Geophysical imaging

L. Métivier[1]

Wednesday 5th October, 2022

[1]LJK, ISTerre, CNRS, Univ. Grenoble Alpes, France

D113, ENSIMAG, Grenoble

Introduction

Geophysical imaging

Objectives of the course: present some key concepts about

- Mathematical side
  - partial differential equations and their discretization
  - inverse problems
- Application/geophysics side
  - propagation of mechanical waves in heterogeneous media (elastodynamics equations)
  - imaging of the subsurface using mechanical waves

Main outline

- Introduction (2 sessions: 05/10/2022, 12/10/2022)
- Full Waveform Modeling (4 sessions: 19/10/2022, 09/11/2022, 16/11/2022, 07/12/2022)
- Full Waveform Inversion (6 sessions: 14/12/2022, 04/01/2023, 11/01/2023, **17/01/2023**, 18/01/2023, 25/01/2023)

Contact: **ludovic.metivier@univ-grenoble-alpes.fr**

Lecture notes and slides: are available on my webpage.

`https://membres-ljk.imag.fr/Ludovic.Metivier/webpage_LMetivier.html`

Outline

Geophysical imaging

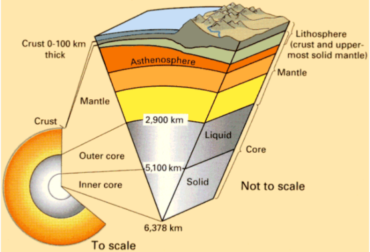
Geophysical imaging = inferring mechanical properties of the subsurface

- rheology
- 3D geometry (structure)

with maximum details

Understanding Earth's geodynamic

- mantle convection, mantle/core boundary
- planet formation
- geomagnetic field generation through convection in the outer core
- plate tectonic

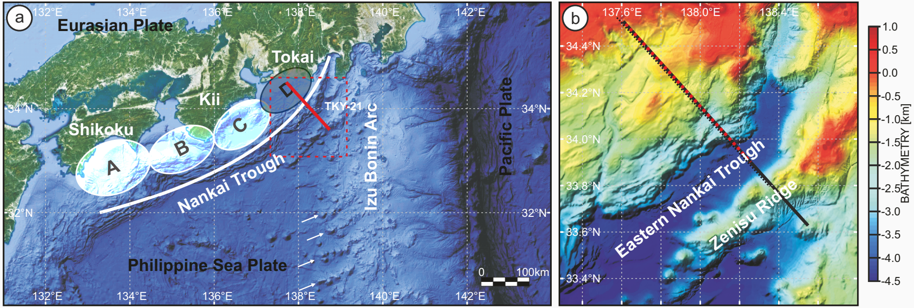


"The layer at the core mantle boundary may serve a the source of material for mantle plumes that give rise to hot spots, which are important in plate tectonics. The thermal properties of this layer might also influence the outward transport of heat from the Earth's core; in turn this could affect the intricate processes that generate the Earth's magnetic field."

Lowrie and Ficthner (2020)

Understanding active zones, preventing seismic hazard

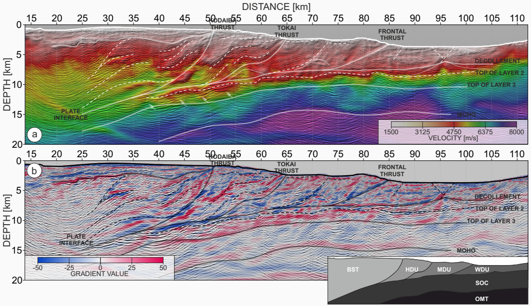
- active zones = active faults, subduction zones, volcanic area
- example: Nankai Trough



Partitioning of the Nankai Trough into four segments as described by Ando (1975). Region D was left unruptured during the most recent sequence of two large earthquakes (1944 Tonankai and 1946 Nankaido). Figure taken from Gorszczyk et al. (2019).

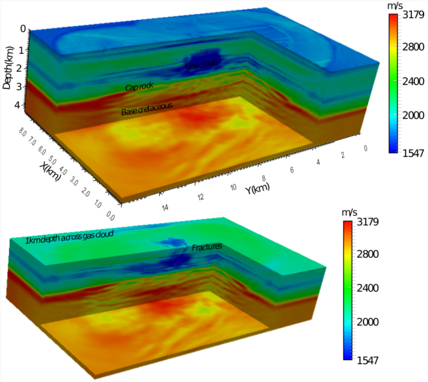
Understanding active zones, preventing seismic hazard

- active zones = active faults, subduction zones, volcanic area
- example: Nankai Trough

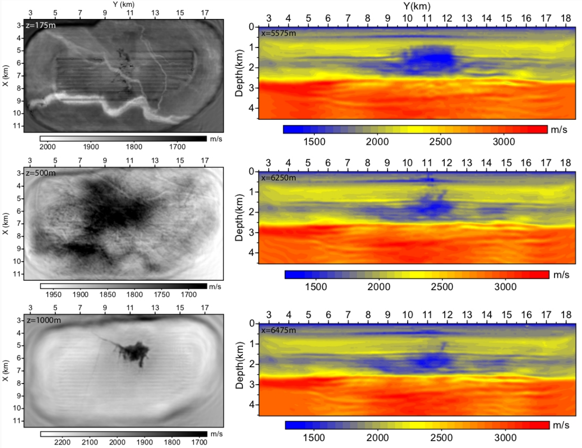


Imaging results and structural interpretation. Migrated section superimposed on: Inset presents different geological block-segments: **OMT** - oceanic mantle; **SOC** - subducting oceanic crust; **WDU** - weakly deformed unit; **MDU** - moderately deformed unit; **HDU** - heavily deformed unit; **BST** - backstop. Figure taken from Gorszczyk et al. (2019).

Localizing and exploiting hydrocarbon resources

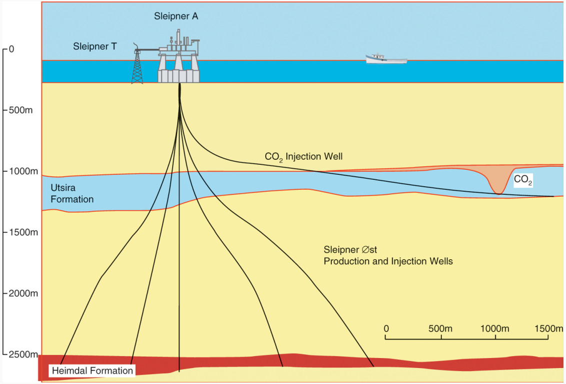


3D imaging from the North sea (Operto et al., 2015)



Left: Horizontal slices 175m depth, 500m depth, 1km depth across the gas cloud. Right: Inline vertical slices passing through the gas cloud ($X = 5.6km$) and near its periphery ($X = 6.25km$). Figure taken from Operto et al. (2015).

Imaging and monitoring CO2 storage zones



Schematic view of the CO2 storage injection in Sleipner (Norway) (Eiken, 2019). Sleipner is a pilot site, which has made possible to test and evaluate the interest of CO2 storage technology since 1996.

Imaging for archaeologists

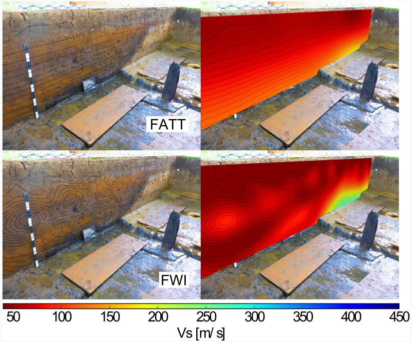


Figure extracted from Koehn et al. (2018). FWI stands for Full Waveform Inversion and FATT for First Arrival travel-time tomography. The latter technique produce a low resolution estimate of the shear wave velocity. FWI provides a higher resolution estimate. Thanks to the excavation, the results can be confronted to the true subsurface rheology. The comparison between the photography and the FWI result illustrates how the higher resolution details conform with the reality. In particular, the target (the “Fossa Carolina” canal) is much more accurately delineated in the bottom right corner of the 2D shear-wave velocity map.

and other purposes

- geothermal energy
- geotechnical engineering
- ...

How to access the subsurface structure: drilling is not (really) an option

Drawback of drilling:

- direct measurement can destroy the target: archeology and geotechnical engineering belong to this category of applications.
- local information only: the subsurface, especially the crust, can not be accurately represented as a layered medium.
- highly technical and complex operation: thus expensive and risky
- for regional scale and global scale imaging, the depth of investigation of a drilling operation is far from being sufficient.

How to access the subsurface structure: drilling is not (really) an option

- Deepest drilling in the world: 12, 2 km $\simeq$ **0.2 % of the Earth's radius**
- Location: Kola Peninsula, Russia
- Drilling duration: 1970-1989 *i.e.* 19 years

Localization of the Kola peninsula on Google Earth (left). Picture of the Kola Superdeep Borehole drilling site(right).

Only feasible approach: remote sensing

Starting point: **subsurface rheology has an impact on the propagation of waves**.

