

IMAGING MAGMA CHAMBERS

INSIDE THE HUMAN BODY

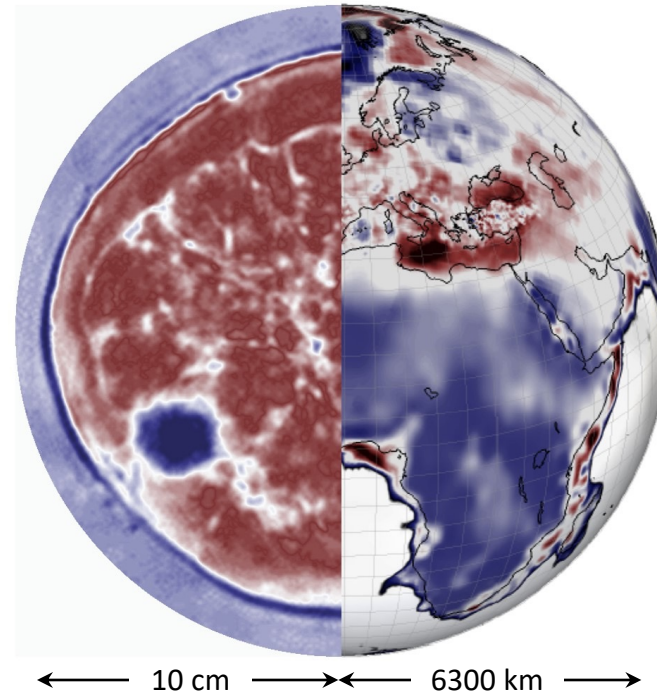
Andreas Fichtner

Christian Boehm

Ines Ulrich

Patrick Marty

Seismology & Wave Physics Group
Department of Earth Sciences
ETH Zurich



Ultrasound waveform tomography of a human breast [courtesy of N. Duric, 2019]

Shear velocity at 100 km depth from full-waveform inversion [Fichtner et al., 2018]

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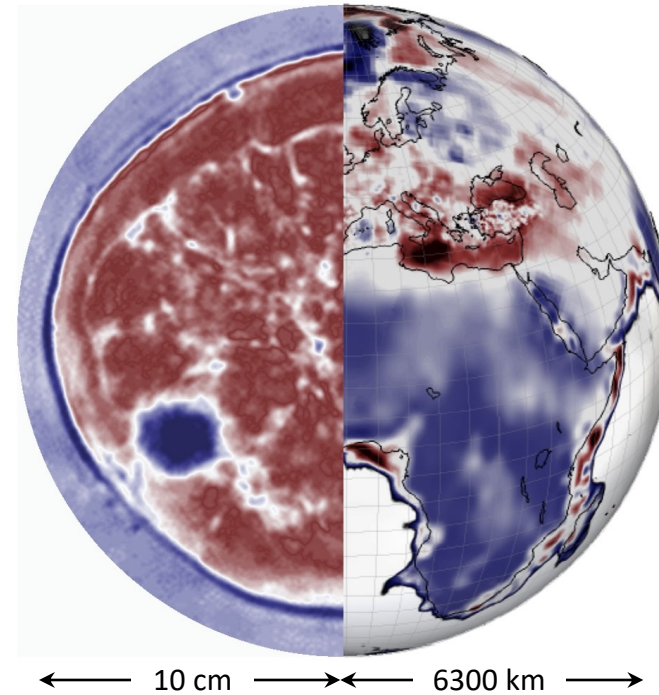
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Purposes of this talk

Introduction to seismic imaging of the Earth using earthquakes

Translation of seismic imaging concepts to medical ultrasound

Focus on fundamental concepts

Whetting your appetite

SEISMIC WAVES IN THE EARTH

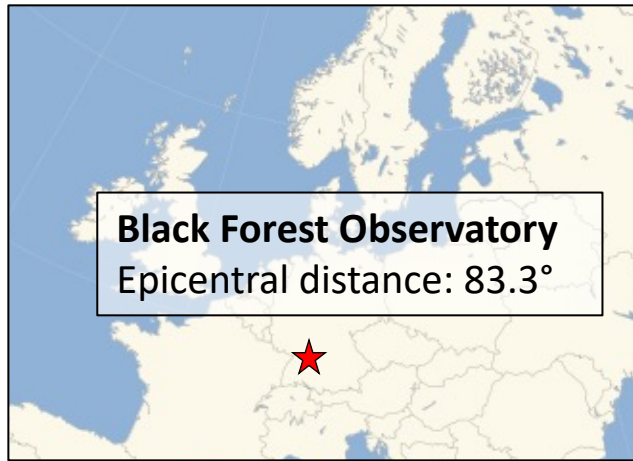


Numerical simulation of the Tohoku earthquake, 11 March 2011

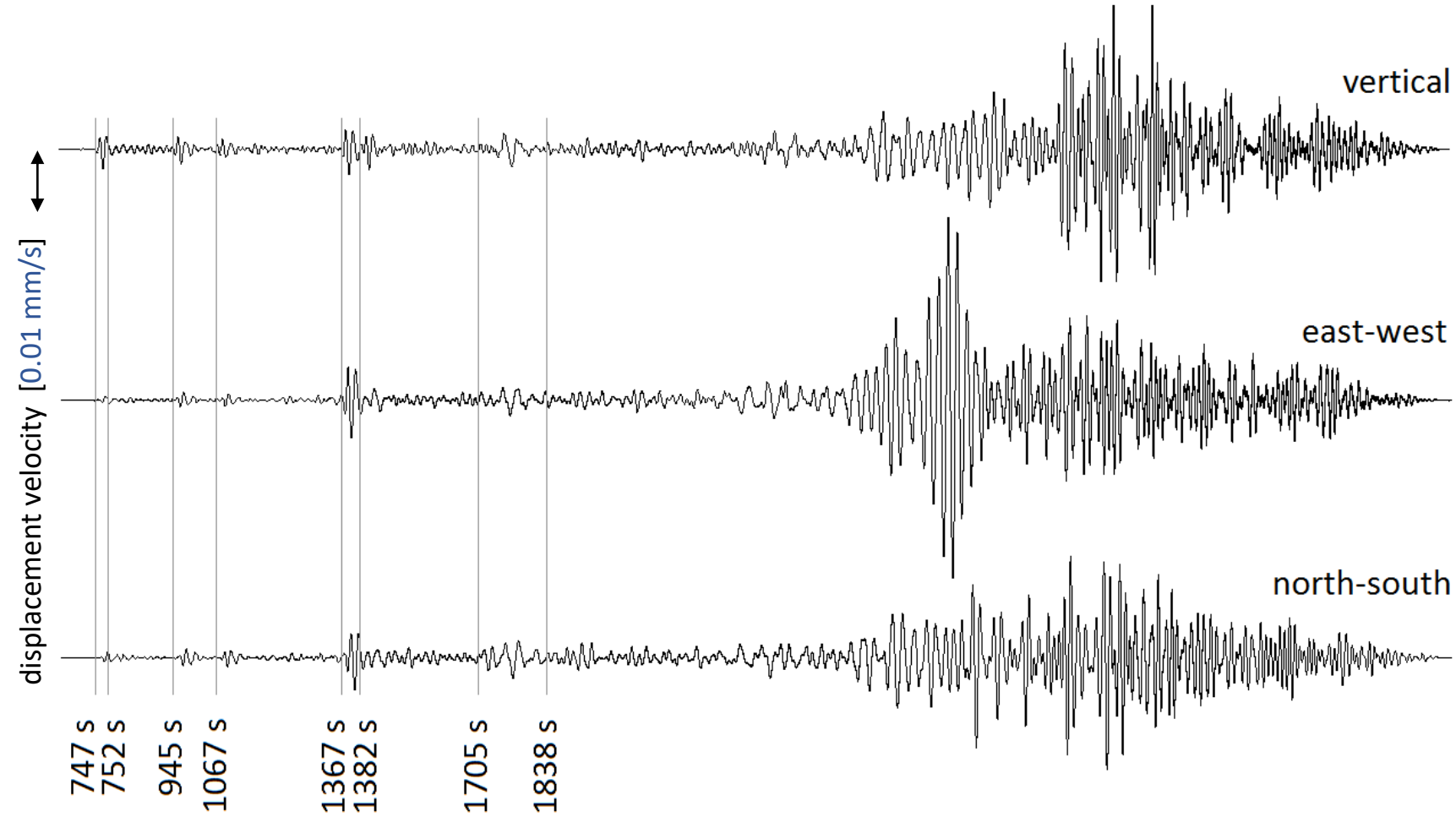
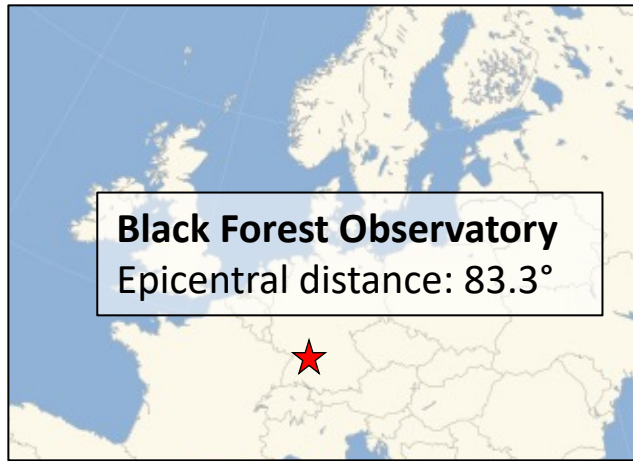
magnitude: 9.1 [4th largest earthquake ever recorded]

liberated energy: $\sim 4 \cdot 10^{22}$ J [70× world energy consumption, $\sim 10^{29}$ × medical ultrasound pulse]

