École de Physique des Houches

October 2022

Earth's rheology: insights from climate (un)loading

Kristel Chanard

Perito Moreno, Argentina, 2017

What is rheology?

What is rheology?

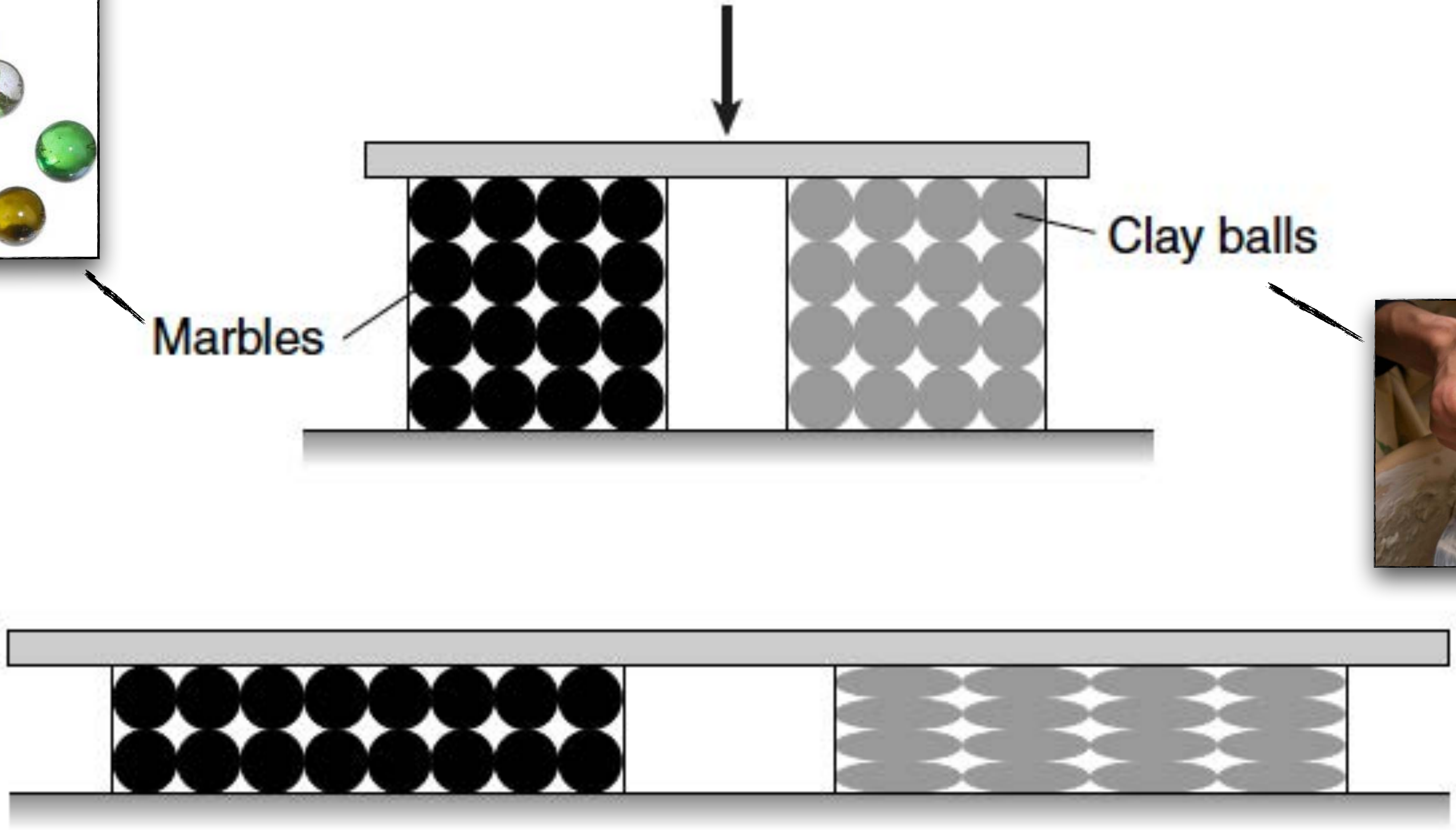
Rheology is the study of the flow of matter
Or the ability of stressed materials to deform or flow

Brittle behaviour

Ductile behaviour

What is rheology?

behavior vs mechanisms of deformation



What is climate (un)loading?

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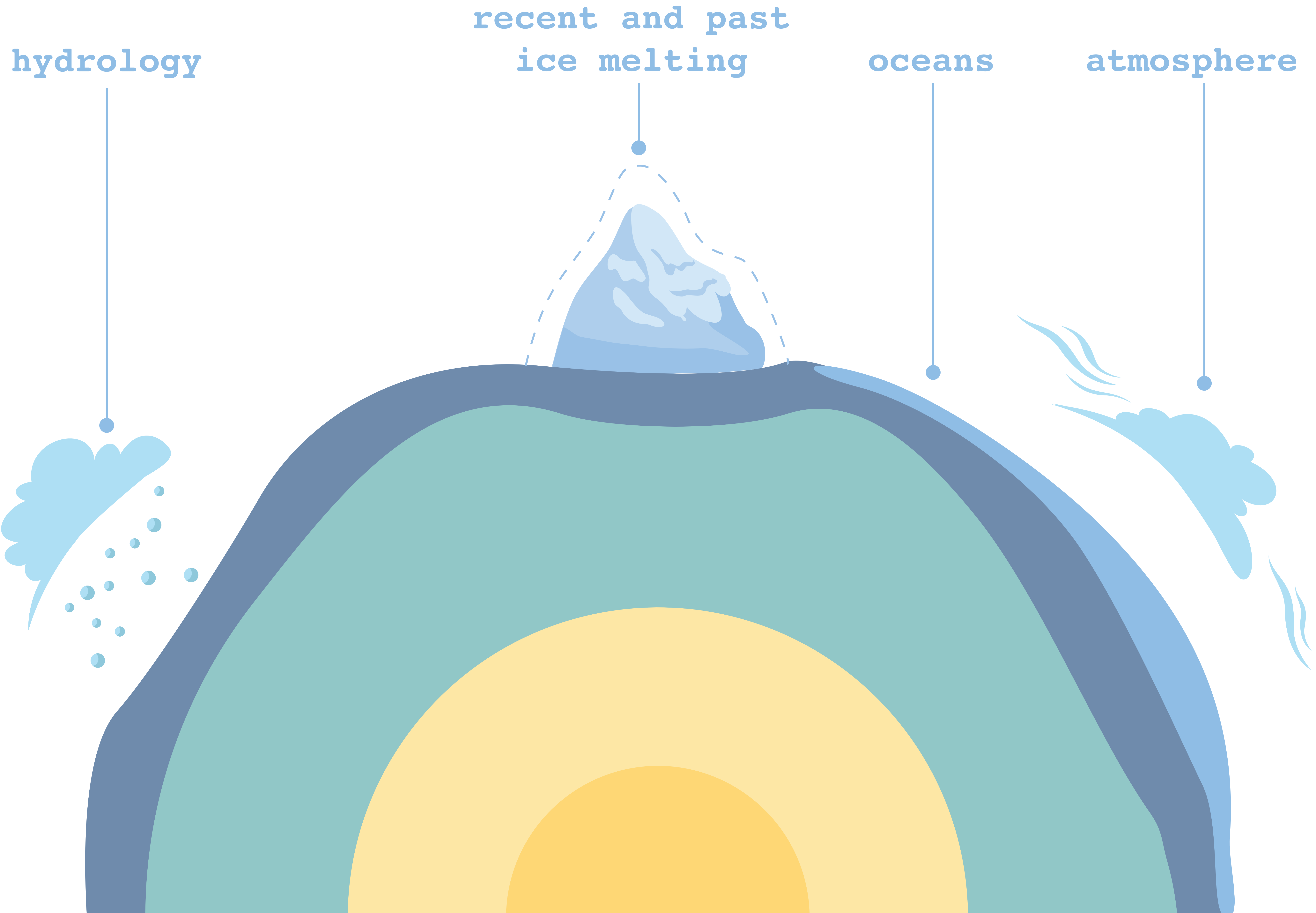
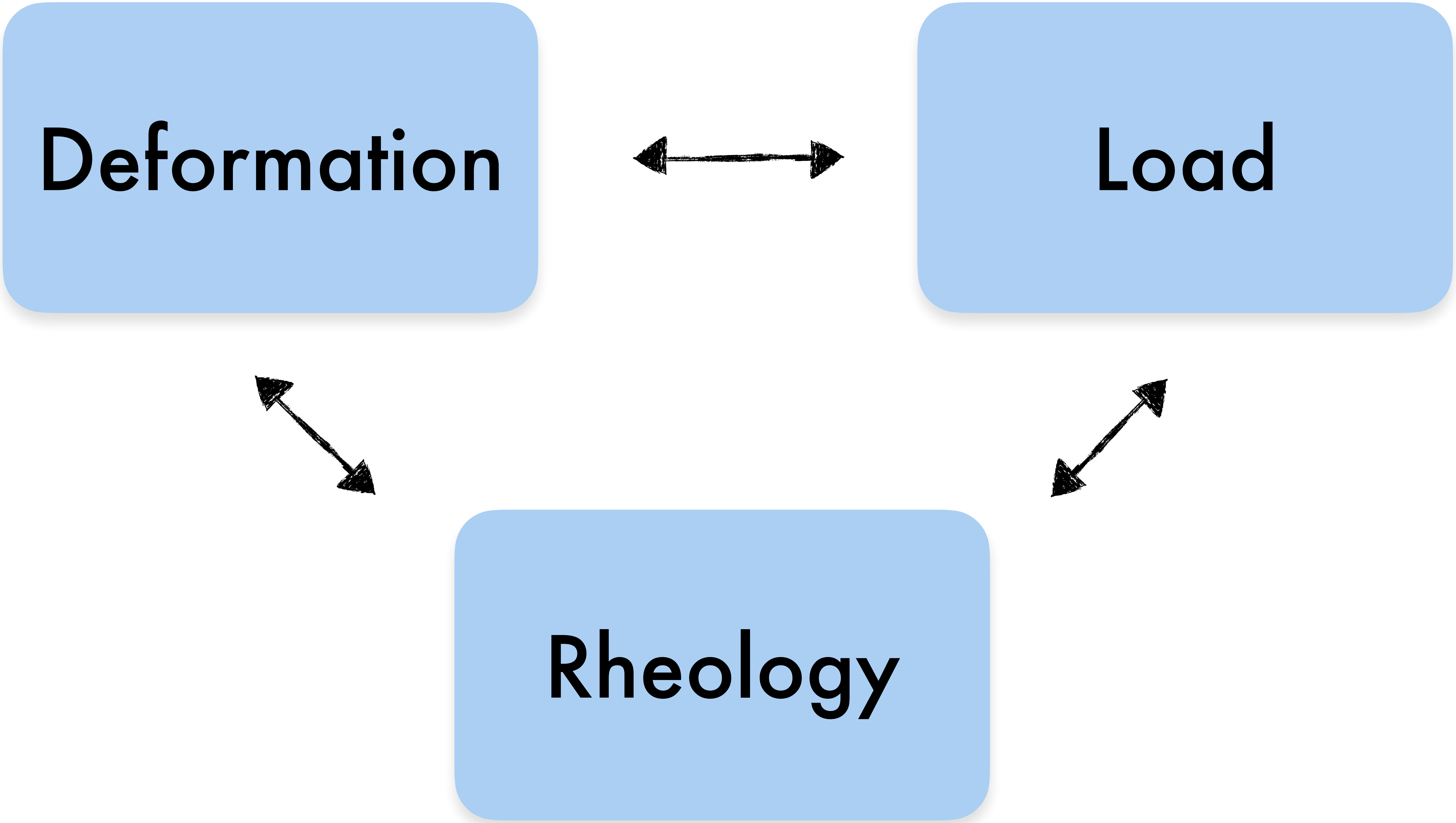


The (unfortunate) circle of knowledge

How to measure deformation associated with surface loads?

How to measure past and present-day climate loads?



How do the Earth deform at the mineral and global scale?

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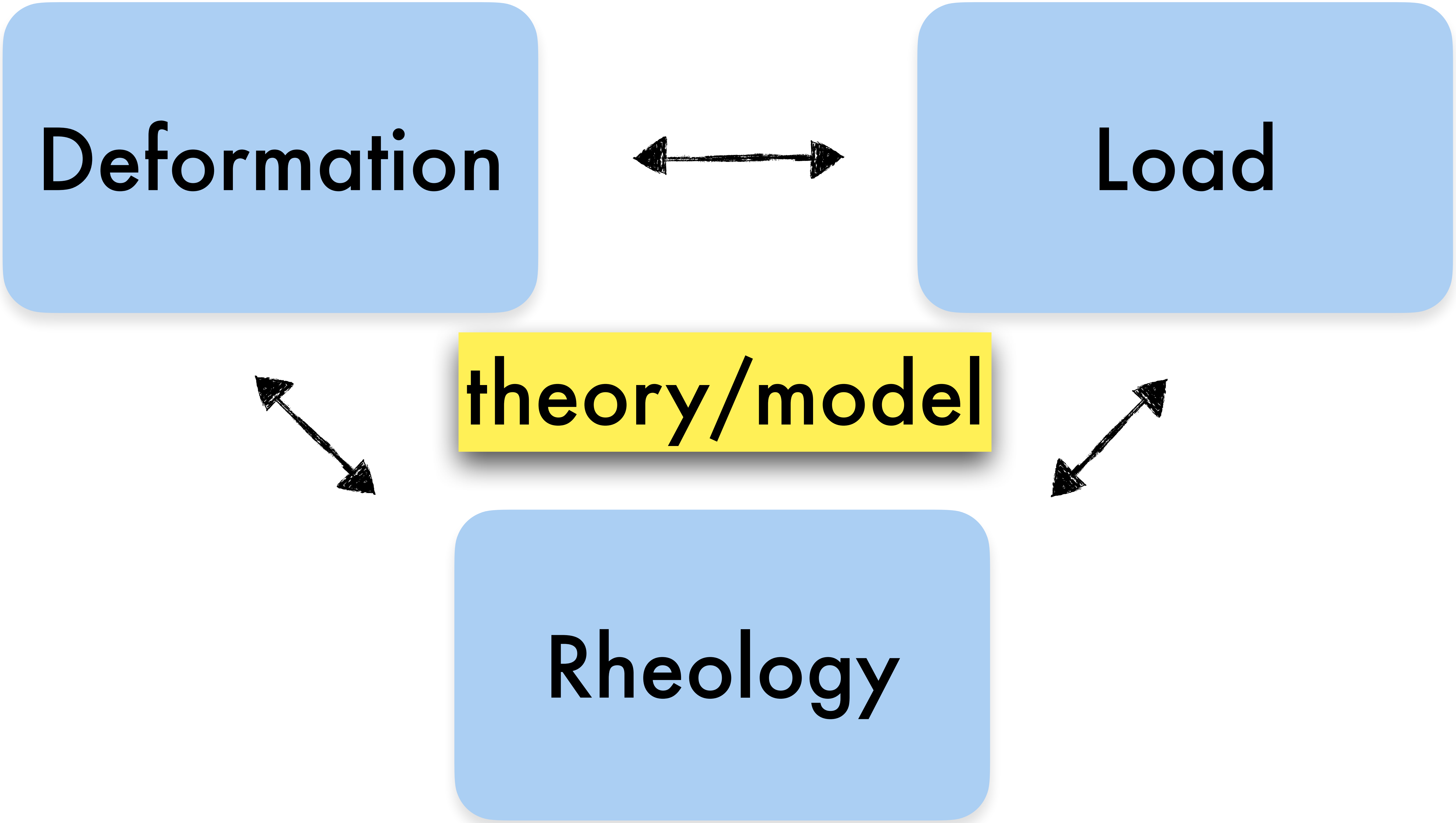

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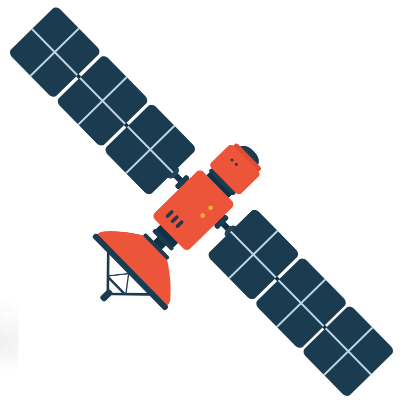


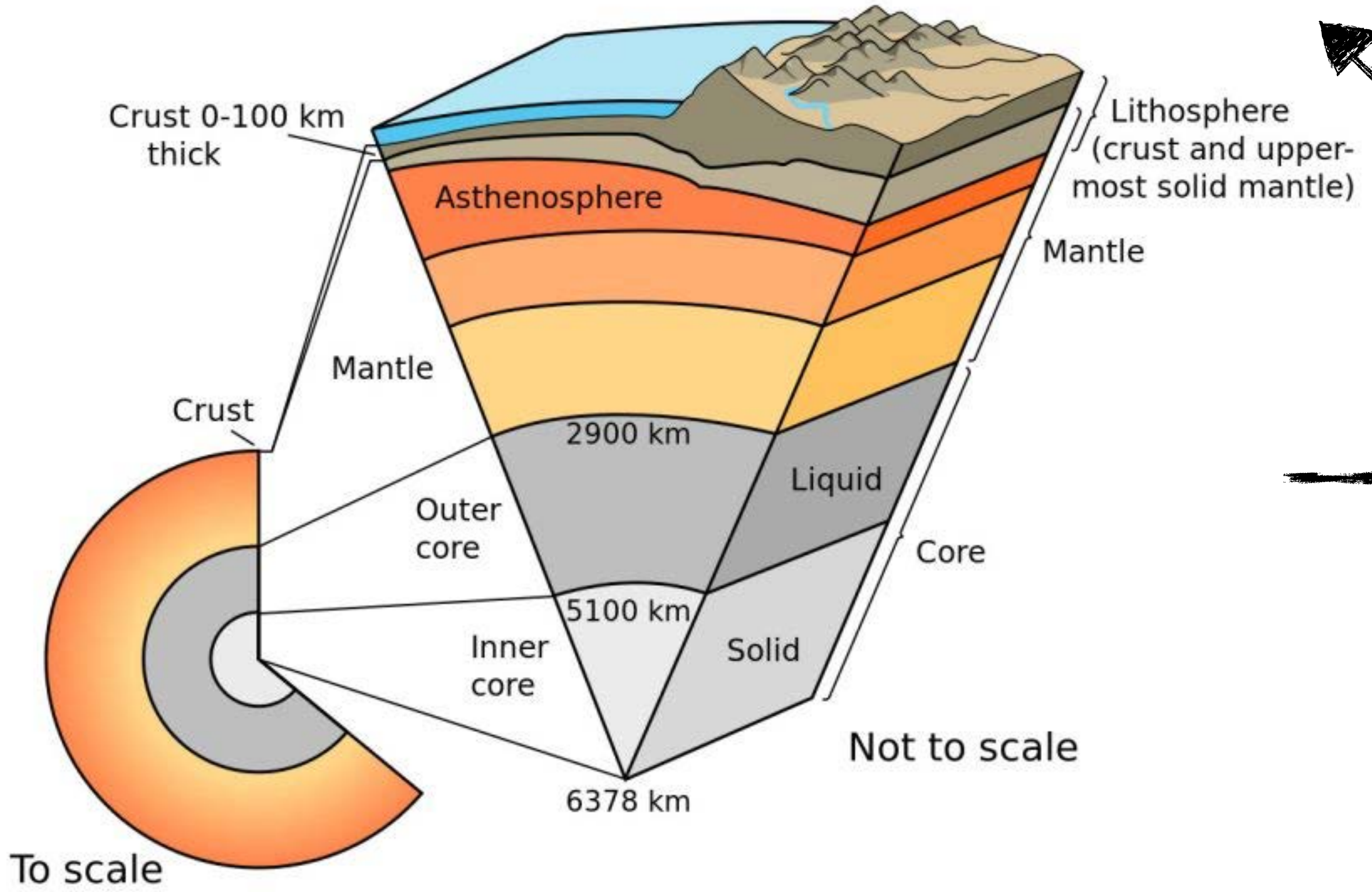
Observations?

Deformation

Load

theory/model

Rheology



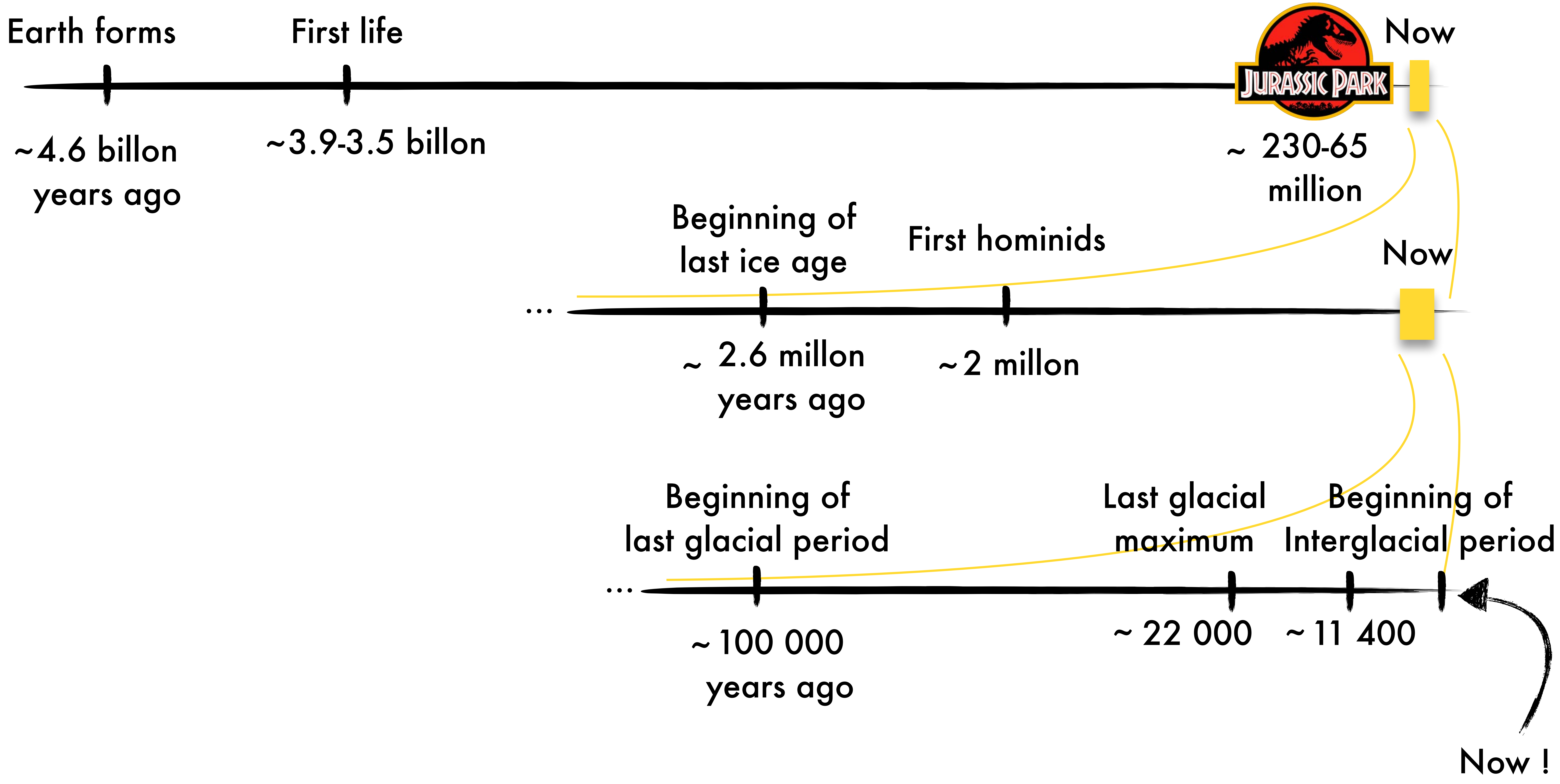
Rheology of the Earth's mantle

Link to laboratory derived rheologies?

The (almost) perfect case of Glacial Isostatic Adjustment (GIA)

1. What is GIA and why study it?
2. Theory: general concepts, modelling and rheology
3. Observations : constraining ice history and monitoring deformation

The Glacial... what?



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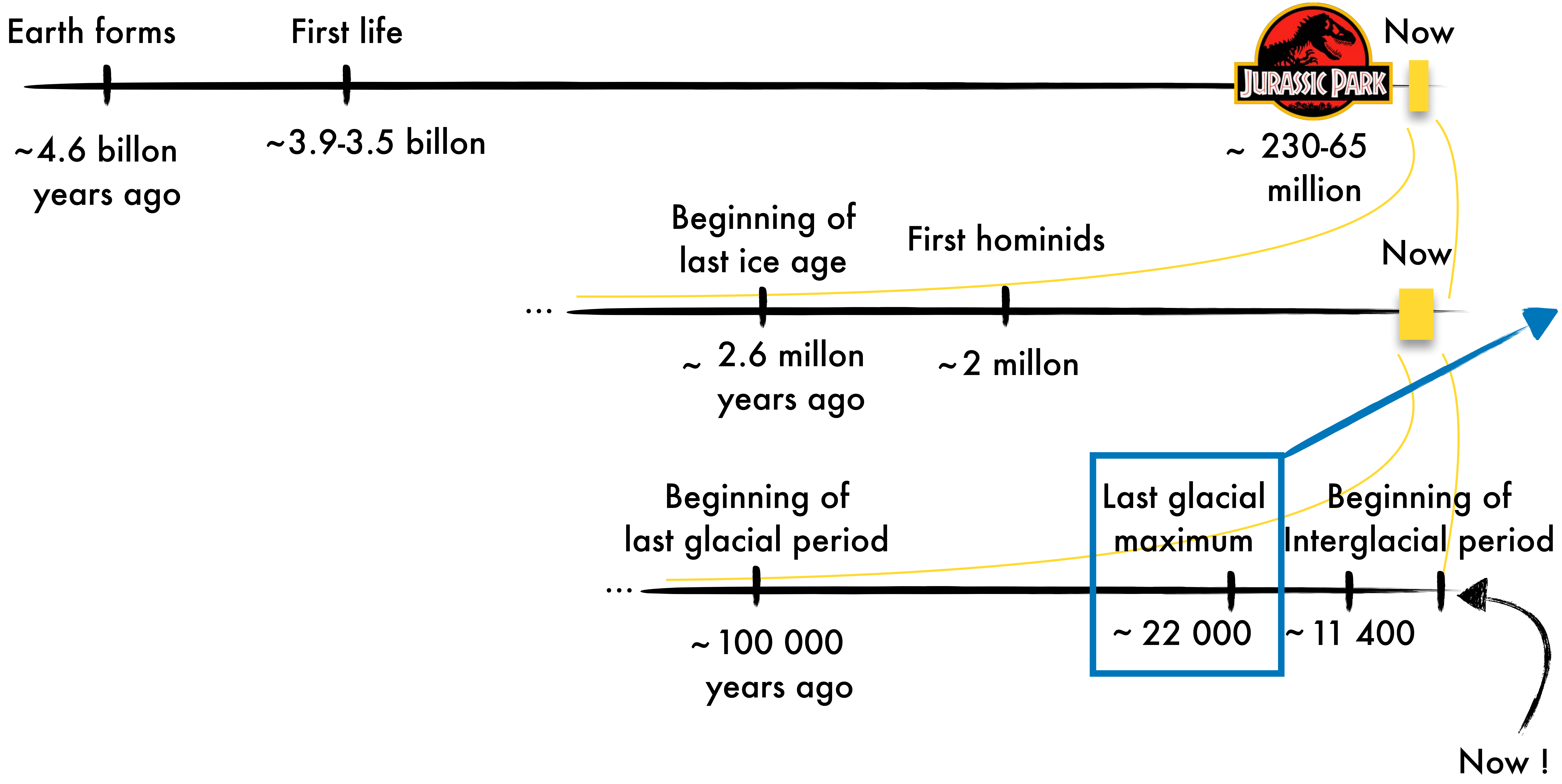
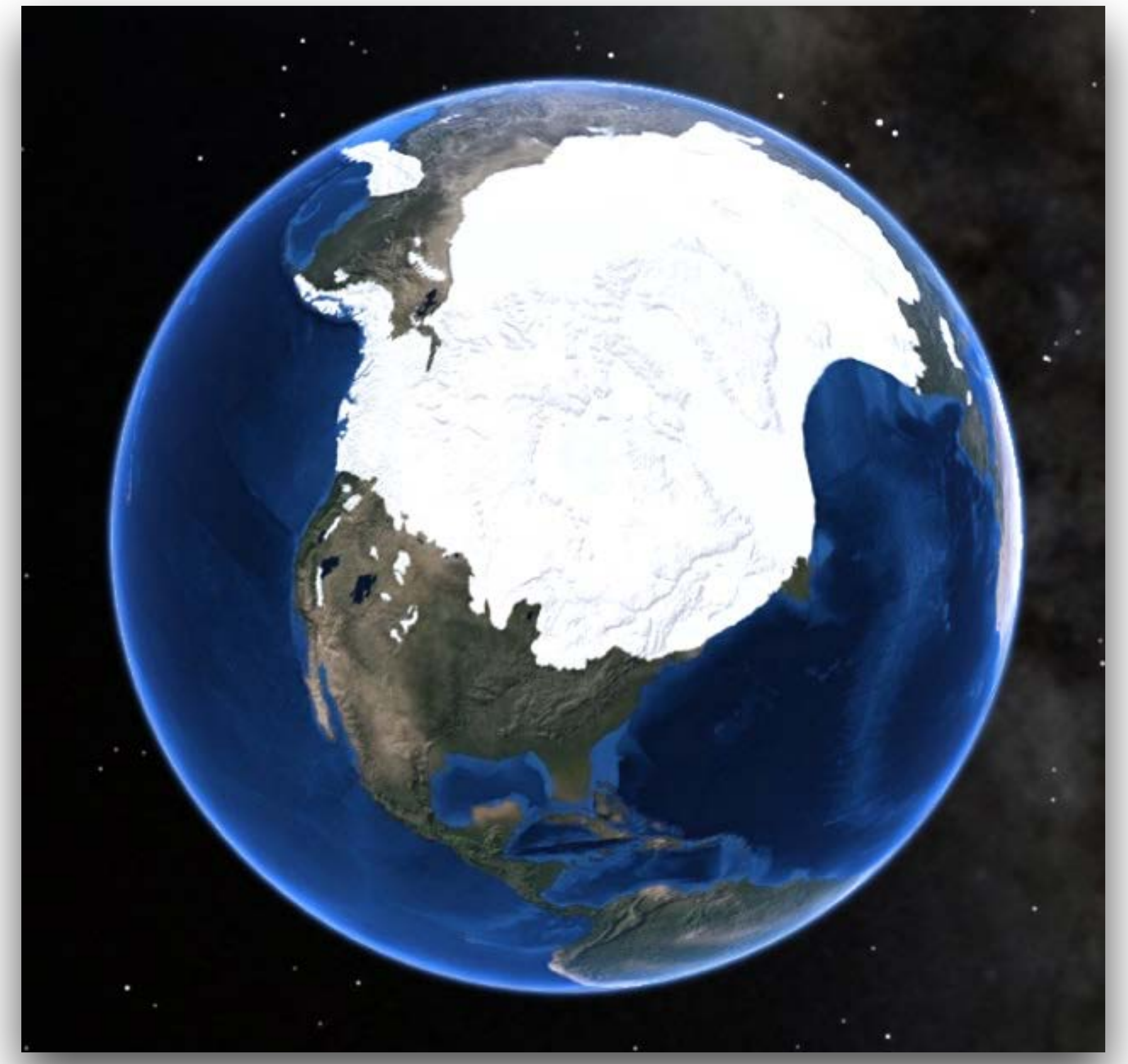


The last glacial maximum
LGM



@NOAA

- Thick ice sheets
- Sea level 120m lower than today

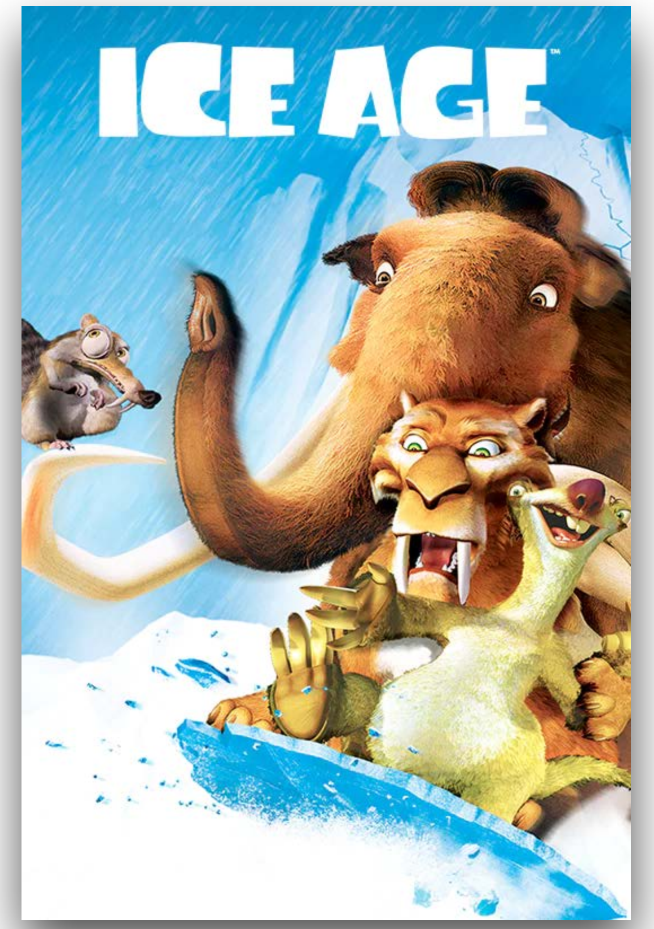
The Glacial… what?

Earth forms — ~4.6 billon years ago
First life — ~3.9-3.5 billon
JURASSIC PARK — ~ 230-65 million
Now

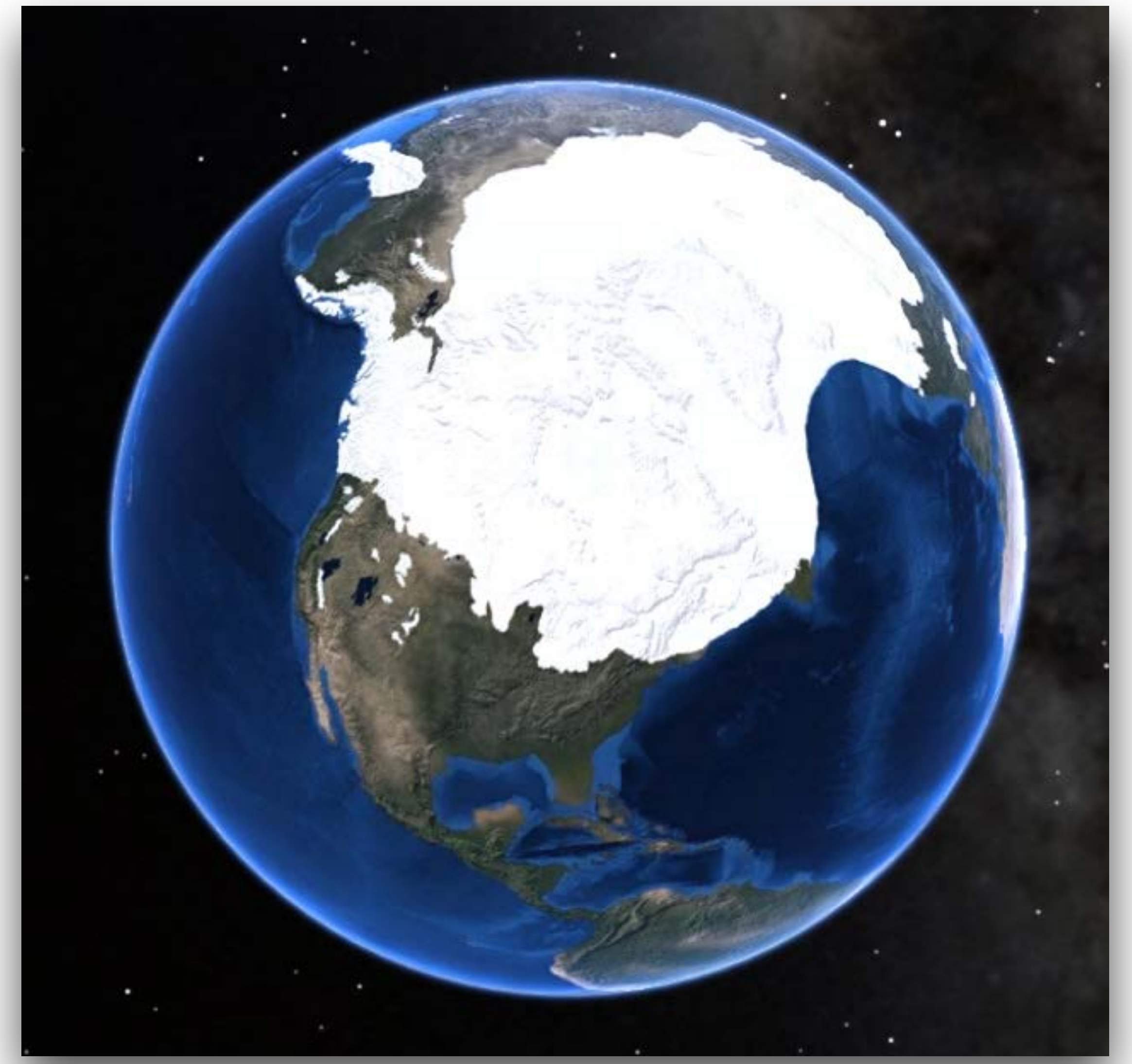
...
Beginning of last ice age — ~ 2.6 millon years ago
First hominids — ~2 millon
Now

...
Beginning of last glacial period — ~100 000 years ago
Last glacial maximum — ~ 22 000
Beginning of Interglacial period — ~ 11 400
Now !

A cycle?



