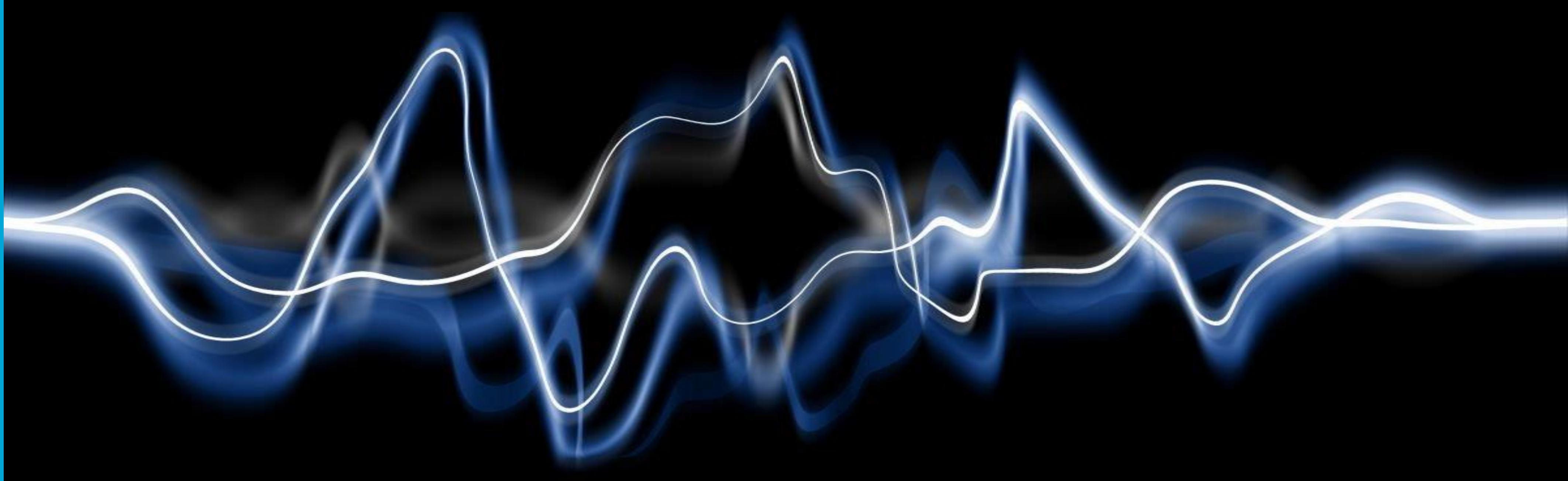
Kijken met geluid



Presentation at the WND conference

Friday 13 Dec 2024 - Noordwijkerhout

Eric Verschuur - TU Delft

TU Delft

Eric Verschuur

- 1976-1982 : Chr. Lyceum, Alphen aan den Rijn
- 1986 : M.Sc. Applied Physics, TU Delft
  Room acoustics (Wigner distributions)
- 1991 : Ph.D. Applied Physics, TU Delft
  Geophysics: Surface-related multiple elimination
- 1992 – 1996 : Research fellow at TU Delft
- 1996 – 1997 : Assistant professor at TU Delft
- 1997 – now : Associate professor at TU Delft
- 2023 : from Applied Physics to Applied Earth Sciences
- Since 2016: Direct of Delphi Research Consortium
  www.delphi-consortium.com

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Outline

- Introduction to acoustic waves
- Part 1: Transmission measurements
  - Basics of tomography
  - Earthquake traveltime tomography
  - Full waveform inversion (FWI)
- Part 2: Reflection measurements
  - Acoustic reflection experiments
  - Applications in seismic, medical, material inspection
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- Concluding remarks

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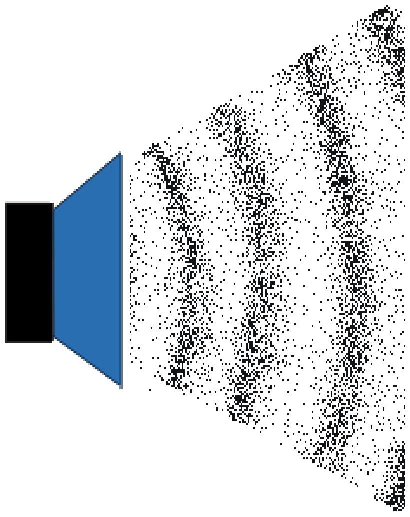
Sound waves



Sound waves are vibrations of the medium (e.g. air, water)

It is caused by (de)compression of the particles of the medium

Humans and animals use it for communication; they can hear it by the pressure changes in the medium that finally make the eardrum (‘trommelvlies’) vibrate

http://www.dangerousdecibels.org/virtualexhibit/4whatissound.html

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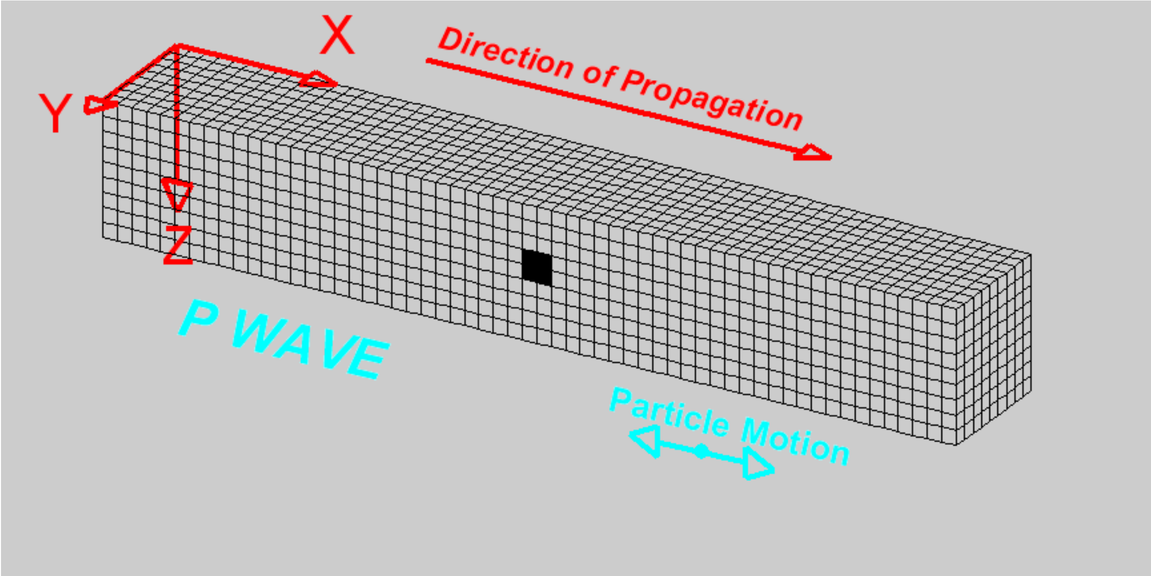
Speed of sound (1)

Sound travels with a certain speed through the medium.

In air it is 340 m/s, in water it is 1500 m/s.
For comparison: Speed of light is 300.000.000 m/s

Therefore, it takes time for a sound wave
to arrive after it was generated

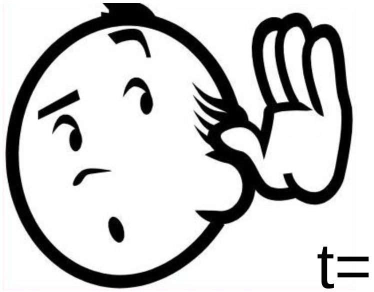
Acoustic
waves are
longitudinal



Speed of sound (2)

Example 1: Passive: calculate distance to lightning

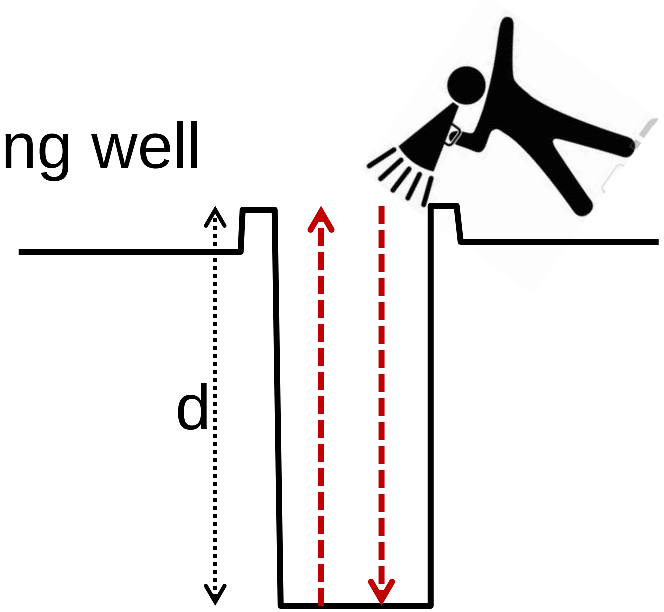
$r = v \times \Delta t$



t=0 defined by the light(ning)!

Example 2: Active: calculate depth of echoing well

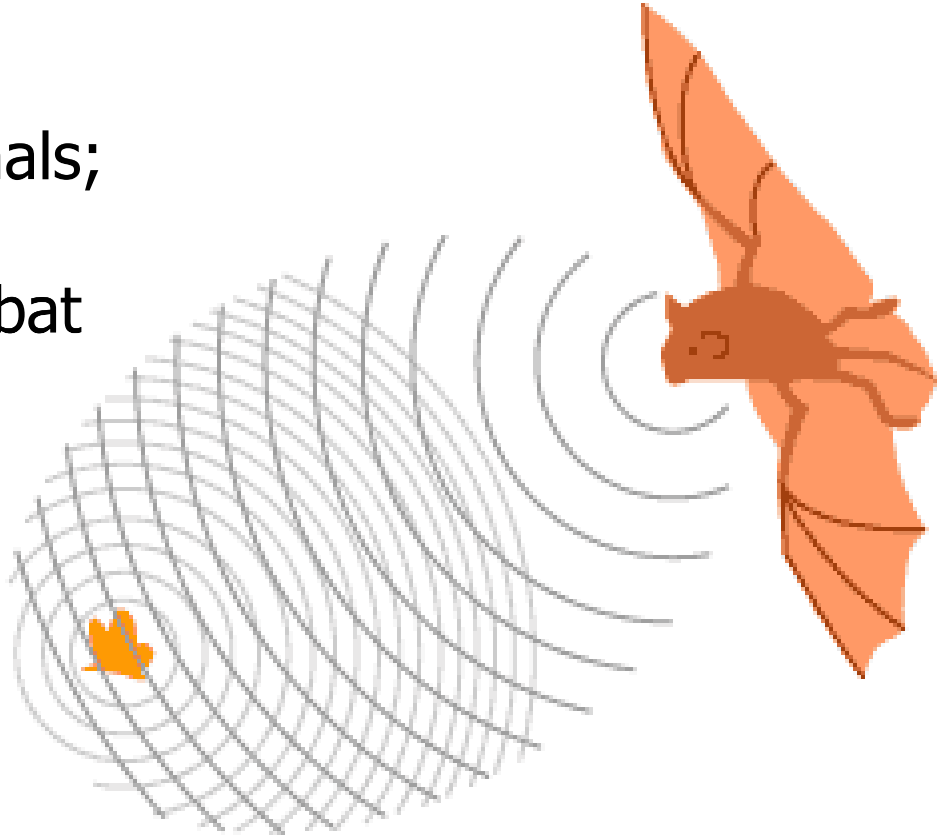
$d = \frac{1}{2} v \times \Delta t$



These are all 1D examples, with one unknown

Active acoustic method: Like a bat ….

Bats send out ultrasonic signals; objects will reflect and the response is detected by the bat



Frequencies from 10 kHz to 120 kHz

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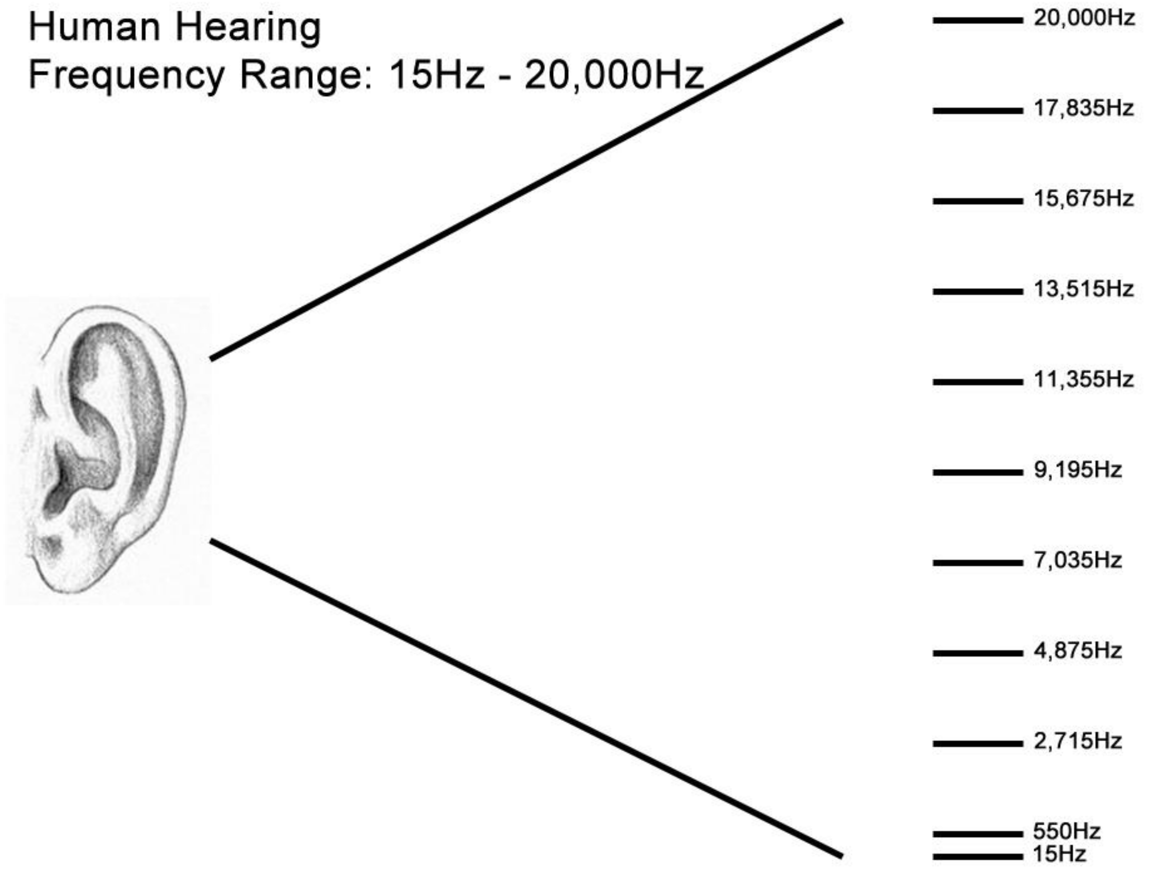
The human ear

Ultrasonic frequencies/ Ultrasound



Infrasonic frequencies / Infrasound

Acoustical imaging/inversion applications

10 MHz
1 MHz
100 kHz
10 kHz
1 kHz
100 Hz
10 Hz
1 Hz
0.1 Hz

Laminated materials (e.g. airplanes) → 0.5 cm deep

Inspections of welds/constructions → 0.5-5 cm deep

Medical ultrasound → 0.2-20 cm deep

Ship wreck detection, geotechnical applications → 1-20 m deep

Near-surface inspection (a.o. wind farming) → 5-500 m deep

Oil/gas exploration, geothermal, CO_2 injection → 0.5-5 km deep

Tectonic imaging → 2-25 km depth

Global seismology (earthquakes) → full earth

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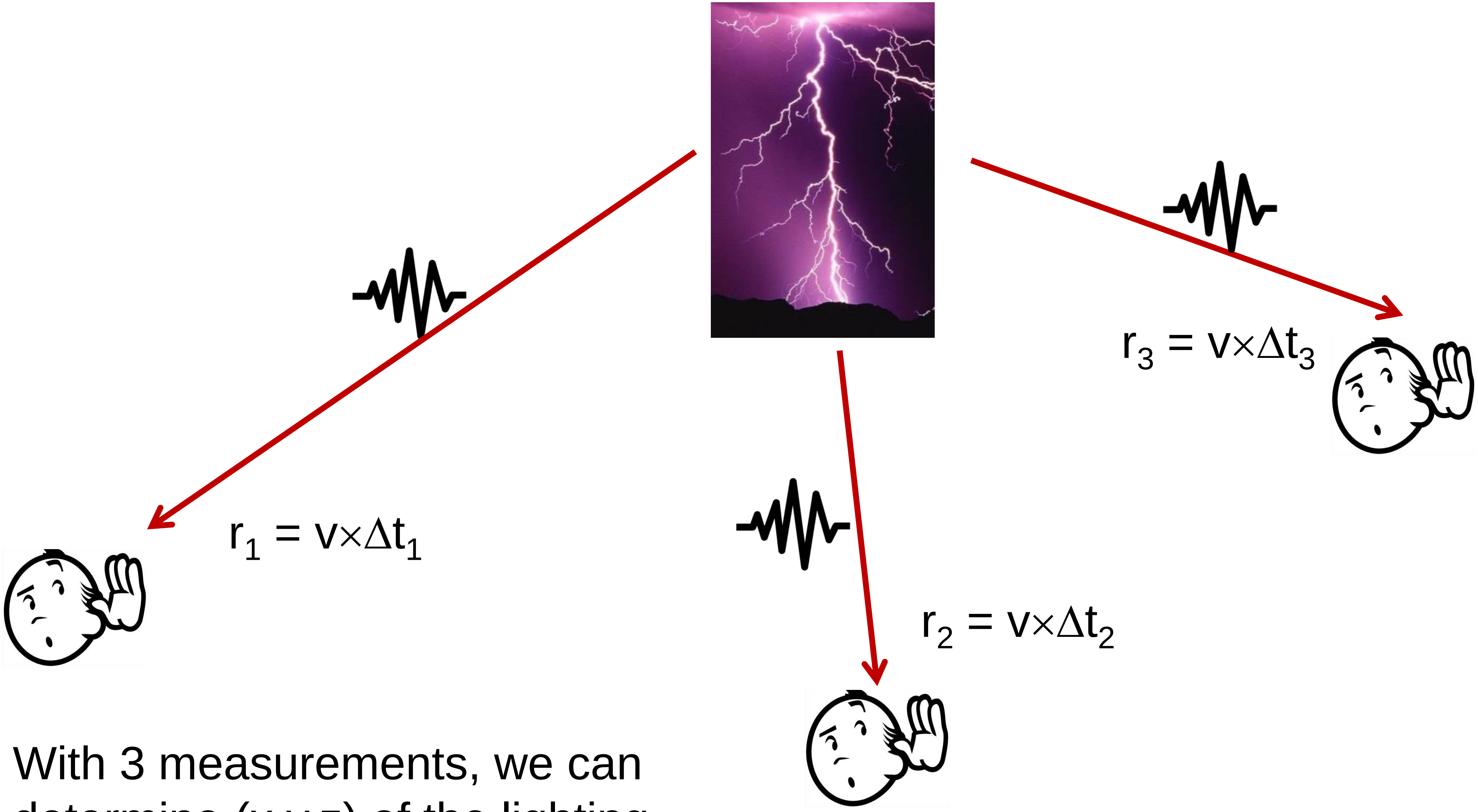
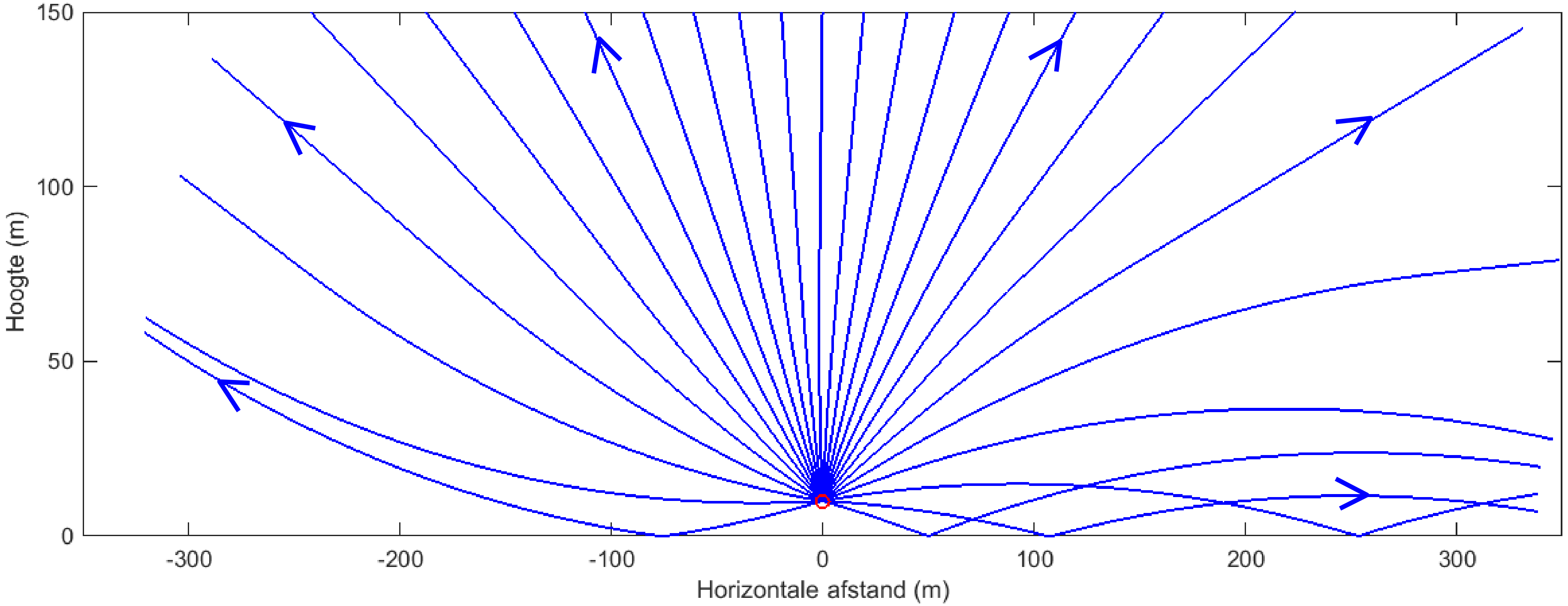
Localizing the lightning…



With 3 measurements, we can determine (x,y,z) of the lighting

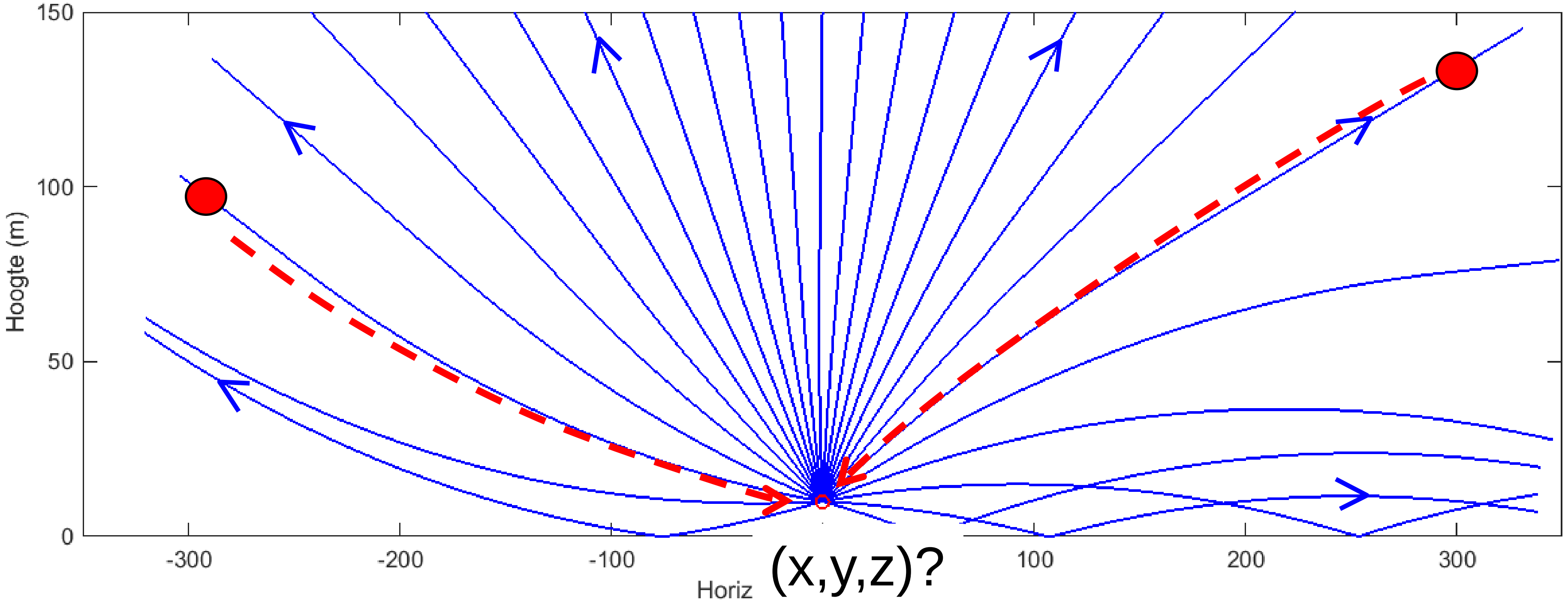
But also with inhomogeneous medium?



