Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Curriculum: Esplorazione Geologica

Anno accademico 2024 - 2025

Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: **Michele Rebesco**

Methods for the analysis of sedimentary basins

Part 1

Geophysical methods: indirect analysis of deposits in the subsoil (+ or less ancient, on land and at sea) = today's lesson by Riccardo Geletti

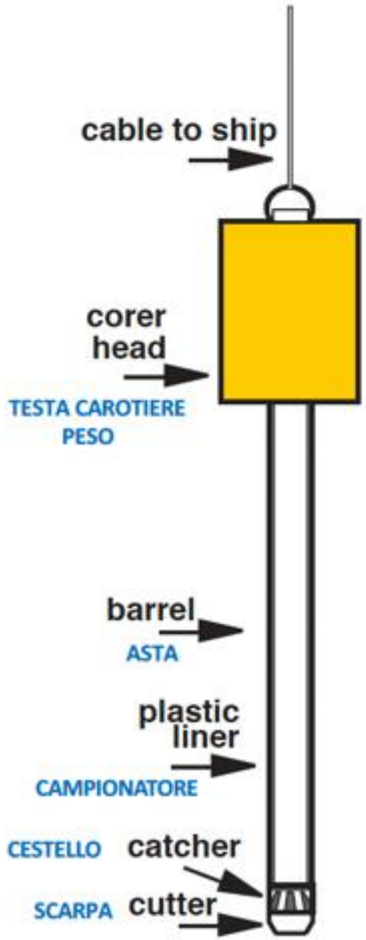
Geological methods at sea: coring (superficial deposits) and drilling (deeper / ancient / lithified deposits) = Course of Marine Geology

Geological methods on land: analysis of rocky outcrops, geological cartography, measurement of stratigraphic sections… (exhumed rock deposits).

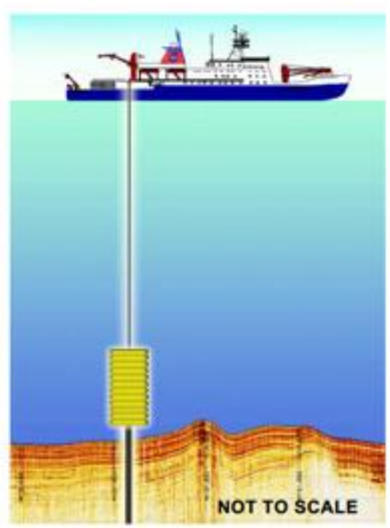
Geological / naturalistic methods: analysis of recent deposits: historical cartography, trenches, ...

Coring of marine sediment

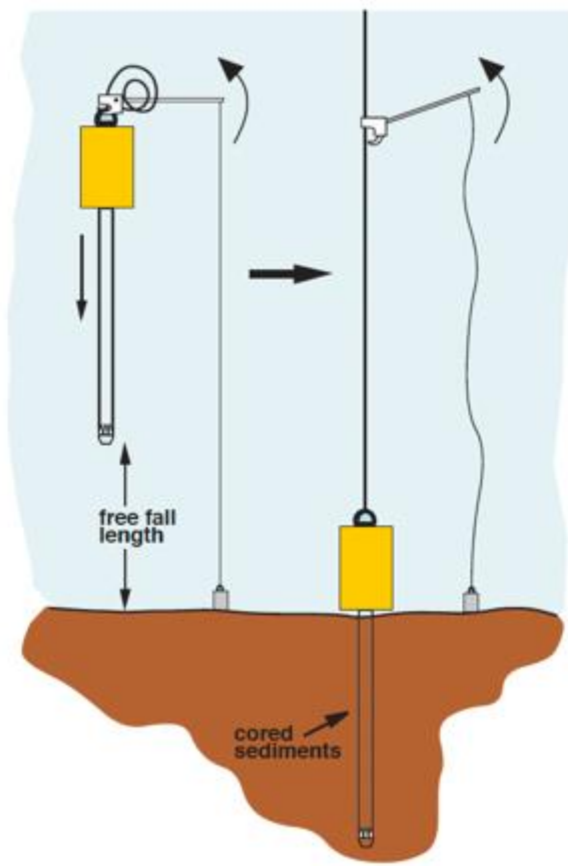
Sediment coring system



A sediment coring system is composed by a weight (corer head) that is used to force the barrel into the sea bottom. Inside the barrel there is a plastic liner that will hold the sampled sediments. At the base of the barrel the core catcher prevents the sampled sediments to flow out the barrel after sampling, and the cutter facilitate the detach of the sampling system from the ground.



This system can work with or without a triggering system

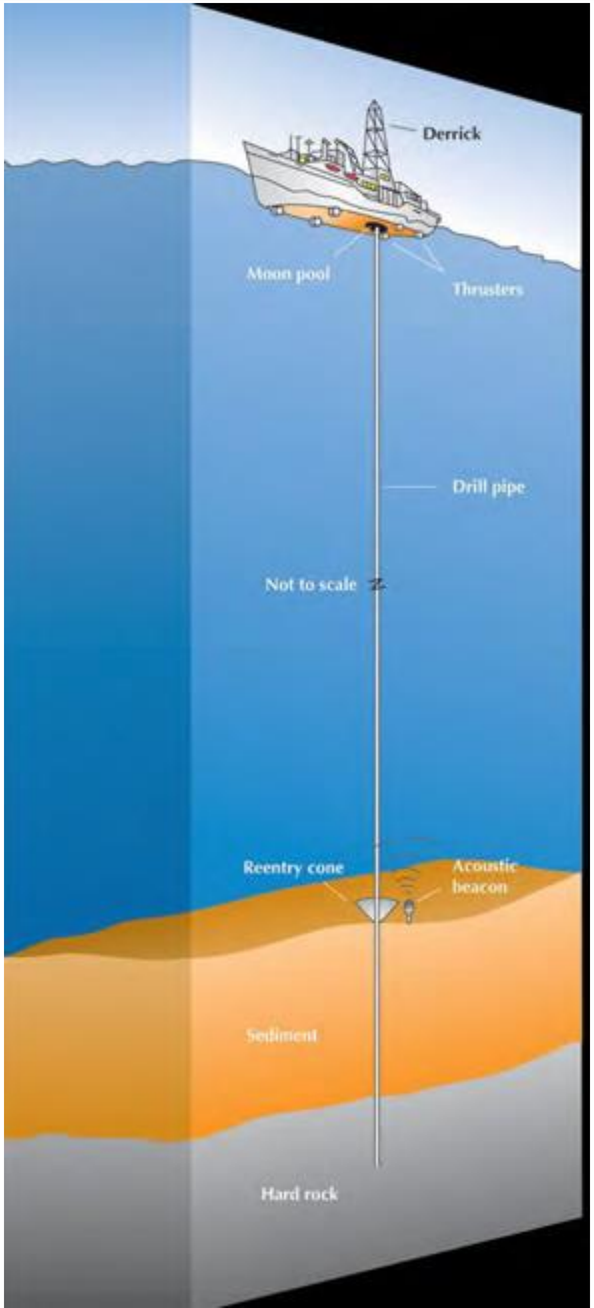


Courtesy: R.G. Lucchi

Drilling

IODP INTERNATIONAL OCEAN DISCOVERY PROGRAM

Joides Resolution



Outcrops

La Baronia

Large scale (outcrop)

10 m

Mid scale (bed)

50 cm

2,5 cm

Small scale (Sedimentary structure)

Martinius, 2011

DOI: 10.1007/978-94-007-0123-6_18

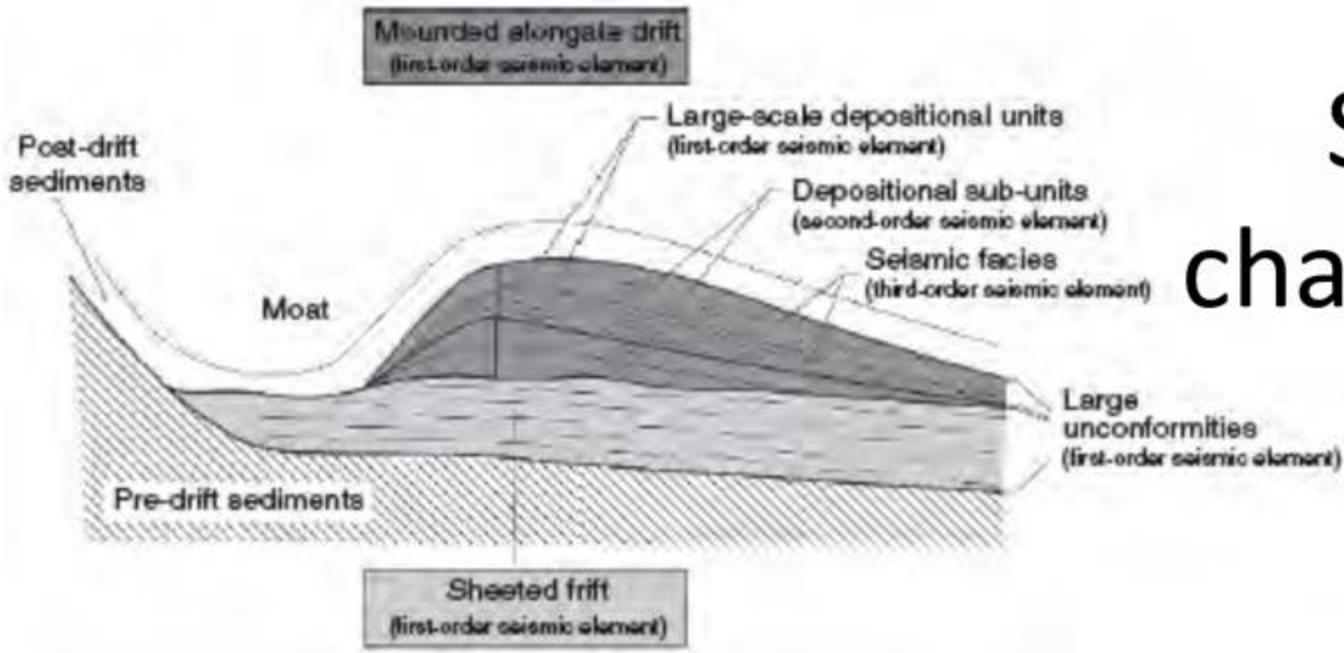
Three-scale approach

A three-scale approach should be attempted, wherever possible, for distinguishing the various facies types (especially the deep-water ones).
It includes:
large-scale (oceanographic and tectonic setting),
regional-scale (architecture and association)
and small-scale (sediment facies) observations.

Stow and Smillie, 2020 Geosciences, 10(2), 68;
https://doi.org/10.3390/geosciences10020068

Recognizing contourite deposits in ancient sedimentary series presently exposed on land, is a difficult task. The distinction between contourites and reworked turbidites is controversial.

Diagnostic criteria are their **facies and ichnofacies, texture and sequences, microfacies and composition**. **Sedimentary structures** are also "diagnostic indicators", but for their interpretation its full context should always be considered. **Medium-scale criteria** (hiatuses and condensed deposits, variation in the thickness, geometry, palaeowater depth, geological context) can be definitive. **Large-scale criteria** (palaeoceanographic features and continental margin reconstructions) are essential, but generally more problematic to apply on outcrops.



Seismics characteristics

triple-scale approach that involves 3 "orders of seismic elements".

Large scale (overall architecture): I-order elements (major changes in current strength and sediment supply): External geometry, Bounding reflectors, Gross internal character.

Medium scale (internal architecture): II-order seismic elements (reflecting smaller fluctuations): lens-shaped, upward-convex geometry; uniform stacking pattern; down-current migration or aggradation;downlapping reflector terminations

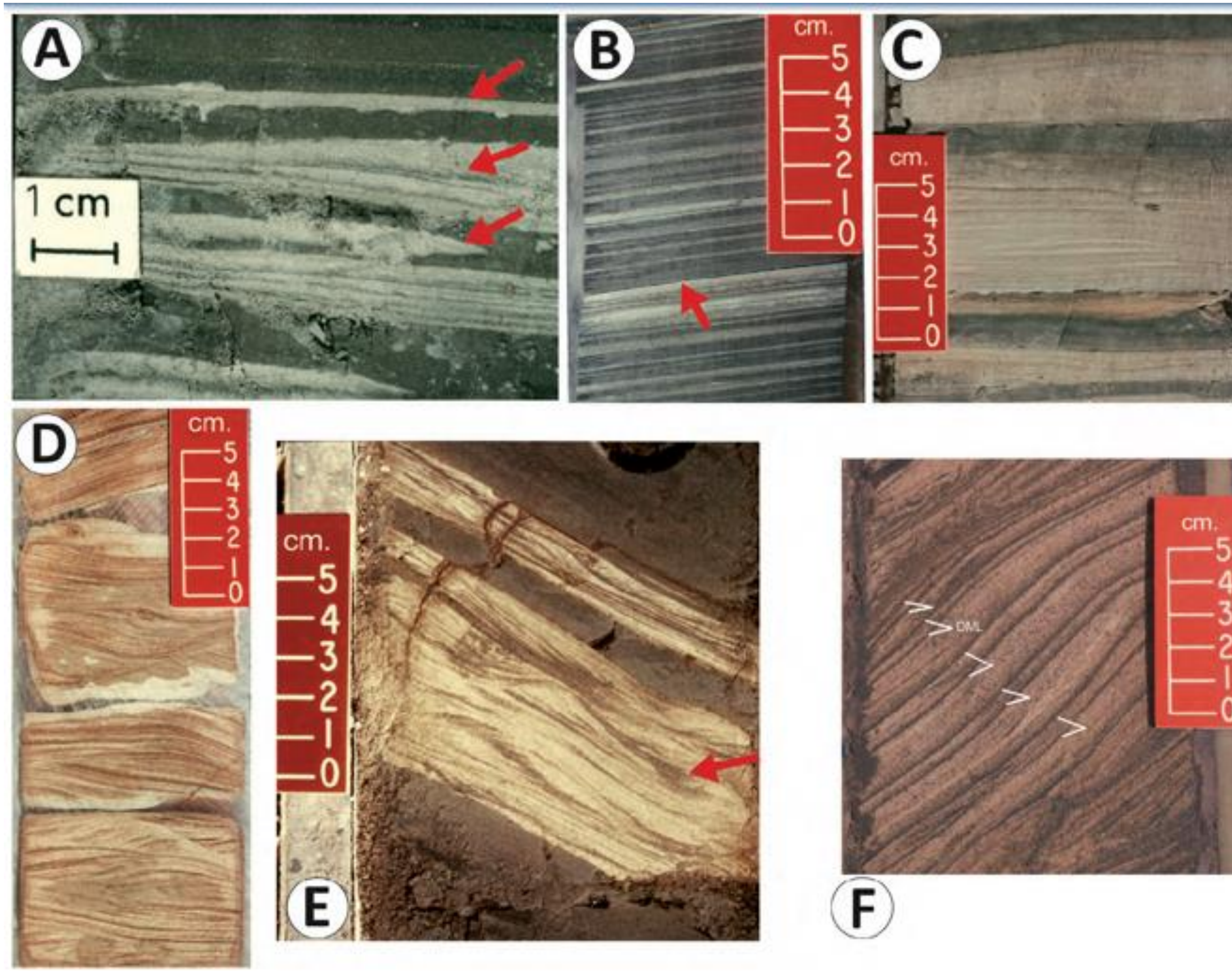
Small scale (internal acoustic character): III-order seismic elements: facies analysis (continuous, (sub)parallel, wavy, structureless), and attribute analysis (bedforms).

Knutz (2008) in: Rebesco &Camerlenghi (Eds.), Contourites, pp. 511-535.

Sedimentary structures in cores

From Rebesco M., Camerlenghi A., (Eds.) 2008. Contourites, Developments in Sedimentology, 60, Elsevier, 666 pp.

Originally in: Shanmugan, 2008; Shanmugam et al., 1993; Shanmugam, 2012



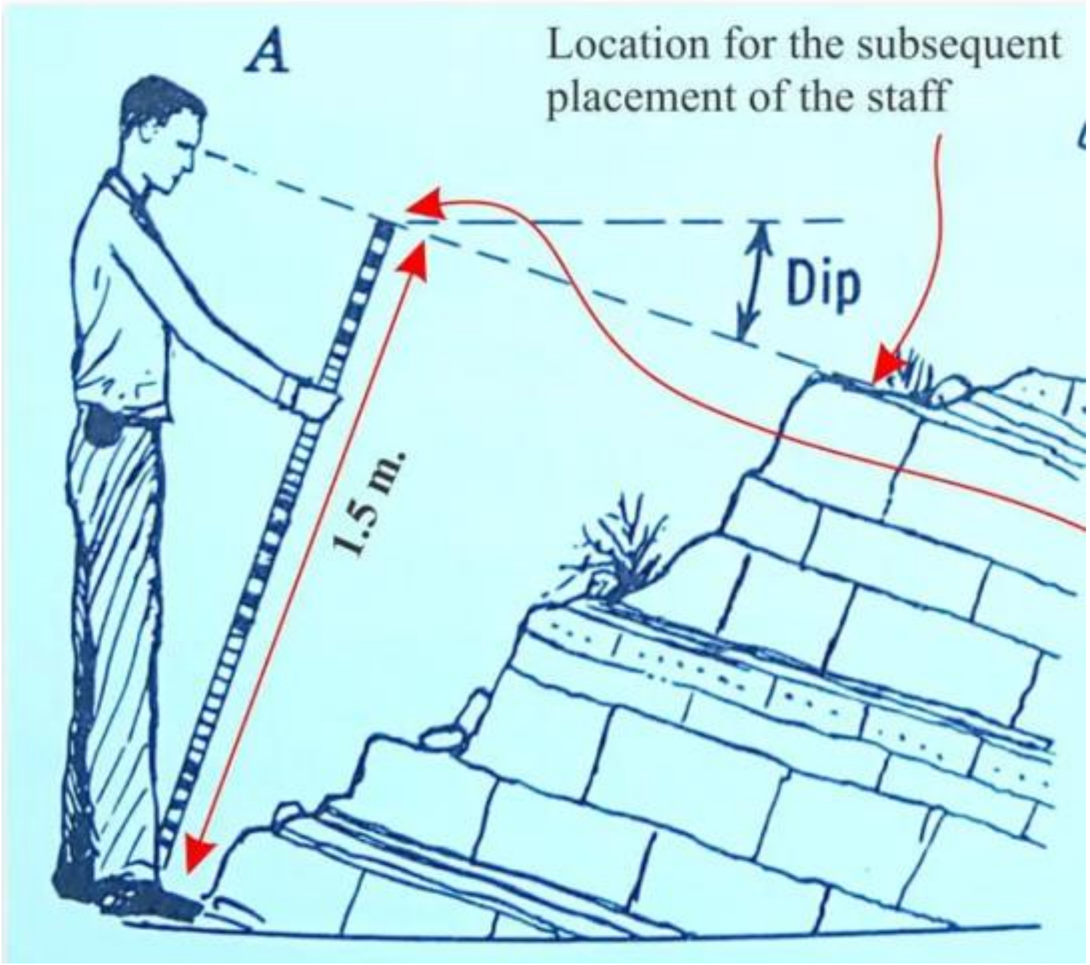
Sedimentary structures in outcrops

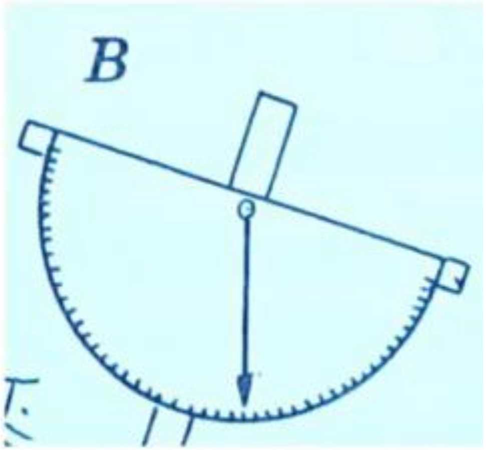
https://uhlibraries.pressbooks.pub/historicalgeologylab/chapter/chapter4-sedimentary-structures/

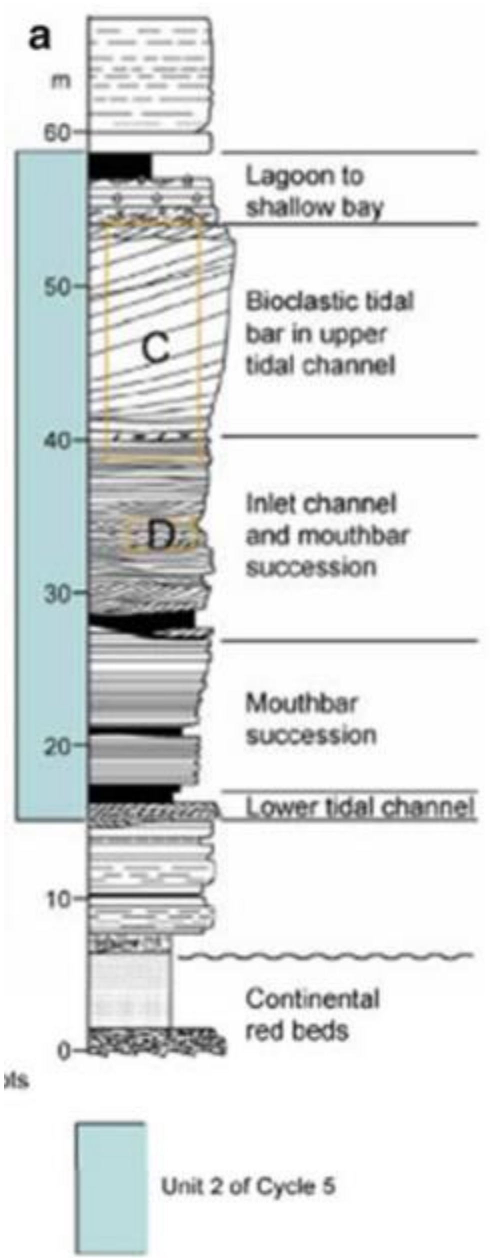
Flute casts from the central Alps, Switzerland. The view is from the underside of the rock. Image credit: Chris Spencer

Symmetrical ripples in Devonian-Missippian age sandstone from Ohio, USA. These are all views from the top. Image credits: James St. John,

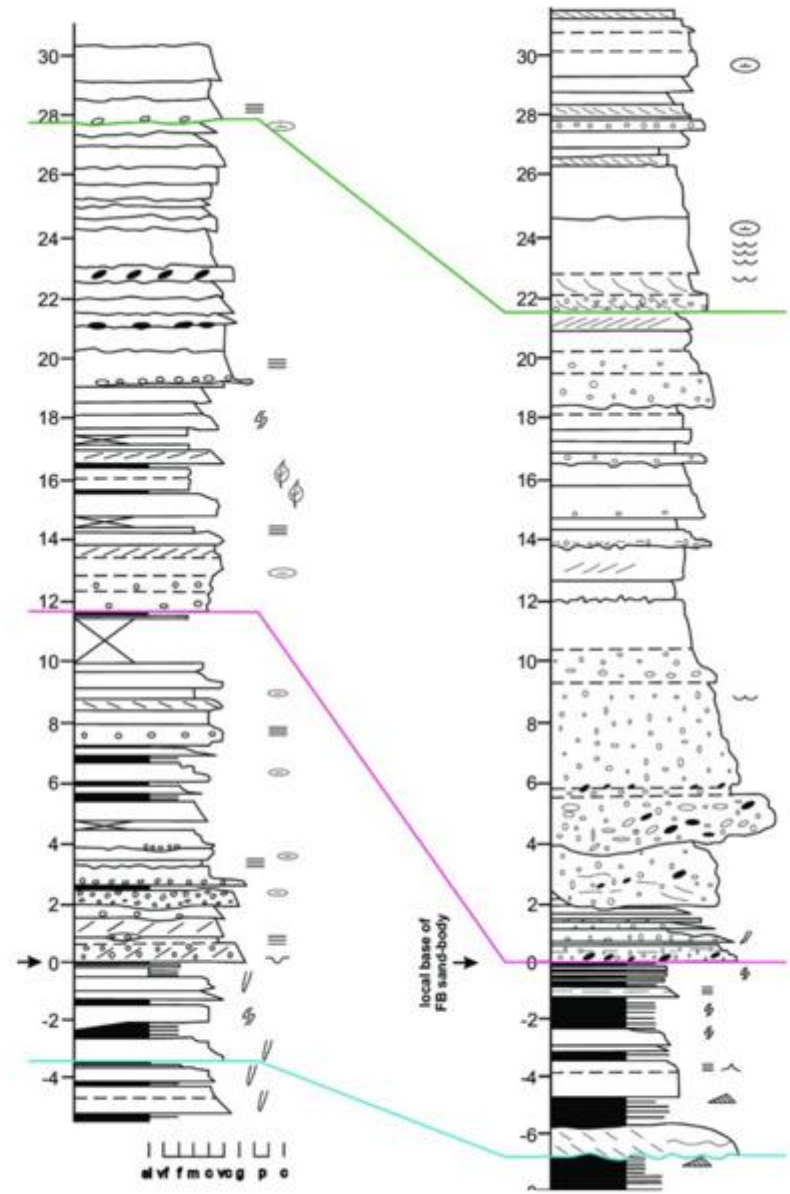
Jacob's staff





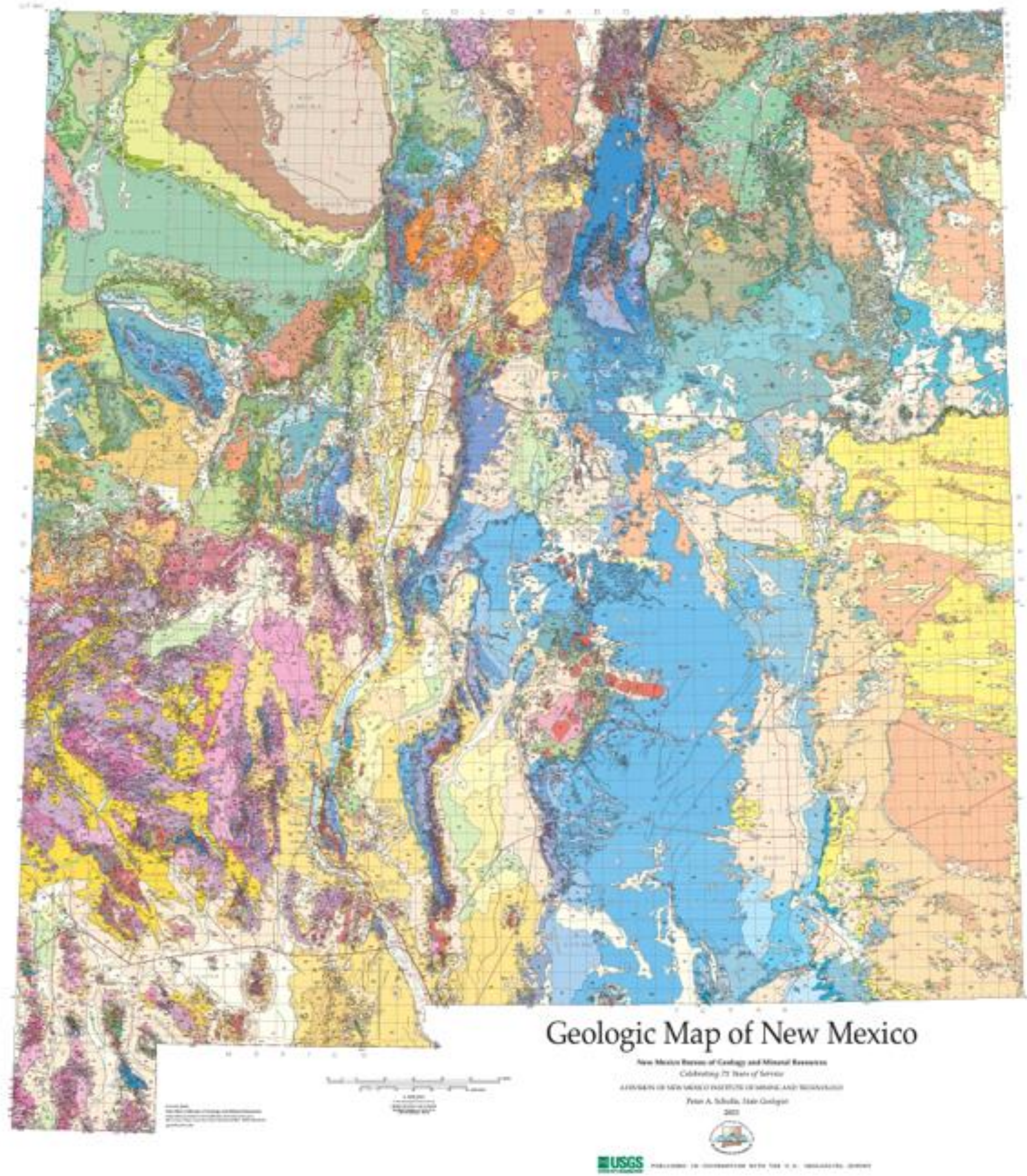


Sedimentary logs



How do you estimate grain size?

Geological mapping

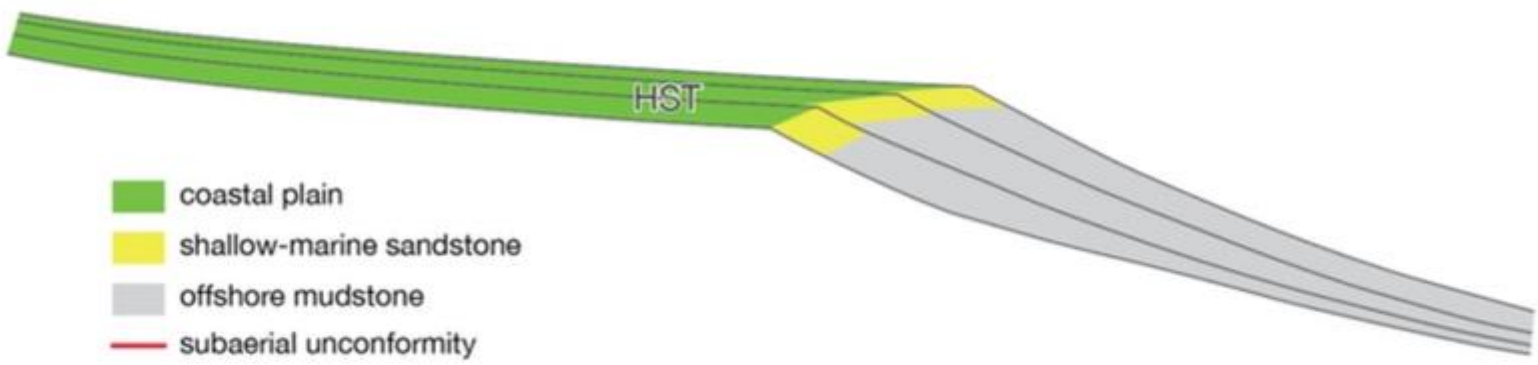


Lithology

The lithology of a rock unit is a description of its physical characteristics visible in outcrop, or with low magnification microscopy. Physical characteristics include color, texture, grain size and composition.

