Geophysical methods in geothermal exploration and reservoir characterization: 3-D seismics

Talking about:

1. Mapping geothermal features
2. Geochemical exploration
3. Seismic exploration
4. Electrical/EM methods and shallow wells for thermal gradient
5. Slim hole

Talking about (2):

1. OBJECTIVES
2. KEY ISSUES (PHYSICAL PROPERTIES, SEISMIC TOOLS)
3. PROBLEMS AND PITFALLS

NOT talking about:

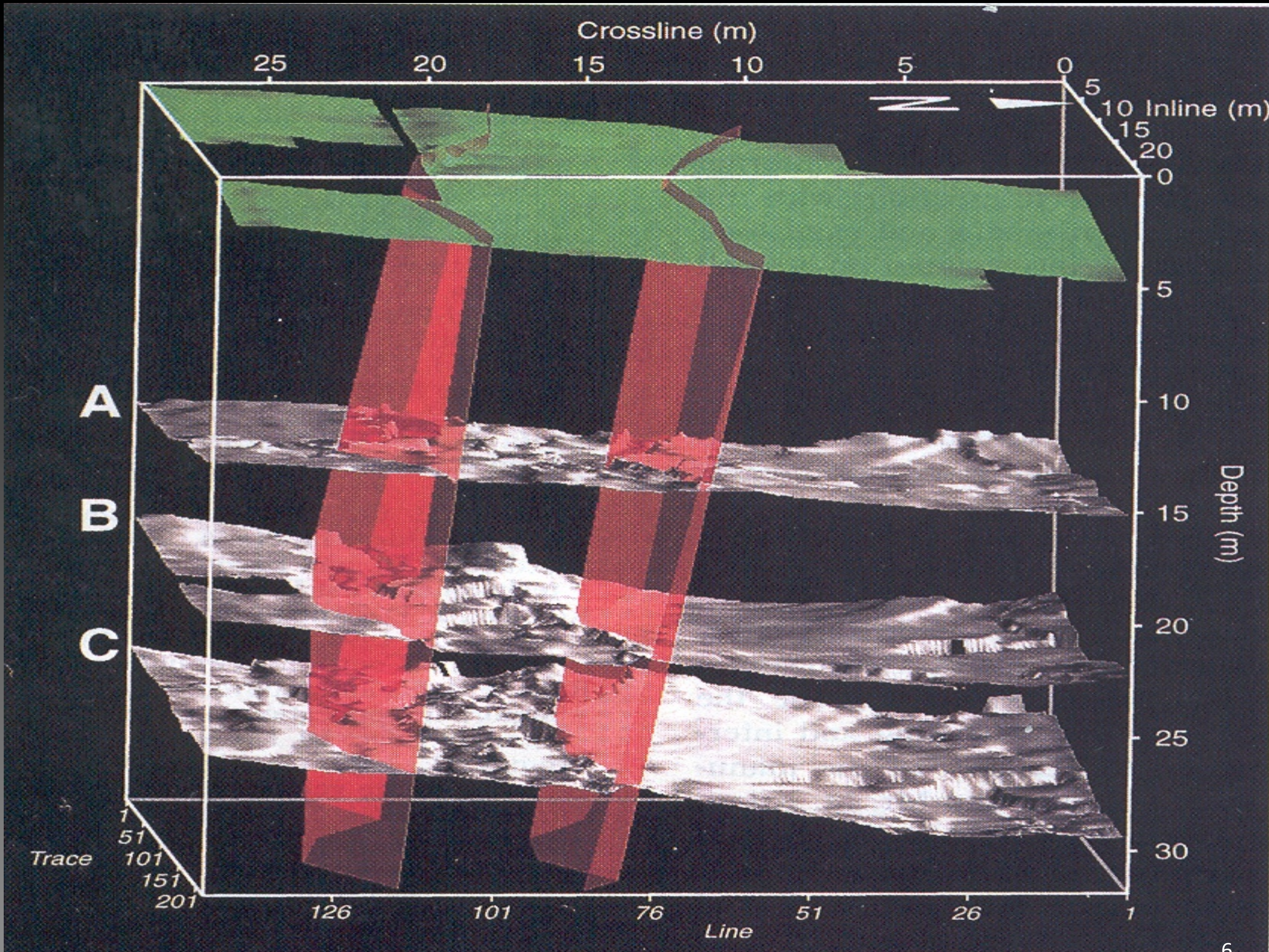
1. Seismic survey design and data acquisition tools

2. Details of seismic data processing

The geophysical problem

- Depth and shape of geological structures

- Characterization of subsurface materials (lithology and fluid information)


Crossline (m)
25 20 15 10 5 0
N
5 10 Inline (m) 15 20
0 5 10 15 20 25 30
Depth (m)
A
B
C
Trace
1 51 101 151 201
126 101 76 51 26 1
Line

Waves

- Elastic waves are generated whenever there is
  - a sudden deformation
  - a sudden movement of a portion of the medium

Waves

- Examples of man-made seismic sources
  - Explosion
  - Weight drop
  - Drilling
  - Vibroseis (tractions), ...

Elastic waves

When a stress is applied (or released) the corresponding strain propagates out from the source.

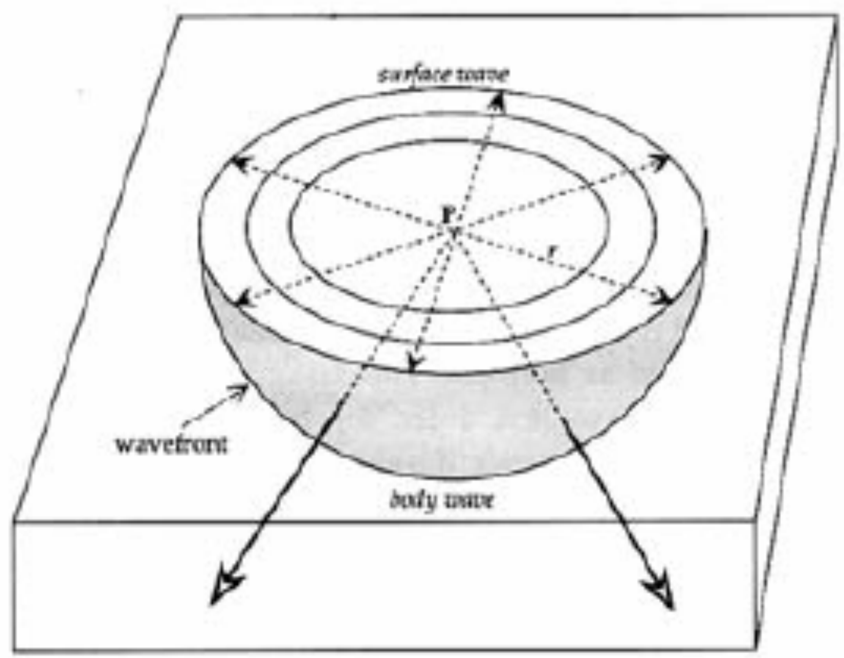


Fig. 3.9 Propagation of a seismic disturbance from a point source P near the surface of a homogeneous medium; the disturbance travels as a body wave through the medium and as a surface wave along the free surface.

Point source seismic disturbance:

- Wavefront expands out from the point: **Huygen's Principle**
- Body waves: sphere
- Surface waves: circle
- **Rays**: perpendicular to wavefront

P and S-velocities

P-velocity

$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

change of shape and volume

S-velocity

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

change of shape only

For liquids and gases $\mu = 0$, therefore

➔ $V_S = 0$ and V_P is reduced in liquids and gases

➔ Highly fractured or porous rocks have significantly reduced V_P

The bulk modulus, κ is always positive, therefore $V_S < V_P$ always

P-waves are the most important for controlled source seismology

- They arrive first making them easier to observe
- It is difficult to create a shear source, explosions are compressional

PARAMETERS AFFECTING VELOCITIES

$$V_p = \sqrt{\frac{K + 4/3\mu}{\rho}}$$

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

DENSITY (ρ) **COMPRESSIBILITY ($1/k$)** **RIGIDITY (μ)**

DEPTH

PORE FLUIDS

LITHOLOGY

CEMENT

POROSITY

COMPACTION

PRESSURE **TEMPERATURE**

ANISOTROPY

GASSMAN FORMULA (1951)

$$\frac{K_{sat}}{K_m - K_{sat}} = \frac{K_d}{K_m - K_d} + \frac{K_{fl}}{\phi(K_m - K_d)}$$

EFFECTIVE BULK MODULUS OF SATURATED ROCKS

As a function of bulk moduli of:

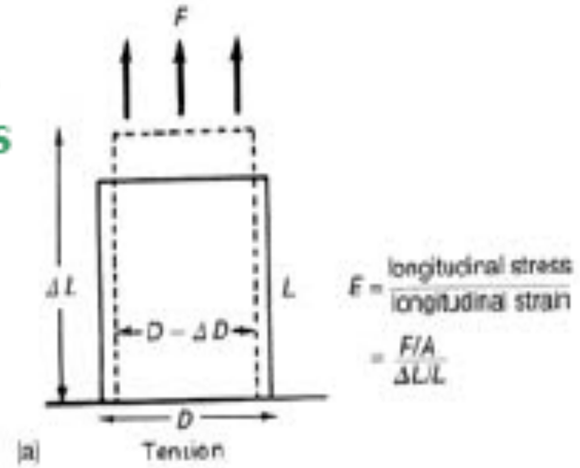
- minerals
- dry rock
- fluids

AND POROSITY

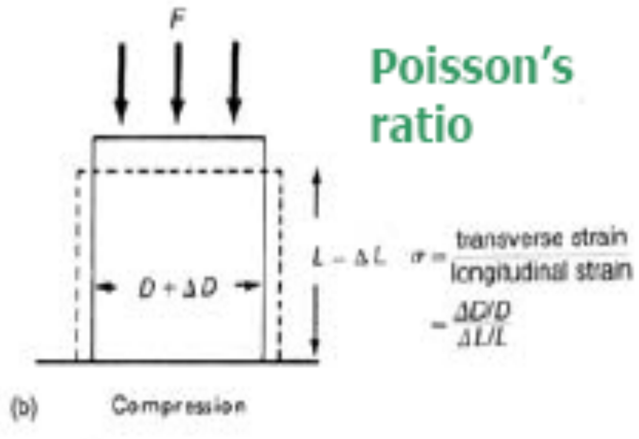
Elastic moduli

describe the physical properties of the rock
...and determine the seismic velocity

Young's modulus

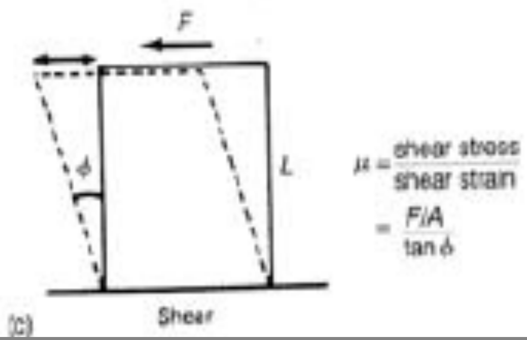


Poisson's ratio



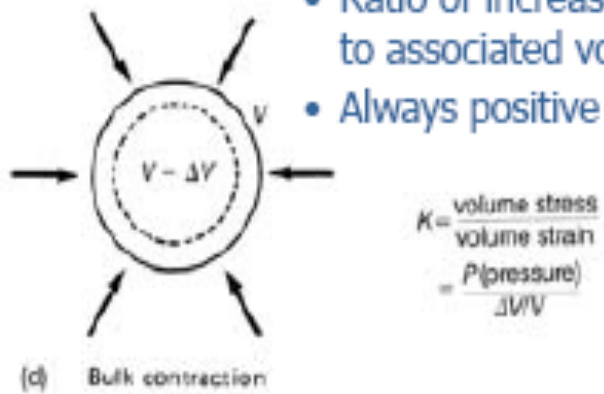
Shear modulus, μ

- Force per unit area to change the shape of the material



Bulk modulus, κ

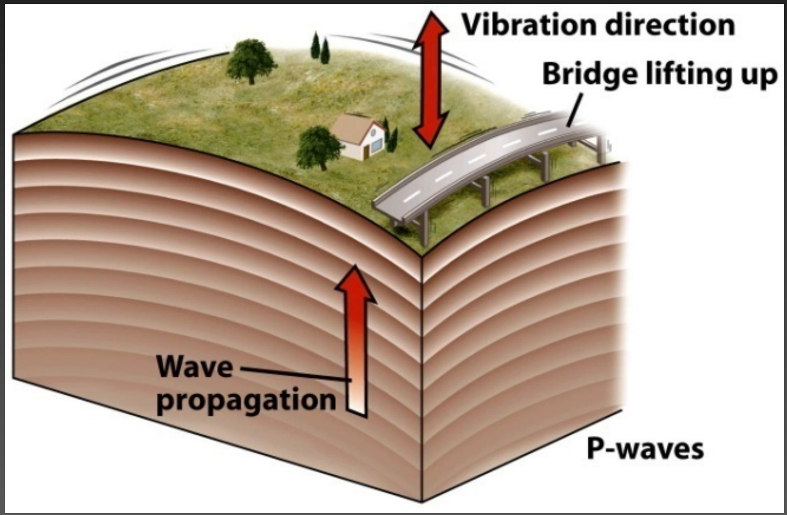
- Ratio of increase in pressure to associated volume change
- Always positive



Two types of deformations

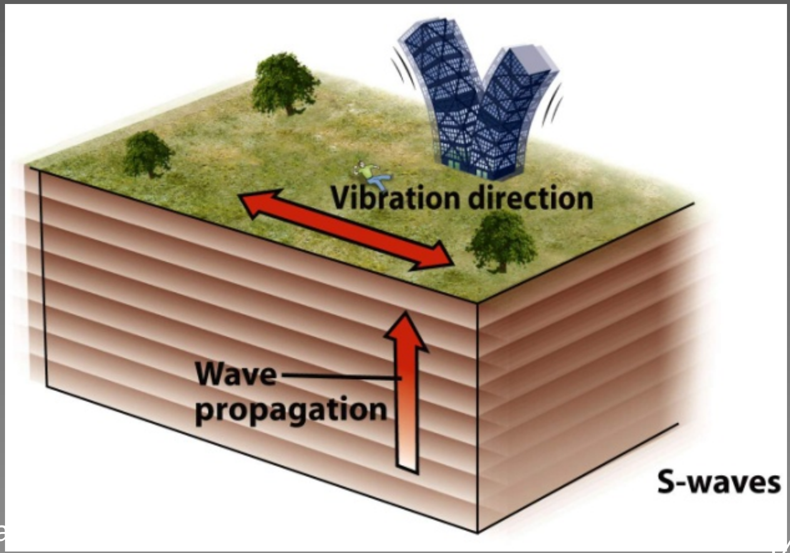
- Volumetric change

  (P-waves, compressional waves)



- Change of shape

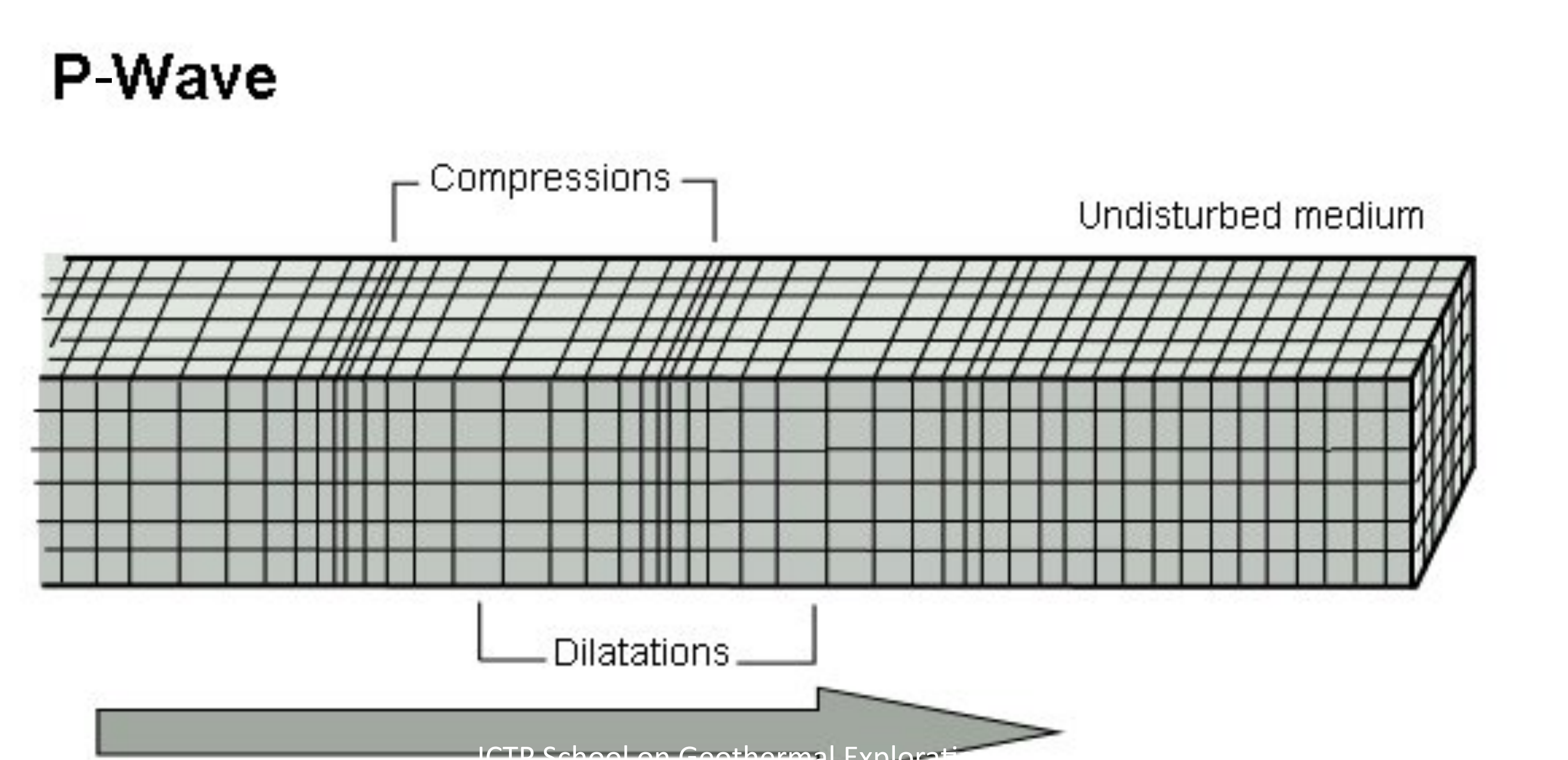
  (S-wave, shear waves)



Source: Duan (2010)

P-waves (compressional waves)

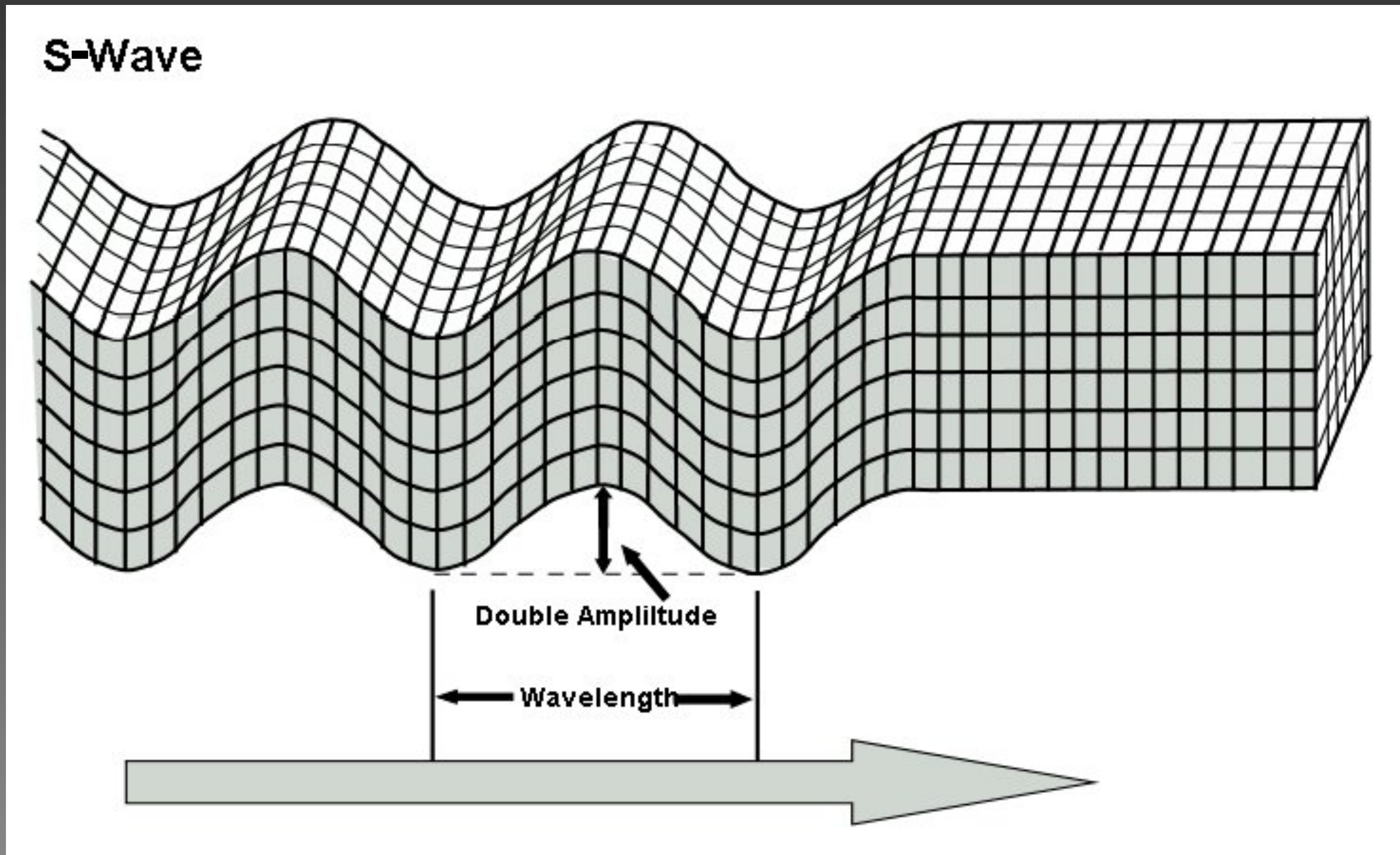
- P-waves (i) similar to sound waves, (ii) series of contractions and relaxations, (iii) fastest, ~5 km/sec (depends on rock type), (iv) travel through solid, liquid and gas



Source: Ikelle and Amundsen (2005); IPS

S-waves (shear waves)

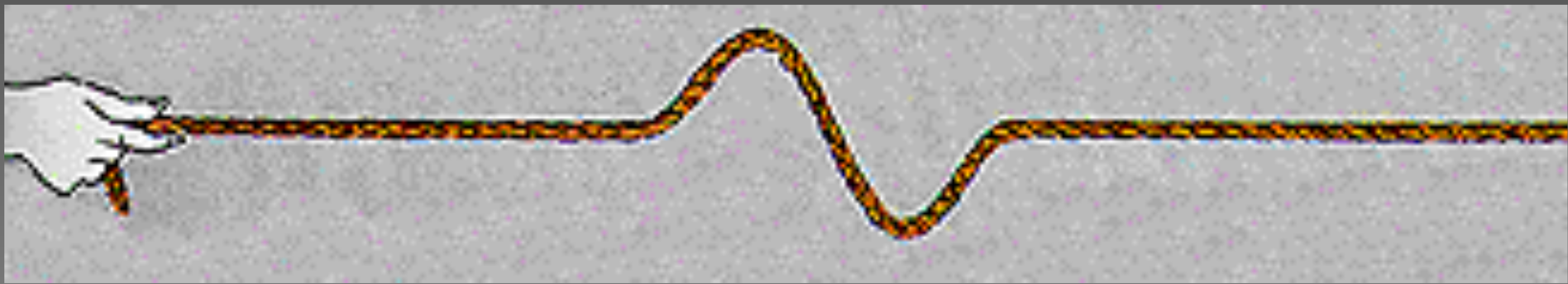
- S-waves motion is (i) right angles to direction of wave, (ii) about half the speed of P waves, and (iii) travel only through solids



Source: Ikelle and Amundsen (2005); IPS

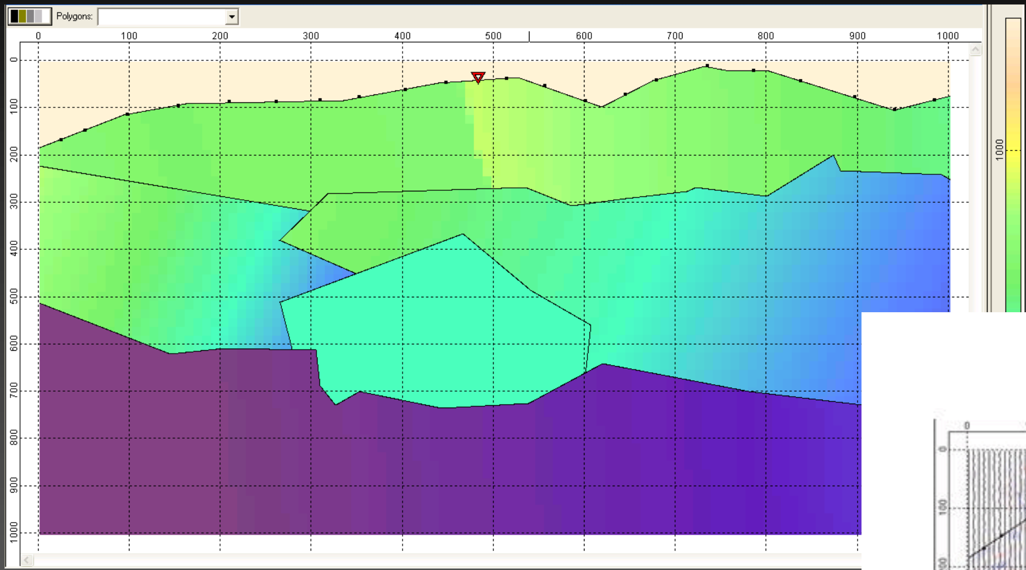
P-wave

S-wave

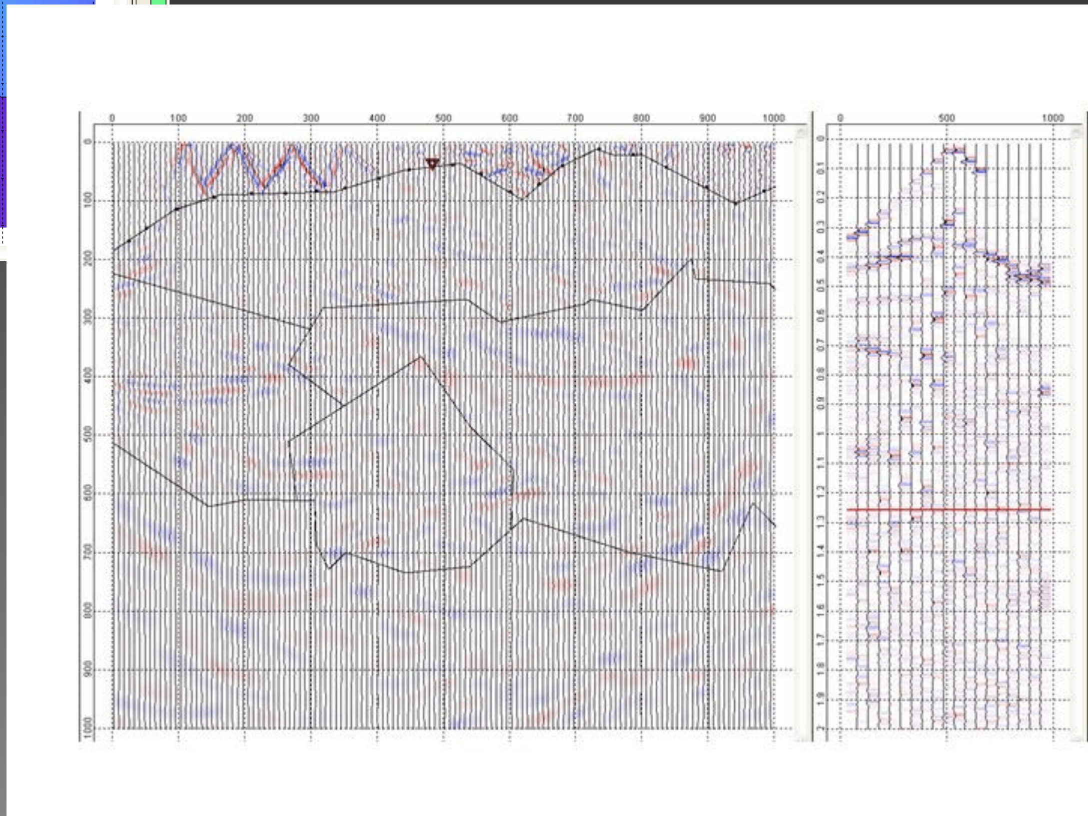


Source: Duan (2010)

