TOWARDS A COMPREHENSIVE SEISMIC MODEL
(OF EUROPE)

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in collaboration with

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Challenges and Frontiers

for

Seismic Tomography

1. **Multi-scale nature of the Earth**
2. **The Earth model zoo**
3. **Bandwidth limitation**
4. **Multi-physics inversion**

CHALLENGES AND FRONTIERS

FOR

SEISMIC TOMOGRAPHY

1. **Multi-scale nature of the Earth**
   - Small-scale structure affects images of large-scale properties.
   - Example: crust contaminates anisotropy.
   - Crust & mantle must be resolved simultaneously.

2. **The Earth model zoo**
3. **Bandwidth limitation**
4. **Multi-physics inversion**

Challenges and Frontiers

for

Seismic Tomography

1. **Multi-scale nature of the Earth**
2. **The Earth model zoo**
   - Plethora of Earth models: different methods, data, scales, ...
   - Various levels of (dis-)agreement
   - ➢ Only image limited aspects of the Earth.
   - ➢ No unifying model, or inversion machinery to produce one.
3. **Bandwidth limitation**
4. **Multi-physics inversion**

CHALLENGES AND FRONTIERS

FOR

SEISMIC TOMOGRAPHY

1. Multi-scale nature of the Earth
2. The Earth model zoo
3. **Bandwidth limitation**
   - High frequencies in traveltime tomography, ...
   - ..., intermediate frequencies in waveform inversion, ...
   - ➢ Limited bandwidth limits tomographic resolution.
   - ➢ Combine both data and methods to improve resolution.
4. Multi-physics inversion

Challenges and Frontiers

for

Seismic Tomography

1. **Multi-scale nature of the Earth**
2. **The Earth model zoo**
3. **Bandwidth limitation**
4. **Multi-physics inversion**
   - Go beyond seismic data to learn about the Earth.
   - Incorporate gravity.
   - Incorporate prior constraints from mineral physics.
   - ...

COMPREHENSIVE EARTH MODEL

ETH, CSCS, U. Utrecht, LMU, U. Rennes, ANU, ...

One Earth model on many scales.
Constrain velocities, anisotropy, Q, ...
Data on wide range of spatio-temporal scales.

COMPREHENSIVE EARTH MODEL

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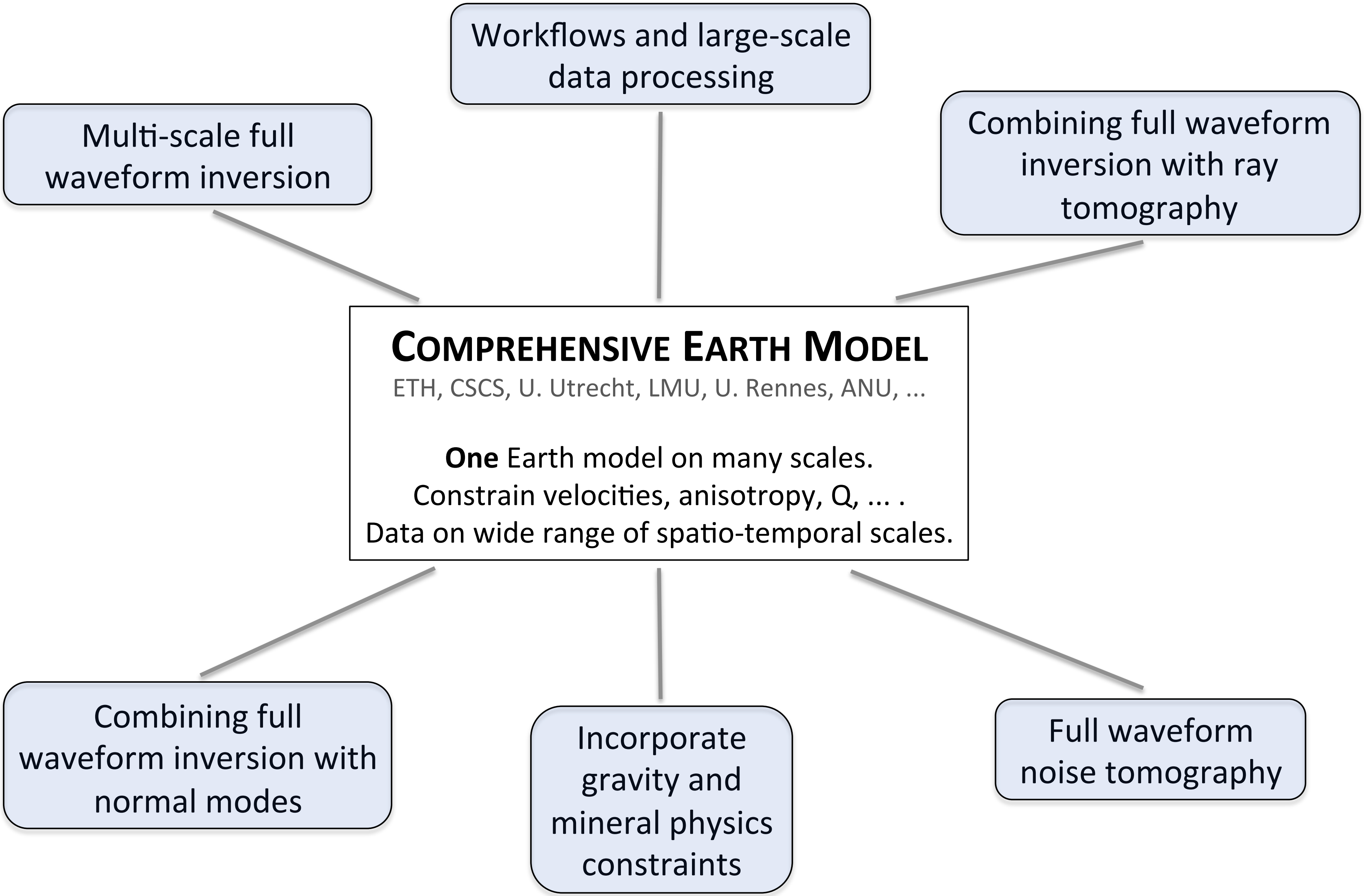
... will not be finished tomorrow.

Necessary technology needs to be developed today.


Workflows and large-scale data processing
Multi-scale full waveform inversion
Combining full waveform inversion with ray tomography
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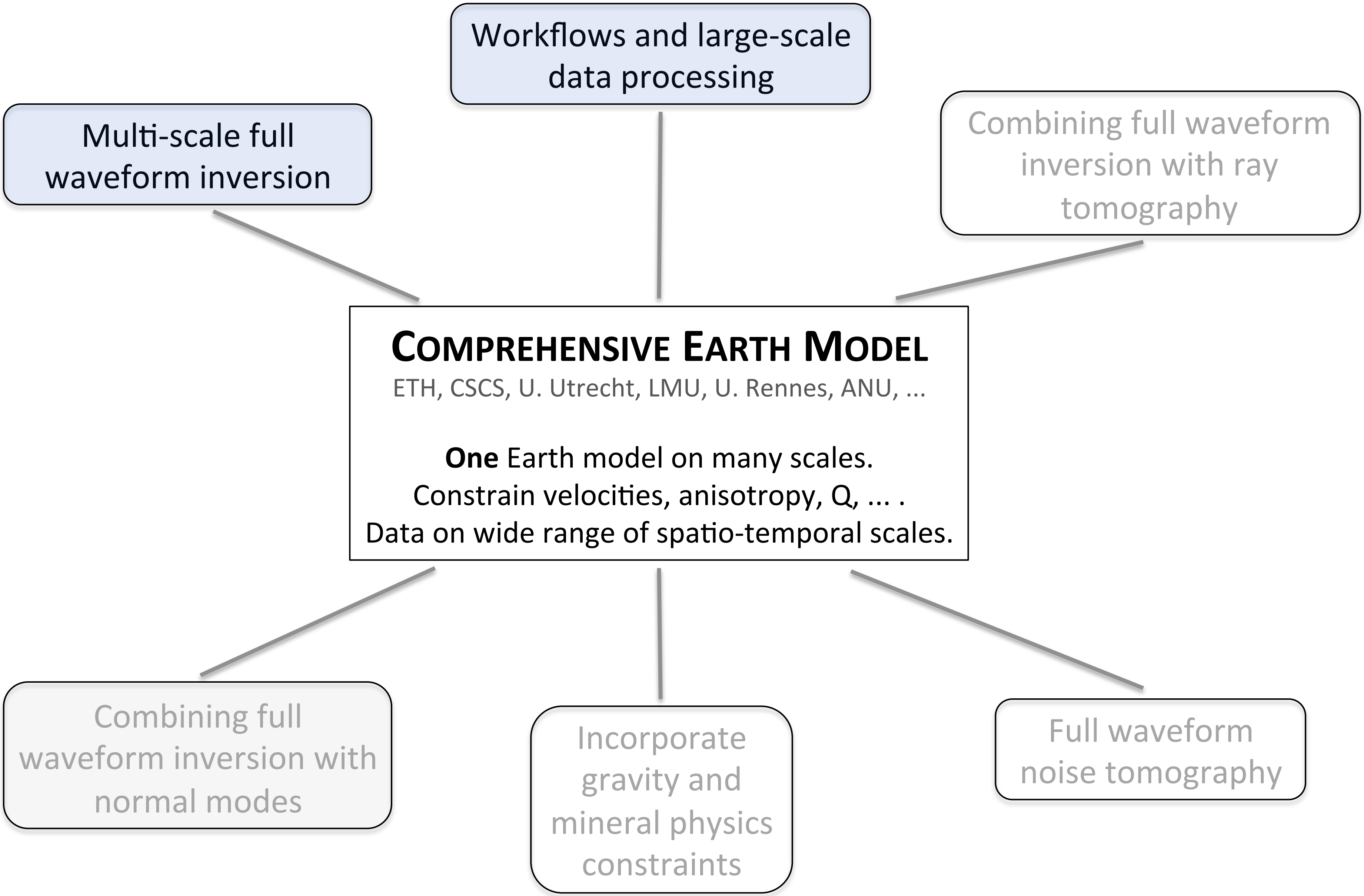
Full waveform noise tomography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MULTI-SCALE FULL WAVEFORM INVERSION

jointly resolving crustal and mantle structure

Fichtner et al., GJI 2013

CHALLENGES

- **combine all available seismic wave types** (full waveform inversion)
- **combine data on different spatio-temporal scales**
  - global-scale longer-period (>30 s) waves → upper-mantle structure
  - regional-scale shorter-period (<30 s) waves → crustal structure
  - …

CHALLENGES

- combine all available seismic wave types (full-waveform inversion)
- combine data on different spatio-temporal scales
  - global-scale longer-period (>30 s) waves → upper-mantle structure
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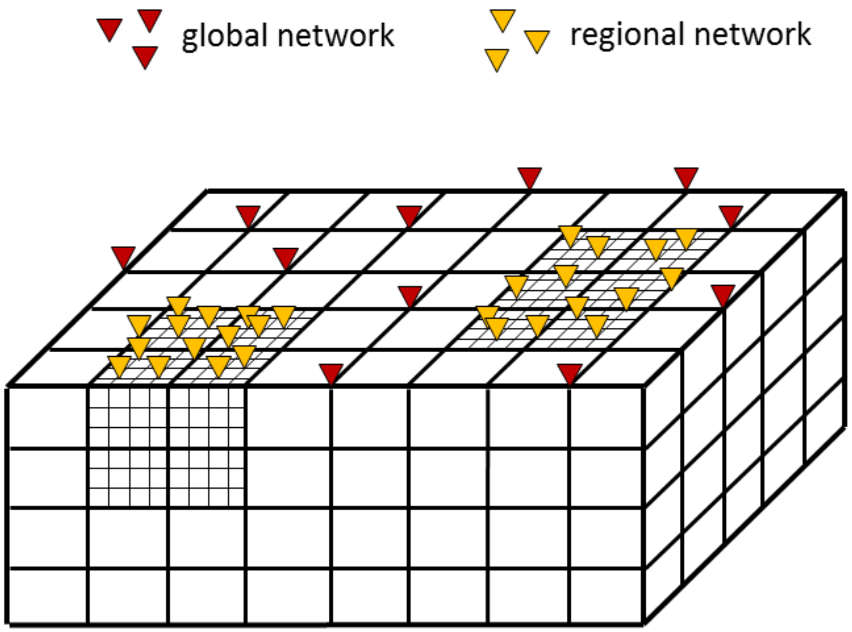
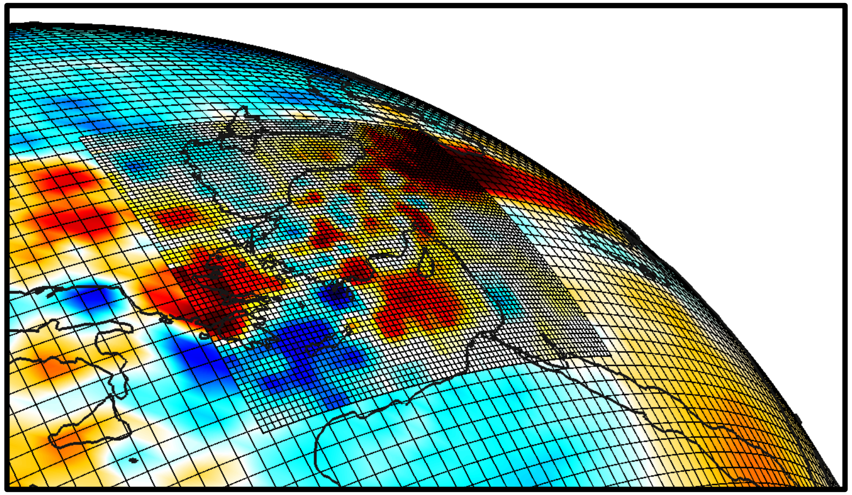


➢ **fully numerical wave propagation**
  - strongly heterogeneous lithosphere

➢ **time step problem**
  - regional grid refinement
  - $\Delta t_{max} \propto \Delta x_{min}$ (CFL condition)
  - small-scale data → extreme computational requirements