The lithology is the basis of the subdivision of the rock sequences into single lithostratigraphic units for the purposes of mapping and correlating the areas.

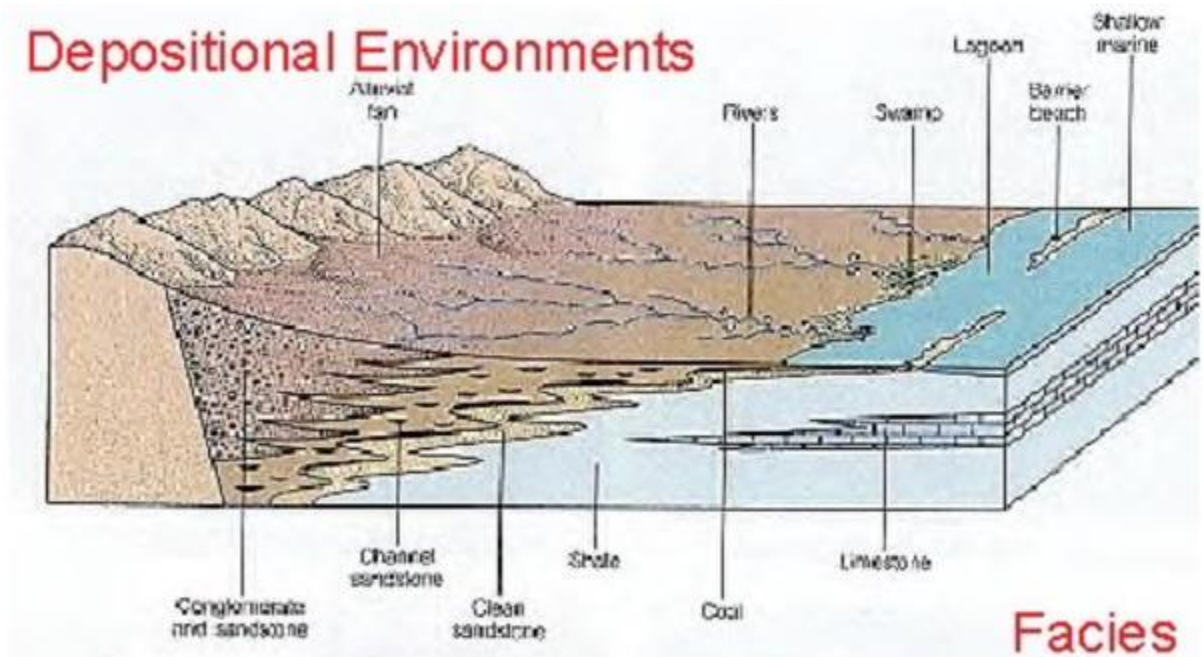
Chronostratigraphic sequences



Facies

The facies is the sum of the overall characteristics of a rock unit, which reflect its origin and differentiate the unit from others around it.

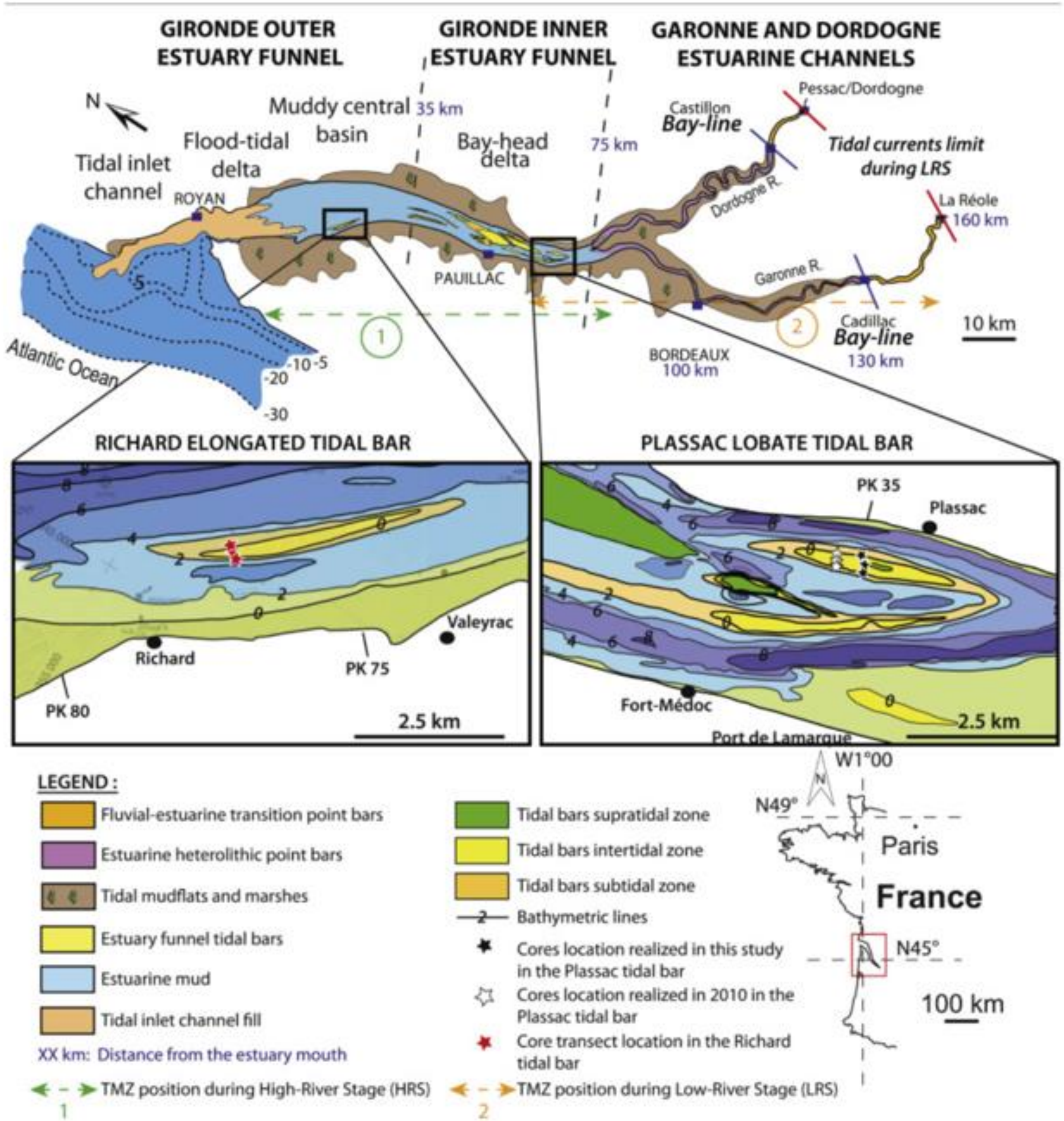
Within the facies, we can distinguish eg lithofacies (stratigraphic unit distinct from the adjacent ones based on lithology),
Biofacies,
Microfacies
Ichnofacies
Seismic facies
...



Modern analog

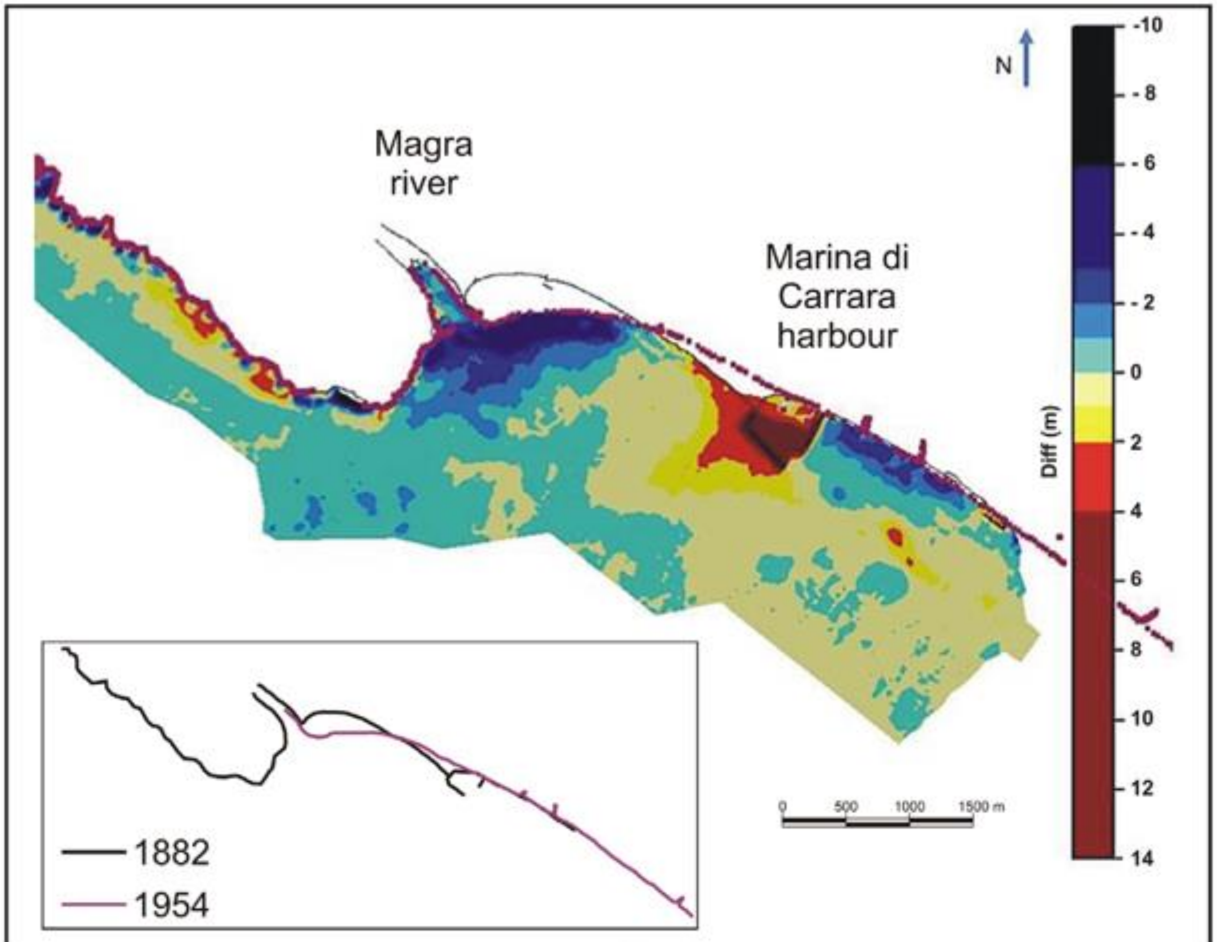
Gironde estuary tidal bars: A modern analogue for deeply buried estuarine sandstone reservoirs

Virolle et al., 2020. Marine Petroleum Geology



Historical data

River-mouth geomorphological changes over > 130 years,
Pratellesi et al., 2018. Marine Geology



Difference surface between the 1882 and 1954 bathymetry; erosion areas are represented in blue and accretion ones in red (values are expressed in meters). Black and purple lines in the inset delineate, respectively, the 1882 and 1954 msl contour lines.

Trenches

stratigraphic soil layers, Vjosa Valley, Albania

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Unit 1.2: Methods

Docente: **Riccardo Geletti**

Outline

- **Introduction**
  - **The seismic section**
  - **Seismic interpretation software**
  - **Seismic data web sites**
  - **Seismic trace display**
- **Raw data e final seismic section: elements of multichannel seismic processing**
- **Resolution: vertical and lateral**
  - **Deconvolution**
  - **Migration**
- **Velocity analysis and Depth migration**
- **Vertical Seismic Profiling (VSP) in seismic interpretation**
- **Coherent Noise in the seismic data: multiple reflections**
- **Some case studies**
- **Conclusion**
- **Questions**
- **Bibliography**

- INTRODUCTION

The Seismic method is the powerful geophysical techniques for imaging the Earth's interior.

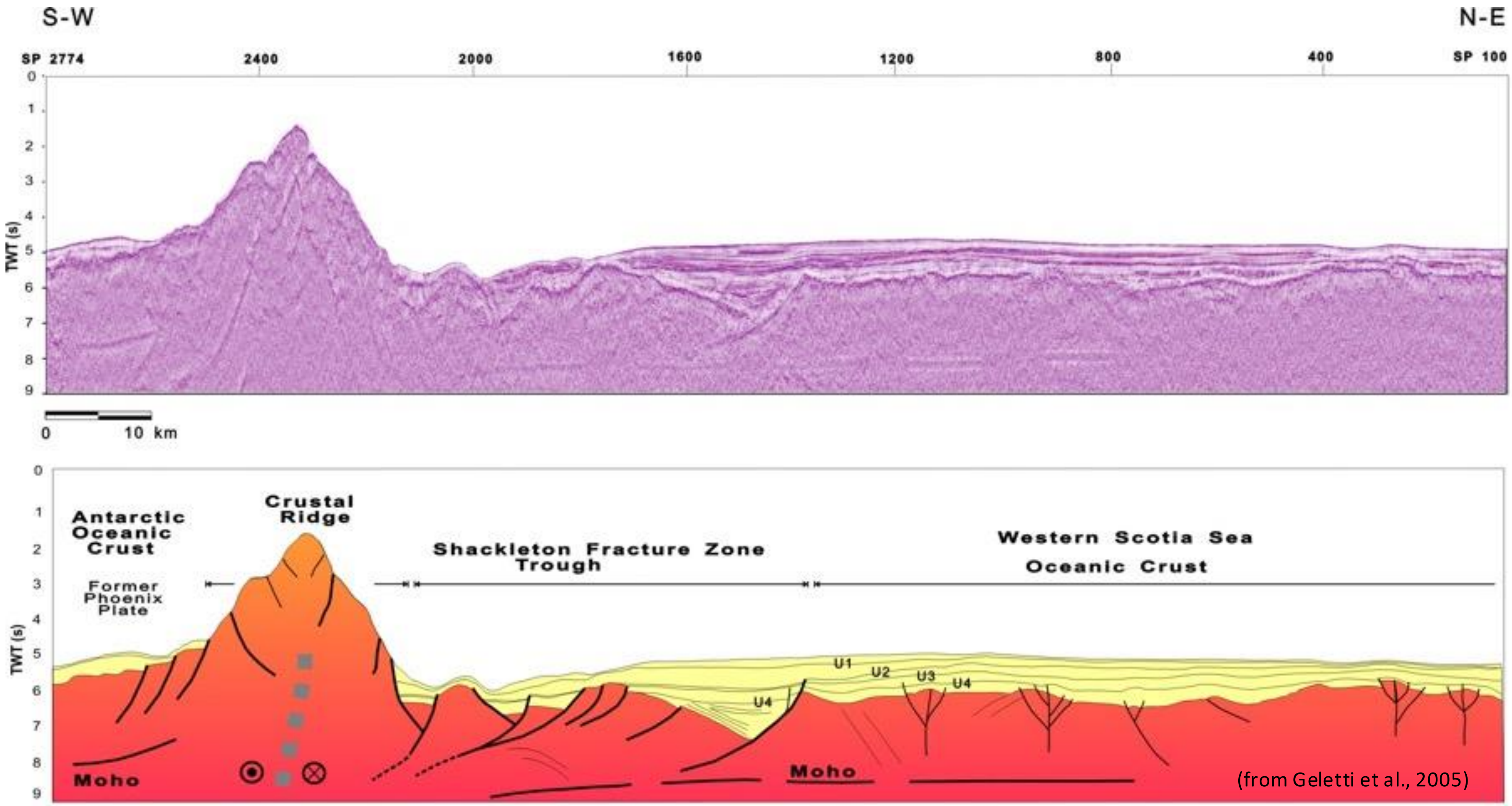
This artificial source method involve the generation of seismic waves whose propagation velocities and transmission paths through the subsurface are mapped to provide information on the distribution of geological boundaries at depth.

An alternative method of investigation subsurface geology is, of course, by drilling boreholes, but these are expensive and provide information only at discrete locations. Nevertheless, seismic surveying does not dispense with the need for drilling because it can give a geological meaning to the seismic reflectors.

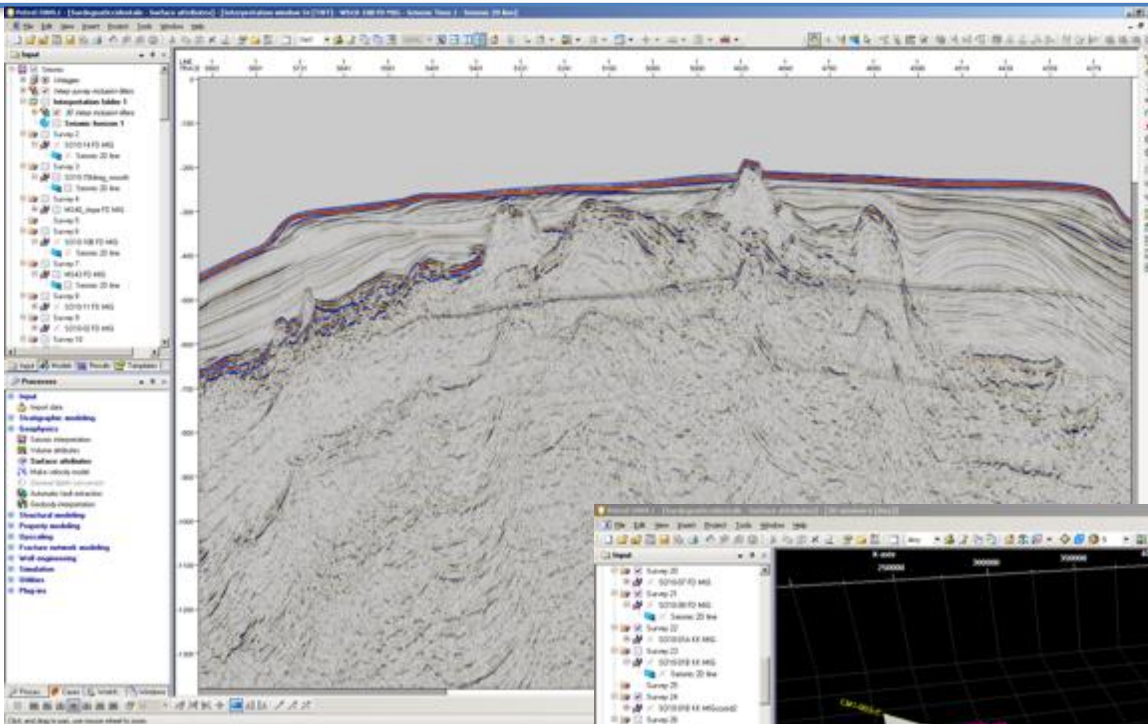
Seismic Reflection Interpretation

- Fundamental in applied research to geosciences
- Provides information regarding:
    - geometries of stratigraphic sequences
    - geometries of structural and tectonic elements
    - velocity of seismic waves
    - lithological characteristics

The seismic interpretation attributes geological meaning to geophysical data and produces reconstructions of:
2D sections, structural maps, fault systems, slumping and geo-hazard etc.

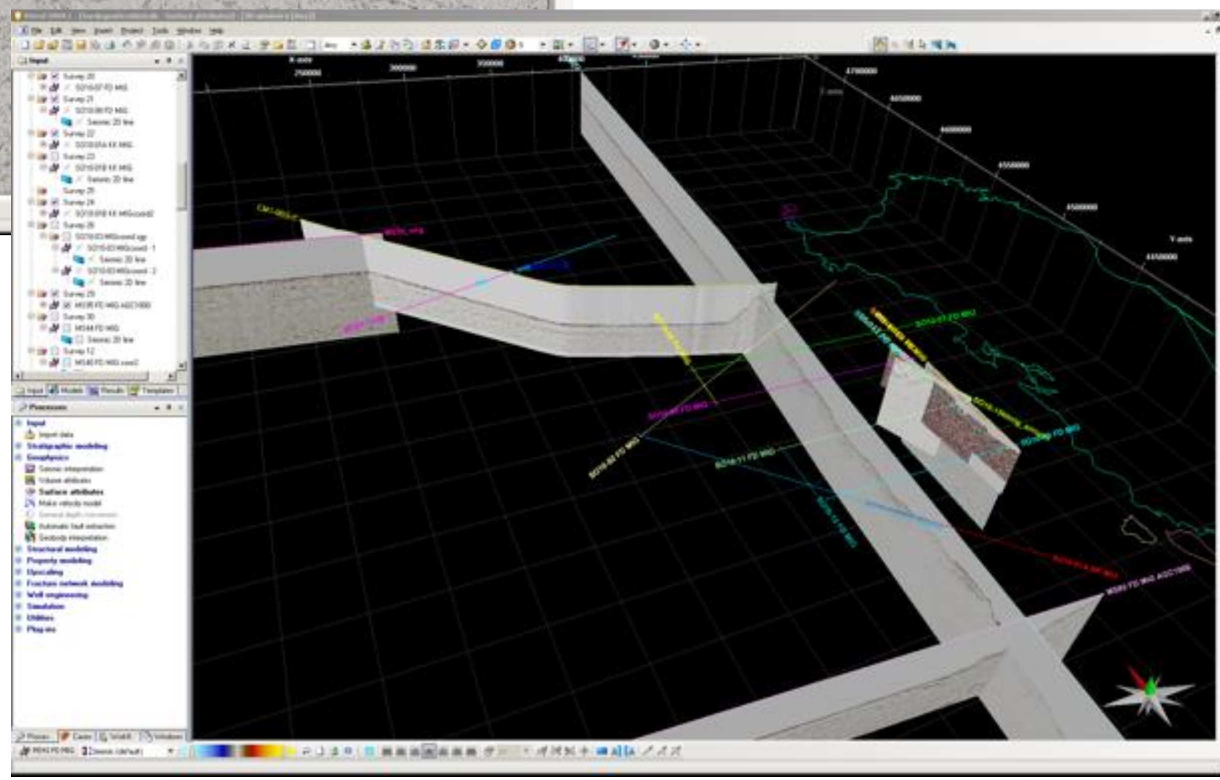


Crustal seismic section: example of seismic interpretation



Interpretation software

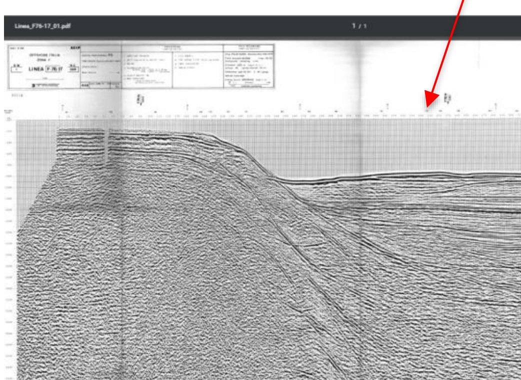
Seismic section



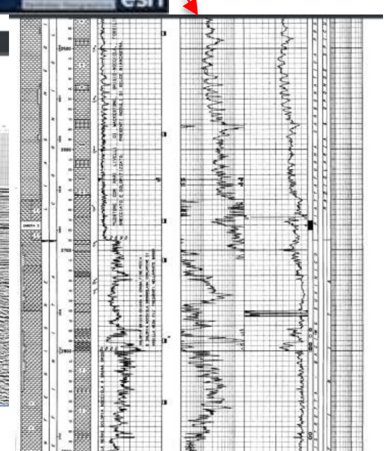
Position map of 2D seismic survey by an interpretation software

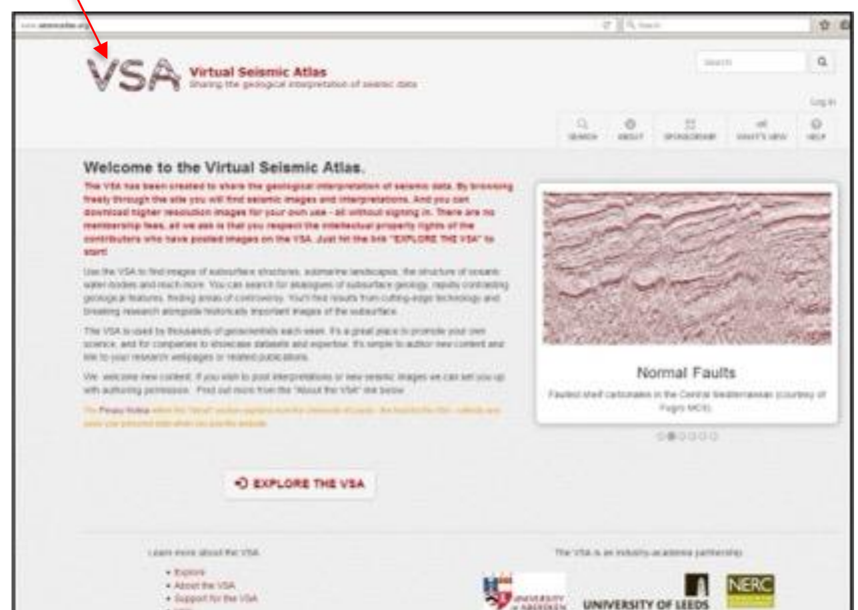
Seismic data websites:

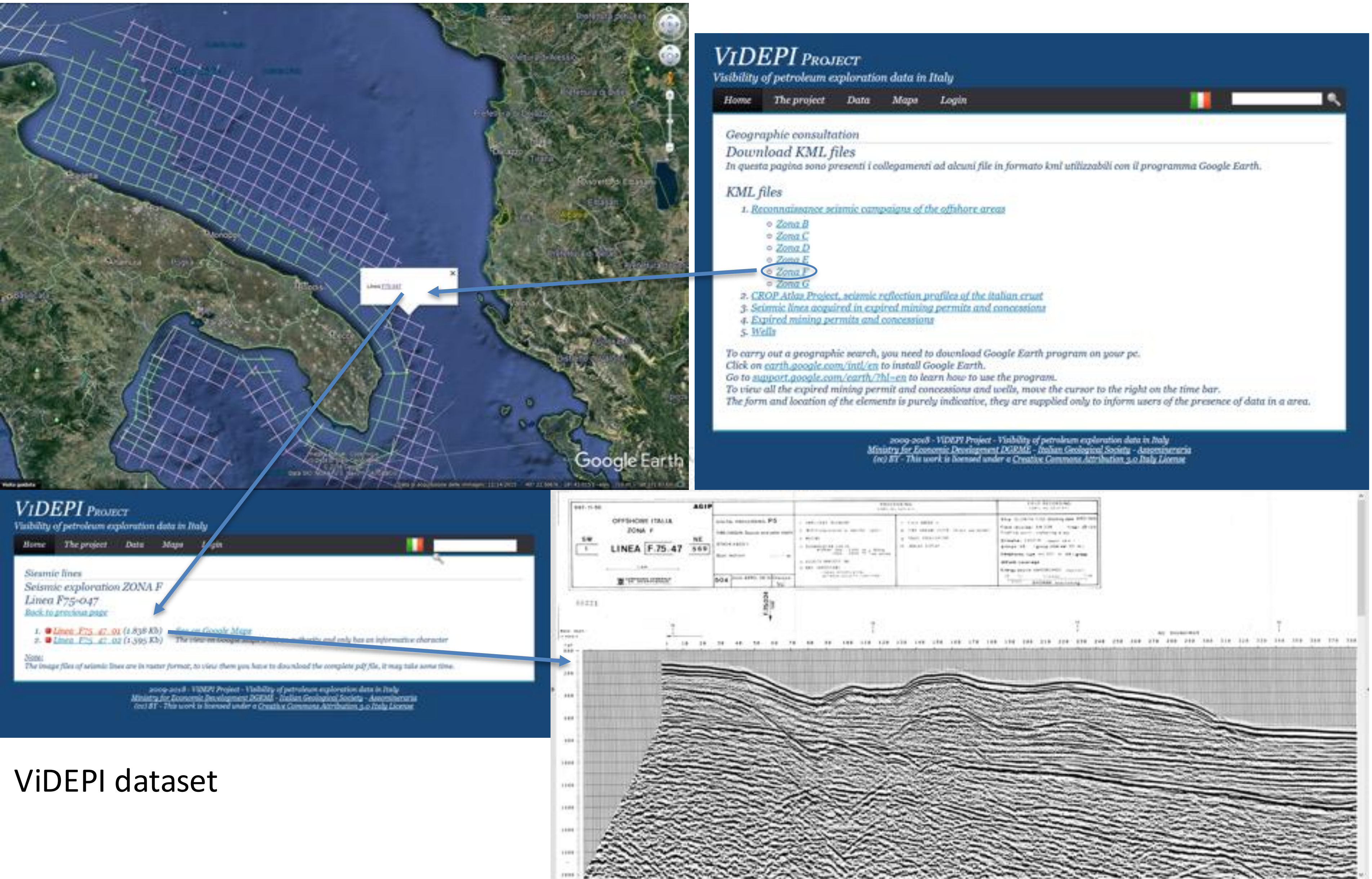
- http://unmig.sviluppoeconomico.gov.it/videpi/
- http://see-atlas.leeds.ac.uk:8080/home.jsp



