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Regional stress field computation along the West Svalbard margin (Vestnesa ridge): Effect of the glacial isostatic adjustment.

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seam|stress

CAGE

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Tectonic context:

The Vestnesa ridge is located in a tectonically active region (figure 1), bordered by the Molloy ridge (MR) and the Molloy transform fault (MFT) in the West. In addition, GPS measurements show that Svalbard is actively uplifting because of the effect of post-glacial rebound (Kierulf et al., 2014; Auriac et al., 2016).

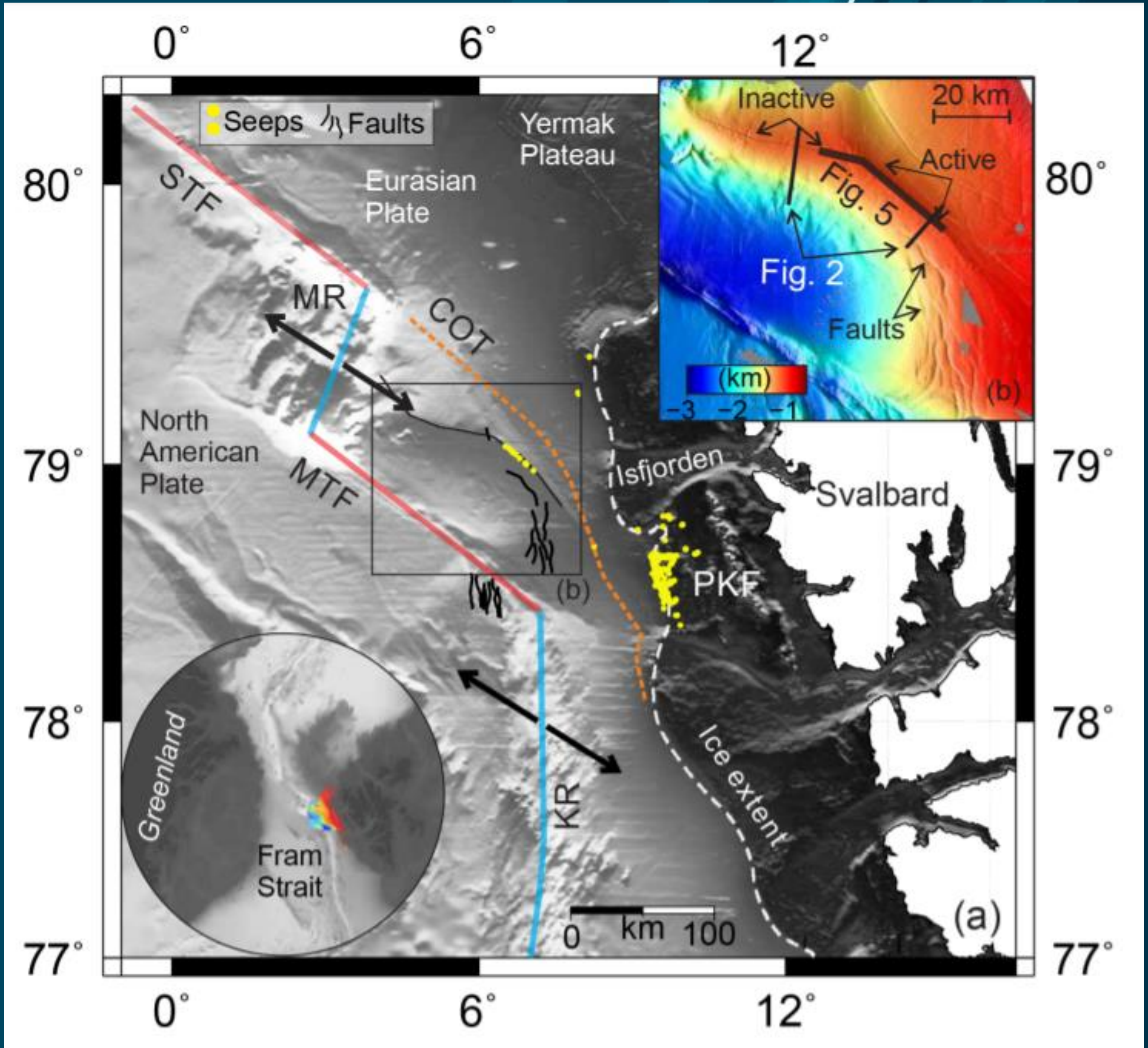
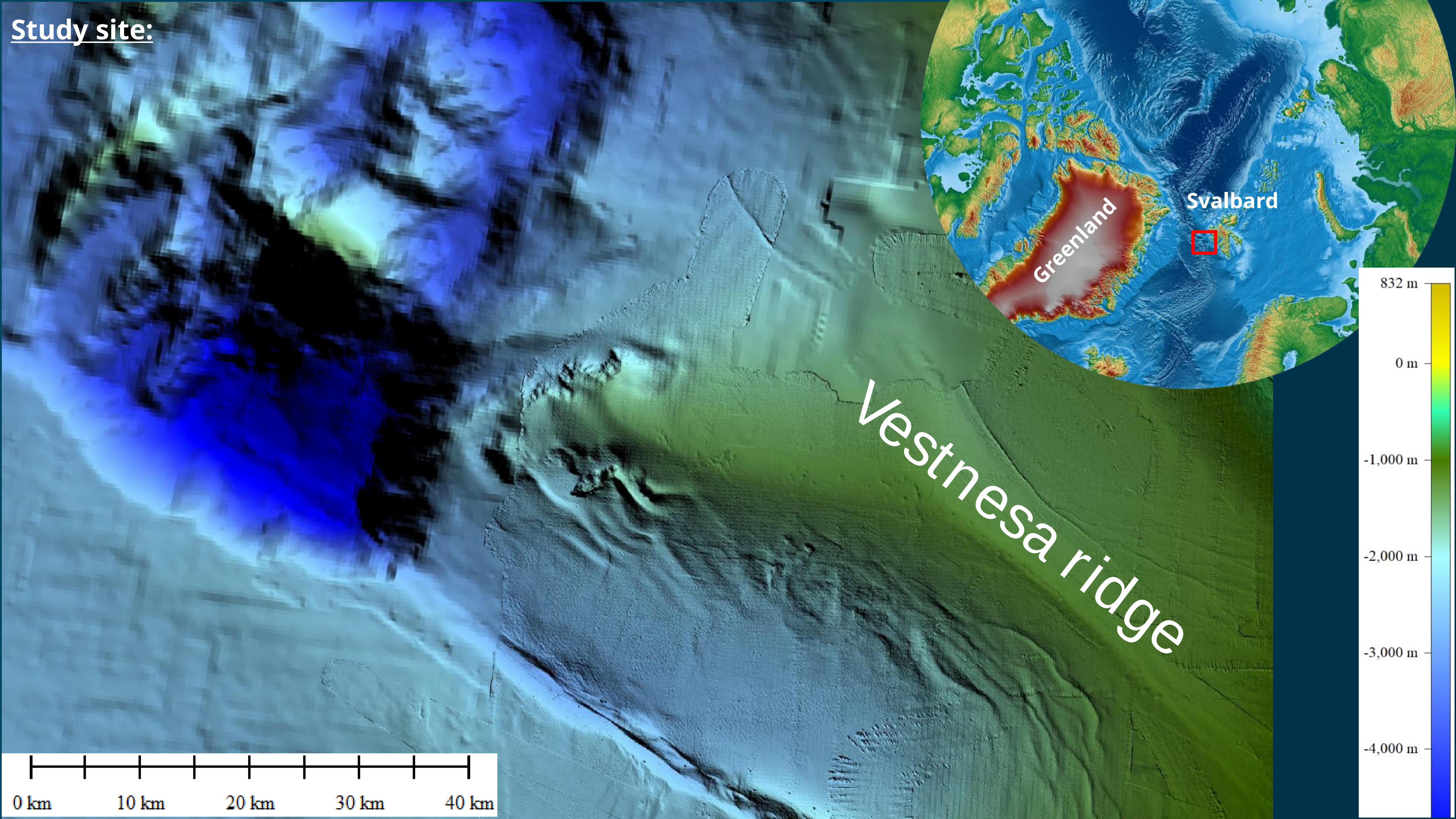