Medium with temperature and/or wind gradient has varying speed-of-sound: sound paths are not straight lines anymore

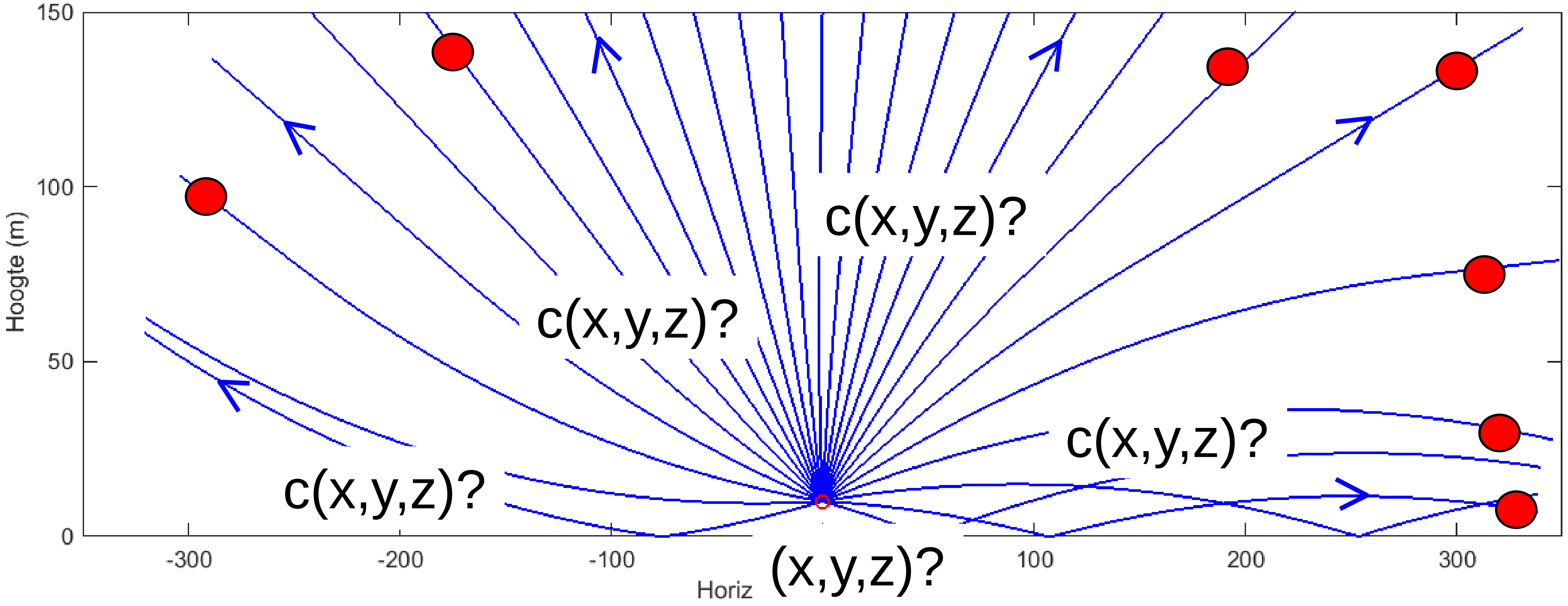
[in this lecture ‘speed-of-sound’ is often called (propagation) ‘velocity’]

Back-tracing the sound to its source



With **a known medium**, we can back-trace the 'recorded' sound arrival time to its source location

Unknown medium parameters?

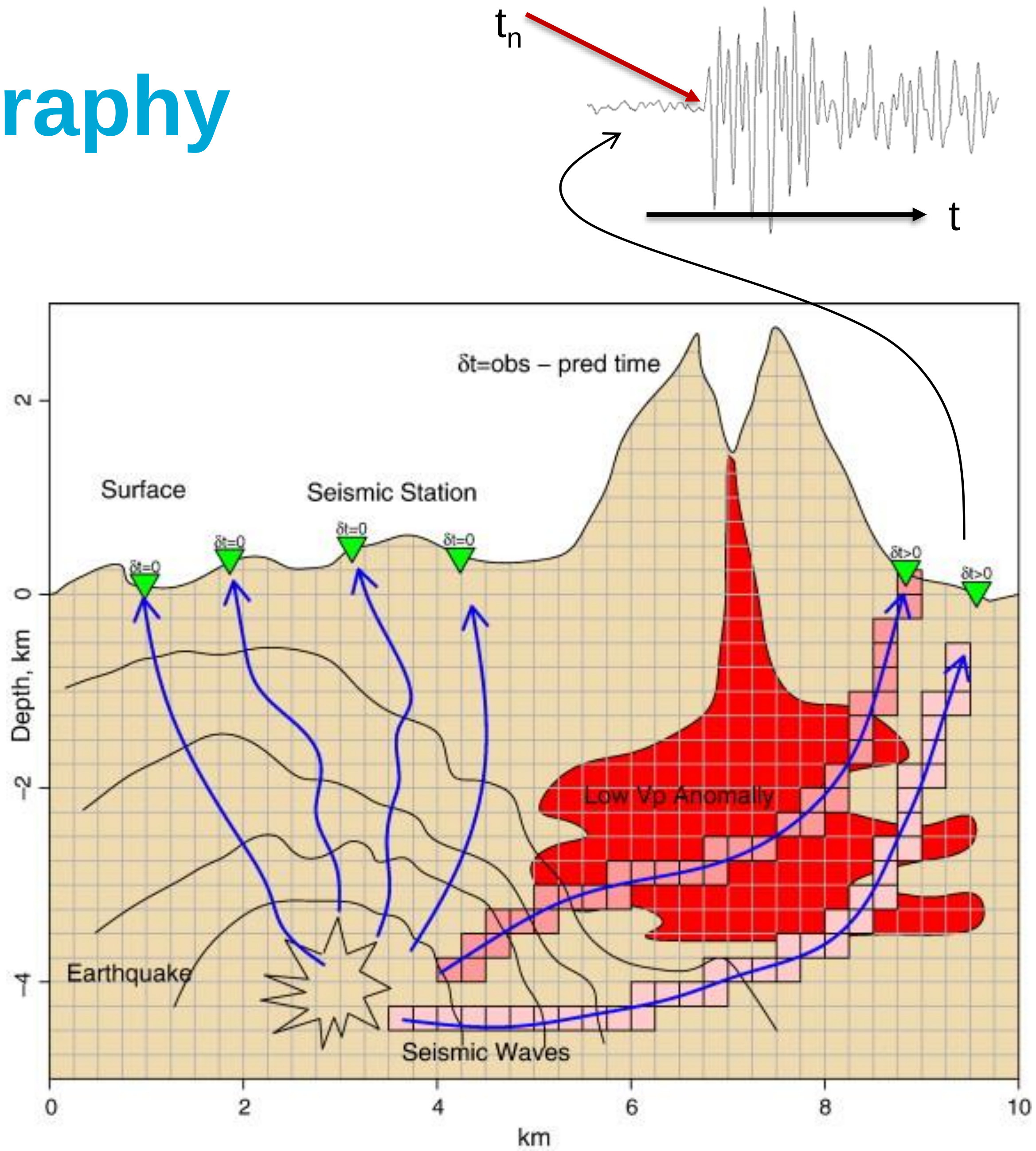


With **an unknown medium**, we need to make the medium (speed-of-sound profile) part of the parameters to be estimated → many measurements required, in a parametric inversion process

Earthquake tomography

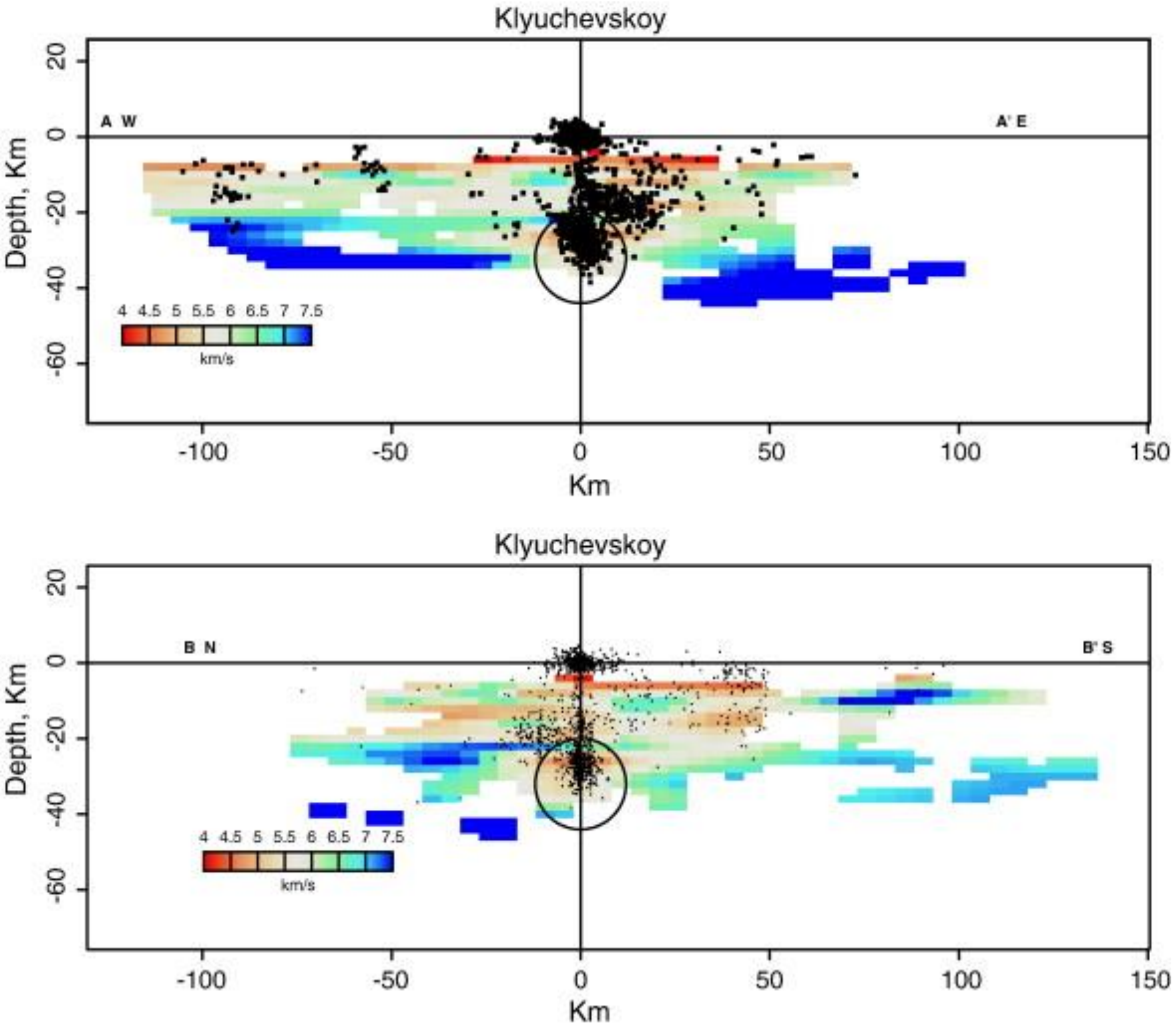
This is the situation in the earthquake seismology problem:

- Pick the arrival time of earthquake at each station
- Divide the Earth in cells and assign one speed-of-sound value to each cell
- Do forward modelling of arrival times and compare to measured ones
- Adapt these cell values until all arrival times fit (all $\delta t=0$)



Picture from: Lees, 2007, Journal of Volcanology and Geothermal Research

Earthquake tomography



Result of inversion of seismic events around the Klyuchevskoy volcano (Russia)

The color represents the estimated speed-of-sound in each cell

Black dots are earthquake locations

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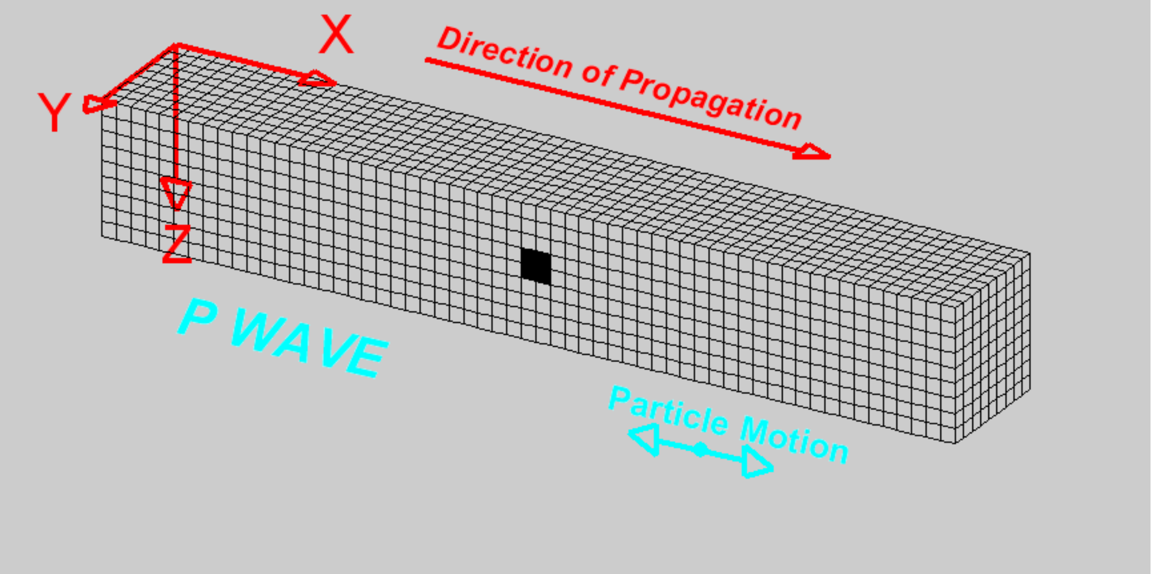
Picture from: Lees, 2007, Journal of Volcanology and Geothermal Research

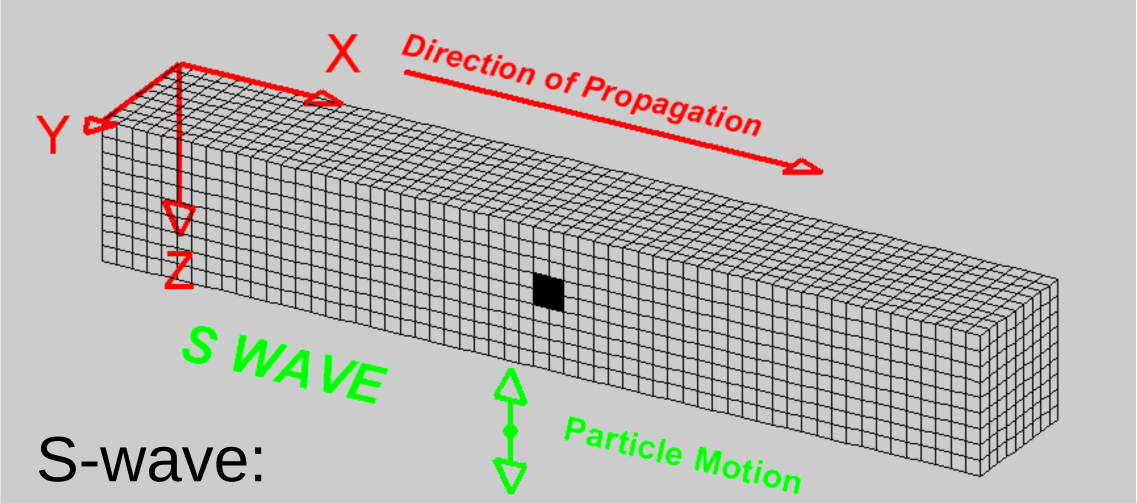
P-waves and S-waves in elastic medium



P-wave:
Pressure wave
Primary wave

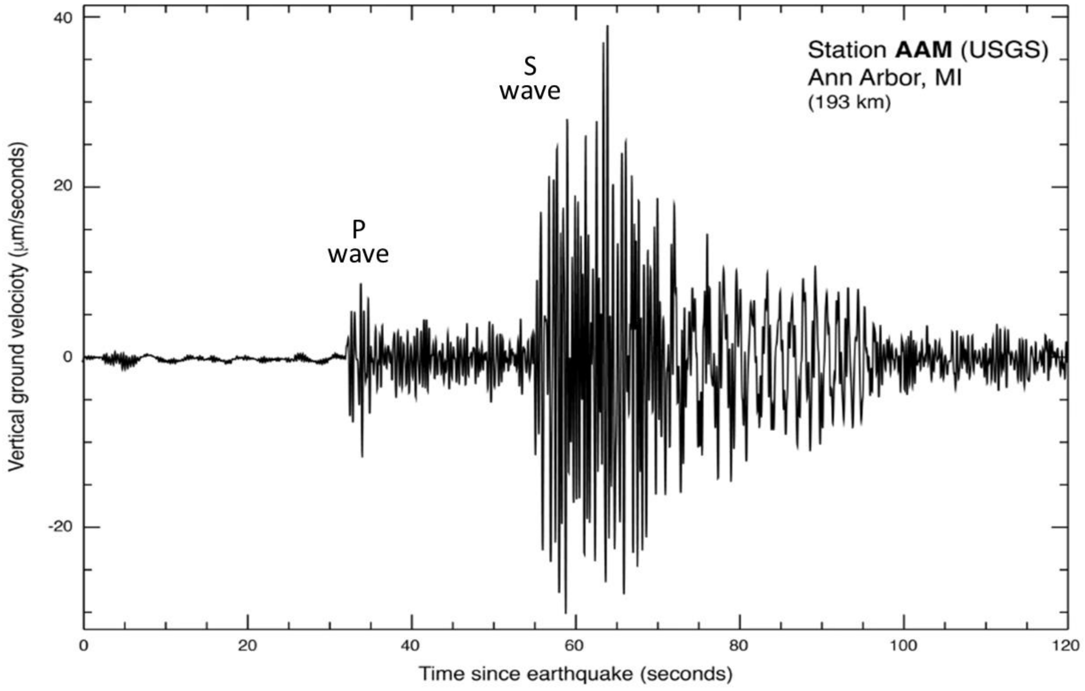
Source mechanism determines type of generated waves;

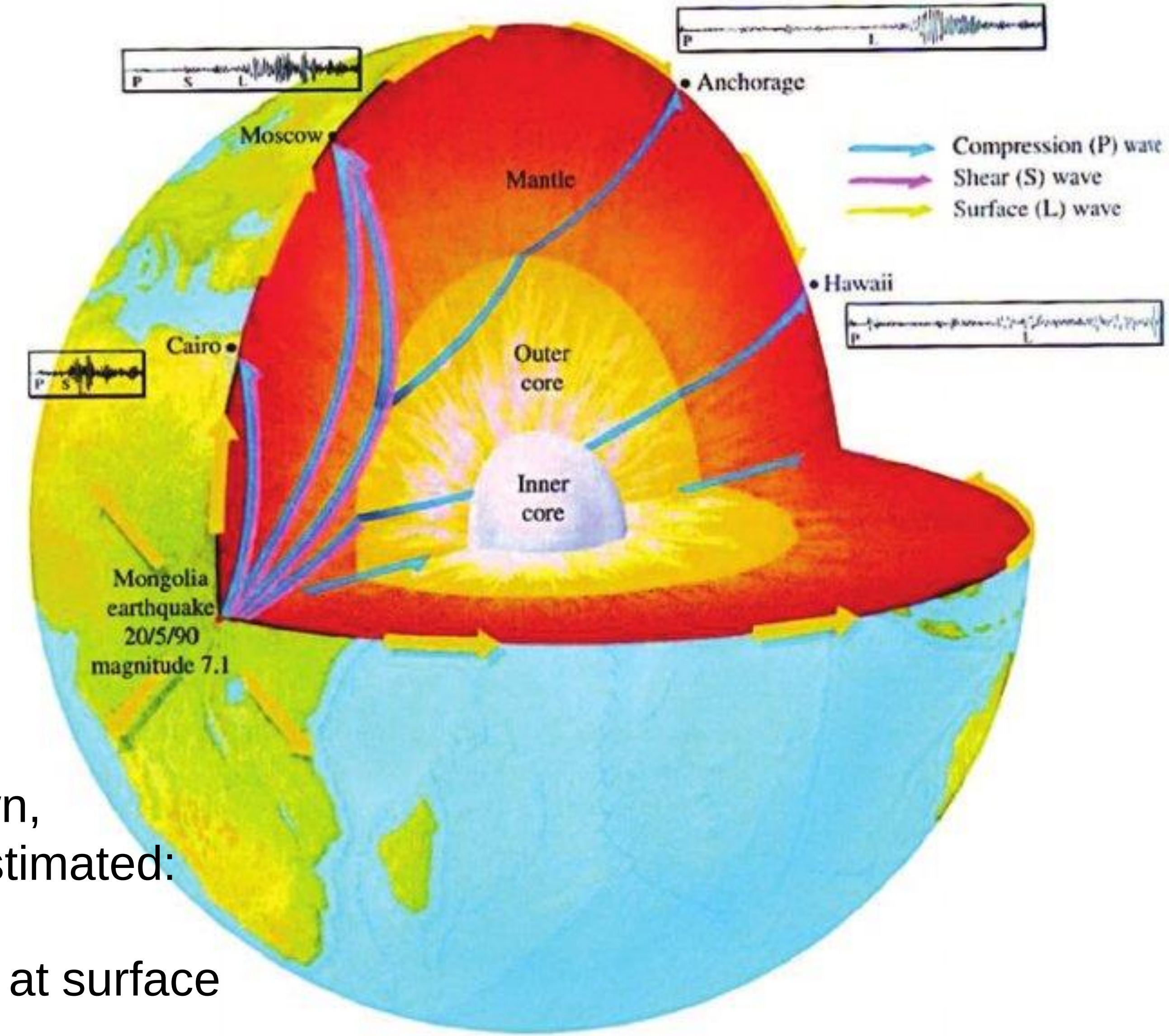
P-wave speed is larger than S-wave speed