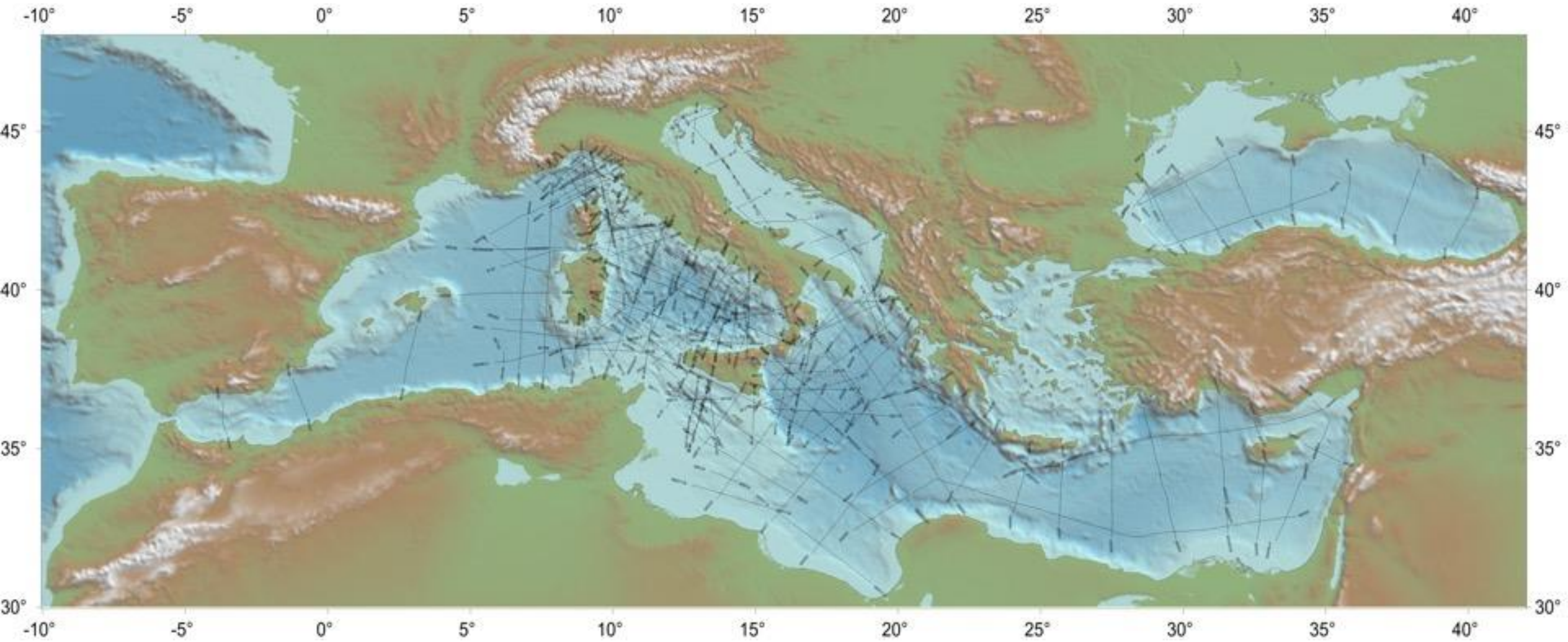
well



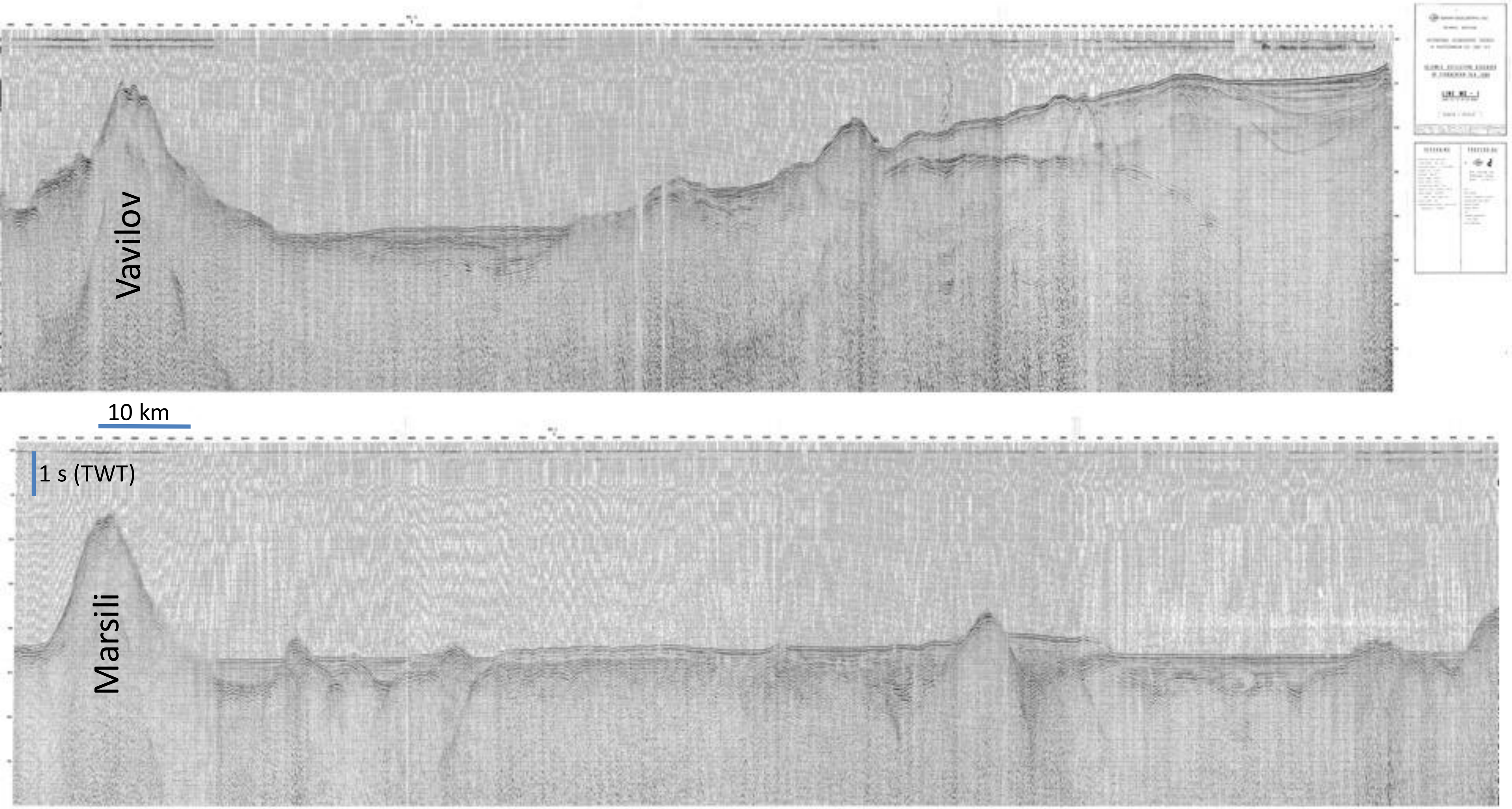




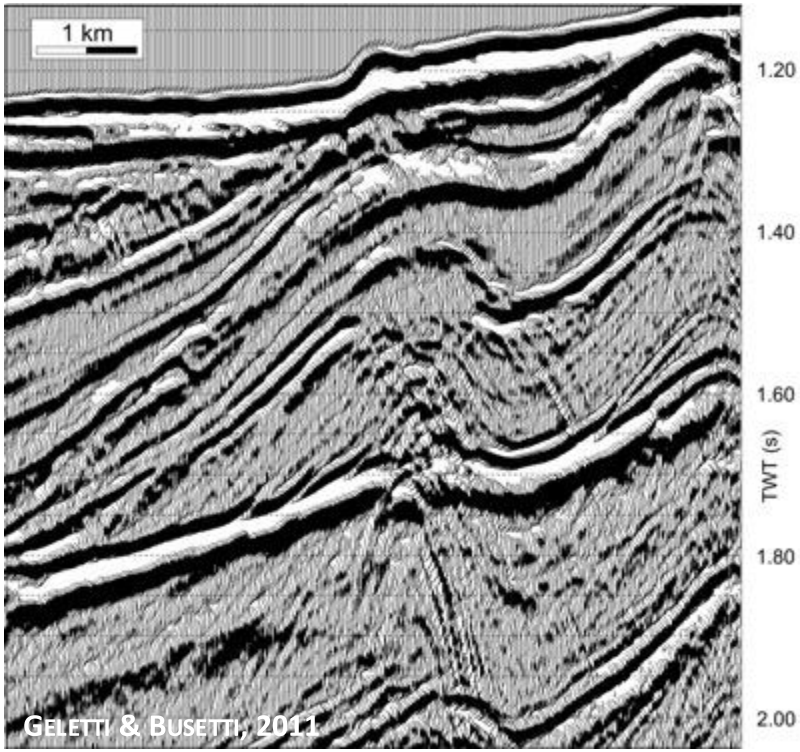
ViDEPI dataset



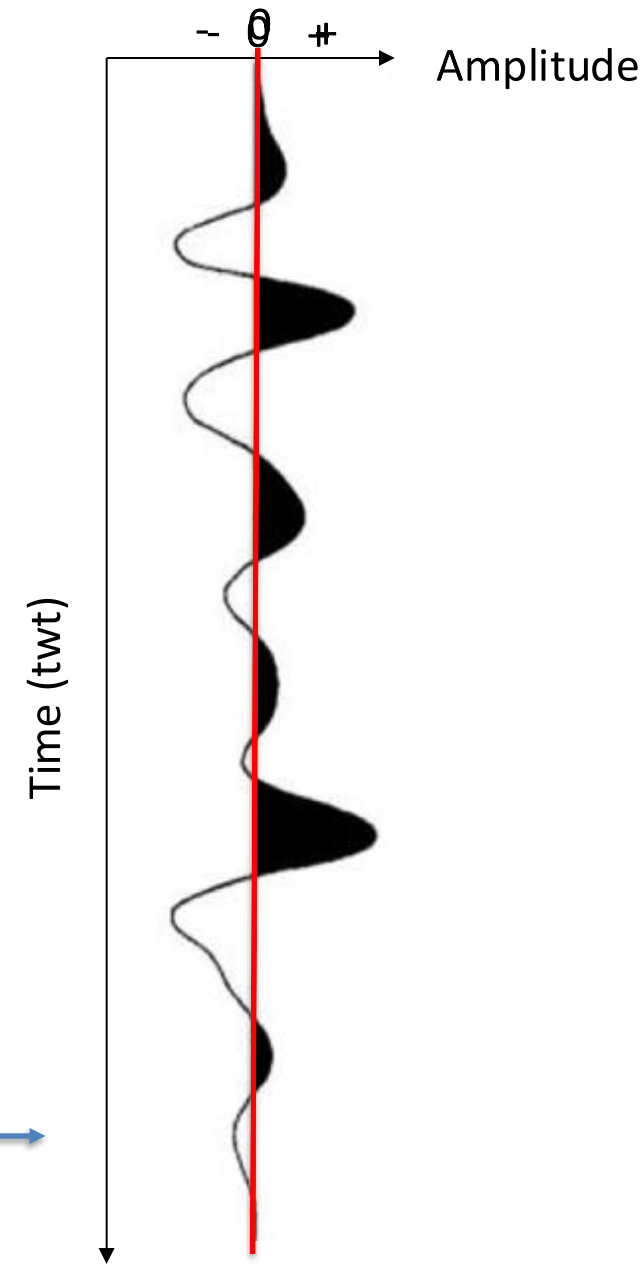
Position map of the seismic profiles of the Italian geophysical exploration projects MS and CROP acquired in 1969–1982 and 1991-1995 respectively



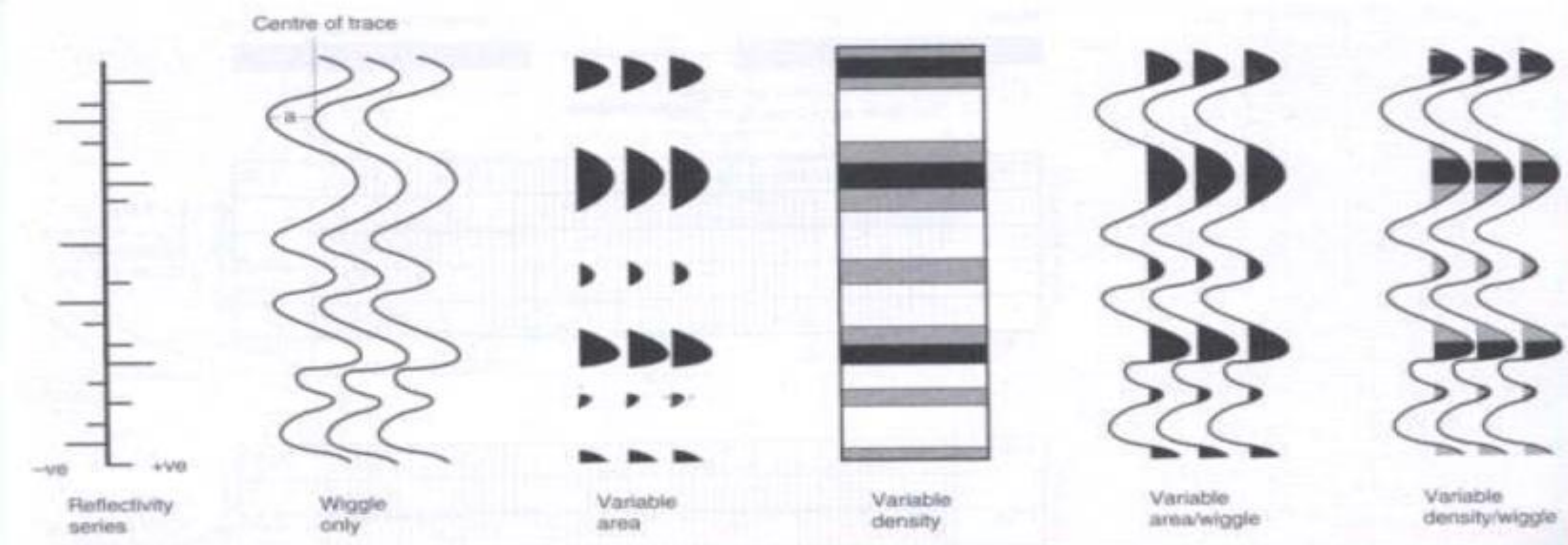
Examples of vintage crustal seismic sections MS 1 acquired in Tyrrenian Sea in 1969



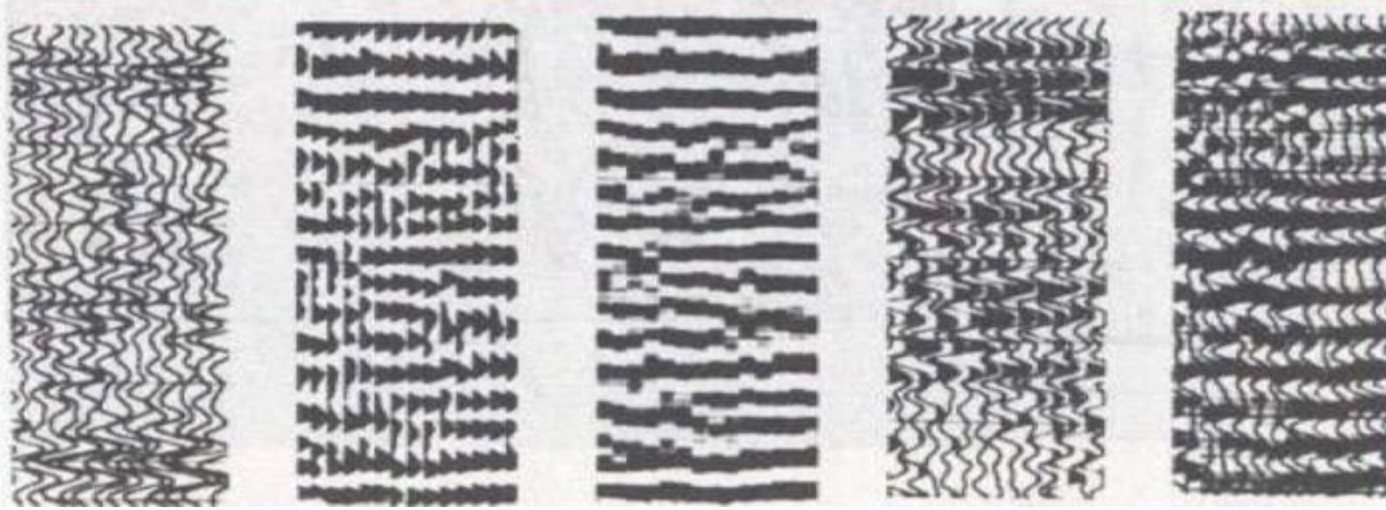
Example of a part of seismic line displayed in wiggle/variable area. On the right is shown a single trace that constitutes the section above (seismogram)

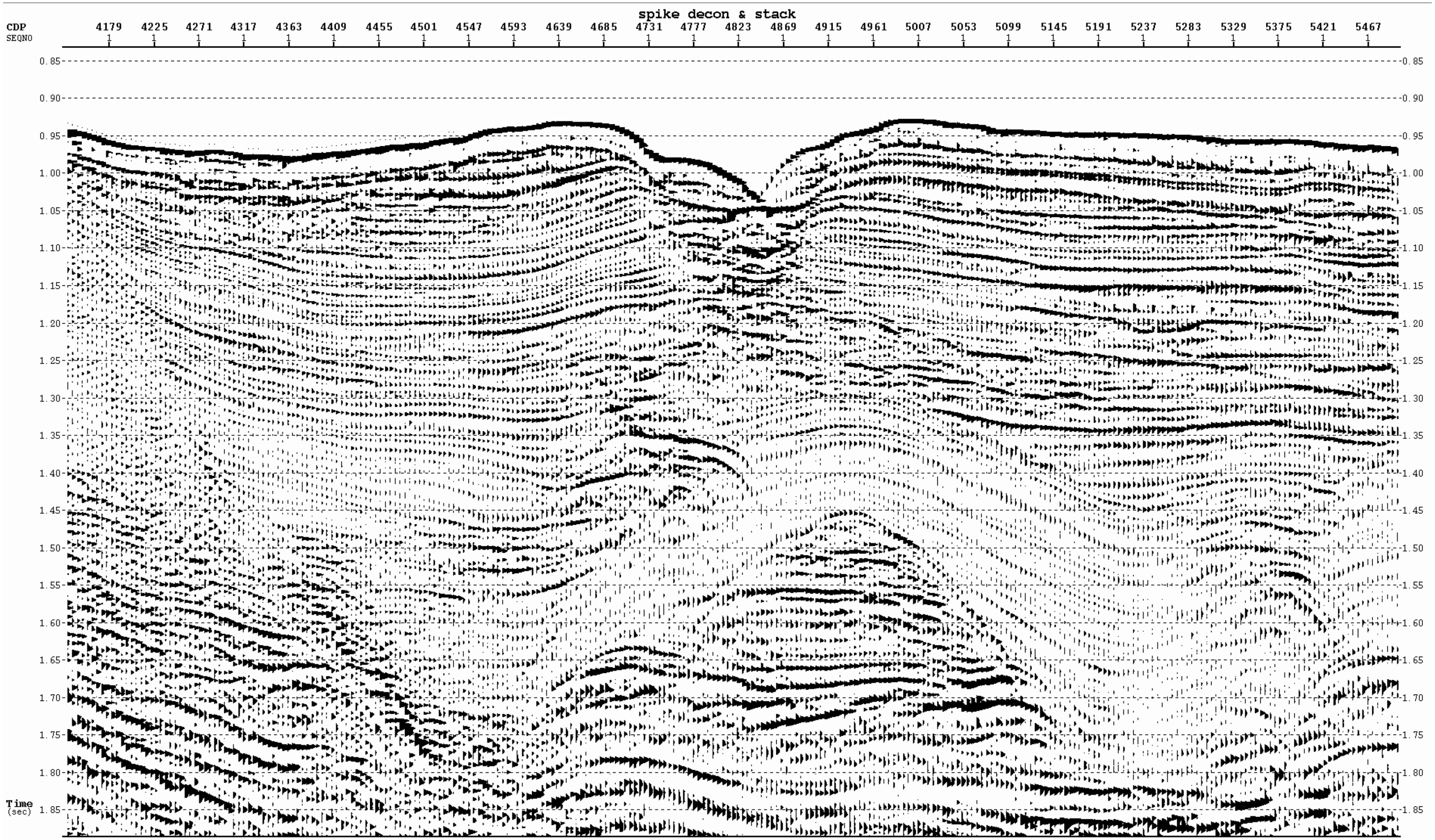


Seismogram: this is an example of a single trace of a seismic profile as shown in the figure above

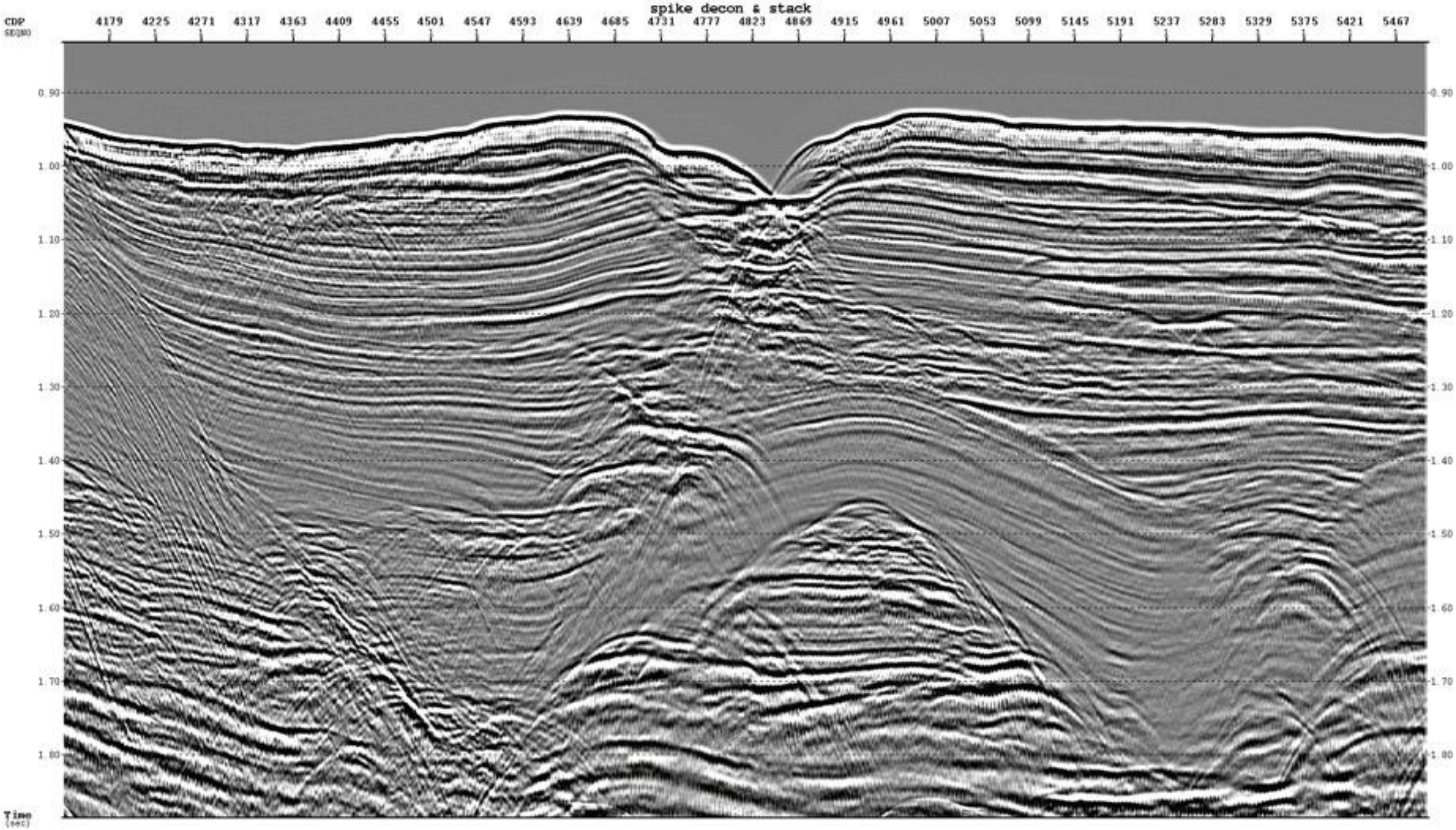


Seimic trace display

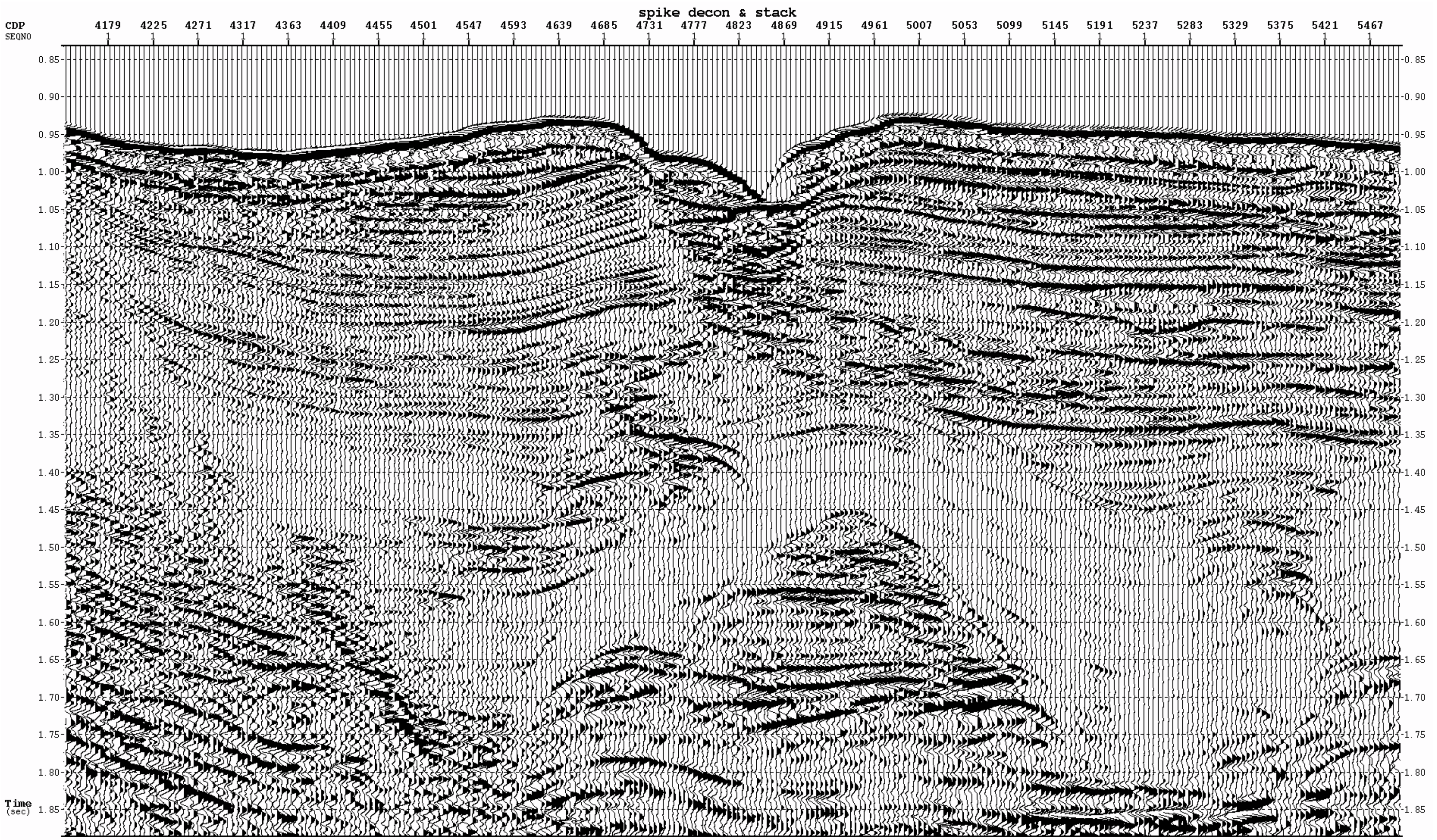




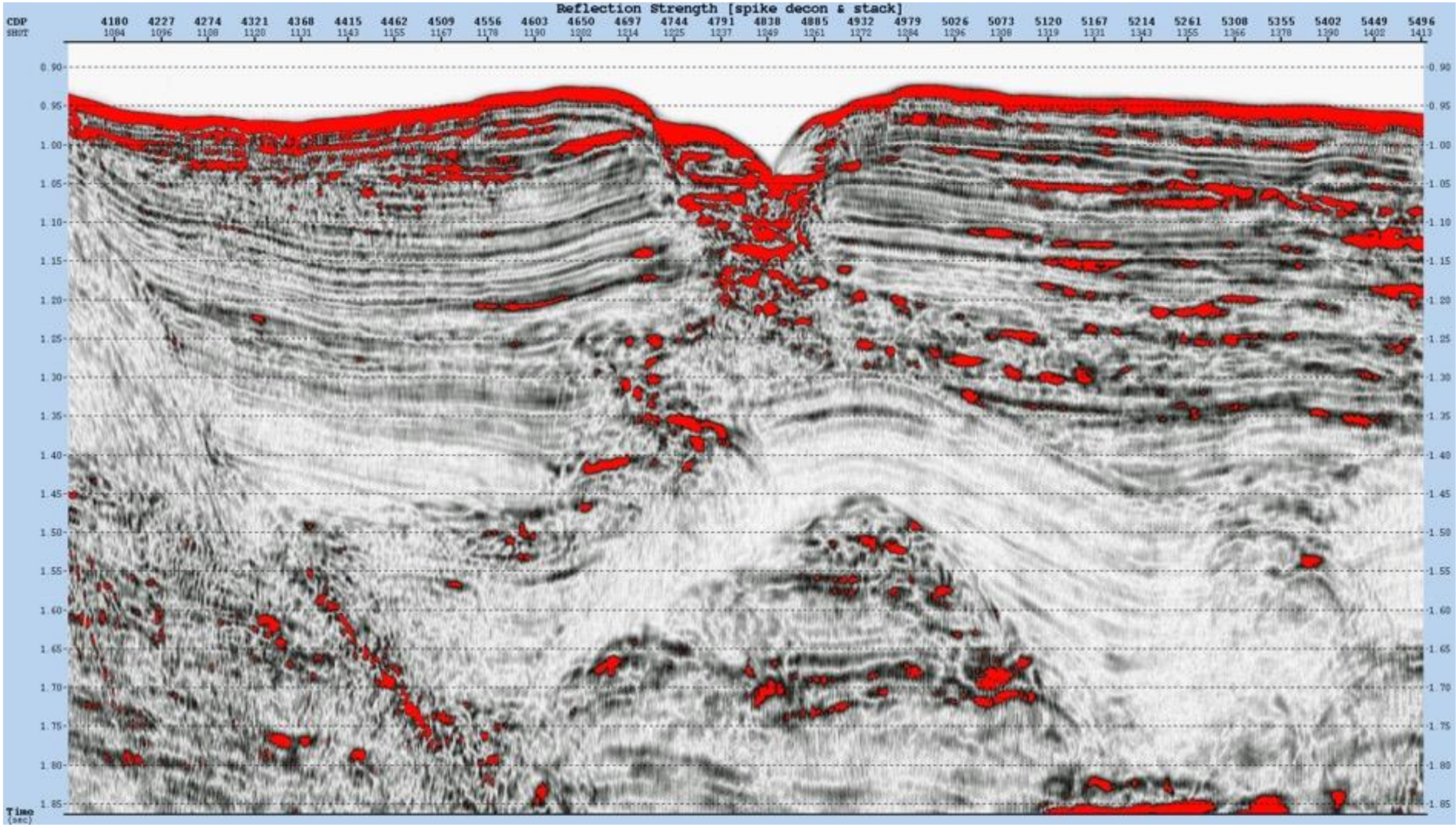
Seismic section displayed in “variable area”



Seismic section displayed in “variable density” in grey scale



Seismic section displayed in “wiggle + variable area”

