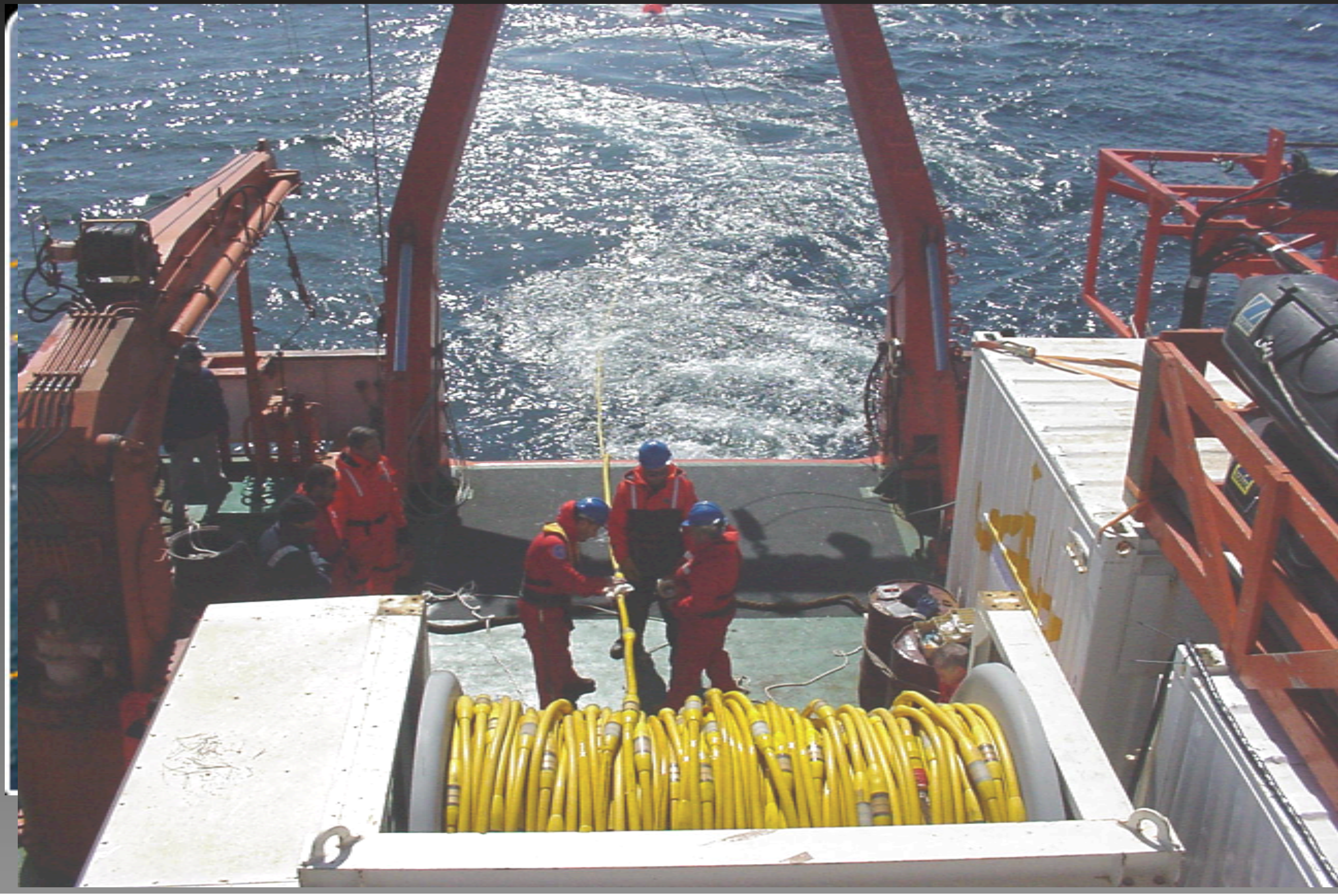
Geophysical methods in geothermal exploration and reservoir characterization: 3-D seismics

ICTP The Abdus Salam International Centre for Theoretical Physics
IGA International Geothermal Association
UNIVERSITÀ DEGLI STUDI DI TRIESTE
UNIONE GEOTERMICA ITALIANA

SUMMARY

- Basic concepts
- Advanced techniques for resource identification/ assessment/monitoring:
  - 3-D imaging
  - Full Waveform Inversion
  - AVO/attributes analysis
  - 4-D time lapse seismic monitoring

3-D reflection seismics



3-D reflection seismics

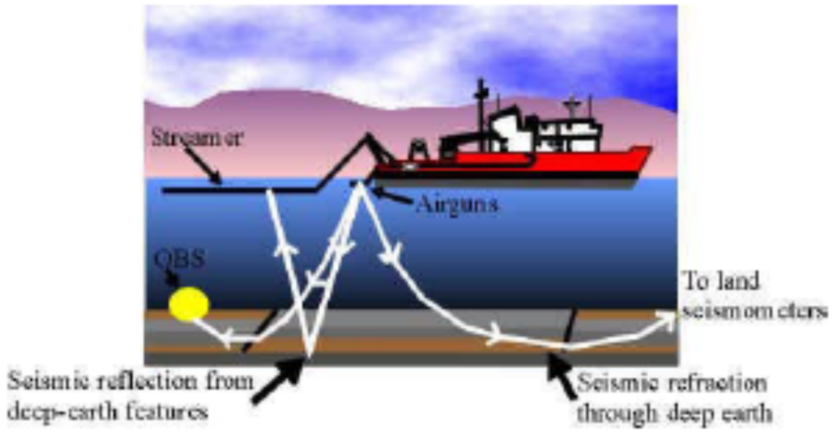
Seismic sources

Consider
- Energy input
- Repeatability
- Cost
- Convenience

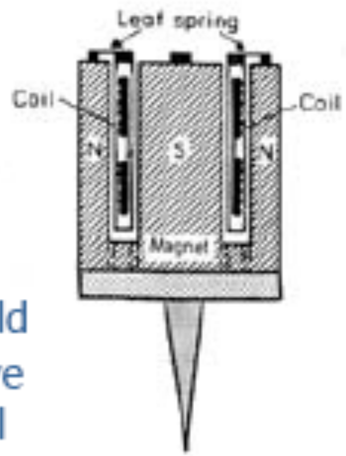
Vibroseis
- No pulse, frequency sweep
- Significant signal with stacking/deconvolution