Domain Decomposition & Multiple Forward Problems

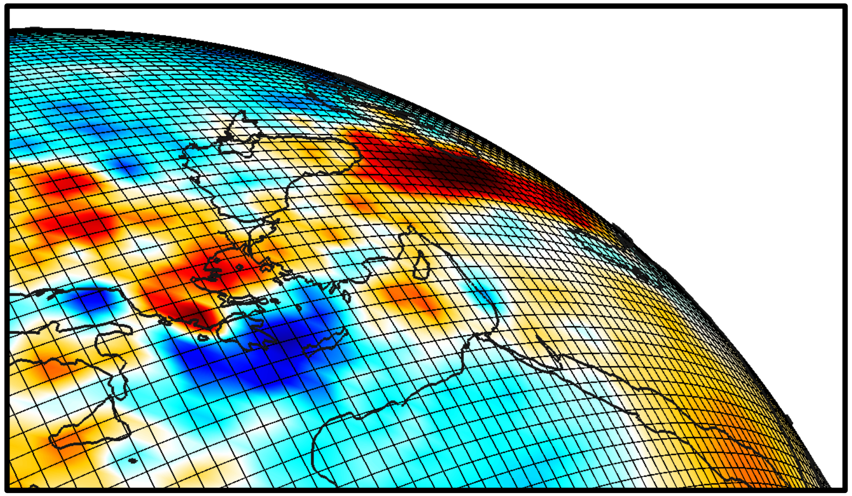


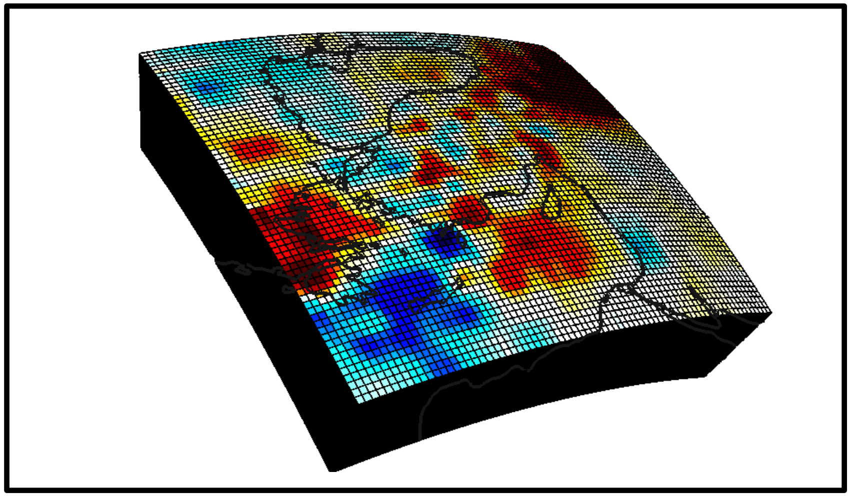
coarse long-wavelength model

- large volume
- large grid size and time step

fine-scale short-wavelength model

- small volume
- small grid size and time step





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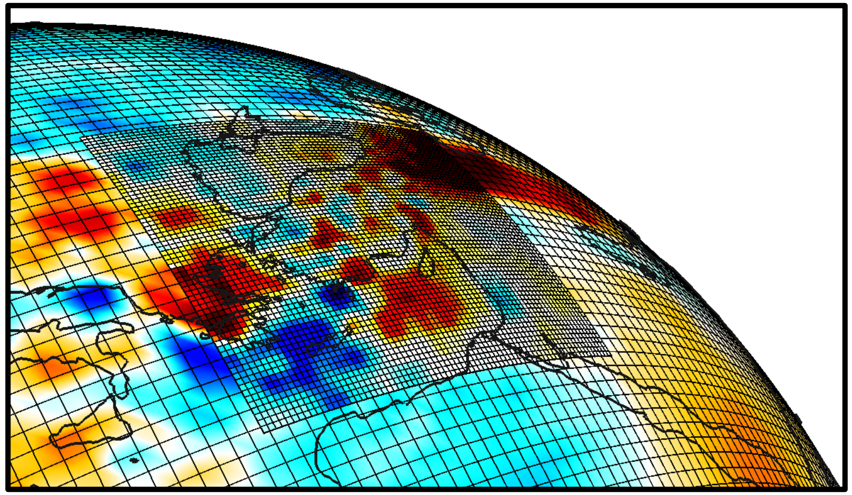
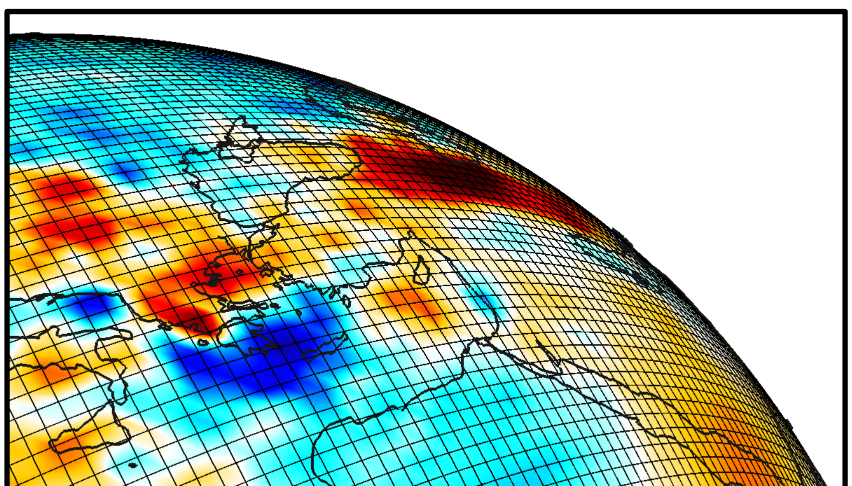


detailed

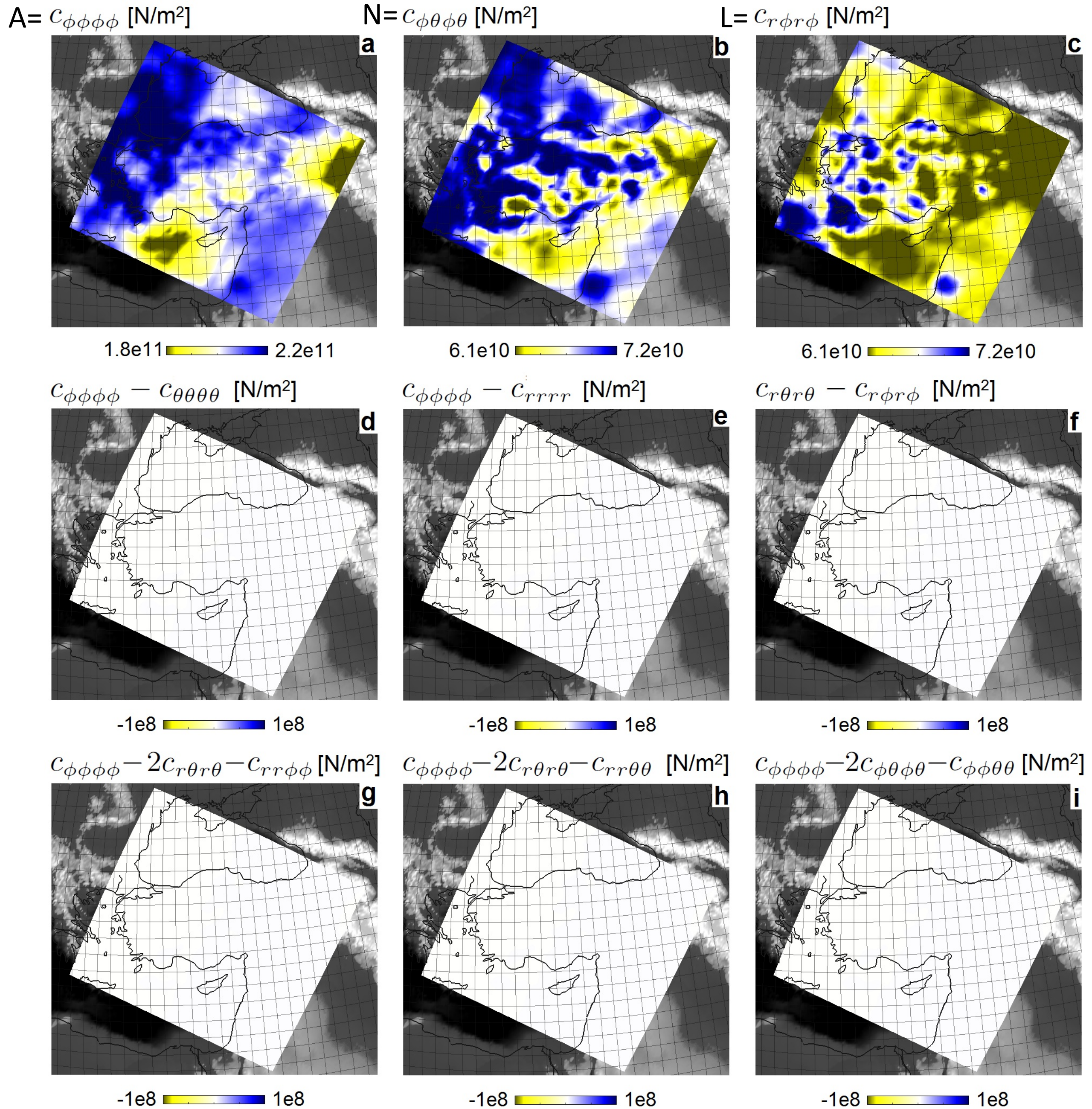
smooth



- **upscaling**
  - 3D non-periodic homogenisation
    (Capdeville et al., 2010; Guillot et al., 2010)
  - induces apparent anisotropy

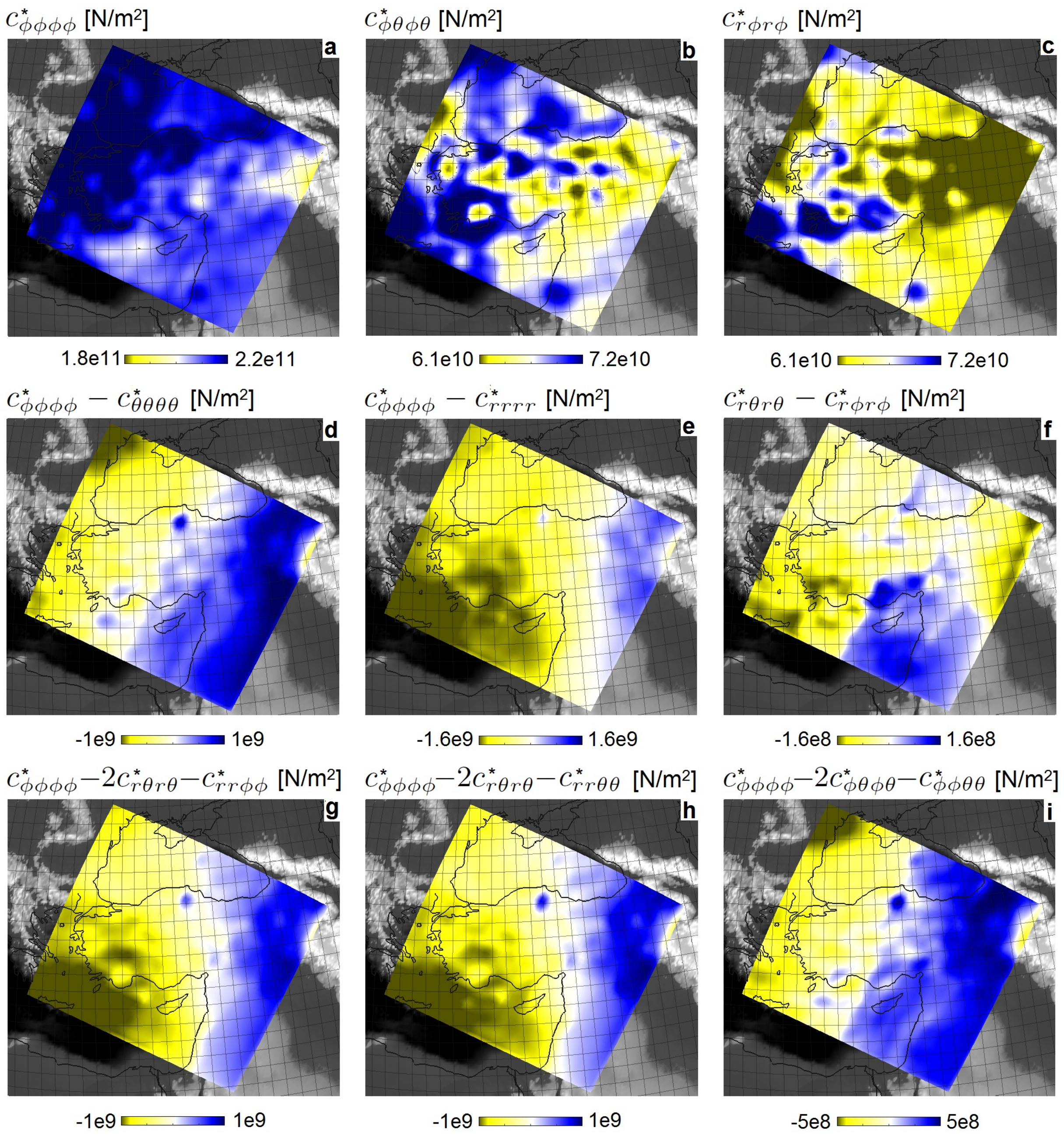
DOMAIN DECOMPOSITION & MULTIPLE FORWARD PROBLEMS

original

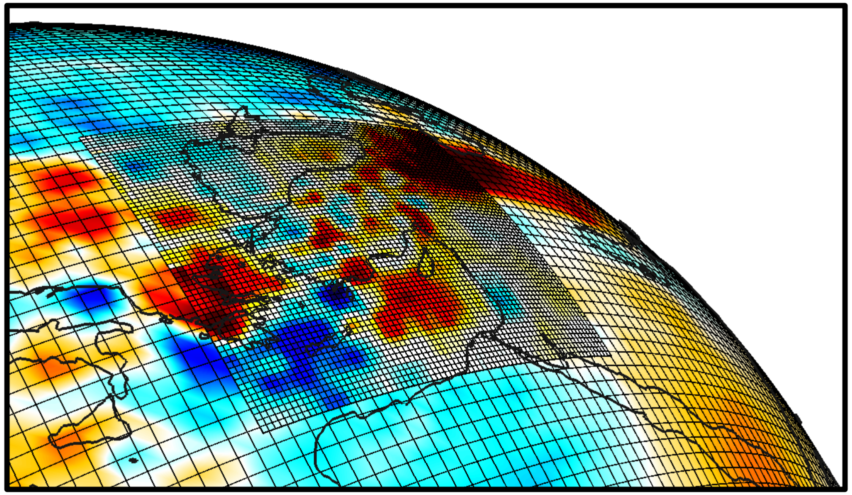


DOMAIN DECOMPOSITION & MULTIPLE FORWARD PROBLEMS

homogenised, smooth long-wavelength equiv.