- Electromagnetic waves. In this case, the subsurface structure/rheology variations affect the mean **permittivity and conductivity** of the subsurface, which have an effect on the propagation of electromagnetic waves.
- Mechanical (elastic) waves. In this case, the subsurface structure/rheology variations affect the mean **velocity, density, anisotropy, and attenuation** of the subsurface, which have an effect on the propagation of mechanical (elastic) waves.

Principle: from the observation of electromagnetic or elastic waves, infer the mean electromagnetic or mechanical properties of the subsurface

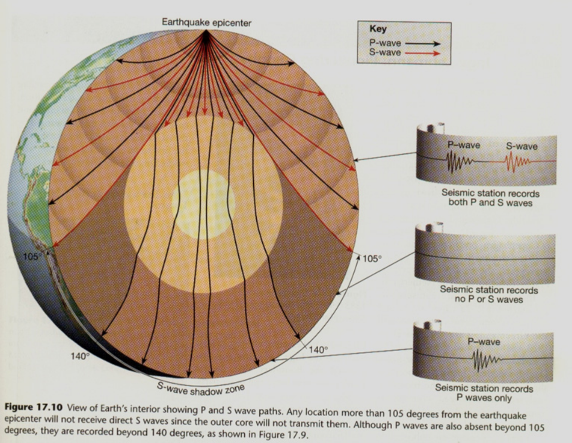
Outline

On board: generalities on inverse problems

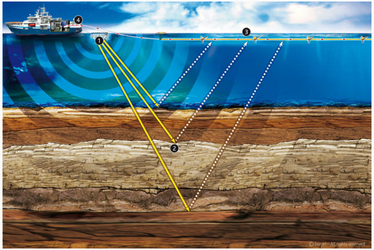
$$g(m) = d \tag{1}$$

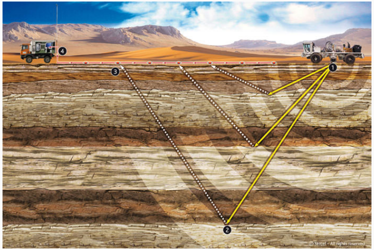
Outline

We can use Earthquakes



Global tomography sketch: an earthquake acts as a source which propagates elastic waves which are recorded by seismic stations spread at different point of the surface





Controlled source acquisition sketch, in a marine environment (left) or on land (right)

Notations for data

In terms of mathematics, the seismic data is thus a collection of time functions $d(t)$ associated with a source s and a receiver r. We will denote it as

$$d_{r,s}(t), \tag{2}$$

in the following, or equivalently

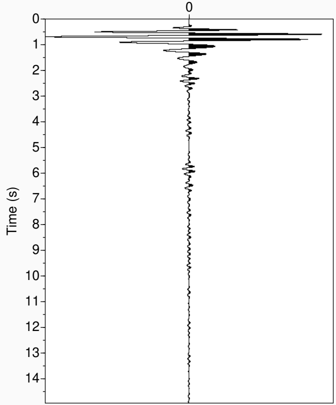
$$d(x_s, x_r, t), \tag{3}$$

or

$$d_s(x_r, t), \tag{4}$$

depending on the context. In these notations x_r and x_s denote the spatial position of the receiver r and the source s respectively. A single function $d_{r,s}(t)$ will be referred to as a *seismic trace* in the following.

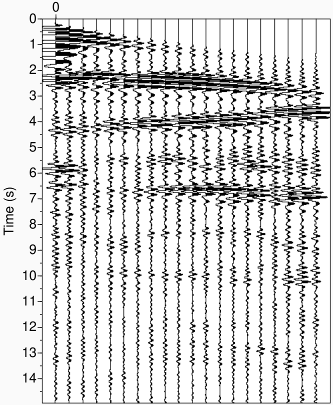
A typical example of a seismic trace is presented in Figure 20.



Typical seismic trace $d(t)$ as a function of time.

Seismogram

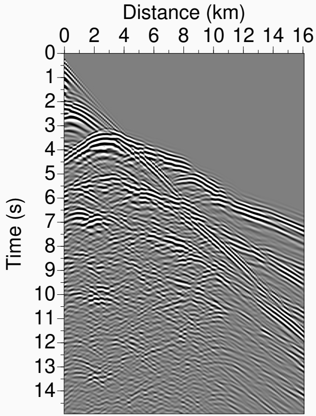
Instead of analyzing the data trace by trace: look simultaneously at several traces.



20 seismic traces $d_r(t)$ as a function of time, depending on the receiver/source distance, also referred to as *offset* in the following.

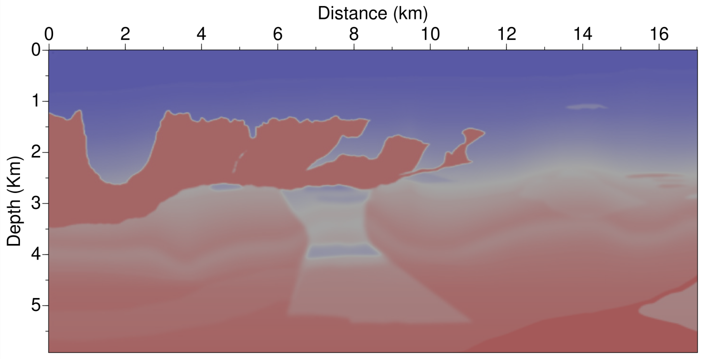
Seismogram

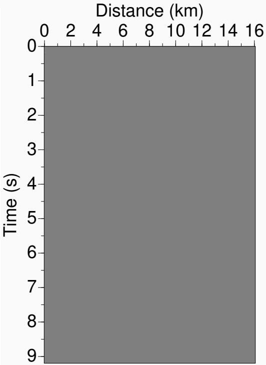
When the number of traces is even larger: use a 2D plot with a black & white chart



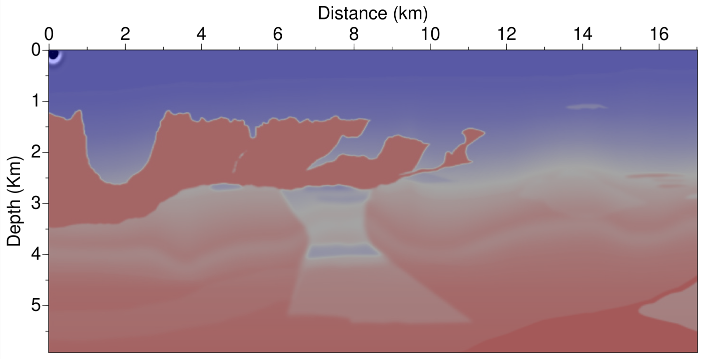
A typical seismogram in black and white representation. 161 traces spanning 16 km are used here. White correspond to negative values, black to positive values, while gray corresponds to 0. This yields the typical seismogram representation, widely used in exploration geophysics.

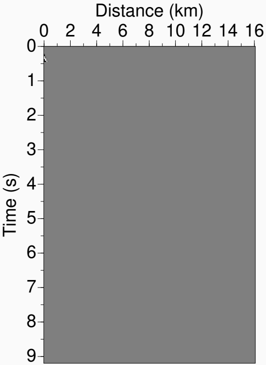
Where does this seismogram come from?



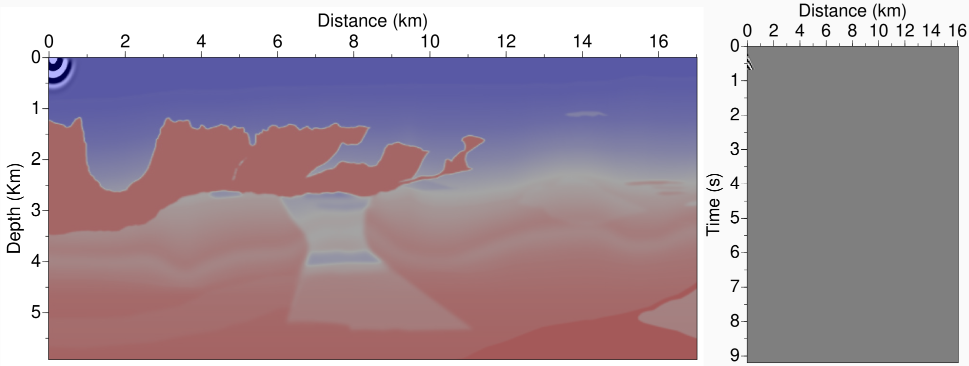


Where does this seismogram come from?

