Christian Berndt, Judith Elger, Aaron Micallef, Sebastian Krastel, Sascha Brune, Jürgen Mienert, Joost Thielsen, Jochen Zschau, Felix Gross, Karolin Dünnbier, Doug Masson, Euan Nisbet, Stephan Sobolev, Pete Talling

Controls on submarine slope stability in the North Atlantic

GEOMAR

Outline

- Motivation
- Storegga Slide
- Hypothesis: Glacial debris flows lead to high overpressures that trigger landslides on glacial margins
- Exception to the rule: the Fram Slide
- Tsunami models and warning system
- Conclusions

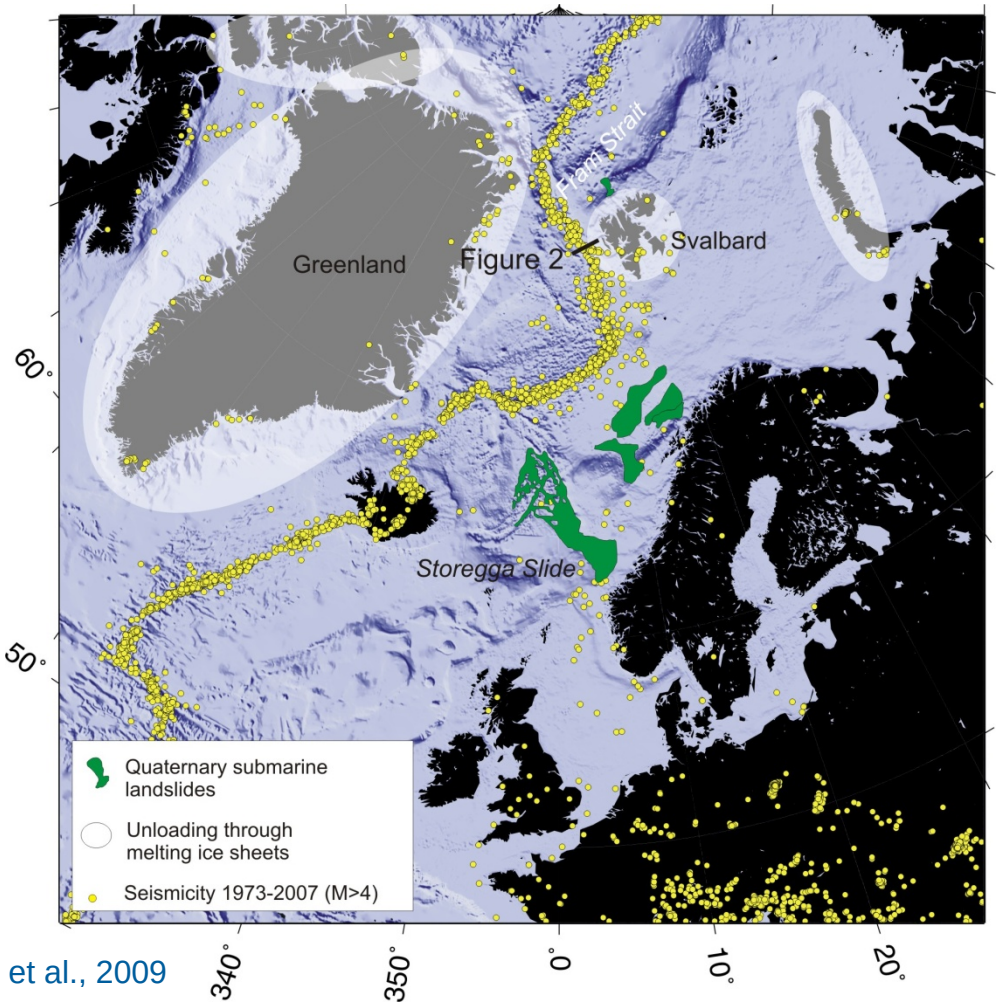
Motivation - hazards

Submarine landslides – a natural hazard

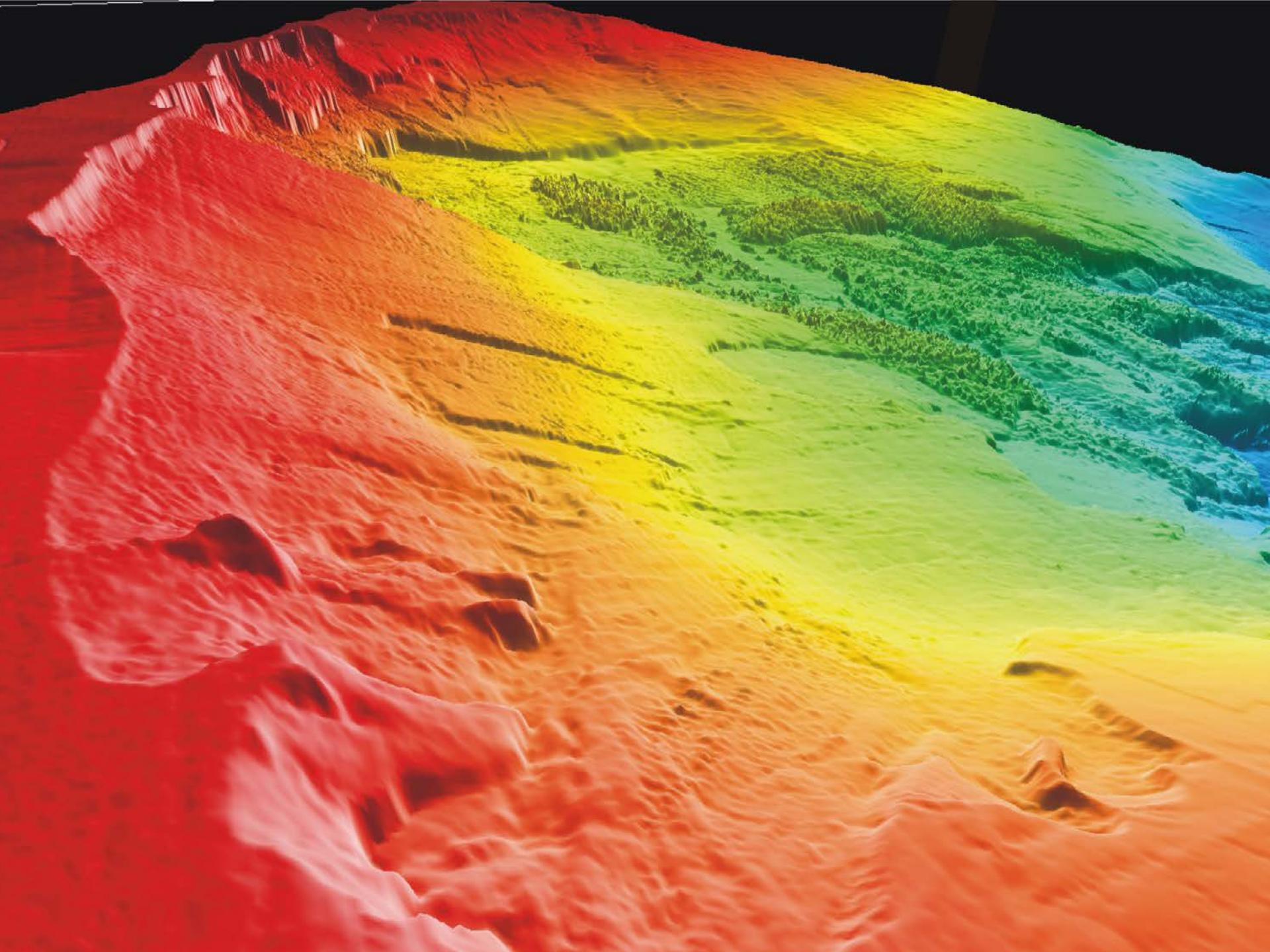
- Destruction of offshore infrastructure
- Destruction of open slope on continental margins
- Generation of tsunamis

Landslides in the North Atlantic

- At least five major slides occurred on the glacial margins of the NE Atlantic since the Pleistocene
- Understanding them is paramount for safe development of Europe's continental margins and coastal communities

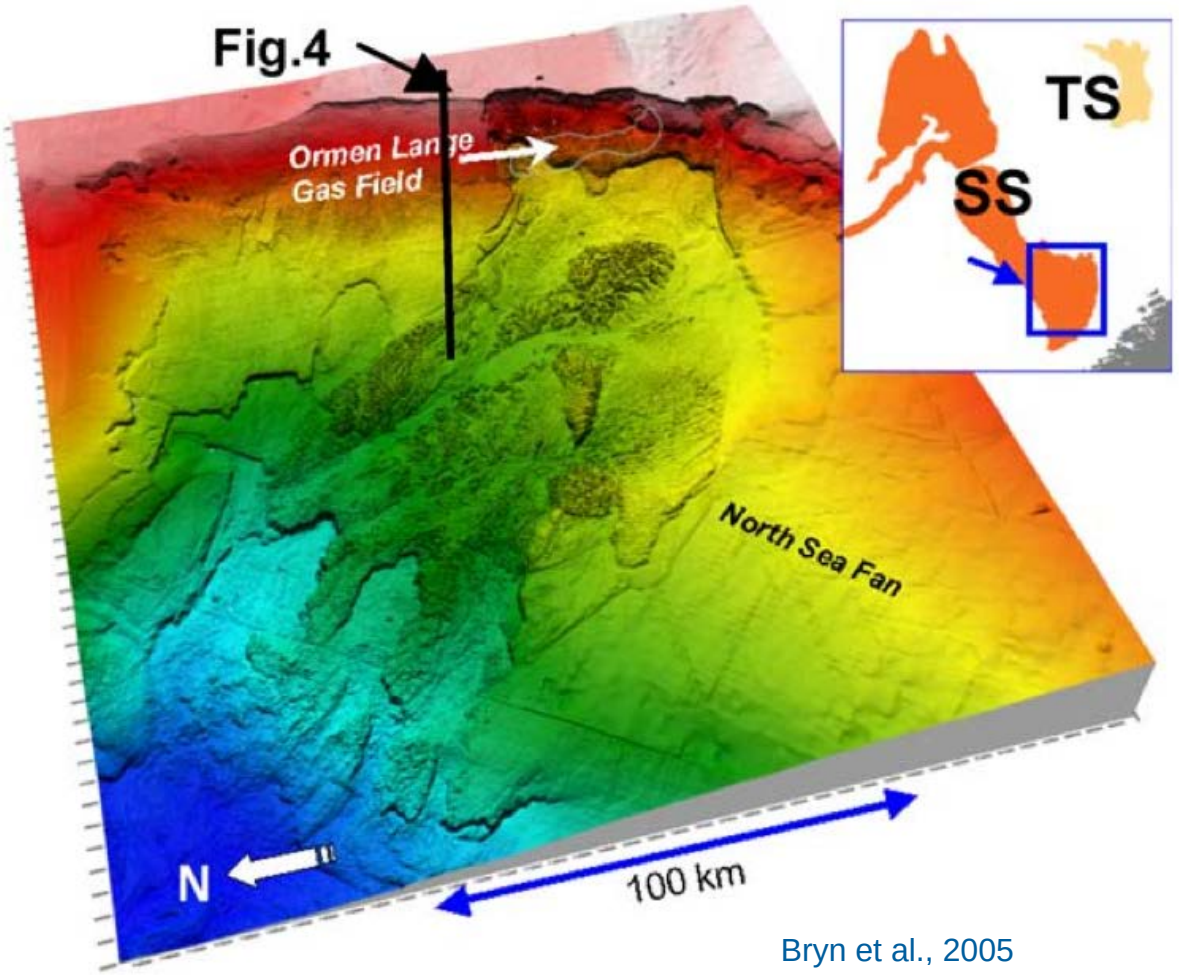


Berndt et al., 2009



The Ormen Lange project

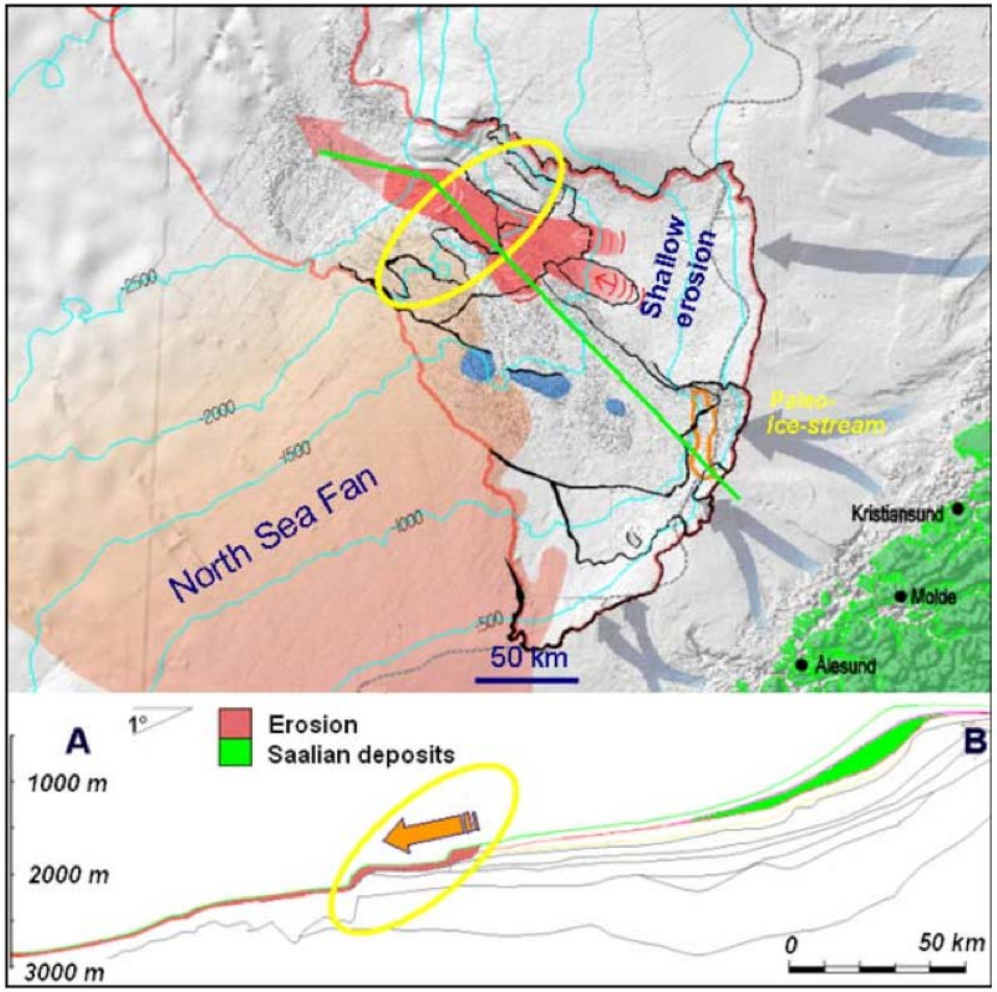
- Site survey for the biggest natural gas field development in Europe
- More than 300 Mio $US spent on understanding Storegga
- Duration from 2000-2004