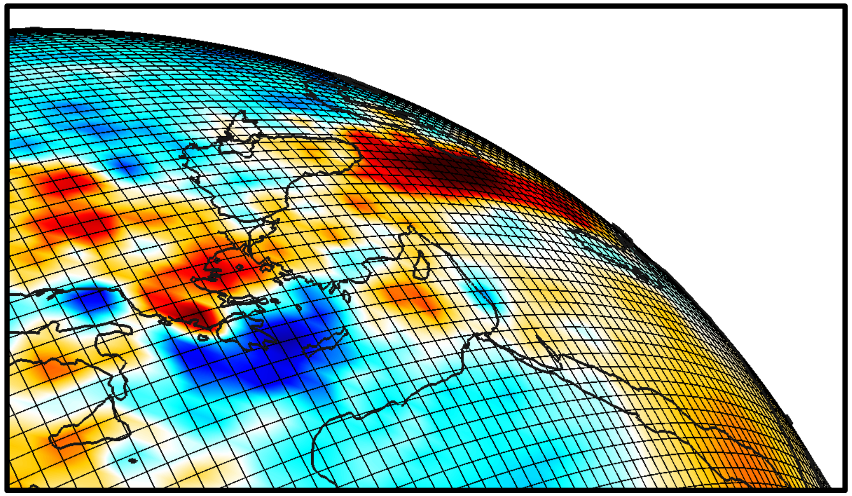
Domain Decomposition & Multiple Forward Problems



detailed

- **interpolation**

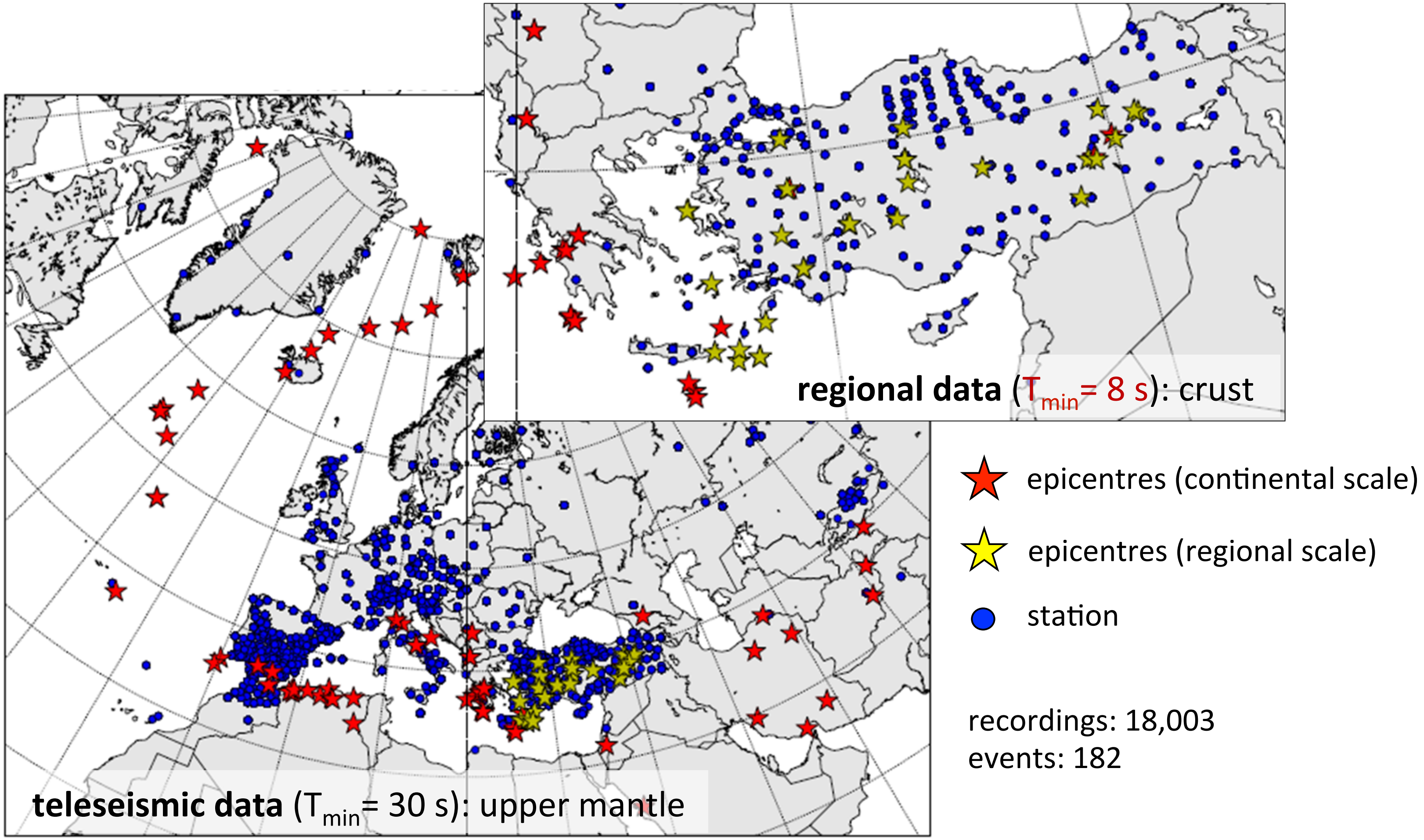
smooth



upscaling & interpolation

iterative joint inversion
teleseismic & regional data for
shallow and deep structure

MULTI-SCALE DATA - MULTI-SCALE INVERSION



recordings: 18,003
events: 182

Simultaneous inversion of:

- longer-period waves on the continental scale (upper mantle)
- shorter-period waves on smaller scales (crust)

Technical details

Forward problem

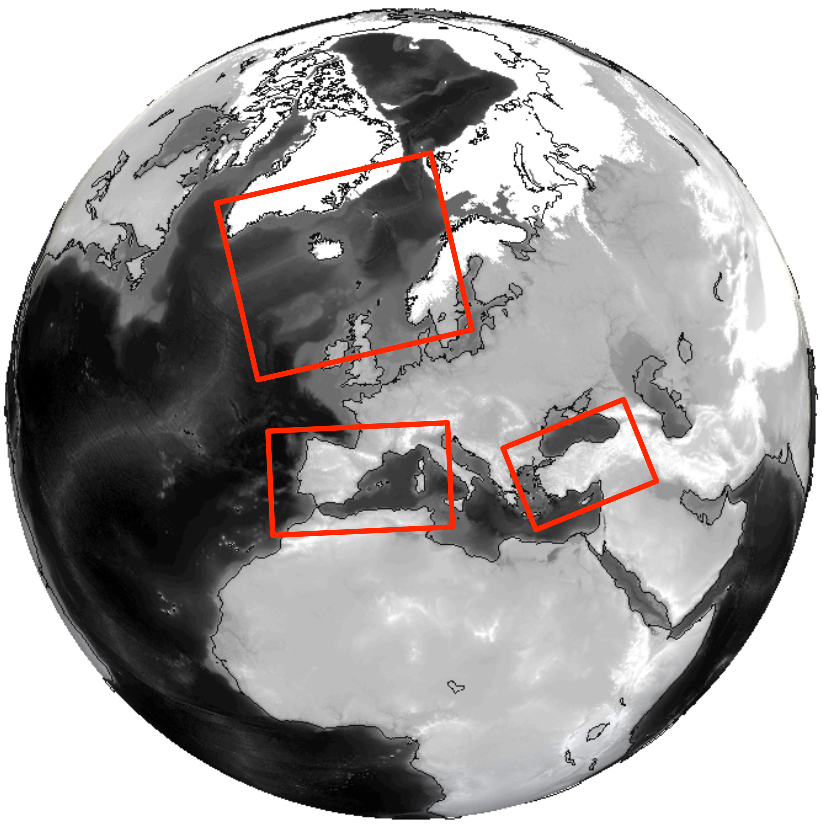
- Spectral elements (SES3D)

Inversion

- Fréchet kernels via adjoint techniques
- Conjugate gradient optimisation

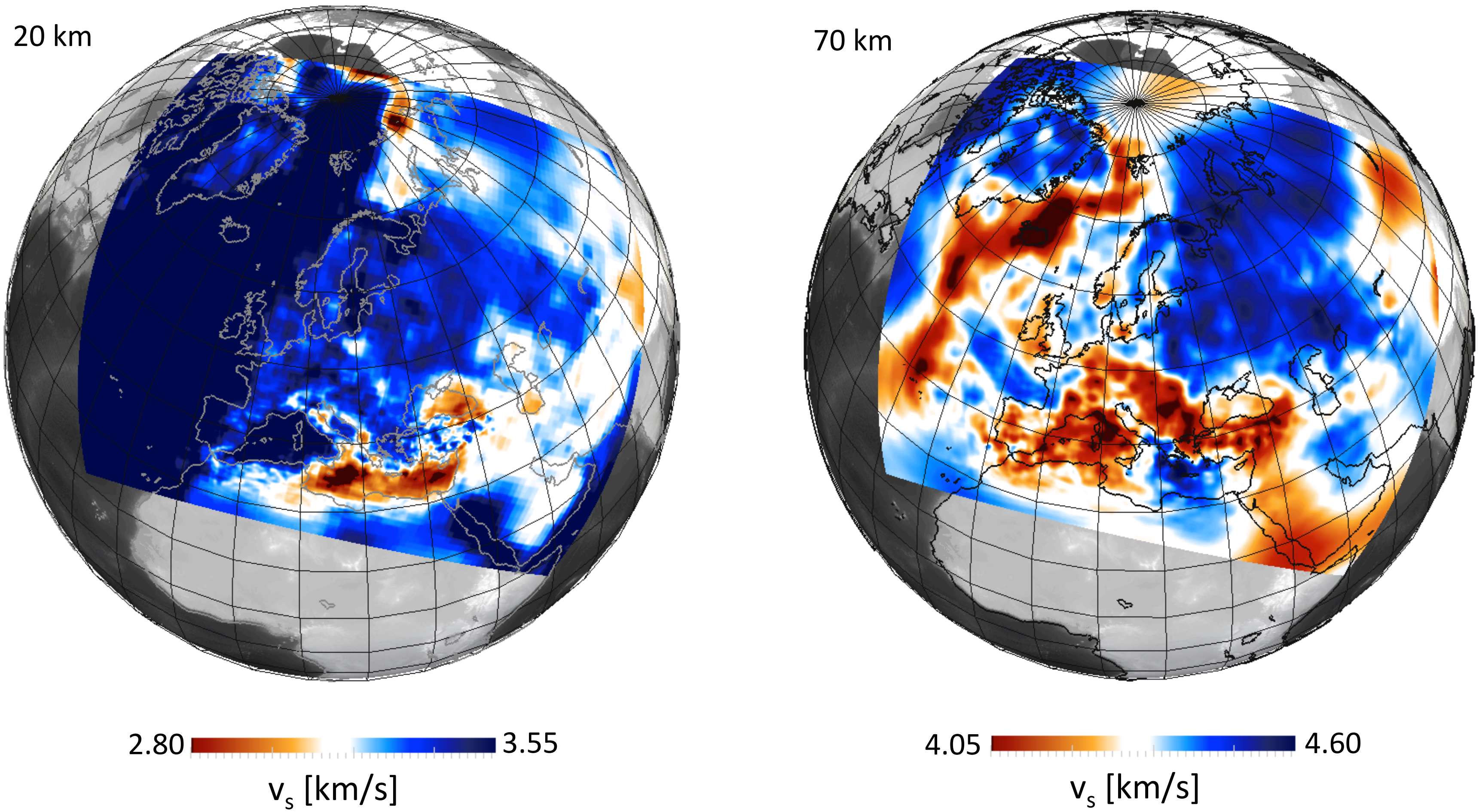
Embedded sub-regions (higher frequencies)

- Anatolia
- North Atlantic
- Western Mediterranean



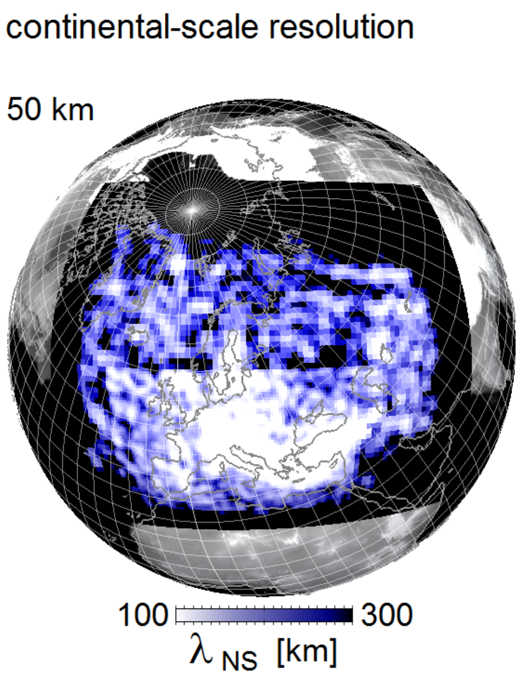
Sub-regions for higher-frequency modelling and inversion

THE CURRENT MODEL **M52** (ISOTROPIC S VELOCITY, 52 ITERATIONS)



Resolution Analysis

- direction- and position-dependent resolution length
    - computed via second-order adjoints (Fichtner and Trampert, 2011a,b)
    - continuous version of point-spread function