Figure 1 (Plaza-Faverola & Keiding., 2019): (a) International Bathymetric Chart of the Arctic Ocean (IBCAO) showing the geometry of mid-ocean ridges offshore of the western Svalbard margin. (b) High-resolution bathymetry along the Vestnesa Ridge (UiT, R/V Helmer Hanssen multi-beam system), Figure 2 and 5 refer to Plaza-Faverola & Keiding., 2019.

Study site:



Svalbard
Greenland
Vestnesa ridge
832 m
0 m
-1,000 m
-2,000 m
-3,000 m
-4,000 m
0 km
10 km
20 km
30 km
40 km

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Introduction and background:

The present work is part of the project SEAMSTRESS that aims at quantifying the effect of tectonic stresses on gas seepage from the West-Svalbard margin.

In this study, we investigate the effect of glacial isostatic adjustment (GIA) on the stress field in the Svalbard and Fennoscandian area.

Objectives:

1) Benchmark GIA finite element models against analytical and pre-existing numerical solutions.

2) Model the principal stresses associated with the Barents Sea and Fennoscandia ice-sheet since the LGM.

3) Model validation: compare the uplift rates predicted by the model with GPS observations.

Modelling methodology

Finite element modelling of GIA related problems:

To set-up the problem in a numerical modelling software, we need:

1) An **Earth model** (geometry, material parameters, and theoretical formulation of its response to a surface load),

2) A time- and space-dependent **ice model** to apply to the Earth's surface,

We use **Comsol Multiphysics** as our modelling tool and implement the **GIA momentum equation** after Wu (2004) and Schmidt et al., (2012):

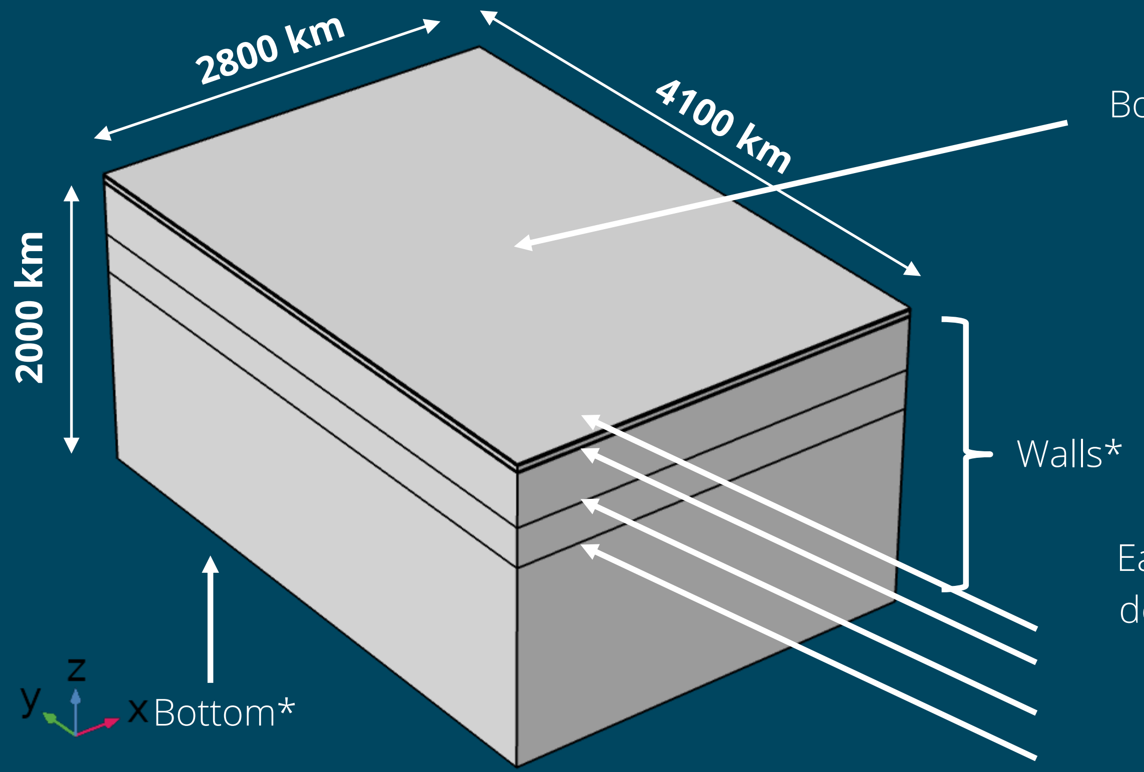
$$\nabla \cdot \boldsymbol{\sigma} - (\rho_0 g_0 \boldsymbol{u} \cdot \hat{\boldsymbol{z}}) = 0$$

With **σ** being the stress tensor, **u** the displacement vector, **z** the unit vector, **ρ** and **g** the material density and gravitational acceleration. The subscript **0** refers to the initial background state and **1** to the perturbed state. This formulation applies to a quasi-static and incompressible earth.

