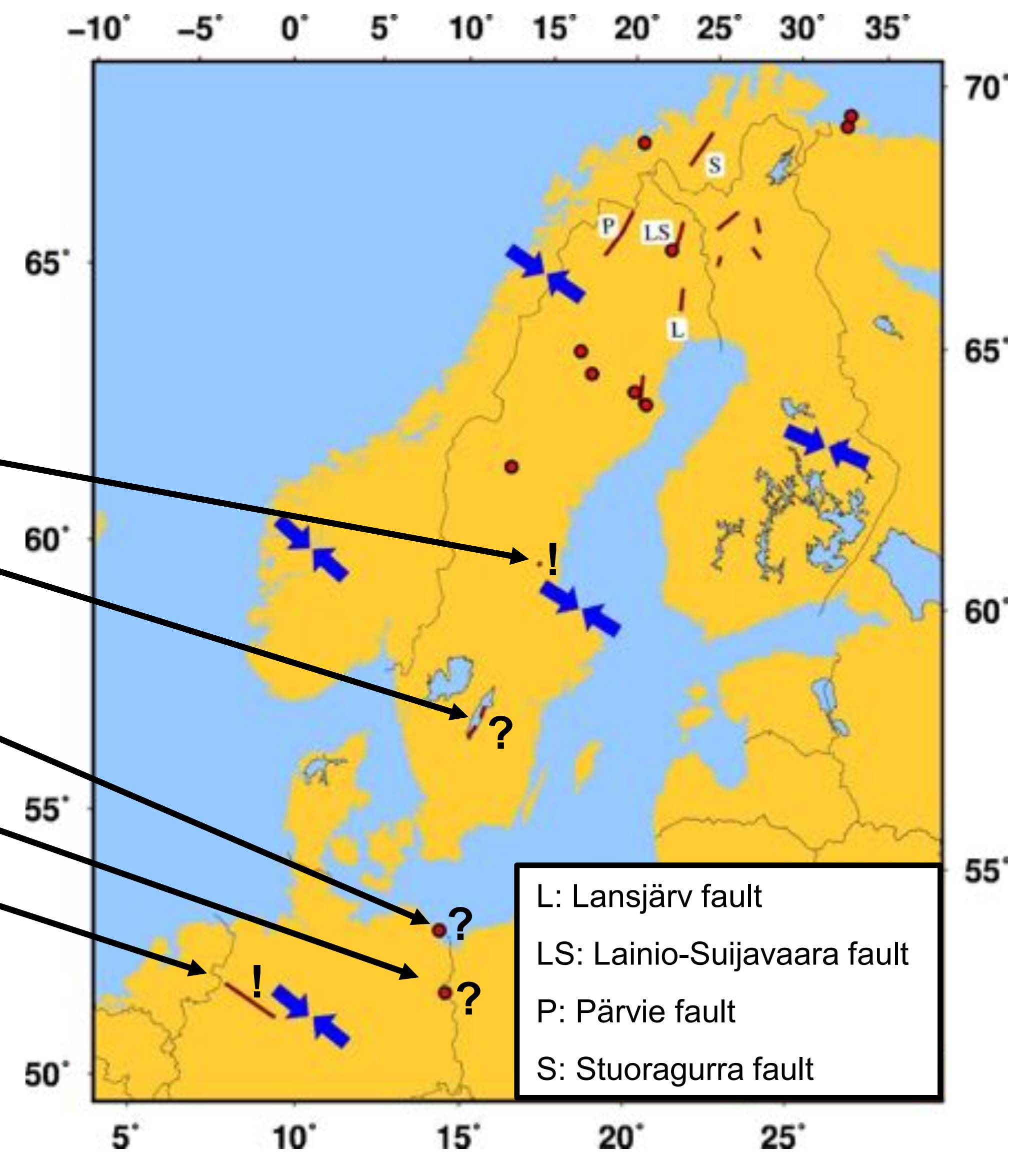
Pärvie fault (Lagerbäck & Sundh, 2008)

