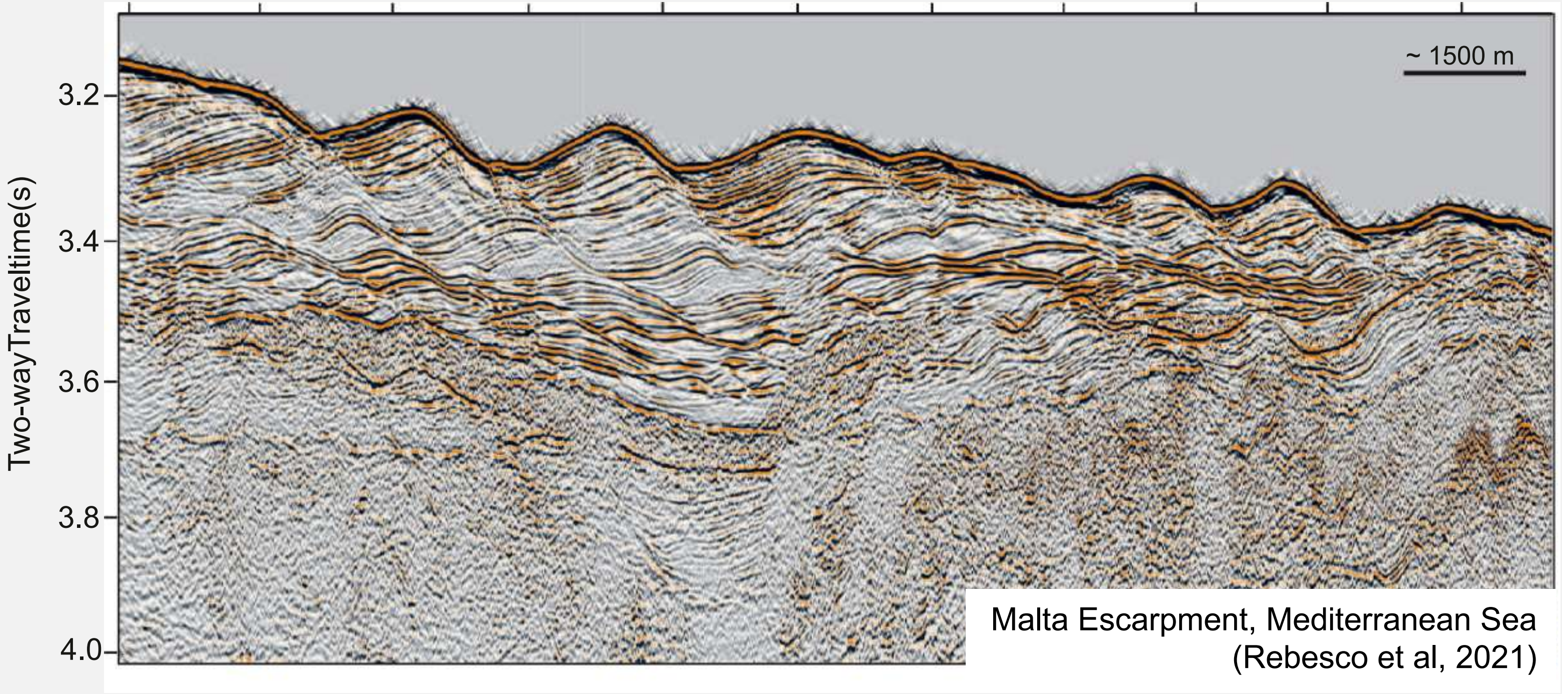


Overview of marine seismic reflection methods

Single- and multi-channel seismic acquisition and processing

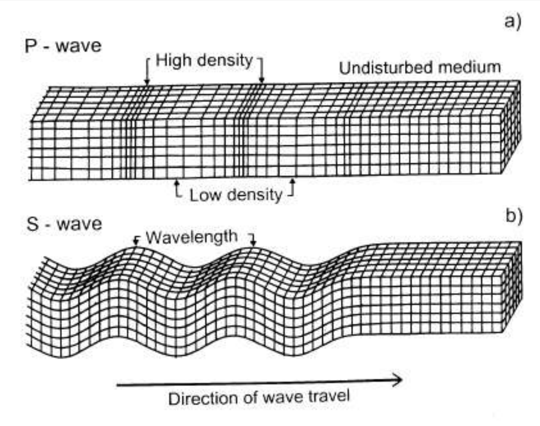
Jonathan Ford (jford@ogs.it), 7th December 2022

Seismic waves – waves that travel through the Earth

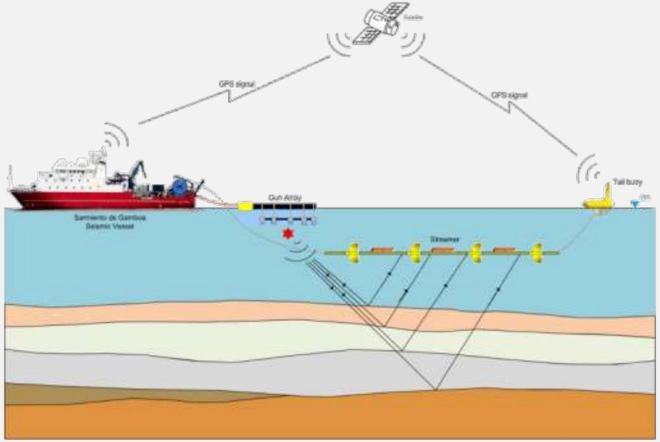
- Reflection methods use reflected <u>body waves</u> to characterise the subsurface

- Active methods generate seismic waves using a seismic source

- Marine seismic: special case where sources and receivers are in the water layer - generate and record <u>P-waves only</u>



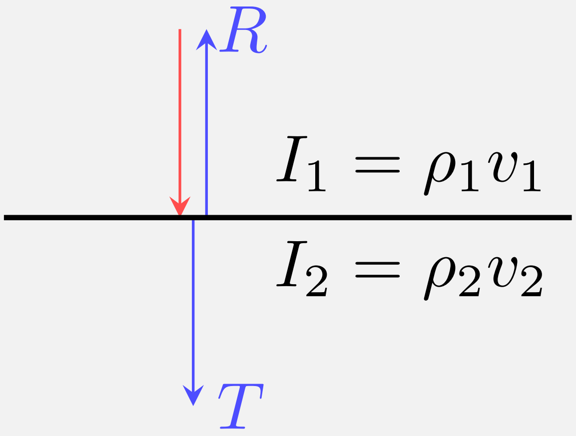
Keary, Brooks and Hill (2002)



http://www.utm.csic.es/index.php/en/servicios/sismica

Impedance and reflectivity

- Reflections generated by energy partitioning at subsurface impedance contrasts

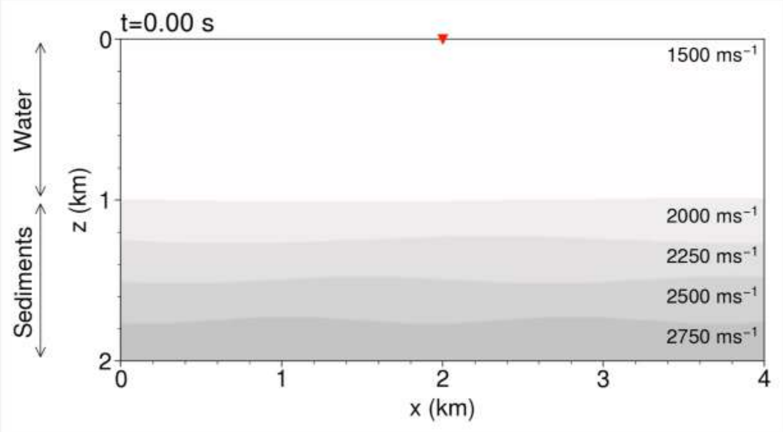


- Impedance is the product of density and velocity

$$I = \rho v$$

- Reflectivity (normal incidence)

$$R_{0^\circ} = \frac{I_2 - I_1}{I_2 + I_1} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}$$



Velocity and density in marine sediments

$$v_P = \sqrt{\frac{K}{\rho} + \cancel{\frac{4\mu}{3}}}$$

Bulk modulus ("stiffness")

Shear modulus

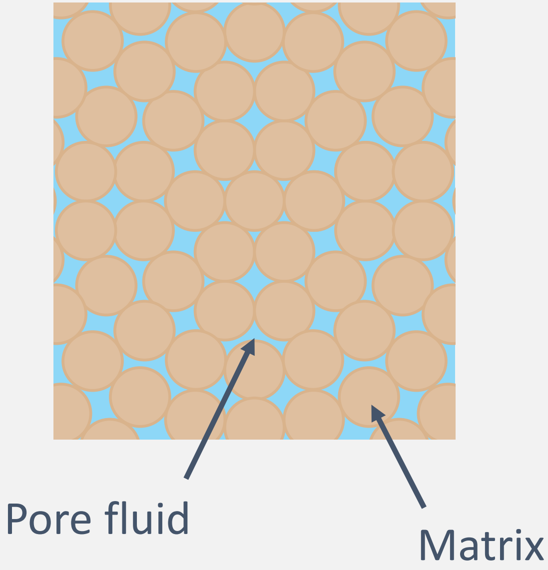
Density

$$\frac{1}{K} \approx \frac{1}{K_{matrix}} + \frac{\phi}{K_\phi + K_{fluid}}$$

$$\rho = \phi\rho_{fluid} + (1-\phi)\rho_{matrix}$$

Small change in pore fraction ϕ gives large change in impedance (v_P and ρ) → marine sedimentary rocks are great reflection generators