1. Finite element modelling.
2. **Model Set-up.**
3. Earth Rheology.
4. Ice Model.

Modelling methodology

Model geometry and boundary conditions:



Each layer interface is described by a spring foundation with

$$k = (\rho_- - \rho_+) \cdot g$$

ρ_- and ρ_+ being the density of the layer underlying and overlying the interface.

* The model is included in a large half-sphere with dimensions equal to 10 times the width of the earth model. We use this method to avoid any boundary effects on the study area. The walls of that half-sphere are fixed in every direction.

I - Background
II - Modelling methodology
III - Model Results
IV - Conclusions and perspective

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Modelling methodology

Earth model's rheology:

	Layer #	Thickness (km)	E Young modulus (GPa)	Poisson ratio	ρ density (kg . m^{-3})	μ viscosity (Pa . s)
Elastic Lithosphere (Varying*)	1	15	64	0.28	2750	-
	2	35	156	0.28	3251	-
	3	Varying*	170	0.28	3378	-
Visco-elastic Mantle (1940 km)	4	350	182	0.30	3433	$1.5x10^{21}$
	5	260	263	0.30	3837	$1.5x10^{21}$
	6	1330	552	0.30	4853	$1.5x10^{21}$

* The depth to the base of the elastic lithosphere varies between 60-160km, thinnest over oceanic regions - thickest over cratonic regions, with a mean value of 120km.

- The elastic parameters are based on the **preliminary reference earth model** (Dziewonsky and Anderson 1980) .
- We use a **Maxwell formulation** to describe the visco-elastic component of our Earth model's rheology.

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1. Finite element modelling.
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4. **Ice Model.**

Ice model: PattonH3C (Patton et al., 2016):

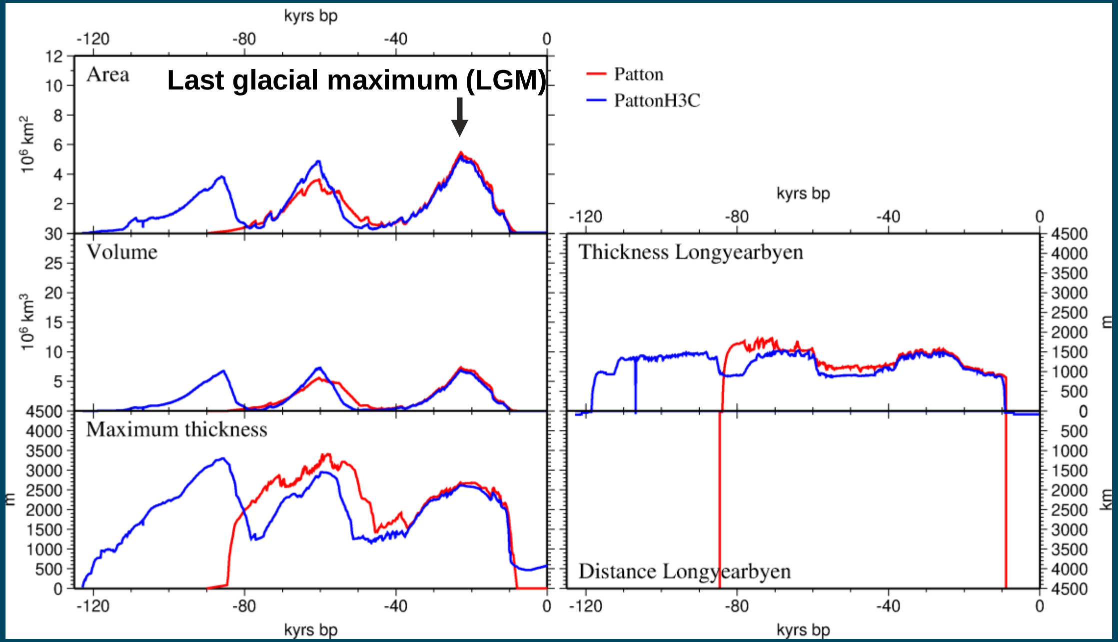

Figure 2: Characteristics of the PattonH3C ice model (extending ice modelling experiments of Patton et al., (2016, 2017). The ice model described in red (Patton et al., 2016) has been tested and compared with solutions from the PattonH3C model.

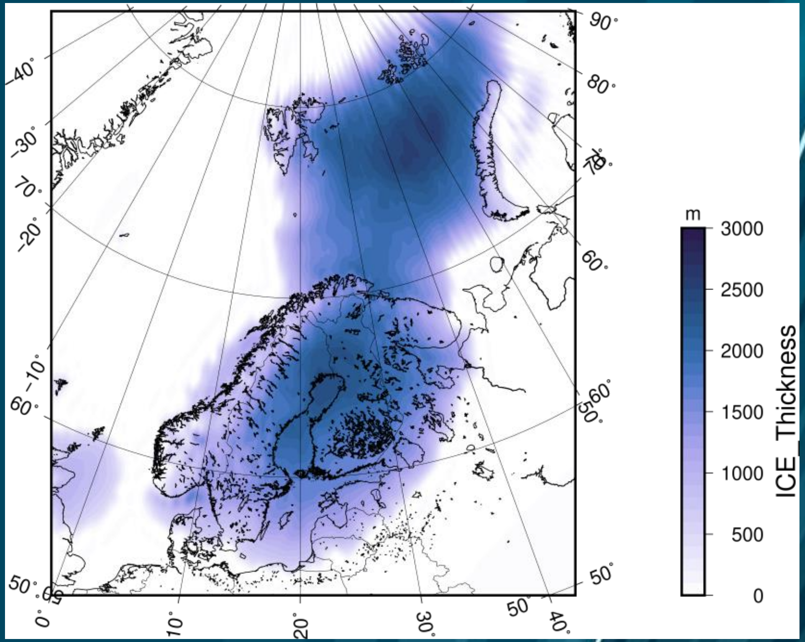

Figure 3: Ice thickness at the last glacial maximum (22 kyrs BP).