DATA: SEISMOGRAMS



DATA: SEISMOGRAMS



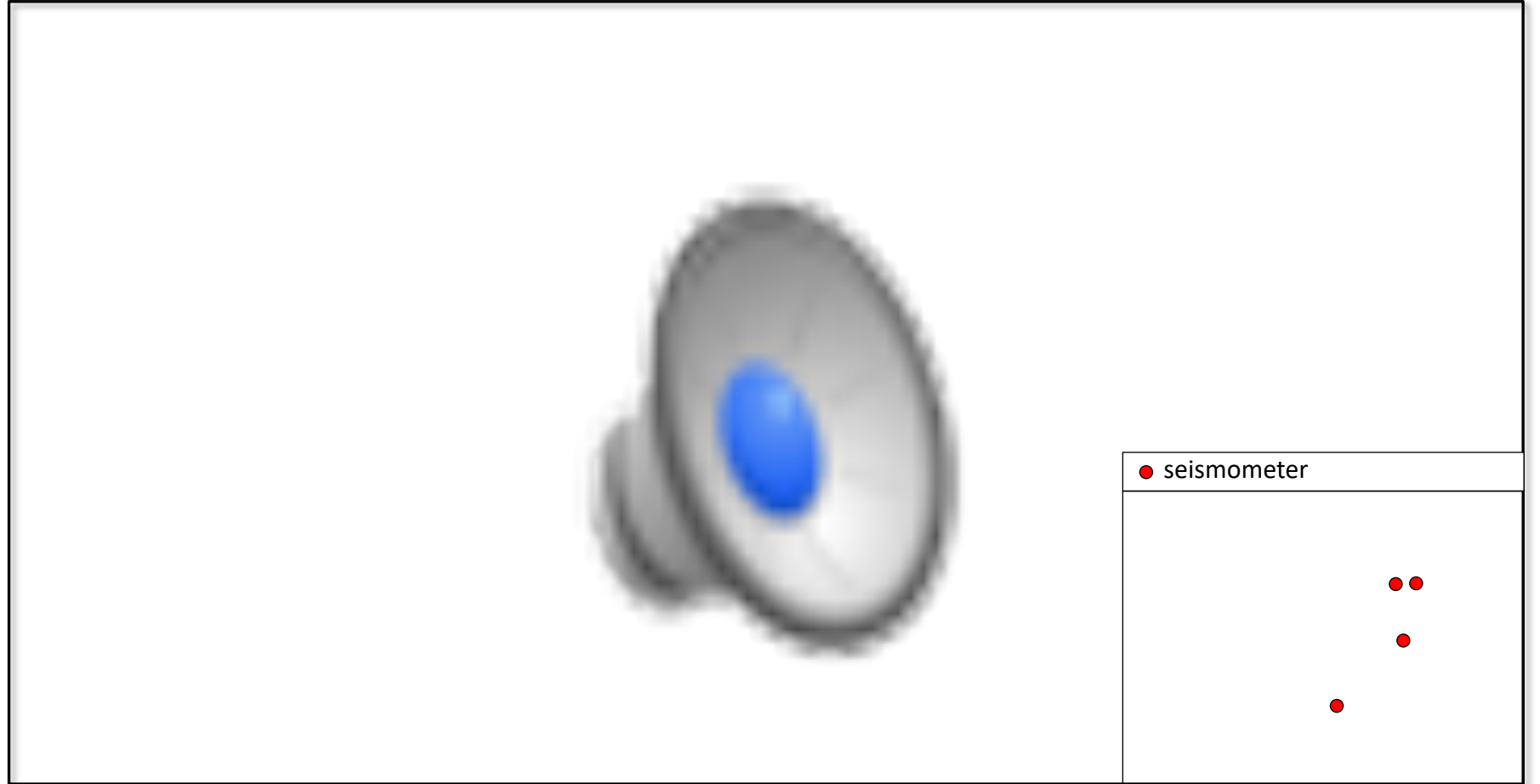
typical frequency range

1 mHz – 1 Hz

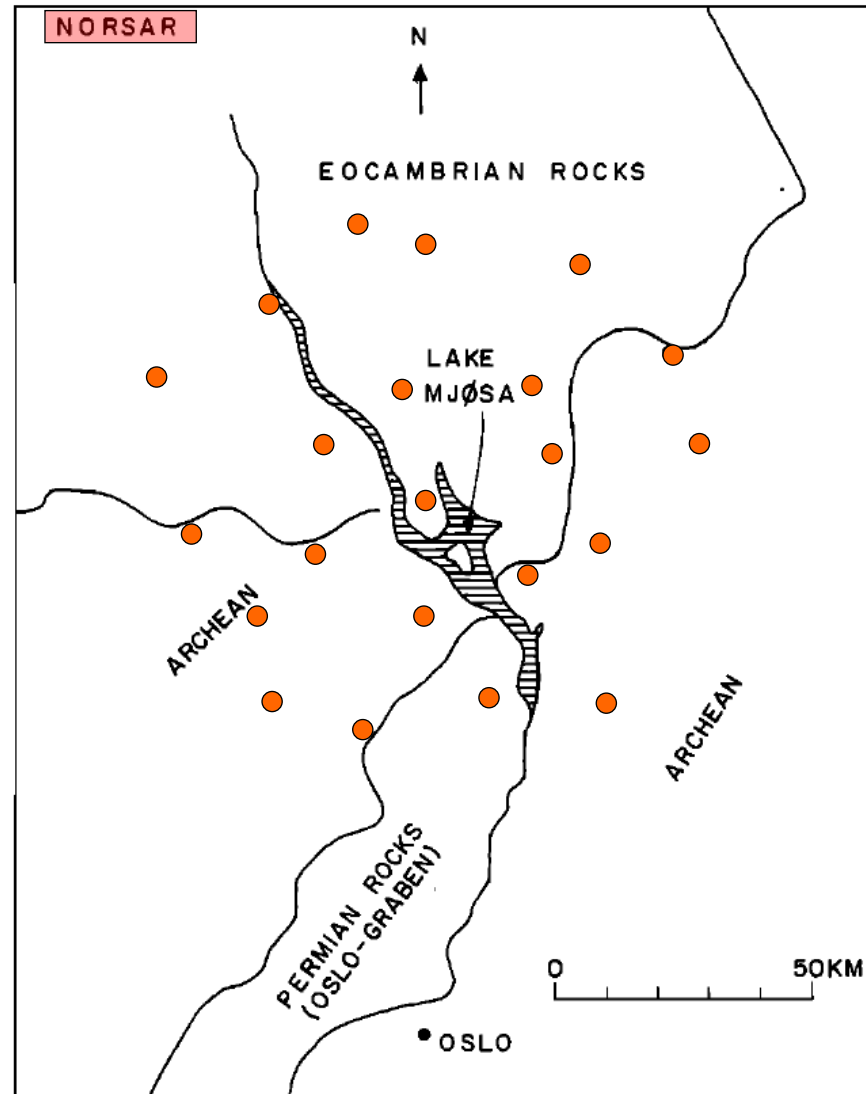
body waves

surface waves

SONIFICATION: PLAYING IT 1500 TIMES FASTER

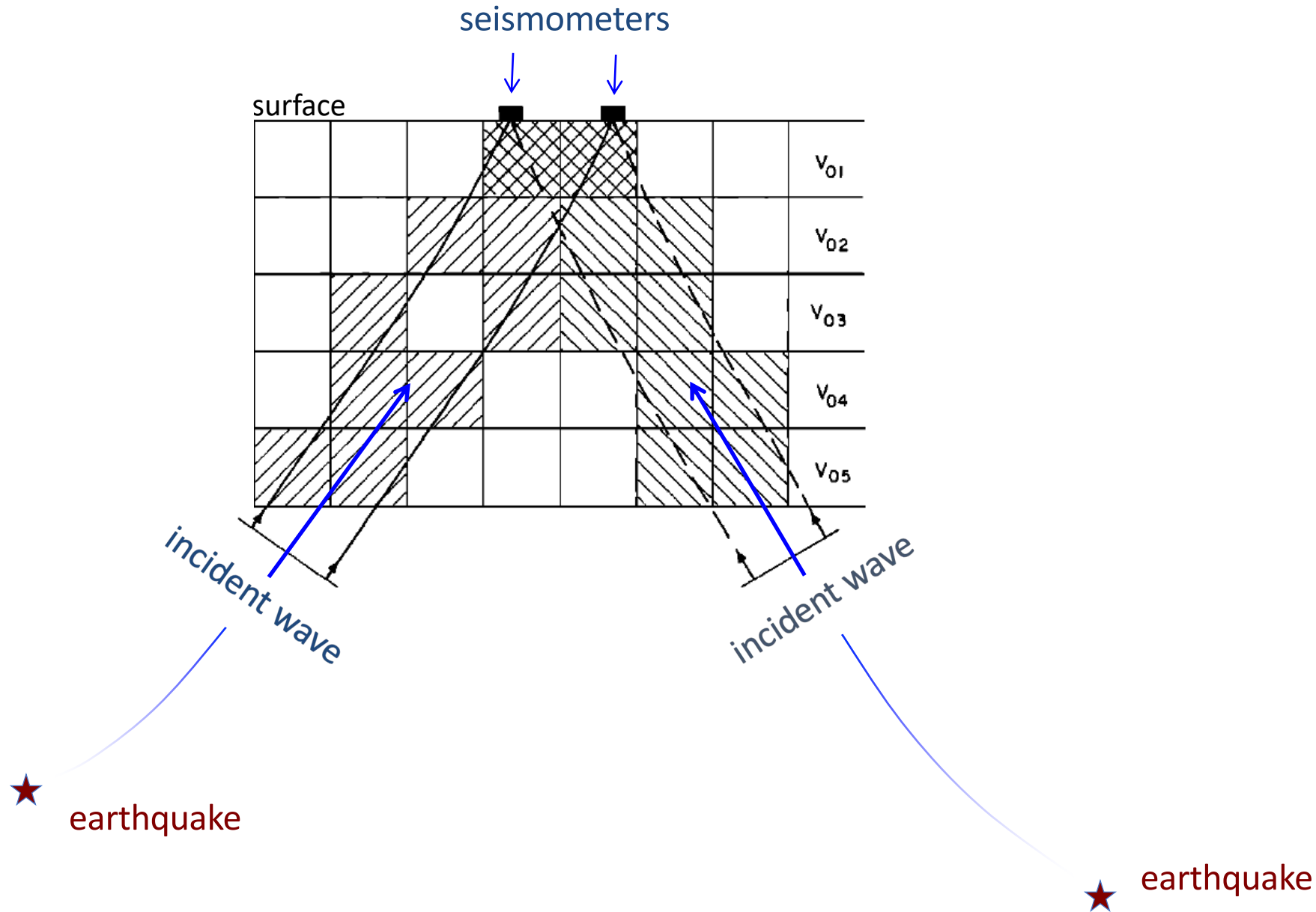


EARLY SEISMIC TOMOGRAPHY INSPIRED BY MEDICAL IMAGING [AKI ET AL., 1977]

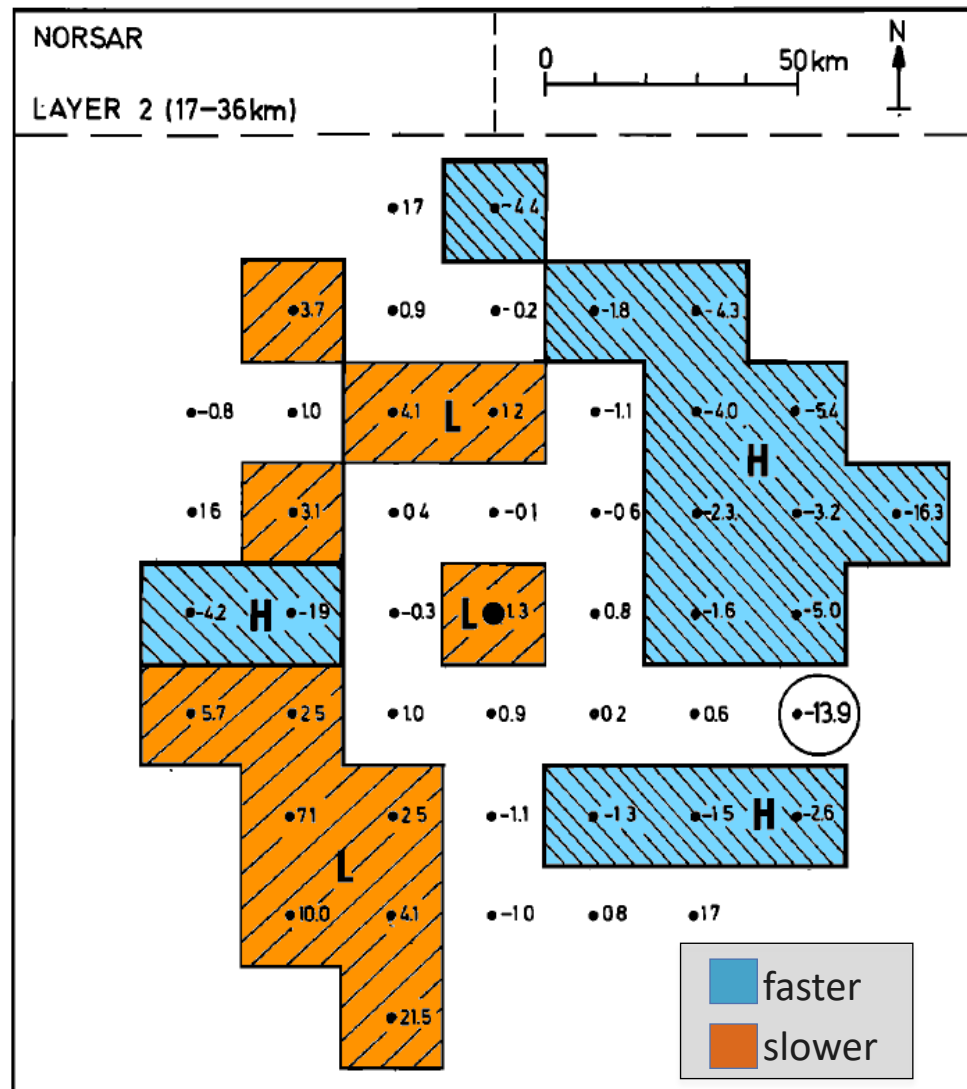


● seismometer

EARLY SEISMIC TOMOGRAPHY INSPIRED BY MEDICAL IMAGING [AKI ET AL., 1977]

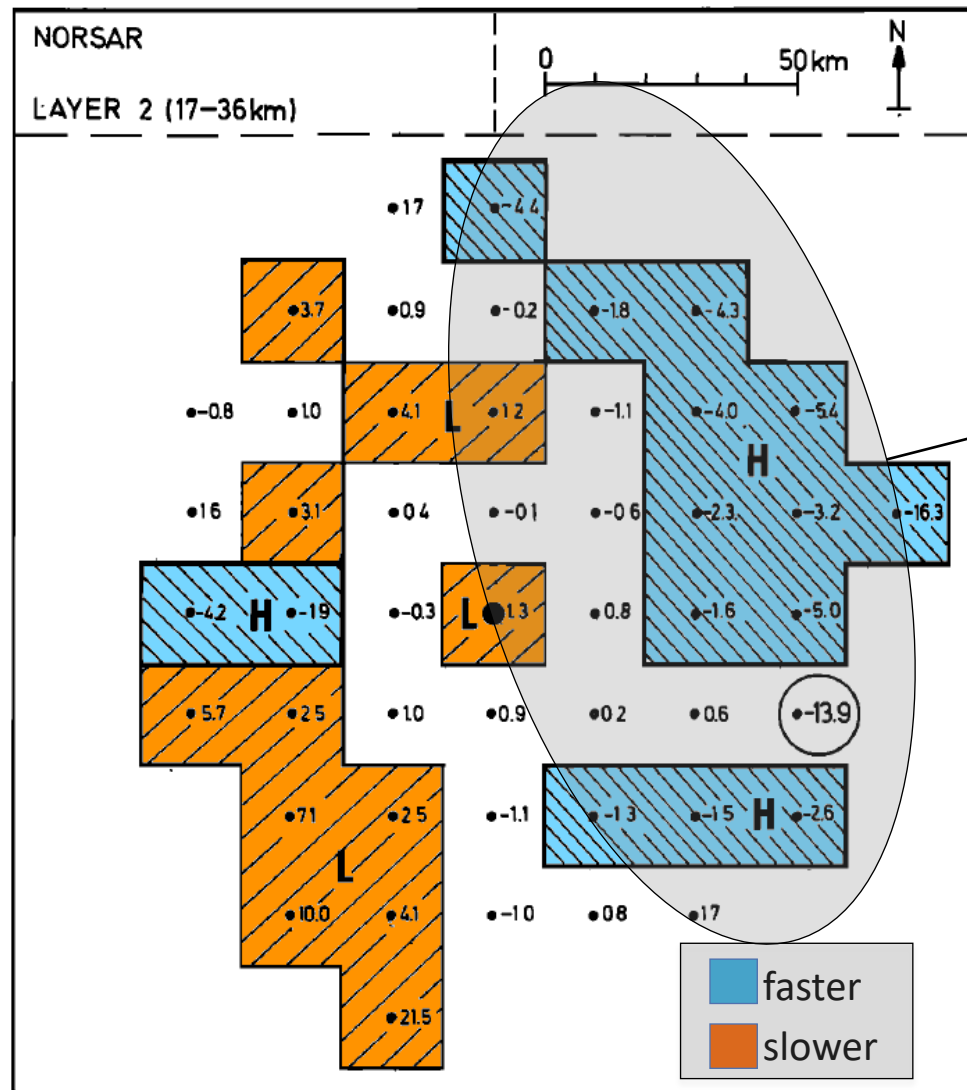


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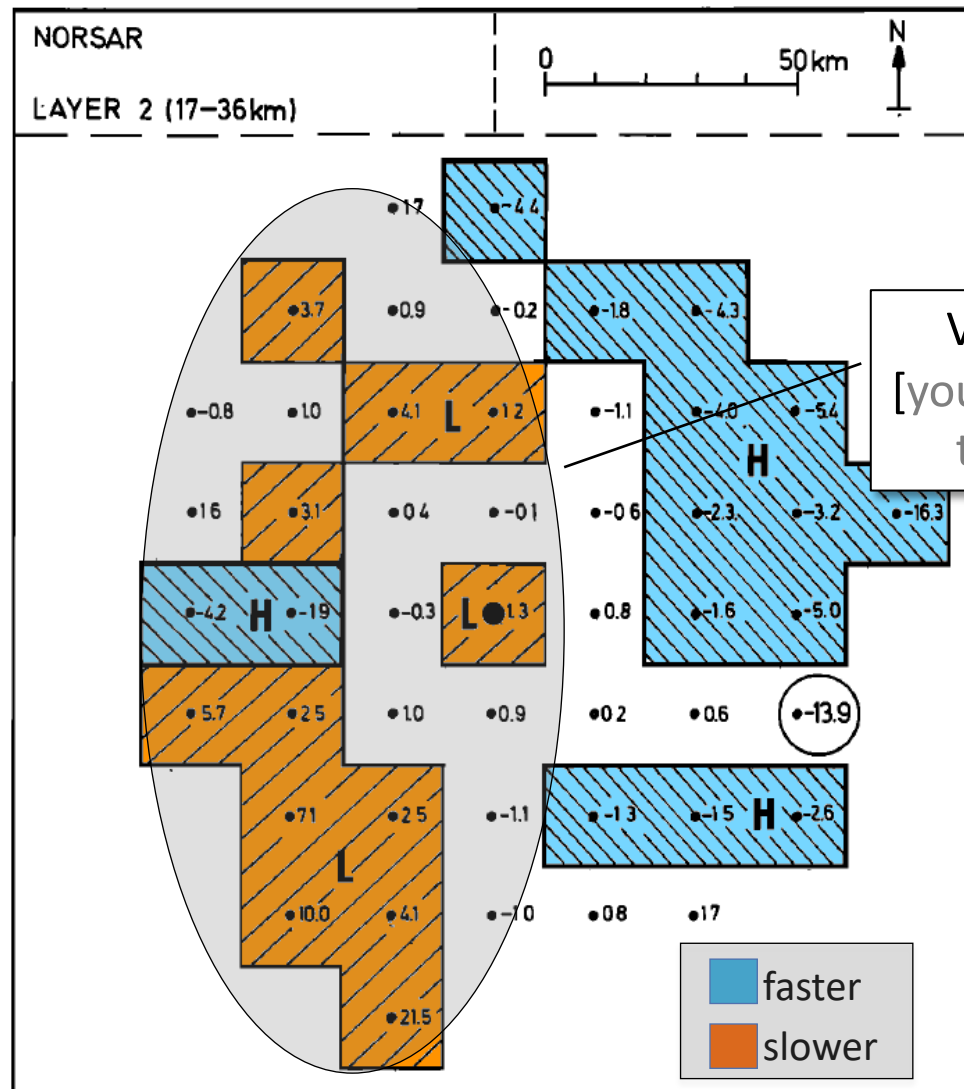
compressional wave velocity between 17-36 km depth