Glacially induced faults

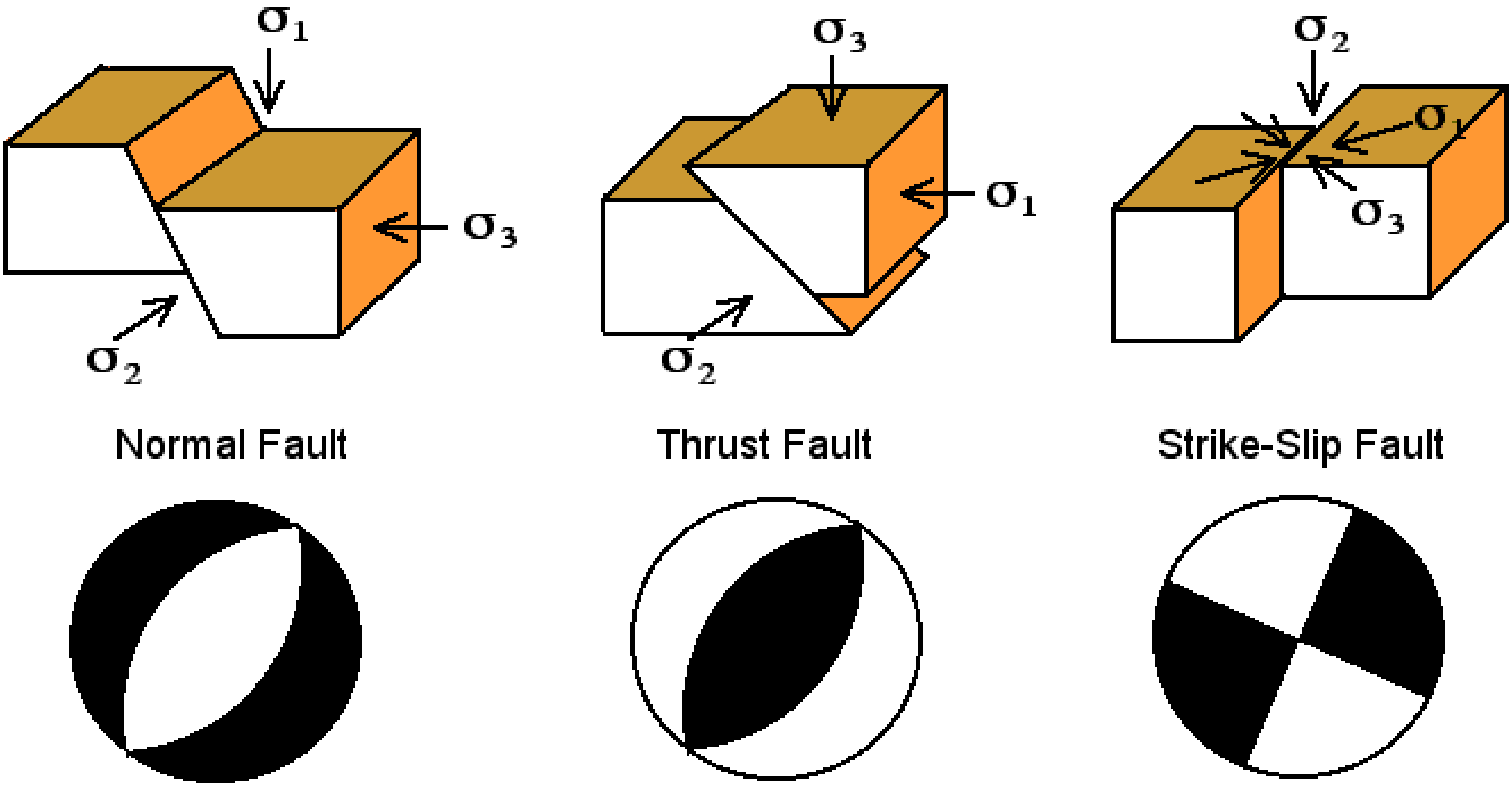
Pärvie fault
(Lagerbäck & Sundh, 2008)

Glacially induced faults in Europe

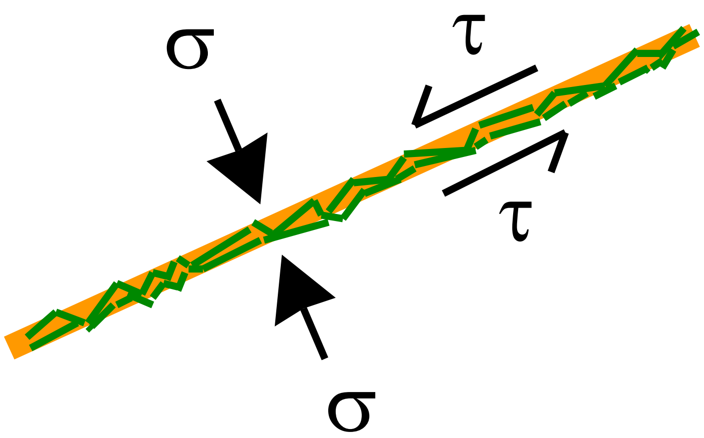
- Bollnäs fault
- Fault in Lake Vättern
- Usedom Island
- W Poland
- Osning Thrust