- The PattonH3C model covers the ice sheet evolution over the **Barents sea, Fennoscandia** and **the British Isles,** starting at 122.8 kyrs BP and ending at present time. The evolution of the **Greenland** ice-sheet is not included.
- Our numerical model computes the **strain and stress tensors** that result from the **full ice load history** of the H3CPatton model (running time = 122.8 kyrs).

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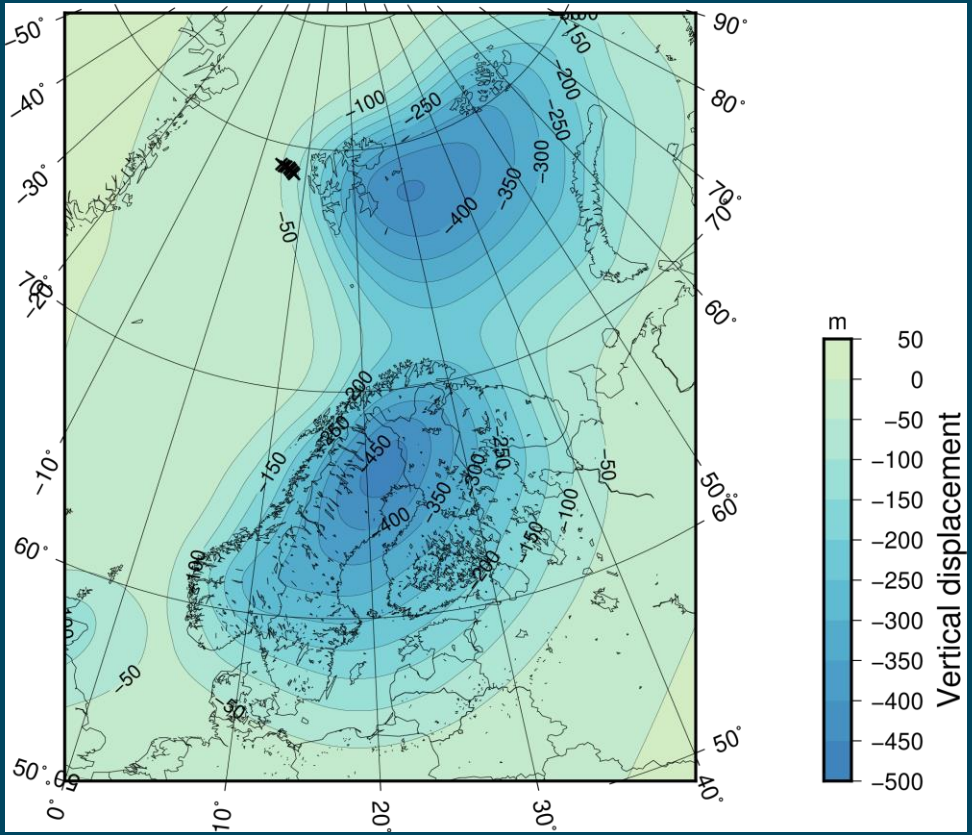
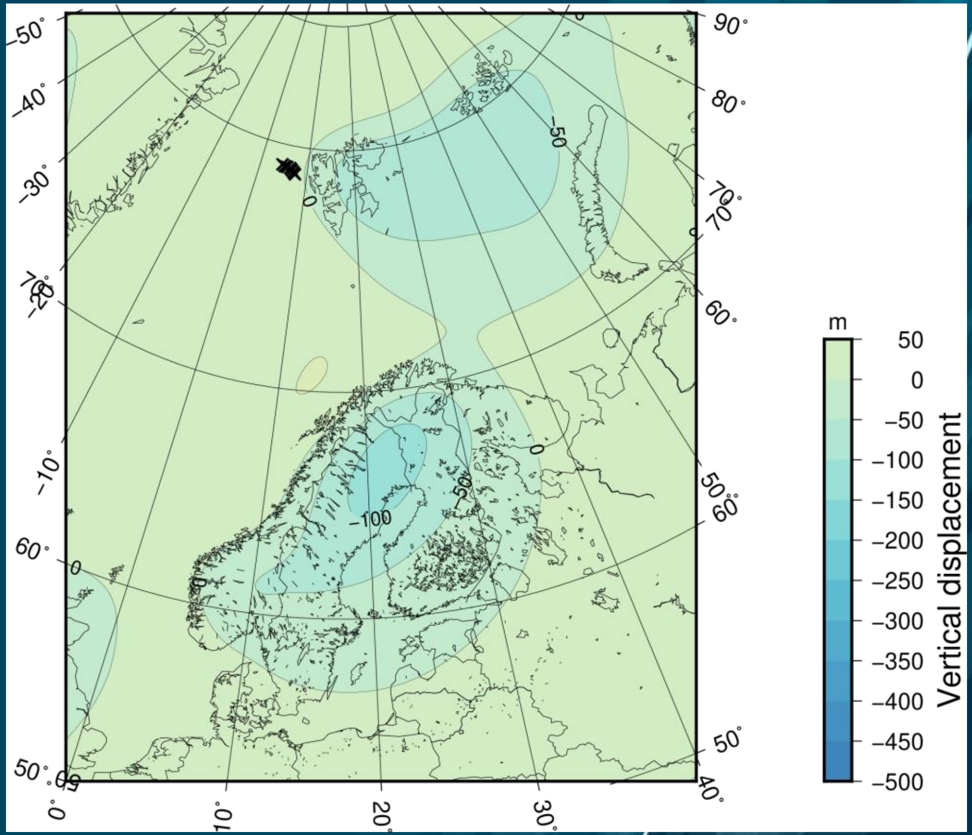
1. **Vertical displacement.**
2. Stress field.
3. Vertical displacement-Svalbard.
4. Stress field - Svalbard.
5. GPS vs Model

Results: Vertical displacement induced by glacial loading – Fennoscandia.