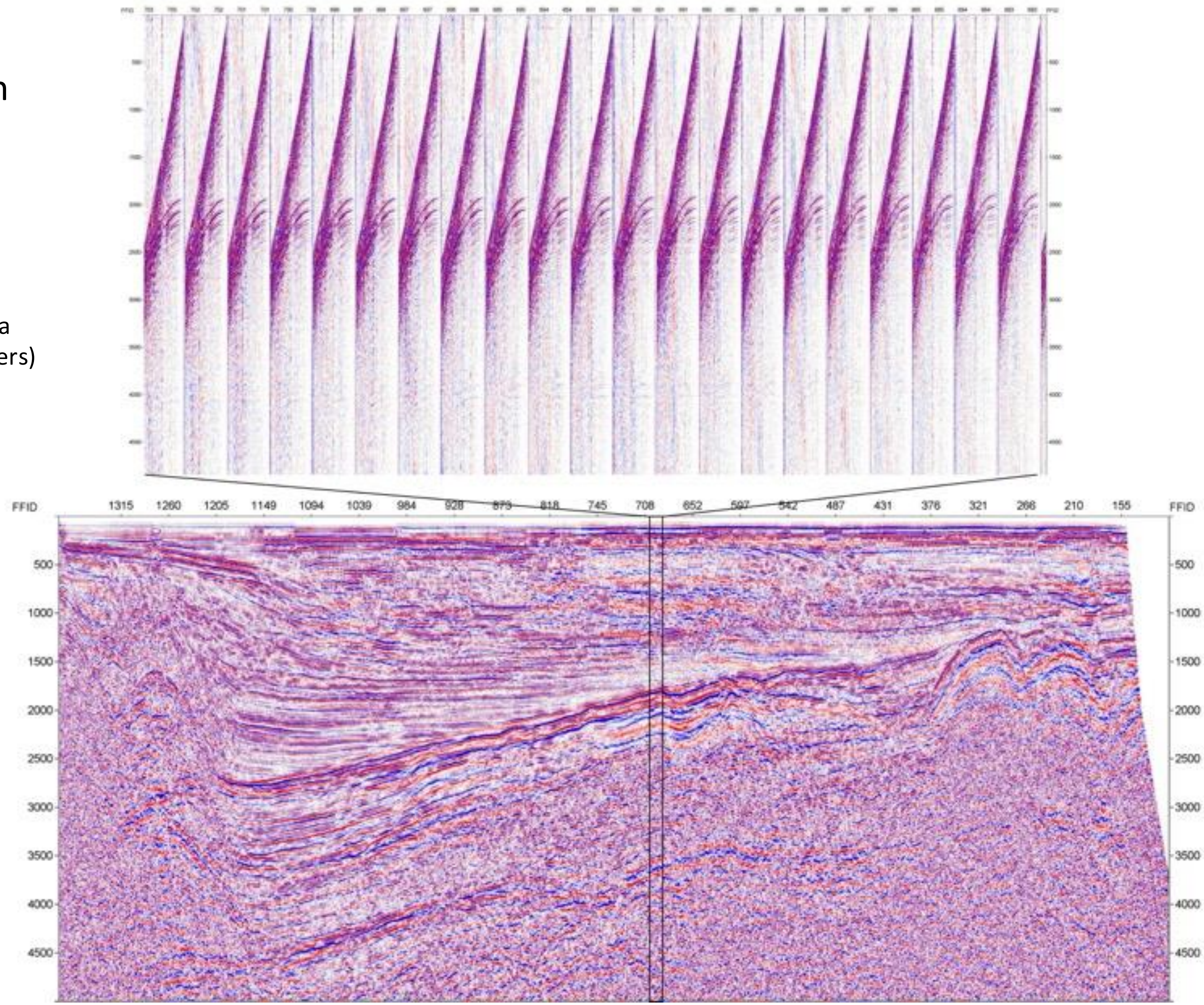


Seismic section displayed in grey scale variable density with the “enhanced reflections” in red colour

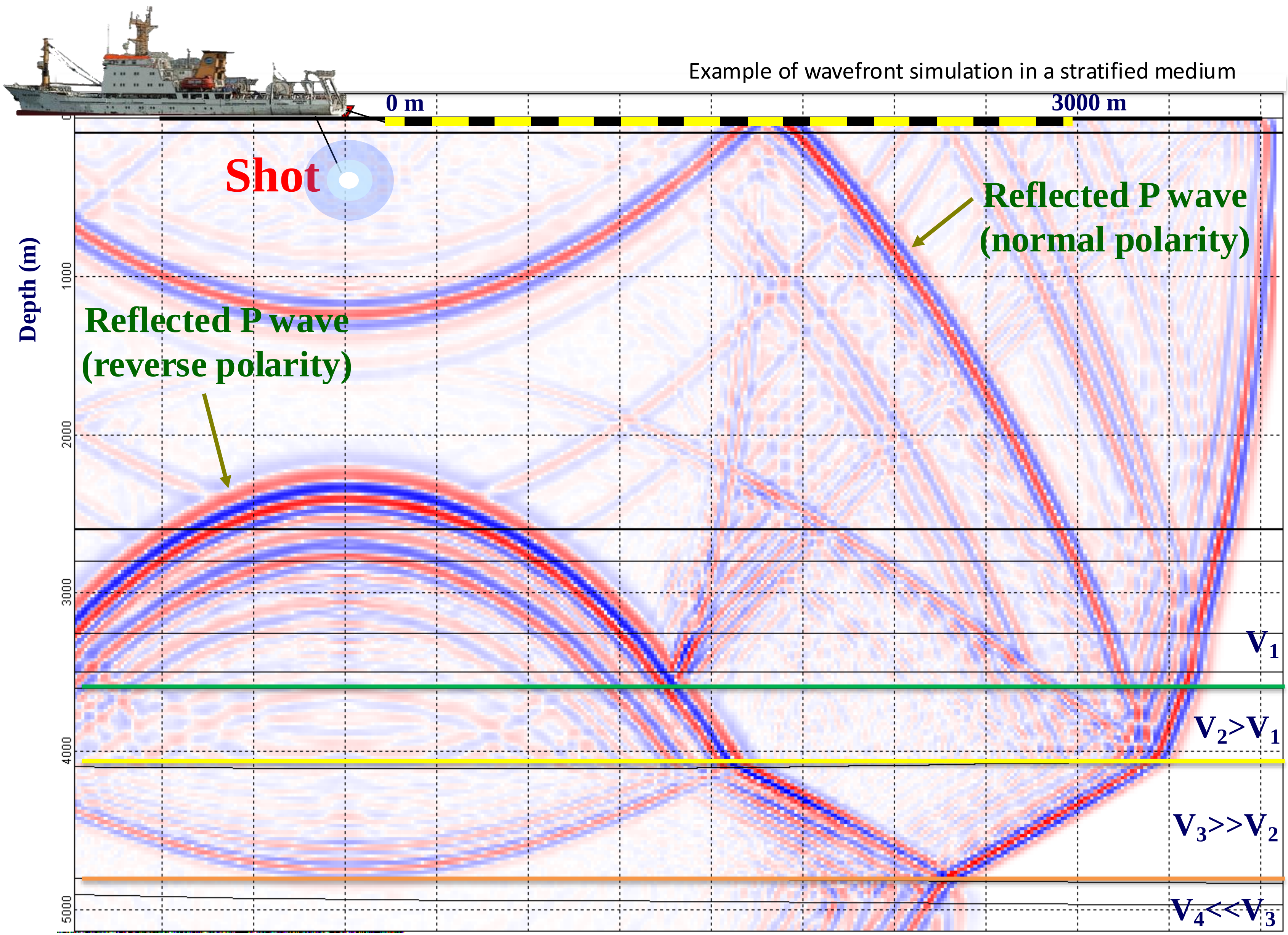
MultiChannel Seismic reflection data (MCS)

Raw data
(shot gathers)

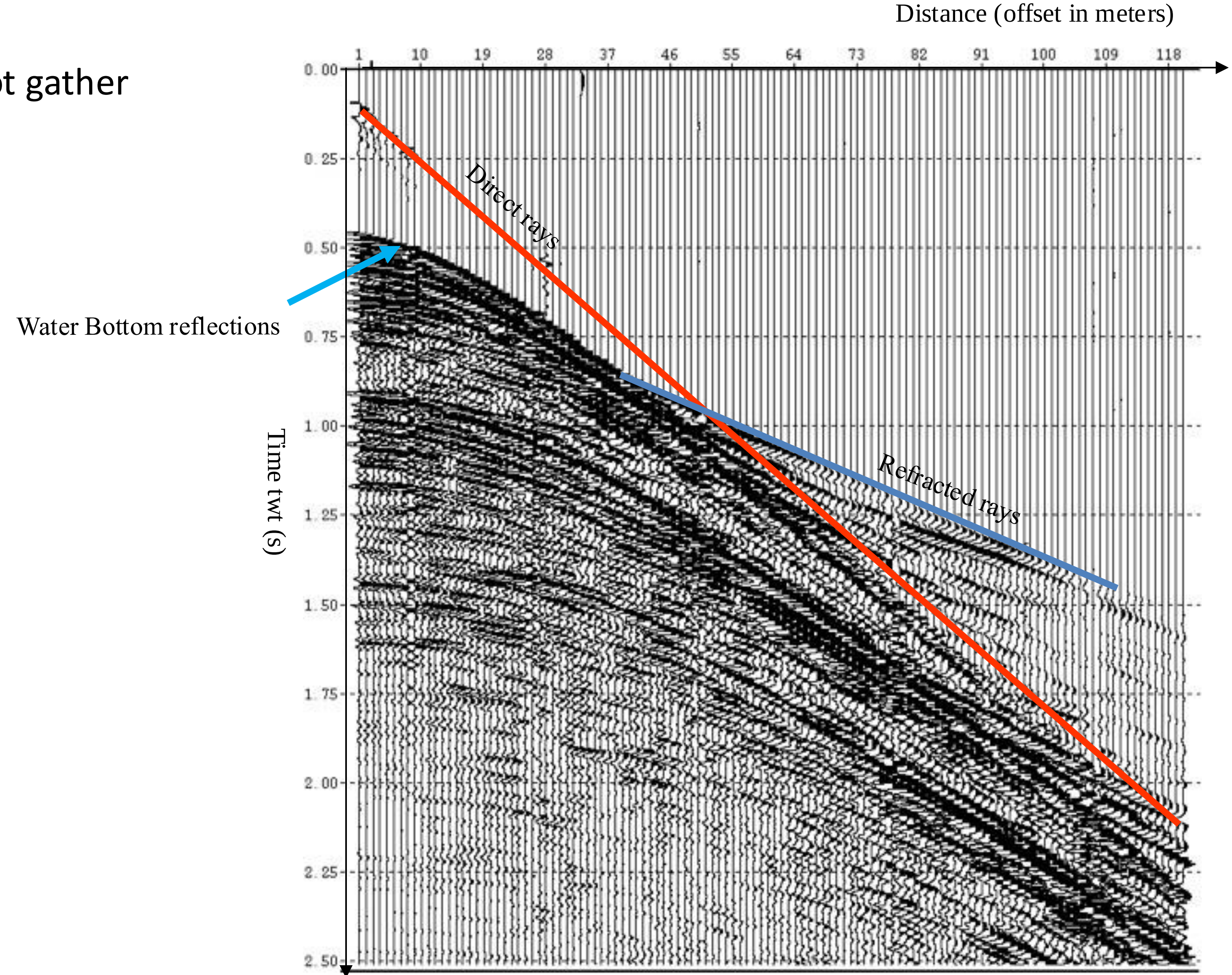
Processed data
(stack section)



Example of wavefront simulation in a stratified medium

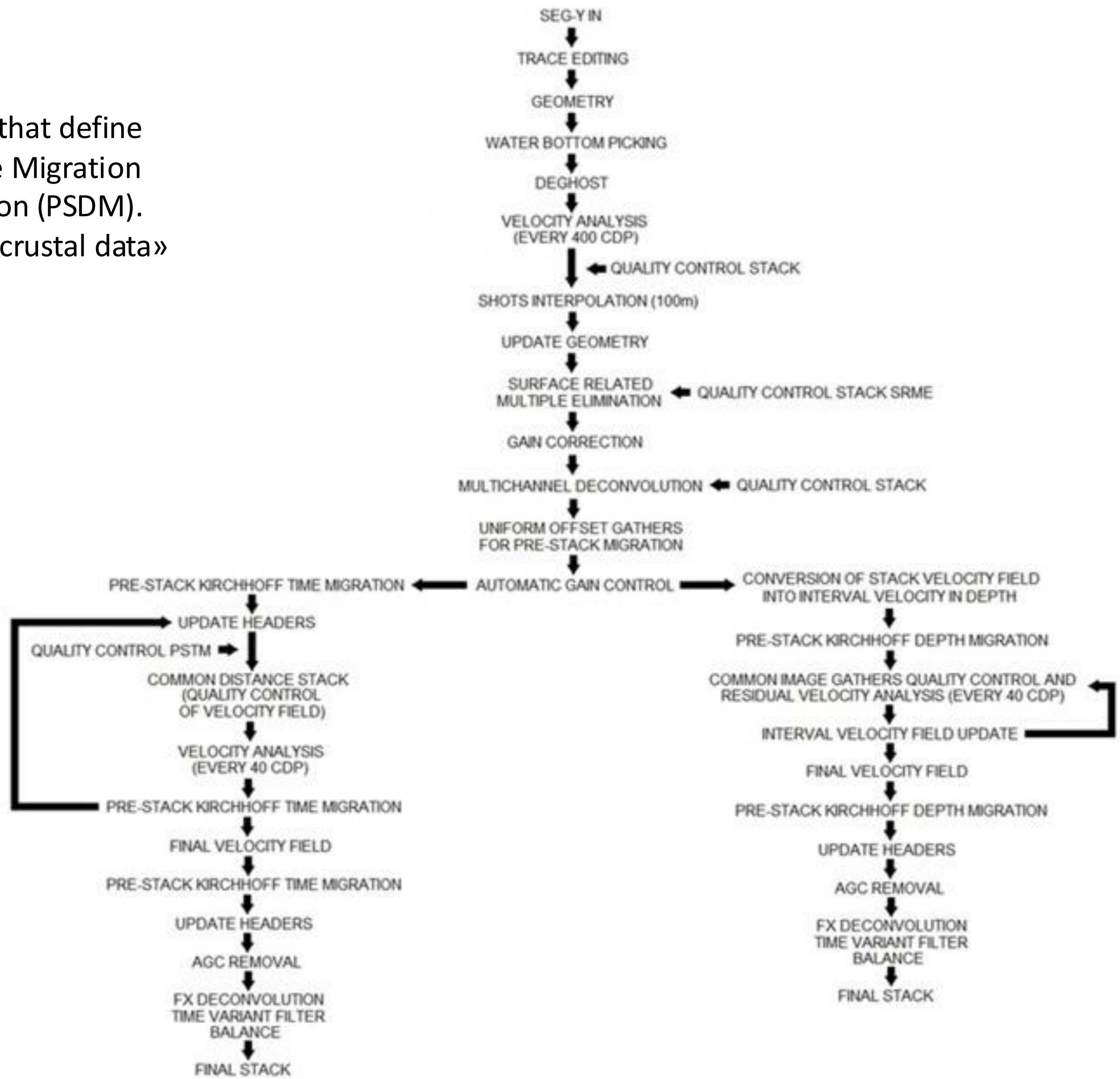


Shot gather


Distance (offset in meters)
1
10
19
28
37
46
55
64
73
82
91
100
109
118
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
Time twt (s)
Direct rays
Refracted rays
Water Bottom reflections

Example of «processing flow chart» that define two different output: Pre-Stack Time Migration (PSTM) and Pre-Stack Depth Migration (PSDM). This sequence has been applied to «crustal data» with «long offset streamer».

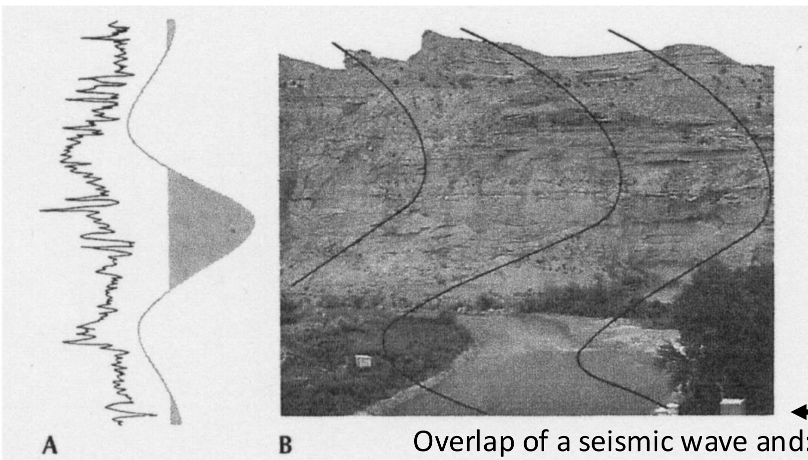
The main steps are the following:
Reformating
Editing
Sorting
Gaining
Deconvolution
Velocity analysis
NMO correction and stacking
Migration



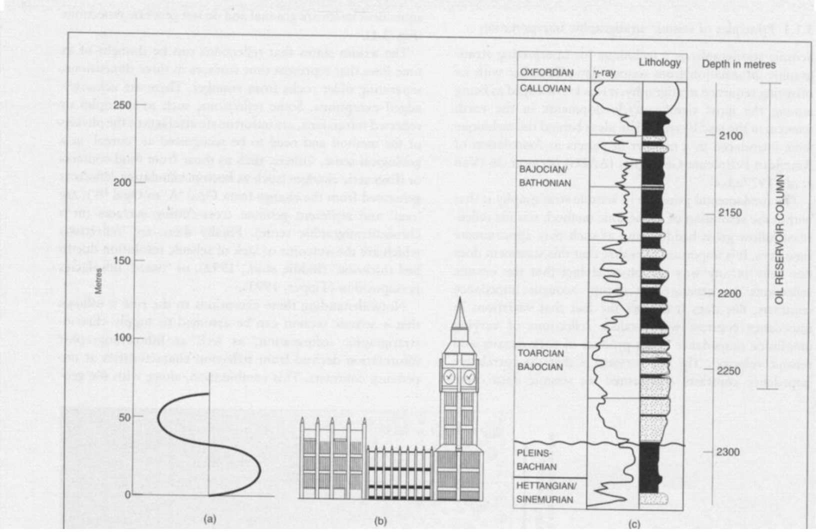
Seismic resolution

Vertical resolution   Lateral resolution

Examples of seismic wave resolution

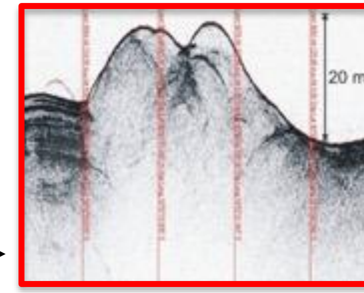


Overlap of a seismic wave and: A) a sonic log, B) a photo of a rock face of about 40 m

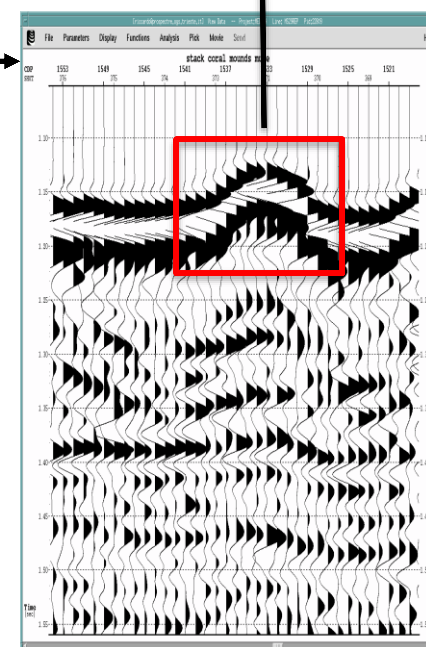


Comparison between a seismic wave and: b) Big Ben of London, c) a well data

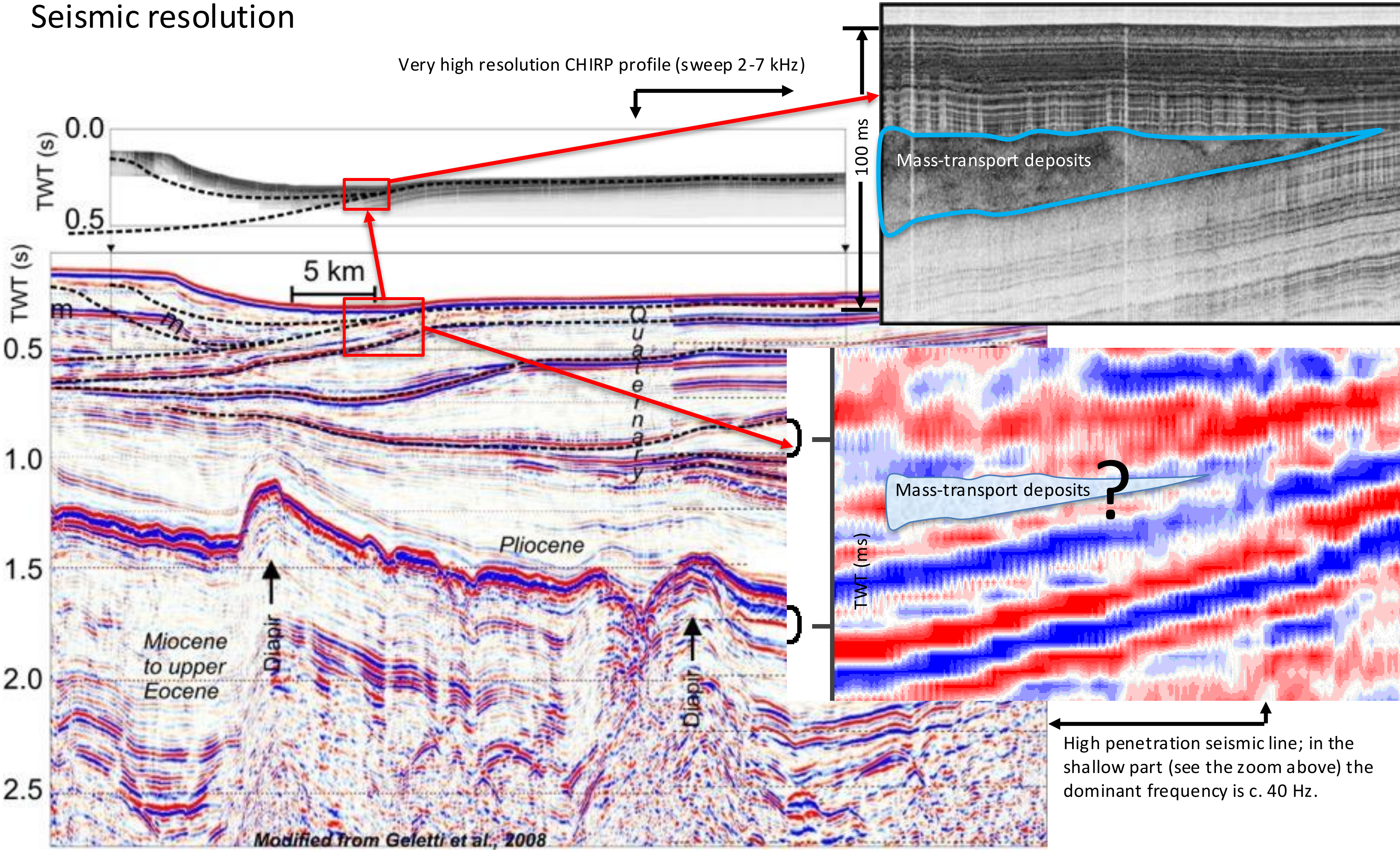
Very high resolution acoustic profile



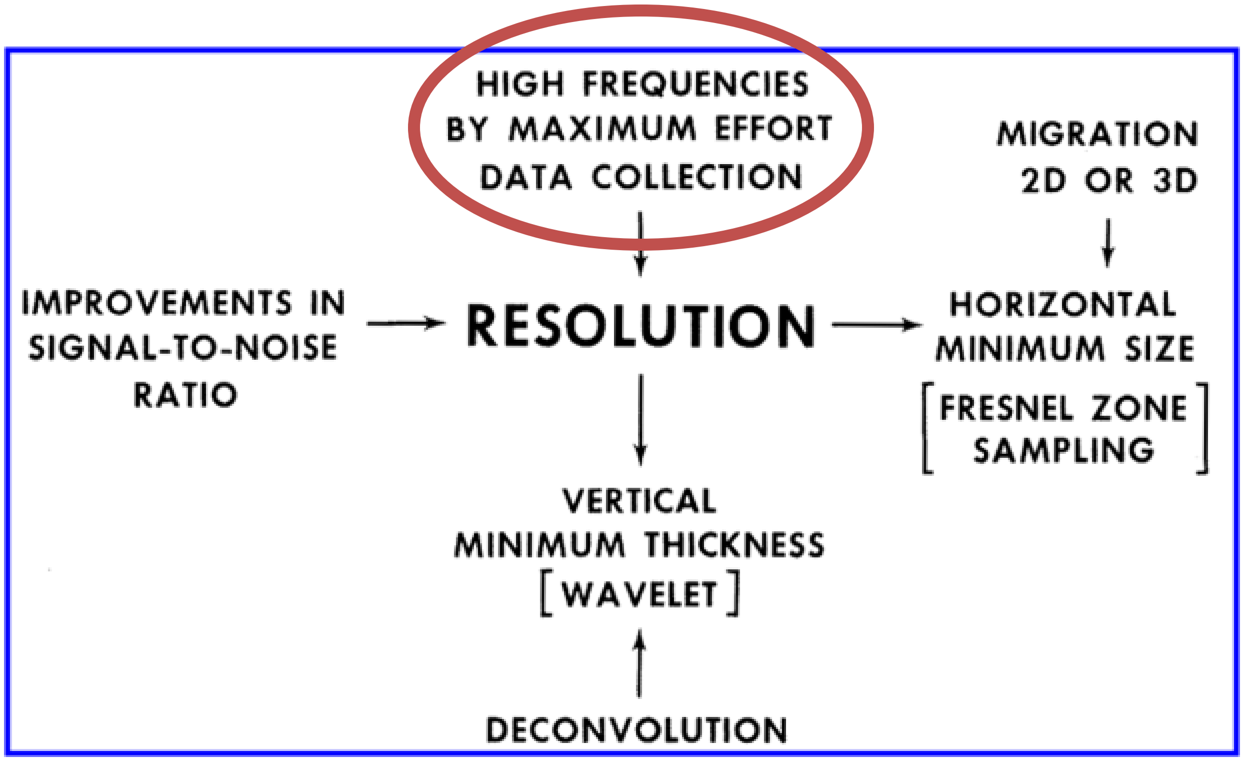
Low resolution seismic profile (crustal data)



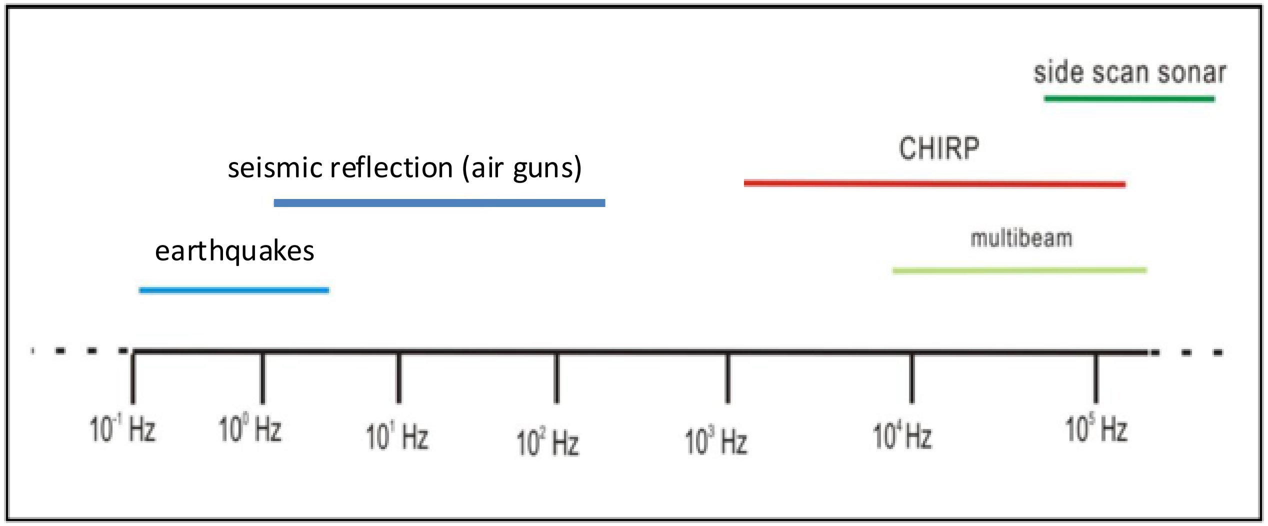
Seismic resolution

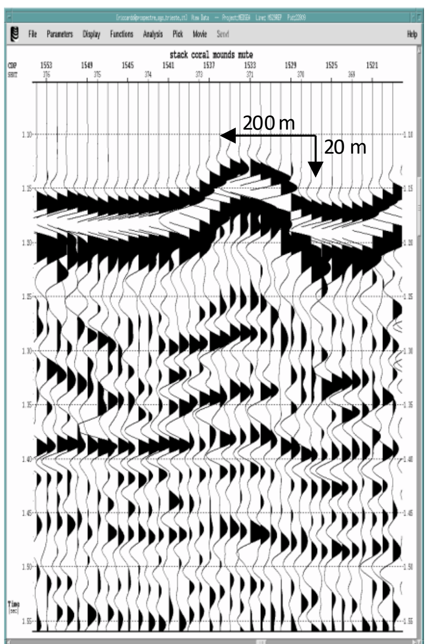


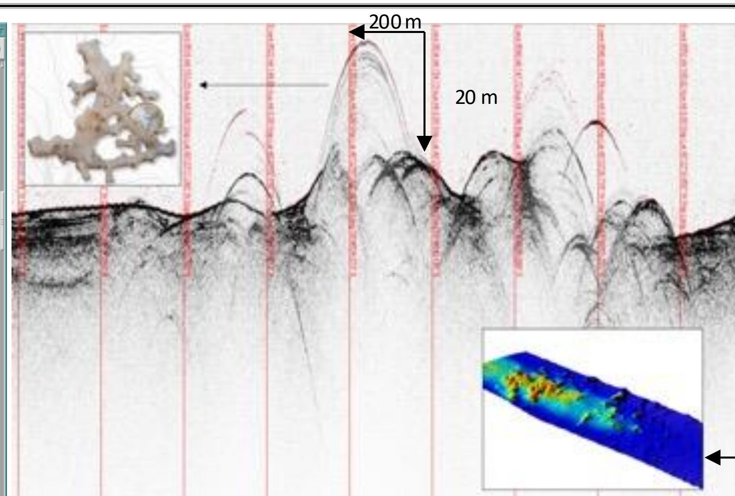
High penetration seismic line; in the shallow part (see the zoom above) the dominant frequency is c. 40 Hz.