Subsurface model and data acquisition geometry

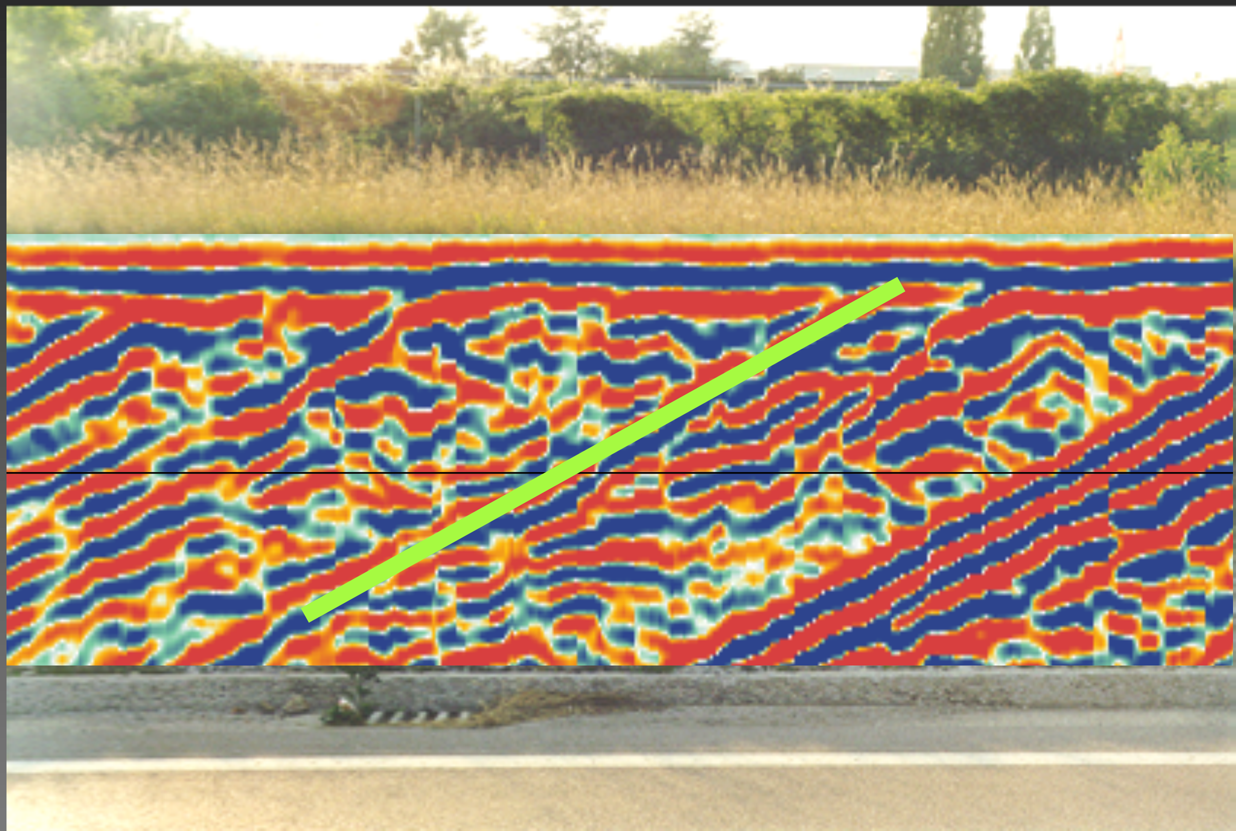


Numerical simulation



MATCH BETWEEN GEOLOGICAL AND GEOPHYSICAL MODEL

MATCH BETWEEN GEOLOGICAL AND GEOPHYSICAL MODEL



Seismic wavefield snaphots (simplified salt dome model)

Seismic data acquisition

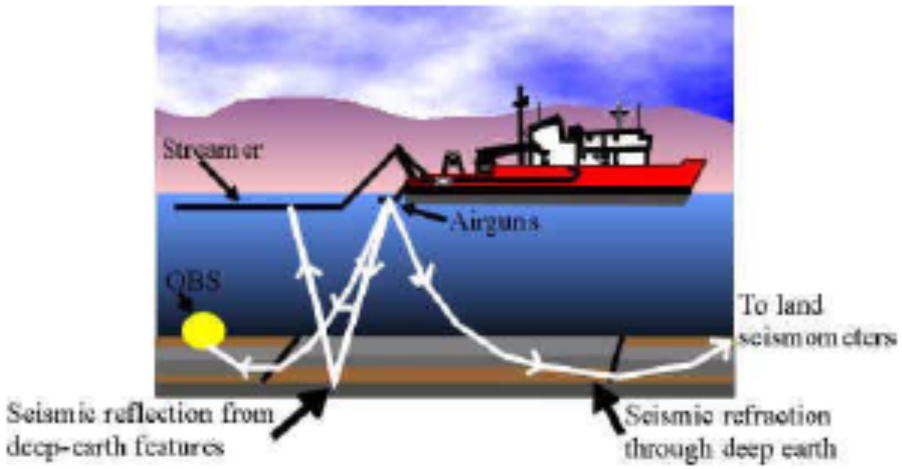
Seismic sources

Consider
- **Energy input**
- **Repeatability**
- **Cost**
- **Convenience**

Vibroseis
- No pulse, frequency sweep
- Significant signal with stacking/deconvolution

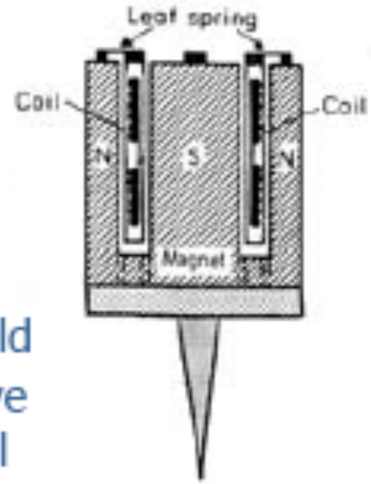
Explosives
- Various sizes – target depth
- Safety and expense can be an issue

Air guns
- At sea
- Very repeatable
- Large array for big signal



Applied Geophysics – Waves and rays - II

Seismic receivers



Geophones

- Cylindrical coil suspended in a magnetic field
- The inertia of the coil causes motion relative to the magnet generating a electrical signal
- Geophones are sensitive to velocity

Hydrophones

- Used at sea
- Use piezoelectric minerals to sense pressure variations

Instrument response

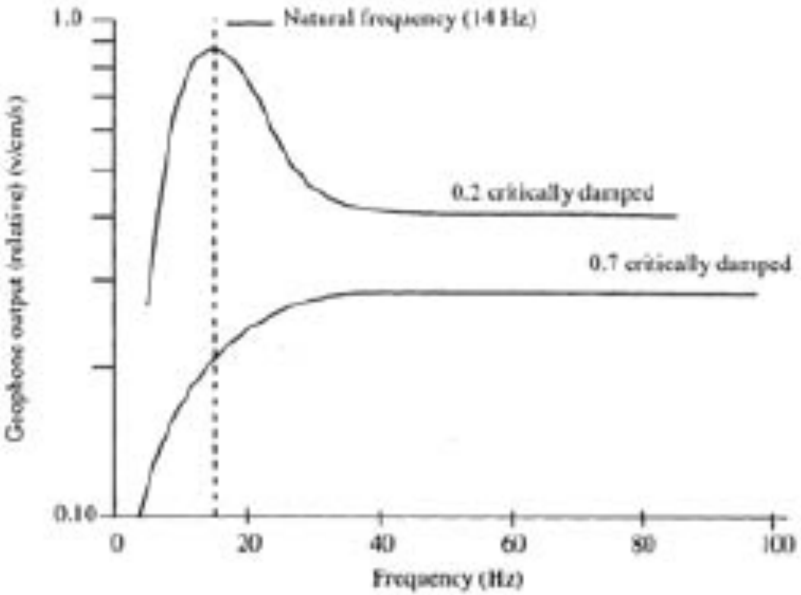
- The relation between the input ground motion and the output electrical signal

Natural frequency

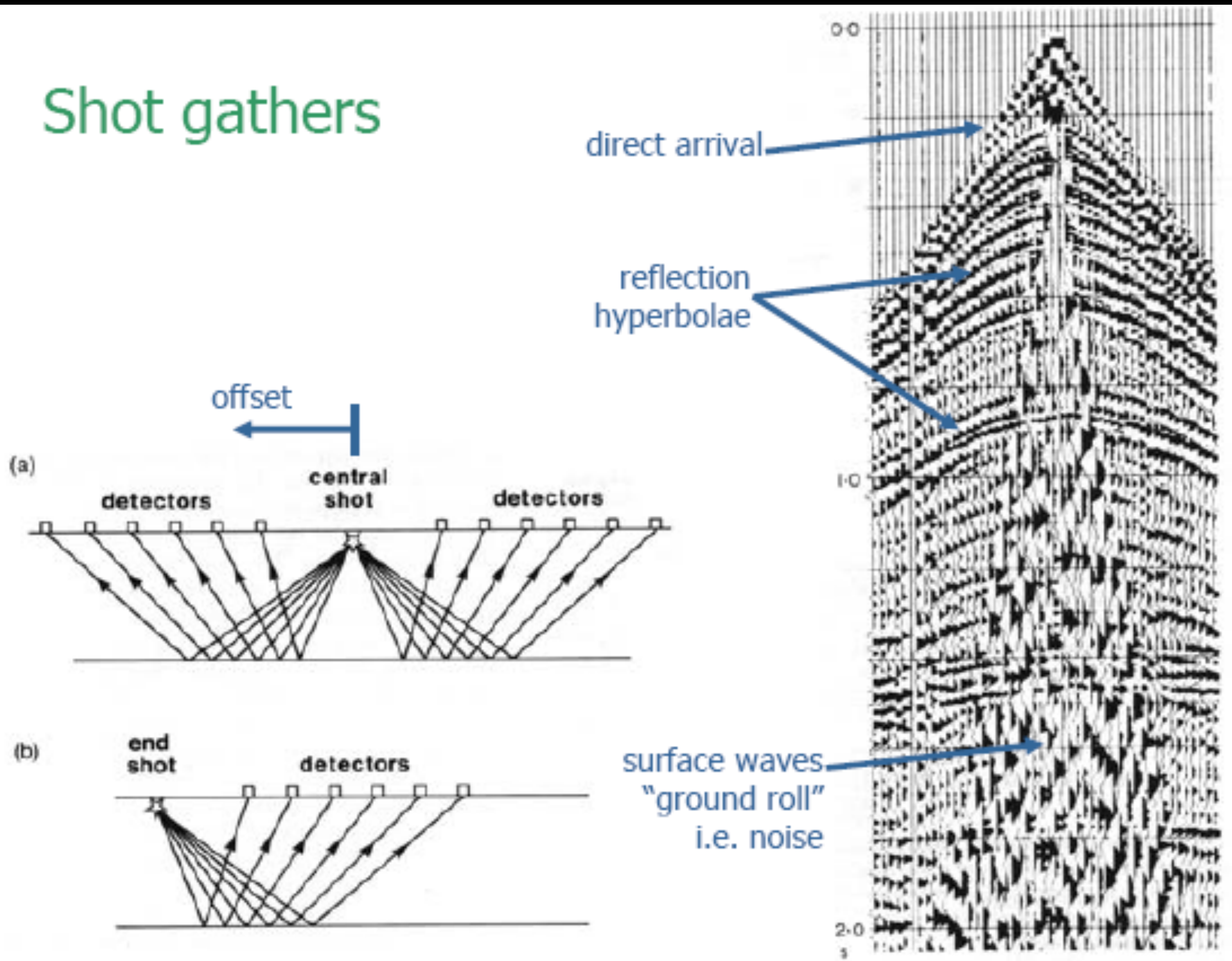
- The frequency which produces the maximum amplitude output

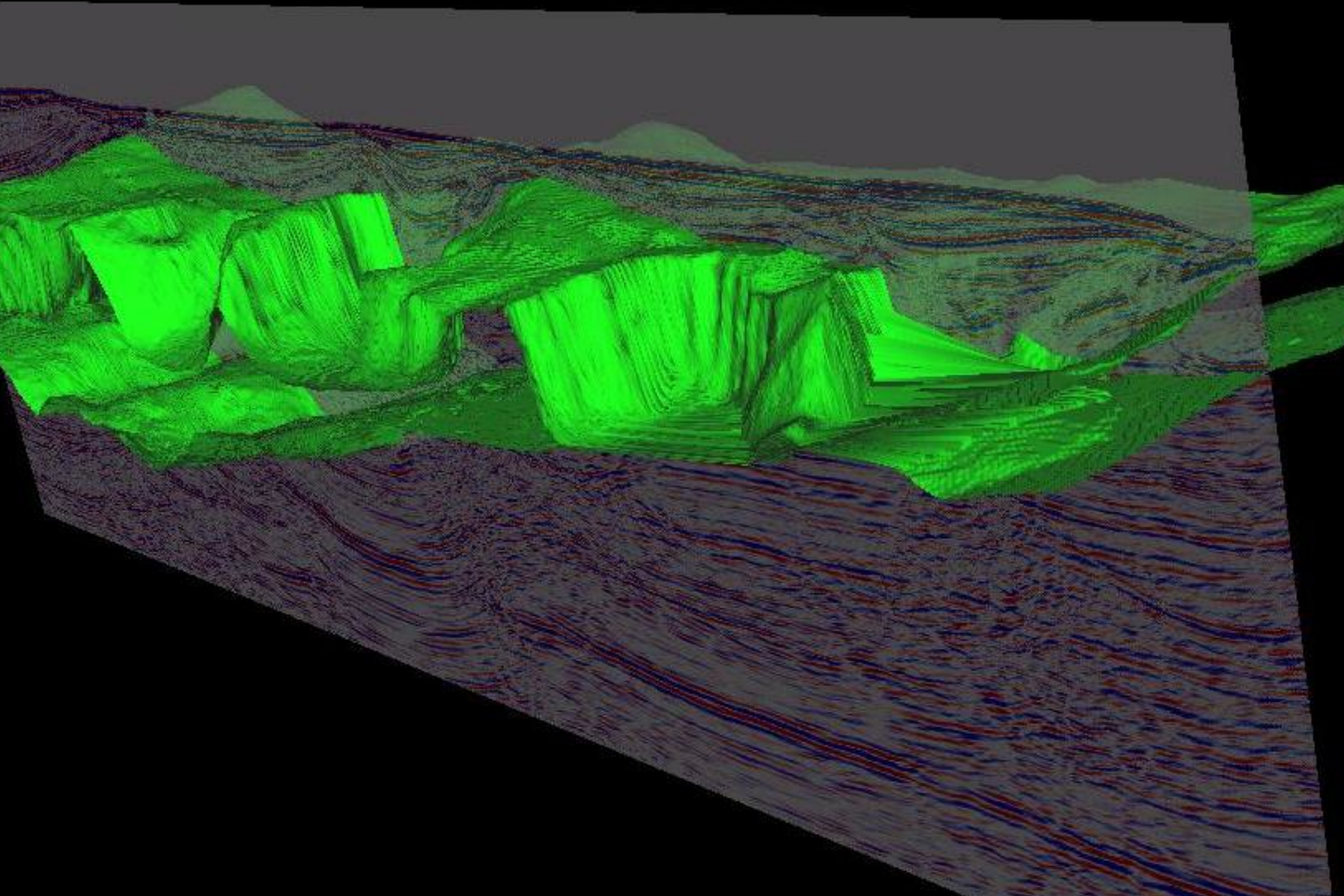
Damping

- Reduces the amplitude of the natural frequency response and prevents infinite oscillations
- Want a **flat response**

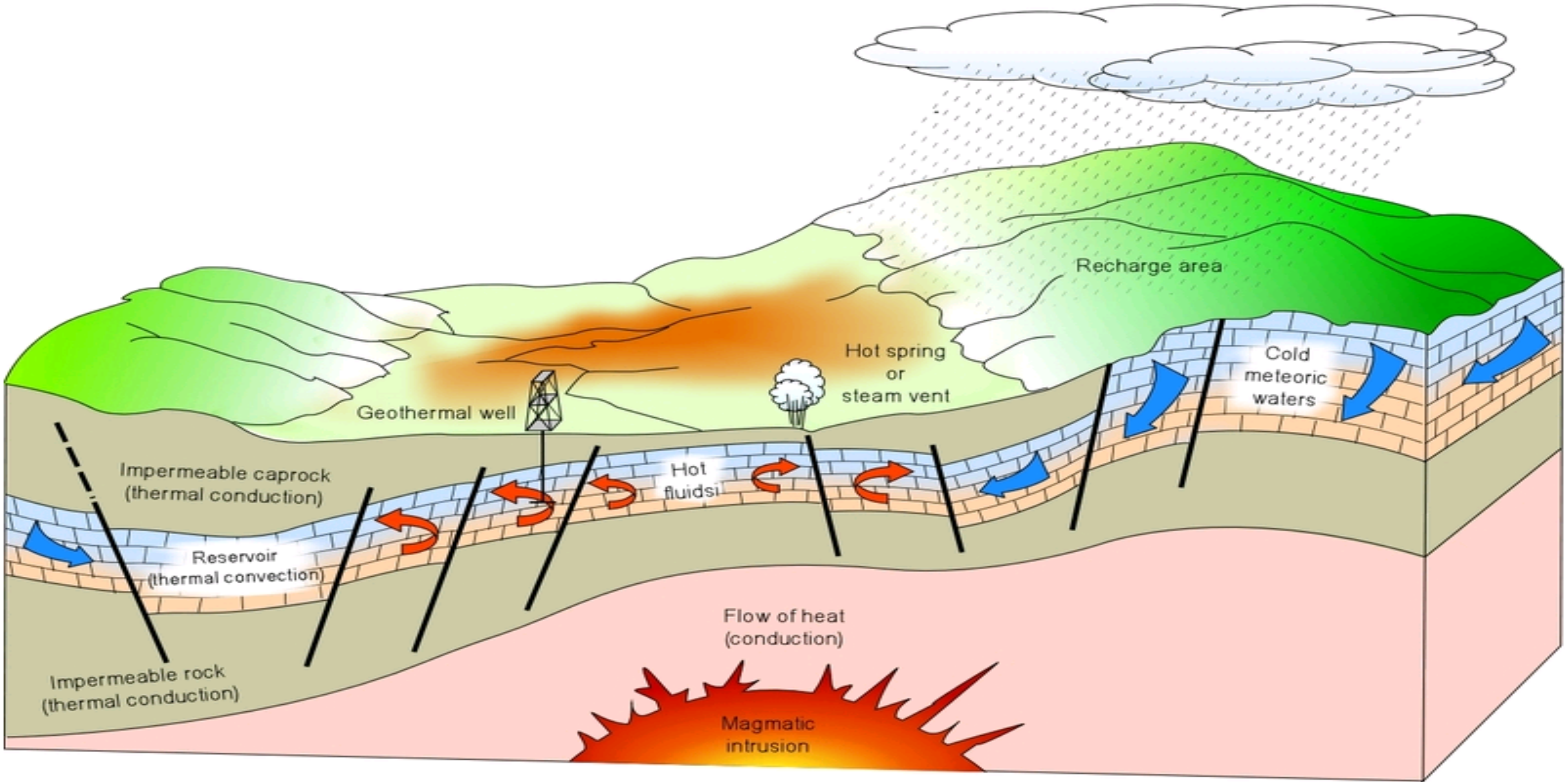


Shot gathers





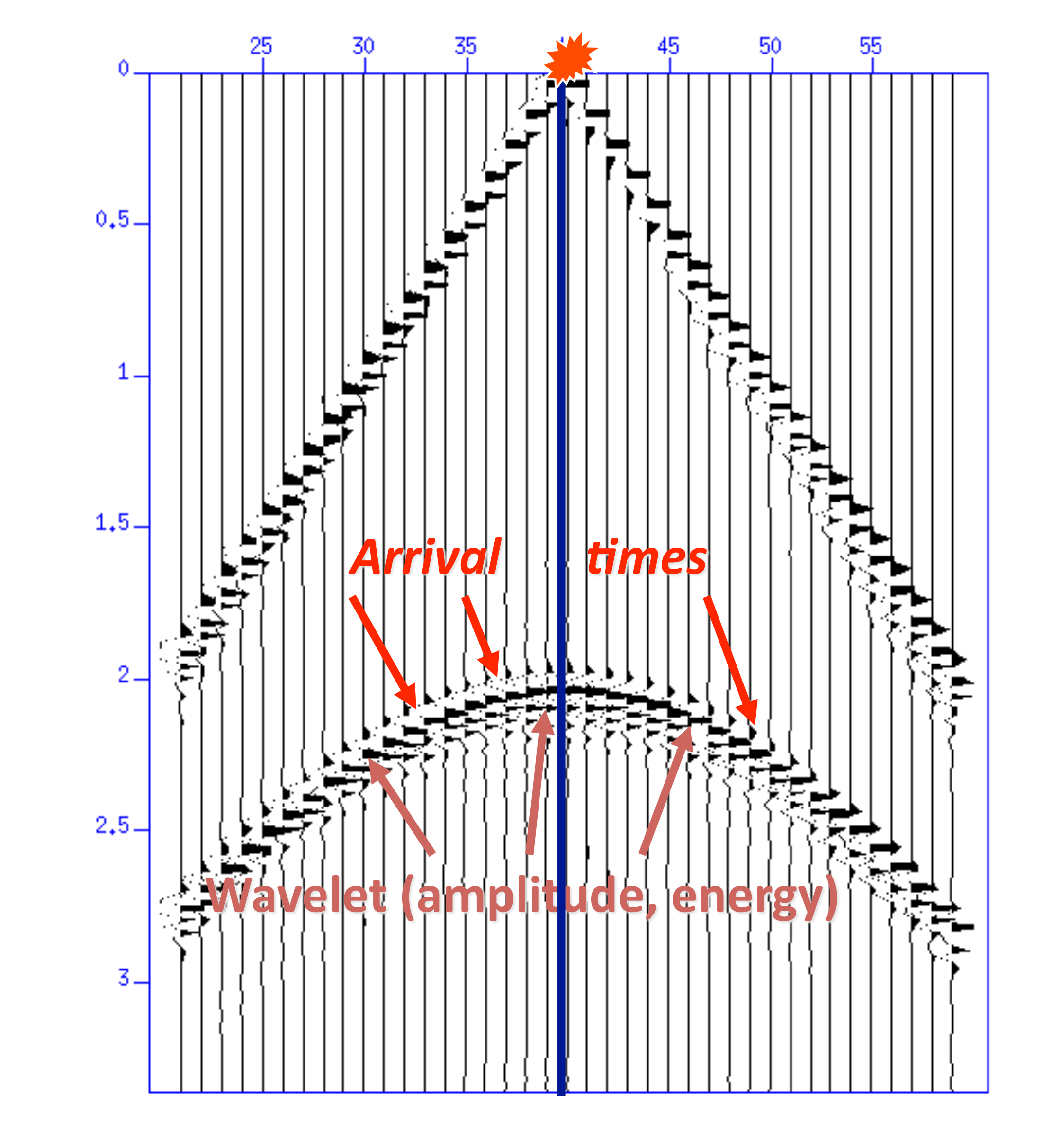
GEOLOGICAL TARGET



The seismic tools

- KINEMATIC: arrival times, velocities
- DYNAMIC: amplitudes

The seismic tools



SEISMIC AMPLITUDES AND REFLECTION COEFFICIENTS

$$RC(\theta) = \frac{(\rho\alpha)_2 - (\rho\alpha)_1}{(\rho\alpha)_2 + (\rho\alpha)_1}\cos^2\theta + \frac{\sigma_2 - \sigma_1}{(1-\sigma_{avg})^2}\sin^2\theta$$