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

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



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

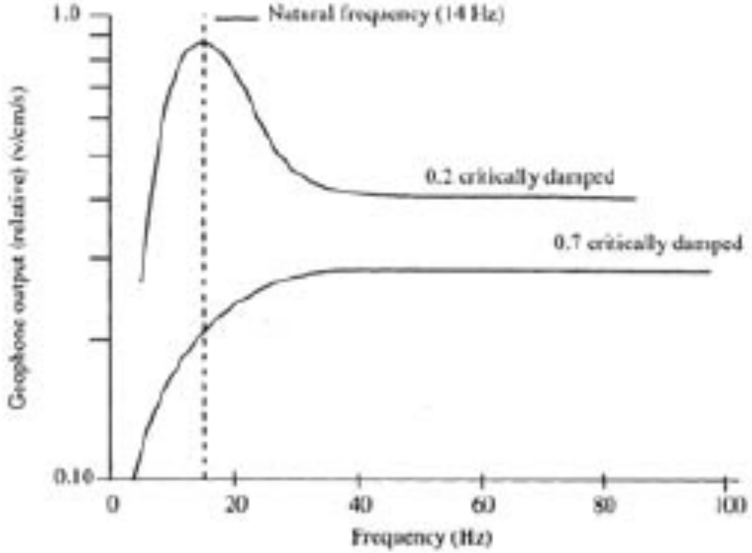
- The relation between the input ground motion and the output electrical signal

Natural frequency

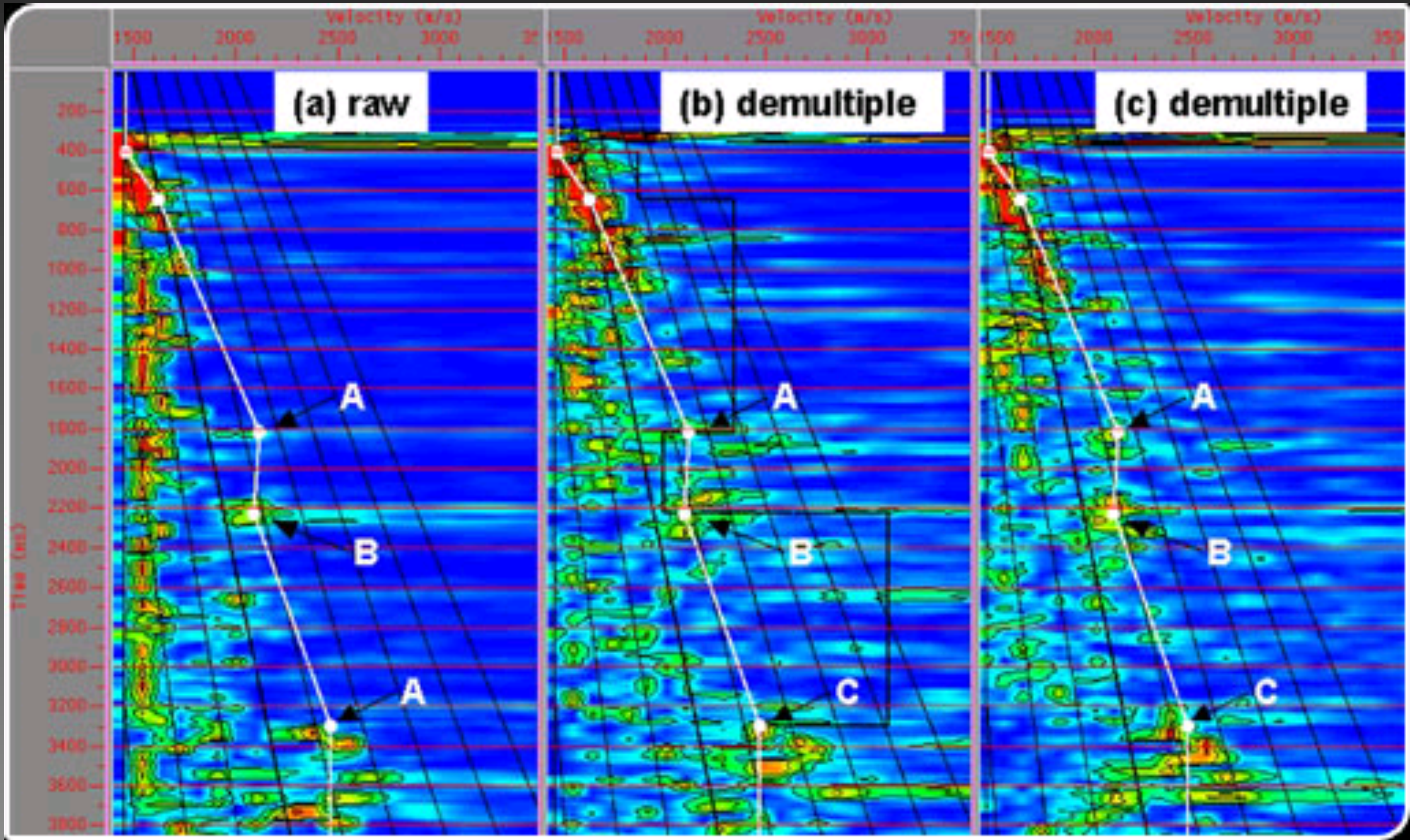
- The frequency which produces the maximum amplitude output