- Sedimentary rocks are <u>two-phase</u>
- In marine environments, usually <u>fully saturated</u> with water



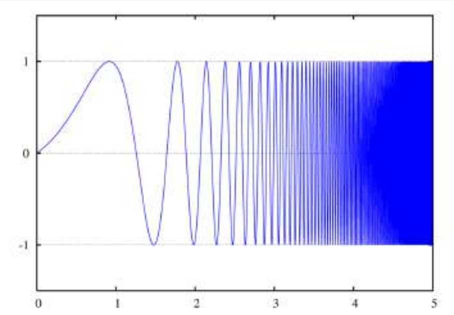
Sub-bottom profiler acquisition

- Source and receiver: electrical transducer(s)
- Zero-offset, single-channel data
- Source pulse: often a “chirp” wavelet (frequency sweep)
- Frequencies depend on target and geology, typically kHz

IxBlue Echos 10000 (7 transducer array)

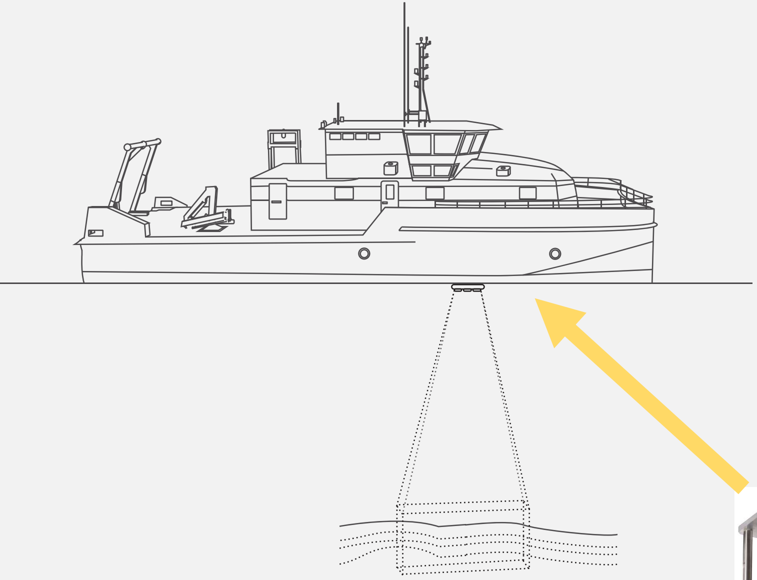
https://www.ixblue.com/store/echoes-10000/

“Chirp” pulse:



Omegatron (CC BY-SA 2.0)

Often hull-mounted on the vessel

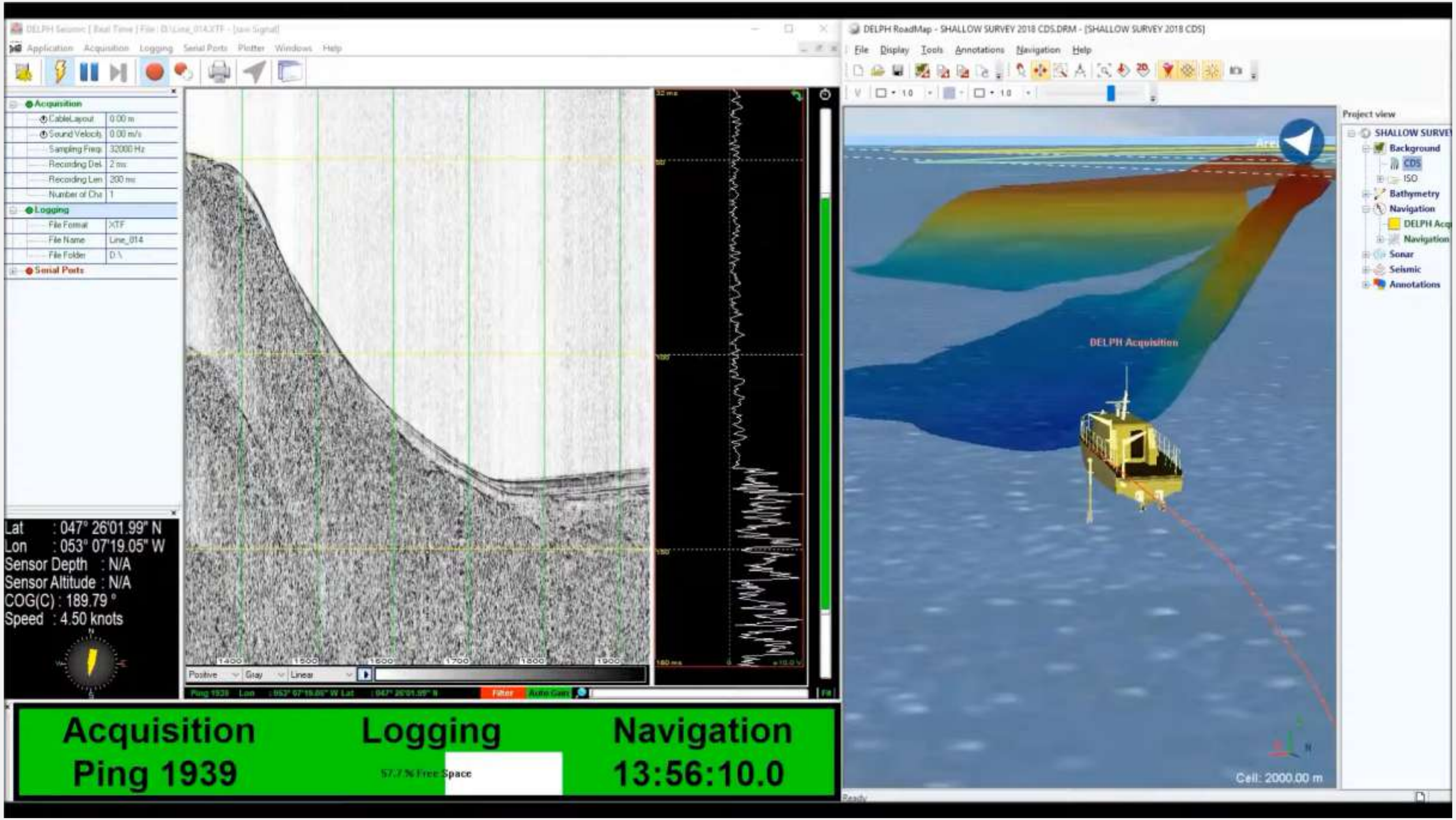


Flexible membrane

N/R Laura Bassi (icebreaker)

https://www.ixblue.com/wp-content/uploads/2021/12/echoes-3500-ds-t1-t3.pdf

Marine sub-bottom profiler acquisition (3x speed)