Fault & focal mechanisms



Mohr-Coulomb failure criterion



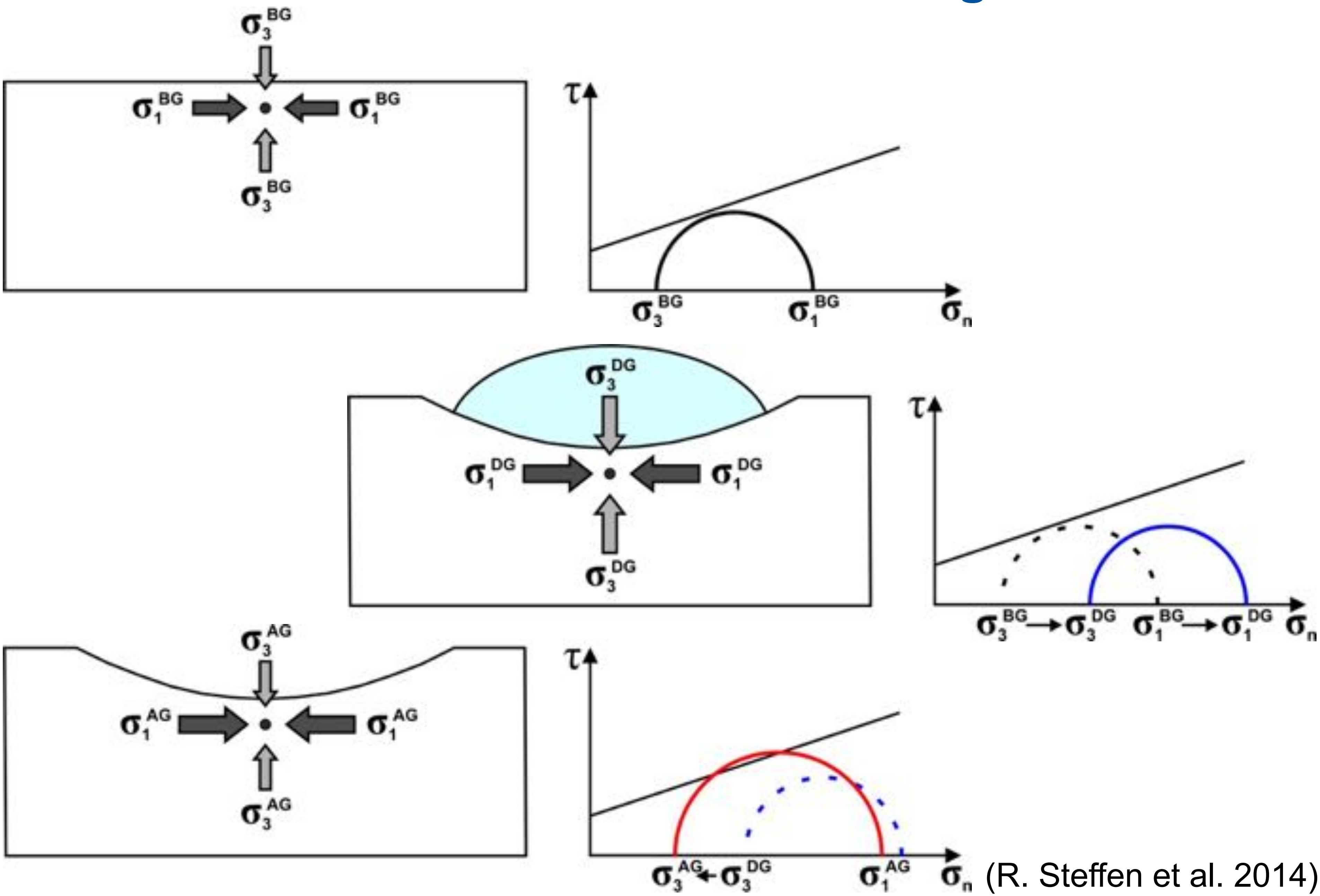
$$\tau = \tau_o + \mu_f \sigma$$

Shear Strength τ_o

Internal friction μ_f

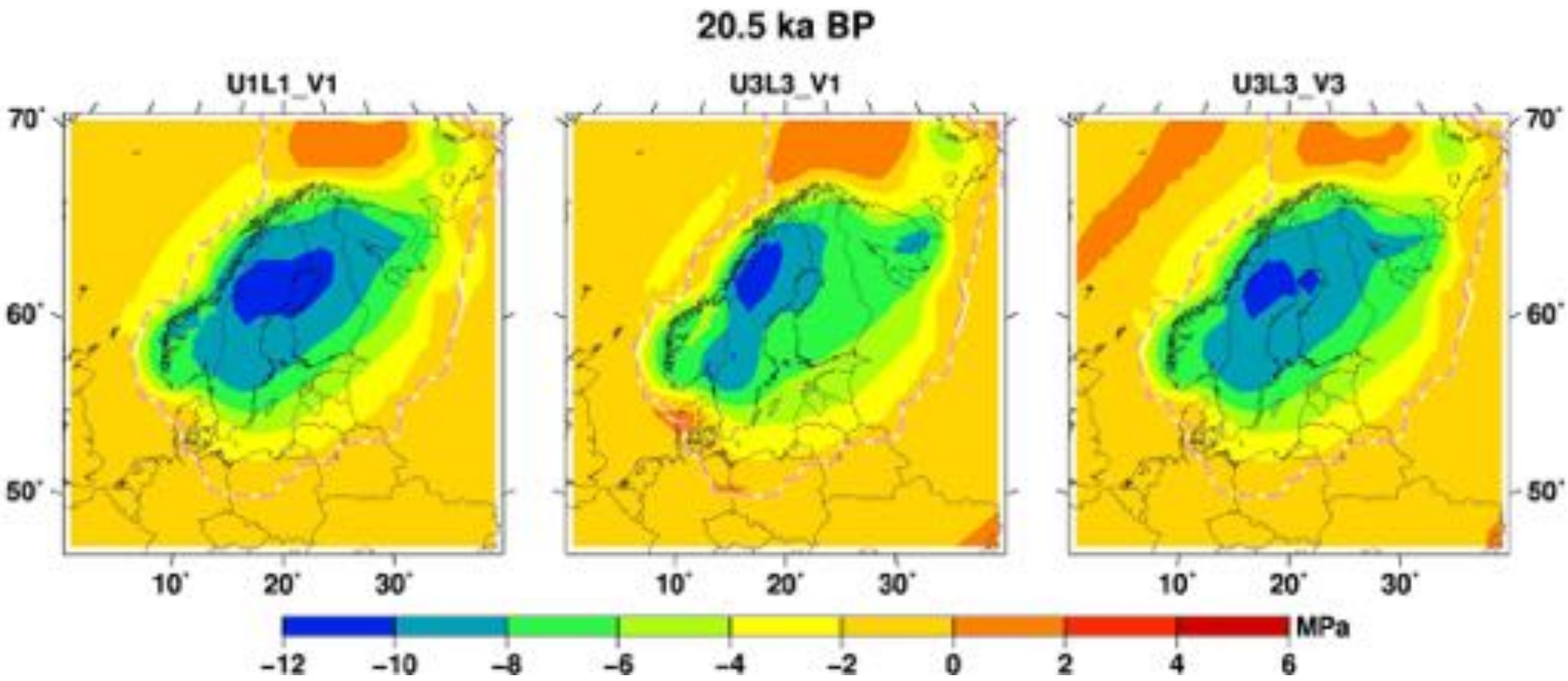
Mechanical strength is controlled by the sliding of one fracture surface on the other - due to the shear stress τ.
On the other hand, the normal stress σ presses the fracture surfaces together, increasing the friction and prevent sliding.