Damping

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



3-D reflection seismics



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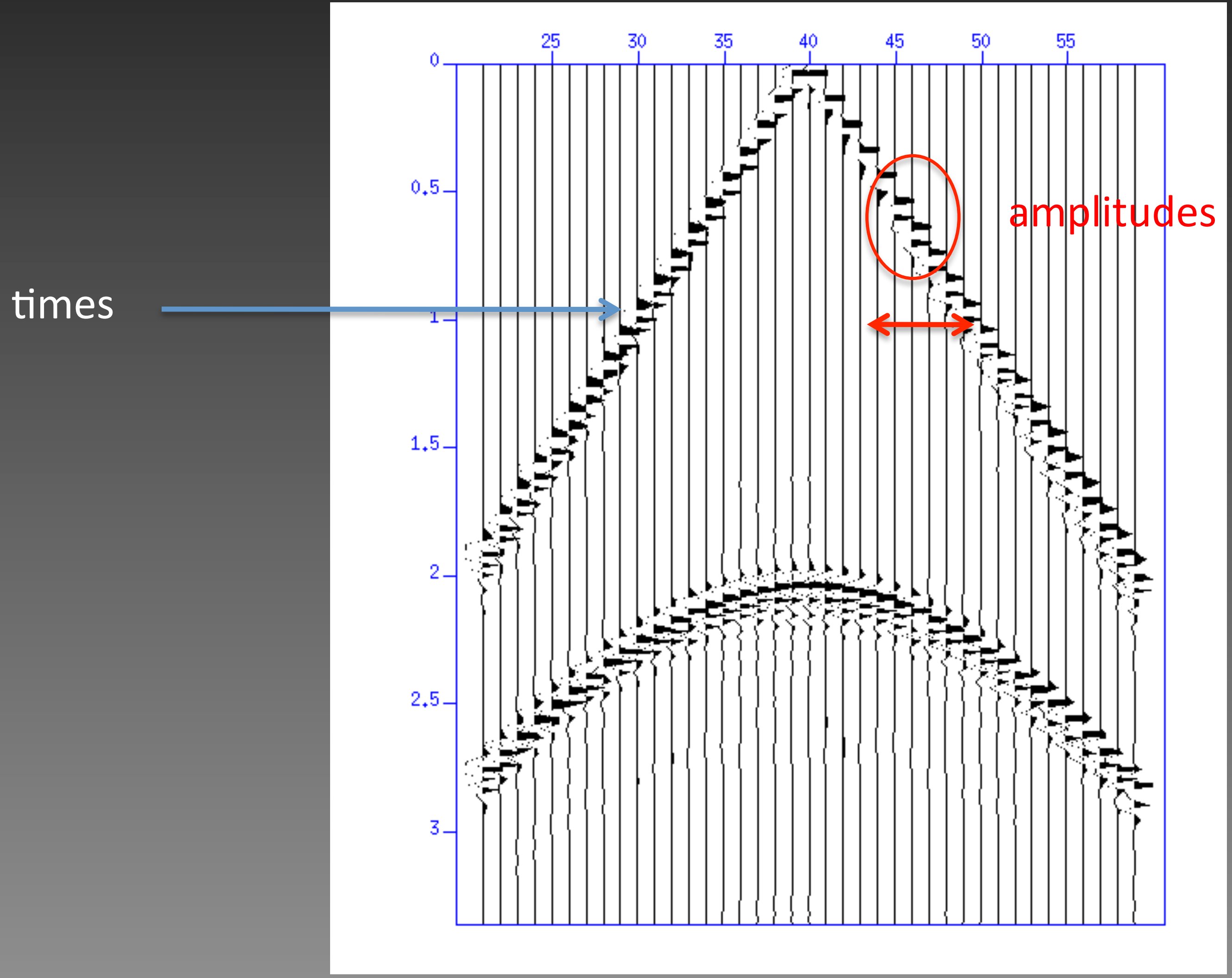
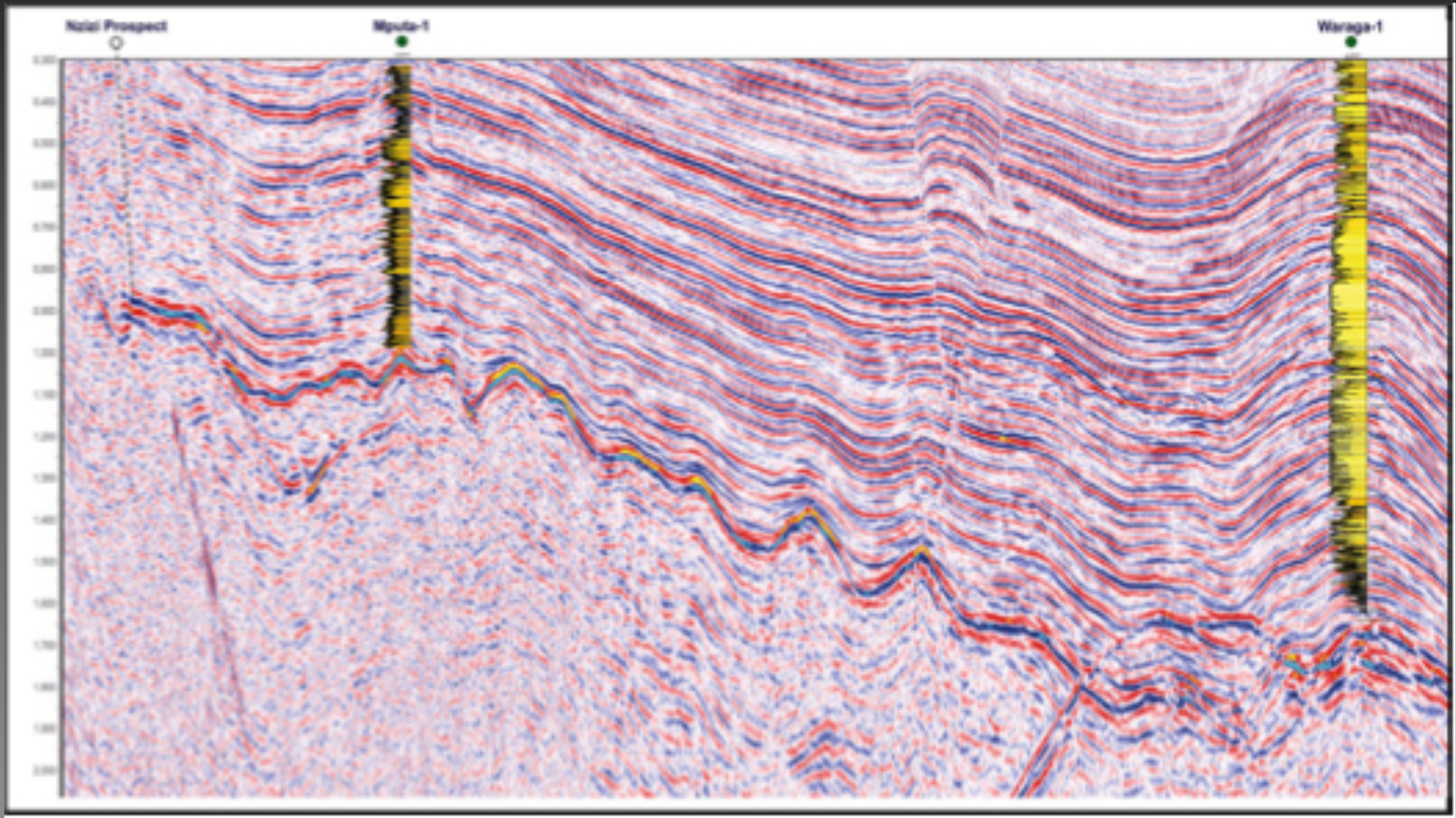
The seismic experiment (what is measured?)