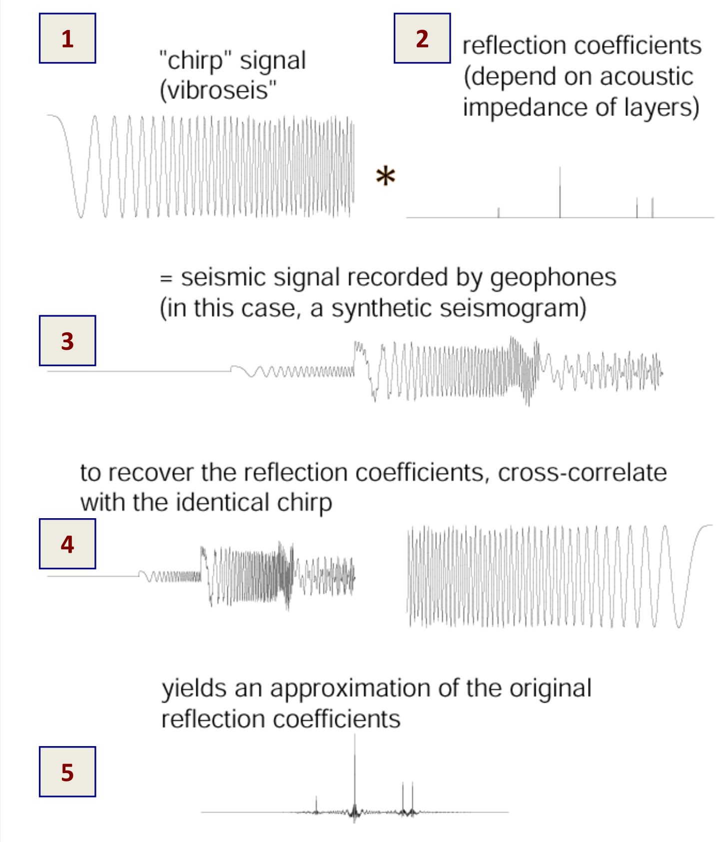


https://www.ixblue.com/store/echoes-10000/

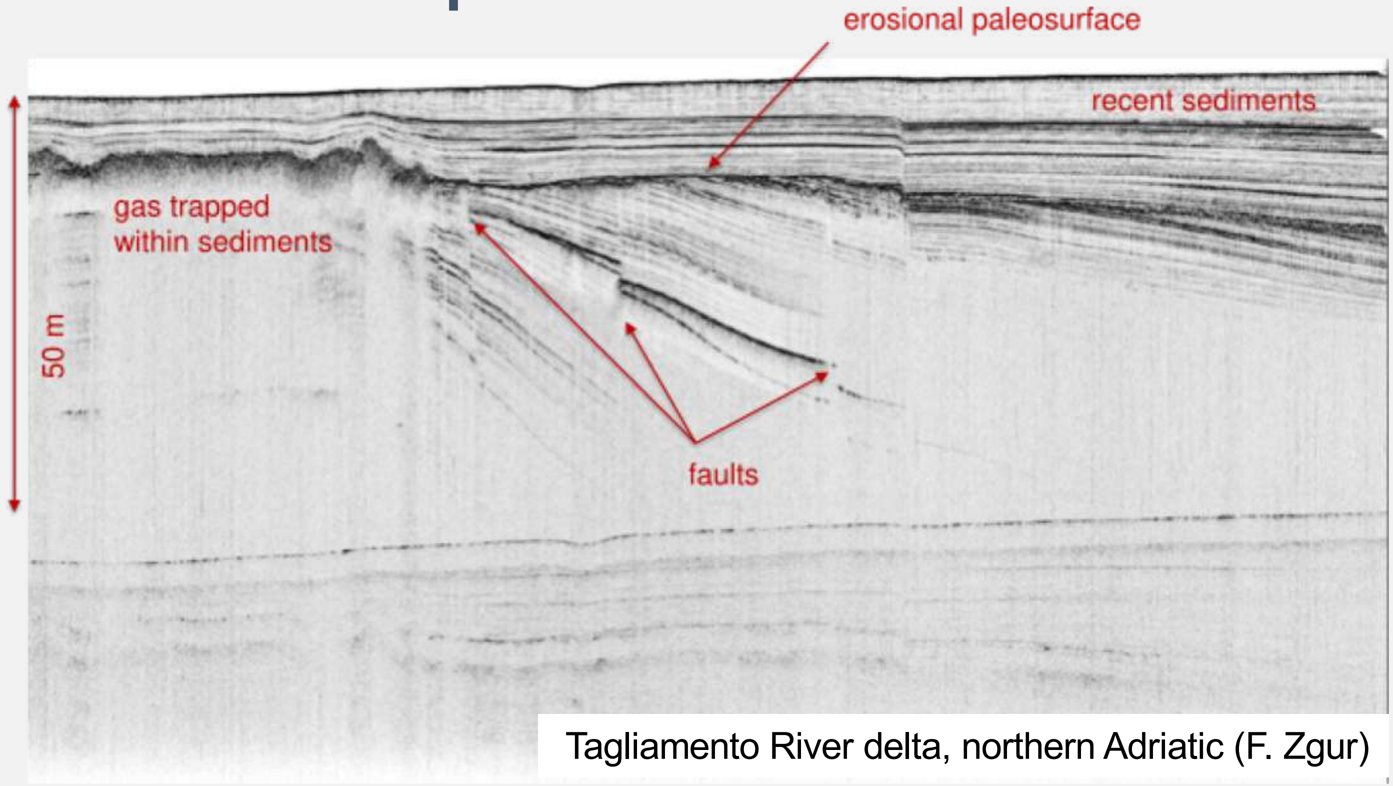
Sub-bottom profiler “chirp” imaging

- Convolution of the recorded signal with the source pulse → approximation of the band-limited subsurface reflectivity
- + trace amplification to compensate for spreading and attenuation
- Note: very often displayed in envelope display to improve reflector continuity (removes polarity and phase info)

But what is a convolution? (3Blue1Brown)
https://www.youtube.com/watch?v=KuXjwB4LzSA



Example sub-bottom profile



Tagliamento River delta, northern Adriatic (F. Zgur)

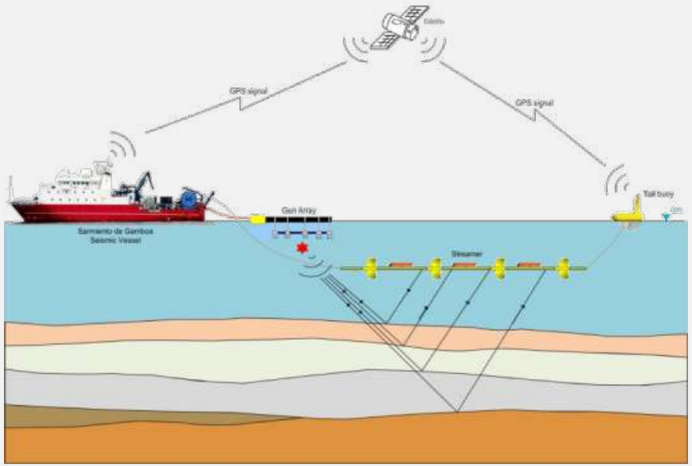
Typical SBP values

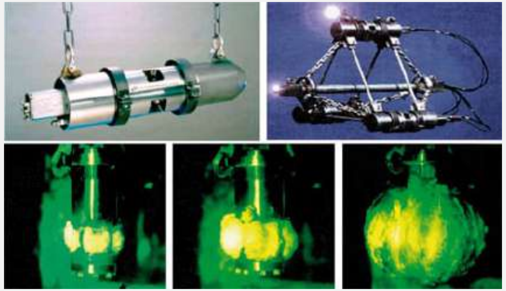
Bandwidth: 1 – 7 kHz
Resolution: 10s of centimetres
Penetration: 10s m (coarse sediments) to 100s m (fine sediments)

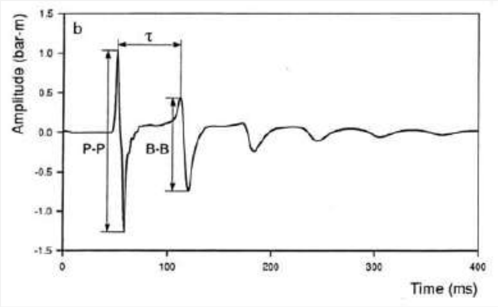
Note: envelope display

Multi-channel towed streamer acquisition (typical)

- Source: impulsive airgun array
- Receivers: linear array of hydrophones ("streamer")
- Multi-channel, multi-offset reflection seismic







Note: much more complicated acquisition geometries are possible (eg 3-D acquisition with multiple streamers)

Airgun sources

- Supplied with compressed air from a compressor on survey ship
- Usually towed in an array of several tuned airguns to improve penetration and frequency content
- Bandwidth: 10s to 100s Hz

Towed streamer acquisition (typical)

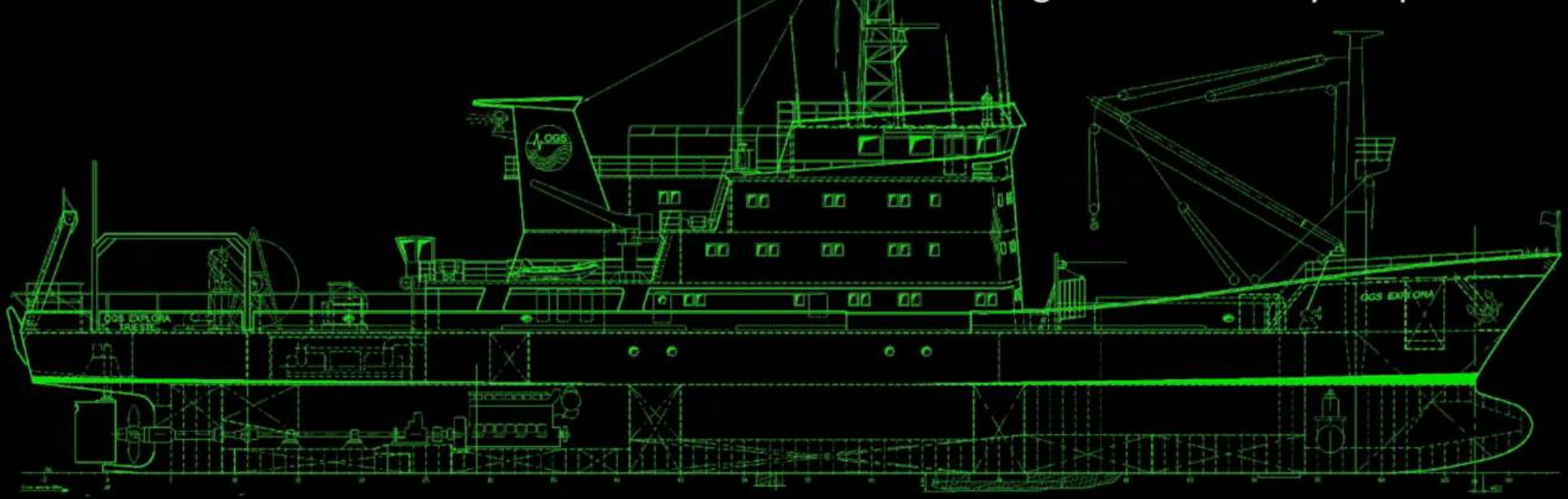
- Receivers: linear array of hydrophones (“streamer”)
  - Multi-channel acquisition
  - Records pressure wavefield
  - Neutrally buoyant
  - Depth control with “birds”
  - GPS/GNSS positioning from tailbuoy

https://www.ntnu.no

OGS EXPLORA

Eurofleet - SALTFLU

Salt deformation and sub-salt fluid circulation in the Algero-Balearic abyssal plain