Bryn et al., 2005

Evolution of the Storegga Slide: Main results

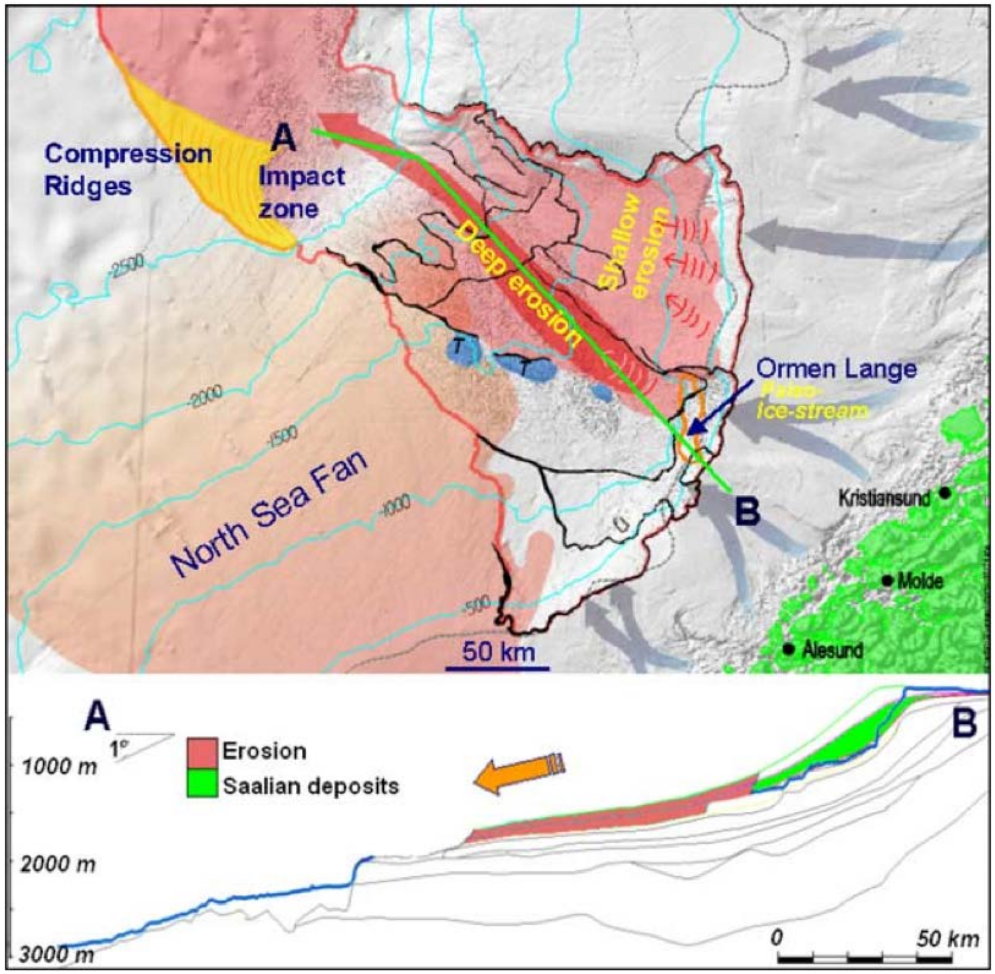
- Initiation in deep water
- Lateral fluid migration in response to loading by the North Sea Fan one of the destabilizing factors
- Trigger most likely a >7.2 earthquake due to post glacial rebound



Bryn et al., 2005

Evolution of the Storegga Slide: Main results

- Retrogression up the slope
- Movement on several distinct slide planes
- Deepest erosion in the Ormen Lange region