The last glacial maximum
Ice Age



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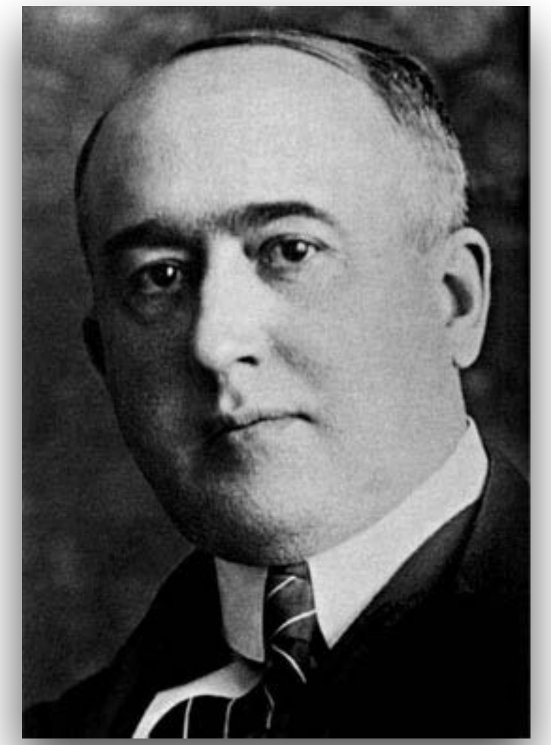

Milutin Milanković
(1879-1958)

"the long-term, *collective effects of changes in Earth's position relative to the Sun are a strong driver of Earth's long-term climate*, and are responsible for triggering the beginning and end of glaciation periods"

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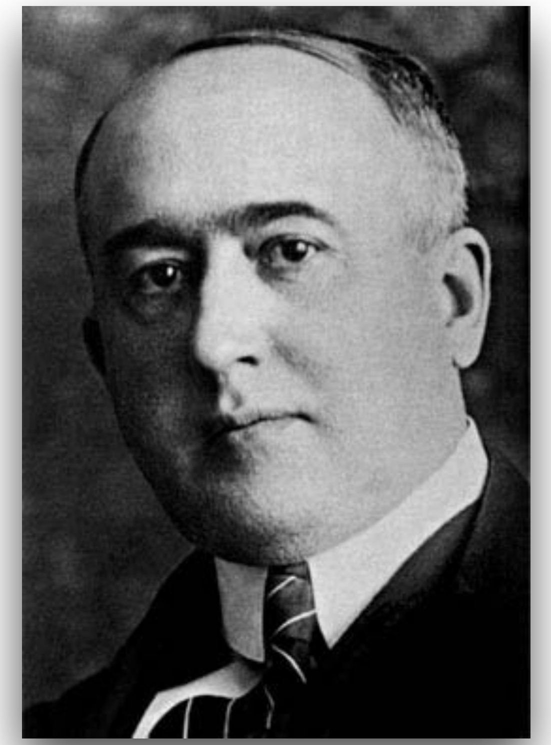

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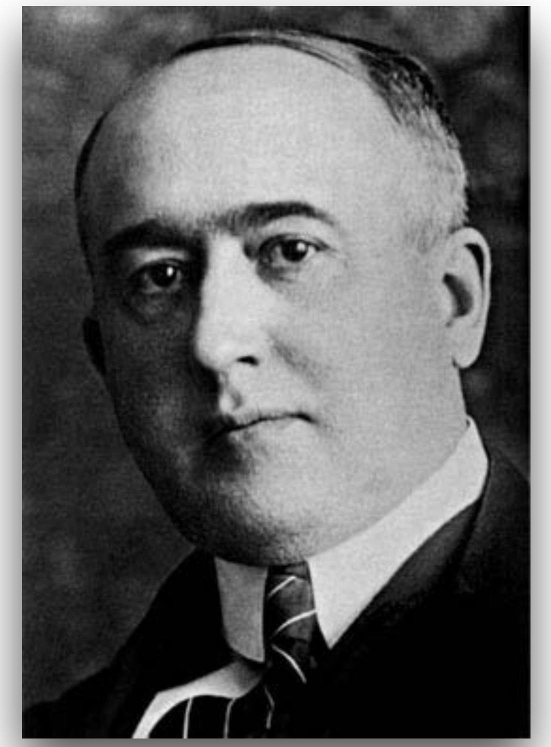

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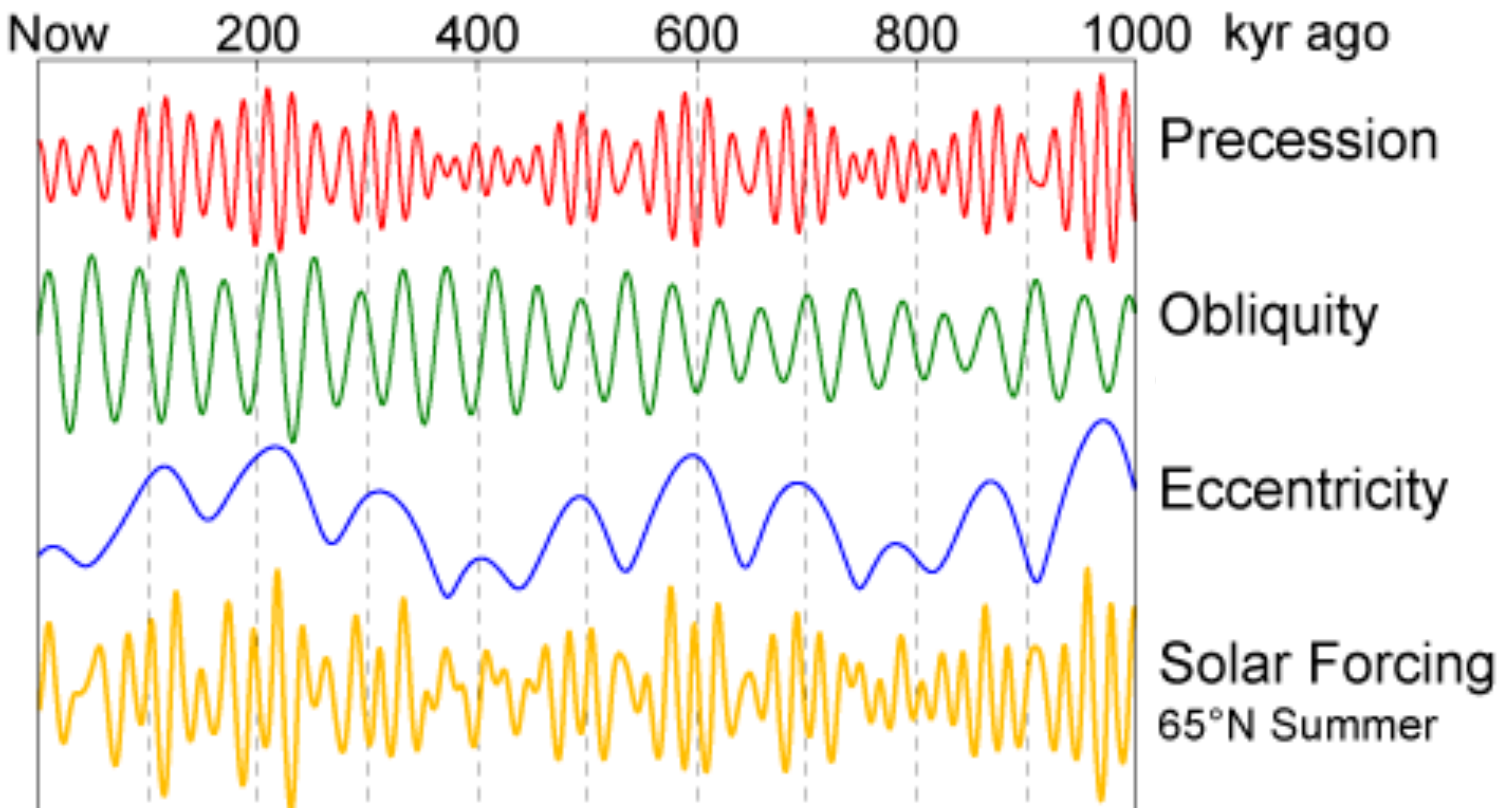
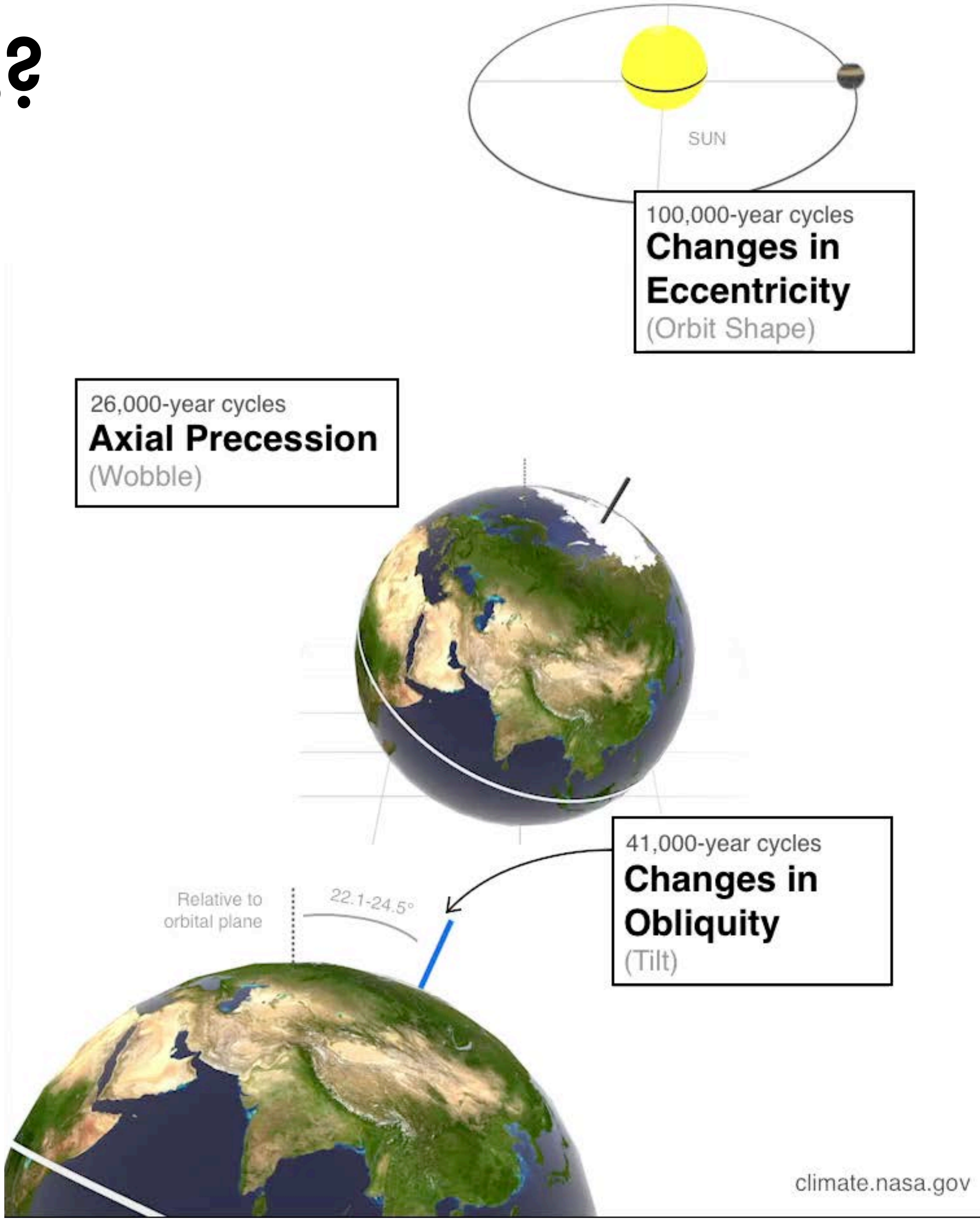


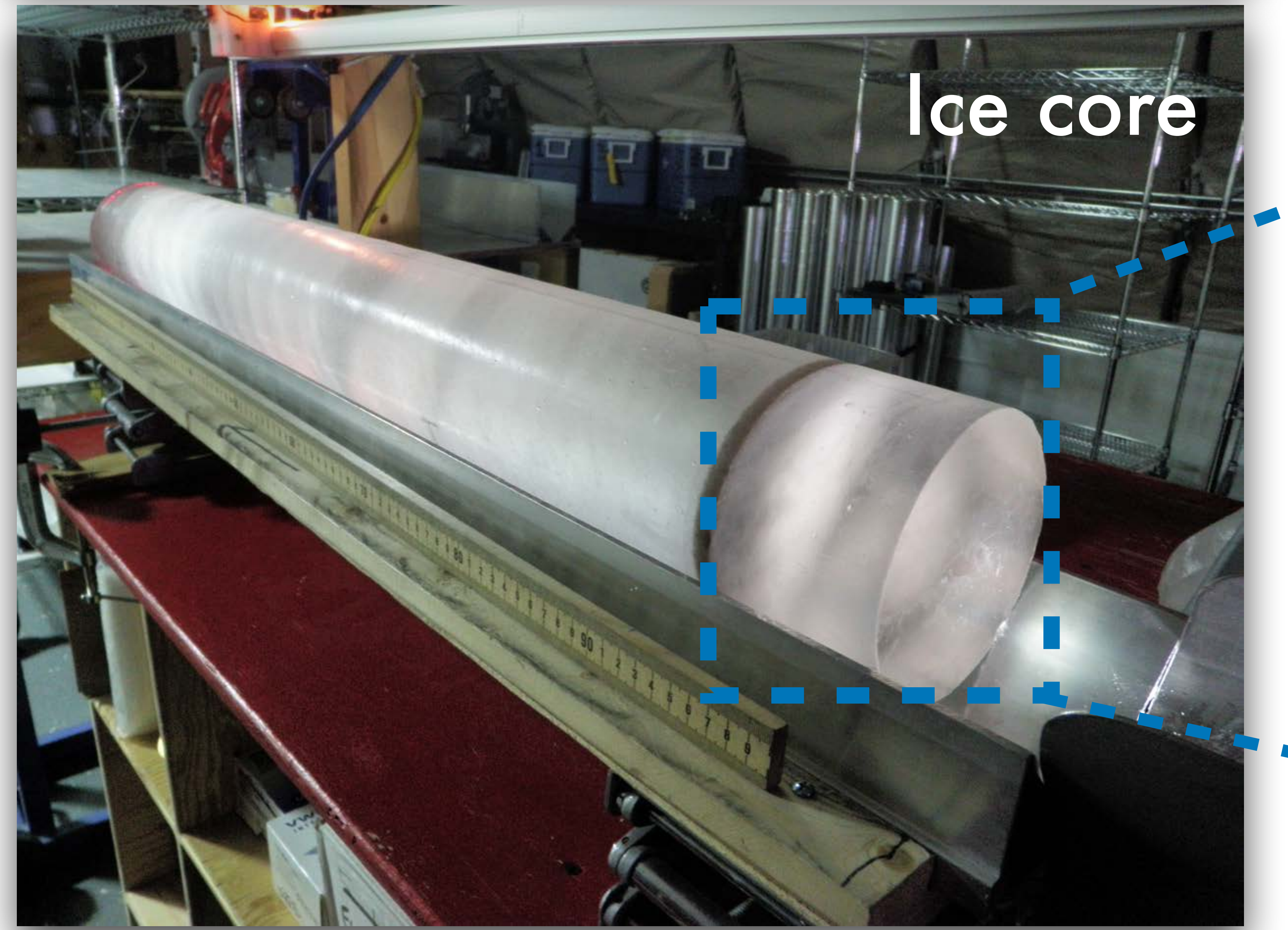


Building ice sheets season by season

Building ice sheets season by season

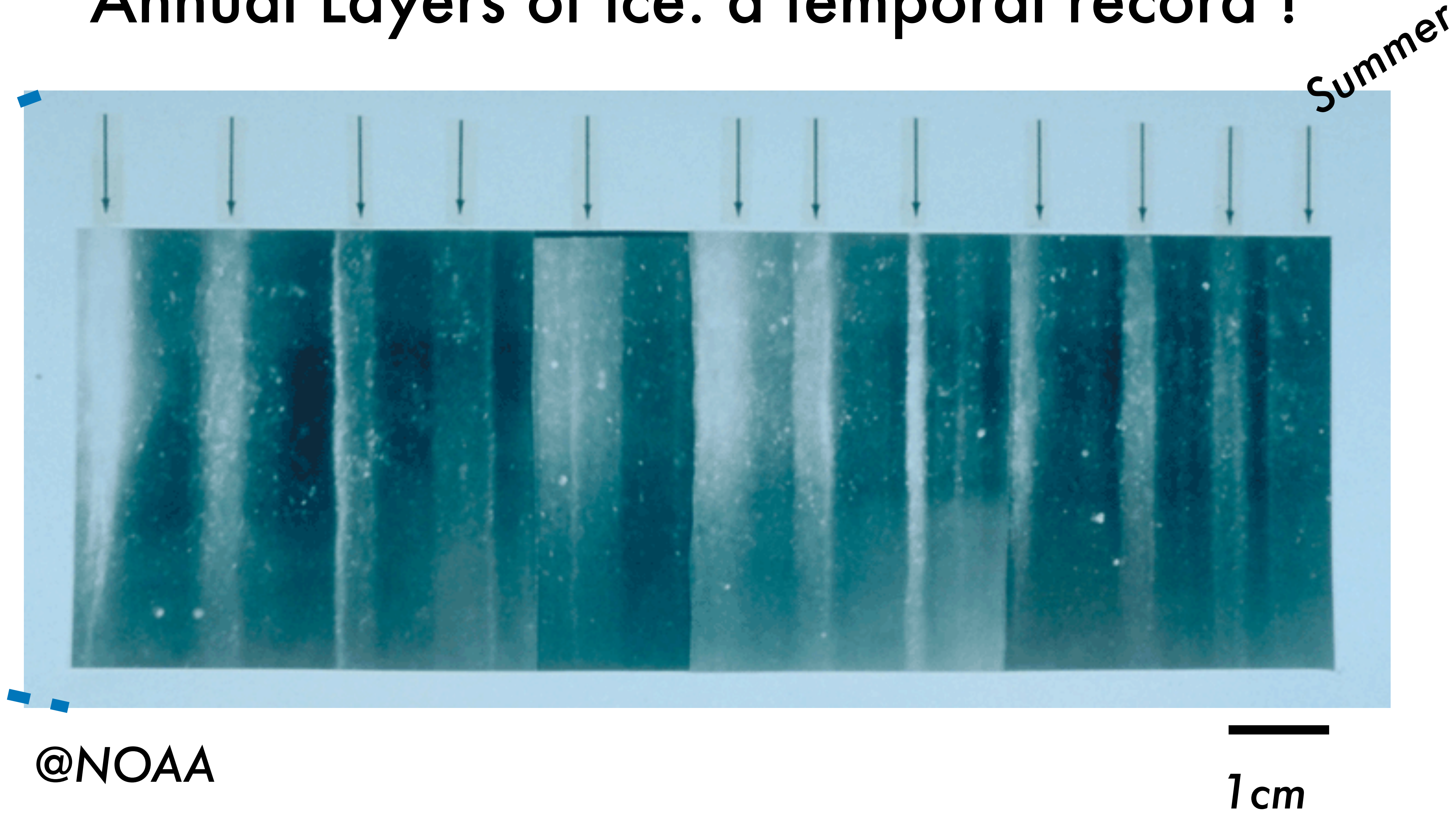
Temperature record is written into the ice

@ Clark, Univ. Washington



@Roop, NSF

Annual Layers of ice: a temporal record !



@NOAA

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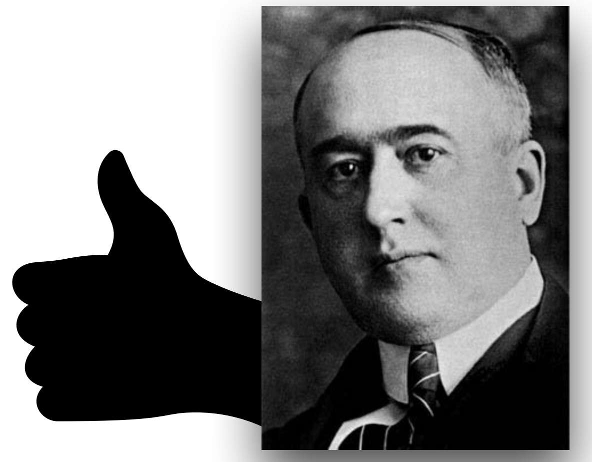

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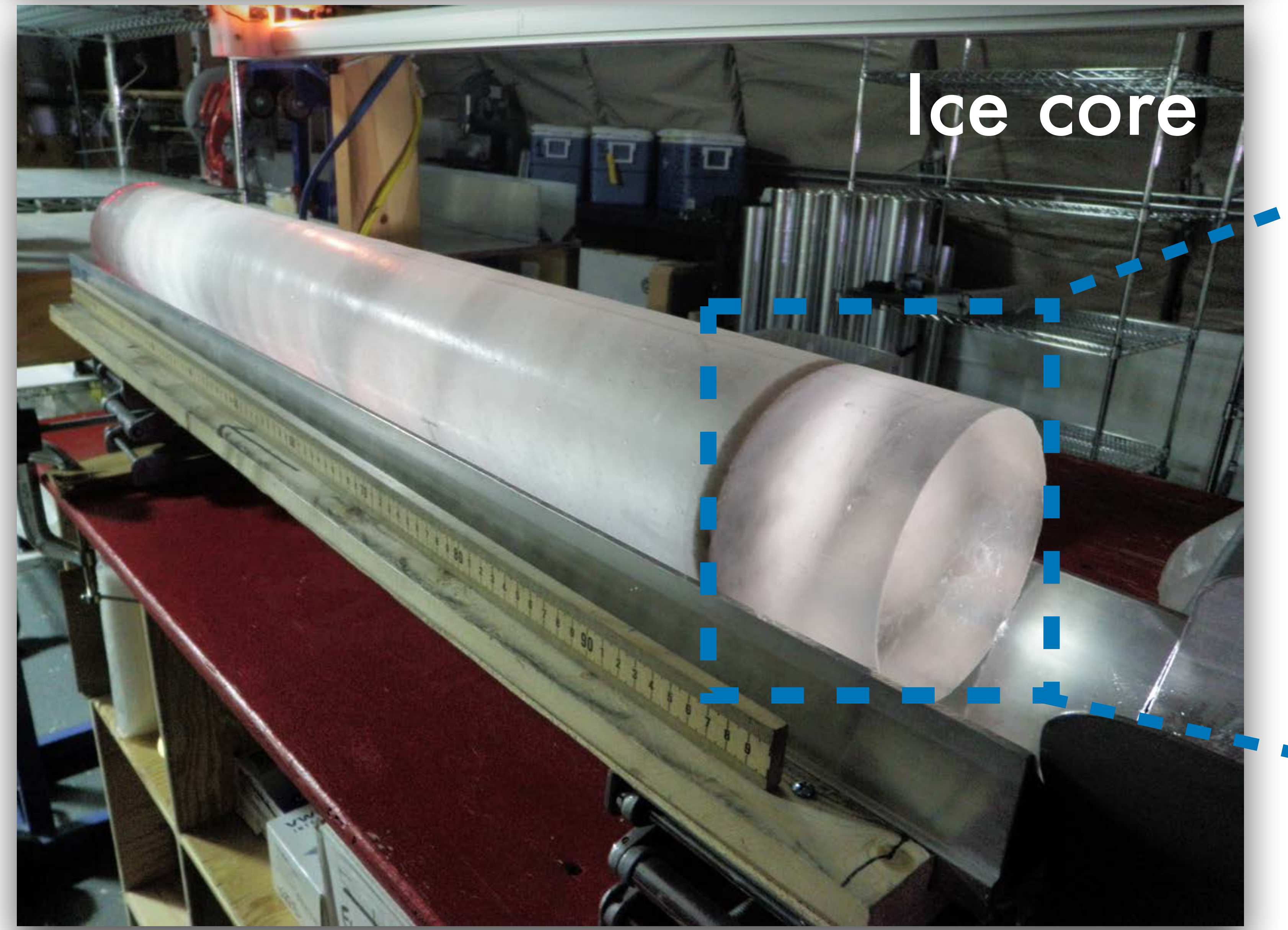
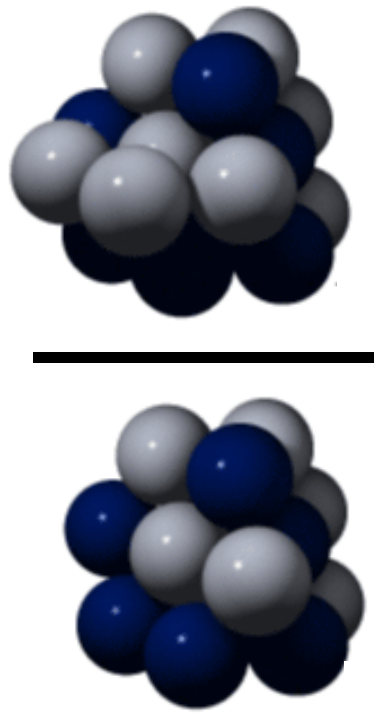


HEAVY!



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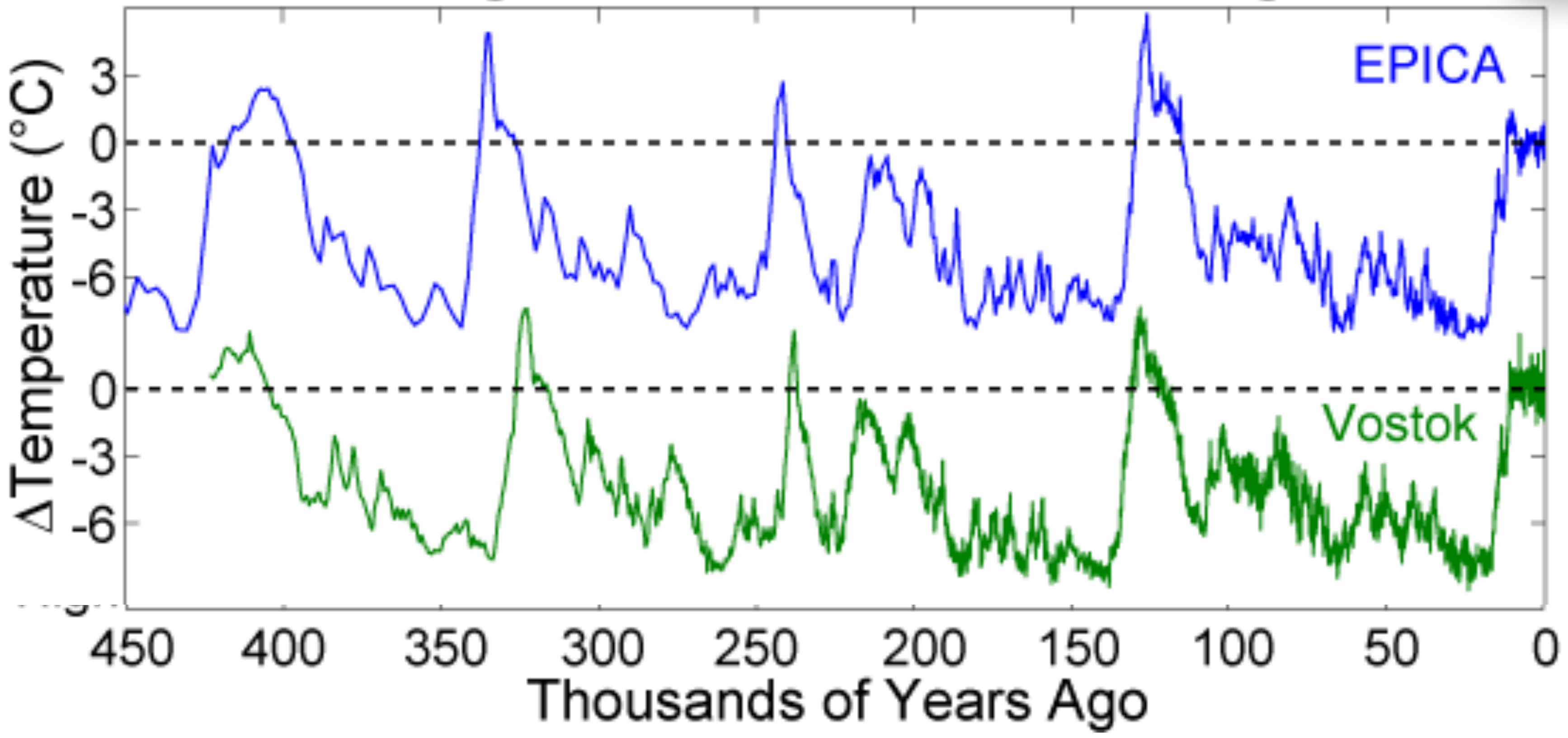
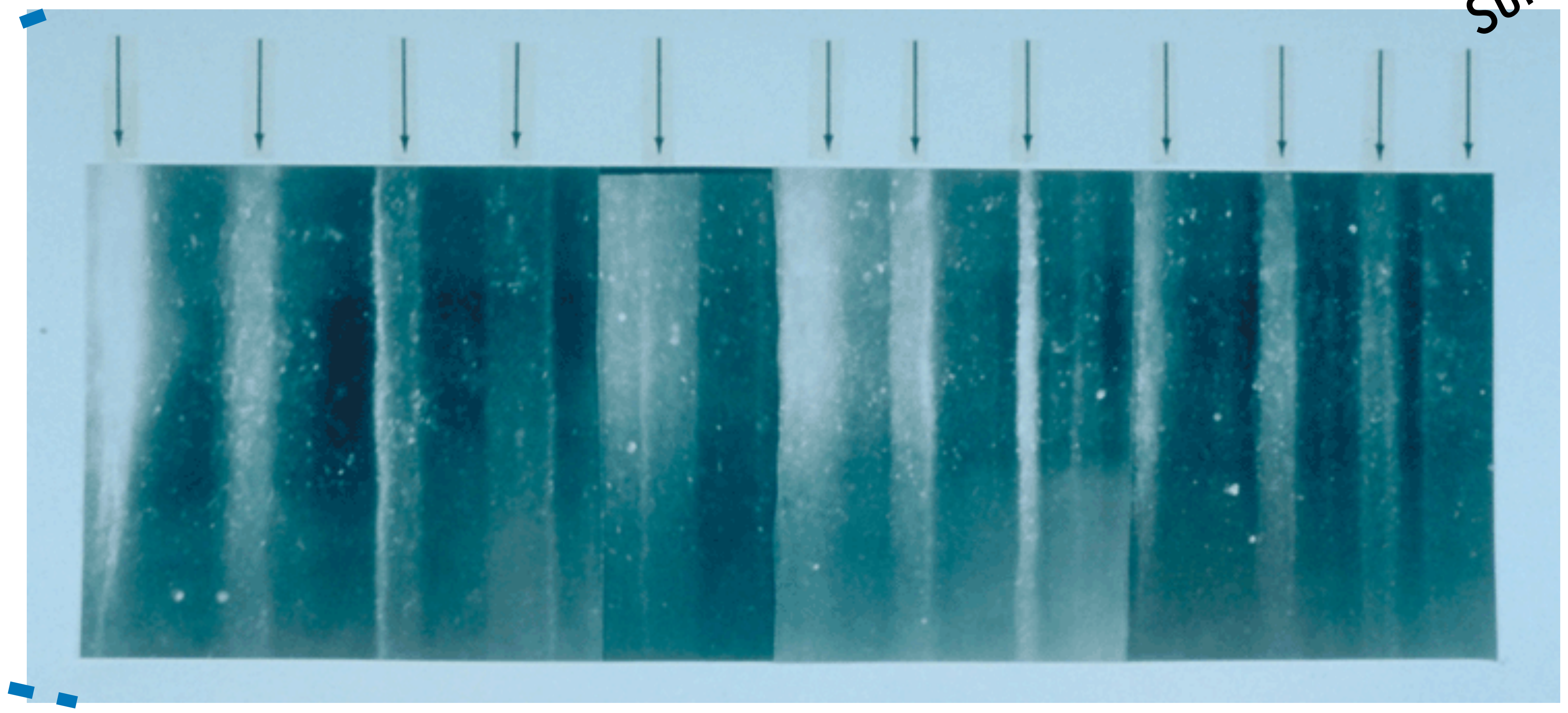


Annual Layers of ice: a temporal record !

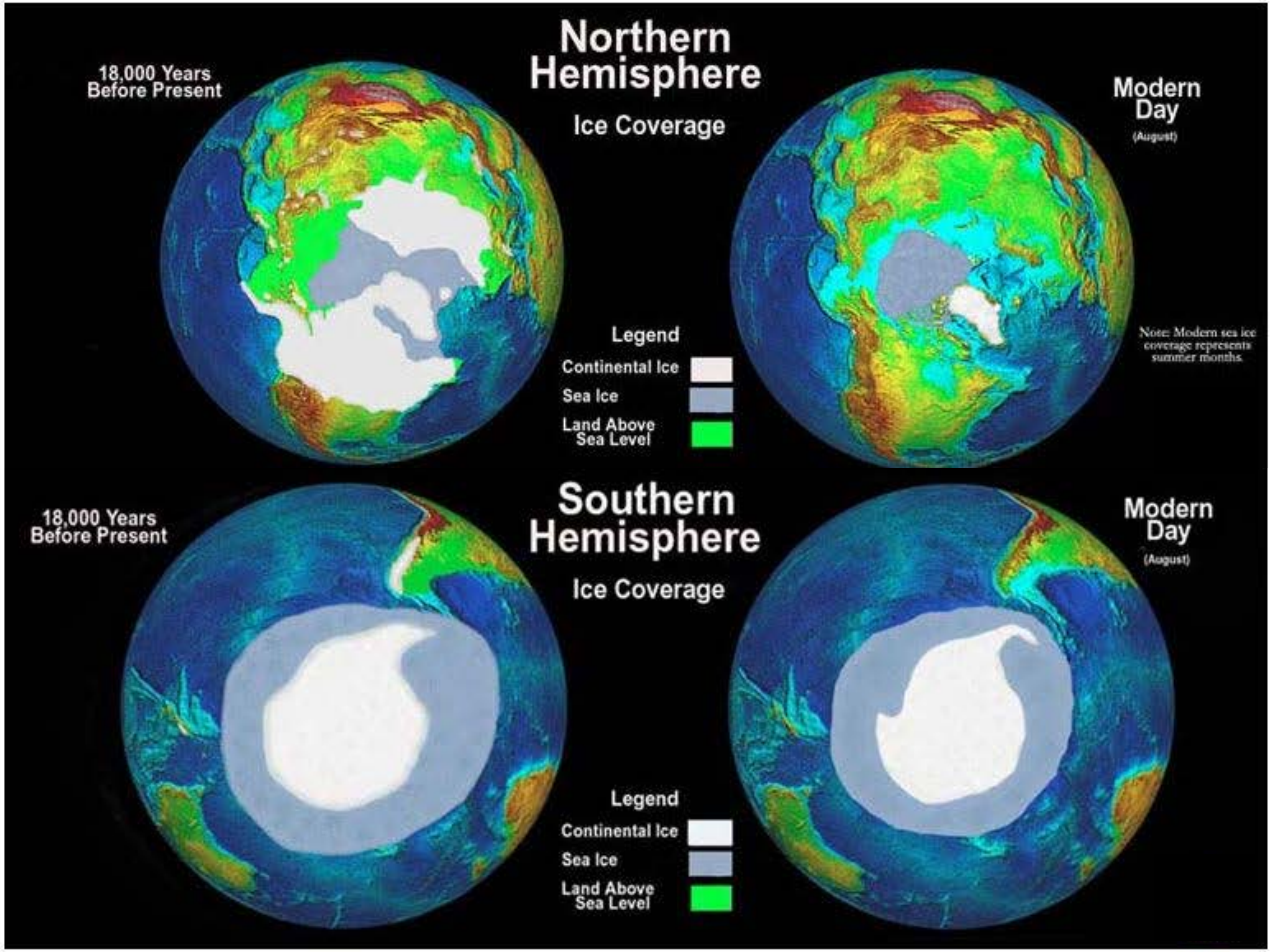
Summer



@NOAA

1cm

Ice Sheets “recent” evolution



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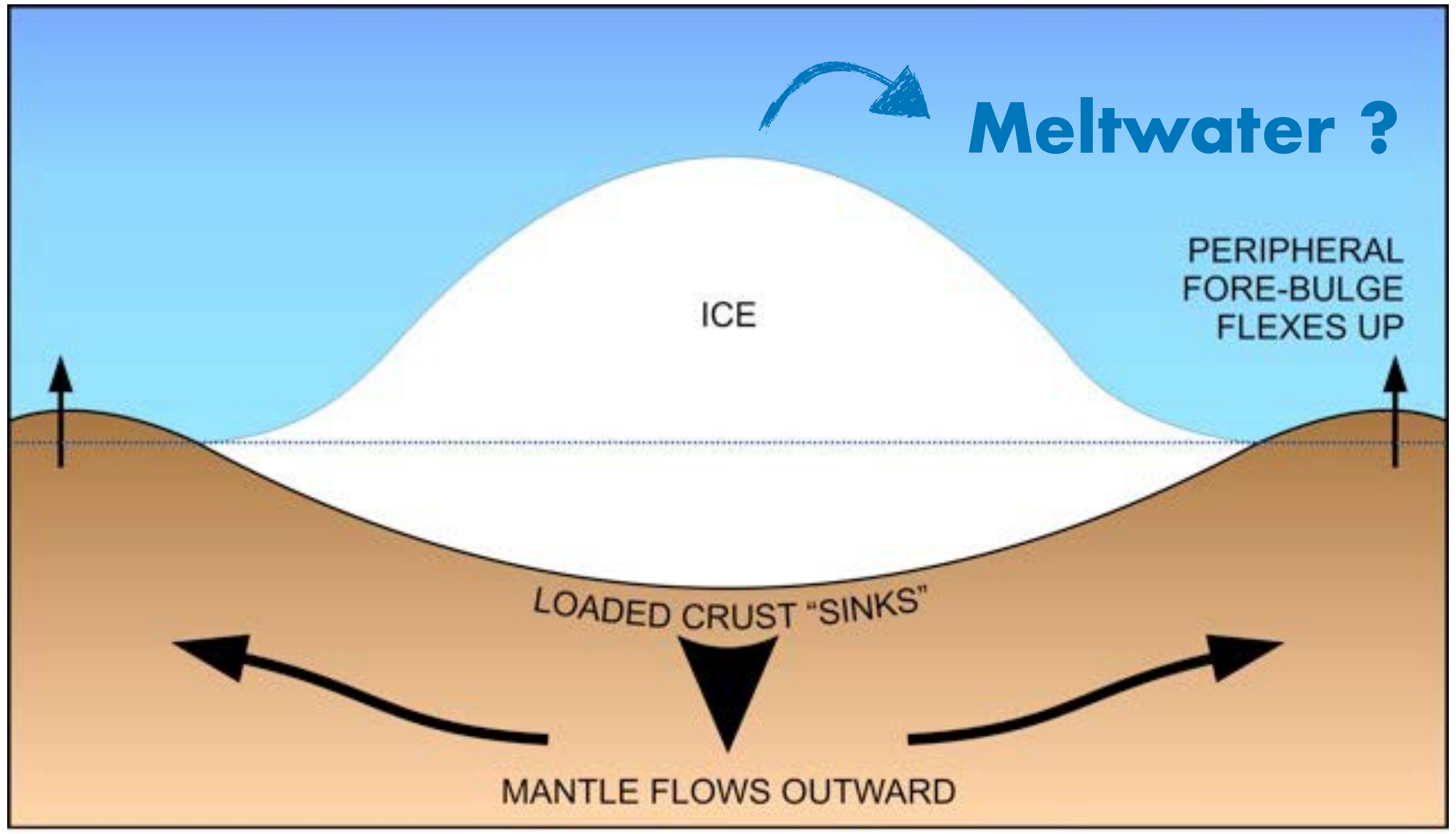
Glacial Isostatic Adjustment (finally!)