GIA and stress in a thrust/reverse regime

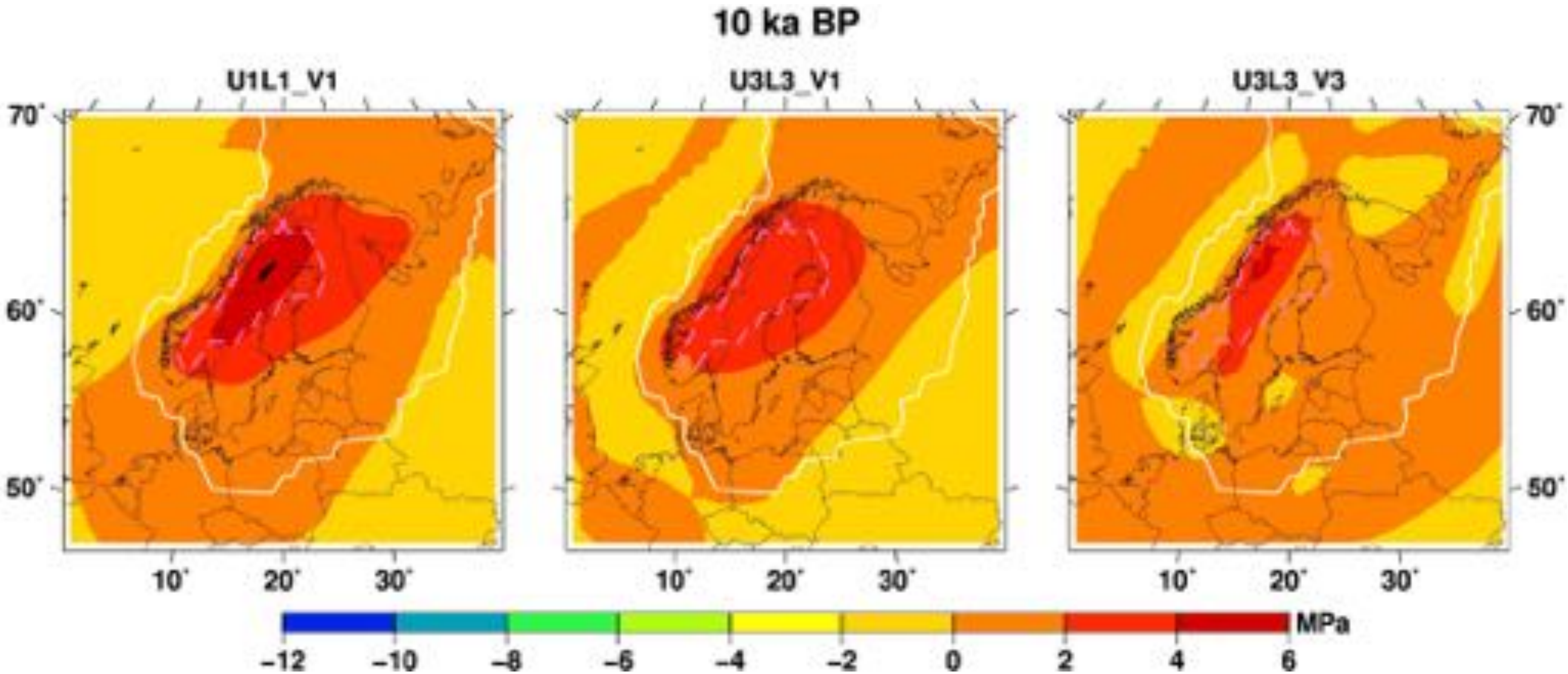


(R. Steffen et al. 2014)