a film by Roberto Romeo

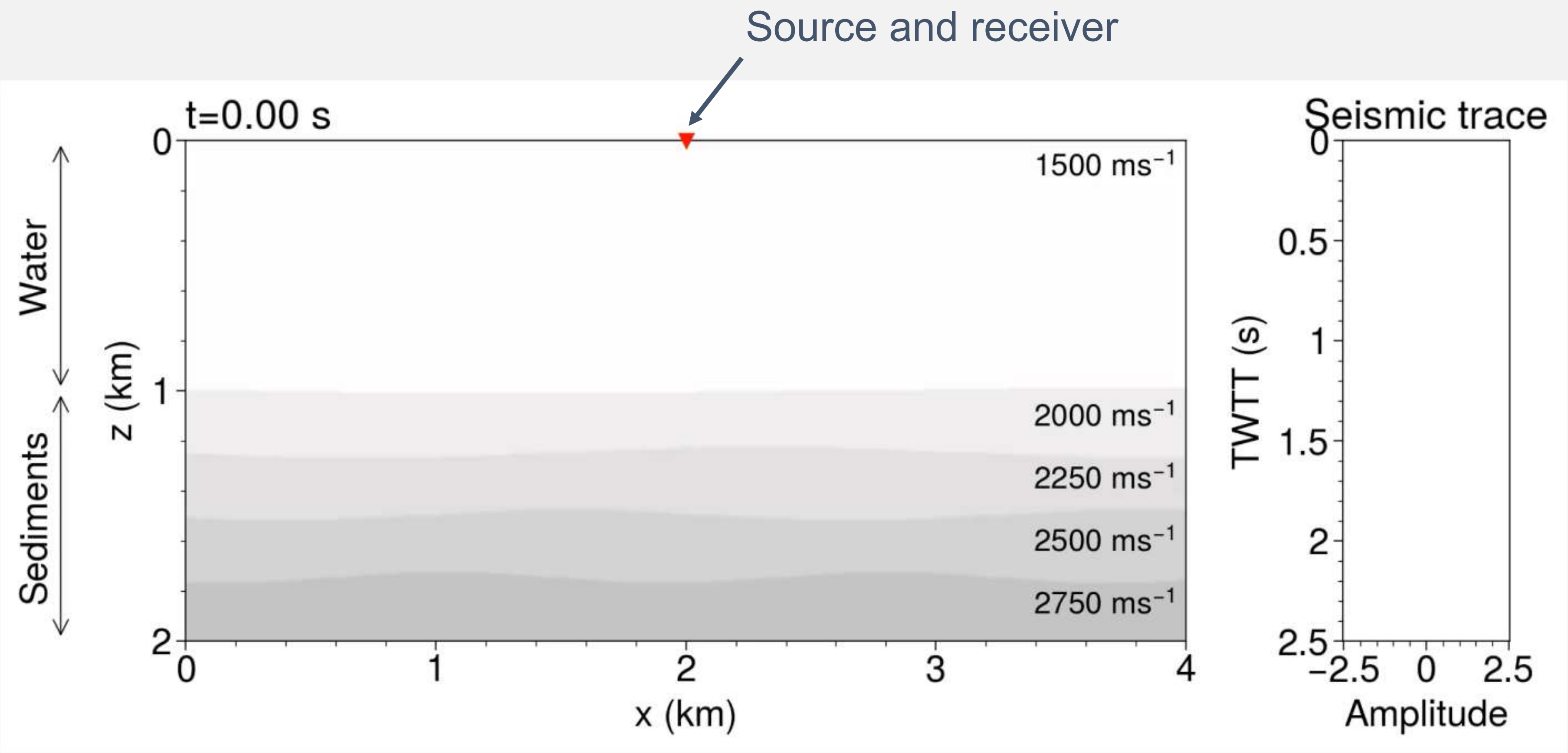
Brief introduction to seismic processing

Öz Yilmaz

Seismic Data Analysis freely available online: dated, but still a useful reference

https://wiki.seg.org/wiki/Seismic_Data_Analysis

Single-channel, zero-offset seismic experiment



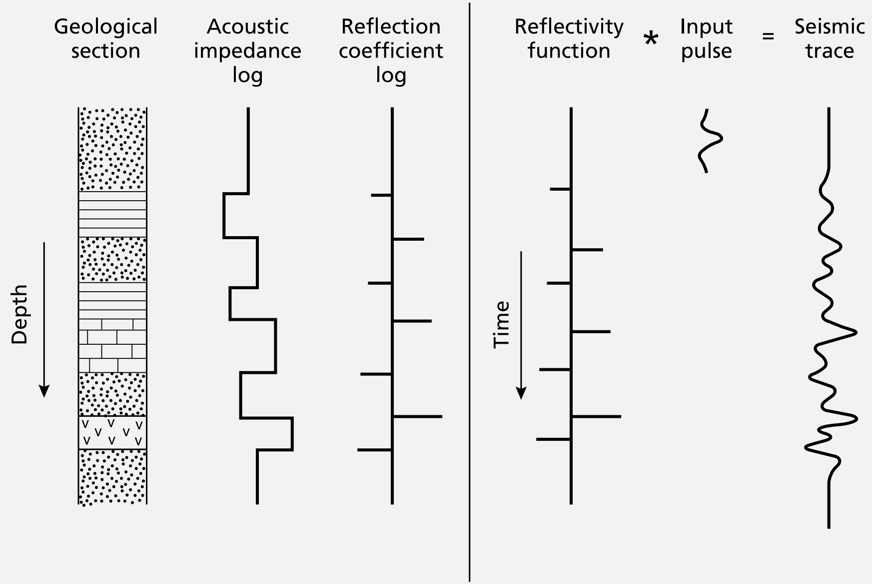
TWTT = two-way travel time

The ideal seismic reflection image

"A convolution of the vertical subsurface reflectivity with a band-limited spike"

$$y(z) = r_0(z) * w(z)$$

- The ultimate goal of seismic reflection imaging (acquisition and processing)
- Can be a useful model but… never obtainable!



Keary, Brooks and Hill (2002)

Amplitude correction

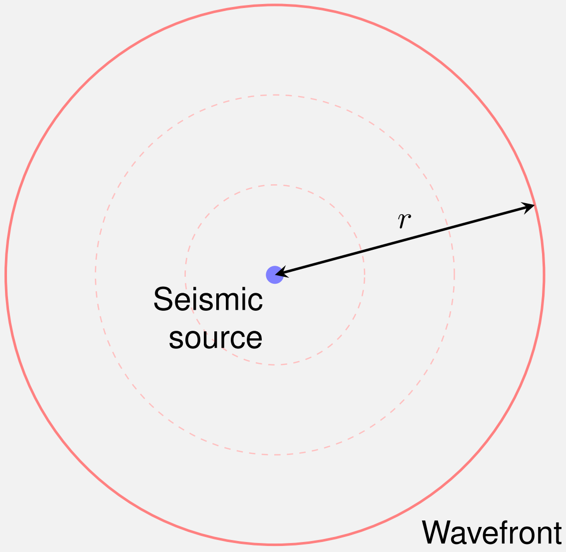
In a homogenous, isotropic medium the seismic wavefront expands as a sphere

$$S = 4\pi r^2$$

Seismic amplitudes decrease with increasing distance from the source:

$$A = \frac{A_0}{4\pi r^2} \propto \frac{1}{r^2}$$

In real geology, need to also account for velocity structure and preferential attenuation of high frequencies with depth (absorption)

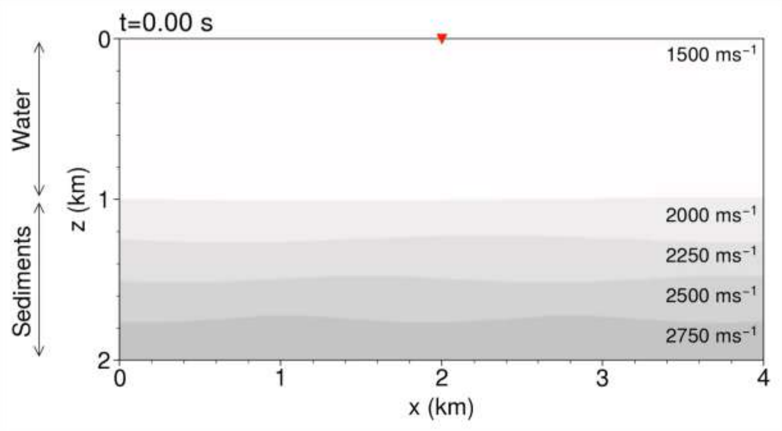


<u>Processing solution:</u> amplification (aka gain, scaling) with time. Ideally physics based (eg spherical divergence), but very often data-driven (eg "AGC" – dangerous!)

Seismic noise

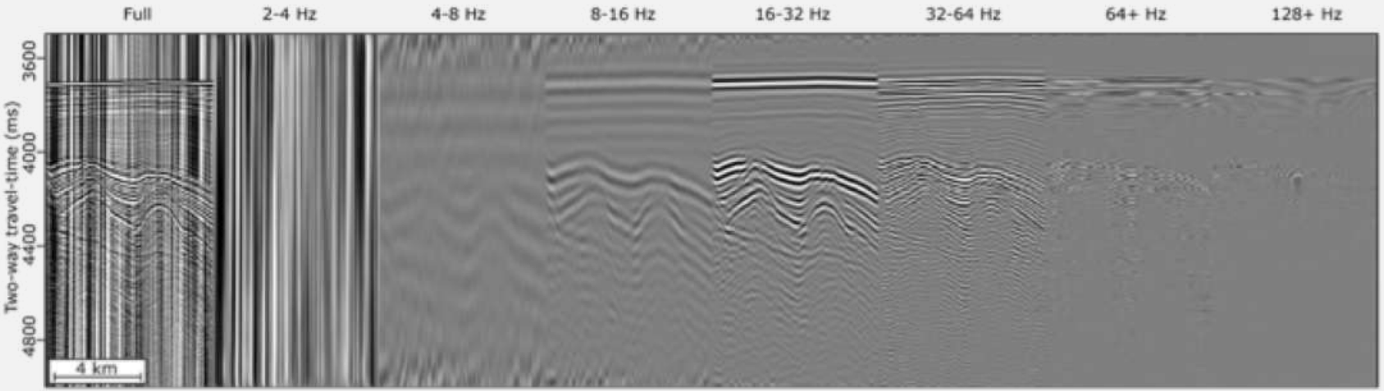
Noise = all energy that is not primary reflections