A classic geodynamical problem of determining the Solid Earth response to changes in ice and ocean surface loading



@UNAVCO

Gravity change, 3D crustal motion

Glacial Isostatic Adjustment (finally!)

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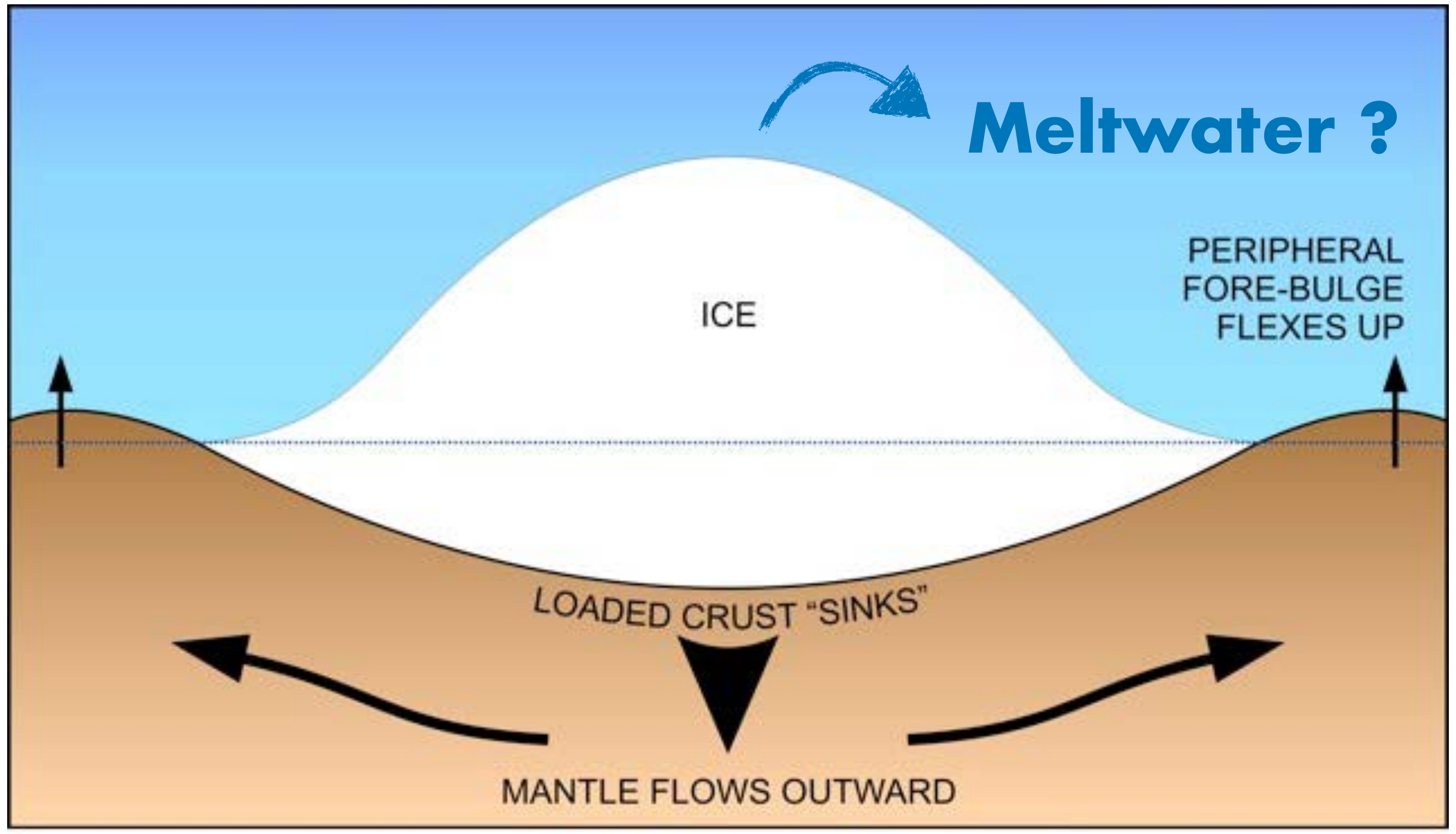
... and solving for a gravitationnally-consistent redistribution of ice and meltwater across the ocean



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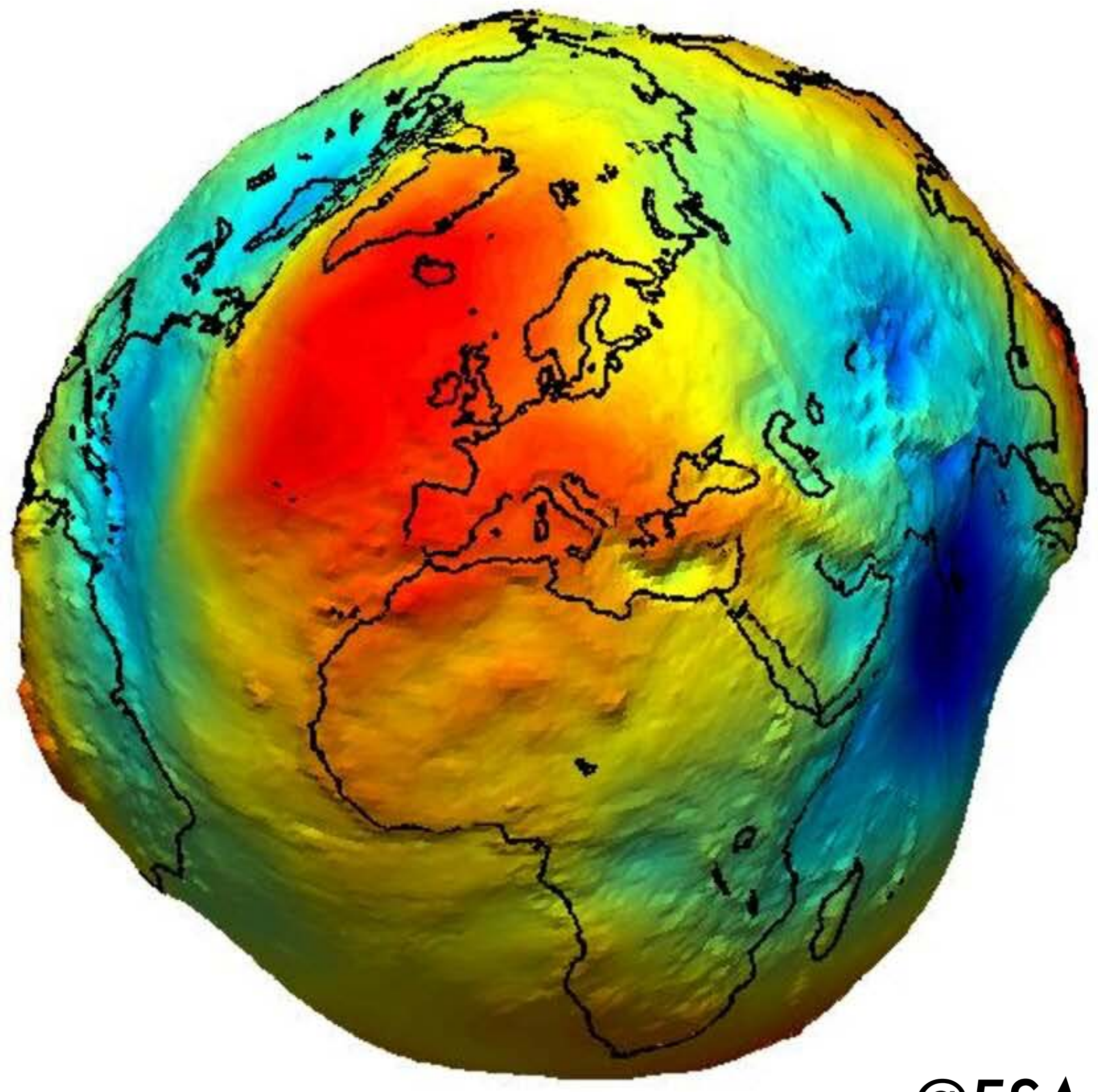

@ESA

Gravity change, 3D crustal motion

Sea level change, solve for the shape of geoid, Earth rotation perturbation, changing ocean is also a load

Iterative equation

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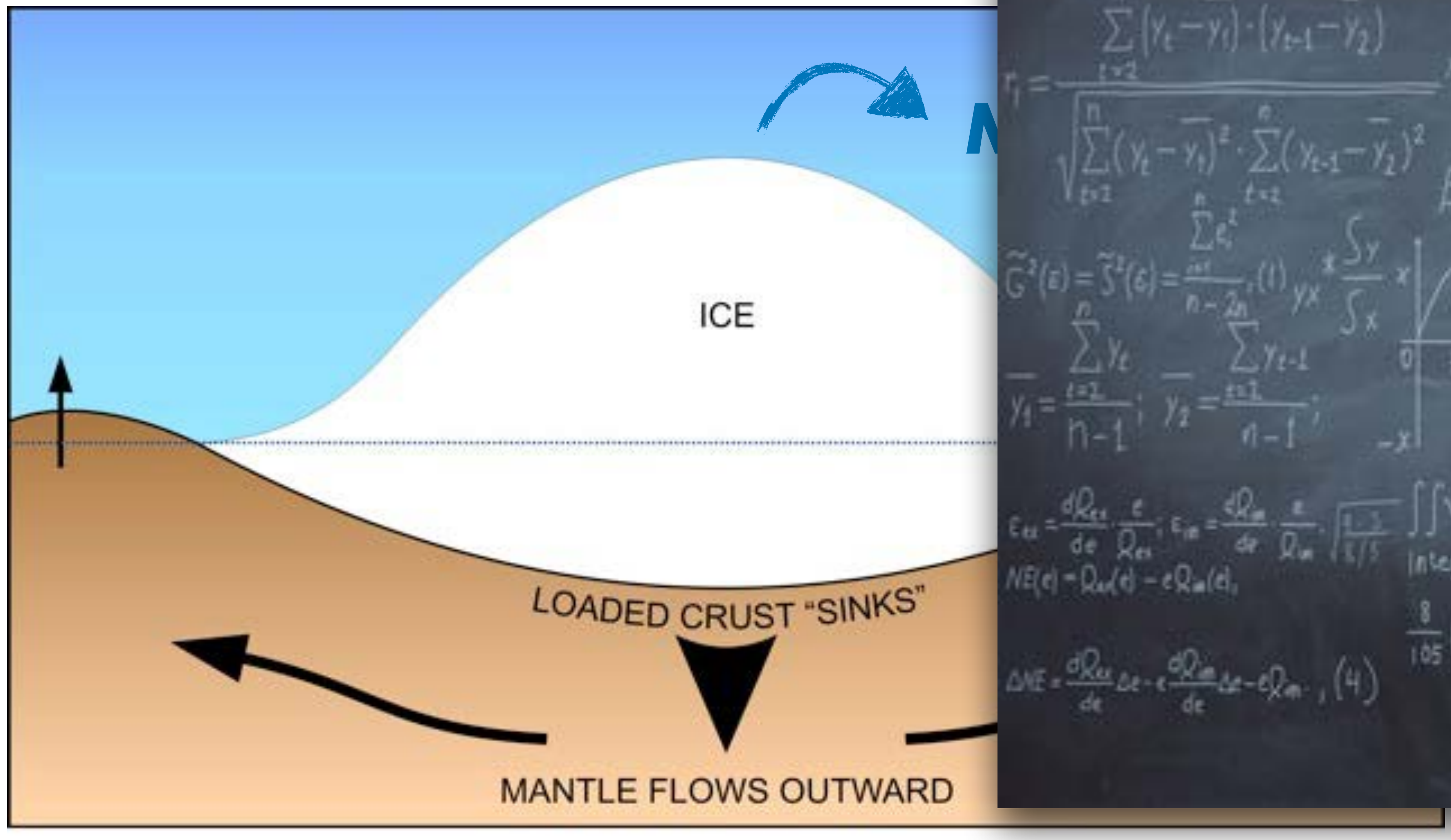

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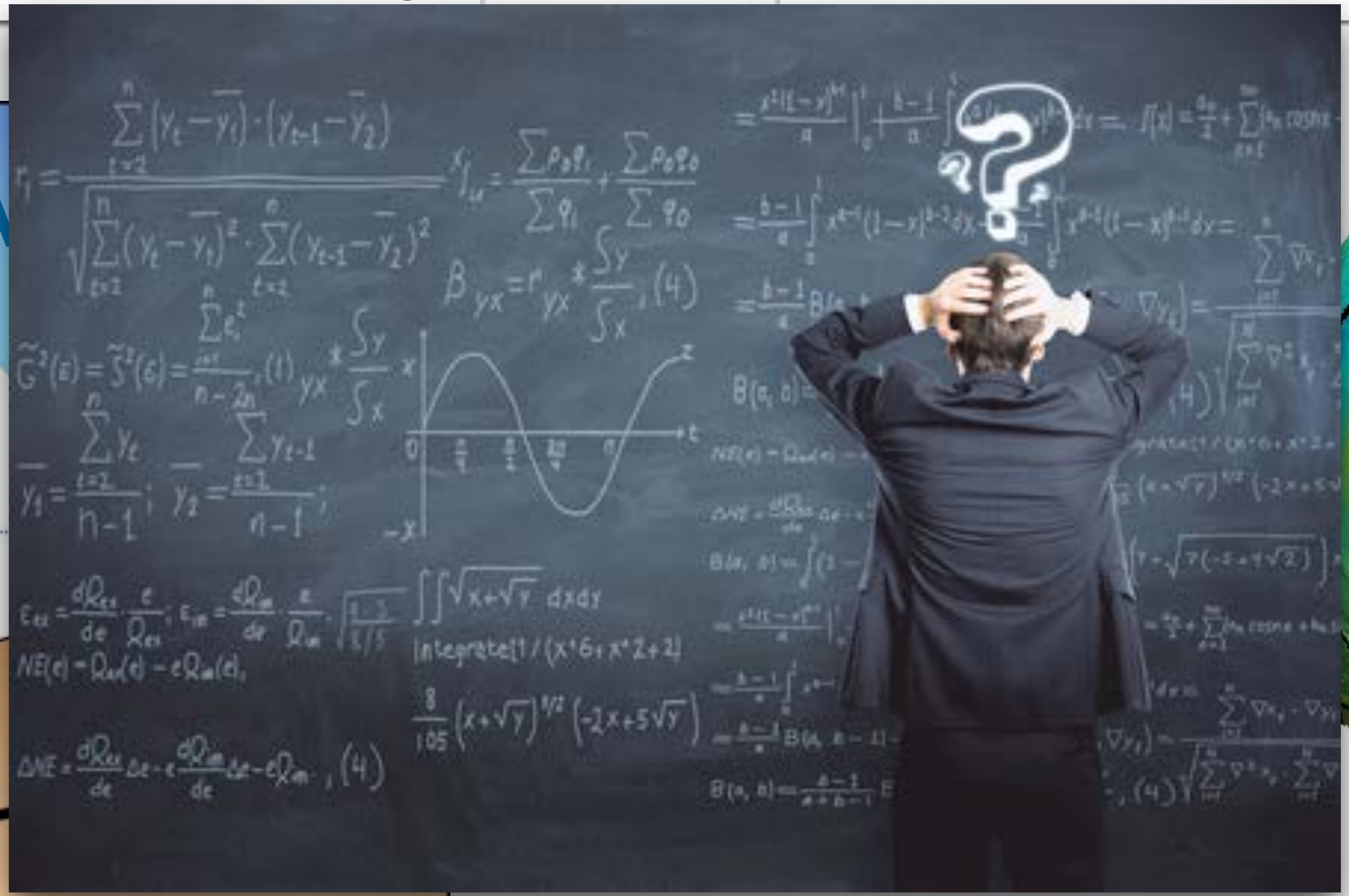

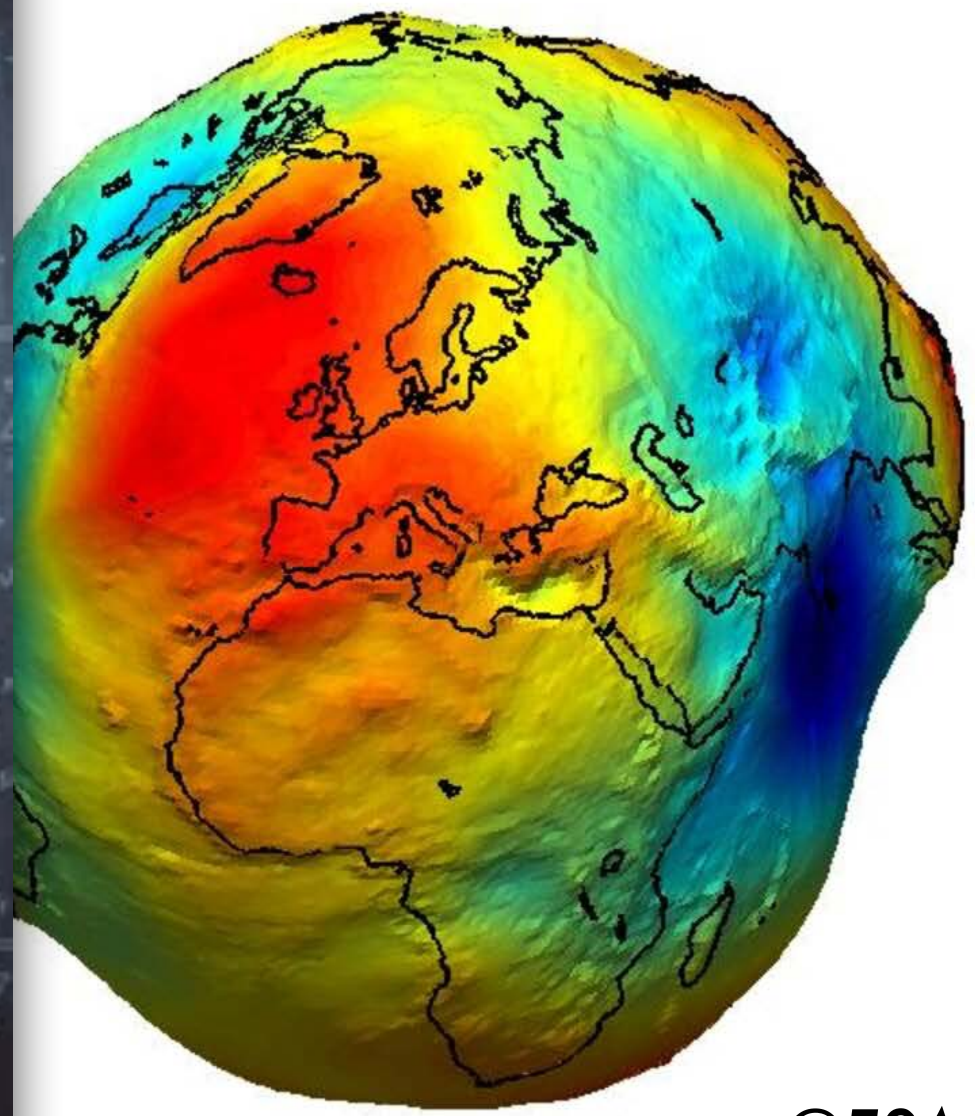

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Iterative equation

GIA, should I care ?

1491
The Swedish government decides to relocate the town of Östhammar because of harbour problems

What is going on?
Why is it going on?
How is it going on?

”During recent years the land has grown outside the town at the sea, so that where some years ago a cargo boat of five or six Swedish läster [about 15 tons] could come from the sea into the town of Östhammar not even a fishing-boat can go nowadays. And the land is still growing and rising every year.”

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Anders Celsius
(1701-1744)

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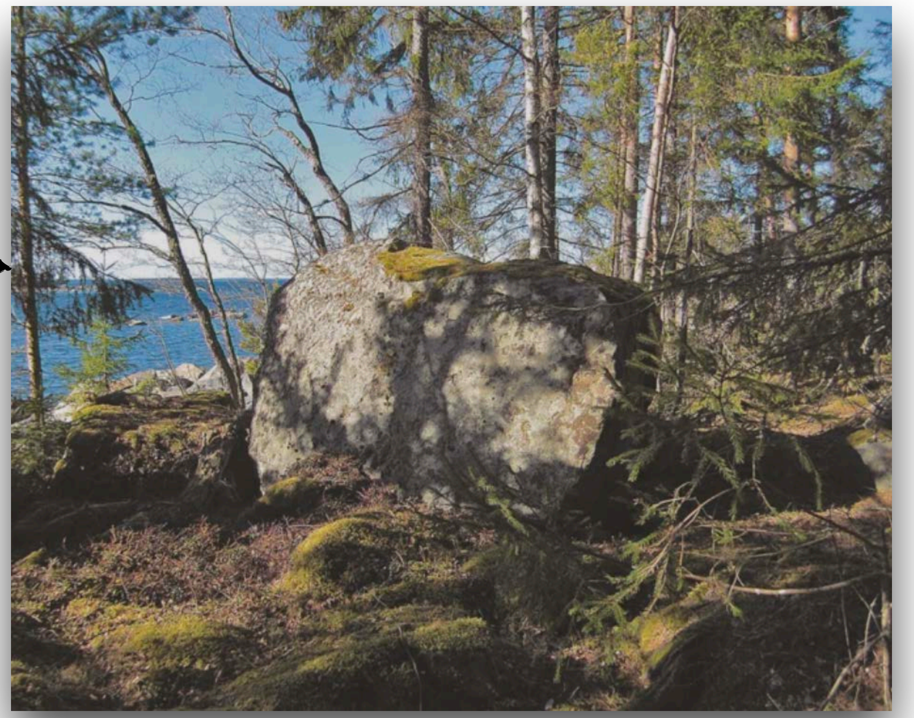
1743 – Land uplift rate: ~1 cm/yr



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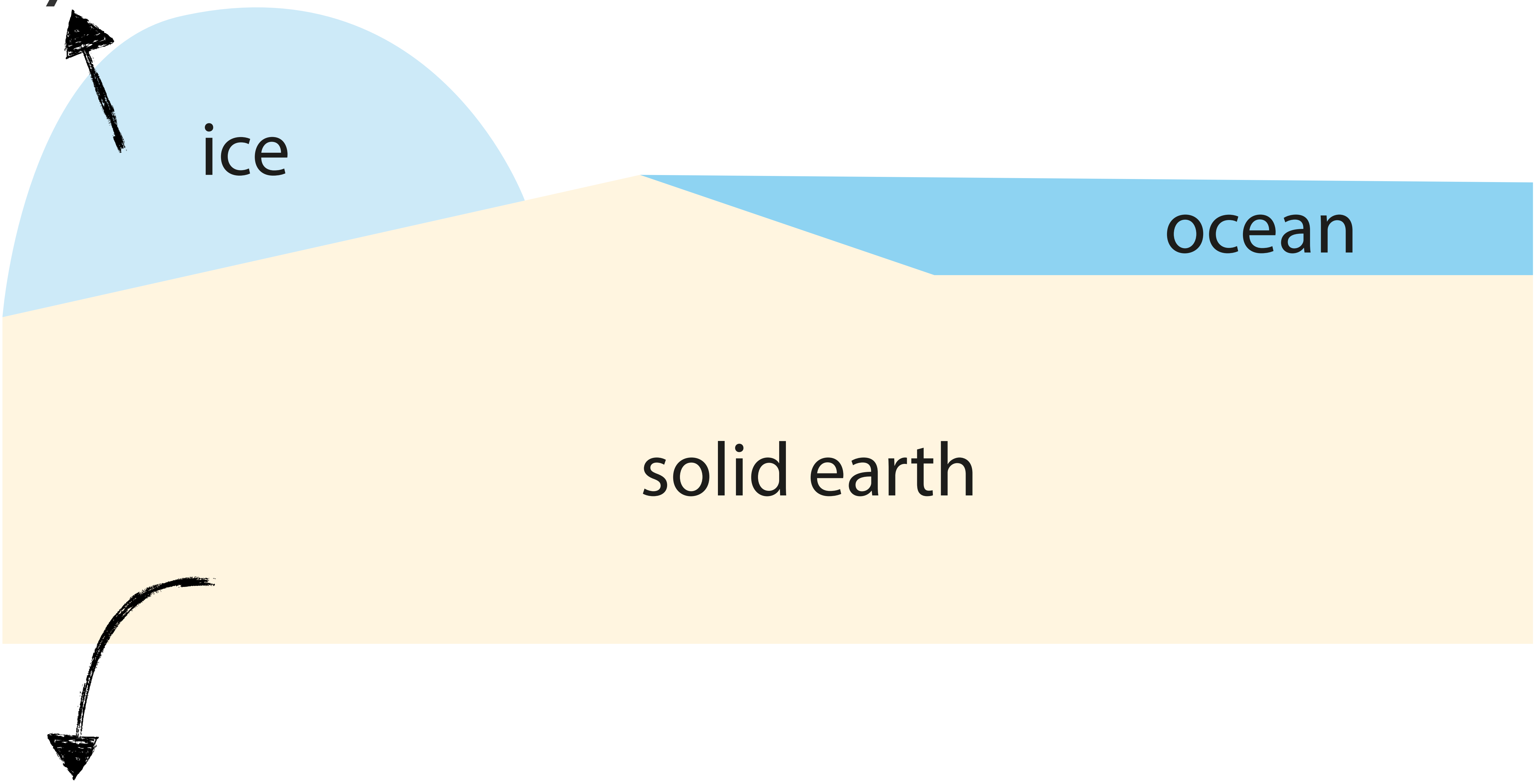
Land uplift: up to several hundreds meters since LGM
up to a few cm/yr

Kiluhiqtuq (Bathurst Inlet), Canada @Beauregard

Lantmäteriet, Sweden @Rehn

Why study GIA today?

What is the history of ice-sheets?
How did they respond to climate change?
How fast is ice melting today?



What is the rheology of the Earth?
Over what timescale and depth is GIA to consider?

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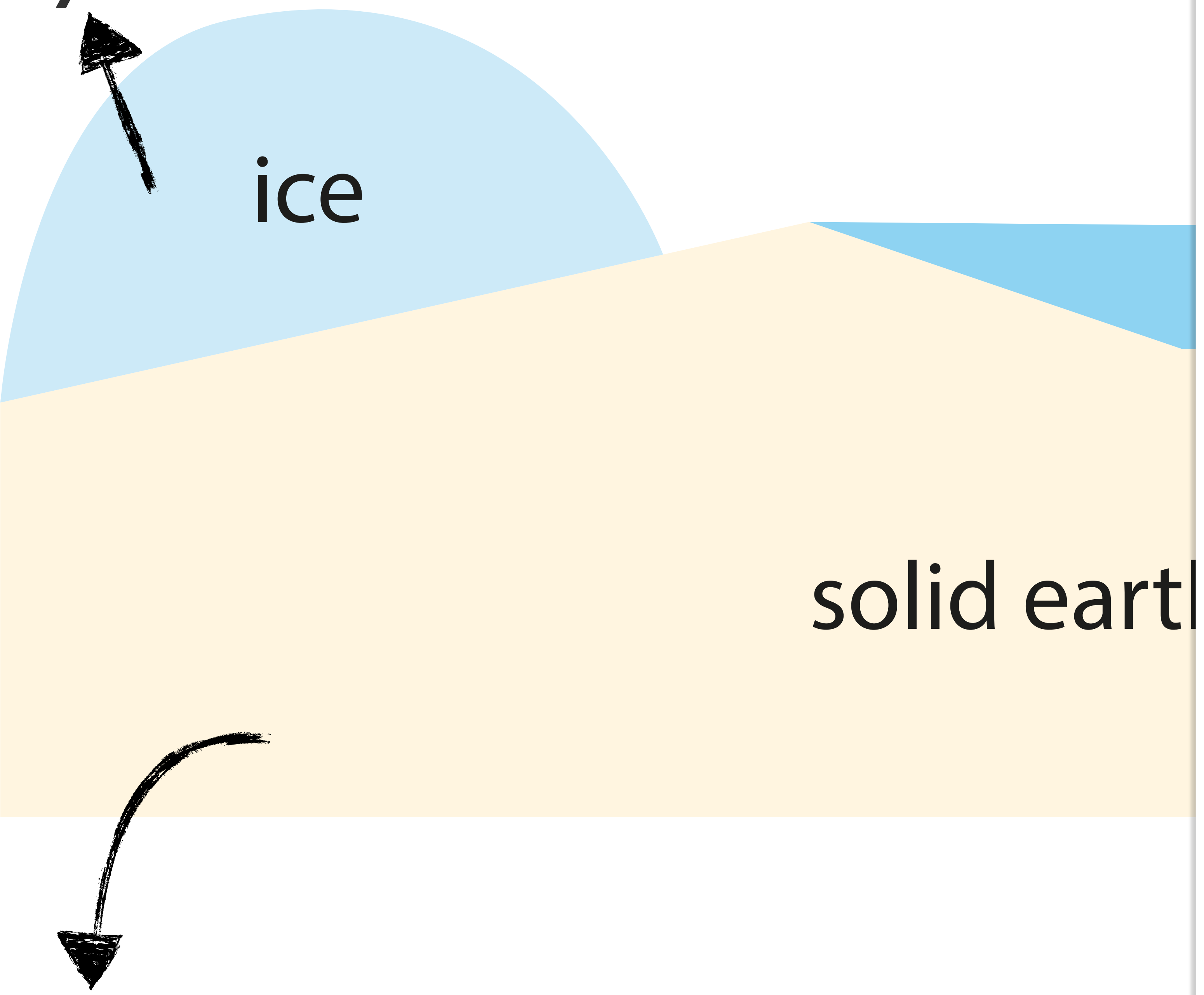

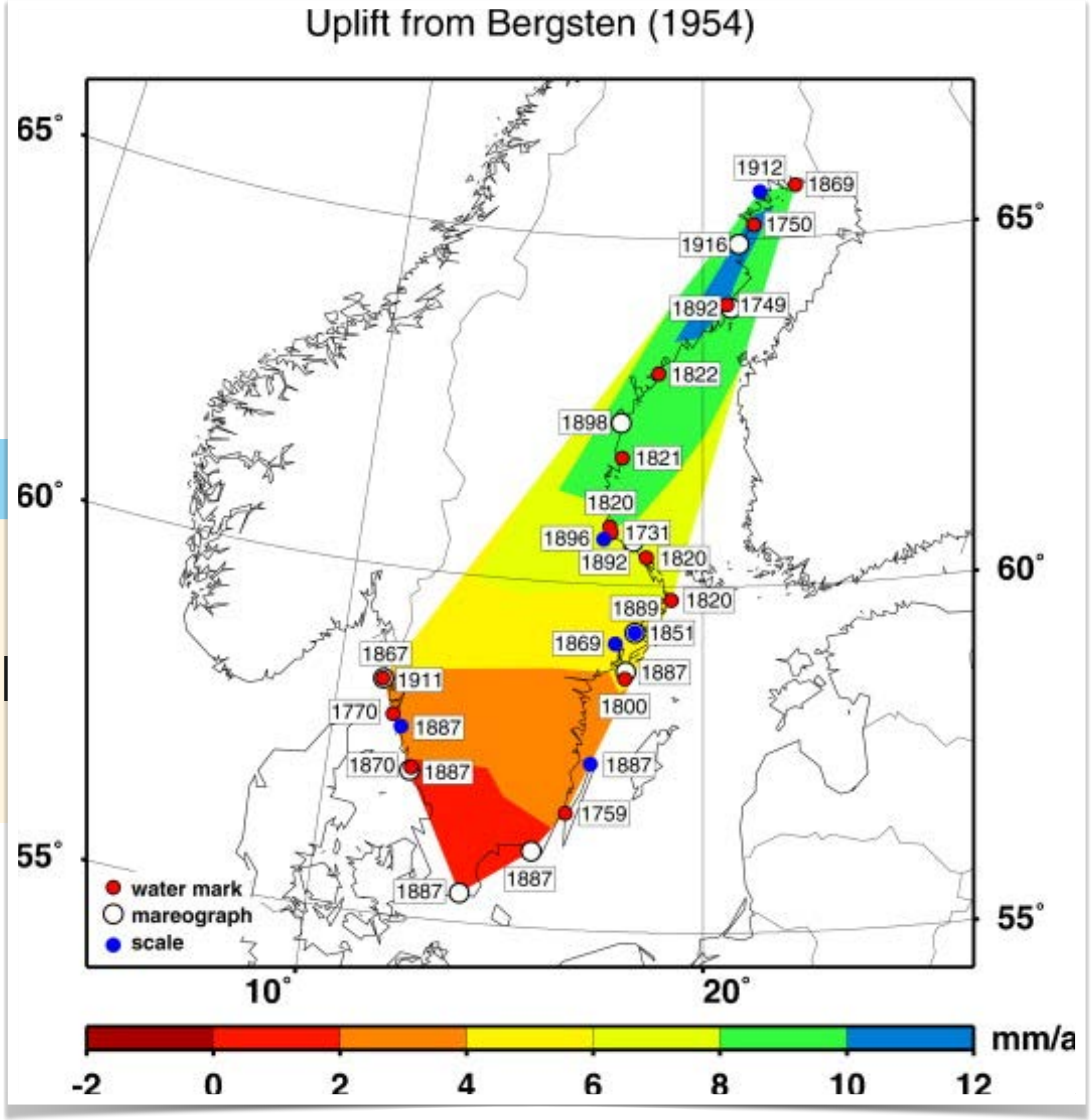

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Steffen & Wu (2011)

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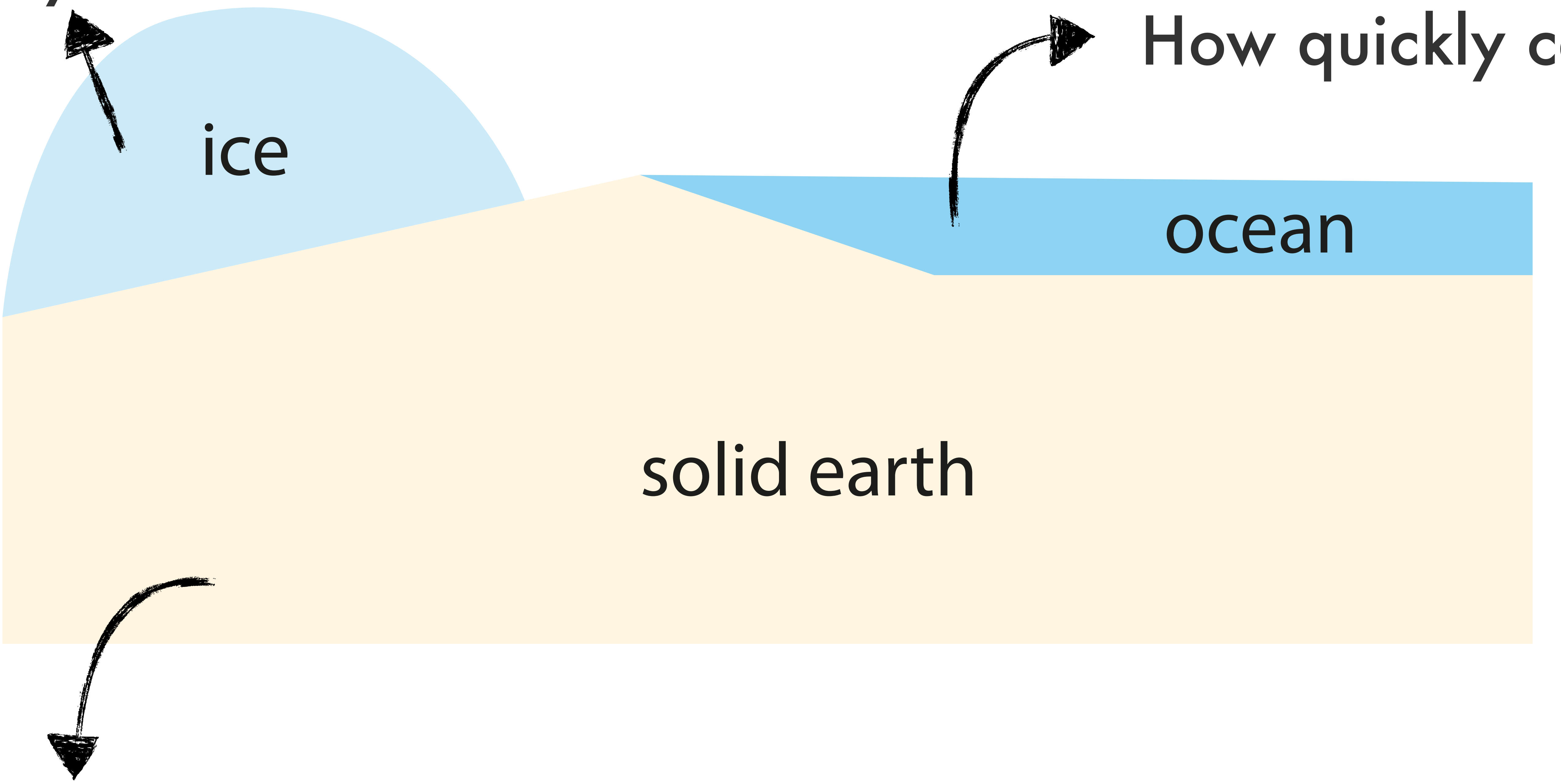
What drives sea-level change today?
How quickly can sea-level change?