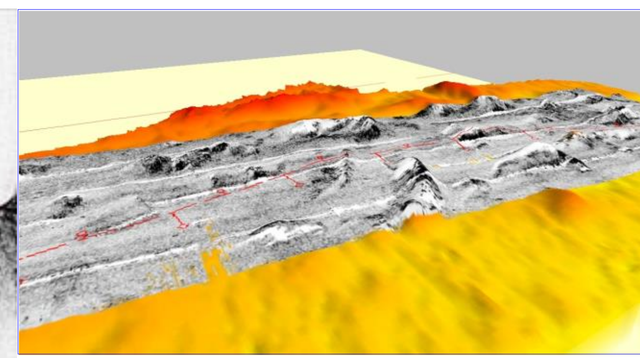


Factors affecting horizontal and vertical seismic resolution









Swath bathymetry: Side Scan Sonar (above) & MultiBeam (left) data

CHIRP profile (Very High Resolution)

High penetration seismic line (low resolution)

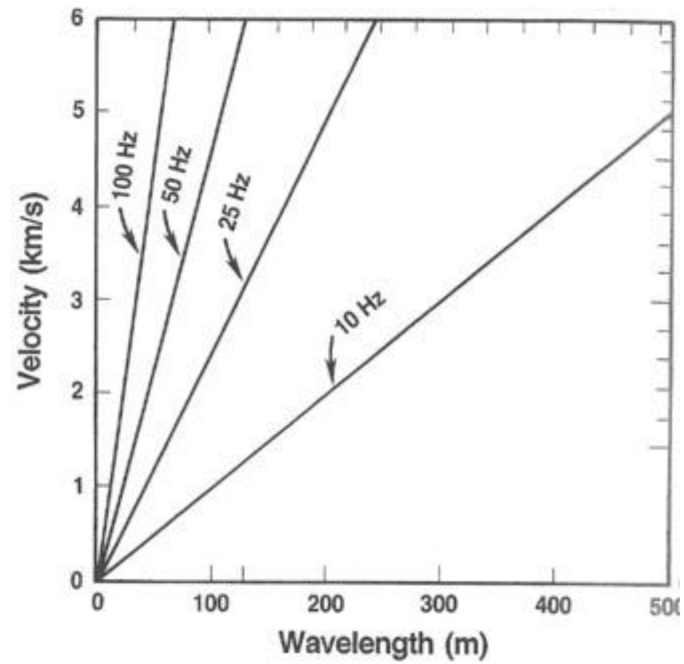
Seismic resolution

Vertical Resolution

$$\lambda/4 = v/4f$$

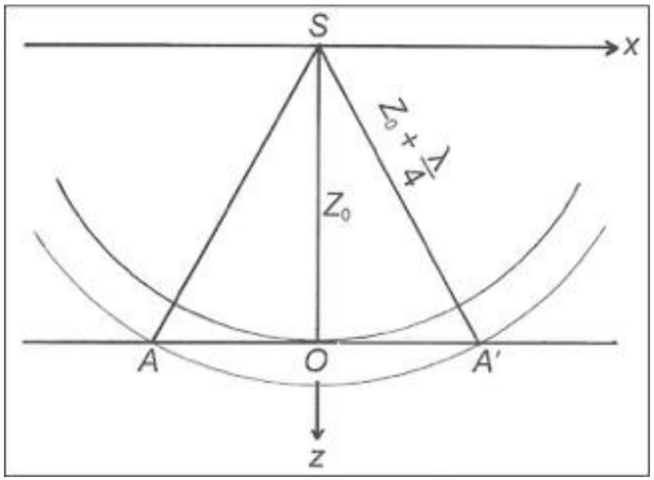
v (m/s)	f (Hz)	$\lambda/4$ (m)
2000	50	10
3000	40	18
4000	30	33
5000	20	62

Threshold for vertical resolution

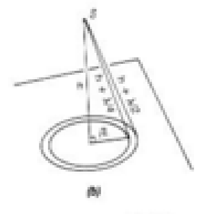


The relationship between velocity (v), dominant frequency (f) and wavelegth ($\lambda = v/f$).

Lateral Resolution



Definition of the Frensnel zone AA'



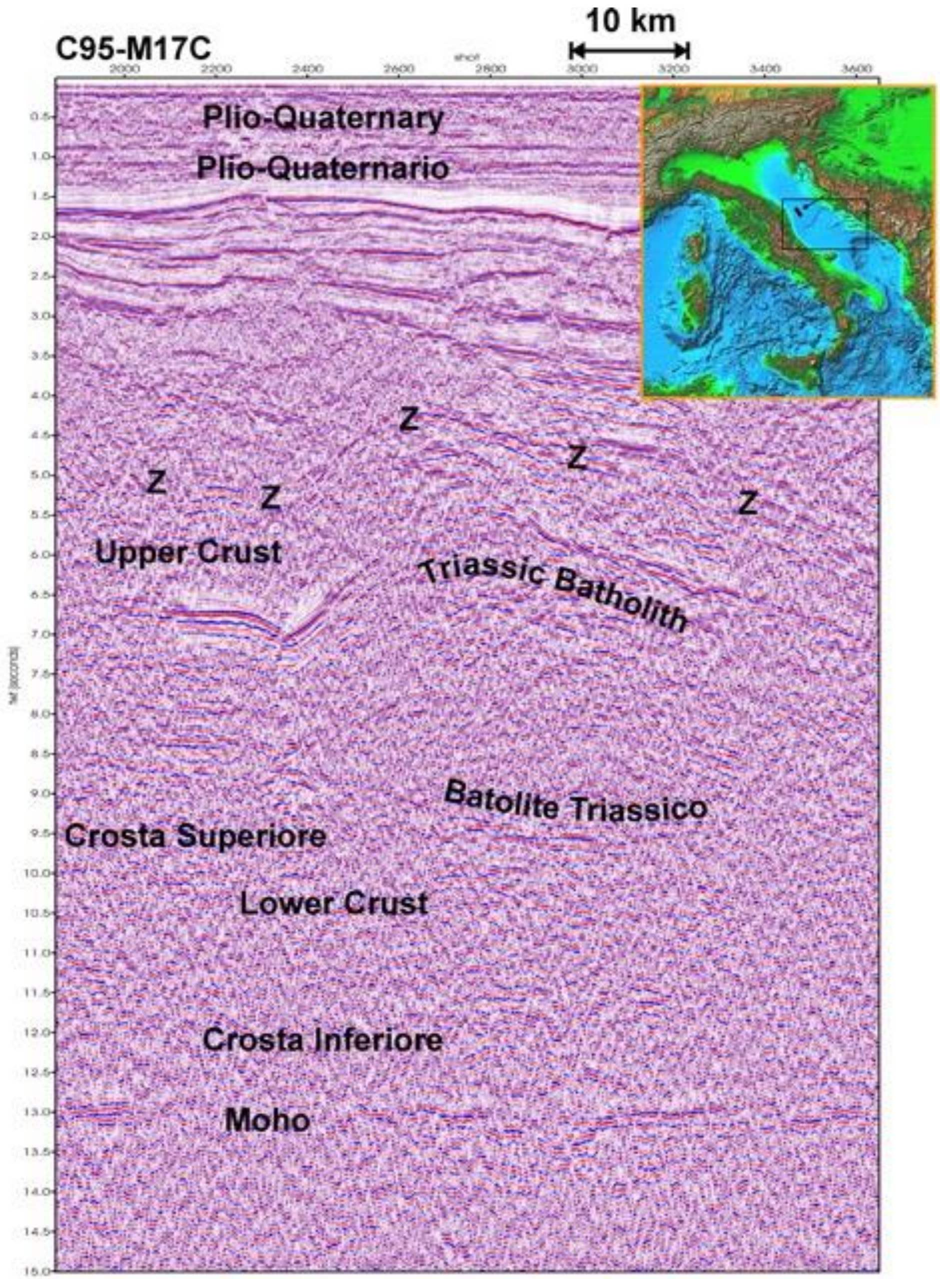
$$r = (v/2)\sqrt{t_0/f}$$

t_0 (s)	v (m/s)	f (Hz)	r (m)
1	2000	50	141
2	3000	40	335
3	4000	30	632
4	5000	20	1118

Threshold for lateral resolution (t0 = 2z/v, r=OA)

Seismic resolution

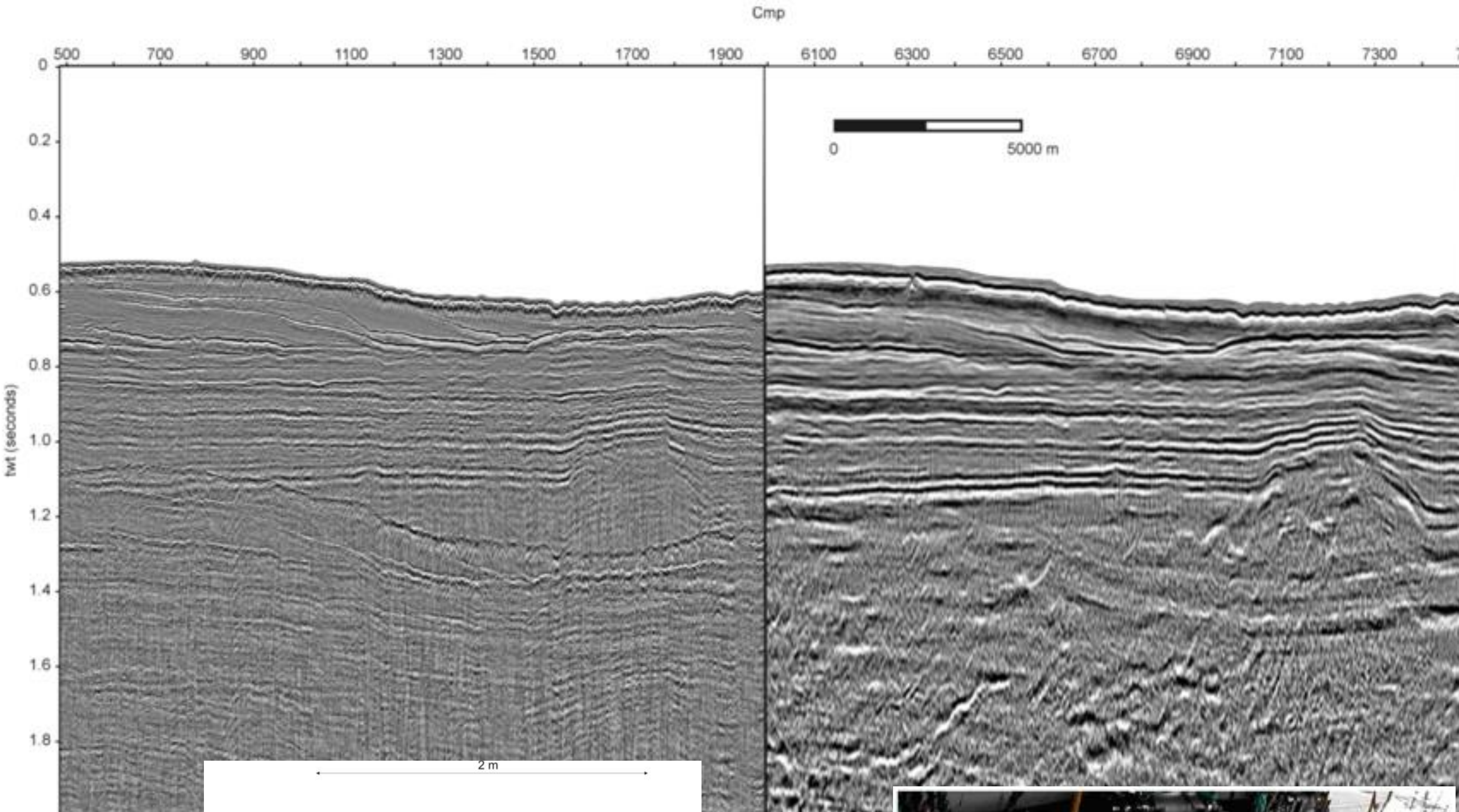
Example of high penetration (low resolution) multichannel seismic reflection profile (CROP project) in Central Adriatic Sea.

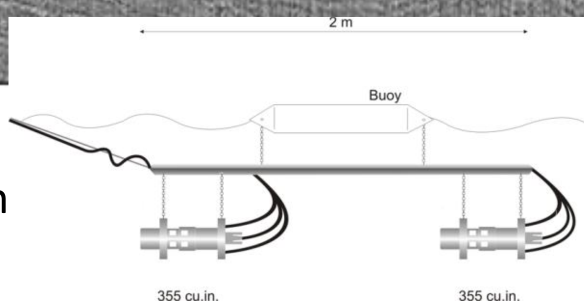


30 km depth

40 km depth

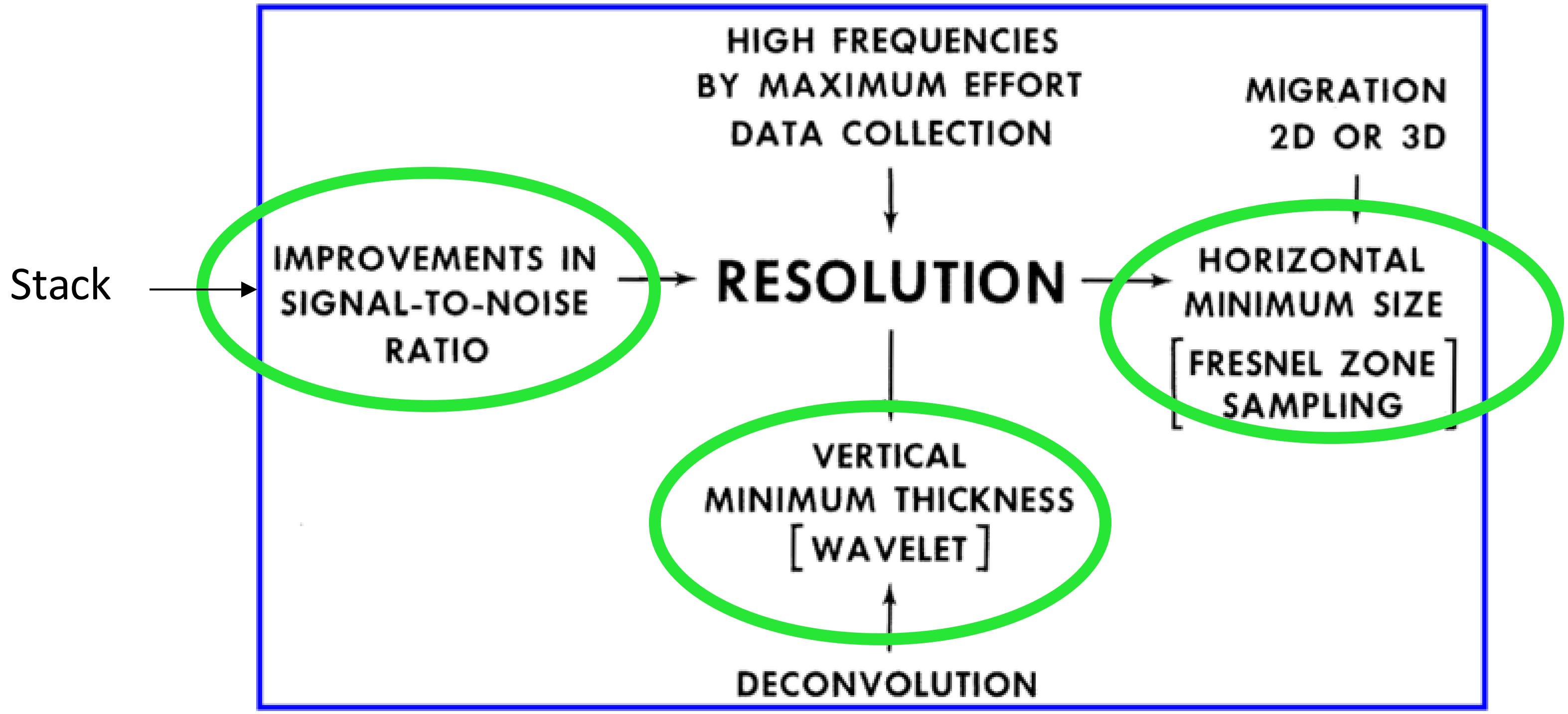
Vertical resolution = 75 m
Lateral resolution = 4840 m
(v=6 km/s; f = 20 Hz)





Seismic resolution

Examples of two seismic sections acquired by different sources: (left) by 2 GI guns (11,6 l); (right) by an array of 16 air guns (70 l)

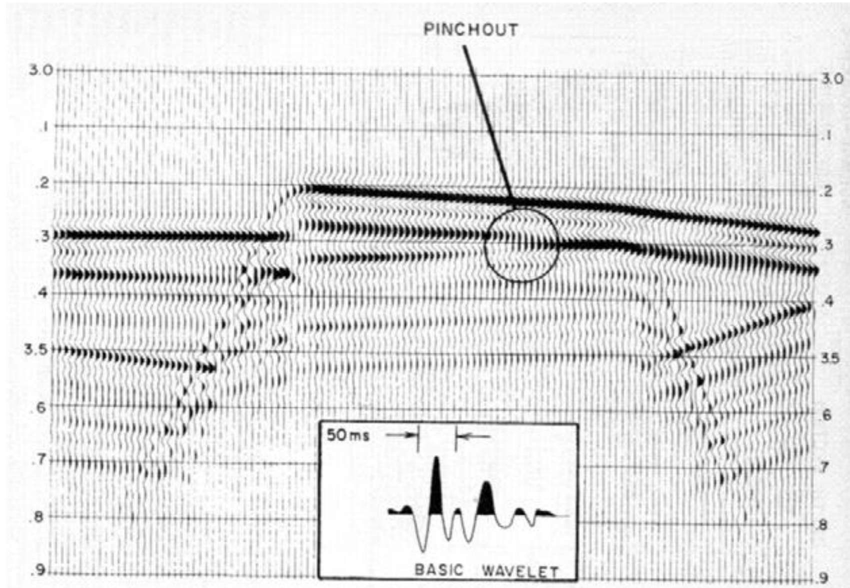


Factors affecting horizontal and vertical seismic resolution: processing solution

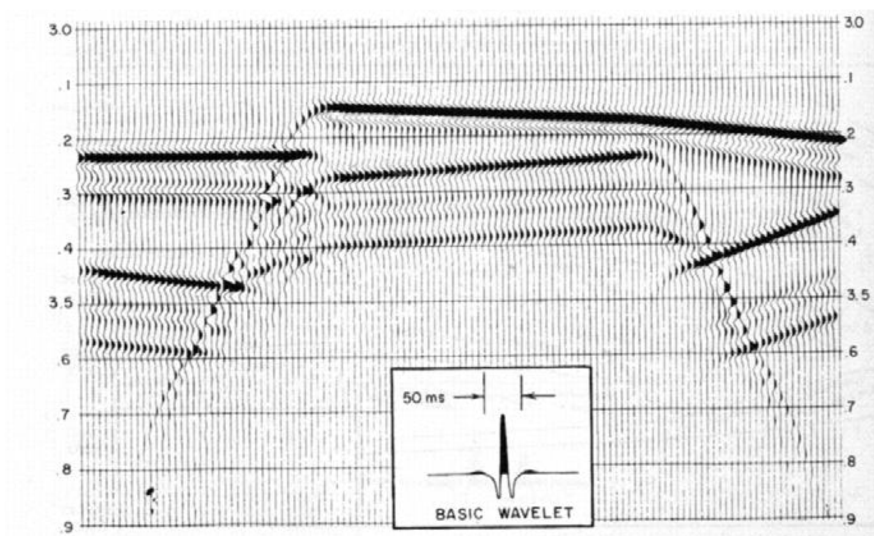
Vertical resolution

Deconvolution

Example of the effect of the deconvolution on the definition of seismic data (synthetic data). The deconvolution "shrinks" the wavelet as shown in the figure (synthetic data)

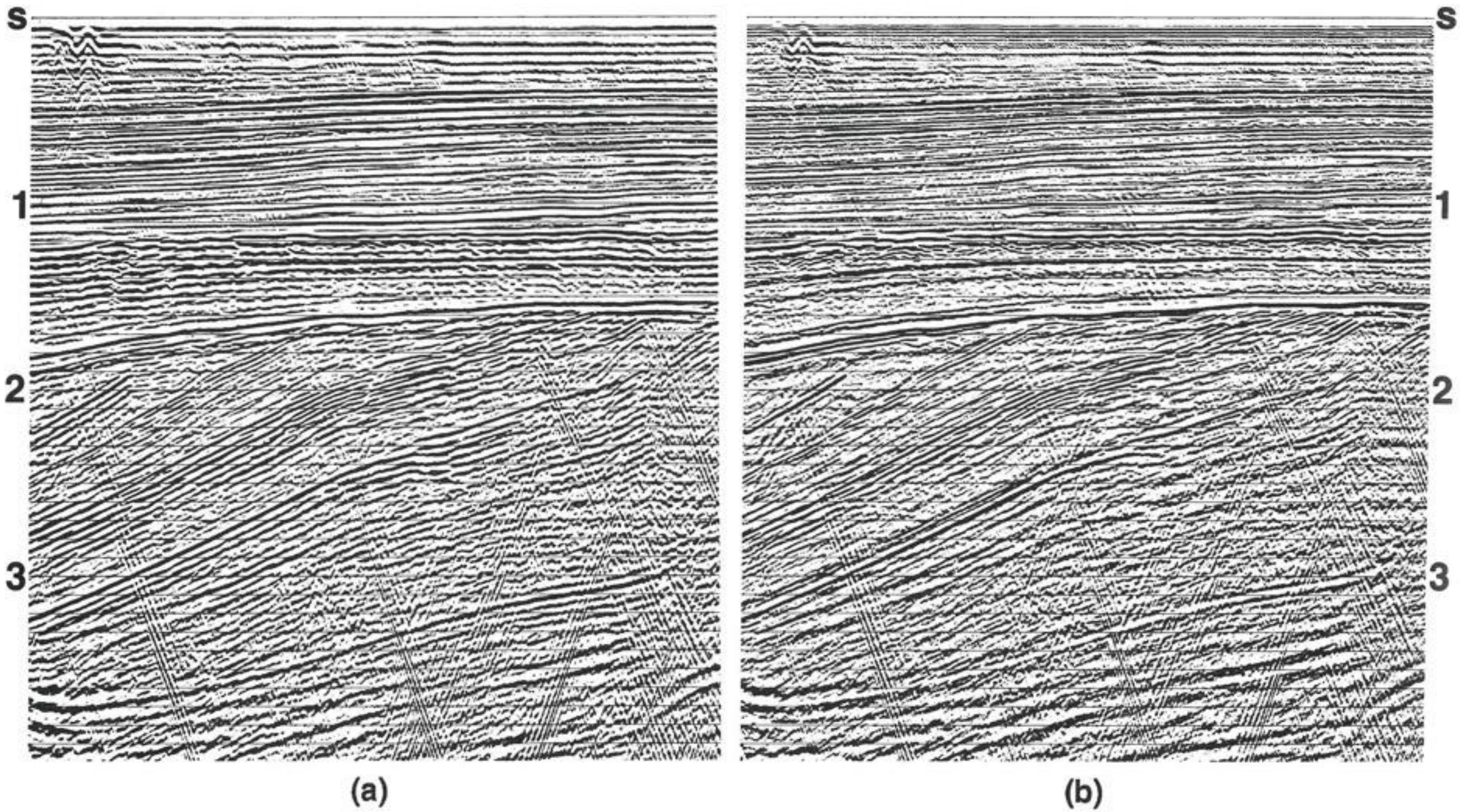


Before the deconvolution



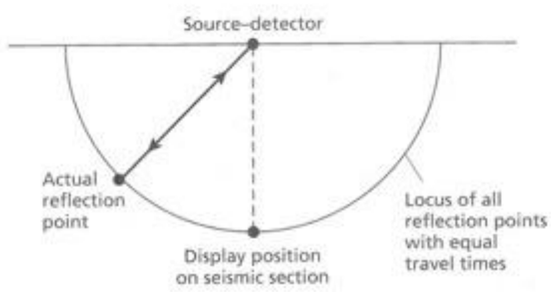
After the deconvoluti

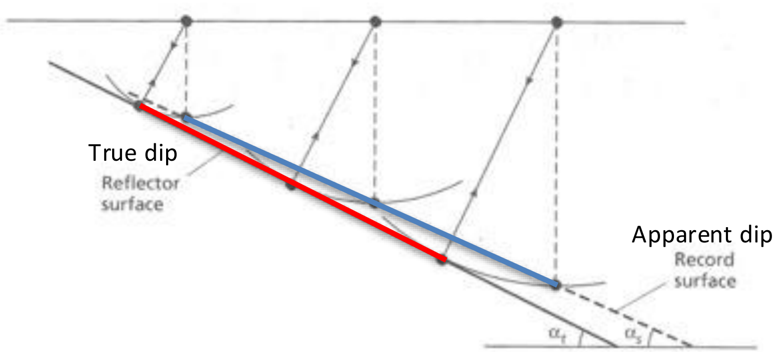
Vertical resolution



Seismic stack section a) before and b) after deconvolution (Yilmaz, 2001)

Lateral resolution

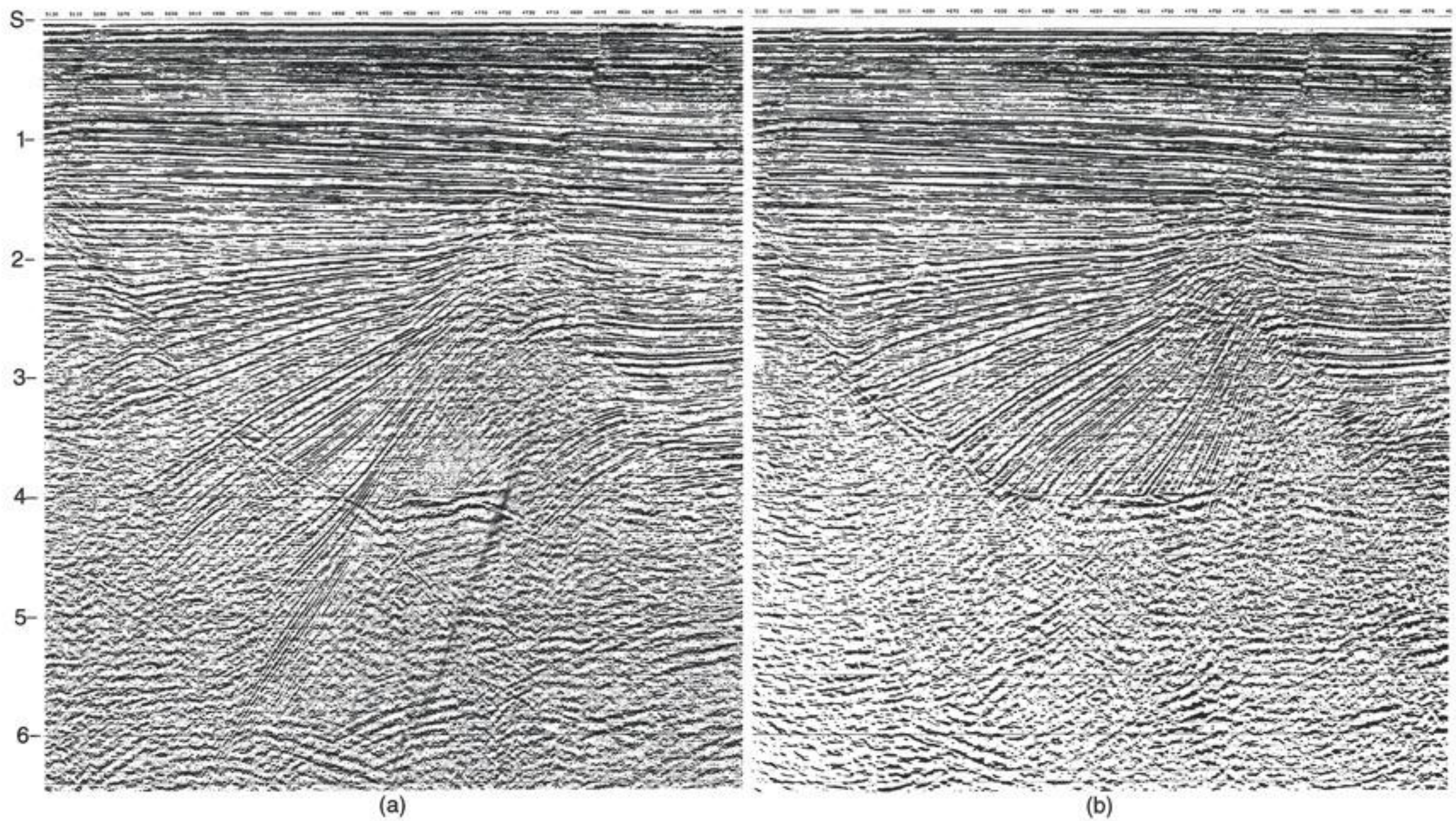




Migration

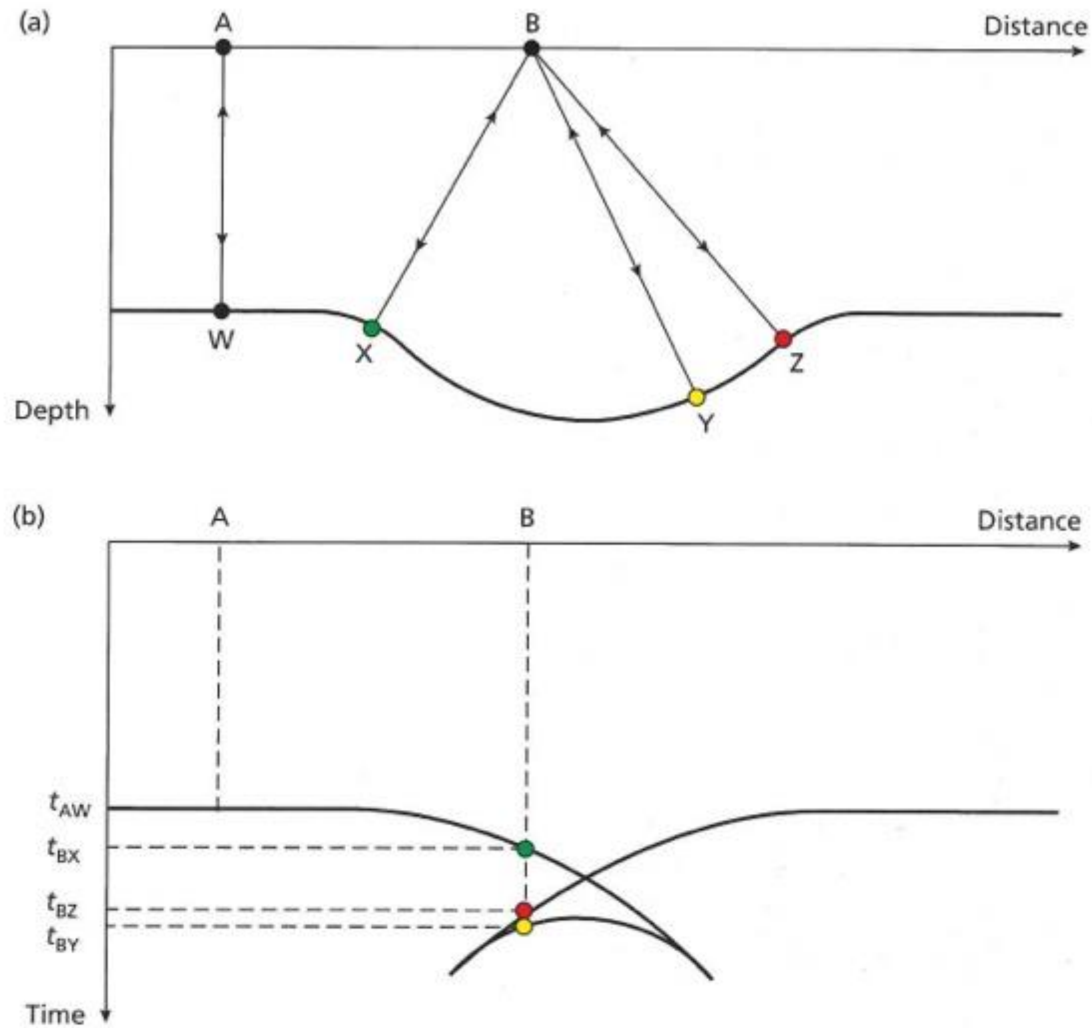
- Consider a source-detector (s-d) on the surface of a medium of costant seismic velocity. For a given reflection time, the reflection point may be anywhere on the arc of a circle centred on the s-d position. On a non migrated seismic section the point is mapped to be immediately below the s-d.