The seismic experiment (what is imaged?)



Elastic waves

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

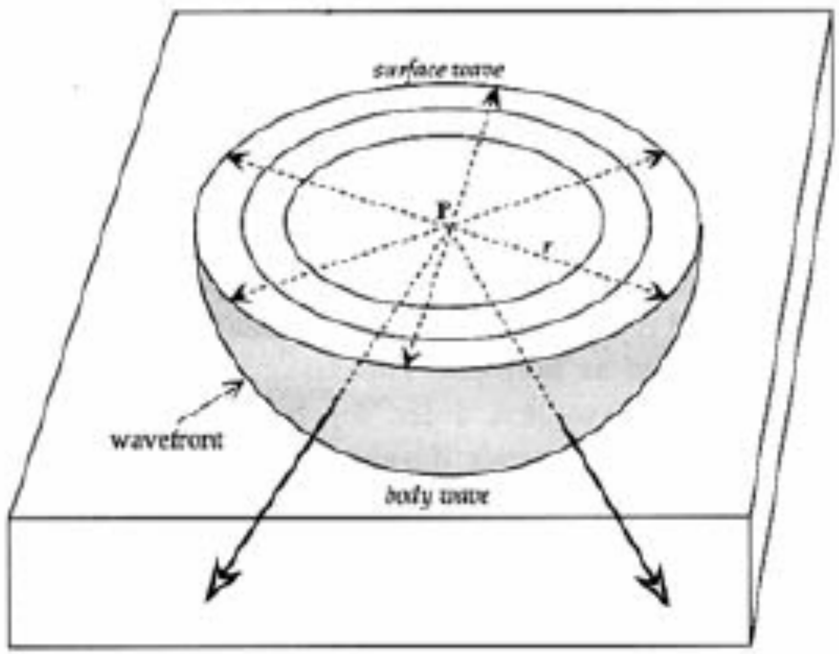


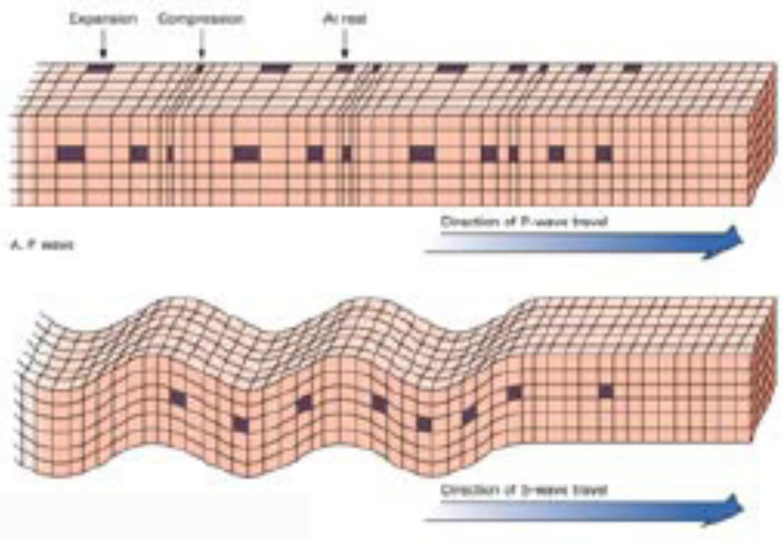
Fig. 3.9 Propagation of a seismic disturbance from a point source P near the surface of a homogeneous medium; the disturbance travels as a body wave through the medium and as a surface wave along the free surface.

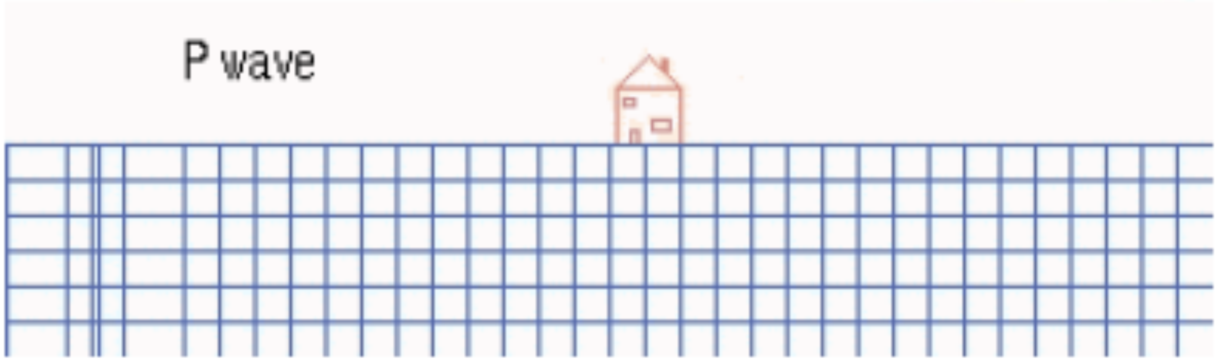
Point source seismic disturbance:

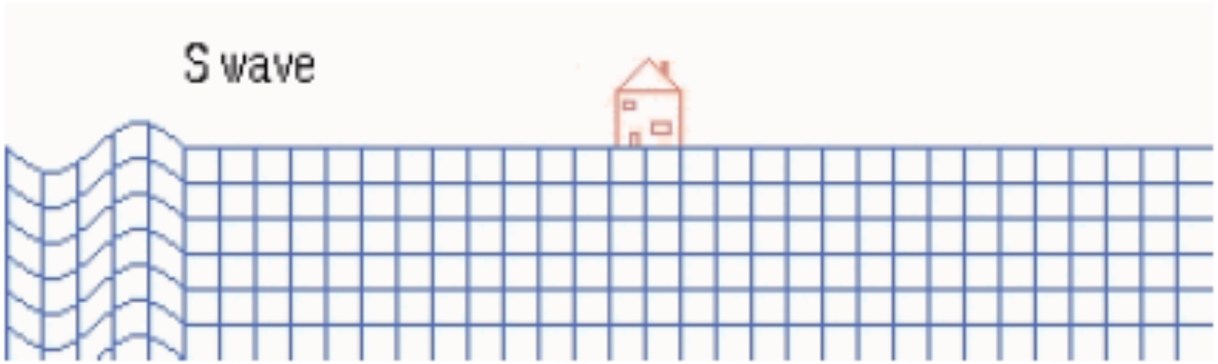
- Wavefront expands out from the point: **Huygen's Principle**
- Body waves: sphere
- Surface waves: circle
- **Rays**: perpendicular to wavefront