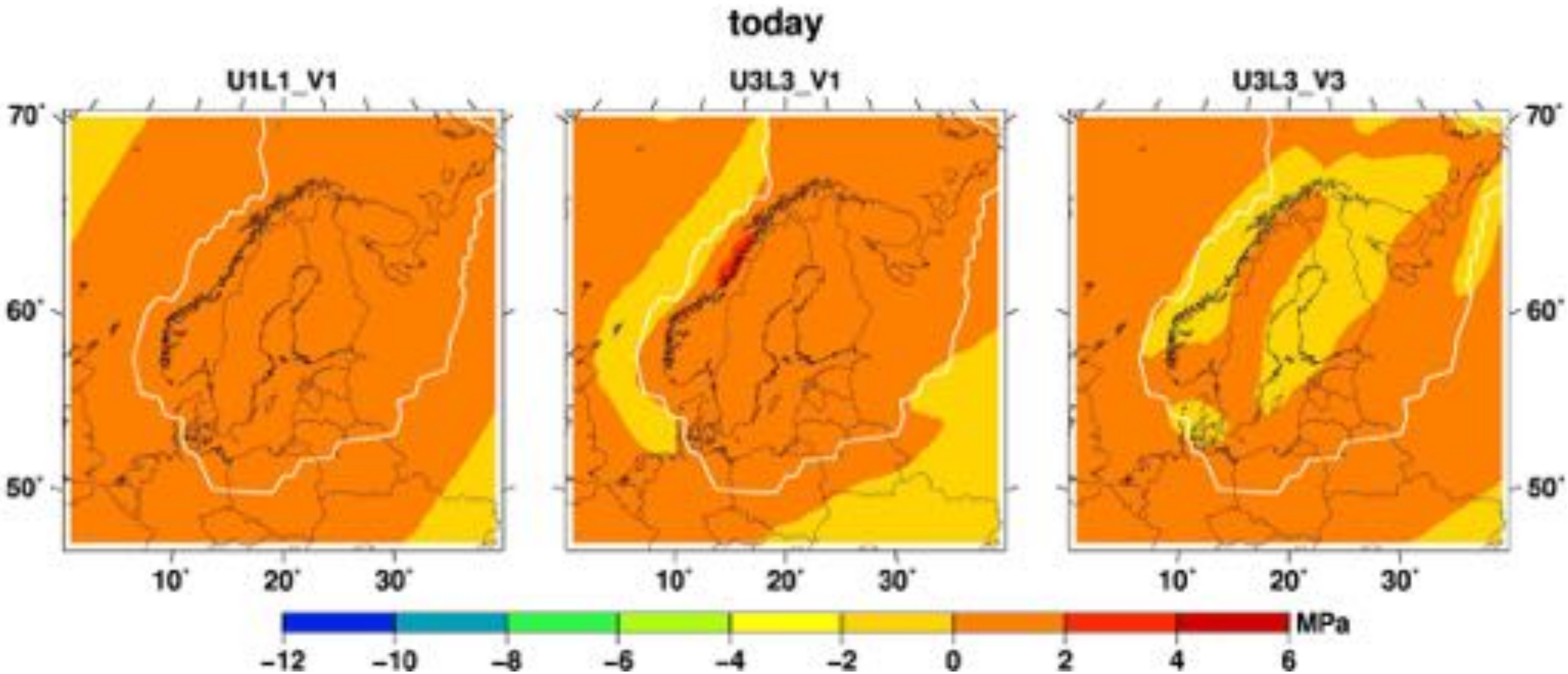
Change in Coulomb Failure Stress



Change in Coulomb Failure Stress

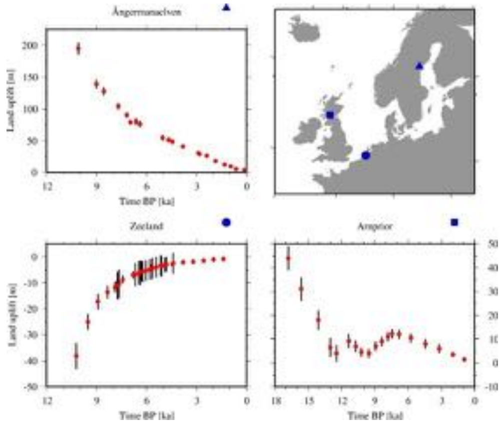


Change in Coulomb Failure Stress

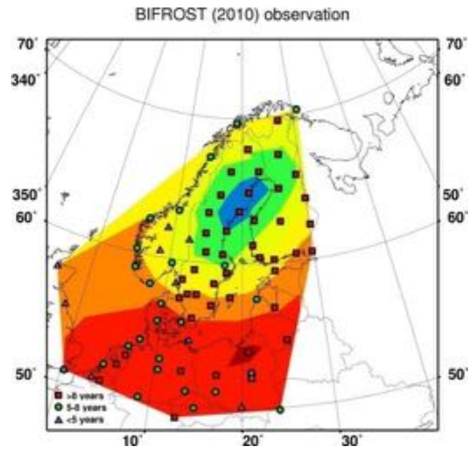


Data summary

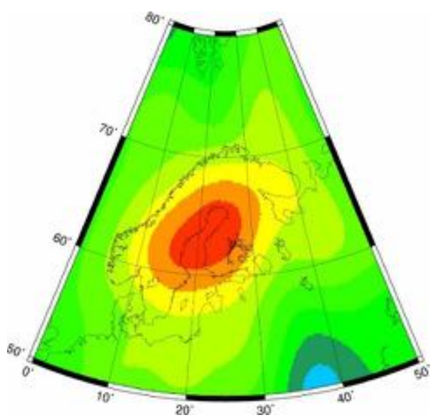