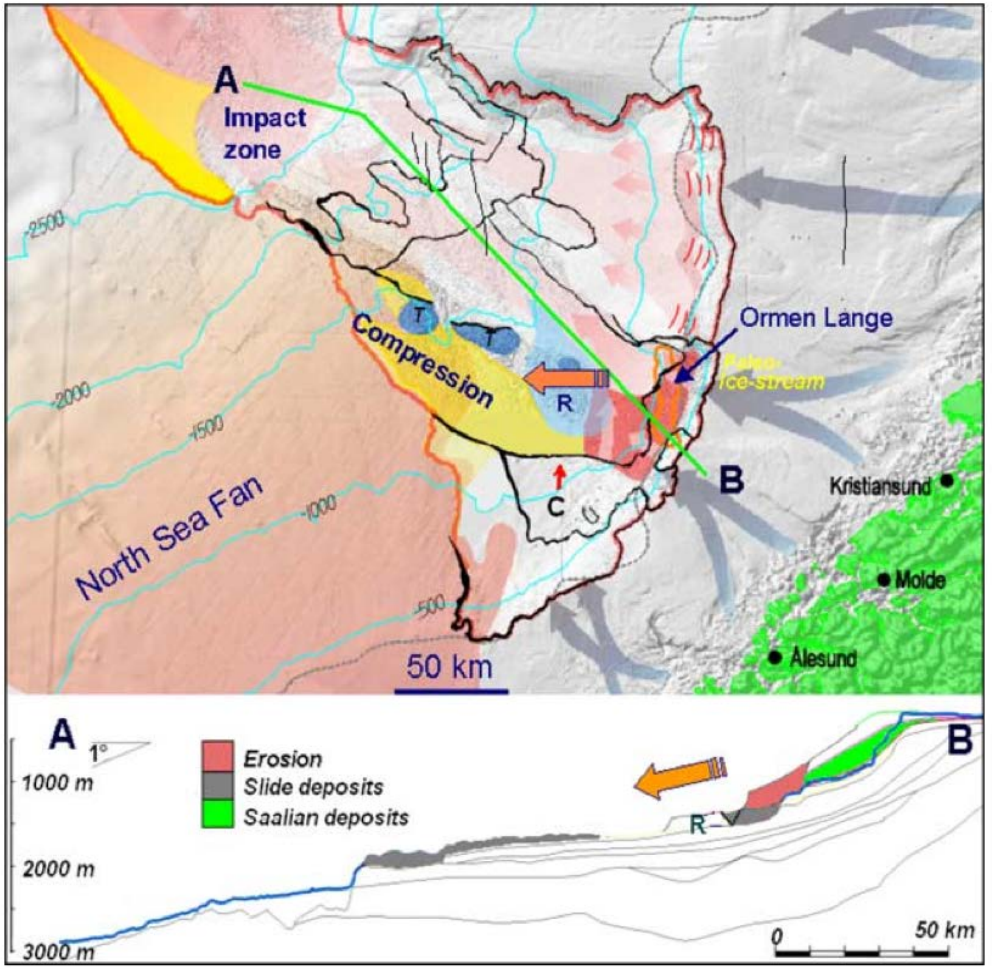


Bryn et al., 2005

Evolution of the Storegga Slide: Main results

Erosion of the Saalian deposits led to

- Movement of block R and compression
- Created the tsunami

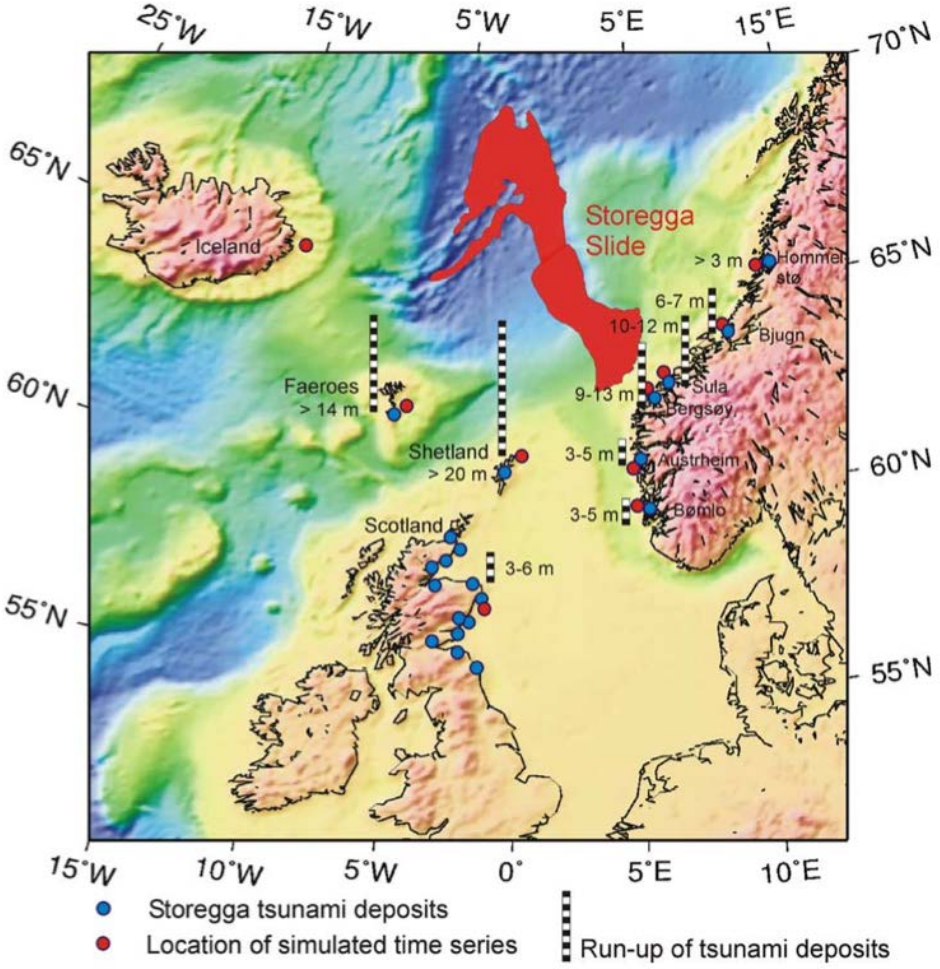


Bryn et al., 2005

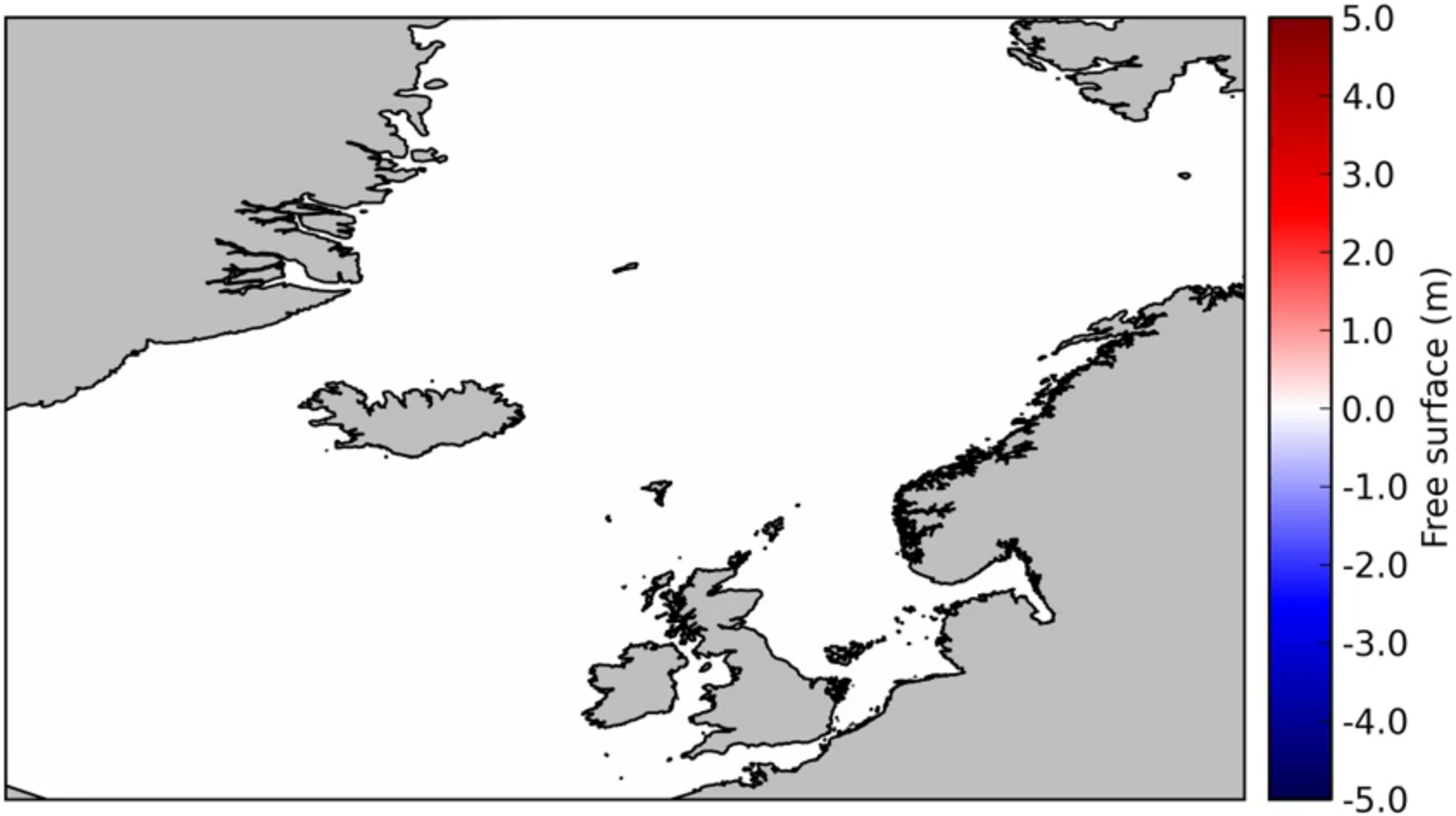
Storegga Tsunami

- Detection in lake sediments
- After taking into account post-glacial isostatic rebound the tsunami run up was at least 20 m

Bondevik et al., 2005



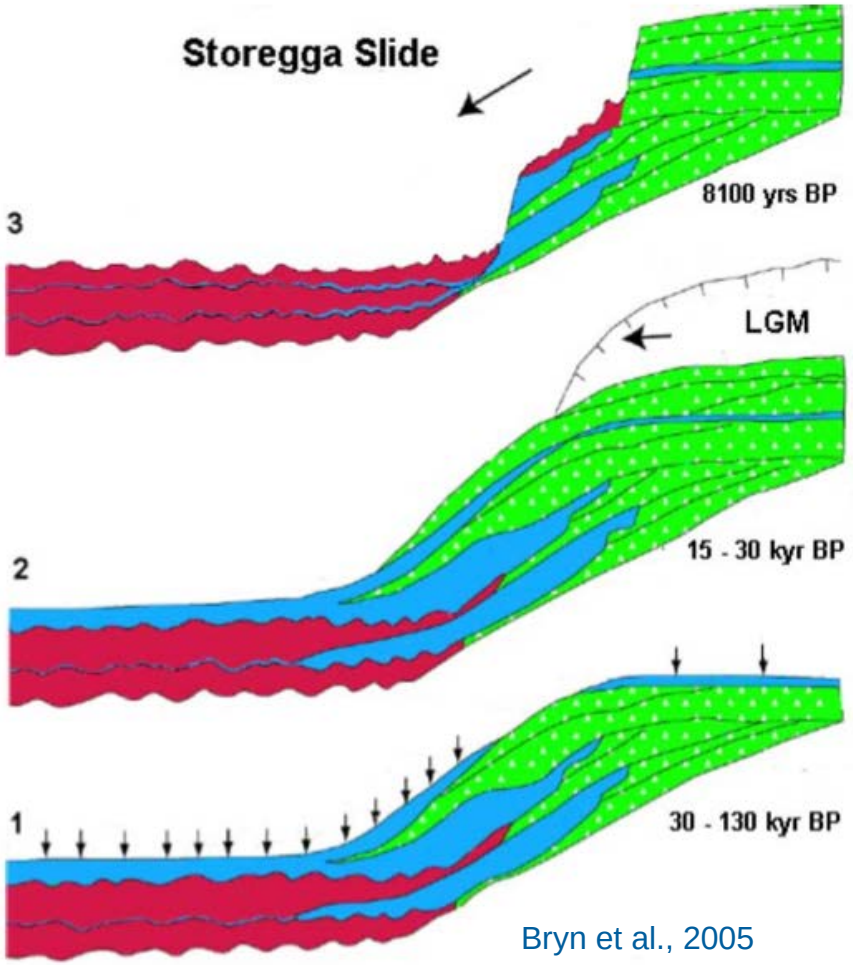
Modeling the Storegga Slide tsunami



Hill et al., 2014

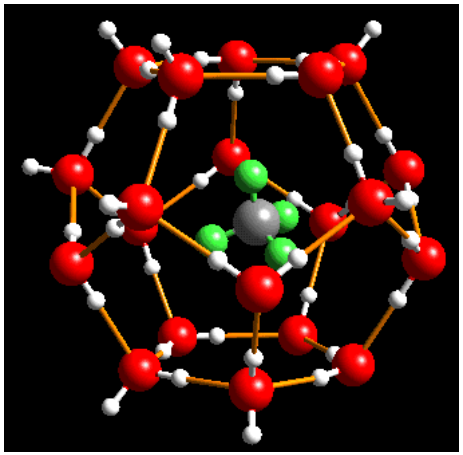
Reasons for the Storegga Slide

- Deposition of water-rich hemipelagic sediments during interstadials
- Deposition of glacigenic debris flow deposits during glaciations
- Low permeability of the glacial deposits prevents normal compaction and builds up pore pressure
- Failure within weak hemipelagic sediments



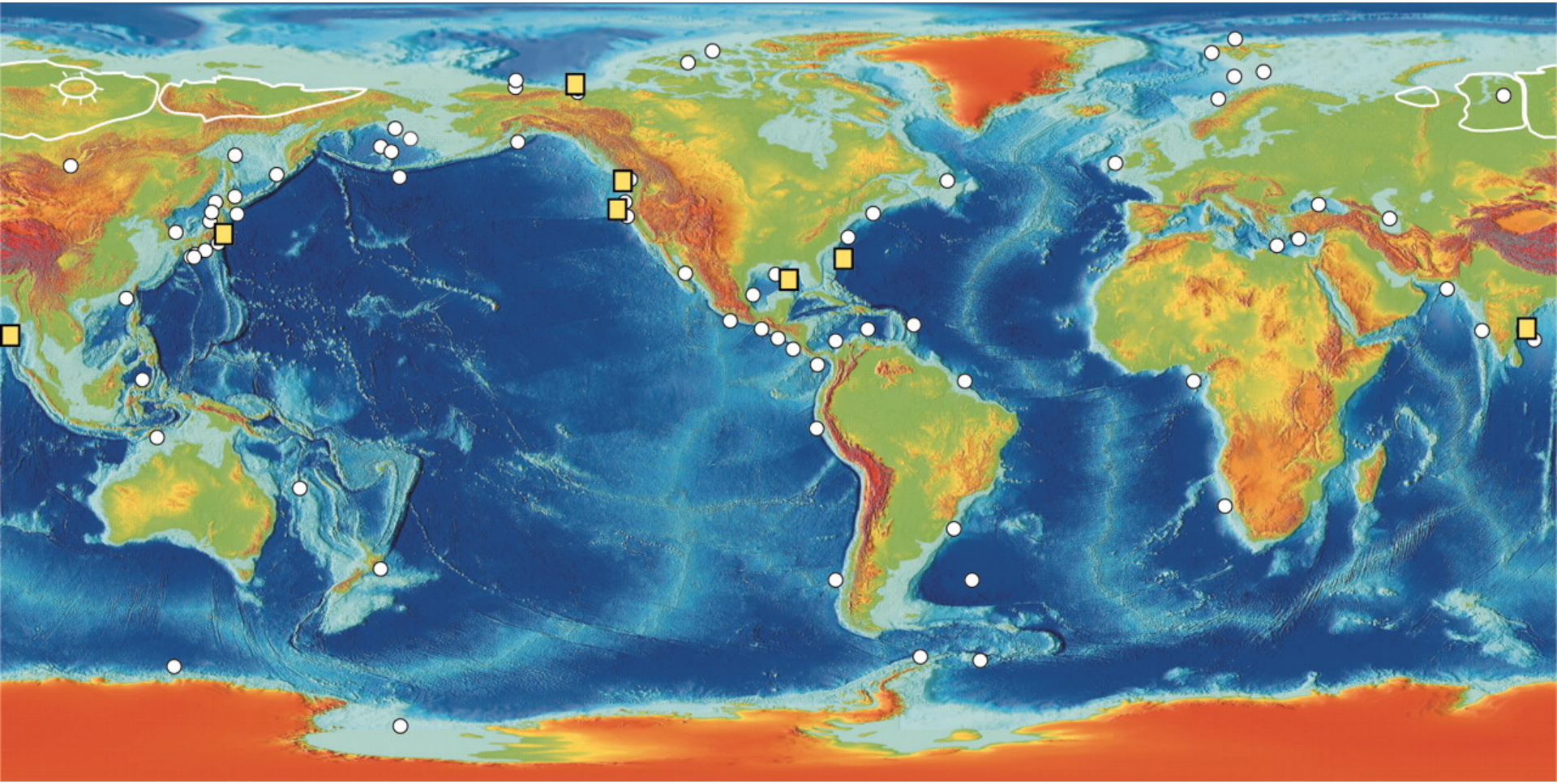
Bryn et al., 2005

Alternative hypothesis: marine gas hydrates



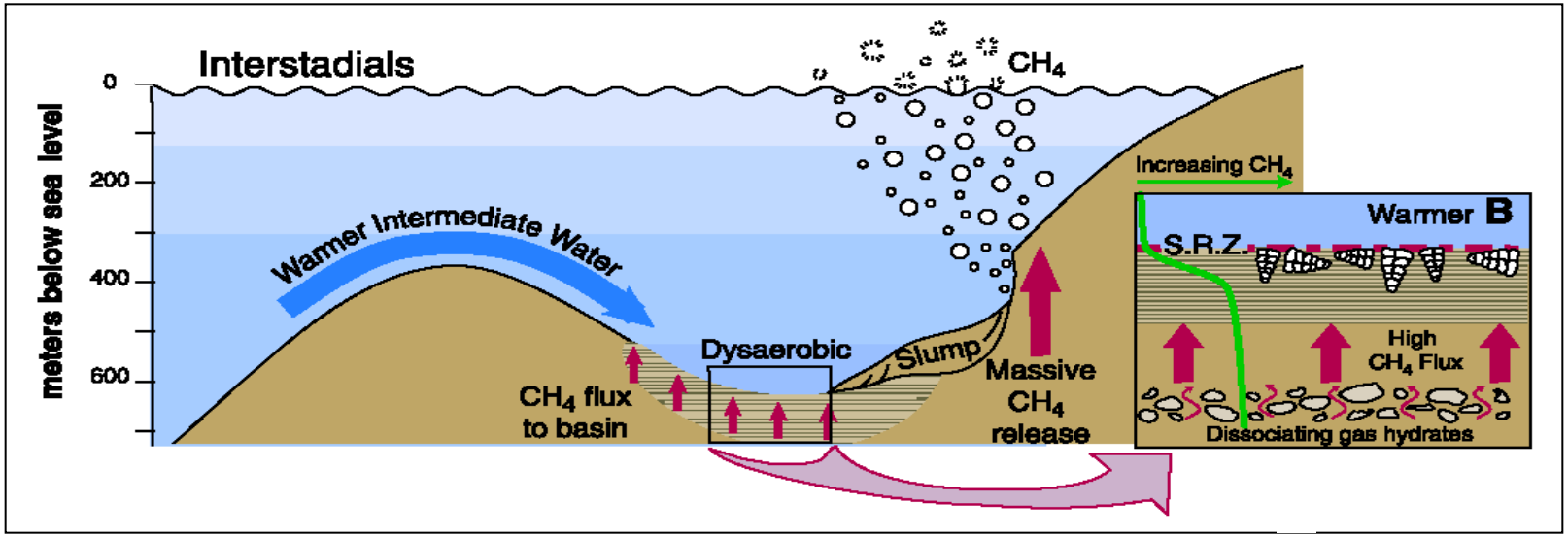
- Gas molecules (predominantly methane) in water cages
- Stable under high pressure and low temperature
- Two types:
  - Permafrost hydrate
  - Continental margin hydrate