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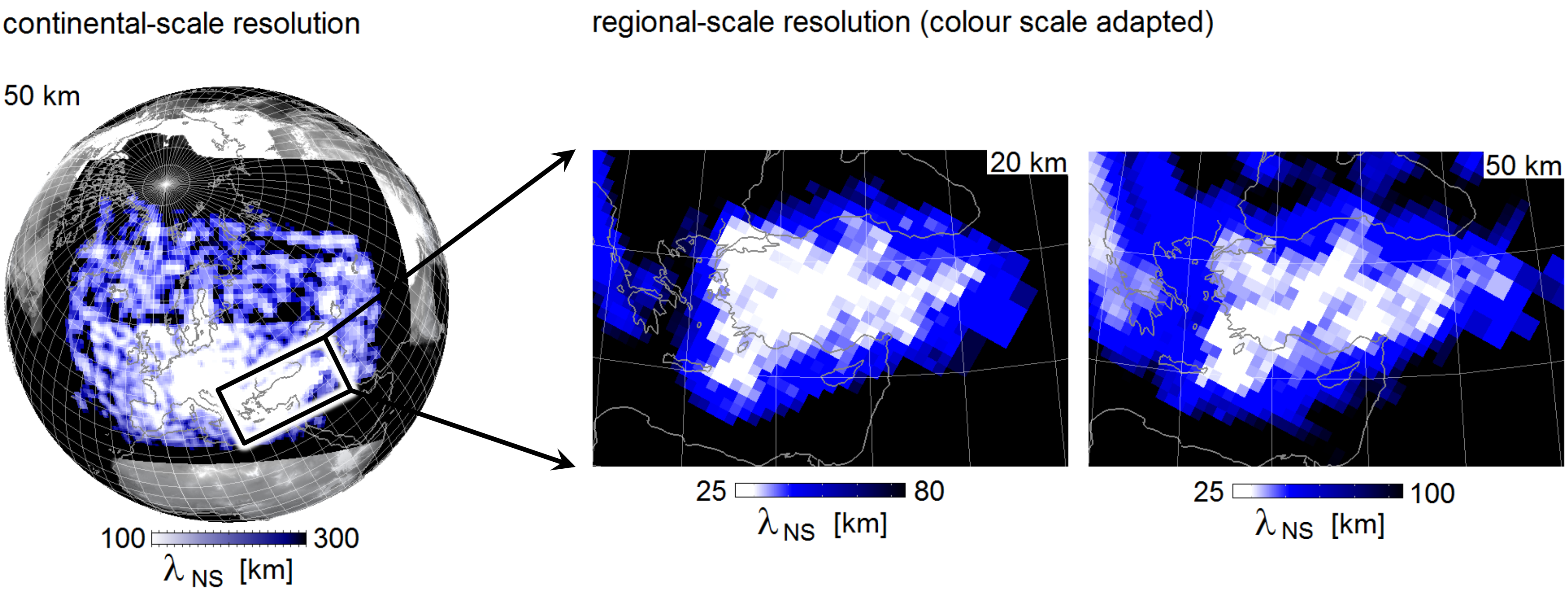
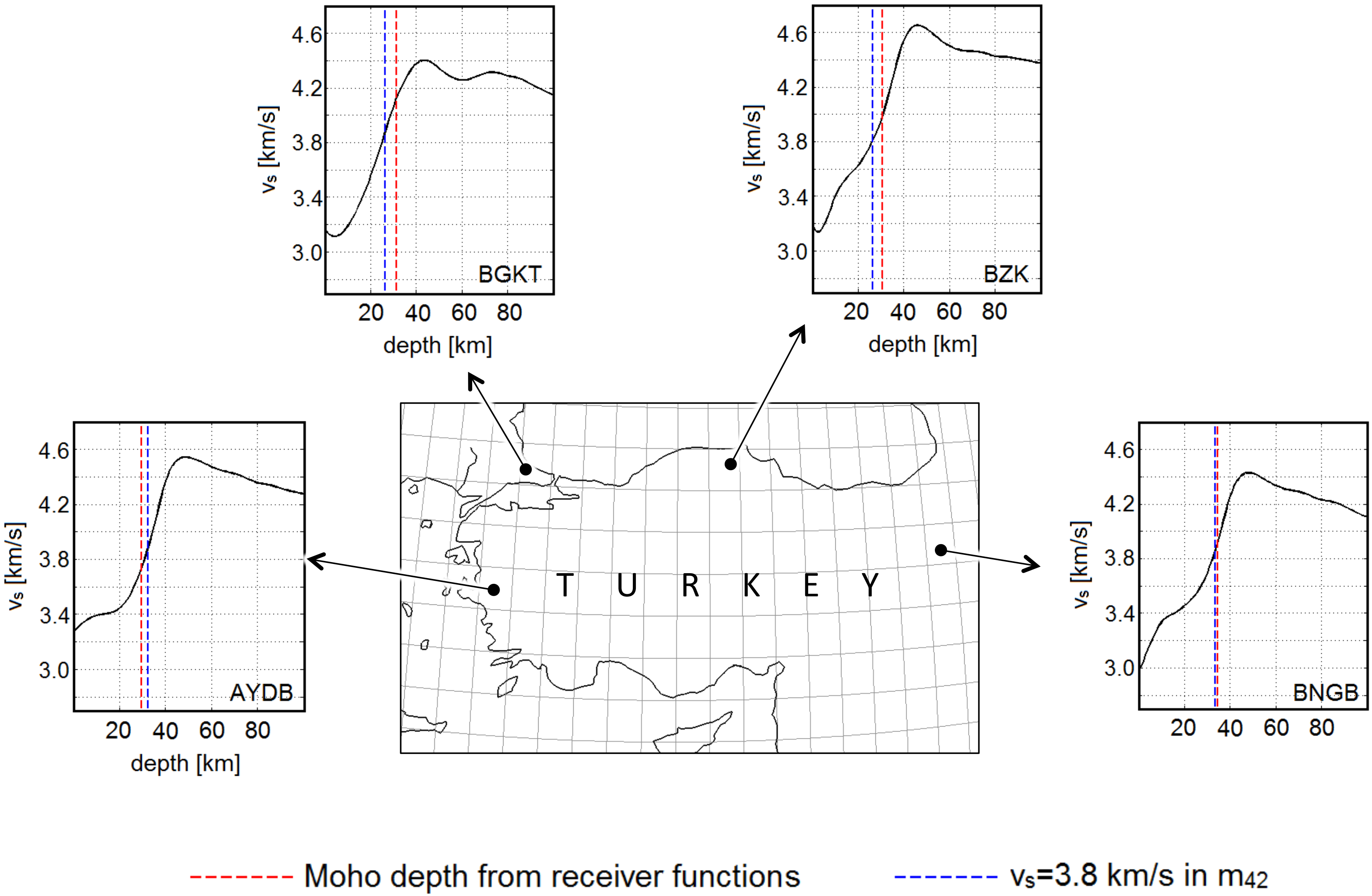
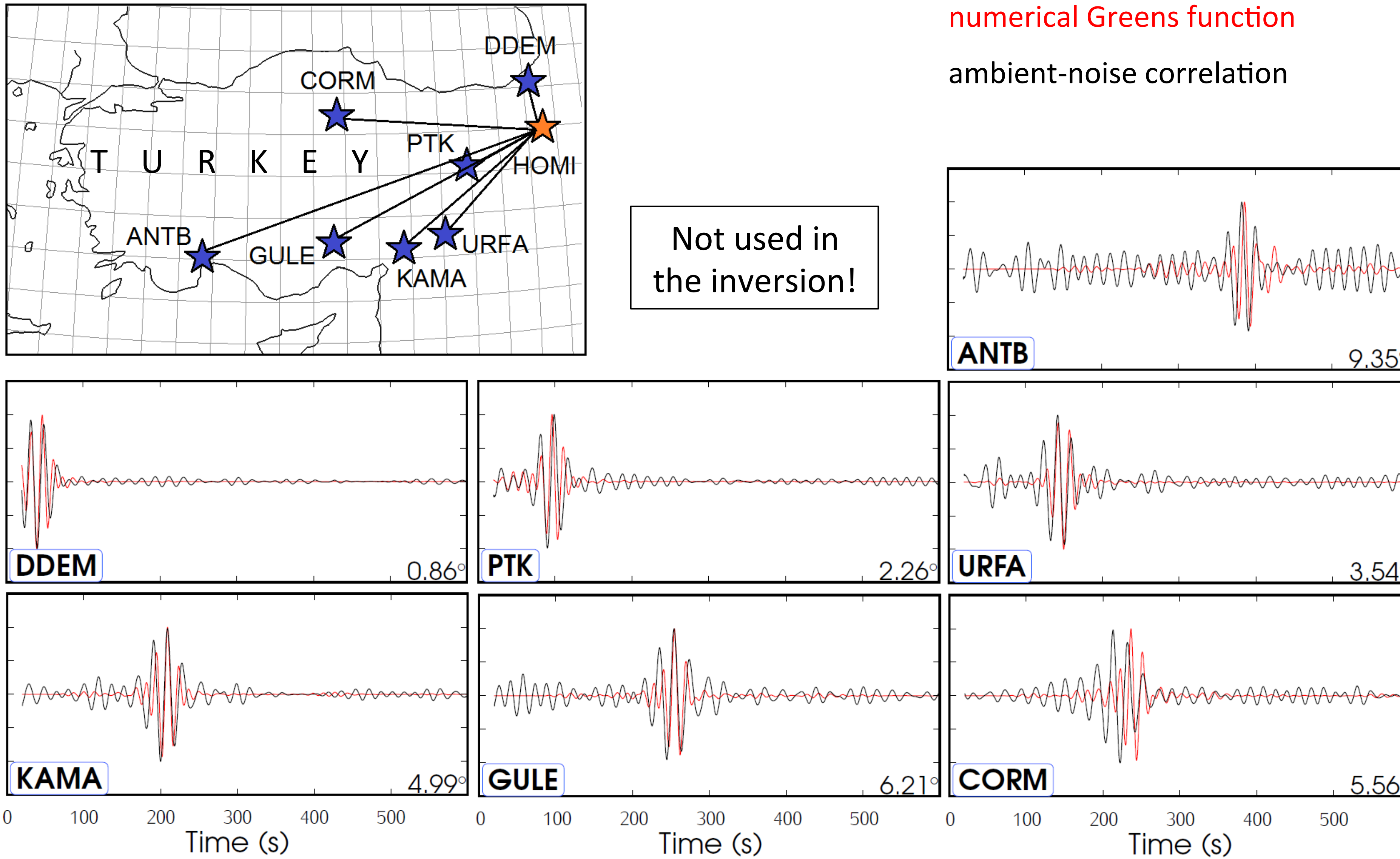


Validation – Comparison To Receiver Functions (Vanacore et al., 2012)