S-wave:
Shear wave
Secondary wave

Seismic waves in the Earth's interior

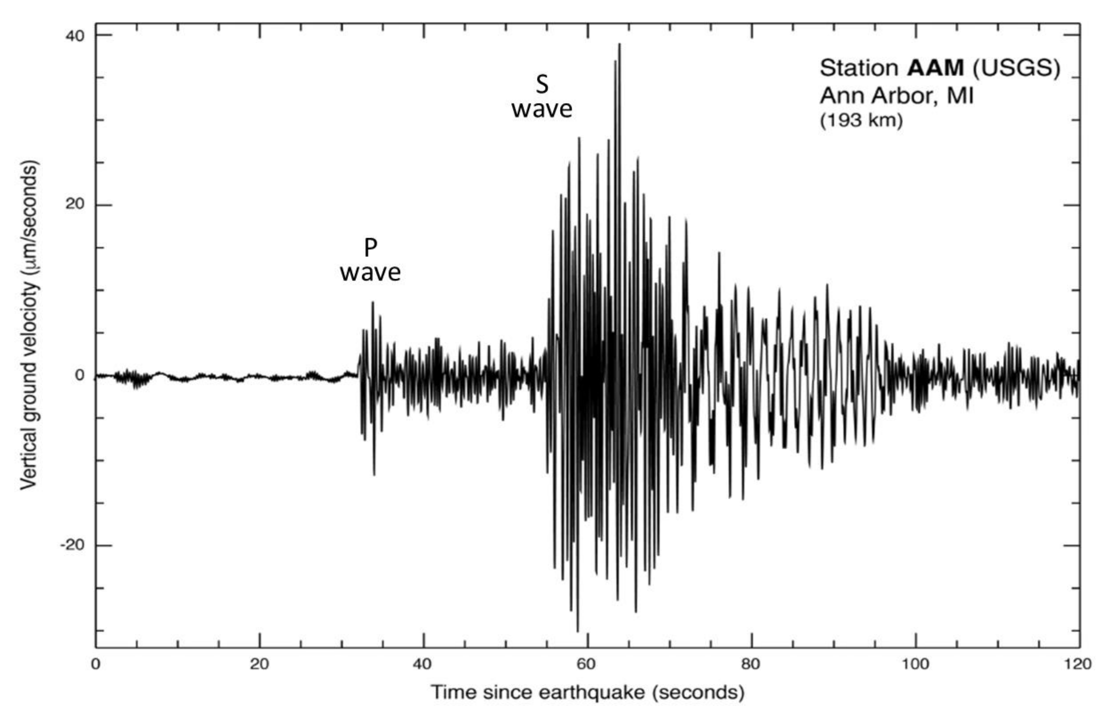


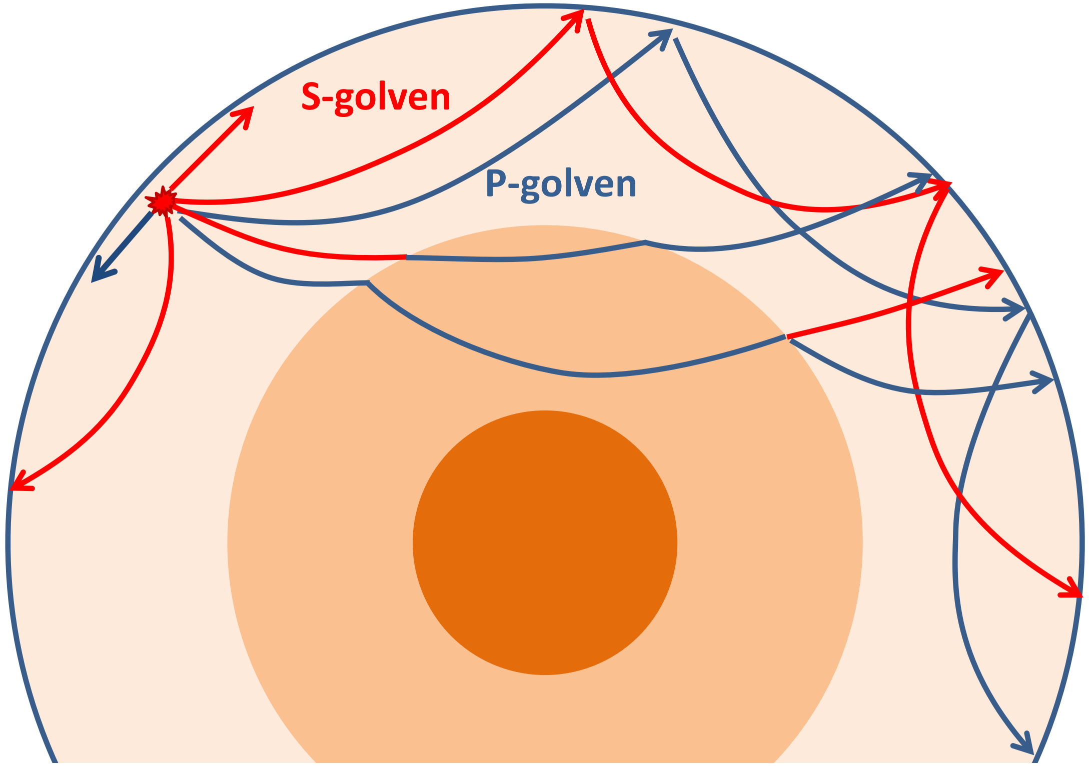


If speed of sound profile known,
earthquake location can be estimated:
Hypocenter – true location
Epicenter – projected location at surface

Picture: Gilan & Price, 2007, Contemporary Physics 48(2):63-80

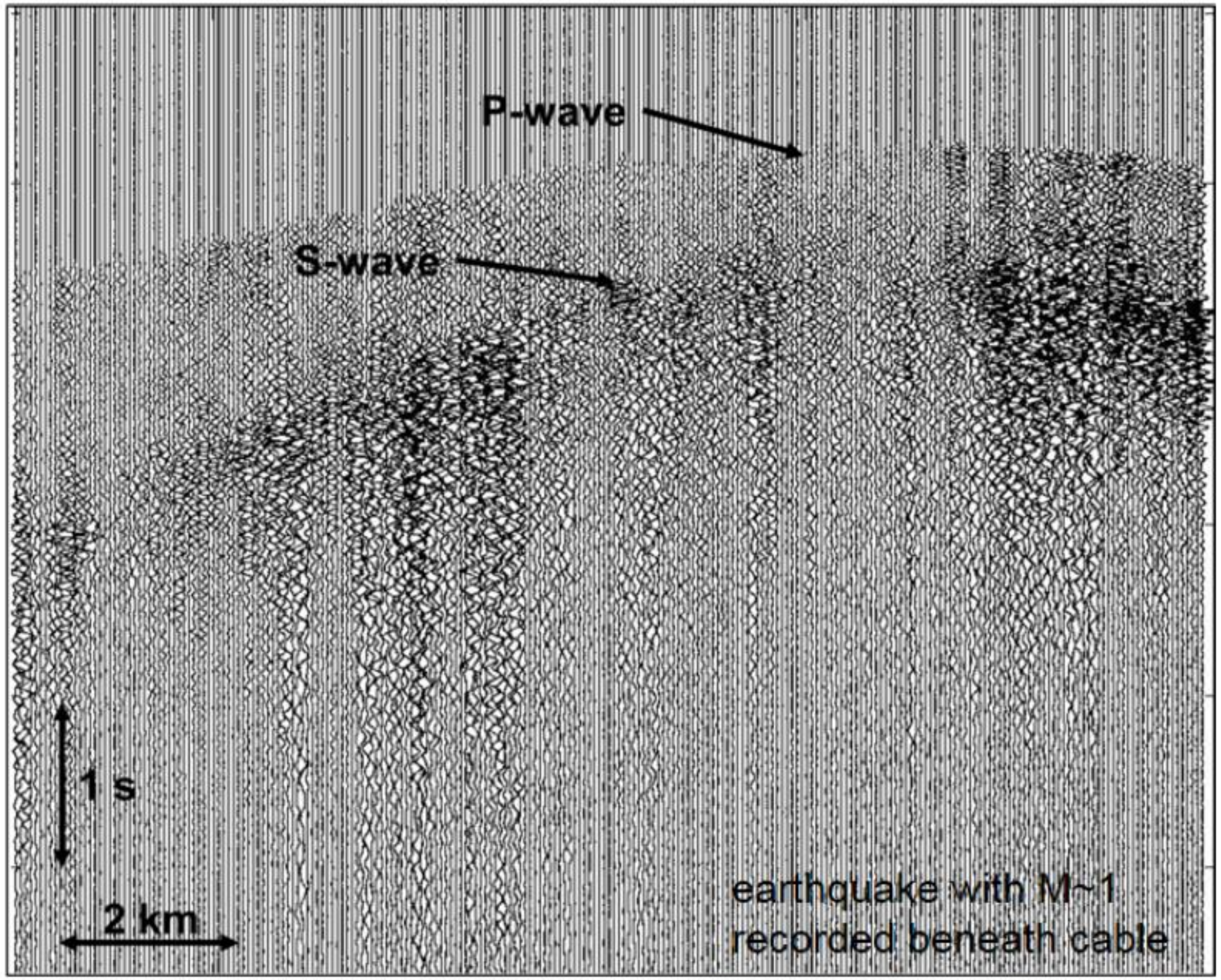
Seismic waves in the Earth's interior





Very complex wave paths of the various arrivals around the globe for large earthquakes: travel time picking and inversion is very complex and ambiguous process

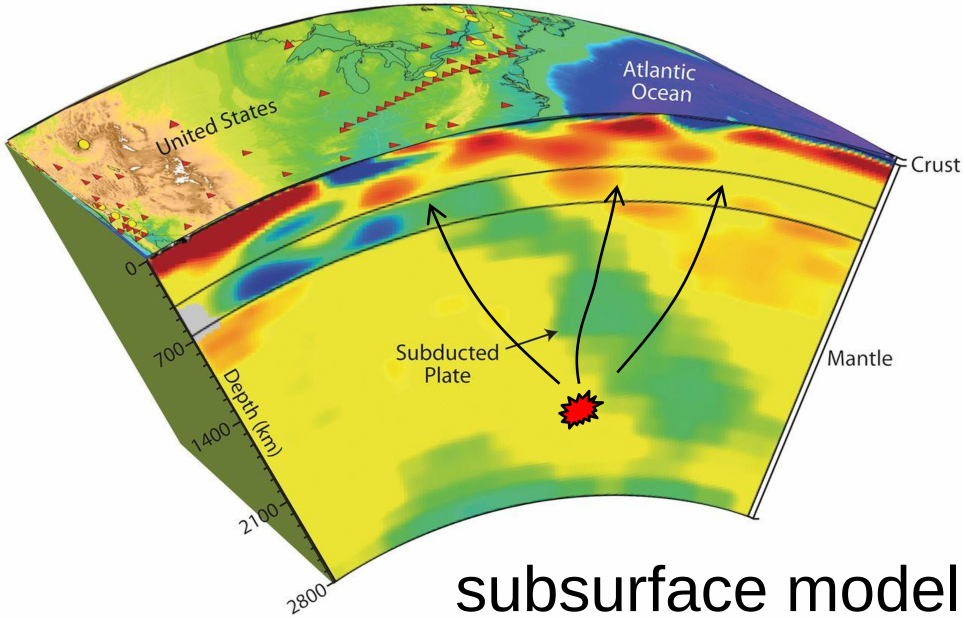
Towards Full Waveform Inversion



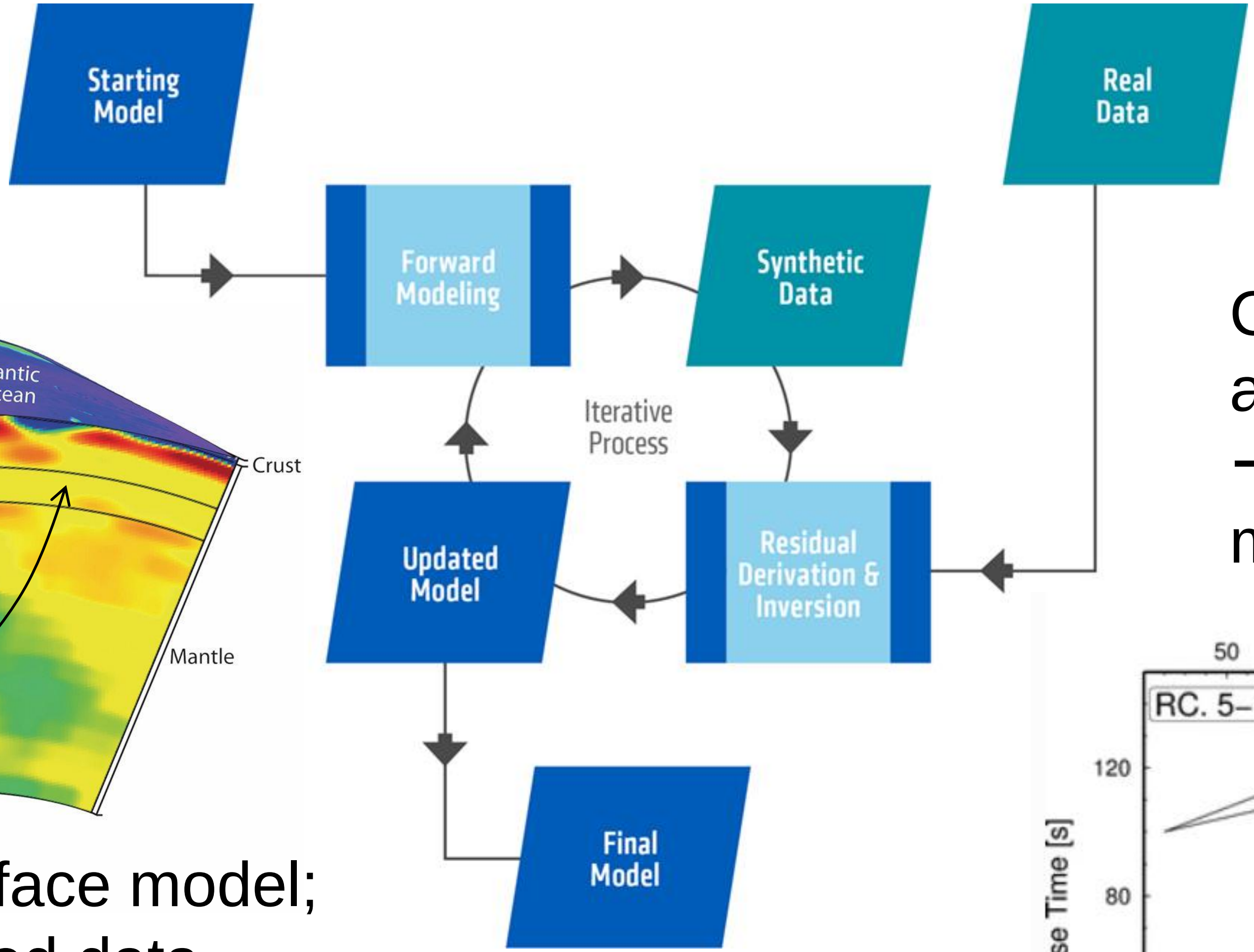
Complex arrivals, identification of events is difficult

Recording earthquake response along ~16 km cable

Towards Full Waveform Inversion



subsurface model;
modelled data



Compare measured and modelled data → residual to drive model update

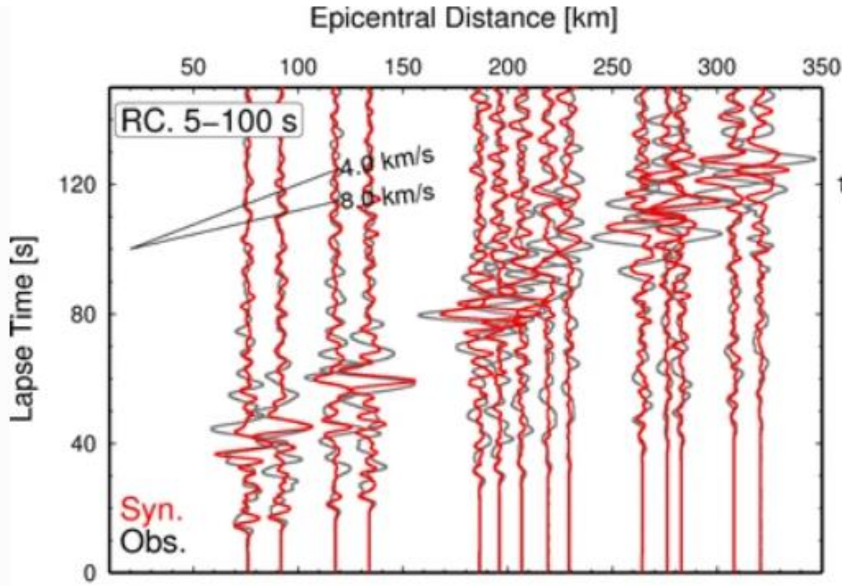
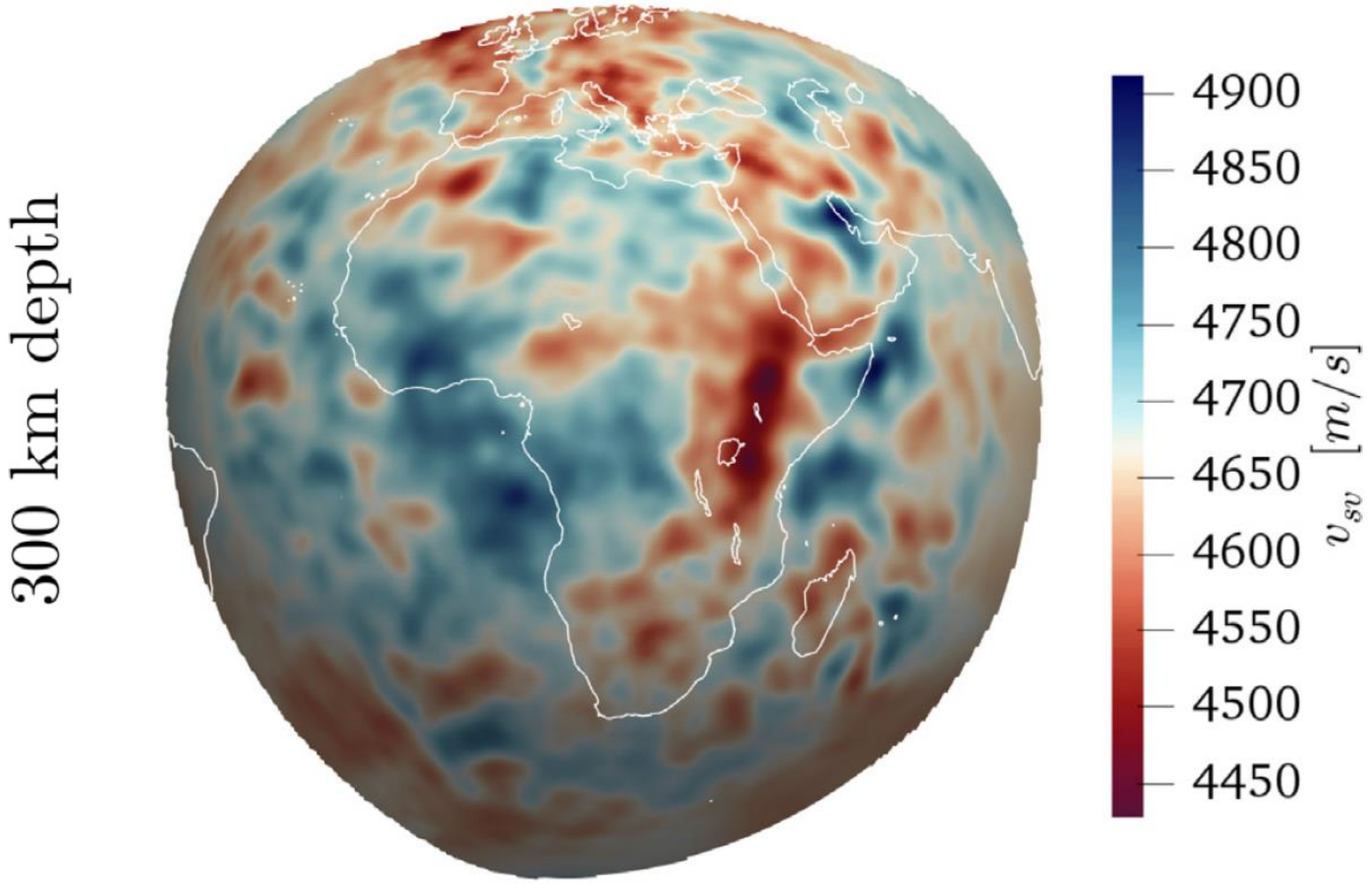