Last glacial Maximum (22kyrs BP):



Present:



Vertical displacement at the last glacial maximum and present time. At the LGM, the largest lithospheric subsidence is localized where the ice-sheet is the thickest. The remaining vertical displacement at present time (the "rebound") is mostly the result of slow viscous relaxation of the mantle.

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1. Vertical displacement.
2. **Stress field.**
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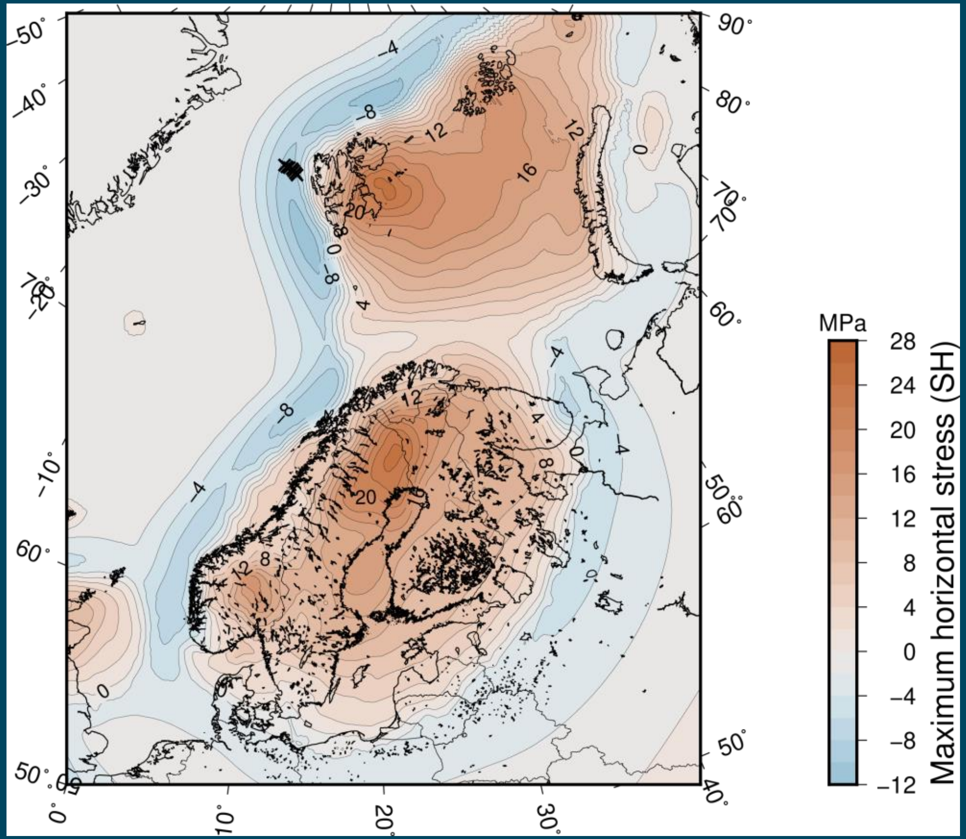
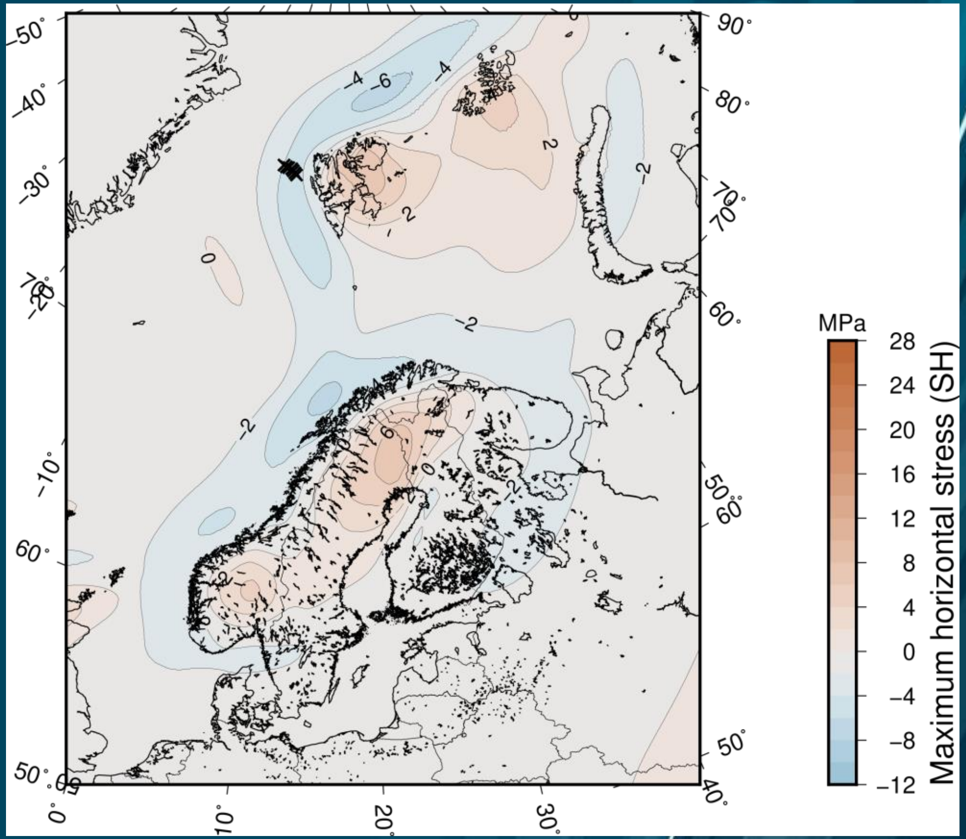
Results: Maximum horizontal stress at 2.5 km depth - Fennoscandia

Last glacial Maximum (22kyrs BP):



Present:



Results only show the glacially induced stresses. The amplitude of the horizontal stress associated with the deformation of the lithosphere is one order of magnitude larger at the LGM than at present time. The largest stresses are generally found in areas with the largest ice loads.

