TOWARDS A COMPREHENSIVE SEISMIC MODEL
(OF EUROPE)

Andreas Fichtner
in collaboration with

Yann Capdeville, Paul Cupillard, Lion Krischer, Florian Rickers, Erdinc Saygin, Jeannot Trampert, Antonio Villasenor
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
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**
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
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.
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... will not be finished tomorrow.
Necessary technology needs to be developed today.
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Multi-scale full waveform inversion
Combining full waveform inversion with ray tomography
Combining full waveform inversion with normal modes
Incorporate gravity and mineral physics constraints
Full waveform noise tomography

Workflows and large-scale data processing
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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 $\rightarrow$ upper-mantle structure
  - regional-scale shorter-period (<30 s) waves $\rightarrow$ 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
  - regional-scale shorter-period (<30 s) waves → crustal structure
  - ...

- fully numerical wave propagation
  - strongly heterogeneous lithosphere

- time step problem
  - regional grid refinement
  - $\Delta t_{\text{max}} \propto \Delta x_{\text{min}}$ (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
Domain Decomposition & Multiple Forward Problems

- upscaling
  - 3D non-periodic homogenisation
    (Capdeville et al., 2010; Guillot et al., 2010)
  - induces apparent anisotropy
DOMAIN DECOMPOSITION & MULTIPLE FORWARD PROBLEMS

original

A = $c_{\phi\phi\phi} [N/m^2]$  
N = $c_{\phi\theta\theta} [N/m^2]$  
L = $c_{r\phi r\phi} [N/m^2]$
DOM Domain Decomposition & Multiple Forward Problems

homogenised, smooth long-wavelength equiv.
Domain Decomposition & Multiple Forward Problems

- interpolation

Upscaling & interpolation

Iterative joint inversion
telesismic & regional data for shallow and deep structure
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

continental-scale resolution

50 km

λ_{NS} [km]
direction- and position-dependent resolution length

- computed via second-order adjoints (Fichtner and Trampert, 2011a,b)
- continuous version of point-spread function
**Validation – Comparison To Receiver Functions** (Vanacore et al., 2012)

![Graphs showing seismic wave velocities](image)

- Moho depth from receiver functions
- $v_s = 3.8$ km/s in $m_{42}$
VALIDATION – MATCH WITH NOISE CORRELATIONS

Numerical Greens function
ambient-noise correlation

Not used in the inversion!

Dominant period: 10 s
ANATOLIAN REGION – CRUST

Tethyan sutures
North Anatolian Fault Zone
Menderes Massif
Updoming of the lower crust due to N-S extension
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Updoming of the lower crust due to N-S extension

Tethyan sutures
North Anatolian Fault Zone
**ANATOLIAN REGION – UPPER MANTLE**

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

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**ANATOLIAN REGION – UPPER MANTLE**

![Map of Tethyan sutures and North Anatolian Fault Zone](image_url)

- Tethyan sutures
- North Anatolian Fault Zone
System of two plumes (Iceland and Jan Mayen)
System of two plumes (Iceland and Jan Mayen)
Separate identities to $\approx$1000 km (weak resolution below)

Rickers et al., EPSL 2013
Low-velocity fingers extending from the plume system

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

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

Steptoe et al. (in prep.)

joint with LMU
Colli et al. (in press.)

Krischer et al. (initial phase)
WORKFLOWS AND LARGE-SCALE DATA PROCESSING

LASIF: LArge-Scale Inversion Framework
Provide standardised workflows
Facilitate management of tomographic inversions
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Facilitate management of tomographic inversions

- Data retrieval and archiving

```bash
$ lasif download_waveforms GCMT_event_Turkey_Mag_5.1_2010-3-24-14-11
```
Provide standardised workflows
Facilitate management of tomographic inversions

- Data retrieval and archiving
- Data processing

```
lasif preprocess_data ITERATION_1
```
Provide standardised workflows
Facilitate management of tomographic inversions

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

```bash
lasif generate_input_files ITERATION_1 EVENT_1 ADJOINT_REVERSE
```
Provide standardised workflows
Facilitate management of tomographic inversions

- Data retrieval and archiving
- Data processing
- Input files for numerical simulations
- Automatic window selection algorithms
Provide standardised workflows
Facilitate management of tomographic inversions

- Data retrieval and archiving
- Data processing
- Input files for numerical simulations
- Automatic window selection algorithms
- Compute misfits and adjoint sources
- Bookkeeping of iterations
Provide standardised workflows
Facilitate management of tomographic inversions

- Data retrieval and archiving
- Data processing
- Input files for numerical simulations
- Automatic window selection algorithms
- Compute misfits and adjoint sources
- 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-Scale Inversion Framework (LASIF)
  • Standardised workflow for full waveform inversion
  • Manage data and iterative updating procedure
SUMMARY

**METHODOLOGICAL**

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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
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OUTLOOK
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

  $\rightarrow$ discrepant inferences on strength, depth-extent and sign of anisotropy

Global tomography with fixed crustal structure

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

crustal model: CRUST2.0

crustal model: 3SMAC

crustal model: CRUST07

modified from Ferreira et al. (2010)
ICELAND-JAN MAYEN PLUME SYSTEMS

Depth 400 km - $\Delta \ln p_{sh}$ w.r.t. 4.705 km/s

Depth 500 km - $\Delta \ln p_{sh}$ w.r.t. 5.174 km/s

Depth 600 km - $\Delta \ln p_{sh}$ w.r.t. 5.488 km/s

Depth 700 km - $\Delta \ln p_{sh}$ w.r.t. 5.913 km/s

Depth 800 km - $\Delta \ln p_{sh}$ w.r.t. 6.141 km/s

Depth 1000 km - $\Delta \ln p_{sh}$ w.r.t. 6.277 km/s
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)

[Diagram showing depth profiles and color-coded maps for different depths.]

C: Depth 150 km
D: Depth profiles for different regions.