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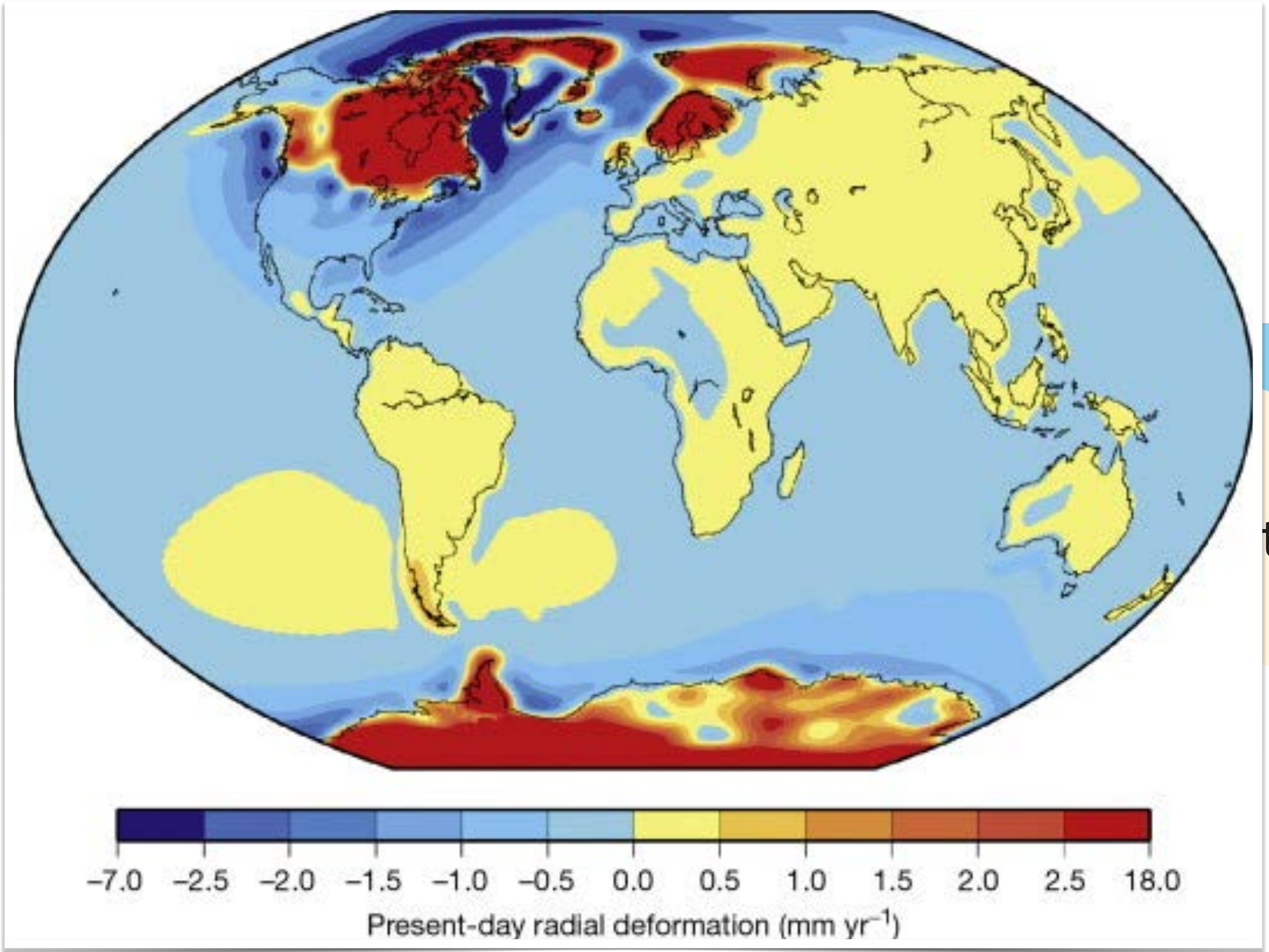

Milne & Shennan (2011)

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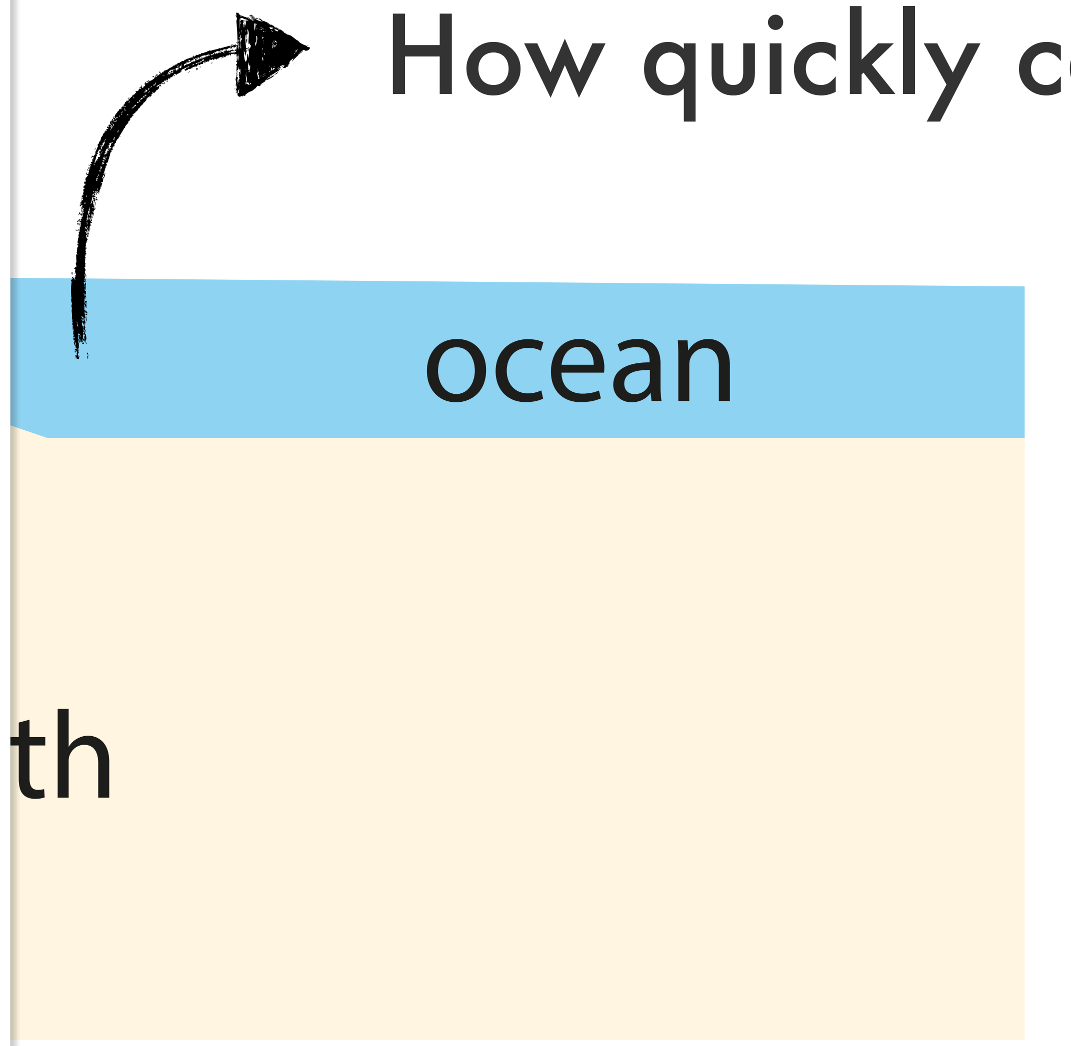

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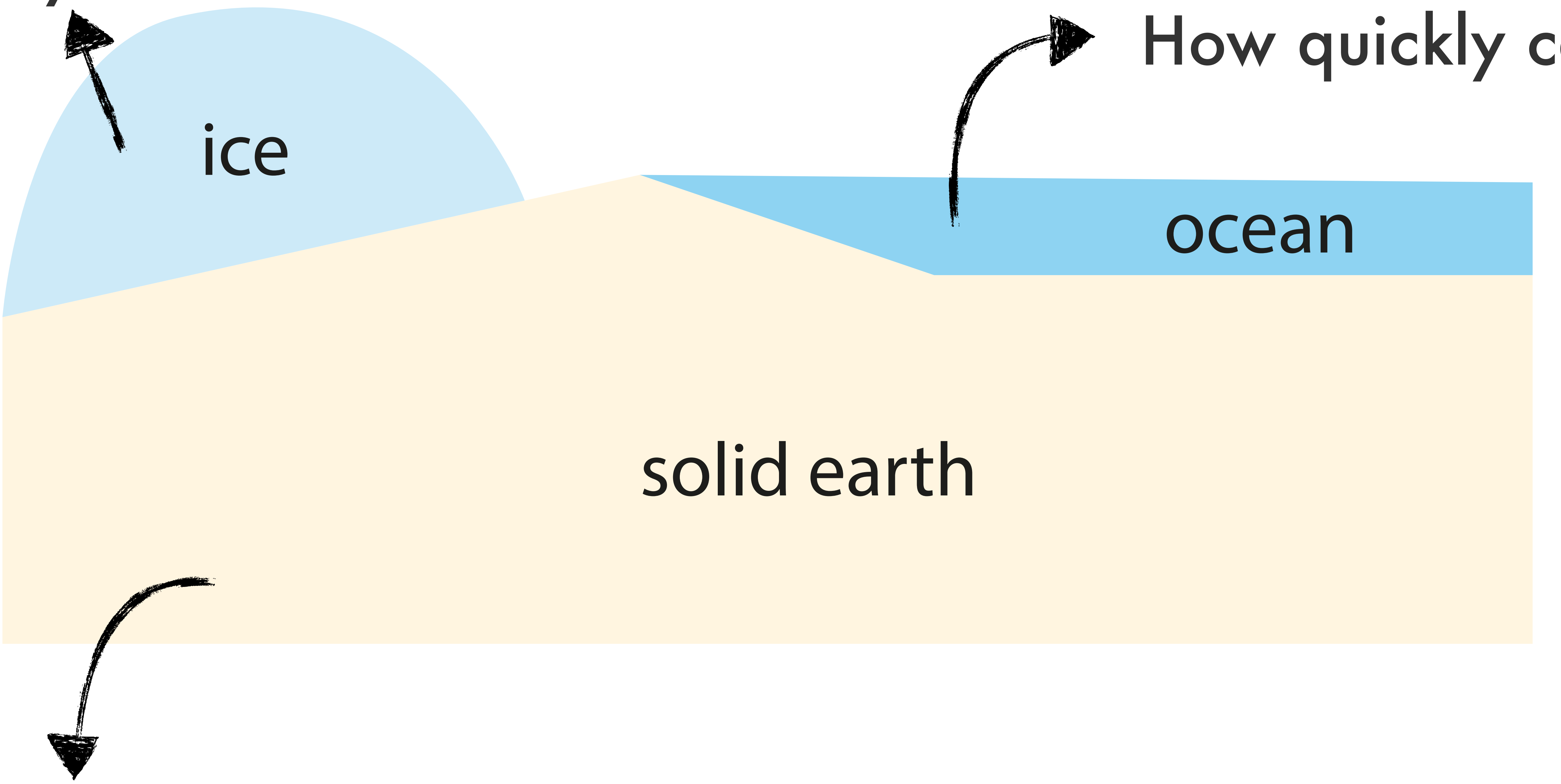

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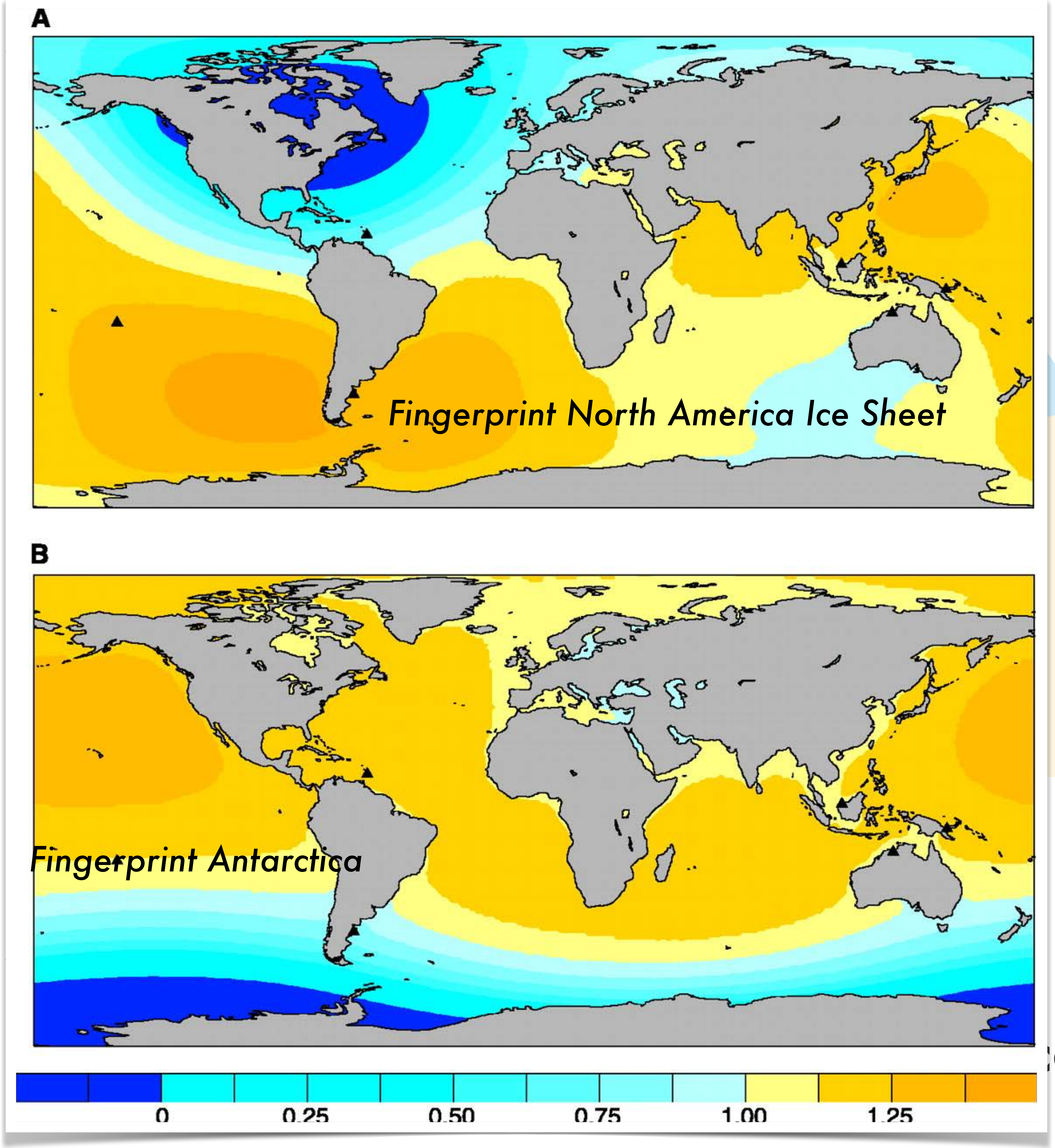
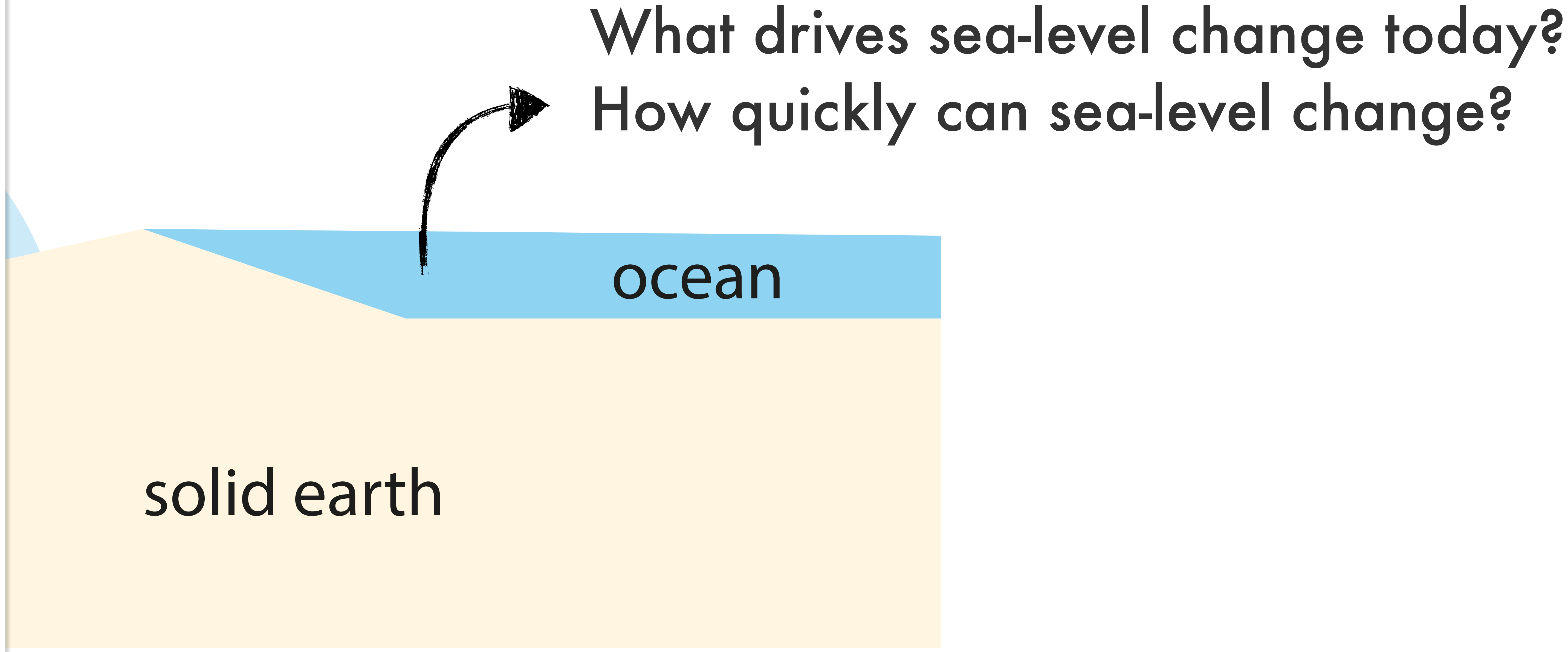


Clarke (2002)



:onsider?

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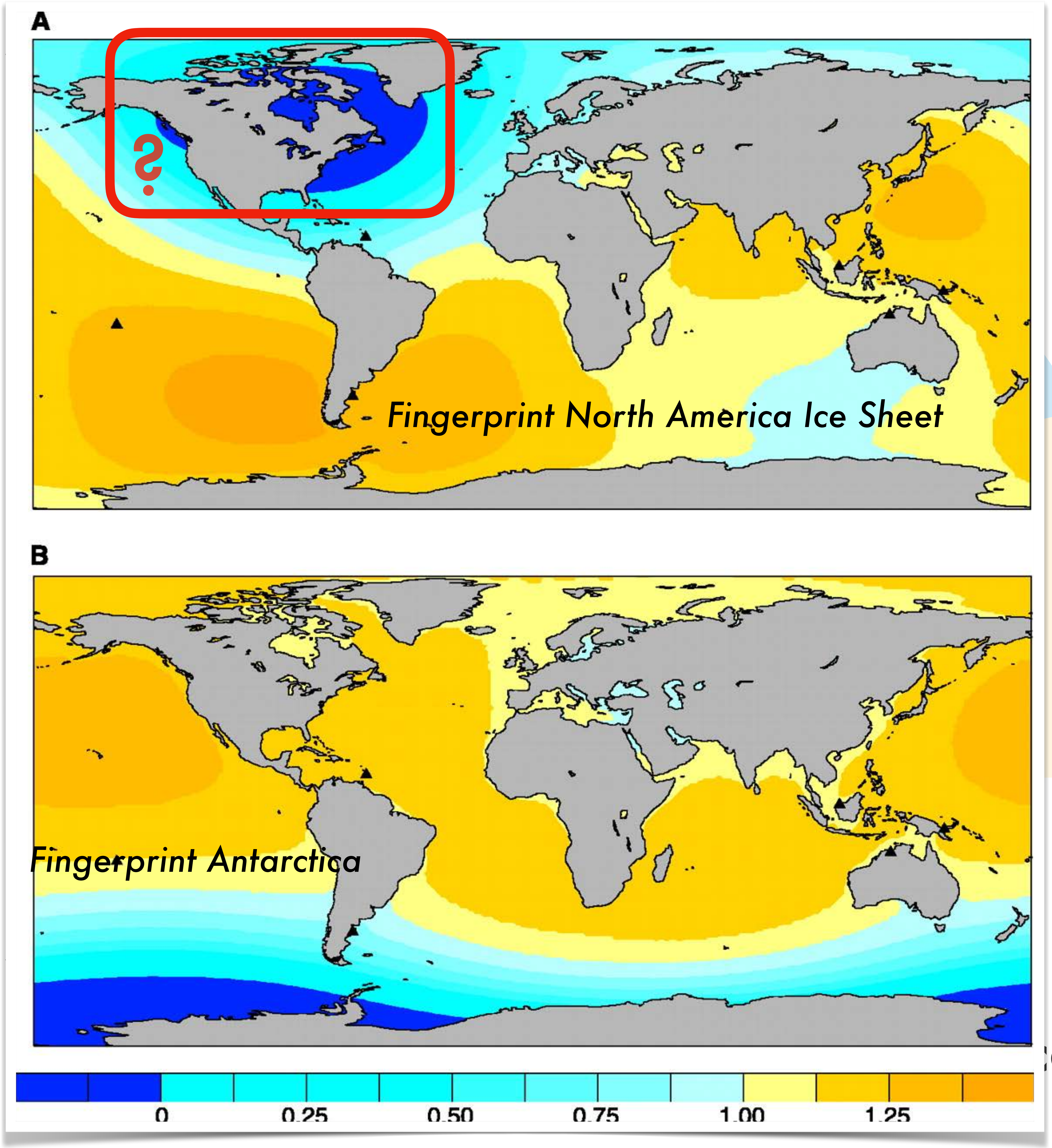

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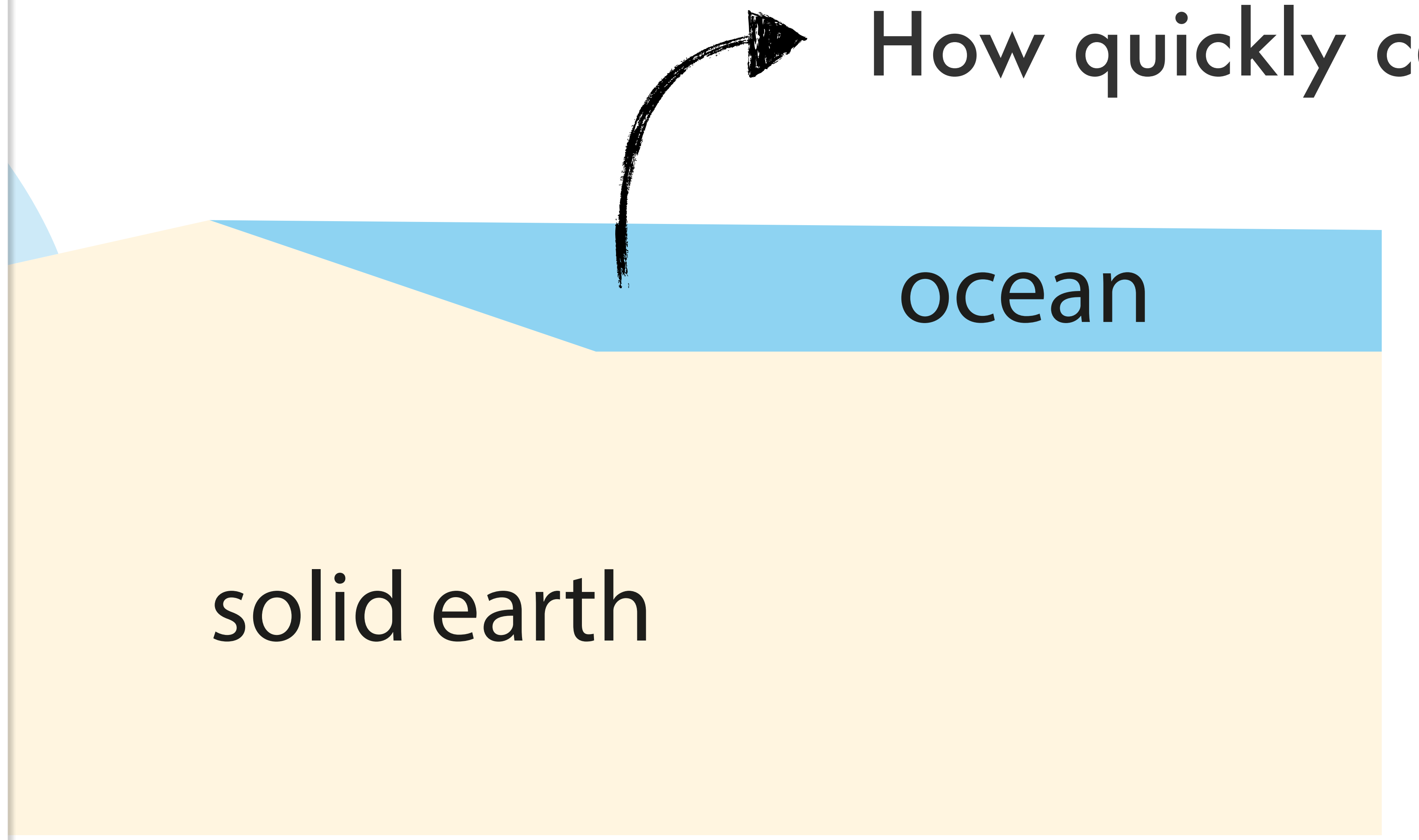

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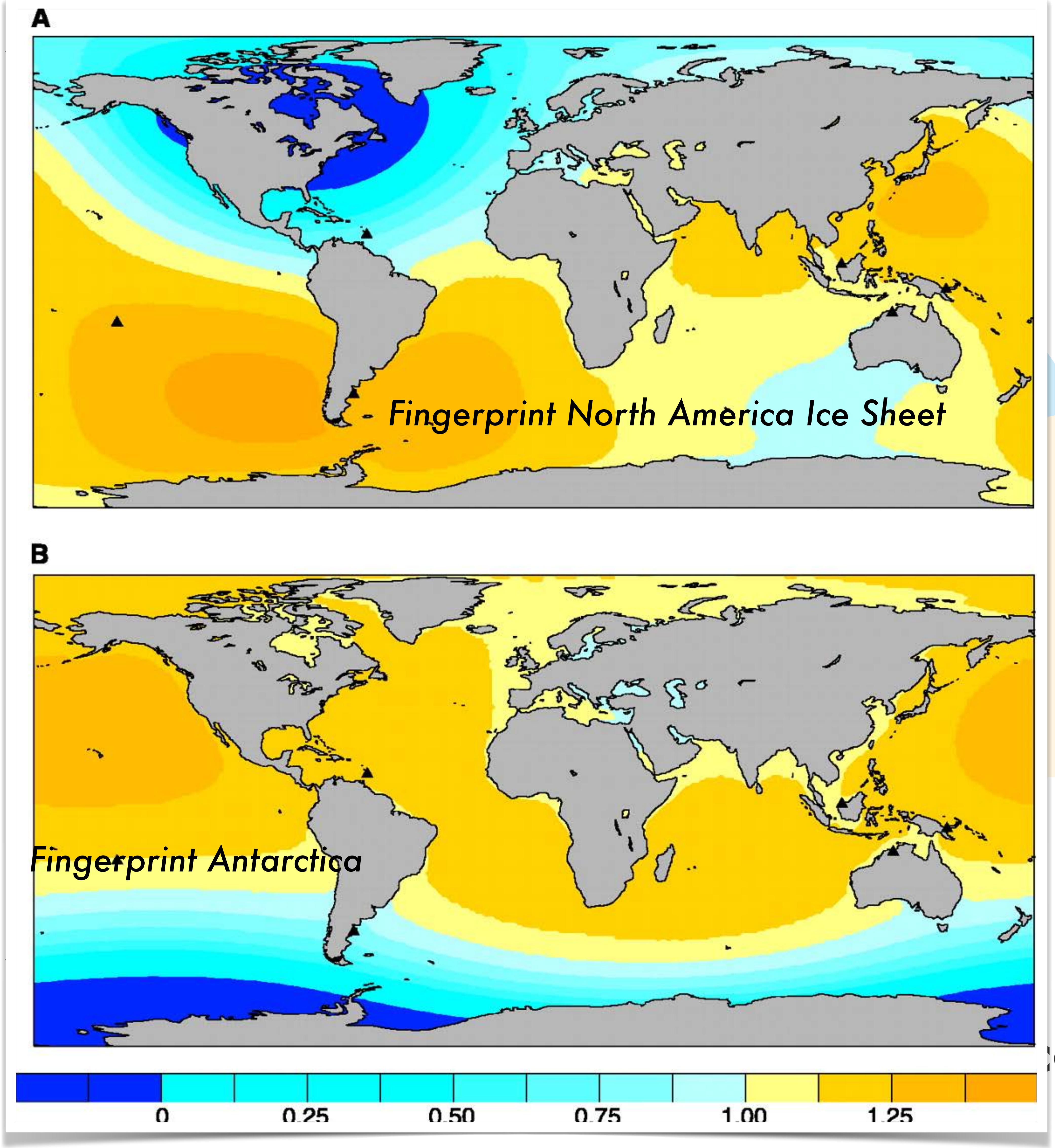

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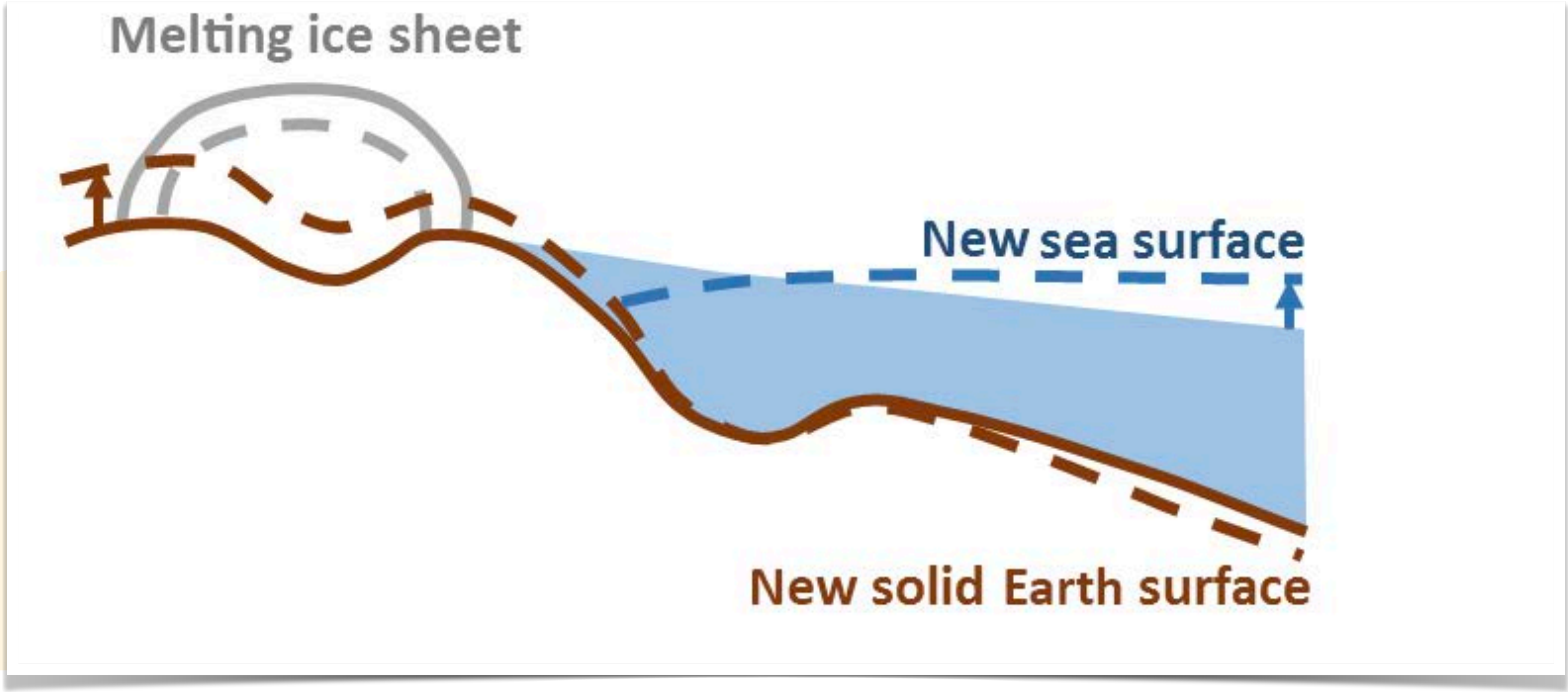

:onsider?

- solid Earth rebound due to ice melting
- decrease in sea surface height due to the decreased gravitational attraction of the ice sheet
- Both processes cause near-field relative sea-level fall

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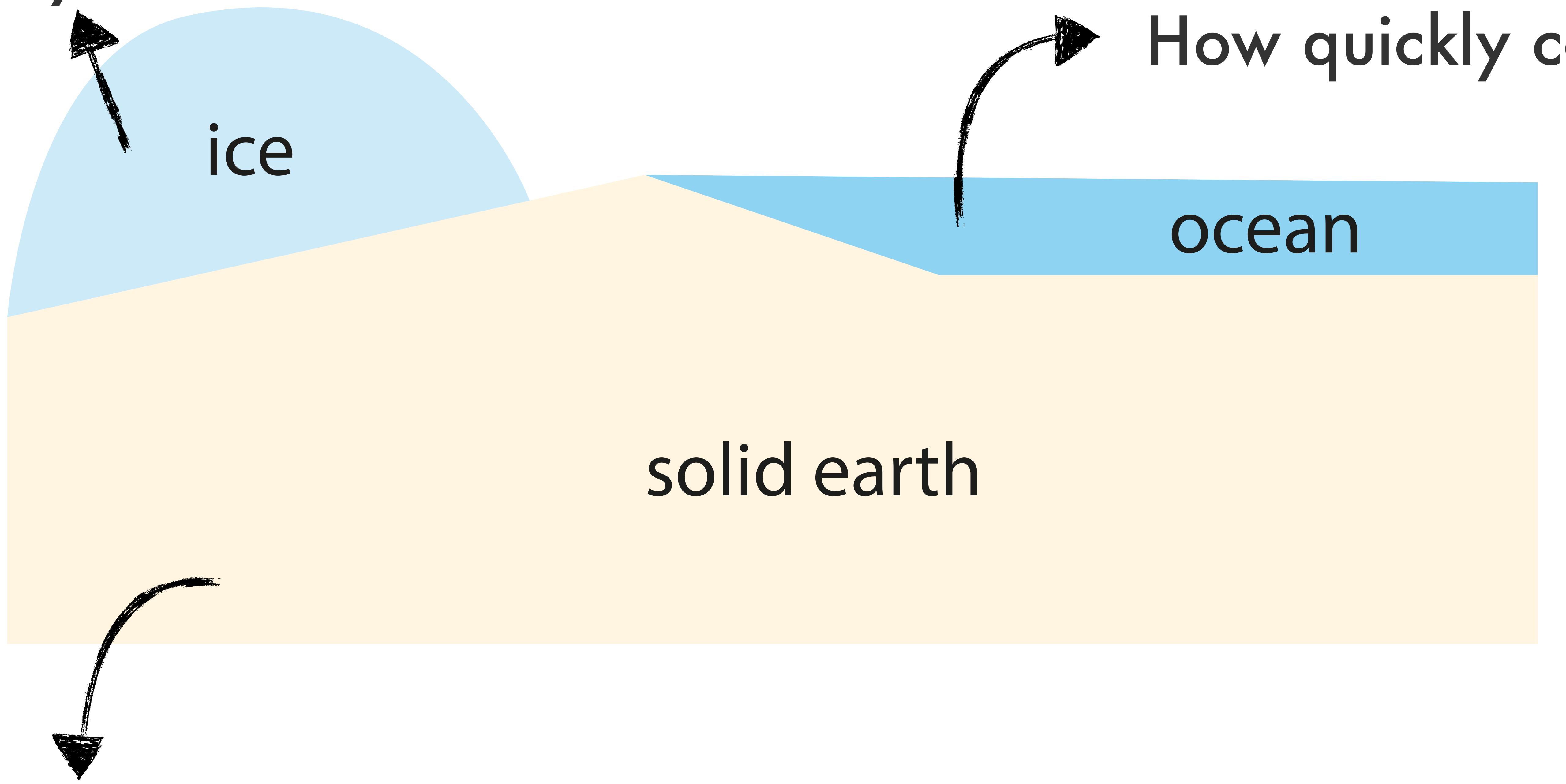

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An old story…

THE TIDES

AND KINDRED PHENOMENA IN THE SOLAR SYSTEM

THE SUBSTANCE OF LECTURES DELIVERED IN 1897 AT THE LOWELL INSTITUTE, BOSTON, MASSACHUSETTS

BY

GEORGE HOWARD DARWIN

PLUMIAN PROFESSOR AND FELLOW OF TRINITY COLLEGE IN THE UNIVERSITY OF CAMBRIDGE

BOSTON AND NEW YORK
HOUGHTON, MIFFLIN AND COMPANY
The Riverside Press, Cambridge
1899

CHAPTER VII

THE ELASTIC DISTORTION OF THE EARTH'S SURFACE BY VARYING LOADS

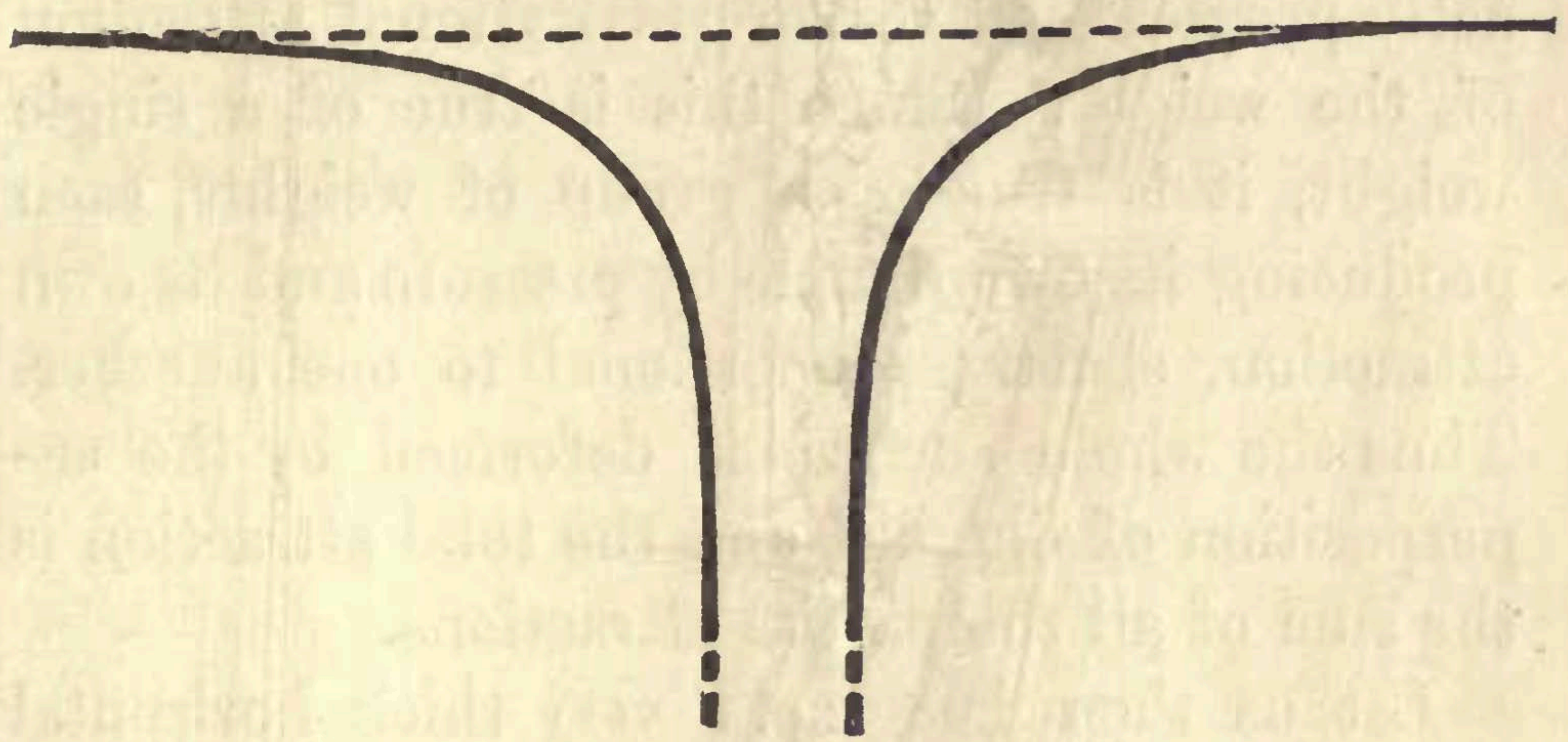
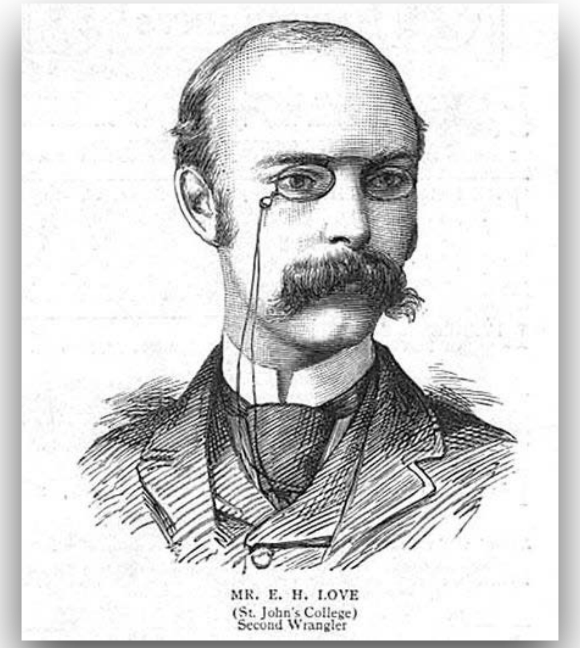


FIG. 27.—FORM OF DIMPLE IN AN ELASTIC SURFACE

A (not so) old story...