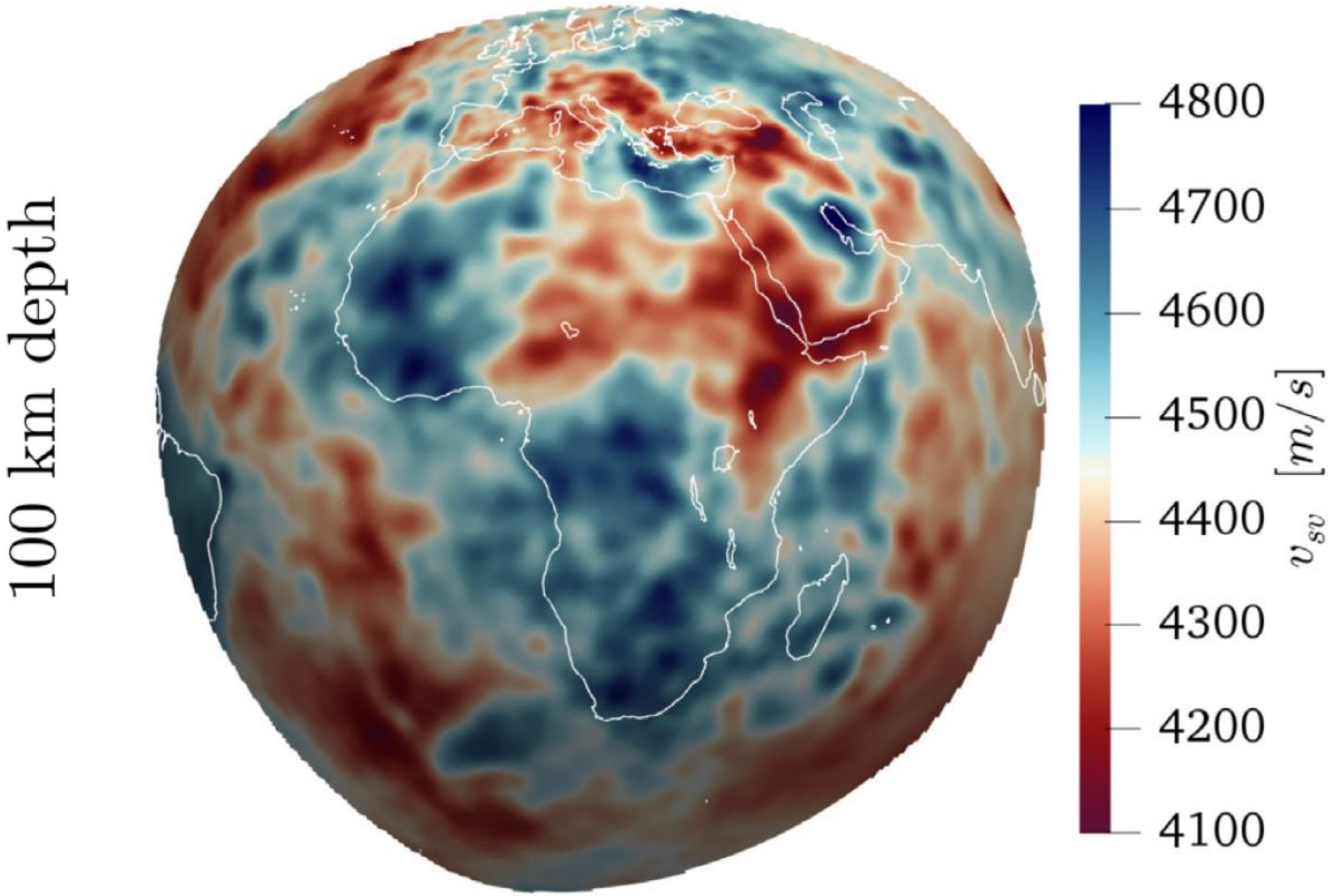
Diagram from www.pgs.com

Full Waveform Inversion result



Picture: van Herwaarden et al., 2020, Geoph. Journal International

Full Waveform Inversion result



Picture: van Herwaarden et al., 2020, Geoph. Journal International

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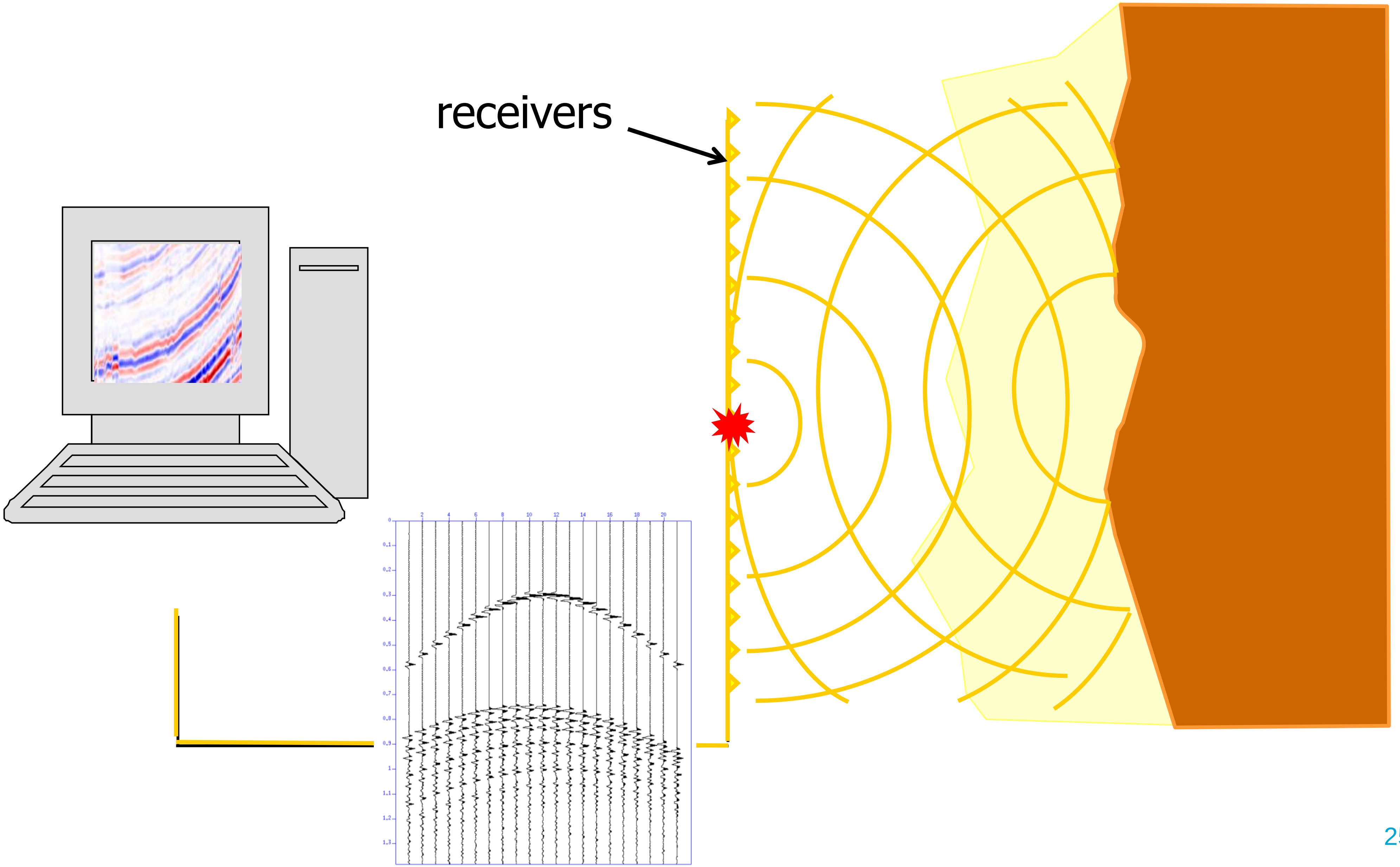
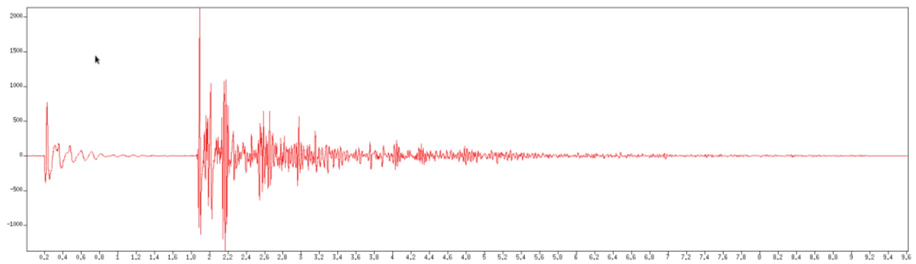
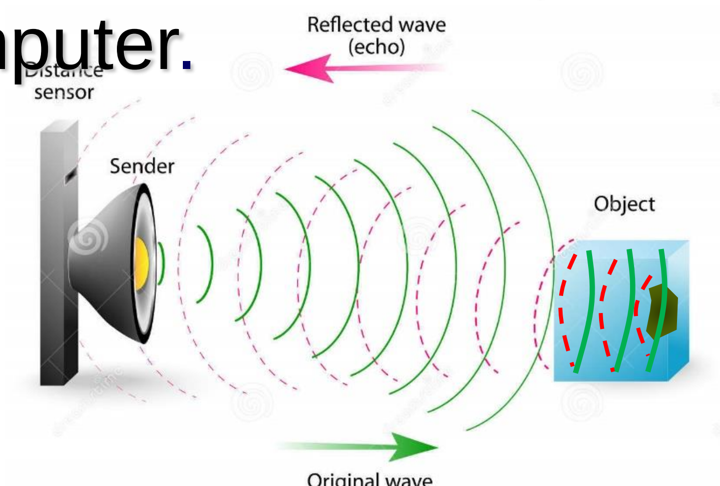
Looking with sound waves …



Why acoustical imaging?

- Acoustic waves are relatively easy to generate and can penetrate in materials where electro-magnetic waves (i.e. light) don't.
- Propagation velocities are small enough (compared to the wavelength) to measure subsequent reflection arrivals separated in time.
- After digitization, 3D images can be calculated by advanced algorithms in the computer.


Recorded reflection signal



Overview of acoustical imaging methods

- Narrow beam (phased array) illumination
  Image via time/distance conversion (just like radar)
  or pre-focused arrays
  - Works in homogeneous media
  - Based on a beam/pre-focused source

- Unfocused measurements, focusing in the computer
  Image created based on scanning all possible reflection points
  - Also works in inhomogeneous media
  - Based on point sources and point receivers

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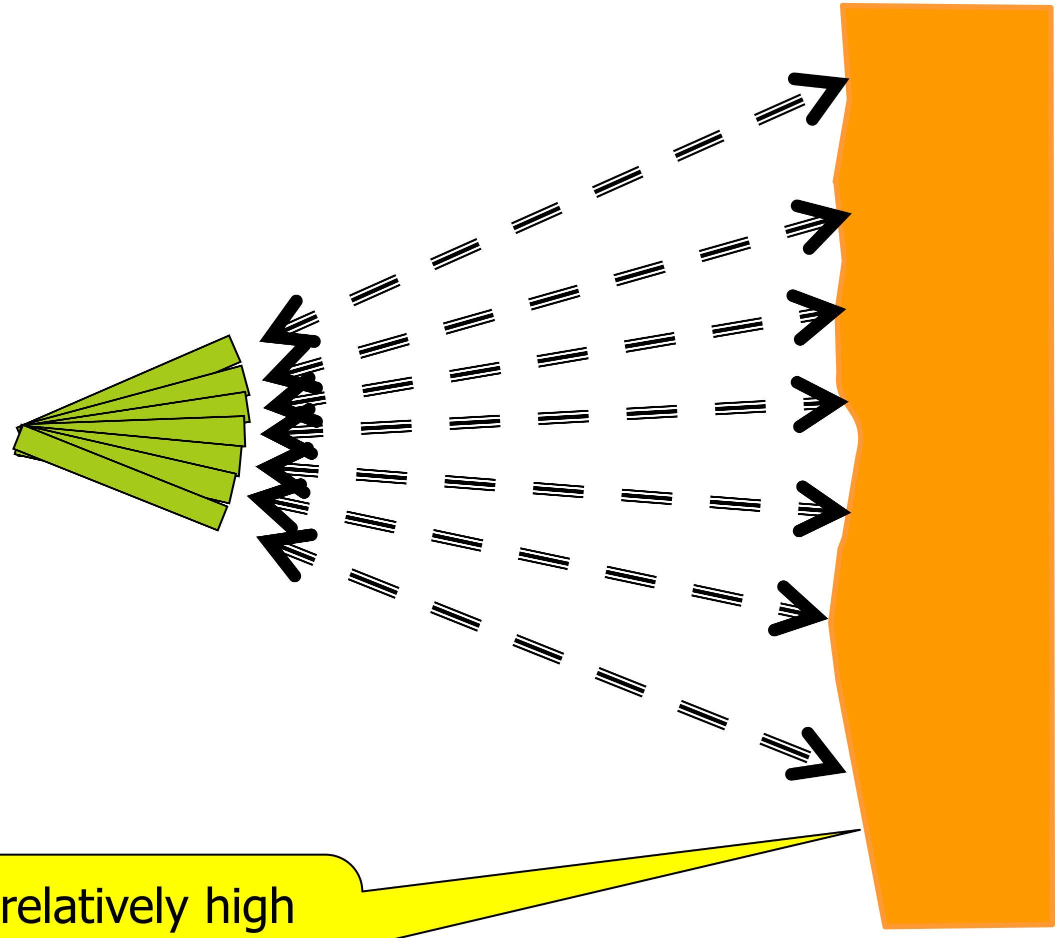
Narrow beam scan



Using relatively high frequencies: object will scatter in all directions

Imaging=time-to-distance conversion

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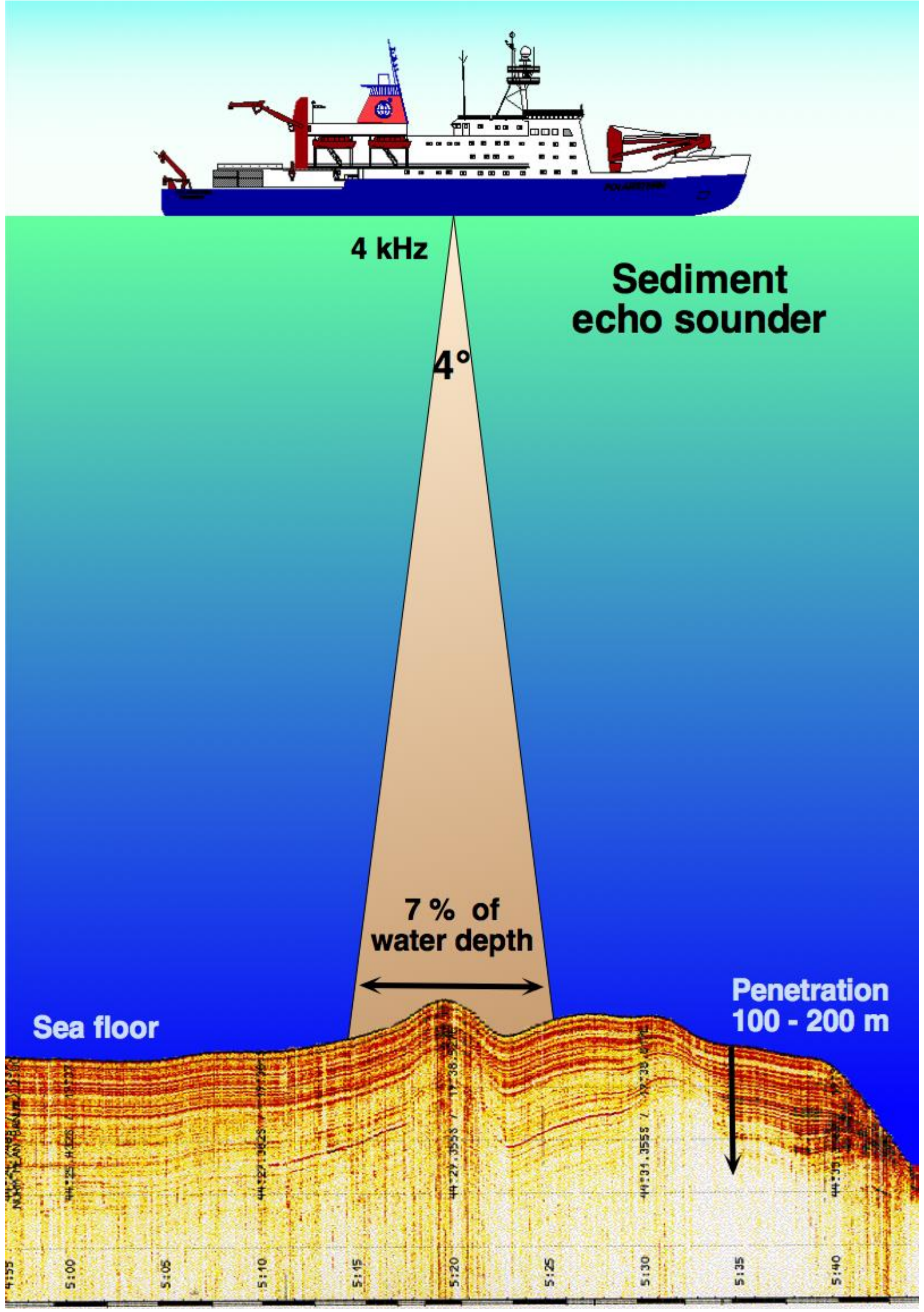
‘Echo sounding’

Use diffractive nature of object at high frequencies (just like laser scanning). Applications: imaging the water bottom and shallow sediments → or finding fish ↓

(source: www.wikipedia.org)



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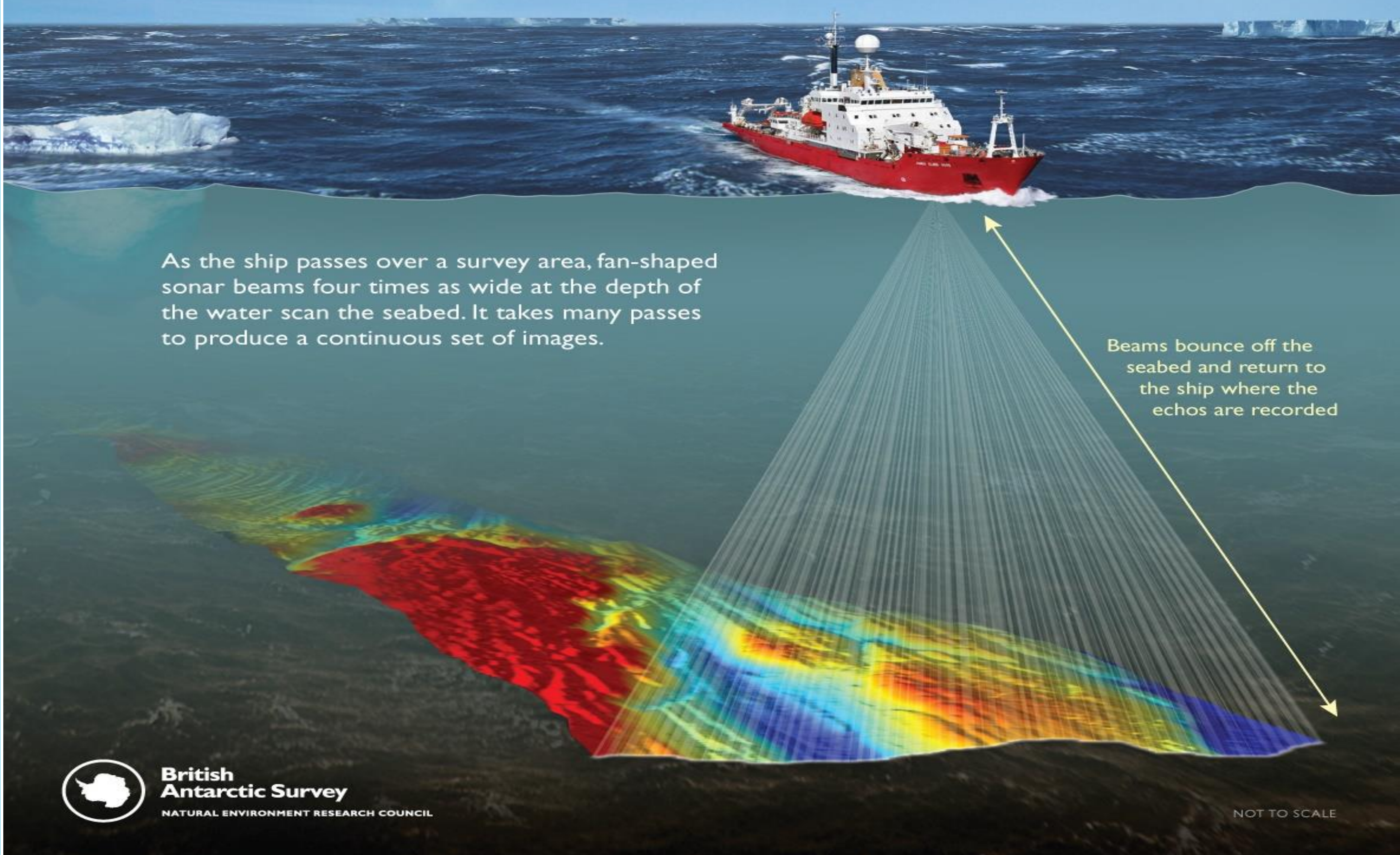
This is how they looked for the 'lost' MH370 plane in Indian Ocean (2014)



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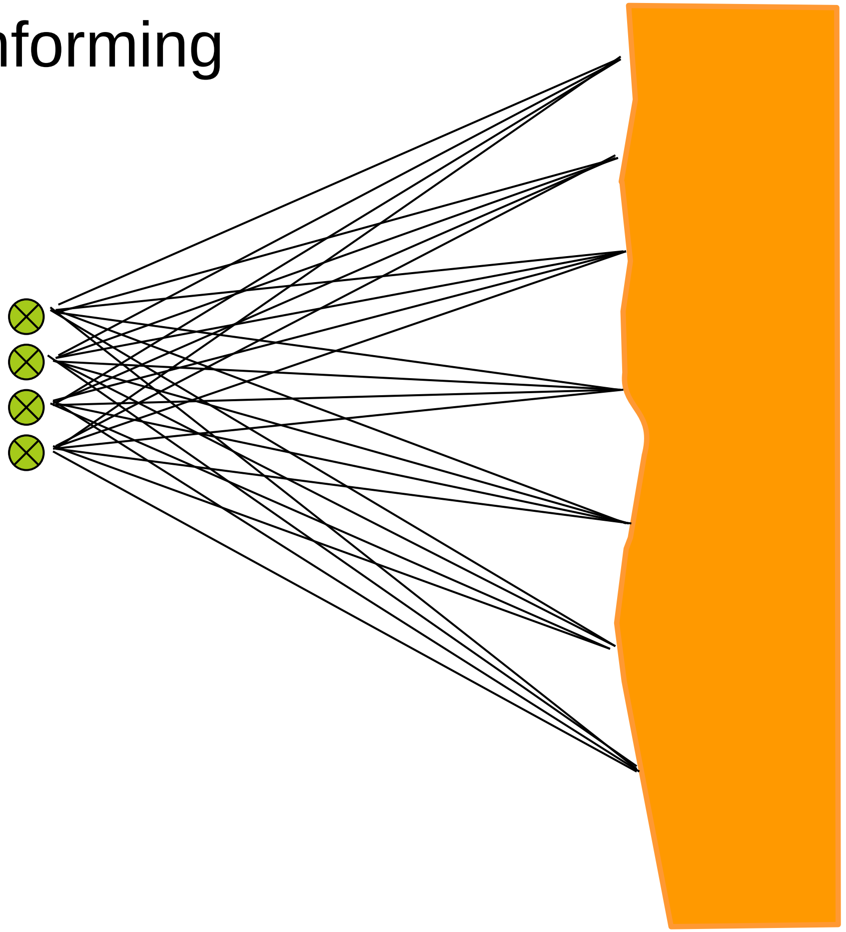
Medical ultrasound transducer

Using an array for beamforming

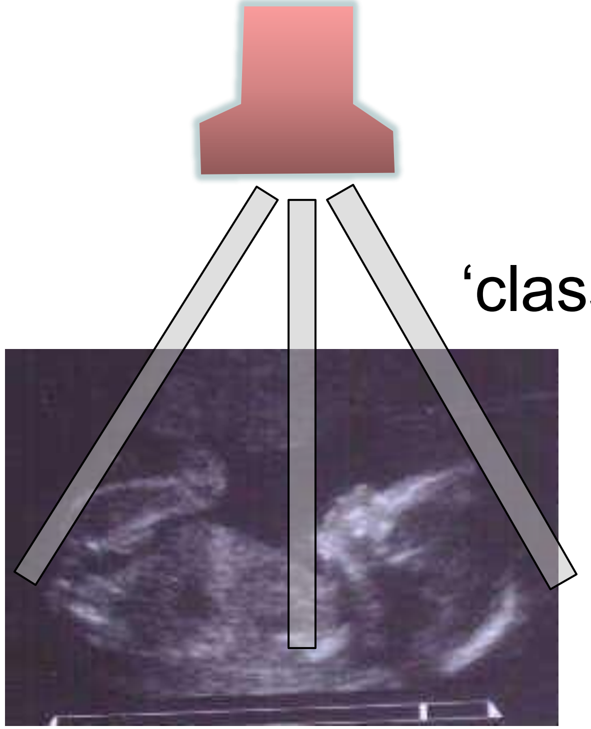


https://en.wikipedia.org/wiki/Ultrasonic_transducer#/media/File:UltrasoundProbe2006a.jpg

Medical ultrasound scanning

modern

create real-time image



'classic'

Ultrasonic source and detectors, focused at 10-20 cm below surface

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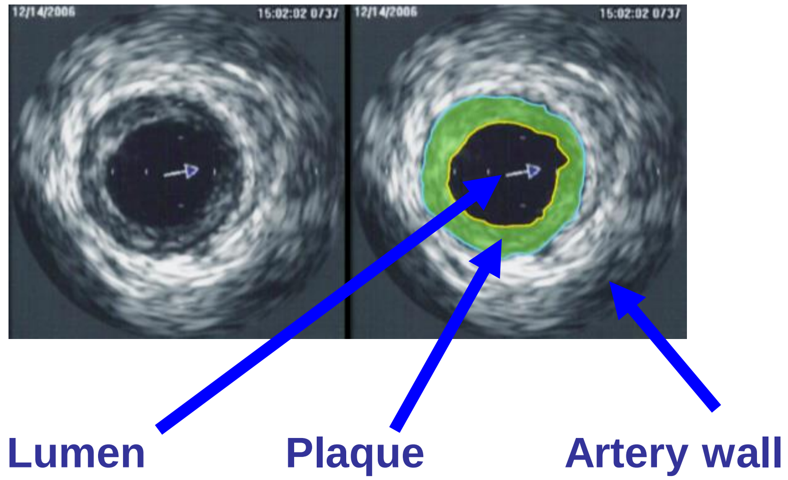
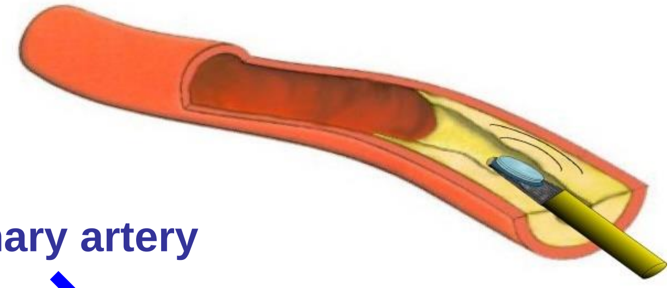
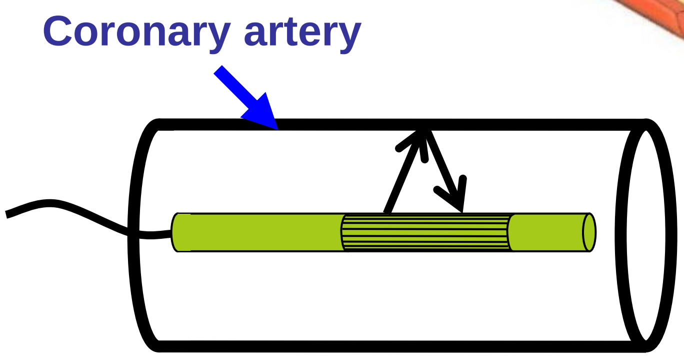
Also imaging ‘from inside out’

A catheter is inserted into coronary arteries and images the tissue of the arterial wall. In this way (vulnerable) plaque caused by atherosclerosis may be detected.



