Seismological imaging of the lithosphere –
in the light of joint inversion / interpretation

Christian Weidle & Thomas Meier
Overview

• Targets in lithospheric imaging
• Seismic observables in the aspect of joint inversion / interpretation
  • Body wave traveltime tomography
  • Surface wave dispersion, Waveform tomography, wavefield imaging, ambient noise
• Receiver Functions
Targets

• Depth-to-...
  – Moho
  – LAB
  – Intra-crustal (depth-to-basement, Conrad)
  – Intra-lithospheric (MLD?)
  – … and their thicknesses (are they sharp?)
• Velocities \( v_p, v_s, v_p/v_s \) ratio
• Anisotropy
  – Azimuthal
    • Crust: frozen-in, ancient deformation
    • Mantle: current stress regime/mantle flow
  – Radial
    • \( SH \) vs. \( SV \)

Broad spectrum → requires broad methodology?, is there ONE solution?
Sample case: Southern Norway

Basement structure of Central Europe

Goes et al., 2000 from Bijwaard et al., 1998

Gregersen et al., 2002

Winchester, 2002
Sample case: Southern Norway

Weidle & Maupin, 2008

Weidle et al., 2010
Seismic observables

**Traveltimes (body waves)**
- Useful approximation, simple to implement
  - Ray theory: 3D globally – Finite Frequency: 1D Kernels
- High frequency, short wavelength
- High spatial resolution (station coverage)
- Global (multi-) scale inversions feasible
- Relative / absolute velocity models
- “simple” data error assessment

**Problem:**
- Anisotropy … possible …
- Consistent determination (manual picks, many data centers, …)
- Useful phases? Depth phases for shallow structure ↔ auto-picking?
Seismic observables

$V_{p_{rel}}$, $V_{p_{abs}}$, $V_{s_{rel}}$

Amplitudes $\pm 3\%$

Medhus et al., 2012
Wawrzinek et al., 2013
Theory light

The perfect world:

\[ G \bullet \overline{m} = \overline{d} \]

- **G**: Full resolution 3-D seismic wavefield
- **\( \overline{m} \)**: “mm-scale” model of all physical parameters
- **\( \overline{d} \)**: error-free data

The real world:

\[ (G \ast \sigma_g) \bullet (\overline{m} \ast \sigma_m) = \overline{d} + \sigma_d \quad \rightarrow \text{regularization} \]

“Filters”:
- **\( \sigma_g \)**: approximation in wave propagation, e.g. ray theory, forward scattering, fundamental modes
- **\( \sigma_m \)**: geometric model parameterization and selection of parameters (e.g. velocity, attenuation)
- **\( \sigma_d \)**: data limitations, e.g. measurement, frequency content, ...
Seismic observables

**Vp**

Consistently parameterized (not joint) Vp, Vs inversion

Amplitudes +/- 2%  
More consistent anomalies in Vp and Vsh  
~ 100 events, ~ 3000 – 4000 traveltimes
Seismic observables

\[ V_{p_{rel}} \]

\[ V_{p}, V_{s} \text{ Finite Frequencies inversion} \]

Amplitudes +/- 2.5%

More consistent anomalies in Vp and Vsh

Covers slightly larger region (at depth)

Medhus et al., 2012

Kolstrup et al., 2015

Wawerzinek et al., 2013
Seismic observables

$V_{p_{rel}}$

Plausible $V_p/V_s$ model

$V_{s_{rel}}$

Variations in lithospheric thickness
+300° temperature S.Norway
Depleted mantle below Sweden

Medhus et al., 2012
Kolstrup et al., 2015
Wawerzinek et al., 2013
Seismic observables

**Surface wave dispersion**

- Useful parameterization of (fundamental) mode waveforms
- Group velocities
  - Single station, no $2\pi$ problem
  - Amplitude measurement, sensitive to interference
- Phase velocities
  - Two-station methods:
    - $2\pi$ problem reduced
    - High accuracy ("relative" measurement)
- Broad sensitivity to shear wave velocity with depth
- Strong sensitivity on anisotropy (azimuthal & radial)

**Problem:**

- Two-step inversion procedures through group-/phase-velocity maps
- Regional-scale resolution
- Error analysis difficult on few data, better on large datasets (automated processing)
Seismic observables

BFO

cross correlation

CLL

Soomro et al., 2015
Seismic observables

Soomro et al., 2015

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Seismic observables

- 70 km grid
- Azimuthal anisotropy
- Rayleigh & Love → radially anisotropic inversion possible

Soomro et al., 2015
Seismic observables

Waveforms
- Fundamental and higher mode waveforms
- Surface and body waves
- Theoretically best approach but in practice limited to long to intermediate periods
- Strong cycle skipping, particularly at higher frequencies

Problem:
- Calibration of amplitudes in recordings
- Little resolution for crust
- Need good starting model
- Errors strongly varying with frequency
Seismic observables

after Lebedev et al., 2005
Seismic observables

Waveforms vs. dispersion:
- Periods: >20s – >8s
- node spacing: 280km – 70km
- model depth: CMB – upper mantle

Soomro et al., 2015

Schaeffer & Lebedev, 2013
Seismic observables

**Ambient noise**
- Surface and body wave observables
- Strong sensitivity for crust
- Know-how from established methods (e.g. surface wave tomography) applicable

**Problem:**
- Qualitative error analysis
- Amplitudes
Seismic observables

- Cross correlation of >12 months of ambient noise recorded at two stations
- Emergence of Greens Function along interstation path
- Surface wave part can be measured as for ambient earthquakes

Köhler et al., 2012
Array observables – wavefield imaging

- Source independent
- Interpolating phase observations at dense network
- “parameter-free” Eikonal / Helmholtz “tomography”