- A planar-dipping record surface derived from a non-migrated seismic section (blu line) and its associated reflector surface (red line).



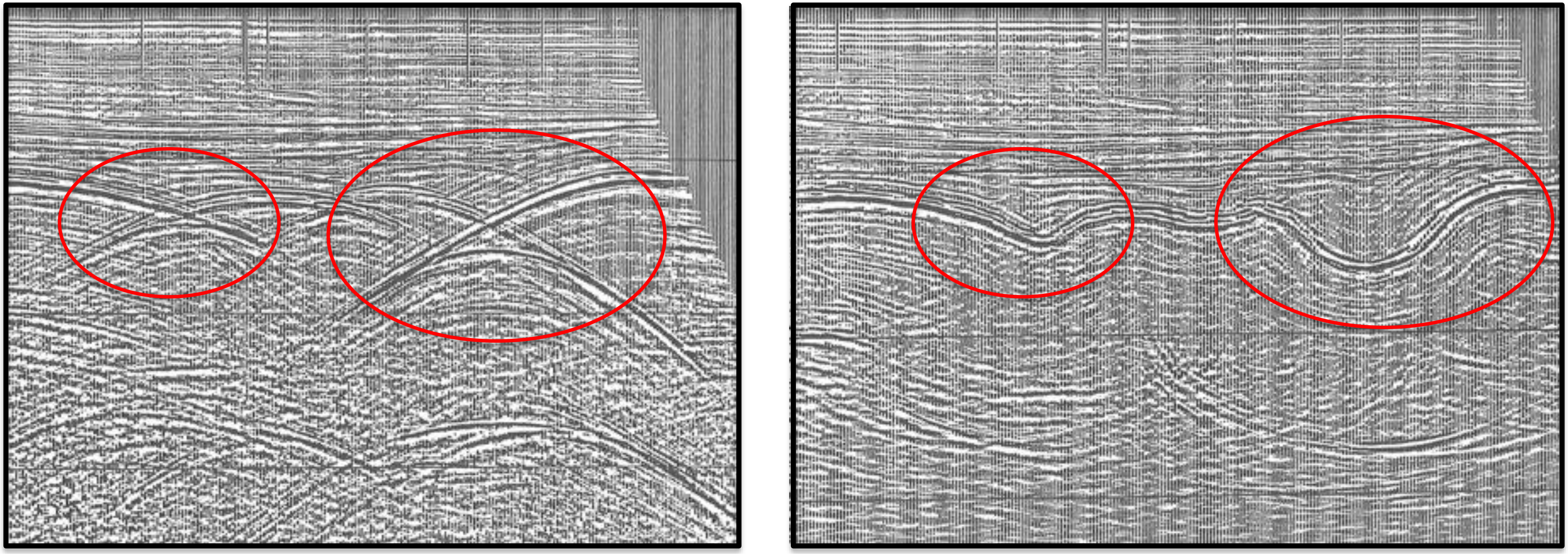
Stack section (a) before and (b) after migration. (from Yilmaz 2001)

Lateral resolution



a) A sharp synclinla feature in a reflecting interface, and
b) (b) the resultant «bow-tie» shape of the reflection event on the non-migrated seismic section.

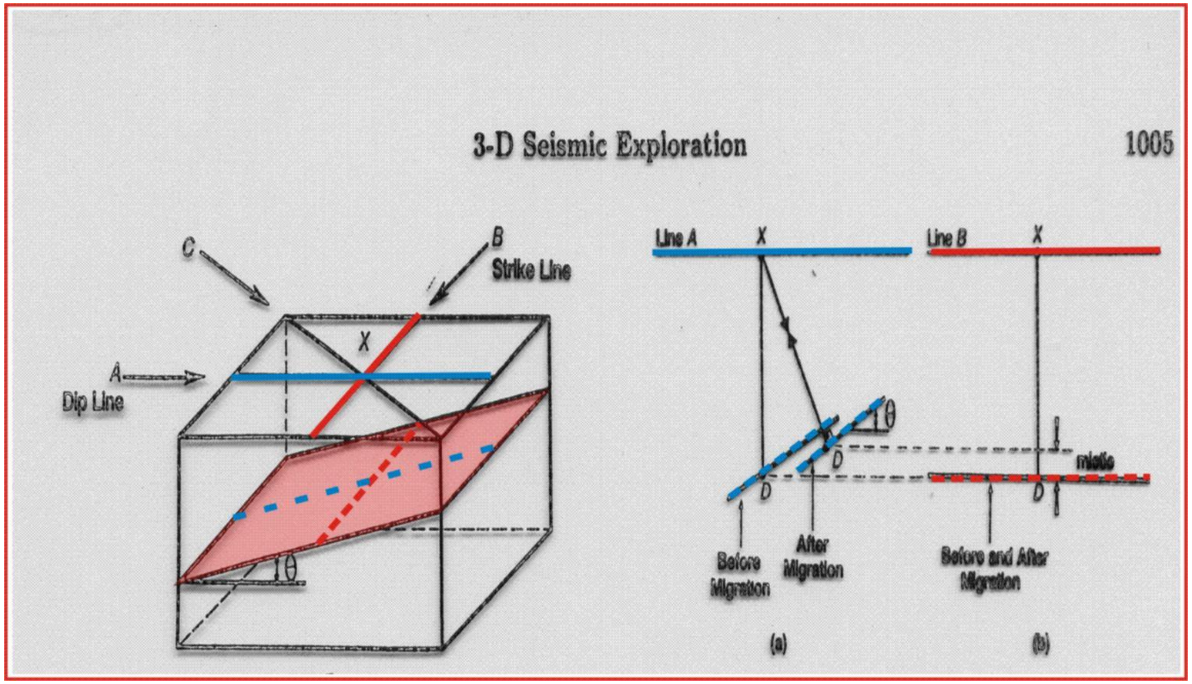
Lateral resolution: migration



a) b)

Example of seismic reflection profile across two buried channels (a) non-migrated section with the presence of «bow-tie» effect (red ellipses) and b) after migration

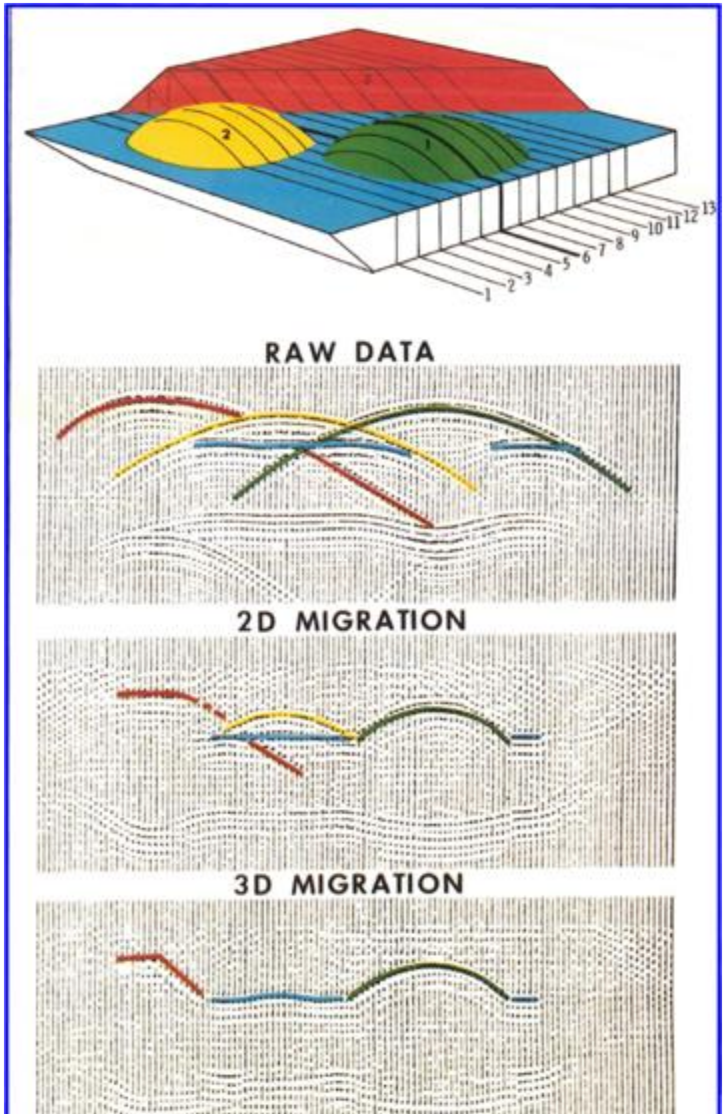
2D migration



2D migration is an imperfect process on the «strike line»

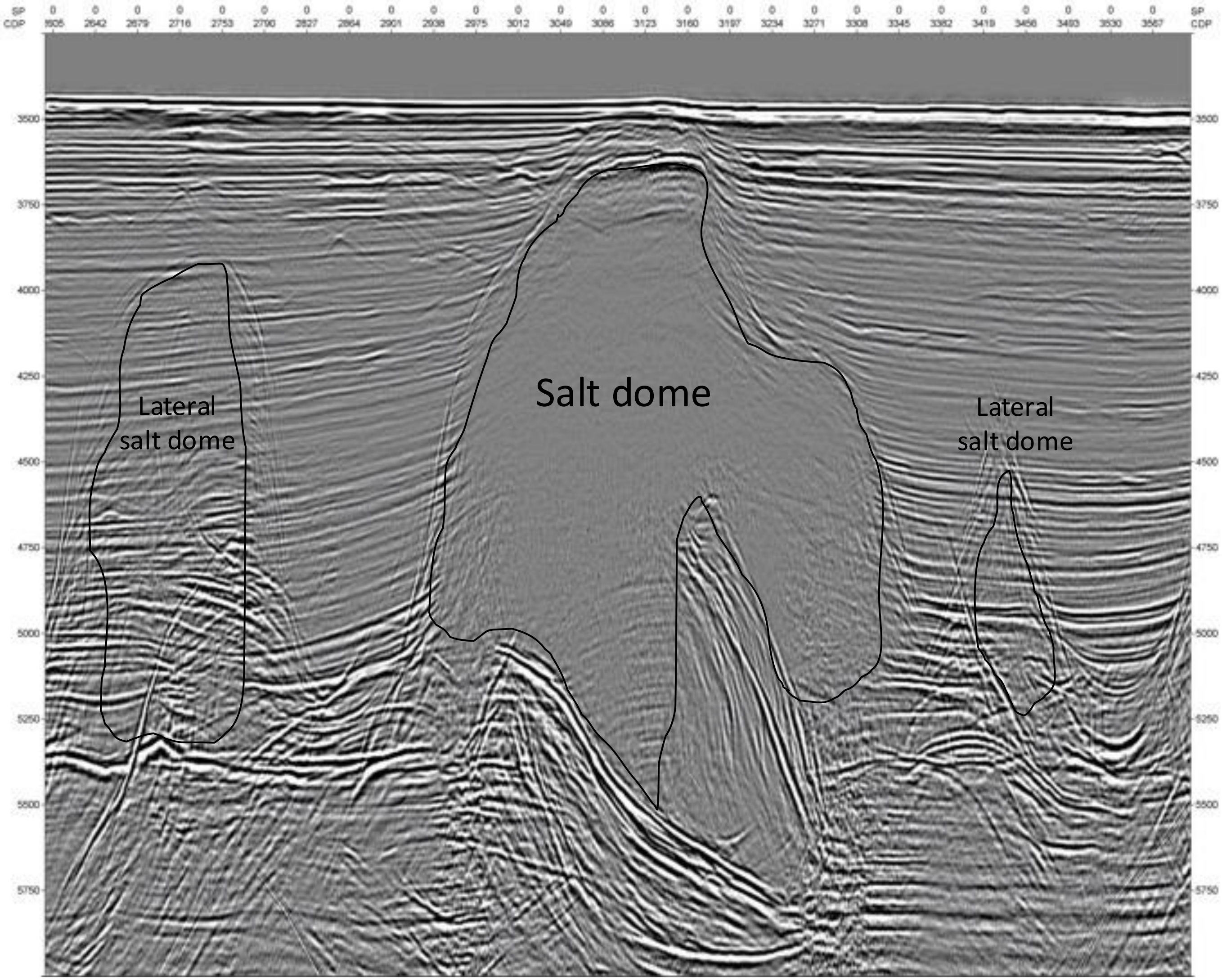
2D and 3D migration

The image shows an example of a 3D geological model with two anticlinals (green and yellow object) and a direct fault (red and blue objects).
The seismic data along line 6 shows the comparative effects of 2D and 3D migration (from French, 1974).
Only 3-D migration is able to provide a seismic profile faithful to the real situation of pending layers. However, the 2-D migration provides an often satisfactory result for interpretation.



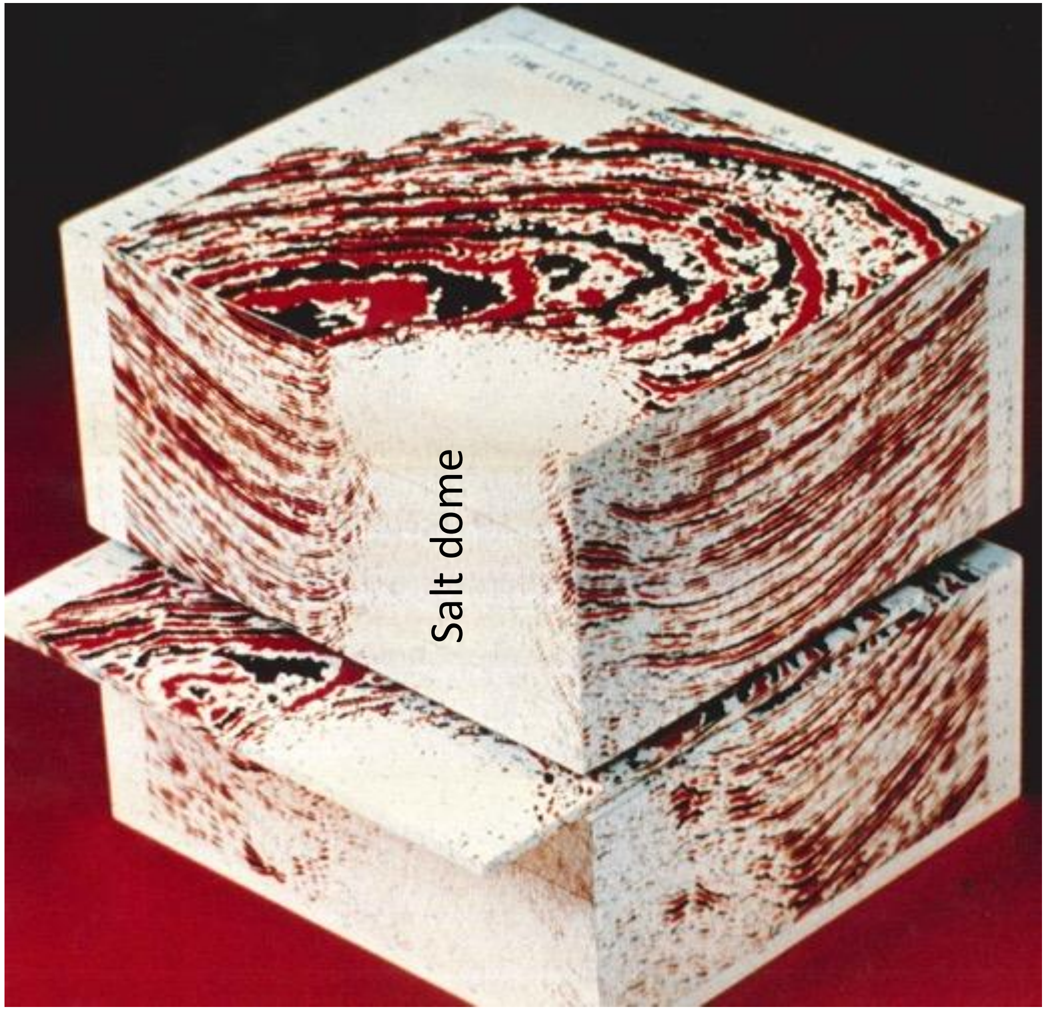
From French, 1974

2D migration



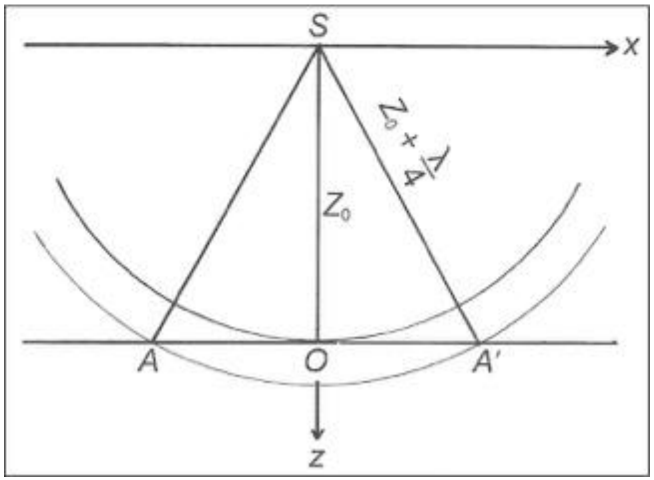
Example of 2D migrated seismic profile with the presence of salt domes, some of which are lateral to the vertical plane of the section.

3D migration

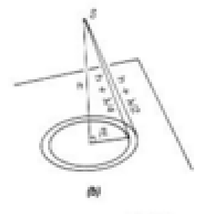


Example of "3D cube" from Brown (1986)

Lateral Resolution



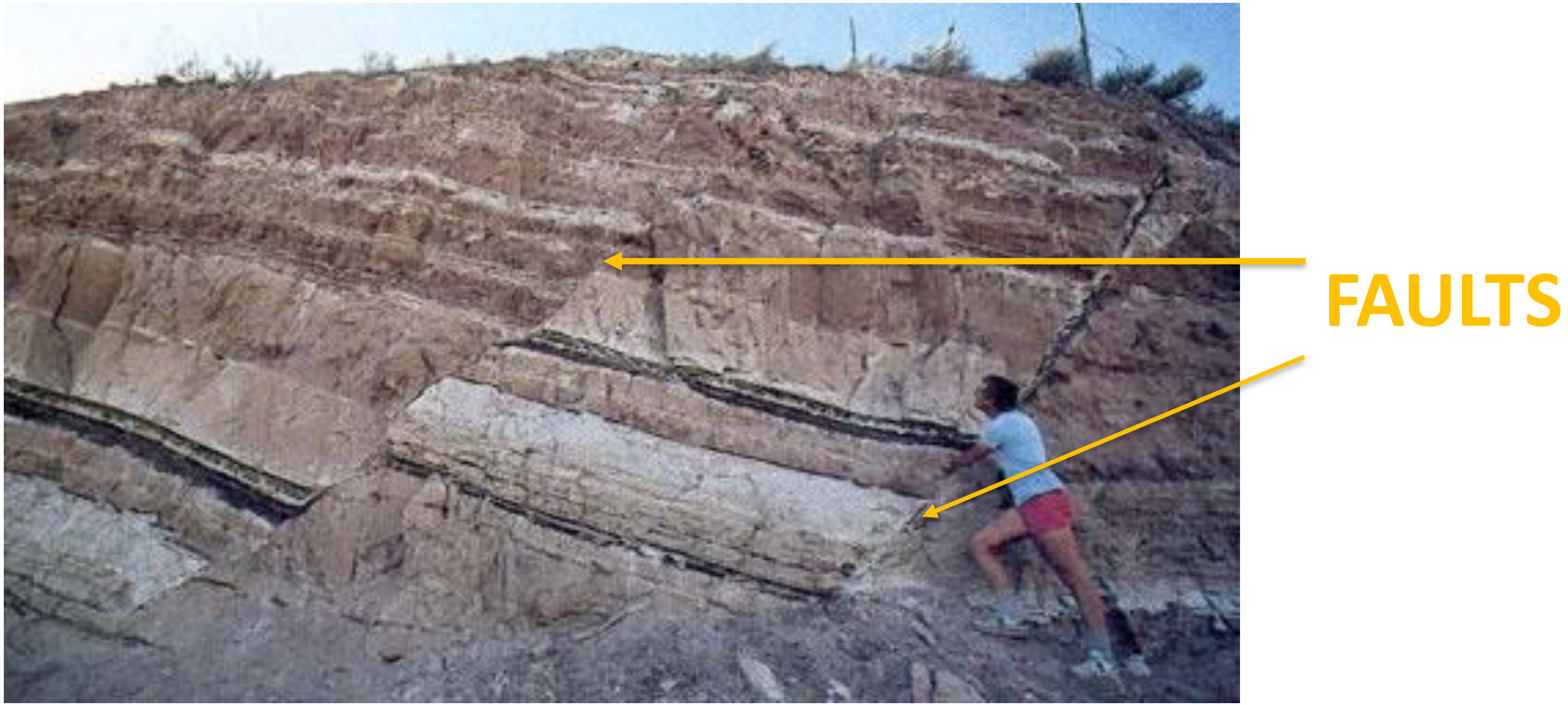
Definition of the Frensnel zone AA'



$$r = (v/2)\sqrt{t_0/f}$$

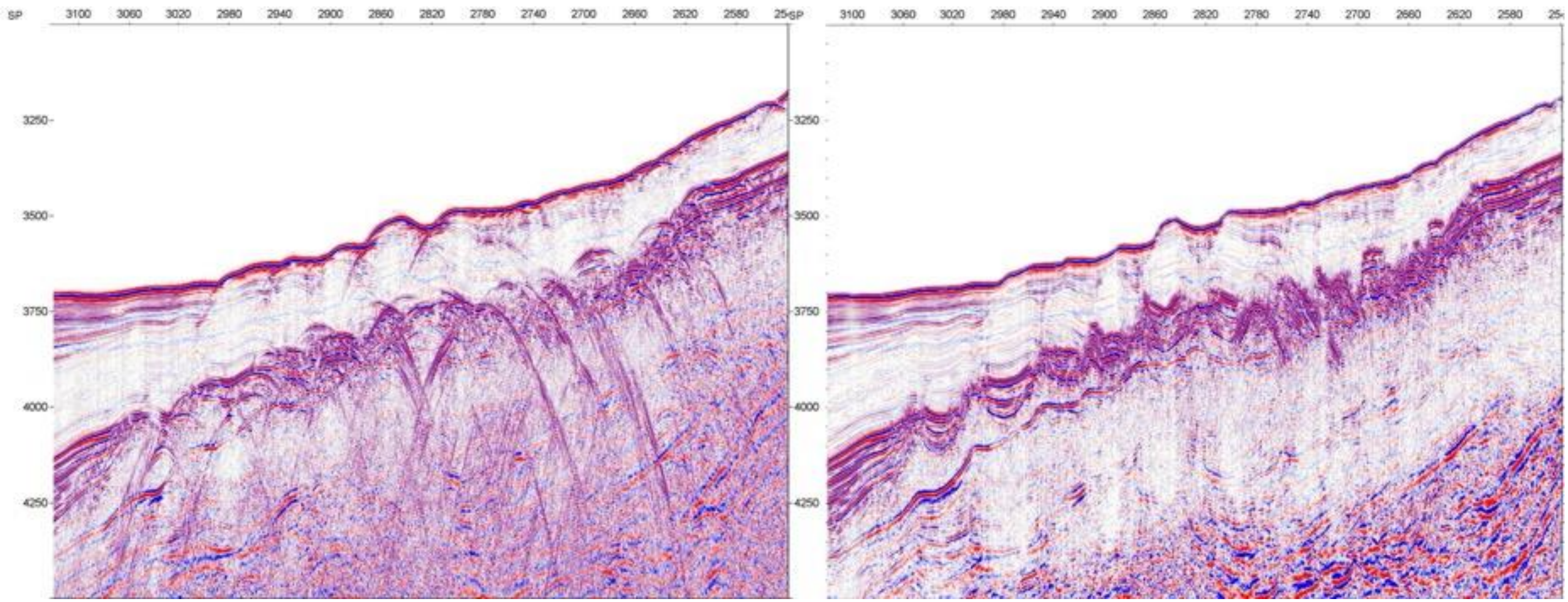
t_0 (s)	v (m/s)	f (Hz)	r (m)
1	2000	50	141
2	3000	40	335
3	4000	30	632
4	5000	20	1118

Threshold for lateral resolution (t0 = 2z/v, r=OA)



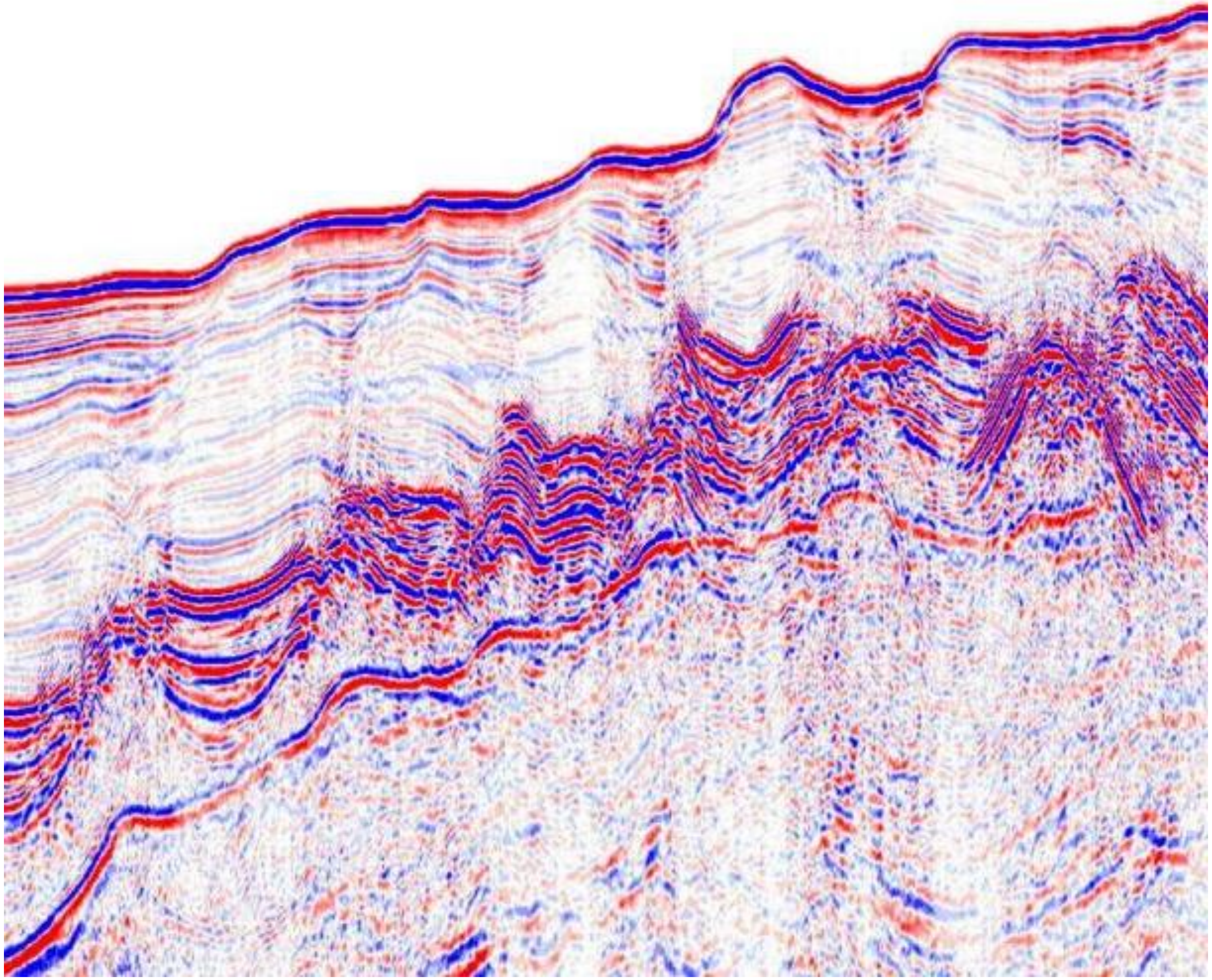
Example of faults in the geological layers.
The faults represent points of inhomogeneity that originate diffractions. You can see the geological layers that are dislocated by the faults

Migration: diffraction collapse



(a) (b)

Seismic section (a) before and (b) after migration: the diffractions have been collapsed and the faults are evident.
The presence of diffractions can sometimes create difficulties of interpretation: the point of breakage of the reflector is not easily identifiable in the non-migrated section. In the case b) the section was migrated and the base of the salt layer is more evident then in stack section a)



Blow up of the previous seismic image

Geologic model
x,y,z

Velocity

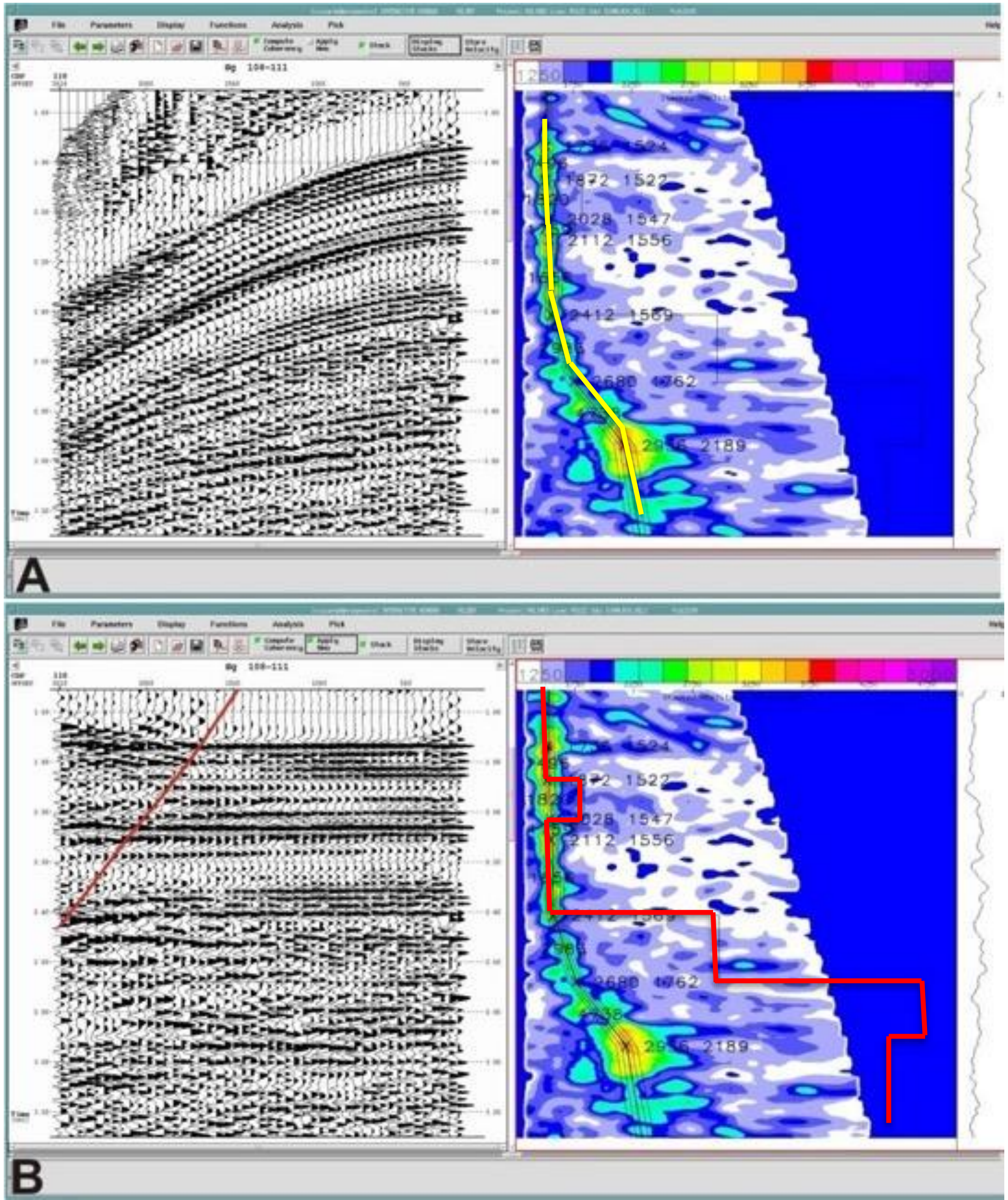
Seismic section:
x,y,t

Velocity field of the seismic waves is the parameter that allow to get the geologic model from the seismic section

Velocity analysis

A: a common mid-point trace gather (left) and semblance coherence contour (right).