Augustus Edward
Hough Love

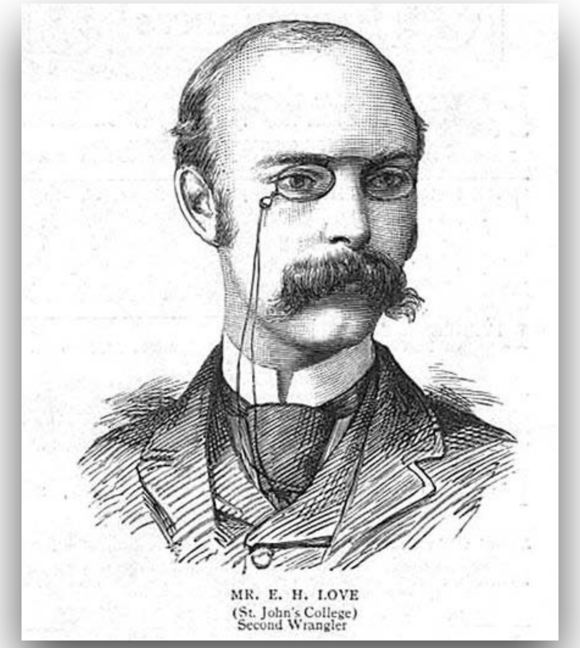


1911

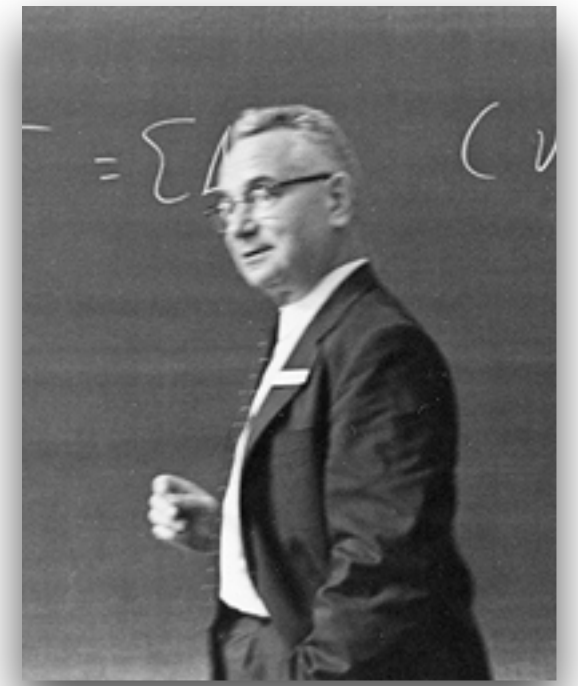
- Deformation of the spherical homogeneous elastic Earth
- Introduction of the Love numbers

A (not so) old story...

Augustus Edward Hough Love

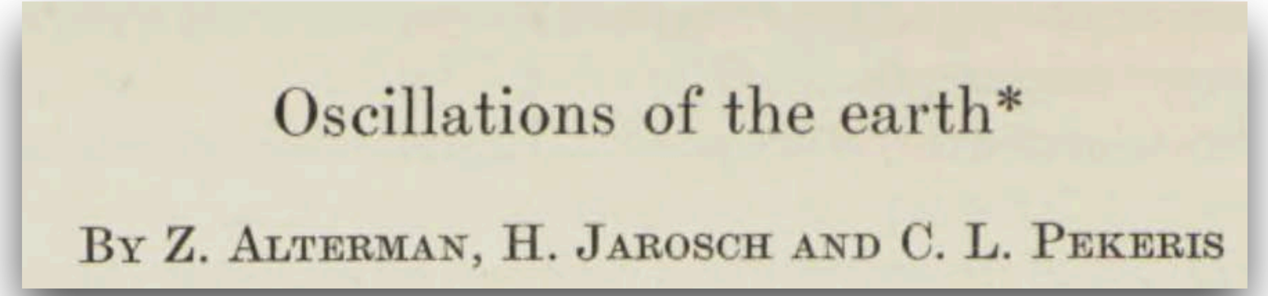


Chaim Lieb Pekeris



Louis B. Slichter

Norman Haskell



Oscillations of the earth*

By Z. Alterman, H. Jarosch and C. L. Pekeris

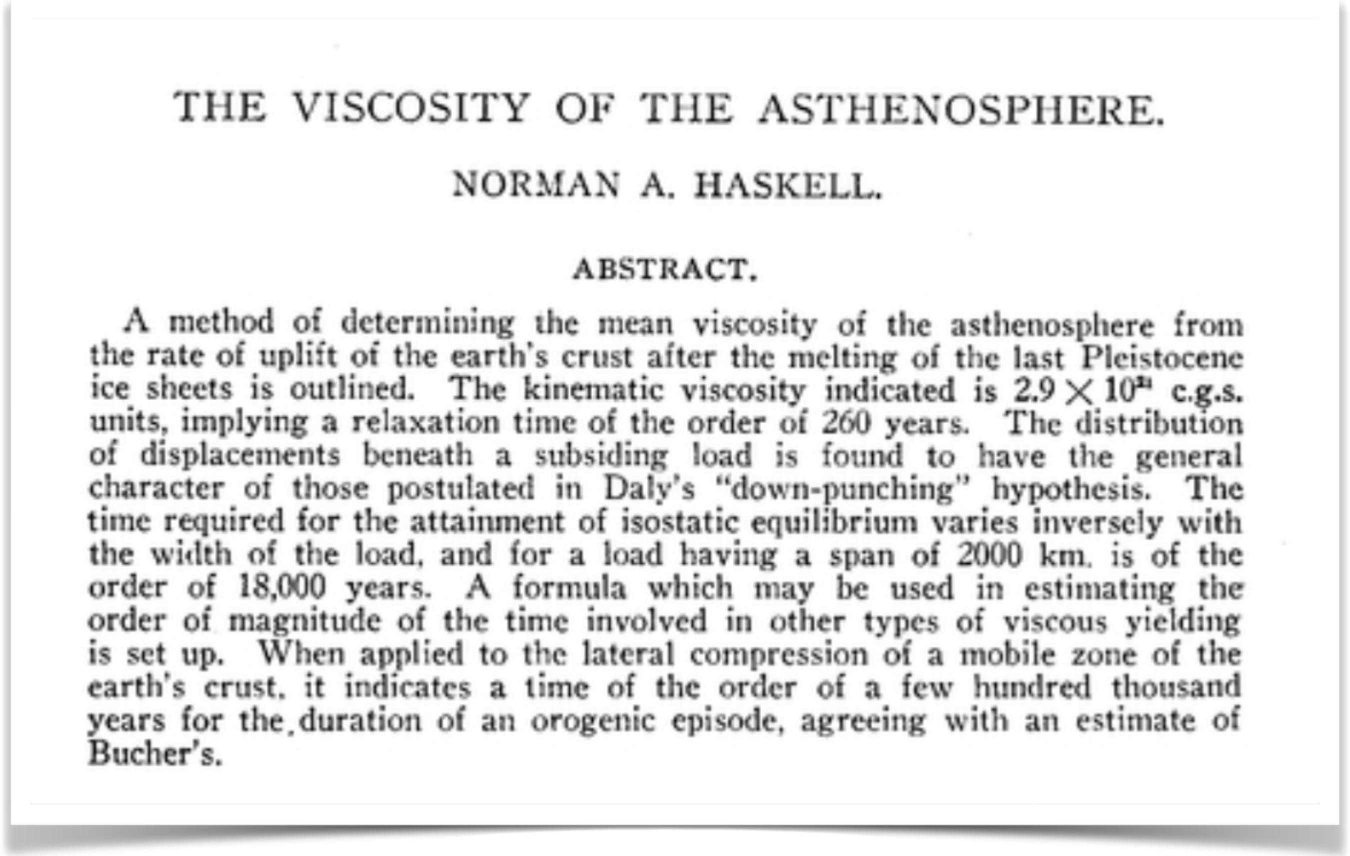
1911 — 1925 — 1935 — 1961

The era of seismologists

- Deformation of the spherical homogeneous elastic Earth
- Introduction of the Love numbers

- Free oscillations of the Earth
- GIA derived viscosity of the mantle using a halt-space model

— 10^{21} Pa.s —



THE VISCOSITY OF THE ASTHENOSPHERE.

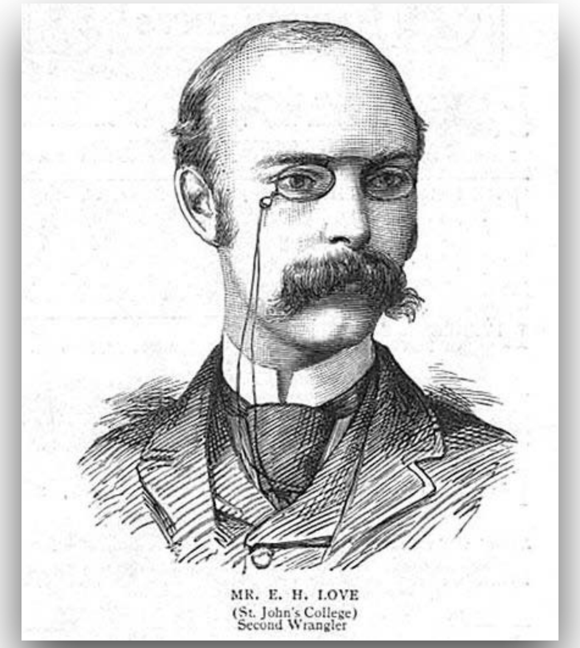
NORMAN A. HASKELL.

ABSTRACT.

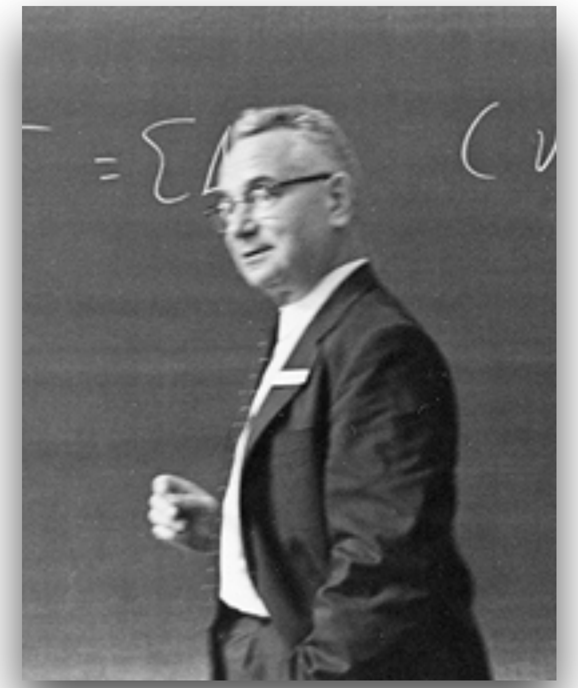
A method of determining the mean viscosity of the asthenosphere from the rate of uplift of the earth's crust after the melting of the last Pleistocene ice sheets is outlined. The kinematic viscosity indicated is 2.9×10^{21} c.g.s. units, implying a relaxation time of the order of 260 years. The distribution of displacements beneath a subsiding load is found to have the general character of those postulated in Daly's "down-punching" hypothesis. The time required for the attainment of isostatic equilibrium varies inversely with the width of the load, and for a load having a span of 2000 km. is of the order of 18,000 years. A formula which may be used in estimating the order of magnitude of the time involved in other types of viscous yielding is set up. When applied to the lateral compression of a mobile zone of the earth's crust, it indicates a time of the order of a few hundred thousand years for the duration of an orogenic episode, agreeing with an estimate of Bucher's.

A (not so) old story…

Augustus Edward Hough Love

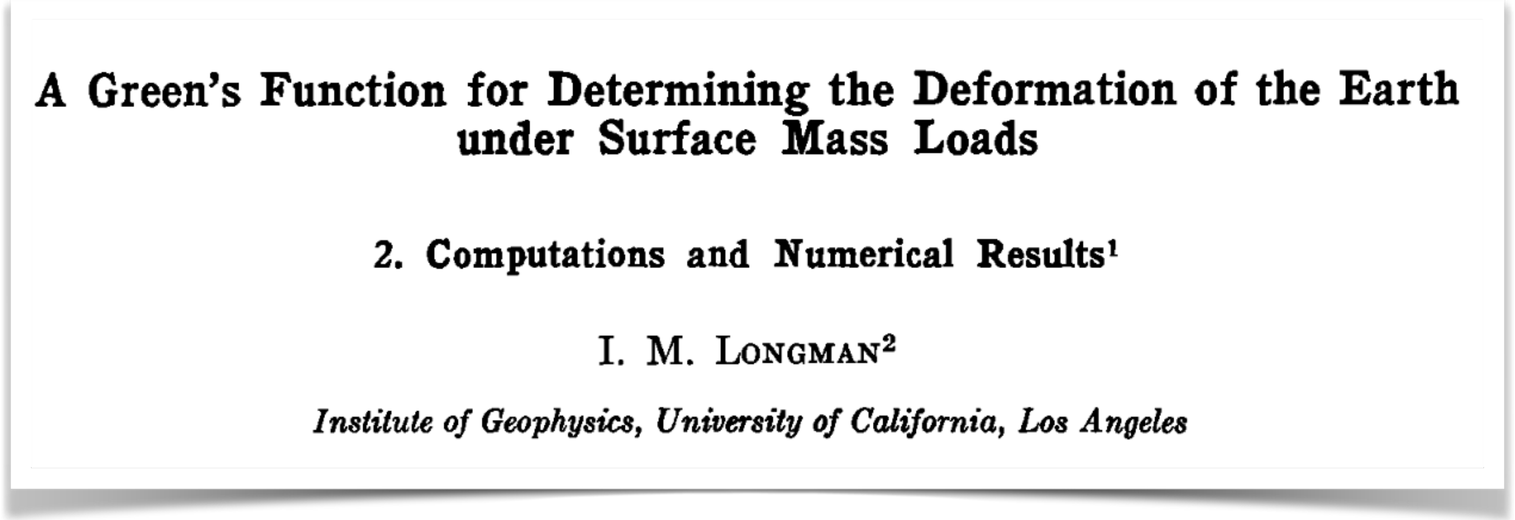


Chaim Lieb Pekeris



Louis B. Slichter

Norman Haskell



A Green's Function for Determining the Deformation of the Earth under Surface Mass Loads

2. Computations and Numerical Results[1]

I. M. Longman[2]

Institute of Geophysics, University of California, Los Angeles

1911 —1925——1935——1961 1963

The era of seismologists

- Deformation of the spherical homogeneous elastic Earth
- Introduction of the Love numbers

- Free oscillations of the Earth
- GIA derived viscosity of the mantle using a halt-space model

— 10^{21} Pa.s –

- Deformation of an elastic spherical layered Earth under surface loading

A (not so) old story…

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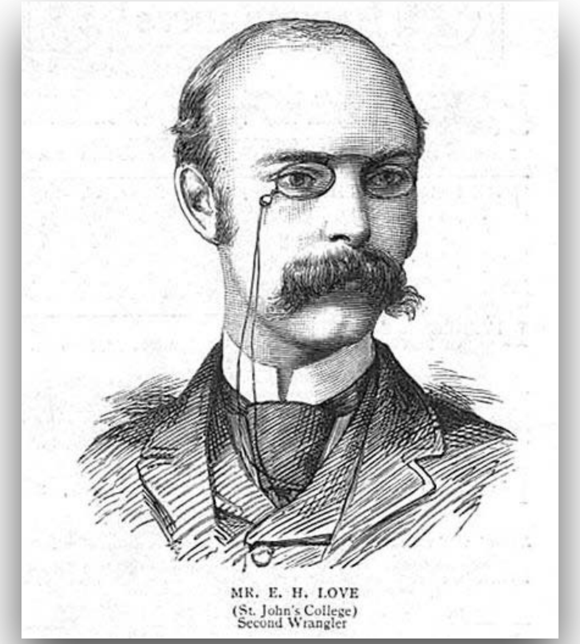

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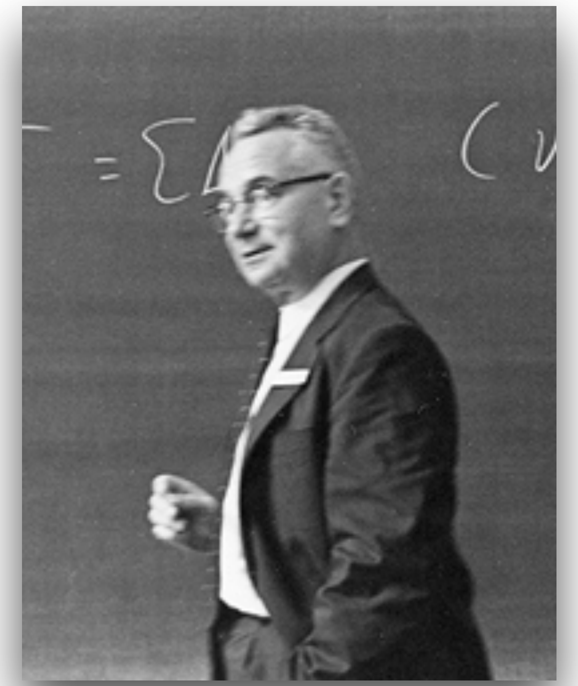

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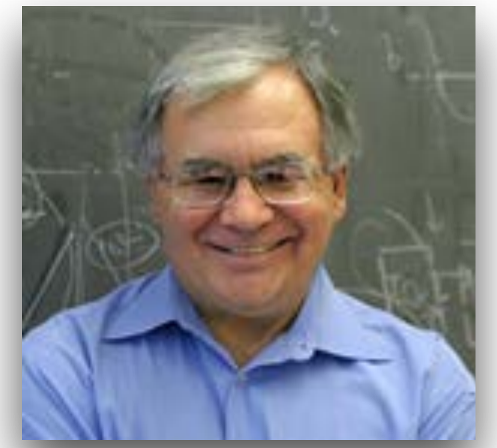
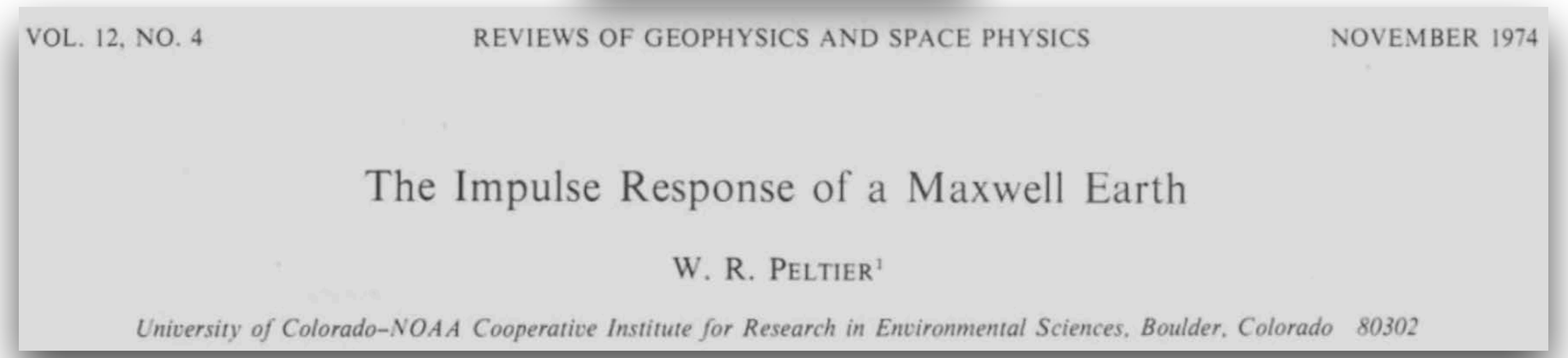



VOL. 12, NO. 4 REVIEWS OF GEOPHYSICS AND SPACE PHYSICS NOVEMBER 1974

The Impulse Response of a Maxwell Earth

W. R. PELTIER[1]

University of Colorado–NOAA Cooperative Institute for Research in Environmental Sciences, Boulder, Colorado 80302

1911

1925 — 1935 — 1961

1963

1974

The era of seismologists

- Deformation of the spherical homogeneous elastic Earth
- Introduction of the Love numbers

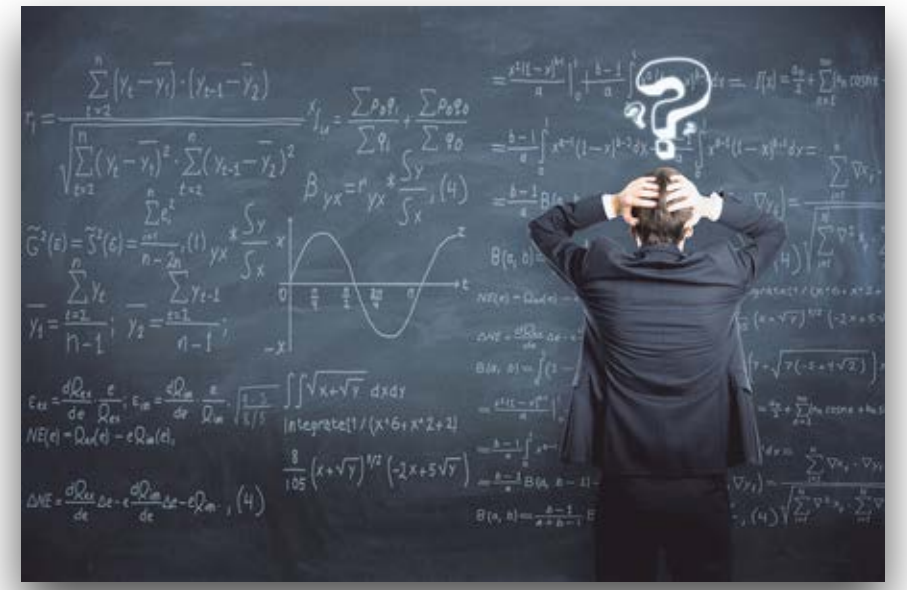
- Free oscillations of the Earth
- GIA derived viscosity of the mantle using a halt-space model

— 10^{21} Pa.s —

- Deformation of an elastic spherical layered Earth under surface loading

- Deformation of a viscoelastic spherical layered Earth under surface loading

OK… now some equations



- The Love h and k, and Shida l numbers *(Love, 1911; Shida and Matsuyama, 1912)* characterize the Earth's response to a potential (ex: the external tidal potential)
- For describing the response to surface load, another type of Love numbers, h', l' and k', were introduced: the loading Love numbers *(Longman, 1963; Farrell, 1972)*
- Load Love numbers are computed by integrating the equations of motion, the **stress-strain relationship** and Poisson equation inside the Earth, from the center to the surface using a spherical Earth model

OK… now some equations

- Linearization of motion and Poisson equation

$$\nabla \cdot \boldsymbol{\tau} - \nabla(\rho g \mathbf{s} \cdot \mathbf{e_r}) - \rho \nabla \phi + g \nabla \cdot (\rho \mathbf{s} \mathbf{e_r}) = 0\,,$$
$$\nabla^2 \phi = -\,4\pi G \nabla \cdot (\rho \mathbf{s})$$

$\boldsymbol{\tau}$ is the incremental stress tensor

ρ and g are the unperturbed density and gravitational acceleration

$\mathbf{s}$ is the displacement vector

ϕ is the perturbed gravitational potential

$\mathbf{e_r}$ denotes the unit vector of the vertical component.

- Supposing a spherically symmetric **elastic** Earth model, solutions of linearised equations become:

$$\mathbf{s} = \sum_{n=0}^{\infty} \left(U_n(r) P_n(\cos\psi) \mathbf{e_r} + V_n(r) \frac{\partial P_n(\cos\psi)}{\partial \psi} \mathbf{e_v} \right),$$
$$\phi = \sum_{n=0}^{\infty} \Phi_n(r) P_n(\cos\psi)\,,$$

where U_n, V_n and Φ_n are transformed variables indicating vertical displacements, tangential displacements and potential, respectively. $\mathbf{e_v}$ denotes the unit vector of the horizontal component.

OK… now some equations

- Linearization of motion and Poisson equation

$$\nabla \cdot \boldsymbol{\tau} - \nabla(\rho g \mathbf{s} \cdot \mathbf{e}_r) - \rho \nabla \phi + g \nabla \cdot (\rho \mathbf{s} \mathbf{e}_r) = 0\,,$$
$$\nabla^2 \phi = -4\pi G \nabla \cdot (\rho \mathbf{s})$$

- Supposing a spherically symmetric **elastic** Ear

$$\mathbf{s} = \sum_{n=0}^{\infty} \left(U_n(r) P_n(\cos\psi) \mathbf{e}_r + V_n(r) \frac{\partial P_n(\cos\psi)}{\partial \psi} \mathbf{e}_v \right),$$
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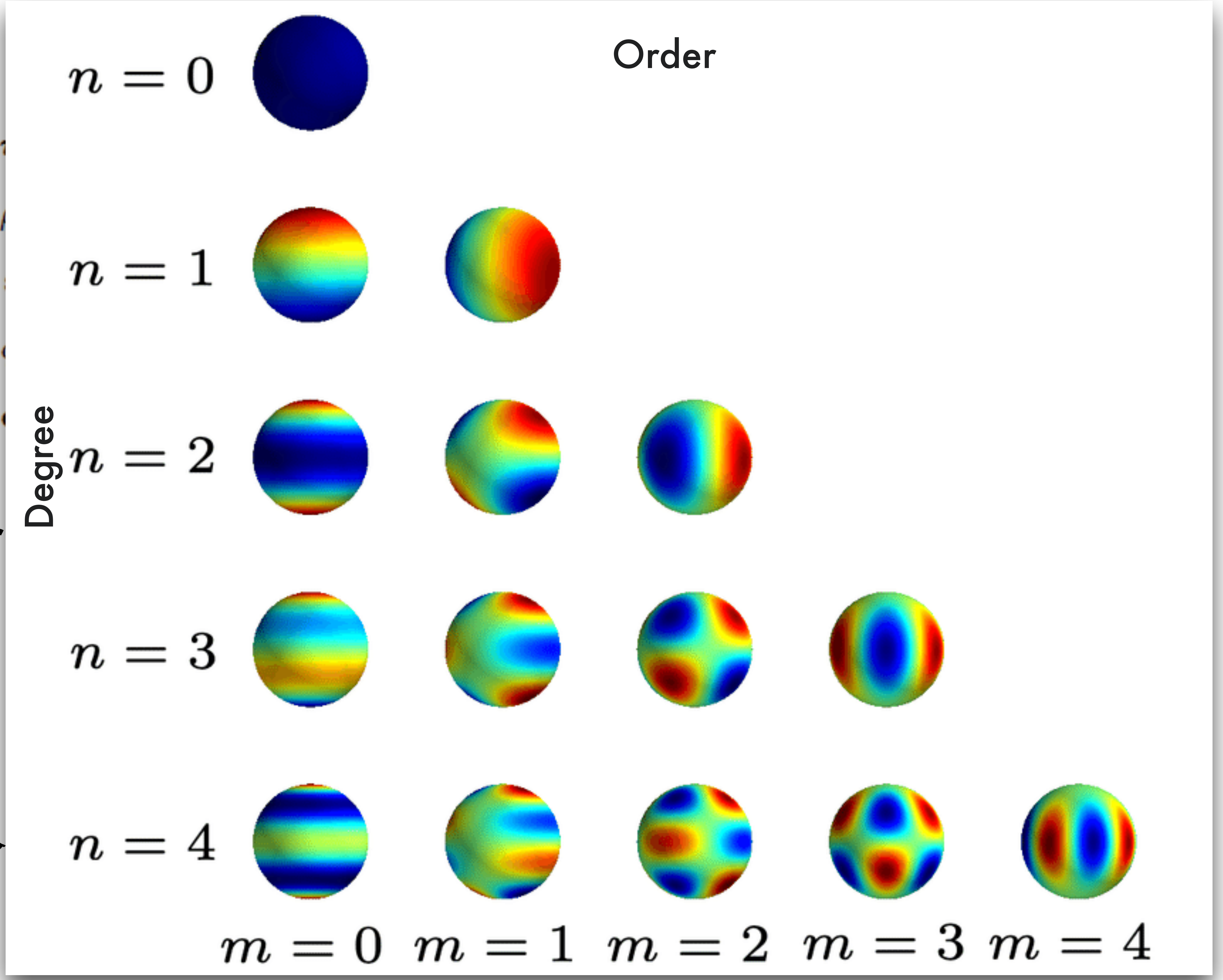


OK... now some equations

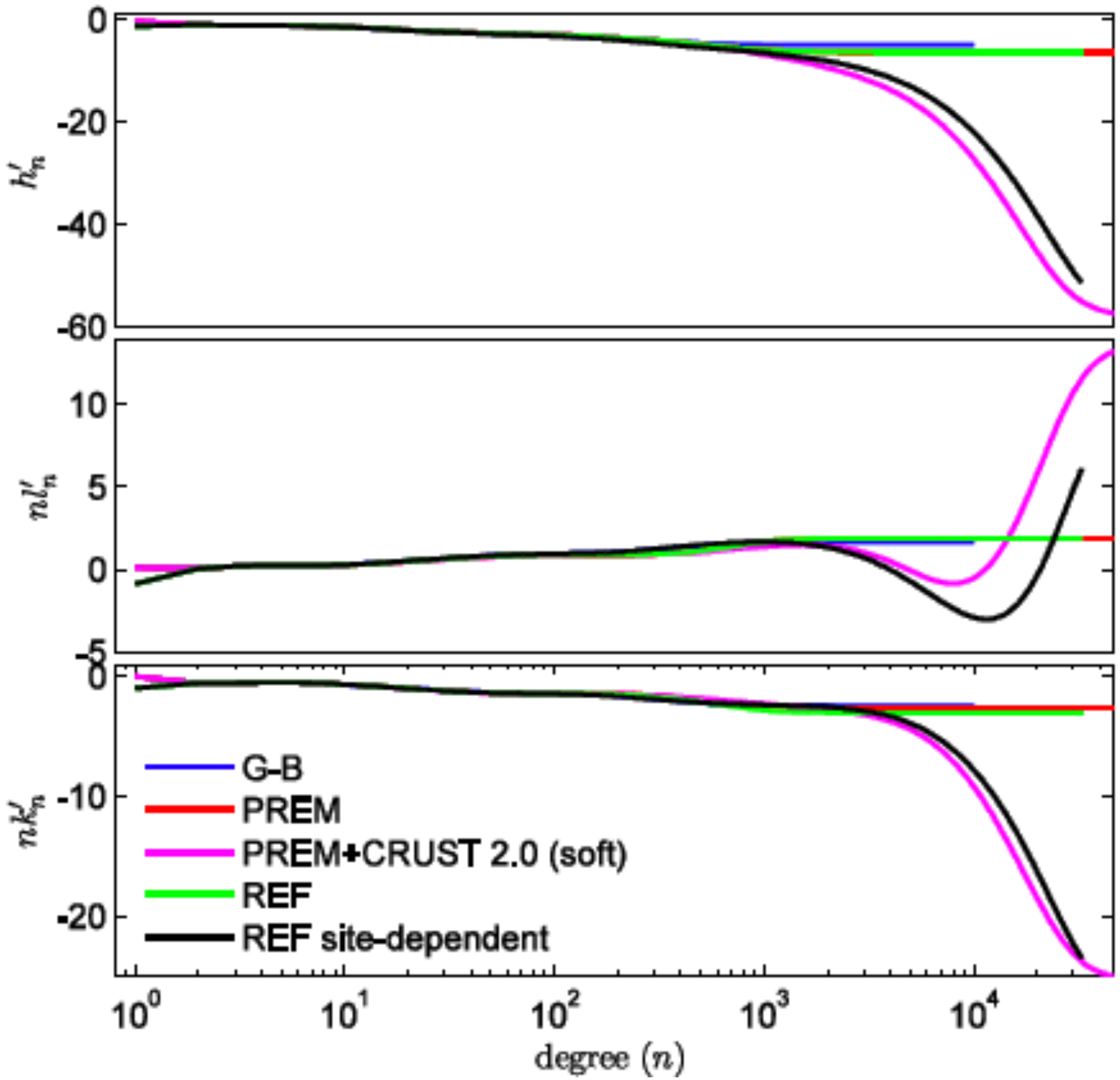
- With a bit of work and some simplifications,

$$\begin{bmatrix} U_n(r) \\ V_n(r) \\ \Phi_n(r) \end{bmatrix} = W(r) \begin{bmatrix} h'_n(r)/g \\ l'_n(r)/g \\ k'_n(r) \end{bmatrix}$$

where $W(r)$ stands for the potential induced by the point mass

- Solving and integrating this equation from the inner Earth to the surface gives the set of loading Love numbers which are based on the given Earth model.

1)Gutenberg-Bullen (Farrell, 1972);
2)PREM (Dziewonski and Anderson, 1981);
3)a modified PREM with crustal structures adapting from CRUST 2.0 model (Wang et al., 2012)
4)REF (Kustowski et al., 2008)
5)REF model with a site-dependent setting (Gegout, 2013).



Predict elastic displacement from surface load

$$\bar{U}(\bar{r}, S, Z, \rho) = \int_{\Omega'} G(|\bar{r}' - r|, S)\rho(\bar{r}')Z(\bar{r}')d\Omega'$$

Predict elastic displacement from surface load

Load Green's function

Load height at
load point r'

$$\bar{U}(\bar{r}, \underline{S}, Z, \rho) = \int_{\Omega'} G(|\bar{r}' - r|, \underline{S})\,\rho(\bar{r}')\,Z(\bar{r}')\,d\Omega'$$

Response at
observation point r

Load density at
load point r'

Integration over
Earth's surface

— Spherically symmetric structure

Predict elastic displacement from surface load

Earth's rheology

Load Green's function

Load height at load point r'

$$\bar{U}(\bar{r}, \underline{S}, Z, \rho) = \int_{\Omega'} \boxed{G(|\bar{r}' - r|, \underline{S})} \rho(\bar{r}') Z(\bar{r}') d\Omega'$$

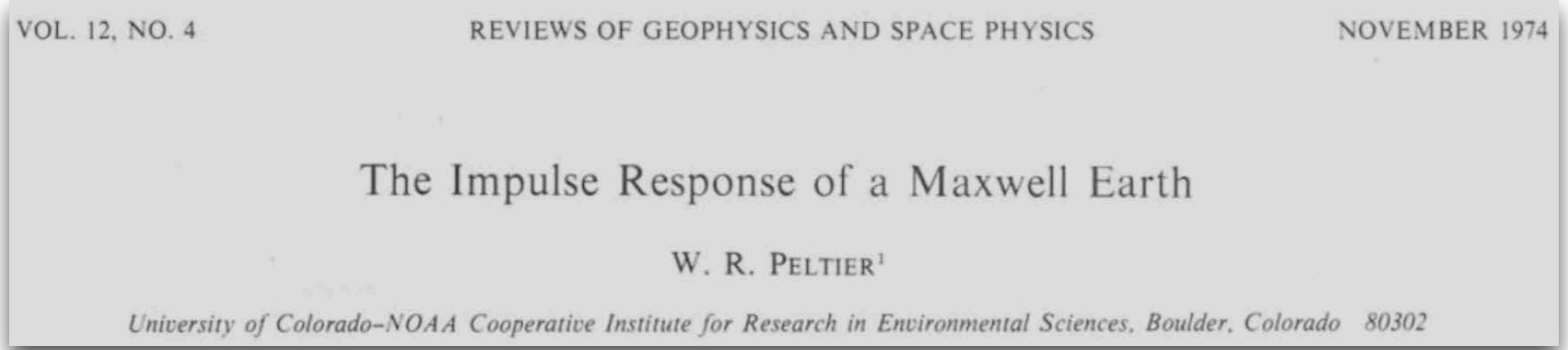
Response at observation point r

Load density at load point r'

Integration over Earth's surface

— Spherically symmetric structure

Predict viscoelastic displacement from surface load?