Marine gas hydrates – global occurrence



Lorenzen et al., 2006

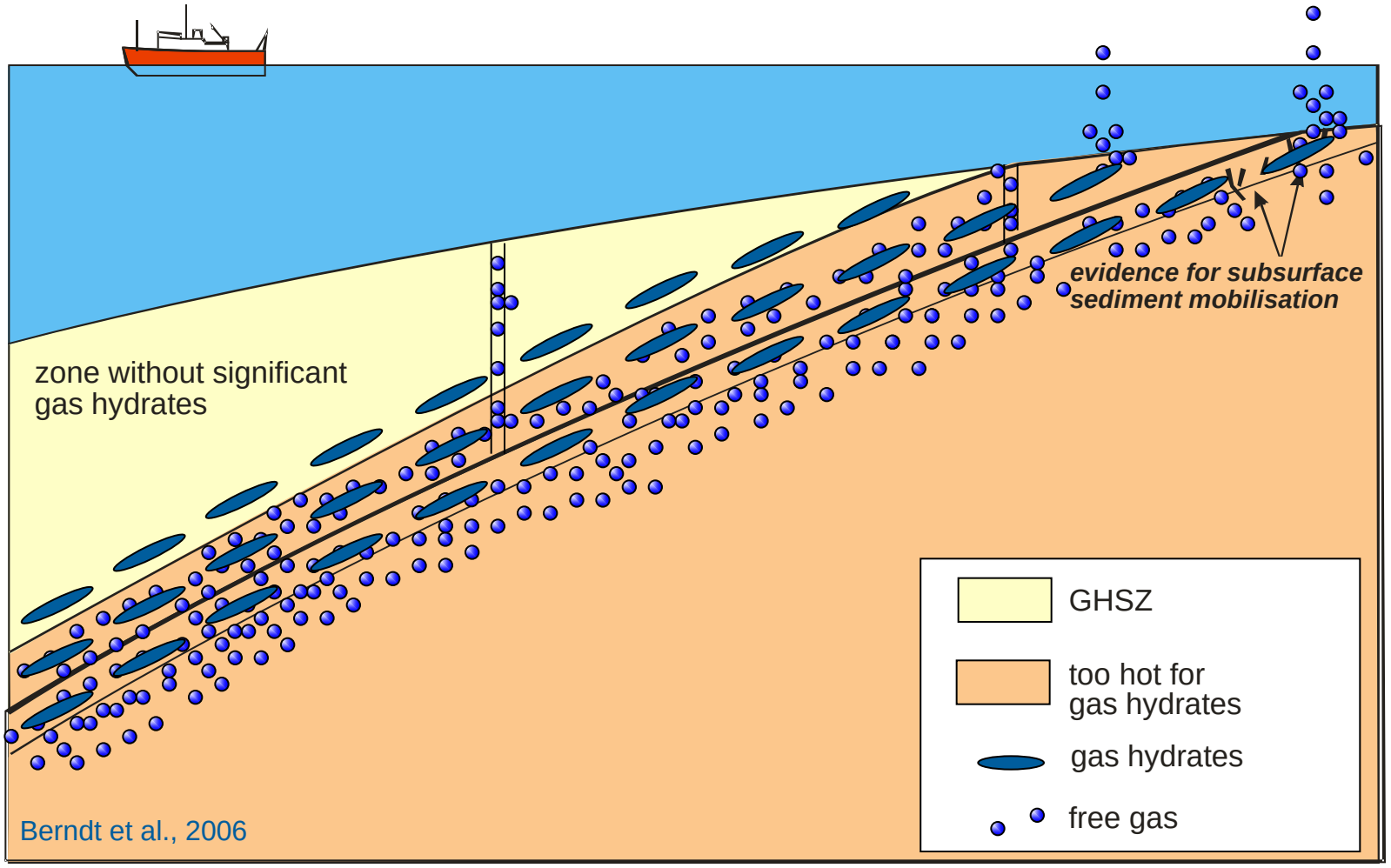
Clathrate Gun Hypothesis

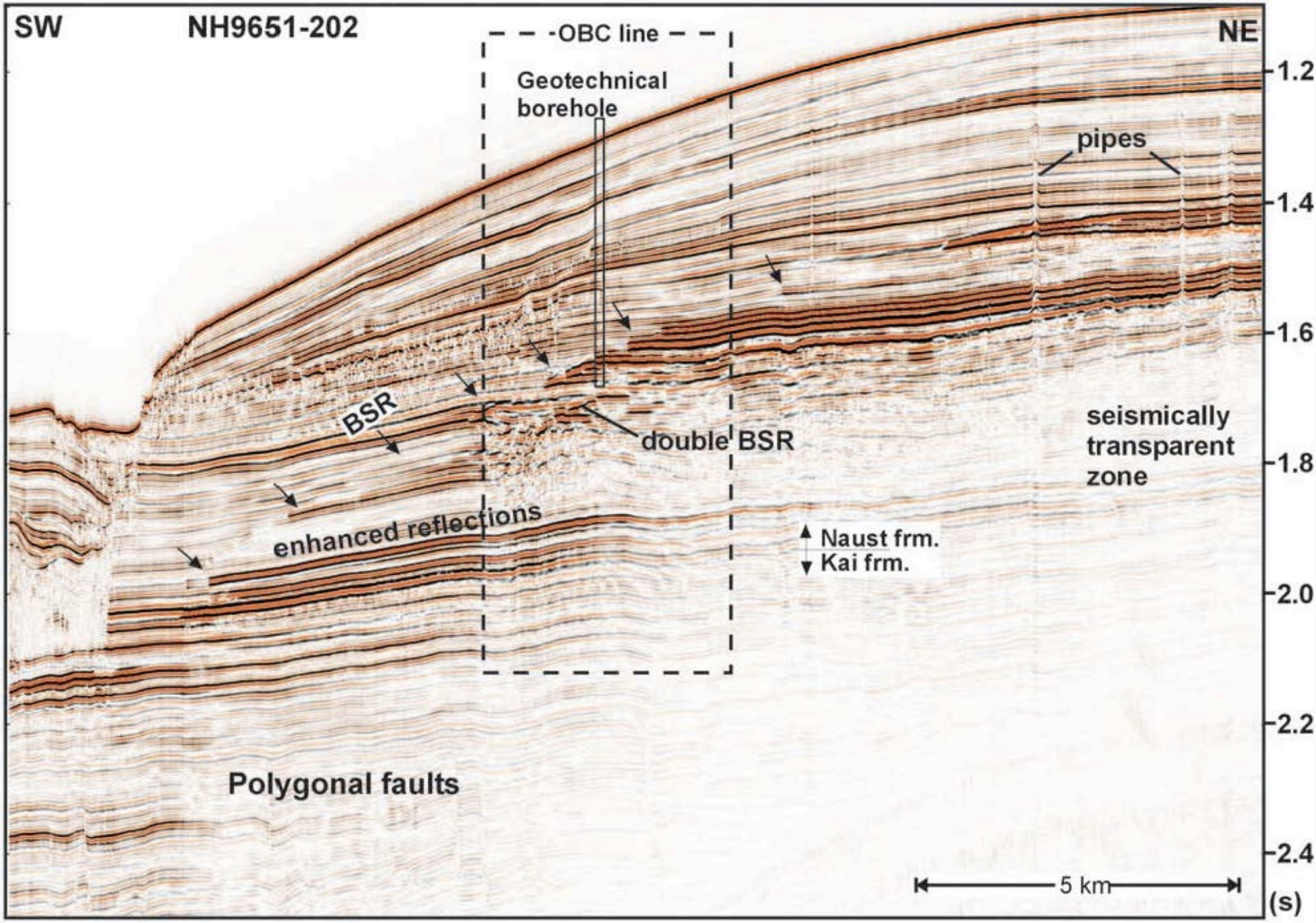


Kennett et al., 2000

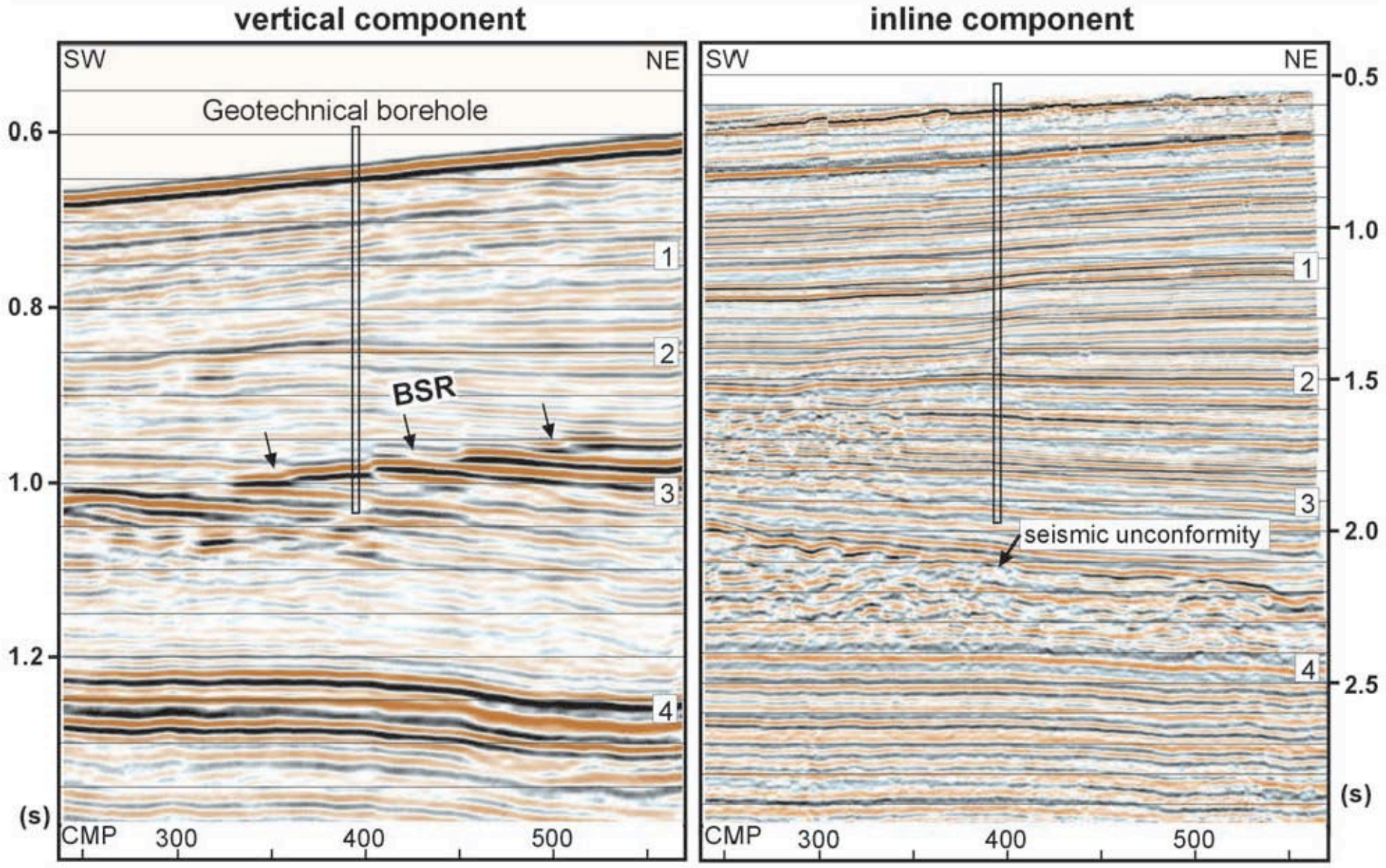
bottom water warming ⇒ gas hydrate dissociation ⇒ pore pressure build-up ⇒ slumping ⇒ methane release ⇒ climate warming ⇒ more bottom water warming ⇒ more hydrate dissociation ⇒ more slumping ⇒ more methane release ⇒ ….