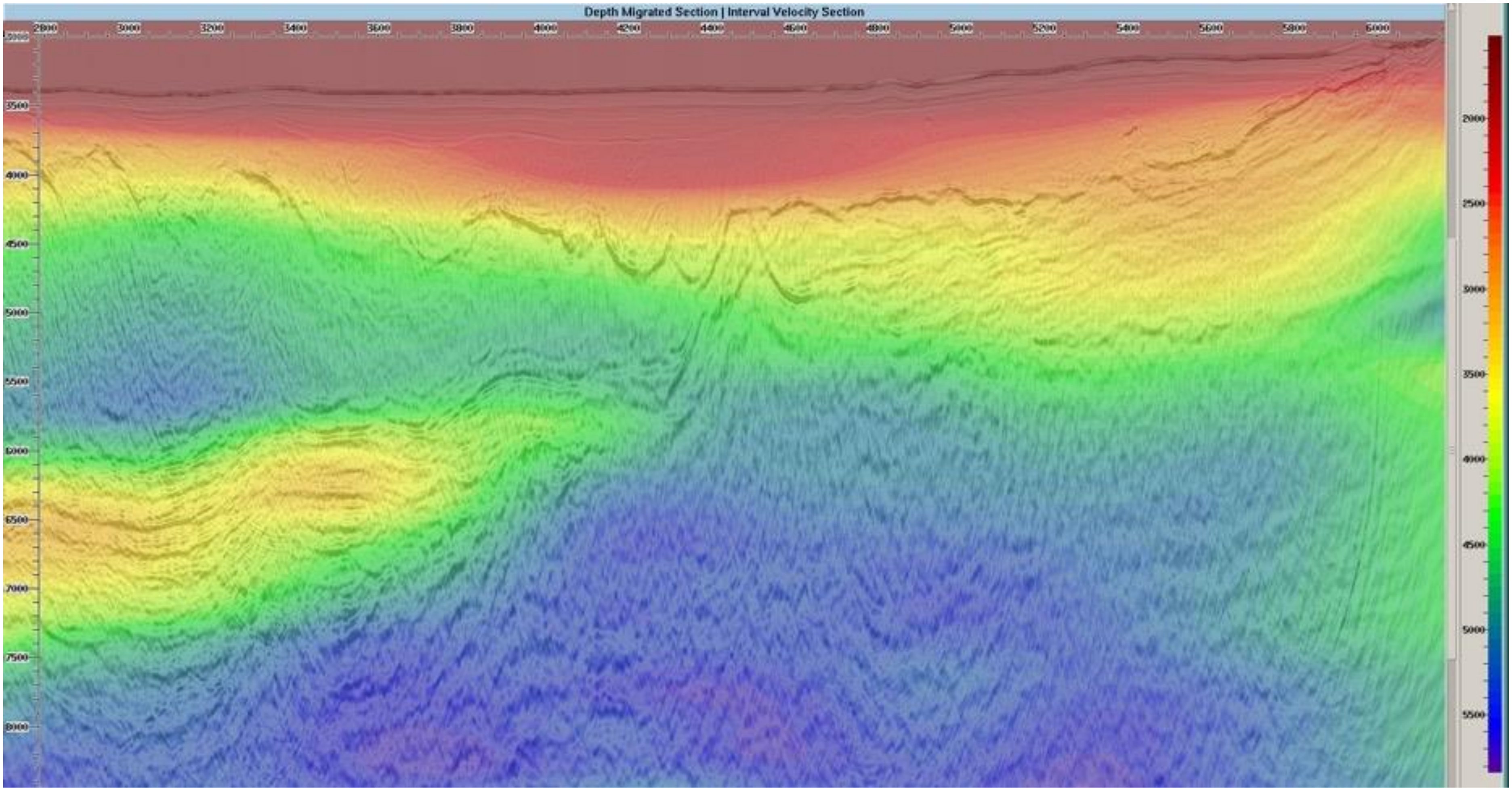
Peaks in coherence give the stacking velocity. (yellow line)



B: The same common mid-point trace gather of A with the normal move-out correction (NMO) after the velocity picking (yellow function). The interval velocity (red function) associated to this stacking velocity it will use in migration process.

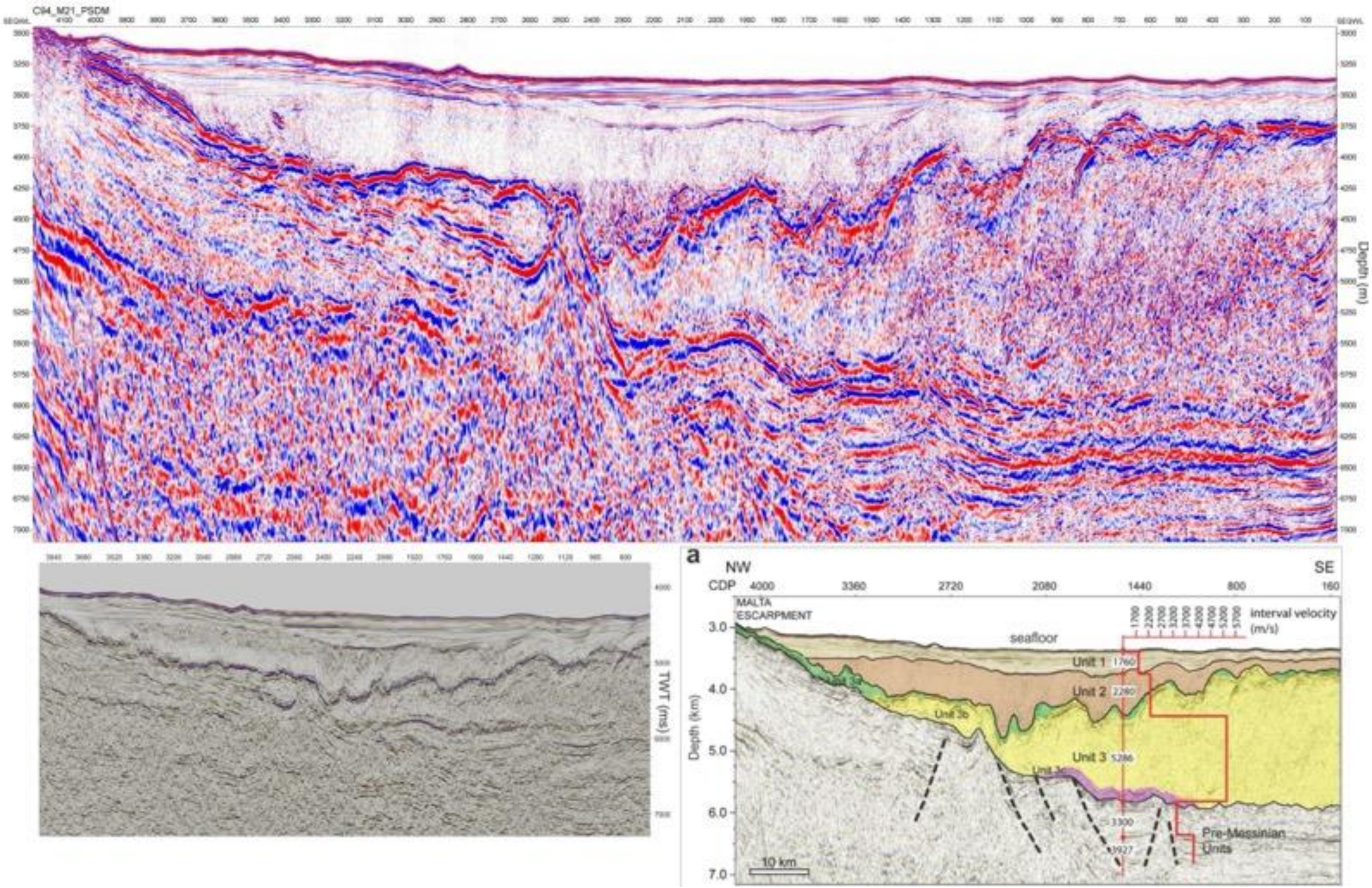
The field velocity section can be obtained from the seismic data using the stack velocities. We are going to flatten the reflections in CDP gather as in the image, picking the maximum coherence in the semblance. In this way velocity functions are obtained which we will interpolate with the others in order to have a section.

Velocity field and depth migrated seismic section



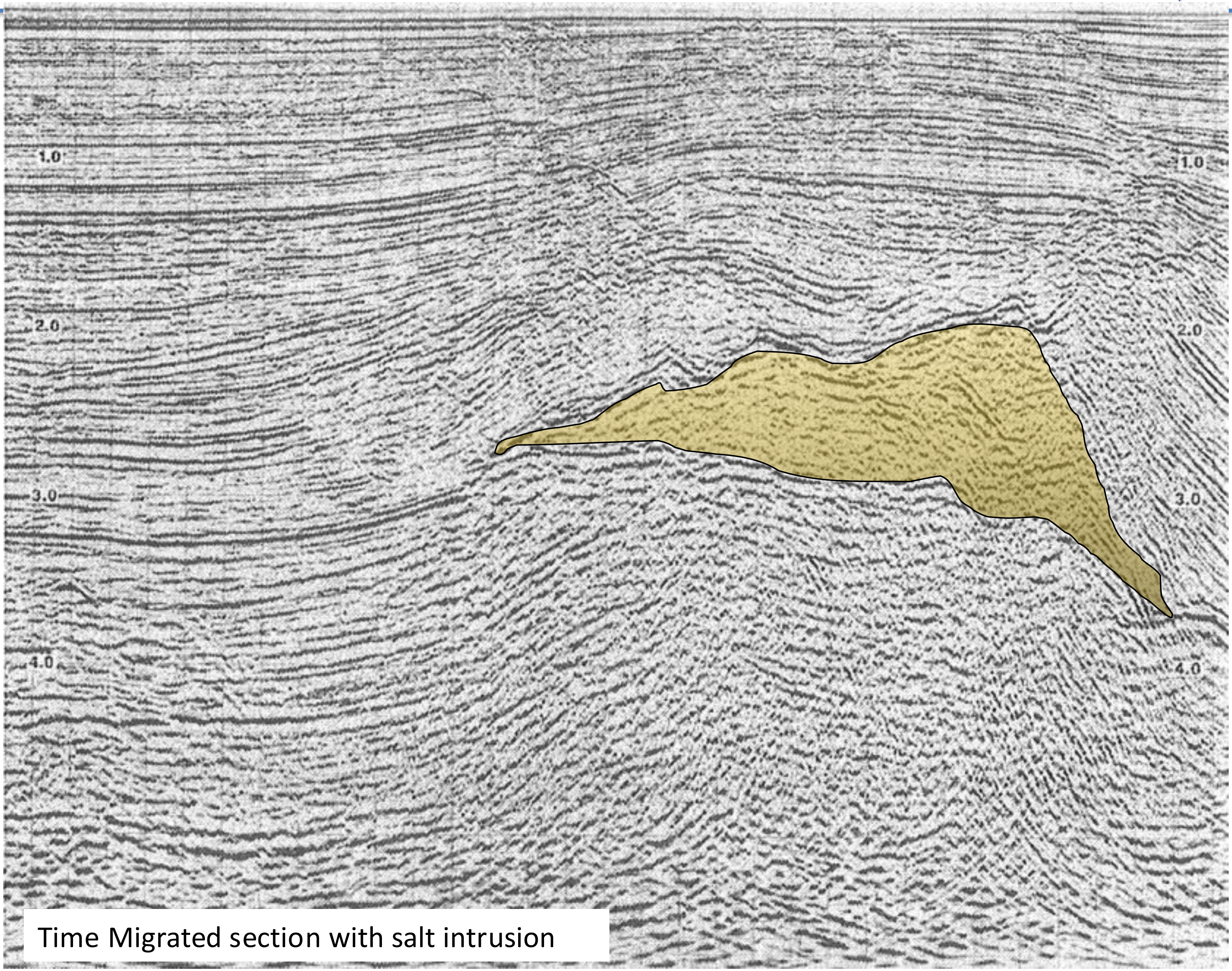
Example of Pre Stack Depth Migrated section with its velocity field superimposed (see next slide for the interpretation)

Depth migrated seismic section

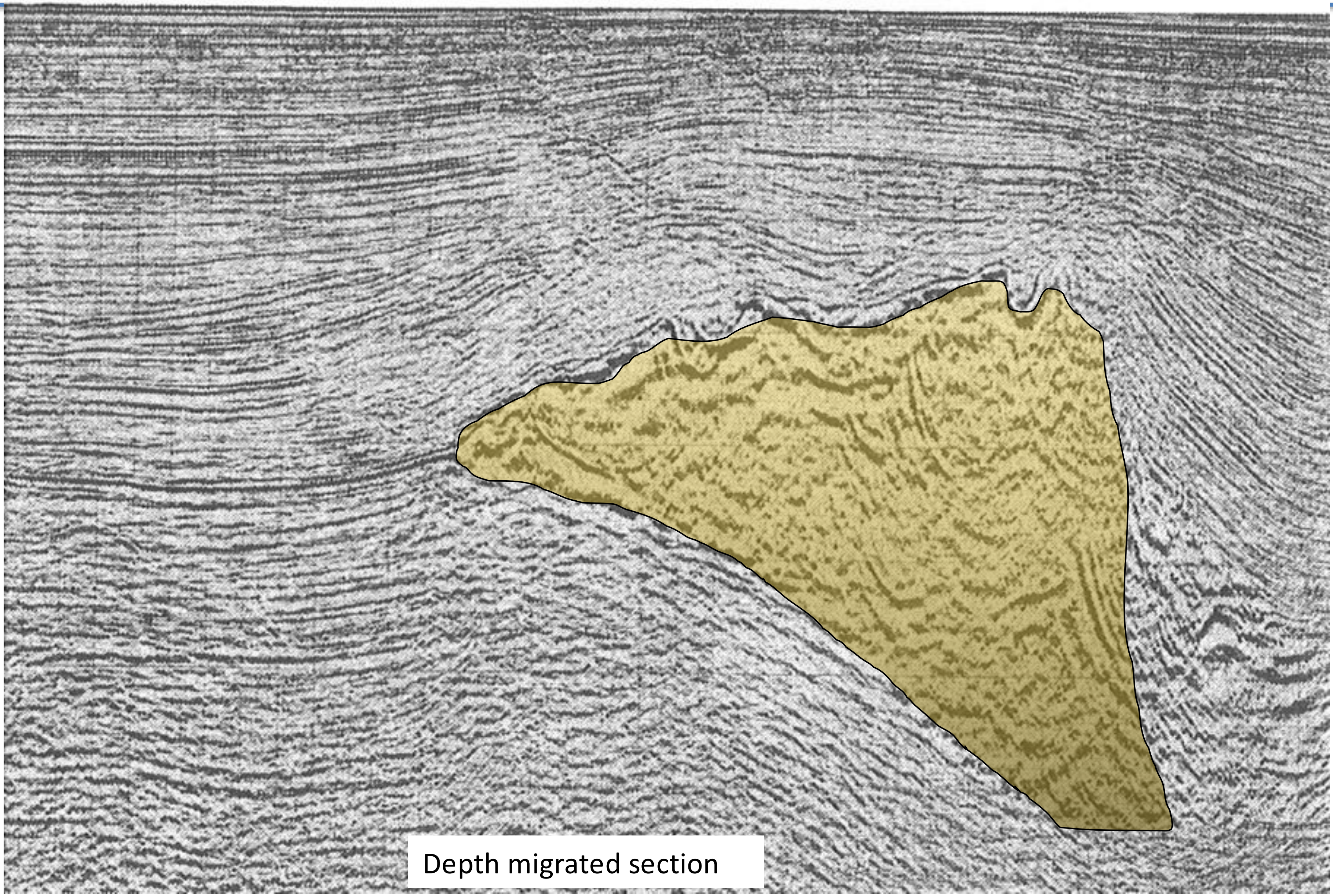


(from Micallef et al., 2018)

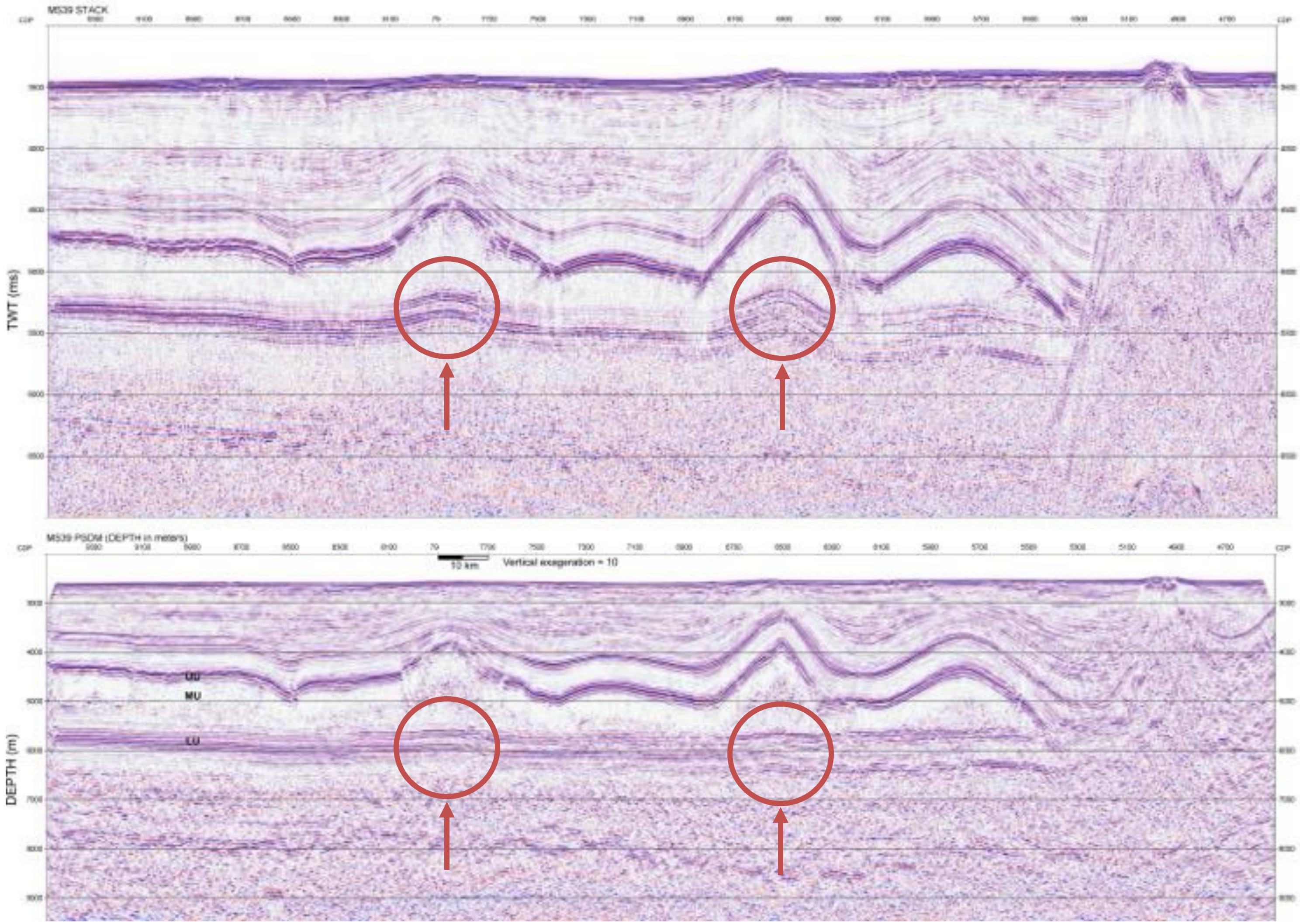
Example of Pre Stack Time/Depth Migration section and the interpretation superimposed with velocity function.



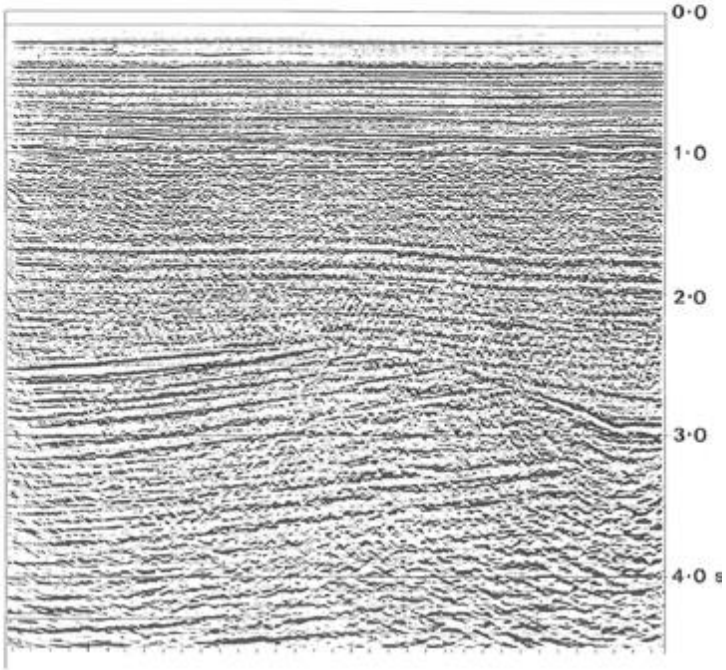
Time Migrated section with salt intrusion


Depth migrated section

Pull up velocity effect



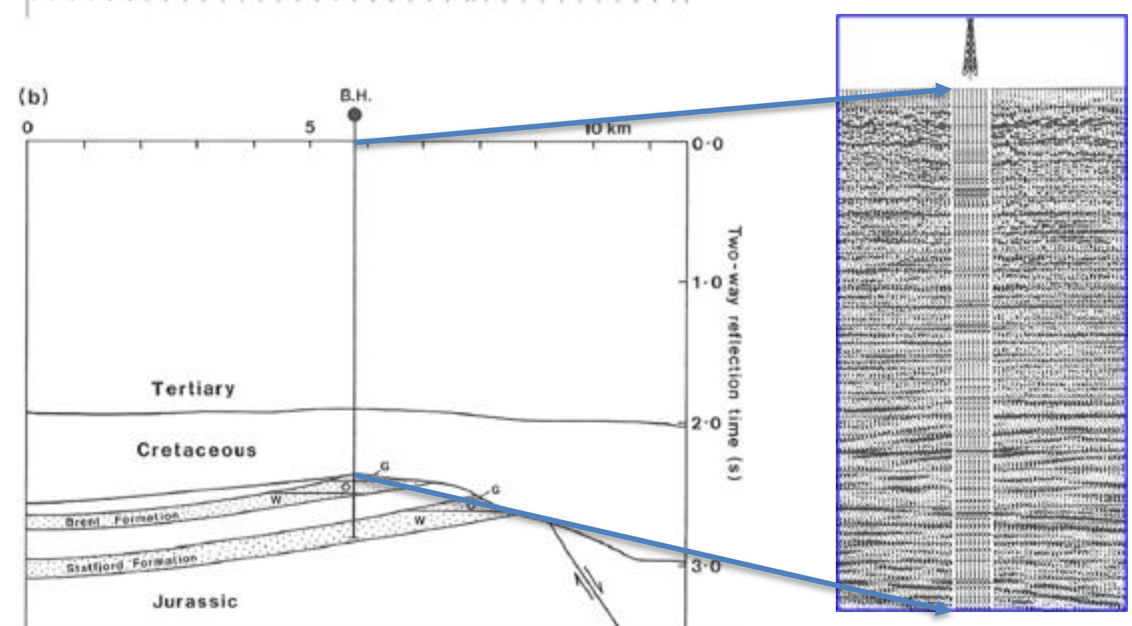
(Above) Result of data processing in time domain: the pull-up event (red circles) of about 200 ms occurs beneath a salt dome and affects the underlying layers. (below) Result of Pre-Stack Depth Migration (PSDM) showing flattened pullup event. (modified from Dal Cin et al. 2016)



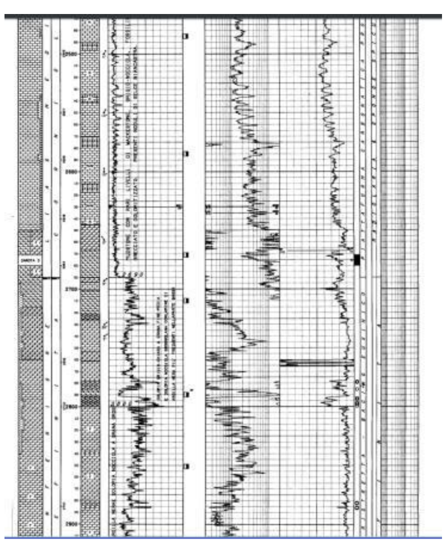
Vertical Seismic Profiling (VSP) in seismic interpretation

Example of correlation of well data (VSP) with the seismic section for geological interpretation

In some case we have a borehole across the seismic section and we can correlate these two type of data. From this we can therefore give a lithological meaning to the individual reflectors of the seismic profile passing through the well. In the image below and on the right, we can see an example of correlation between the seismic profile and the data obtained from the registration of the VSP in a borehole. The VSP was made after the geologic sampling in the same borehole.