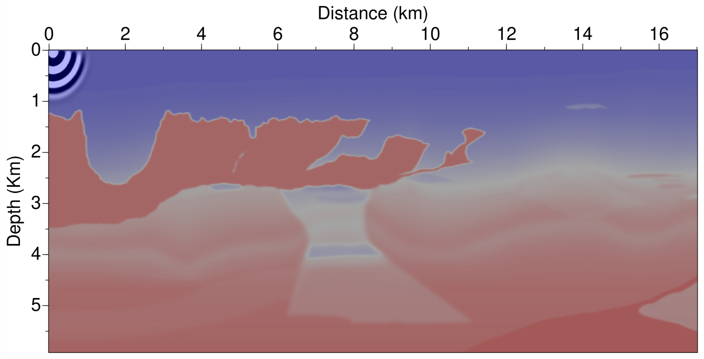


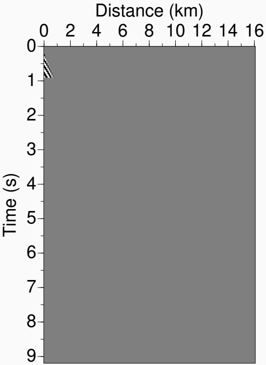


Where does this seismogram come from?

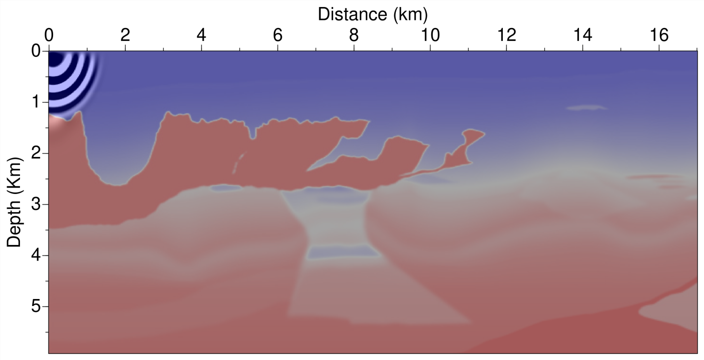


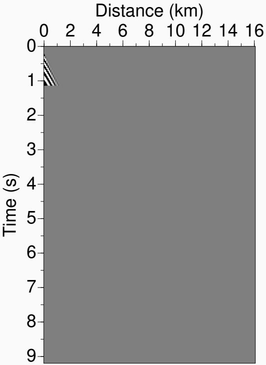
Where does this seismogram come from?



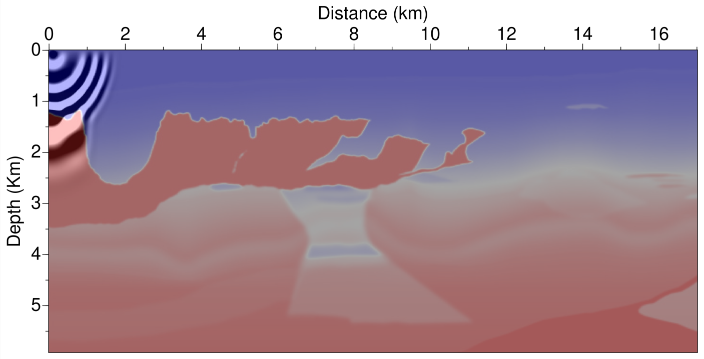


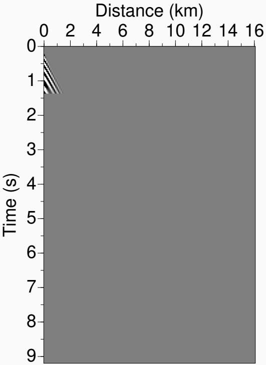
Where does this seismogram come from?



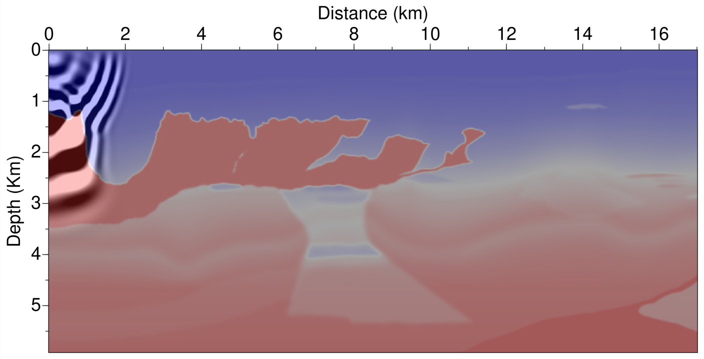


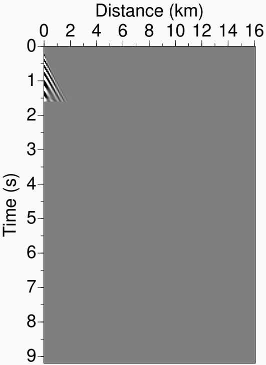
Where does this seismogram come from?



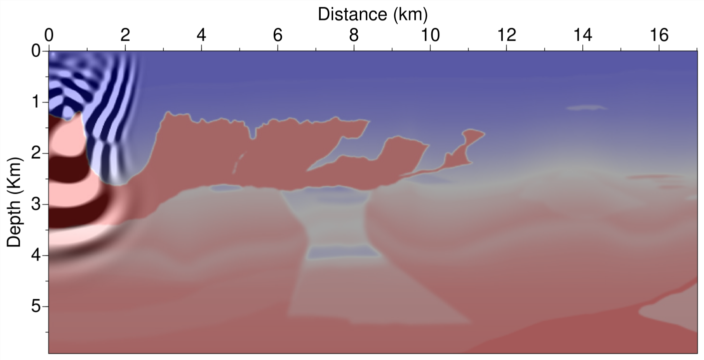


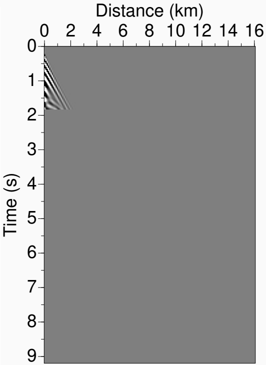
Where does this seismogram come from?



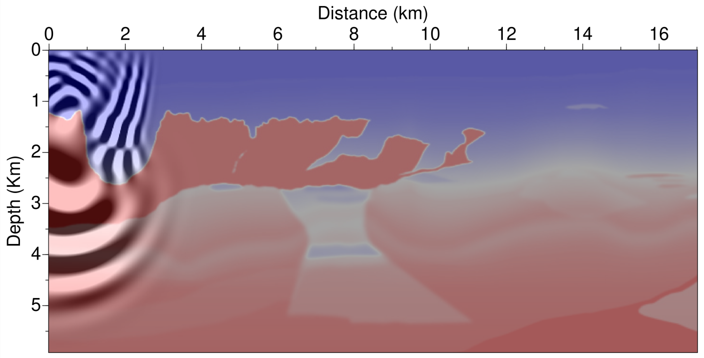


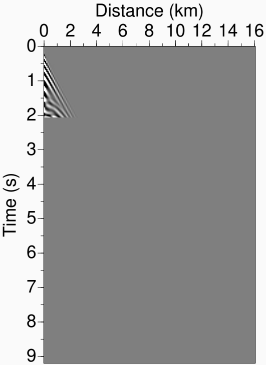
Where does this seismogram come from?



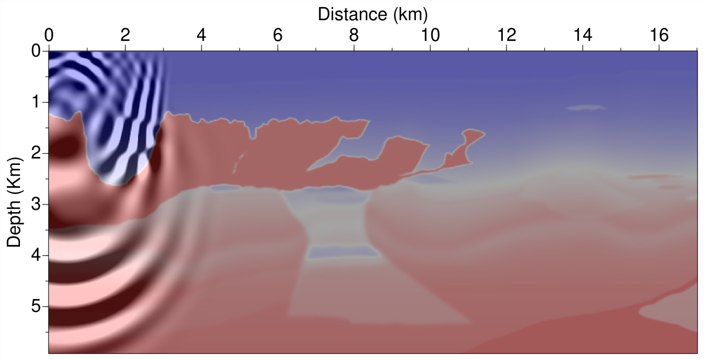


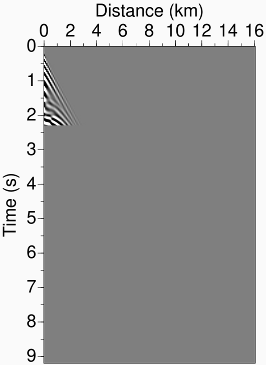
Where does this seismogram come from?



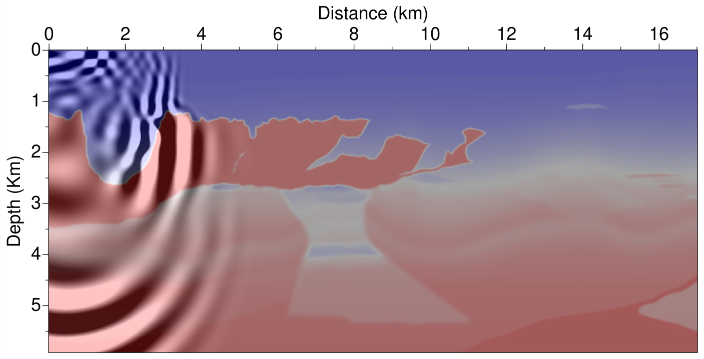


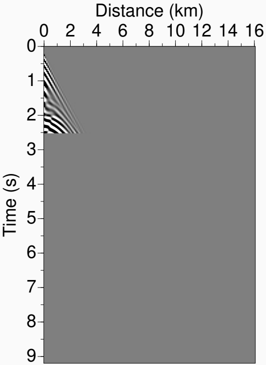
Where does this seismogram come from?