Dynamics of the polar gas hydrate systems

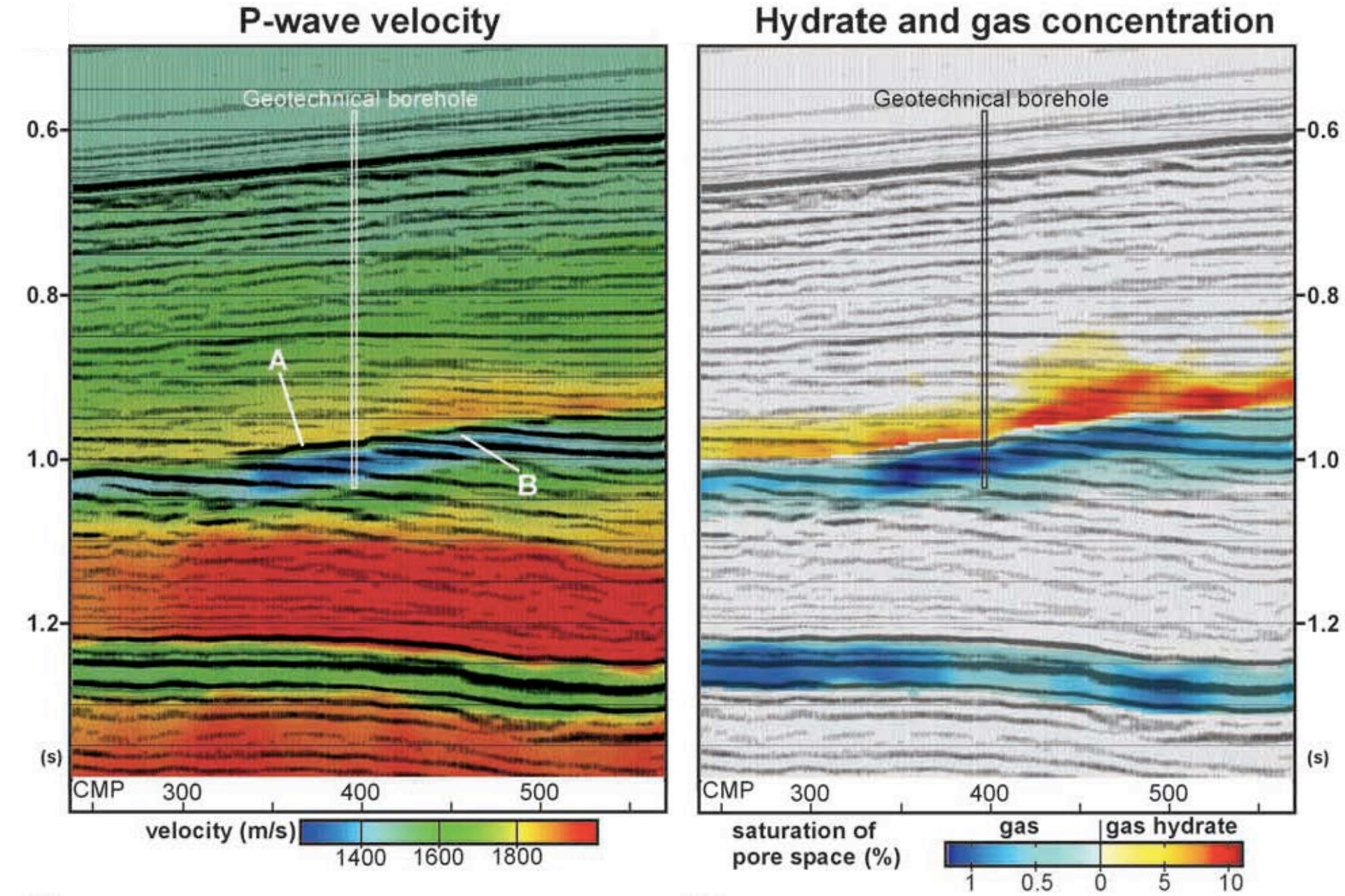




Bünz and Mienert, 2004



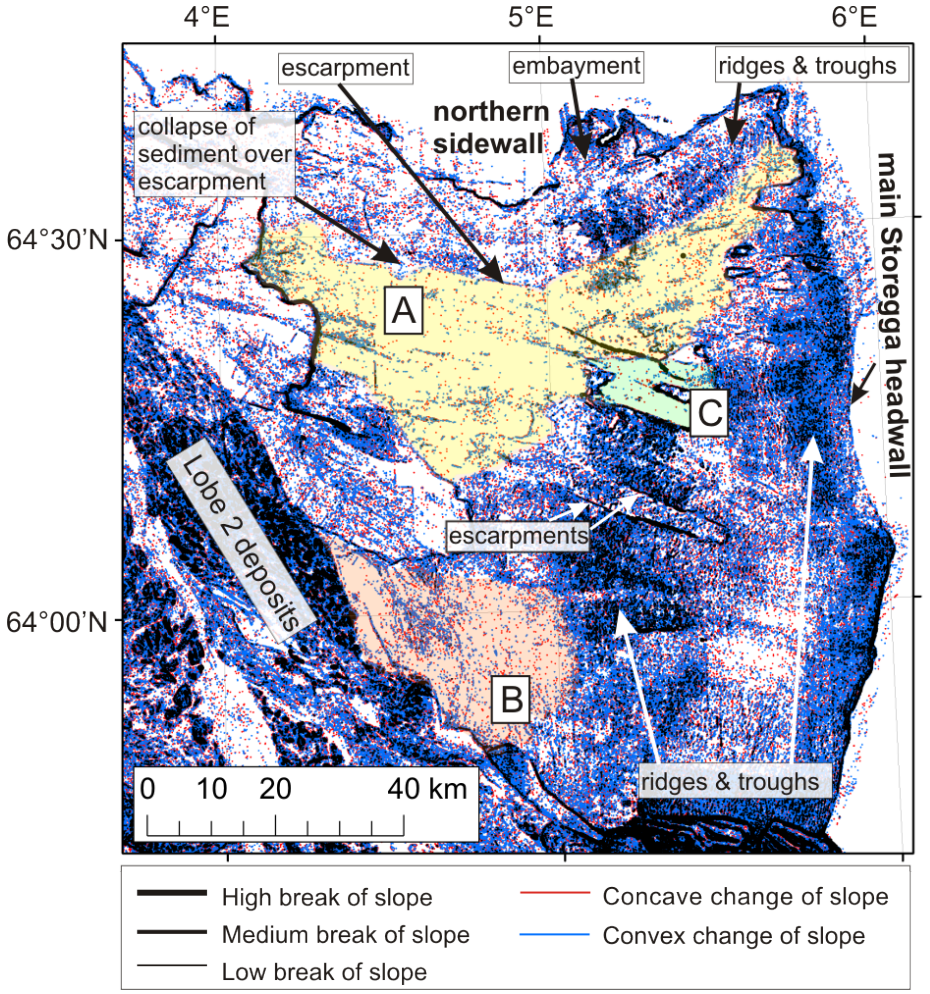
Bünz and Mienert, 2004



Bünz and Mienert, 2004

Northern Storegga Slide

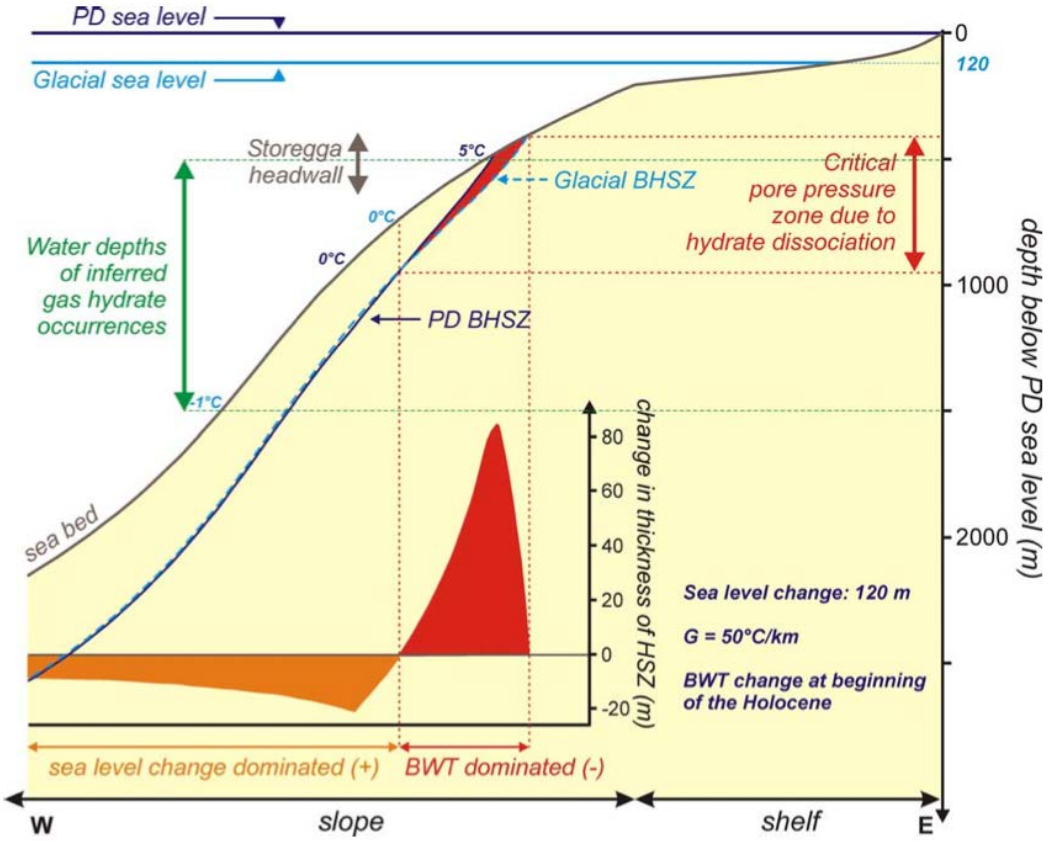
- Spatial correlation of gas hydrates and smooth seabed morphology
- Fluid escape structures and slide planes align
- Influence of gas hydrate occurrence on the evolution of the slide
- No evidence for triggering of the slide through hydrate dynamics



Micallef et al., 2009

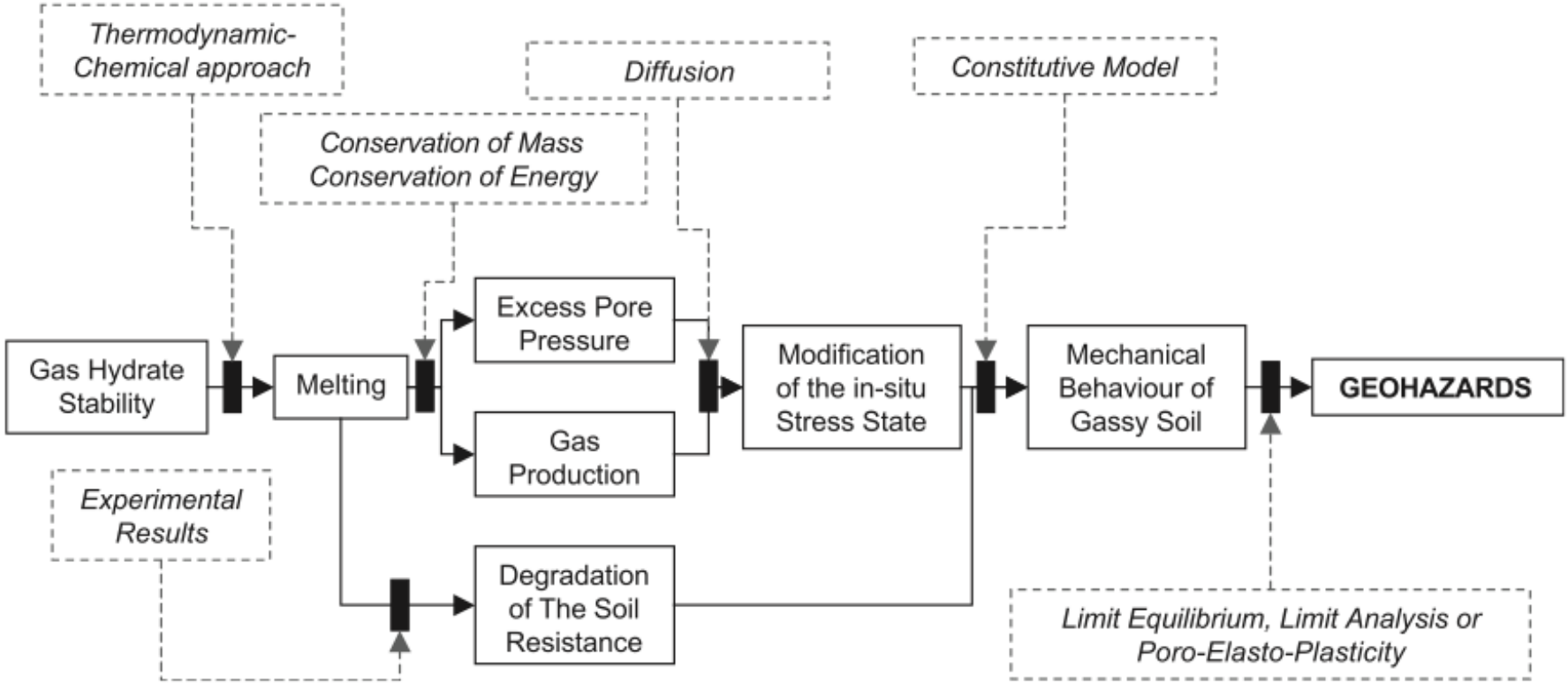
P/T effects on hydrate stability

- BWT increase changes dominate the shallow part of the shelf
- P increase dominates the deep part of the slope
- Storegga initiated in >3000 m water depth
- Hydrate triggering extremely unlikely



