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# 3D modeling of the crust and upper mantle in the epicontinental Barents Sea region

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# The crustal structure of the Barents Sea: An unstable epicontinental region

- Introduction
  - Background and motivation; two US DoE projects
- **Previous project:** Development of a Three-dimensional Velocity Model for the Crust and Upper Mantle of the Barents Sea, Novaya Zemlya, Kara Sea and Kola-Karelia Regions
  - Conducted 2003-2005
  - Classical approach; resulting in a new 50x50 km 3D model
- **New project:** Development and Tuning of a 3-D Stochastic Inversion Methodology to the European Arctic
  - To be conducted 2008-2010
  - Markov Chain Monte Carlo approach, based on multiple types of data
  - Refine methodology; create an updated 3D model
- Conclusions

# Introduction

- The main motivation of the sponsor (US Dept. of Energy) for such research are:
  - Support CTBT (Comprehensive Test Ban Treaty) work
  - Improve the local accuracy for events in Barents Sea region
  - Improve the seismic monitoring capabilities in this region
- This calls for basic research:
  - The lithospheric structure is very complex
  - Much new and different types of data are available
  - Therefore the work is methodologically challenging

# Previous project:

## Development of a Three-dimensional Velocity Model for the Crust and Upper Mantle of the Barents Sea, Novaya Zemlya, Kara Sea and Kola-Karelia Regions

Project participants:

**University of Oslo (Norway)**

**NORSAR (Kjeller, Norway)**

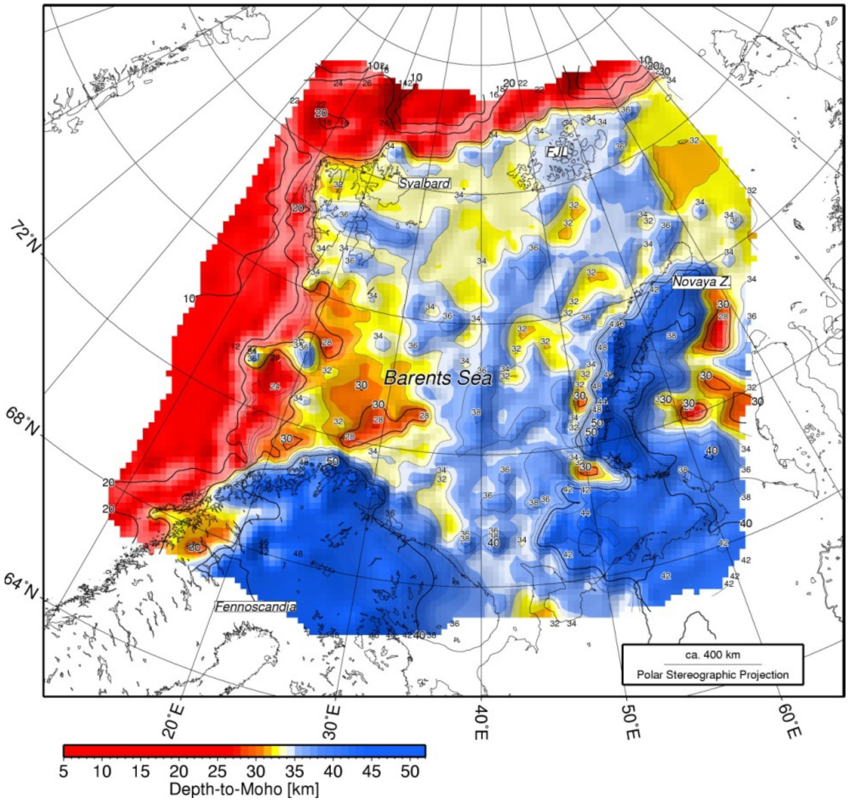
**USGS (Menlo Park, USA)**

in coperation with

**University of Colorado, Boulder**

**Institut de Physique du Globe, Paris**

Depth-to-Moho map



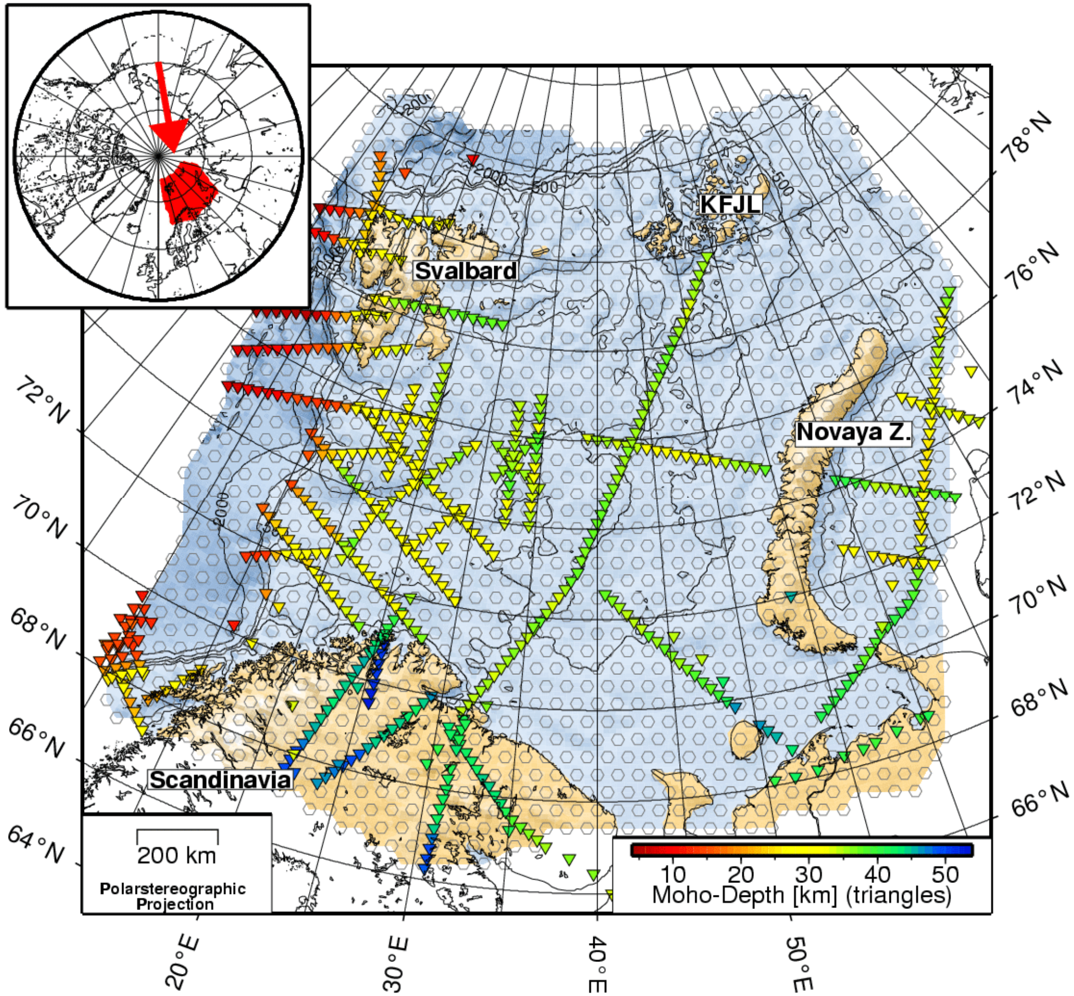

**From Bungum et al. (2005)**

# Barents Sea target region

The greater Barents Sea region is about 3 million km$^2$.

Triangles mark the position of velocity profiles; color coding indicates the Moho depth.

The small hexagons are tiles spaced 50 km apart indicting the velocity model nodes.




From Bungum et al. (2005)

# Barents Sea geologic history

Time span from the Early Archean to the late Cenozoic:

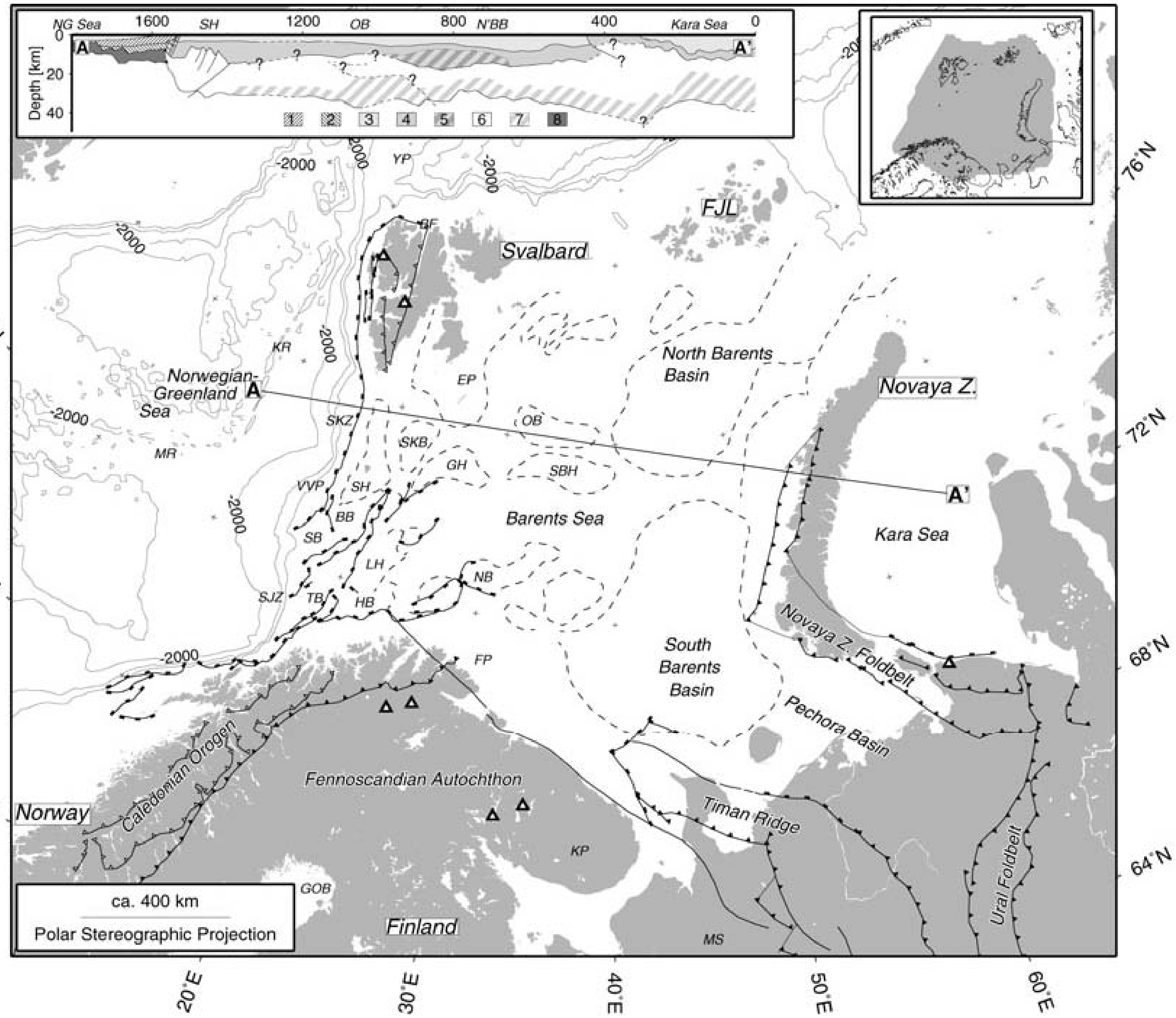
1. The oldest rocks in the greater Barents Sea region are of Archean/Proterozoic age and are found on the Kola Peninsula and surrounding provinces
2. The Caledonian Orogen extends along western Norway
3. The Pechora Basin developed between the Vendian Timan Ridge, a collision structure between the Baikalia/Fennoscandia and the Uralian Foldbelt south of Novaya Zemlya
4. The Post-Caledonian rift basins in the western Barents Sea exhibit smaller dimensions compared to the large single trough in the east
5. The Pai-Khoi-Novaya Zemlya Foldbelt is located in the northern continuation of the Uralian Foldbelt between the East-European and the Siberian Platforms.

# Barents Sea - geologic overview

Dashed lines show prominent structural elements

Top insert (left) shows a geological profile from the Knipovich Ridge to the Kara Sea (A-A')

Top insert (right) shows the outline of the target region in grey.