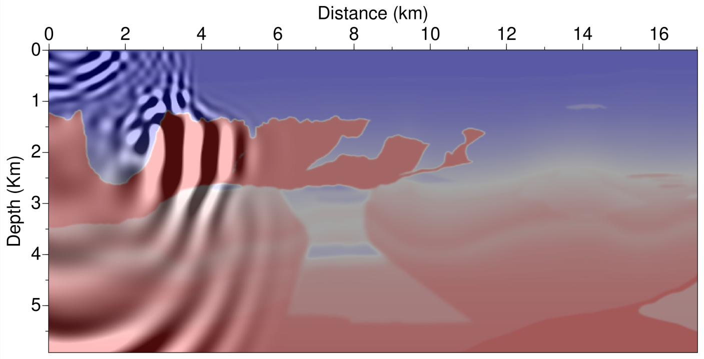


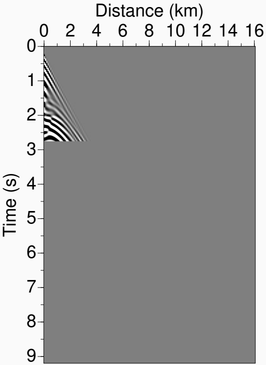
Where does this seismogram come from?



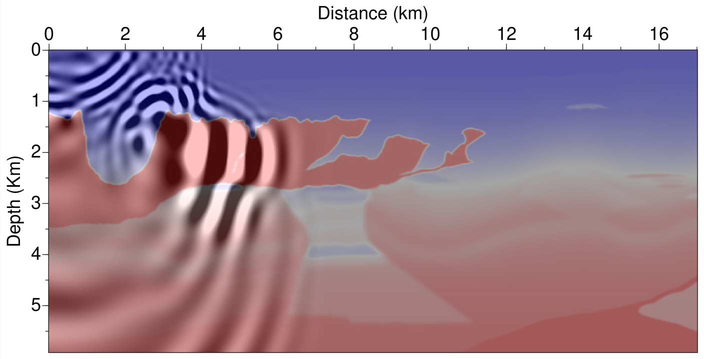


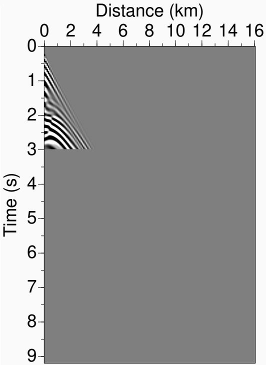
Where does this seismogram come from?



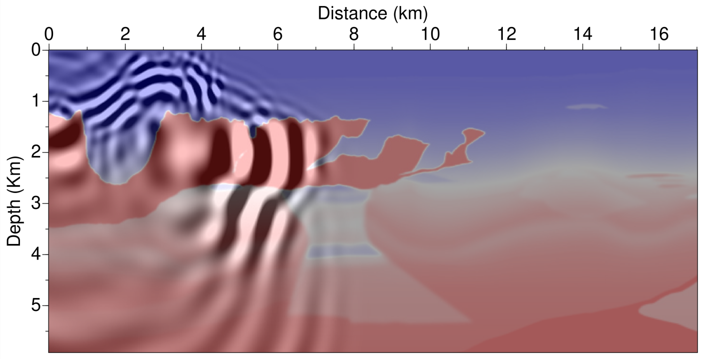


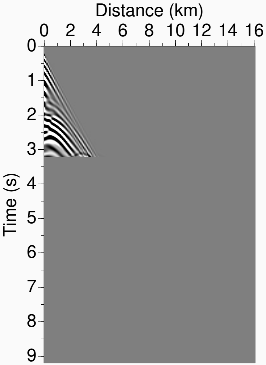
Where does this seismogram come from?



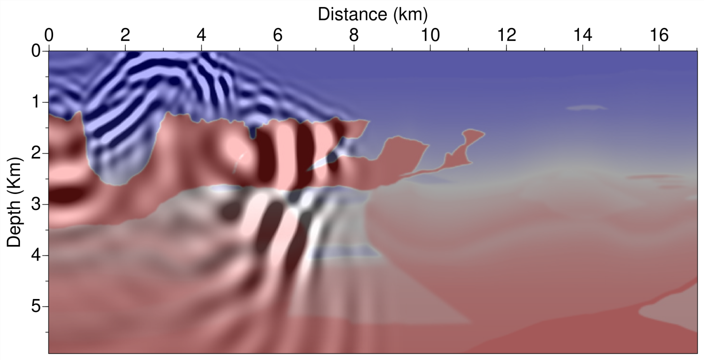


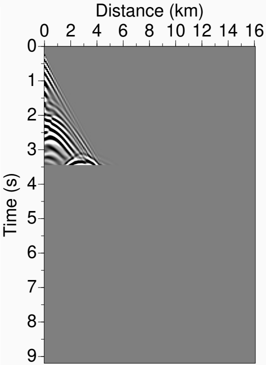
Where does this seismogram come from?



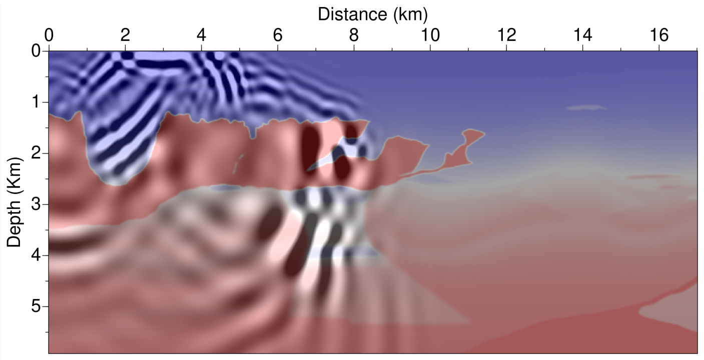


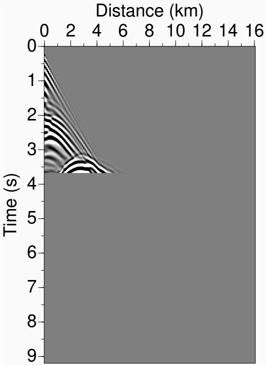
Where does this seismogram come from?



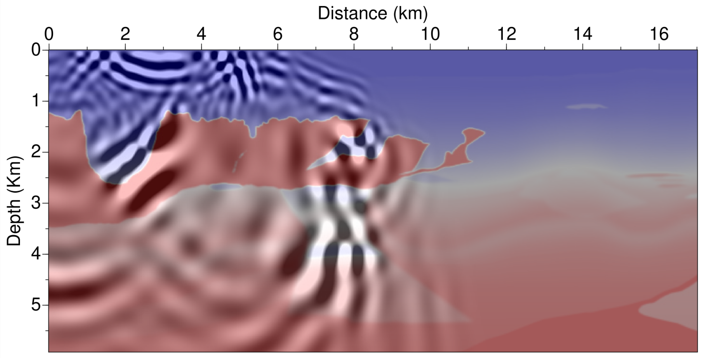


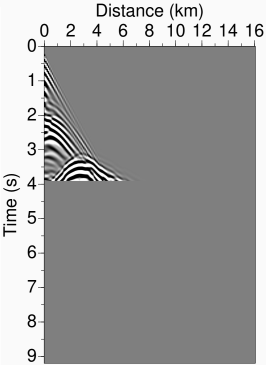
Where does this seismogram come from?



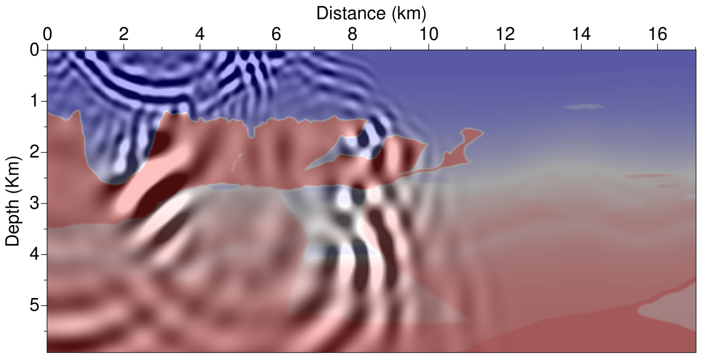


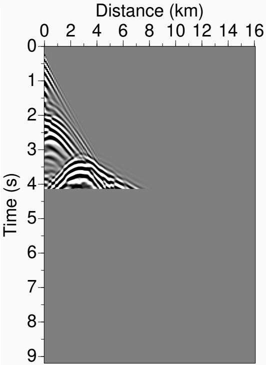
Where does this seismogram come from?