Seismic wavefield snaphots (simplified salt dome model)

Body waves
P and S-waves



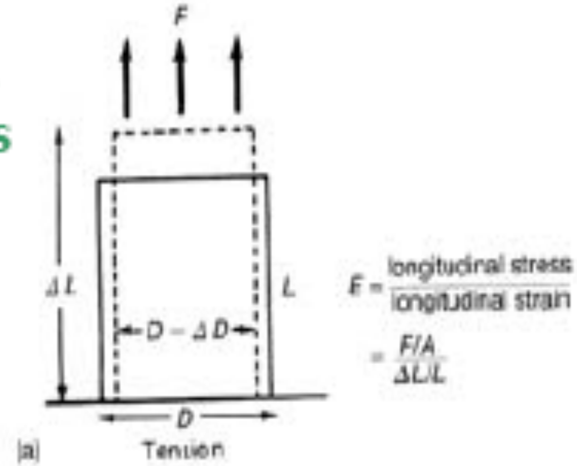




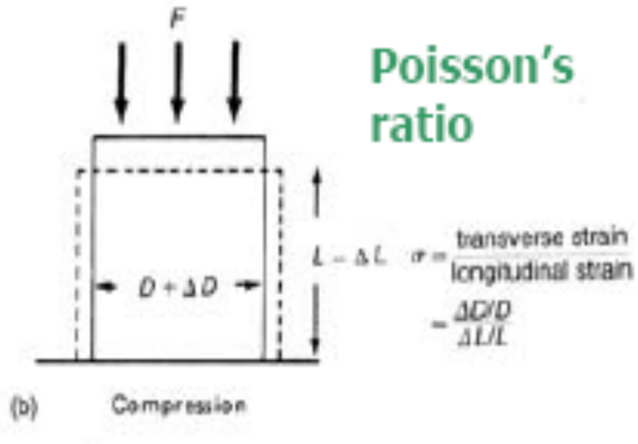
Elastic moduli

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

Young's modulus

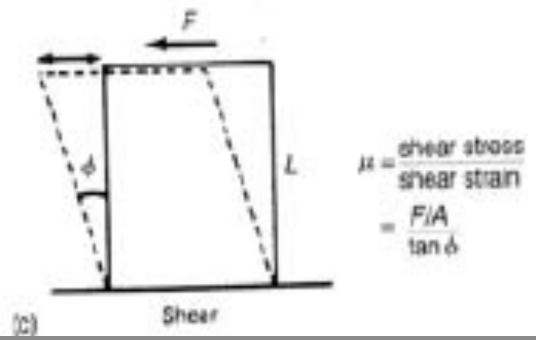


Poisson's ratio



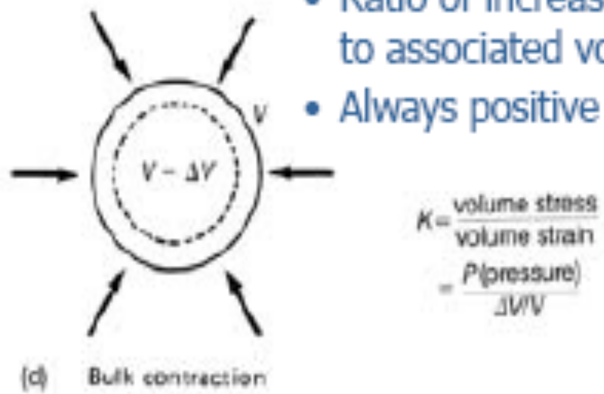
Shear modulus, μ

- 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



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

Vp , Vs and rock properties

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

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

COMPRESSIBILITY (matrix & fluid)

RIGIDITY (matrix)

DENSITY (matrix & fluid)

Poisson's ratio

$$\sigma = \frac{\lambda}{2(\lambda + \mu)}$$

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

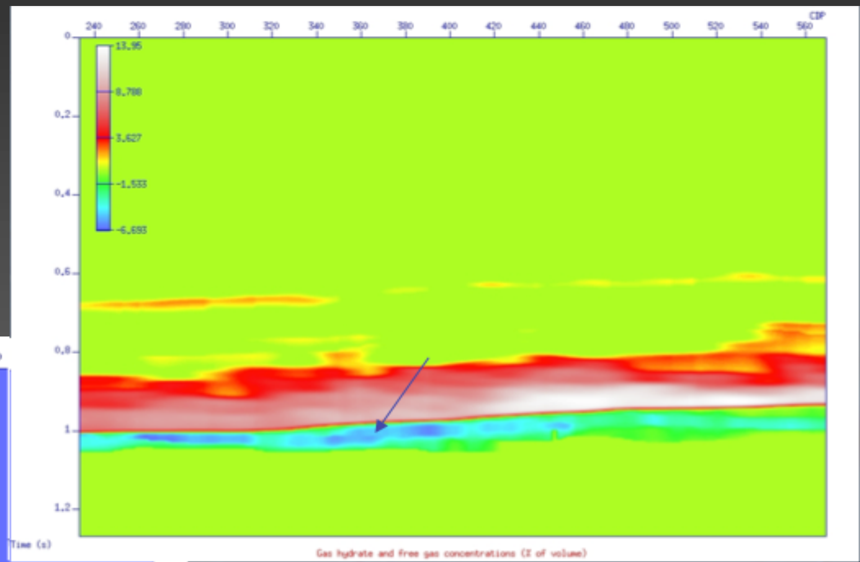
Velocity, fluid modulus, density

- The rock elastic bulk modulus normally stiffens with a less compressible pore fluid
- The effect of fluid is larger in soft (low-velocity) rocks
- The bulk density increases form a dry to a water-saturated rock
- Velocity depends on the ratio of elastic modulus to density: it may therefore increase or decrease