I - Background

II - Modelling methodology

III - Model Results

IV - Conclusions and perspective

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1. Vertical displacement.
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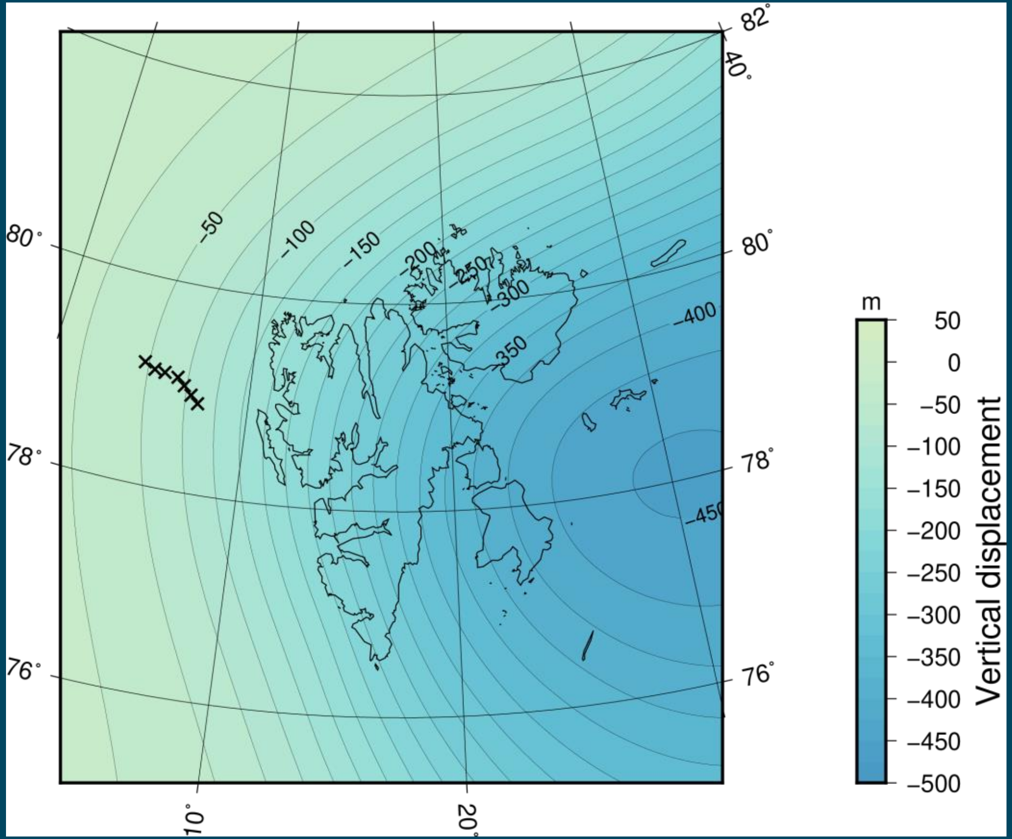
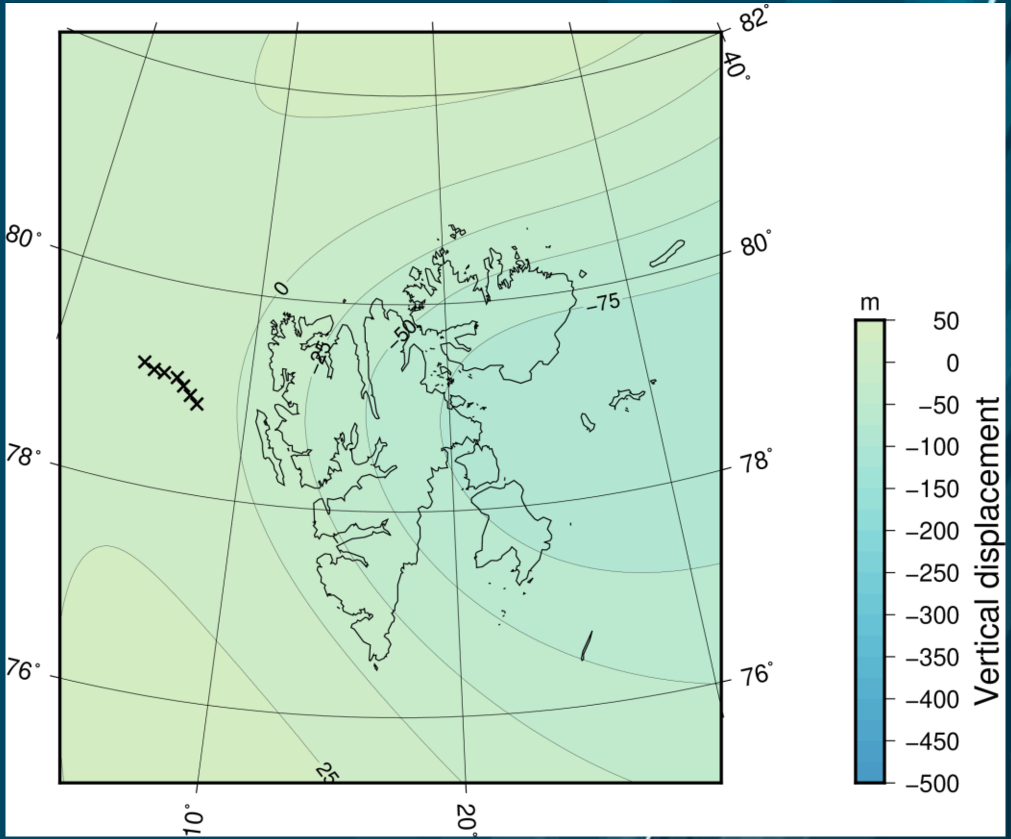
Results: Vertical displacement induced by glacial loading – Svalbard.

Last glacial Maximum (22kyrs BP):



Present:



At the LGM, the Vestnesa ridge (crosses) is located at the upper part of the subsidence bowl. At present time, the seepage formation is located on the saddle point that forms between the uplifts (+25 m) located North and South of the ridge, with the depression in the East.