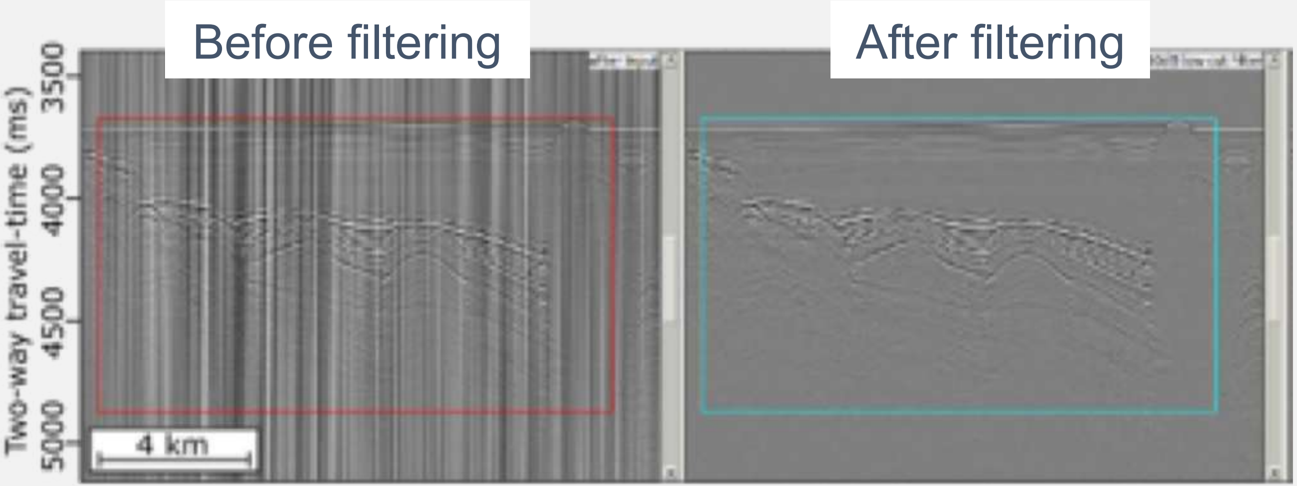
- Coherent noise (usually source generated)
  - Intra-bed multiples
  - Direct arrival/headwaves
  - Out-of-plane reflections
- Random noise
  - Swell noise
  - Propellor/boat noise
- Long period multiples
- Signal:noise decreases with increasing depth → controls seismic penetration
- Processing aims to reduce noise, but it can also introduce new noise (aliasing, ringing etc)



<u>Single-channel processing solution:</u> frequency filtering

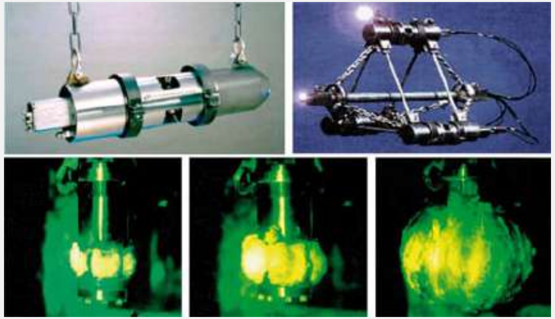
Swell noise example (Balearic Abyssal Plain)





Blondel et al.,
in review

Designature and zero-phasing

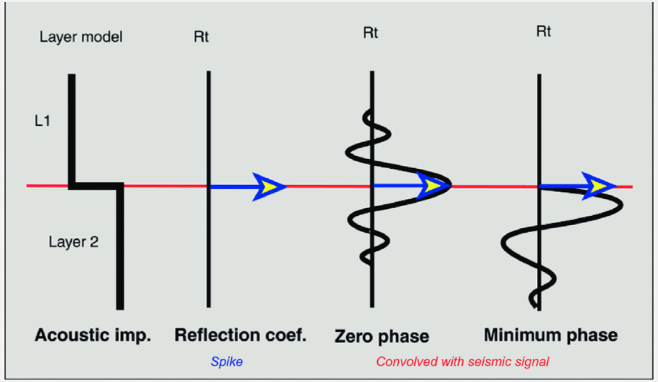


Effective source wavelet is mixed phase:

+ airgun pulse is ~minimum phase

+ time-delayed, negative polarity “ghost” from sea surface

+ bubble pulse

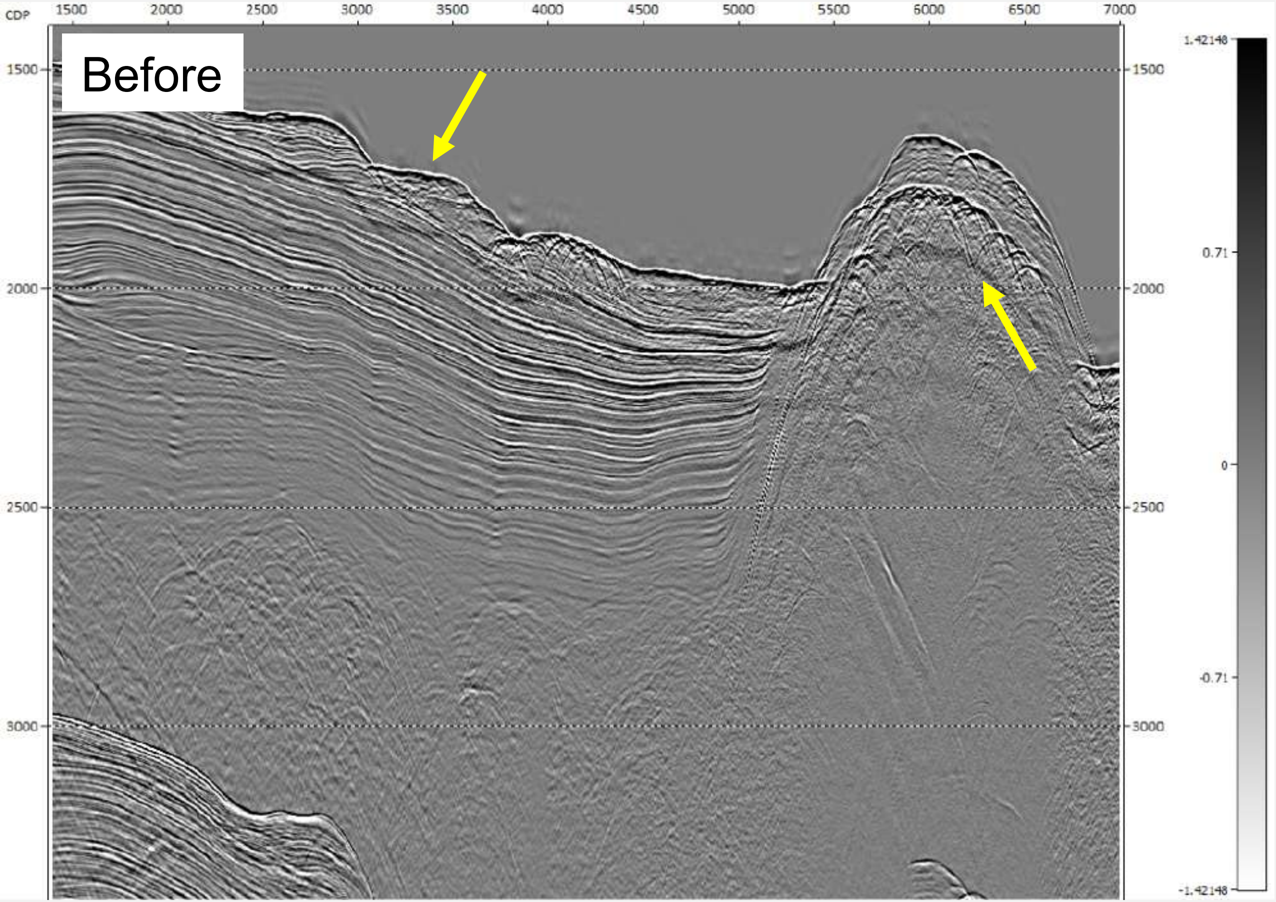


We want a sharp peak (band-limited spike) centred on the interface

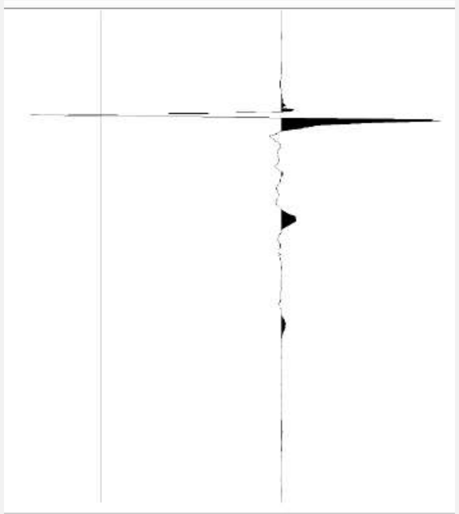
- Improves vertical resolution
- Peak/trough = impedance contrast

Processing solution: designature, deghosting and zero-phasing - estimate the source wavelet, design a filter to transform to a zero-phase wavelet

