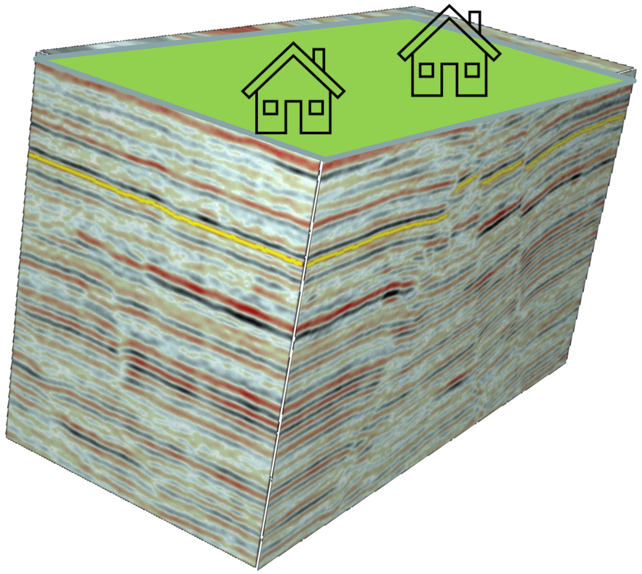
Seismic imaging-
a method to see under the ground…



Dr Rebecca (Becky) Bell,

Dr. Parastoo Salah and Raul Adriaensen

1st floor, office 1.38

rebecca.bell@imperial.ac.uk

Imperial College London

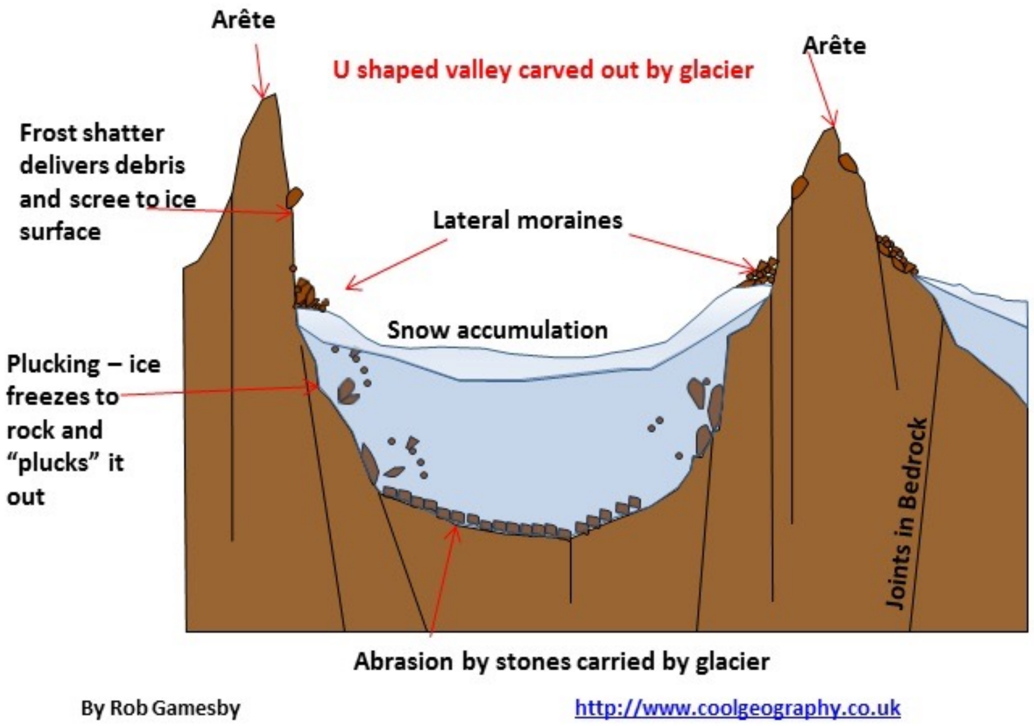
A bit about me...

I am a **geologist** and have been for more than 20 years. Please shout if I use any geological terminology you don't know…!

Case study

Offshore wind-turbine installation

- Want to avoid glacial valleys
- Glaciers extended over much of northern Europe 20-70,000 years ago



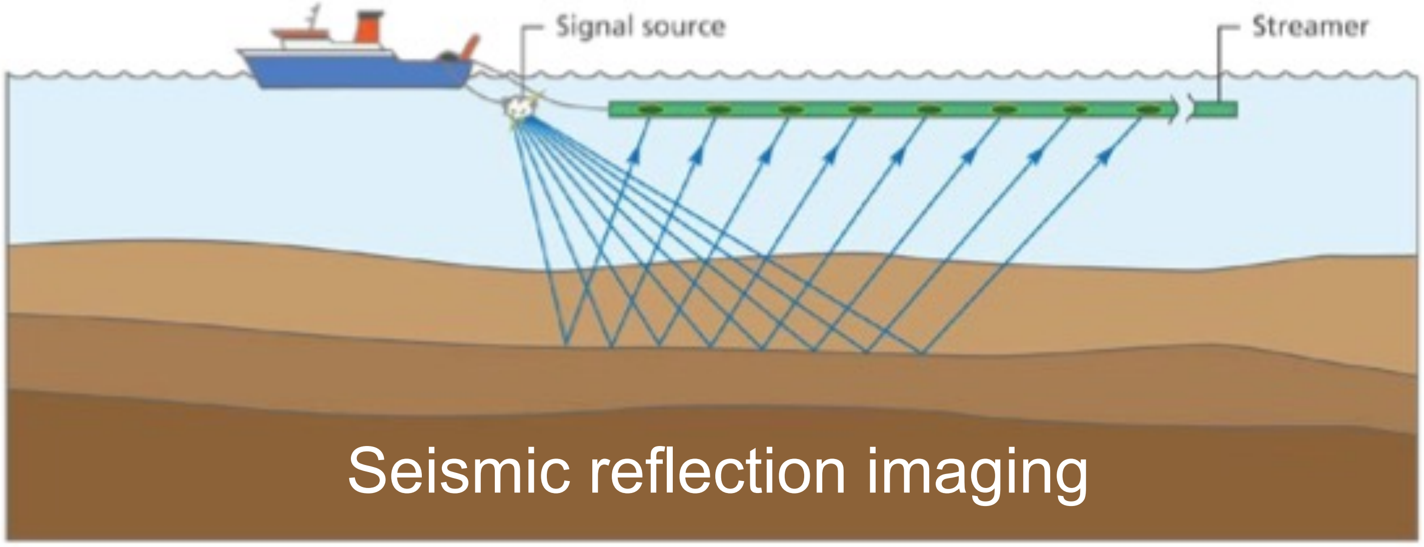
USGS

Seismic imaging

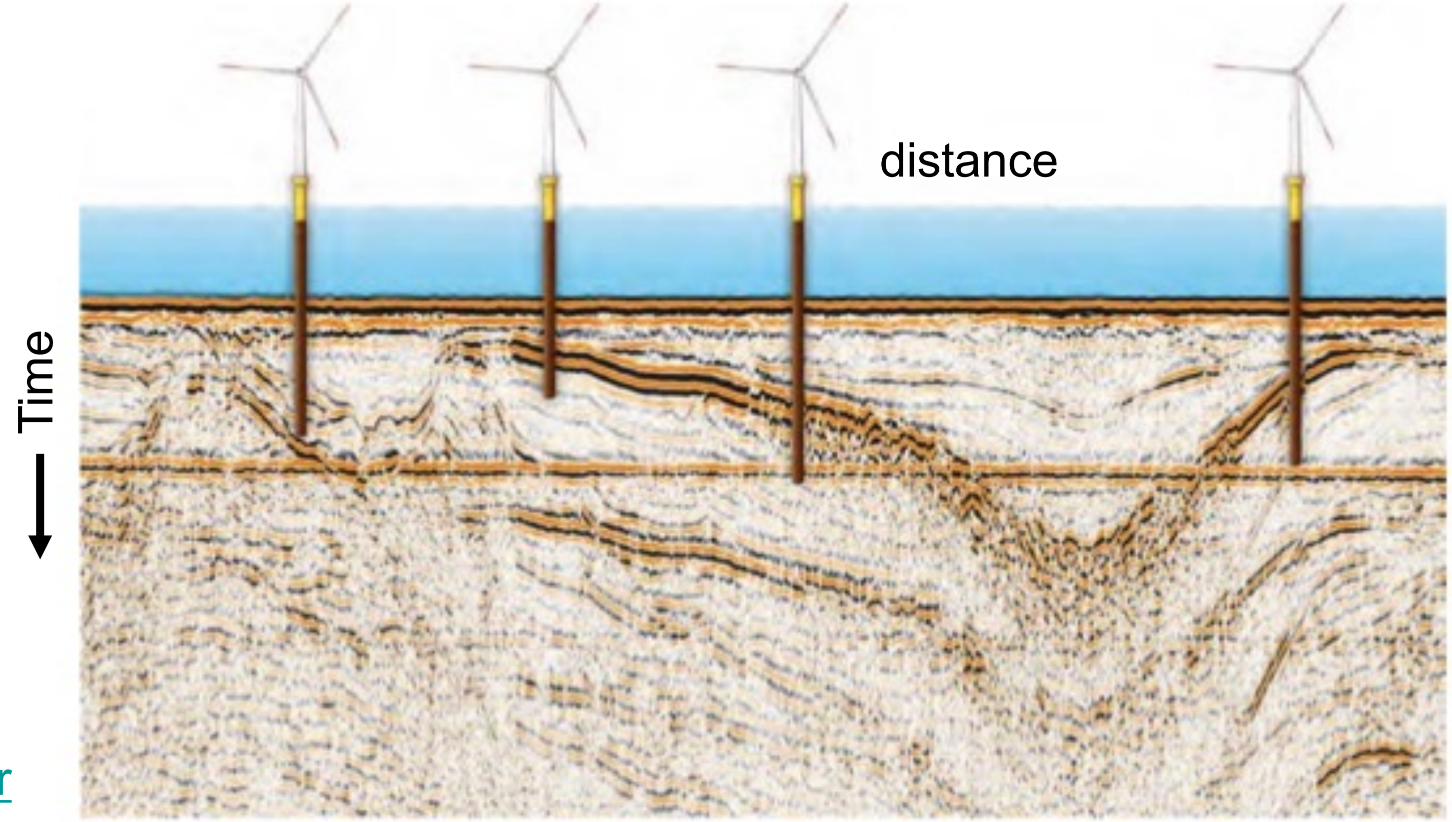
<u>Monday 15th Jan</u>

<u>Morning</u>- Brief introduction to seismic data- 3 mini lectures

<u>Afternoon</u> – Exercises to help you better understand the seismic method (in Jupyter notebooks)