Mienert et al., 2005

Hydrate cementation of sediments

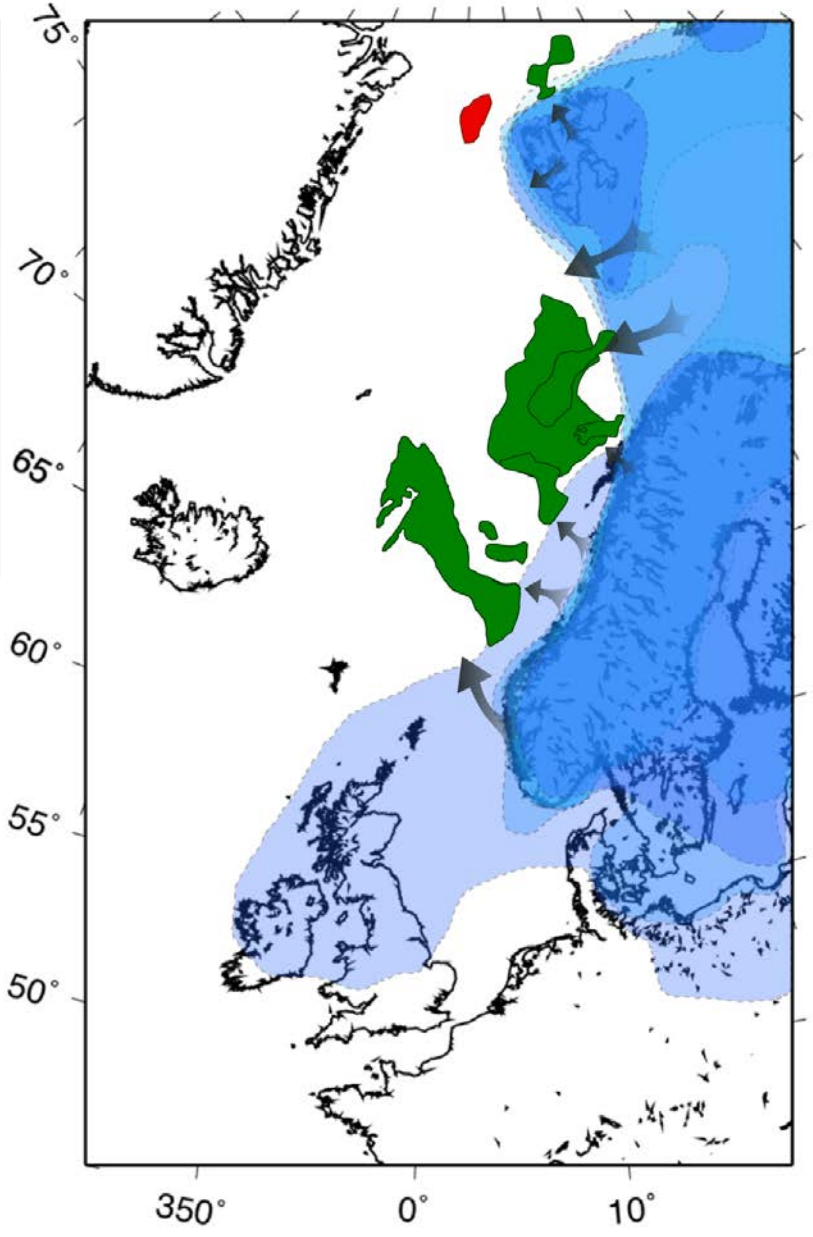


Sultan et al., 2004

Testing the hypothesis elsewhere

Re-assessment of the glacial debris flow / hemipelagic interlayering hypothesis:

- Does it apply everywhere on the glacial margins?
- What about the Fram Strait where there are only few trough mouth fans?



Why in the Arctic?

- The Arctic is most affected by climate change
- ACIA models using B2 greenhouse gas emission scenario of IPCC, 2001 predict:
  - 2.5° C increase until 2050 north of 60° N
  - Up to 9° C warming over the central Arctic Ocean by 2100

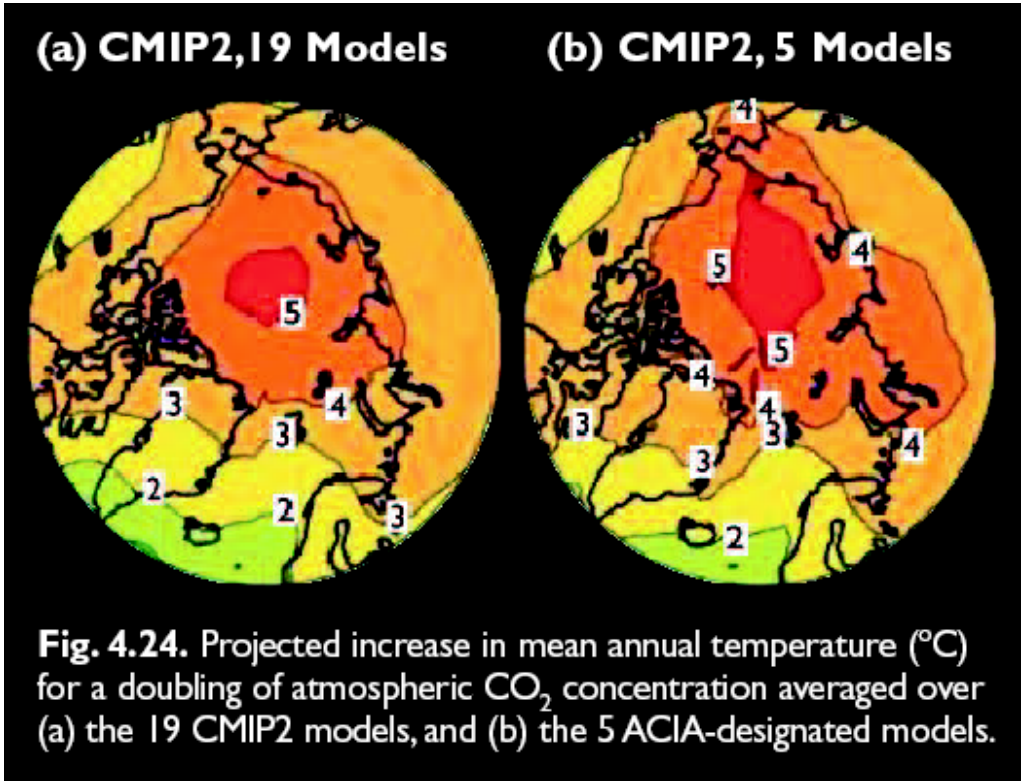
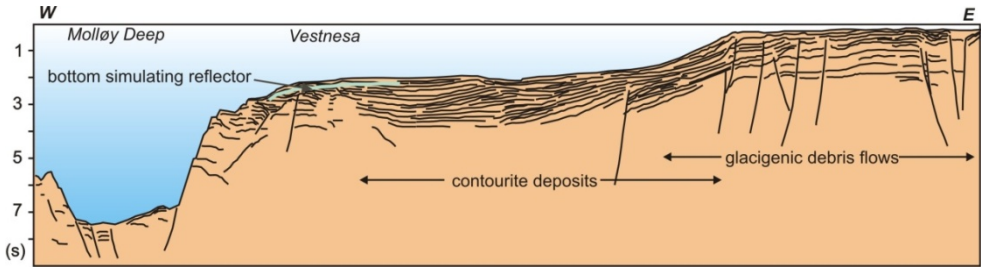


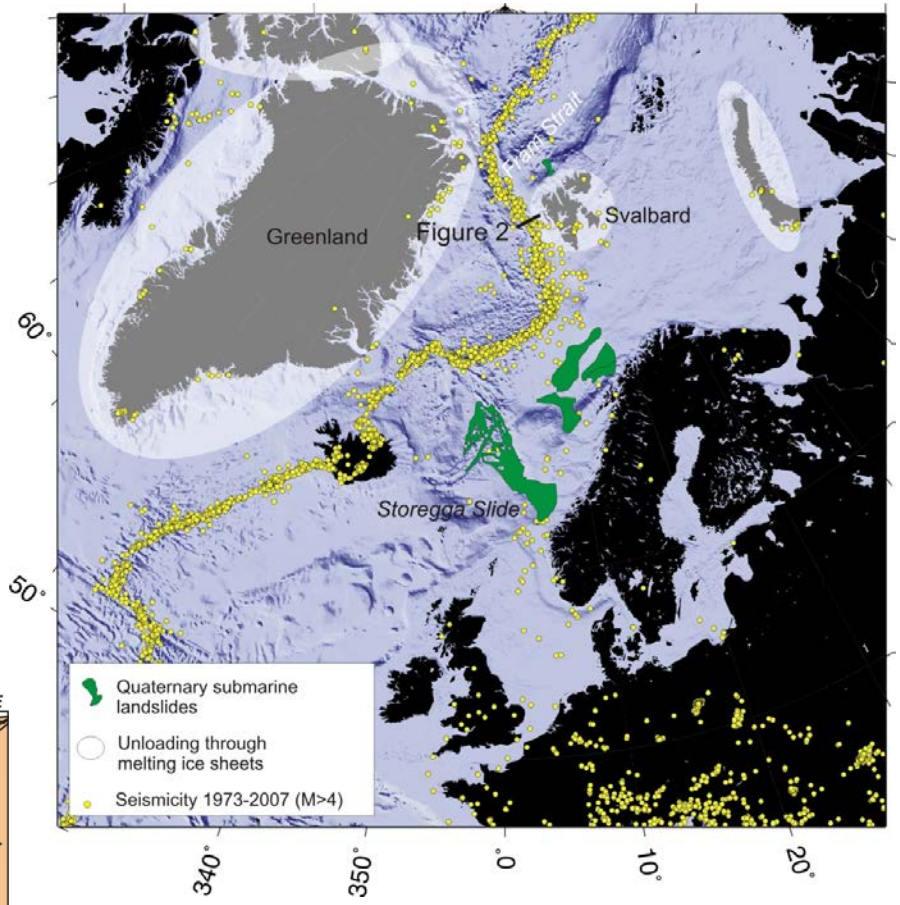
Fig. 4.24. Projected increase in mean annual temperature (°C) for a doubling of atmospheric CO_2 concentration averaged over (a) the 19 CMIP2 models, and (b) the 5 ACIA-designated models.

Kattsov et al., ACIA, 2004

Fram Strait setting

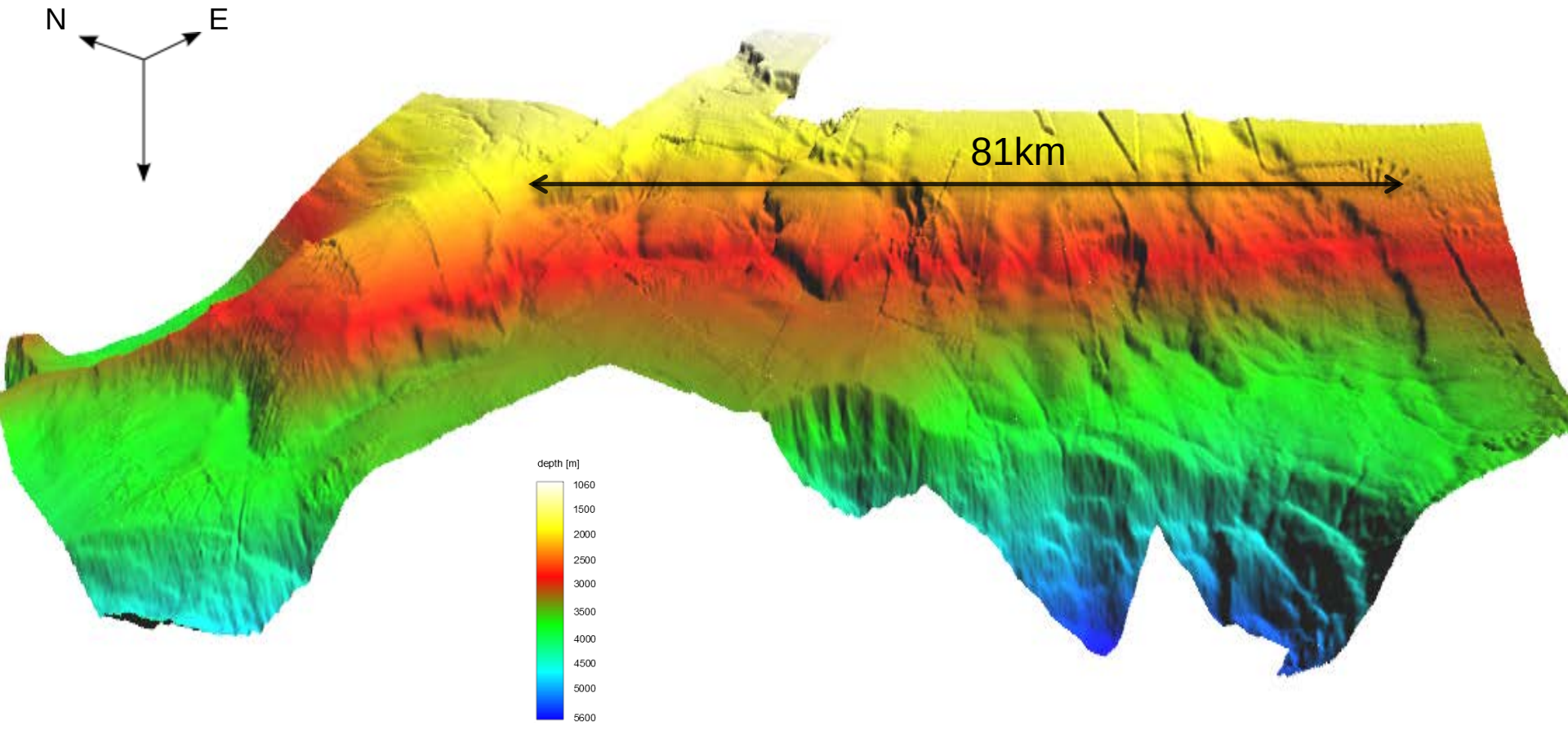
- Inter-layering of glacial and hemipelagic sediments
- Strong seismicity getting stronger
- Active fluid flow system