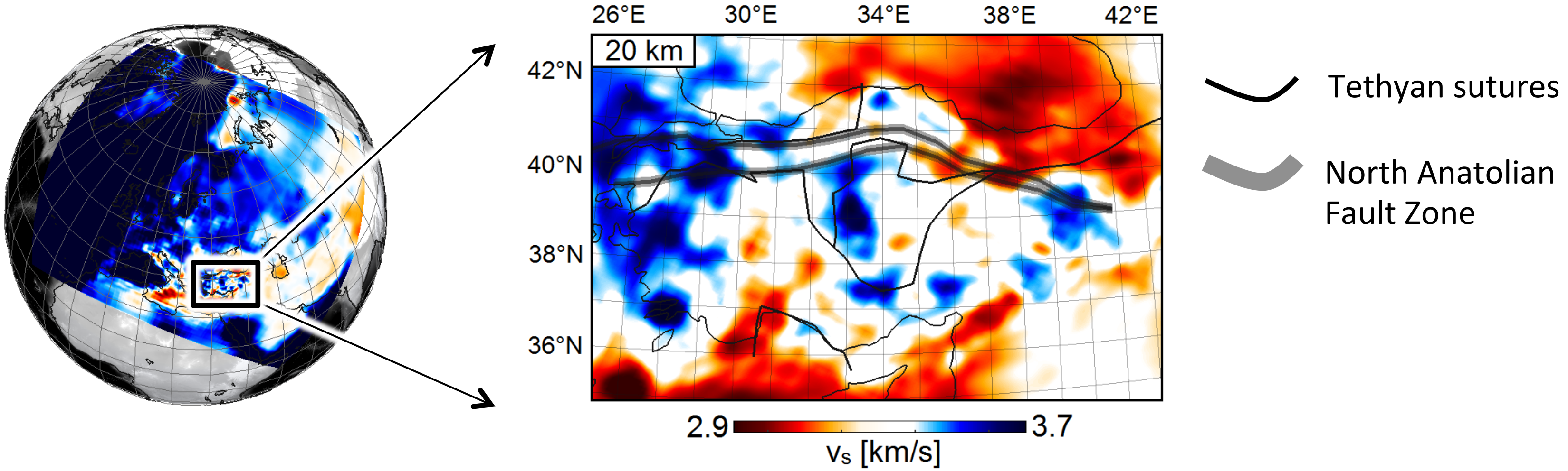


Validation – Match With Noise Correlations



dominant period: 10 s

Anatolian Region – Crust



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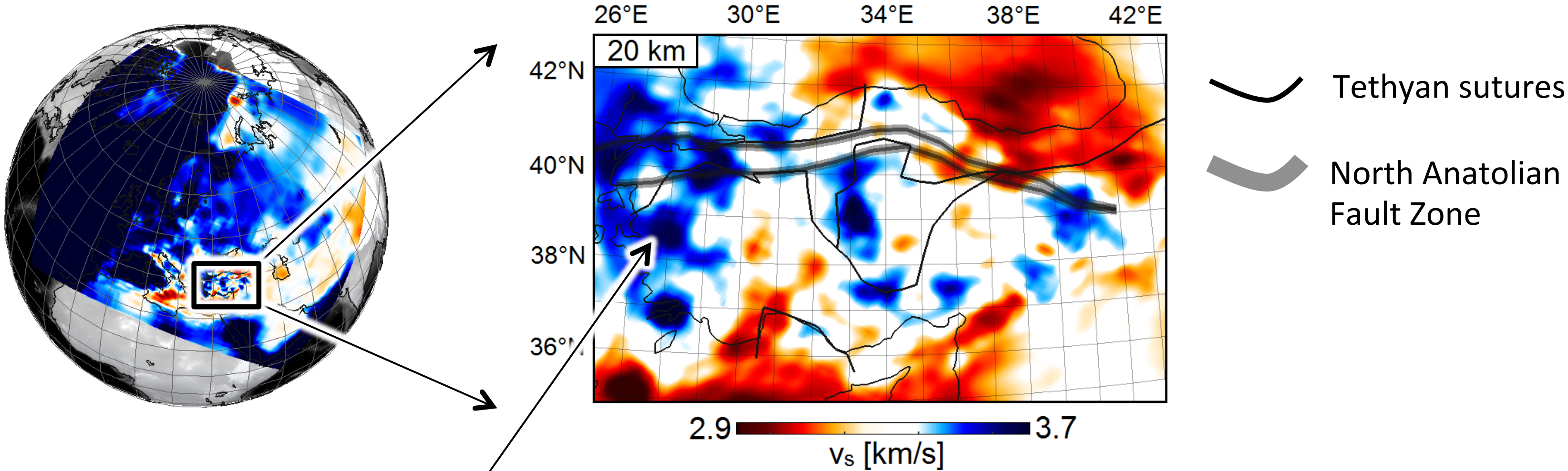
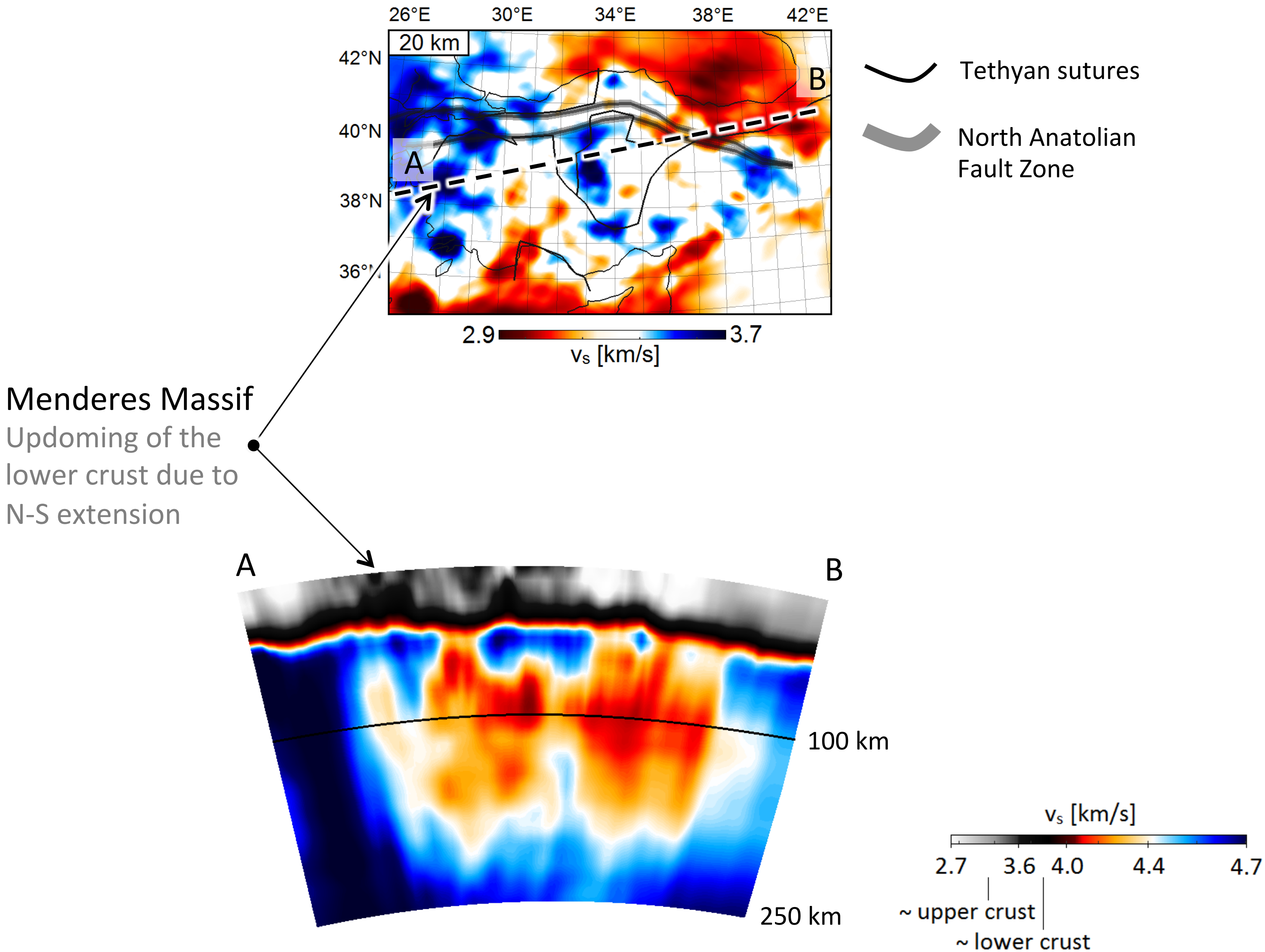


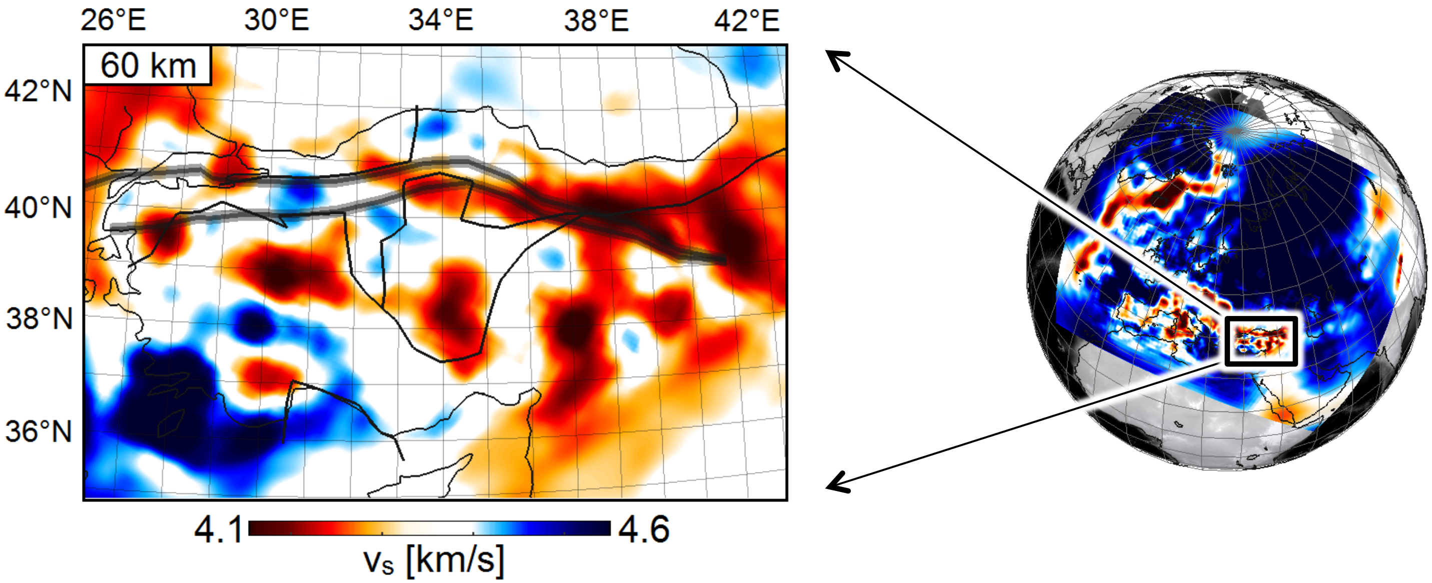
Menderes Massif

Updoming of the lower crust due to N-S extension

ANATOLIAN REGION – CRUST



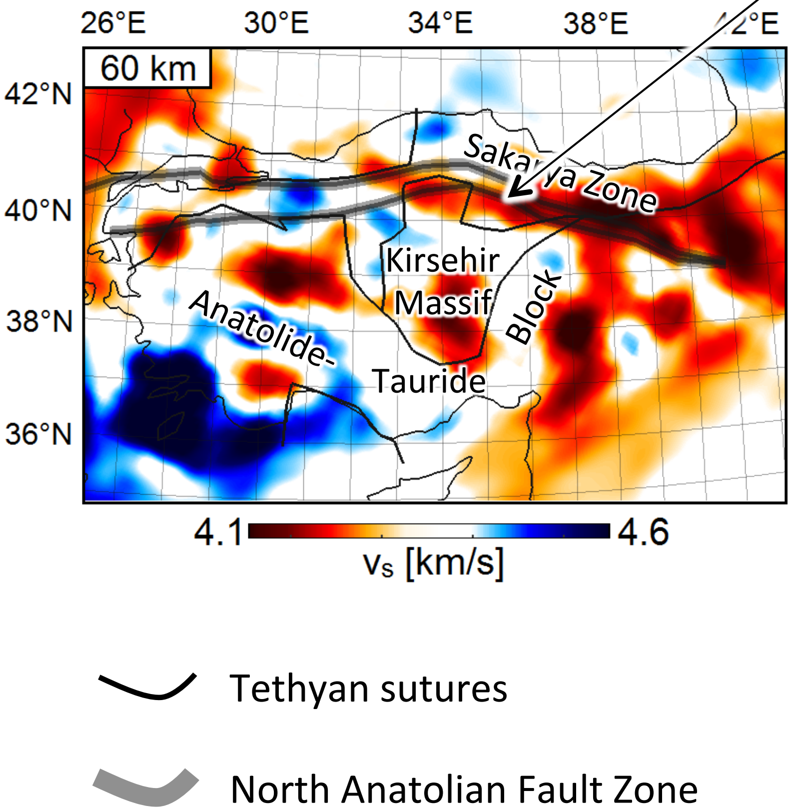
Anatolian Region – Upper Mantle



Tethyan sutures

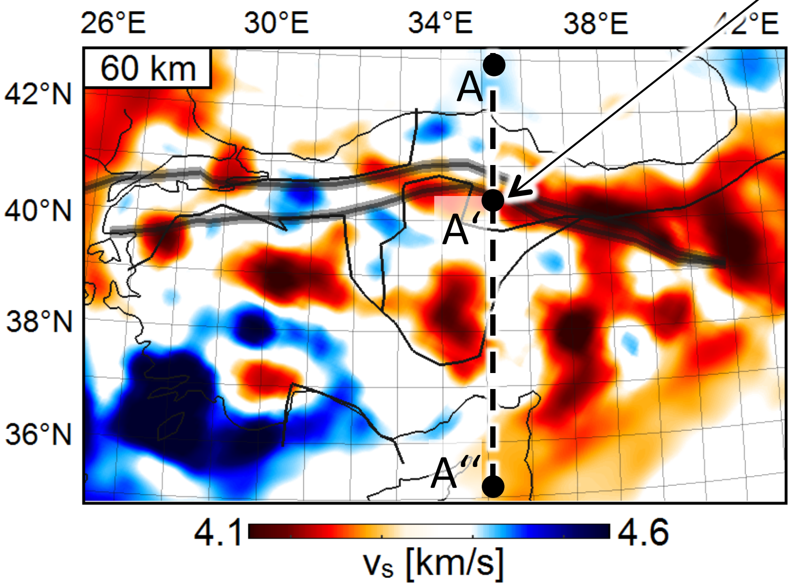
North Anatolian Fault Zone

Anatolian Region – Upper Mantle



- **Suture** (60-15 Ma) **between**:
  - Sakarya Zone (**Laurasia**)
  - Kirsehir Massif & Anatolide-Tauride Block (**Gondwana**)

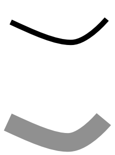
Anatolian Region – Upper Mantle

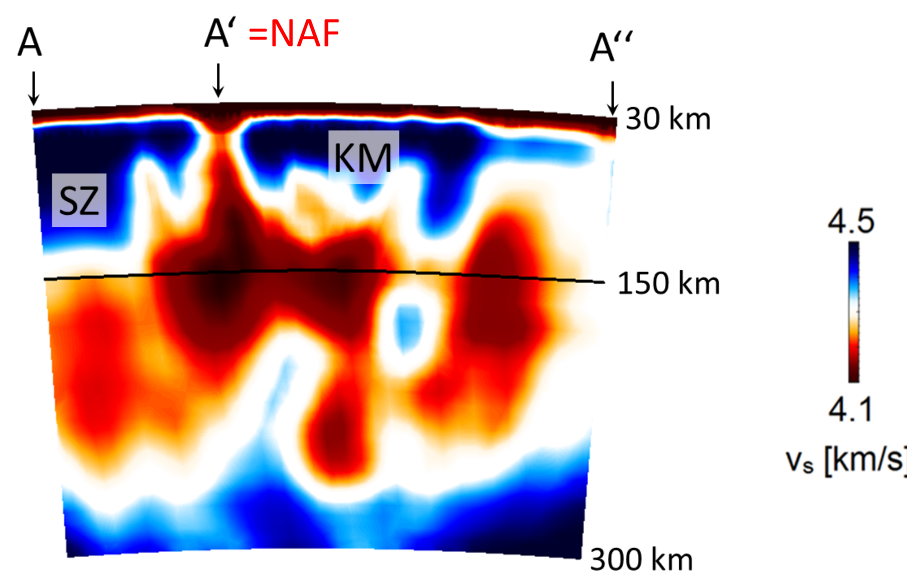


- **Suture** (60-15 Ma) **between**:
  - Sakarya Zone (**Laurasia**)
  - Kirsehir Massif & Anatolide-Tauride Block (**Gondwana**)

  - Narrow zone low-velocity zone
  - Persistent structural weakness along the suture
  - Reaches to ≈100 km depth