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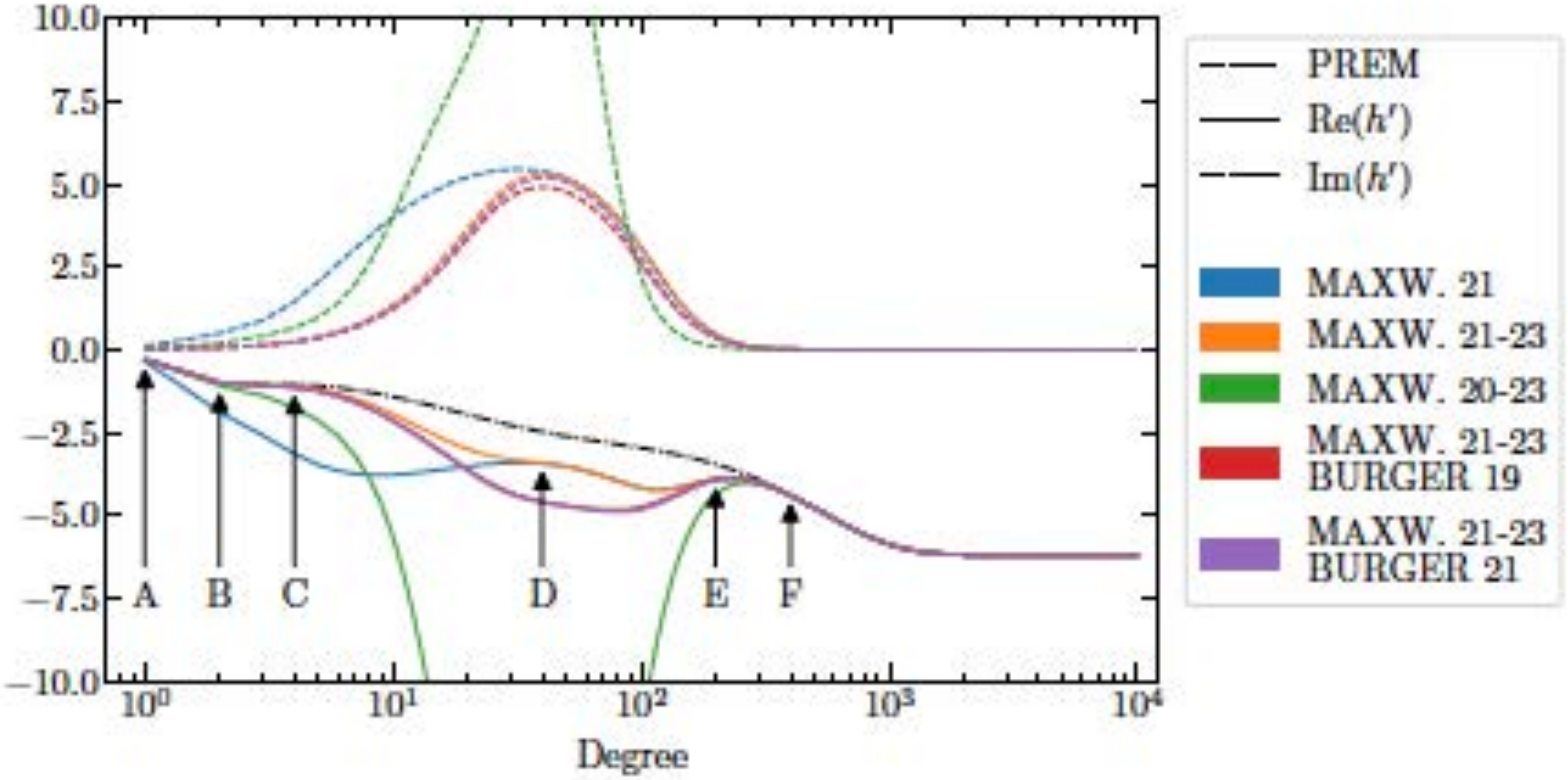
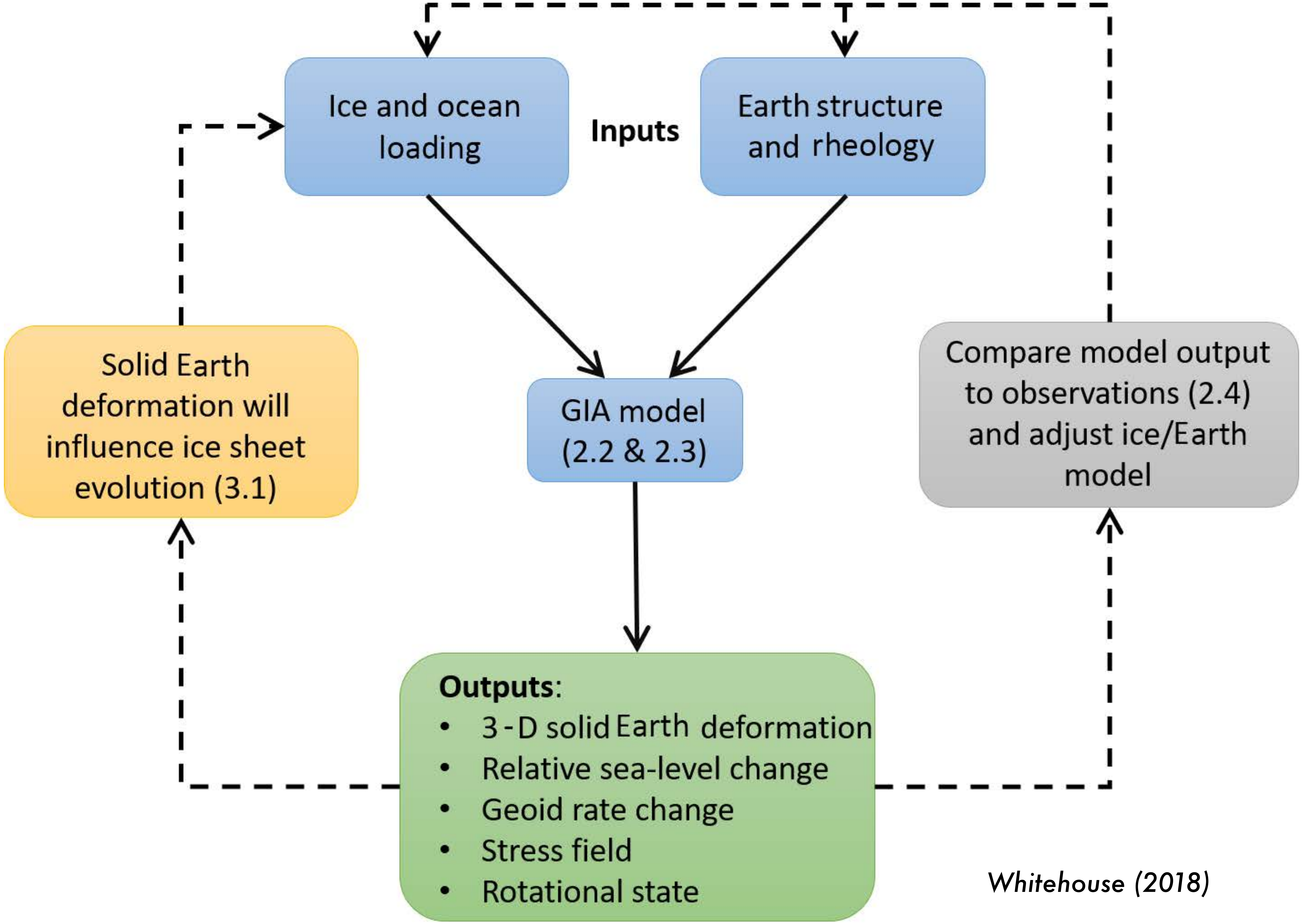
Correspondance principle in the Laplace (or Fourier) domain



GIA theory ready to go !

An iterative scheme



Whitehouse (2018)

But what to use for Earth rheology?

David T. Griggs
(1911-1974)
The father of rock deformation studies

American Journal of Science

SEPTEMBER 1939

A THEORY OF MOUNTAIN-BUILDING.

DAVID GRIGGS.

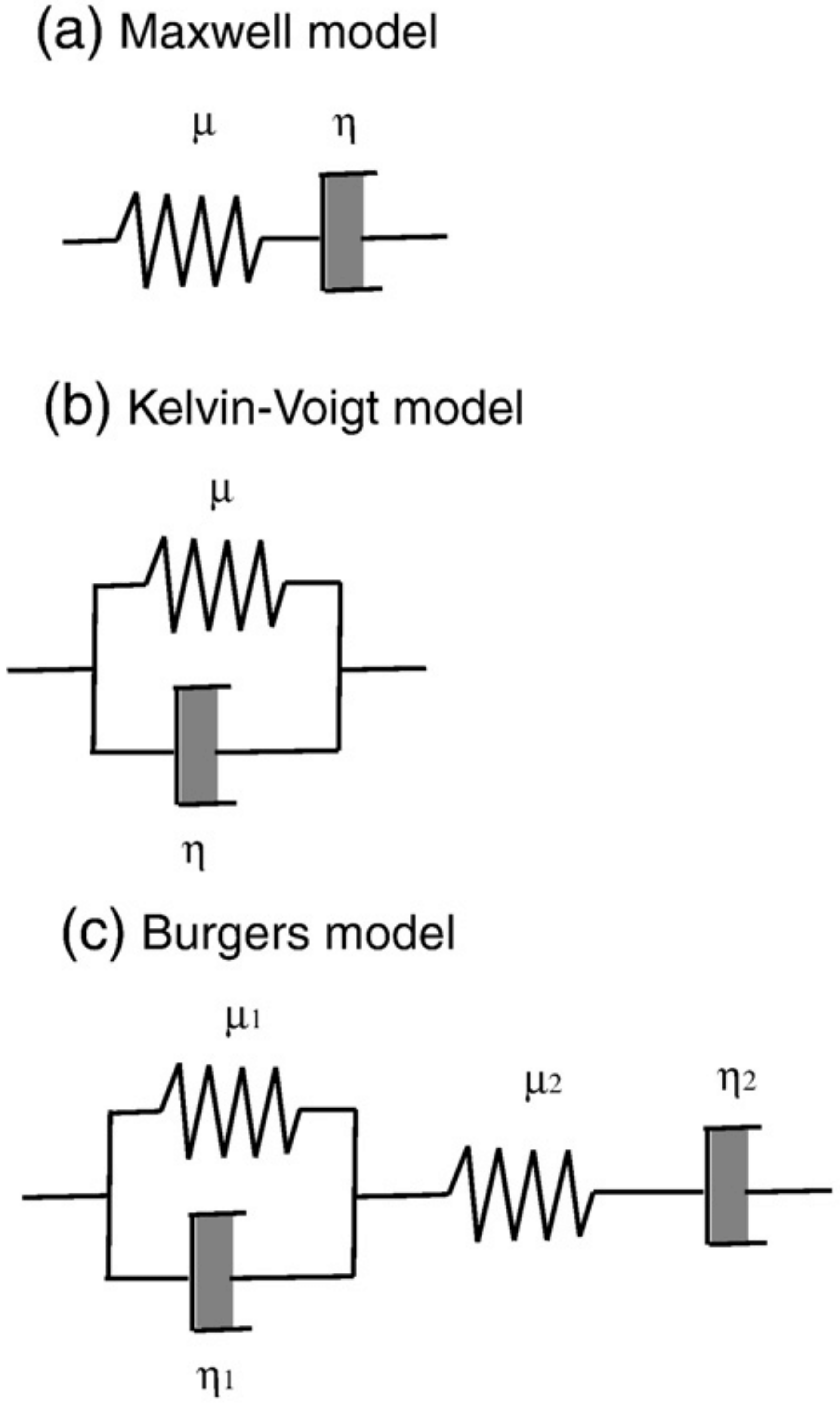
The fact that a natural phenomenon admits of one mechanical explanation is proof that there is an infinity of such explanations.
(Paraphrase from Poincaré.)

& Creep of rocks, Journal of Geology, 1939

— based on Haskell mantle viscosity study, and on experimental work, he advocates that we need a better theory for rheology —

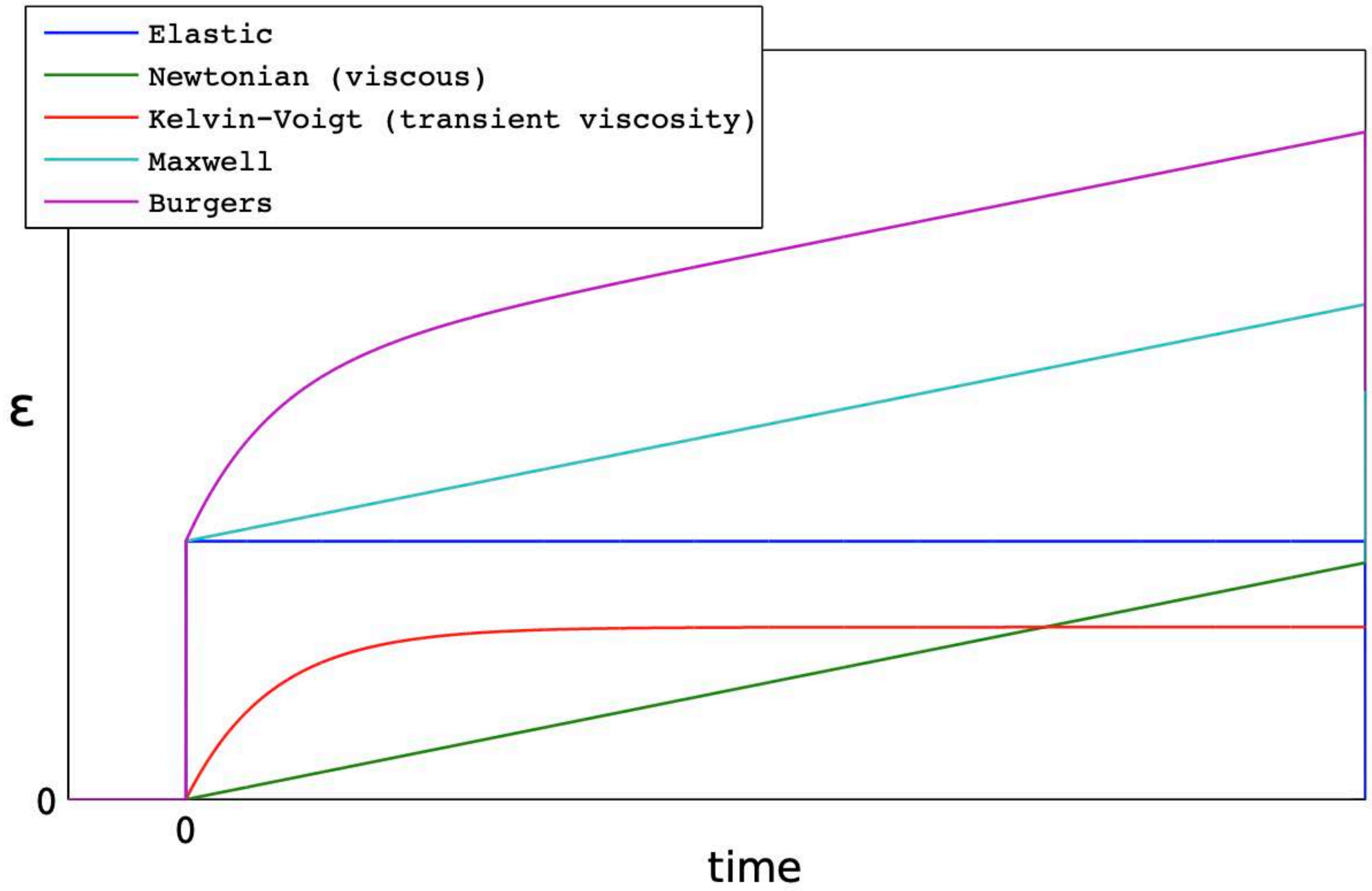
In the 1960s, it is understood that elastic/density properties of the Earth's mantle can be well explained by using olivine laboratory derived rheologies

Linking the short and long term behaviours

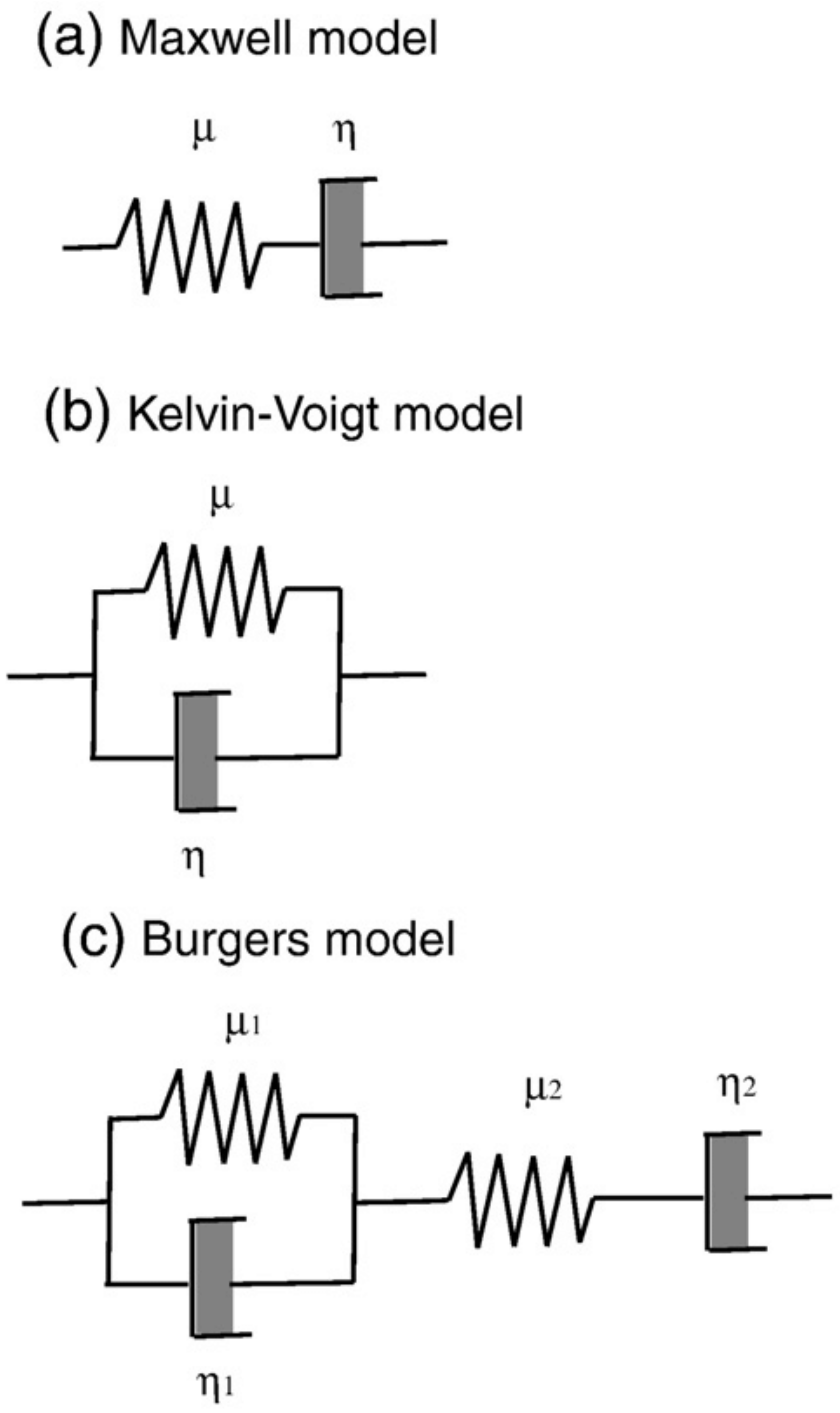


CREEP FUNCTIONS

Elastic (seismic constraints) to viscoelastic (postseismic) to VISCOelastic (GIA)



Linking the short and long term behaviours



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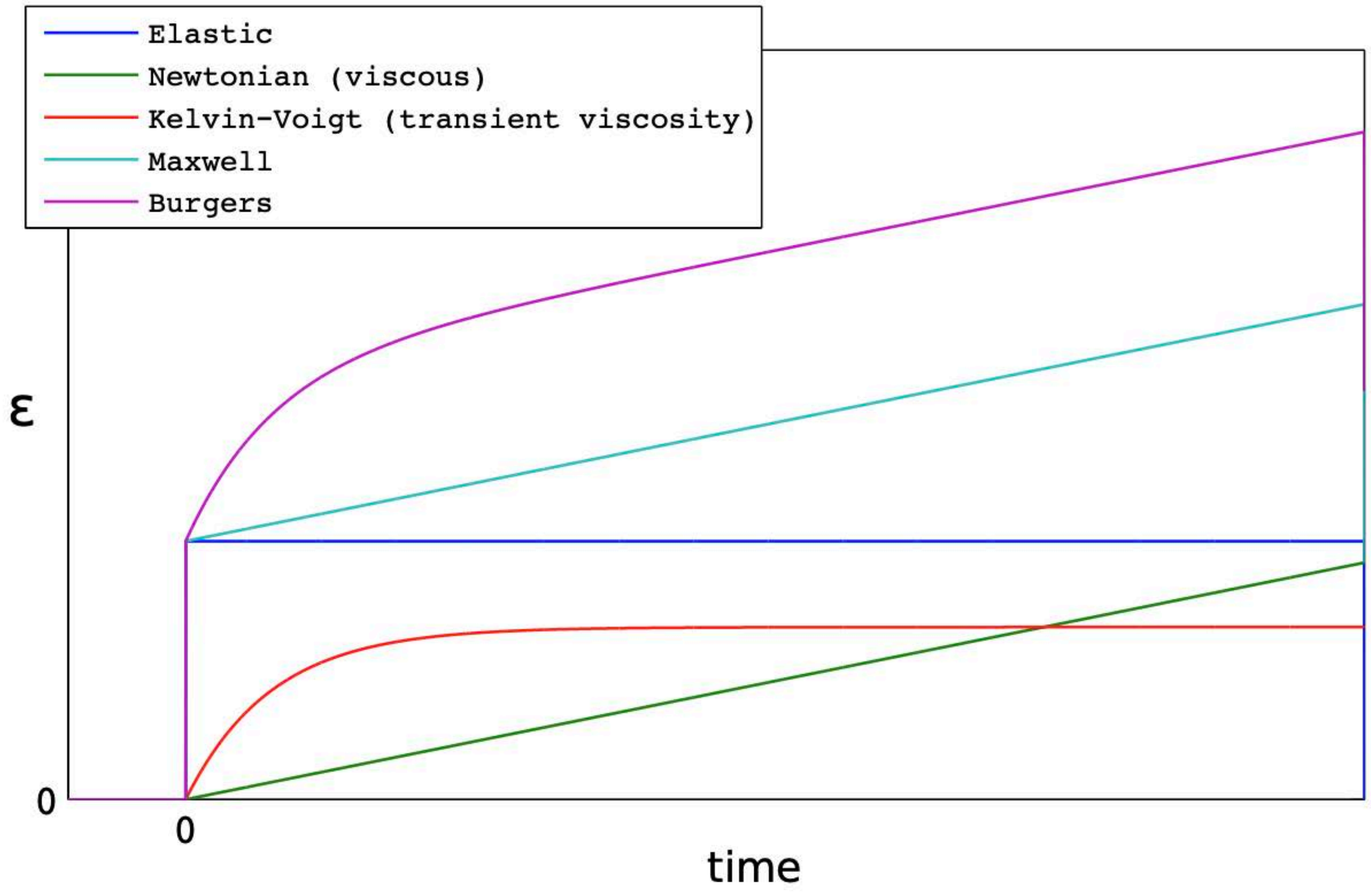
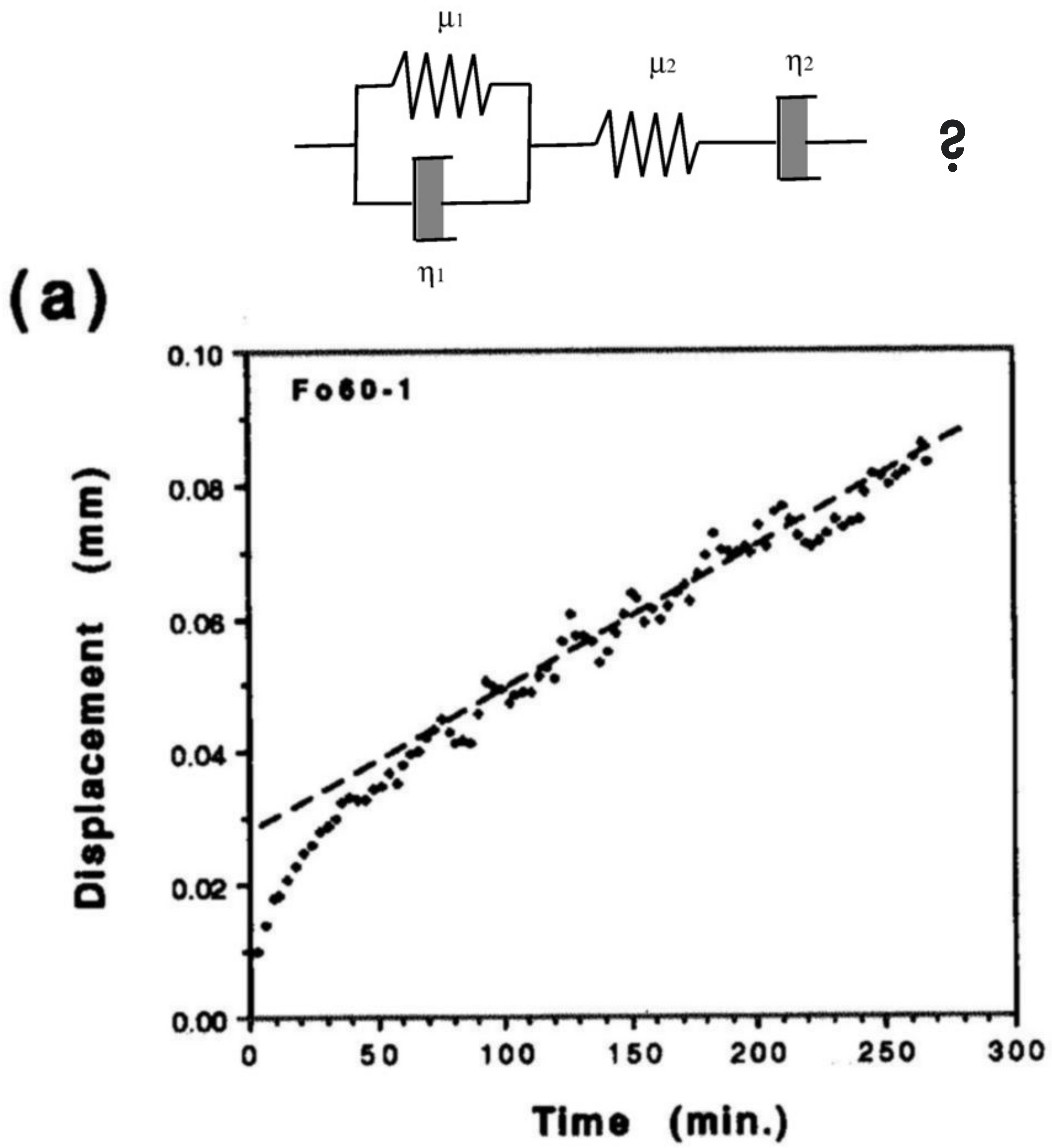


A Burgers rheology to fit observations… but why?

CREEP EXPERIMENT

on a mixture of olivine and pyroxenes



?

!

A Burgers rheology to fit observations… but why?

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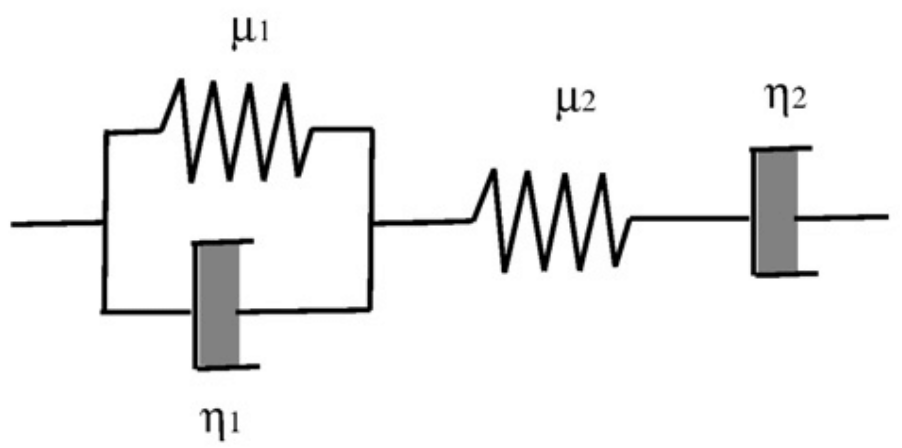
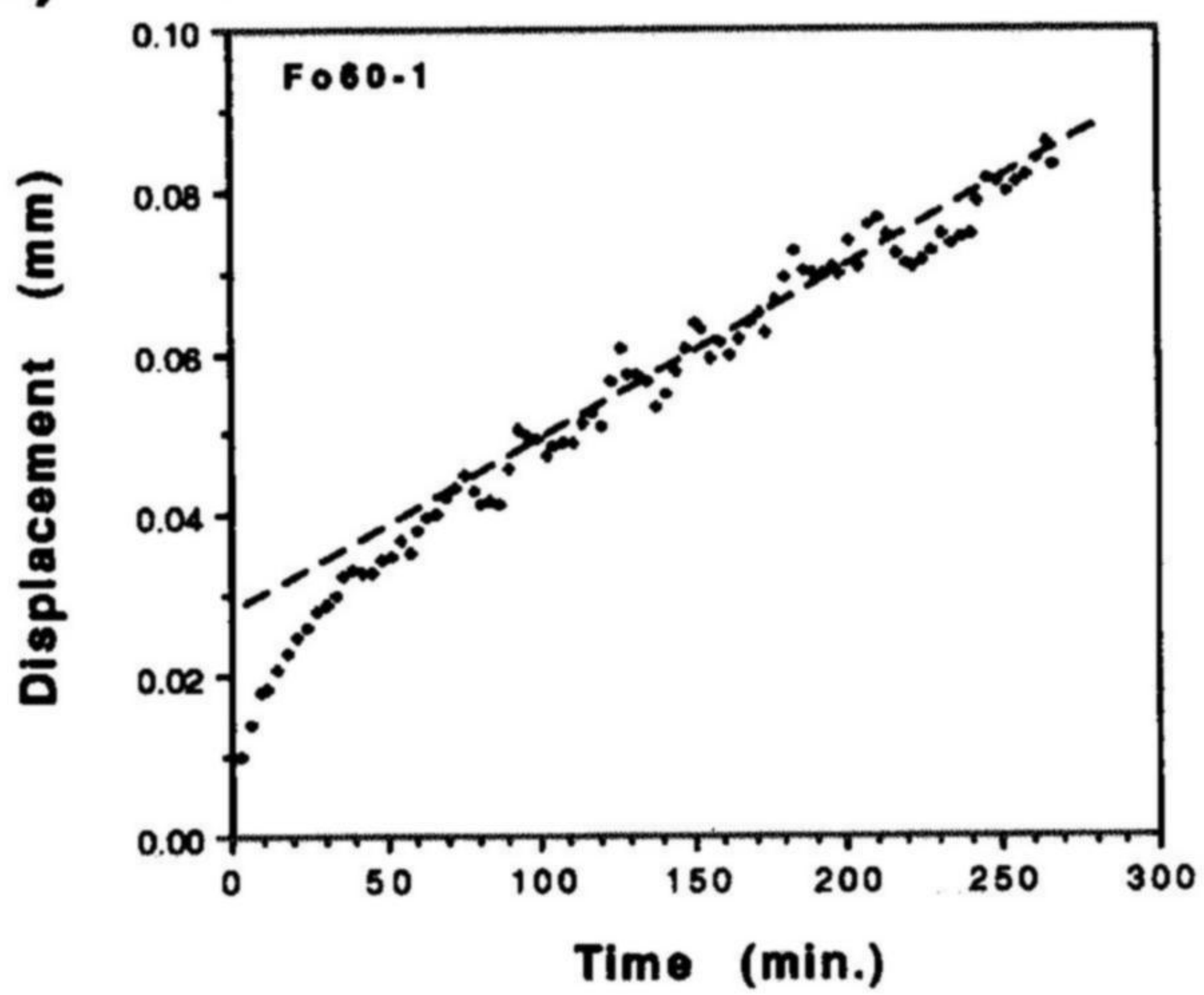


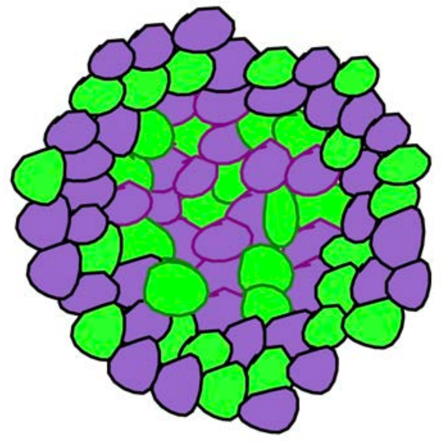
?

(a)



Self-consistent homogenization model

(elastic or viscoelastic parameters)



A mixture of two minerals with different viscosities

$$1 = \frac{f_1}{1 + \frac{3(K_1 - K)}{3K + 4\mu}} + \frac{f_2}{1 + \frac{3(K_2 - K)}{3K + 4\mu}}$$

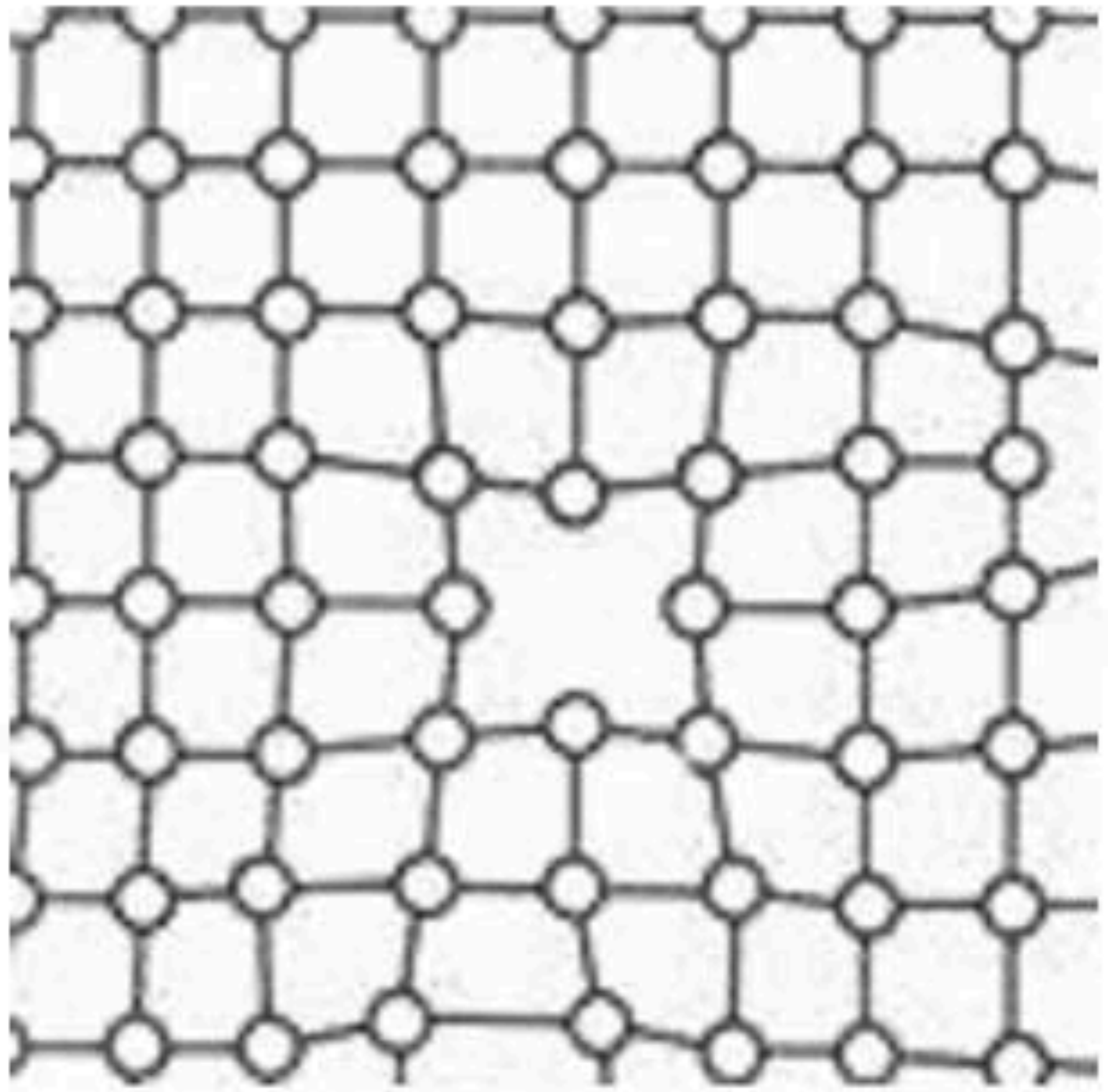
$$1 = \frac{f_1}{1 + \frac{6(K + 2\mu)}{5(3K + 4\mu)} \frac{(\mu_1 - \mu)}{\mu}} + \frac{f_2}{1 + \frac{6(K + 2\mu)}{5(3K + 4\mu)} \frac{(\mu_2 - \mu)}{\mu}}$$

The mixture of two Maxwell materials behaves like a Burgers model !