**From Ritzmann et al. (2007)**

# Previous crustal inversion approaches

- Velocity models developed at a variety of scales
  - local, regional, plate-wide, global
- and they are based on a variety of methods, such as
  - body and surface-wave tomography
  - receiver function analysis
  - thermodynamic modelling
  - first-order velocity data from active-source seismic refraction experiments (present approach)
- Data coverage limits the model quality; crustal seismic experiments usually are unevenly distributed
  - Data coverage is uneven also here, but with the advantage that there are large amounts of first-order data

# Present inversion approach (1 of 2)

- Based on a large number of 1D velocity profiles sampled from 2D seismic refraction transects
- Seismic reflection data used for density modelling and subsequent density-to-velocity conversion
- Velocities from the profiles binned into two sedimentary and three crystalline crustal layers (i.e., a 5-layer crust)
- Layer-wise interpolation of velocities and thicknesses

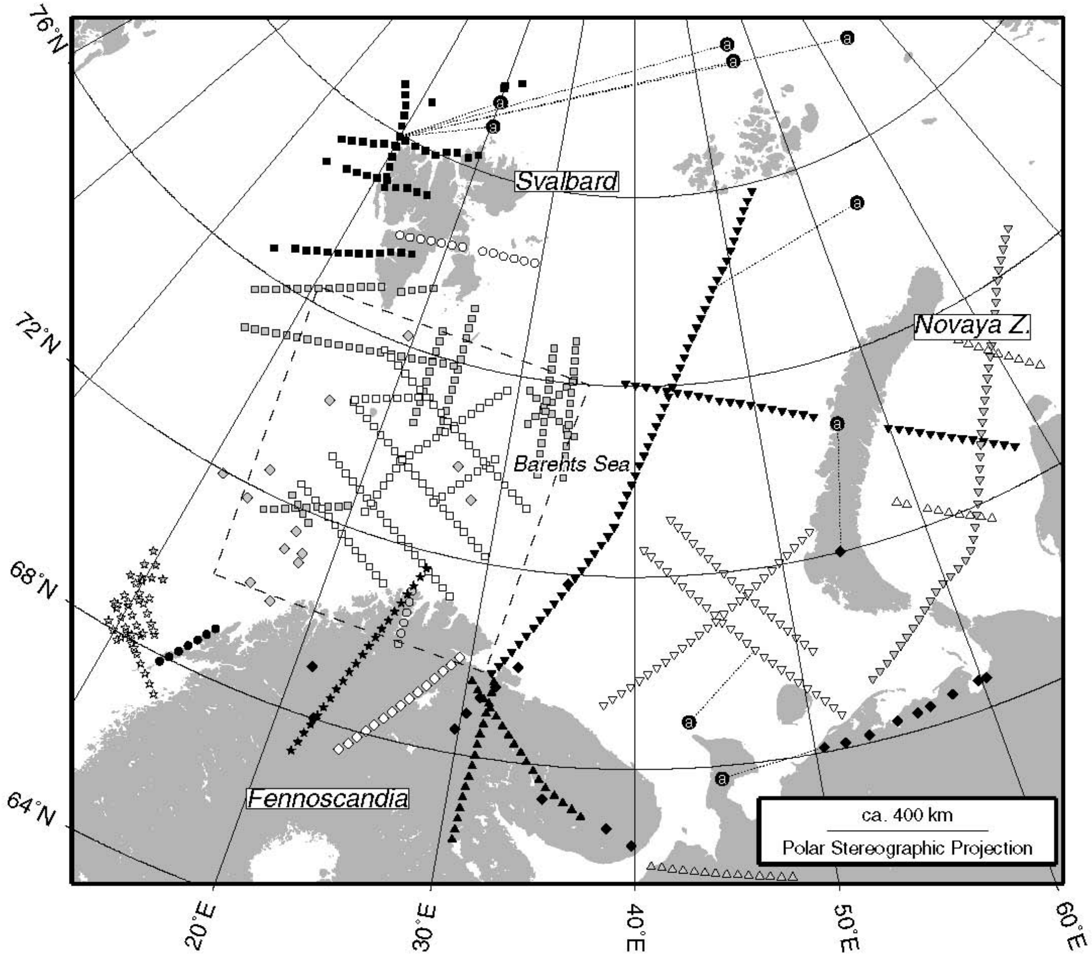
# Present inversion approach (2 of 2)

- For different geological provinces, linear relationships between sedimentary thickness and crystalline thickness were developed
- In this way sediment thickness data were used to adjust the total crystalline crustal thickness in cases when no constraints from 1D velocity profiles existed
- The P-wave velocity model was subsequently used for gravity modelling to obtain 3D density structure
- The resulting model is based on an equidistant hexagonal grid with a node spacing of 50 km

# Database transect locations

Data base consists of:

- 680 1D seismic profiles, from
- 23 2D transects, and
- 34 studies (references), with
- 4 quality classes




From Ritzmann et al. (2007)

# Observed P-wave velocity histograms

a) Provinces with oceanic crust

b) Continent-ocean transition zones

c) The Cretaceous Volcanic province

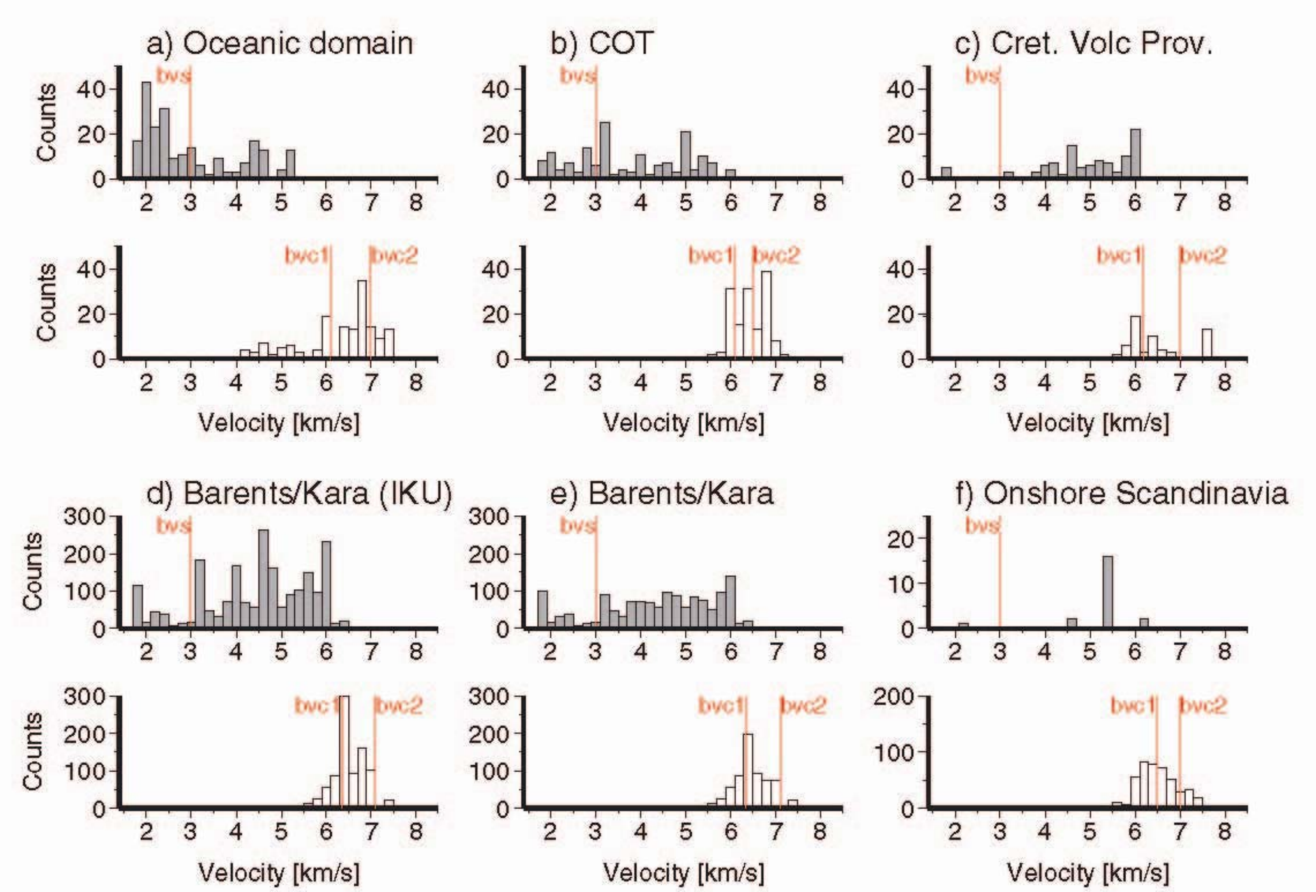
d) Remaining areas of Barents and Kara Seas, converted from density

e) Same as d), but without conversion from density

f) Caledonian and Precambrian provinces

bvc1 = separating upper and middle crystalline crust

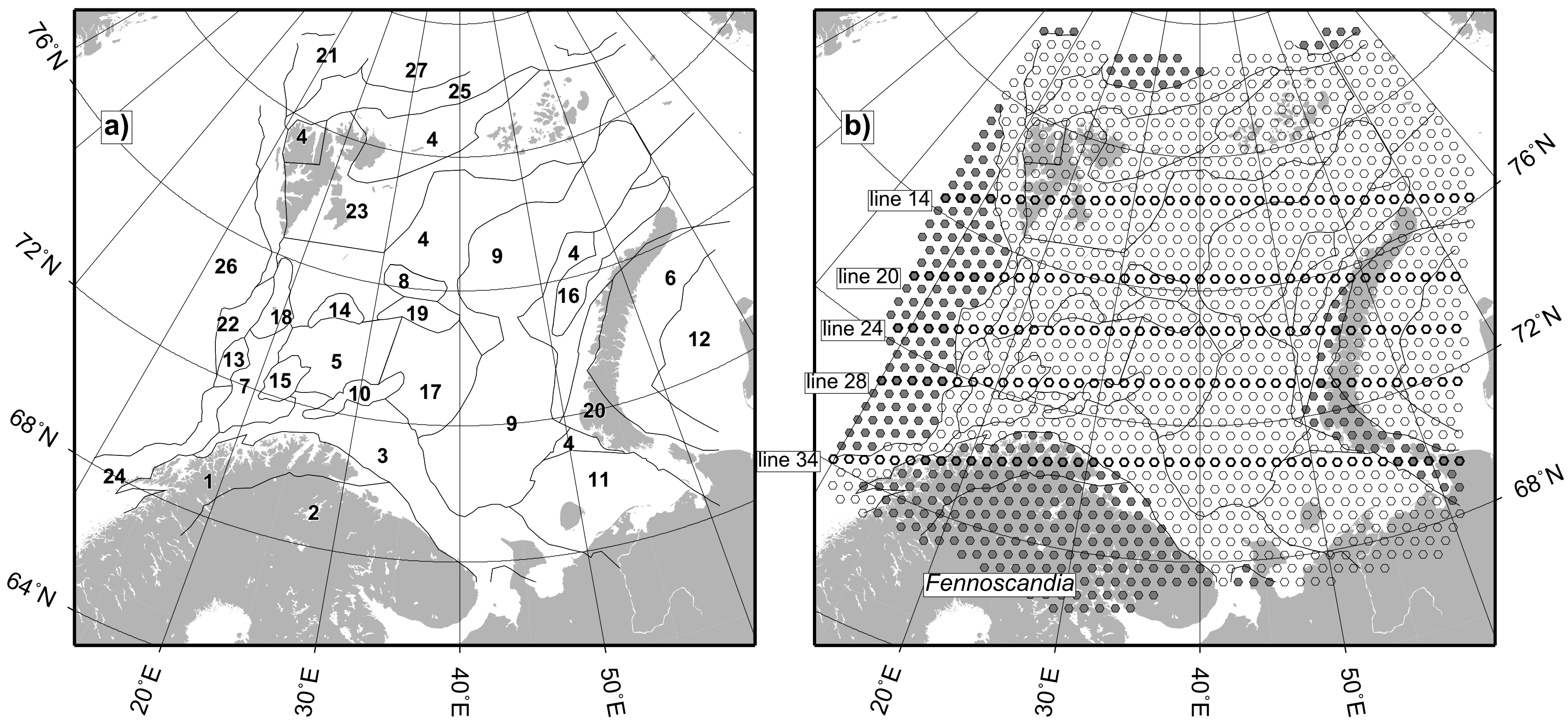
bvc2 = separating middle and lower crystalline crust




From Ritzmann et al. (2007)

# Geological provinces and grid node setup

- 23 different geologic provinces (used for interpolation)
- 50x50 km grid nodes (gray shaded in oceanic areas and sediment-free cratons)