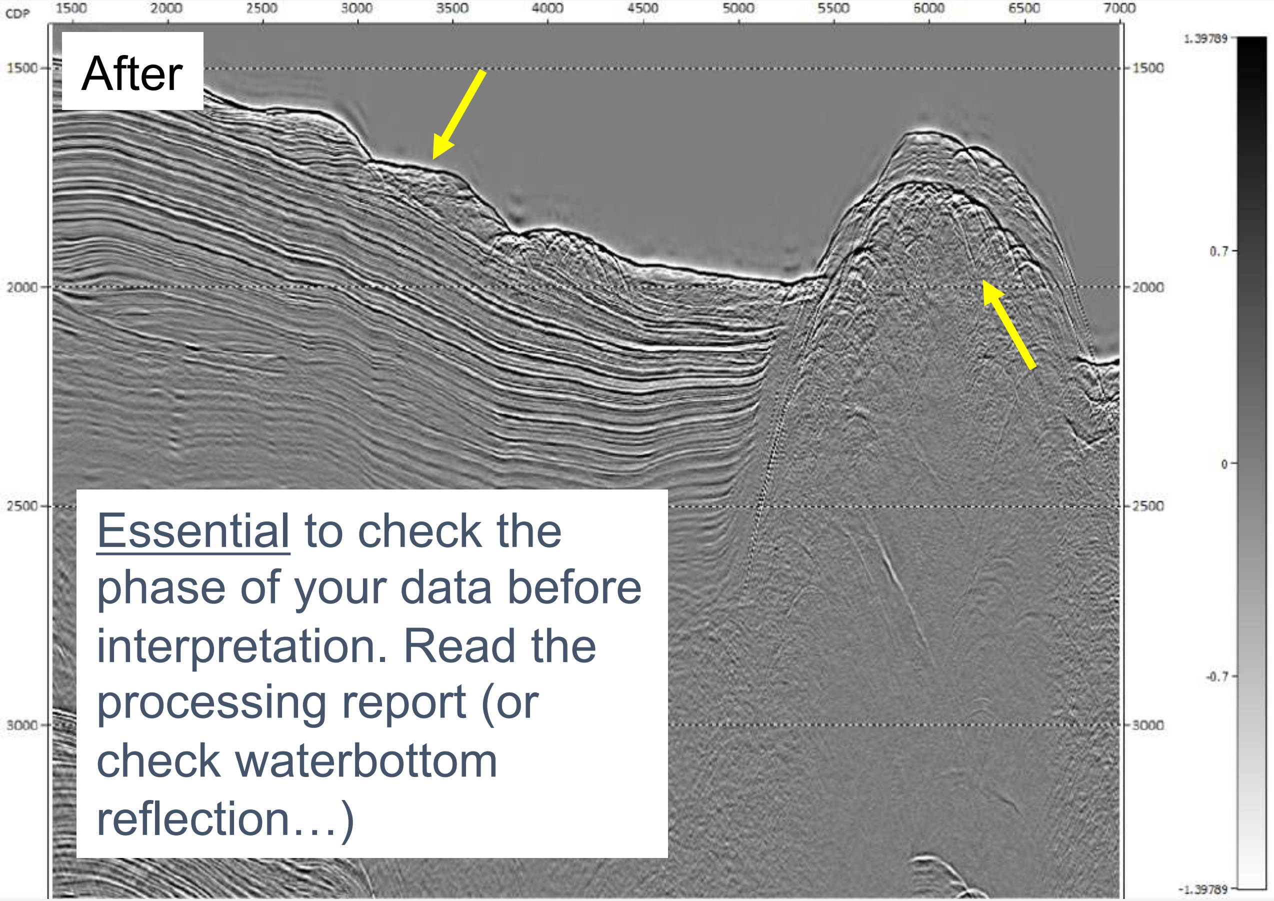
Deghost, debubble, zero-phase example (Gulf of Cadiz)



Estimated source wavelet

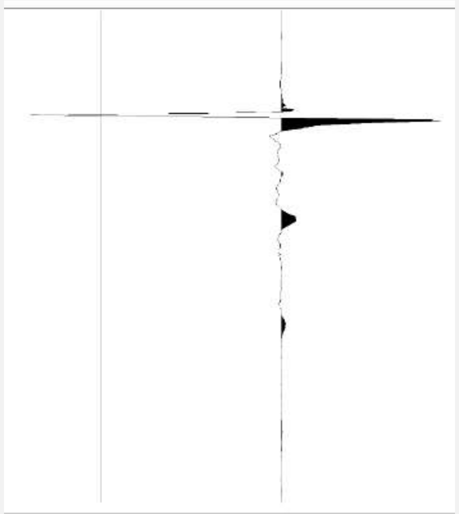


Deghost, debubble, zero-phase example (Gulf of Cadiz)



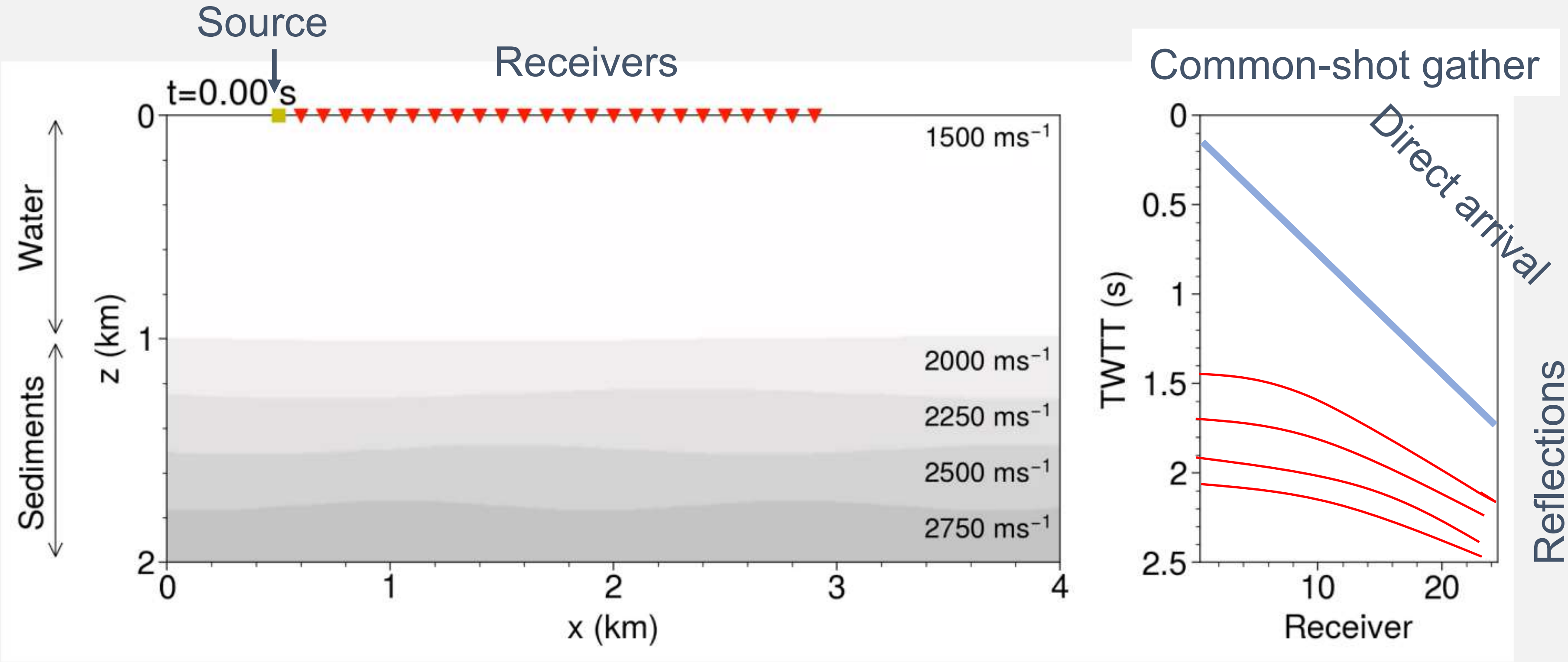
Essential to check the phase of your data before interpretation. Read the processing report (or check waterbottom reflection…)

Estimated source wavelet



Multi-channel processing

Gather = collection of seismic traces



Hyperbolic moveout of reflections with offset

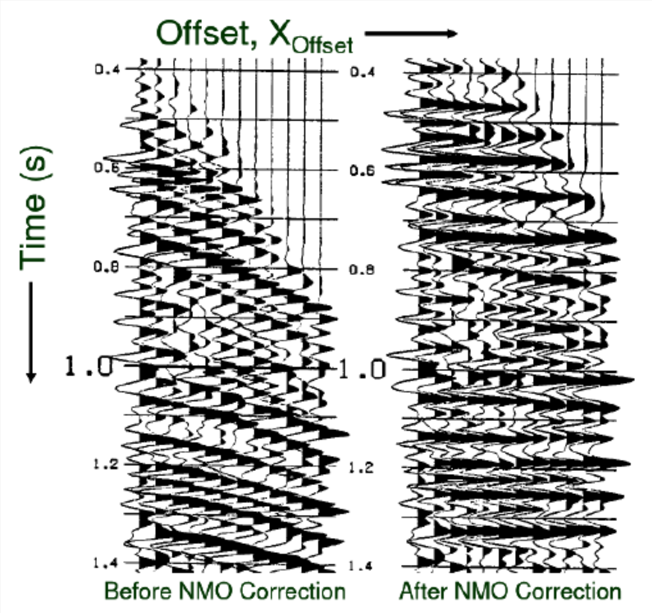
Time-shifting (moveout correction)