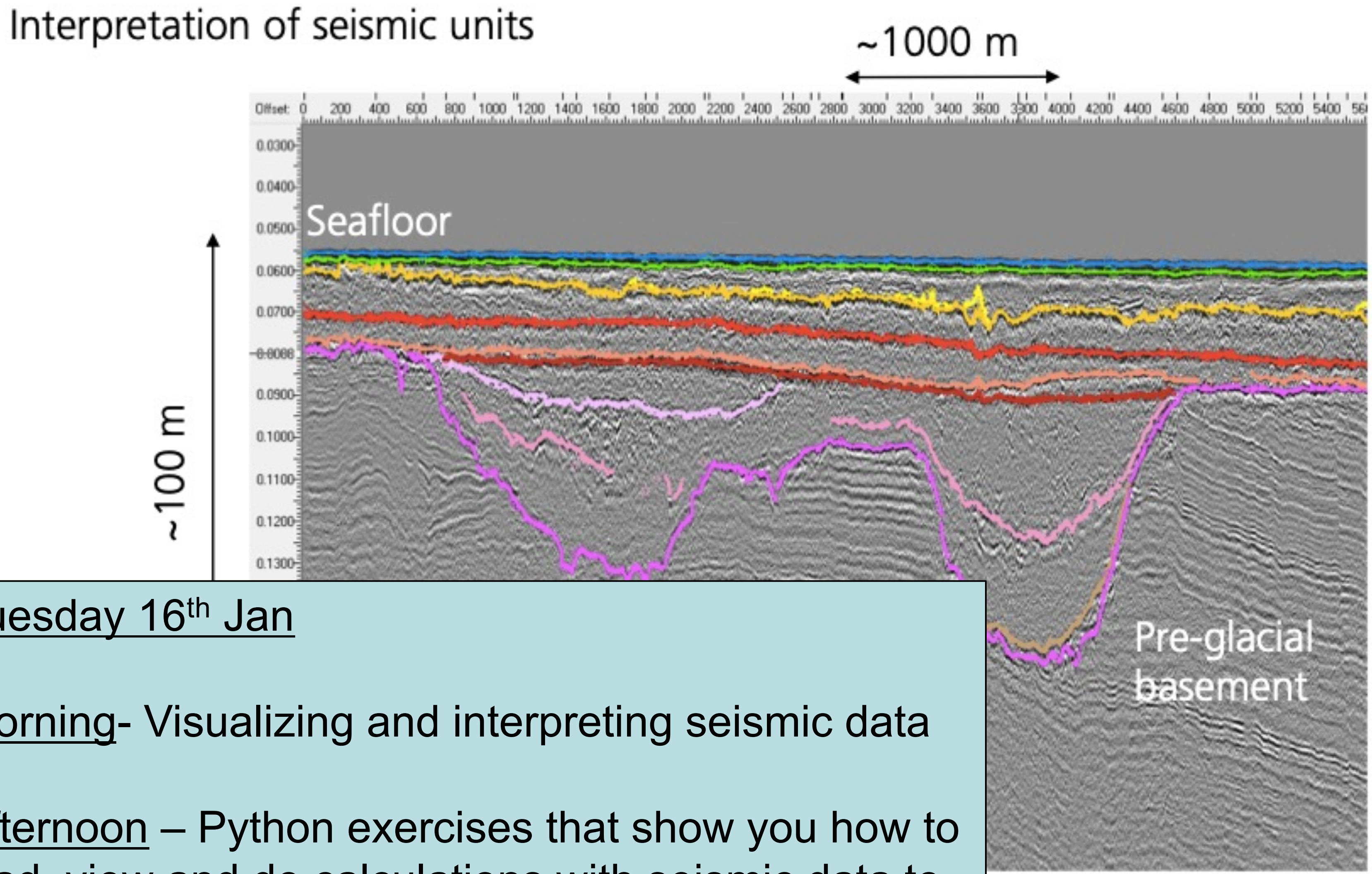


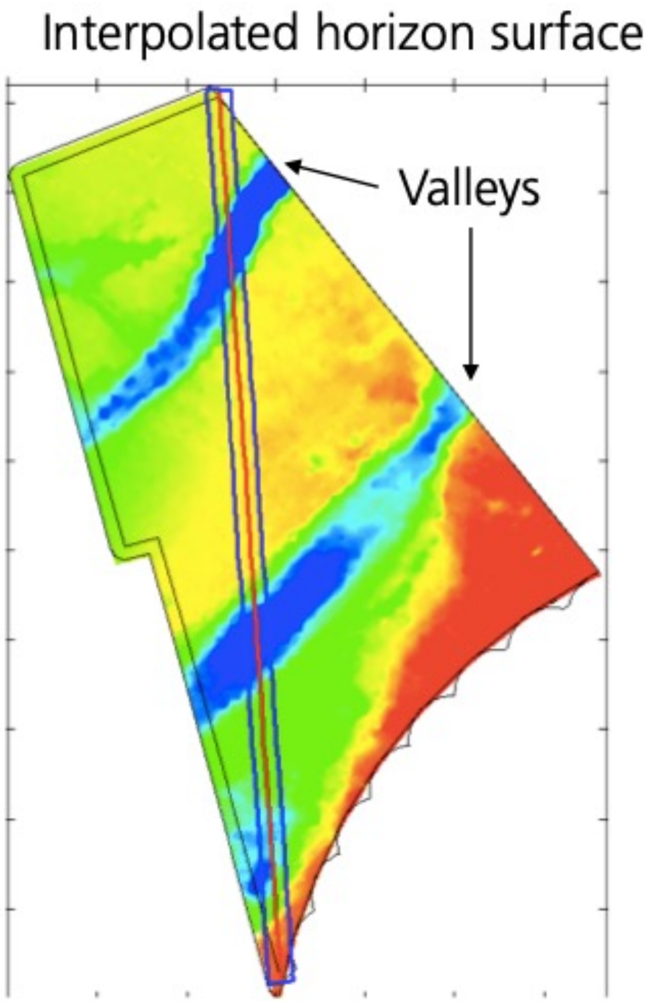
Note- vertical axis is TIME not DEPTH. We can convert seismic reflection data to depth if we know the speed seismic waves travel through the rocks (one way we can get that Information is by drilling…)



[Fraunhofer]

Seismic interpretation





Tuesday 16th Jan

Morning- Visualizing and interpreting seismic data

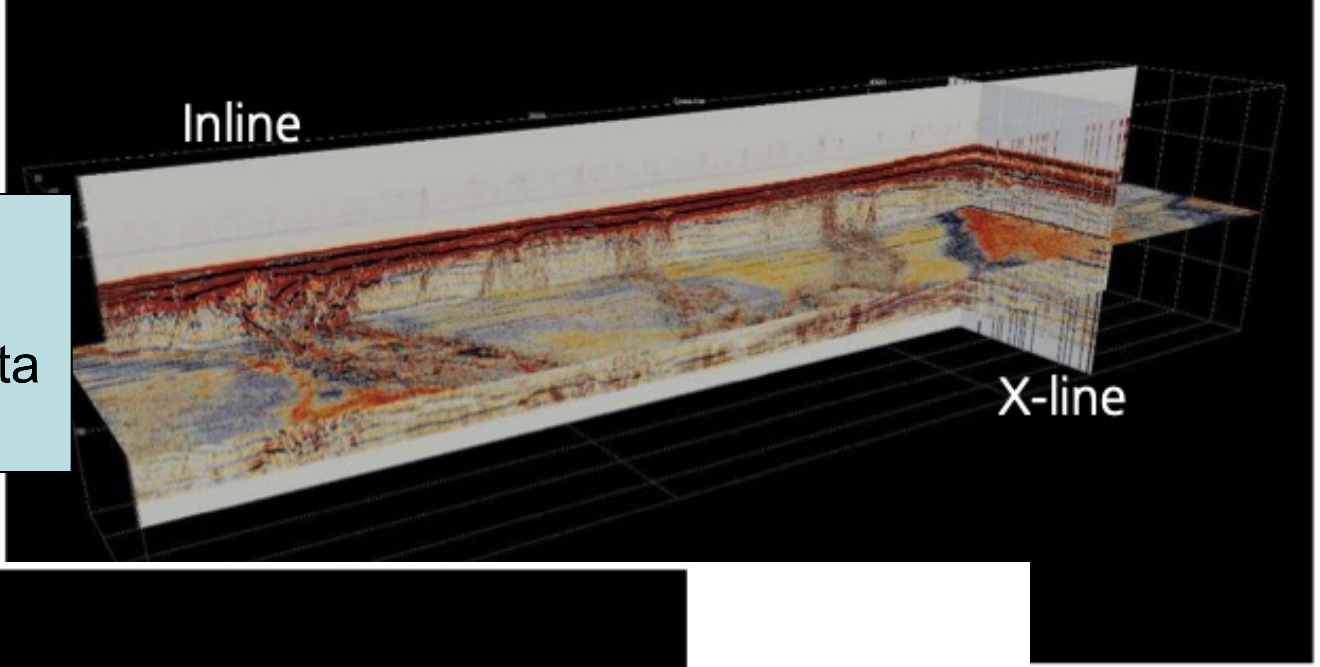
Afternoon – Python exercises that show you how to load, view and do calculations with seismic data to enhance environmental/geological interpretations

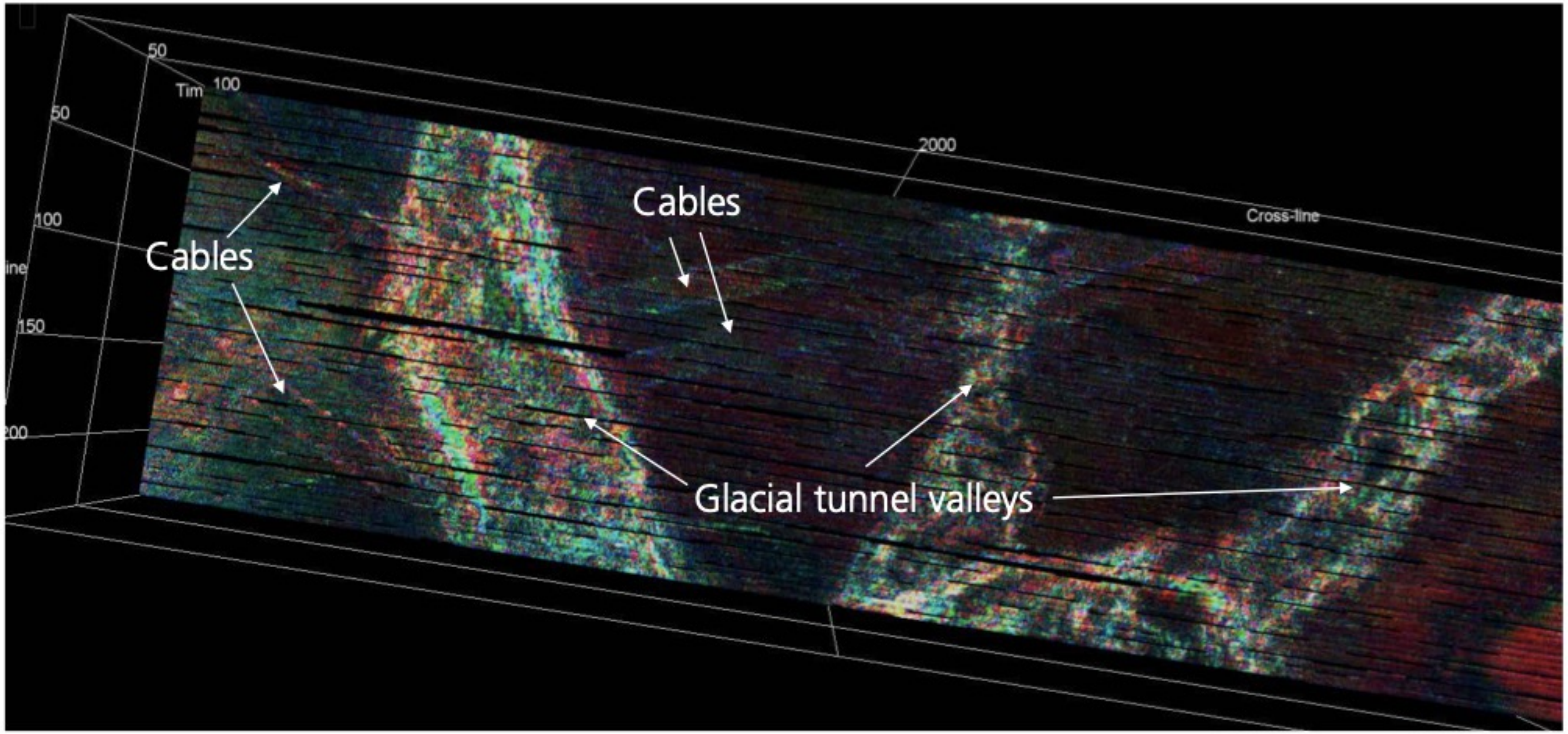
Fraunhofer

Advanced analysis

Wed 17th Jan

Morning– short machine learning and seismic data lecture and group exercise

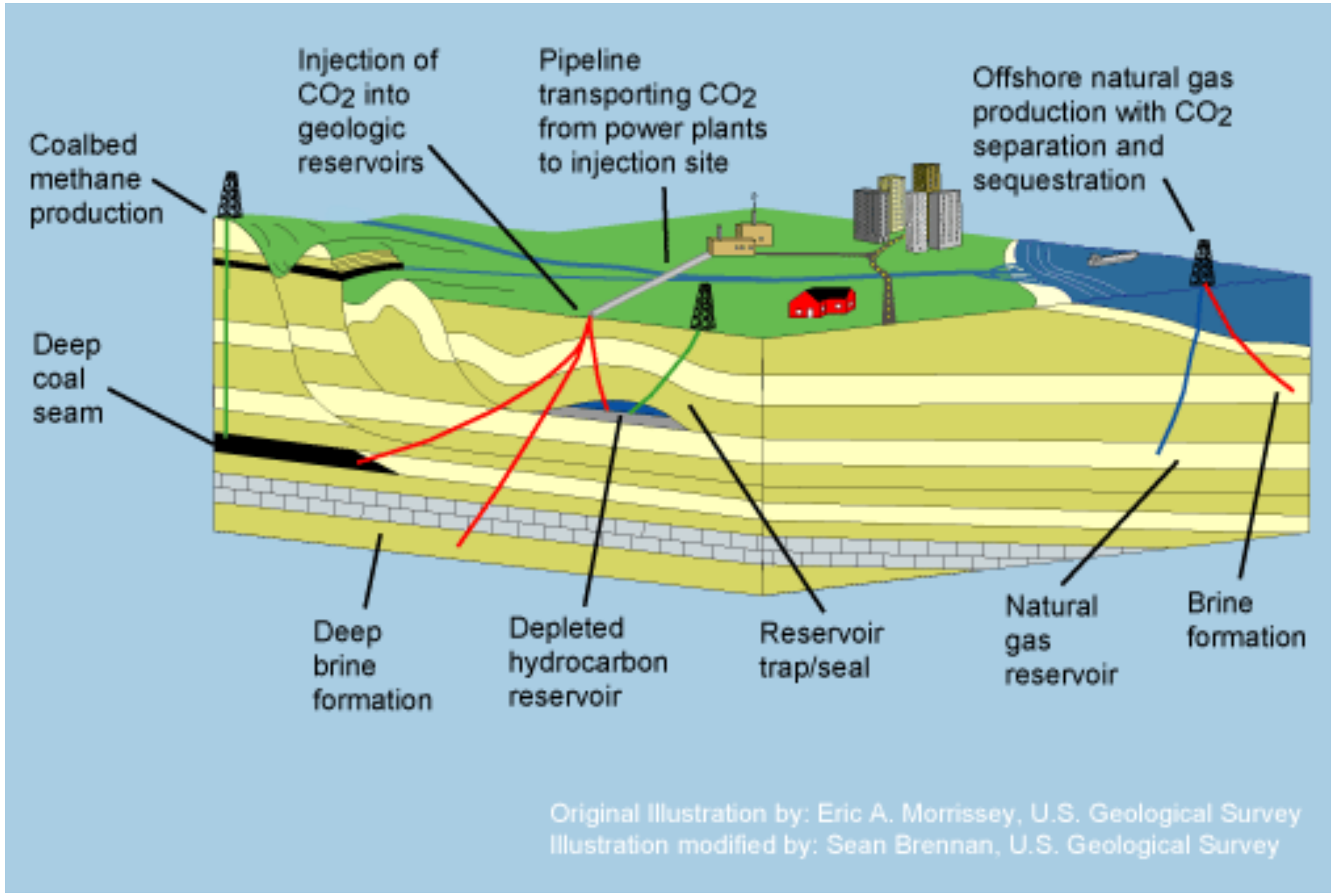




Spectral decomposition RGB

Fraunhofer

Seismic reflection environmental/geoenergy applications



CO_2 capture and storage

- Site characterization:

- locate porous and impermeable rock ***layers/units***
- Locate ***faults*** (cracks in the rock layers) which could be conduits for fluid or seals

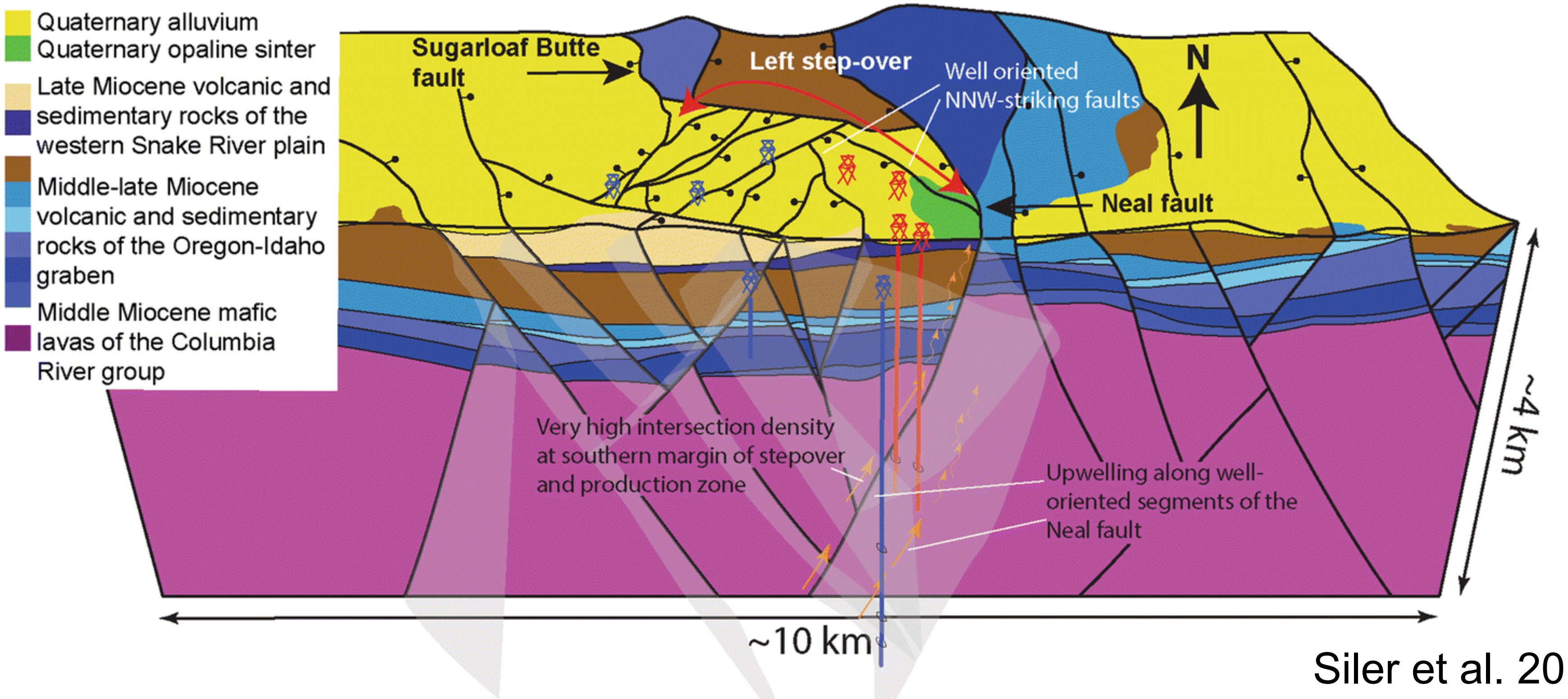
- Monitoring: image the injected CO_2 and assess leakages over time

https://www.quintessa.org/co2fepdb/v2.0.0/

Seismic reflection environmental/geoenergy applications

Geothermal energy

- Largest cost in geothermal projects is deep drilling
- Seismic reflection data allows you to characterize the fault system so drilling can be targeted and more successful

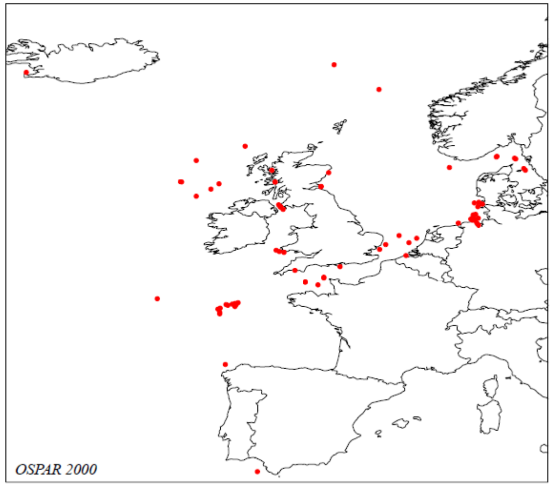


Siler et al. 2019, Geothermal Energy

Seismic reflection environmental/geoenergy applications

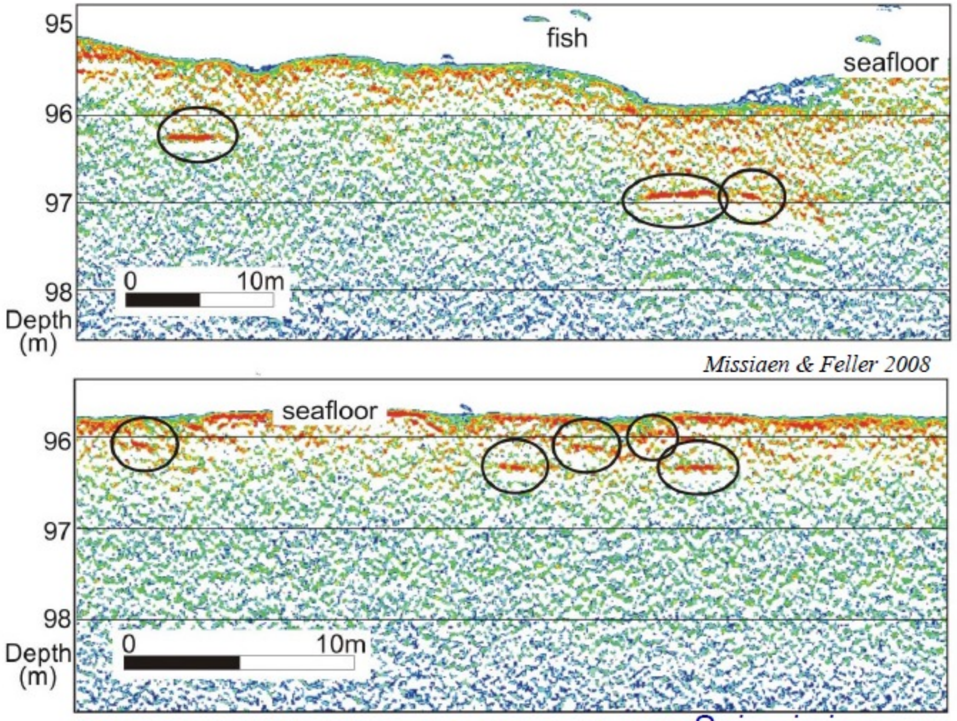
Unexploded ordnance (UXO) and debris detection

Dr. Tine Missiaen
Missiaen and Feller 2008



After WW1 and WW2 large amounts of conventional and chemical weapons were dumped in European Seas
- shells, mines, bombs, drums, containers, ships
- Arsenic and mustard gas

Aerial mustard gas bomb type KC 250



Seismic image

Large objects > 2 m

Drums & containers?

Small objects < 2 m

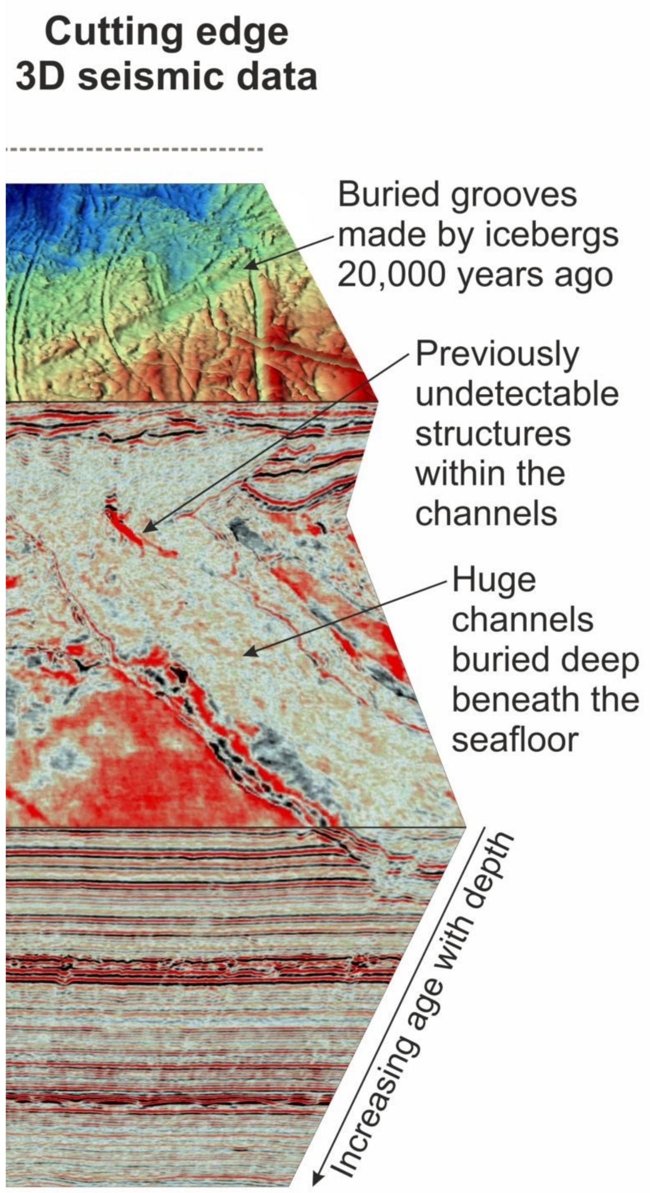
Shells and bombs?

Seismic reflection imaging in 2, 3 or 4 dimensions…

Seismic reflection imaging is our primary method to produce detailed images of below the Earth's surface

- 2D seismic data provides a cross-section through the Earth
- 3D seismic data provides a data volume, allowing you to look under the ground in 'map view' as well as in a cross-section
- 4D seismic data provides time-lapse 3D data

(important for monitoring the subsurface)



Kirkham et al. 2021, Geology

Have you heard of seismic reflection imaging?

No, I have never heard of this thing before

I think I might have heard of it?

Yes, I have had a lecture on it

Yes, I have worked with these data

Why are we learning about it in EDSML/GEMS?

- Seismic interpretation is predominantly done by geoscientists using proprietary software as complex ‘black-boxes’
- Traditionally seismic interpretation has been very manual- involves tracing (drawing) seismic horizons and faults
- There is now a focus on doing seismic interpretation in a more automated way so i) larger volumes of data can be analysed in a realistic time, ii) the interpretations are less subjective, and iii) multiple interpretations can be produced so uncertainty can be explored.

WE NEED DATA SCIENTISTS- you could revolutionise this field!

Overall learning objectives

1. Understand the common data format for seismic reflection data (SEGY)- the primary method for creating high-resolution images of the Earth's subsurface from 10's m to km depths

2. Demonstrate technical competency in handling SEGY data and identify relevant open-source data repositories

3. Identify and design suitable data analysis strategies for analysing seismic reflection data. Appreciate the potential for data scientists to revolutionize the field of seismic data analysis.

4. Understand the limitation of seismic data and data analysis products. Understand sources of errors and uncertainties, how these are currently dealt with in traditional workflows and appreciate the potential for data science to help better characterise these uncertainties

By the end of this week you should feel confident that this is a type of environmental data that you know how to load, view and work with. Understand its application in geoenergy/environmental studies and appreciate how machine learning/artificial intelligence could help us get the most out of these data.

What to expect…

- Theory lectures on Mon & Tue morning with quiz questions/short exercises
- Jupyter notebook exercises Mon & Tue afternoon, which you can work through at your own pace- **led by Parastoo Salah and Raul Adriaensen**
- Wed morning will involve a short lecture on machine learning and seismic data followed by a short (2 hr) group exercise
- GEMS students will NOT have an assessment for this part of GEMS1
- EDMSL students will do a group exercises on Thur and Fri. The aim of this group exercise is to help you consolidate your knowledge of seismic imaging in preparation for the assessed quiz next week.
- There is no need to “revise”- and you don’t need to understand every tiny detail on the slides to be able to do well in the assessment.