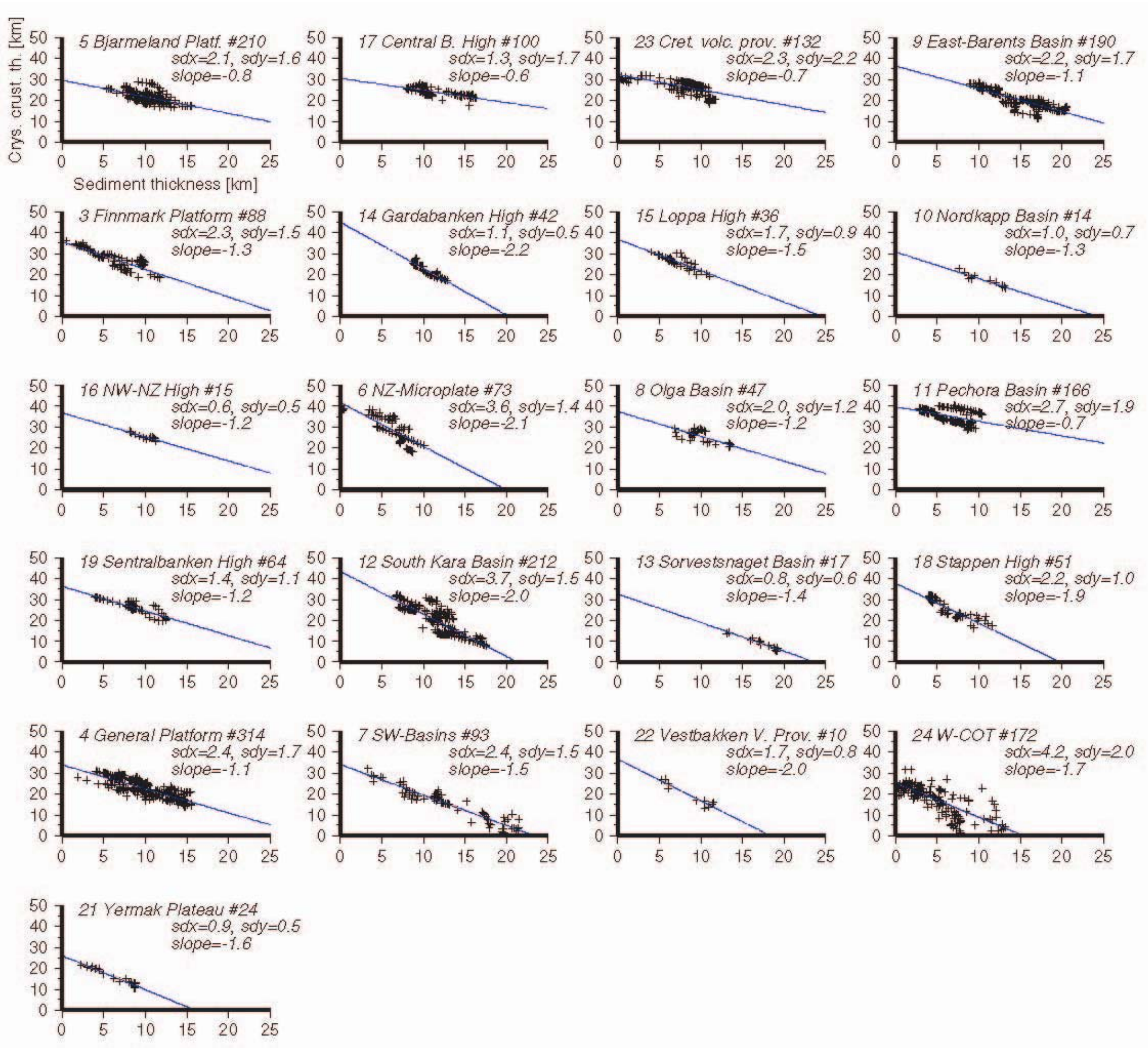

From Ritzmann et al. (2007)

# Thickness relationships

Sediment thickness plotted against crystalline crustal thickness for all provinces

Black crosses are data points extracted from the profile database

Solid lines show the calculated linear regressions

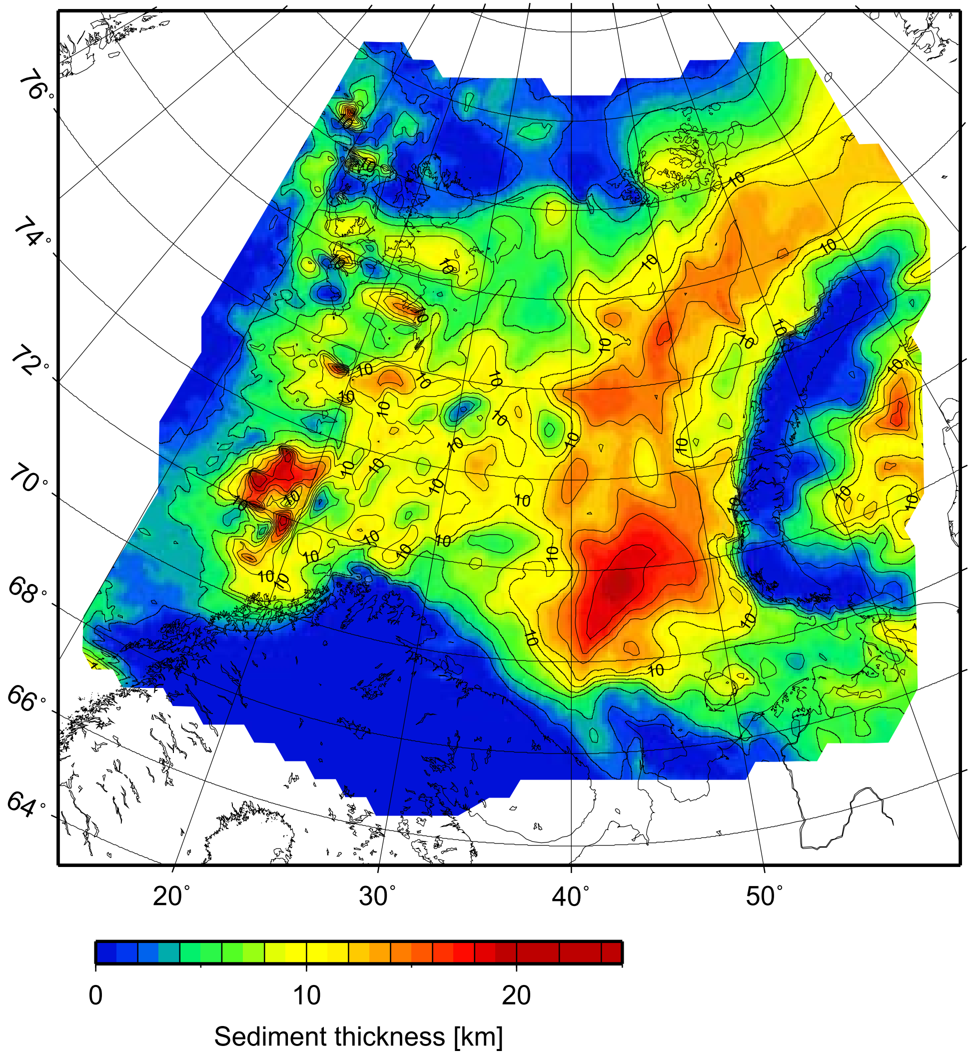



**From Ritzmann et al. (2007)**

# Sediment thickness map

Sediment thickness map used for layer thickness adjustments of the preliminary model

Applied where no nearby data constraints (1D velocity profiles) were given.




From Ritzmann et al. (2007)

# Developing an S-wave model

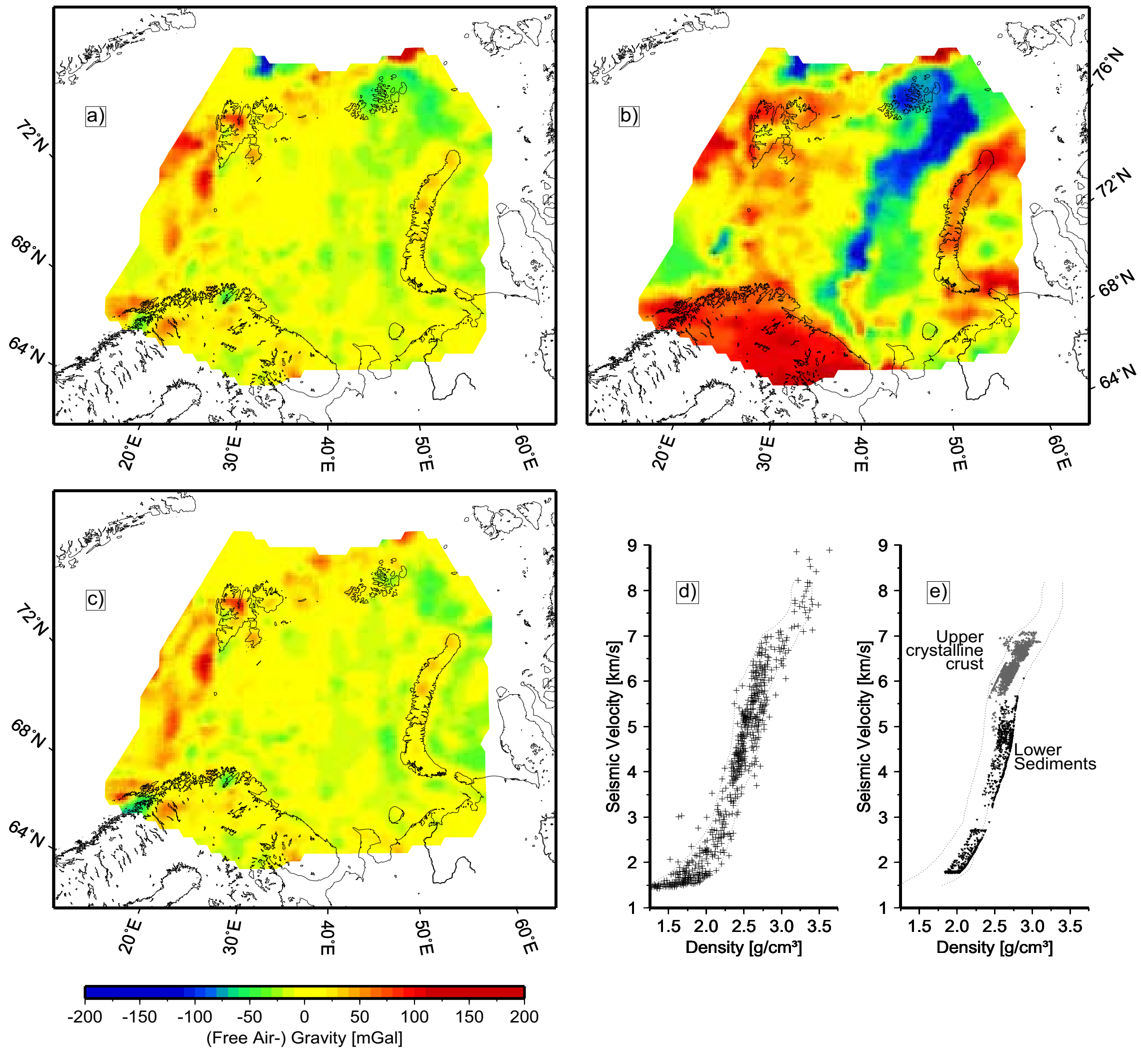
- After the compilation of the P-wave velocity model, the model was extended by including S-wave velocities for every crustal layer.
- Average Vp/Vs-ratios were extracted from the lithosphere model of Levshin et al. (2005, 2007) and used for the conversion of the present P-wave velocities.
- The mean Vp/Vs-ratios for the upper and lower sedimentary layers are 3.01 and 1.73, respectively.
- Below, the three crystalline crustal layers exhibit ratios of 1.70, 1.72 and 1.75, respectively.

# Density modeling

- The velocity model was converted to a density model and used for gravity calculation.
- The obtained gravity field was subsequently compared to the observed gravity field and locally adjusted using a grid search method.
- With the exception of the western Barents Sea, where the velocity model was predominantly derived from density modelling, this implied an independent test of the P-wave velocity model.
- We expected a minimum fit using standard relations between seismic velocity and density outside this area.