- Travel-time equation

$$t^2 = t_0^2 + \frac{x^2}{v^2}$$

- Implies hyperbolic moveout of reflections with offset (far offsets are shifted to later TWTT)
- Strictly valid only for the constant velocity case
- NMO equation:

$$\Delta t = t_x - t_0 \approx \frac{x^2}{2v_{nmo}^2 t_0}$$

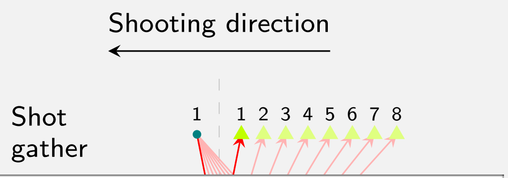


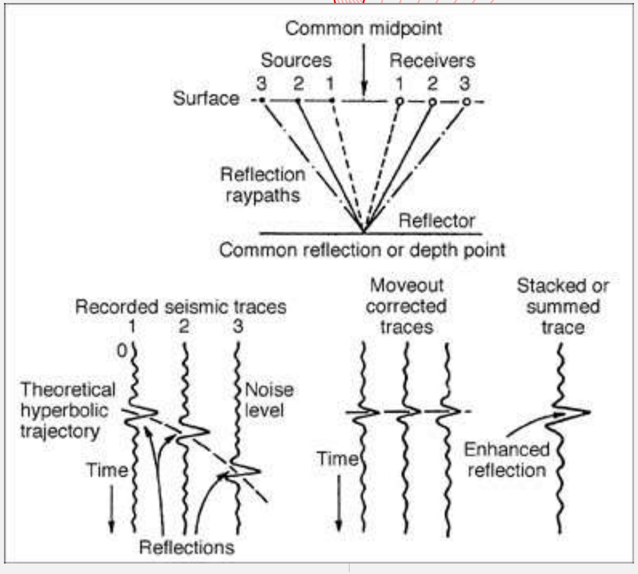
<u>Processing solution:</u> velocity analysis and normal-moveout correction

Common-midpoint stacking

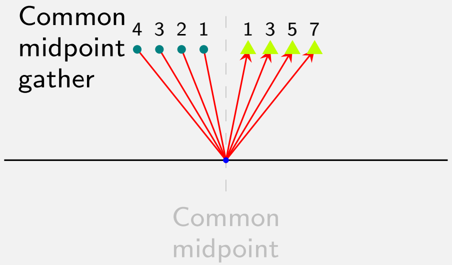
- Multi-channel data: acquire data <u>regularly</u> in a way that gives us data redundancy
- CMP gather: more than one trace where the reflection point (midpoint) is in the same location
- Stacking = summing traces laterally
  - Correlated signals constructively interfere ("stacks in")
  - Uncorrelated information is cancelled out ("stacks out")

<u>Note:</u> multi-channel seismic profiles are often referred to as "stacks"





https://glossary.slb.com

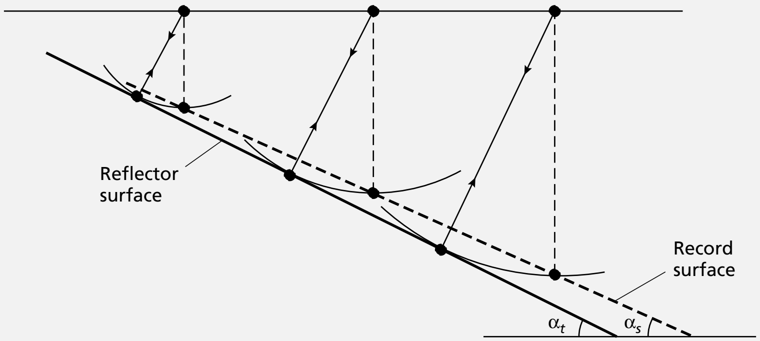


Migration

Why? Reflection points from dipping interfaces are not at the midpoint – dipping interfaces appear less steep than in reality

Goals of migration:

- Correct geometry
- Improve the lateral resolution (collapse the Fresnel zone)
- Collapse diffracted energy

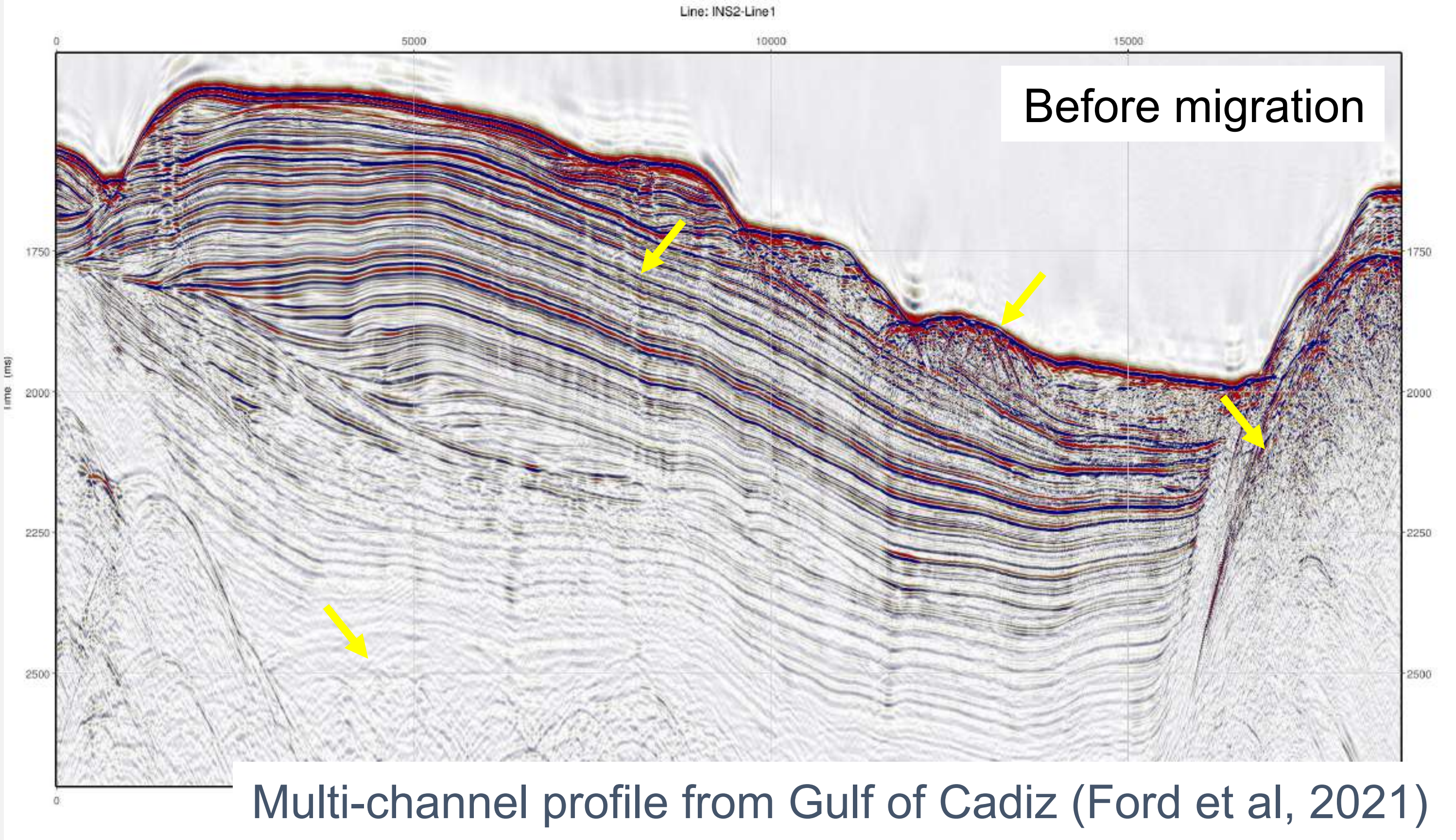


Side effect: improved signal:noise, improved reflector continuity

Migration is a huge topic (“seismic imaging”), many many migration approaches exist