The composition of the arterial wall is derived from the amplitude and arrival time of backscattered ultrasound.





Ultrasonic signals are sent and received by the same array of transducers.
Based on acoustic modeling the design of the acoustic probe is optimized.

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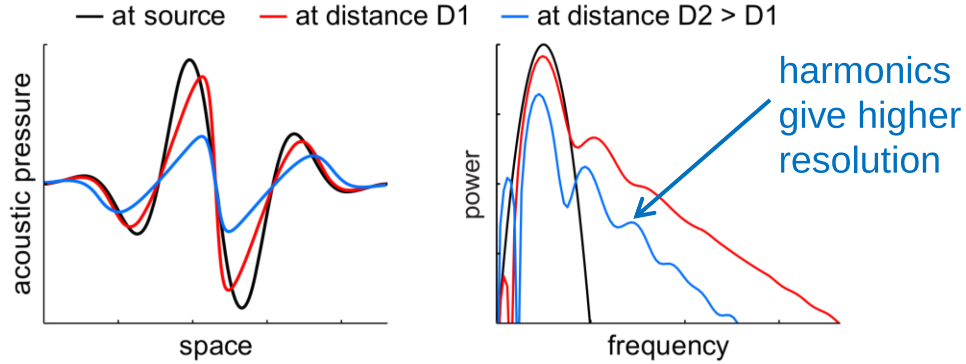
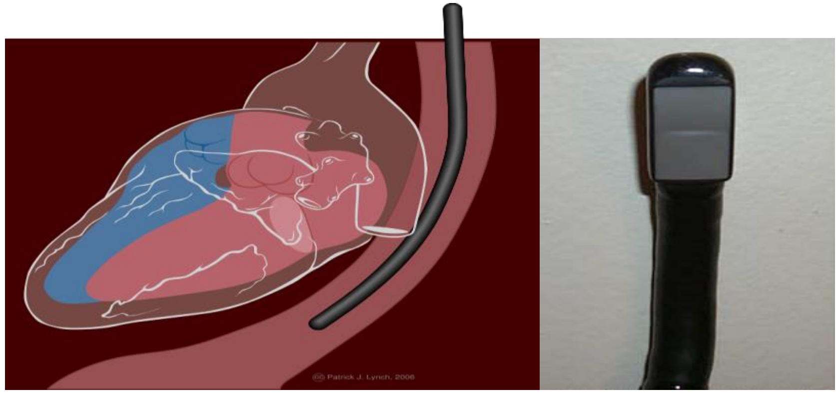
Using non-linear acoustics: harmonics

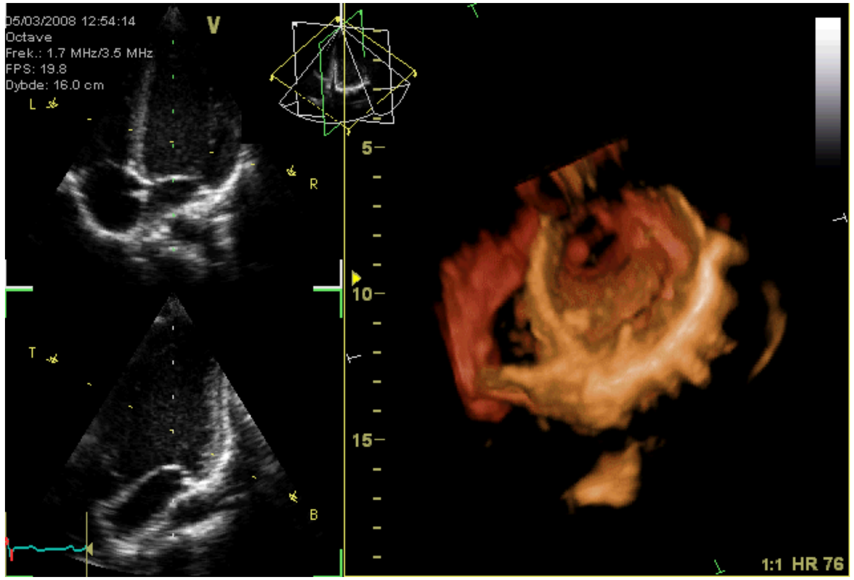
Nonlinear wave propagation



Nonlinear ultrasound is used, for instance, to image the heart in real-time and 3D.



Array technology is used to focus and steer the beam, while nonlinear acoustics is employed to suppress the effect of grating and side lobes for steered beams.



Movie of heart using nonlinear ultrasound imaging

Overview of acoustical imaging methods

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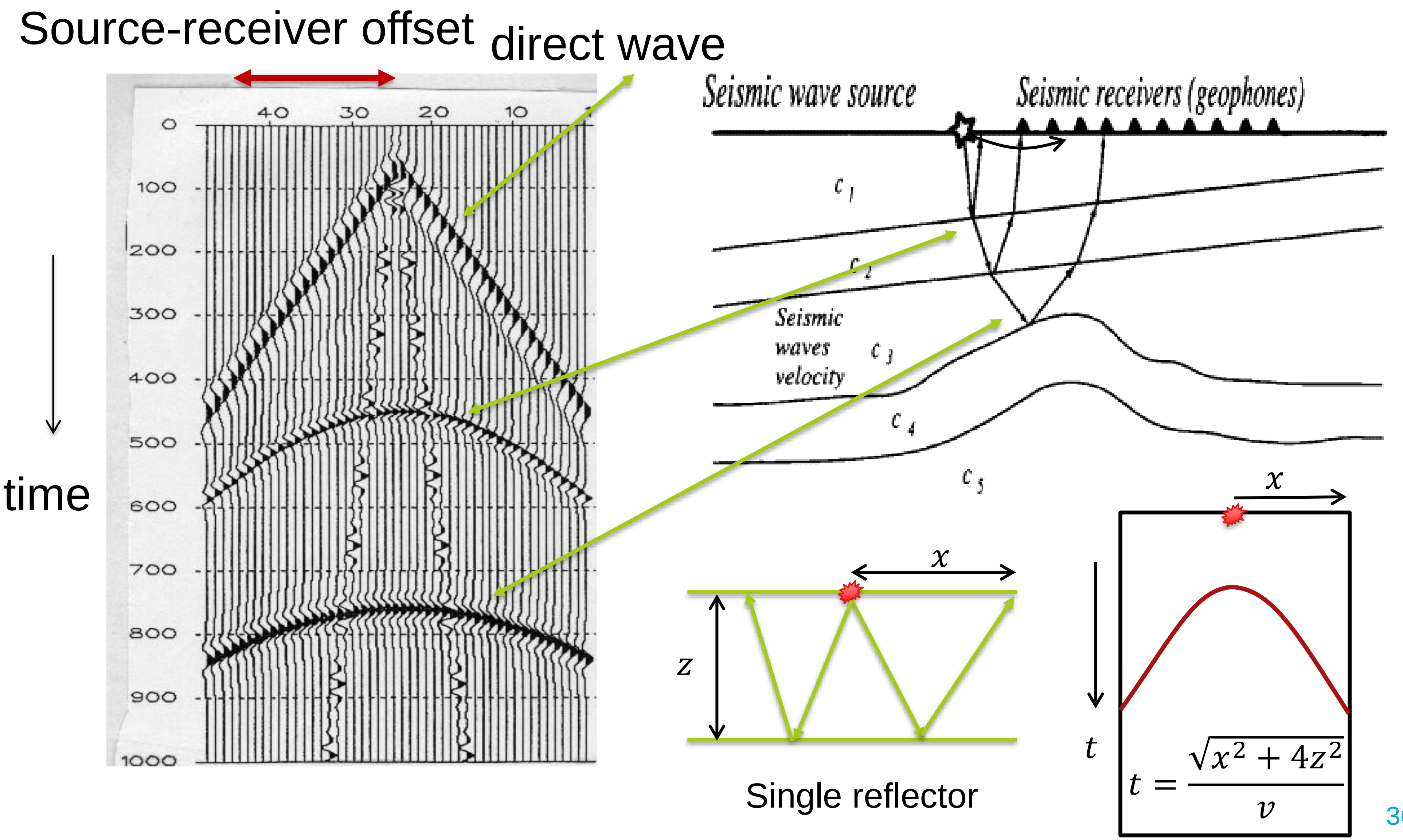
- Unfocused measurements, focusing in the computer
  Image created based on scanning all possible reflection points
  - Also works in inhomogeneous media
  - Based on point sources and point receivers

Unfocused measurements: seismic imaging



Single reflector

Seismic imaging: Imaging the subsurface

The earth is very inhomogeneous:
(P-wave) velocities vary from 1500 m/s to 6000 m/s

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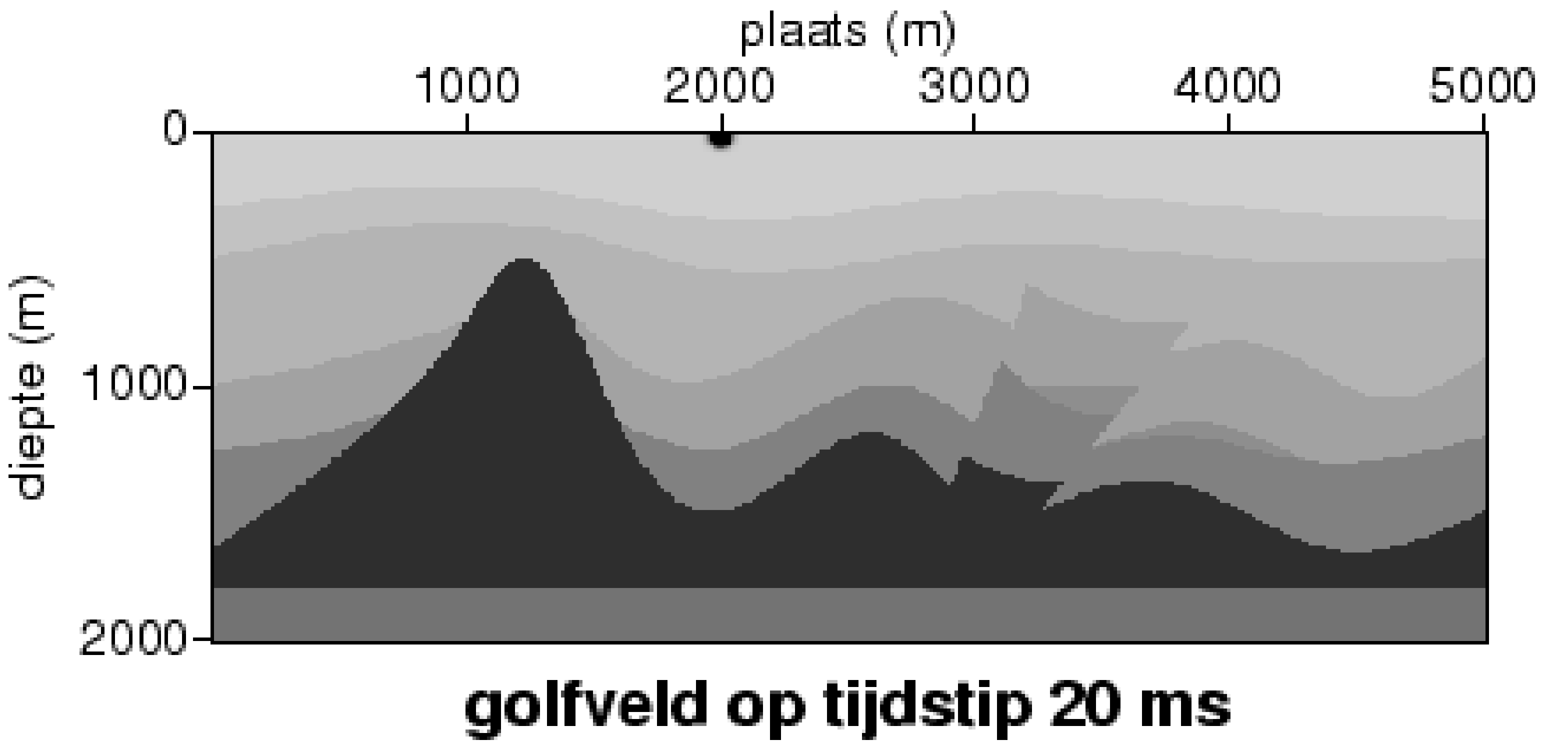
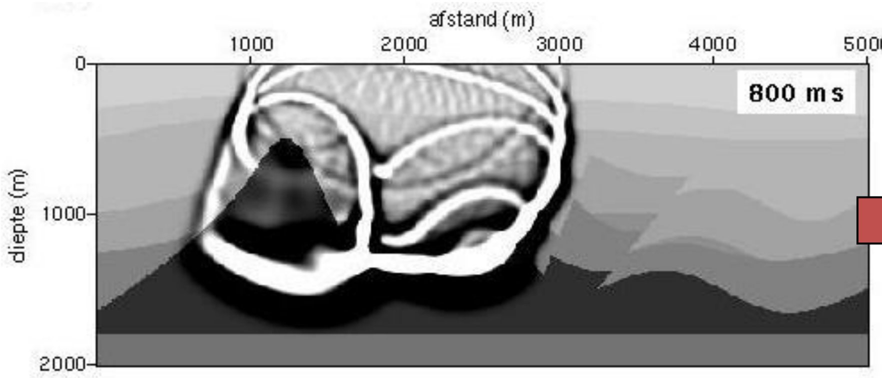
Simulating a seismic response



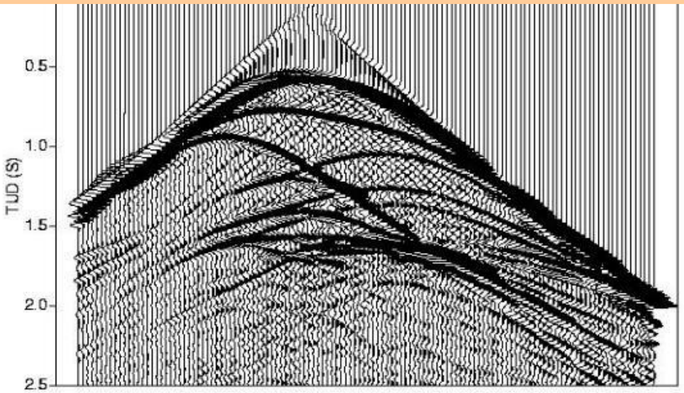
Seismic imaging process

Obtain an image from a medium from acoustic reflection measurements

Transmit a sound wave into the medium

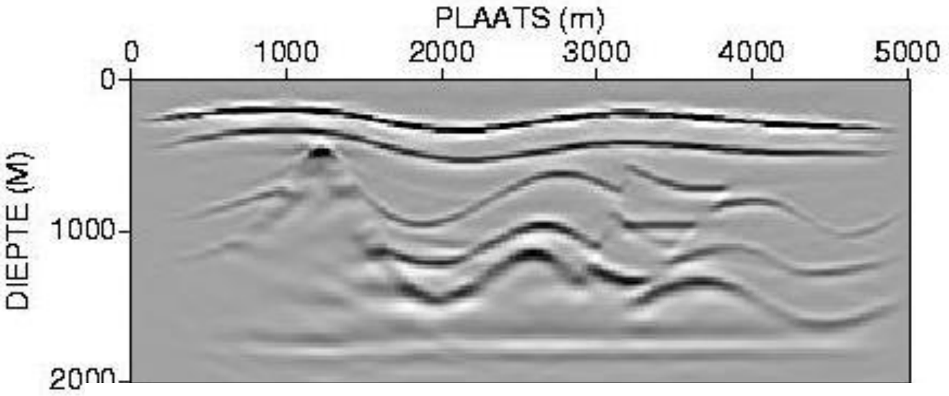


Measure the response with many channels



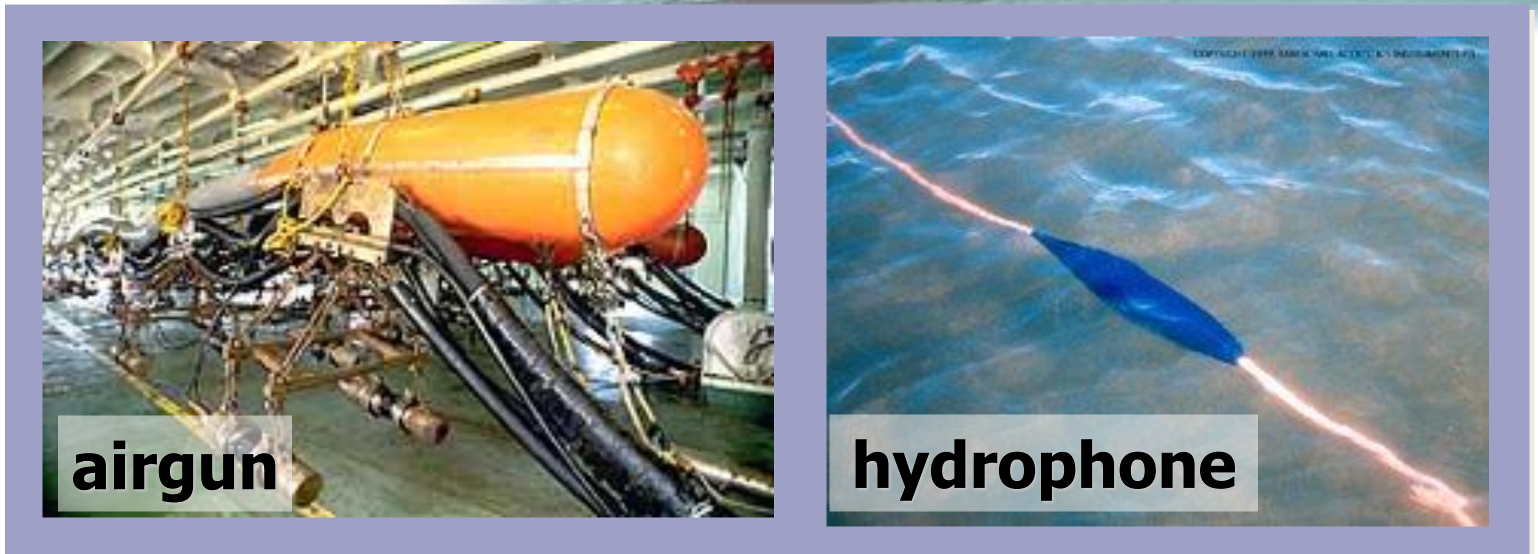
Seismische response gemeten aan oppervlak