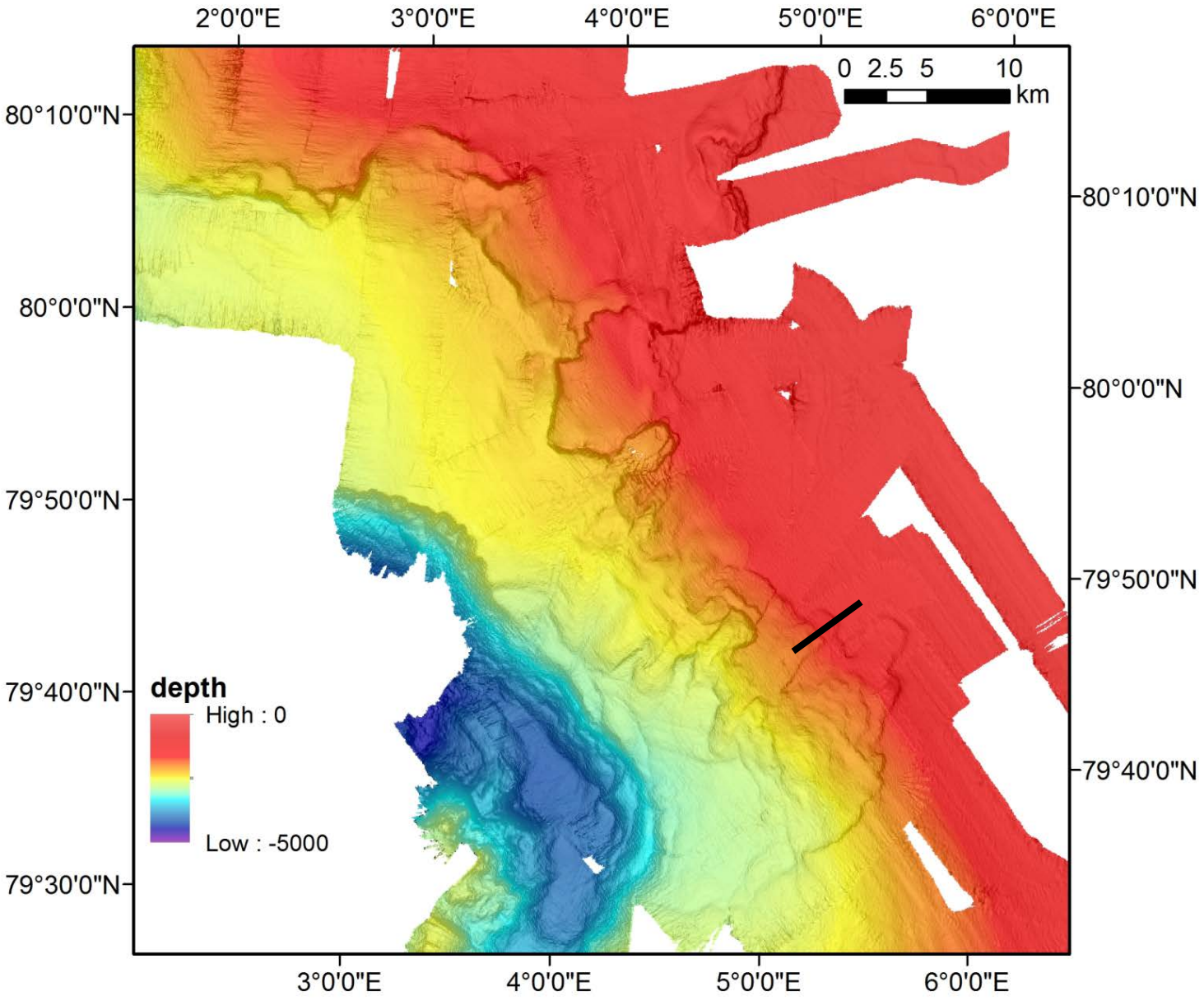


Berndt et al., 2009

Bathymetry data



Seismic data



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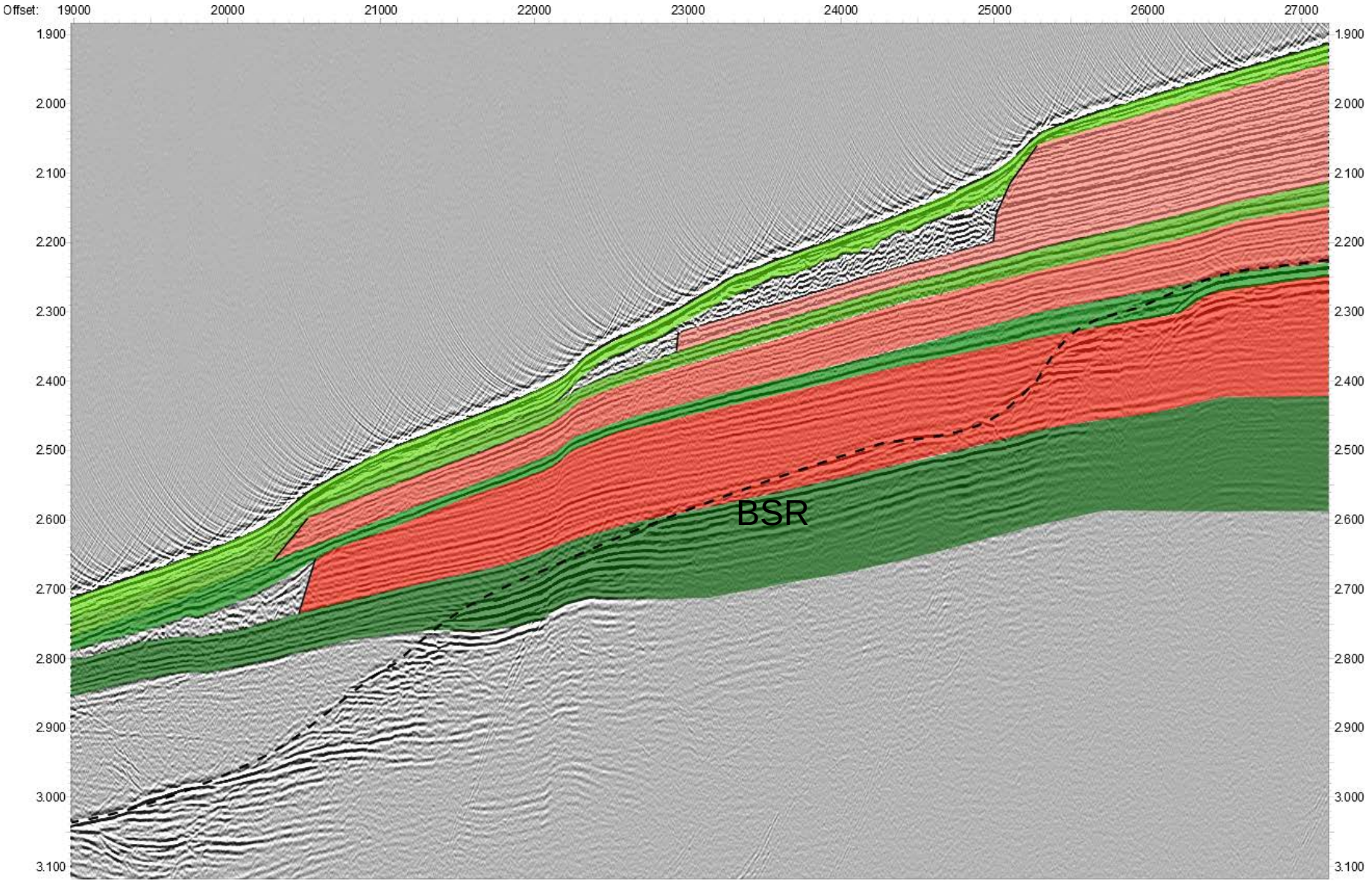

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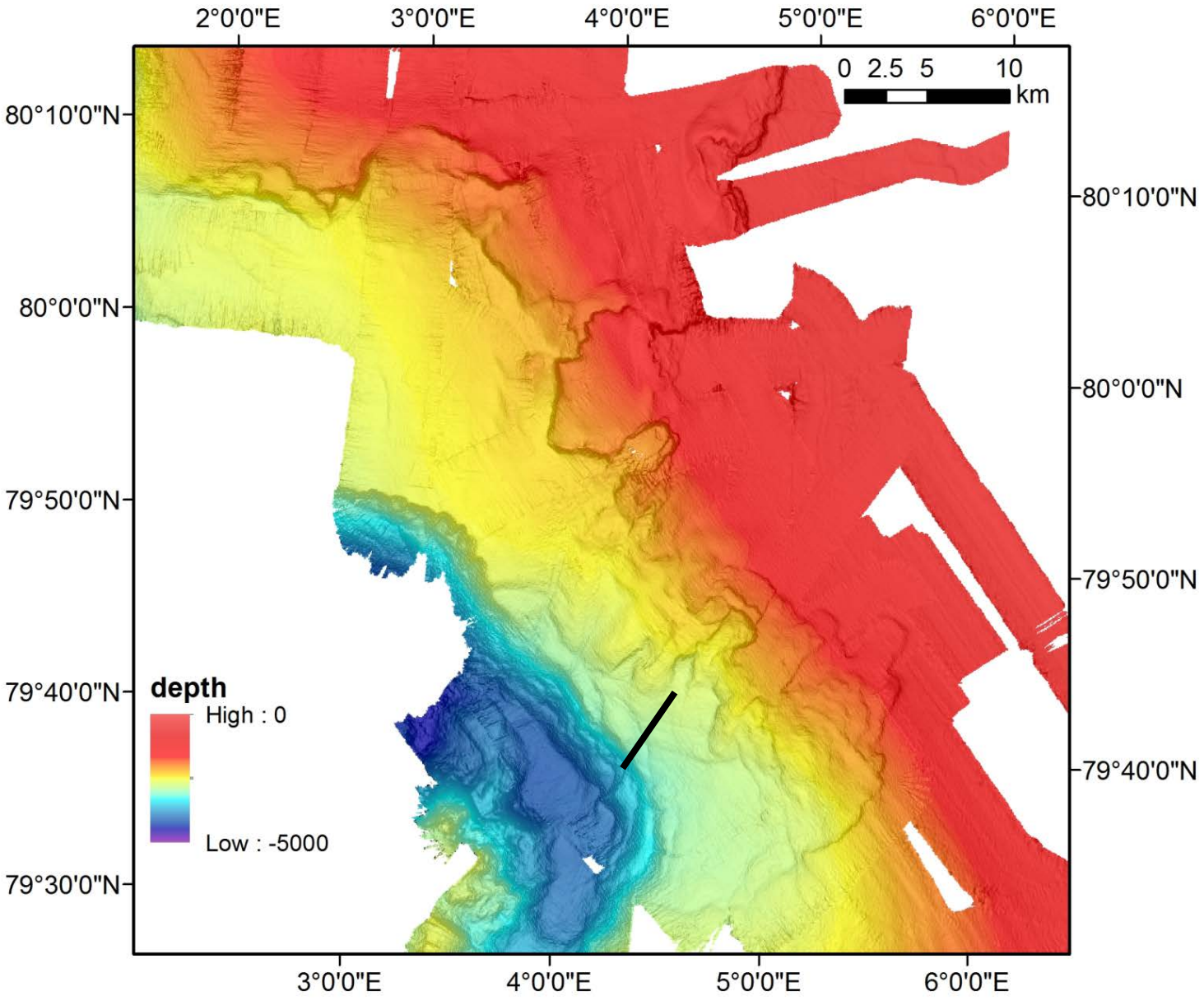