NORMAL INCIDENCE REFLECTIVITY

POISSON's REFLECTIVITY

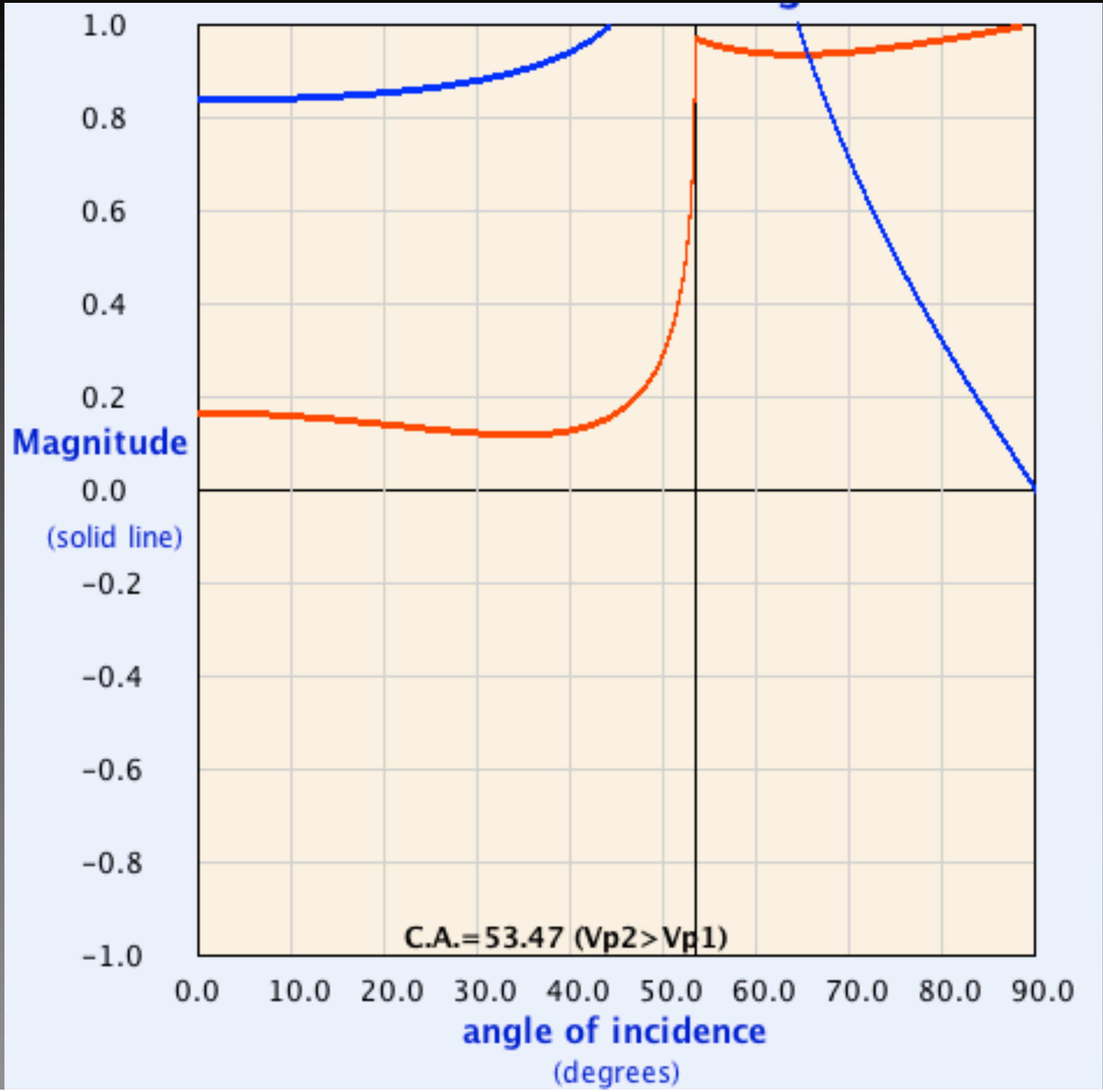
RC = reflection coefficient

θ= incidence angle

ρ= density

α = P-wave velocity

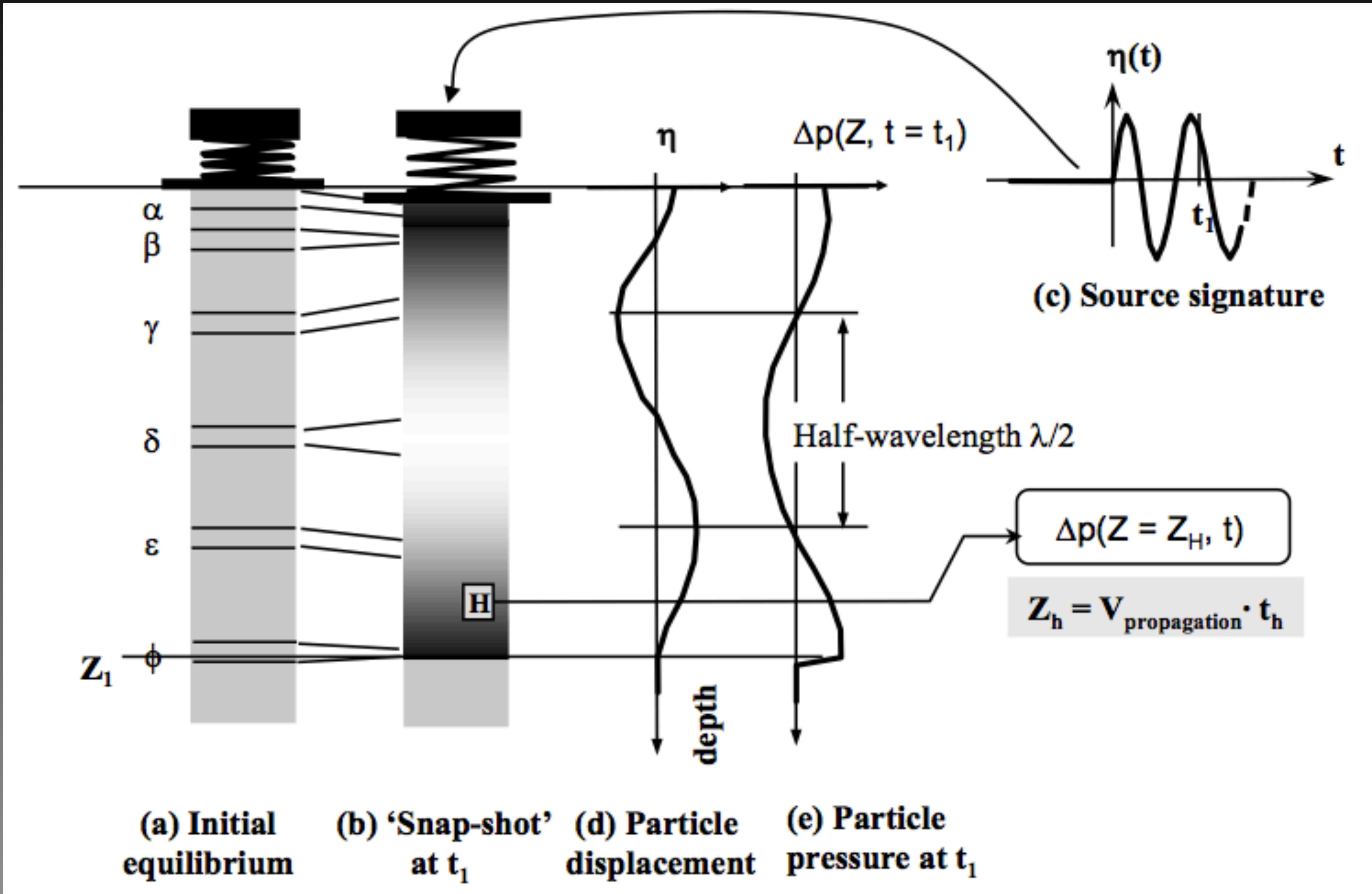
Reflection coefficients as a function of incidence angle

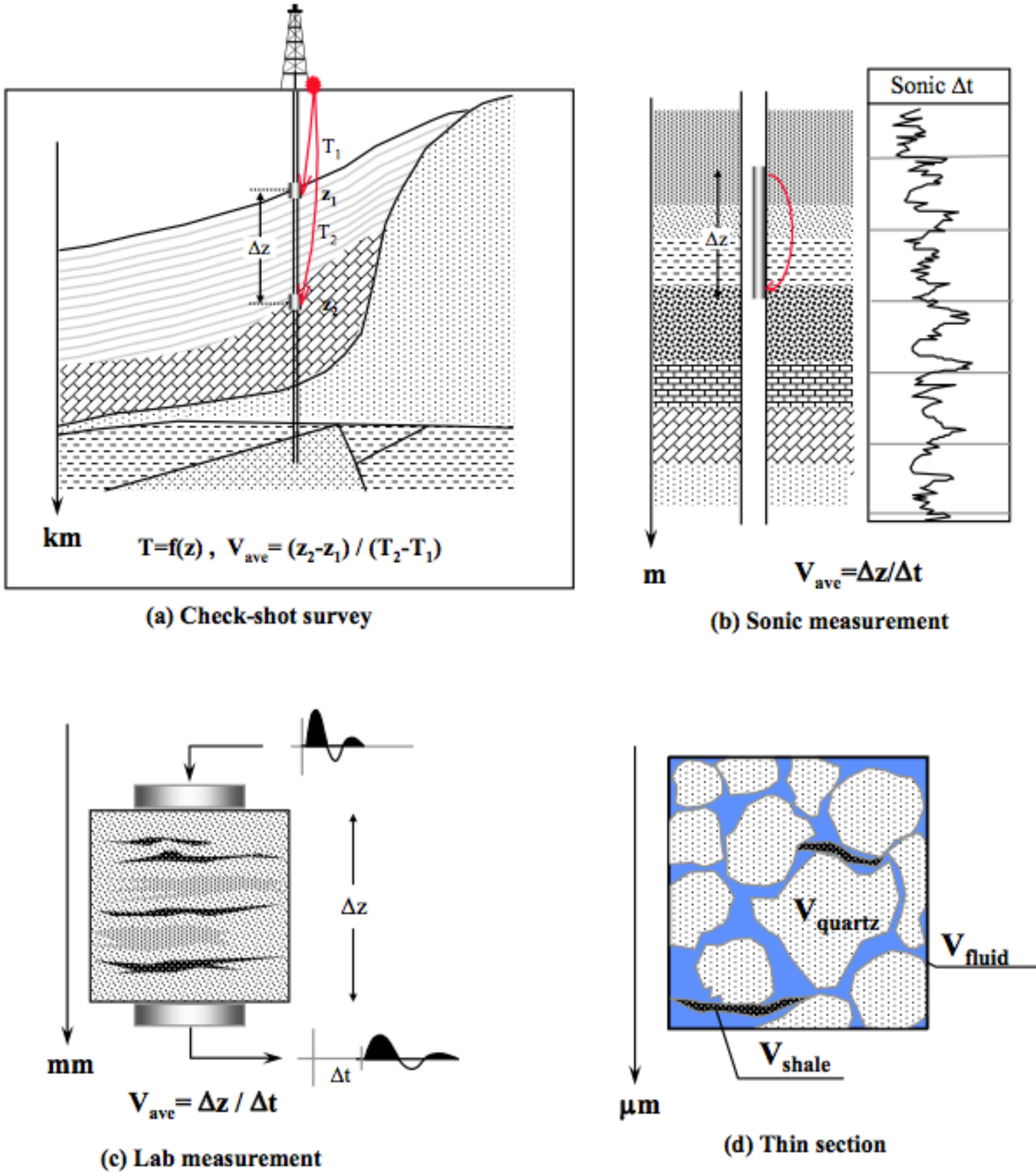


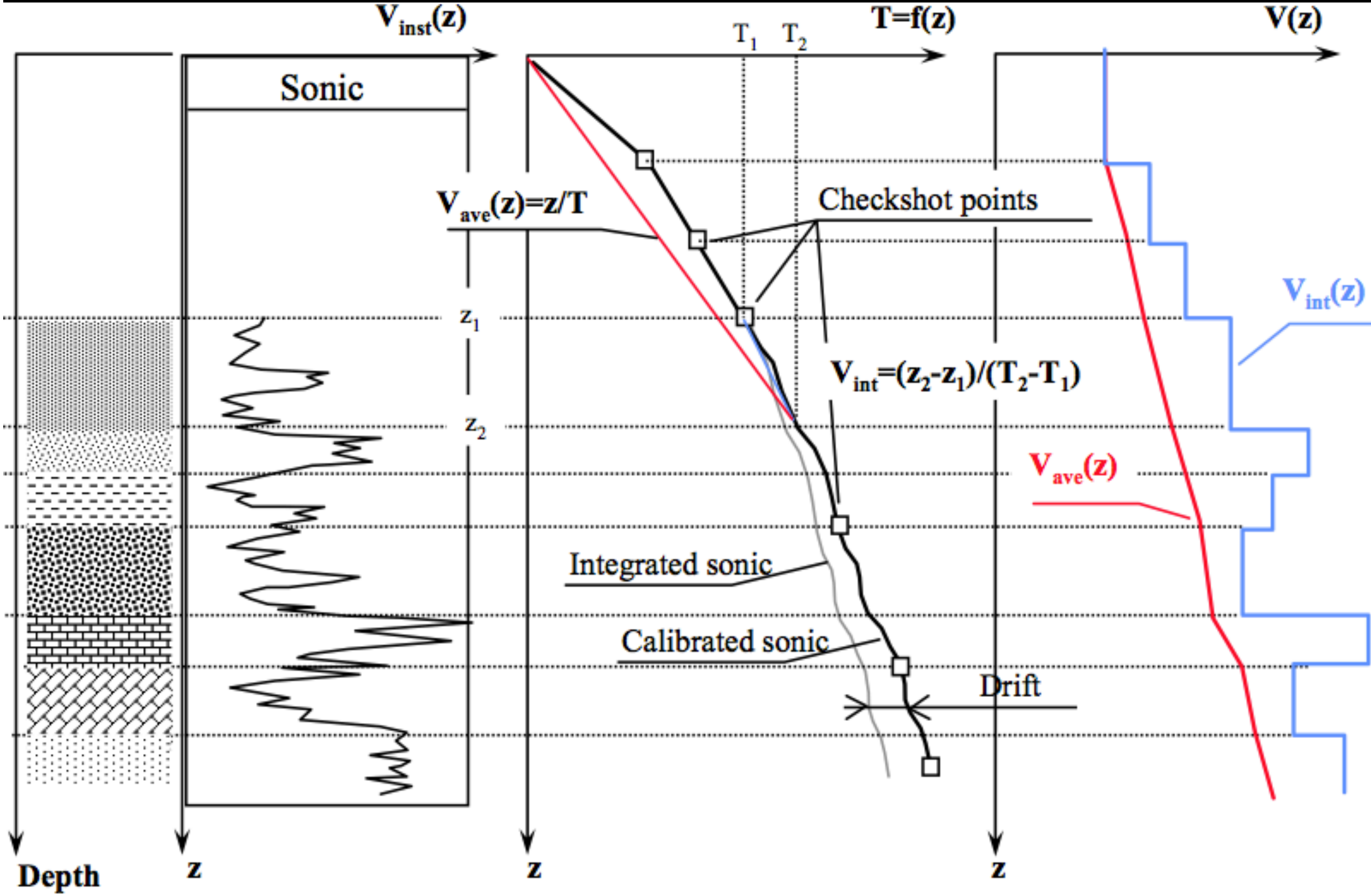
POISSON's ratio and seismic velocities

$$\frac{\beta}{\alpha} = \sqrt{\frac{\mu}{(\lambda + 2\mu)}} = \left(\frac{0.5 - \sigma}{1 - \sigma}\right)^{\frac{1}{2}}$$

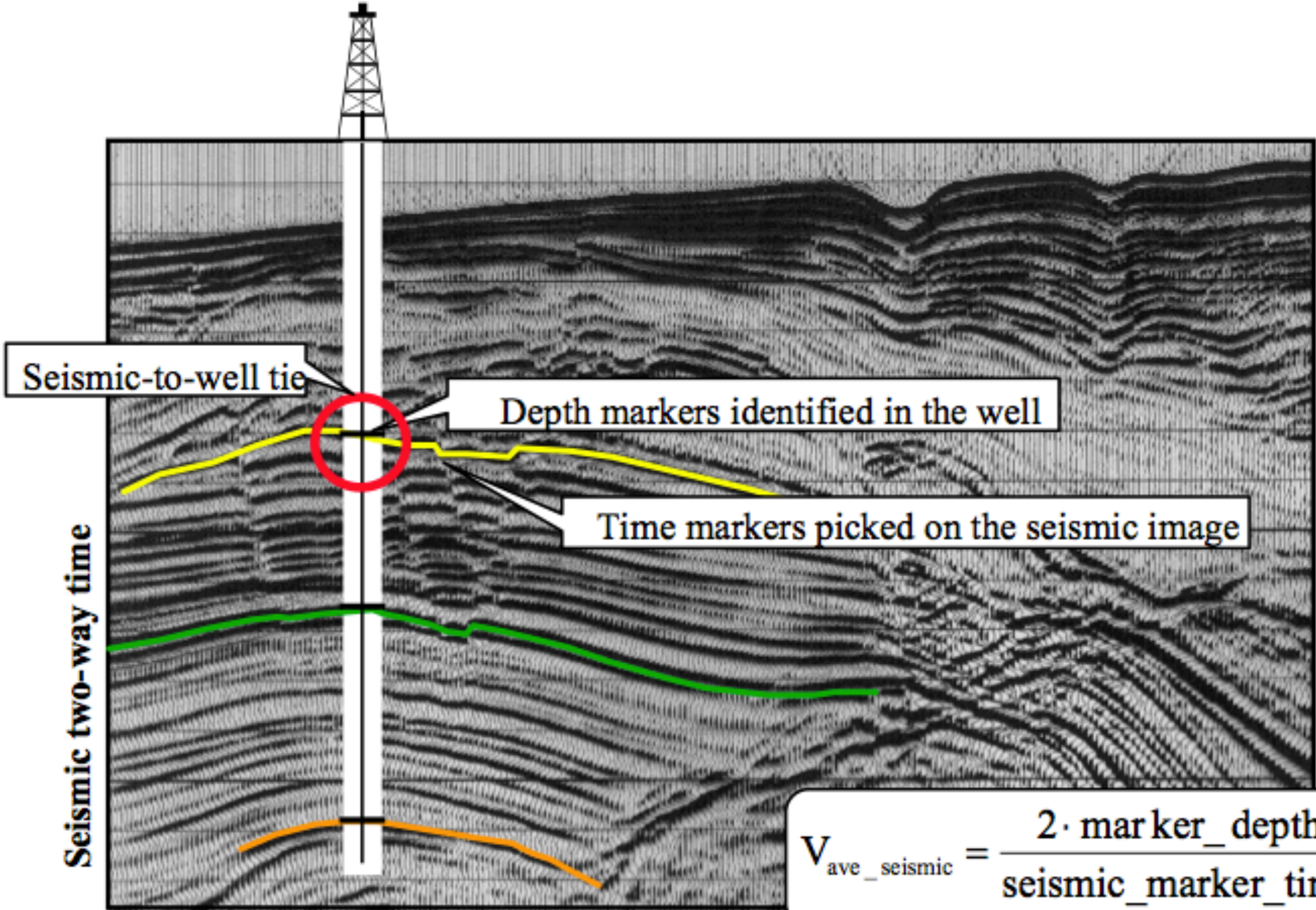
Velocities: the scale problem




T1
z1
T2
Δz
z2
km
T=f(z) , Vave= (z2-z1) / (T2-T1)
(a) Check-shot survey
Sonic Δt
Δz
m
Vave=Δz/Δt
(b) Sonic measurement
Δz
Δt
mm
Vave= Δz / Δt
(c) Lab measurement
Vquartz
Vfluid
Vshale
μm
(d) Thin section



Depth
Sonic
$V_{inst}(z)$
z
$T=f(z)$
T_1
T_2
z
$V(z)$
z
$V_{ave}(z)=z/T$
Checkshot points
z_1
z_2
$V_{int}=(z_2-z_1)/(T_2-T_1)$
$V_{int}(z)$
$V_{ave}(z)$
Integrated sonic
Calibrated sonic
Drift



$$V_{ave\_seismic} = \frac{2 \cdot marker\_depth}{seismic\_marker\_time}$$

Dix Formula

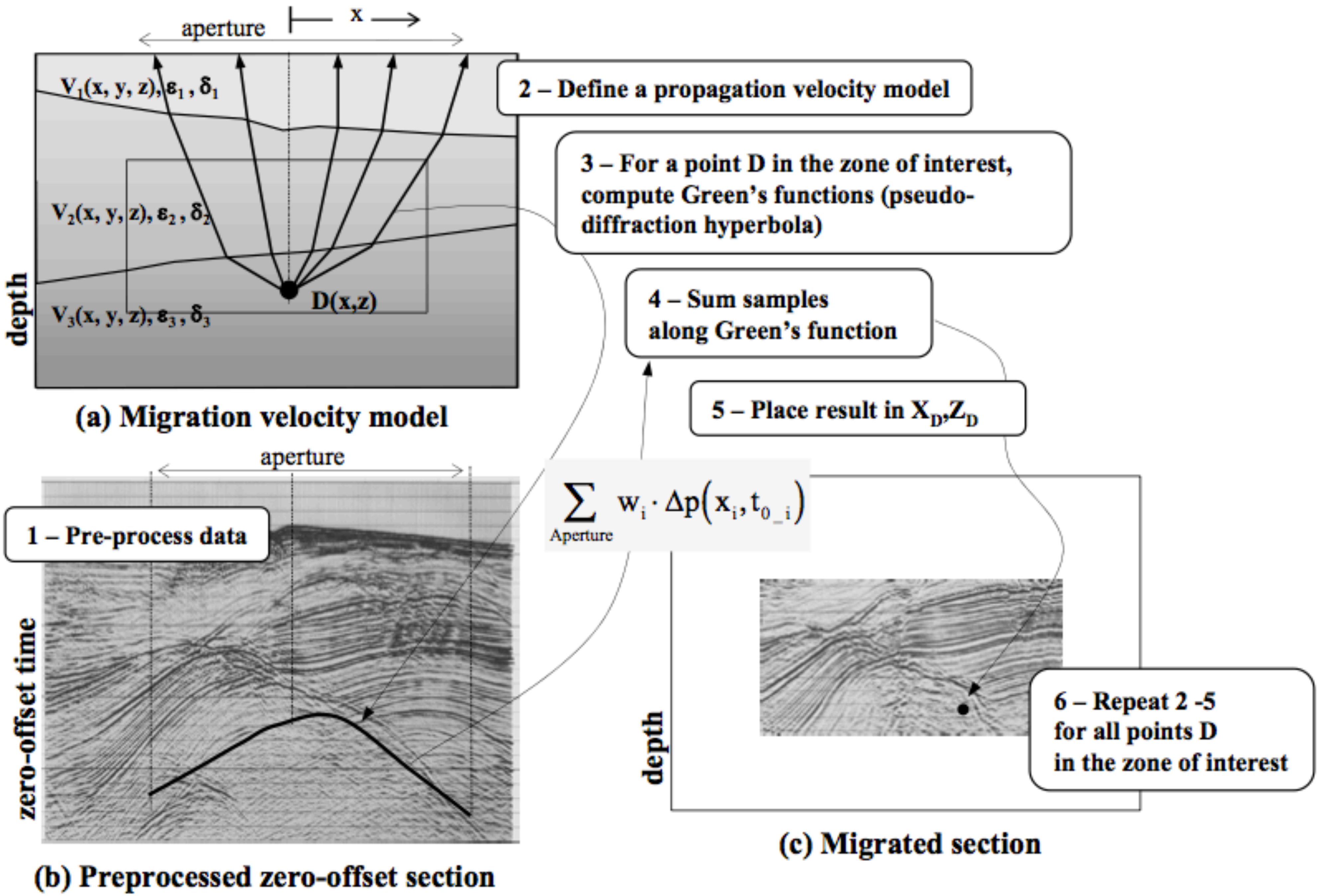
$$t_{SPR}^2 \approx t_0^2 + \frac{4 \cdot h^2}{V_{rms}^2} = \left(\frac{2 \cdot Z}{V_{ave}}\right)^2 + \left(\frac{2 \cdot h}{V_{rms}}\right)^2$$

$$V_{ave} = \frac{\sum_i v_i \Delta t_i}{\sum_i \Delta t_i}$$

$$V_{rms}^2 = \frac{\sum_i v_i^2 \Delta t_i}{\sum_i \Delta t_i}$$

Inverse Dix Formula

$$V_{\mathrm{int},T1-T2} = \sqrt{\frac{T_2 V_{RMS}^2(T_2) - T_1 V_{RMS}^2(T_1)}{T_2 - T_1}}$$



aperture
x
$V_1(x, y, z), \varepsilon_1, \delta_1$
$V_2(x, y, z), \varepsilon_2, \delta_2$
$V_3(x, y, z), \varepsilon_3, \delta_3$
D(x,z)
depth
2 – Define a propagation velocity model
3 – For a point D in the zone of interest, compute Green's functions (pseudo-diffraction hyperbola)
4 – Sum samples along Green's function
5 – Place result in X_D, Z_D
(a) Migration velocity model
aperture
1 – Pre-process data
$\sum_{Aperture} w_i \cdot \Delta p(x_i, t_{0\_i})$
zero-offset time
depth
6 – Repeat 2 -5 for all points D in the zone of interest
(b) Preprocessed zero-offset section
(c) Migrated section

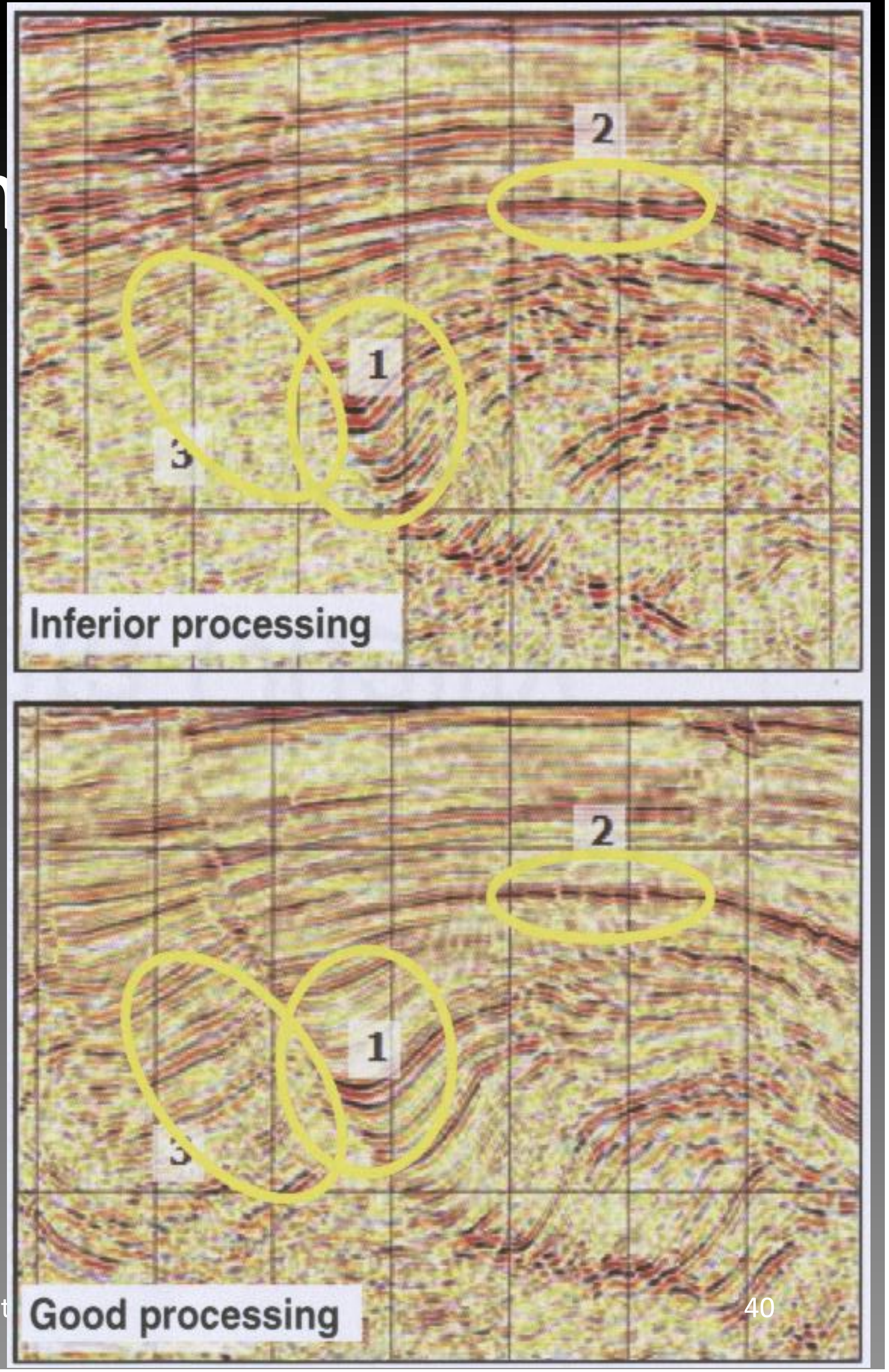
Seismic processin

To produce accurate subsurface images:

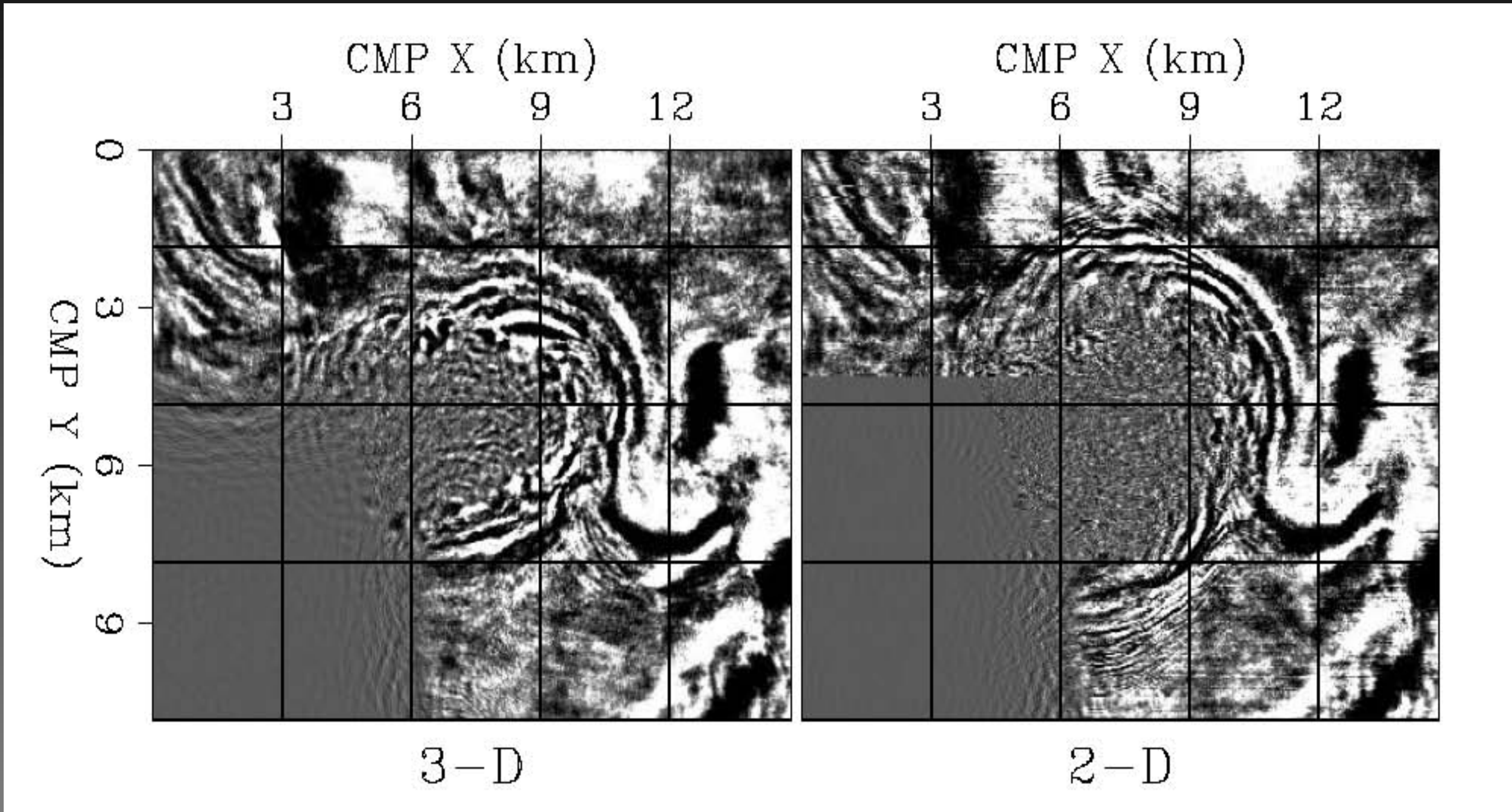
Correct geometry /amplitudes (i.e. to remove distortions due to wave propagation)

Noise attenuation: enhance S/N

In synthesis:
recover true Earth response to stress applied at the surface

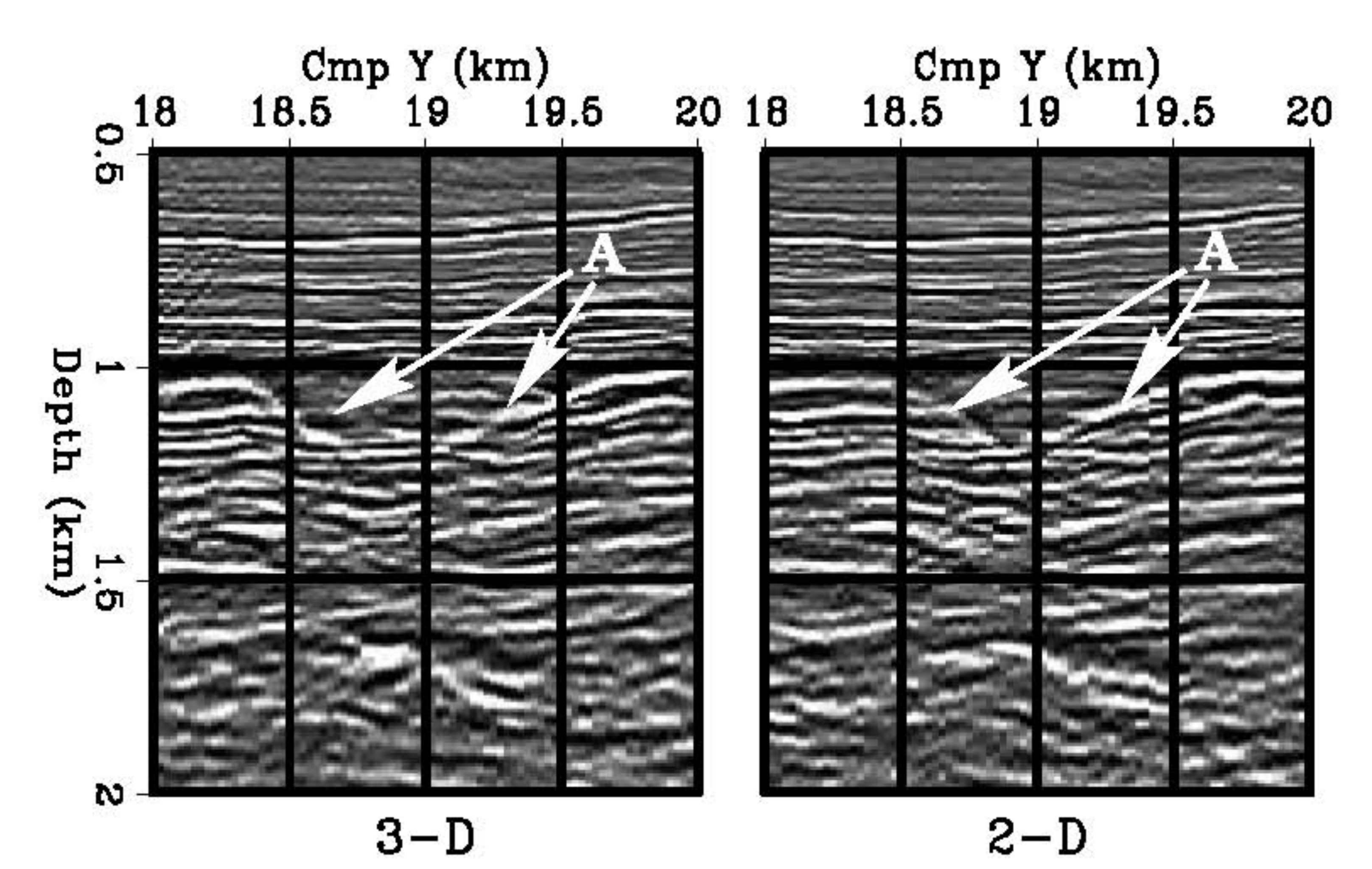


2-D imaging of a 3-D world: pitfalls and errors (1) lateral mispositioning of structural boundaries



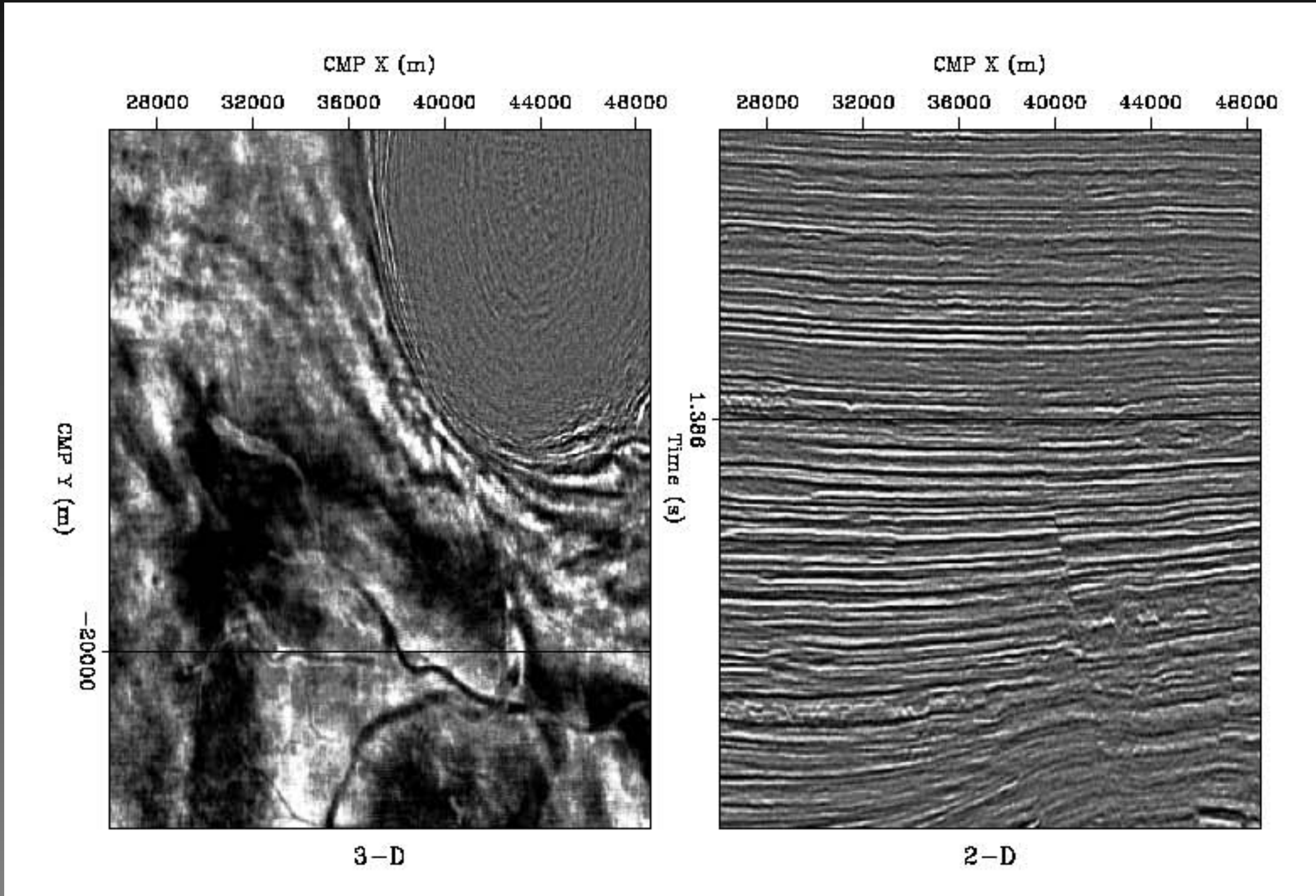
Example of depth slice at 3.5 km: 2-D/3-D

2-D imaging of a 3-D world: pitfalls and errors (2)



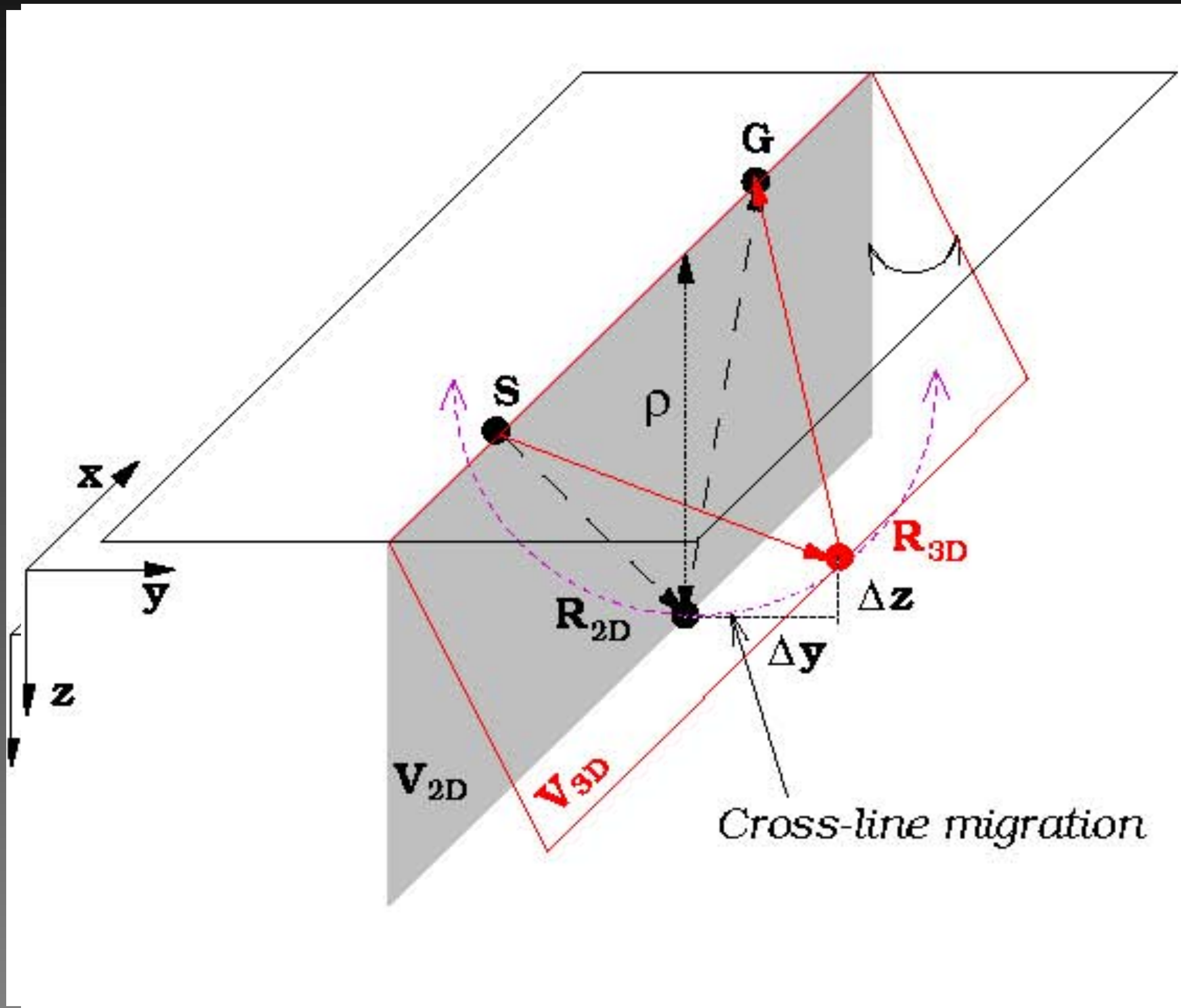
Dipping reflectors: mispositioning in 2-D