# Gravity modeling

a) Free-air gravity anomalies in the study region
b) Gravity field, inferred from the initial density model
c) Gravity field, inferred from the adjusted density model using grid search
d) Relationship between seismic P-wave velocity and density




From Ritzmann et al. (2007)

# Discussion points from this work

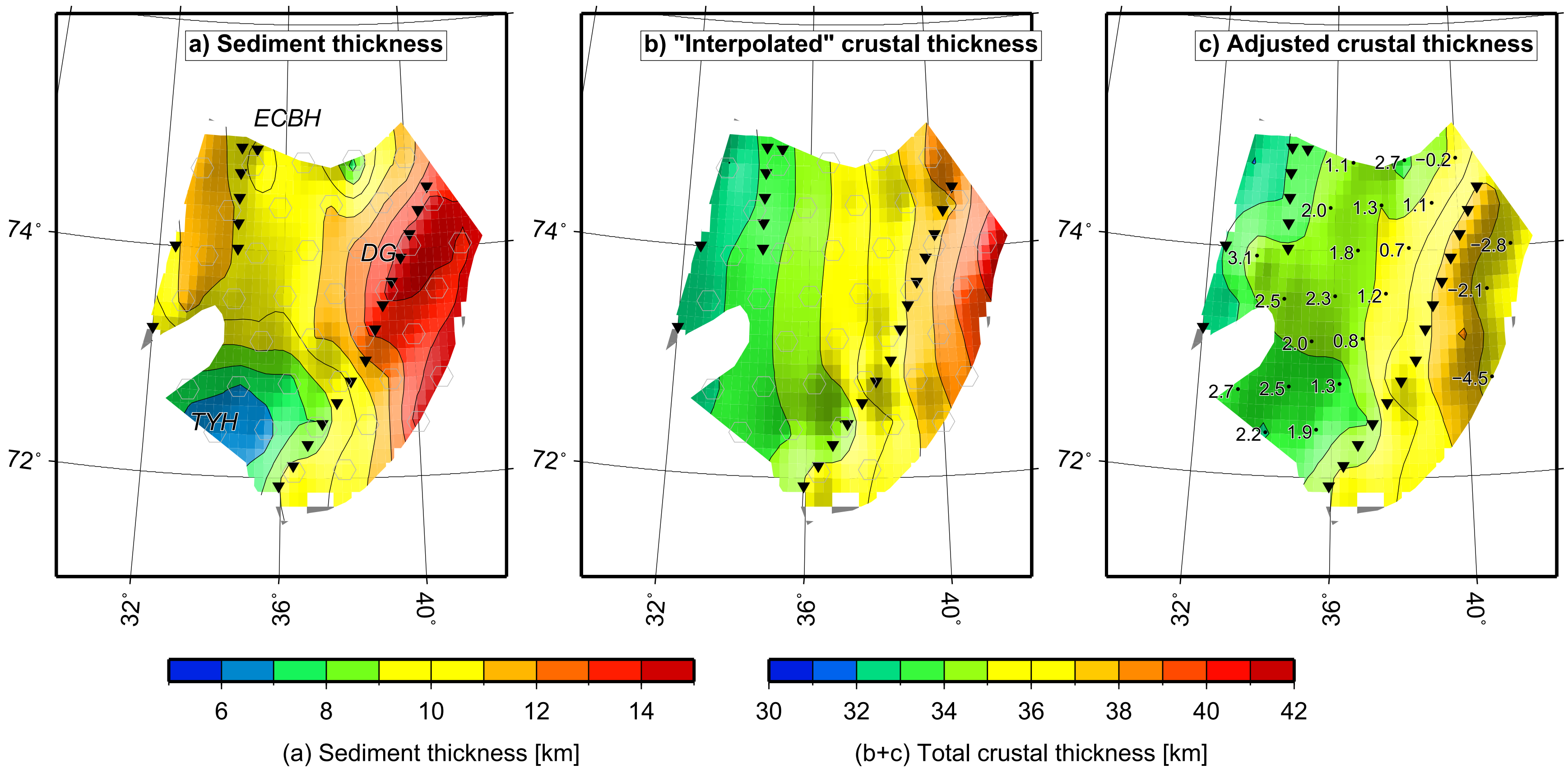
- The adjusting of crustal thickness according to relationships between the sediment and crystalline thicknesses as a function of geological provinces has important geological (physical) implications.
- The comparison with three earlier models demonstrates the increased resolution of the present model. The defined geological provinces have a strong effect on the travel time distribution.
- Parallel W-E crustal transects reveal much of the basic characteristics of the crust since we consistently have two sedimentary layers and three crystalline layers everywhere.
- The depth-to-Moho distribution is a small but important part of the new model.
- The combination of a consistent seismic database and a reliable use of secondary geological constraints helped significantly to establish the new higher-resolution geophysical model.

# Effect of the thickness adjustments

a) Sediment thickness in province 17, Central Barents Sea High

b) Interpolated crustal thickness

c) Adjusted crustal thickness using the thickness relations (km)




From Ritzmann et al. (2007)

# Model comparisons, travel time to Moho

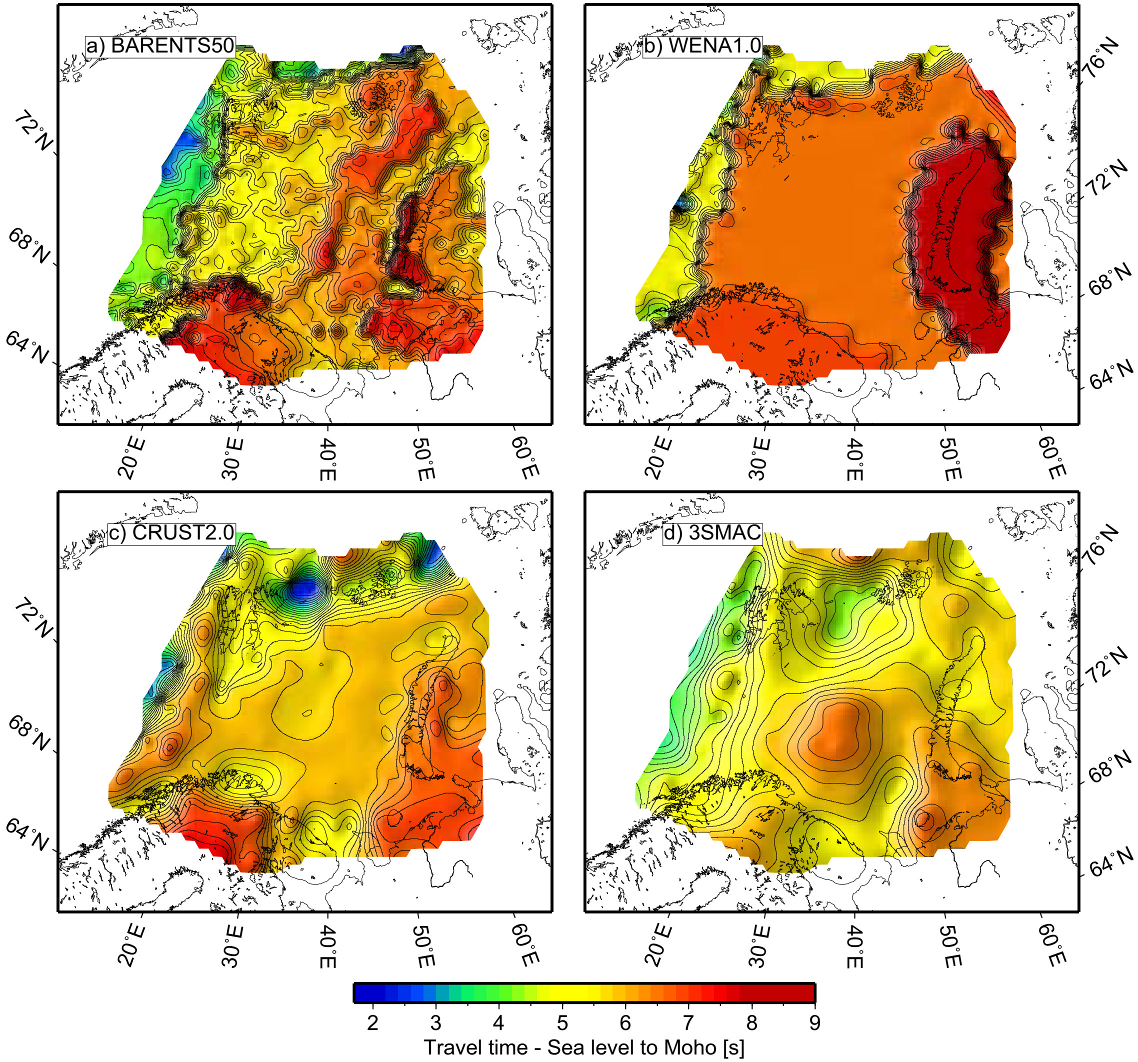
Four models compared:

a) **BARENTS50, this study**

b) **WENA1.0 (Pasyanos *et al.* 2004)**

c) **CRUST2.0 (Bassin *et al.* 2004)**

d) **3SMAC (Nataf & Ricard 1996)**




**From Ritzmann et al. (2007)**

# Crustal transects

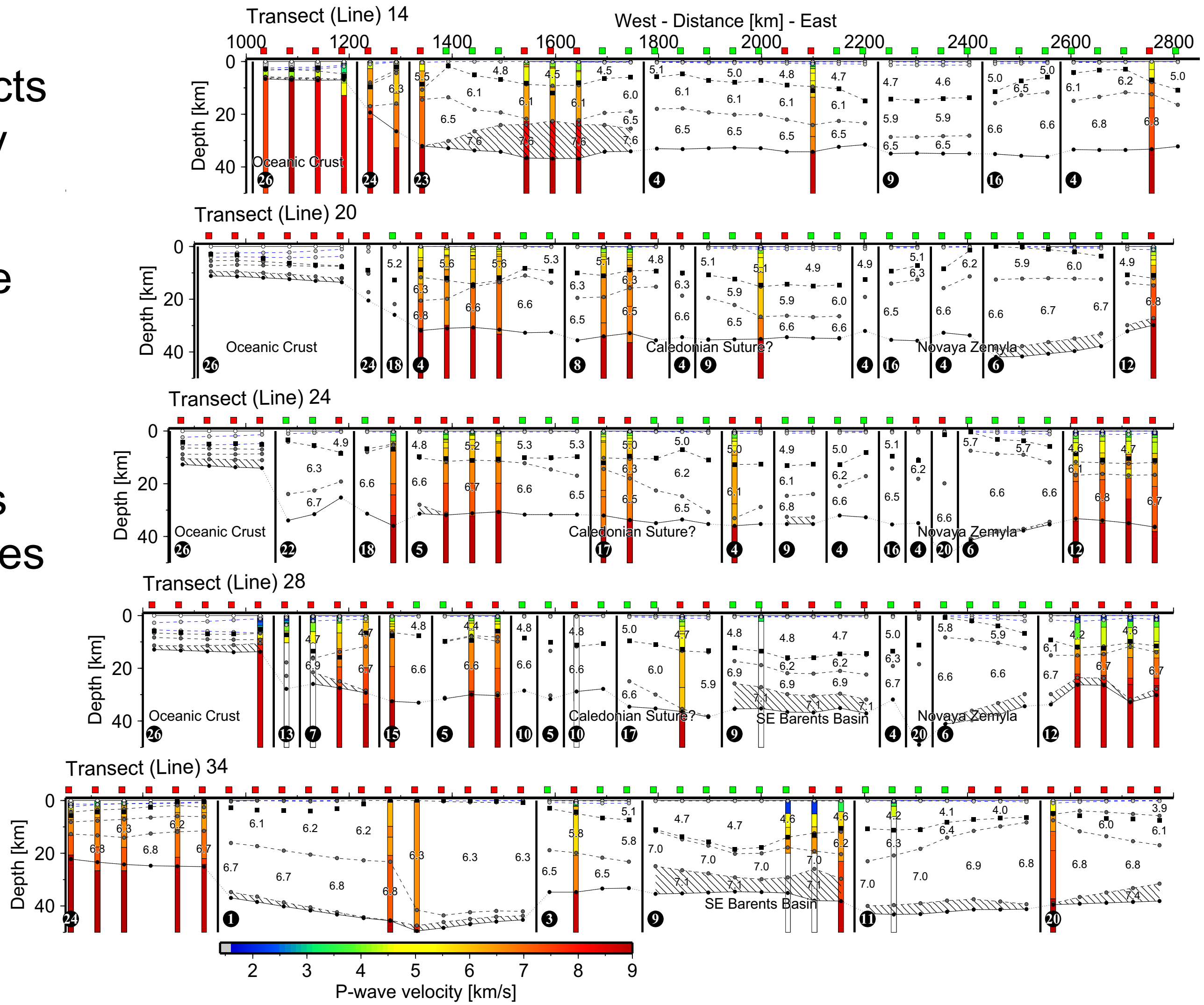
Five W-E crustal transects through the final velocity model