The reliable past



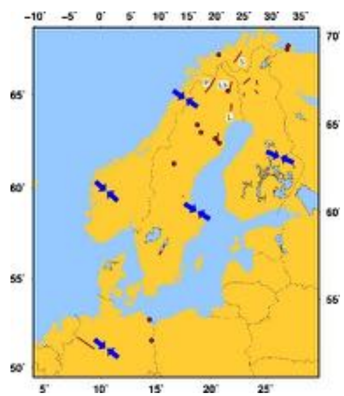
Today's accurate snapshot



The blurry future



Helpful constraint

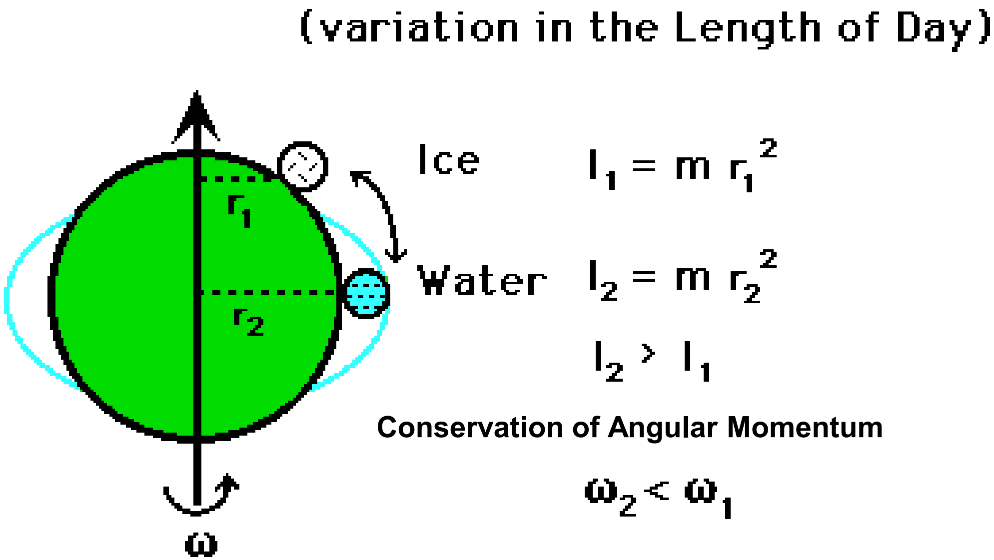


A model that can describe all that (and more) will provide us the best view into the future!