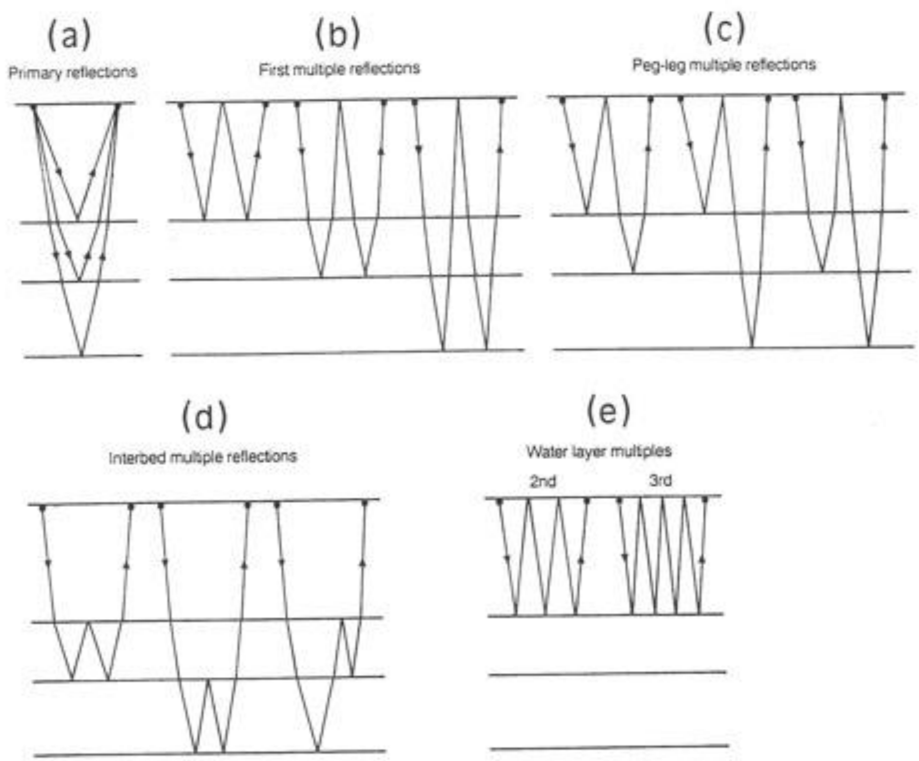


Well



- MULTIPLE REFLECTIONS –

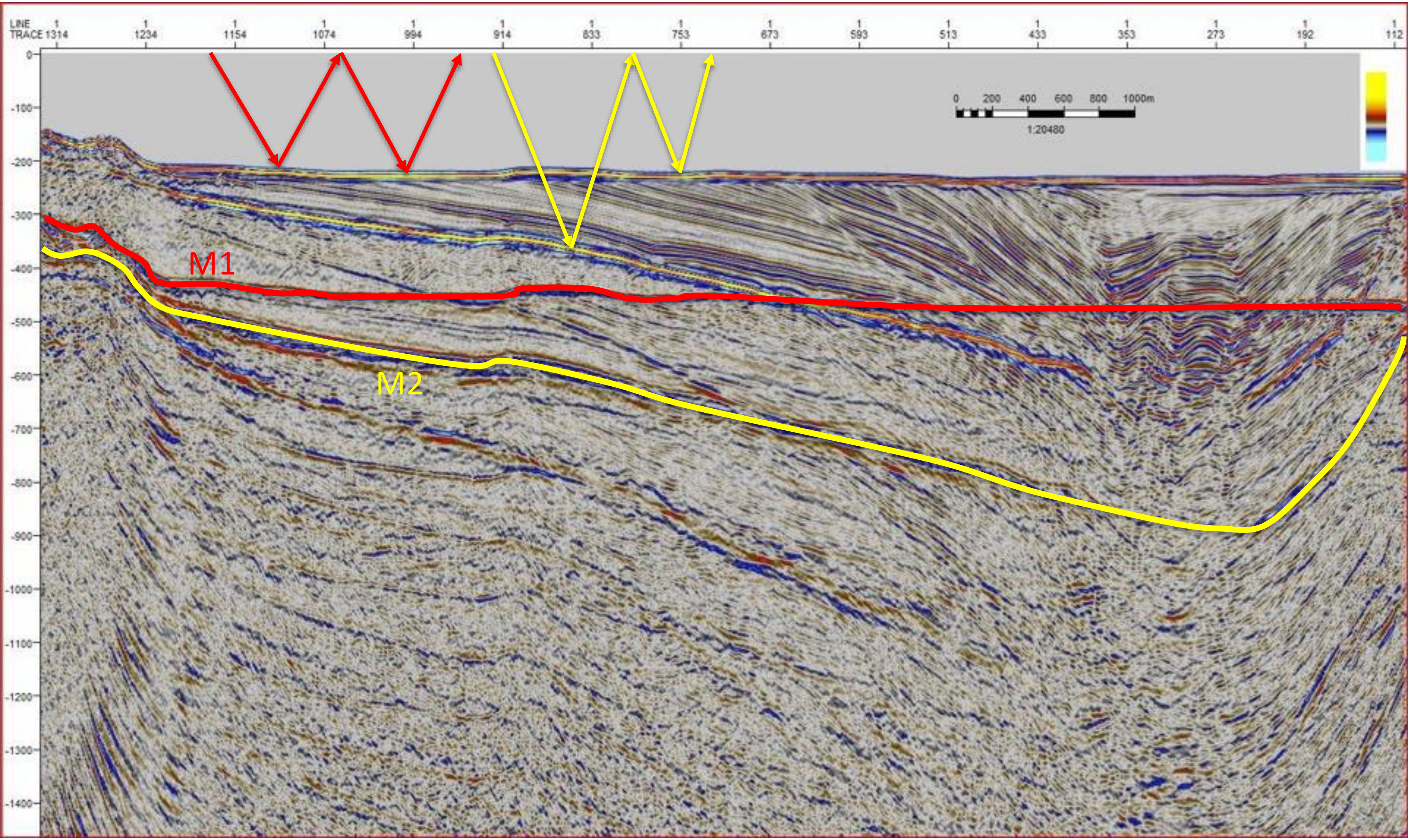
The problem of cherent noise in marine seismic profiles



Long-path multiples appear as distinct events. Short-path multiples are added to primary reflections and tend to come from shallow subsurface phenomena

The marine seismic dataset is often characterized by the presence of multiple reflections that affect the quality of the section itself. The multiple are the coherent noise that it leads to the misinterpretation of real reflective horizons. There are a lot of type of coherence noise, but the first water bottom multiple reflections are the most frequently.

MULTIPLE REFLECTIONS

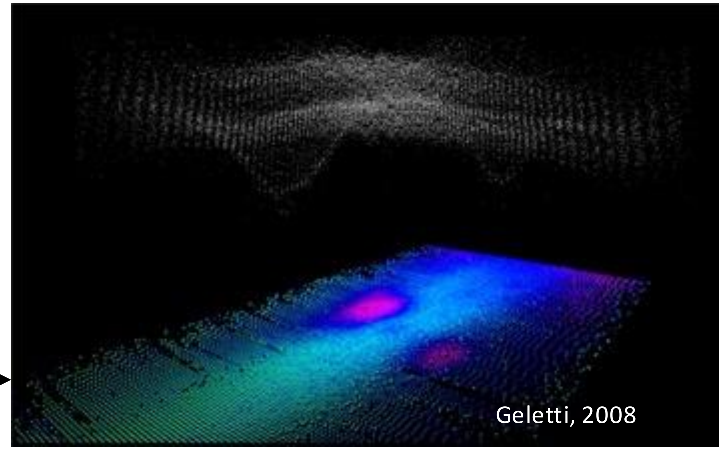


Example of seismic stack section with multiple reflections (M1 and M2)

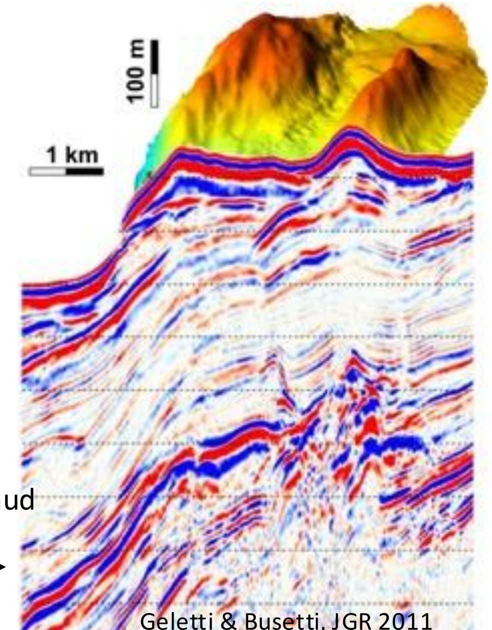
Gas seeping features

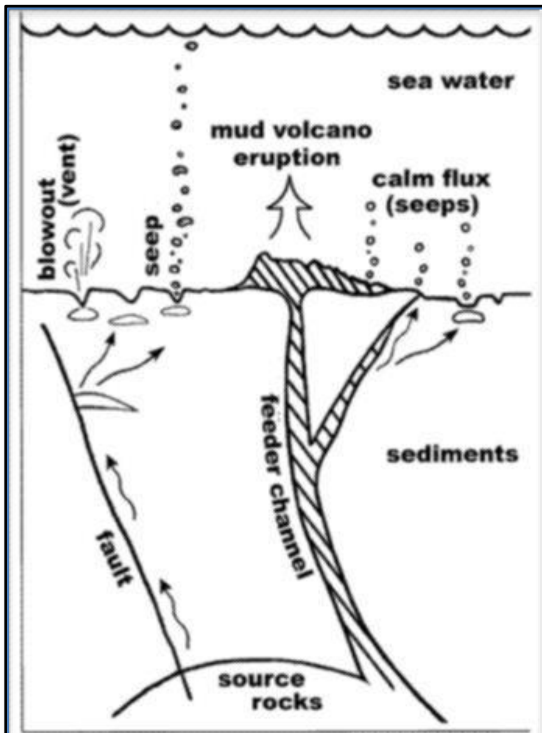
Mud volcanoes and pockmarks

MB data with pockmarks

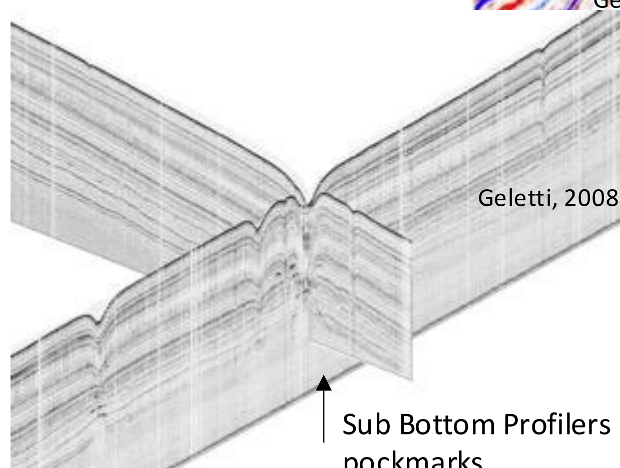


Seismic line & MB image with mud volcano



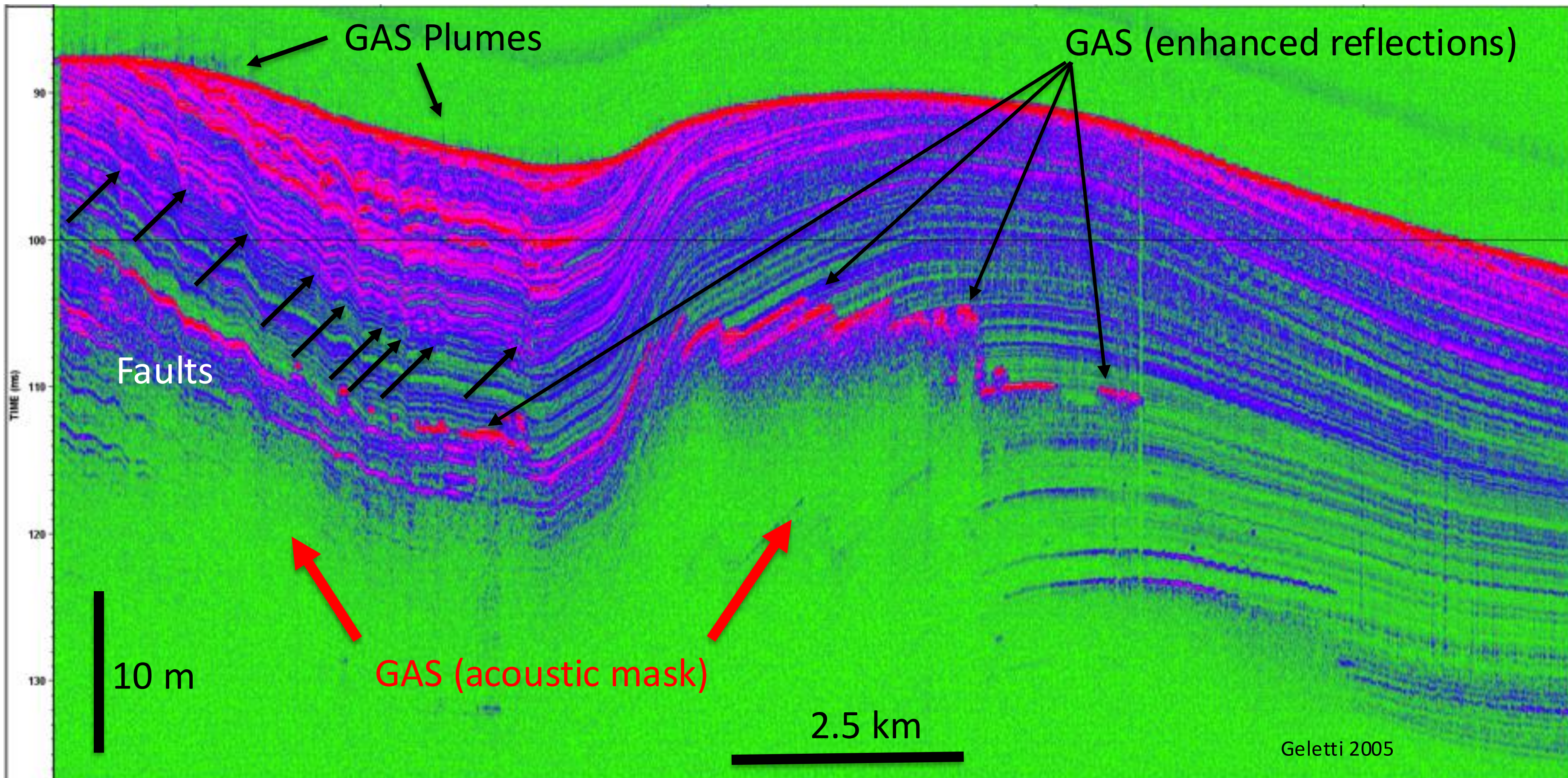


Schematic model of gas seeping related upward fluid migration

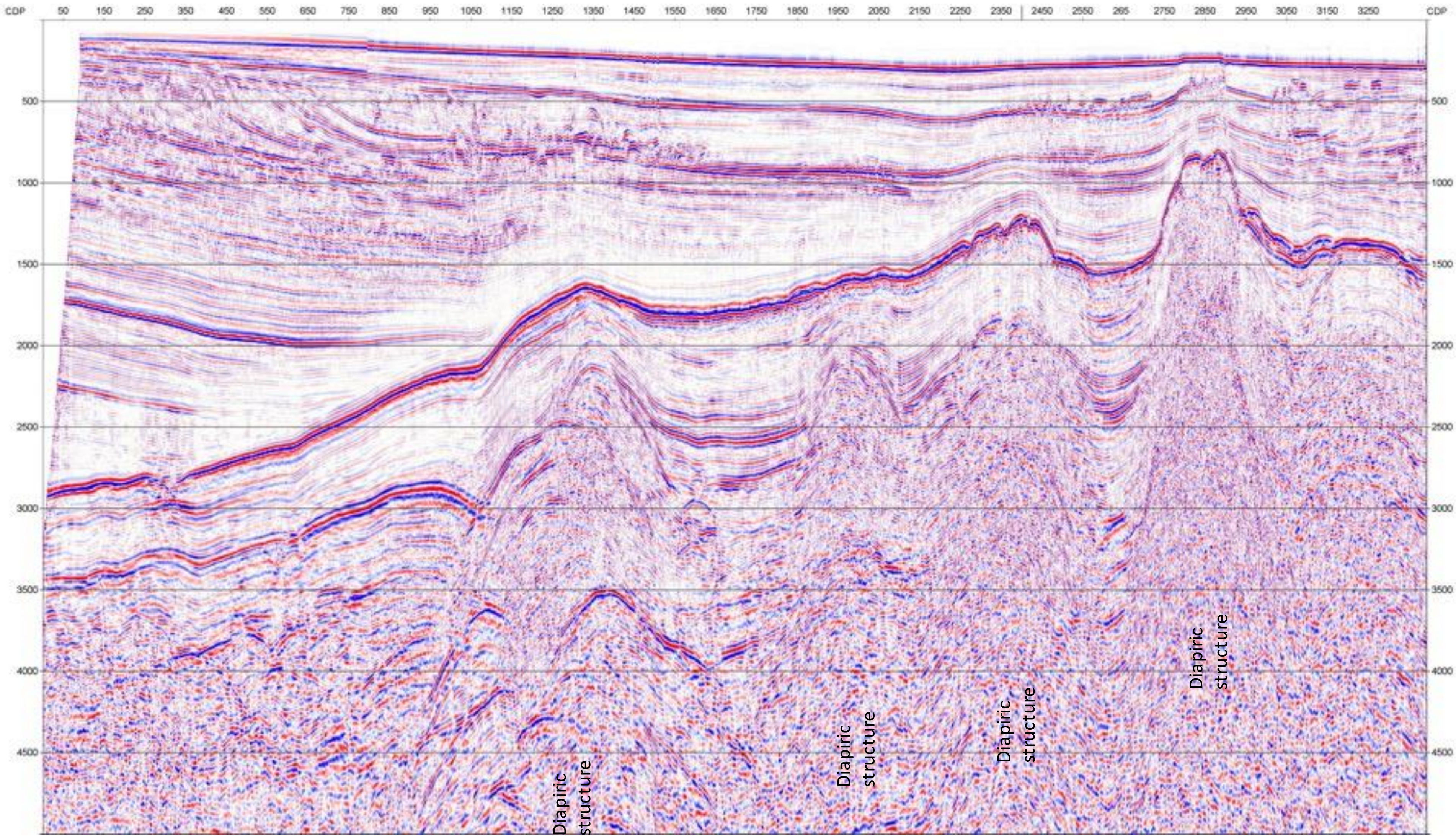


Sub Bottom Profilers (CHIRP) with pockmarks

Some example of gas seeping features. Sea bed fluid flow, also known as submarine seepages, involves the flow of gas and liquids through the seabed. This geological phenomenon has widespread implications in seabed slope instability, drilling hazard, hazards to seabed installations and so on. Seabed fluid flow affects seabed morphology (pockmarks, mud volcanoes). Natural fluid emissions also have a significant impact on the composition of the oceans and atmosphere: methane emissions have important implications for the global climate change.



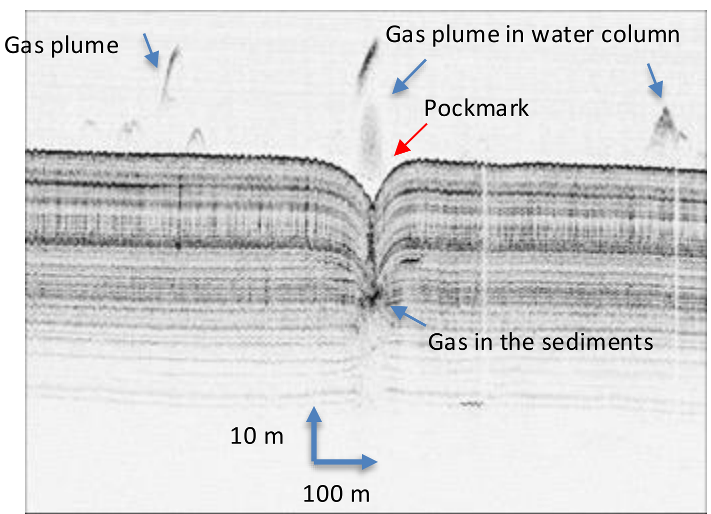
Echosounder CHIRP profile where there are gas evidences

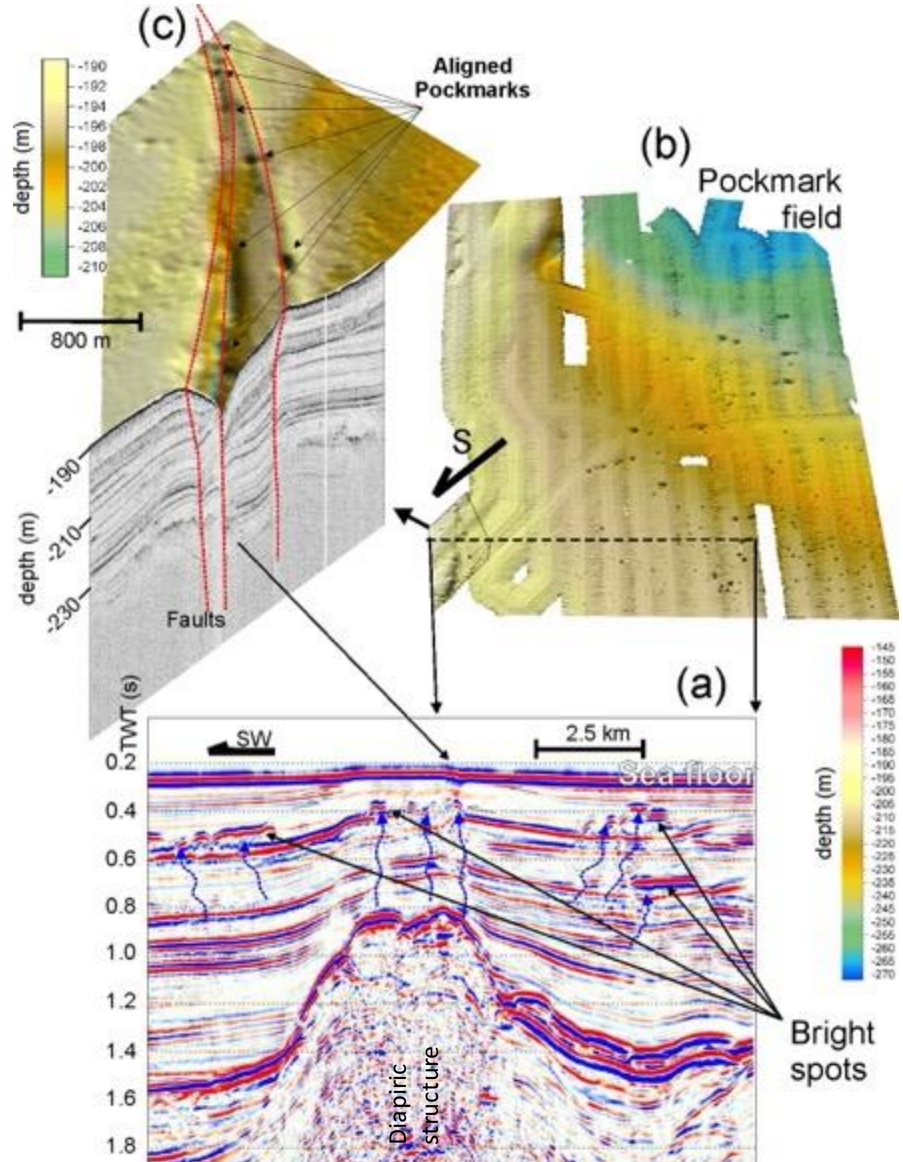


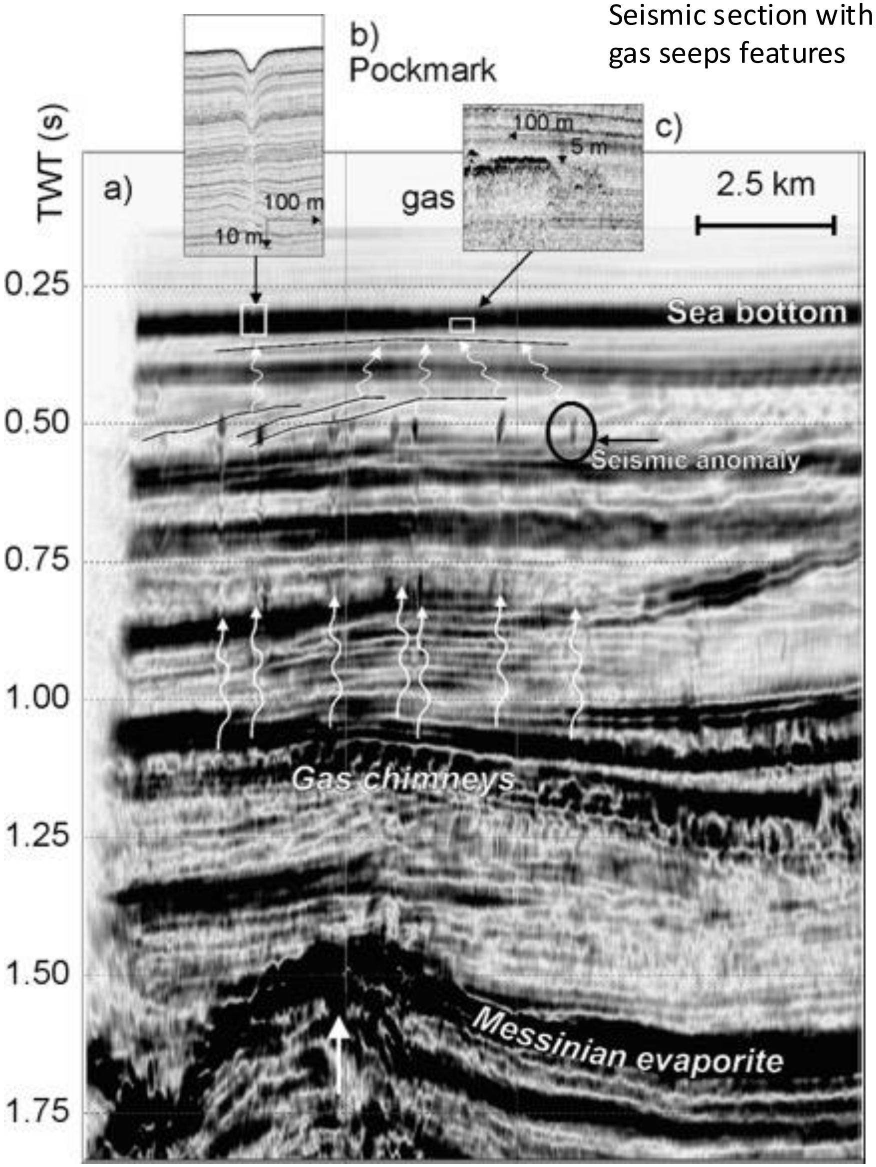
Crustal seismic profile CROP- M15

a) Image of the seismic reflection profile with the evidence of bright spots indicating the presence of gas in the Plio-Quaternary sediments, b) multibeam bathymetry (MB) and a pseudo 3D image (c) with CHIRP profile and MB where it is highlighting a system of active faults along which some pockmarks can be identified. The seismic line shows the presence of a deep diapiric structure that also deforms the sea floor

Detail of the CHIRP line with evidence of gas plume



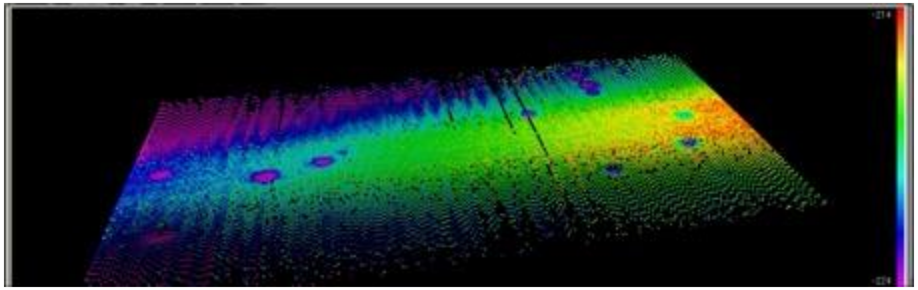


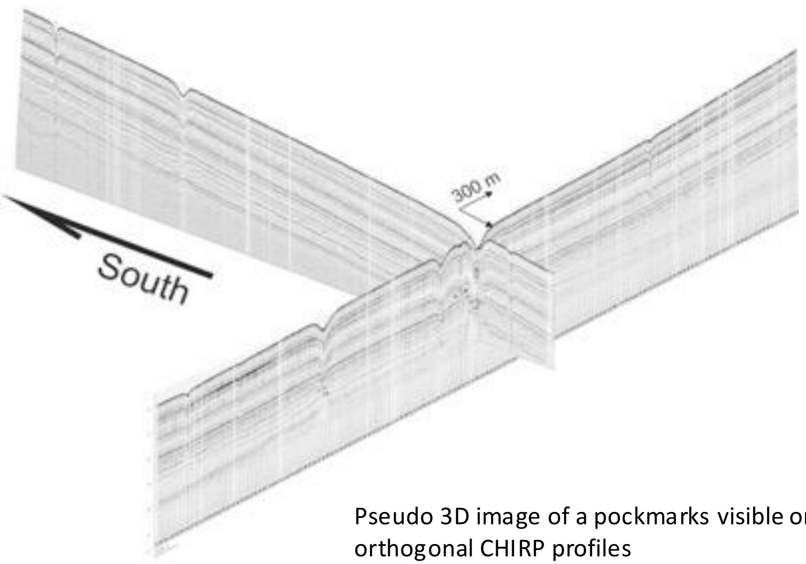


Seismic section with gas seeps features

In this slide there are some images of gas/fluid presences within the sediments. On the right, above you see an image of pockmarks on swath bathymetry of multibeam. Below, two chirp profiles. On the left side you see a seismic section where at a deep of 400/450 m there are seismic anomalies below superficial gas evidence in chirp profiles

Image of Pockmarks in MB data





Pseudo 3D image of a pockmarks visible on two orthogonal CHIRP profiles

Conclusion - 1

The Multi-Channel Seismic Reflection (MCS) method is:

- The most widespread method for the geophysical prospecting of the subsoil, fundamental in the exploration of hydrocarbon reservoir.
- It provides more detailed information than any other non-invasive method on stratigraphy, structure and properties of materials.
- It uses arrival times, amplitude and phase of the echoes from the discontinuity in the elastic properties present in the subsoil to obtain its position and physical properties (acoustic impedance, velocity propagation of seismic waves, elastic parameters, ...).

Disadvantages of the MCS method:

- High costs of data acquisition (R/V OGS Explora ship time - > 15-20 K€ a day)
- Complex signal processing required
- Numerous specialized people needed
- For a survey, numerous permits and authorizations are required

Conclusion - 2

The seismic reflection interpretation attributes geological meaning to geophysical data.
Interpretation provides information on:

- geometry of stratigraphic sequences and structural/tectonic elements
- seismic wave velocity
- Lithological characteristics

Applications for reconstructions of 2D section, structural maps, fault systems, slumping and seismic hazard.
The interpretation is made by a team of geologists / geophysicists / physicists with different skills who work in synergy.

“Interpretation is a combination of both art and science “ (Lines and Newrick, 2004)

Questions

1. What is a seismic section?
2. What is the difference between seismic and geological section?
3. What is the vertical scale in a seismic section?
4. Which is the difference between seismic stack section and migrated section?
5. What is a diffraction?
6. What is a «bow-tie» event?
7. What is a multiple reflection?
8. What are the advantages of a migrated section?
9. Which seismic parameter is fundamental in depth migration?
10. Which is the first reflection in a marine seismic section?
11. What is the *acoustic basement*?
12. What is a « bright spot» in a seismic section?
13. What are the seismic characters that identify the possible presence of gas in the sediments?
14. What are the gas seeping structures?
15. What is the best acoustic method to study these structures?

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- Lines and Newrick - FUNDAMENTALS OF GEOPHYSICAL INTERPRETATION
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- Anstey - SEISMIC INTERPRETATION - The Physical Aspects
- Herron – FIRST STEP IN SEISMIC INTERPRETATION
- Hovland & Jadd - Seabed Pockmarks and Seepages
- Jadd & Hovland – Seabed Fluid Flow

Websites:

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- Virtual Seismic Atlas: http://see-atlas.leeds.ac.uk:8080/home.jsp