Solid black lines indicate Moho

P-wave velocities given

Thick vertical black lines show province boundaries

Colored vertical bars indicate 1D velocity profiles



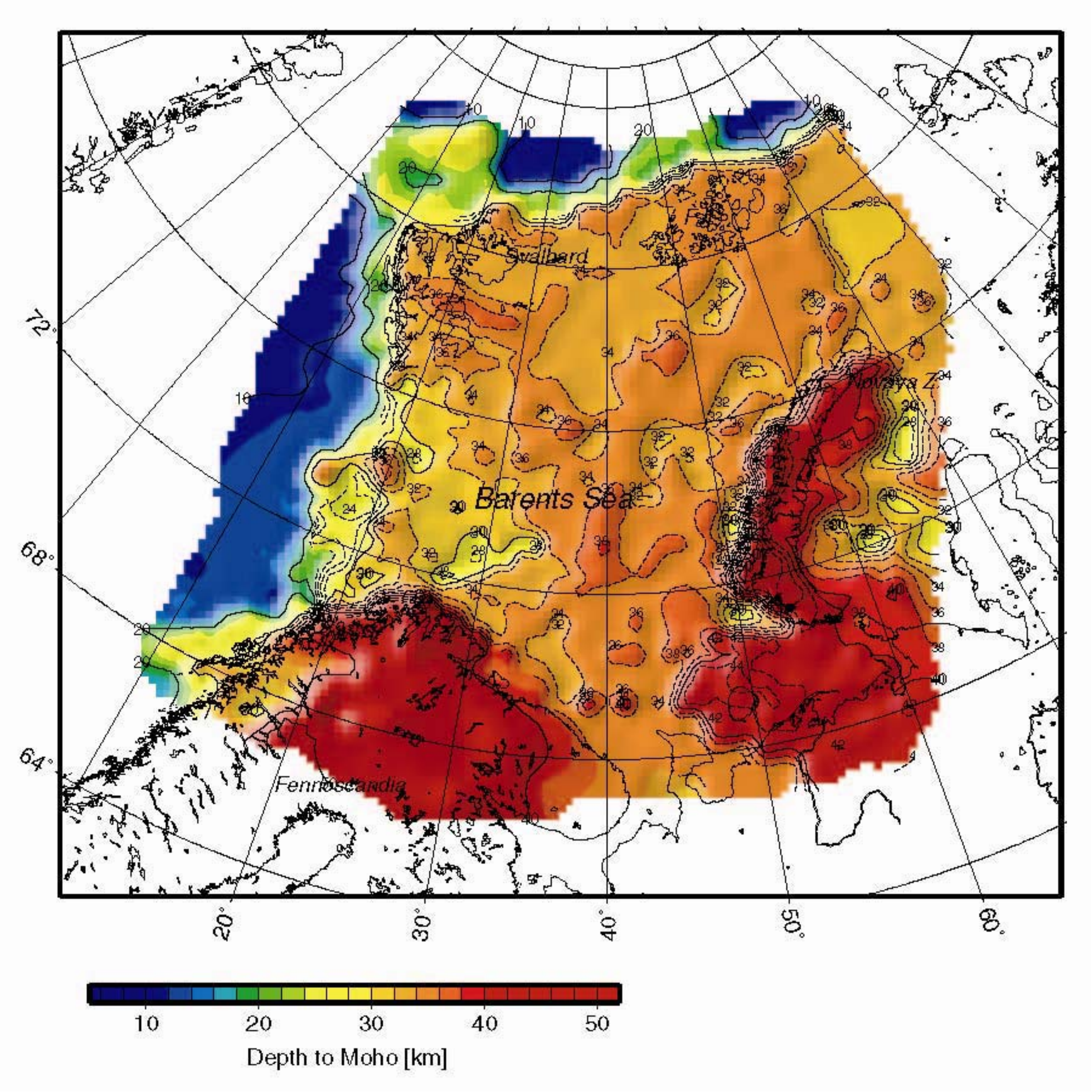

From Ritzmann et al. (2007)

# Final Depth-to-Moho map

Depth-to-Moho from the BARENTS50 model.

Provinces in the central Barents Sea, Novaya Zemlya and Kara Sea are detailed contoured

Every 2 km, dashed; other contours: 10 km, solid



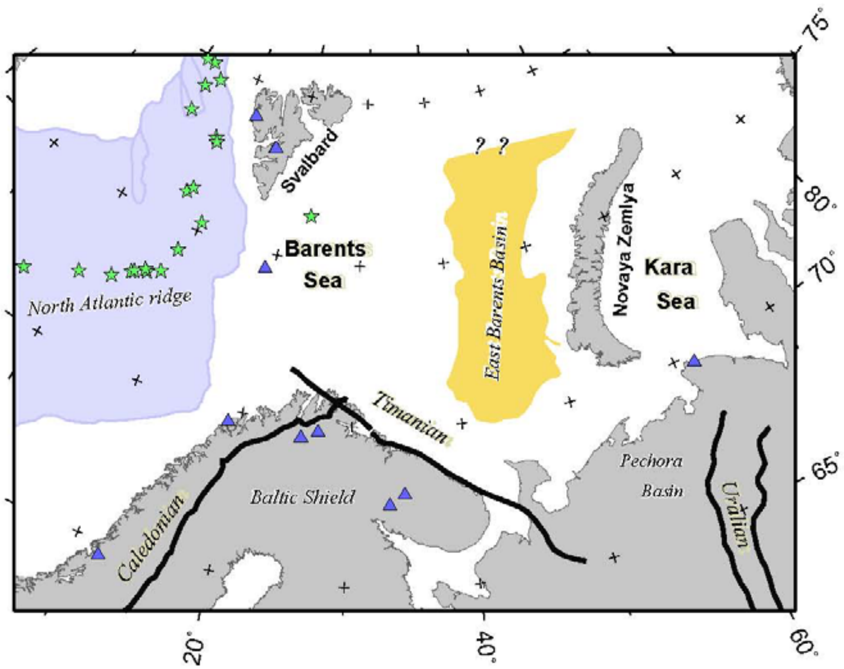

From Ritzmann et al. (2007)

# But something is missing …

- We now have a new and greatly improved model for the crust
- But most regional ray paths go through the upper mantle
- So we need a new upper mantle model too!

# Complementary project :

## Surface Wave Tomography of the Barents Sea and surrounding Regions



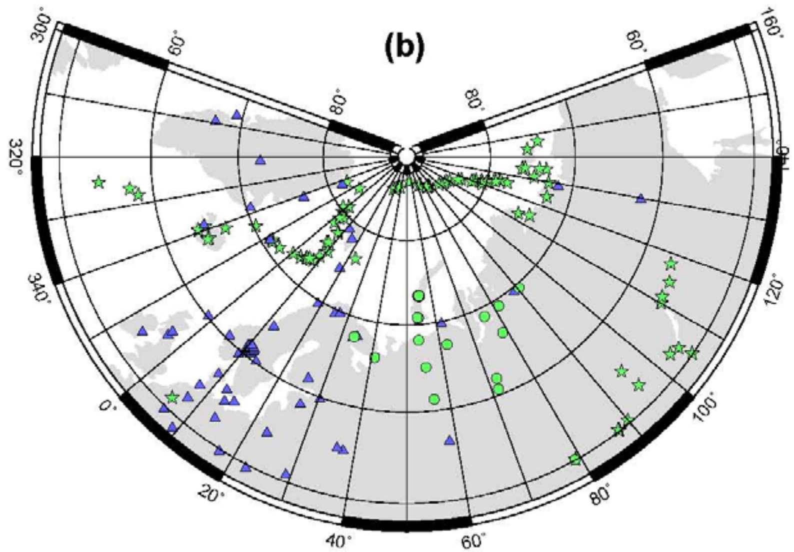

Project participants:

**University of Colorado, Boulder**

**Institut de Physique du Globe, Paris**

**University of Oslo**

**NORSAR**

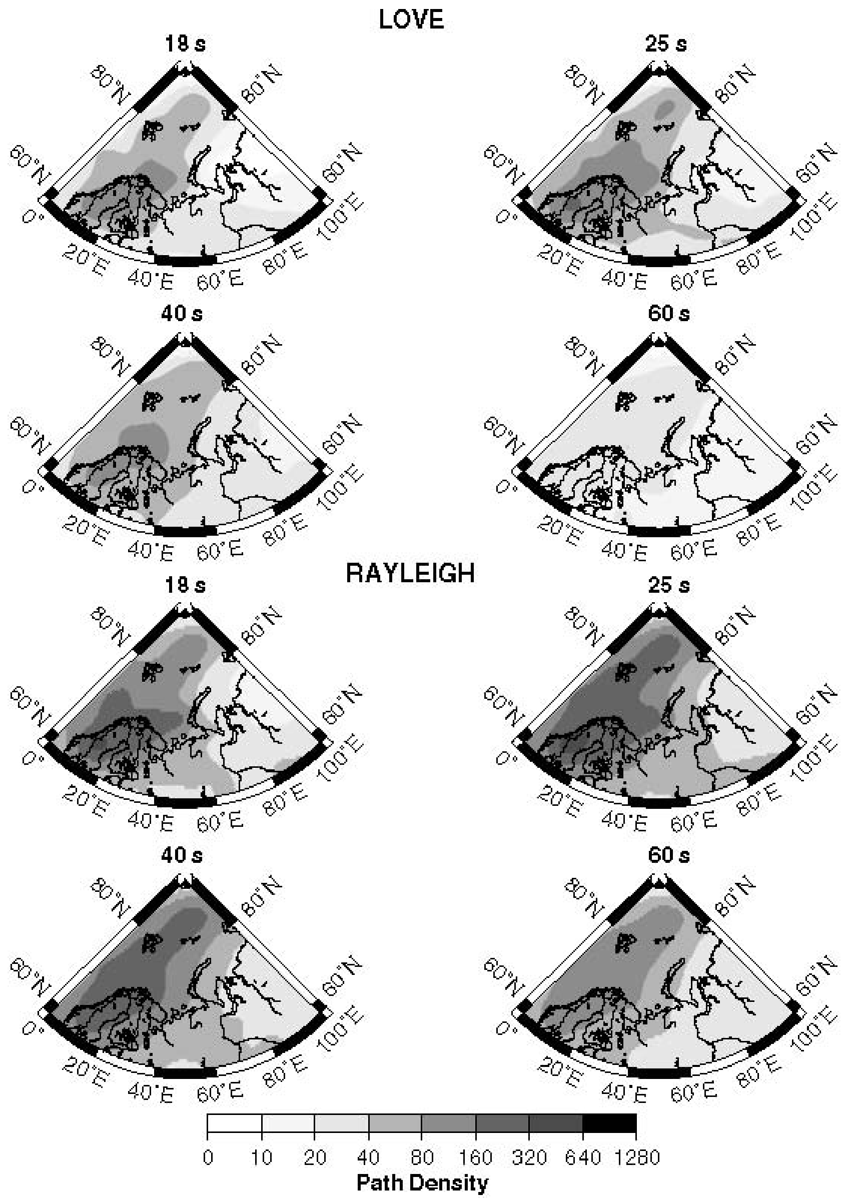



**From Levshin et al. (2007)**

# Surface wave tomography – path density

For Love and Rayleigh waves at different periods

Path density is number of paths crossing an equatorial 1x1 degree cell

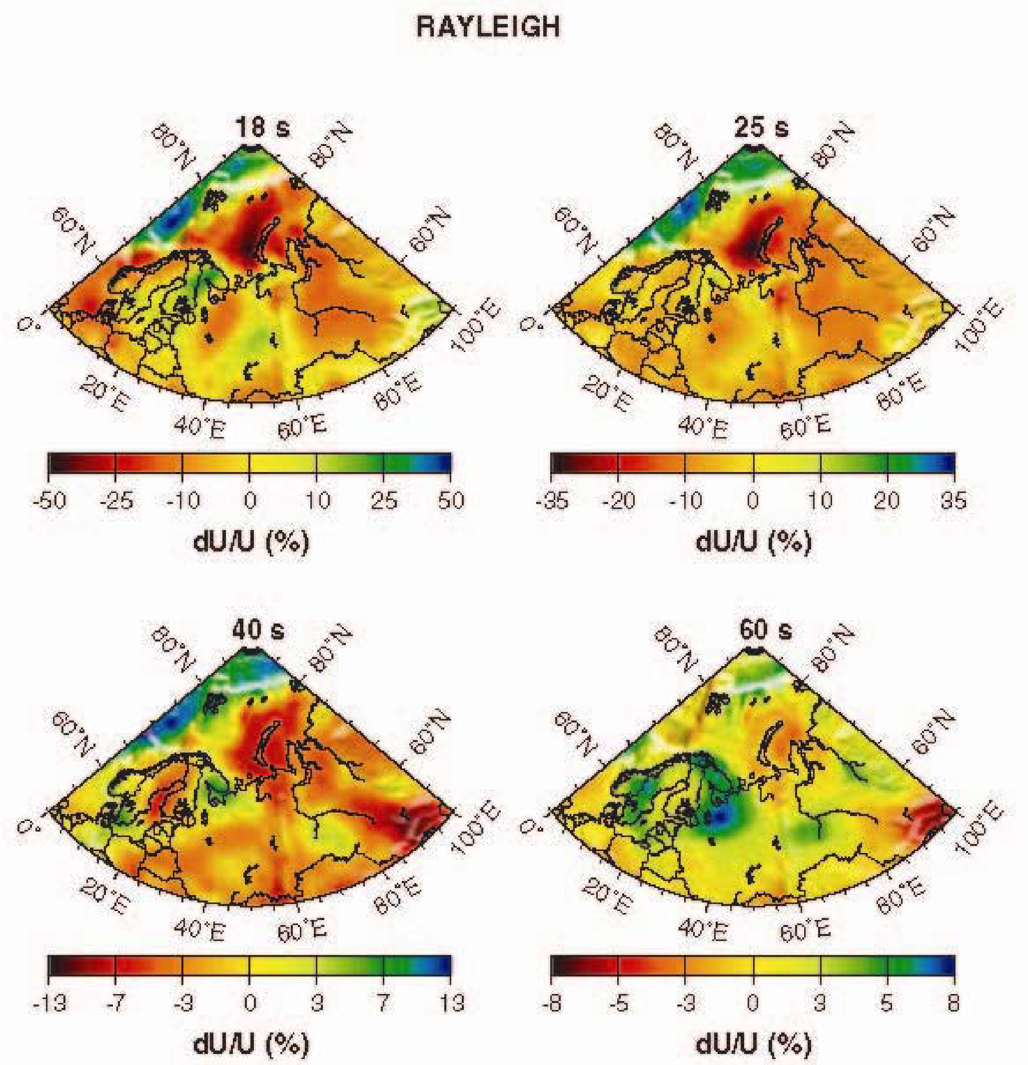



**From Levshin et al. (2007)**

# Rayleigh wave group velocities

Results of the 2-D inversion for the group velocities of Rayleigh waves with period of 18, 25, 40 and 60 s.