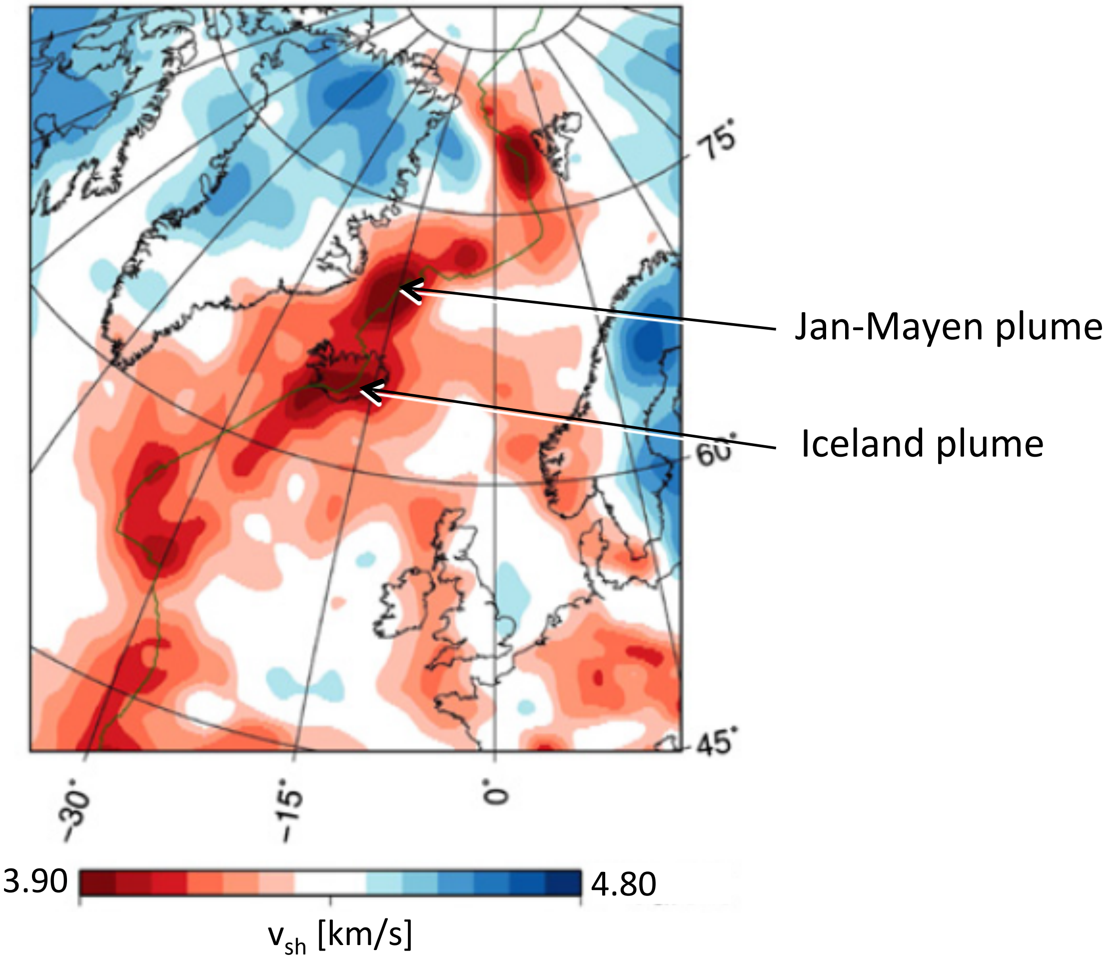
  - **Attracted the North-Anatolian Fault zone** (<10 Ma)
  - **Crustal fault zone controlled by older features within the lithospheric mantle**





North Atlantic – The Iceland-Jan Mayen Plume System

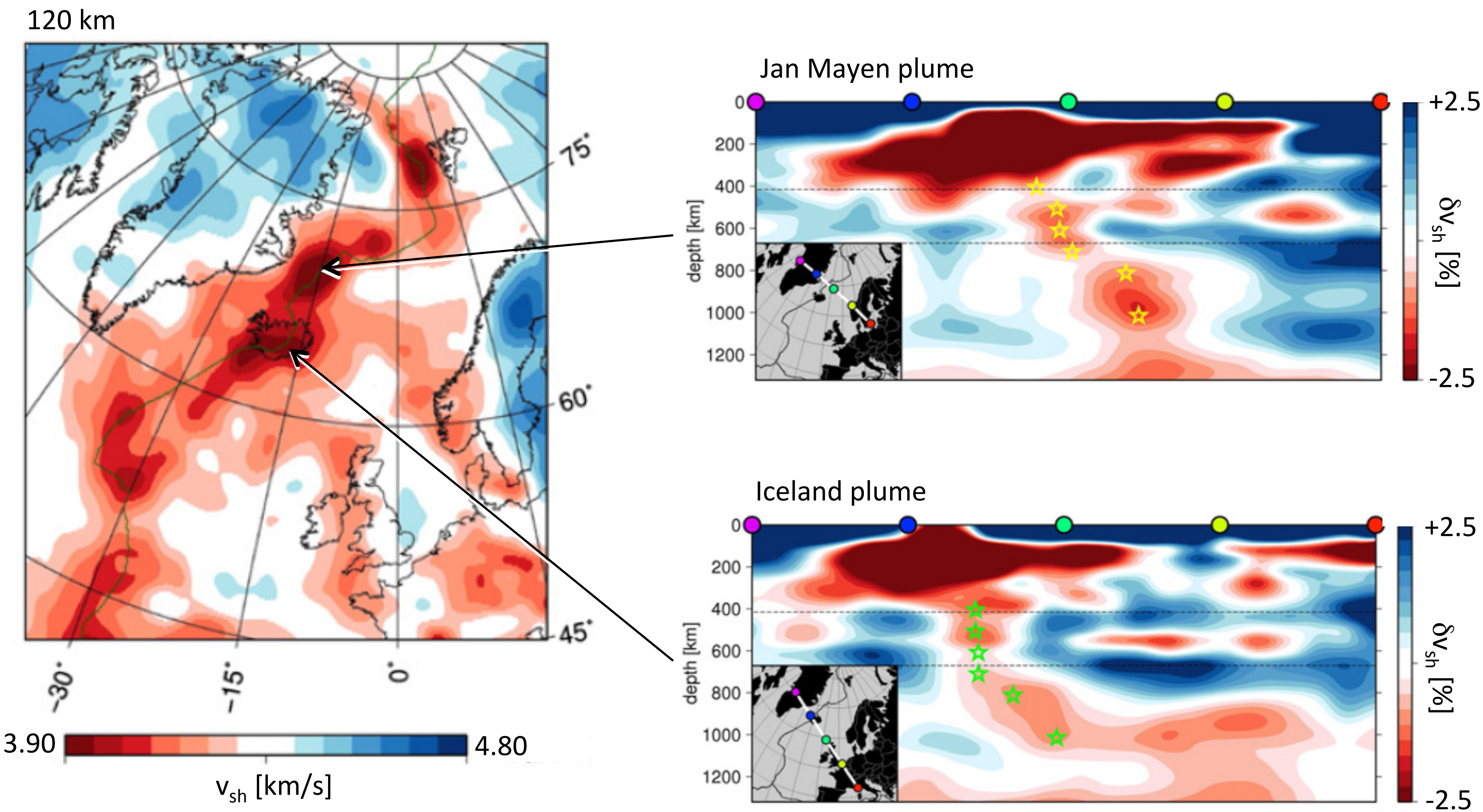
120 km



System of two plumes (Iceland and Jan Mayen)

Rickers et al., EPSL 2013

North Atlantic – The Iceland-Jan Mayen Plume System

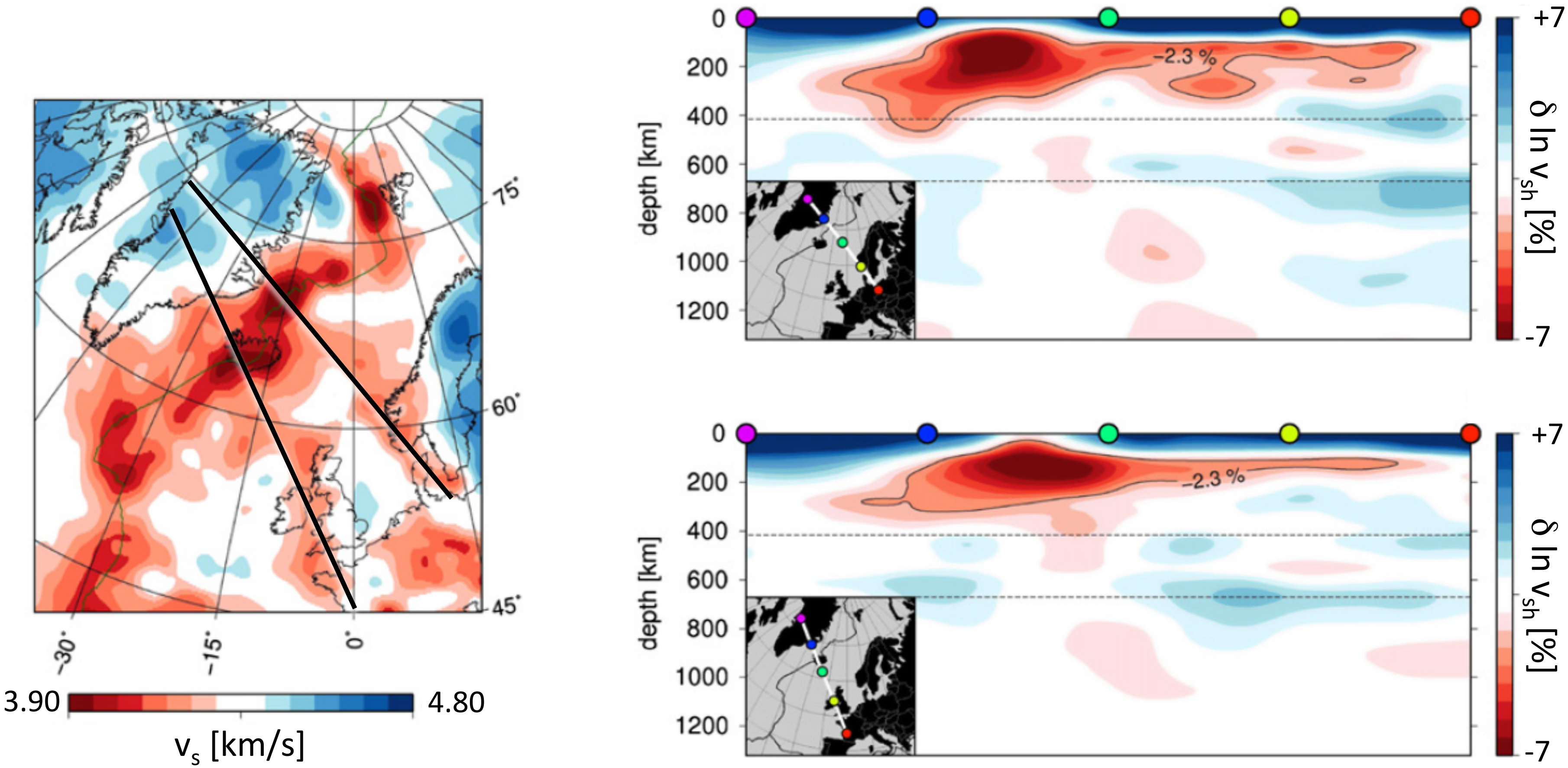


System of two plumes (Iceland and Jan Mayen)

Separate identities to ≈1000 km (weak resolution below)

Rickers et al., EPSL 2013

North Atlantic – The Iceland-Jan Mayen Plume System

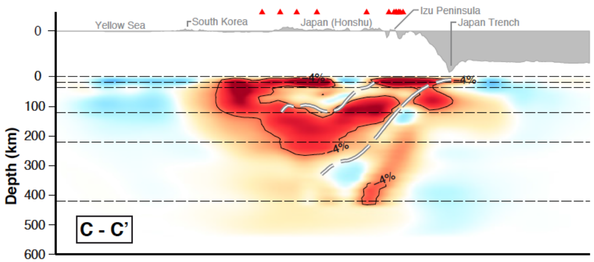


Low-velocity fingers extending from the plume system

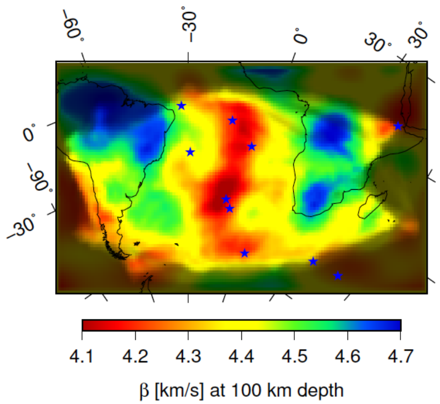
- Injections of plume material into the asthenosphere.
- Close correlation with regions of Neogene uplift.

Rickers et al., EPSL 2013

Beyond Europe

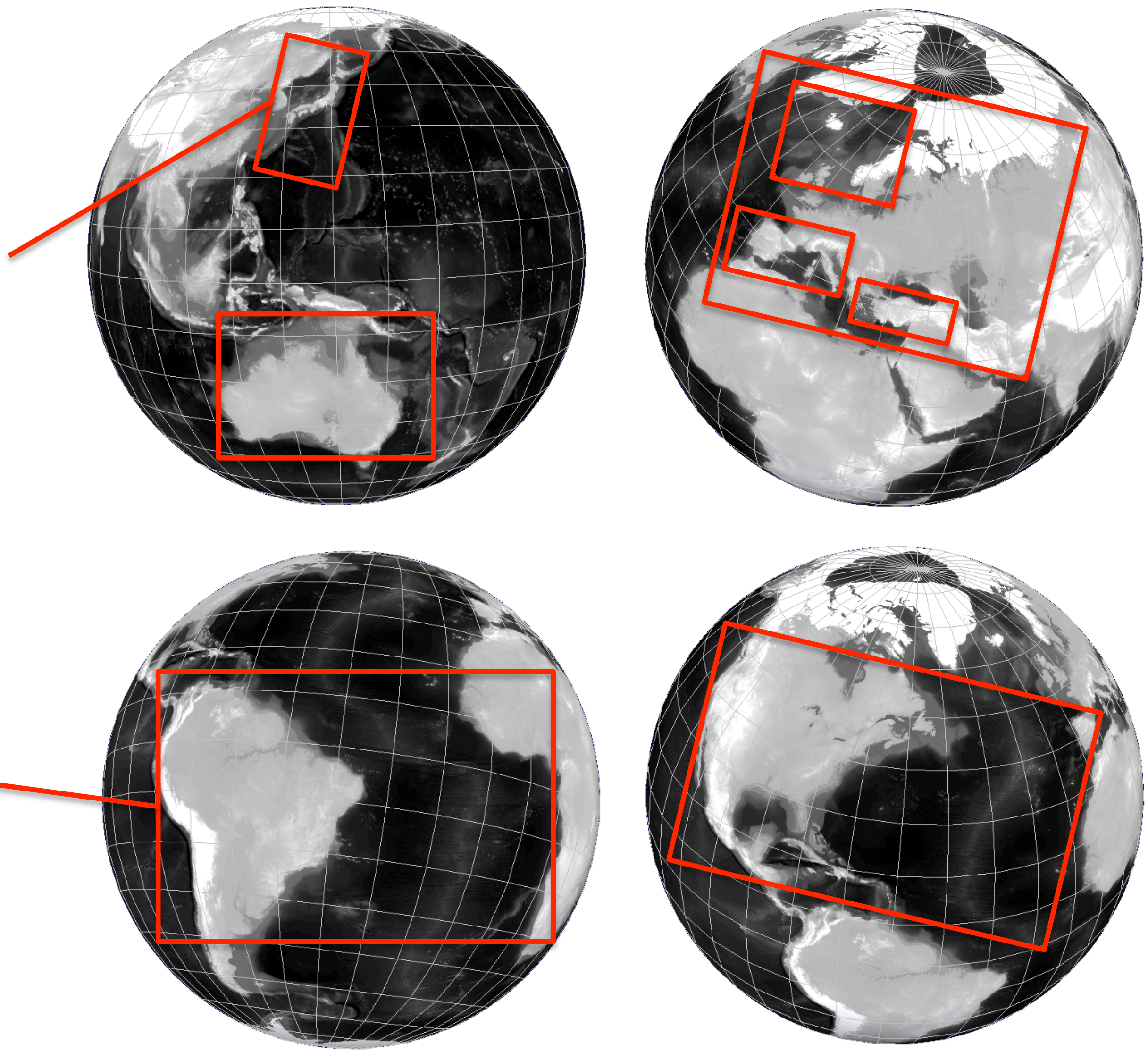


Steptoe et al. (in prep.)



joint with LMU

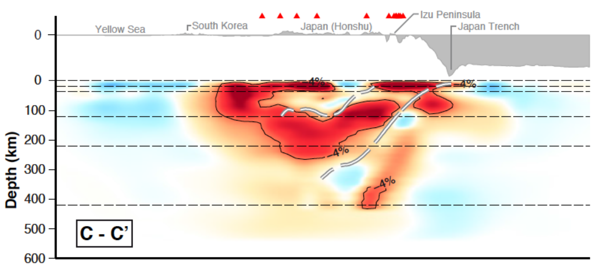
Colli et al. (in press.)