Changes in Moments of Inertia

- GIA causes mass (ice and mantle masses) to redistribute around the globe, thus disturbs the gravity field
- Movement of mass also affect the Moment of Inertia, thus the rotational motion of the Earth (polar wander and changes in the Length of Day)

GIA affects Earth's Rate of Rotation



Length of Day decreases by ~0.7 ms/century

Measurements of non-tidal acceleration

Source	$\dot{\omega}_3/\Omega$ (10^{-10}/year)	
Currot (1966)	0.7	+ 0.3
Muller & Stephenson (1975)	1.5	+ 0.3
Morrison (1973)	2.9	+ 0.6
Lambeck (1977)	0.69	+ 0.3
Stephenson & Morrison (1995)	0.69	+ 0.2

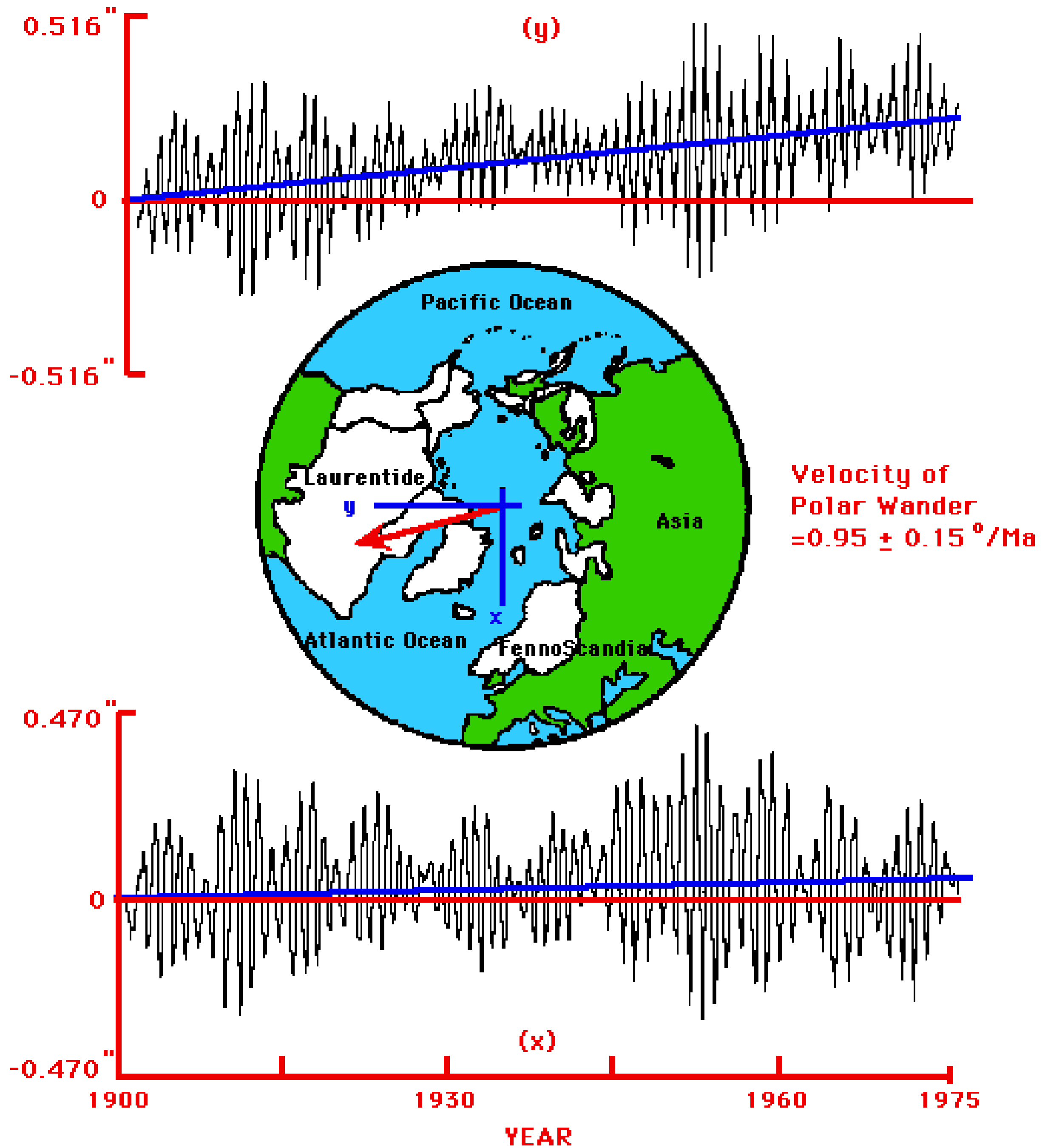
i.e. Length of Day decrease by ~0.7 ms/century

Wu & Peltier (1984) : Non-tidal acceleration is related to the time rate of change of J_2 multiply by the constant $\frac{2M_E R_E^2}{3C}$