The maps present the 2-D distribution of the inverted group velocities as deviations from the average velocity (in per cent).

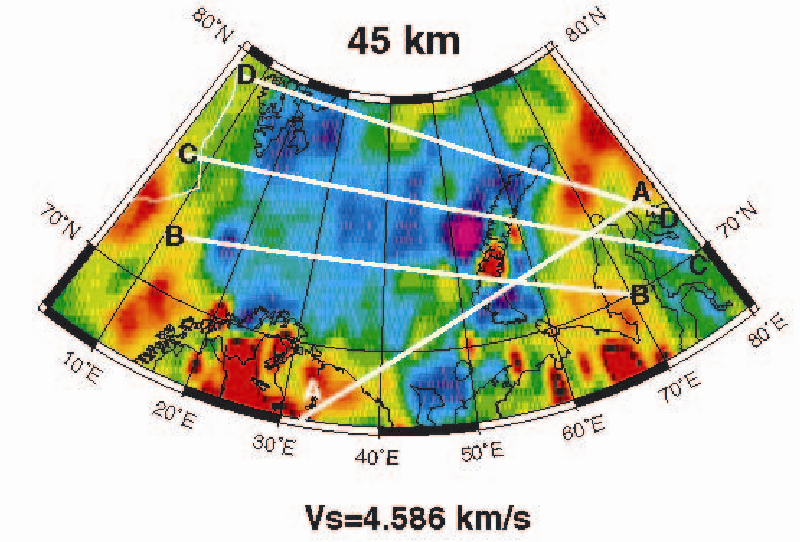


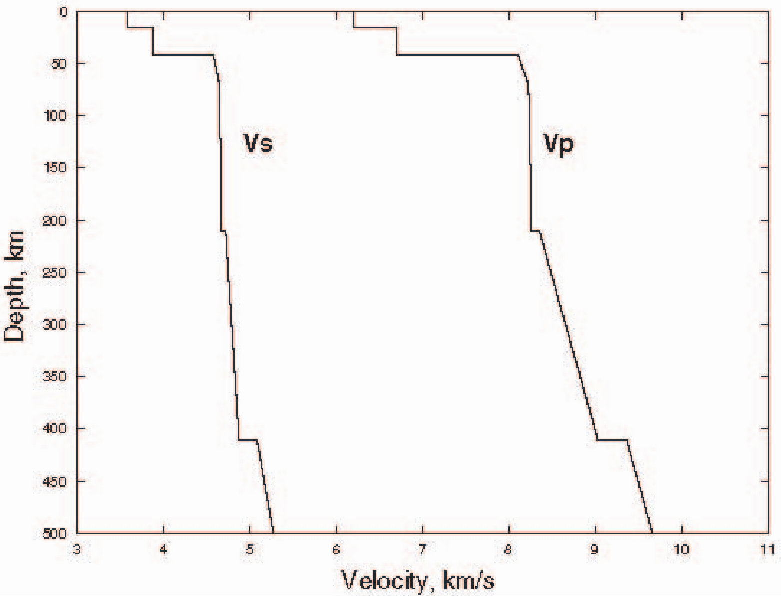

From Levshin et al. (2007)

# Resulting Crust and Upper Mantle Model

Top:
Results of the 3-D tomographic inversion: isotropic shear wave velocities at 45 km relative to the 1-D model *Barey,* with location of transects

Bottom:
The *Barey* model (Schweitzer & Kennett 2002) used
in this study as 1-D reference model

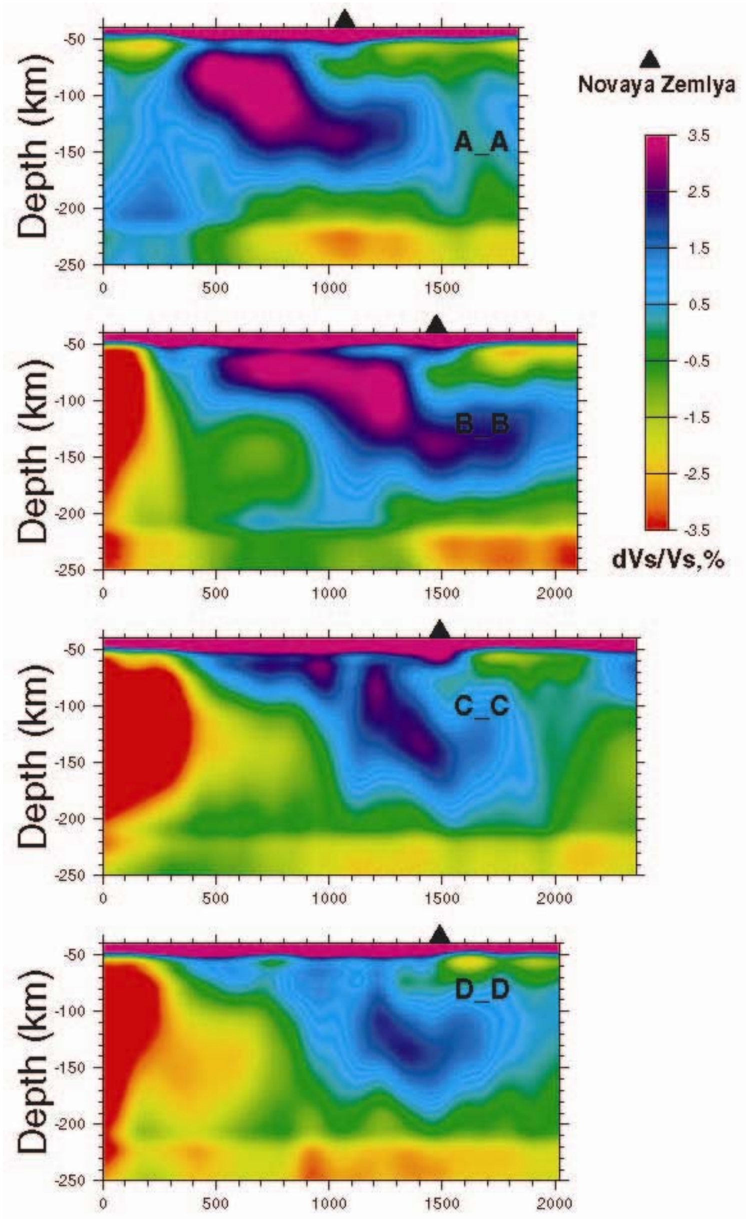



From Levshin et al. (2007)

# Resulting Crust and Upper Mantle Model

Isotropic *S*-velocity perturbations relative to the *Barey* model along the four transects shown in the previous slide



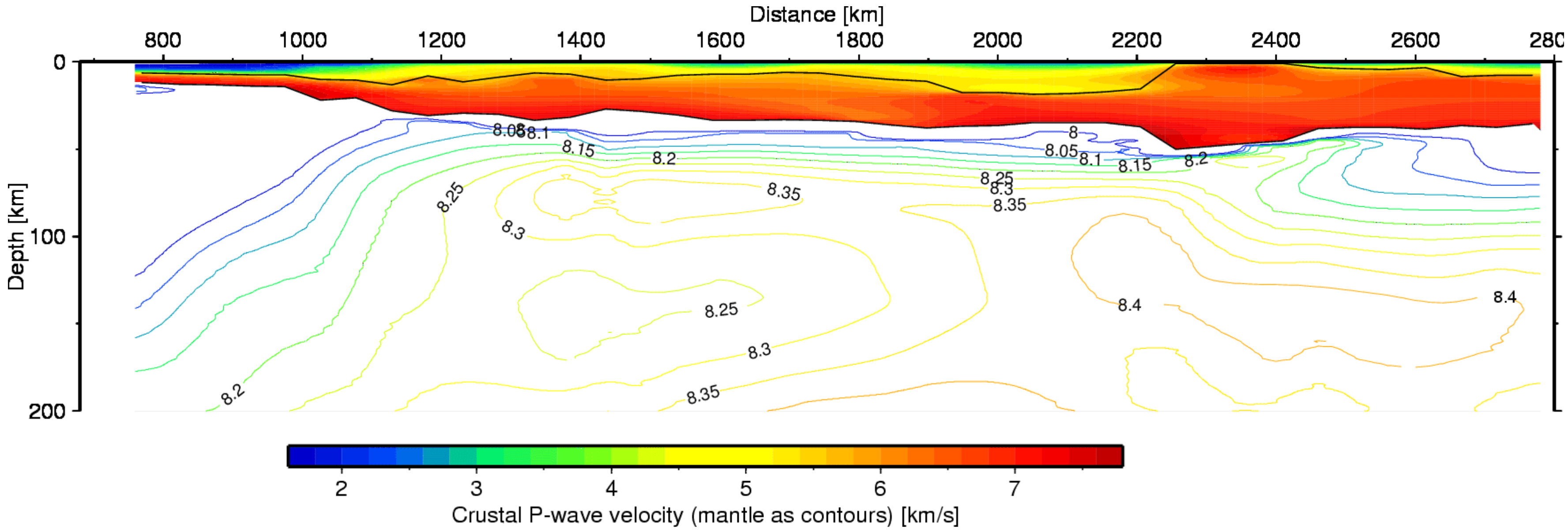

From Levshin et al. (2007)

# Combining Crust and Upper Mantle Models

The new crustal model, **BARENTS50** (Ritzmann et al., 2007)
has been combined with the new
crust and upper mantle model, **BARMOD** (Levshin et al., 2007)
into a new hybrid
crust and upper mantle model, **BARENTS3D**,
available for download from the NORSAR web site
http://www.norsar.no/

# A 1D transect thru the BARENTS3D model

- A west-east transect through the new combined crust and upper mantle models at around 72°N
- Crustal velocities are displayed by color shading and  mantle velocities by contours, respectively
- The two black lines indicate the basement and Moho



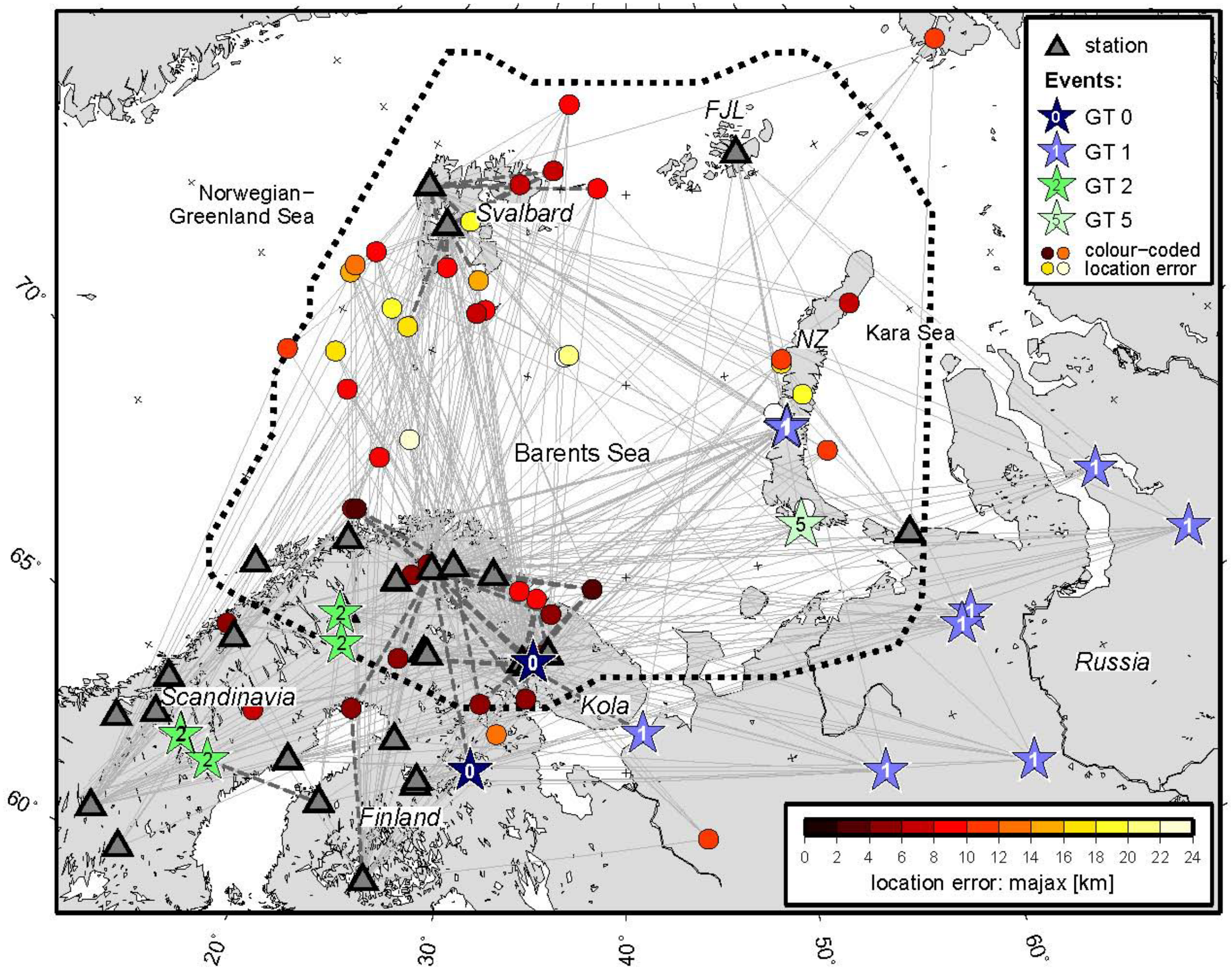
# Testing the model for travel times

Selected reference GT ("Ground Truth") events (stars, circles)