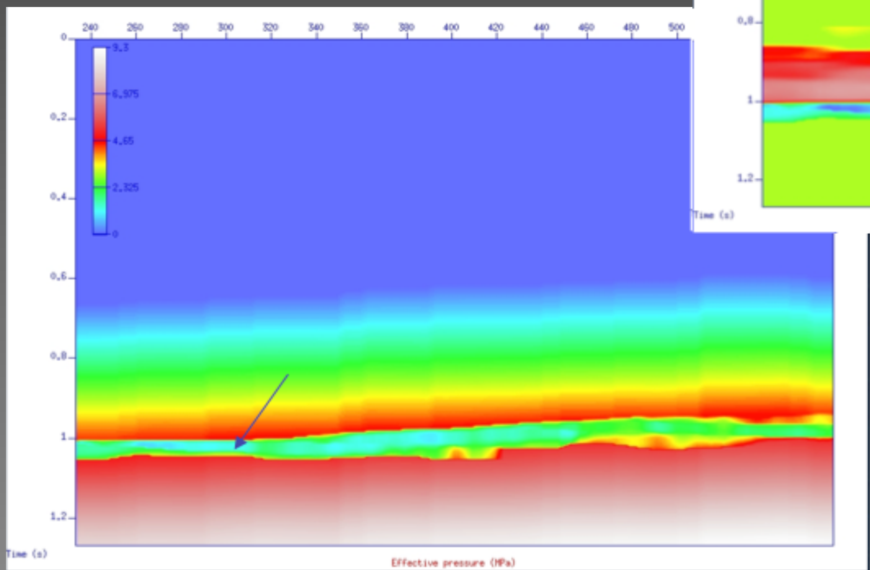
Velocity and pore pressure

- Cracks and flaws open with increasing pore pressure: velocity consequently decreases
- Pore fluids become less compressible with increasing pore pressure: velocity consequently increases
- Saturation can change with changing pore pressure: velocity can be sensitive to saturation
- High pore pressure over long periods may inhibit diagenesis and preserve porosity: velocity tends to be low in such conditions

From Vp and Vs velocities interpreted through theoretical models (Voigt, Reuss, Gassmann, Biot) we get information about gas concentration and overpressure