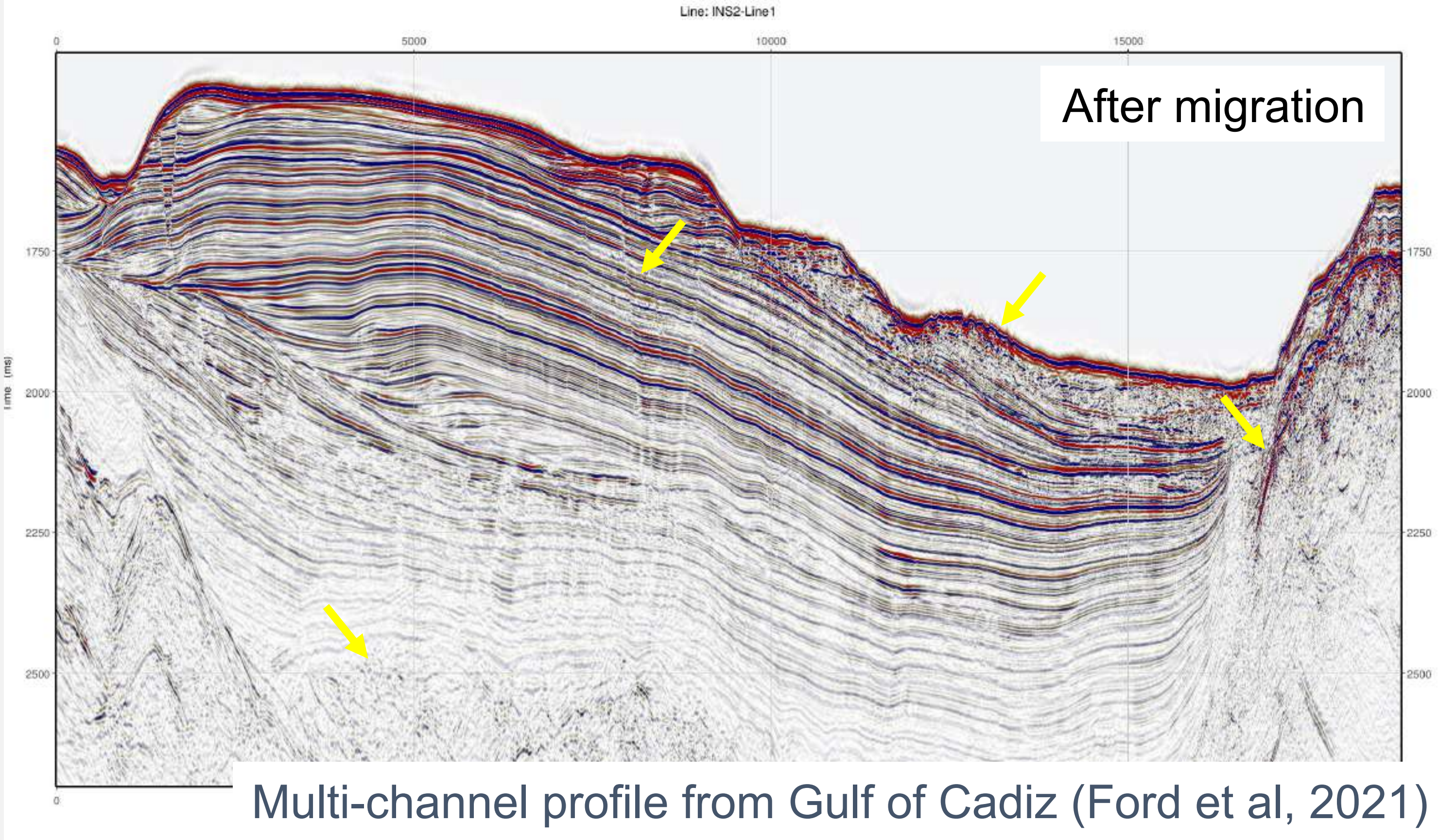
Note: single-channel data rarely migrated

Example of post-stack Kirchhoff migration



Multi-channel profile from Gulf of Cadiz (Ford et al, 2021)

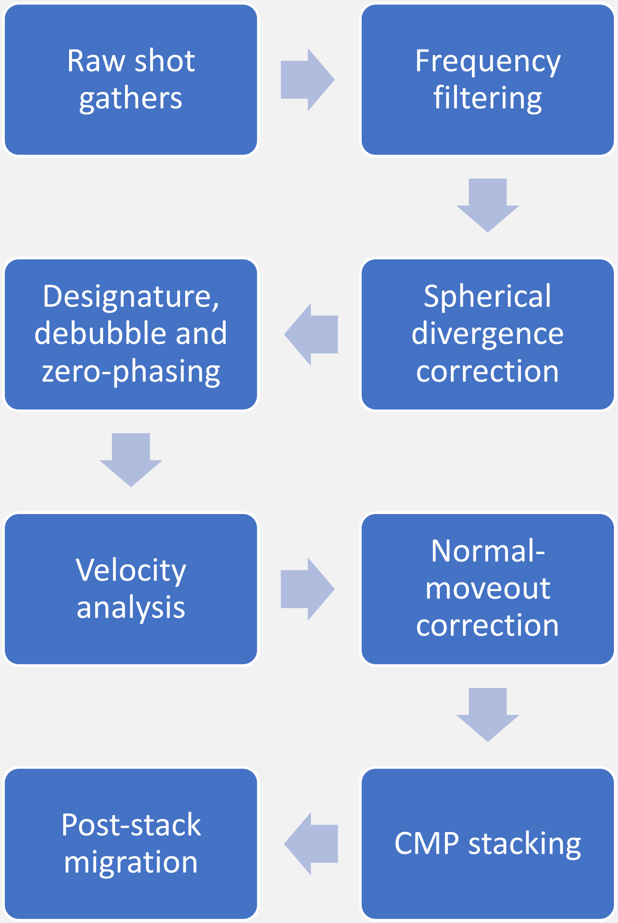
Example of post-stack Kirchhoff migration



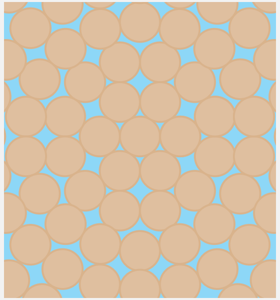
Multi-channel profile from Gulf of Cadiz (Ford et al, 2021)

A simple multi-channel processing flow

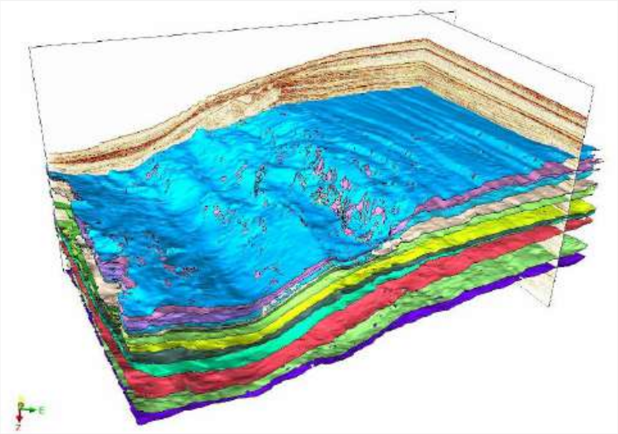
- Huge variety of pre-processing and imaging workflows exist
- Often strongly constrained by
  - acquisition geometry
  - water depth
  - subsurface velocities
  - available compute
- Modern imaging (eg LS-RTM, FWI): directly invert for the subsurface reflectivity by modelling the field data



Why is marine seismic reflection data useful?



- Marine environment = fully saturated porous rocks = great reflection generators
- Ideal seismic image gives us convolution of the subsurface reflectivity with a band-limited spike
- Applications:
  - Geometry → structural geology
  - Seismic horizons → geological timelines → stratigraphy
  - Spatial correlation between and away from boreholes



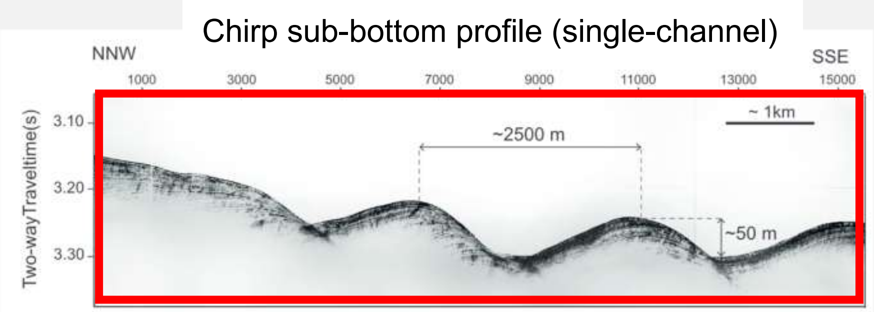
https://www.geoexpro.com/articles/2015/05/guinea-bissau-improved-imaging-and-new-insights

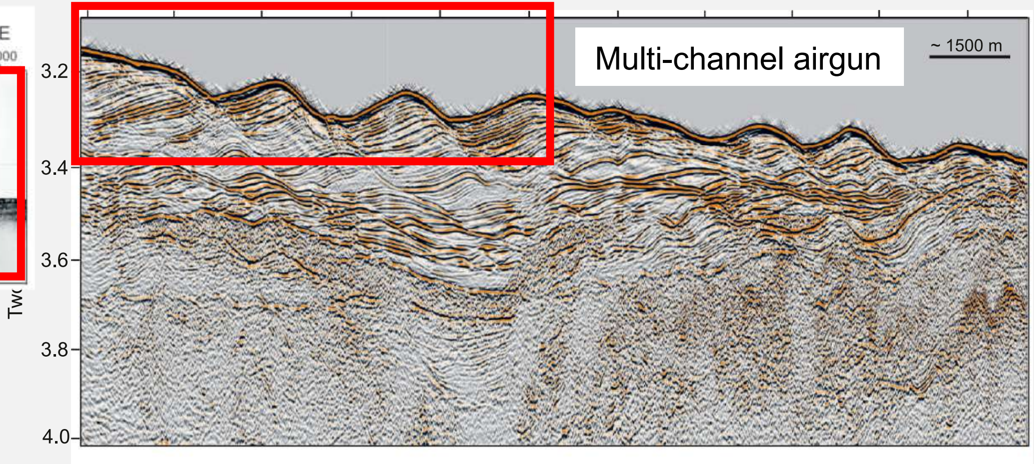
Before interpreting a seismic profile

- Single-channel or multi-channel?
- Seismic bandwidth → controls the maximum resolution (vertical and lateral)
- Phase and polarity of the data
  - What designature has been applied?
  - Careful: often single-channel data is in envelope display
- Amplitude compensation applied?
  - Geometrical spreading
  - Attenuation compensation
- y-axis: time or depth? How was the data migrated? With what subsurface velocity model? 2-D or 3-D migration?

Take aways

- Seismic reflections tell us about changes in geology
- Use different source bandwidths to study geology at different scales
  - Single-channel sub-bottom profiler (~1-10kHz)
  - Multi-channel airgun data (~10-100 Hz)
- Understanding acquisition and processing are extremely important for correct interpretation – read the processing report!





Malta Escarpment, Mediterranean Sea
(Rebesco et al, 2021)