I - Background

II - Modelling methodology

III - Model Results

IV - Conclusions and perspective

UiT Norges arktiske universitet

1. Vertical displacement.
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3. Vertical displacement-Svalbard.
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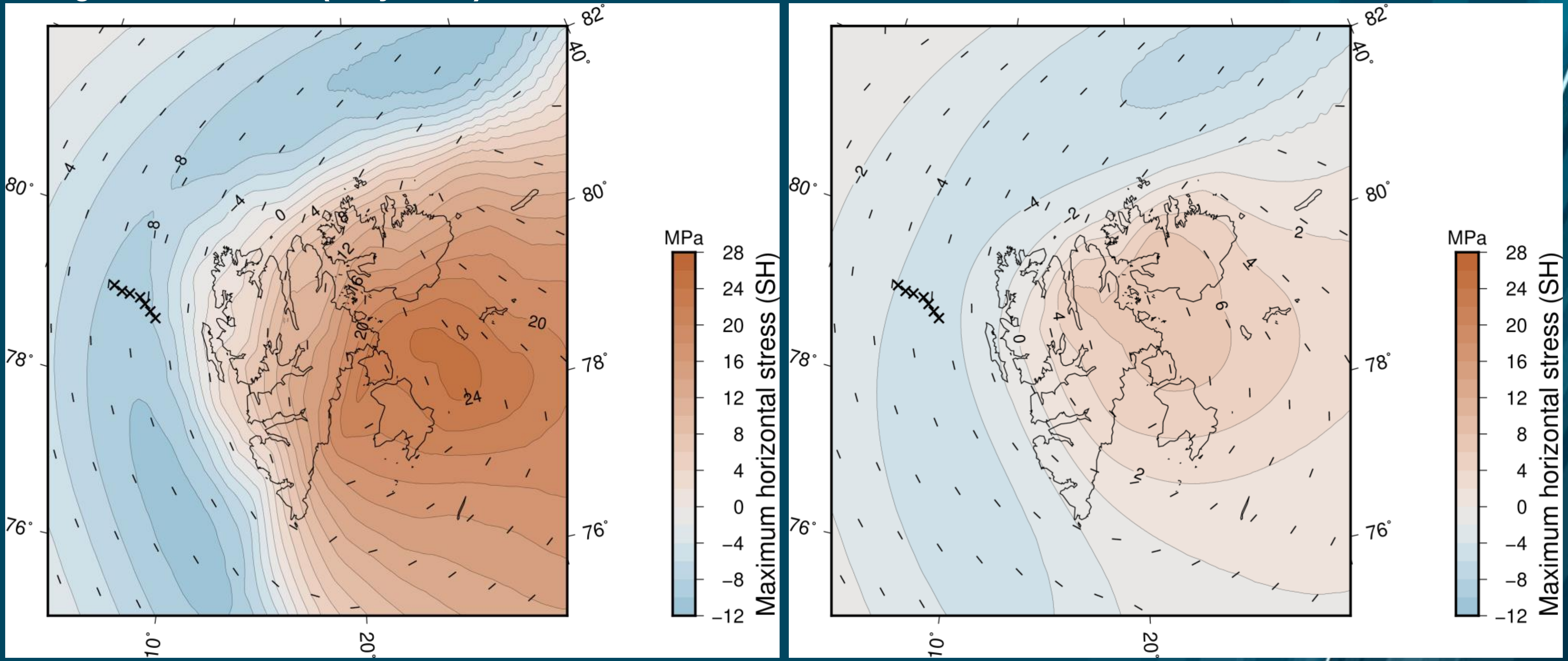
5. GPS vs Model

Results: Maximum horizontal stress at 2.5 km depth– Svalbard.

Last glacial Maximum (22kyrs BP): **Present:**



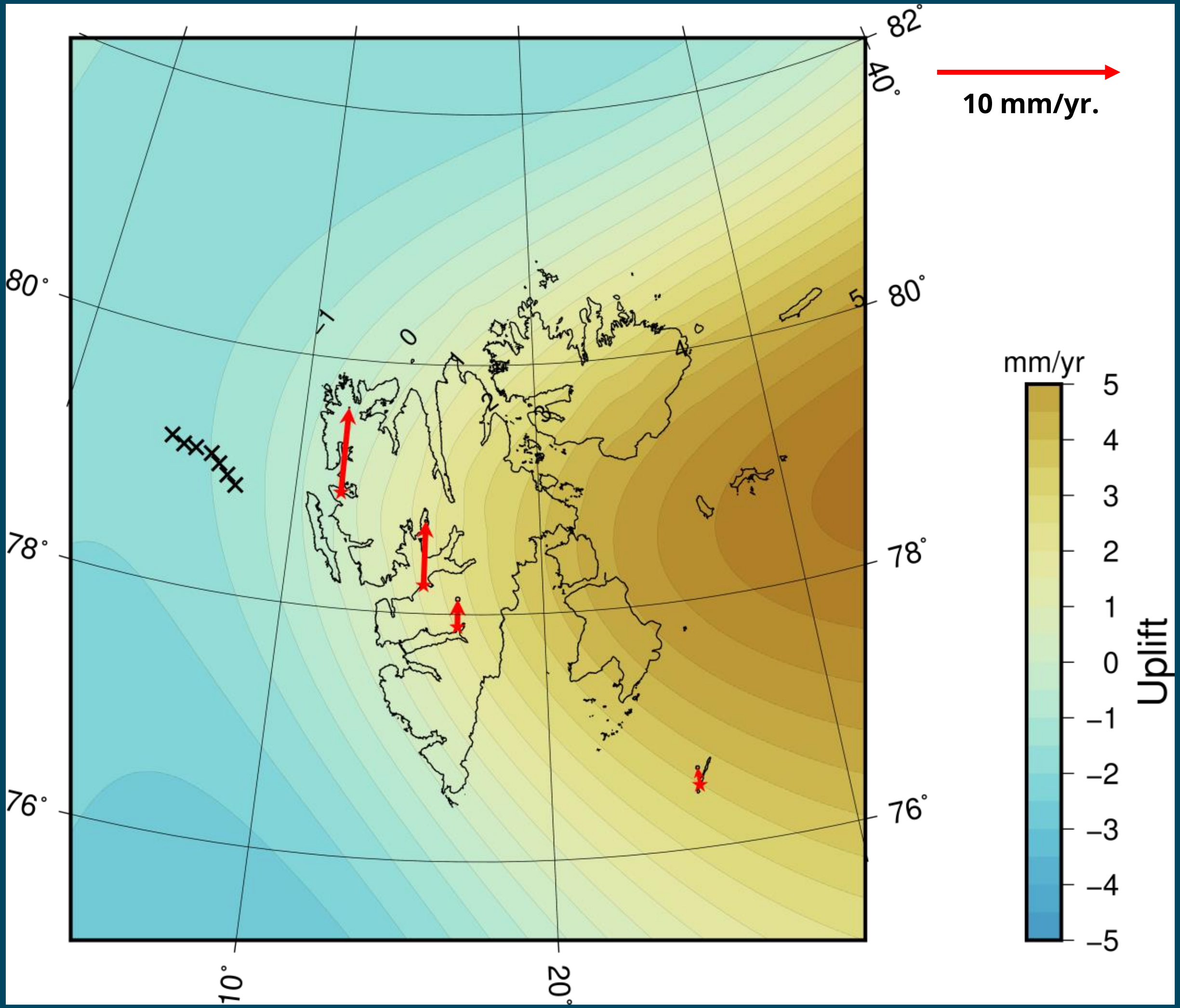
Results only show the glacially induced stresses. At LGM and present time, the Vestnesa ridge is located in the subsidence bowl and saddle point, respectively, but the maximum horizontal stress remains tensile. The σ_H orientation (tick marks) follows the former ice edge. North-South normal faults would tend to be reactivated if the glacial stress is the principal player.