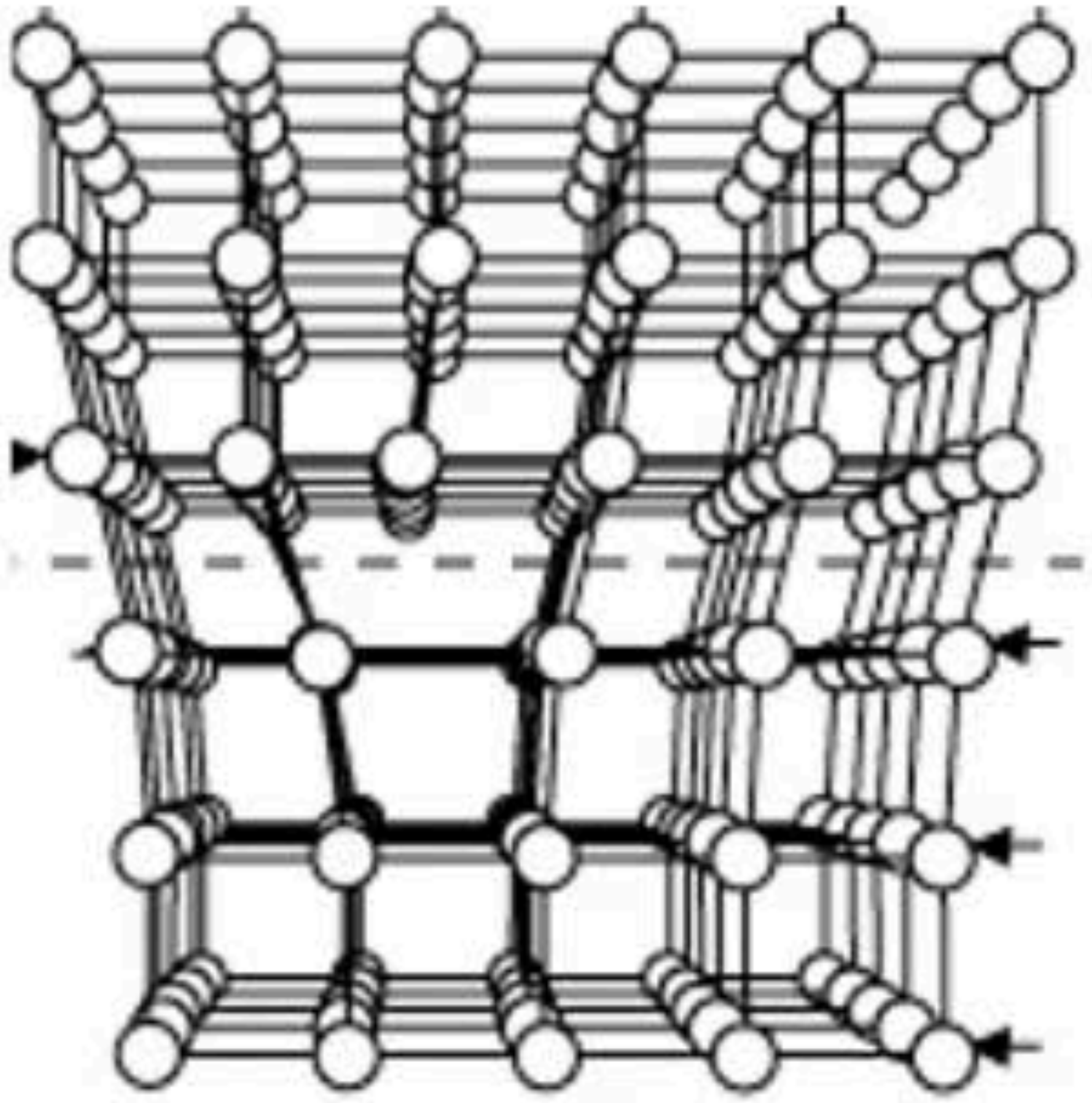
What is a rock and how does it deform?

What is a rock and how does it deform?

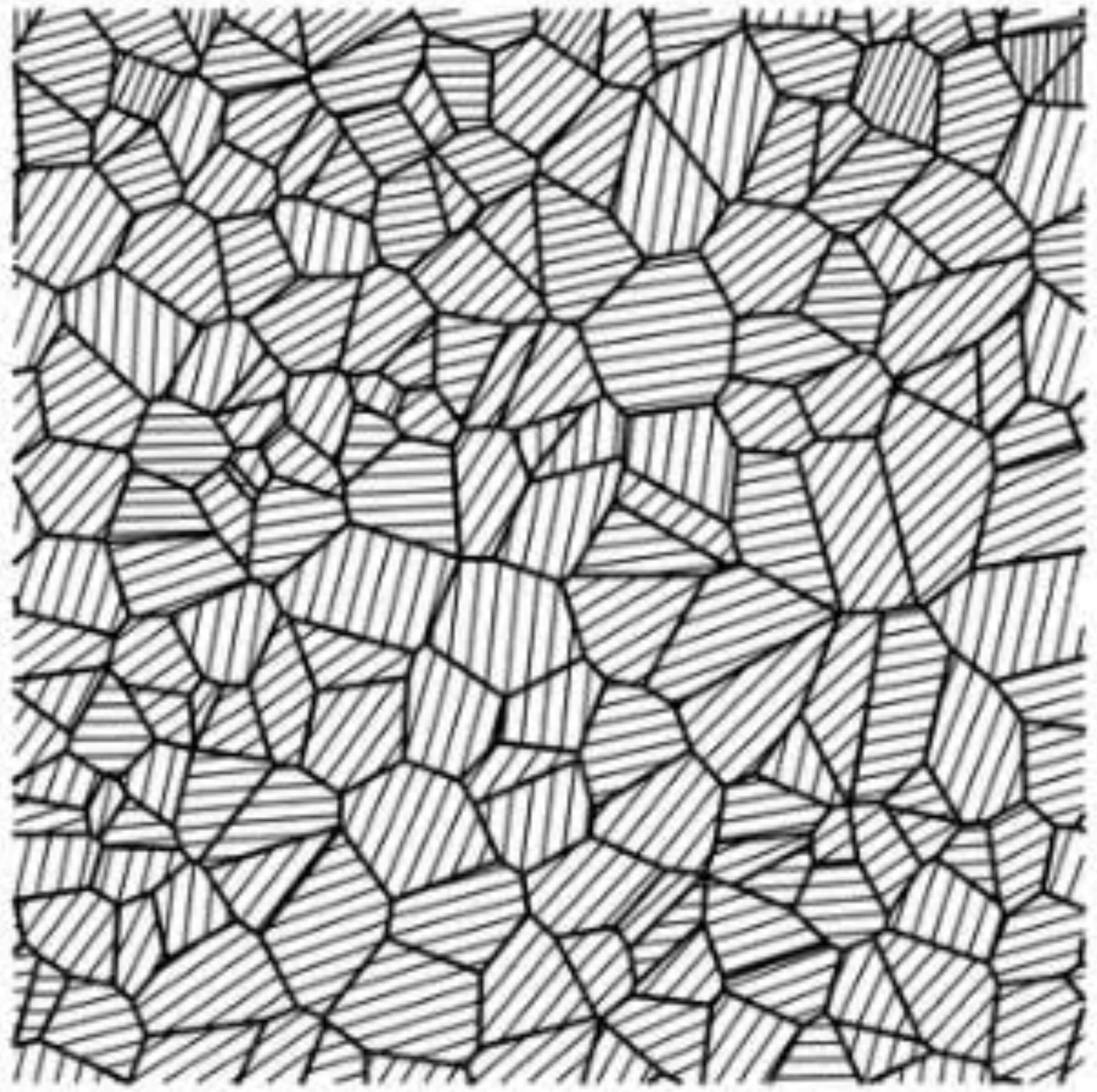
Vacancies



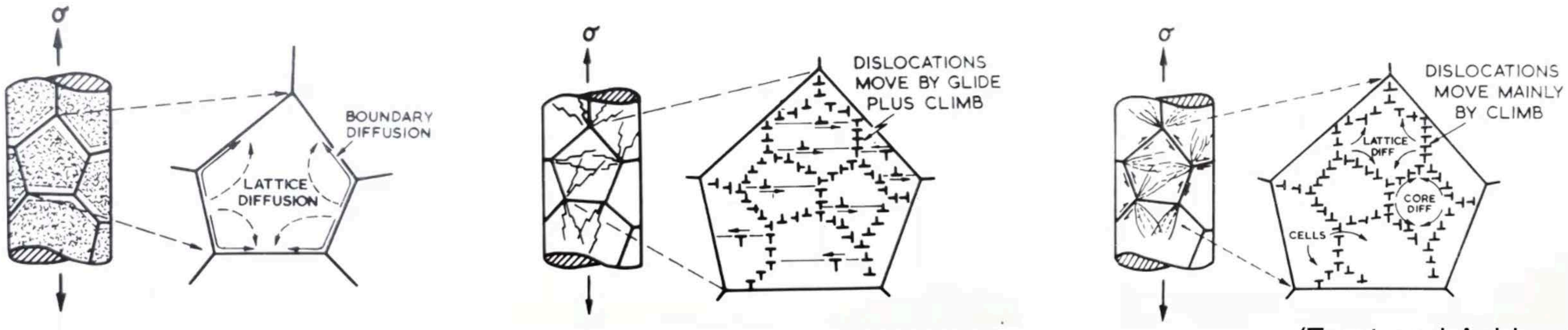
Dislocations



Grain Boundaries



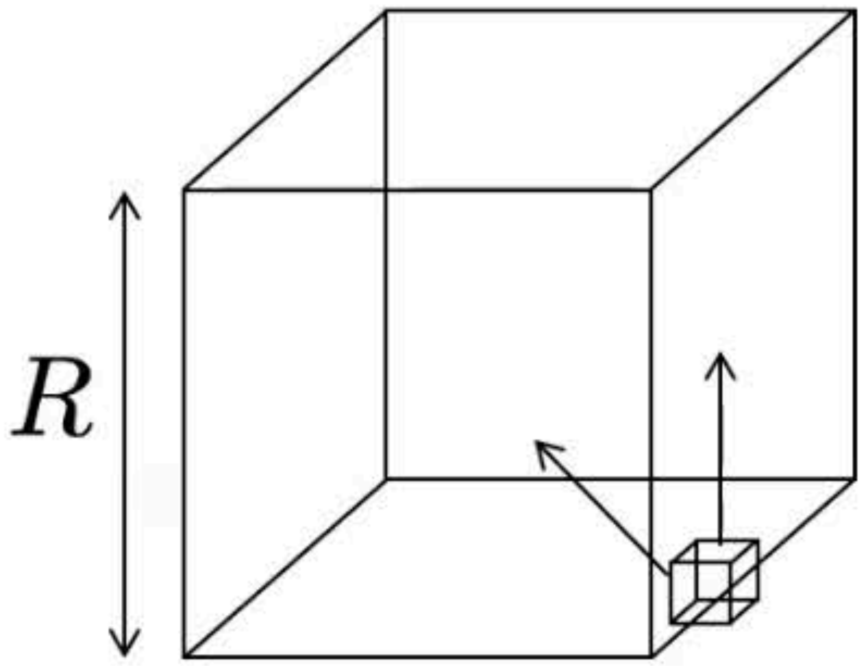
Micromechanisms of rock creep in the mantle



(Frost and Ashby, 1982)

Microphysical Theory Prediction

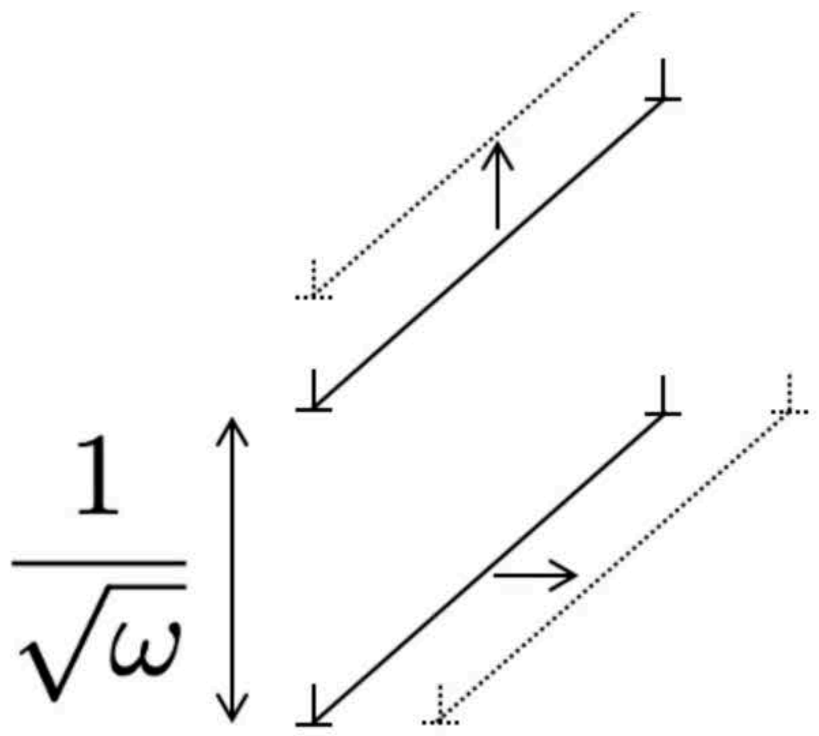
<u>Diffusion creep:</u> variation in vacancy concentrations due to stress drives vacancy fluxes between grain boundaries



$$\dot{\epsilon}_{diff} \sim \frac{\sigma}{R^2}, \frac{\sigma}{R^3}$$

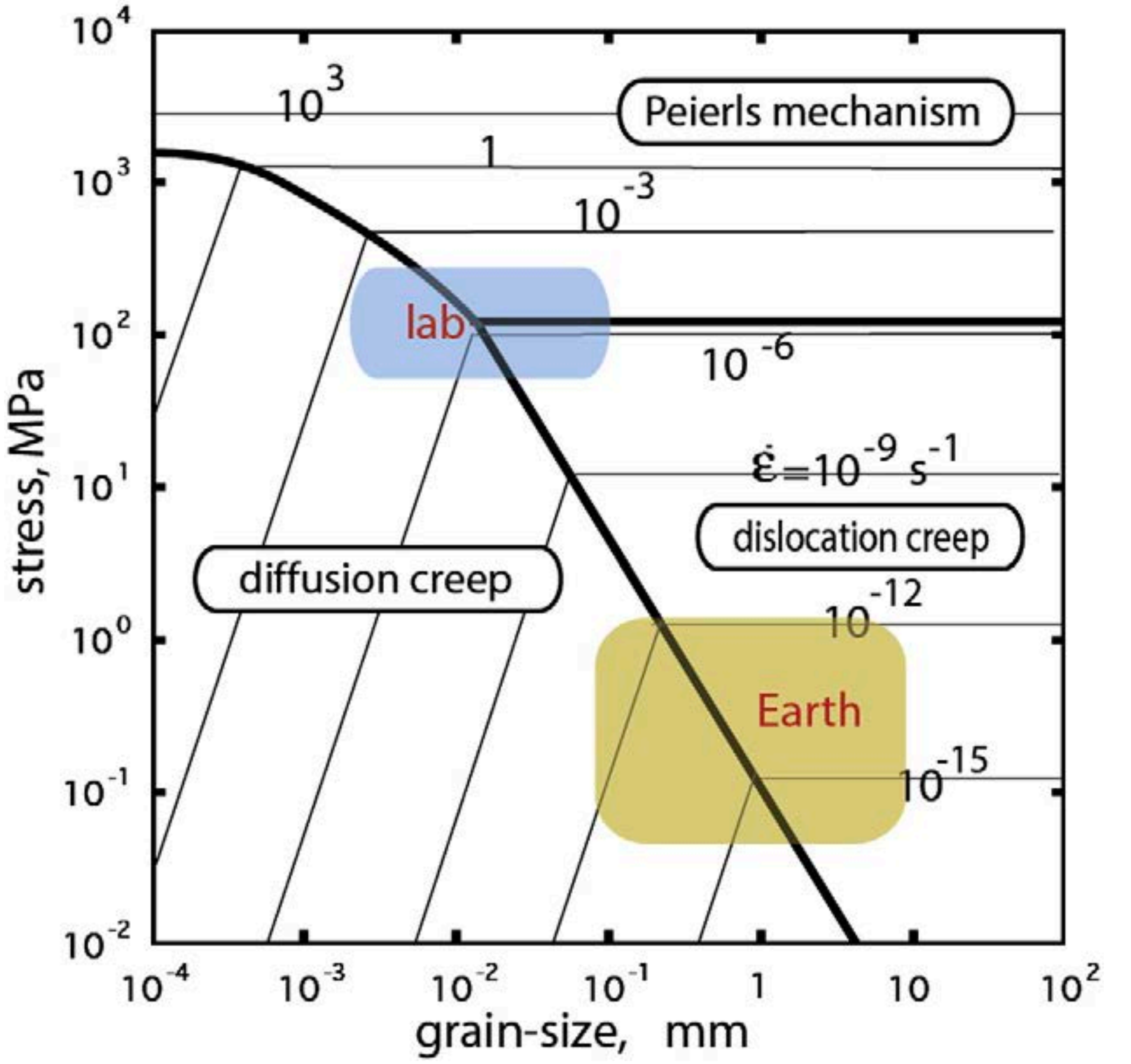
$$\dot{\epsilon}_{diff} = \frac{B}{R^m}\sigma$$

<u>Dislocation creep:</u> stress generates and moves dislocations by climb and glide



$$\dot{\epsilon}_{disl} \sim \omega v \sim \sigma^n$$

$$\dot{\epsilon}_{disl} = A\sigma^n$$

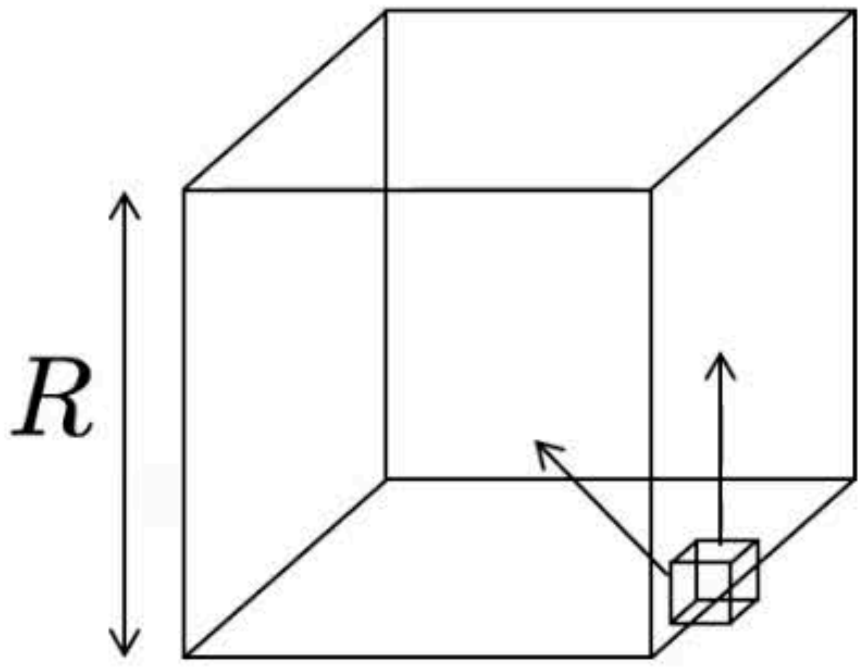


Karato (2010)

Microphysical Theory Prediction

At low GIA strain rate, newtonian rheology?

<u>Diffusion creep:</u> variation in vacancy concentrations due to stress drives vacancy fluxes between grain boundaries



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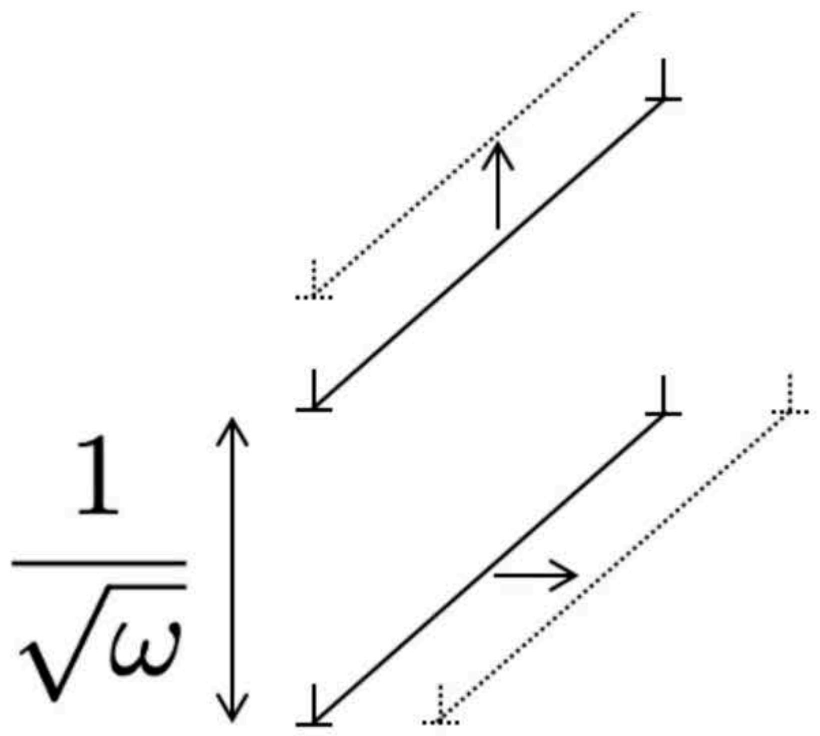

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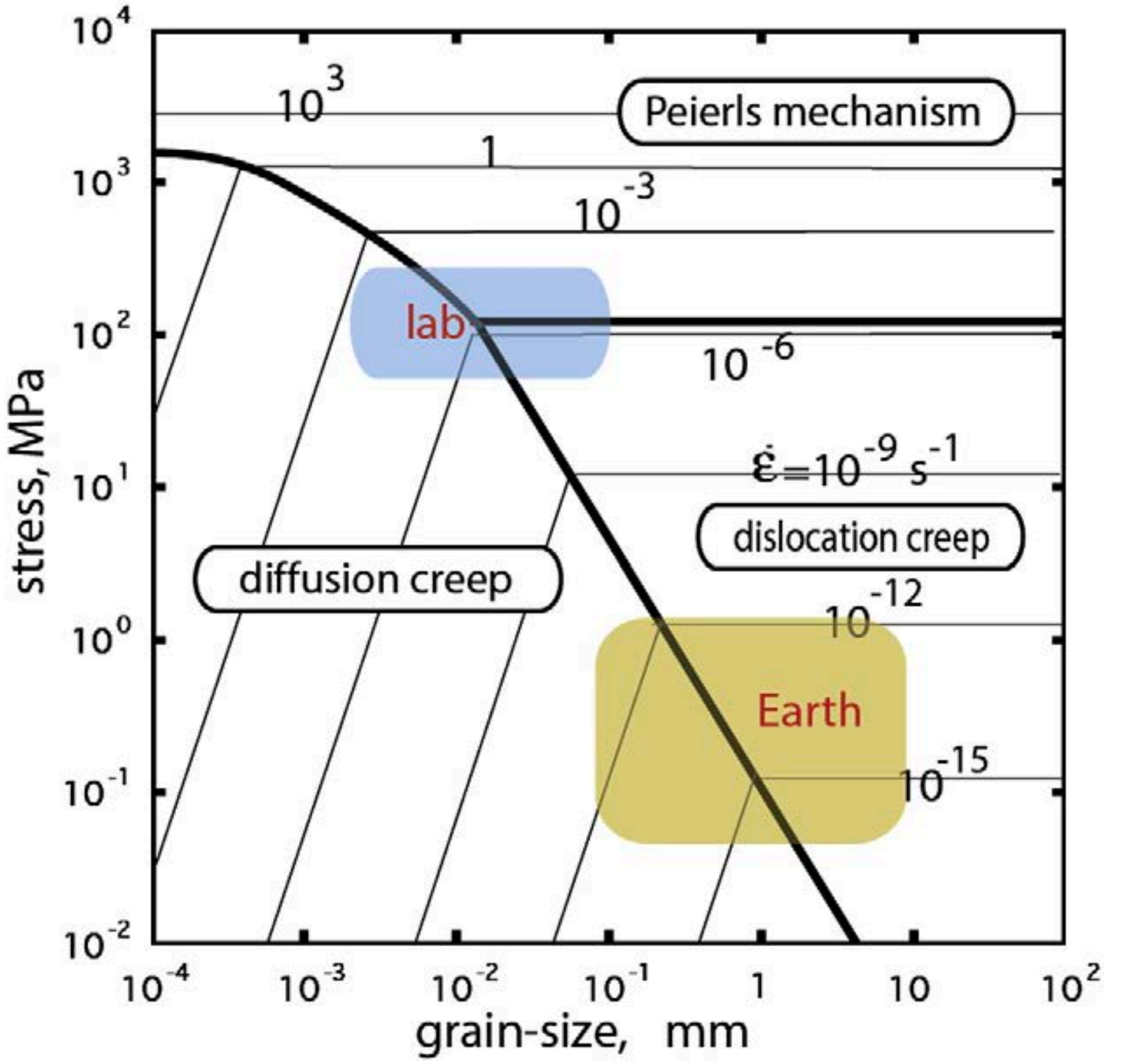


Karato (2010)

But these processes are still poorly studied under low strain rate in the laboratory... please help?

The (almost) perfect case of Glacial Isostatic Adjustment (GIA)

1. What is GIA and why study it?
2. Theory: general concepts, modelling and rheology
3. Observations : constraining ice history and monitoring deformation

Forward modelling of Glacial Isostatic Adjustment (GIA)

Deformation

Load

theory/model

- *Relative sea level*
- *geopotential*
- *Rotation*
- *Surface deformation*

- *relative sea level*
- *Grounded ice*
- *Rock erosion/deposition*

Rheology

- *Generally… a Maxwell layered rheology (sometimes a Burgers)*

Forward modelling of Glacial Isostatic Adjustment (GIA)

Prediction: Deformation

Load

Collect data and model

- *relative sea level*
- *Grounded ice*
- *Rock erosion/deposition*

Comparaison

- *Relative sea level*
- *geopotential*
- *Rotation*
- *Surface deformation*

theory/model +

Rheology

- *Generally... a Maxwell layered rheology (sometimes a Burgers)*

Adjust to fit observations

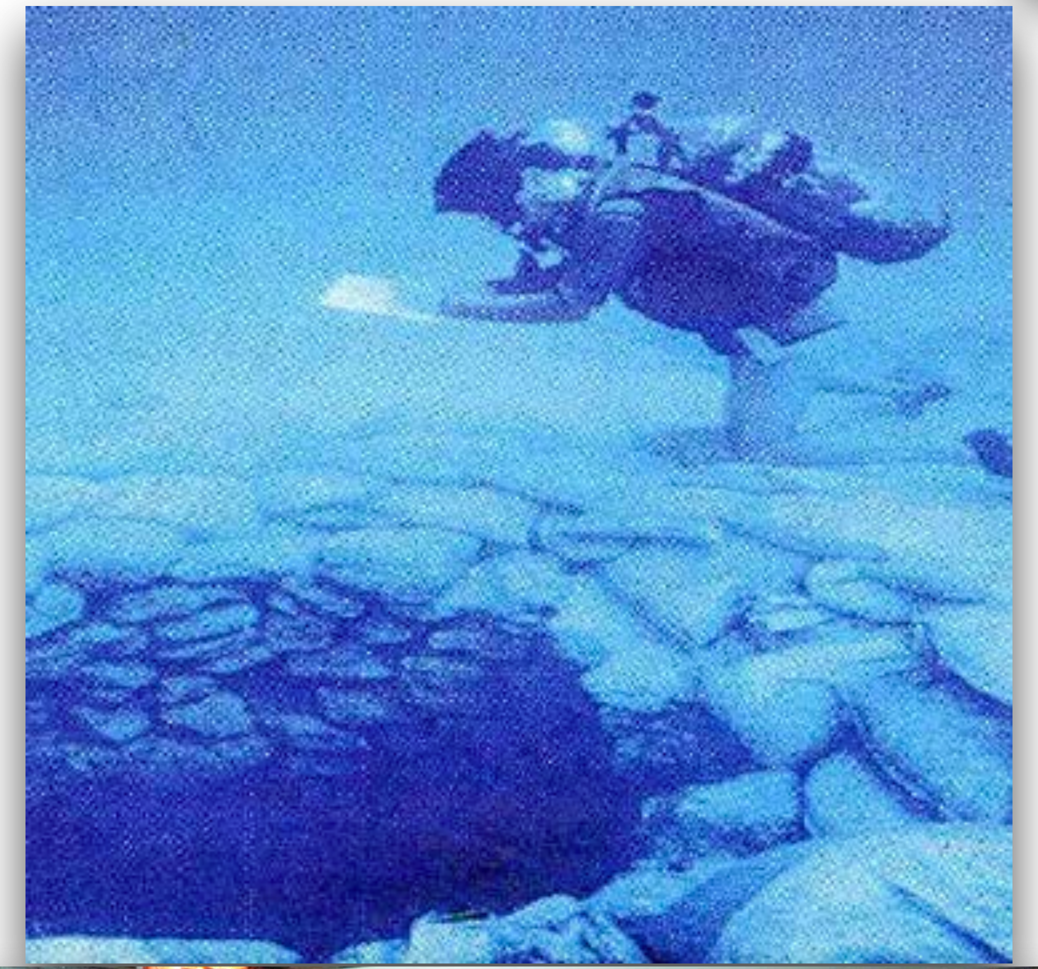
What observations?

What observations?

Relative sea level

corals

Submerged well
from coast of Israel



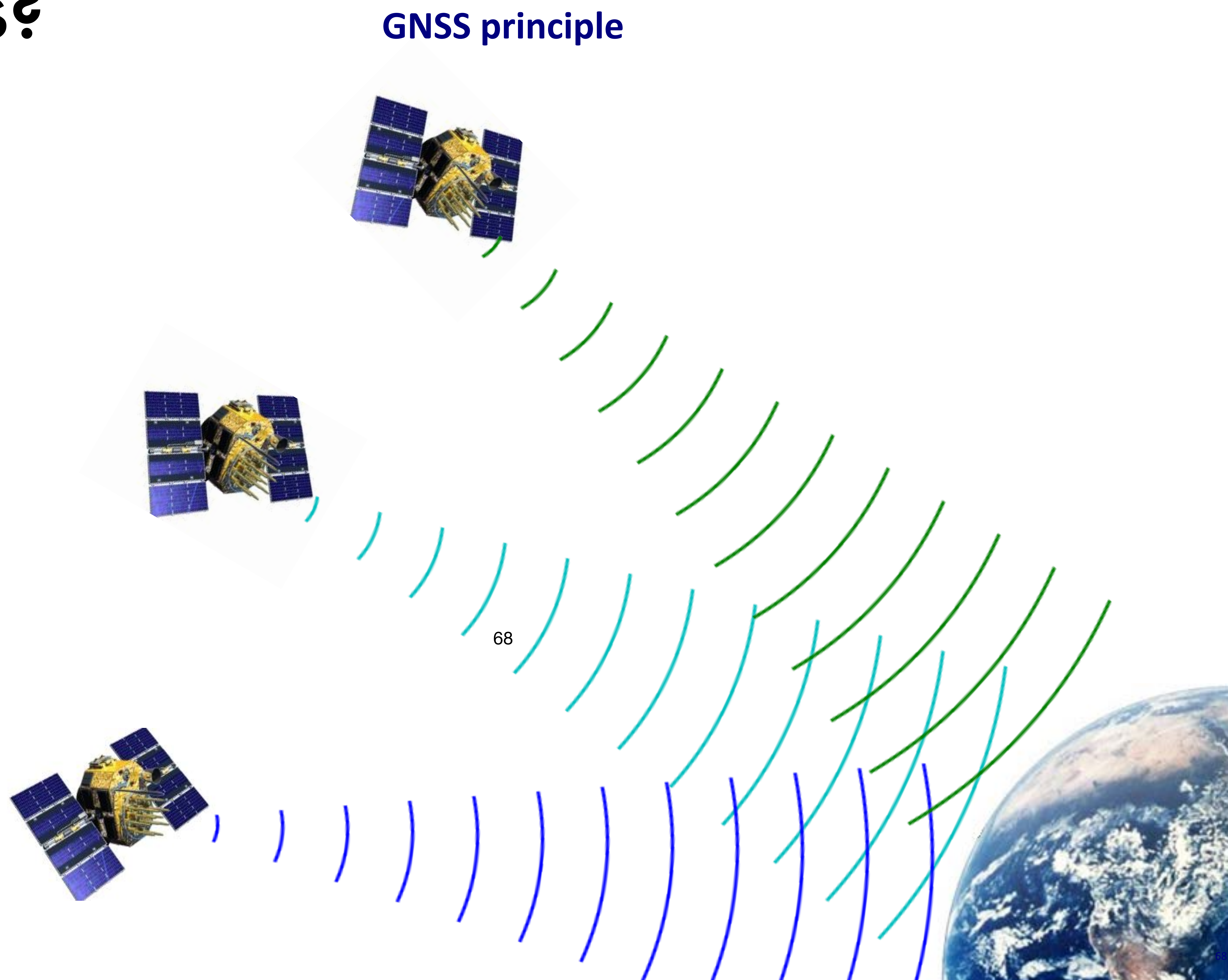
Bronze-Age carvings
from former coastal
dwelling site now
inland , SW Sweden

Ice core

Uplifted beaches

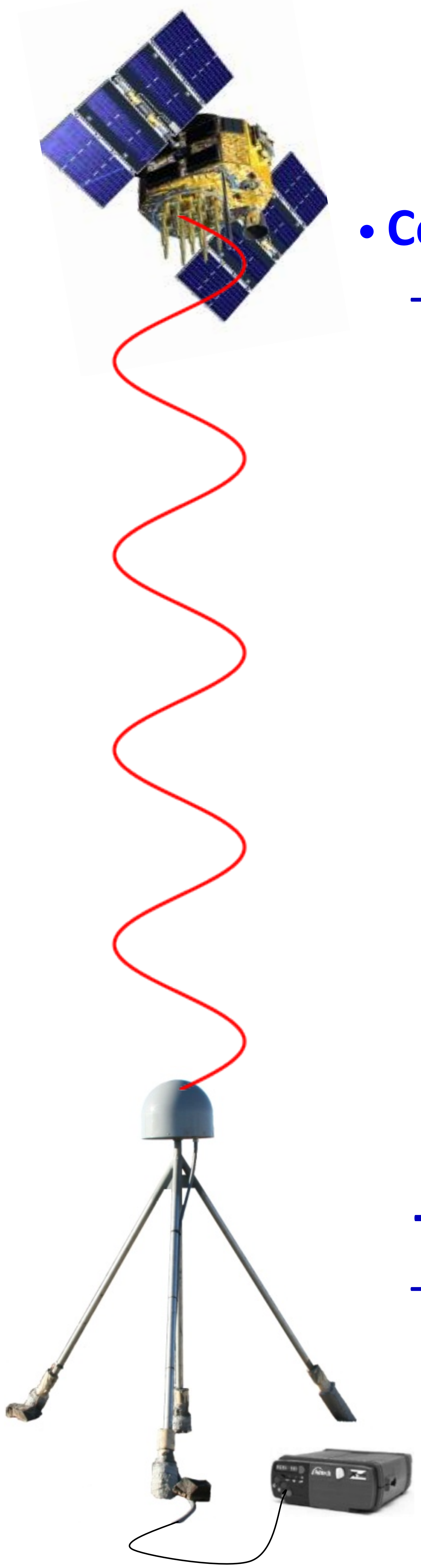
What observations?

Land uplift

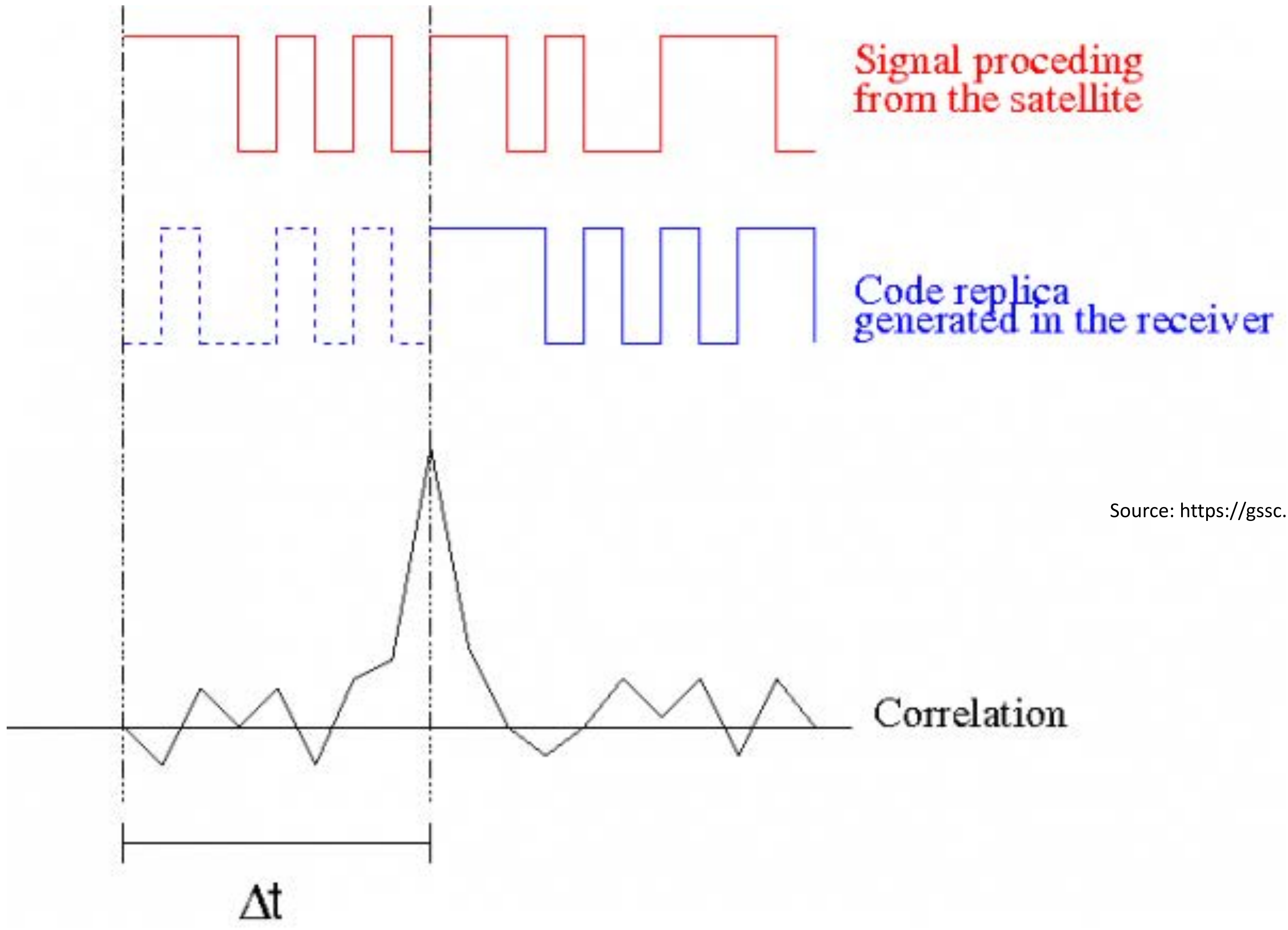


What observations?