2-D imaging of a 3-D world: pitfalls and errors (3) imaging complex targets

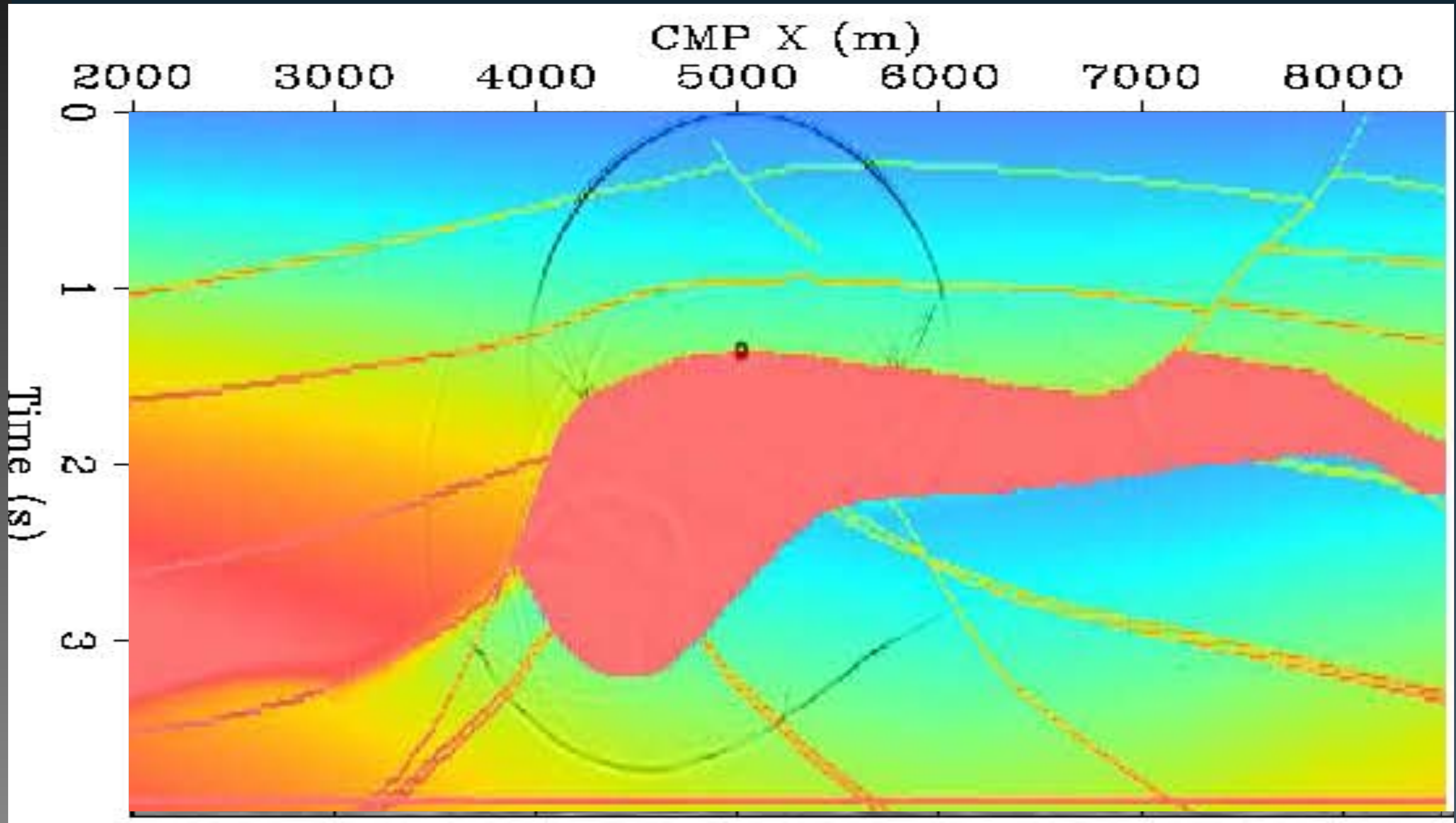


Time-slice 1.3 s In-line cross-section

Geometric reasoning in 3-D

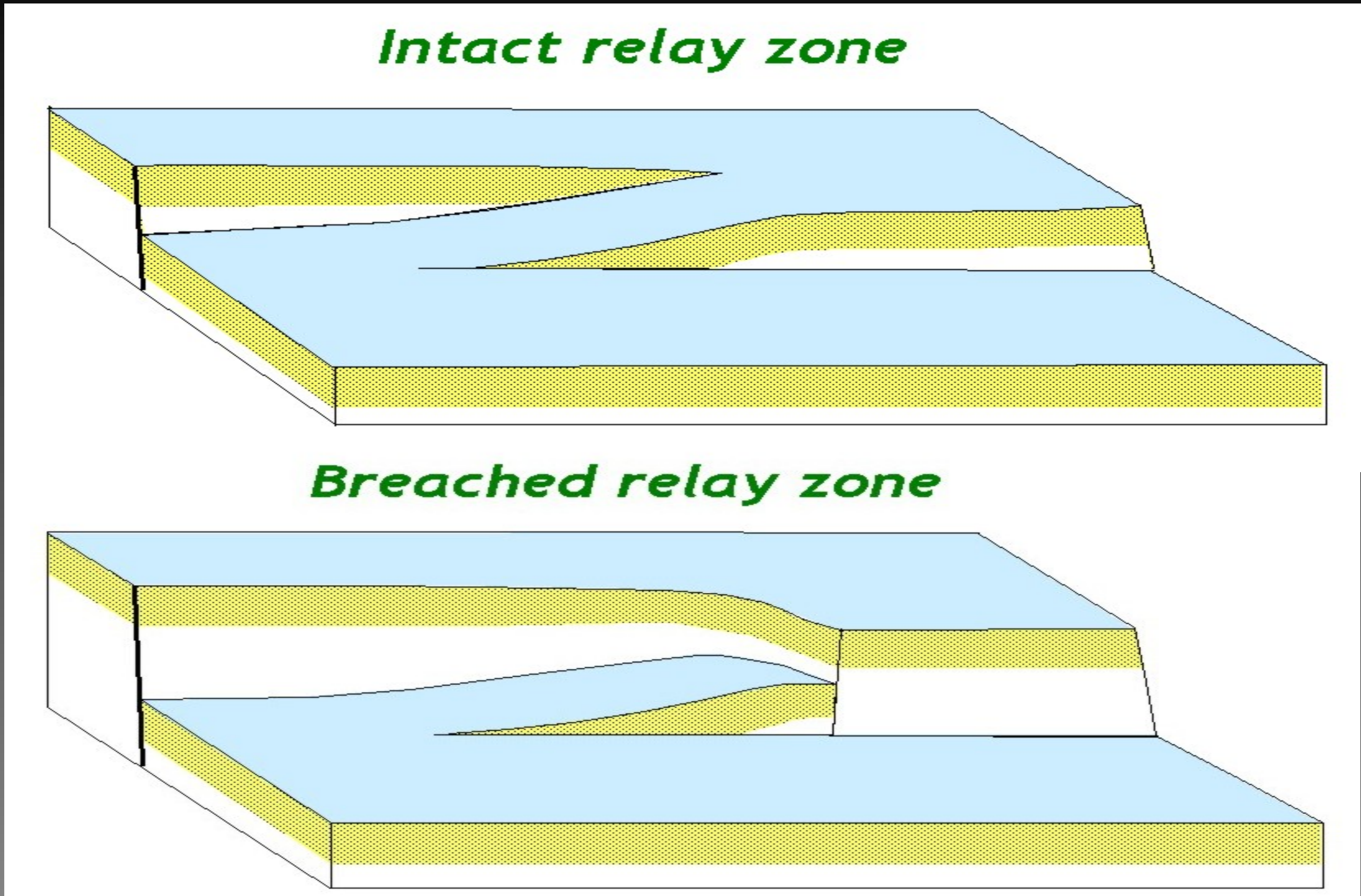


Structural model enhancement from 3-D imaging

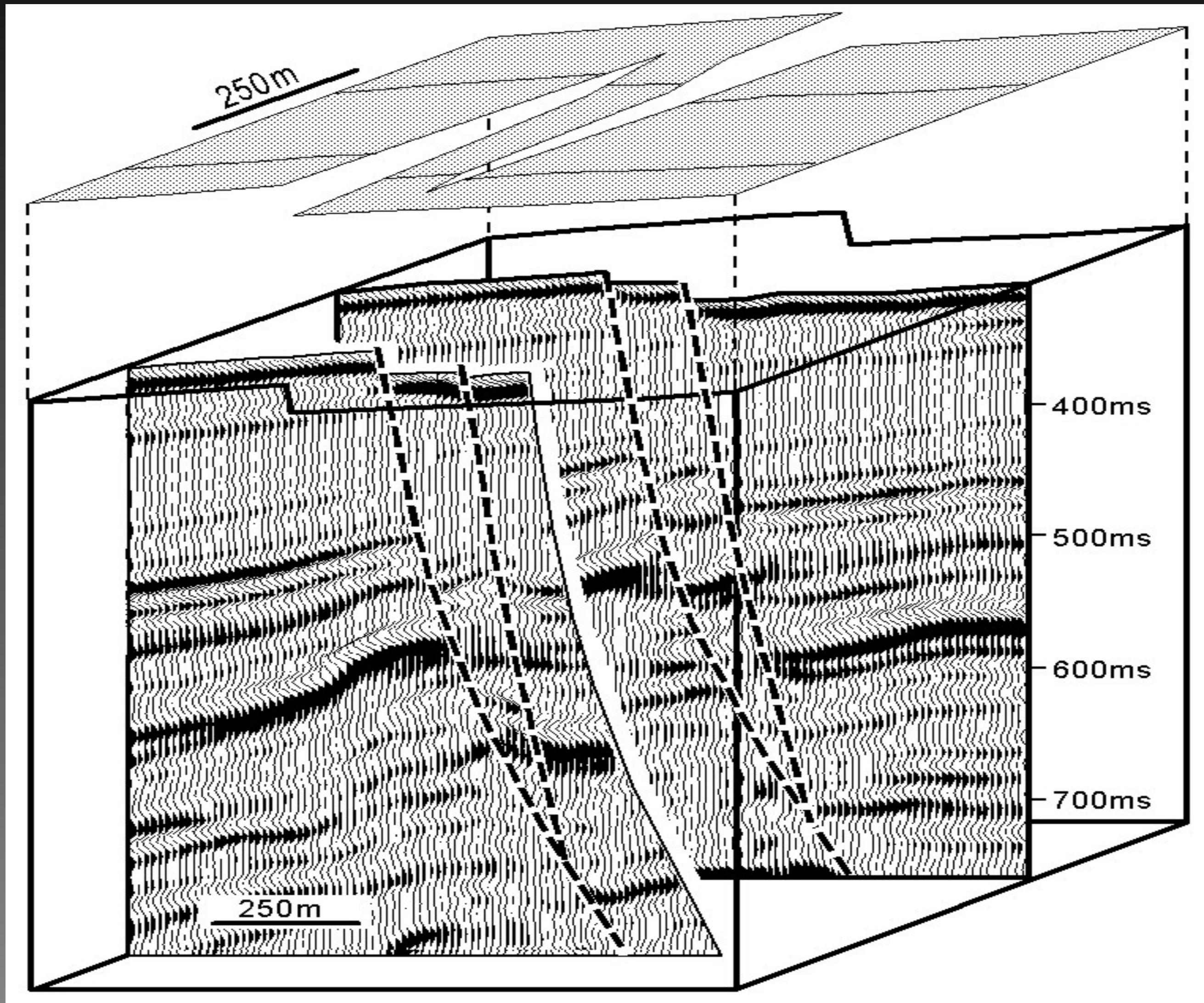


Strained and fractured Earth: the ground truth…

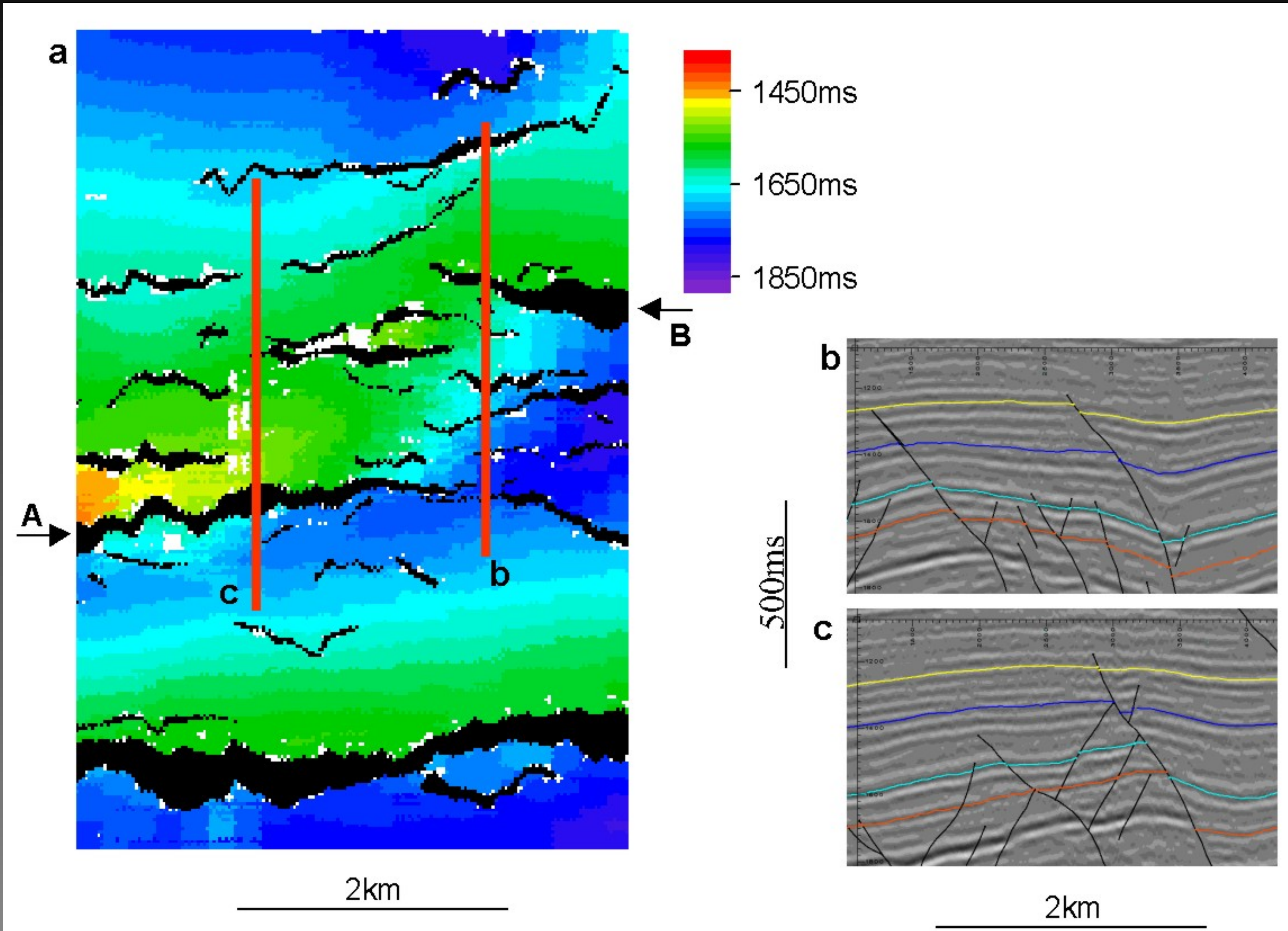
… the subsurface model…



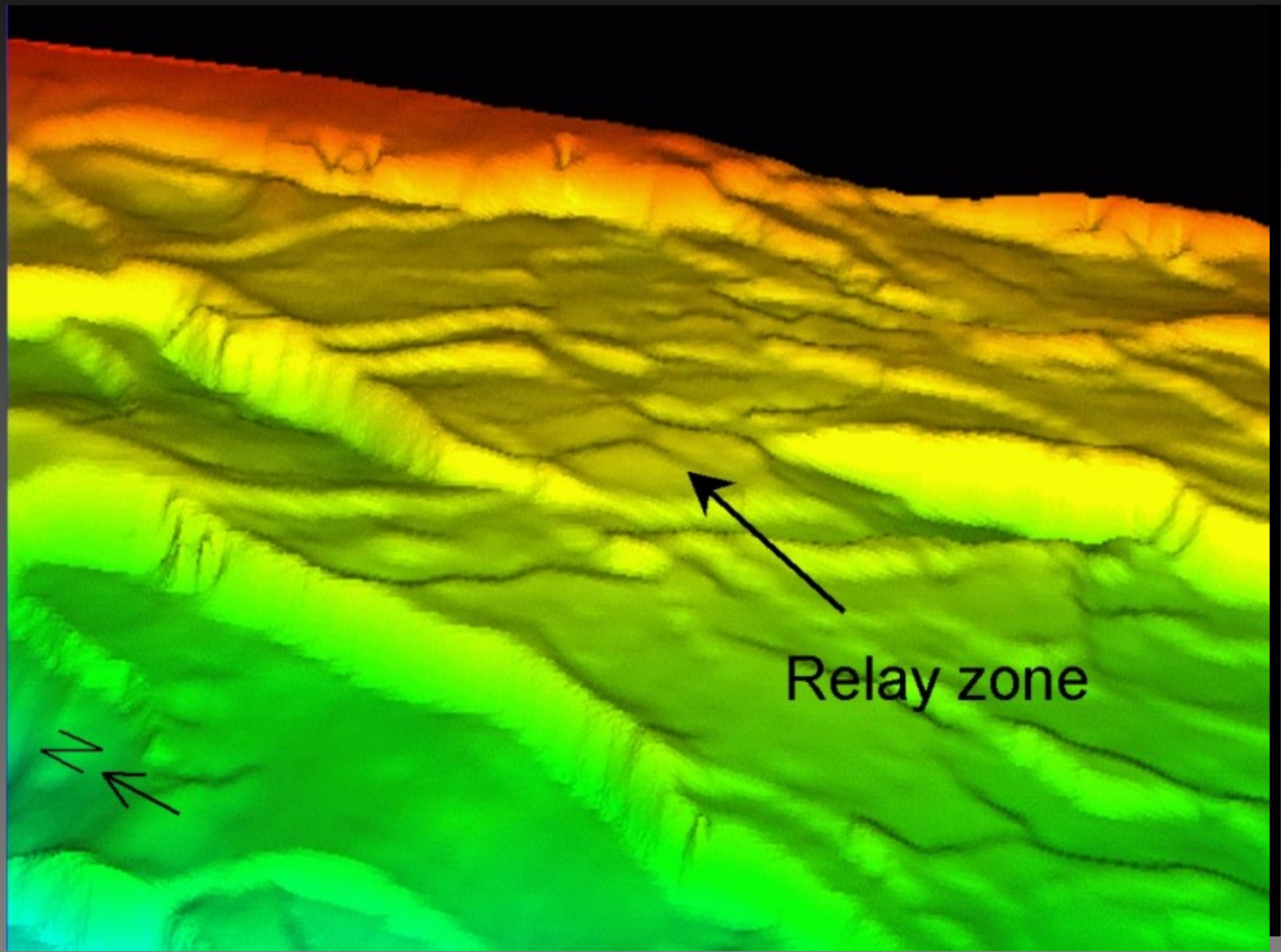
…the seismic image…



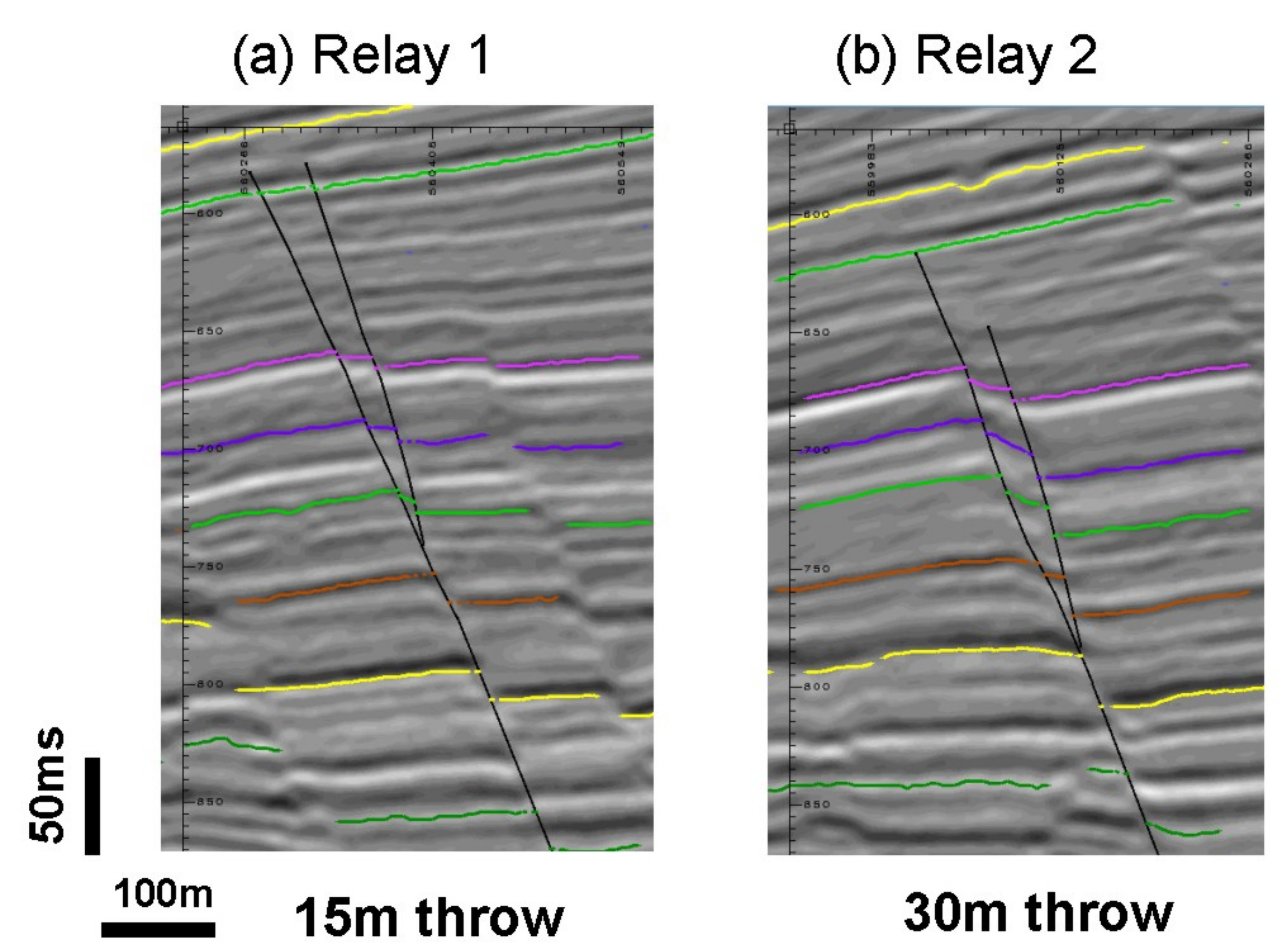
3-D seismic study of a strained and fractured Earth..



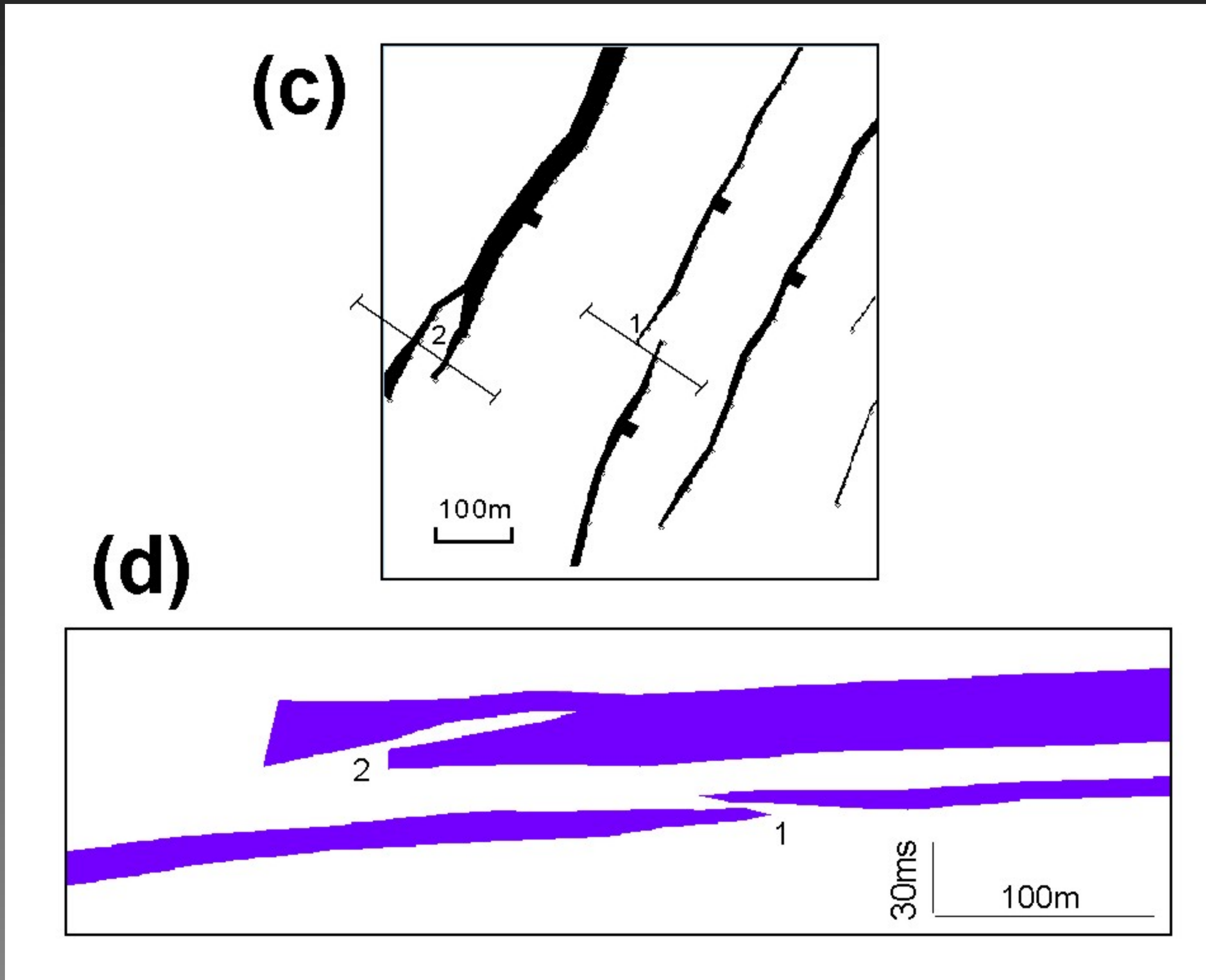
…at regional scale



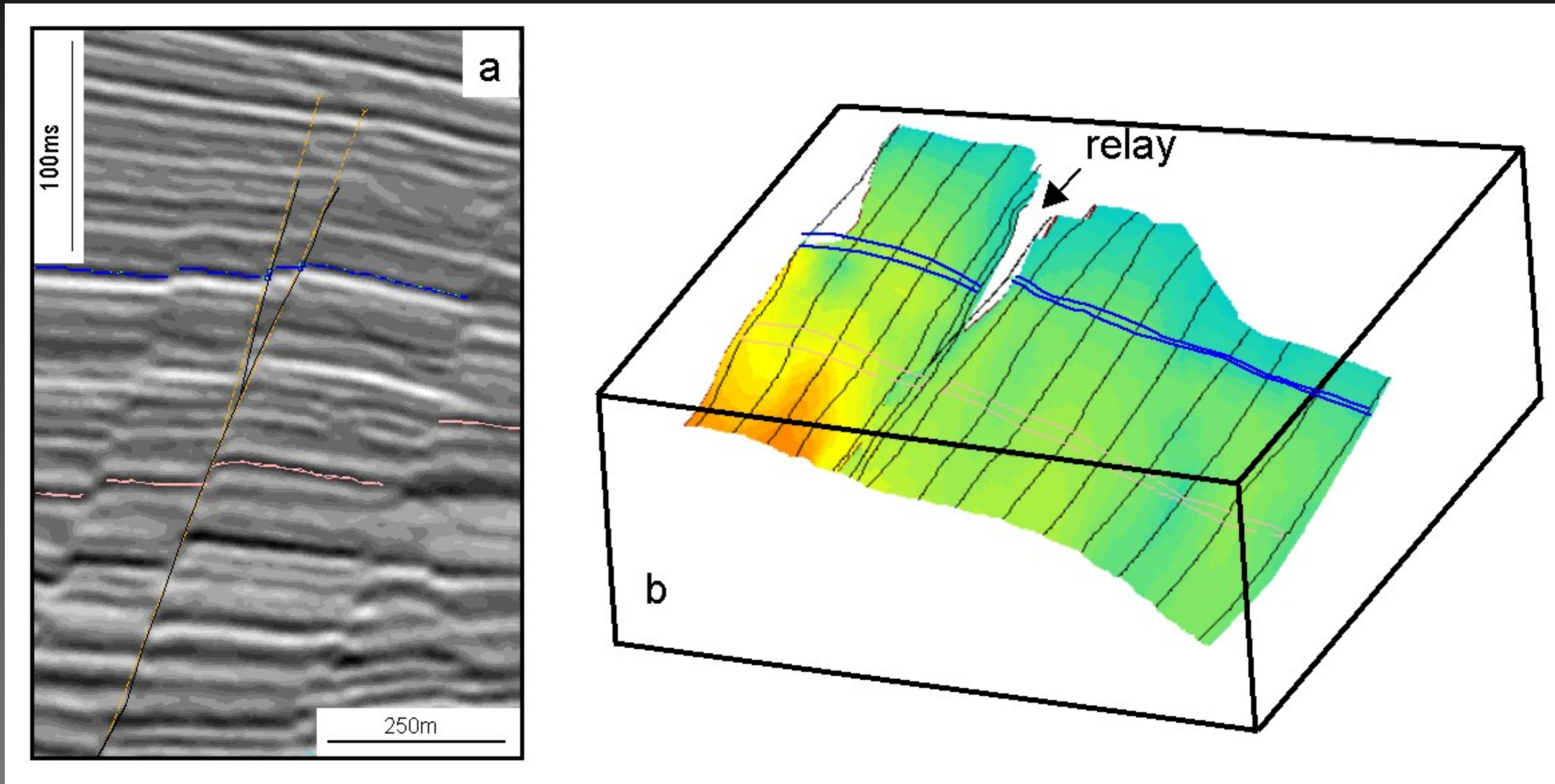
Resolving power in 3-D cross-sections..



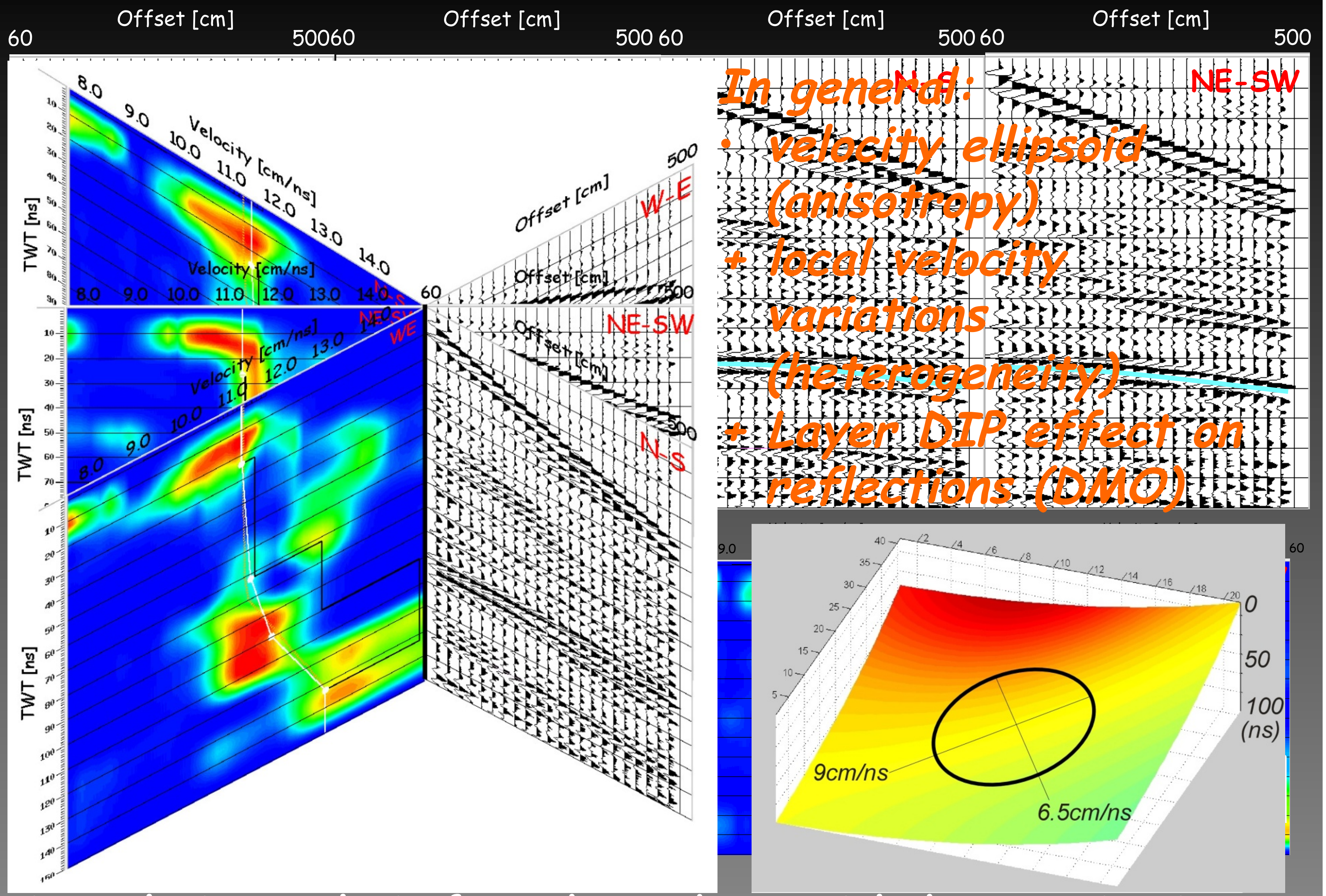
..maps and strike projections …



..3-D subsurface models



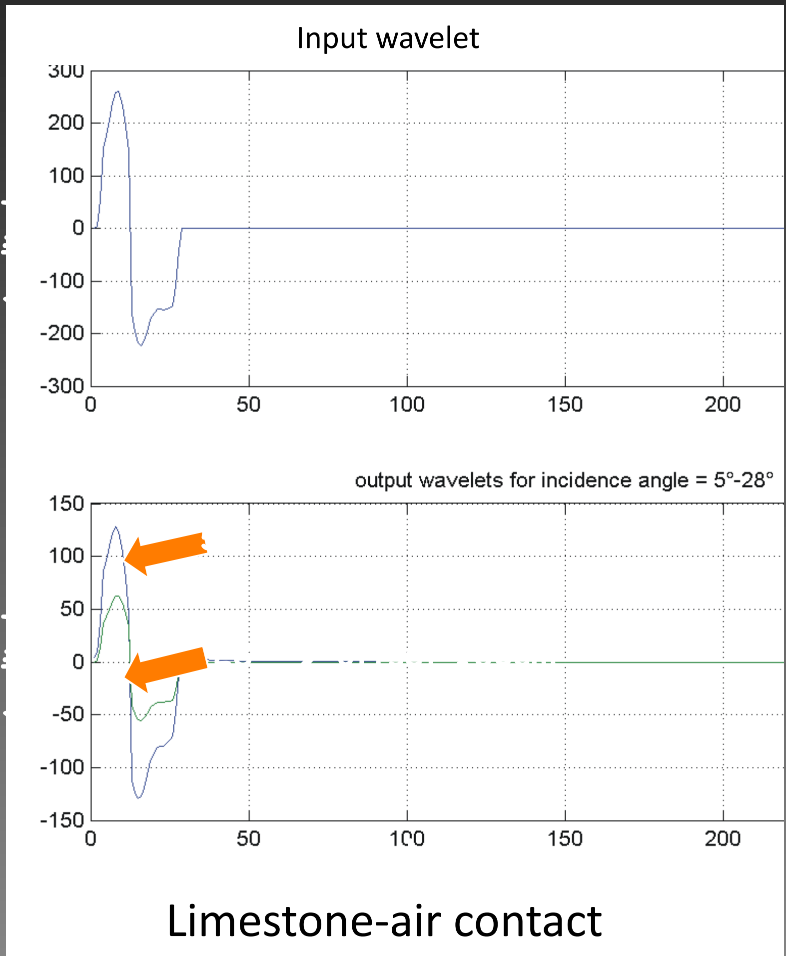
Velocity analysis

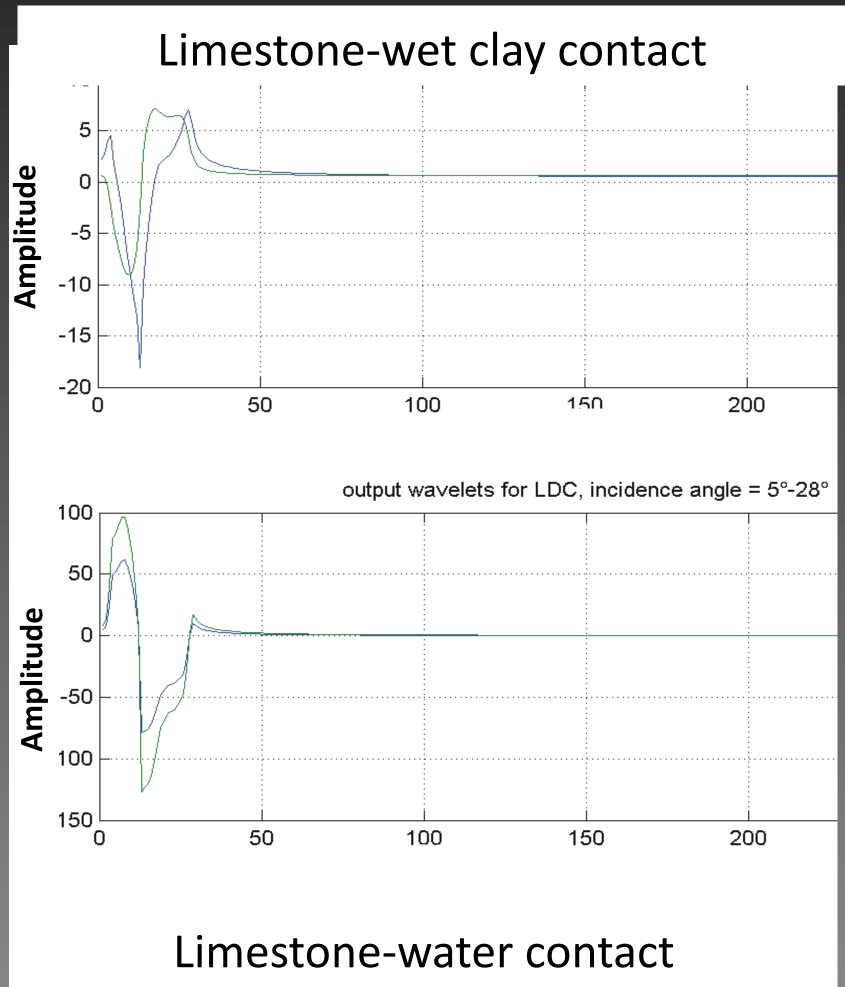


Migration velocity analysis for enhanced material characterization

Characterization of materials and fractures (numerical simulation and Comparison with field data)