Seismic stations (triangles)

Pn and P (light grey) travel paths

Pg (dark grey, dashed) travel paths




**From Maercklin et al. (manuscript)**

# Testing the model for travel times

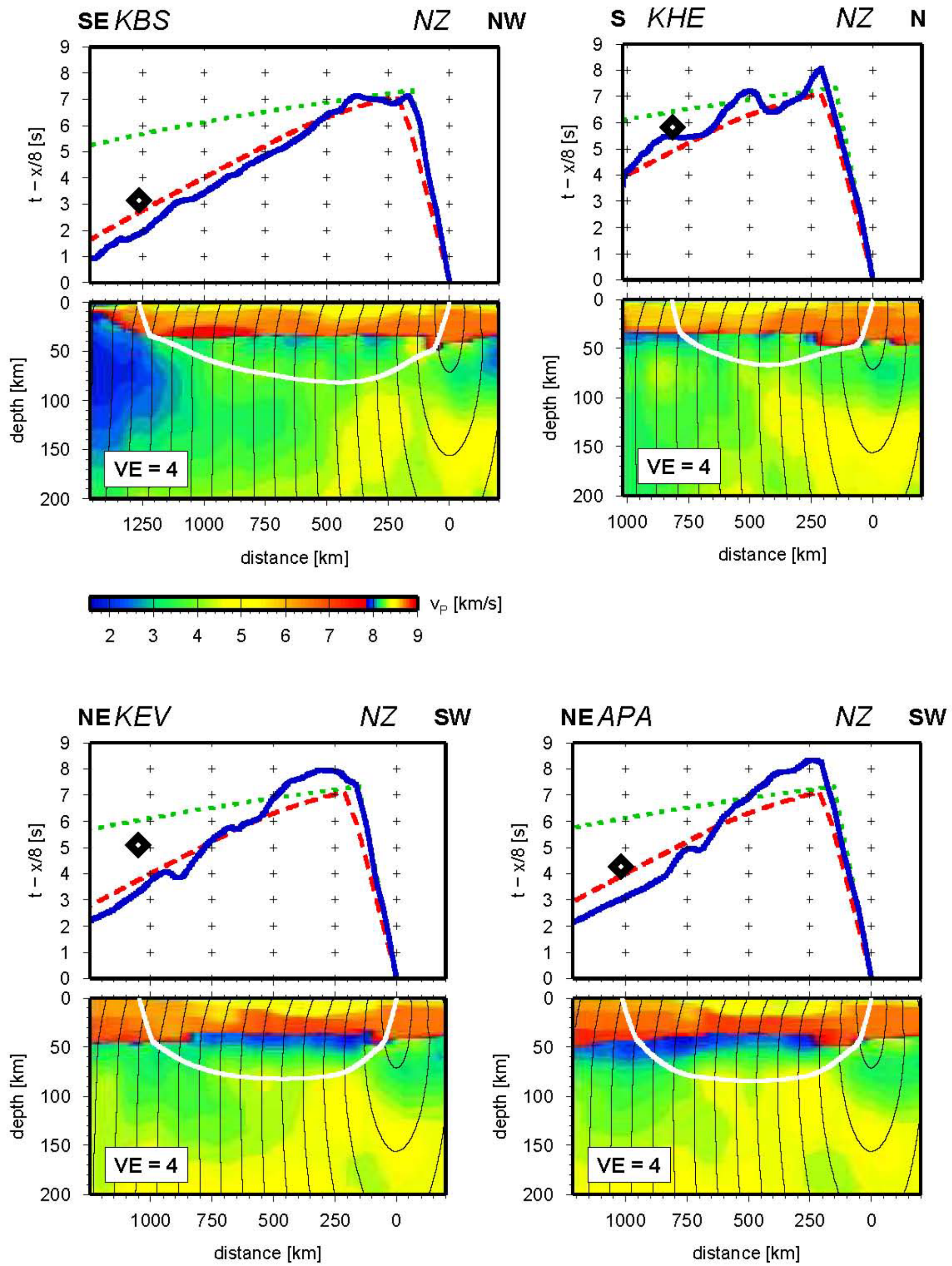
P velocity transects and corresponding wave fronts (black, 10 s interval)

Ray paths (white)

Travel time curves (blue)

originating from the former central Novaya Zemlya (NZ) nuclear test site

to the four stations KBS, KHE, KEV, and APA




From Maercklin et al. (manuscript)

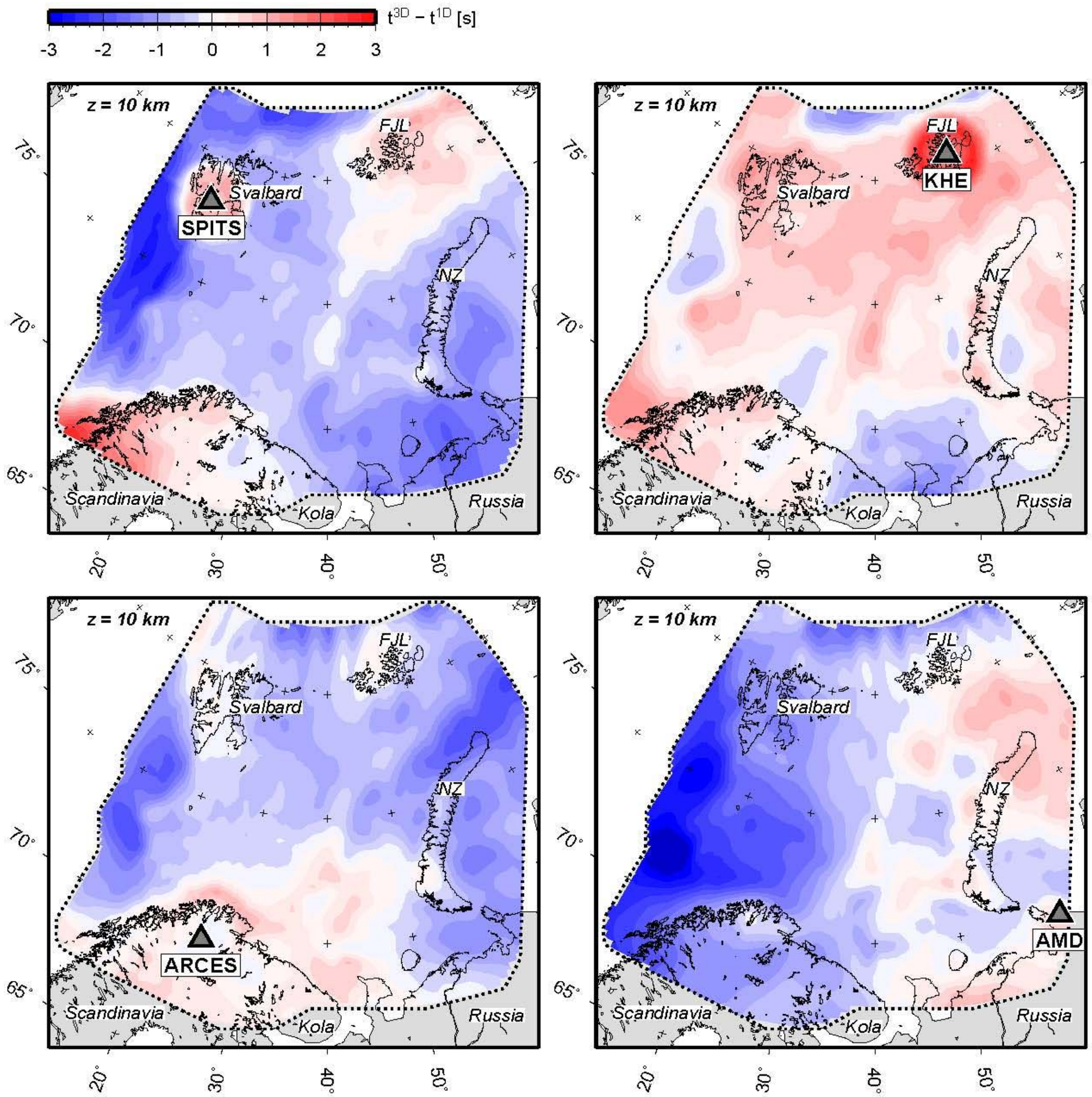
# Testing the model for travel times

Source specific station corrections (SSSCs)

from the 3-D model (P velocities)

For four stations (triangles) within the model region and for

events located at 10 km depth




From Maercklin et al. (manuscript)

# So what is the next step?

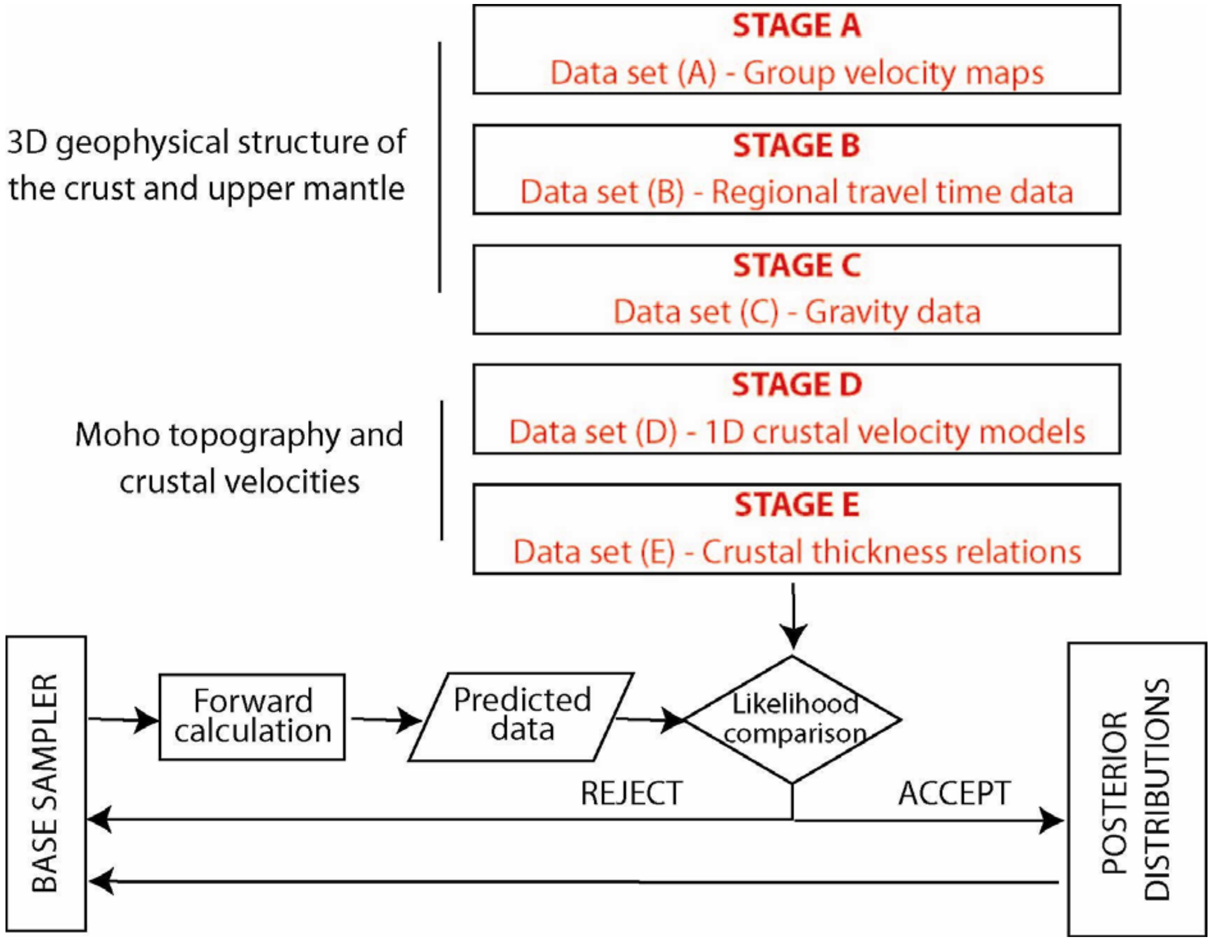
- We have a greatly improved model for this region and we still want to improve it. Why?
- We still have lots of unused geophysical data with great potentials for improving the model
- The Markov Chain Monte Carlo (MCMC) approach offers a solution for this
- A high-velocity region not seen in gravity data poses a scientific challenge that this approach may help to solve
- The MCMC approach allows a critical examination of the tradeoffs among model parameters
- This region is well covered with different types of data and is therefore ideal for developing further the MCMC methodology
- Improved travel times are useful for many additional purposes

# The new project (just starting):

## Development and Tuning of a 3-D Stochastic Inversion Methodology to the European Arctic

Schematic diagram of the stochastic Markov Chain Monte Carlo (MCMC) inversion methodology.