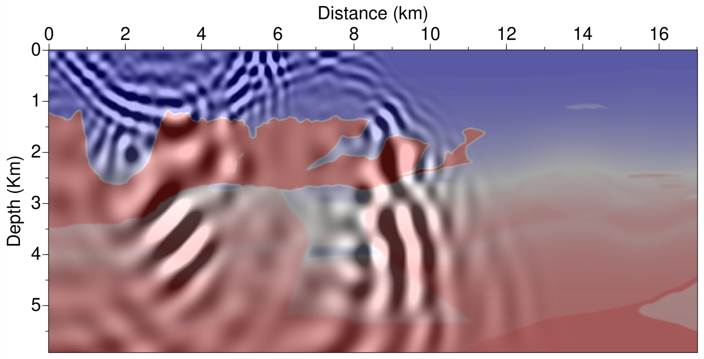


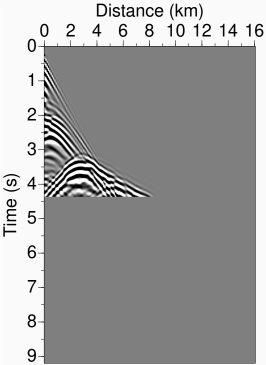
Where does this seismogram come from?



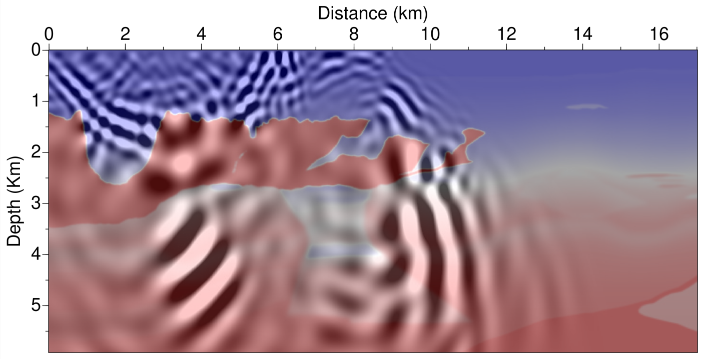


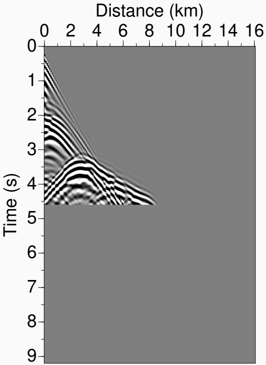
Where does this seismogram come from?



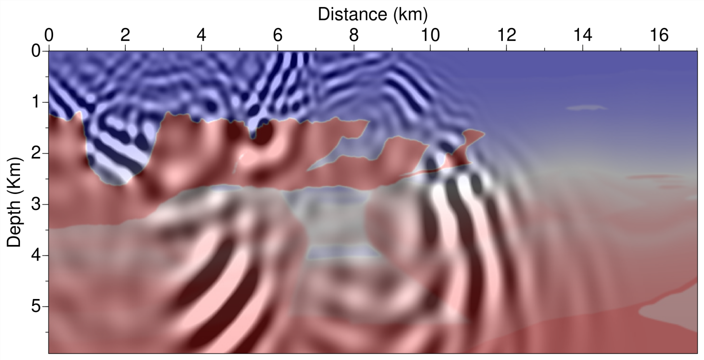


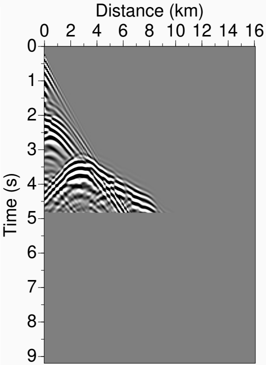
Where does this seismogram come from?



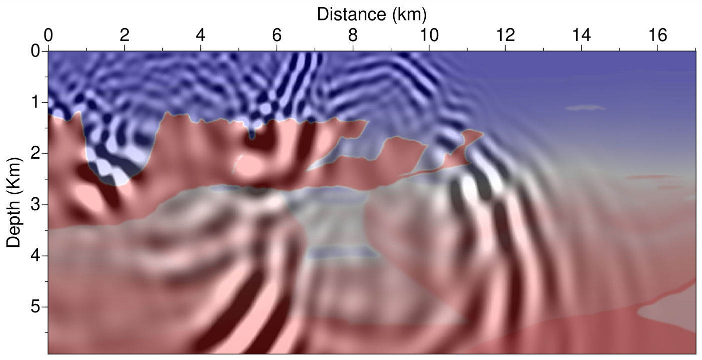


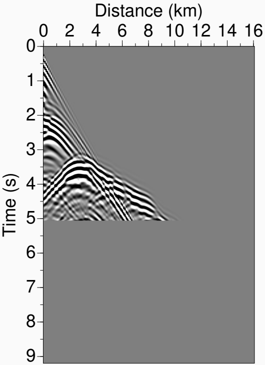
Where does this seismogram come from?



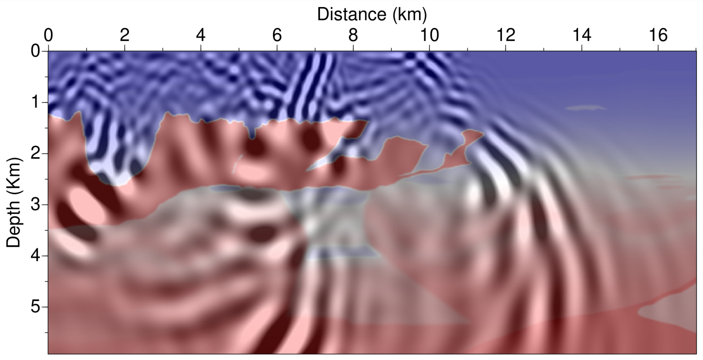


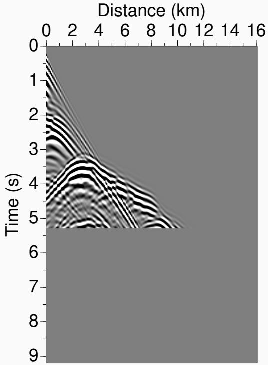
Where does this seismogram come from?



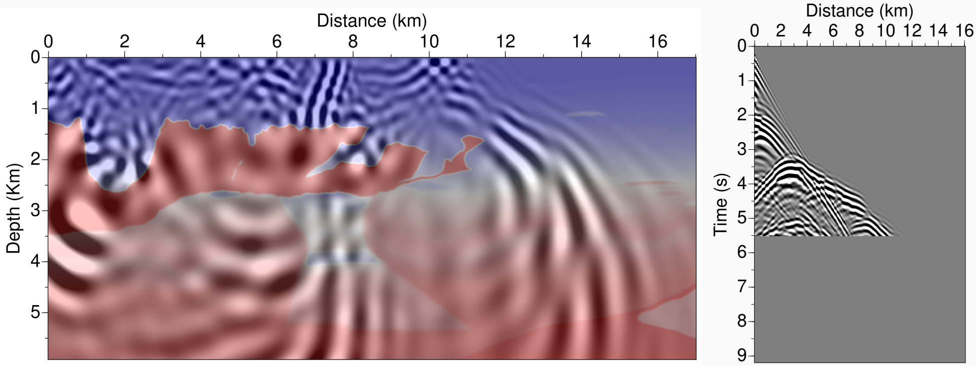


Where does this seismogram come from?

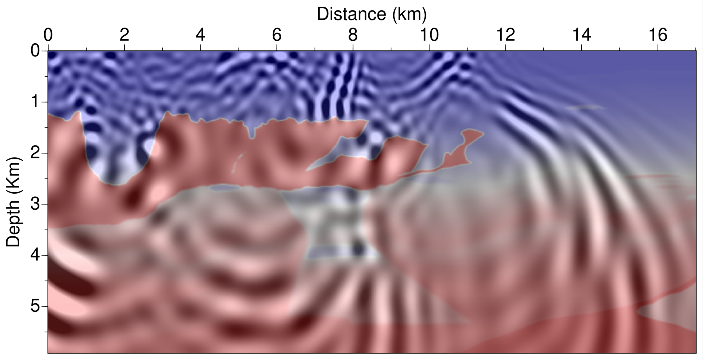


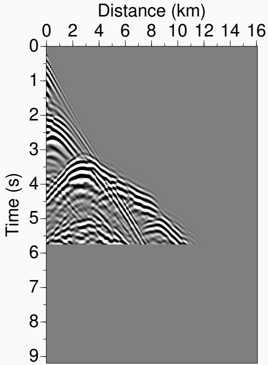


Where does this seismogram come from?