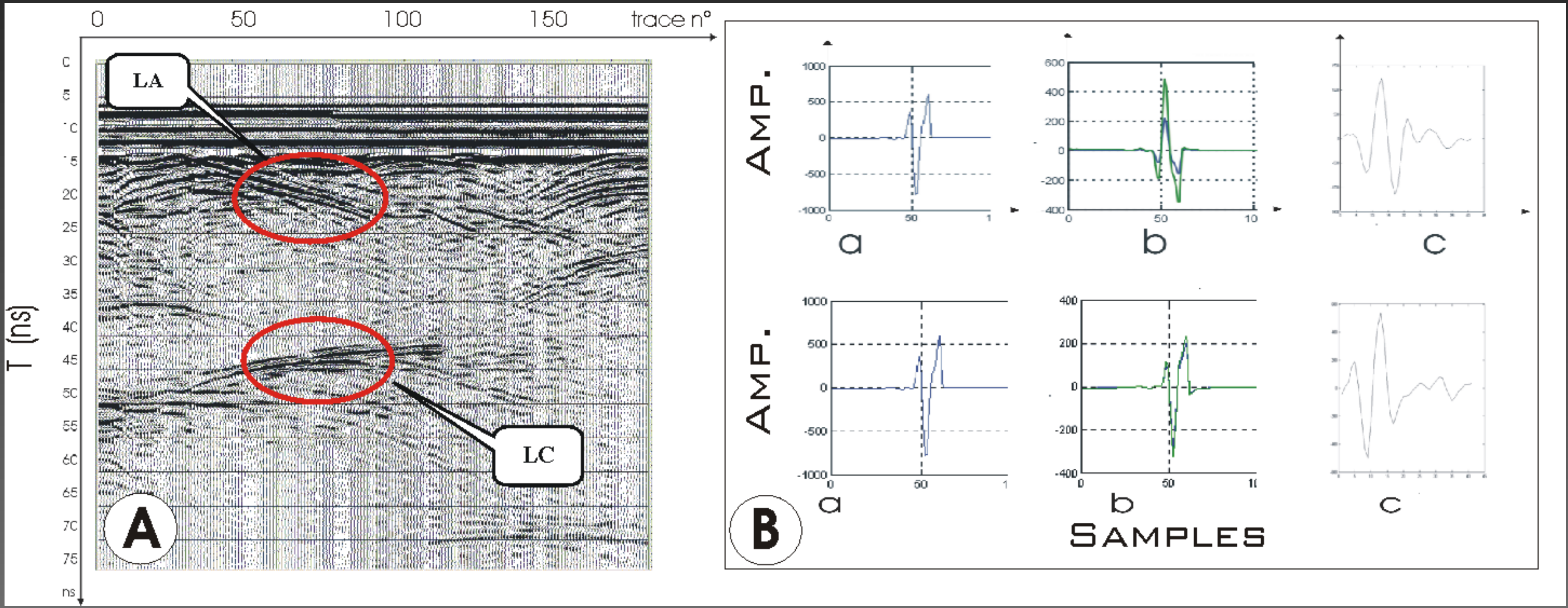
Synthetic data for different materials and incidence angles





Discontinuities characterization using MODELING

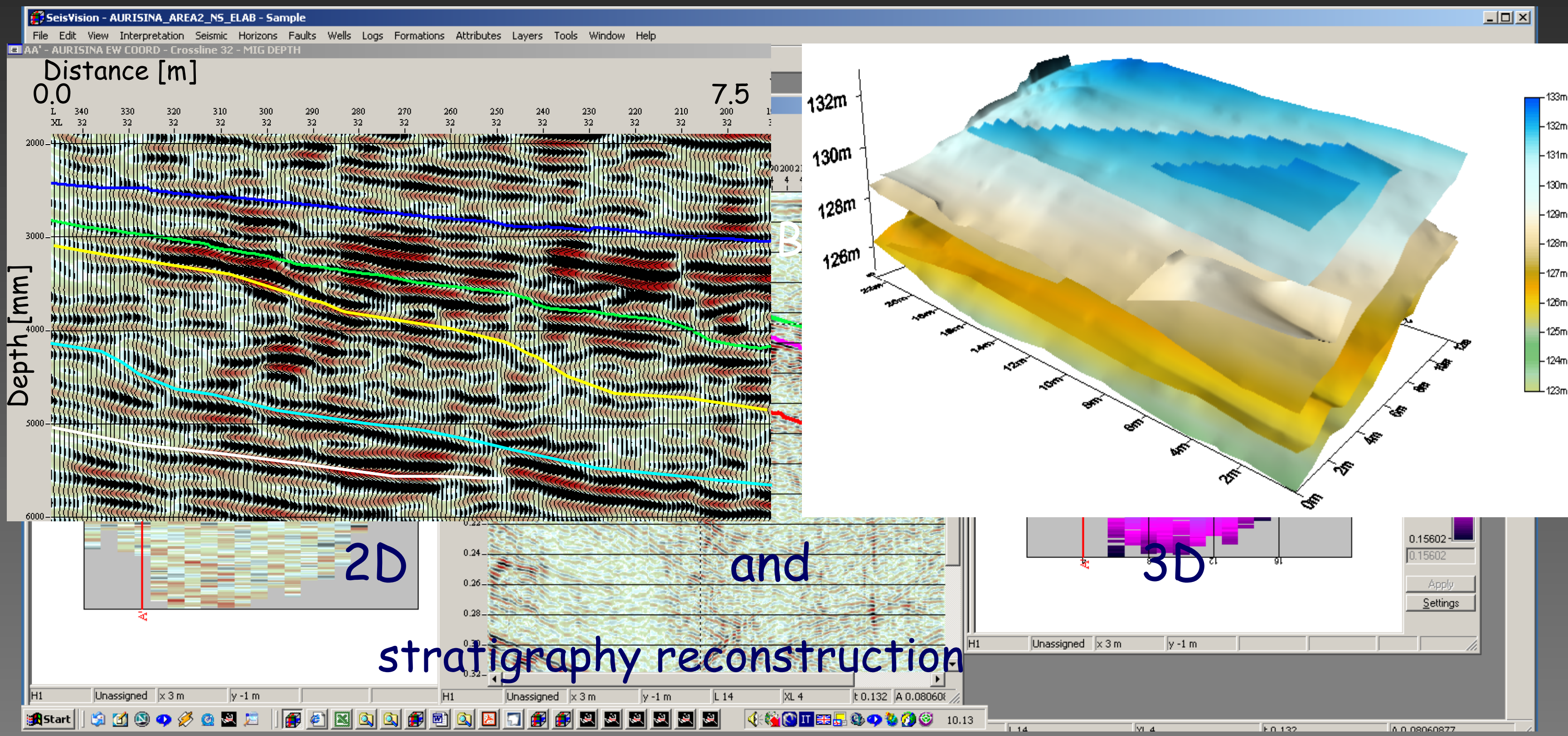
Comparison between field and synthetic data



Estimation of discontinuities characteristics:
opening, filling materials, water presence, lateral/vertical joint variations,...

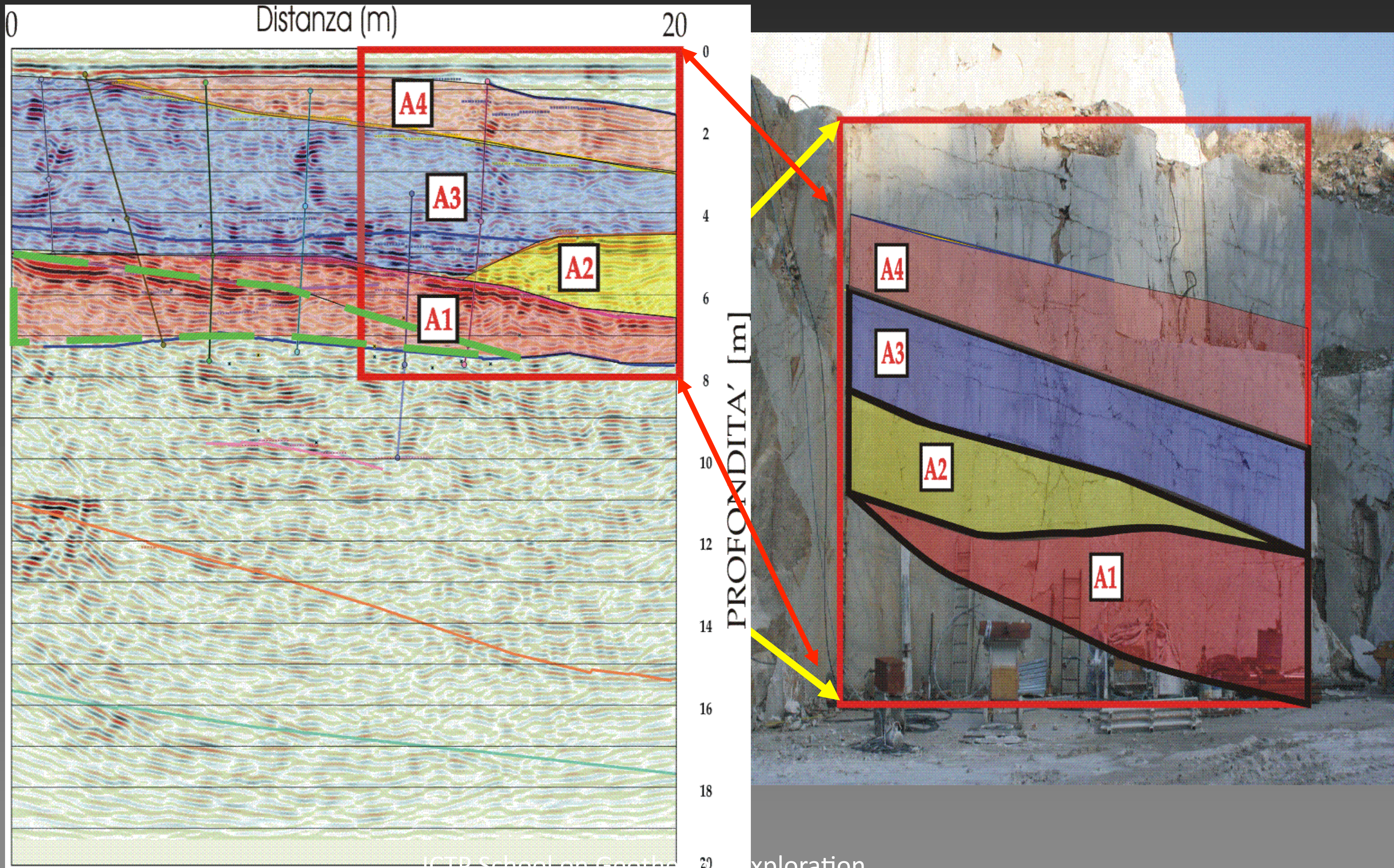
Data integration-interpretation

From 2D interpretation to 3D stratigraphy reconstruction

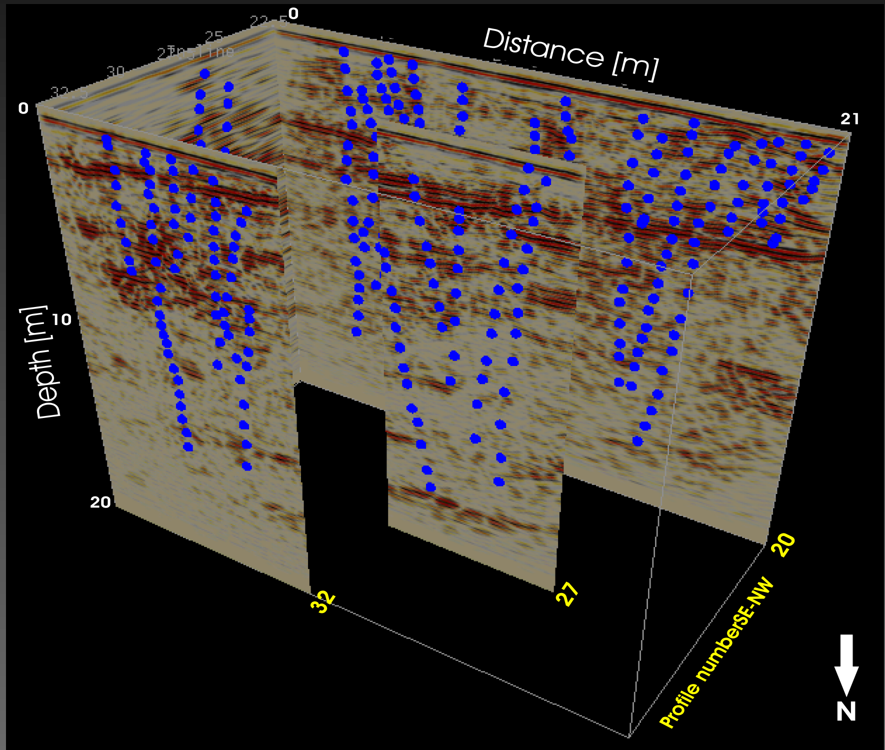


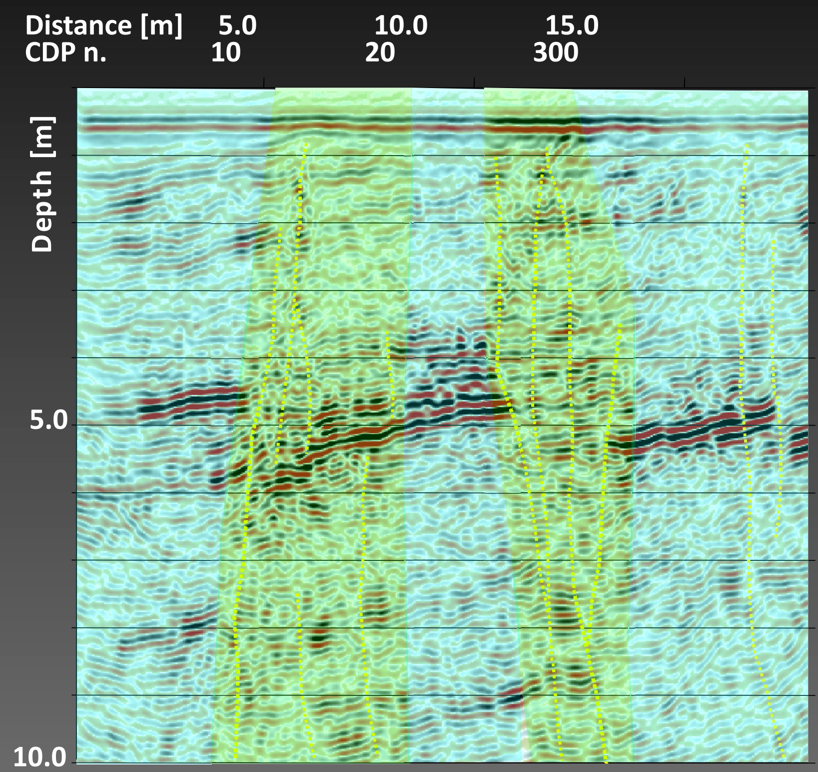
Data integration-interpretation

Correlation, calibration and validation with outcrops



Data integration-interpretation





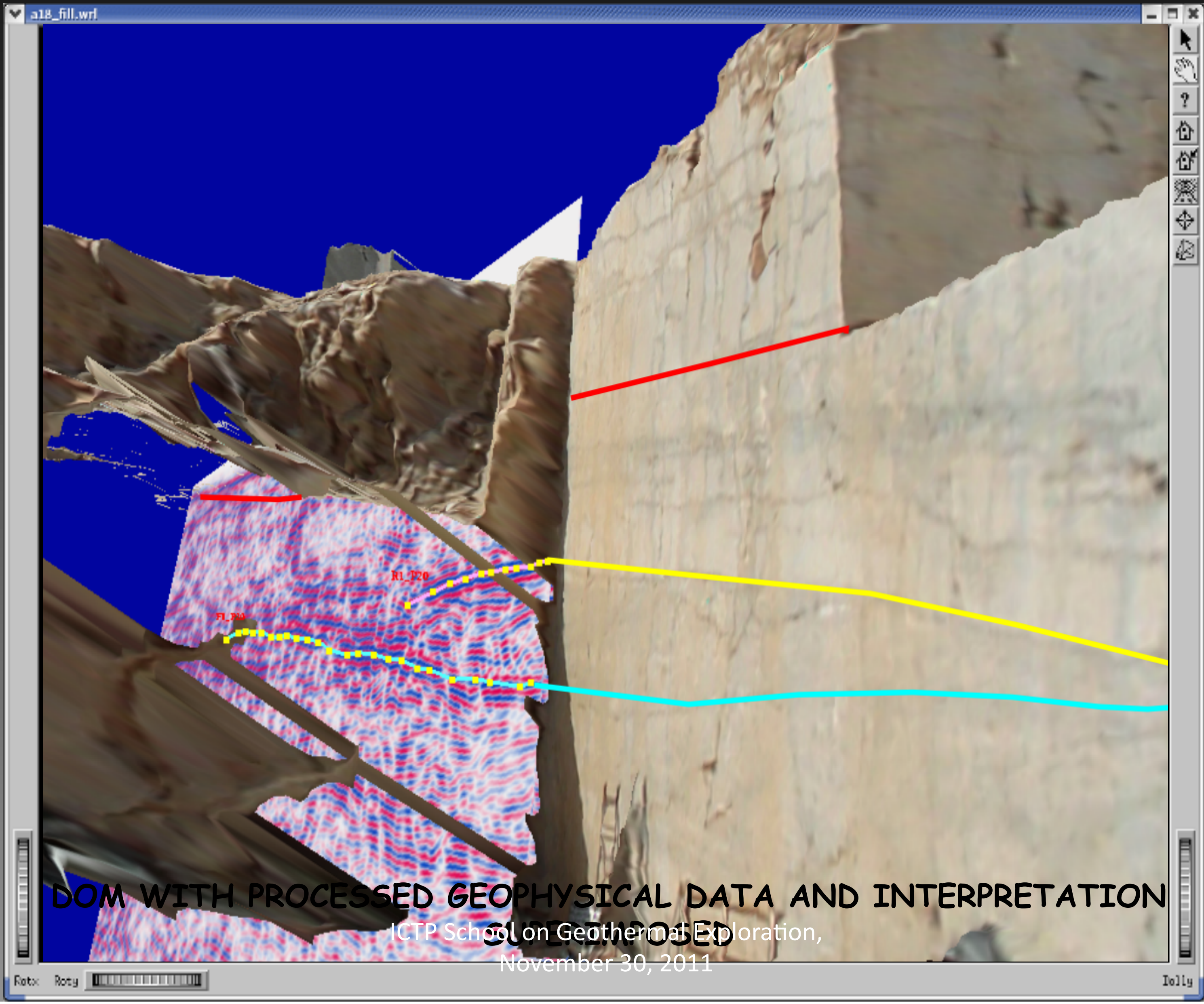
3D Discontinuities mapping and

HIGH fractures density

LOW fractures density

Homogeneous zones definition → geomechanic rock characterization

3D data integration, visualization and analysis



DOM WITH PROCESSED GEOPHYSICAL DATA AND INTERPRETATION SUPERIMPOSED

Interpretation pitfalls (Structural)

- ASSOCIATED WITH:

➢ VELOCITY: because seismic data are often displayed in time rather than in depth

➢ GEOMETRY: because seismic events from a 3-D world are displayed in a 2-D section

➢ RECORDING/PROCESSING: because the content of a seismic section is not only geological and the non-geological components can mask geology (e.g. multiple reflections)

Interpretation pitfalls (material characterization)

- EXAMPLE >> BRIGHT SPOTS AND FALSE BRIGHT SPOTS

➢ BRIGHT SPOT: DHI (direct hydrocarbon indicator, 1970s)

- Gas/light oil in soft sand increase compressibility, decrease velocity, produce strong negative amplitude anomalies (negative bright spots)

Interpretation pitfalls (material characterization)

- EXAMPLE >> BRIGHT SPOTS AND FALSE BRIGHT SPOTS

➢ BRIGHT SPOT: DHI (direct hydrocarbon indicator, 1970s)

- Hard sand saturated by brine may induce a (positive) bright spot
- Gas-filled sand may be transparent, thus causing a weak reflection (dim spot)

BUT…

Interpretation pitfalls (material characterization)

- EXAMPLE >> BRIGHT SPOTS AND FALSE BRIGHT SPOTS

➢ Associated with:

- Volcanic intrusions and volcanic ash layers
- Sands with calcite cement in thin pinch-outs
- Low-porosity heterolithic sands

AND…

Interpretation pitfalls (material characterization)

- EXAMPLE >> BRIGHT SPOTS AND FALSE BRIGHT SPOTS

➢ Associated with:

…

- Overpressured sands or shales
- Coal beds
- Top of salt diapirs

The last 3 have same polarity of gas sands

AMERICAN vs. EUROPEAN polarity

- American

➢ Increase in impedance gives positive amplitude (normally black in VA or red in VD)

- European/Australian

➢ Increase in impedance gives negative amplitude (normally white in VA or blue in VD)

HARD (i.e. high impedance) or SOFT (low imp.) events ?

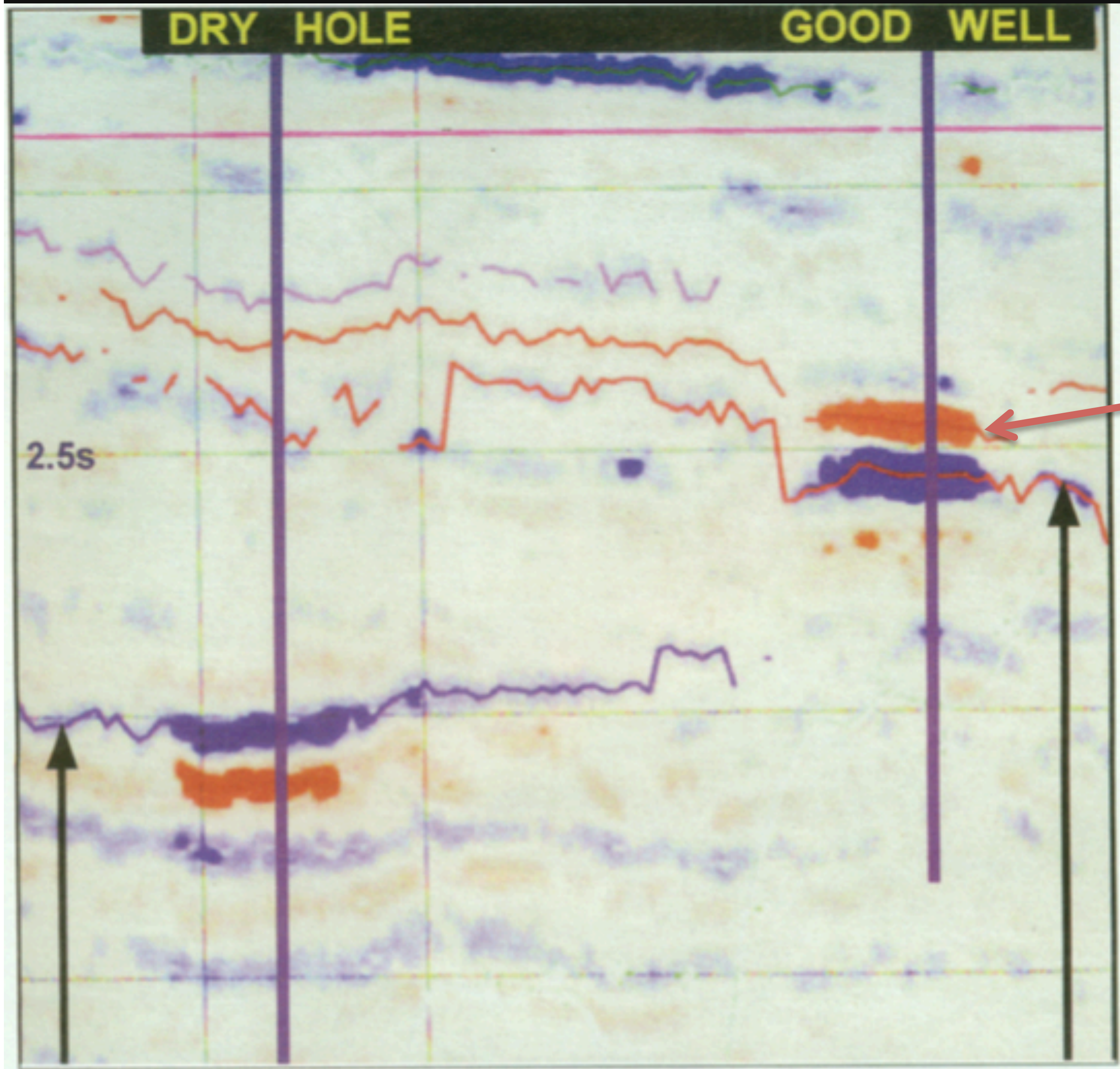
- HARD
  - shallow sands at normal pressure embedded in pelagic shales
  - Cemented sandstones with brine saturation
  - Carbonate rocks embedded in siliciclastics
  - Mixed lithologies like shaly sands, marls, volcanic ashes

HARD (i.e. high impedance) or SOFT (low imp.) events ?