Shows the algorithm for a multiple-stage problem as intended in this study.



# The Markov Chain Monte Carlo (MCMC) approach

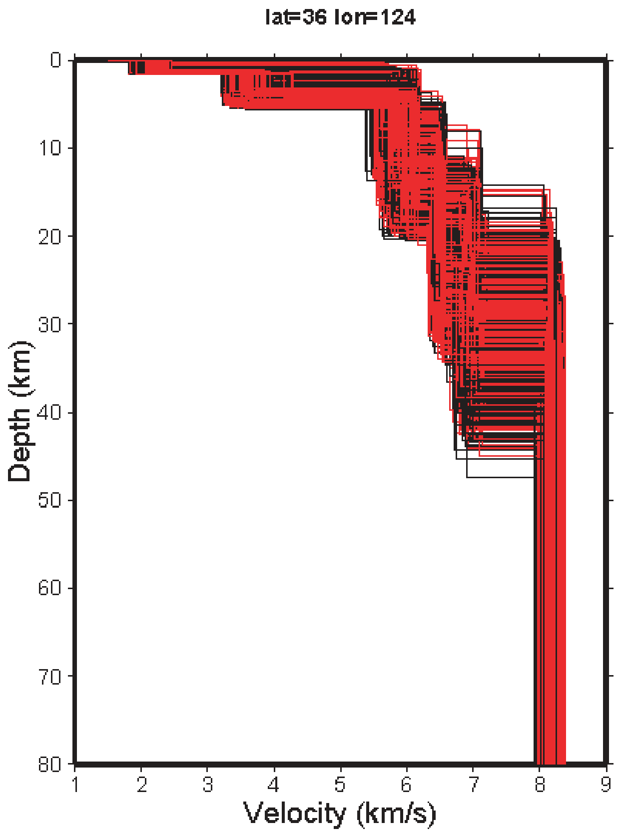
A comparison of prior (left) and posterior (right) model profile distributions for a location in the Yellow Sea-Korean Peninsula region.

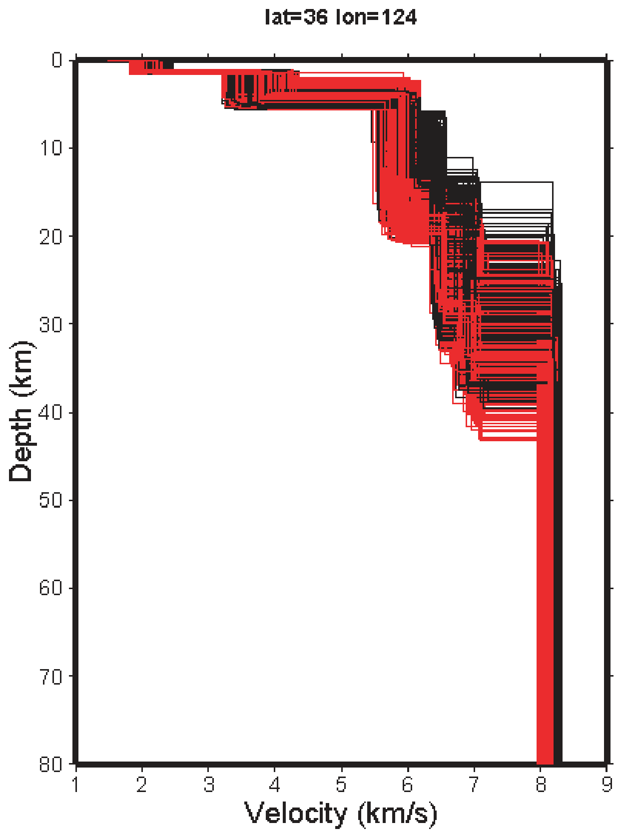
Red and black lines show models from each Markov Chain

The range of model parameters has decreased significantly between prior and posterior

(note, for example, the sediment depths in the two profiles)

indicating the narrowing range of acceptable models.

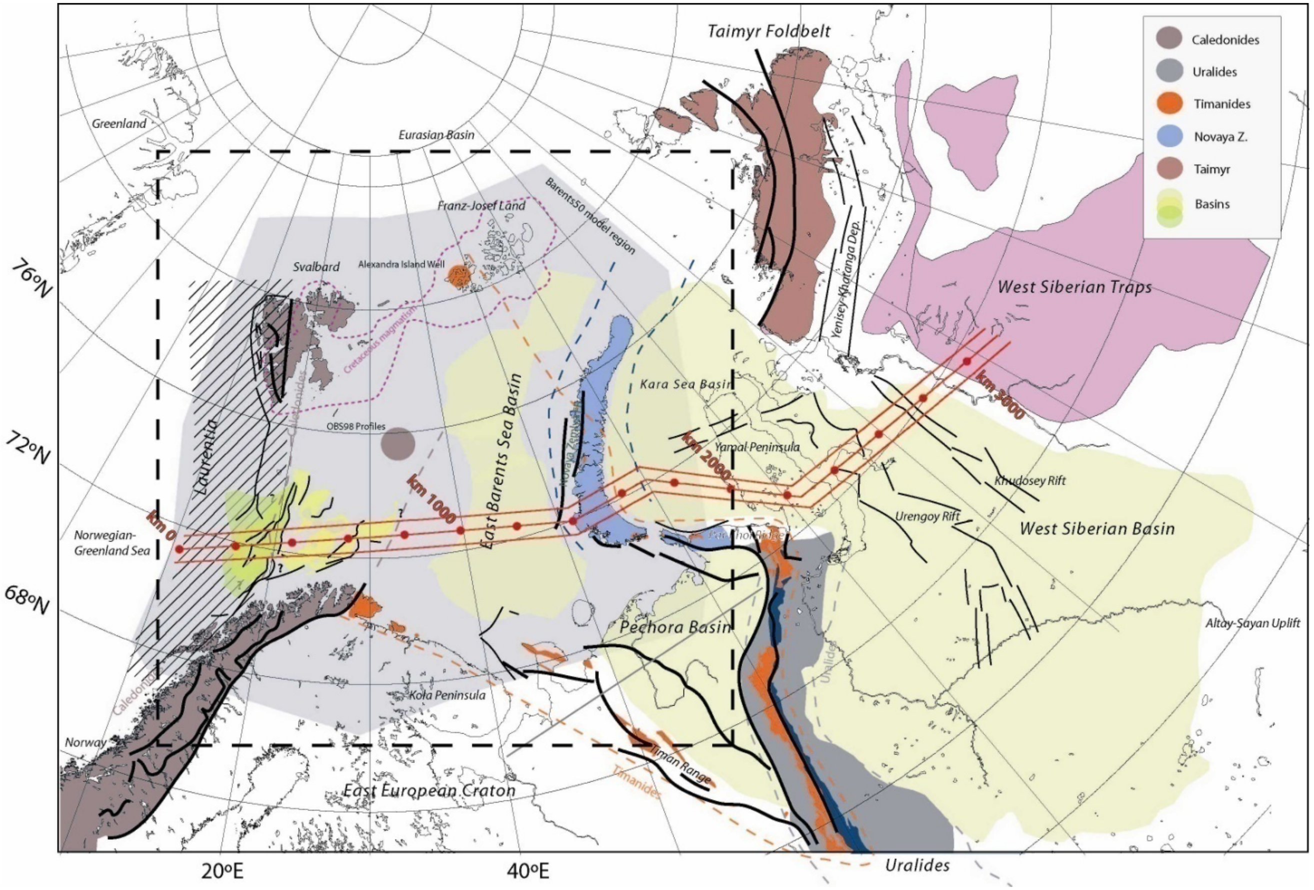



**From Pasyanos et al. (2006)**

# Geologic setting for the new study

- The greater Barents region with main geological features.
- The black dashed box indicated the target region for this study.
- Thick red lines show the location of a transect (next slide).

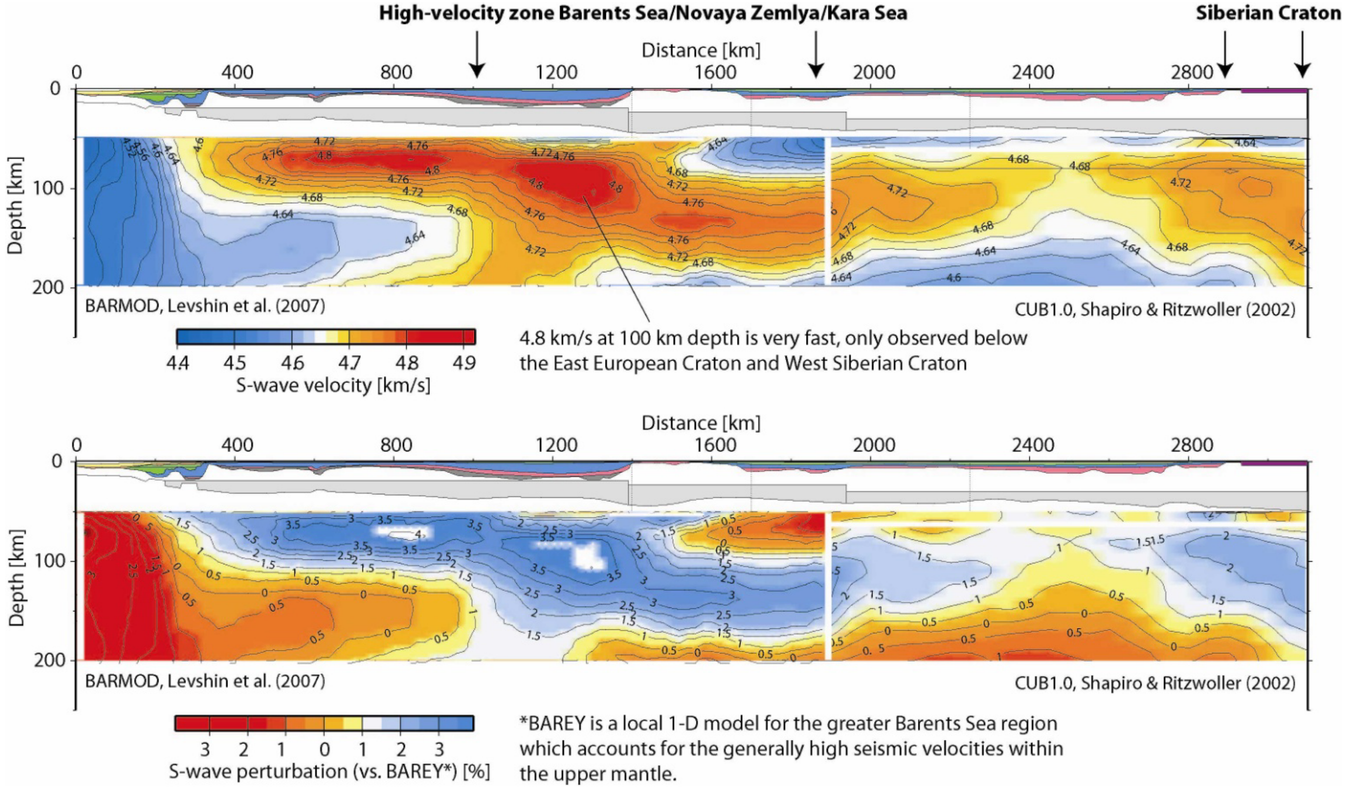



From Ritzmann & Faleide (2008)

# West-East transect from the Norwegian-Greenland Sea (left) across Novaya Zemlya (km 1500) to the Siberian Craton (right).

Upper panel: absolute S-wave seismic velocities

Lower panel: velocities relative to the local 1D model BAREY.




It was first assumed that the eastwardly dipping high mantle velocities could be a slab-like structure (Levshin et al., 2007).

However, seismic velocity anomalies within the upper mantle are predominantly caused by temperature variations, rather than compositional effects, which makes it more likely that the eastern Barents Sea is underlain by a cold cratonic keel similar to the Siberian Craton).



**From Ritzmann & Faleide (2008)**

# MCMC model development

- First, a starting model is needed (from previous study)
- Then a base sampler is needed; to select a model given the model parameterization and set of constraints
- Then we conduct sequential comparisons with sets of independent data, such as
  - Group velocity data
  - Regional travel time data
  - Gravity data
  - 1D crustal velocity profiles
  - Regionally dependent thickness relations
- Uncertainty considerations are essential
  - Assessing uncertainties on both the seismic models and on observables
  - Calculate and check travel times for posterior models
  - Consistency between predicted observables and input data

# Conclusions

- Previous study:
  - The new 3D model is a great improvement over earlier 1D models
  - Travel times can now be calculated with greater precision
  - Events can thereby be located more accurately
- New study:
  - Simultaneous inversion with different types of data
  - The MCMC approach is also offering an advanced treatment of uncertainties
  - Results will be testable and applicable
  - Will provide improved geologic understanding, in particular of ”incompatabilities” between travel times and gravity