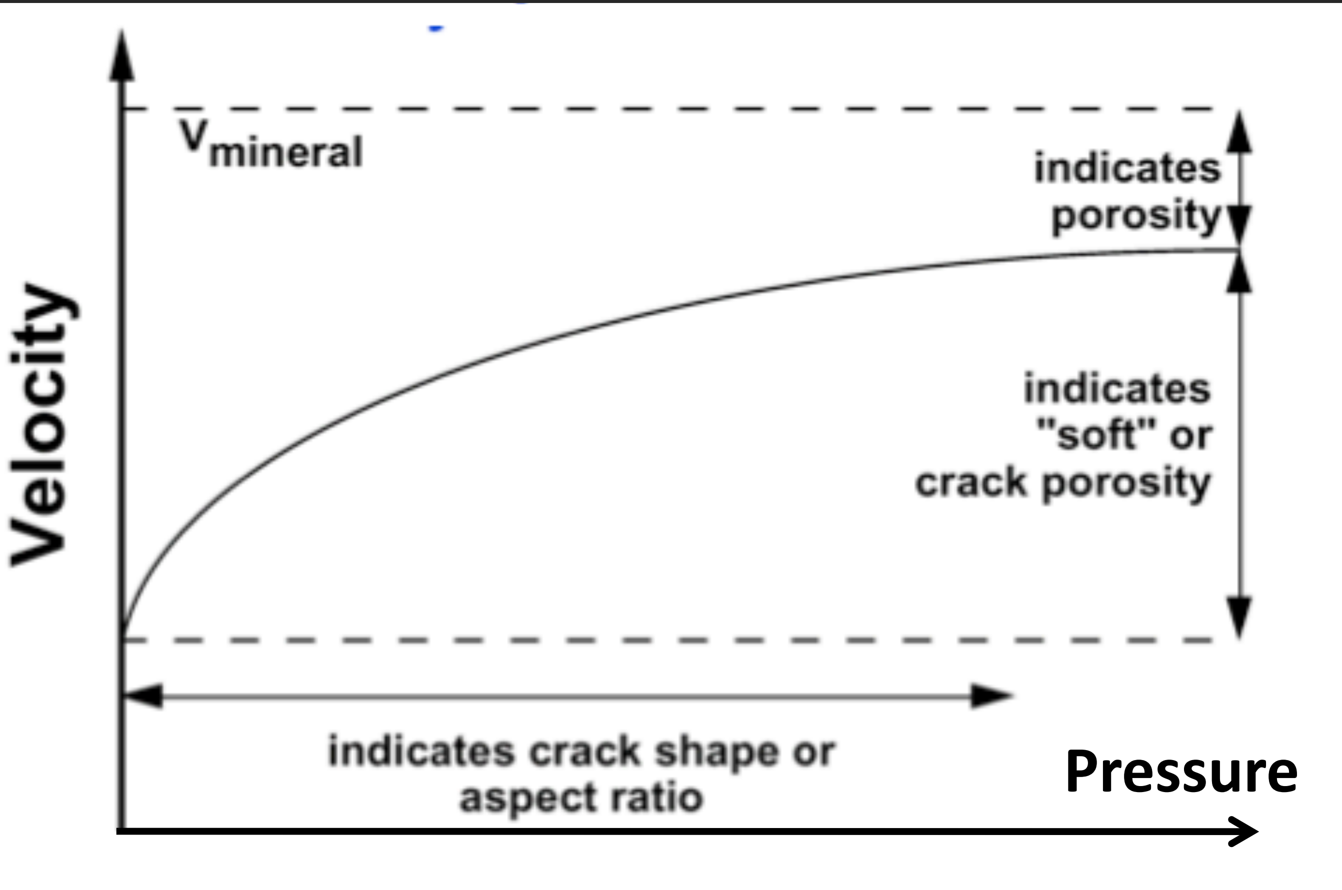


Gas content

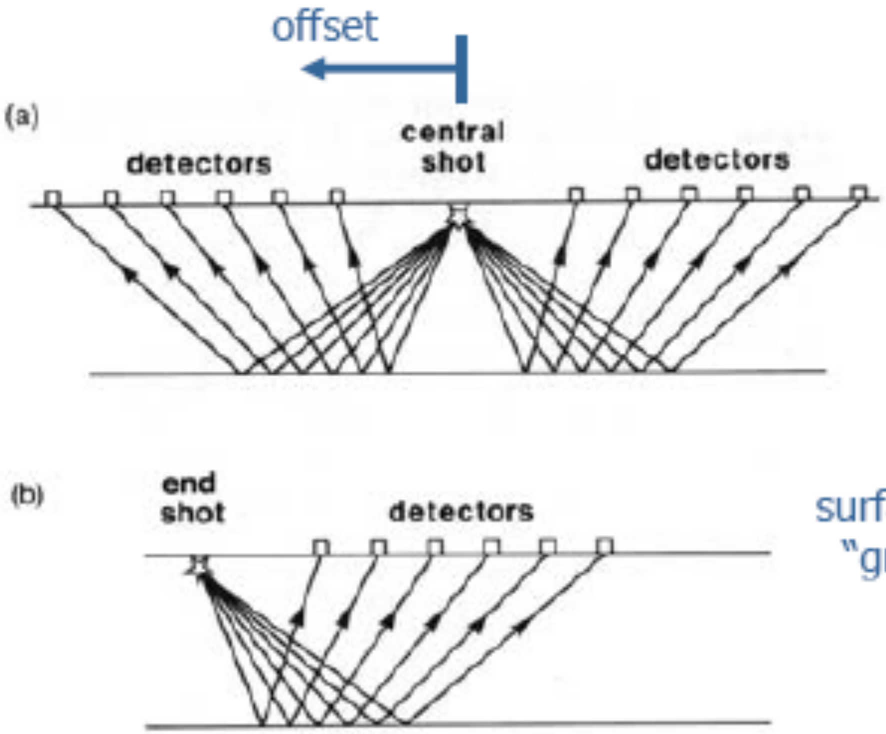


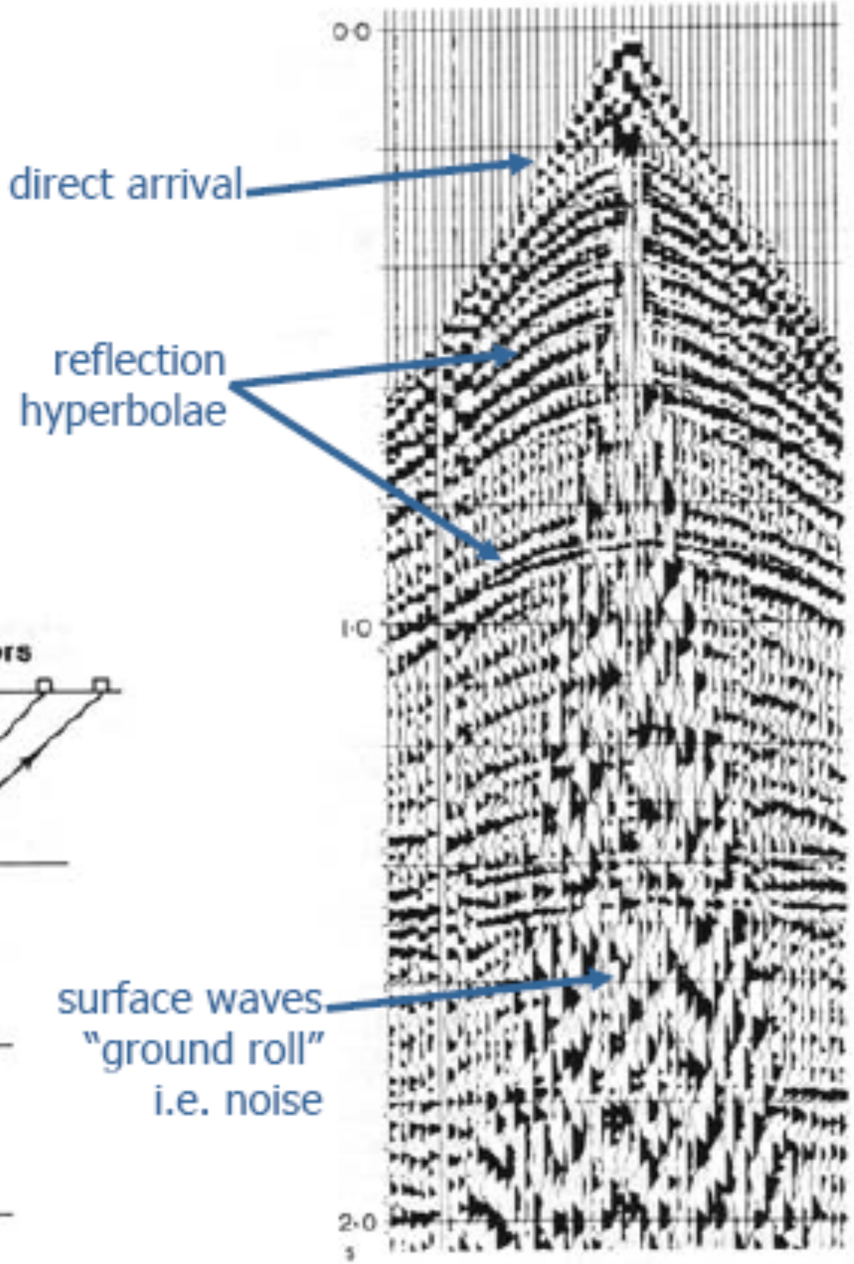
Effective pressure

(Tinivella, 2006)


Velocity
$V_{mineral}$
indicates porosity
indicates "soft" or crack porosity
indicates crack shape or aspect ratio
Pressure