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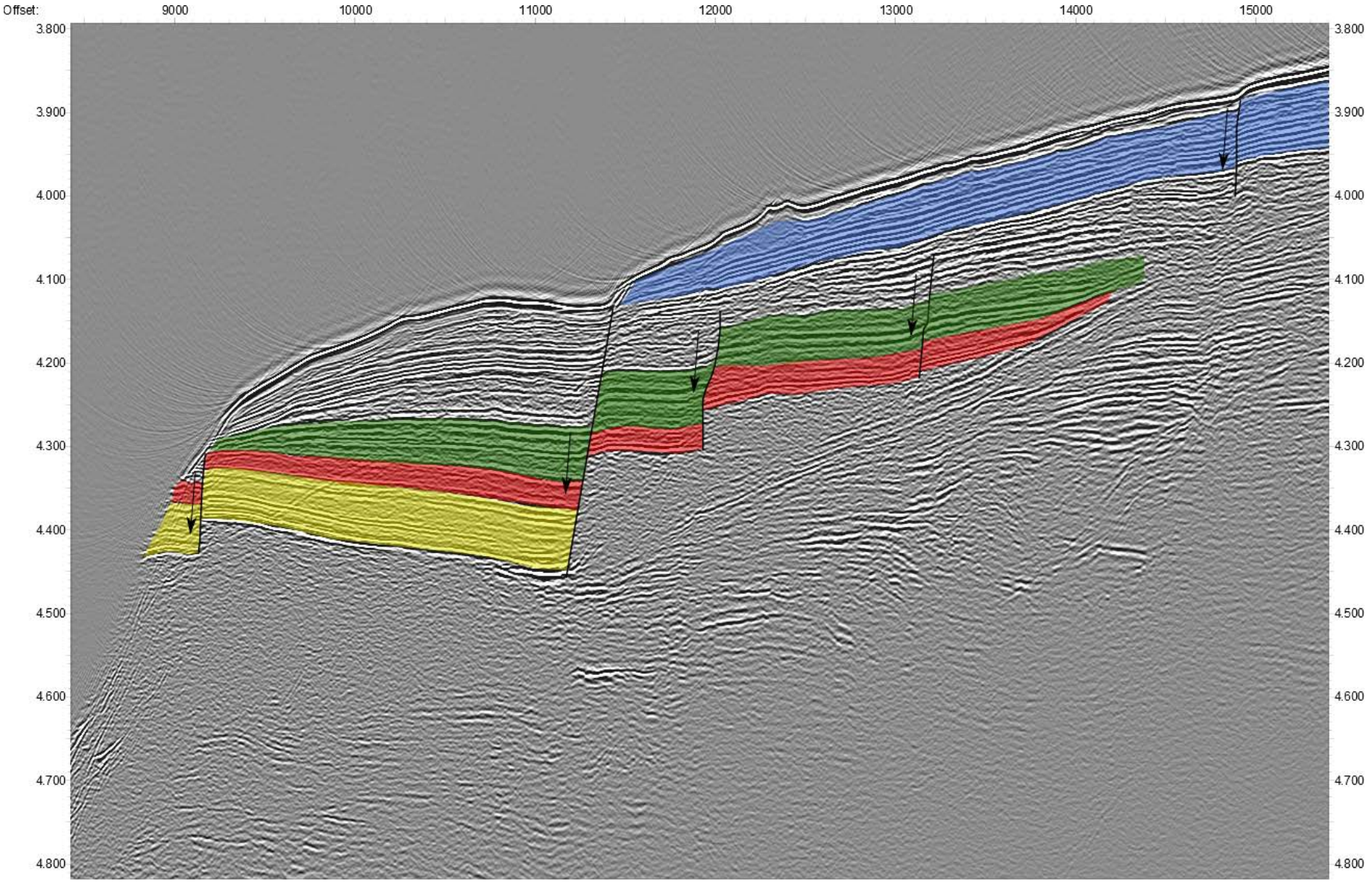


Preliminary results for the Fram Slide

The glacial debris flow hypothesis to explain the occurrence of submarine landslides does not fit the Fram Slide complex.

There is a long history of landslides at the Fram Slide complex with different age, recurrence frequency and volume in the different parts of the complex.

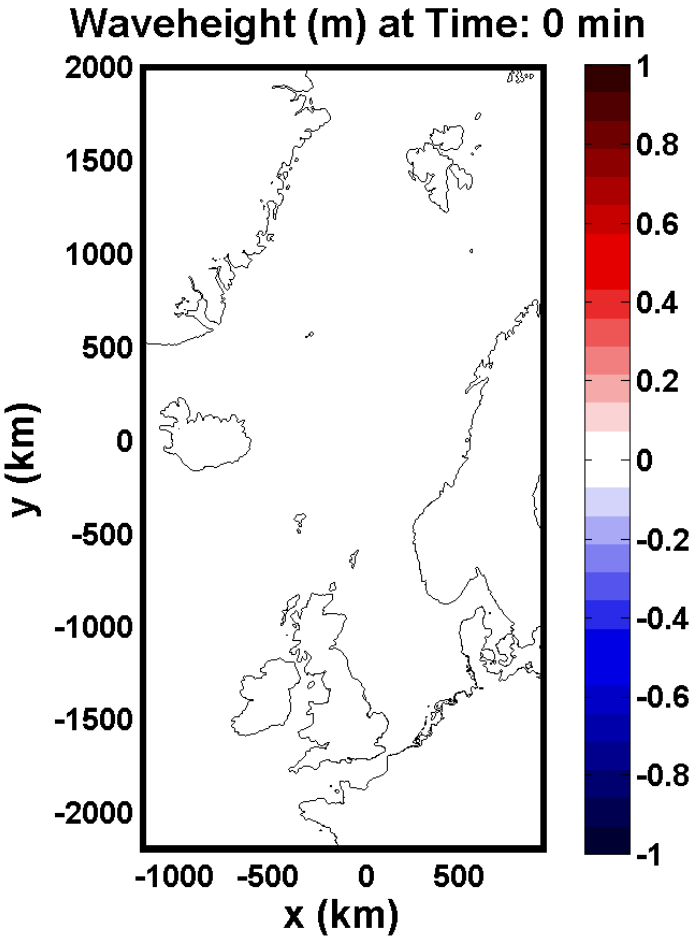
Mechanisms destabilizing the slope might be different within the Fram Slide complex.

For the southern part it is likely that a combination of unstable sediments due to contourite currents, tectonic movement and/or fluid migration has played a major role.

In the northern part the effect of tectonic movement seems to play a less prominent role.

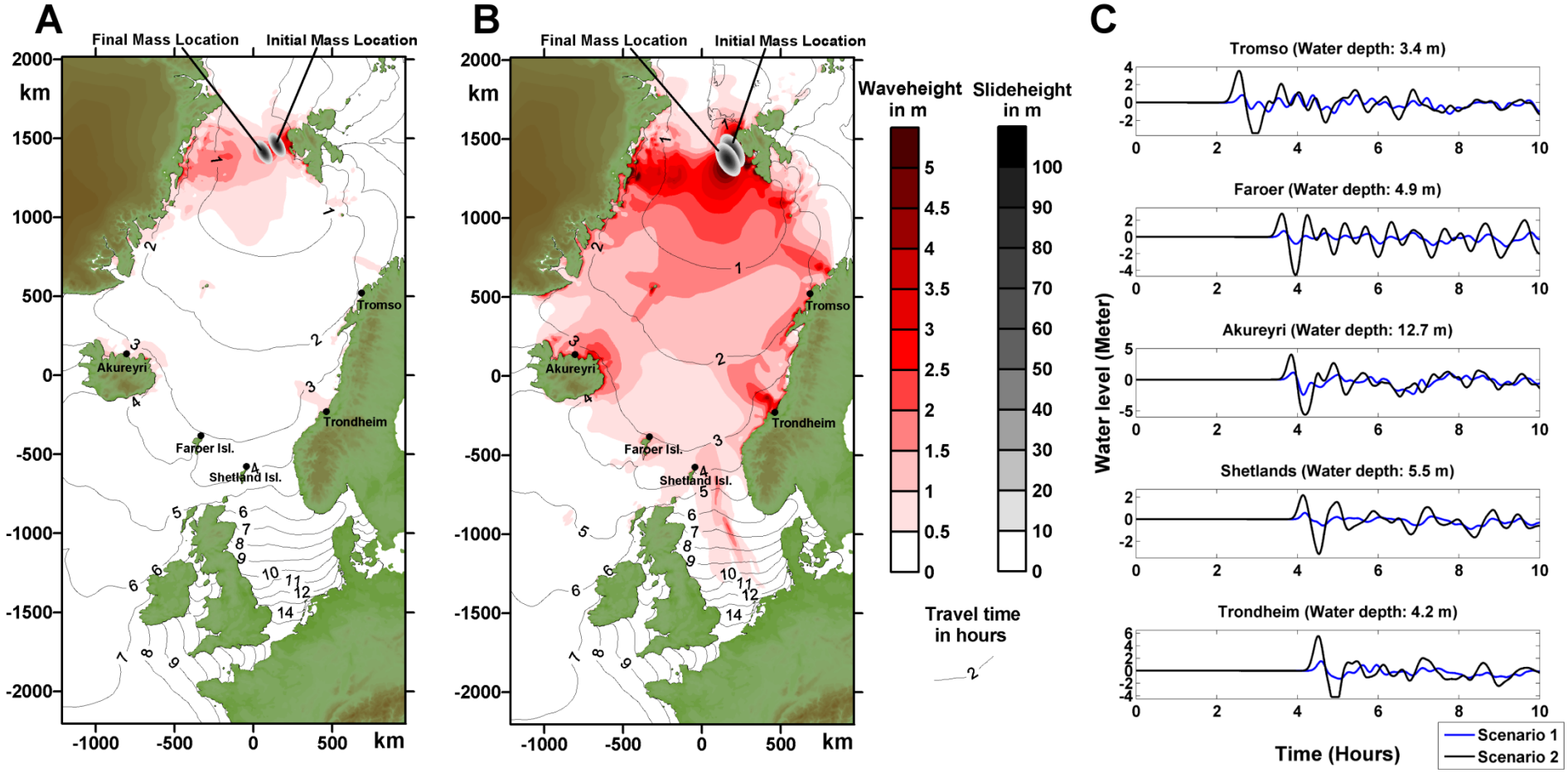
Tsunami model

- Assuming landslide 1/3 of Storegga size
- Assuming all other parameters (velocity, acceleration) match Storegga
- Boussinesq equation using North Atlantic bathymetry
- Analysis of the effect of different landslide directions



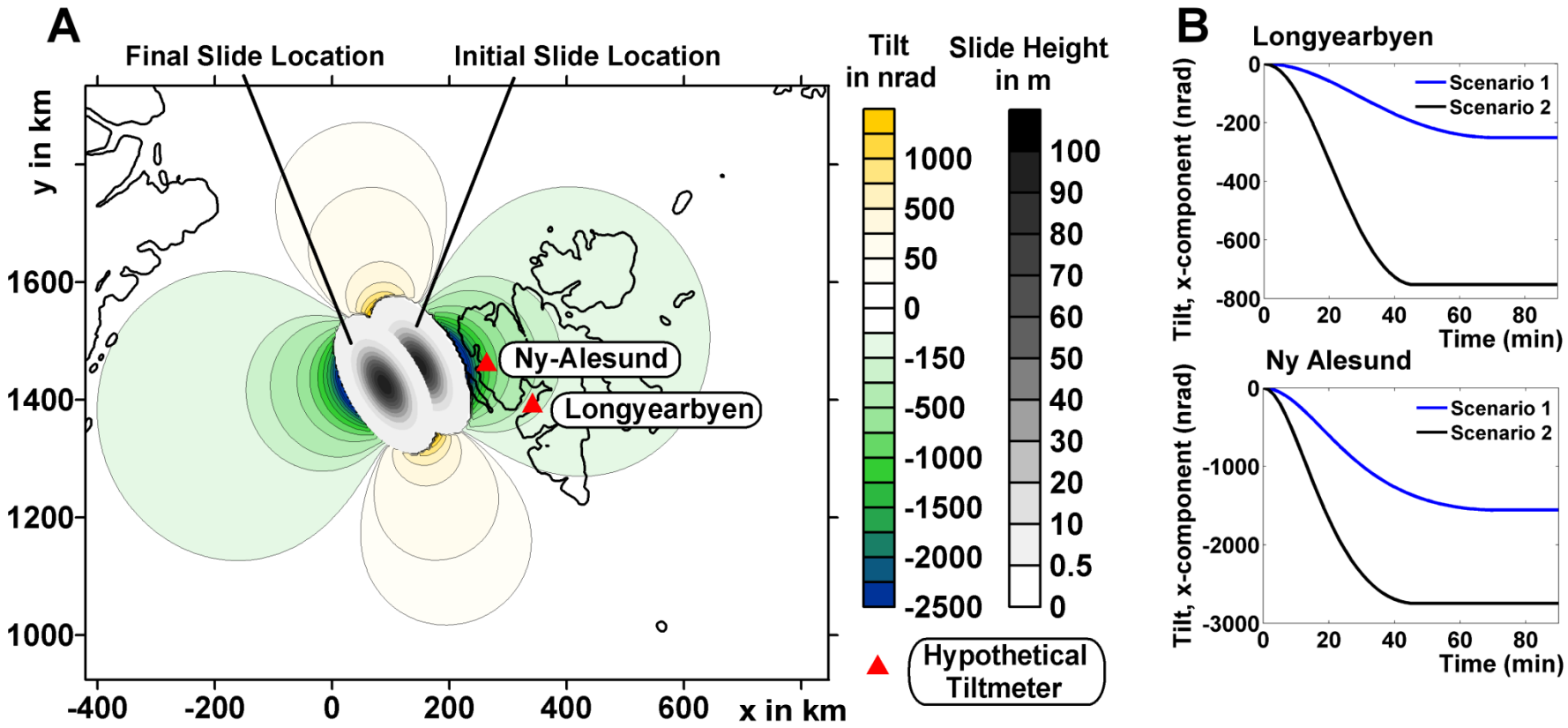
Berndt et al., 2009

Tsunami model



Berndt et al., 2009

Tsunami warning system



Berndt et al., 2009

Conclusions

- Storegga Slide was facilitated by interlayering of hemi-pelagic and glacigenic sediments typical for trough mouth fans

- Storegga was retrogressive and hydrate dynamics cannot have played a role in triggering the Slide. Geomorphological analysis suggests that the presence of hydrate changed the way the slide propagated

- There are anomalous slides in the North Atlantic for which a different explanation has to be found. Toe erosion or fluid migration seem likely candidates

Thank you very much for your attention!

GEOMAR