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compressional wave velocity between 17-36 km depth

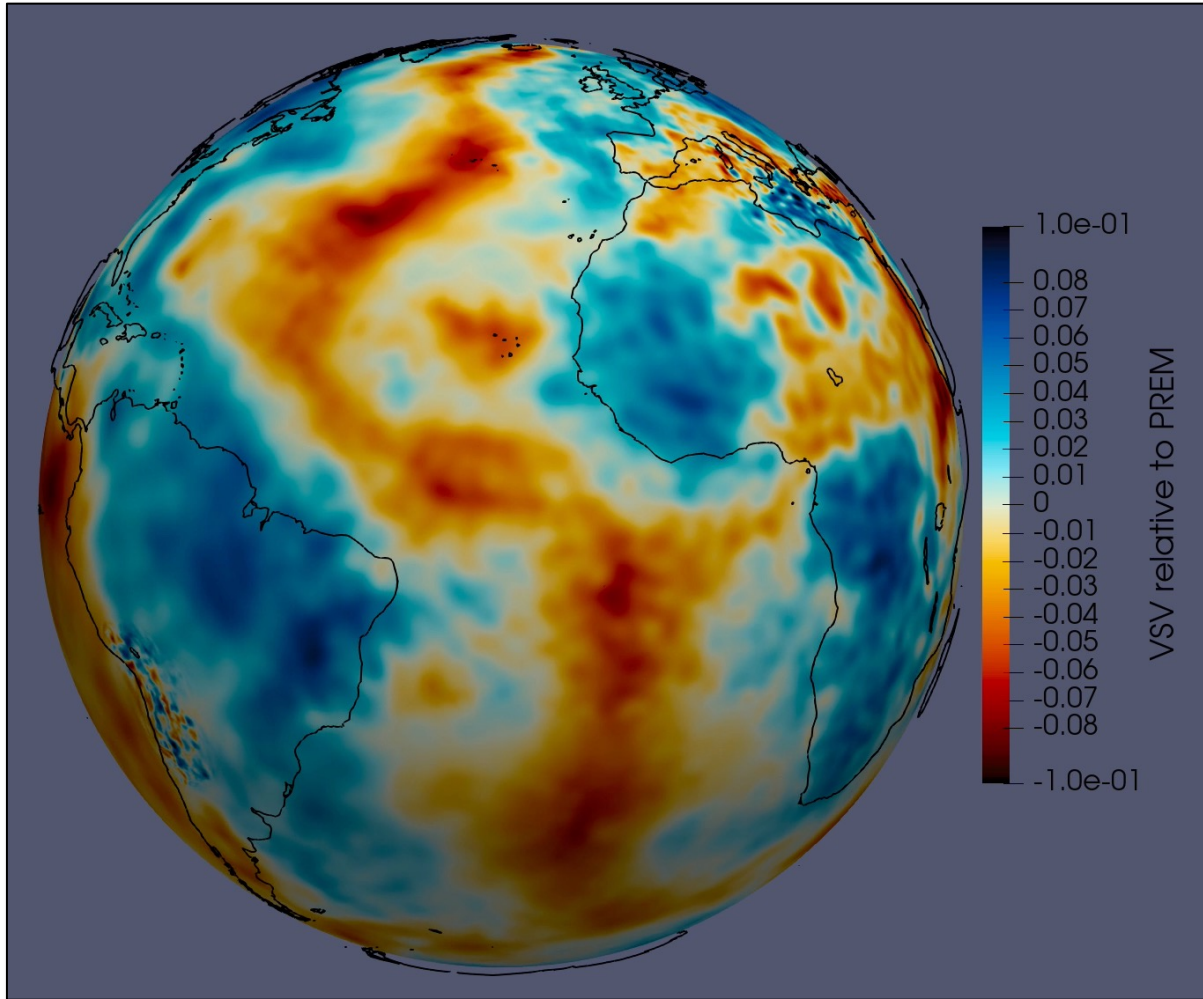
EARLY SEISMIC TOMOGRAPHY INSPIRED BY MEDICAL IMAGING [AKI ET AL., 1977]



Volcanically active
[young and hot rocks of
the Oslo-Graben]

compressional wave velocity between 17-36 km depth

Multi-scale full-waveform inversion (FWI) of the whole Earth



THE BIGGER FWI PICTURE

-
- Dynamics, evolution and composition of the Earth
-
-
-
-
-
-
-

THE BIGGER FWI PICTURE

Scale	
1'000'000 km	▪ Internal structure of the Sun
100's – 10'000 km	▪ Dynamics, evolution and composition of the Earth ▪ ▪ ▪ ▪ ▪ ▪ ▪

THE BIGGER FWI PICTURE

Scale

1'000'000 km

- Internal structure of the Sun
- Dynamics, evolution and composition of the Earth

100's – 10'000 km

- Earthquake source inversion
- Reliable tsunami warnings
- Monitoring of the Comprehensive Nuclear-Test-Ban Treaty

-
-
-
-

THE BIGGER FWI PICTURE

Scale

1'000'000 km

- Internal structure of the Sun
- Dynamics, evolution and composition of the Earth

100's – 10'000 km

- Earthquake source inversion
- Reliable tsunami warnings
- Monitoring of the Comprehensive Nuclear-Test-Ban Treaty

100 m – 10 km

- Exploration and reservoir monitoring

10 – 100 m

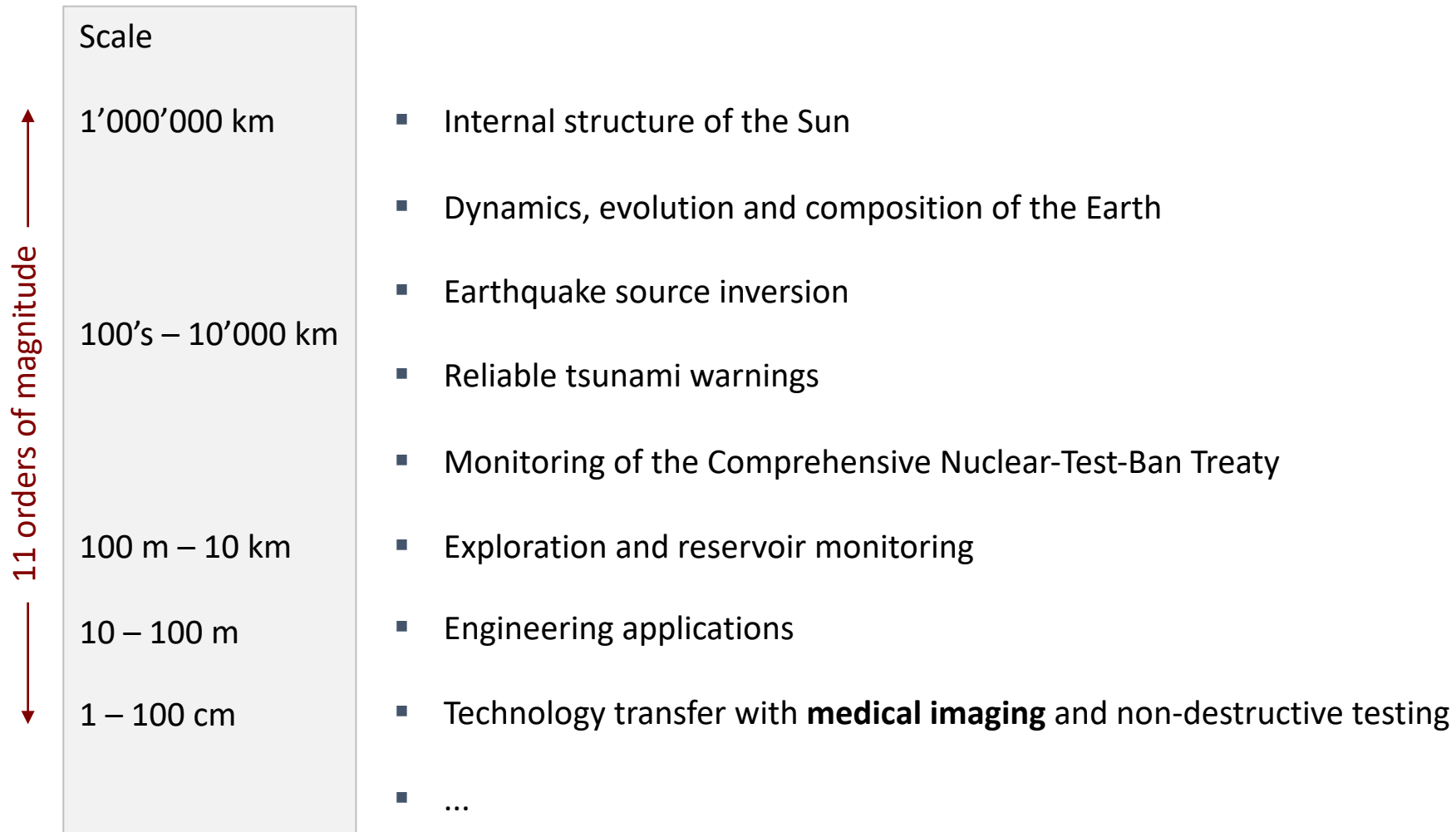
- Engineering applications

1 – 100 cm

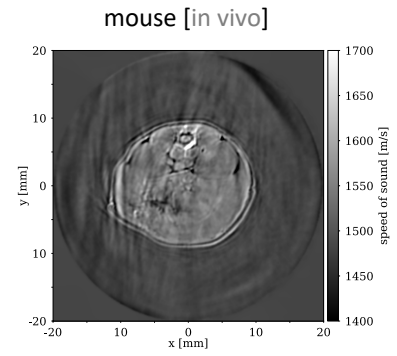
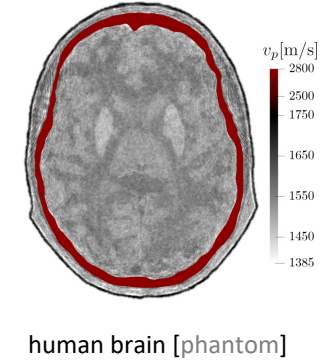
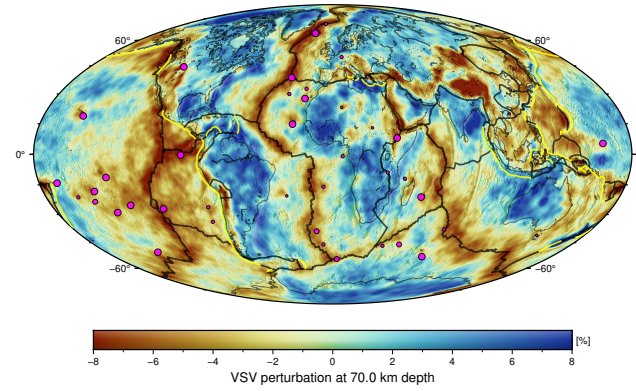
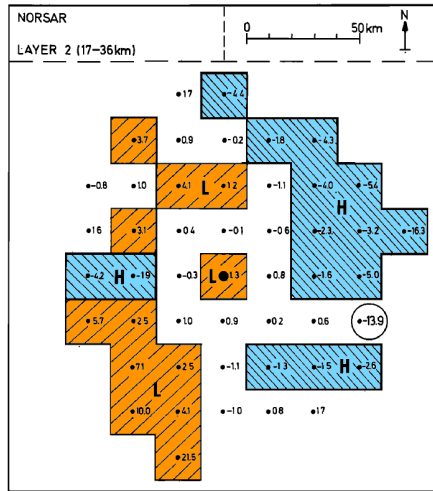
- Technology transfer with **medical imaging** and non-destructive testing

- ...