- SOFT

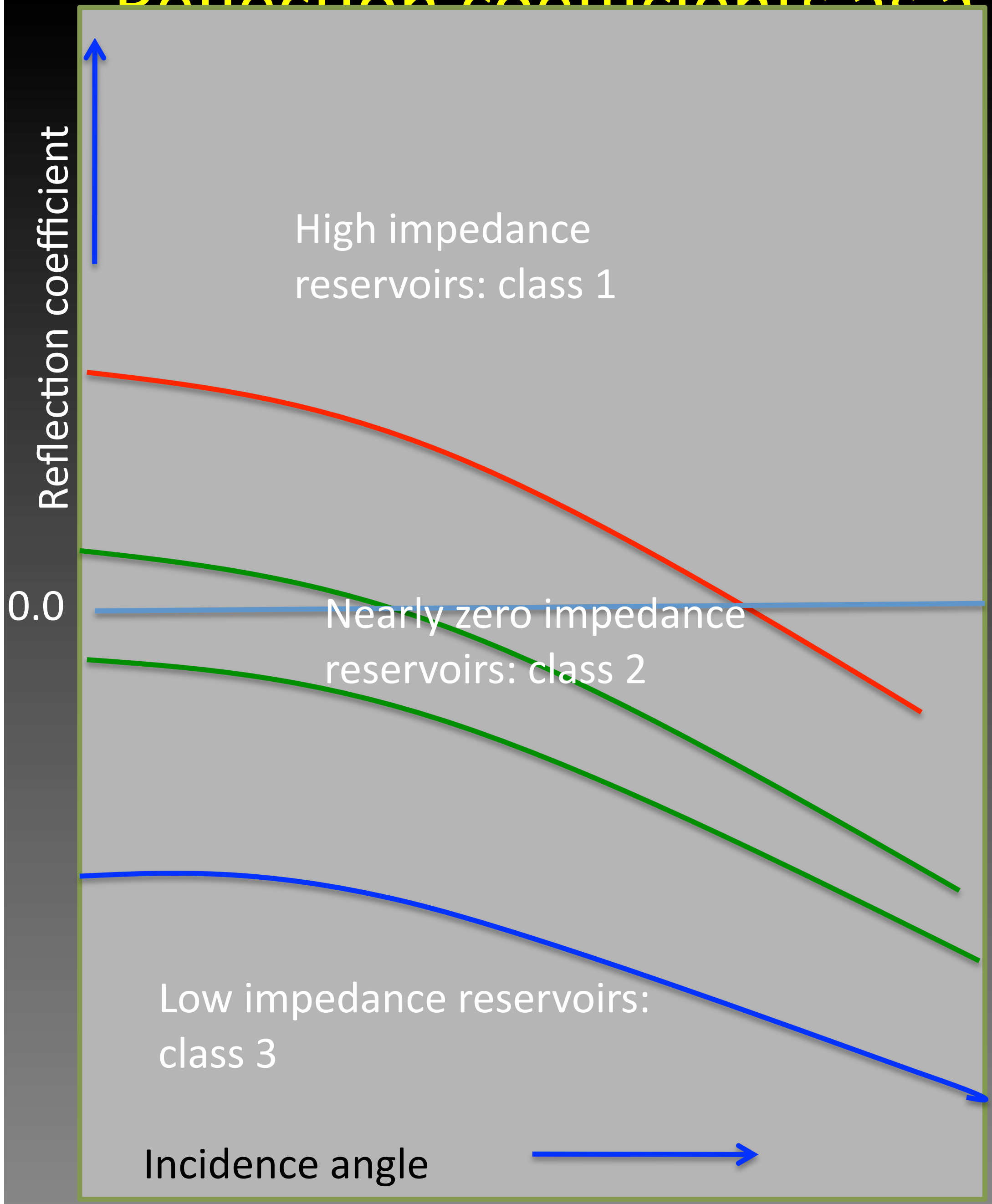
- Pelagic shale
- Shallow unconsolidated sands (any pore fluid) embedded in normally compacted shales
- Hydrocarbon accumulations in clean, unconsolidated sands
- Overpressured zones

Interpretation pitfalls (material characterization)



Through-over-peak = low-impedance target

Reflection coefficients as a function of incidence

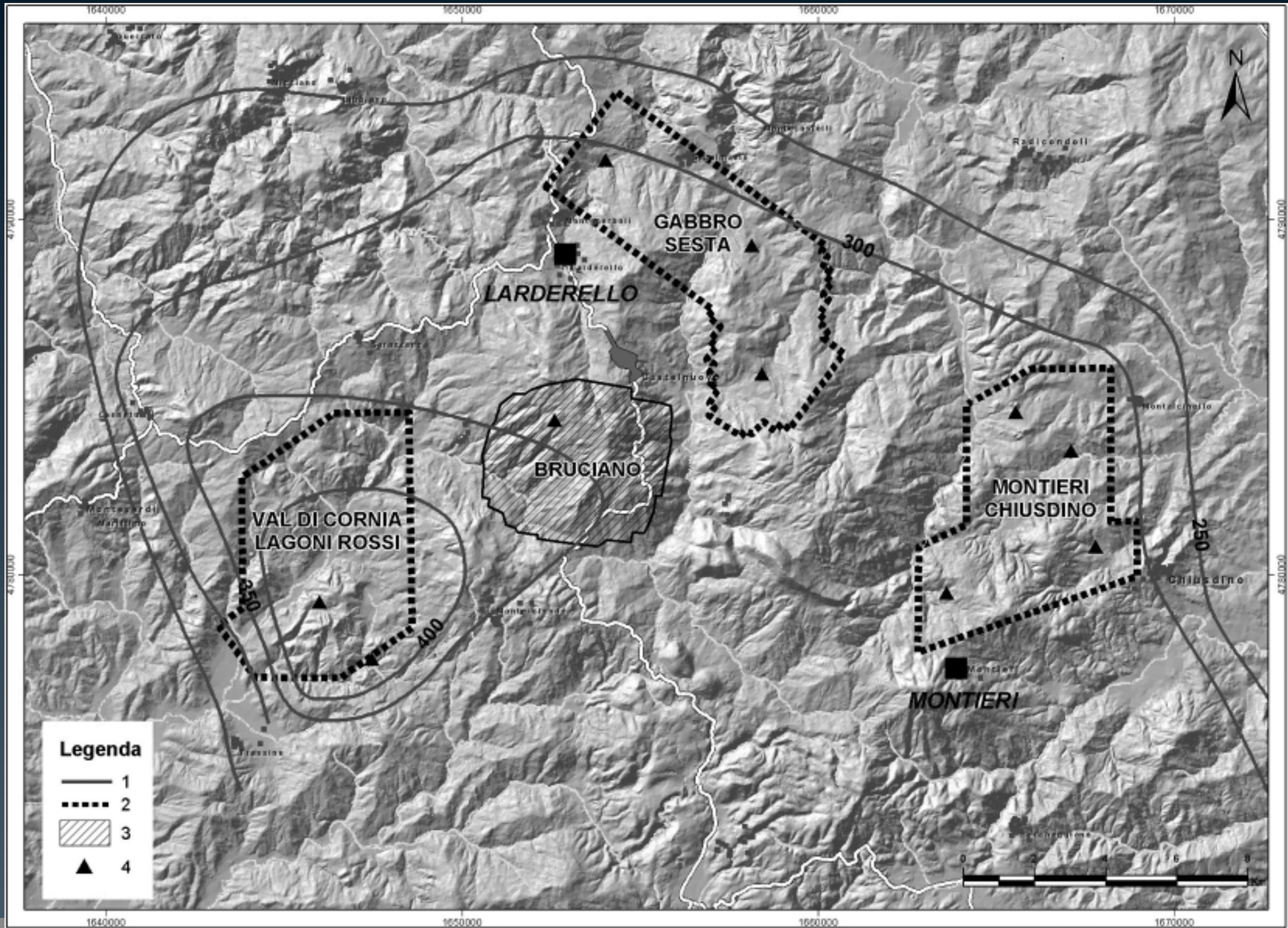


Class 1 can be associated with gas reservoirs at great depth

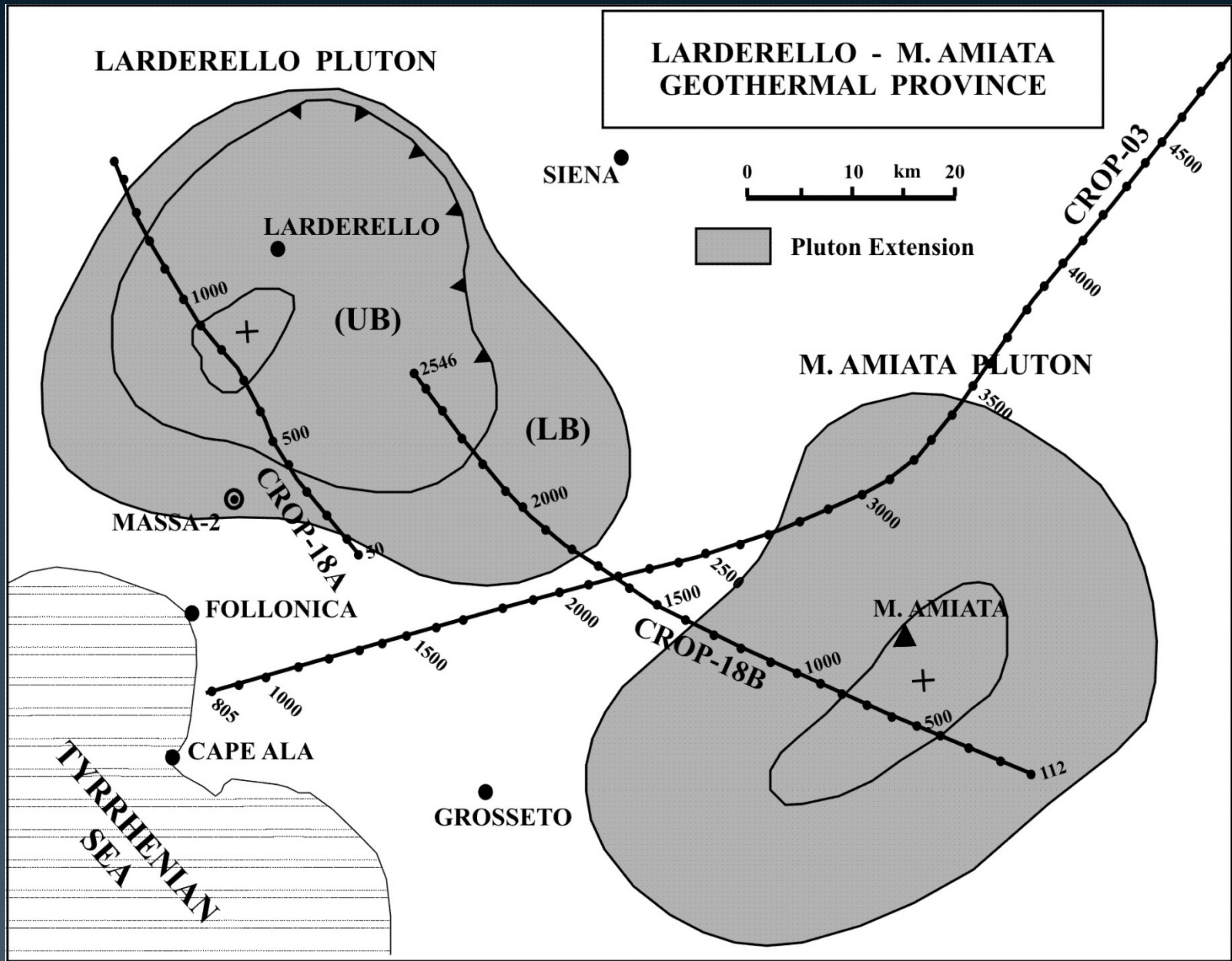
Class 2 can only be identified through partial stacks

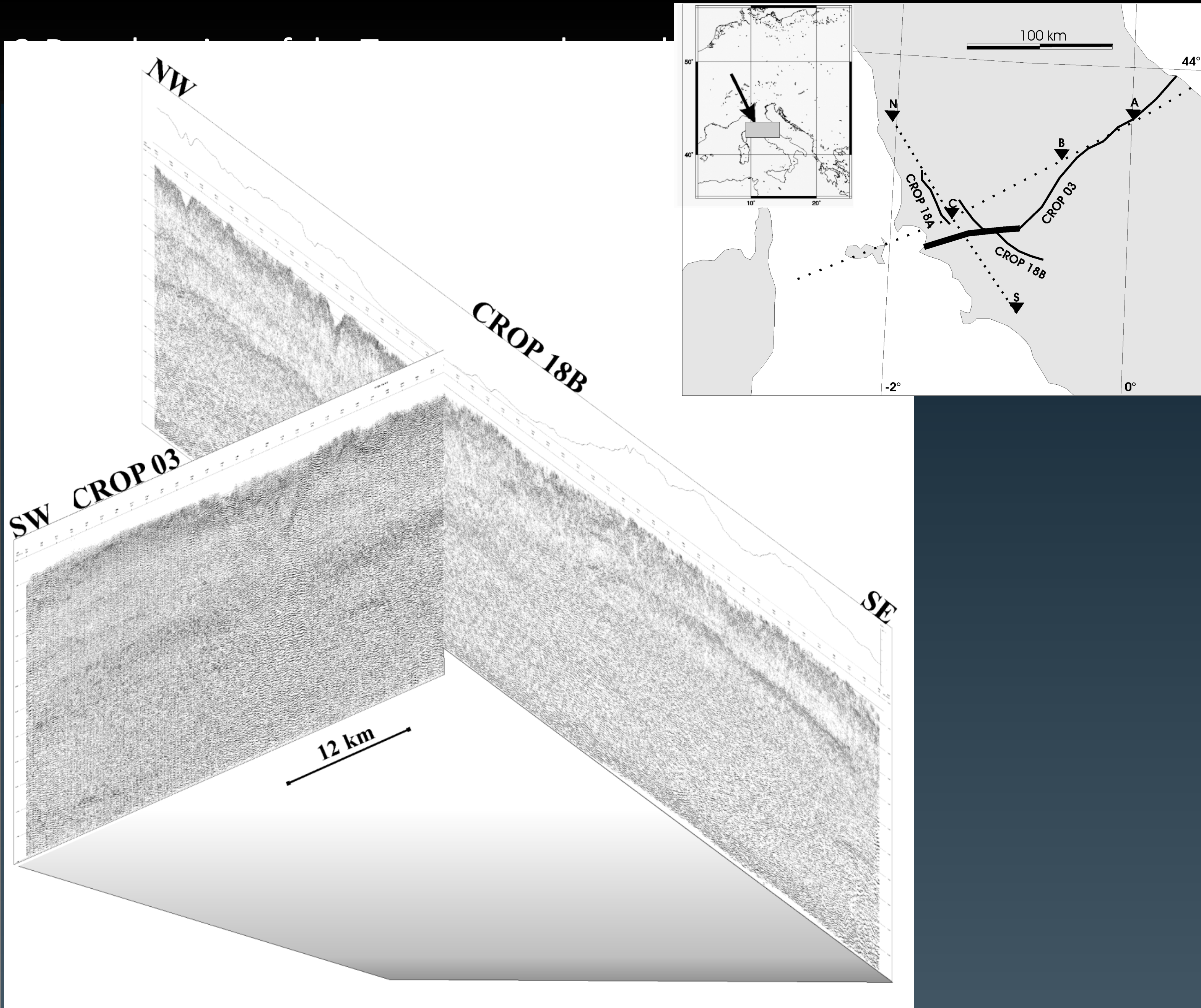
Class 3 describes bright spot anomalies (normally associated with large gas reservoirs)

3-D exploration of the Tuscany geothermal province (Italy)

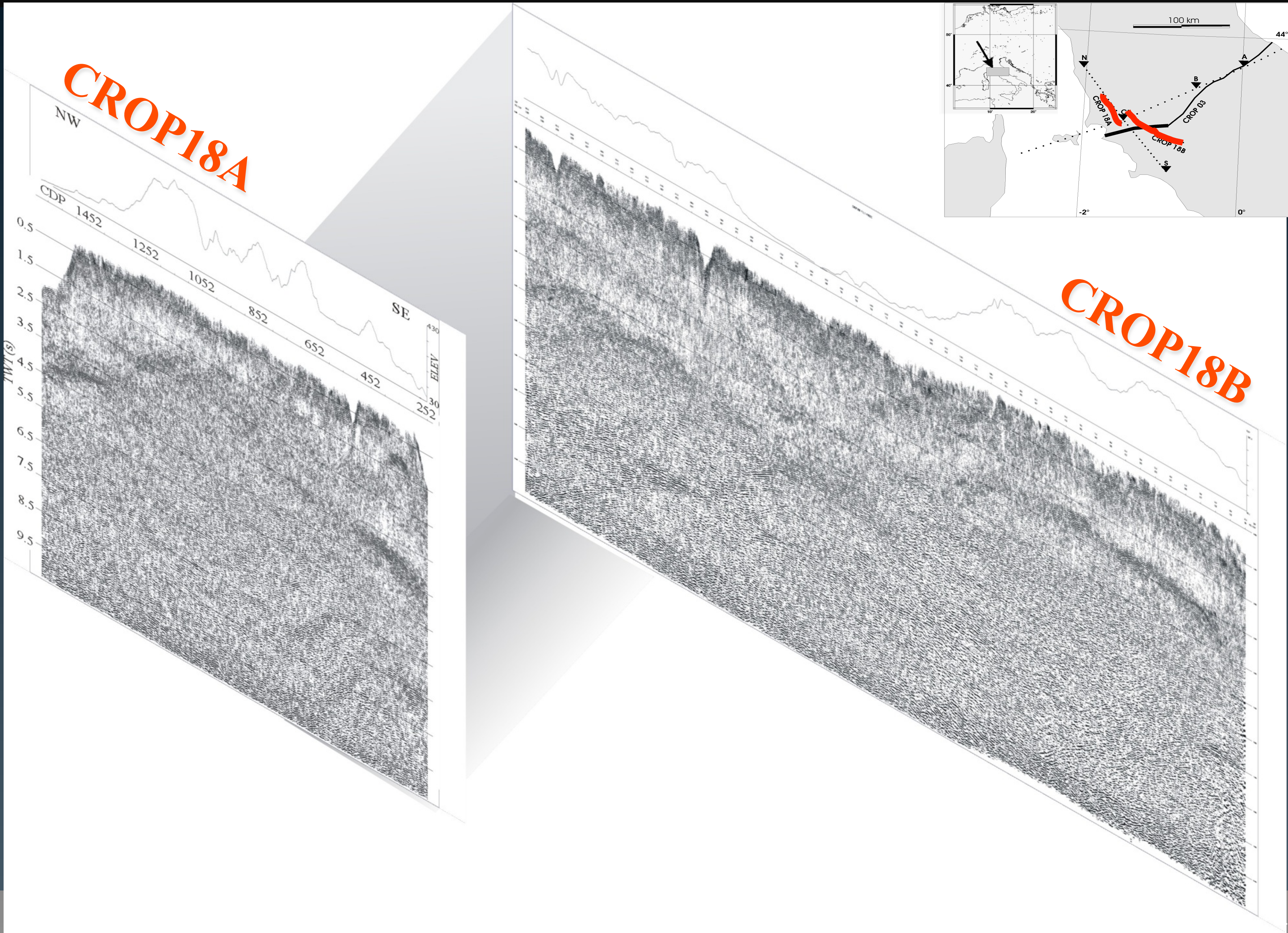


3-D exploration of the Tuscany geothermal province (Italy)

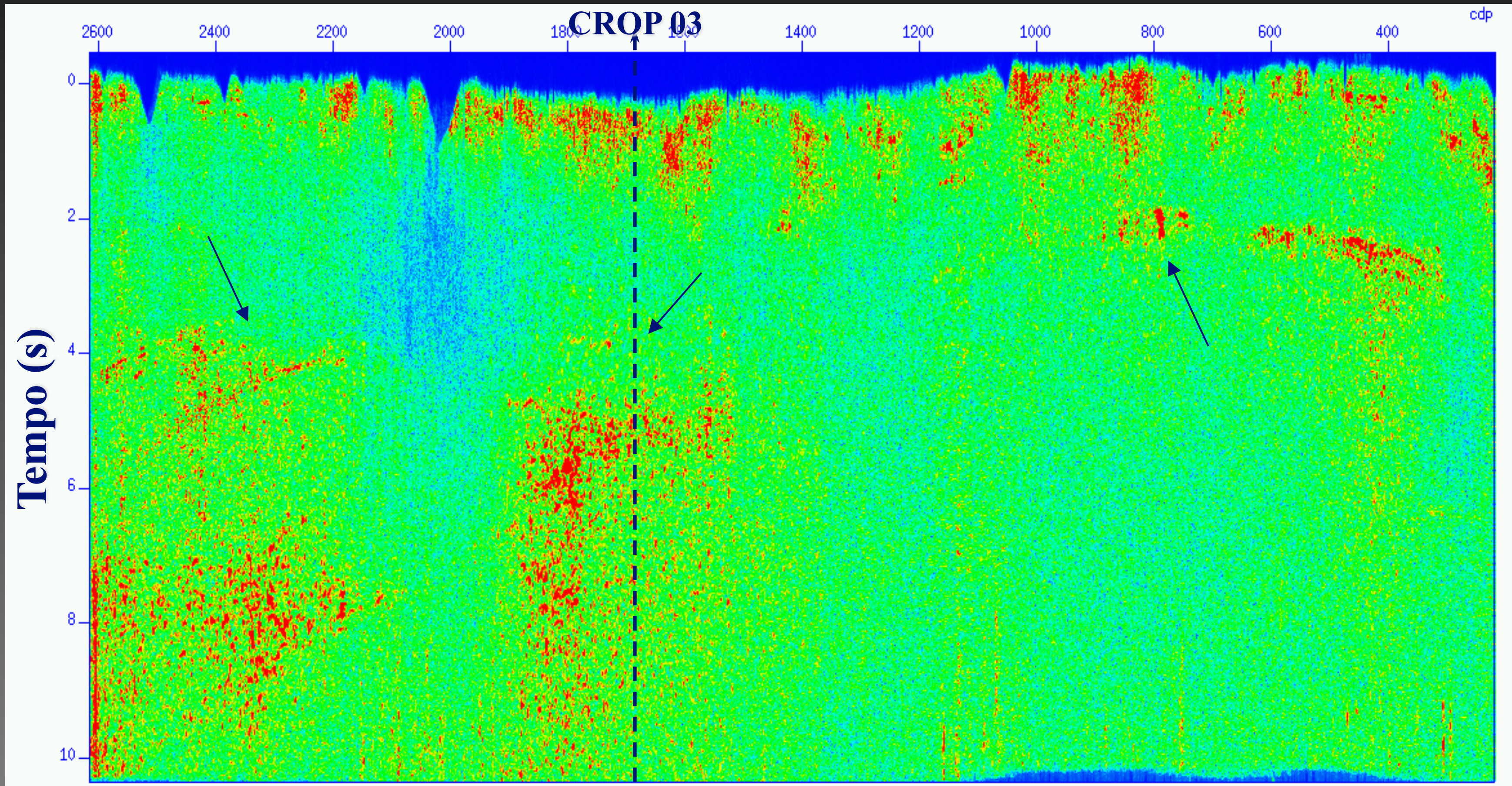



NW
CROP 18B
SW
CROP 03
SE
12 km
100 km
44°
N
A
B
C
S
CROP 18A
CROP 03
CROP 18B
-2°
0°

3-D exploration of the Tuscany geothermal province (Italy)