I - Background
II - Modelling methodology
III - Model Results
IV - Conclusions and perspective

1. Vertical displacement.
2. Stress field.
3. Vertical displacement-Svalbard.
4. Stress field - Svalbard.
5. **GPS vs Model**

Model validation: Present Uplift rates caused by post-glacial rebound.

Model (color map) vs GPS data (red vectors; Kierulf et al., 2014; Auriac et al., 2016):



Observed uplift rates and model predictions compare well over Fennoscandia.

But when locally comparing vertical velocities at the GPS stations over Svalbard, we observe a **clear mismatch** between the **observed uplift rates** and the **computed solution (model).**

Why such a difference between the model and observations over the Svalbard area?

- Effect of the **Greenland ice loading history** on the GIA solution ?
- Other mechanisms to consider ? **Push from the Atlantic ridge, faulting, gravitational potential energy ?**
- The **rheology of the earth model** that we use in this study might **not be suitable** for the Svalbard region.

I - Background
II - Modelling methodology
III - Model Results
IV - Conclusions and perspective

Conclusions:

- By **only considering glacial stresses**, our model predicts that the seepage sites along Vestnesa ridge are located in **a tensile region at present time**.
- In this configuration, **North-South normal faults** would be **reactivated** along the ridge. This could have a major influence on the seepage dynamics.
- We demonstrate that the **vertical velocities** predicted by our ice load scenario **does not match** the GPS observations.
- Other mechanisms could have a **major role to play** on the regional stress field, such as the **push of the Atlantic ridge**.

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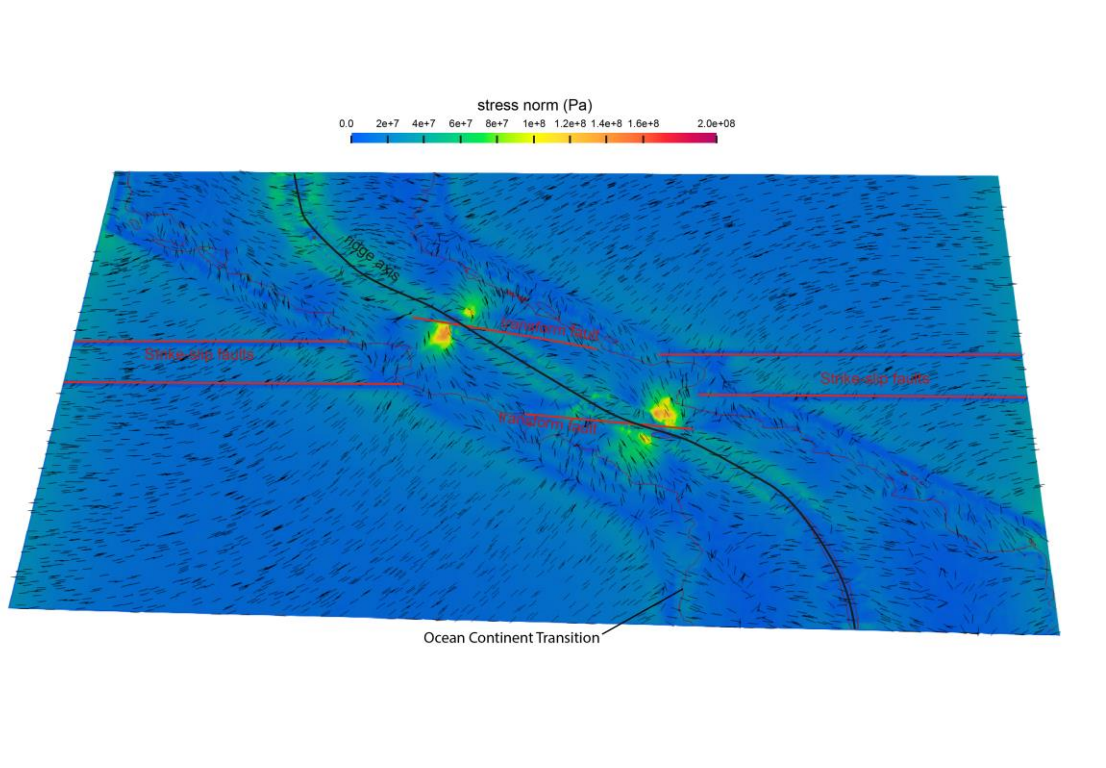

Perspective:

- To test the effect of the ridge push on the regional stress, a geodynamics model of the Fram Strait region has been set-up by Stefan Beaussier from ETH Zurich. The stress tensor obtained from the geodynamics model (picture on the right) will be added to the glacially induced stress tensor as a background stress.

- The evolution of the Greenland ice-sheet could potentially affect the stress field over the Vestnesa ridge and must be included in future models.

- We aim to include pre-existing major faults in the model to test the effect of stress accommodation.