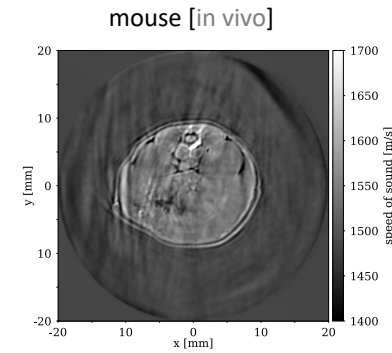
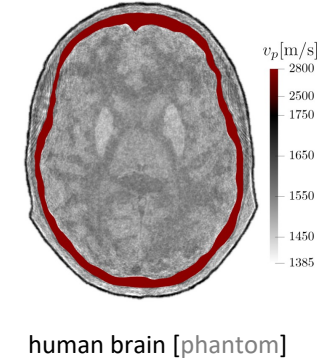
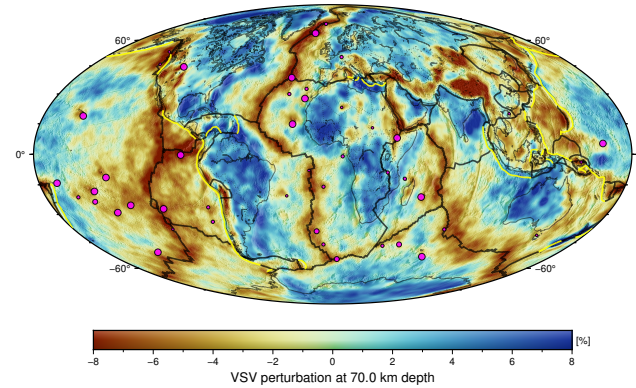
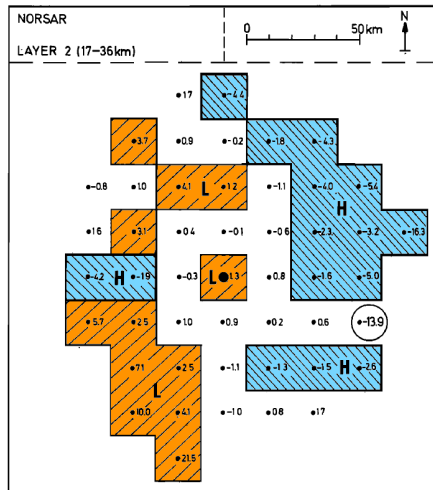
THE BIGGER FWI PICTURE



OUTLINE



OUTLINE



Part I: Seismic Full-Waveform Inversion

1. The FWI Dream
2. Simulating seismic waves in complex media
3. How wiggles see the Earth

Part II: Medical Full-Waveform Inversion

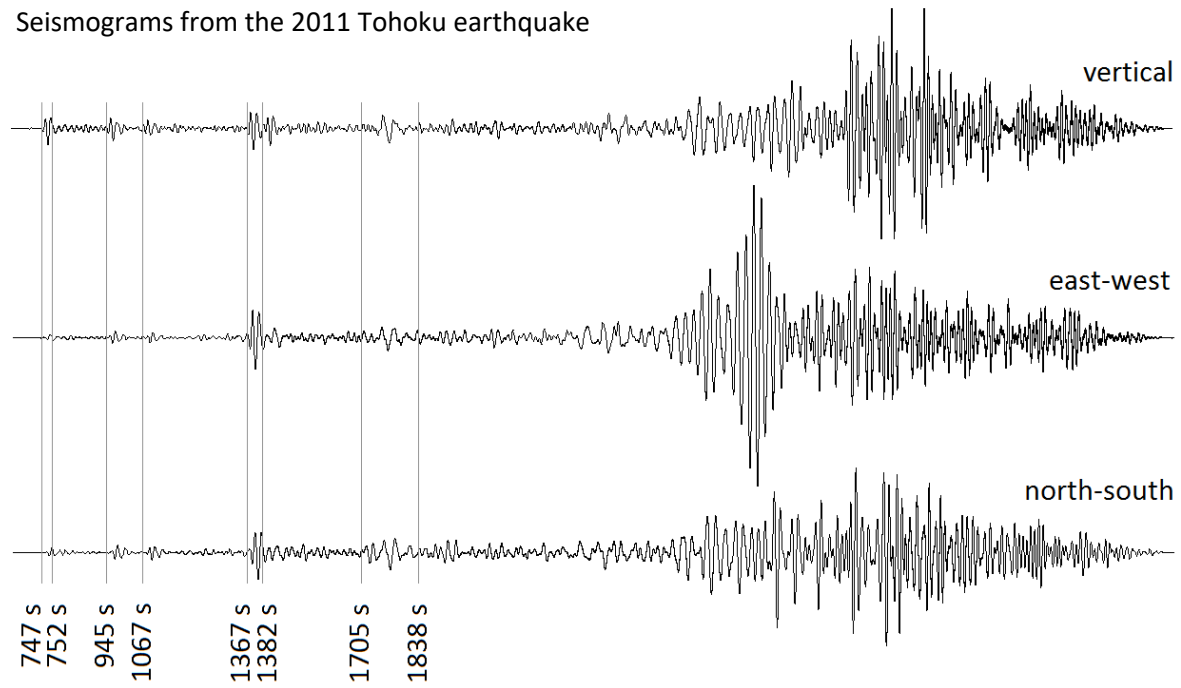
4. Motivation & challenges
5. In-vivo imaging of a mouse
6. Ultrasound imaging of the human brain

PART I

SEISMIC FULL-WAVEFORM INVERSION [FWI]

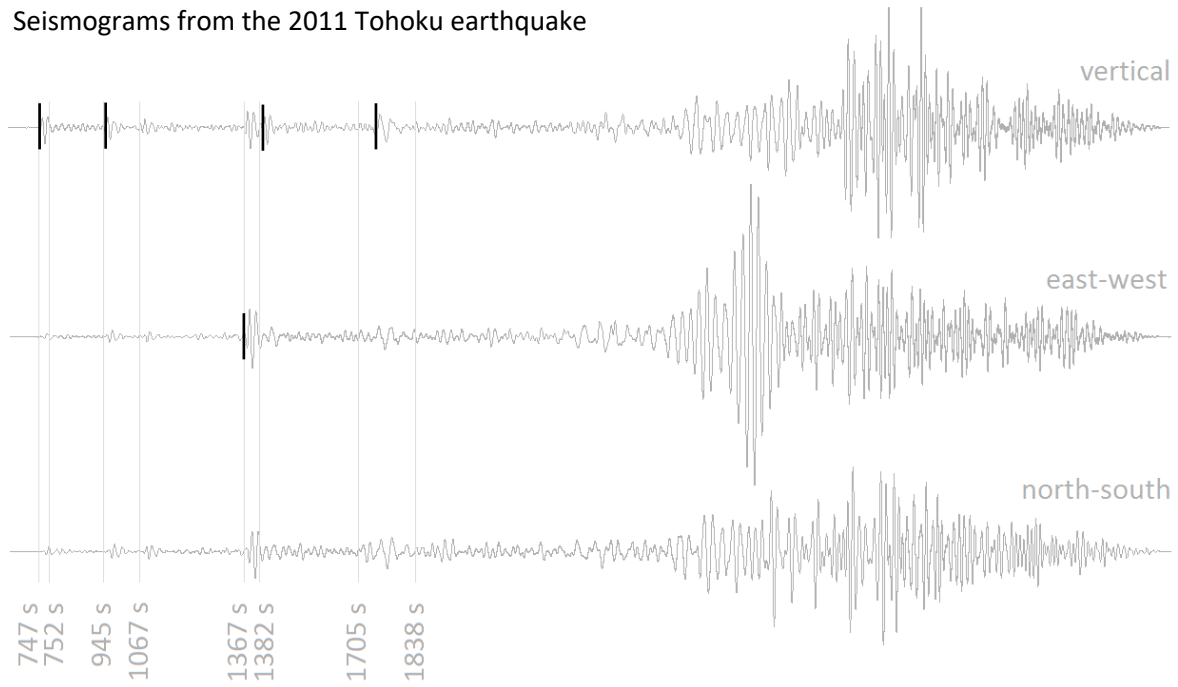
THE FWI DREAM

Seismograms from the 2011 Tohoku earthquake



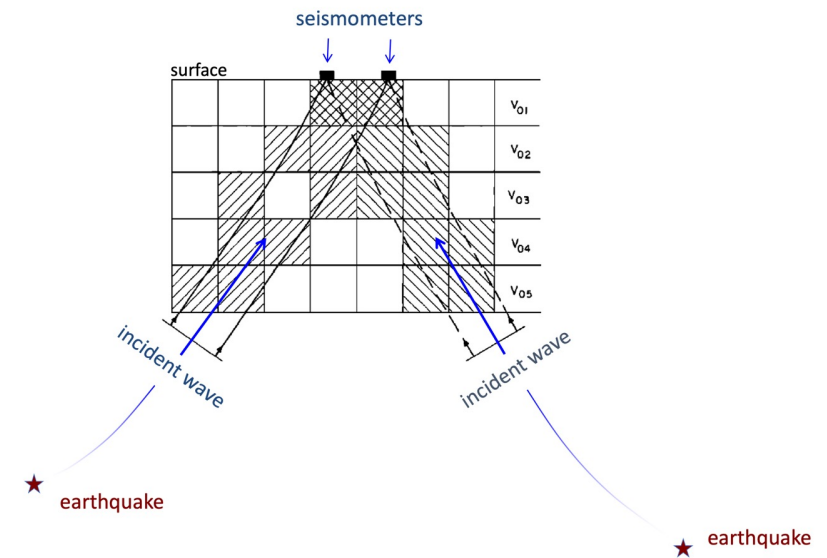
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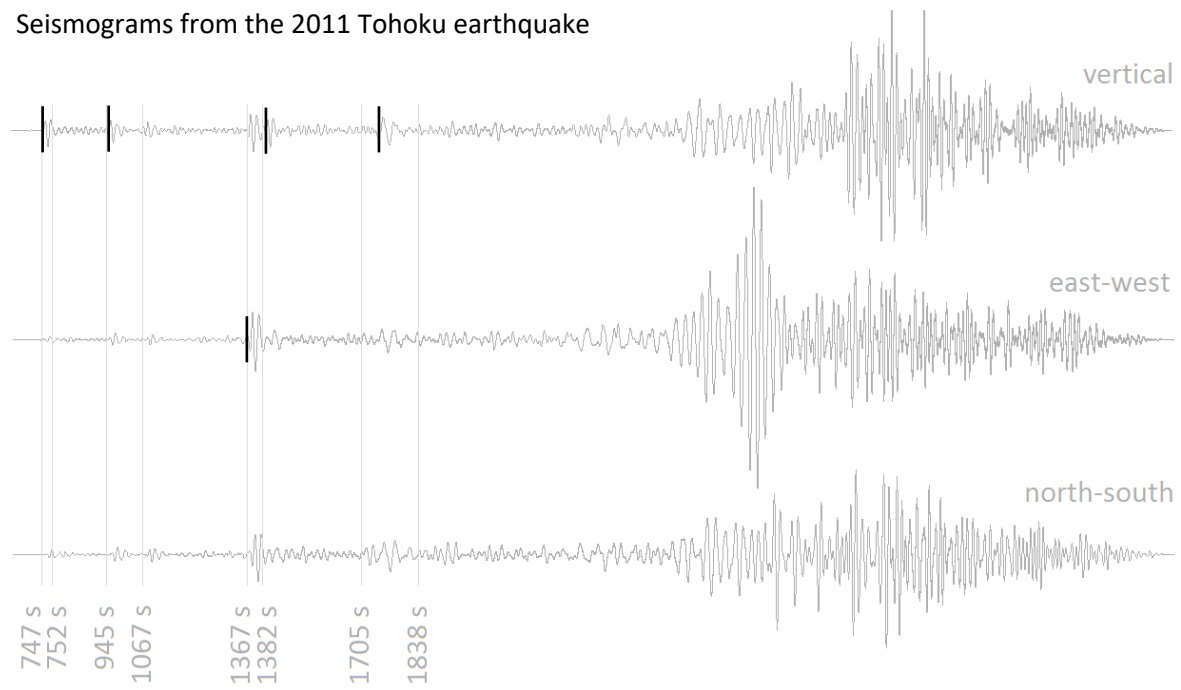
Traveltime tomography

- Measure arrival times of few identifiable waves
- Model and invert using geometric ray theory [as in optics]



THE FWI DREAM

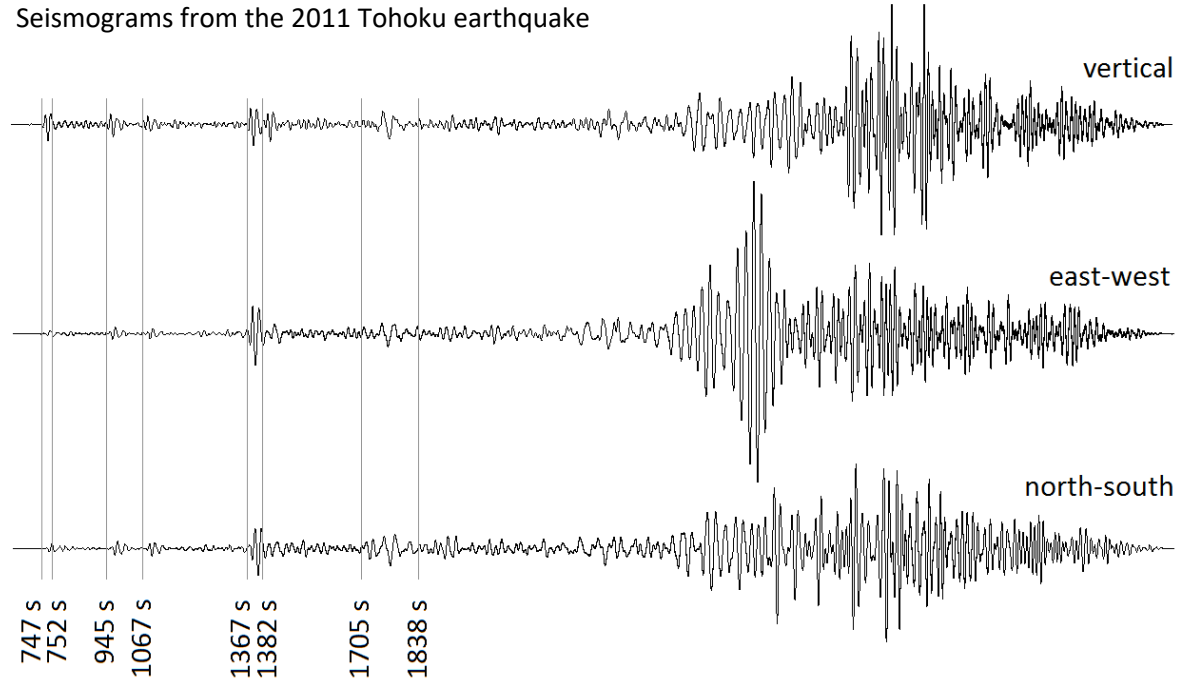
Seismograms from the 2011 Tohoku earthquake



Traveltime tomography

- Measure arrival times of few identifiable waves
 - Model and invert using geometric ray theory [as in optics]
- 😊 Fast and inexpensive
- 😞 Valuable information is discarded.