Example of seismic attributes: instantaneous amplitude from Hilbert transform



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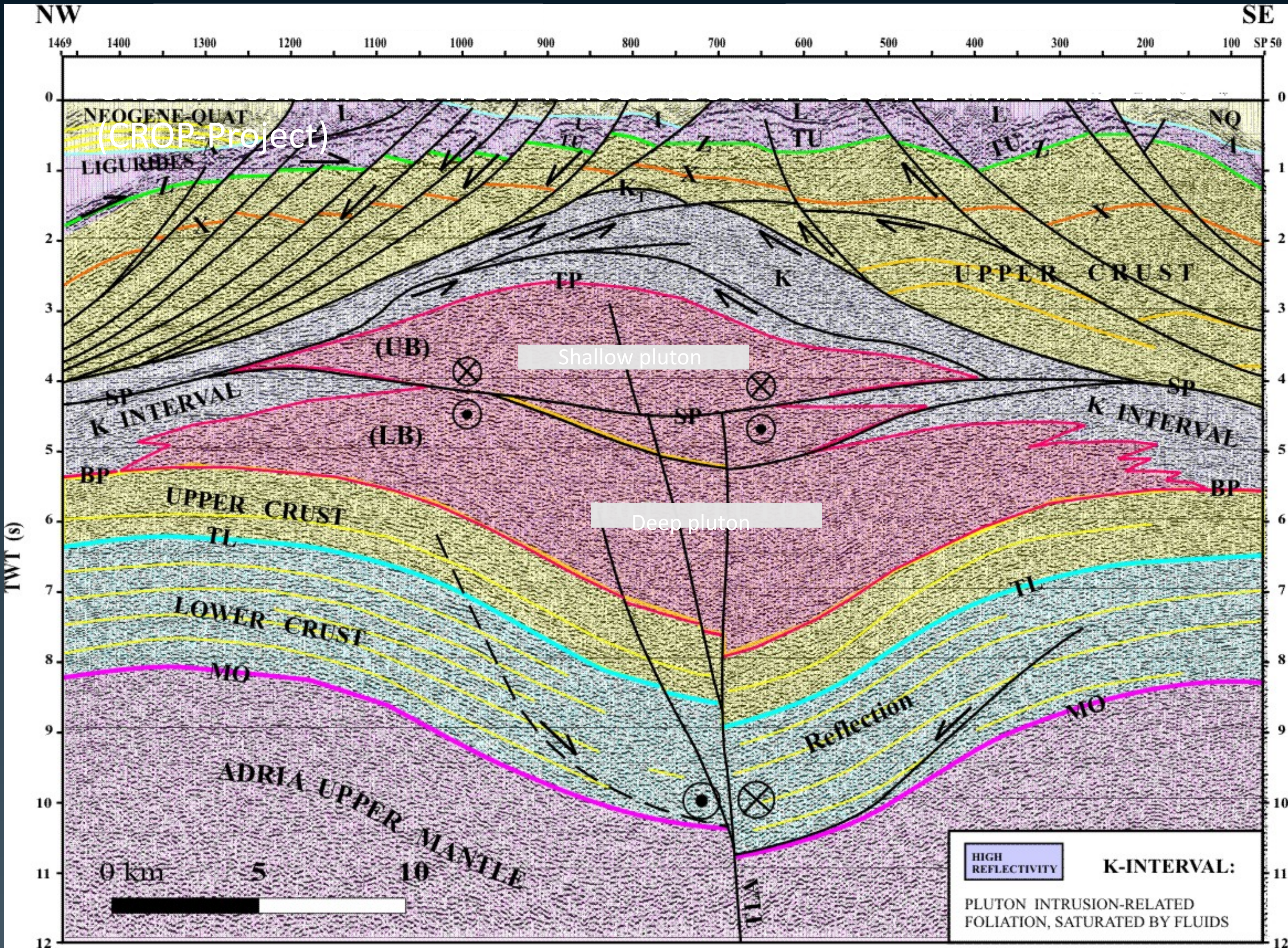
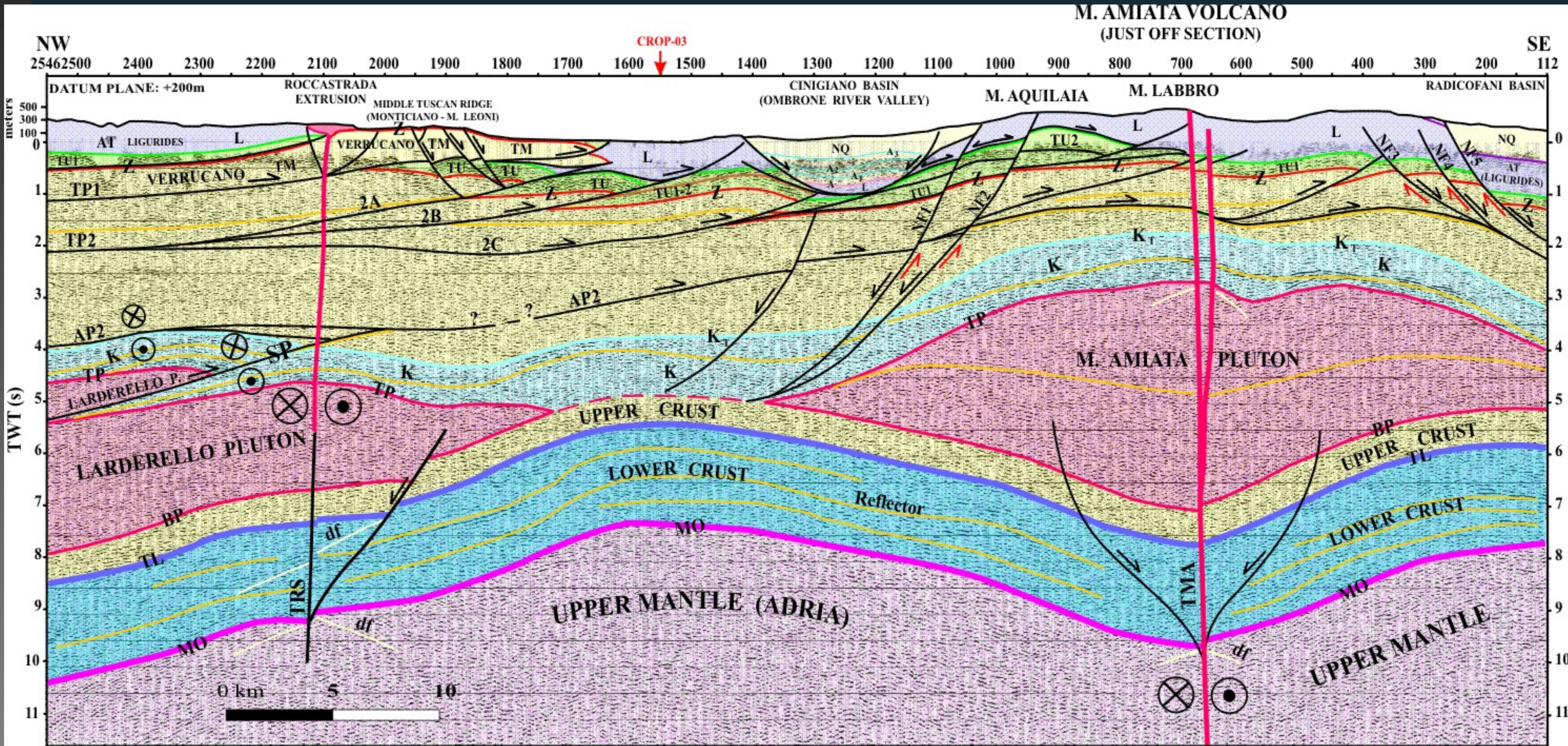
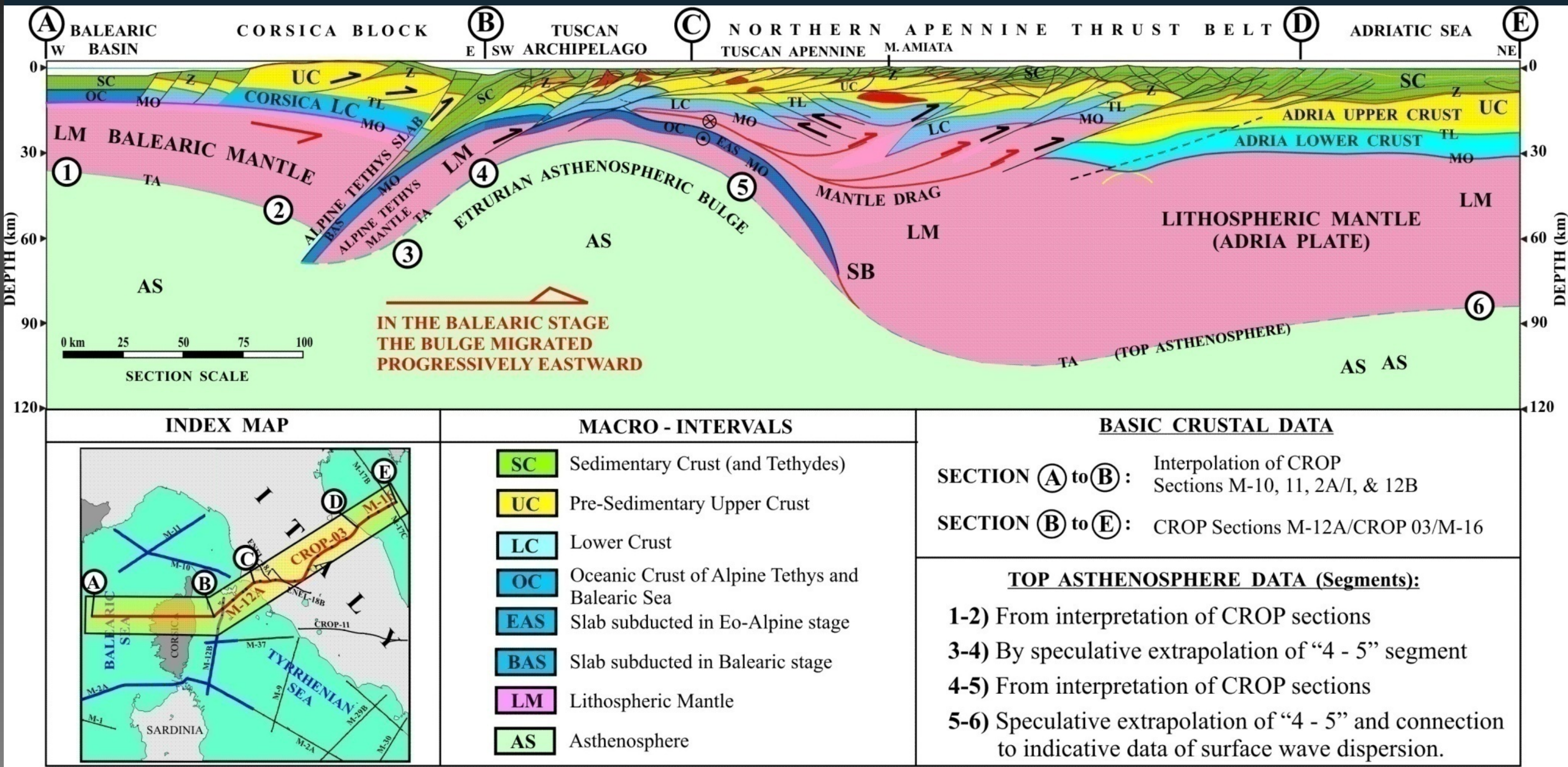
3-D exploration of the Tuscany geothermal province (Italy)



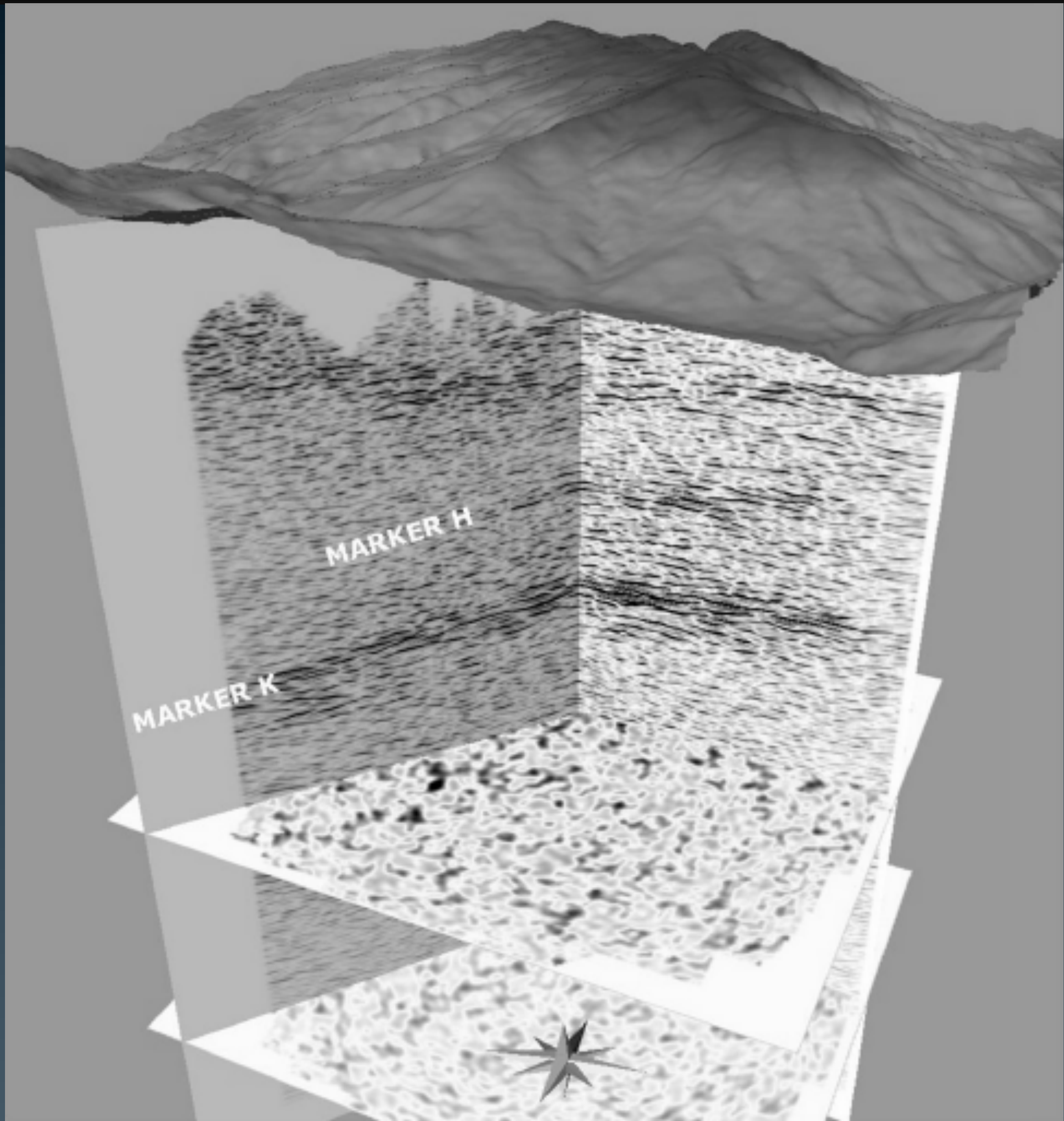
3-D exploration of the Tuscany geothermal province (Italy)



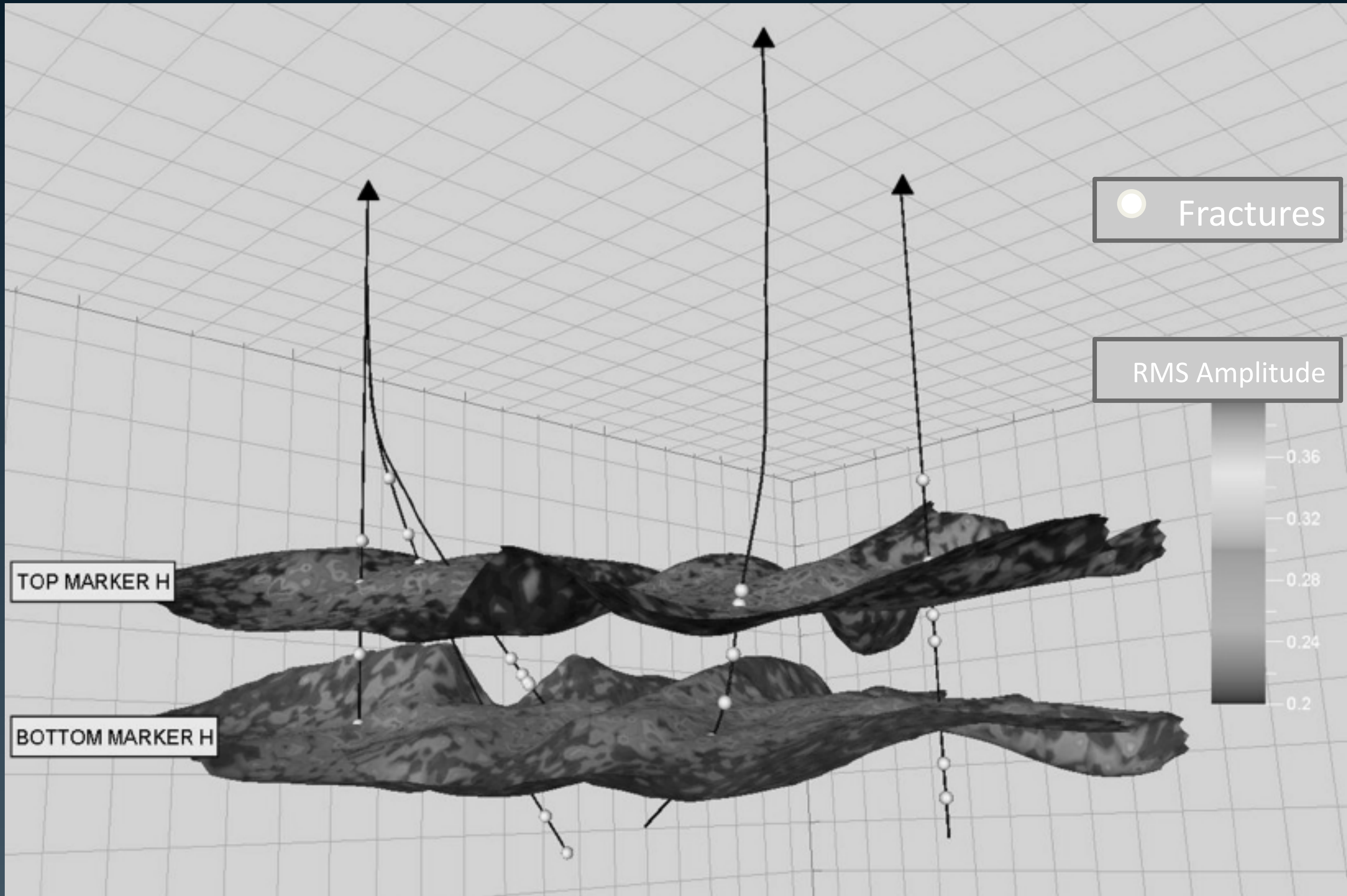
3-D exploration of the Tuscany geothermal province (Italy)



3-D exploration of the Tuscany geothermal province (Italy)



3-D exploration of the Tuscany geothermal province (Italy)



How to extract more geology out of 3-D seismic data

- Expect detailed subsurface information
- Do not rely on "automatic" procedures to find answers
- Use all the data
- Understand the data and appreciate its defects
- Use time (or depth) slices/horizontal sections
- Visualize subsurface structure
- Use machine autotracking and snapping
- Select the color scheme with care
- Question data phase and polarity
- Tie seismic data to well data on character
- Believe seismic amplitudes
- Understand the seismic attributes you use
- Prefer horizon attributes to windowed attributes
- Use techniques that maximize signal-to-noise ratio

Conclusions

- 3-D seismic imaging is a powerful tool to:
  - ➢ unravel complex structural features
  - ➢ identify faults and fractures with adequate precision for exploratory/production drilling purposes
  - ➢ obtain detailed 3-D structural models of use in the identification and assessment of geothermal resources

NONETHELESS…

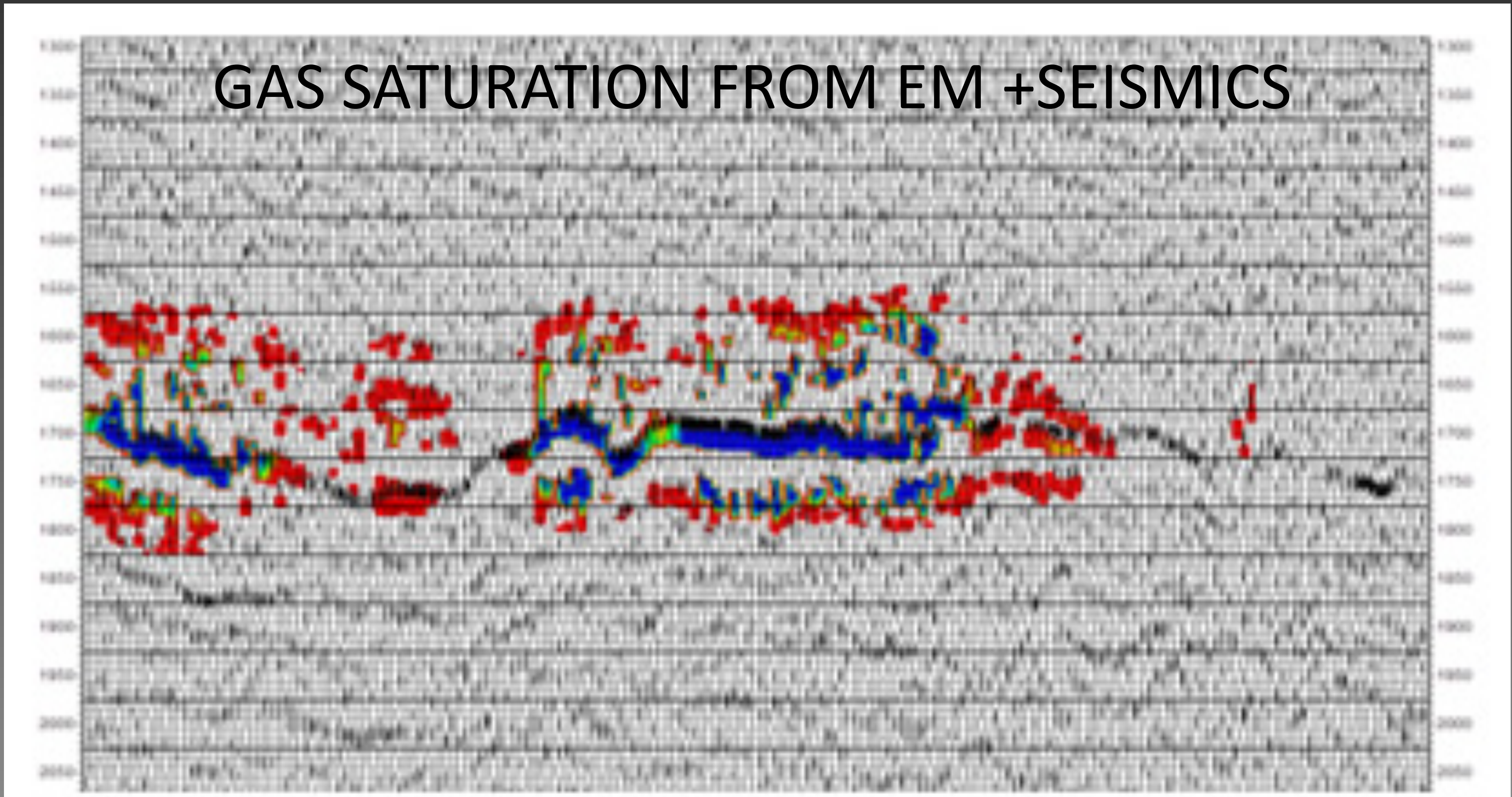
Conclusions (2)

- Seismic data are sensitive to acoustic impedance contrasts
- Different types of fluids and/or variations of temperature may have little effect on acoustic impedance
- Even seismic AVO response and instantaneous seismic attributes do not allow convincing discrimination between fluid/lithology variations

THEREFORE…

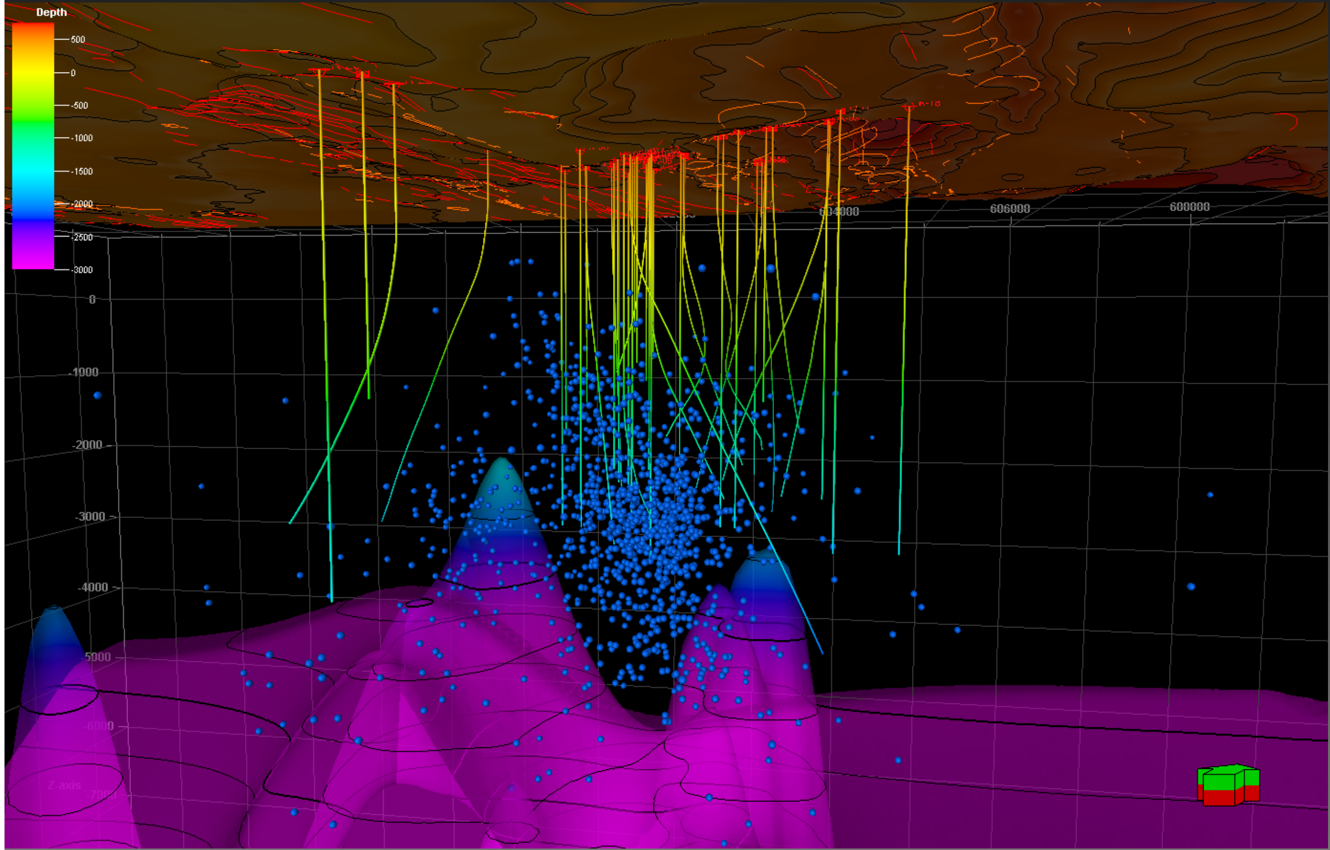
THE ROAD AHEAD IN GEOTHERMAL EXPLORATION:

Joint Seismic/EM imaging and inversion



A final word about passive techniques:

IMAGING AND CHARACTERIZATION OF DEEP GEOTHERMAL RESERVOIRS



Pre-drilling exploration results:

Resistivity shows a conductive body at average 4-5 km depth but with pinnacles up to 2km.

•Micro-earthquakes show that seismicity occurs above the conductive body indicating T higher than 700°C

Drilling results:

•A borehole pointing towards a pinnacle hit acidic magma at 2,1 km

Combined results of resistivity soundings (TEM/MT) and micro-seismicity analysis at the Krafla geothermal field (Iceland)