Module schedule – week 2

	Monday	Tuesday	Wednesday	Thursday-GEMS	Thursday-EDSML	Friday - GEMS	Friday-EDSML
09:00 - 12:00	Introduction to seismic imaging	Visualising and interpreting seismic data	Machine learning and seismic imaging Practical: Machine learning group practical	Introduction to wireline log data Practical: QC of wireline log data	10 am start- Group project	Stratigraphy and structure Sedimentary basins	Group project
	Lunch	*Lunch*	*Lunch*	*Lunch*	*Lunch*	*Lunch*	Submit 12 noon
14:00 - 17:00	Practical: Introduction to seismic imaging	Practical: Visualising and interpreting seismic data		Identifying rock types in wireline logs Practical: wireline log interpretation	Group project	Practical: Sedimentary basins	Independent study

Module outline

Day 1 morning- Introduction to seismic data

Lecture 1: Physical principles

Lecture 2: Data acquisition

Lecture 3: Key data processing steps

Day 1 afternoon- Exercises

Exercise 1: Synthetic seismic sections

Exercise 2: NMO corrections and velocity analysis

Solution notebooks will be provided but we may discuss the solutions to the exercises at points during the afternoon sessions (we will try record this content - but don’t rely on it. Attend the session).

Lecture outline

Objective of lecture 1:
Understand the fundamental principles behind the seismic reflection method

1) Seismic waves and propagation

2) Acoustic impedance and reflection coefficients

3) What is a seismic trace?

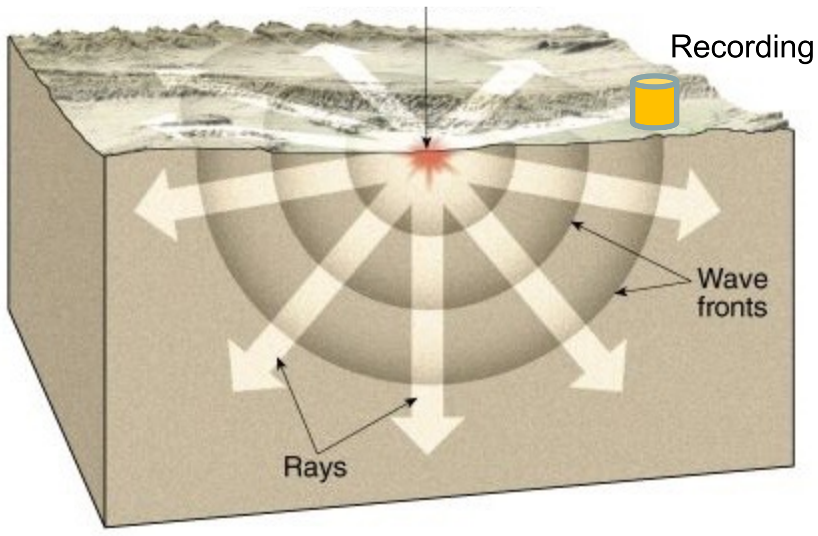
Exercise 1- 2D Synthetic seismic models

Seismic reflection principles

- Seismic waves are "parcels" of elastic strain energy that propagate outwards from a seismic source, e.g. earthquake, explosion or impact
- Seismic waves travel spherically from a seismic source, but we often consider their direction of travel as linear "**ray paths**" which travel 90^o to the "**wavefronts**"
- In seismic reflection imaging we detect the MAN-MADE seismic waves with recording instrument after they have travelled through the Earth

<u>Key things we need:</u>

SOURCE of seismic waves
RECIEVERS to detect propagated waves

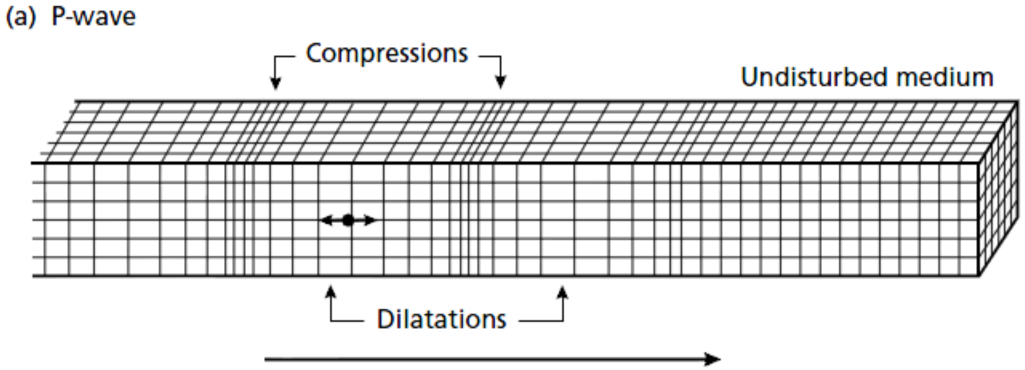


http://principles.ou.edu/eq_seismo/seismo_interior_simple.html

Background- seismic waves

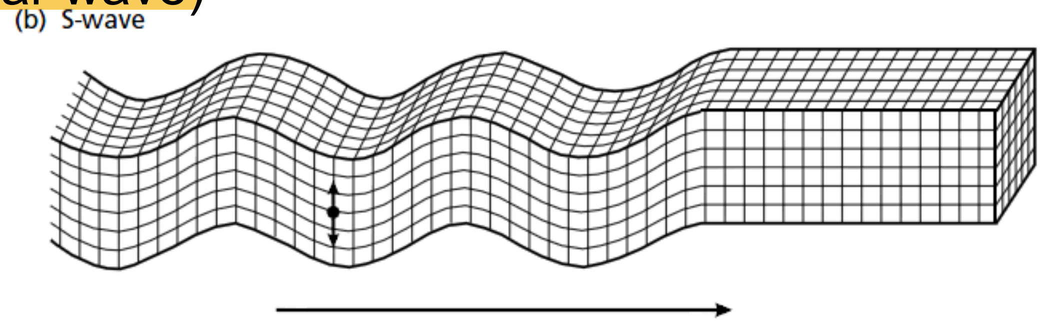
- There are a number of different types of seismic wave, which differ in how they propagate and the particle motion they experience

- P (primary) -waves propagate by compression and dilation, with particle motion in the direction of travel (compressional wave)



P-waves used in seismic reflection imaging (fastest waves)

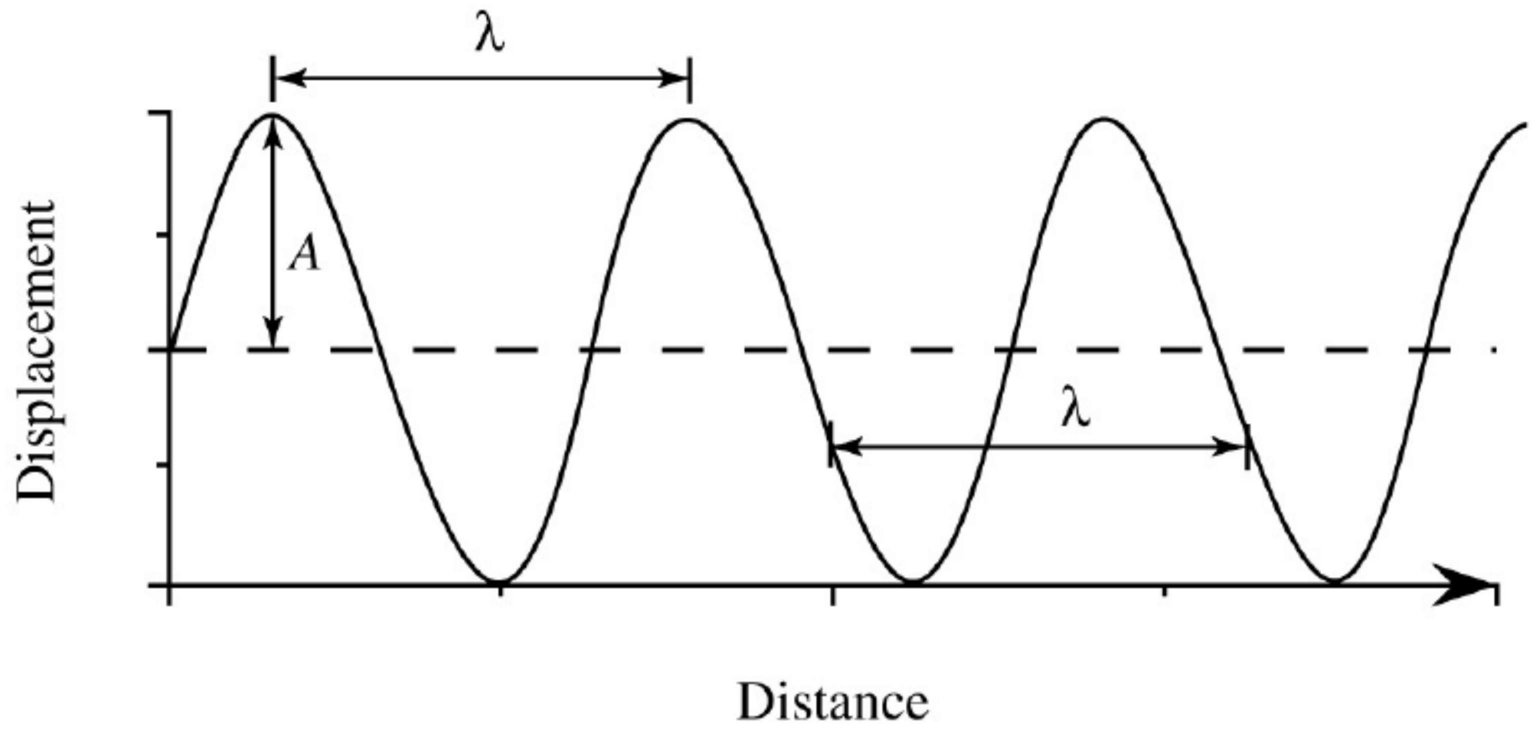
- S (secondary) –waves propagate by pure shear strain in a direction perpendicular to the direction of travel (transverse/shear wave)



Bolt 1982

Wave revision

Seismic wavelength (λ) is distance between successive peaks



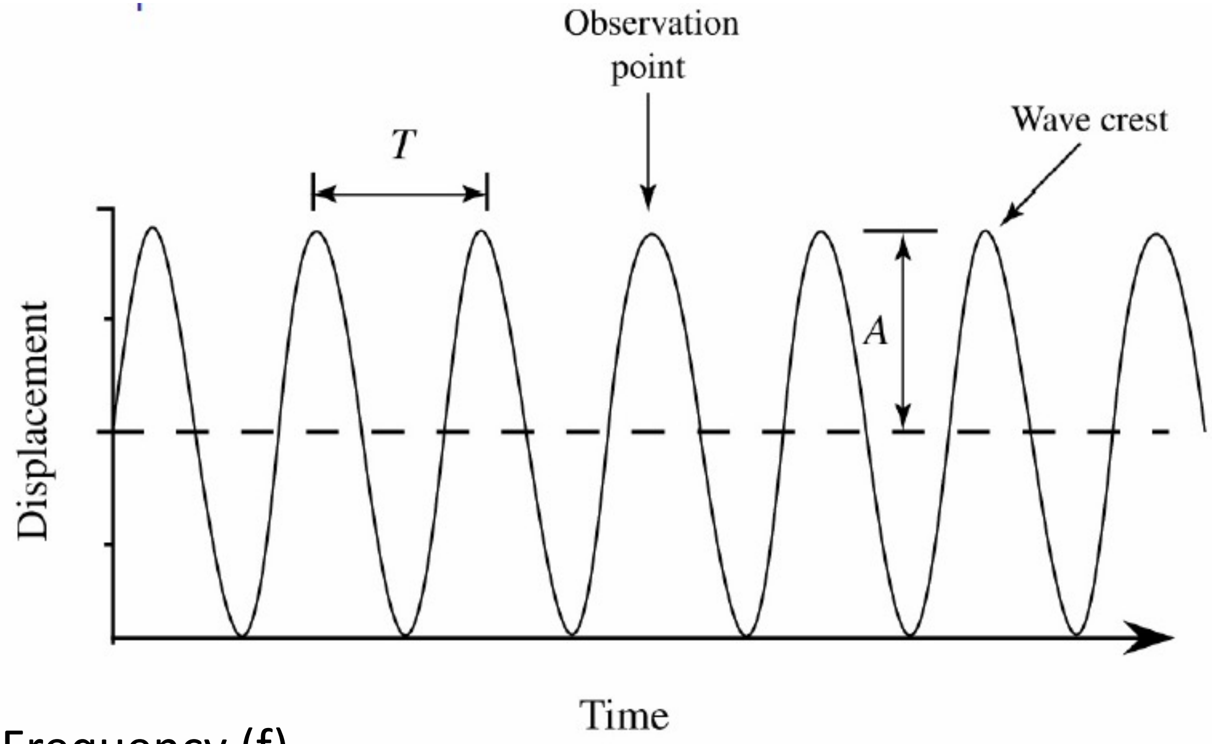
P-wave velocity (v) = frequency (f) x seismic wavelength (λ)

$$v = f\lambda$$

As velocity increases the distance between compressions (and dilations) increases

Wave revision

Period (T) = time difference between successive peaks arriving at an observation point



Period (T) = 1 / Frequency (f)
Frequency is measured in Hz (cycles per second)

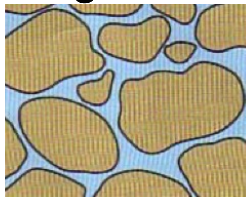
If T = 0.1s, Frequency = 10 Hz
If T = 0.01s, Frequency = 100 Hz

$$\boxed{T = 1/f}$$

P-wave velocity

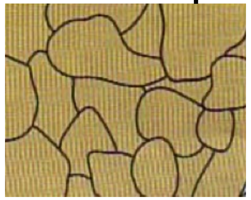
Table 3.1 Compressional wave velocities in Earth materials.