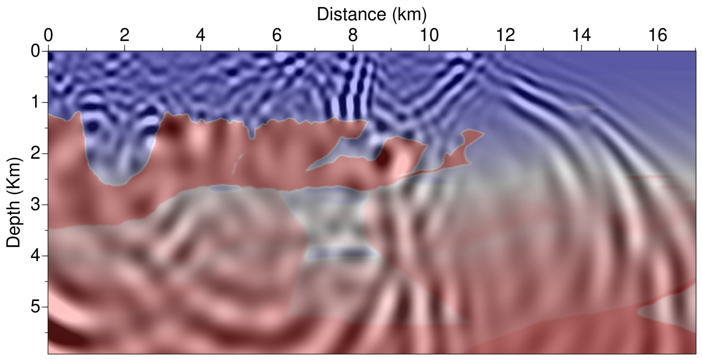


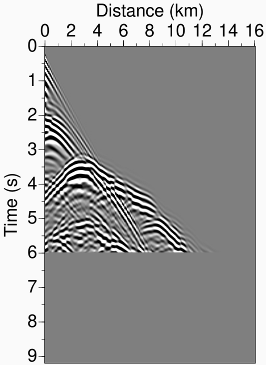
Where does this seismogram come from?



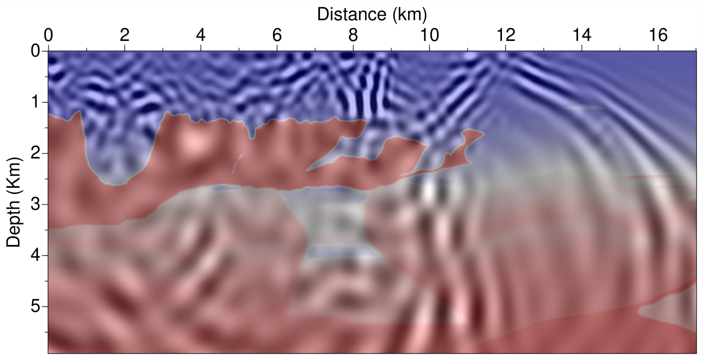


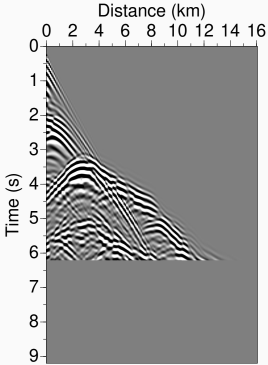
Where does this seismogram come from?



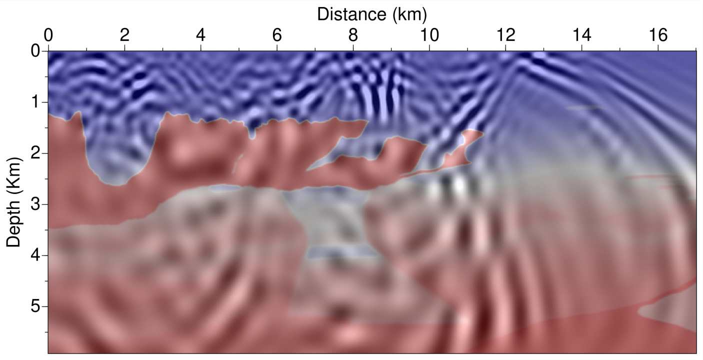


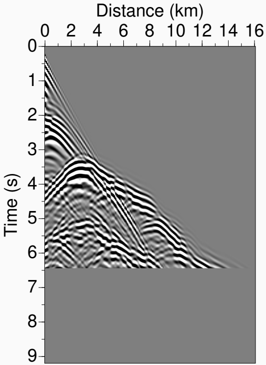
Where does this seismogram come from?



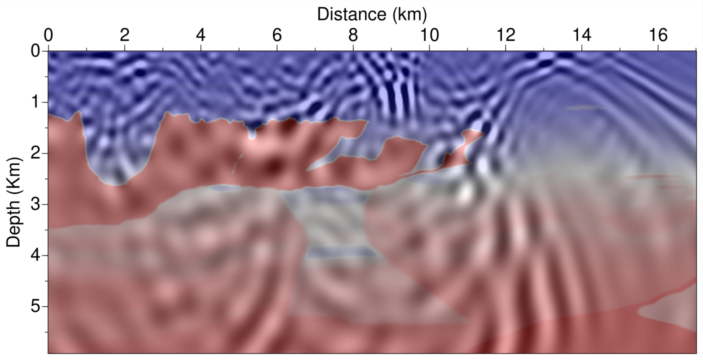


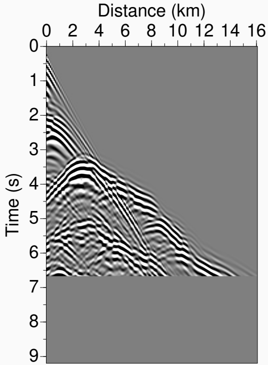
Where does this seismogram come from?



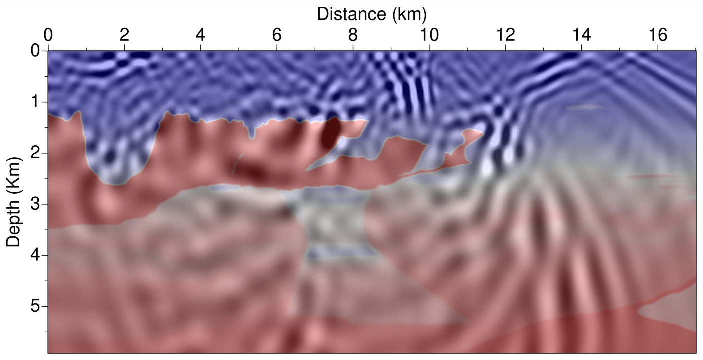


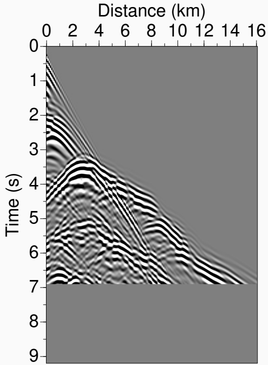
Where does this seismogram come from?



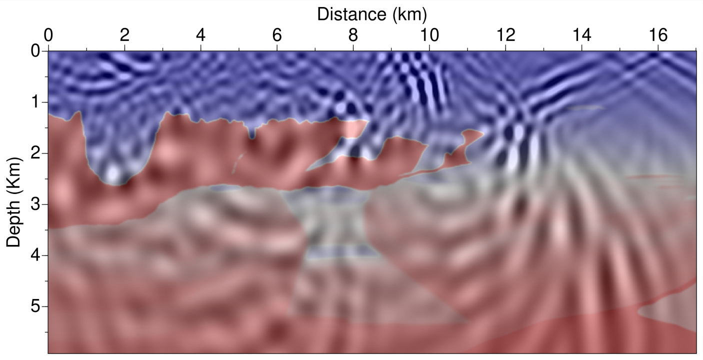


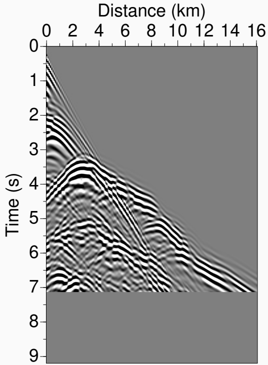
Where does this seismogram come from?



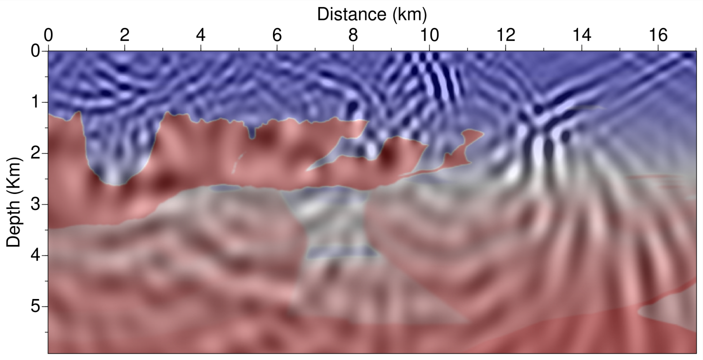


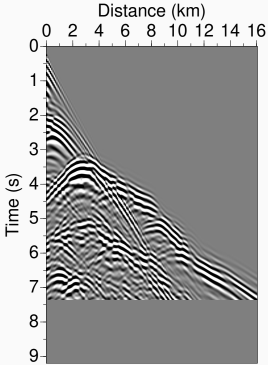
Where does this seismogram come from?



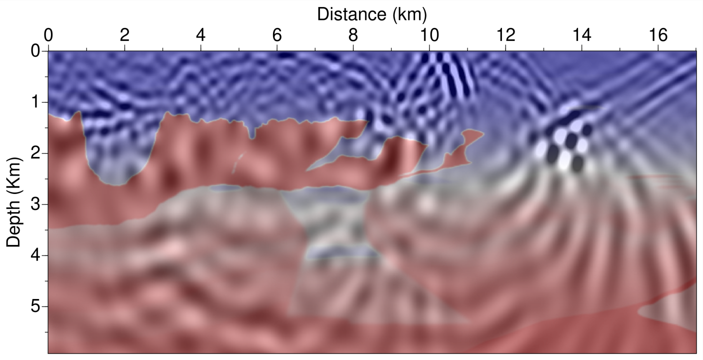


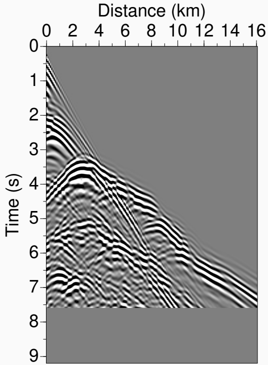
Where does this seismogram come from?