Krischer et al. (initial phase)

Beyond Europe

... in the process of being incorporated into a global multi-scale model.



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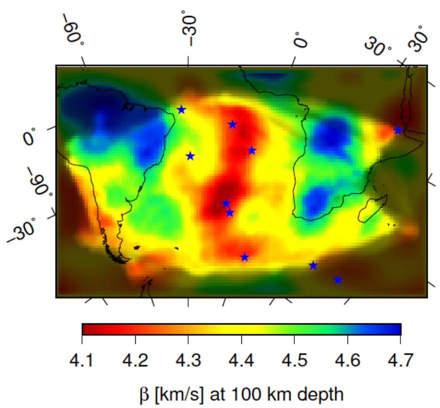

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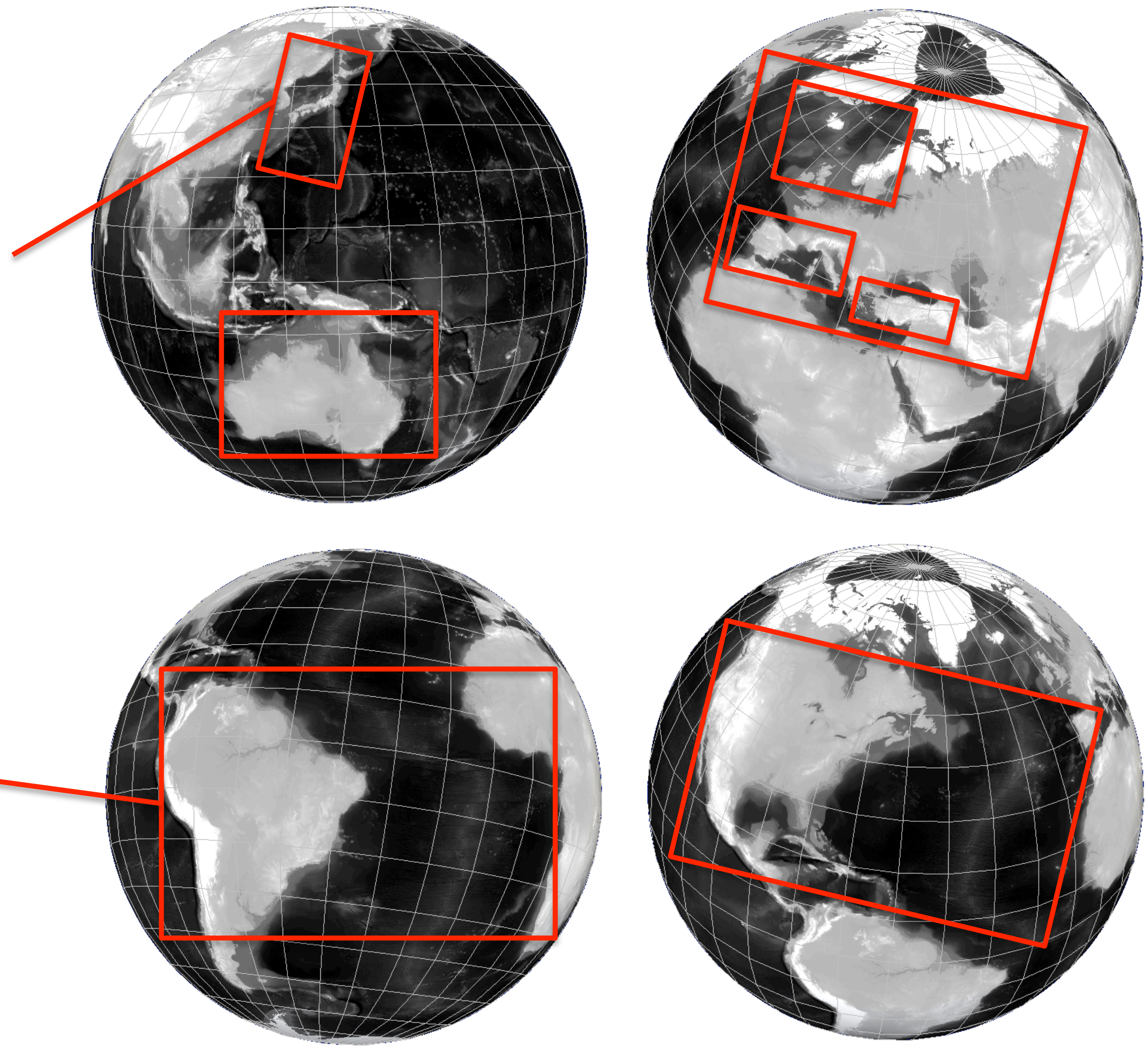

Krischer et al. (initial phase)

Workflows and Large-Scale Data Processing

LASIF: **LA**rge-**S**cale **I**nversion **F**ramework

LASIF

LArge-scale Seismic Inversion Framework

Provide standardised workflows
Faciliate management of tomographic inversions

LASIF

LArge-scale Seismic Inversion Framework

Provide standardised workflows
Faciliate management of tomographic inversions

- Data retrieval and archiving

```
$ lasif download_waveforms GCMT_event_Turkey_Mag_5.1_2010-3-24-14-11
```

LASIF

LArge-scale Seismic Inversion Framework

Provide standardised workflows
Faciliate management of tomographic inversions

- Data retrieval and archiving
- Data processing

```
$ lasif preprocess_data ITERATION_1
```

LASIF

LArge-scale Seismic Inversion Framework

Provide standardised workflows
Faciliate management of tomographic inversions

- Data retrieval and archiving
- Data processing
- Input files for numerical simulations

```
$ lasif generate_input_files ITERATION_1 EVENT_1 ADJOINT_REVERSE
```

LASIF

LArge-scale **S**eismic **I**nversion **F**ramework

Provide standardised workflows
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- Data retrieval and archiving
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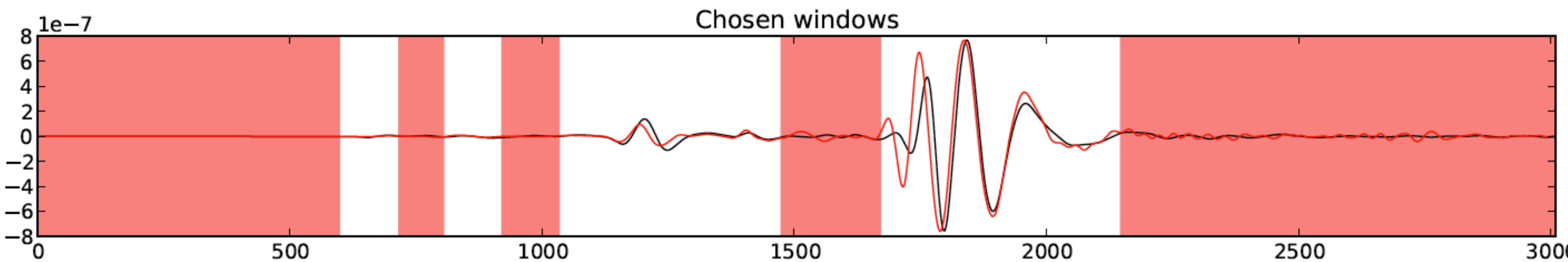
- Input files for numerical simulations
- Automatic window selection algorithms



LASIF

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- Compute misfits and adjoint sources
- Bookkeeping of iterations

LASIF

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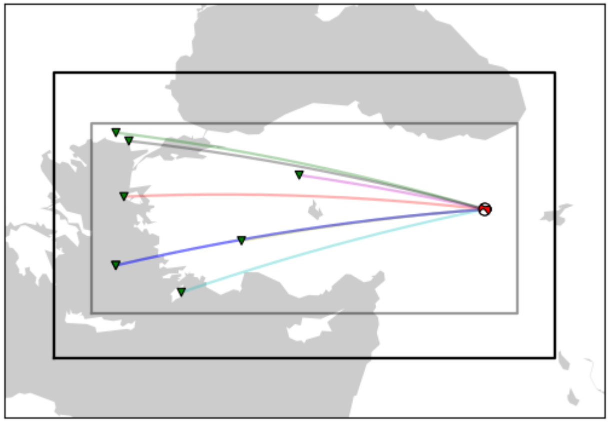
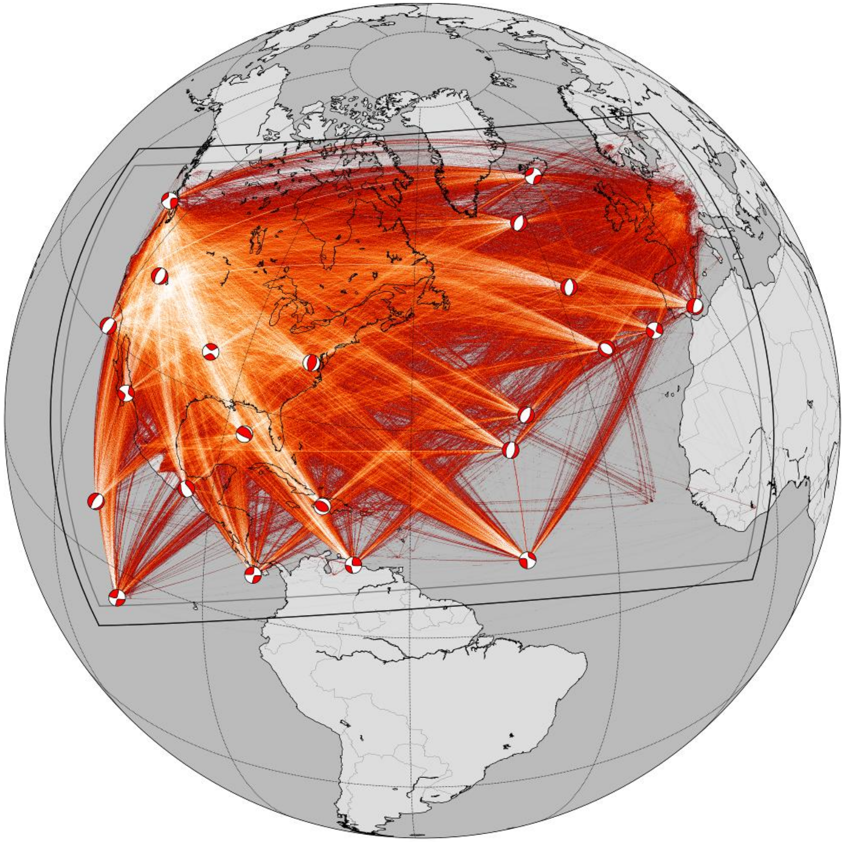
- Bookkeeping of iterations
- Plotting routines





SUMMARY

METHODOLOGICAL

Multiscale Full Waveform Inversion

- Multiple nested inversions on various spatio-temporal scales
- Simultaneous resolution of crustal and mantle structure
- Based on non-periodic homogenisation

LArge-**S**cale **I**nversion **F**ramework (LASIF)

- Standardised workflow for full waveform inversion
- Manage data and iterative updating procedure

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GEO-SCIENTIFIC

Anatolia

- Deep structure of the North Anatolian Fault Zone
- Formation above an ancient suture zone that persists to 100 km depth

North Atlantic

- Iceland-Jan Mayen plume system (2 instead of 1)
- Persist into the lower mantle
- Injection of plume material into the asthenosphere -> low velocity fingers + Neogene uplift

Outlook

Comprehensive Earth Model

ETH, CSCS, U. Utrecht, LMU, U. Rennes, ANU, ...

One Earth model on many scales.
Constrain velocities, anisotropy, Q, ...
Data on wide range of spatio-temporal scales.

- Workflows and large-scale data processing
- Multi-scale full waveform inversion
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- Combining full waveform inversion with normal modes
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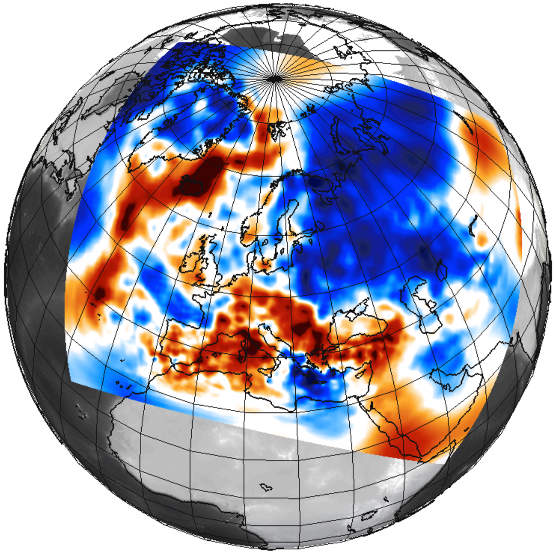


Thanks for your attention!