Young/shallow



High porosity

Old/deep



Low porosity

	v_p (km s^{-1})
Sedimentary rocks	
Sandstones	2.0–6.0
Young/shallow — Tertiary sandstone	2.0–2.5
Pennant sandstone (Carboniferous)	4.0–4.5
Old/deep — Cambrian quartzite	5.5–6.0
Limestones	2.0–6.0
Cretaceous chalk	2.0–2.5
Jurassic oolites and bioclastic limestones	3.0–4.0
Carboniferous limestone	5.0–5.5
Dolomites	2.5–6.5
Salt	4.5–5.0
Anhydrite	4.5–6.5
Gypsum	2.0–3.5

	v_p (km s^{-1})
Igneous/Metamorphic rocks	
Granite	5.5–6.0
Gabbro	6.5–7.0
Ultramafic rocks	7.5–8.5
Serpentinite	5.5–6.5
Pore fluids	
Air	0.3
Water	1.4–1.5
Ice	3.4
Petroleum	1.3–1.4
Other materials	
Steel	6.1
Iron	5.8
Aluminium	6.6
Concrete	3.6

Kearey, Brooks & Hill. An introduction to Geophysical Exploration

Quiz Question

Which of the following would have the slowest P-wave velocity (Vp):

- Water-saturated sandstone?
- Oil-saturated sandstone?
- Gas-saturated sandstone?

P-wave velocity

- Velocity and density are closely correlated

- Nafe-Drake curve

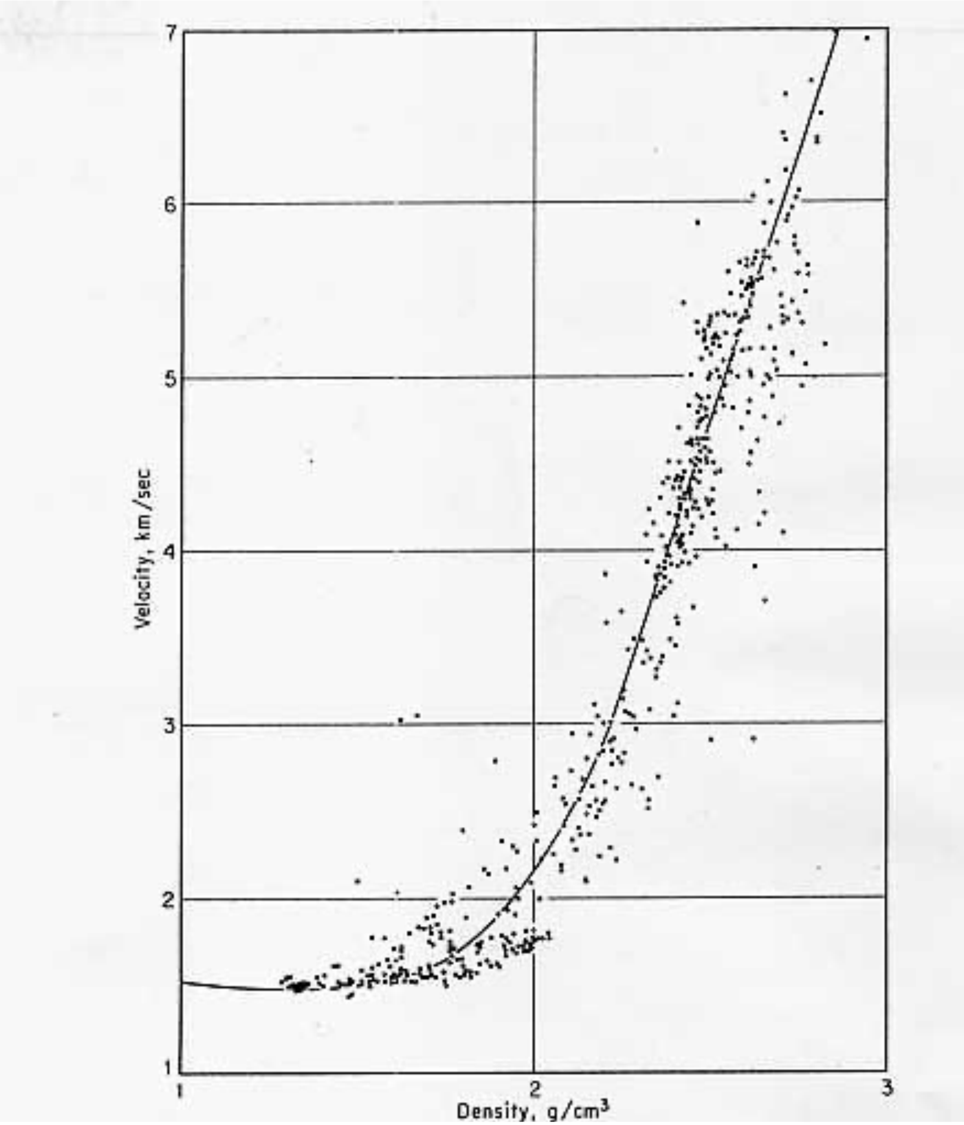
- Velocity usually increases with depth due to compaction. Fractures close and porosity decreases

- Sediments usually have lower velocities than metamorphic and igneous rocks

The Gardner relationship is an empirical relationship Between density and velocity:

You will use this in Ex 1

$$\rho = 0.31 V_p^{0.25}$$



Nafe & Drake 1961

Seismic wave propagation

Seismic waves produced by a source propagate through the Earth in a number of different ways:

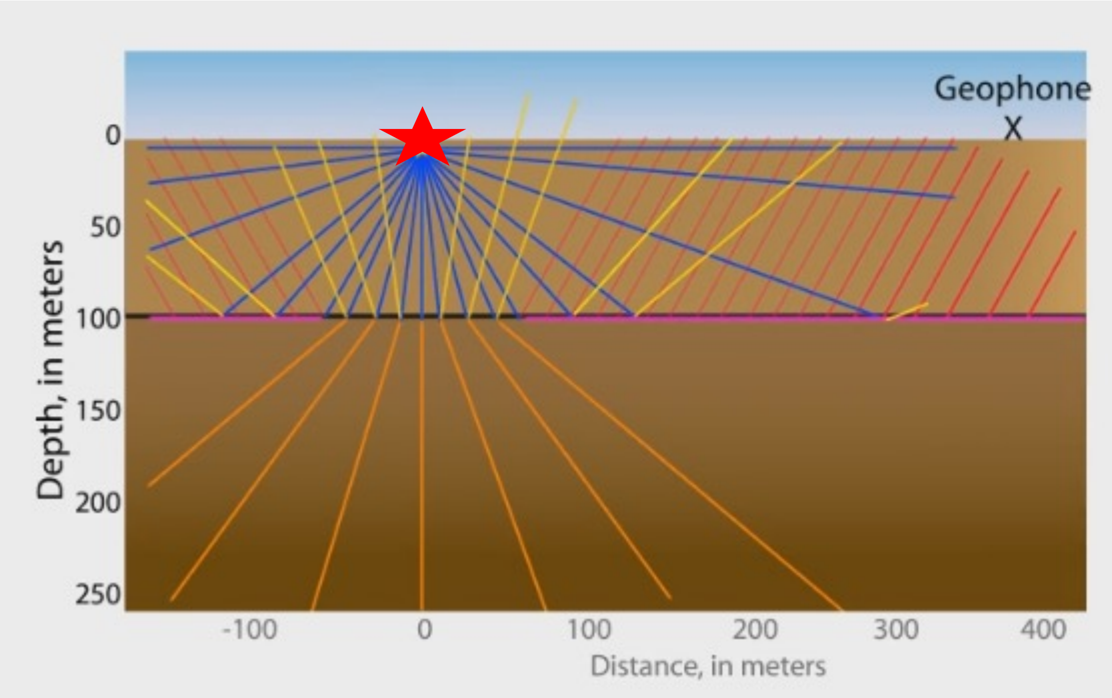
Direct waves (blue): These travel from source to receiver directly

Reflected waves (yellow): These travel from the source, reflect from an interface before being detected at the receiver

Refracted Head waves (pink): These travel from the source, bend at an interface and travel within a deeper layer before being detected at the receiver

Refracted/Transmitted waves (orange): Travel across an interface (they can then later be reflected or refracted)

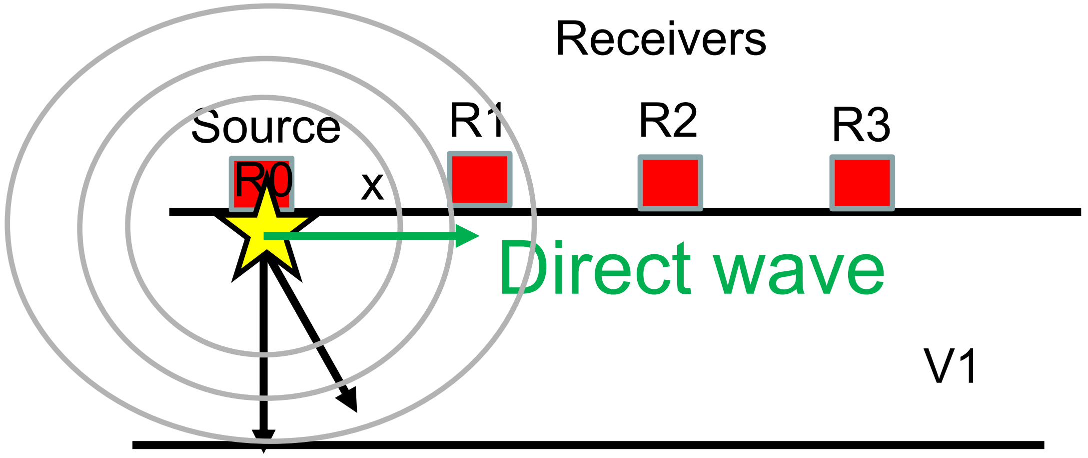
The reflected waves are key for seismic reflection imaging



Seismic wave propagation movie from IRIS (Incorporated Research Institutions for Seismology)-

https://www.iris.edu/hq/inclass/animation/seismic_wave_behavior_a_single_boundary_refracts__reflects

Seismic wave propagation – Direct wave

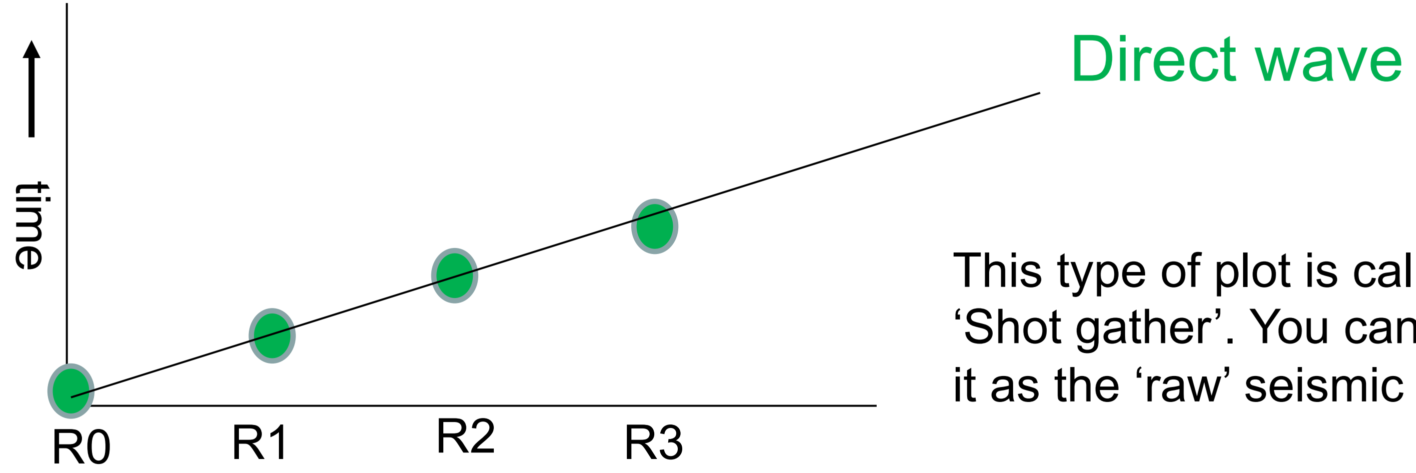


Direct waves arrive at receivers close to the source first.