Land uplift



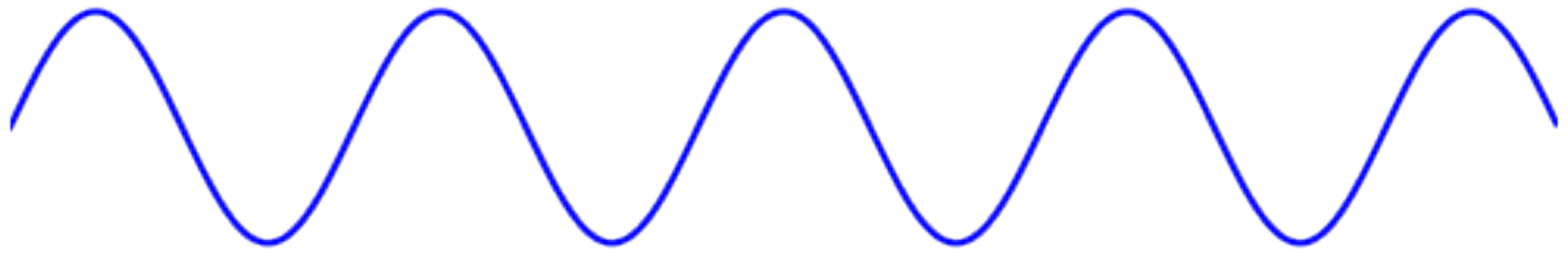
- **Code measurement:**
  - **Based on pseudo-random code that modulates the signal**



Source: https://gssc.esa.int/

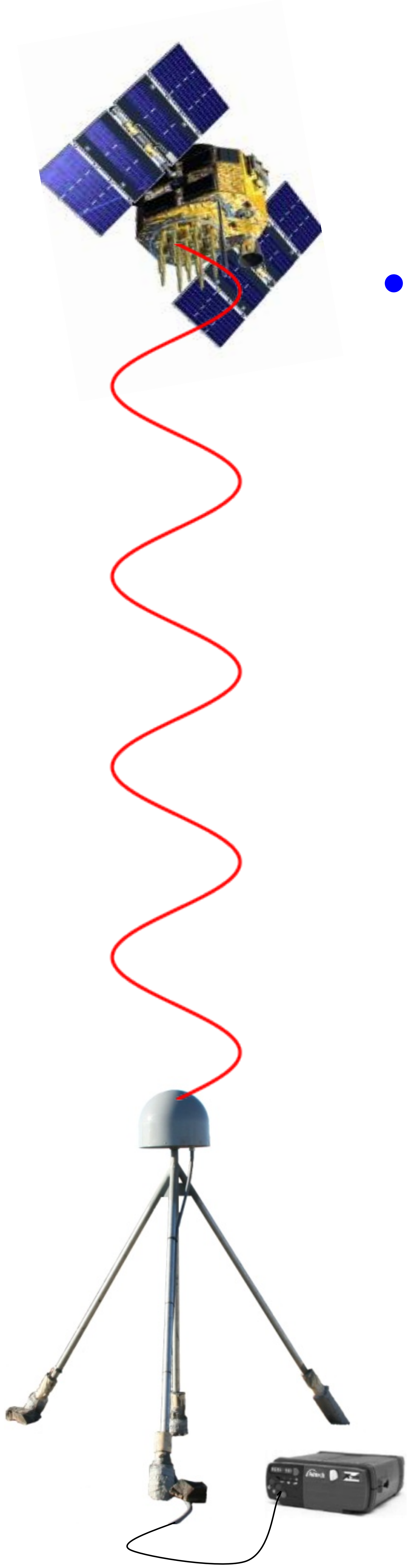
→Propagation time, up to synchronization errors

–Precision: ≈ 1 ns (≈ 30 cm)

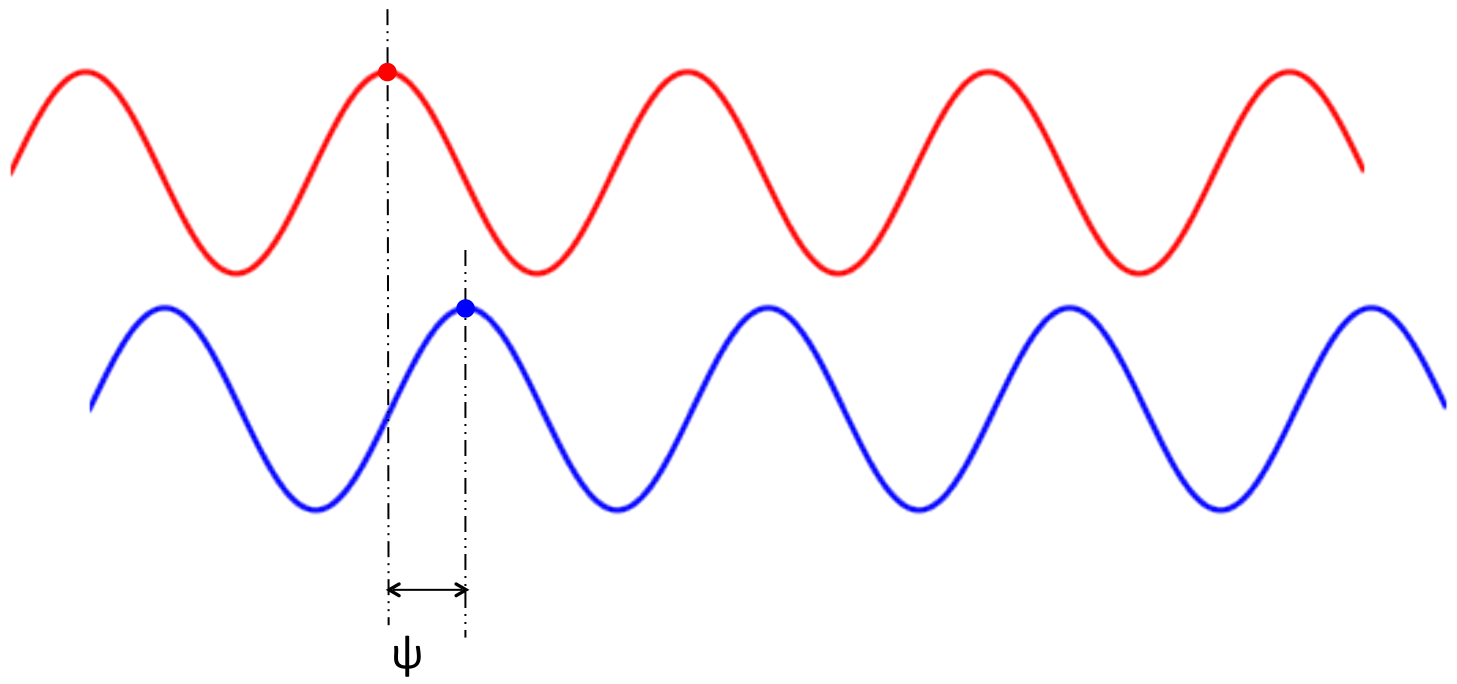


What observations?

Land uplift

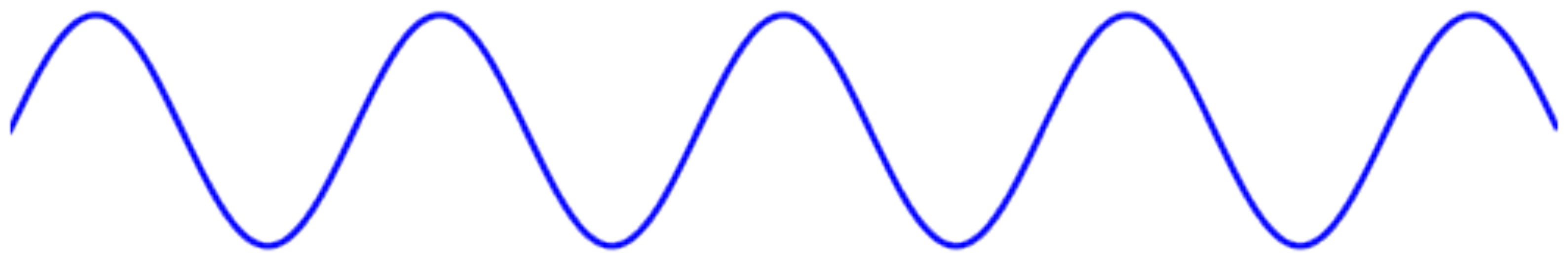


- **Phase measurement:**



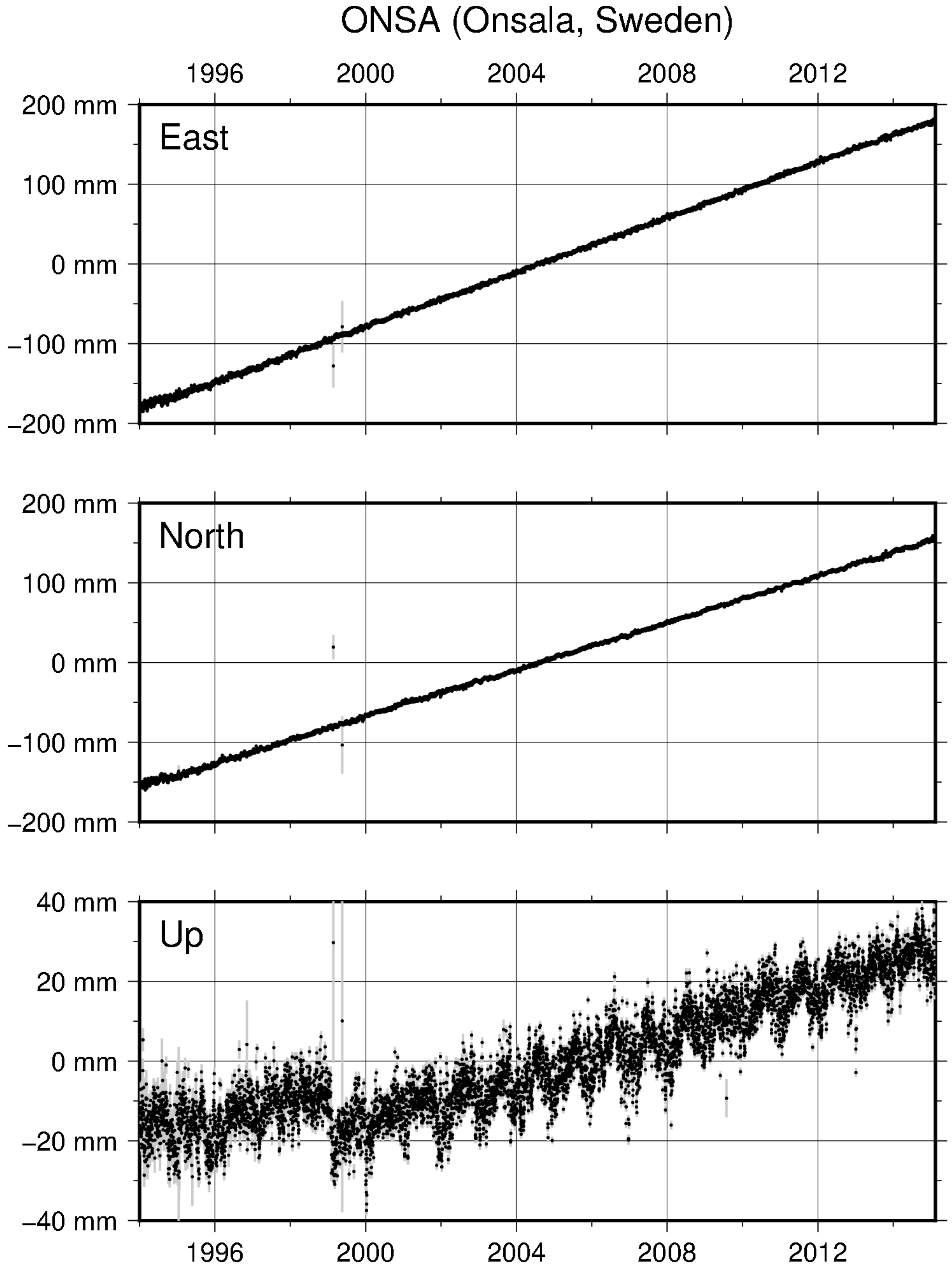
Source: https://gssc.esa.int/

  - **Precision: ≈ 0.01 cycle (≈ 2 mm)**



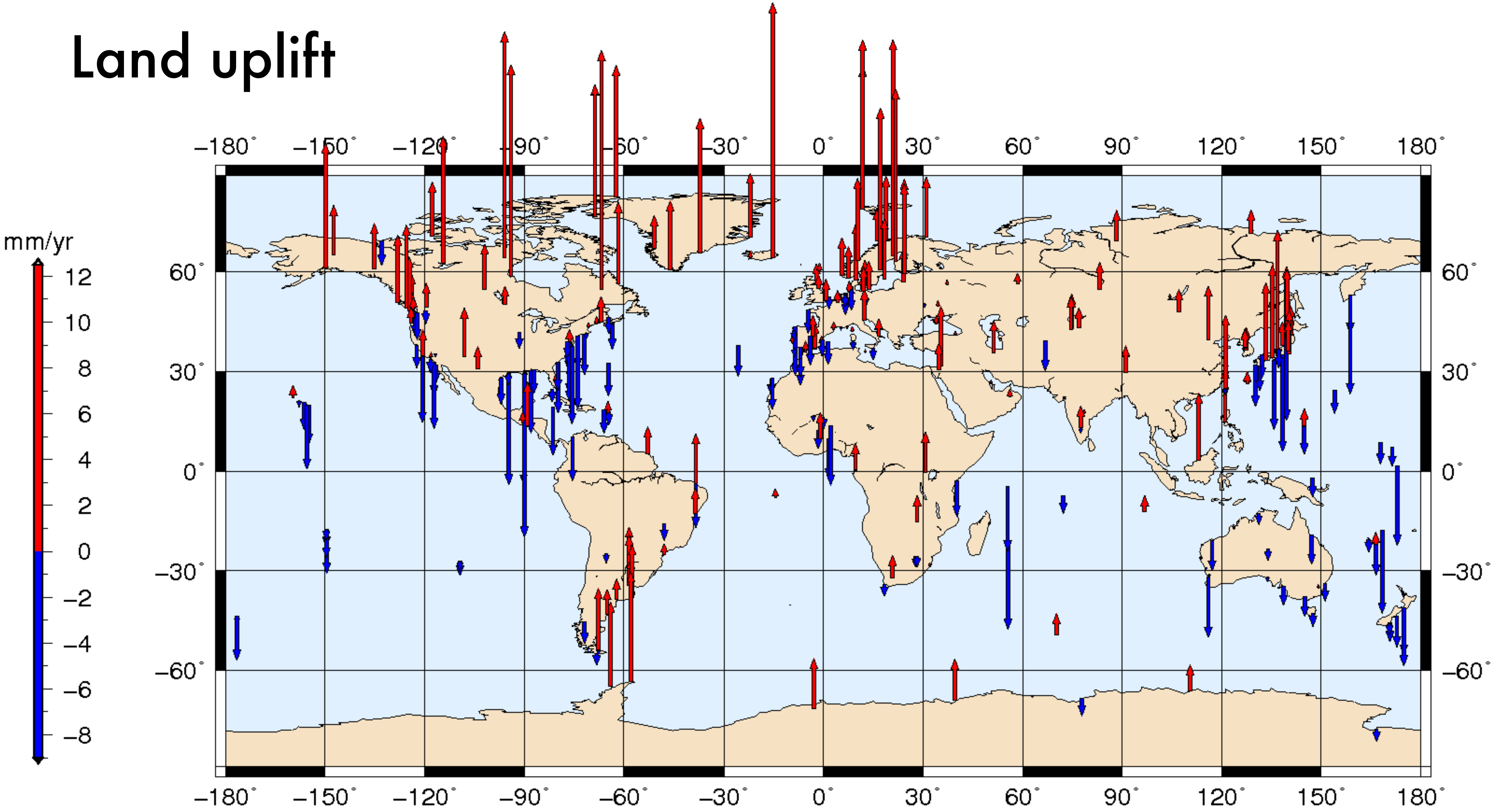
What observations?

Land uplift



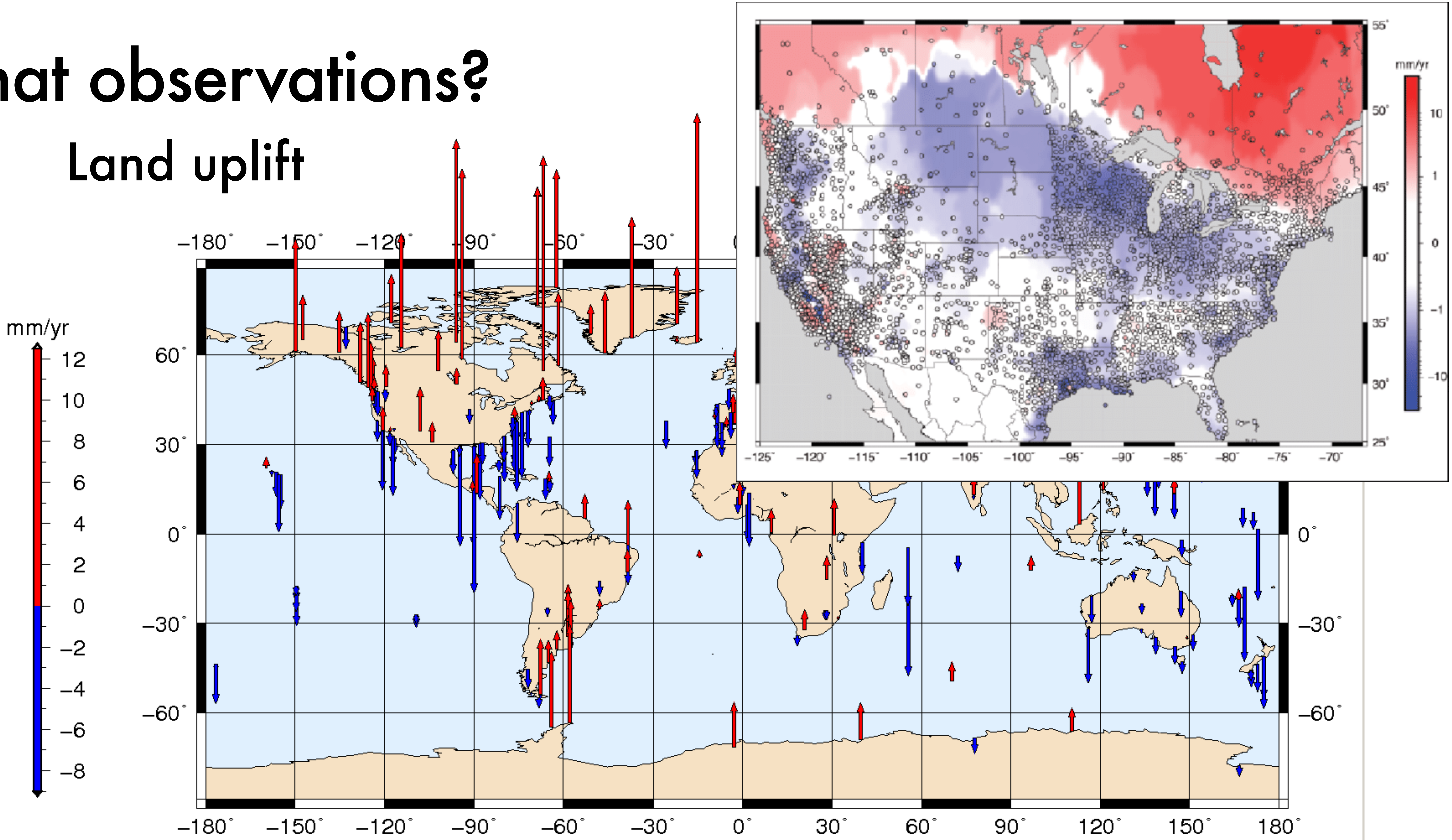
What observations?

Land uplift



What observations?

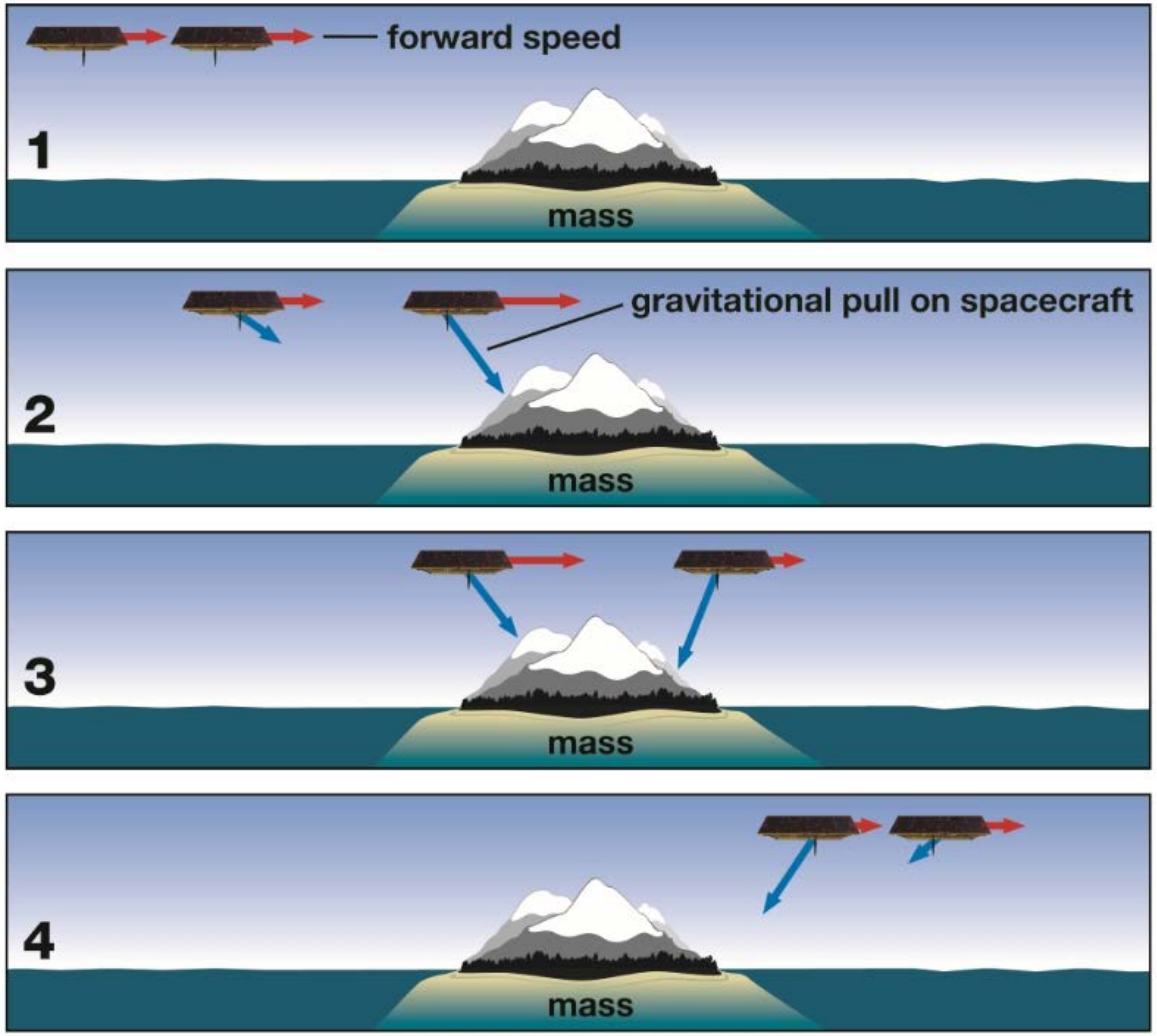
Land uplift



What observations?

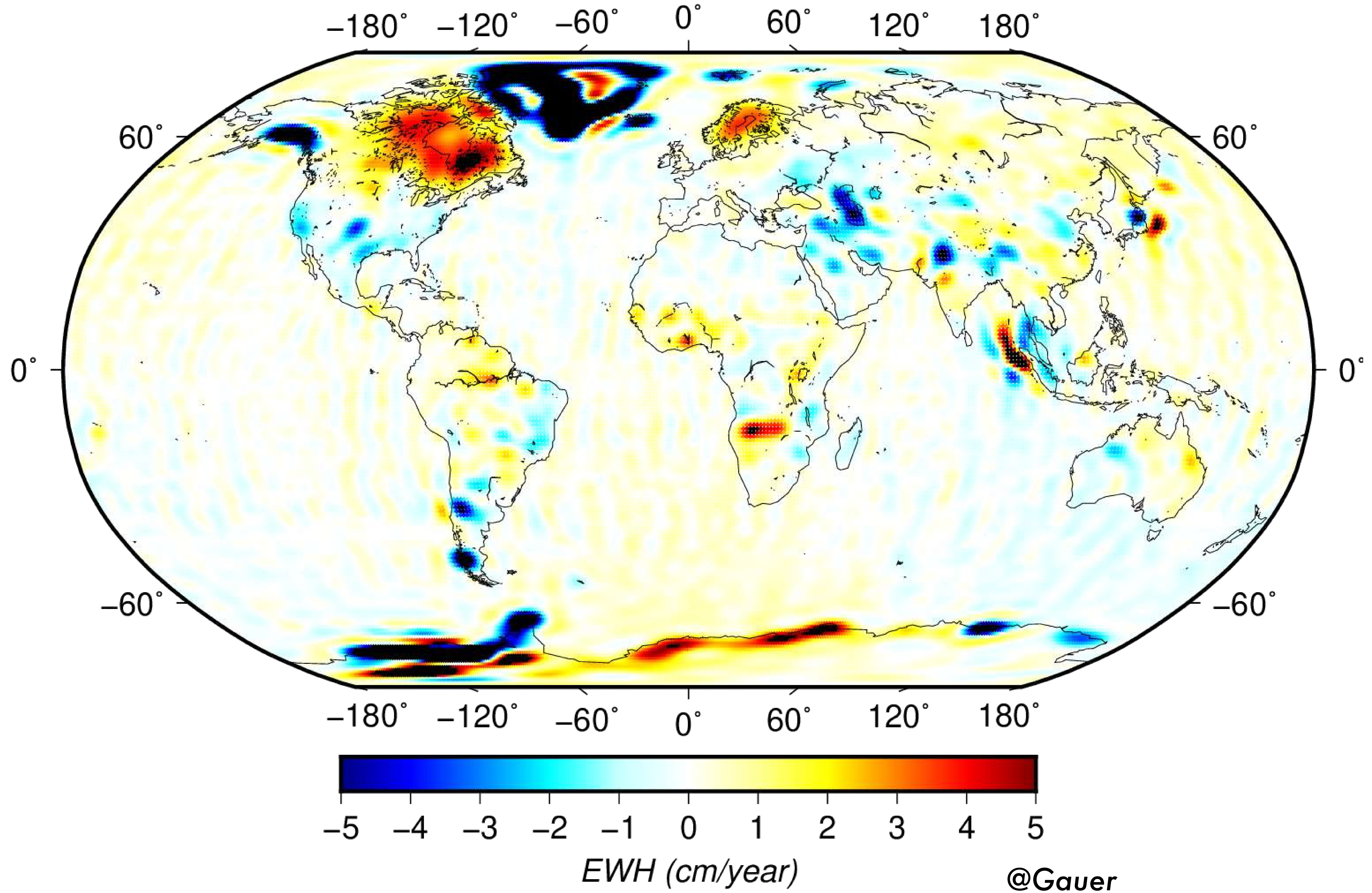
Gravity data

Gravity and Recovery Climate Experiment (GRACE)



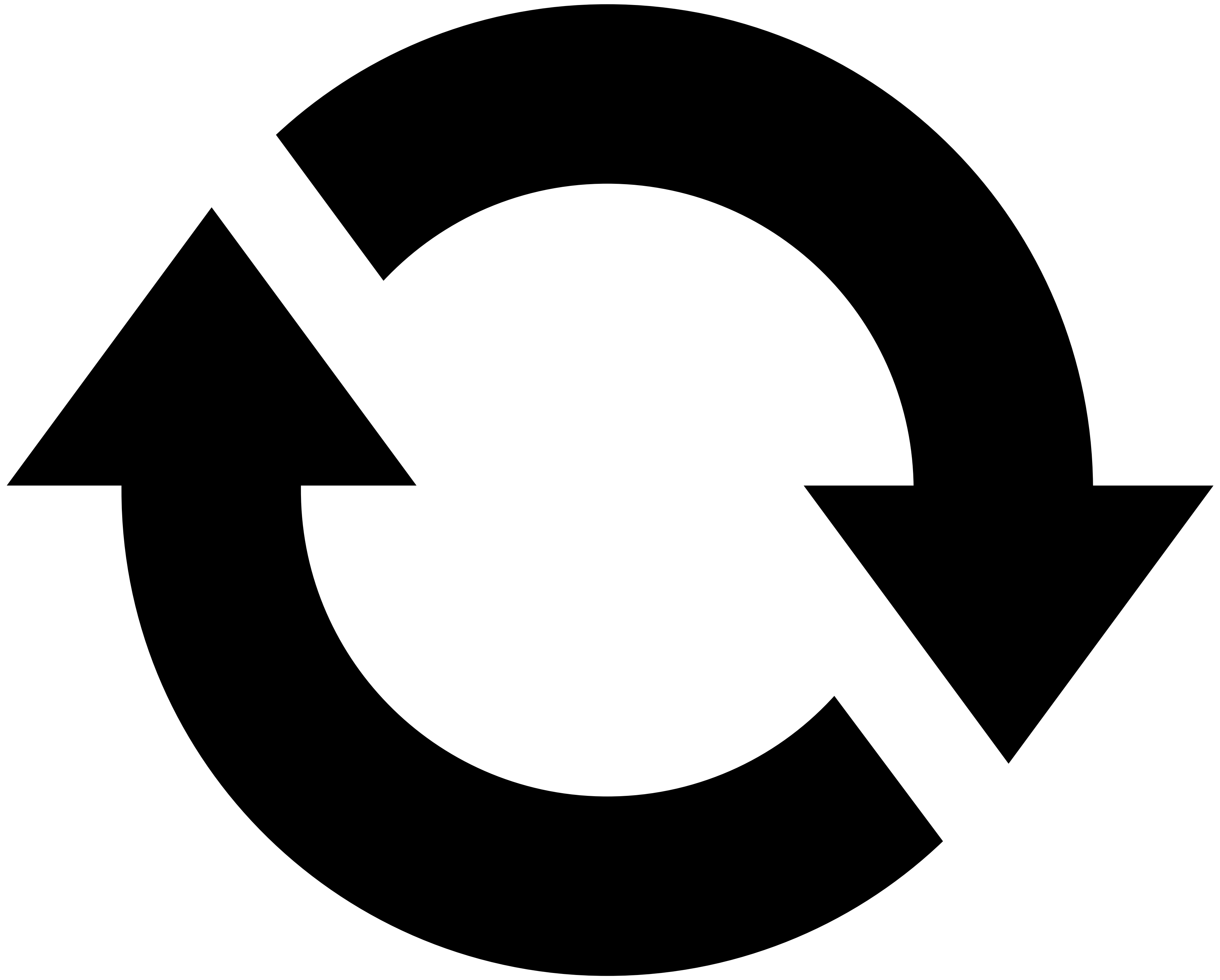
@Nasa JPL

GRACE 2003-2015



@Gauer

Solving GIA + Sea level equation until data are best fitted



Iteration model - data comparaison
or inversion

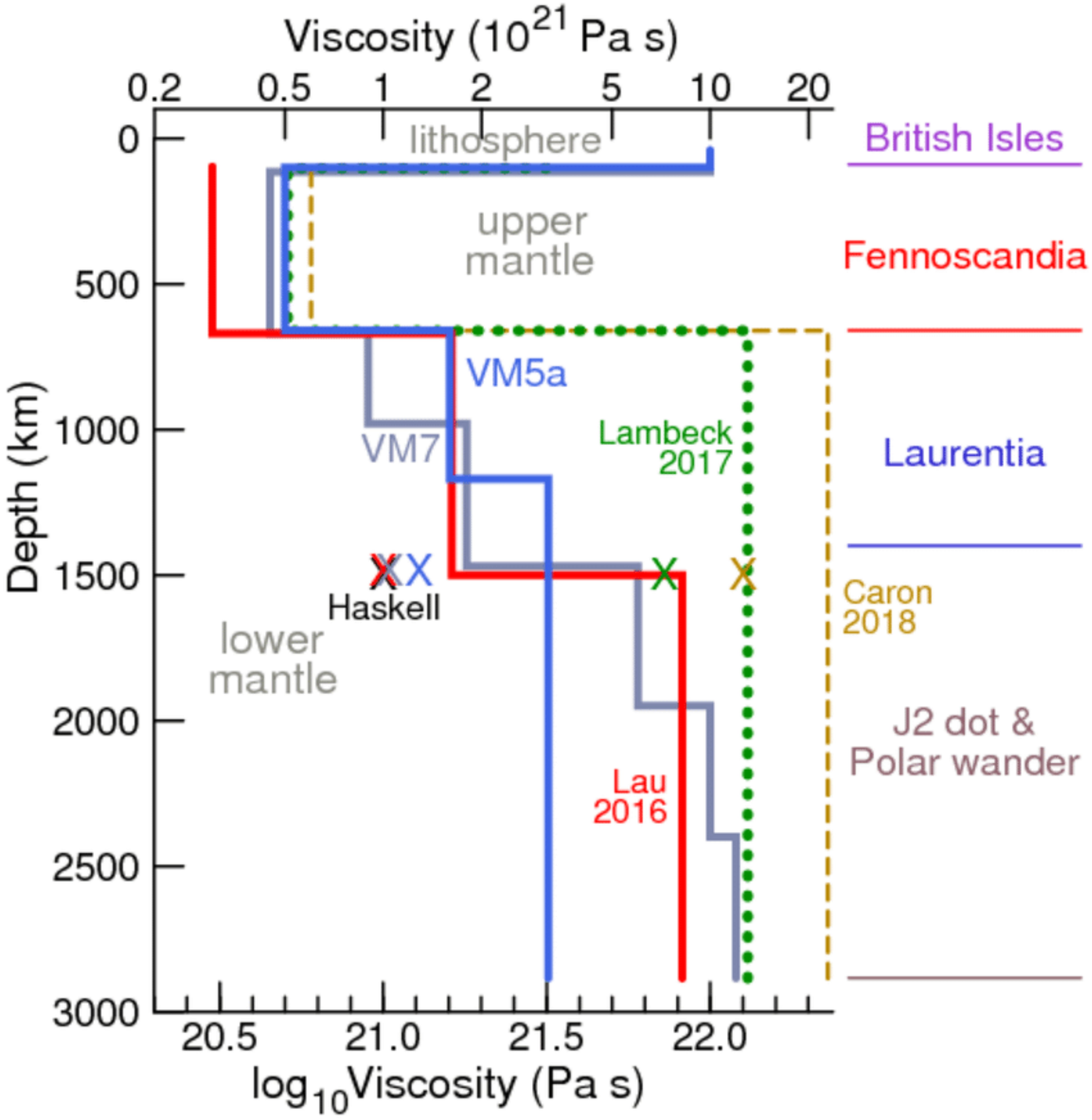
And finally...

Outstanding questions?

- large uncertainty on the total volume of ice melt since LGM

- Average mantle viscosity of 10^{21} Pa.s what is the upper/lower mantle contrast?

Norman Haskell 1935



Argus et al. (2019)

- Simple rheologies : lateral heterogeneities, Burgers vs Maxwell?

Take home message

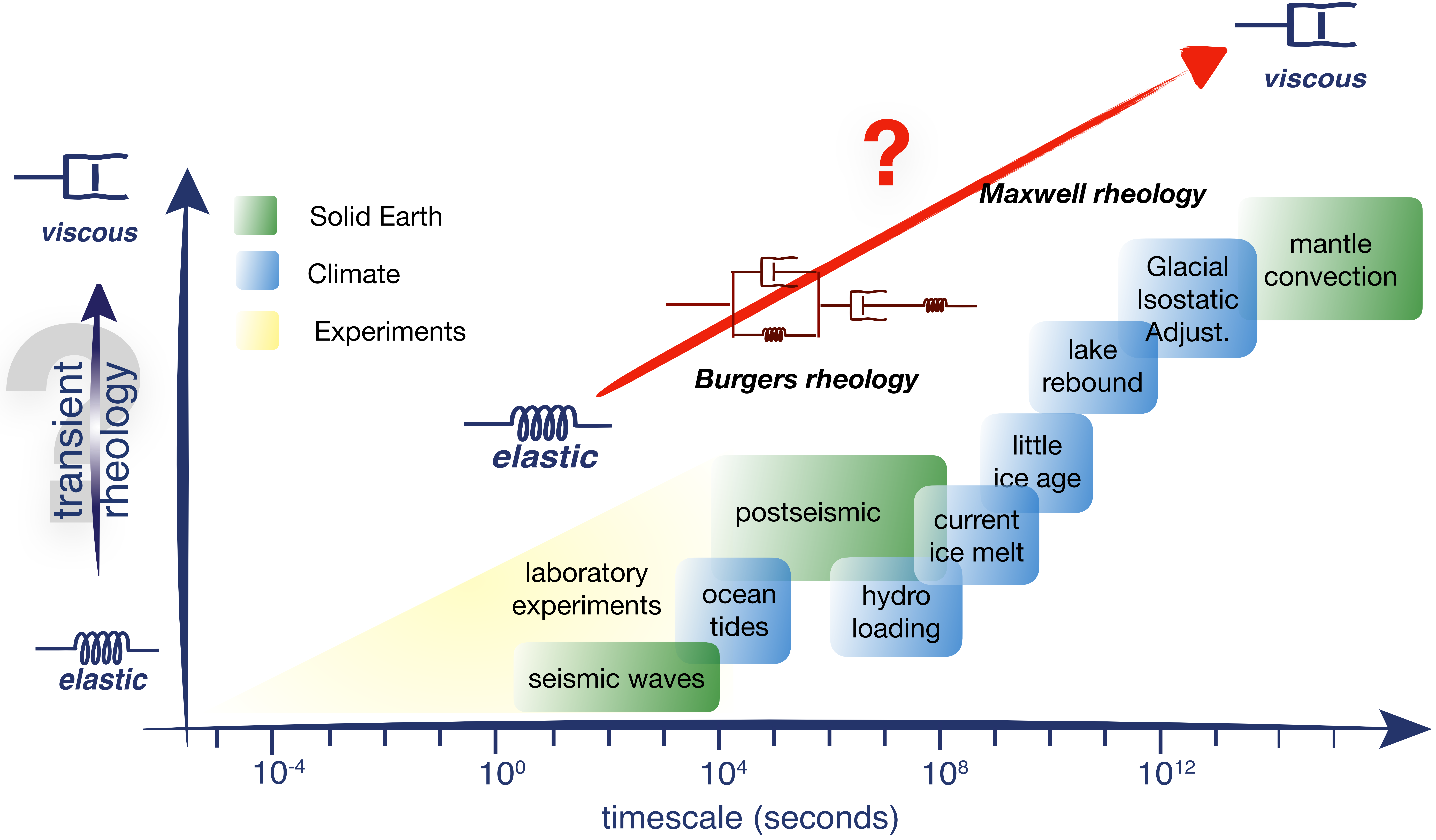
1) Looking at the surface loads is interesting to probe the Earth rheology, ice history, better understand present day melting and improve sea level predictions in a changing climate

2) It's a *messy problem* (but nice equations) with some poorly constrained parameters (ideas?)

3) Linking large scale and laboratory derived rheological laws is not easy

4) The story of the Earth's mantle viscosity is probably not over...

What's next?


viscous
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Solid Earth
Climate
Experiments
?
Maxwell rheology
Burgers rheology
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mantle convection
Glacial Isostatic Adjust.
lake rebound
little ice age
postseismic
current ice melt
laboratory experiments
ocean tides
hydro loading
seismic waves
10^{-4}
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