Motivation: The Scale-Dependence of Seismic Tomography

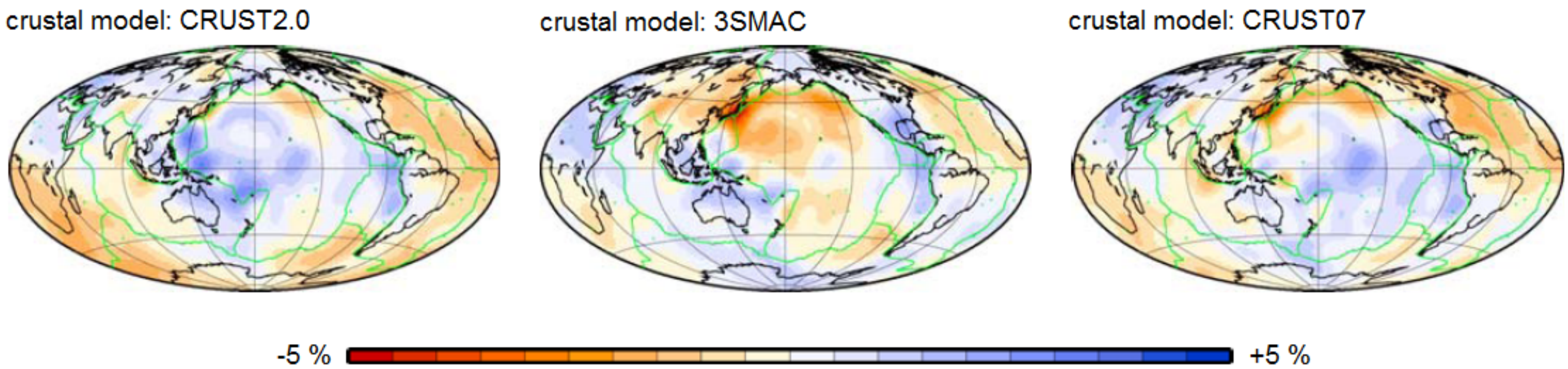
Unresolvable small-scale structure may lead to incorrect images of large-scale structure.

- **small-scale isotropic crustal structure** trades off with **large-scale anisotropy**

  → discrepant inferences on strength, depth-extent and sign of anisotropy

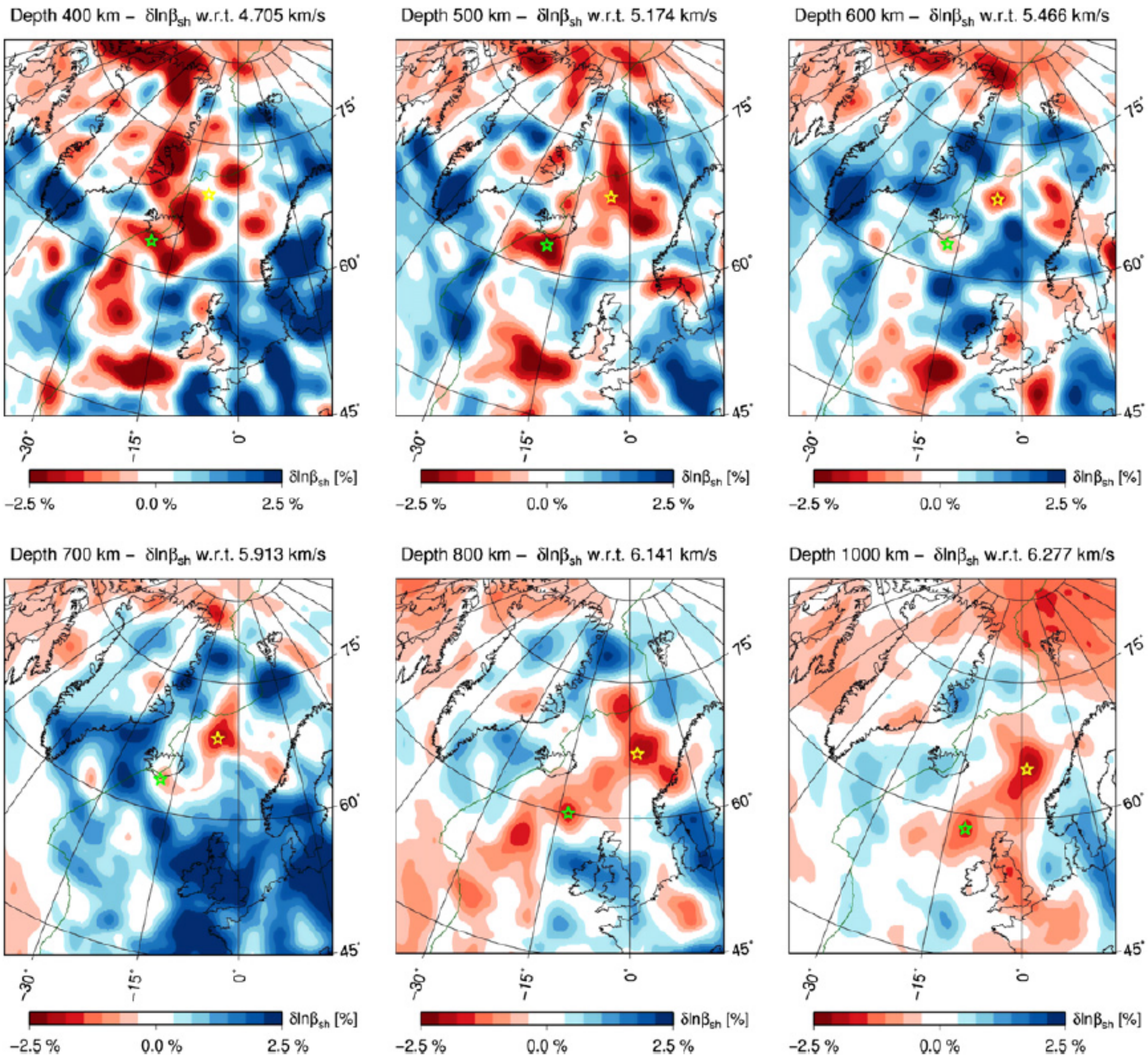
Global tomography with fixed crustal structure

radial anisotropy @ 100 km depth, $(v_{sh}-v_{sv})/v_s$



modified from Ferreira et al. (2010)

ICELAND-JAN MAYEN PLUME SYSTEMS



CORRELATION WITH DYNAMIC TOPOGRAPHY (RICKERS, FICHTNER, TRAMPERT, EPSL 2013)

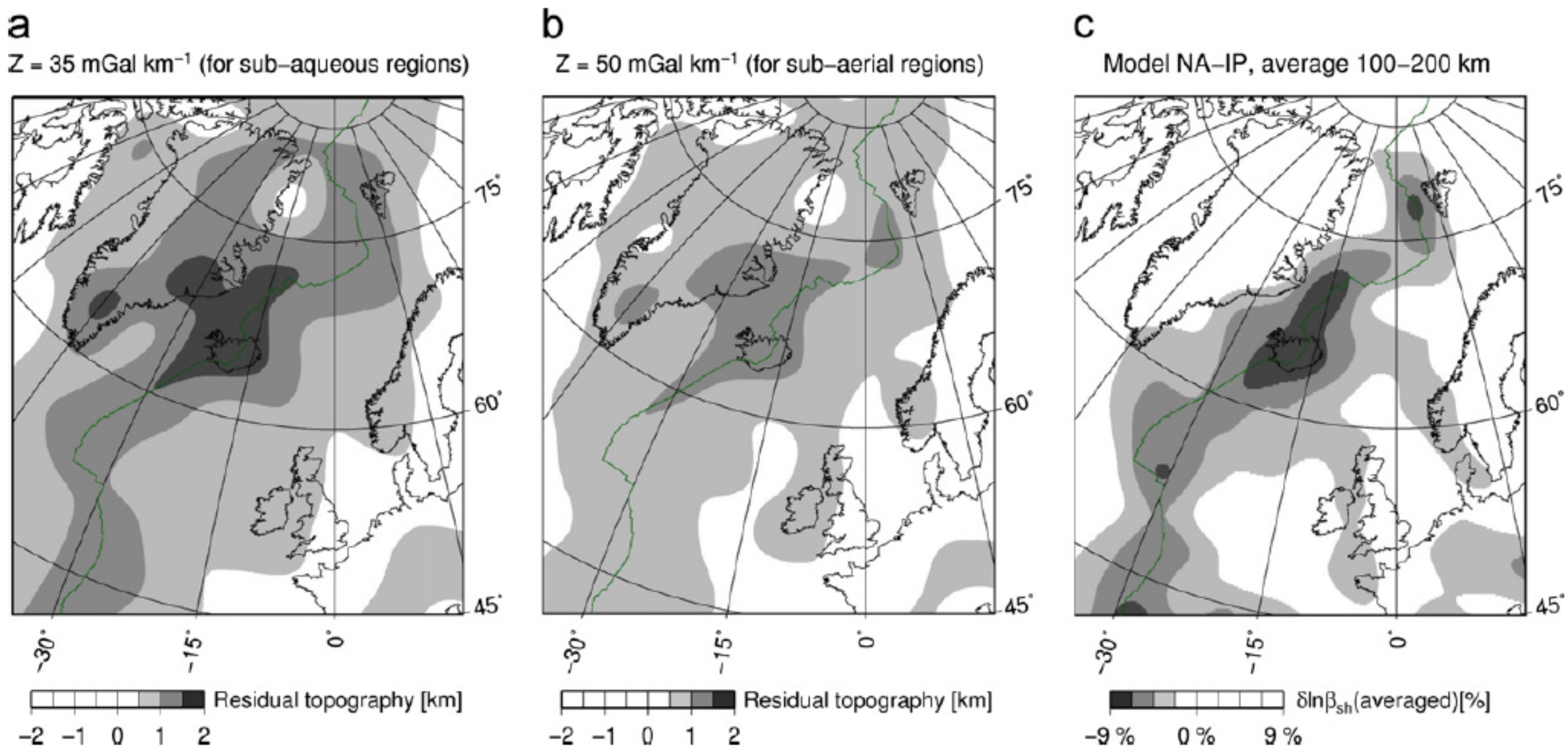
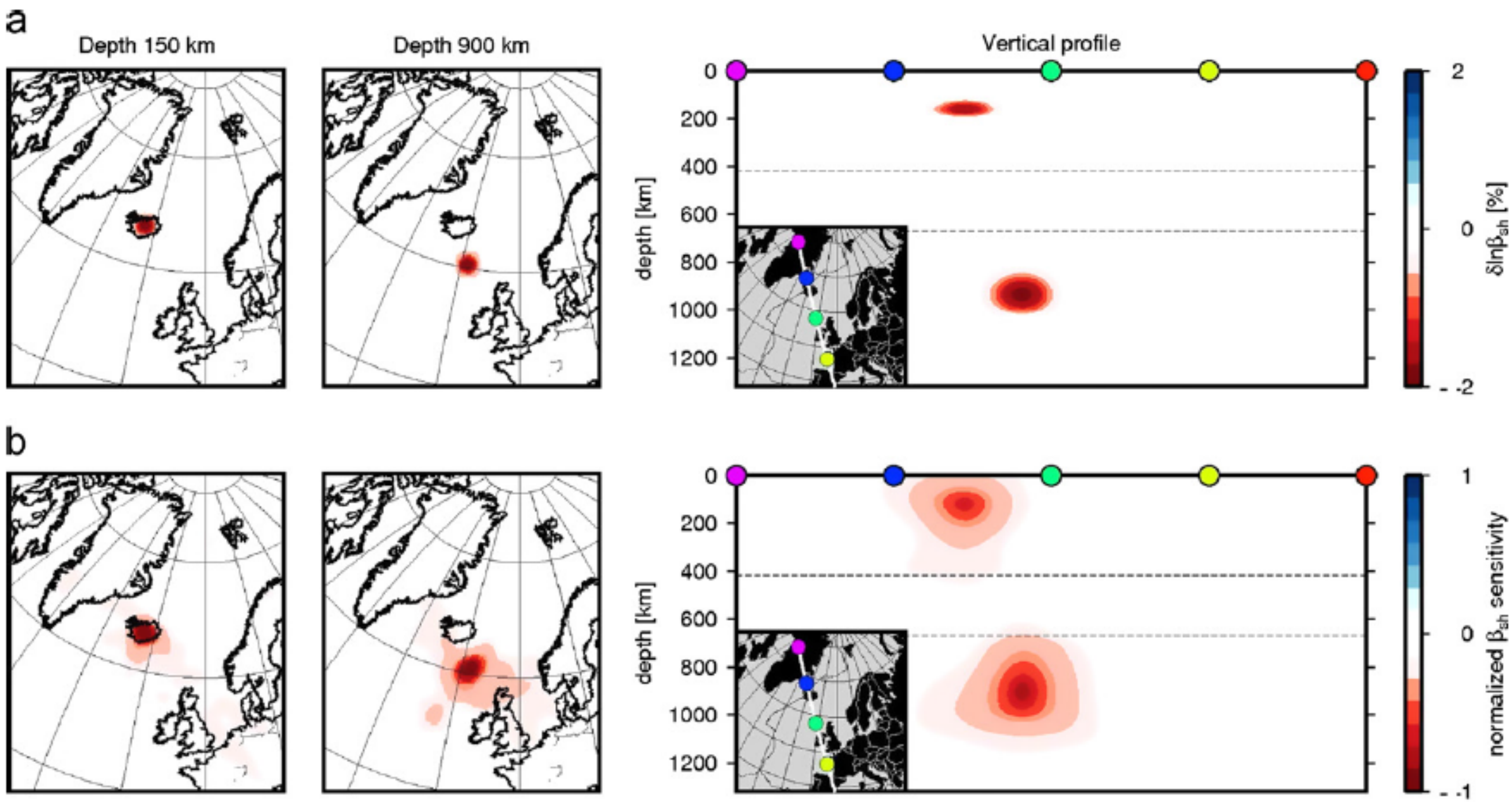


Fig. 8. (a and b) Estimates of present-day dynamic support in the North Atlantic region, calculated according to (Jones et al., 2002) through division of the long-wavelength free-air gravity anomaly field by a constant admittance Z. For estimates of dynamic support in sub-aqueous regions, $Z=35$ mGal km^{-1} is considered appropriate, for sub-aerial regions $Z=50$ mGal km^{-1}. (c) Long-wavelength average velocity perturbation between 100 km and 200 km depth of model NA-IP. To facilitate comparison with the estimated dynamic support, the average velocity is lowpass-filtered by convolution with a Gaussian of width 800 km.

POINT-SPREAD FUNCTIONS I (RICKERS, FICHTNER, TRAMPERT, EPSL 2013)



POINT-SPREAD FUNCTIONS II (RICKERS, FICHTNER, TRAMPERT, EPSL 2013)