Reconstruct an image of the medium using wave theory

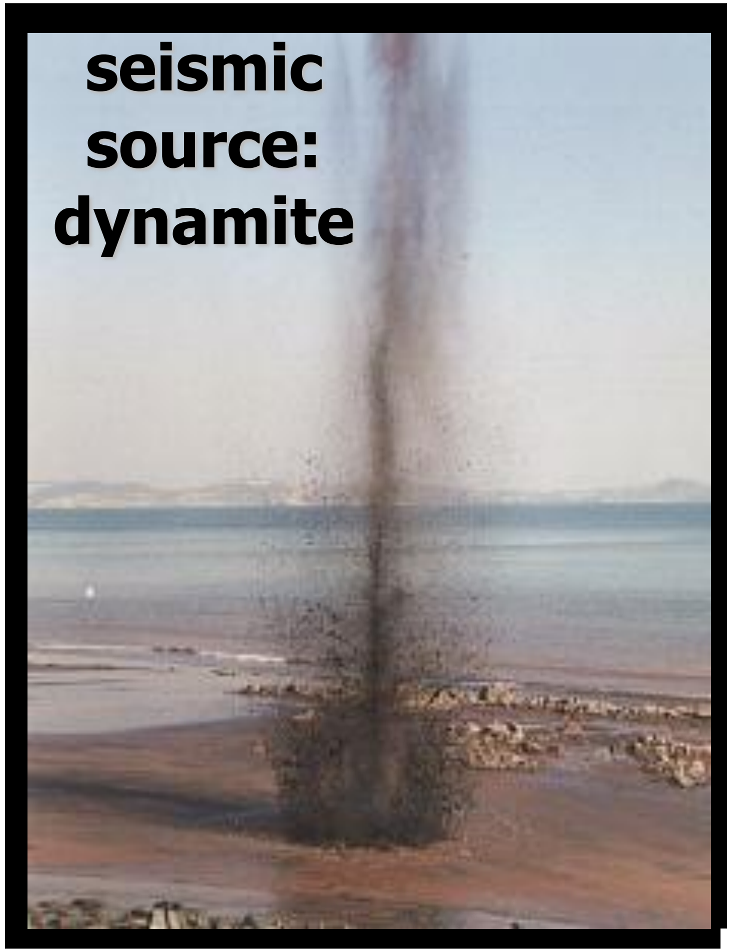


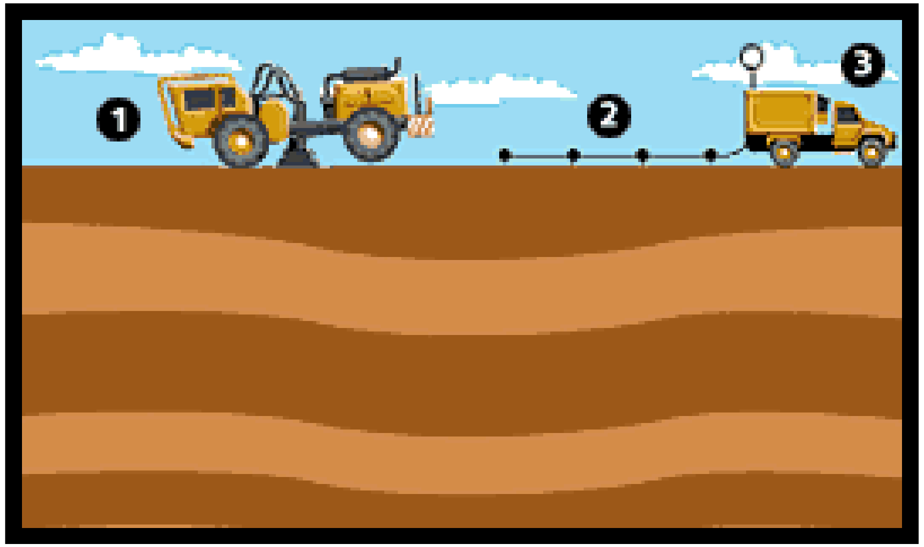
Vertical transect

Seismic measurements at sea



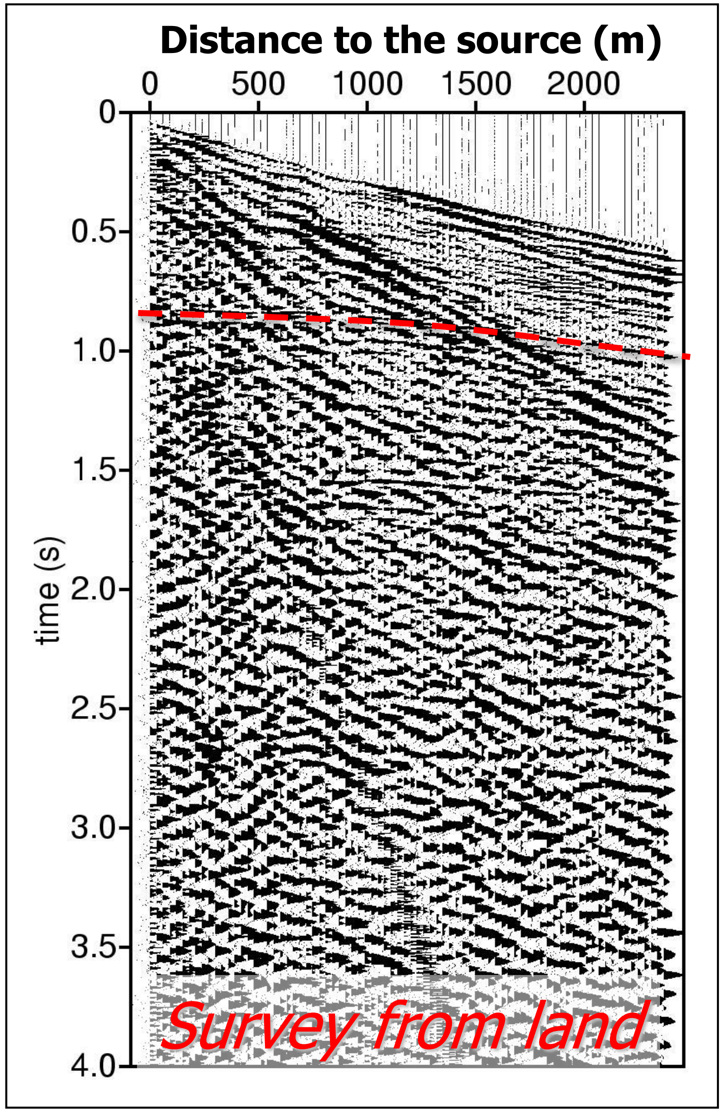
Seismic measurements on land

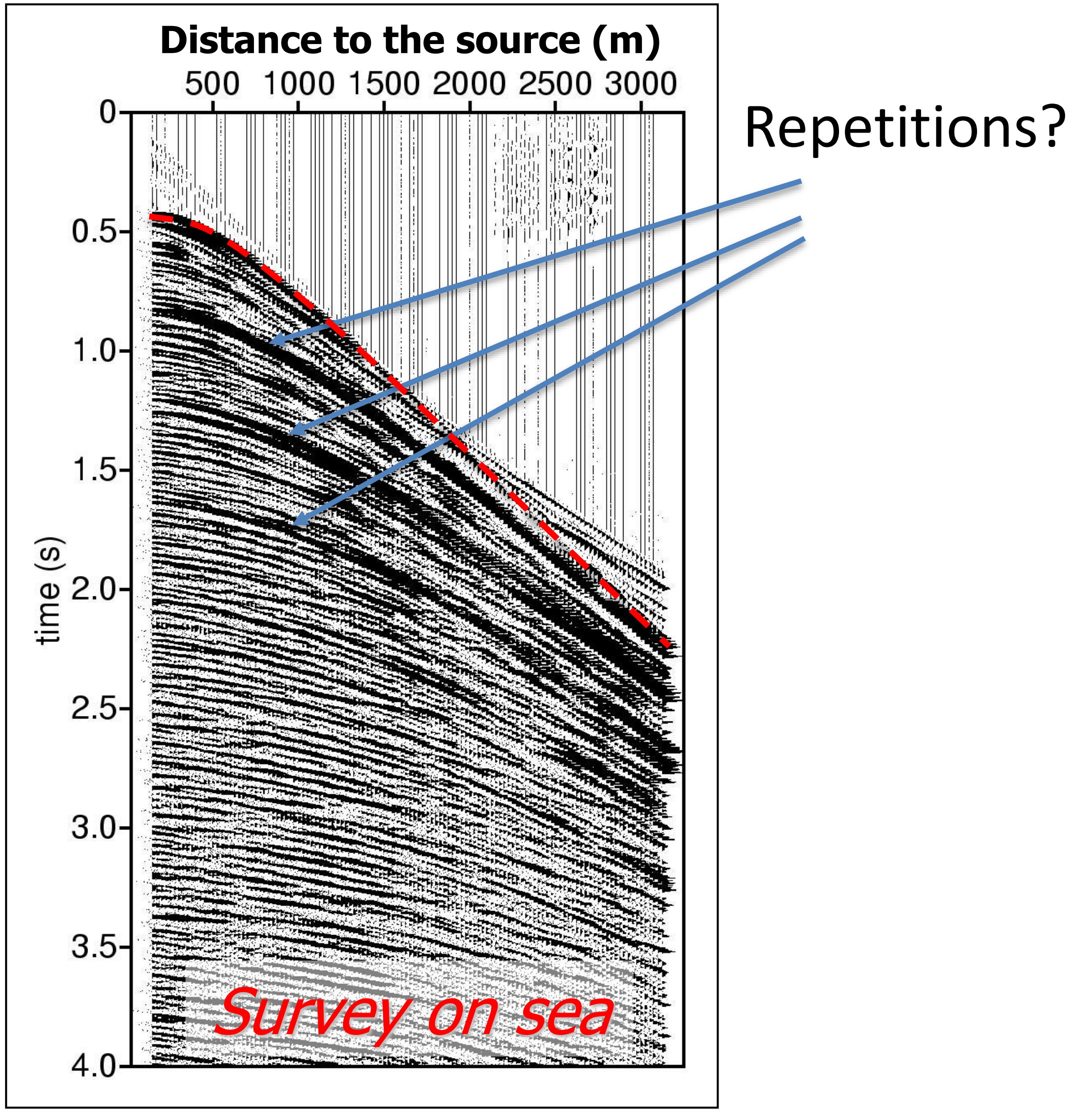




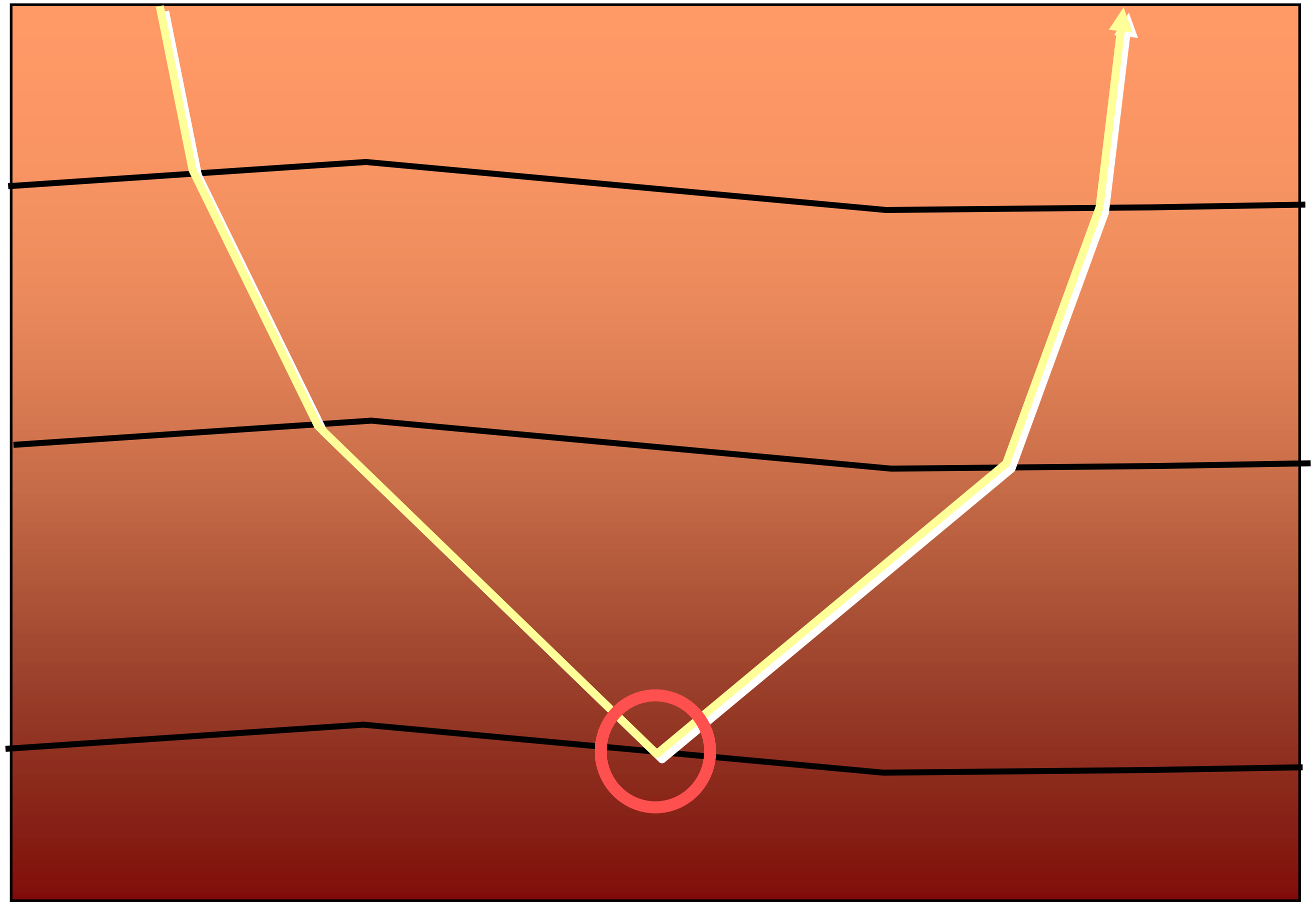
measurement with 3-component geophone: Vx, Vy, Vz