Their travel times depend on:

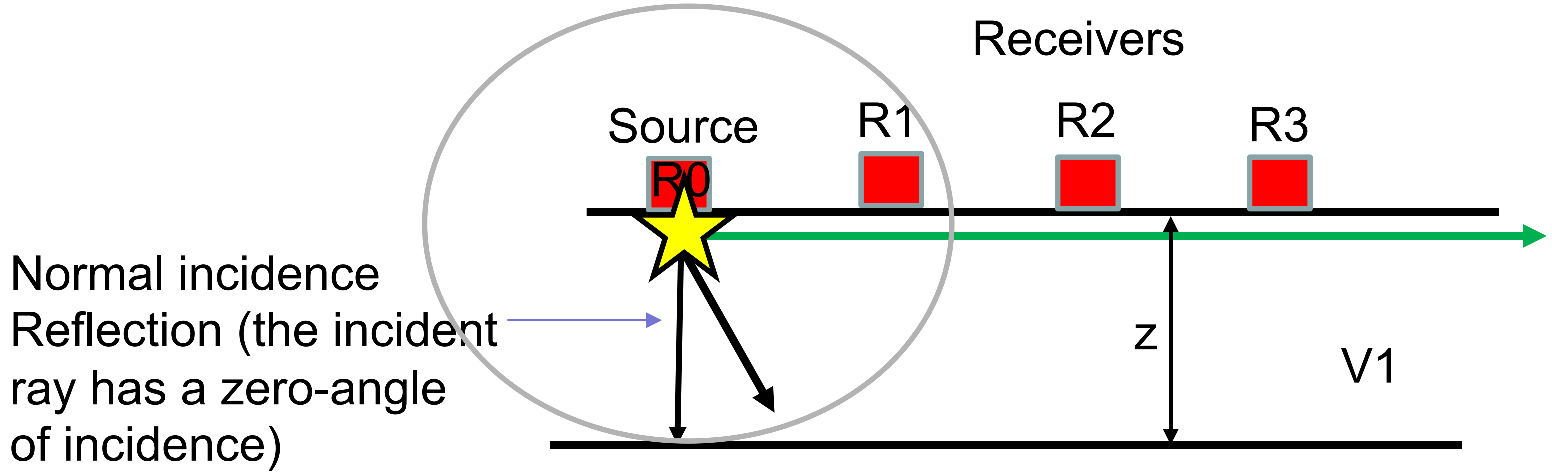
Velocity = distance/time

Time = x/V1



This type of plot is called a 'Shot gather'. You can think of it as the 'raw' seismic data

Seismic wave propagation – reflections

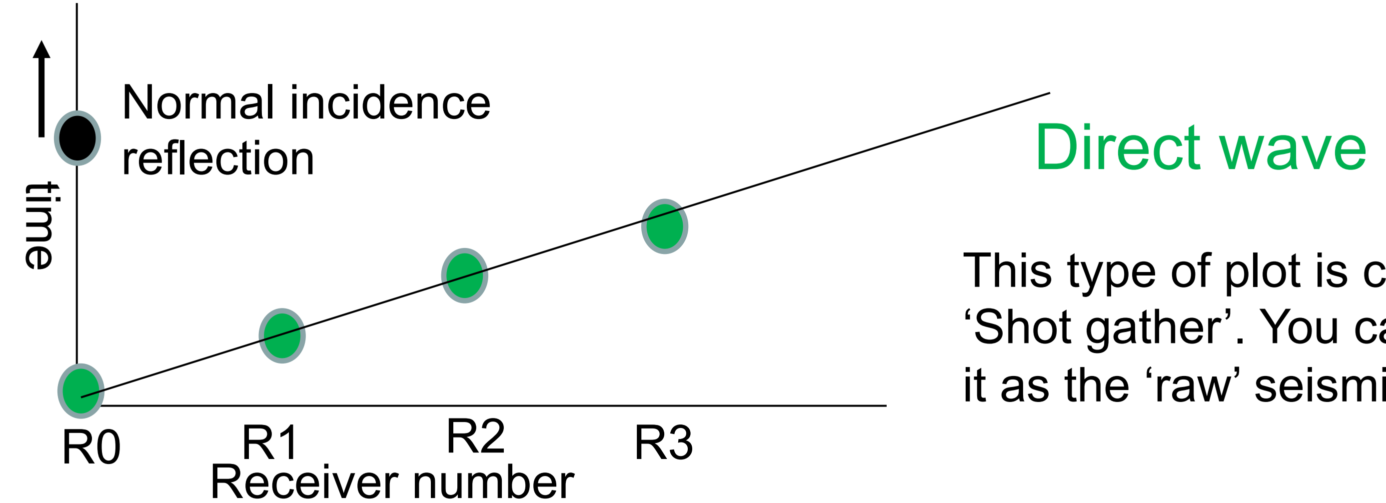


The first reflection to be detected
Is the 'normal incidence reflection'
This is the reflection with shortest
travel path.

The normal incidence reflection
Travel time can be calculated with:

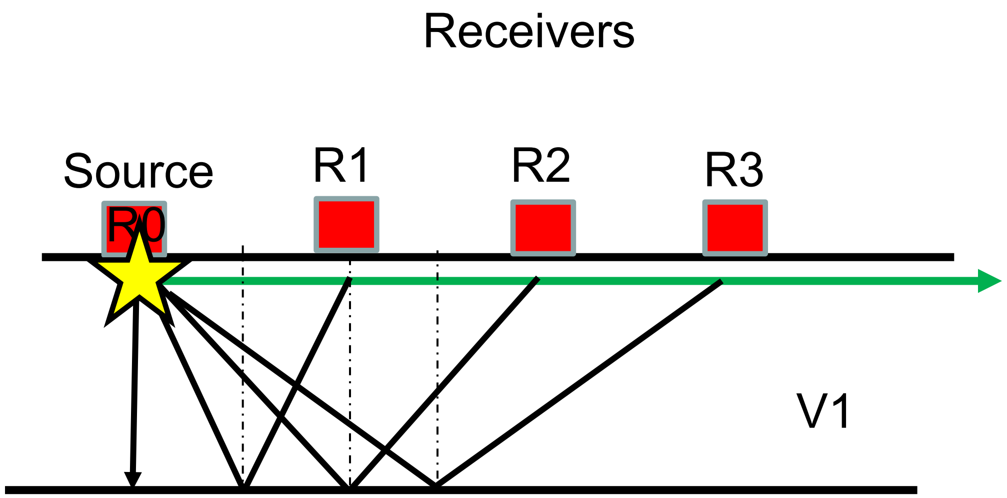
V = distance/time

Two-way Time = 2z / V1



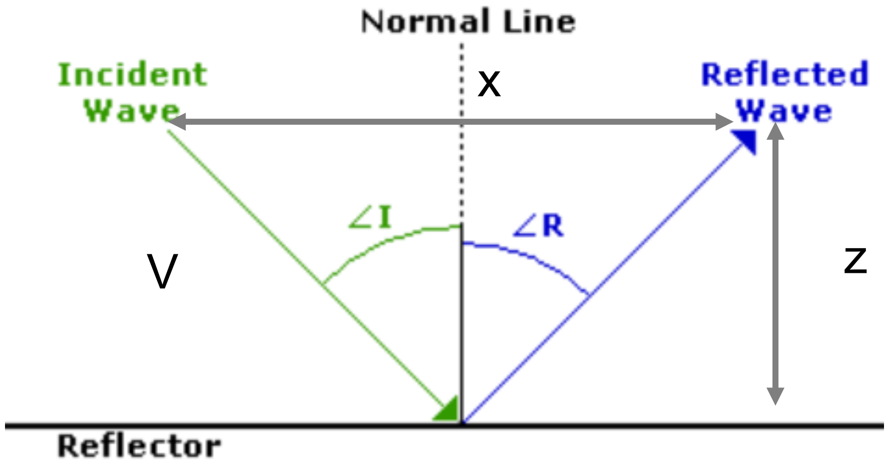
This type of plot is called a 'Shot gather'. You can think of it as the 'raw' seismic data

Seismic wave propagation – reflections



Other receivers away from the source will detect reflections from the point on the horizon half way between the source and receiver- because for a reflection the angle of incidence= angle of reflection

Can you derive an equation for the travel time of reflections in terms of x, z and V?



Receiver number

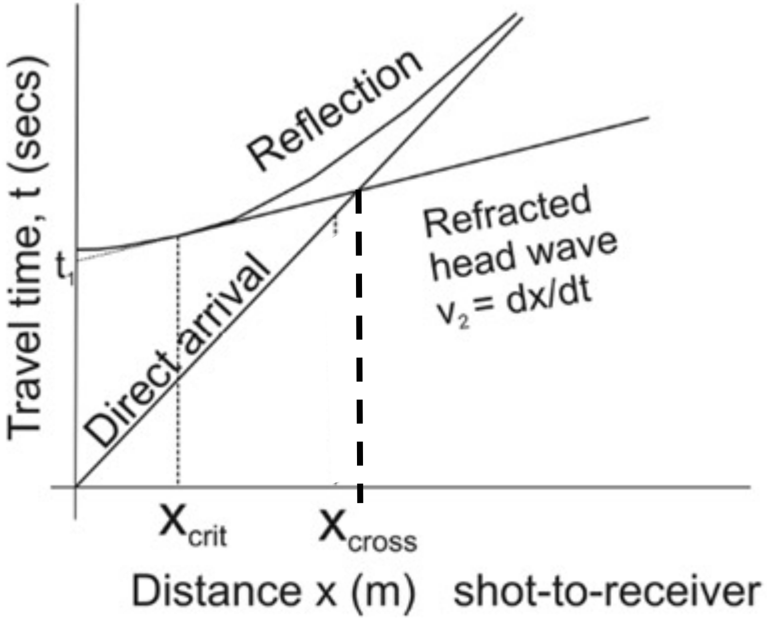
x = distance between source and receiver (we call this ‘offset’)
z = depth to geological horizon
V = velocity of the layer

Seismic wave propagation

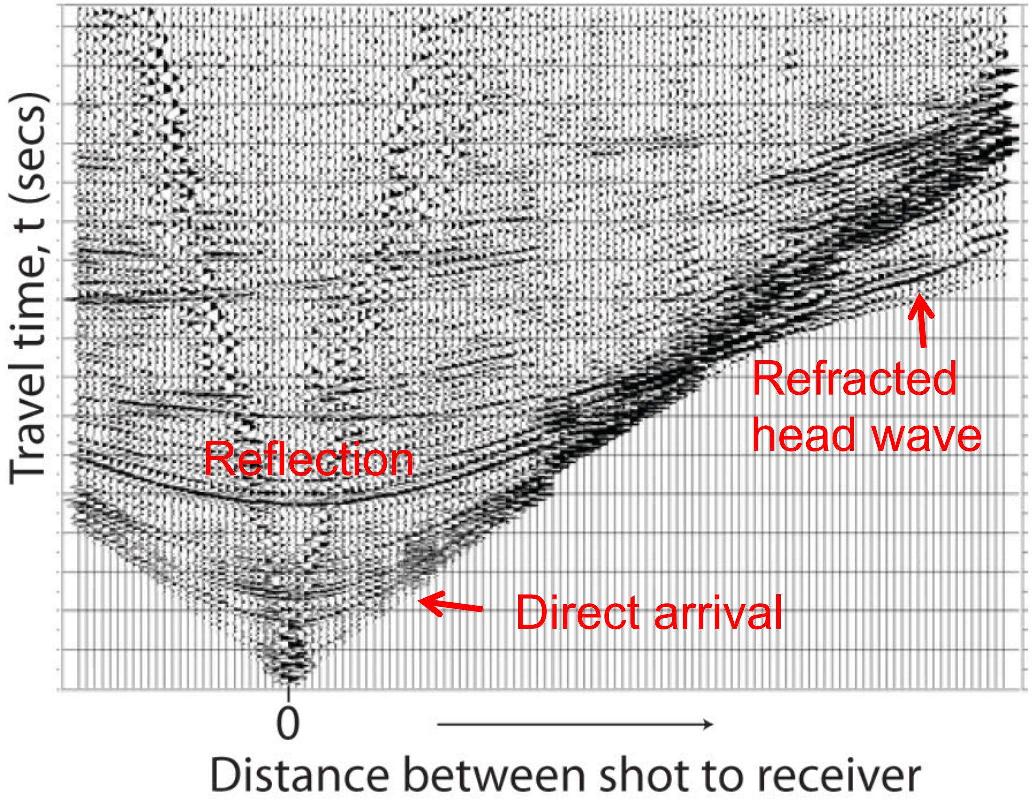
Travel time equation tor reflections

$$t_x^2 = \frac{x^2}{v^2} + \frac{4z^2}{v^2}$$

On a plot of distance Vs time, reflections are hyperbolic and direct waves linear



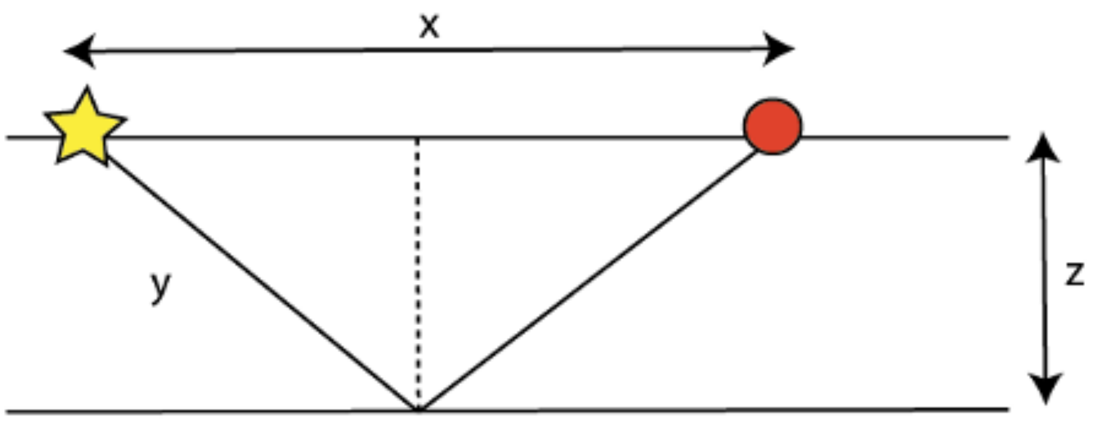
Shot Gather (raw data)



Reflections are all we use in seismic reflection imaging
Everything else is noise we want to remove.