Seismograms from the 2011 Tohoku earthquake

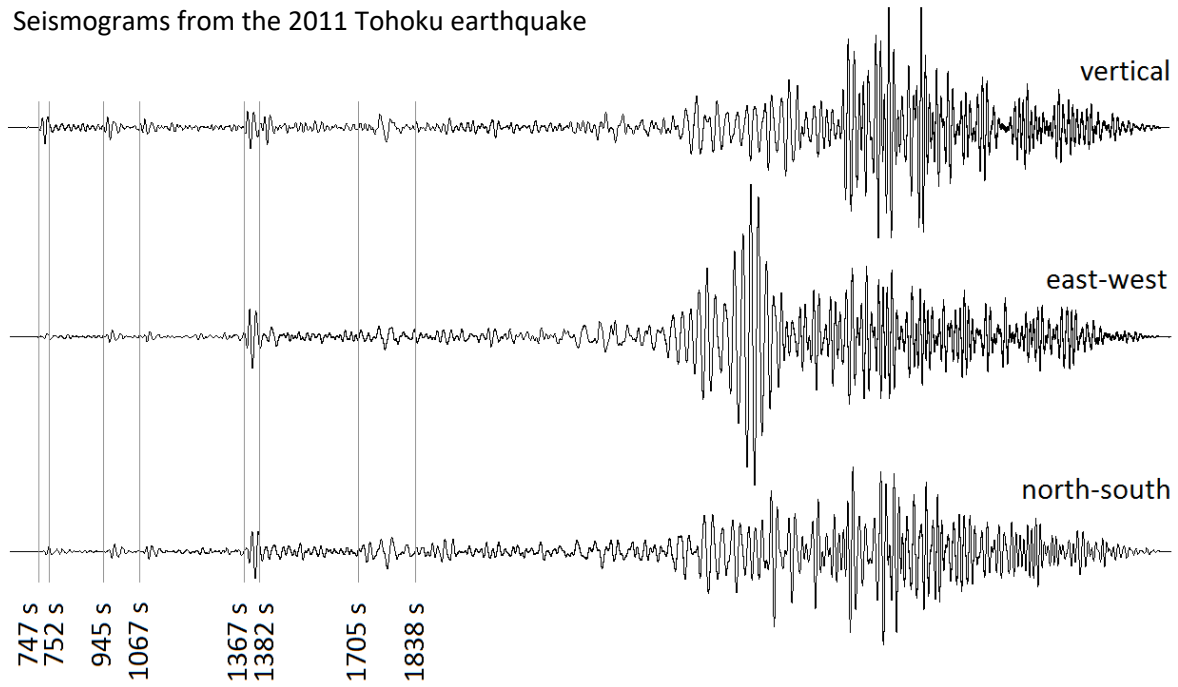


Full-waveform inversion

- Exploit complete recordings
- Model and invert using numerical solutions of the wave eq.



Seismograms from the 2011 Tohoku earthquake



Full-waveform inversion

- Exploit complete recordings
- Model and invert using numerical solutions of the wave eq.
- 😊 More information >> higher resolution
- 😞 Methodologically complex and computationally expensive

How can we model complete wavefields in complex media?

Seismograms from the 2011 Tohoku earthquake



Full-waveform inversion

- Exploit complete recordings
- Model and invert using numerical solutions of the wave eq.

How do the wiggles depend on 3-D [Earth, human, ...] structure?

More information >> higher resolution
Methodologically complex and computationally expensive

How can we model complete wavefields in complex media?

Seismograms from the 2011 Tohoku earthquake

>> spectral-element method

Full-waveform inversion

Explicitly recorded

- Model and invert using numerical solutions of the wave eq.

How do the wiggles depend on 3-D [Earth, human, ...] structure?

More information >> higher resolution

Methodologically complex and computationally expensive

>> adjoint method



Principal desiderata

- Operates in complex media [irregular topography, complex shapes of human body parts]
- Flexible and realistic material properties [attenuation, anisotropy]
- Solid, fluid and solid-fluid coupled media [solid Earth, soft tissue, oceans, human head]

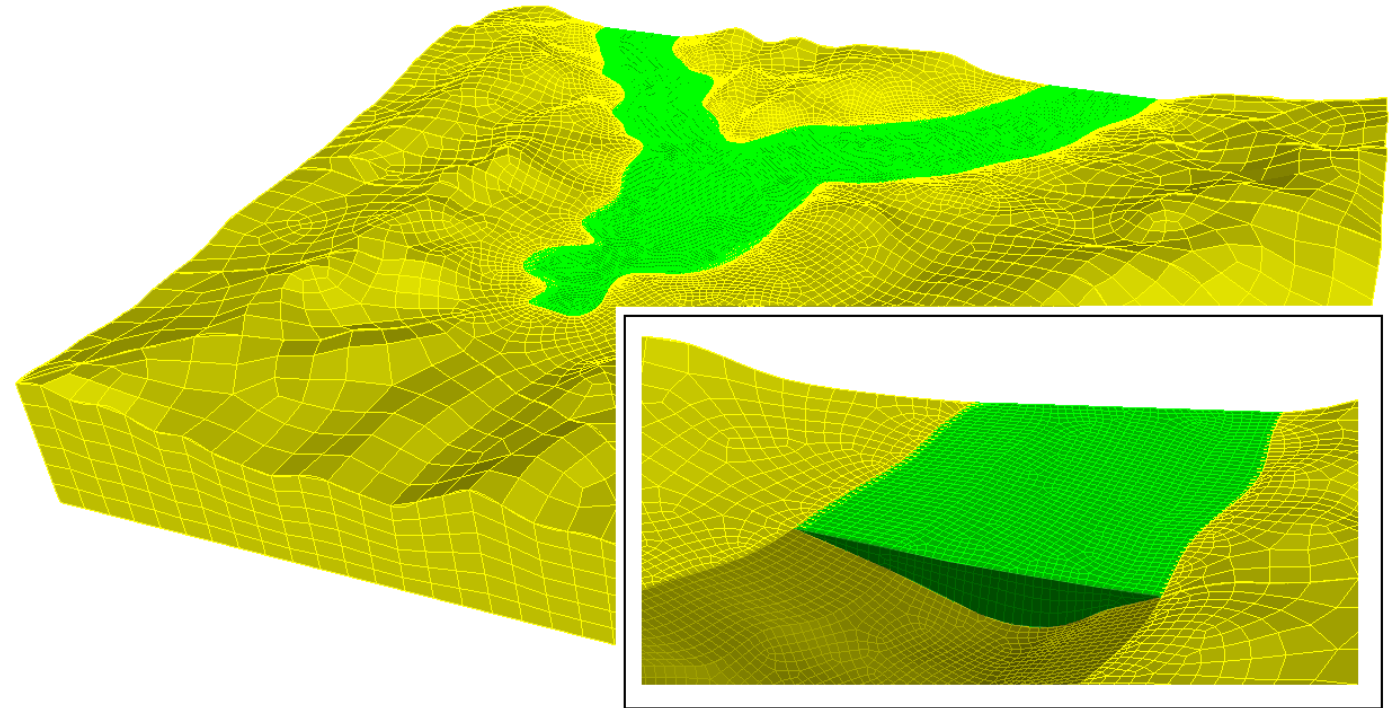
THE SPECTRAL-ELEMENT METHOD (SEM)

Principal desiderata

- Operates in complex media [irregular topography, complex shapes of human body parts]
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SEM basics

- Consider weak form of the wave equation
- Discretise into hexahedral elements



Stupazzini et al. 2009

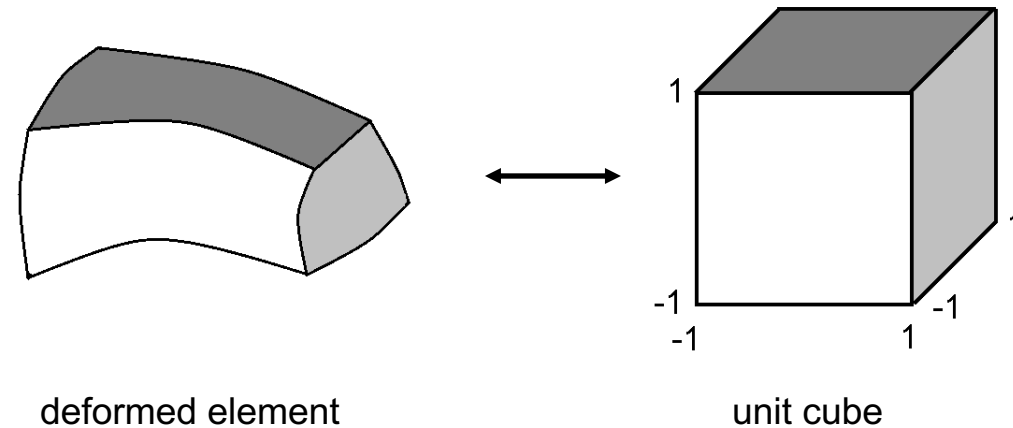
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- Integrate in space using Gauss-Lobatto-Legendre (GLL) points >> diagonal mass matrix

$$\ddot{\mathbf{u}} = \mathbf{M}^{-1} \cdot (\mathbf{f} - \mathbf{K} \cdot \mathbf{u})$$

\mathbf{u} = discrete wavefield

\mathbf{M} = mass matrix

\mathbf{K} = stiffness matrix

\mathbf{f} = external force

THE SPECTRAL-ELEMENT METHOD (SEM)

Principal desiderata

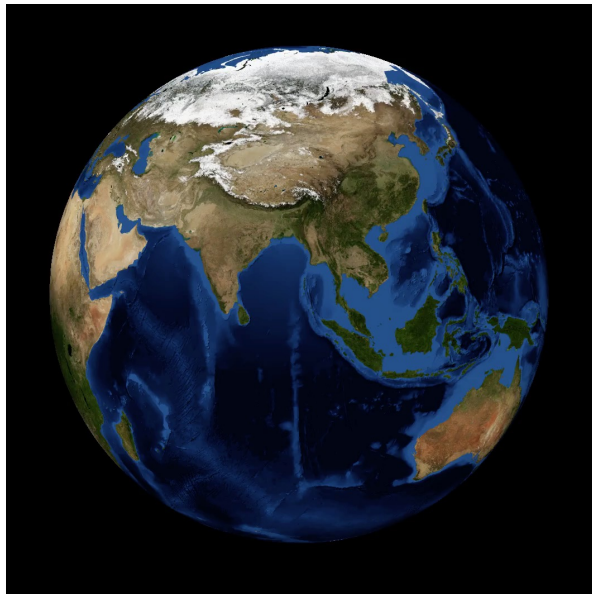
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SEM basics

- Consider weak form of the wave equation
- Discretise into hexahedral elements
- Map elements onto unit cube
- Integrate in space using Gauss-Lobatto-Legendre (GLL) points \gg diagonal mass matrix
- Integrate in time using an explicit method