Problem:
- Aperture and density of network $\leftrightarrow$ frequencies
- Typical edge effects of velocity maps
- Classical inversion for velocity-depth
Seismic observables

**Synthetic experiment**

\[ c = \frac{2\pi}{(T \times |\nabla \varphi|)} \]

- Anomaly at 70 km depth causes perturbation (scattering) in phase and amplitude of the wavefield
- Stacking of many events from different azimuths (Eikonal tomography)
- Correction of the “dynamic” phase velocity with amplitude term (Helmholtz tomography)

*Weidle, 2012*
Seismic observables

Synthetic experiment – stacking of 12 (noisy) events

Model

Result

Error

Promising, inversion-free approach
Applicable to dense networks

Weidle, 2012
Application to real data

Köhler et al., 2012
Sensitivity of surface waves to Moho depth and thickness

Depth sensitivity

Phase

Group

$\rightarrow$ surface waves don't see contrasts very well!

Lebedev et al., 2013
Seismic observables

**Receiver Functions**
- Single station method
- Best(?) method to determine depths to discontinuities
- Image velocity/impedance contrast

**Problem:**
- Trade-off velocity ↔ depth ↔ contrast
- ... influences error estimate (→ also filtering)
- qualitative “mismatch” of Moho depths with wide-angle seismics
- Gradual Moho (→ need for joint inv!)
- LAB “100 km” problem → Mid-lithospheric discontinuity
Seismic observables

CSS Moho

RF Moho

Different filters in deconvolution

Stratford et al., 2011

Frassetto & Thybo, 2013
Seismic observables

Stratford et al., 2011

CSS Moho

RF Moho

Difference to CSS
→ decrease in conversion amplitude in NE
→ gradual Moho

Frassetto & Thybo, 2013
Seismic observables
• Joint inversion of surface wave dispersion and Receiver Functions
  – Established approach, resolves
  – … Vs structure with SW
  – … depth of discontinuities with RF
Moho, RF & Surface waves

SW dispersion

RF Moho

Joint inversion

Frassetto & Thybo, 2013

Köhler et al., 2012

Kolstrup & Maupin, 2013
Moho, RF & Surface waves

Joint inversion

Kolstrup & Maupin, 2013
Seismic observables

Receiver Functions

- Single station method
- Best(?) method to determine depths to discontinuities
- Image velocity/impedance contrast

Problem:

- Trade-off velocity ↔ depth ↔ contrast
- … plus filters → influences error estimate
- qualitative “mismatch” of Moho depths with wide-angle seismics
- gradual Moho (→ find better method)
- LAB “100 km” problem → Mid-lithospheric discontinuity
Seismic observables

RF LAB “problem”

Kind et al., 2012

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Seismic observables

RF LAB “problem”

Anisotropy from surface waves

Kind et al., 2012

Yuan & Romanowicz, 2010
Seismic observables

RF LAB “problem”

Anisotropy from surface waves

Kind et al., 2012

Yuan & Romanowicz, 2010
Theory light

The perfect world:

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The real world:

\[ (\mathbf{G} \ast \sigma_G) \cdot (\bar{\mathbf{m}} \ast \sigma_m) = \bar{\mathbf{d}} + \sigma_d \longrightarrow \text{regularization} \]

“Filters”:
\( \sigma_G \): approximation in wave propagation, e.g. ray theory, forward scattering, fundamental modes
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Promising examples

- Joint P & S Receiver Functions
  - Plus P & S traveltime residuals $\rightarrow$ $v_p$, $v_s$, $v_p/v_s$ models

Kiselev et al., 2008
Promising examples

• Joint P & S Receiver Functions
  – Plus P & S traveltime residuals → vp, vs, vp/vs models
  – Propagation of errors into weakest parameter → vp/vs

Kiselev et al., 2008
Promising examples

• Joint P & S Receiver Functions
  – Plus P & S traveltime residuals \(\rightarrow\) \(v_p\), \(v_s\), \(v_p/v_s\) models
  – Propagation of errors into weakest parameter \(\rightarrow\) \(v_p/v_s\)
Summary

• Methods:
  – Body wave traveltimes: robust, large-scale, high-resolution (onshore), joint inversion (P&S) feasible
  – Receiver Functions: image depth to discontinuities, tradeoff to velocities, interpretation with other methods, highly suited for joint inversion
  – Surface wave dispersion: robust, large-scale, frequencies for entire lithosphere, strong sensitivity for anisotropy (azimuthal and radial)
  – Waveforms: robust at long to intermediate periods, deeper lithosphere, needs good starting model to converge
  – Wavefield imaging: no inversion, dense networks, tradeoff network geometry
    – frequencies, high (crustal) frequencies challenging
  – Ambient noise: stable, high frequency extension of earthquake based surface wave observations (→ upper crust)
Summary

• Targets:
  – (upper) crust: ambient noise, Pg/Sg traveltimes
  – Crust & Moho depth: Pn/Sn traveltimes, ambient noise + surface waves, Receiver Functions
    • Anisotropy: surface waves (+ambient noise)
  – Mantle lithosphere: body & surface wave tomography, waveforms, wavefields, Receiver Functions
    • Anisotropy: surface waves (EQ based), SKS splitting
Summary

• Joint inversion and interpretations:

\[(G \cdot \sigma_g) \cdot (\bar{m} \cdot \sigma_m) = \bar{d} + \sigma_d\]

- Keep problem in all terms as consistent as possible → merge results from different methods
- Consistent parameterization often already a big step forward
- Need for consistent data sets
- Consistent uncertainties
- Still there are different sensitivities ...