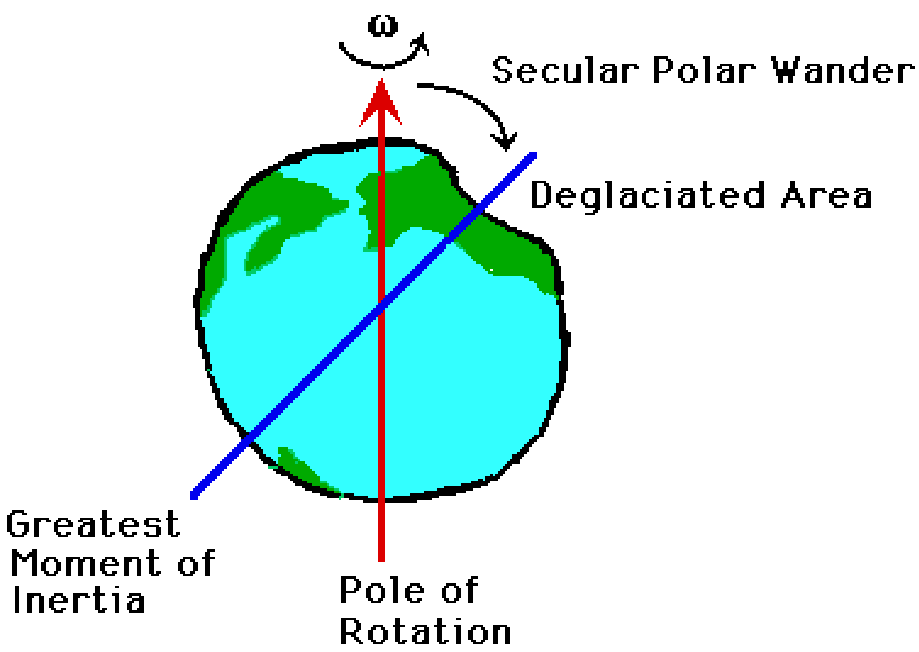
ILS data

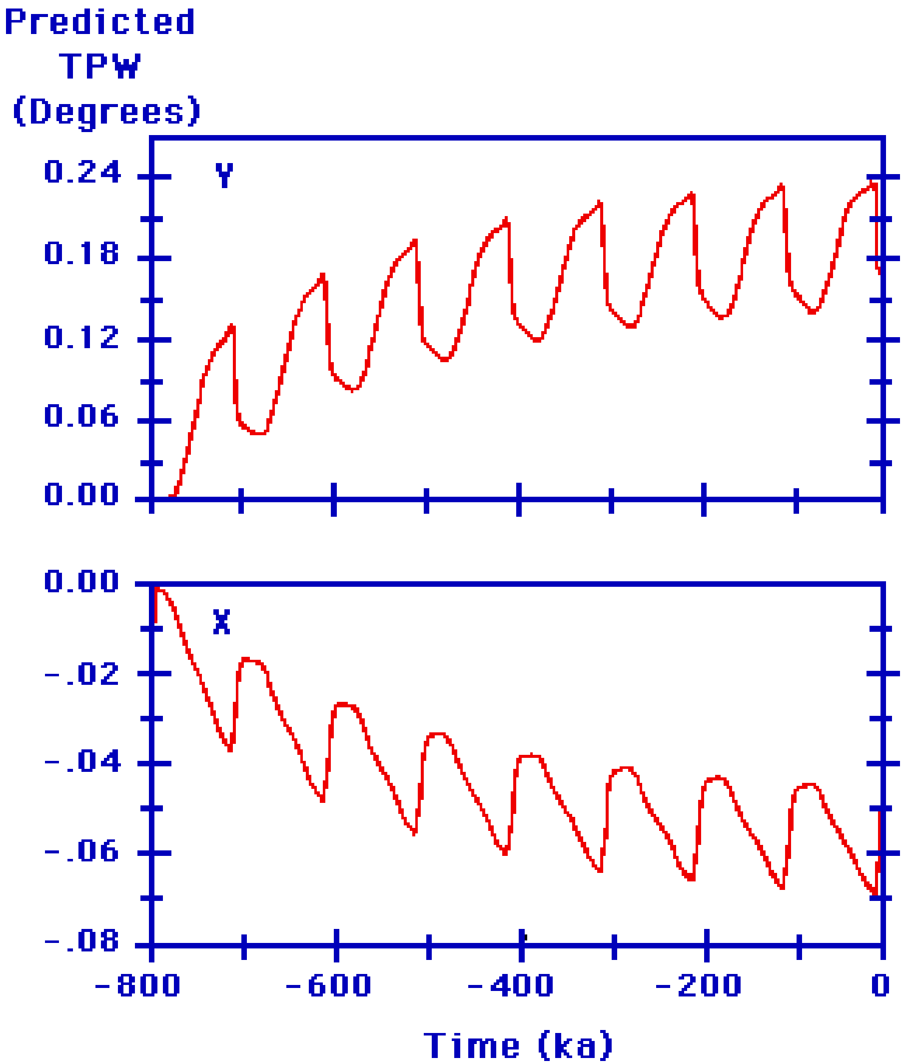
Show Secular (True) Polar Wander (blue lines) superposed on the oscillatory signal.

The 7 year beat in the signal is a consequence of the superposition of the 12 month forced annual wobble and the 14 month Chandler wobble.



Secular Polar Wander





Earth's spin axis tend to align itself with the axis of greatest moment of inertia