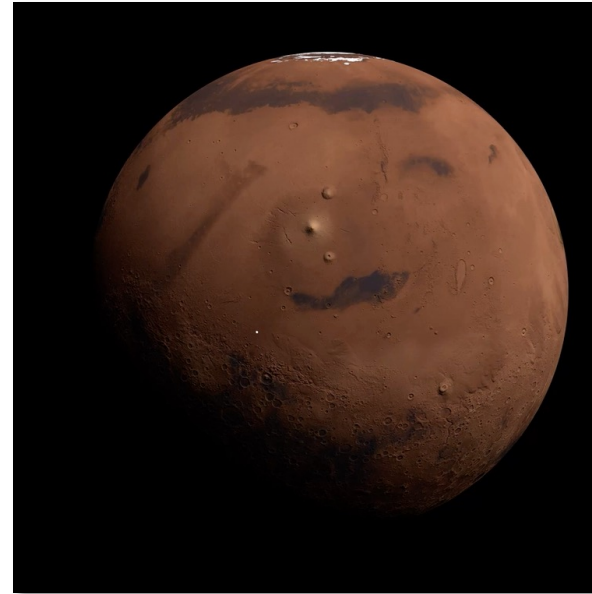
Earth and planetary scale

10'000 km - fluid/solid



11 March 2011 Tohoku earthquake

5'000 km - fluid/solid



Hypothetical marsquake

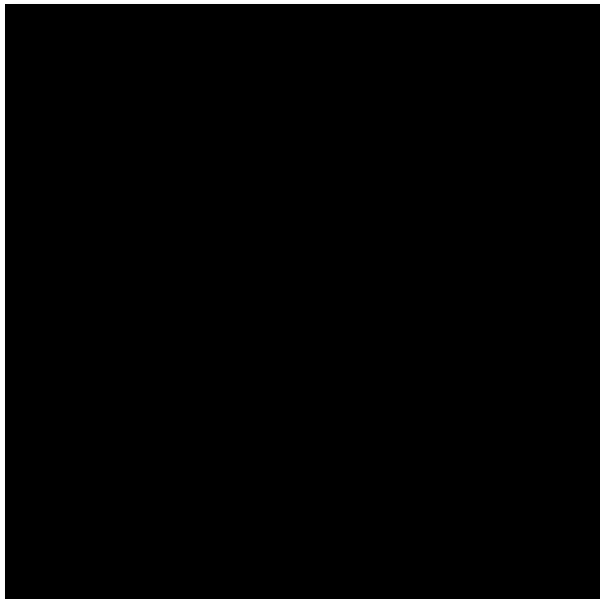
1 km - fluid/solid



Sub-sea sedimentary layers and salt body

Engineering and medical scale

10 cm - solid



elastic wave inside a clamp

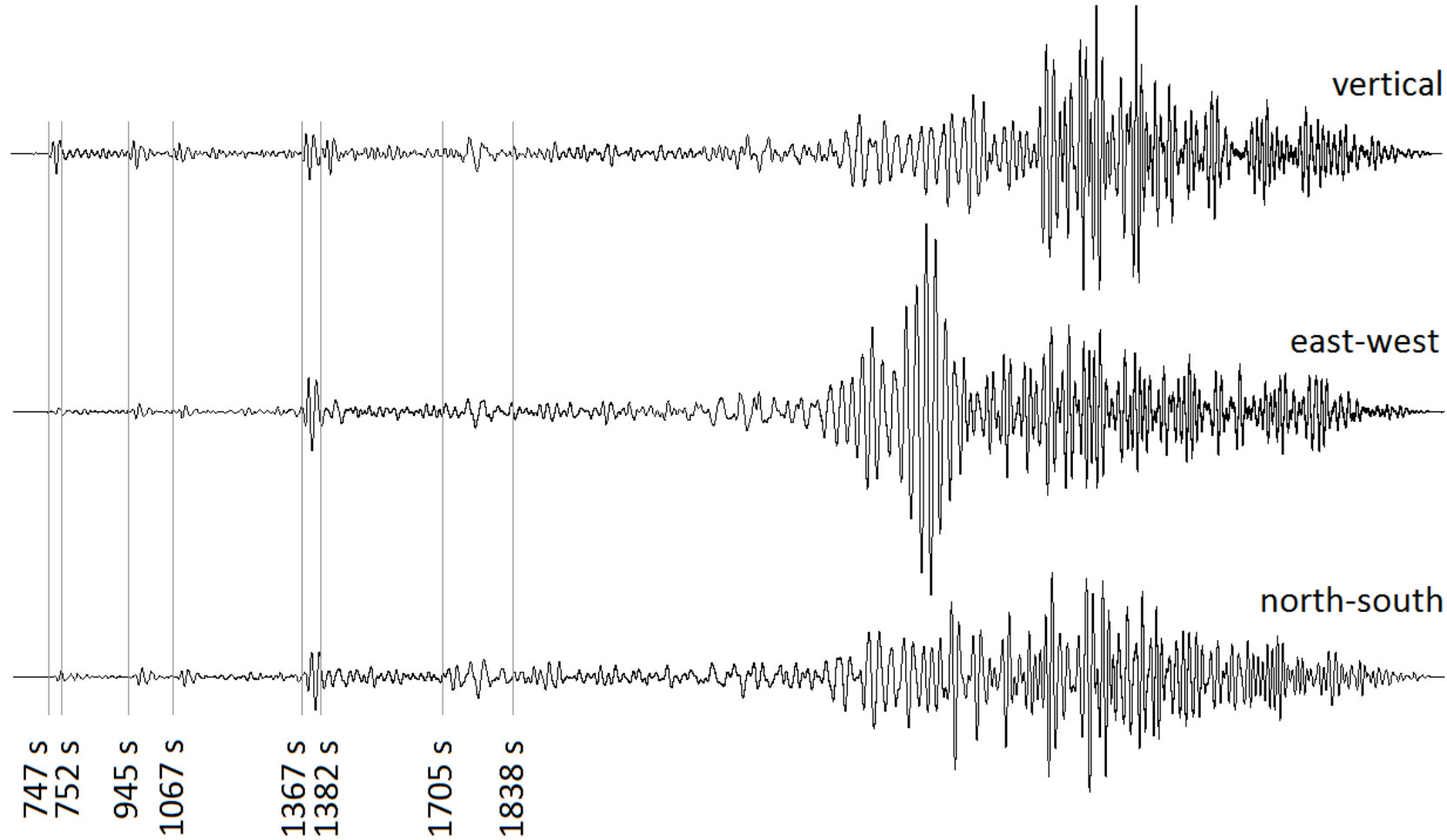
20 cm - solid



acoustic wave inside a human breast

ADJOINT METHOD & SENSITIVITY KERNELS

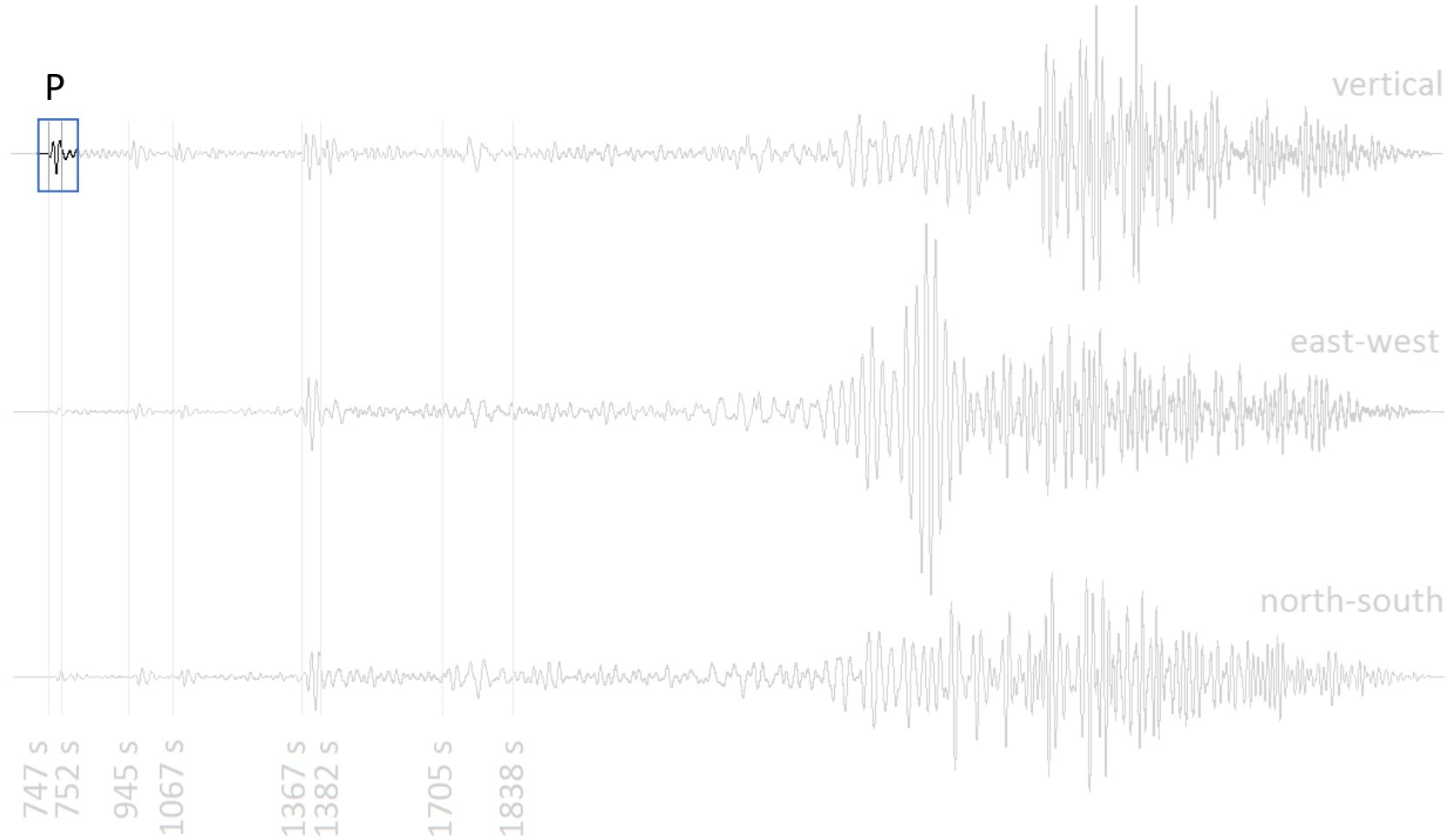
Given sufficient computational resources we can model complete seismograms.



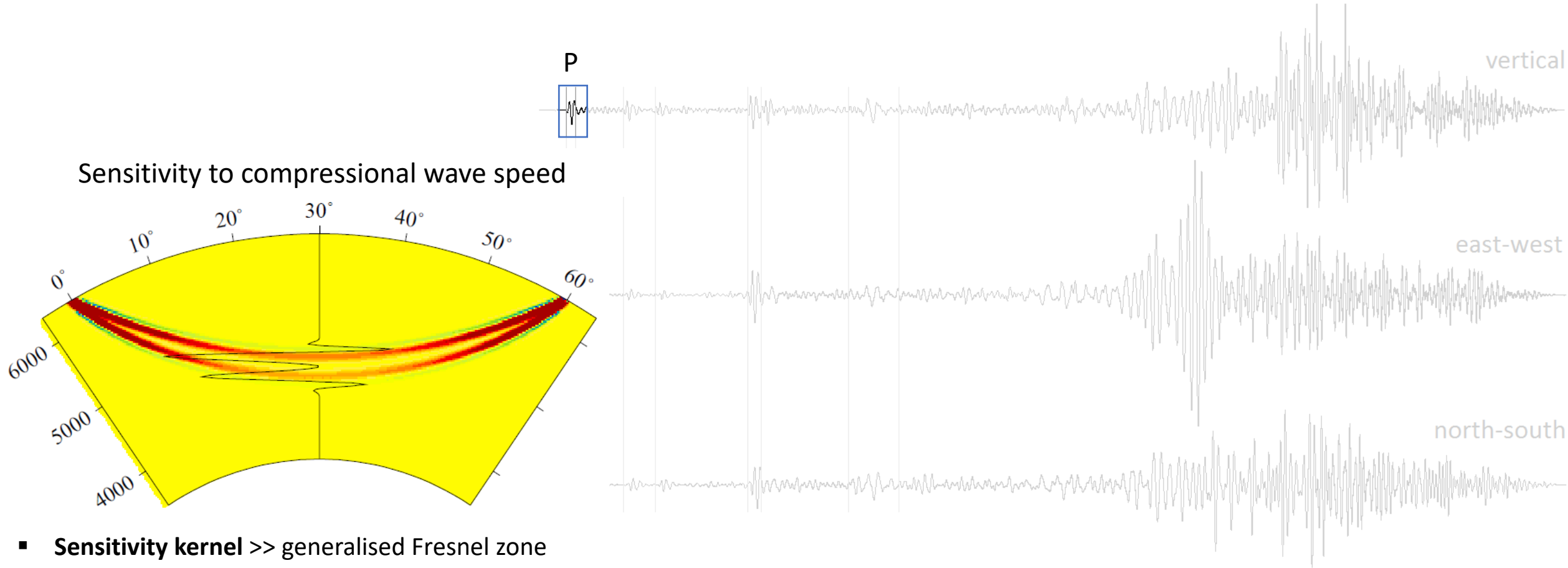
ADJOINT METHOD & SENSITIVITY KERNELS

Given sufficient computational resources we can model complete seismograms.

How does this [or any other] wiggle see the Earth?

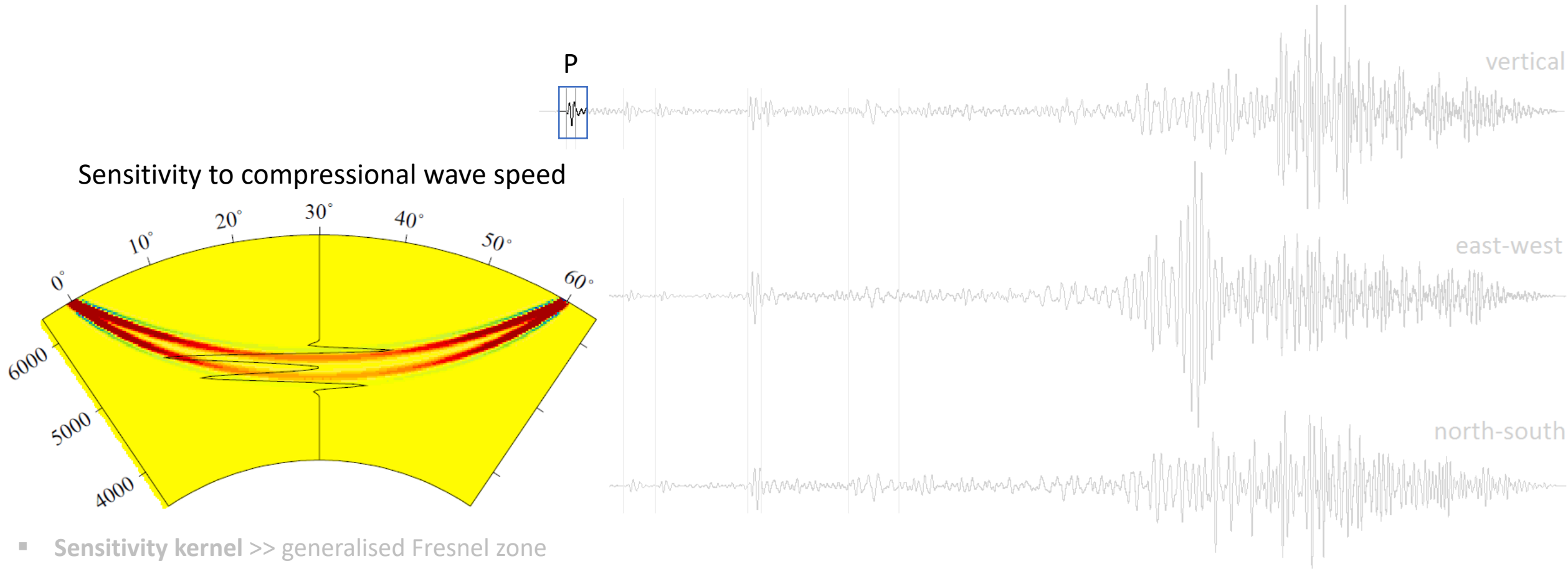


ADJOINT METHOD & SENSITIVITY KERNELS



- **Sensitivity kernel** >> generalised Fresnel zone
- 3-D representation of the partial derivatives of data w.r.t. medium parameters

ADJOINT METHOD & SENSITIVITY KERNELS

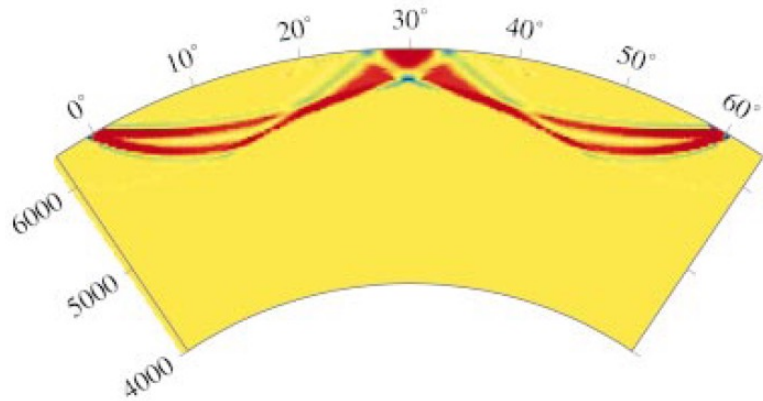


- **Sensitivity kernel** >> generalised Fresnel zone
- 3-D representation of the partial derivatives of data w.r.t. medium parameters
- Efficiently computed using the **adjoint method**
 - 1 forward simulation
 - 1 adjoint simulation [same cost as forward simulation]
- Enable iterative updating of the medium