Seismic traces from a single shot are grouped together to form a shot gather

Travel time equation derivation



$$y^2 = \left(\frac{x}{2}\right)^2 + z^2$$

$$t = \frac{2y}{V}$$

$$t^2 = \frac{4}{V^2}\left(\left(\frac{x}{2}\right)^2 + z^2\right)$$

$$t^2 = \frac{x^2}{V^2} + \frac{4z^2}{V^2}$$

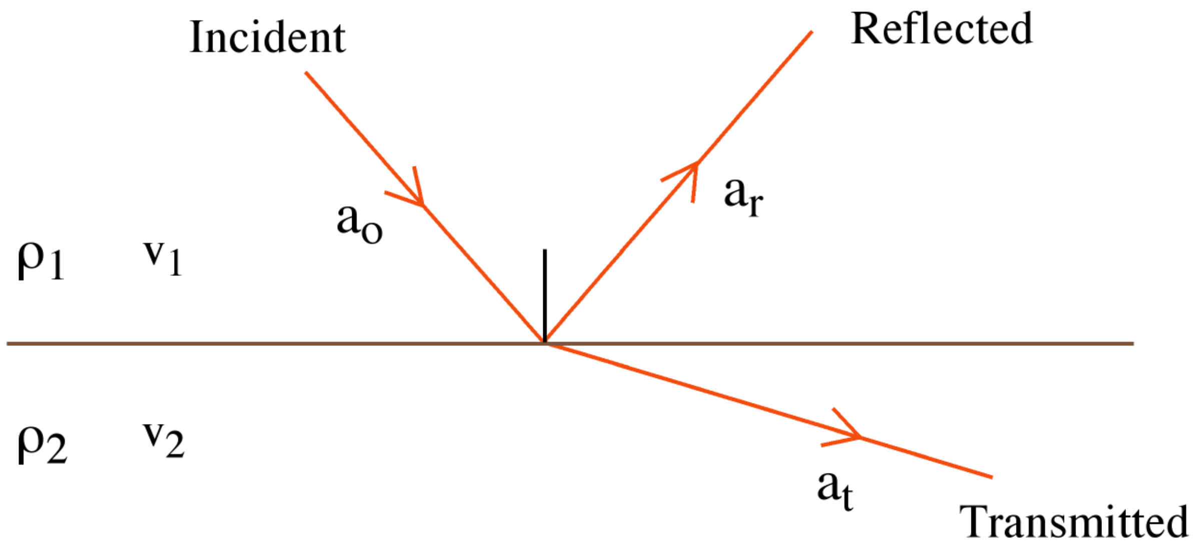
Acoustic impedance

- The amount of energy reflected back from each interface is dependent on the Acoustic Impedance (Z) contrast.

- The acoustic impedance for a medium is defined as the product of density and P-wave velocity:

$$Z = \rho \times V$$

- The acoustic impedance contrast is the relative impedance change across a boundary.



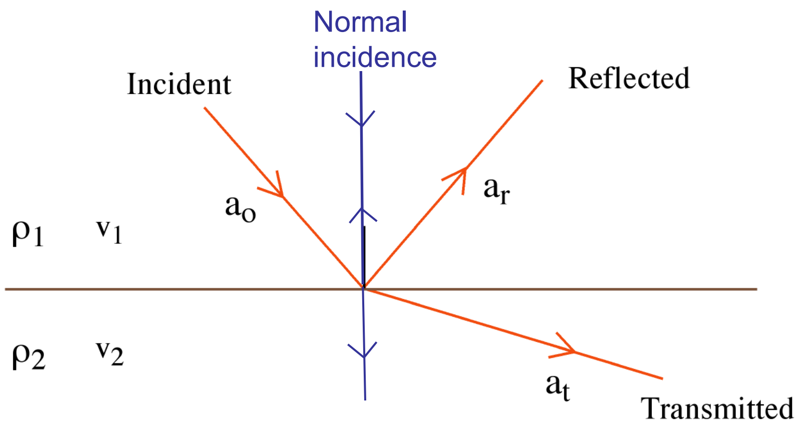
Reflection coefficients

- The reflection coefficient "R" or "Rc" is the ratio of the amplitude a_r of the reflected ray to the amplitude a_o of the incident ray

$R = a_r / a_o$

- The reflection coefficient can also be written in terms of the acoustic impedance across a boundary.

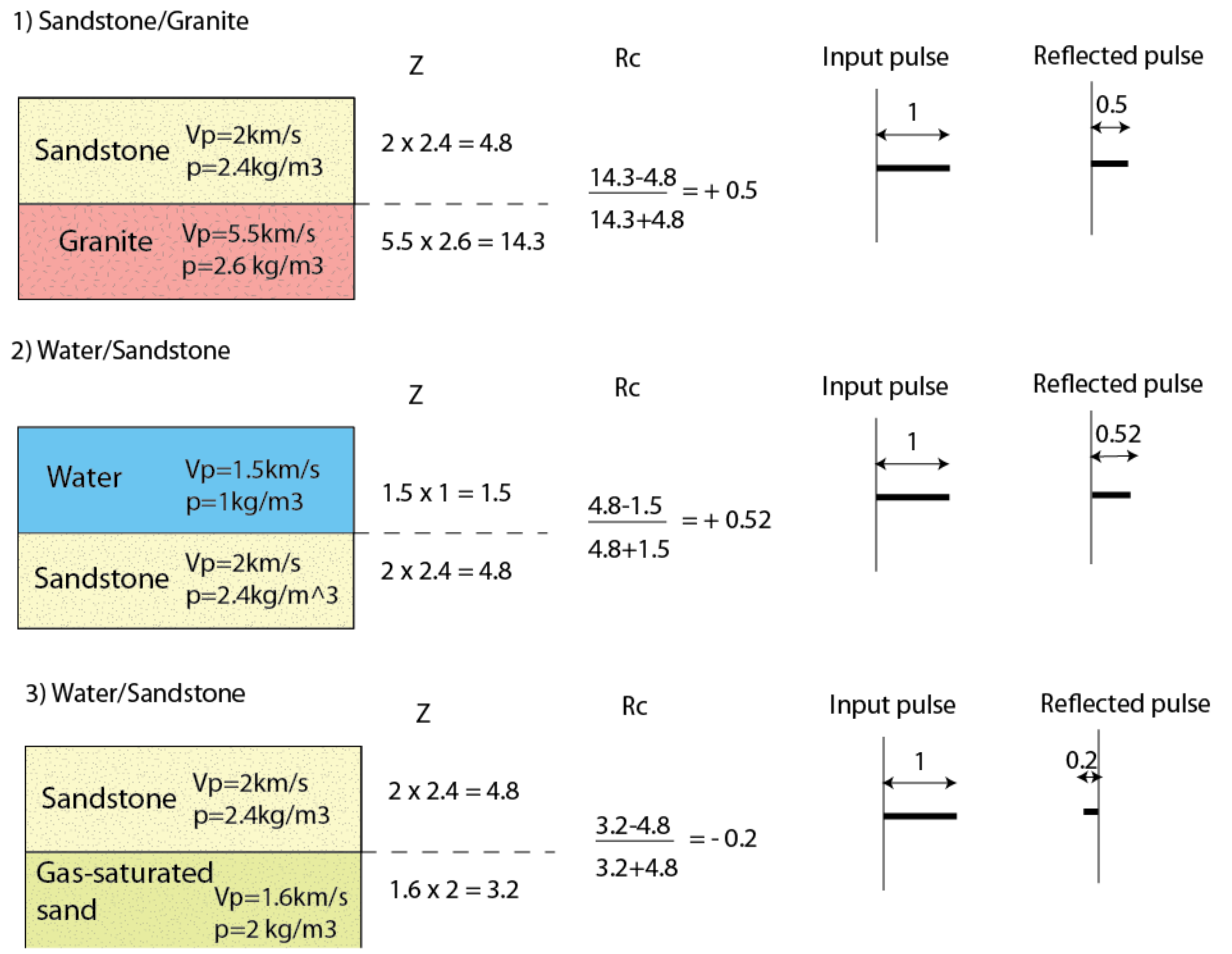
For a "normal incidence" ray:



$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

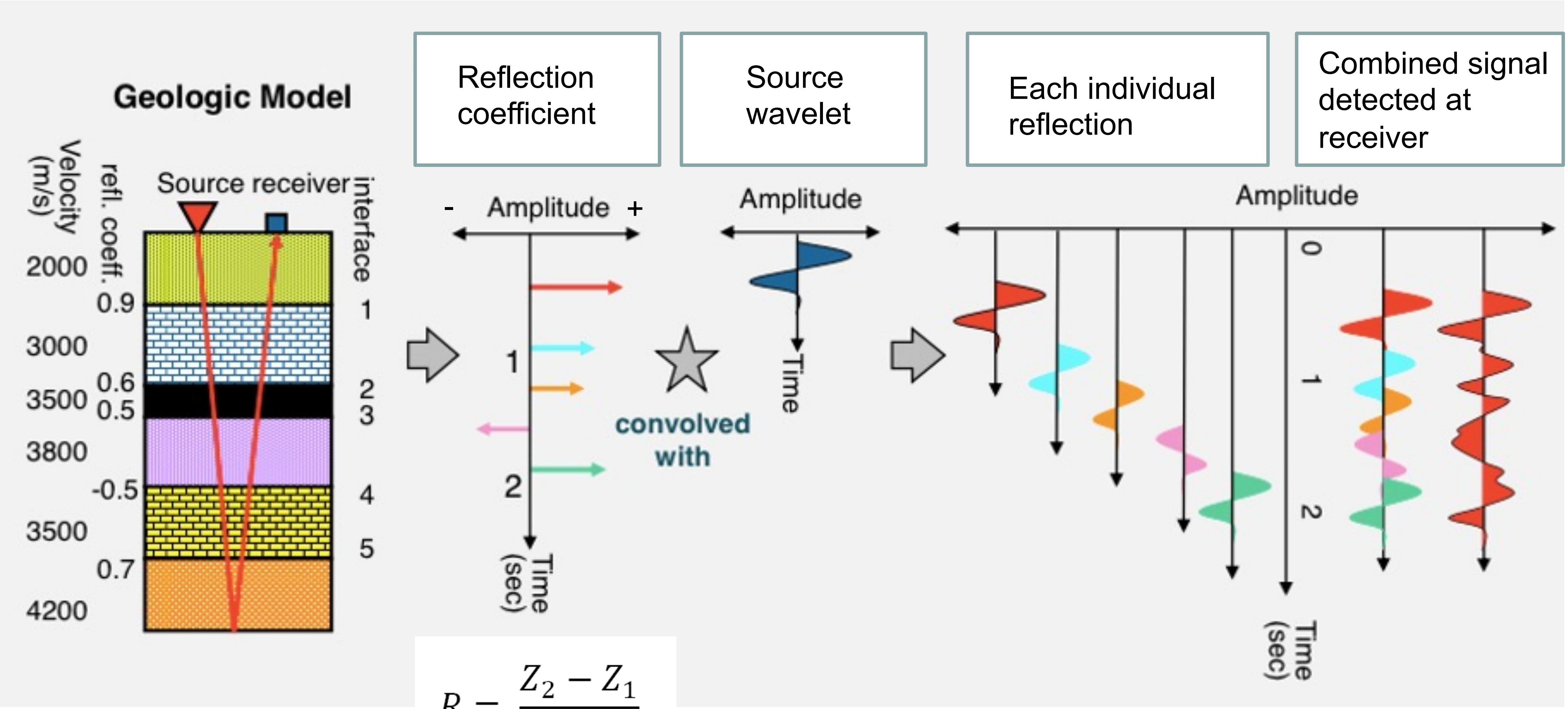
Reflection coefficients



Reflection coefficients are non-unique. Very different geological boundaries produce similar reflection amplitudes

Negative reflection Coefficients cause the polarity of the input wavelet to reverse