Examples of seismic measurements



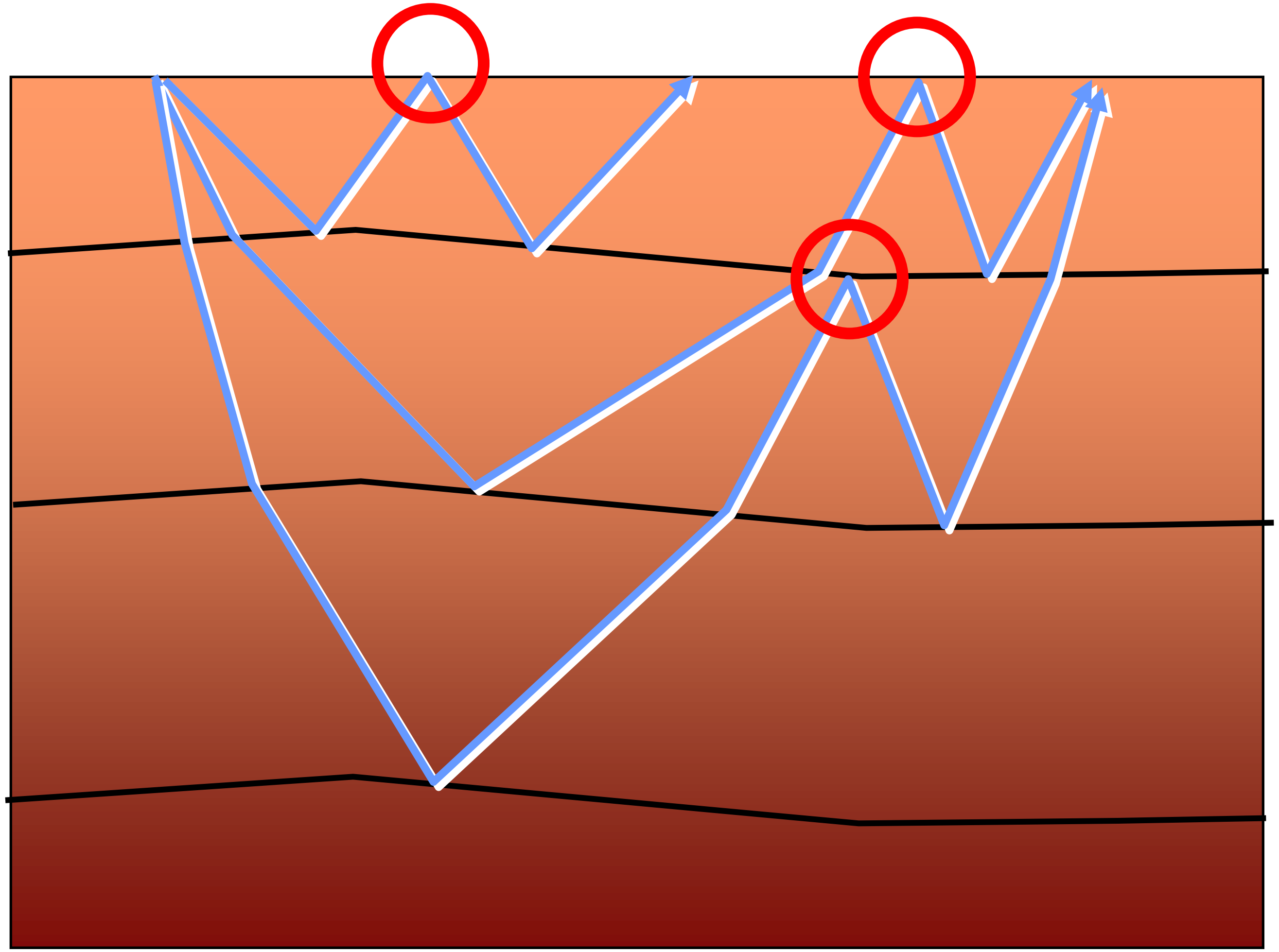


Multiple reflections



Primary reflection: one upward reflection in the subsurface

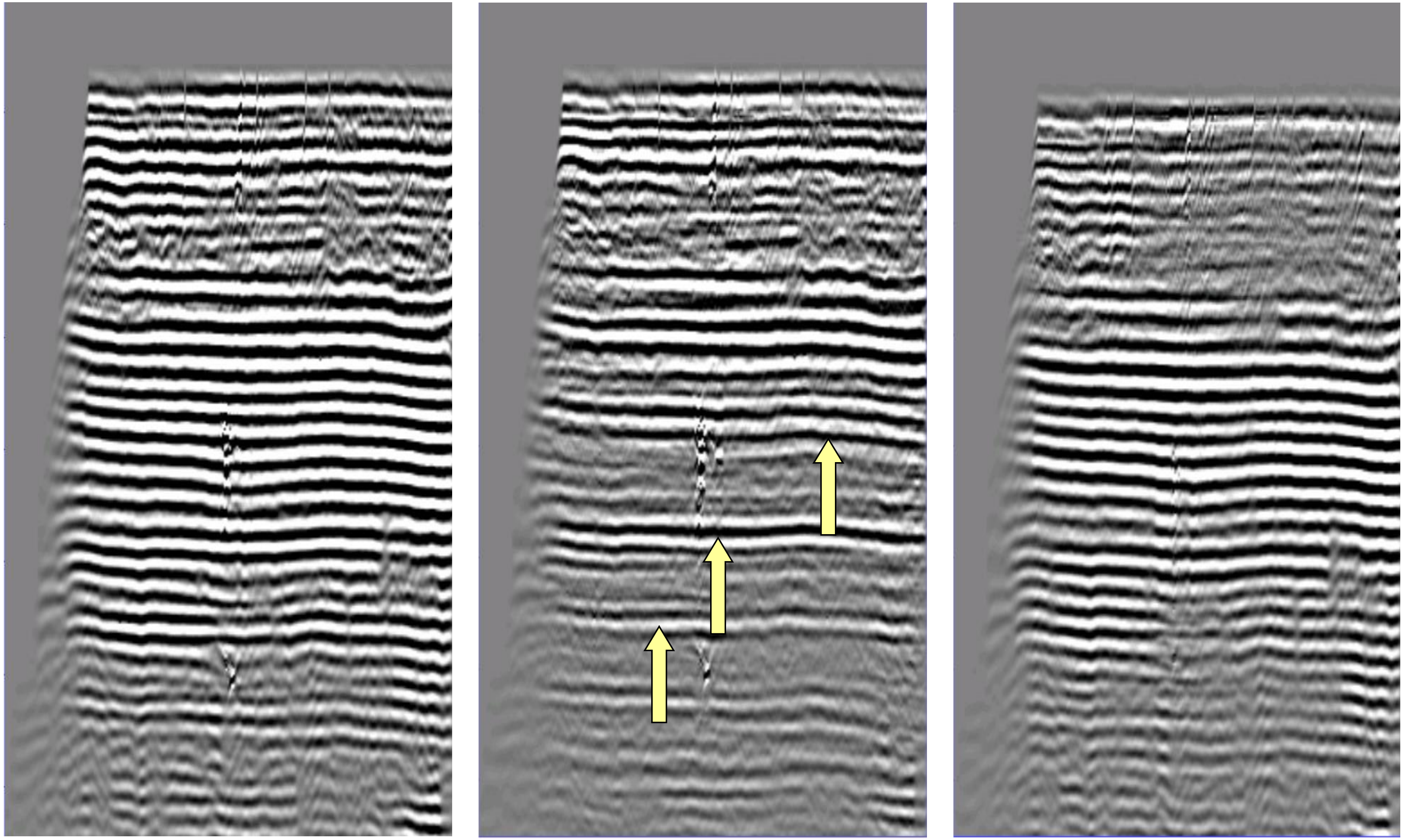
Multiple reflections



Multiple reflection: at least one downward reflection

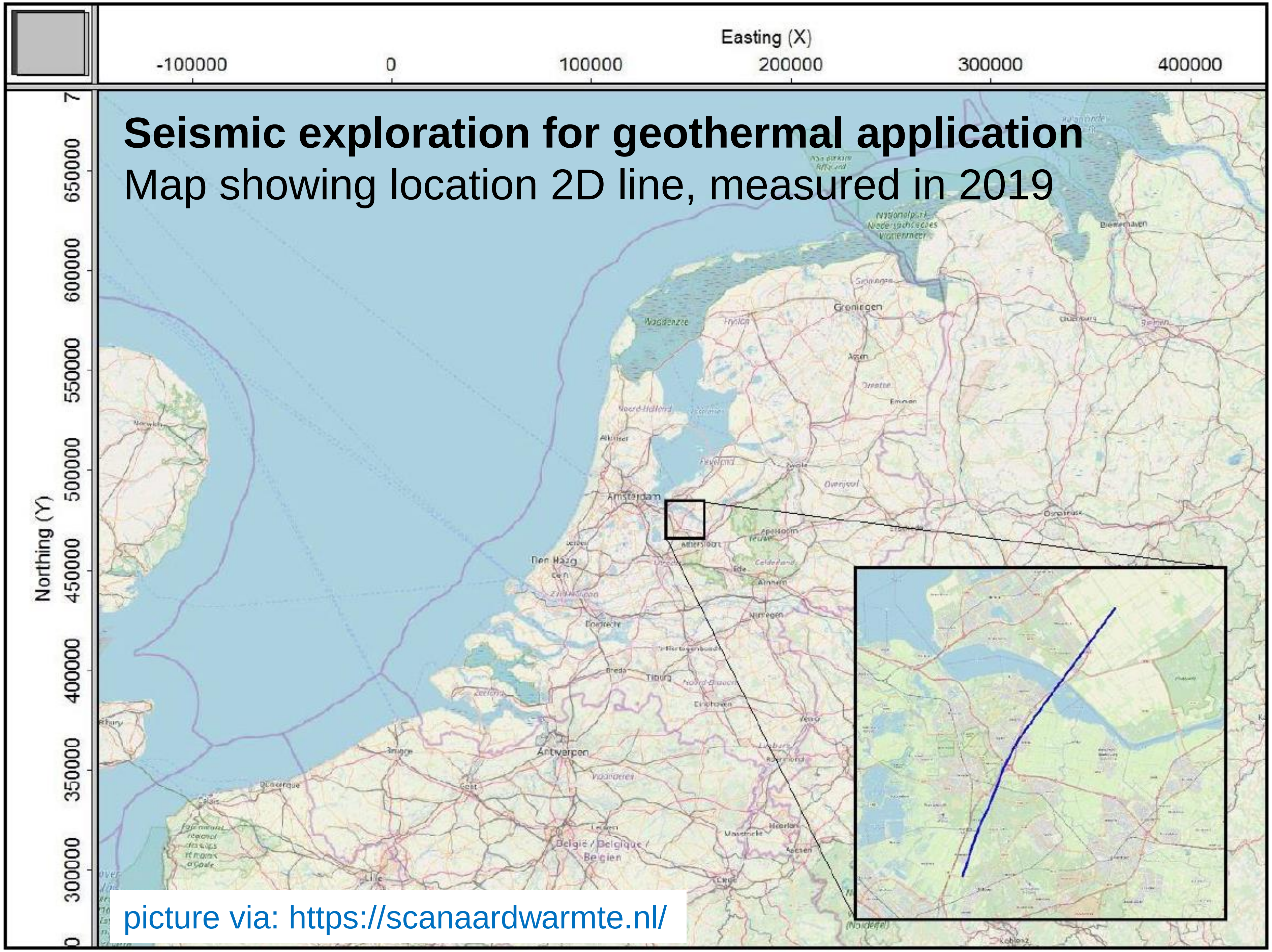
Removal of multiple reflections

Image of input | Image after multiple suppression | Difference

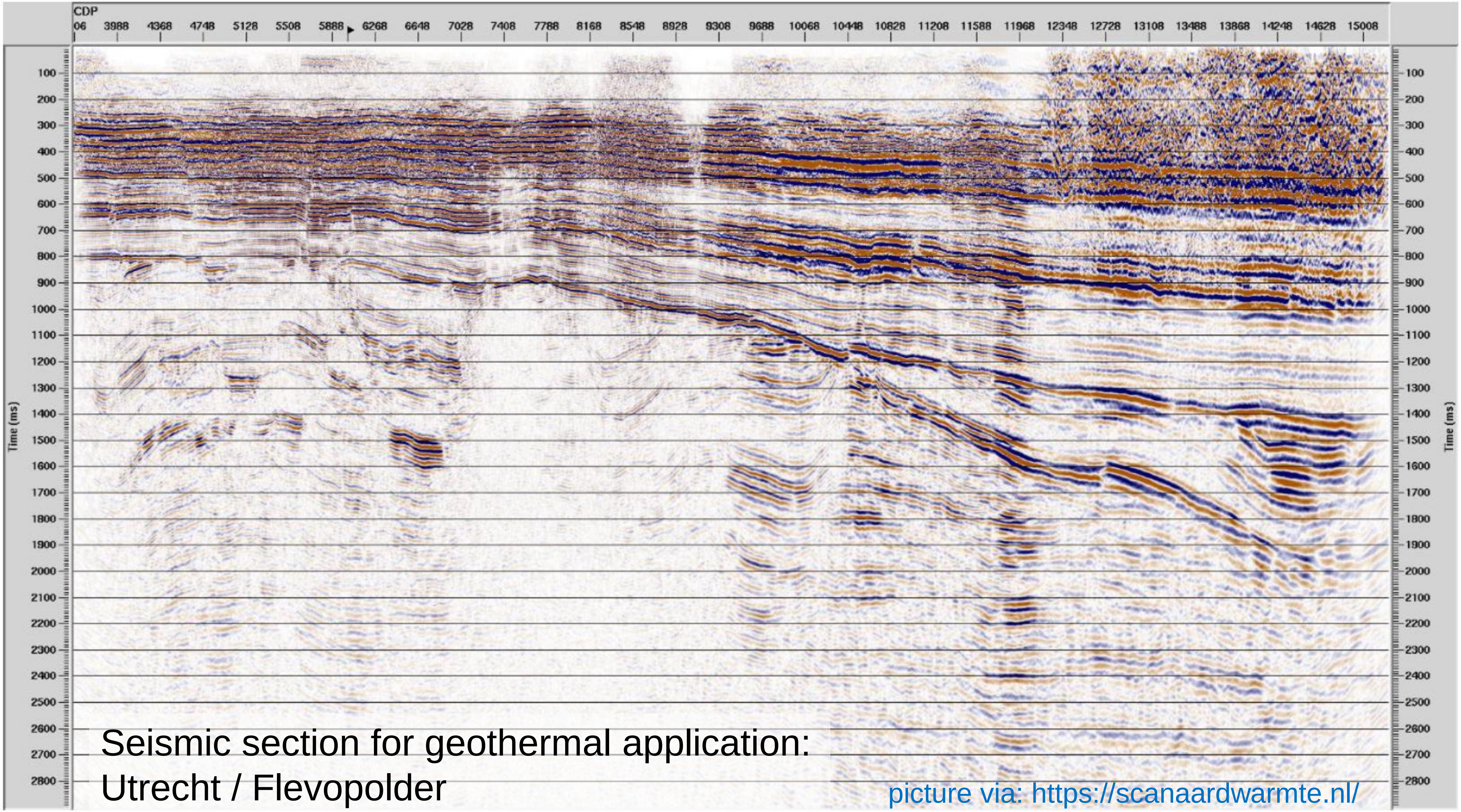


Seismic exploration for geothermal application

Map showing location 2D line, measured in 2019



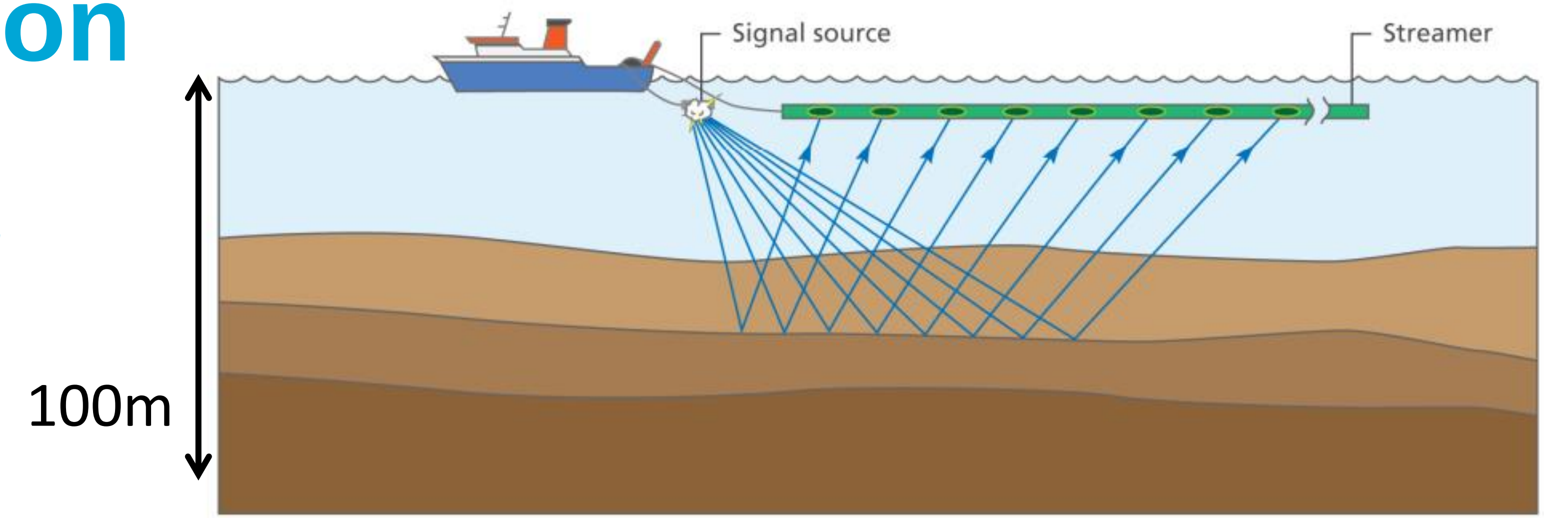
picture via: https://scanaardwarmte.nl/



Seismic section for geothermal application:
Utrecht / Flevopolder

picture via: https://scanaardwarmte.nl/

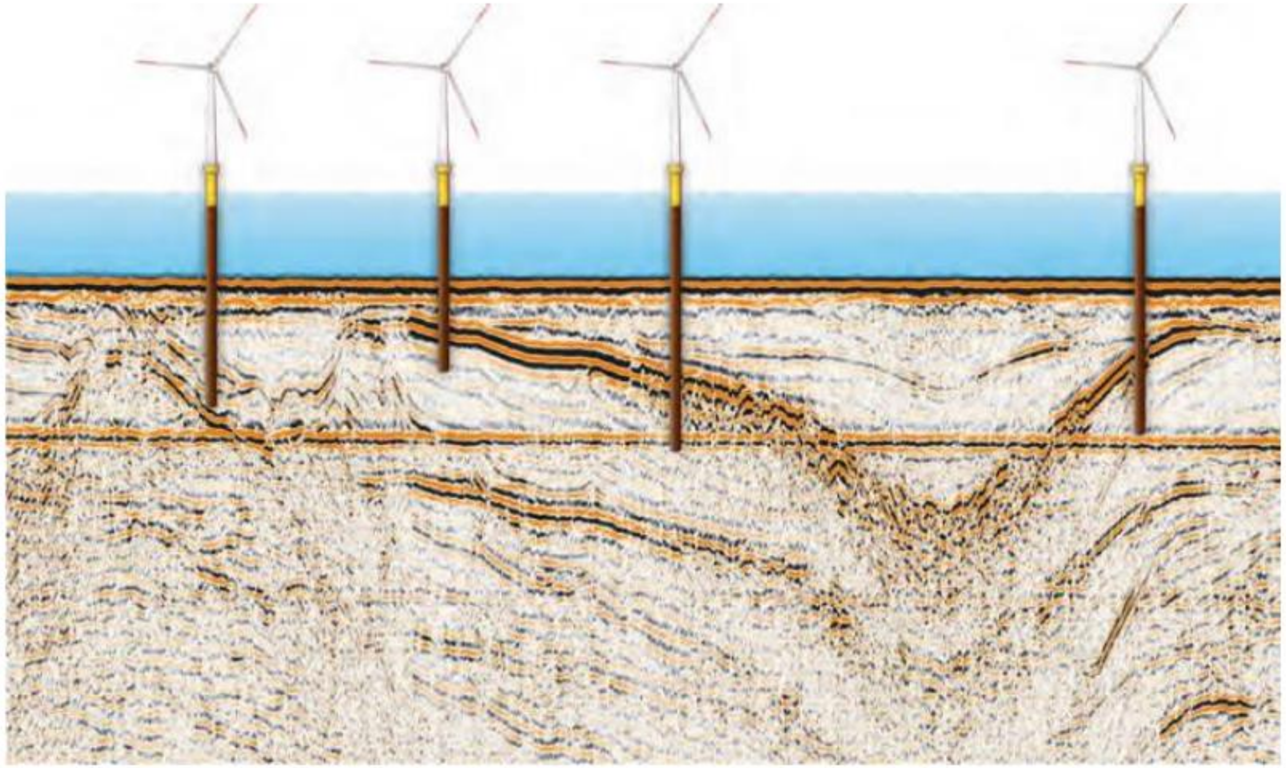
High-resolution seismic for wind farming



water bottom reflection

1^{st} order multiple ('ghost')

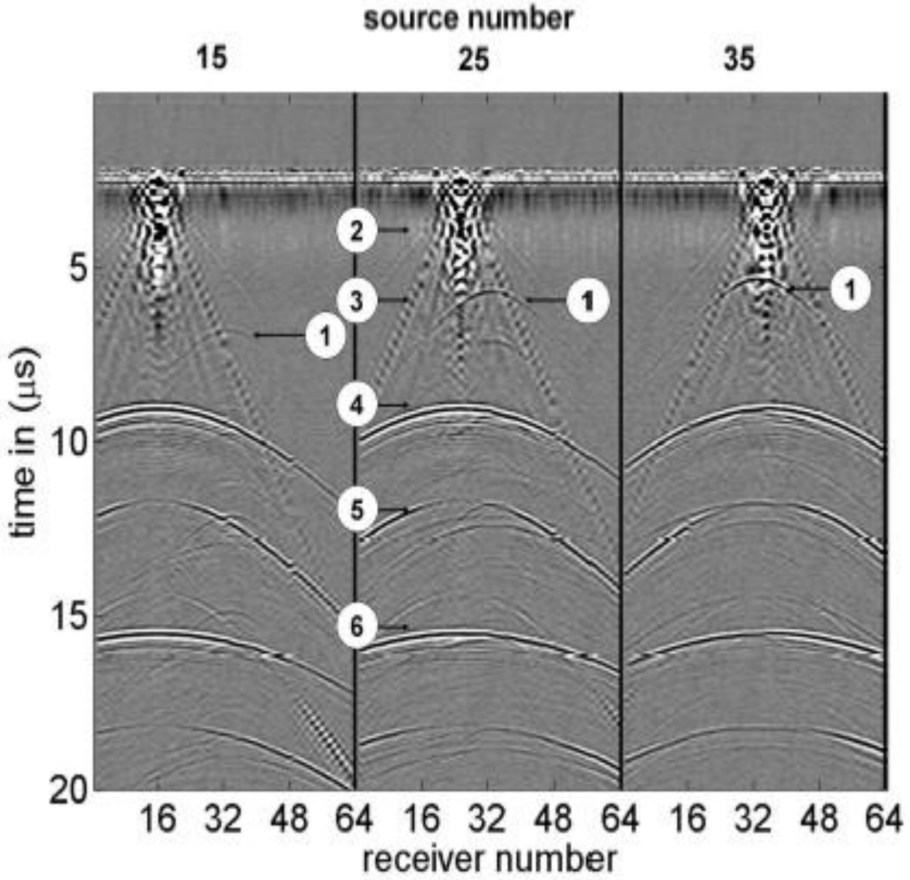
2^{nd} order multiple ('ghost')



(image from www.fraunhofer.de)

Cross-fertilization: non-destructive material testing

TOFD



Cross-fertilization: similar to seismic measurements, but at different scale

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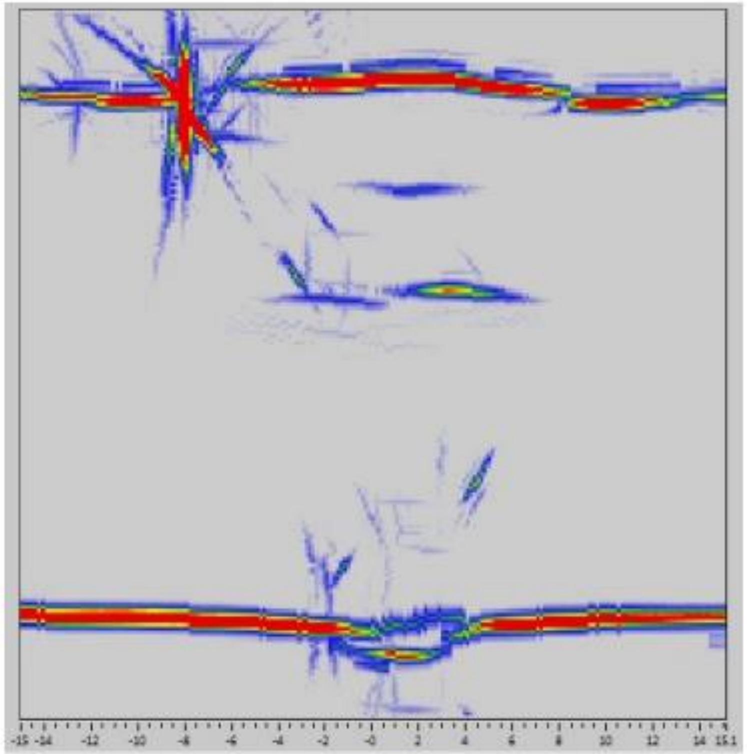
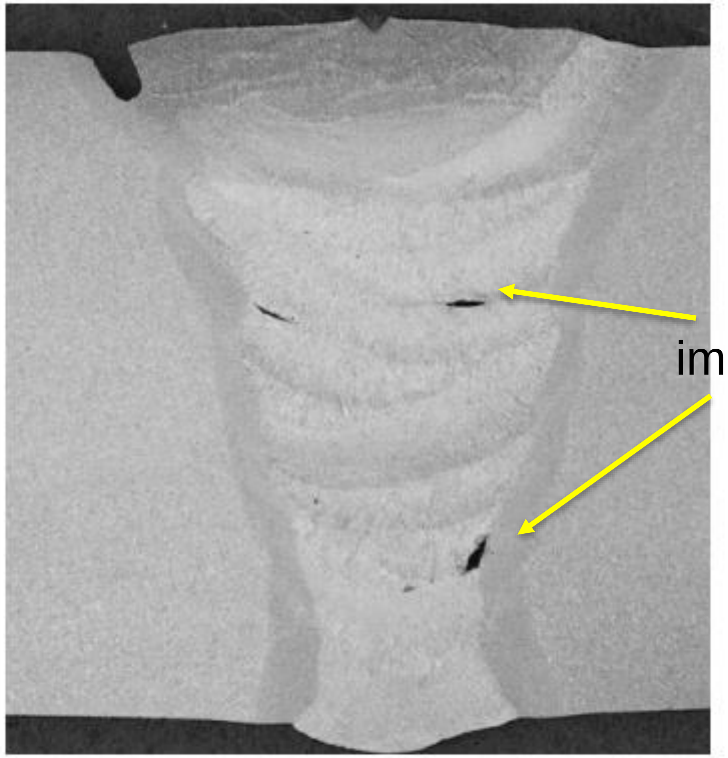
Cross-fertilization: non-destructive material testing

Cross-section weld using ultrasound



Cross-section weld using X-ray

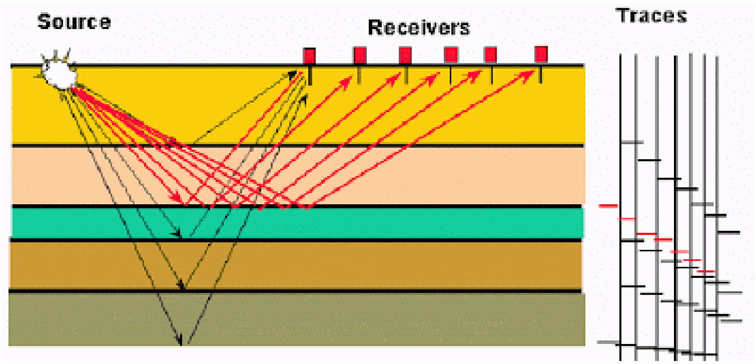


imperfections

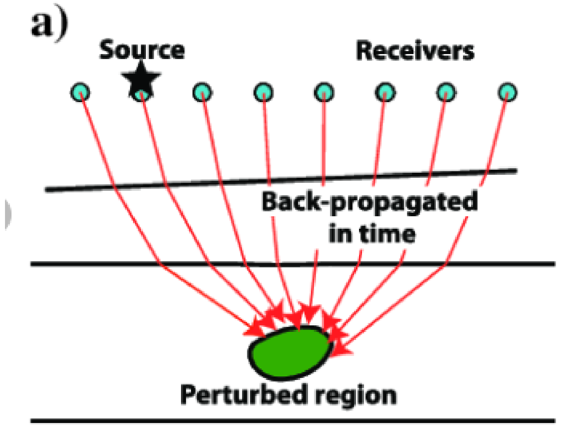
(image from applus.com)

Background propagation velocity estimation

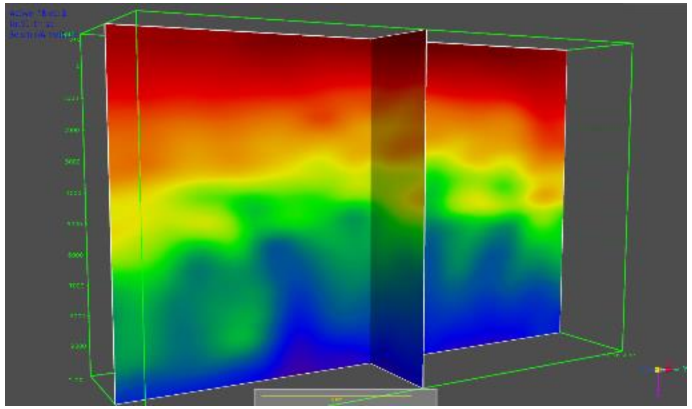
Make unfocussed measurements with overlap



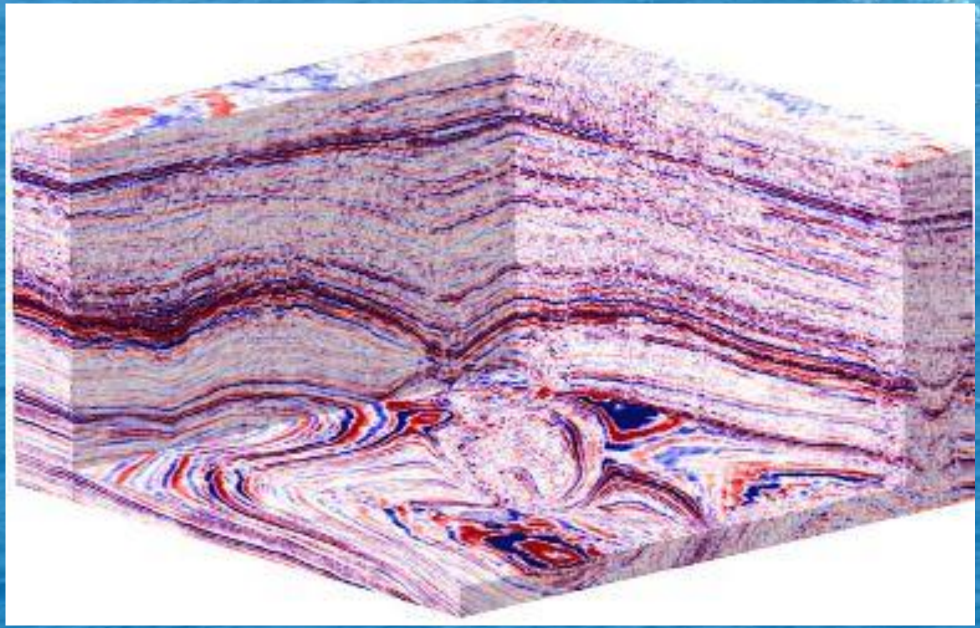
Imaging via back-propagation using wave equation, including influence velocity profile



Velocity profile unknown, need be estimated -
iterative approach: update profile until all measurements are well focused (sharp image)



Seismic imaging in 3D



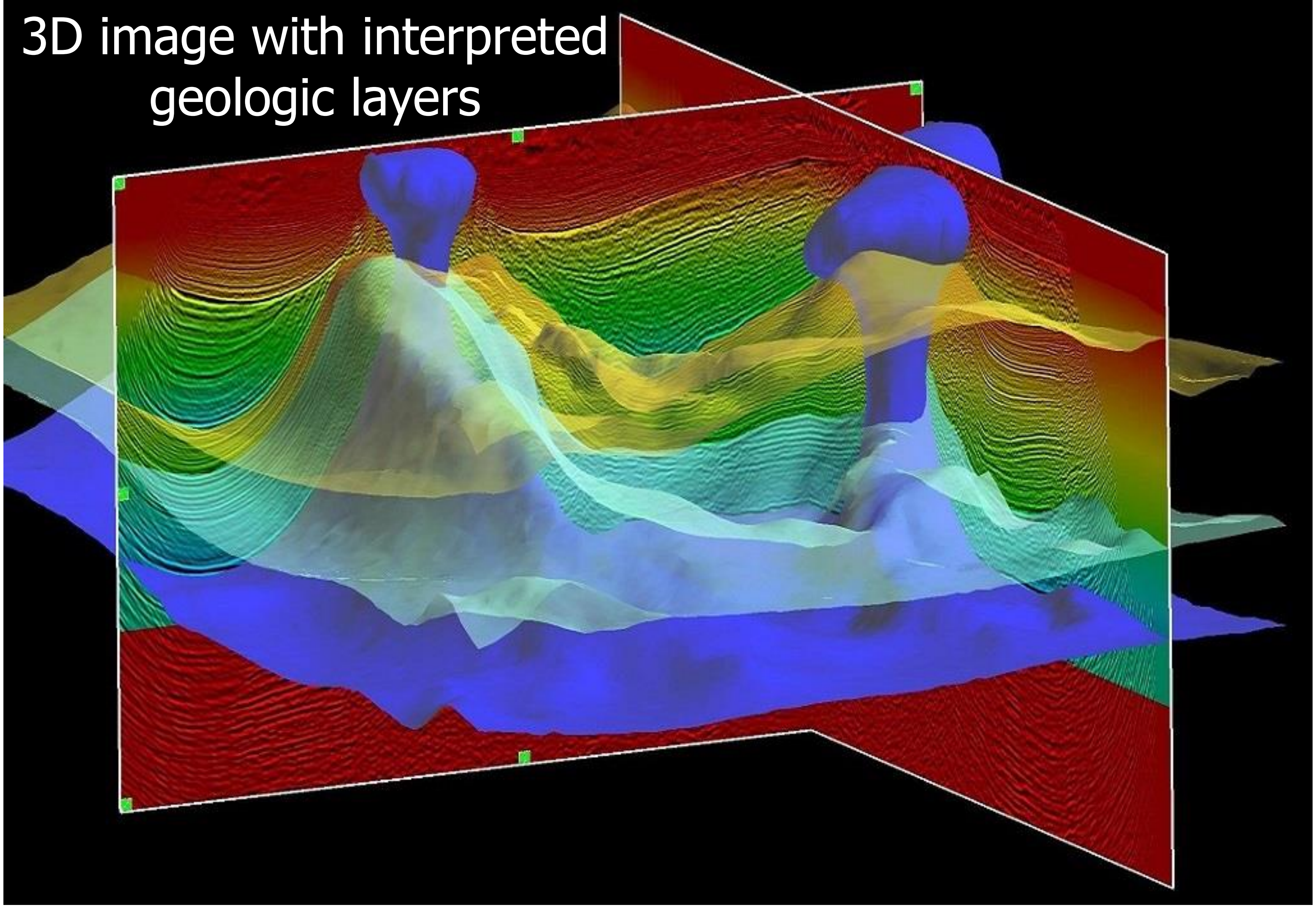
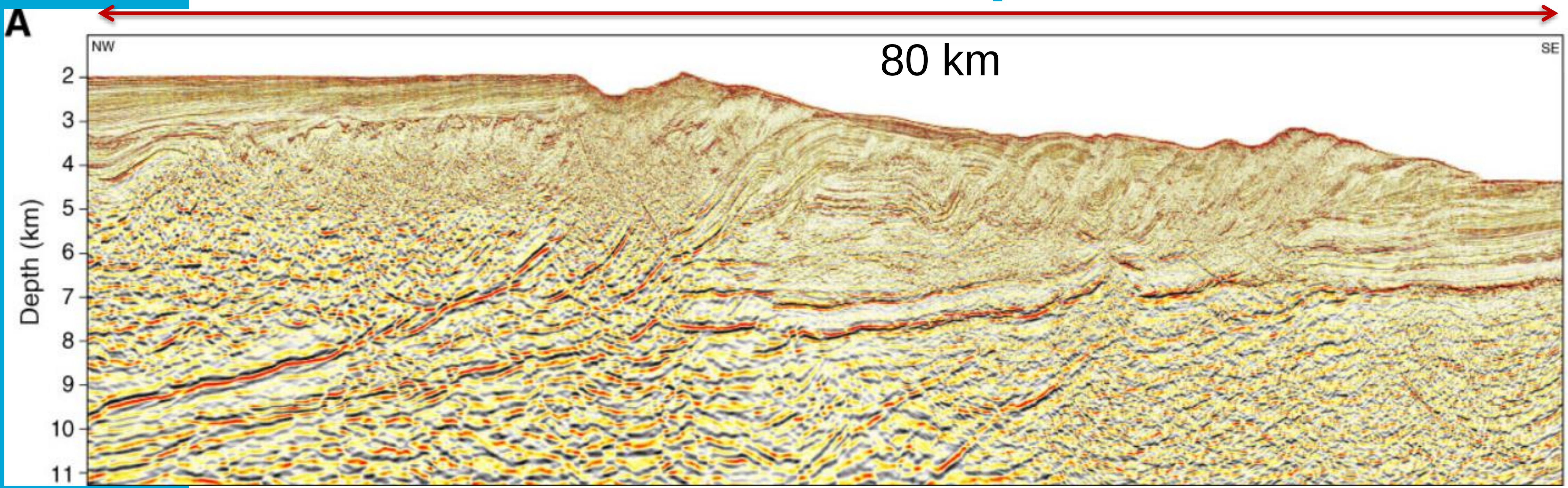
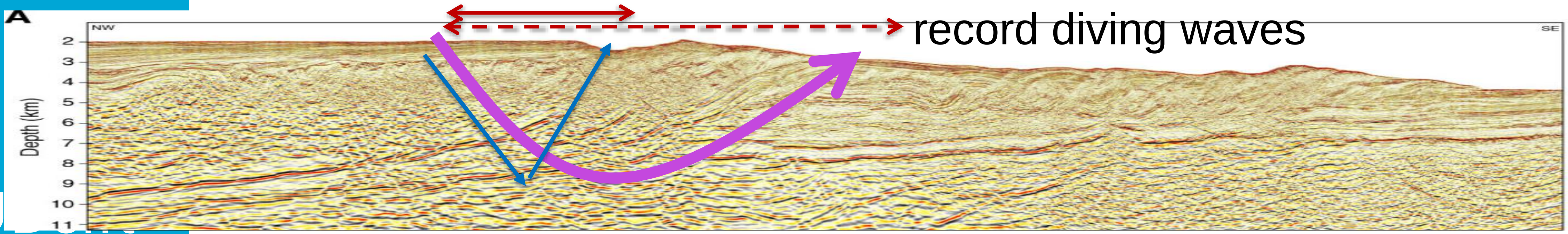