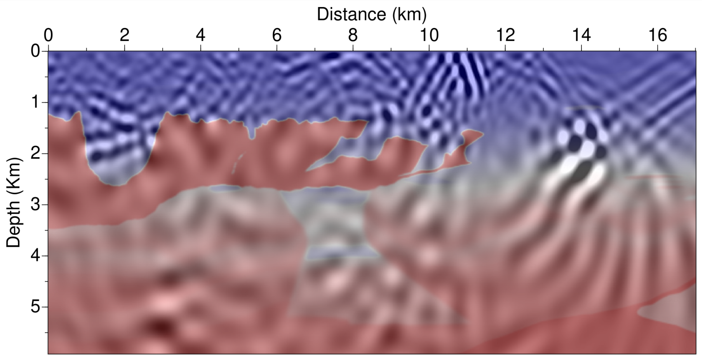


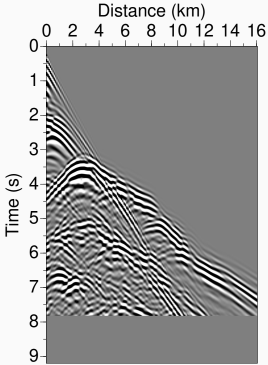
Where does this seismogram come from?



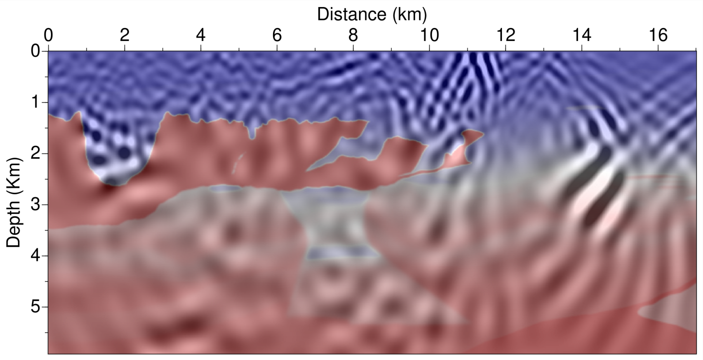


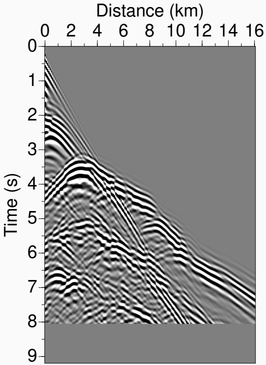
Where does this seismogram come from?



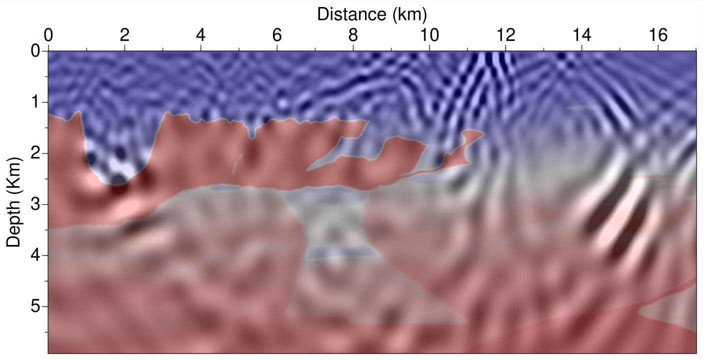


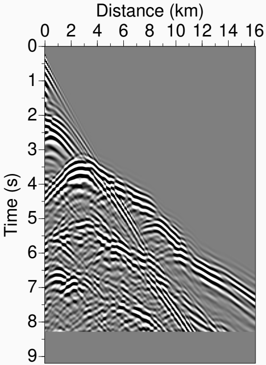
Where does this seismogram come from?



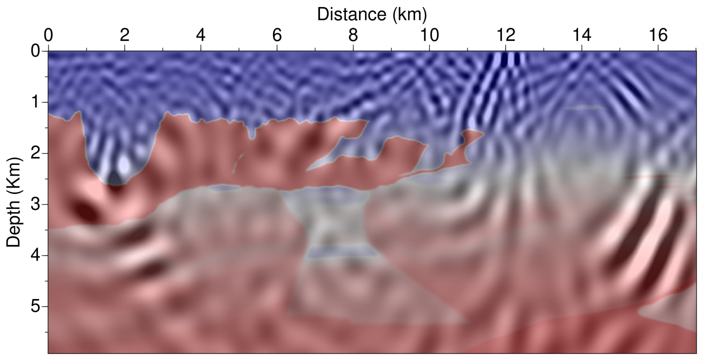


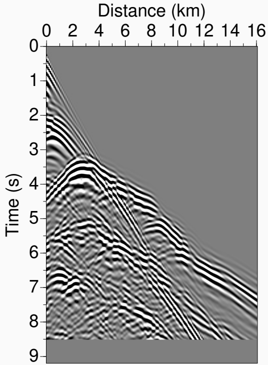
Where does this seismogram come from?



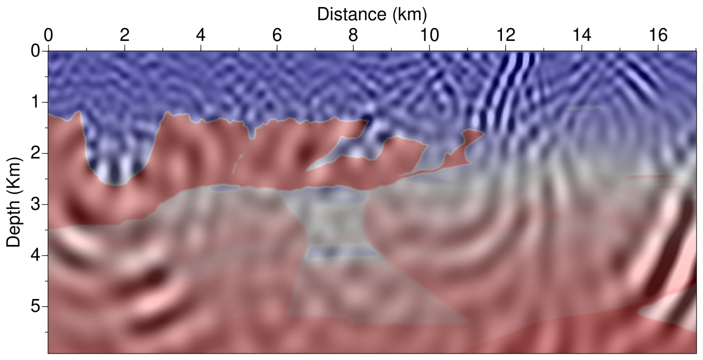


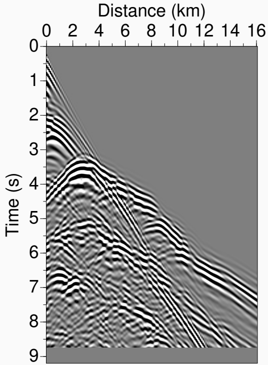
Where does this seismogram come from?



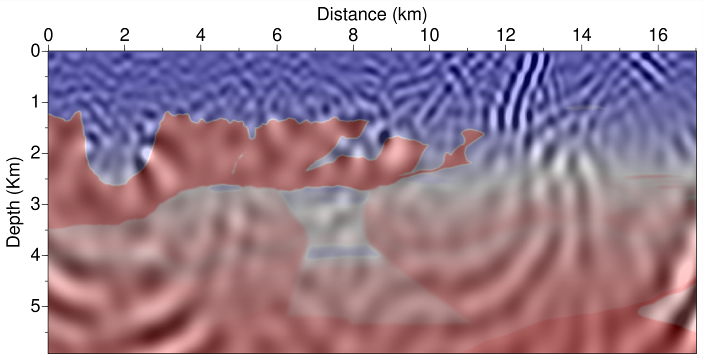


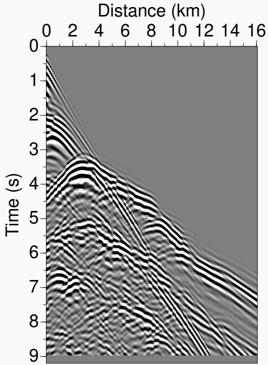
Where does this seismogram come from?



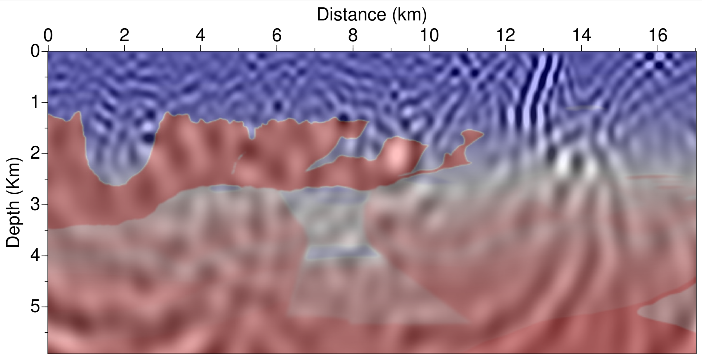


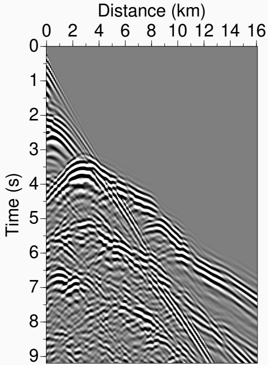
Where does this seismogram come from?