ADJOINT METHOD & SENSITIVITY KERNELS

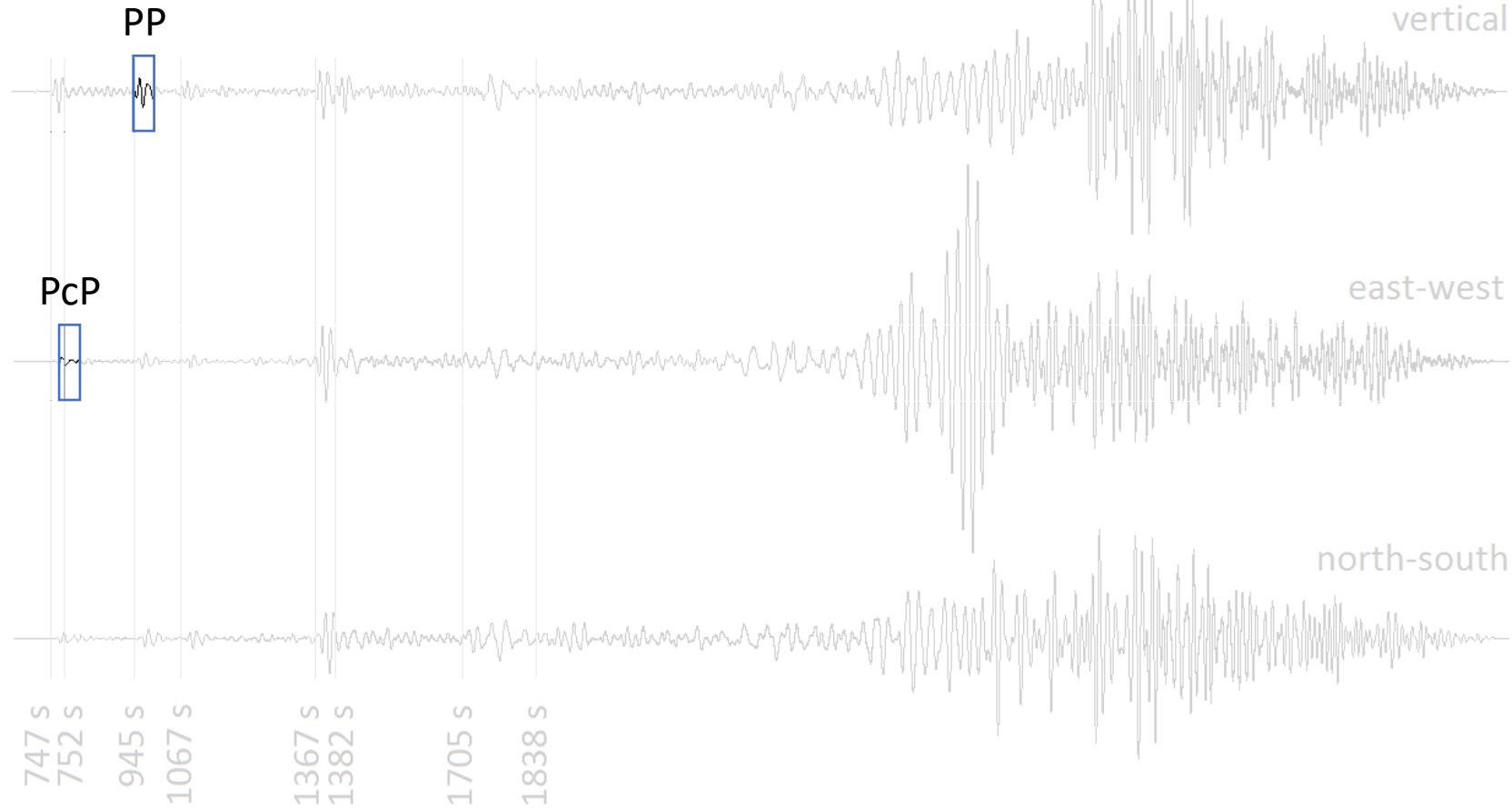
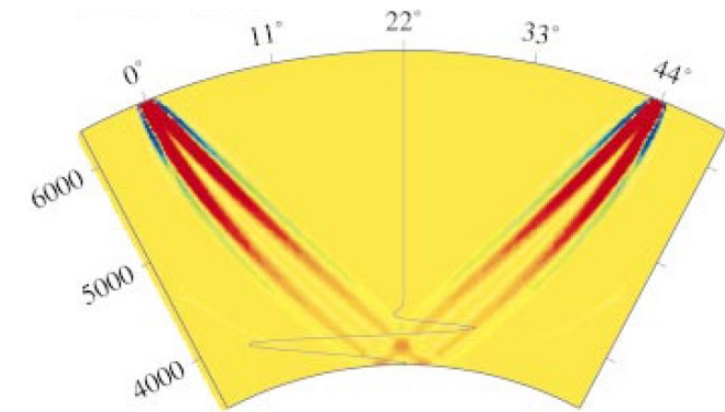
PP wave at 20 s period

sensitivity to compressional wave speed



PcP wave at 20 s period

sensitivity to compressional wave speed



... use the right type of waves [wave type, frequency, amplitudes, traveltimes, ...]
to learn what you want to know.

PART II

MEDICAL FULL-WAVEFORM INVERSION

Key Motivations

- Free of ionising radiation
- Inexpensive
- Enable frequent, repetitive analyses
- Quantitative imaging for improved diagnoses

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- Inexpensive
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Major challenges

- Small bandwidth of standard transducers
- Computational cost at high frequencies
- Complex geometry and meshing
- Fluid-solid wavefield interactions

EXAMPLE I: IN-VIVO IMAGING OF A MOUSE

Goals

- Workflow development with realistic data
- Towards improved cancer diagnoses without human experiments

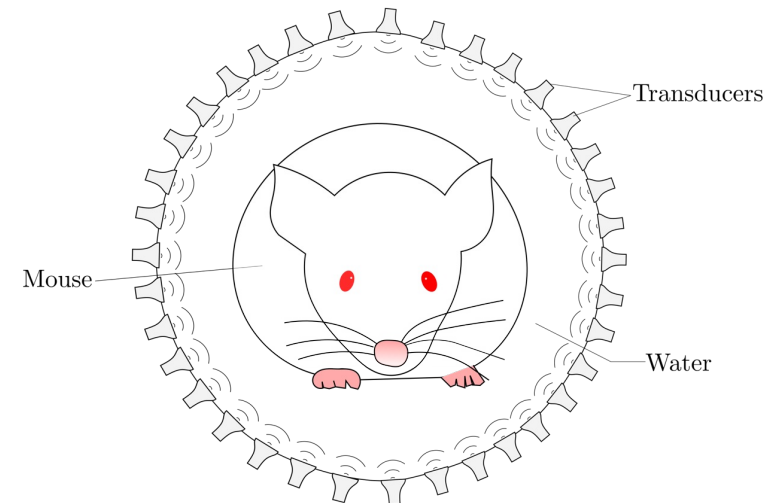
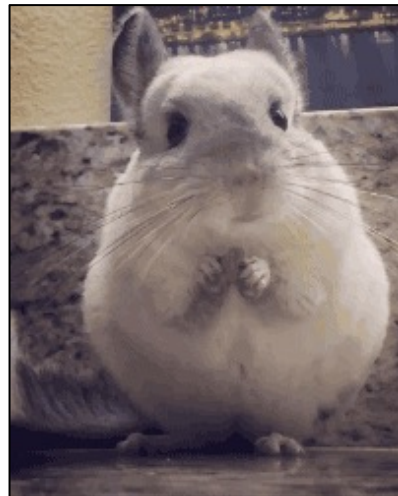
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Setup

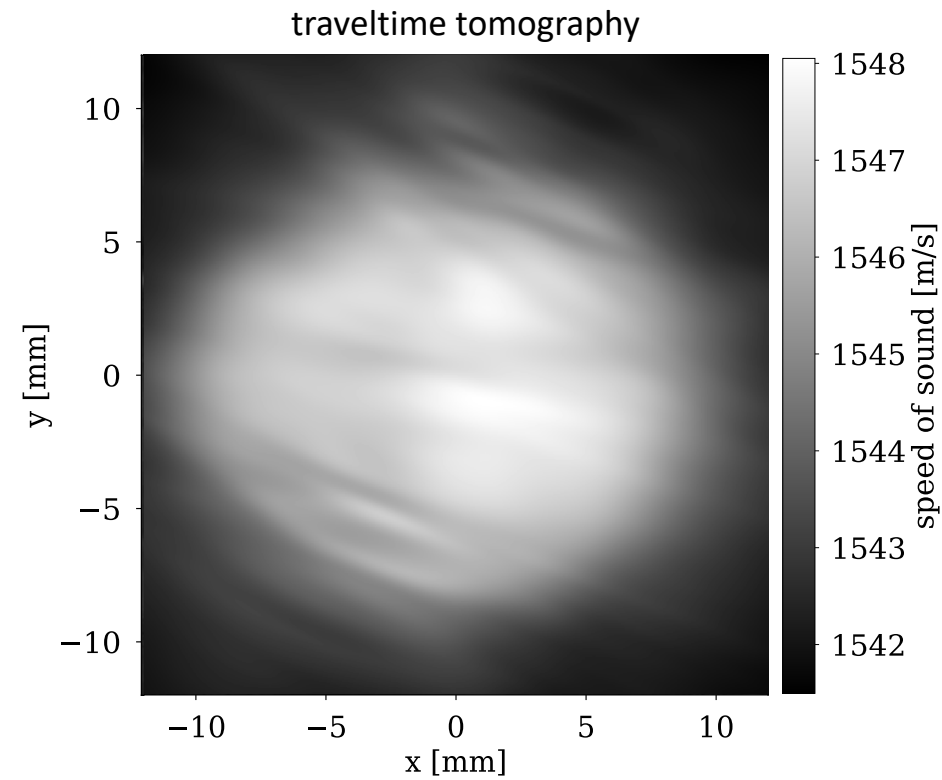
- in-vivo dataset of a mouse
- acquired with a transmission-reflection ultrasound imaging platform [Mercep et al., 2020]



EXAMPLE I: IN-VIVO IMAGING OF A MOUSE

Step 1:

- Traveltime tomography using first-arriving ultrasound pulses
- Initial model for FWI



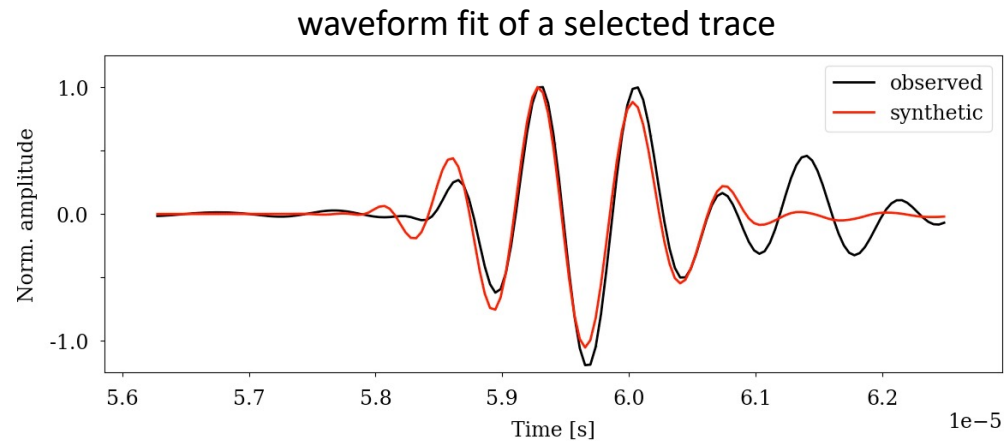
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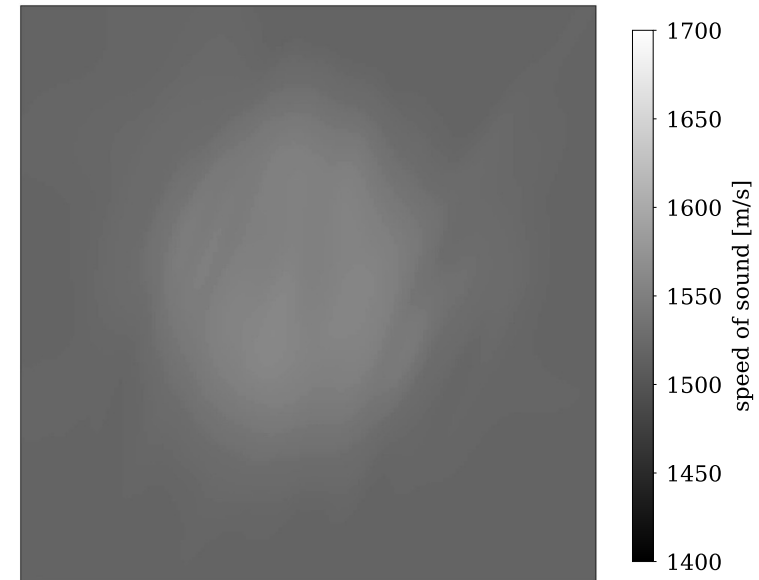
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Step 2:

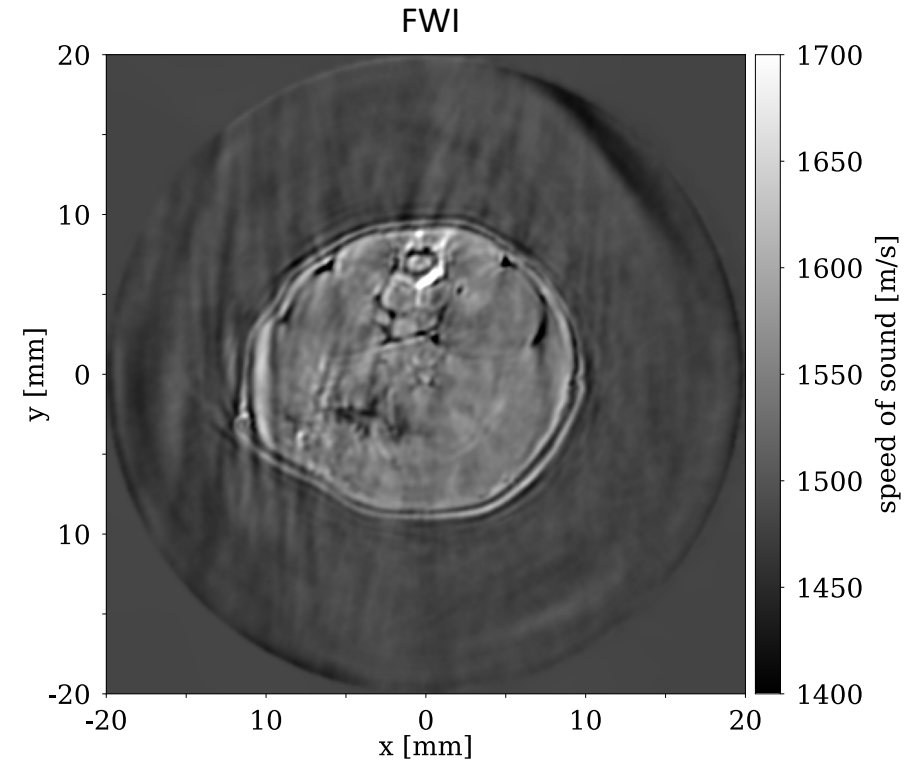
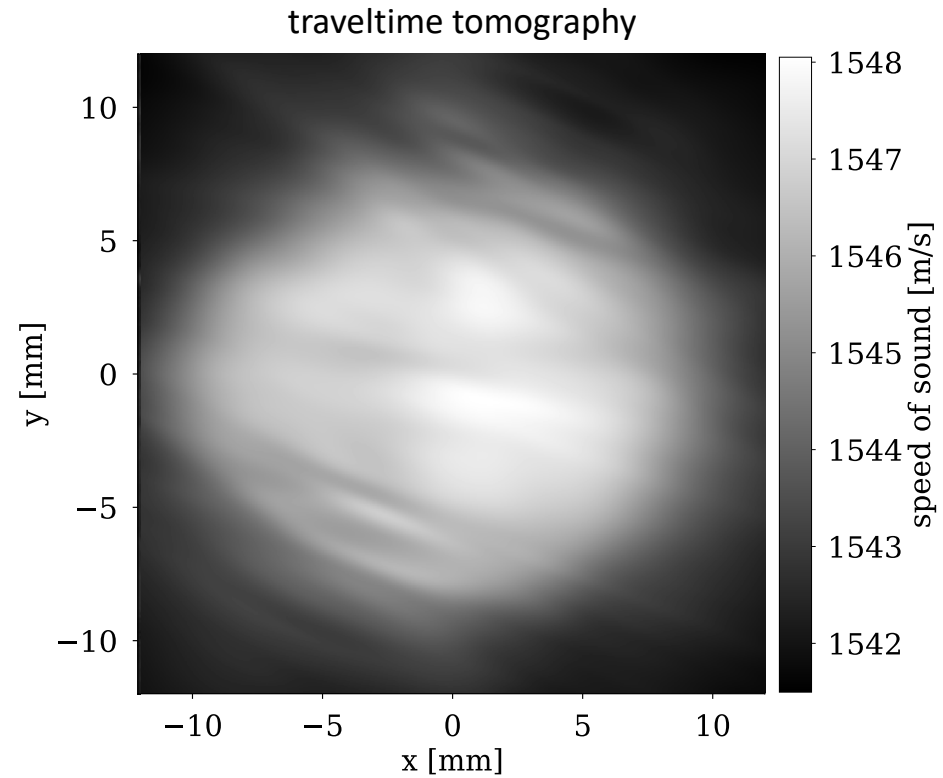
- FWI with successively increasing bandwidth
 - 750 kHz – 1.5 MHz
 - 750 kHz – 2.5 MHz
 - 750 kHz – 2.85 MHz
 - 750 kHz – 3 MHz
- 84 gradient descent (L-BFGS) iterations in total