Image from: http://www.pdgm.com/

Seismic lines and its aspect ratio



antenna size is 7-10 km or sometimes ~20km



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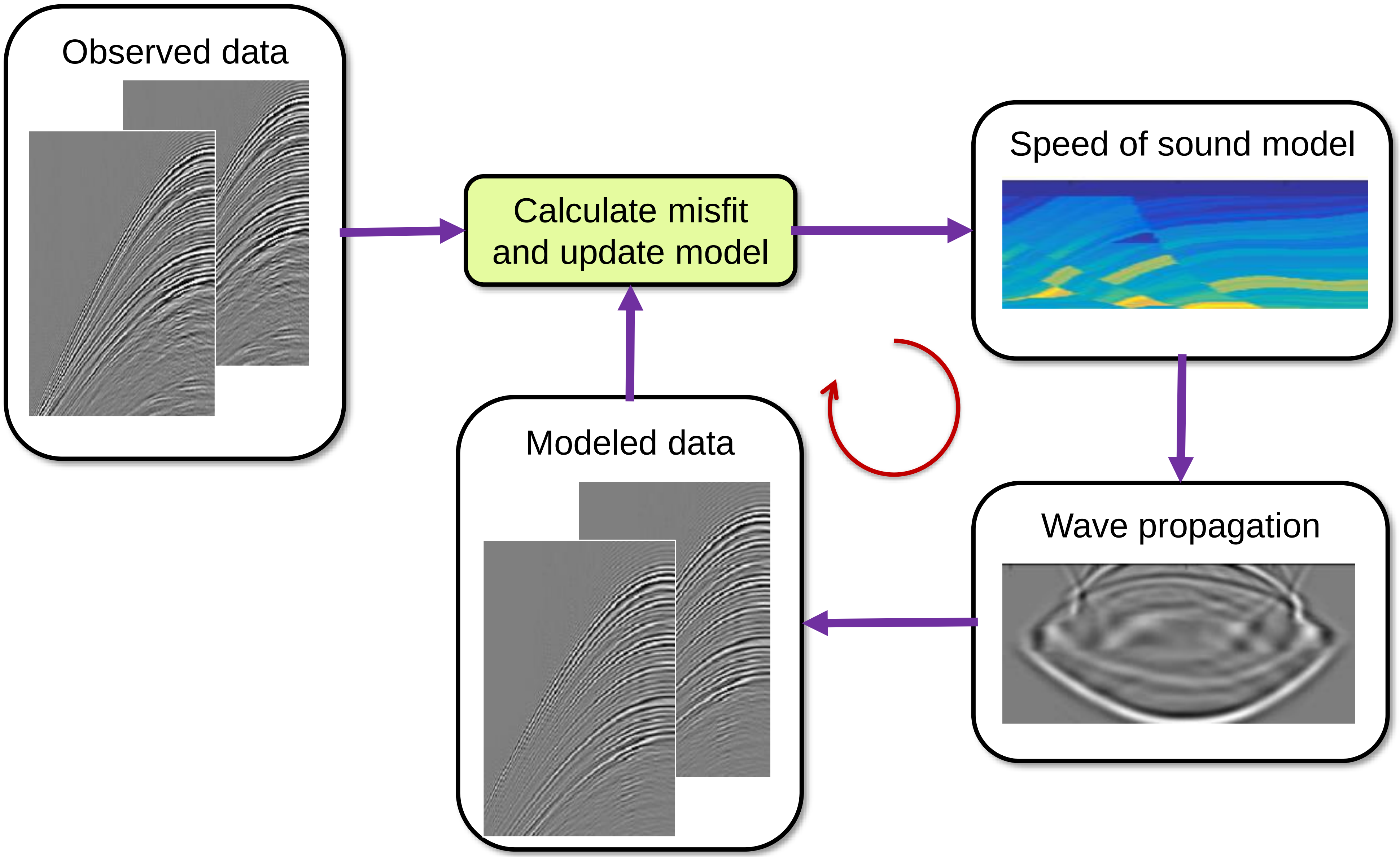
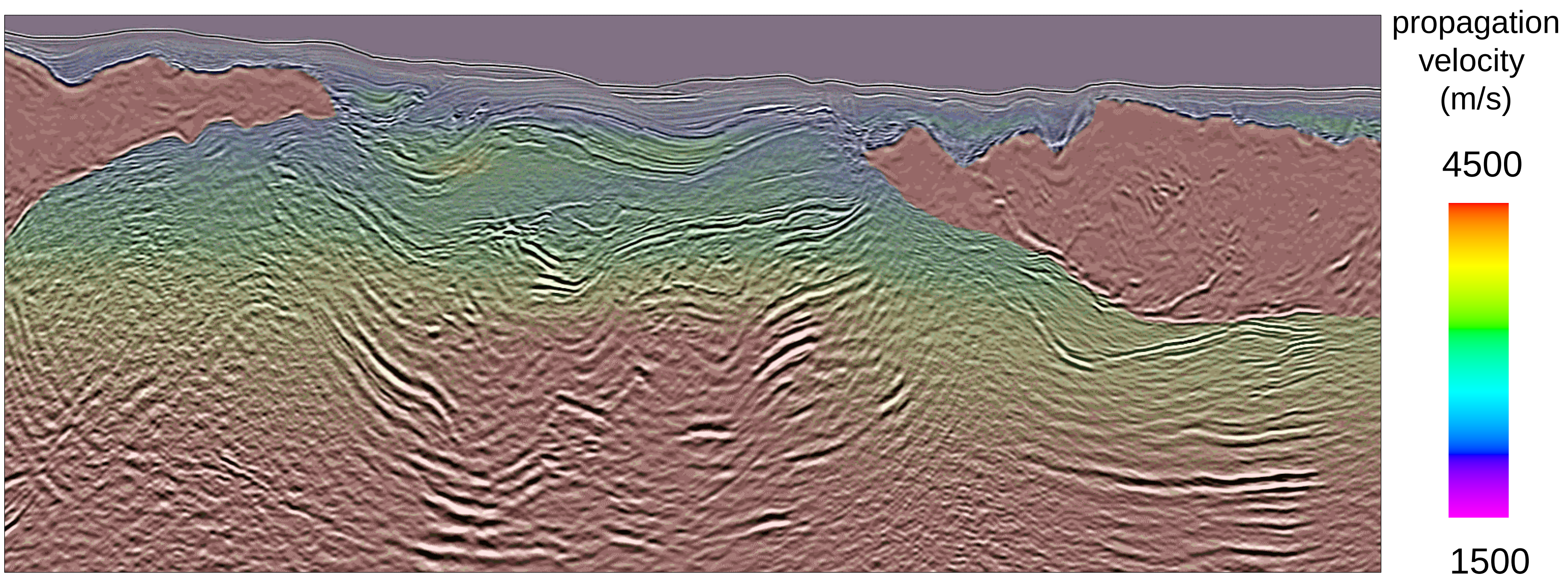
Full Waveform Inversion



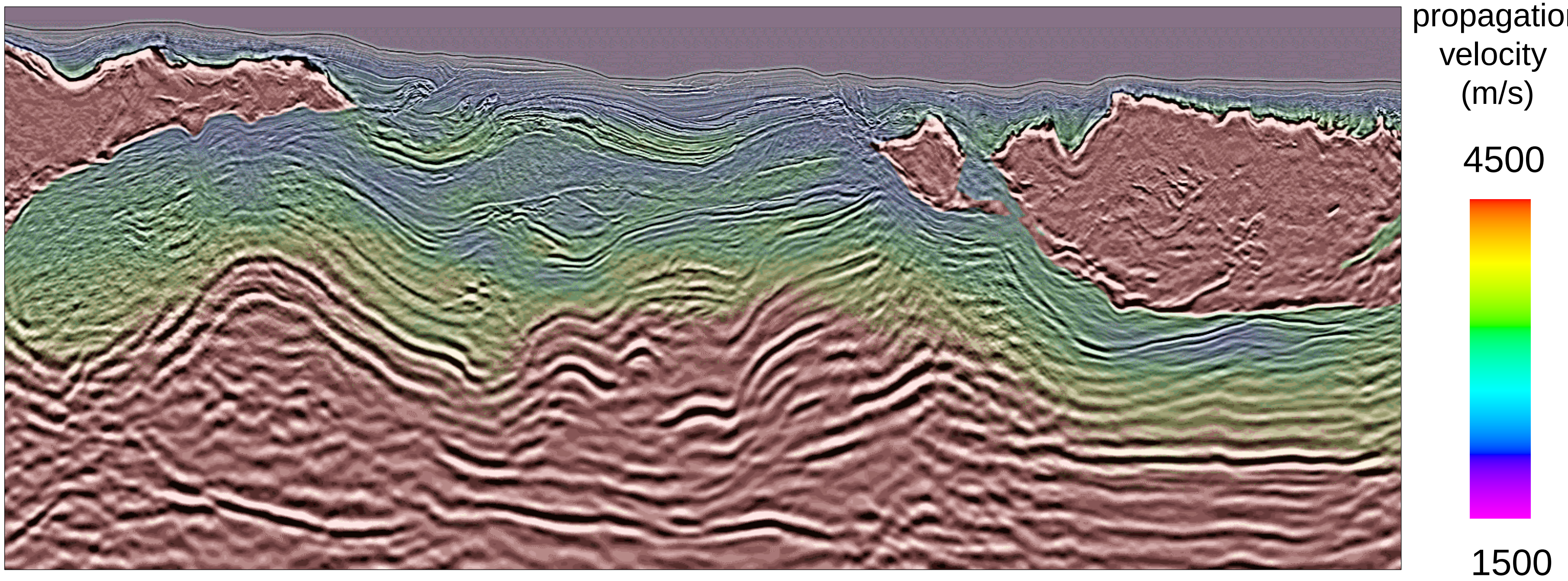
Full Waveform Inversion result



Result of traditional seismic imaging workflow

Picture: Schlumberger

Full Waveform Inversion result

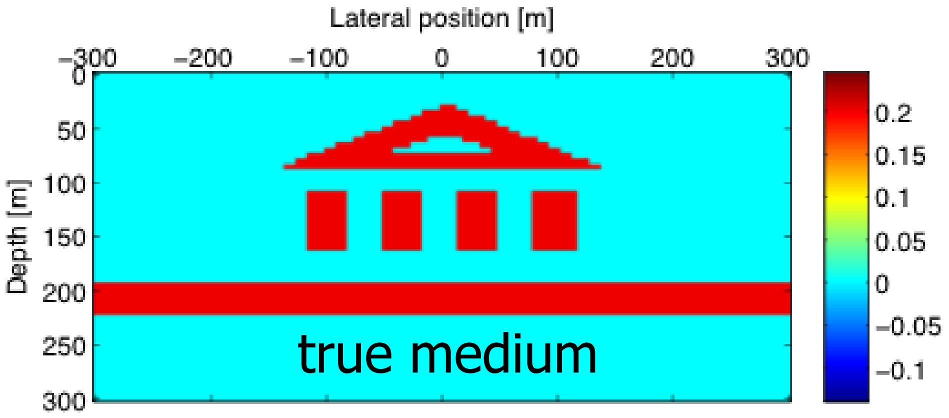


Result of FWI process, followed by imaging

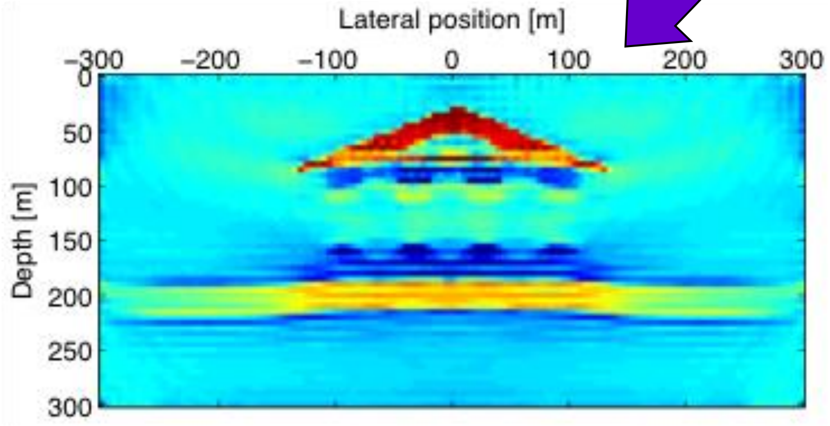
Picture: Schlumberger

From imaging to inversion

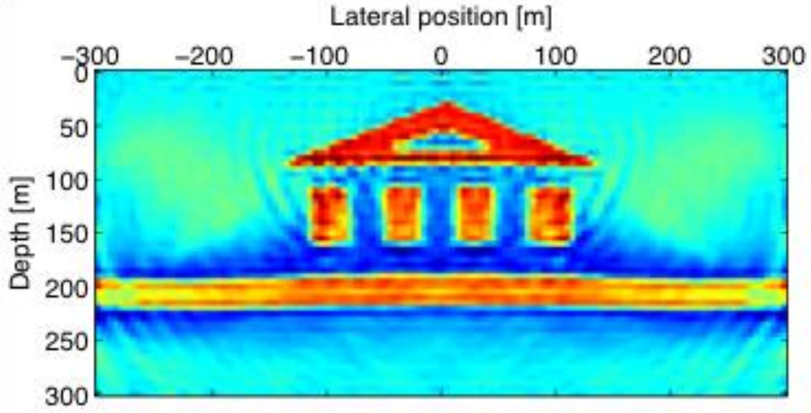
Use all complex scattering to obtain high-resolution medium properties



Traditional image



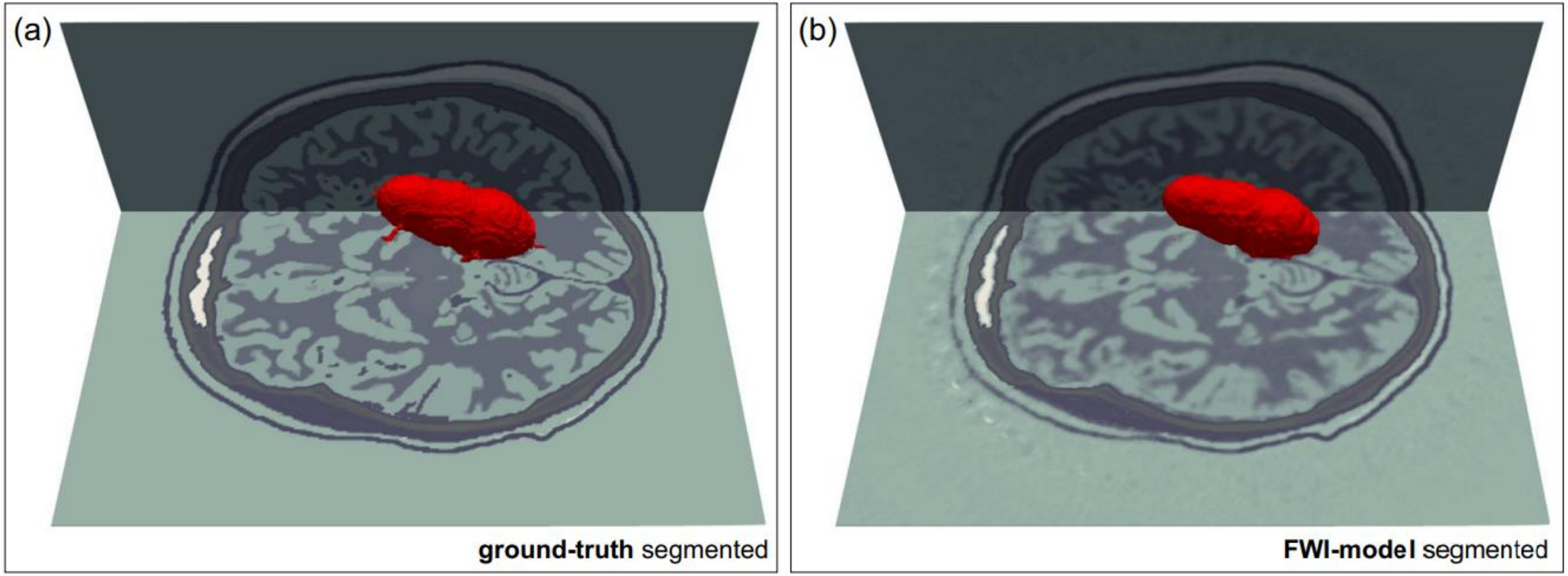
Result of full waveform inversion



Cross-fertilization to medical imaging

True brain model with haemorrhage (Dutch ‘bloeding’)

Result of FWI from ultrasound data with interpreted anomaly



Simulation study using full waveform inversion (FWI) to human brain imaging

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Image from Guasch et al, NPJ, 2022

Outline

- Introduction to acoustic waves
- Part 1: Transmission measurements
  - Basics of tomography
  - Earthquake traveltime tomography
  - Full waveform inversion (FWI)
- Part 2: Reflection measurements
  - Acoustic reflection experiments
  - Applications in seismic, medical, material inspection
  - Full waveform inversion (FWI)
- Concluding remarks

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Concluding remarks

- Acoustic imaging has a wide field with applications across different scales:
  from mm’s to km’s

- Advanced inversion methodologies can create a new step in resolution improvement

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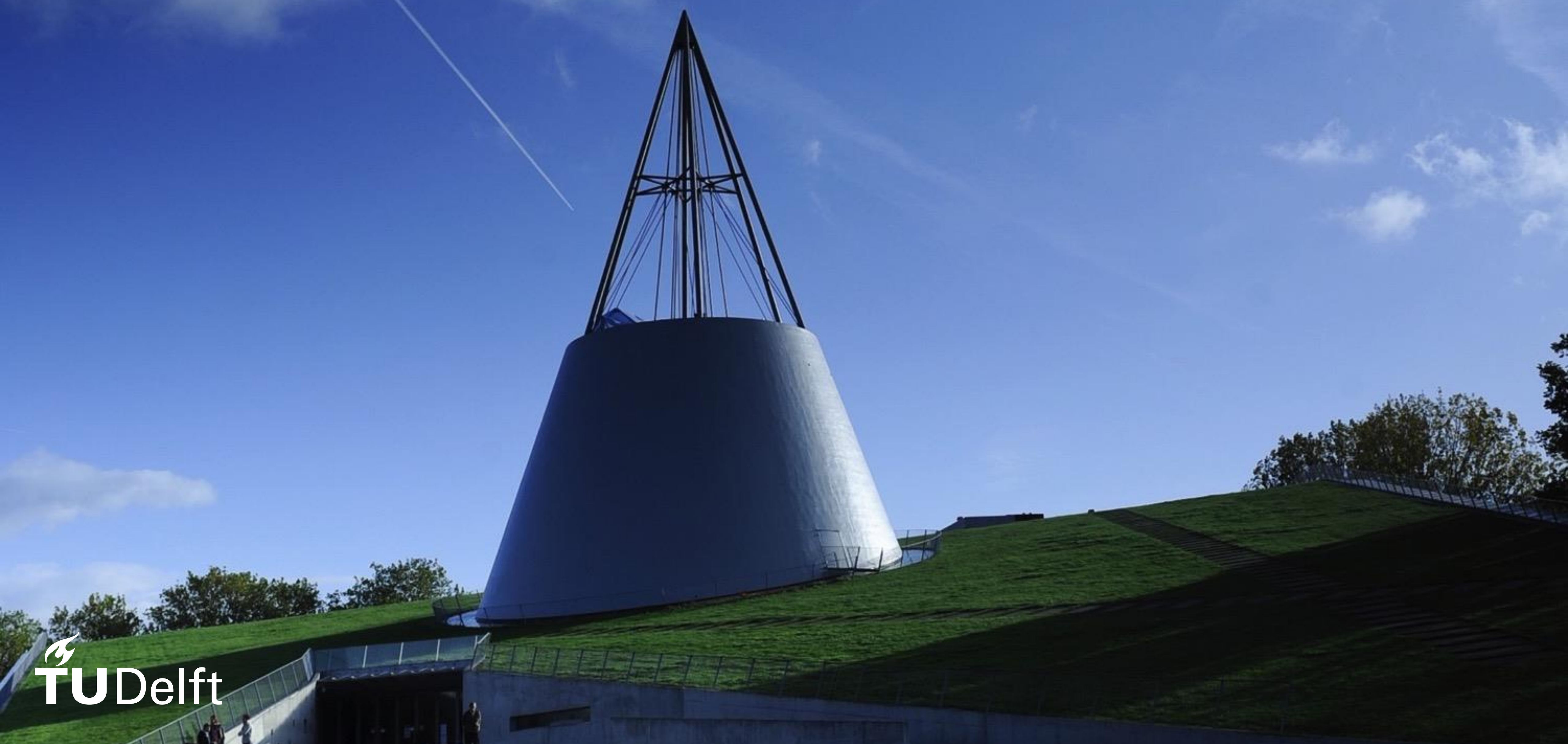
Thanks for your attention



Advertisement

BSc Technische Natuurkunde

In het kort

Voertaal: Nederlands

Numerus fixus: nee

Verplichte studiekeuzecheck: ja

Start: september

Vereiste vakken: Natuurkunde / Wiskunde B

Vorm: voltijds (on campus)

BSc Earth, Climate and Technology

In het kort

Voertaal: Engels

Numerus fixus: Nee, geen selectie

Start: September

Vereiste vakken: Wiskunde B, Natuurkunde en Scheikunde

Vorm: Voltijds- on campus

Buitenland: Veldwerk binnen het curriculum

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