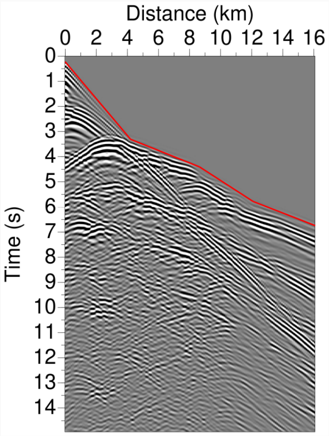
Where does this seismogram come from?





Outline

Tomography



Same seismogram as in Figure 22 with first-arrival travel time denoted by the red line.

Tomography

Inverse tomography problem

$$d_{obs} = t_{obs}(x_s, x_r), \quad m = v_P \tag{5}$$

where $t_{obs}(x_s, x_r)$ denotes the picked travel times from source s to receiver r, and v_P is the pressure wave velocity.

Least-squares first-arrival travel time tomography

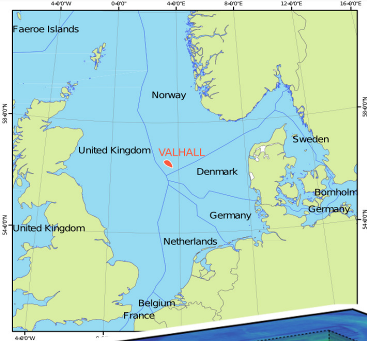
$$\min_{v_P} \frac{1}{2} \left\| t_{cal} - t_{obs} \right\|^2 + \eta R(v_P), \quad t_{cal} = g(v_P). \tag{6}$$

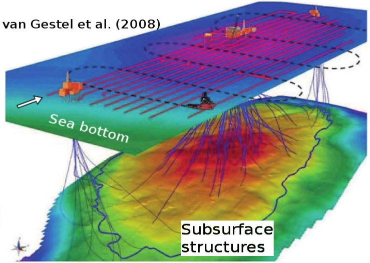
Full waveform inversion: exploiting all the data

Idea: replace the forward modeling operator $g(m)$ by a full wave modeling solver, and to compare the resulting synthetic data to the full observed data $d_{obs}(x_s, x_r, t)$. The FWI problem is thus formulated as

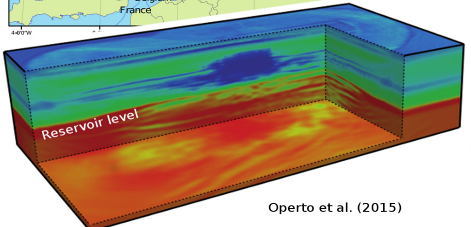
$$\min_m \frac{1}{2}\|d_{cal} - d_{obs}\|^2 + \eta R(m), \quad d_{cal} = g(m) \tag{7}$$

Valhall target





van Gestel et al. (2008)

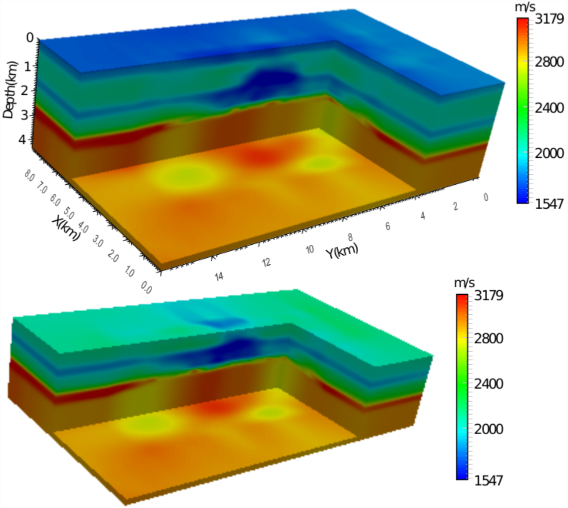


Operto et al. (2015)

- Area: ~ 145 km^2
- $\sim$50,000 shots at 5 m depth
- $\sim$2,300 receivers (4C) at 75 m depth (12 OBCs)
- Reservoir level $\sim$2.5 km depth
- Frequency-domain strategy : time-harmonic

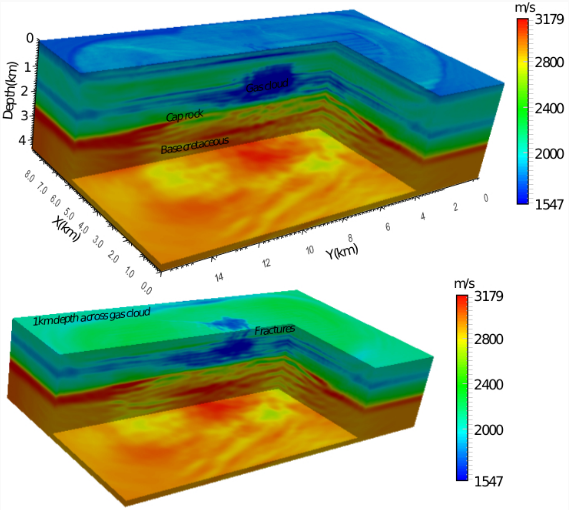
3D acoustic FWI of the Valhall data (Operto et al., 2015)

Initial model



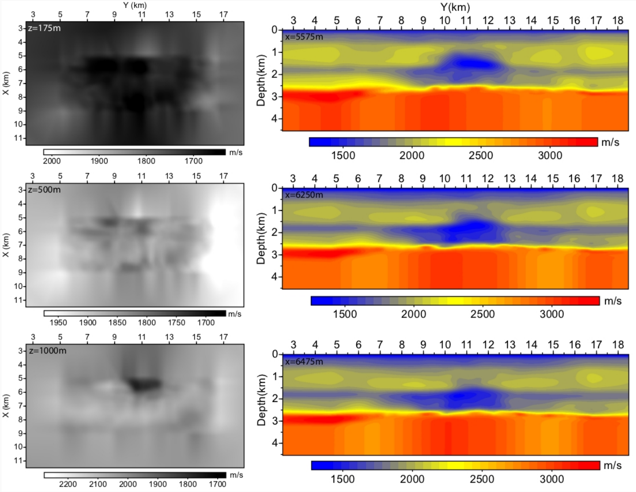
3D acoustic FWI of the Valhall data (Operto et al., 2015)

Final FWI model



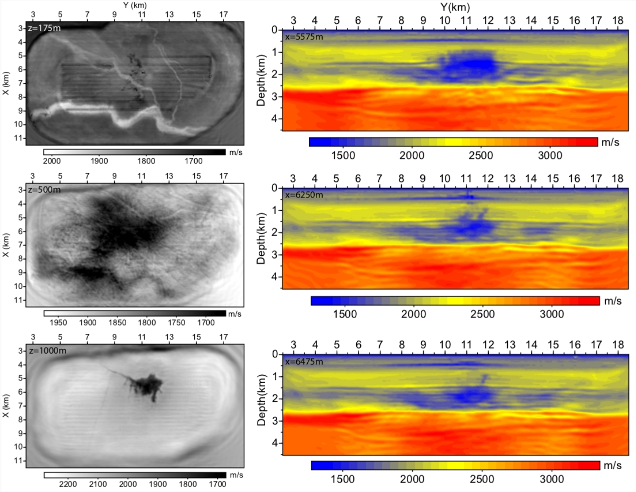
3D acoustic FWI of the Valhall data (Operto et al., 2015)

Horizontal and vertical 2D slices: initial model



3D acoustic FWI of the Valhall data (Operto et al., 2015)

Horizontal and vertical 2D slices: final FWI model



References

Eiken, O. (2019). Twenty years of monitoring CO2 injection at Sleipner. In Davis, T. L., Landrø, M., and Wilson, M., editors, *Geophysics and Geosequestration*, pages 209–234. Cambridge University Press.

Gorszczyk, A., Operto, S., Schenini, L., and Yamada, Y. (2019). Crustal-scale depth imaging via joint FWI of OBS data and PSDM of MCS data: a case study from the eastern nankai trough. *Solid Earth*, 10:765–784.

Koehn, D., Wilken, D., Wunderlich, T., De Nil, D., Rabbel, W., Werther, L., Schmidt, J., Zielhofer, C., and Linzen, S. (2018). Seismic SH full waveform inversion as new prospection method in archaeogeophysics. In *Conference Proceedings, 24th European Meeting of Environmental and Engineering Geophysics*, pages 1–5. European Association of Geoscientists & Engineers.

Lowrie, W. and Ficthner, A. (2020). *Fundamentals of Geophysics*. Cambridge University Press, 3 edition.

Operto, S., Miniussi, A., Brossier, R., Combe, L., Métivier, L., Monteiller, V., Ribodetti, A., and Virieux, J. (2015). Efficient 3-D frequency-domain mono-parameter full-waveform inversion of ocean-bottom cable data: application to Valhall in the visco-acoustic vertical transverse isotropic approximation. *Geophysical Journal International*, 202(2):1362–1391.