FWI iterative improvement



EXAMPLE I: IN-VIVO IMAGING OF A MOUSE

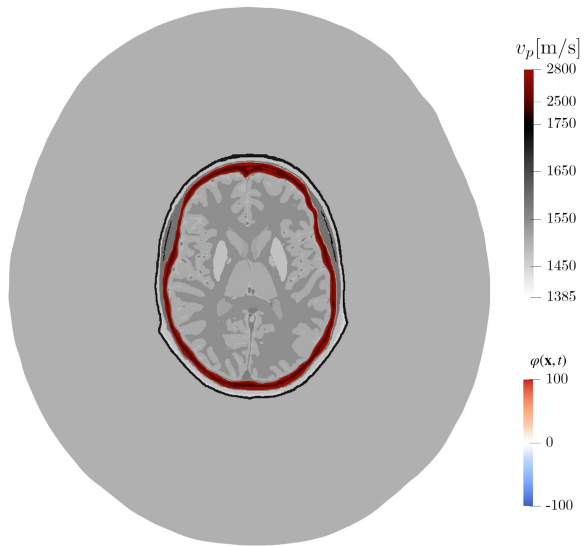


EXAMPLE II: IMAGING THE HUMAN BRAIN

Goals

- Proof of concept. Does it work at all?
- Development of an inversion strategy.

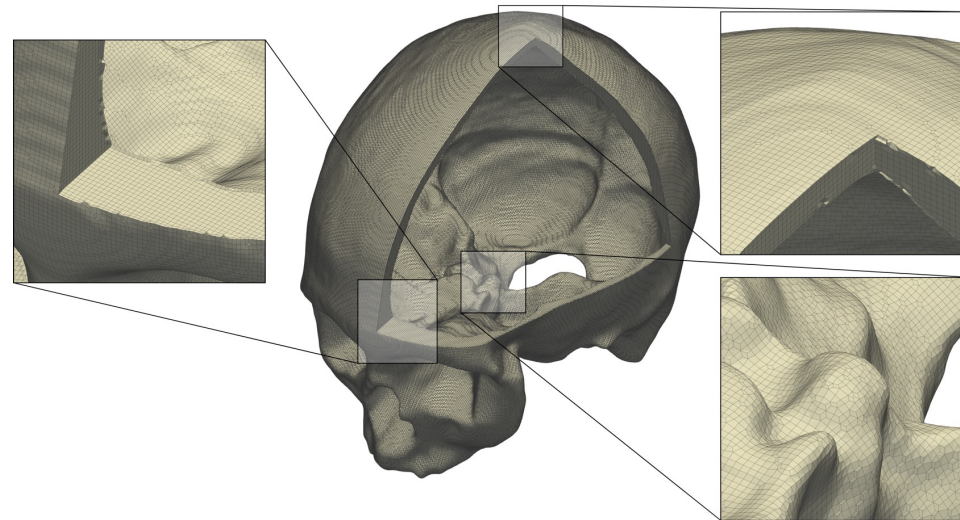
Challenges



Much of the energy is reflected off the skull.

EXAMPLE II: IMAGING THE HUMAN BRAIN

Challenges



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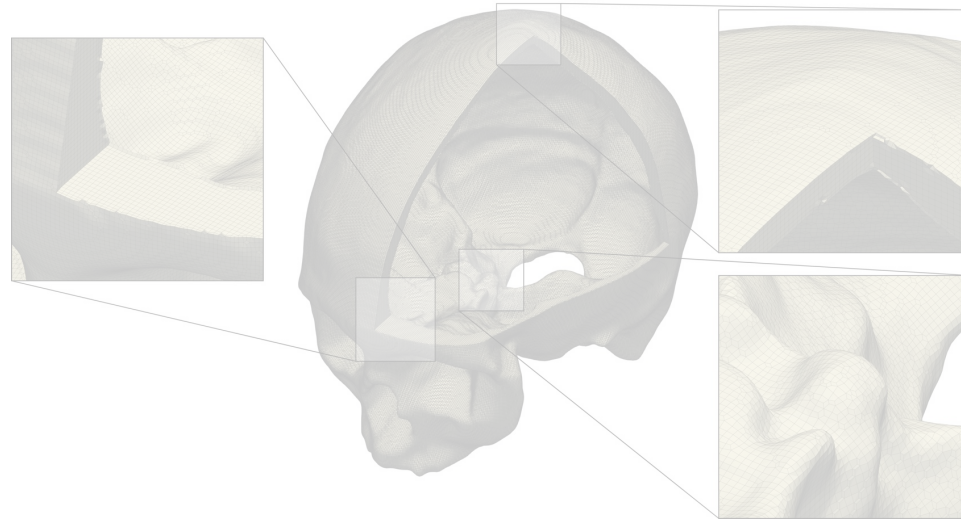
The skull is geometrically complex and difficult to mesh.

EXAMPLE II: IMAGING THE HUMAN BRAIN

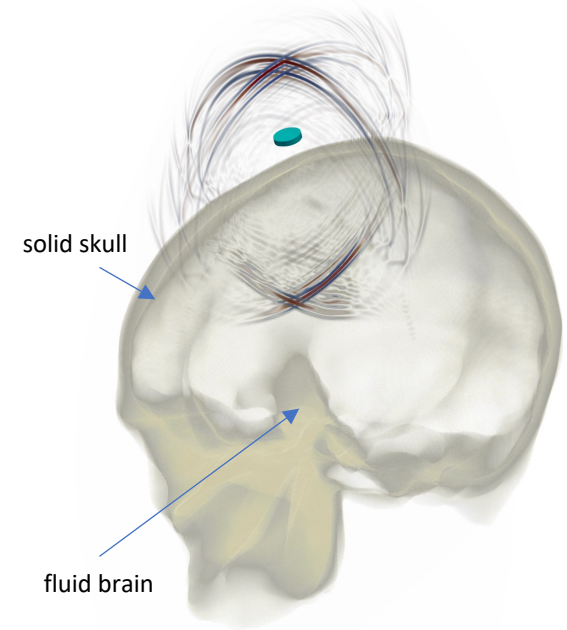
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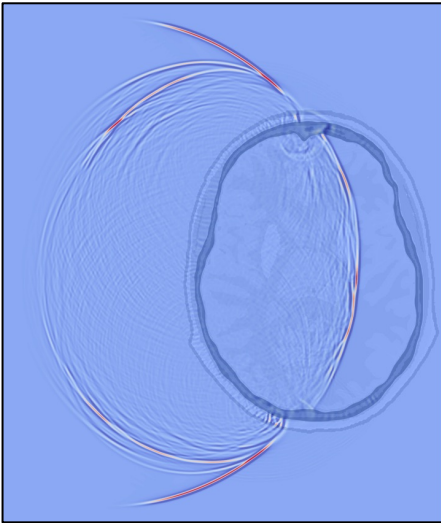


The head is a coupled fluid-solid system.

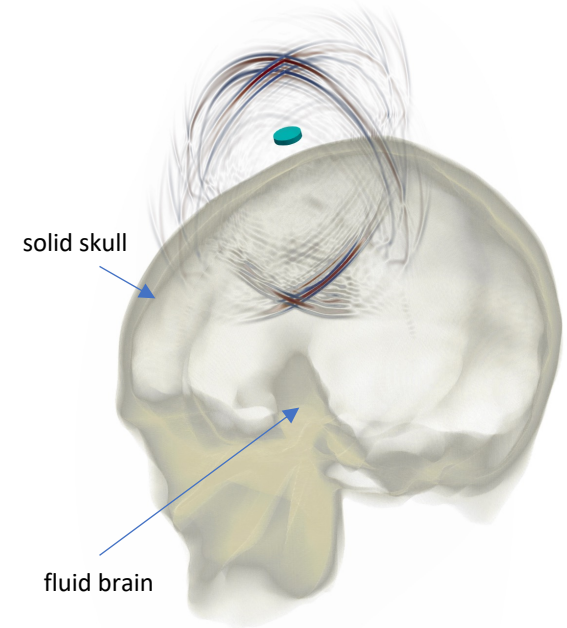
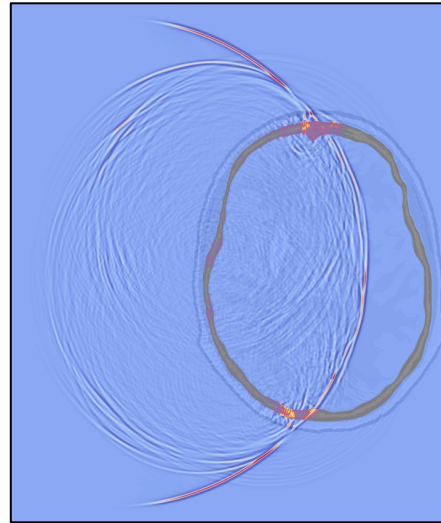
EXAMPLE II: IMAGING THE HUMAN BRAIN

Effect of fluid-solid interaction

simplified acoustic [fluid]
model and wavefield



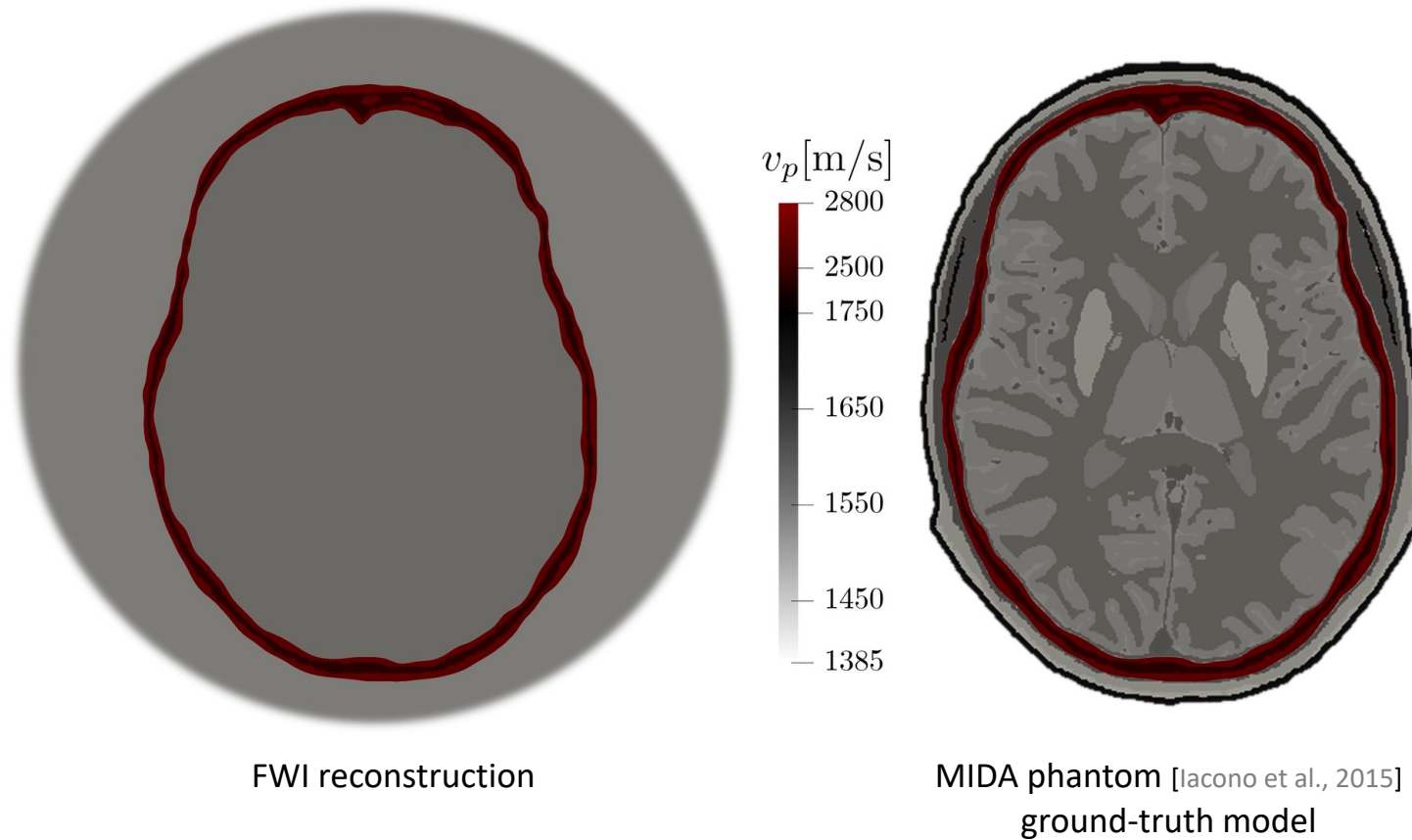
more realistic elasto-acoustic
[fluid-solid] model and wavefield



The head is a coupled
fluid-solid system.

EXAMPLE II: IMAGING THE HUMAN BRAIN

Synthetic, *in-silico*, FWI experiment



Transferability

- Scale-independence ensures that FWI math is identical in seismic and medical imaging.
- Codes [SEM] can be transferred rather easily.

Preliminary results

- Detailed images of soft tissue using in-vivo data [mouse experiment].
- Successful in-silico experiment for acousto-elastic brain imaging.
- Promising and worth pursuing further [towards in-vivo FWI of human body parts].

Challenges

- Bandwidth of existing ultrasound devices.
- Computational cost at high frequencies.
- Cultural and regulatory barriers.

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Thanks for your attention!