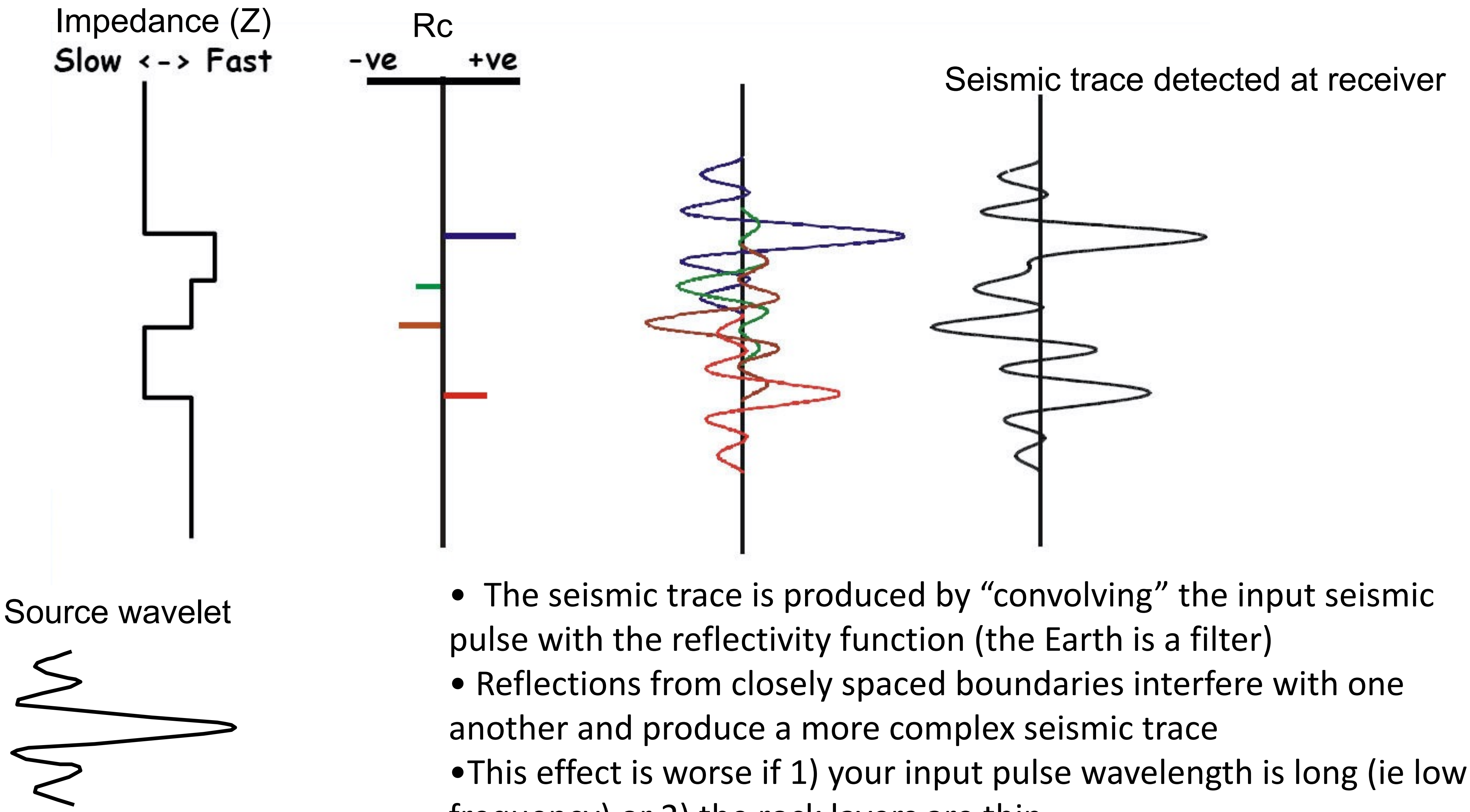
The convolution model of the Earth



$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

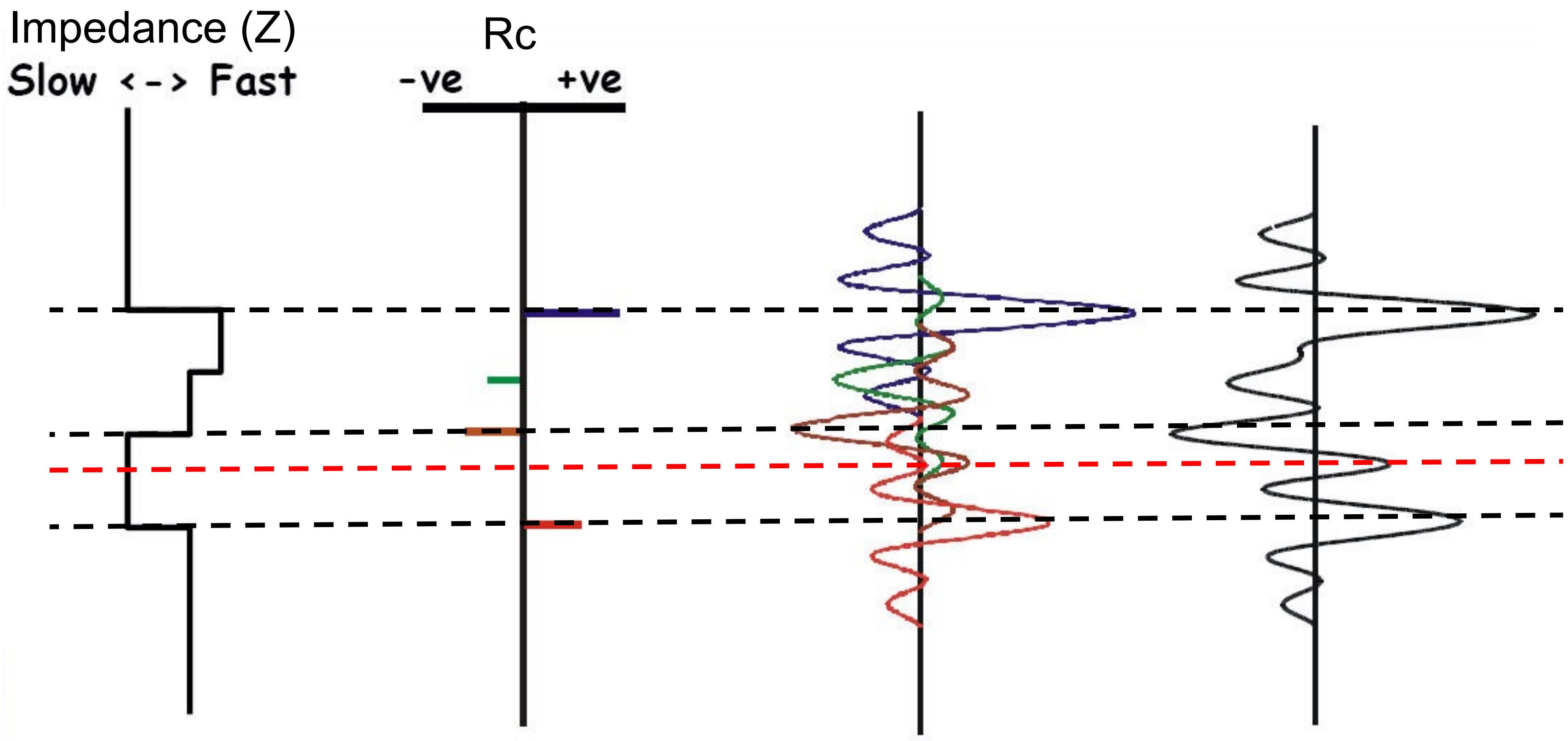
Yanghua Wang, pers comm

The convolution model of the Earth

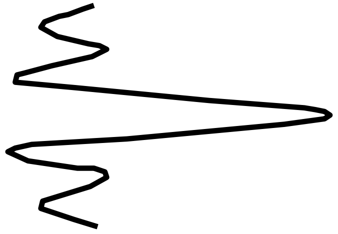


- The seismic trace is produced by “convolving” the input seismic pulse with the reflectivity function (the Earth is a filter)
- Reflections from closely spaced boundaries interfere with one another and produce a more complex seismic trace
- This effect is worse if 1) your input pulse wavelength is long (ie low frequency) or 2) the rock layers are thin

The convolution model of the Earth



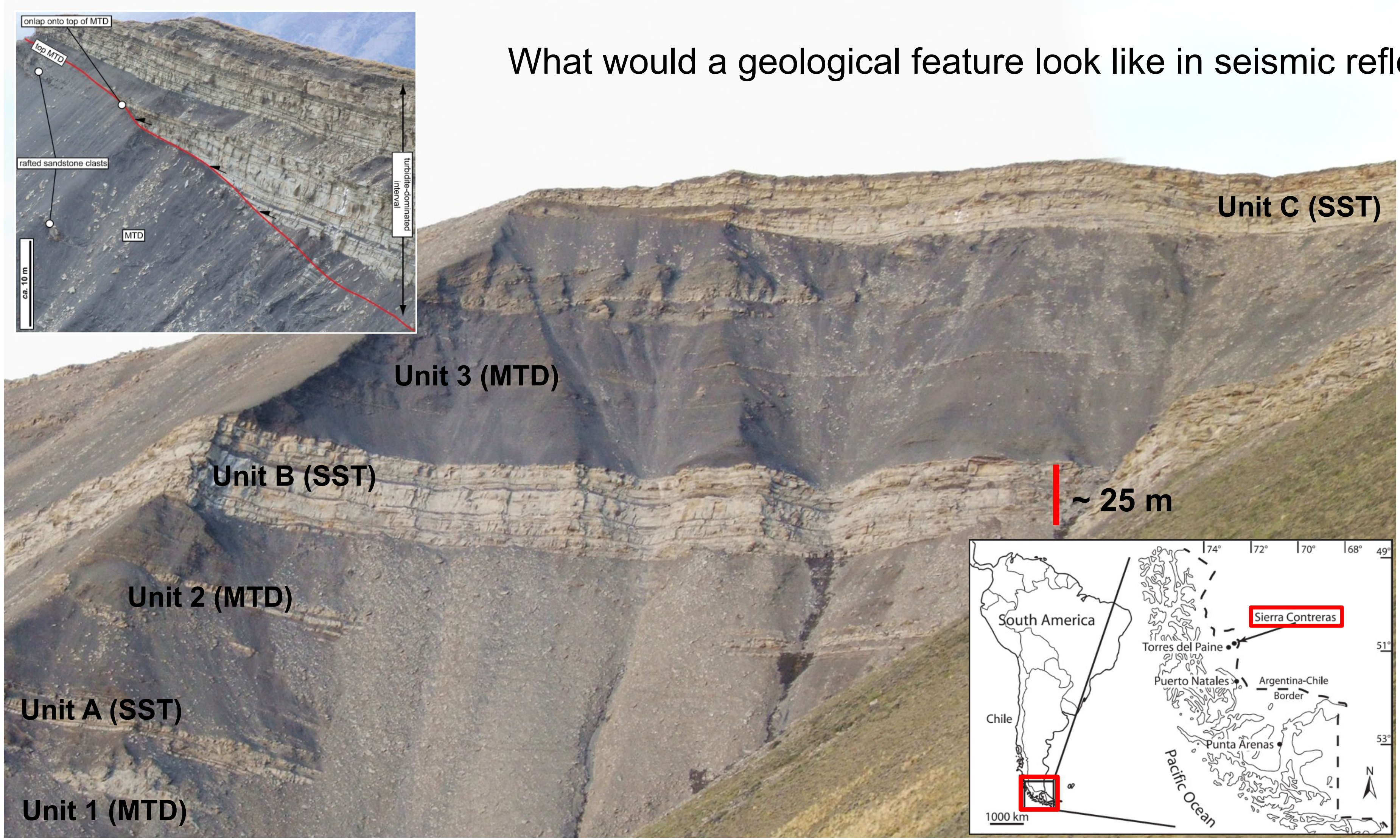
Source wavelet



- The seismic trace is produced by "convolving" the input seismic pulse with the reflectivity function (the Earth is a filter)
- Reflections from closely spaced boundaries interfere with one another and produce a more complex seismic trace
- This effect is worse if 1) your input pulse wavelength is long (ie low frequency) or 2) the rock layers are thin

Introduction to Exercise 1: Synthetic modelling

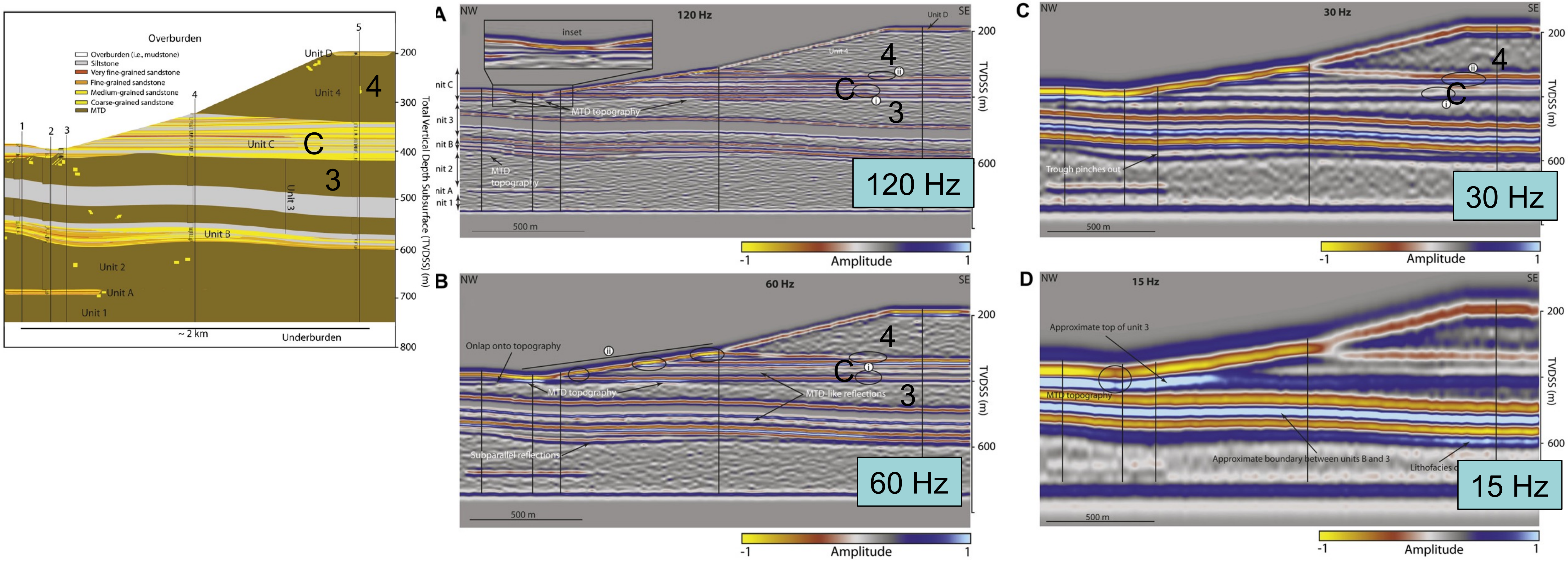
What would a geological feature look like in seismic reflection data?



- Cerro Toro and Tres Pasos formations, Cretaceous, southern Chile

Armitage & Stright 2009

Introduction to Exercise 1: Synthetic modelling



As the frequency of the source wavelet gets lower, we can't resolve such fine details of the geology. Seismic resolution gets poorer (geological features need to be bigger before we can see them) as frequency reduces.

Key points

- Seismic reflection is the only way we can provide detailed images of the ***subsurface*** (under the ground)
- Seismic traces are a convolution between reflection coefficients between rock units and a source wavelet
- If the source wavelet is wide (low frequency) reflections from closely spaced rock units will interfere and the details will be lost
- Seismic reflection data is limited in the details we can see
- If you want really high-resolution data for environmental/ archeological work we need to collect data using a very high-frequency source (see lecture 2)…