Shot gathers





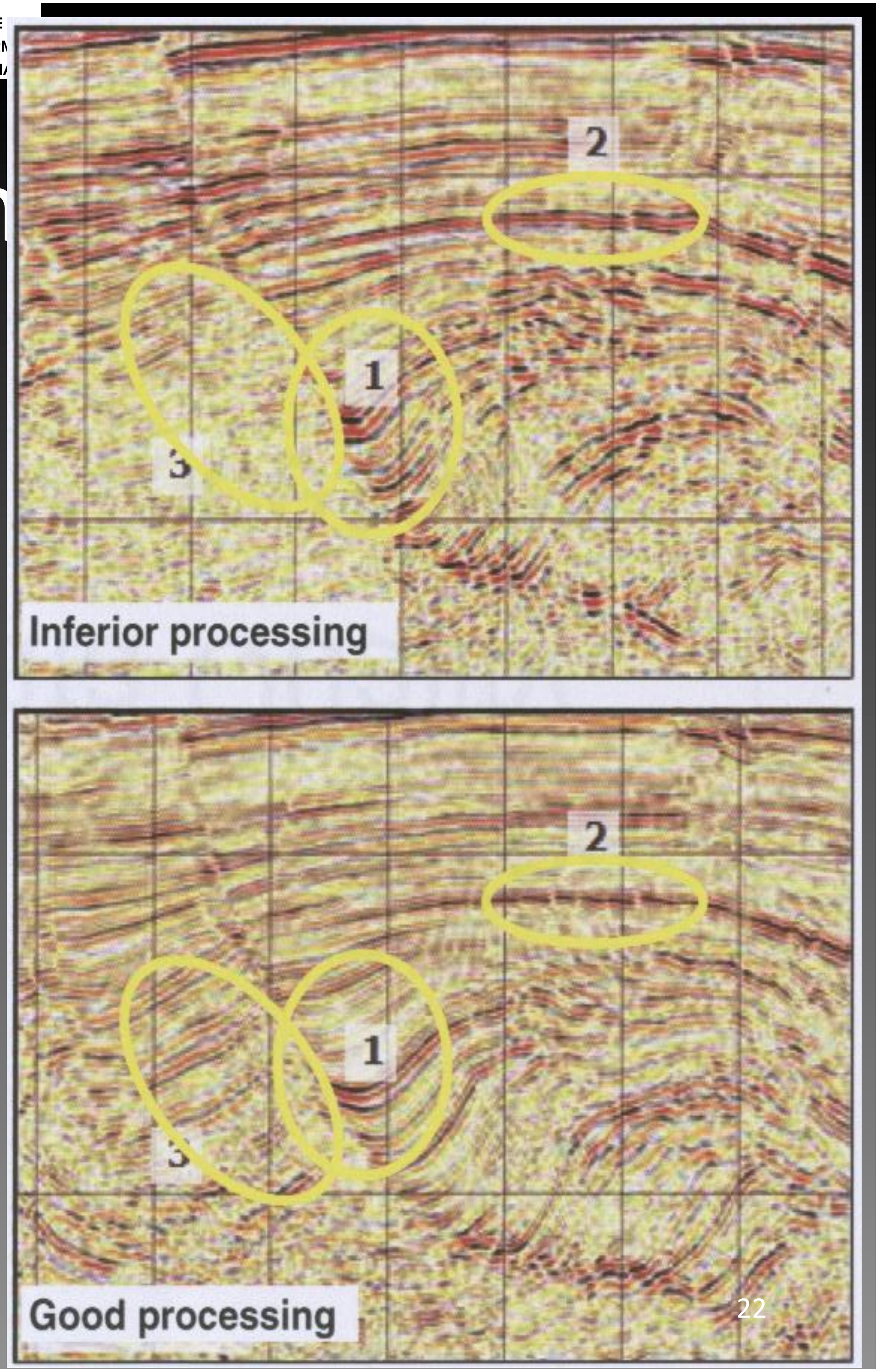
Seismic processin

To produce accurate subsurface images:

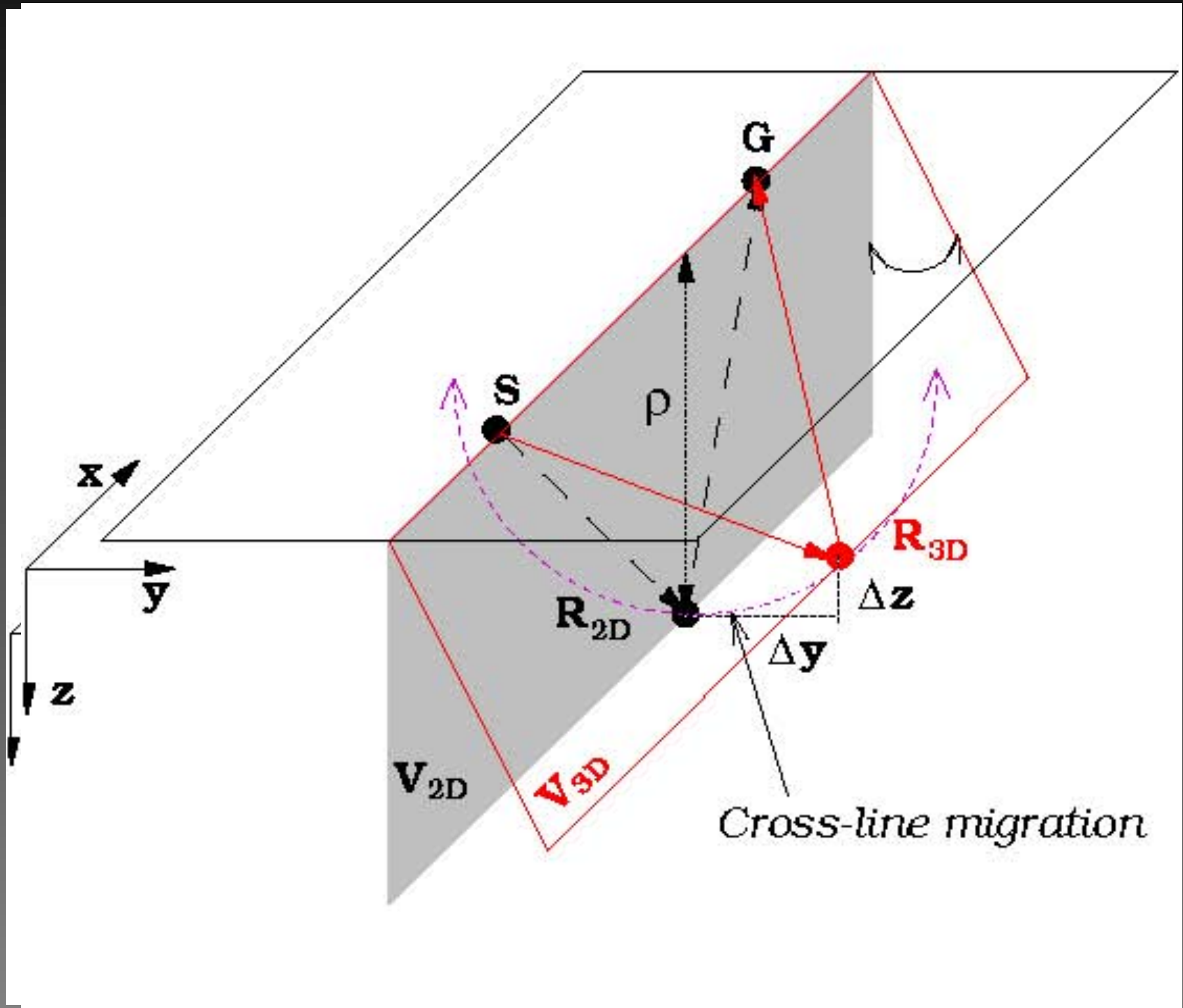
Correct geometry /amplitudes (i.e. to remove distortions due to wave propagation)

Noise attenuation: enhance S/N

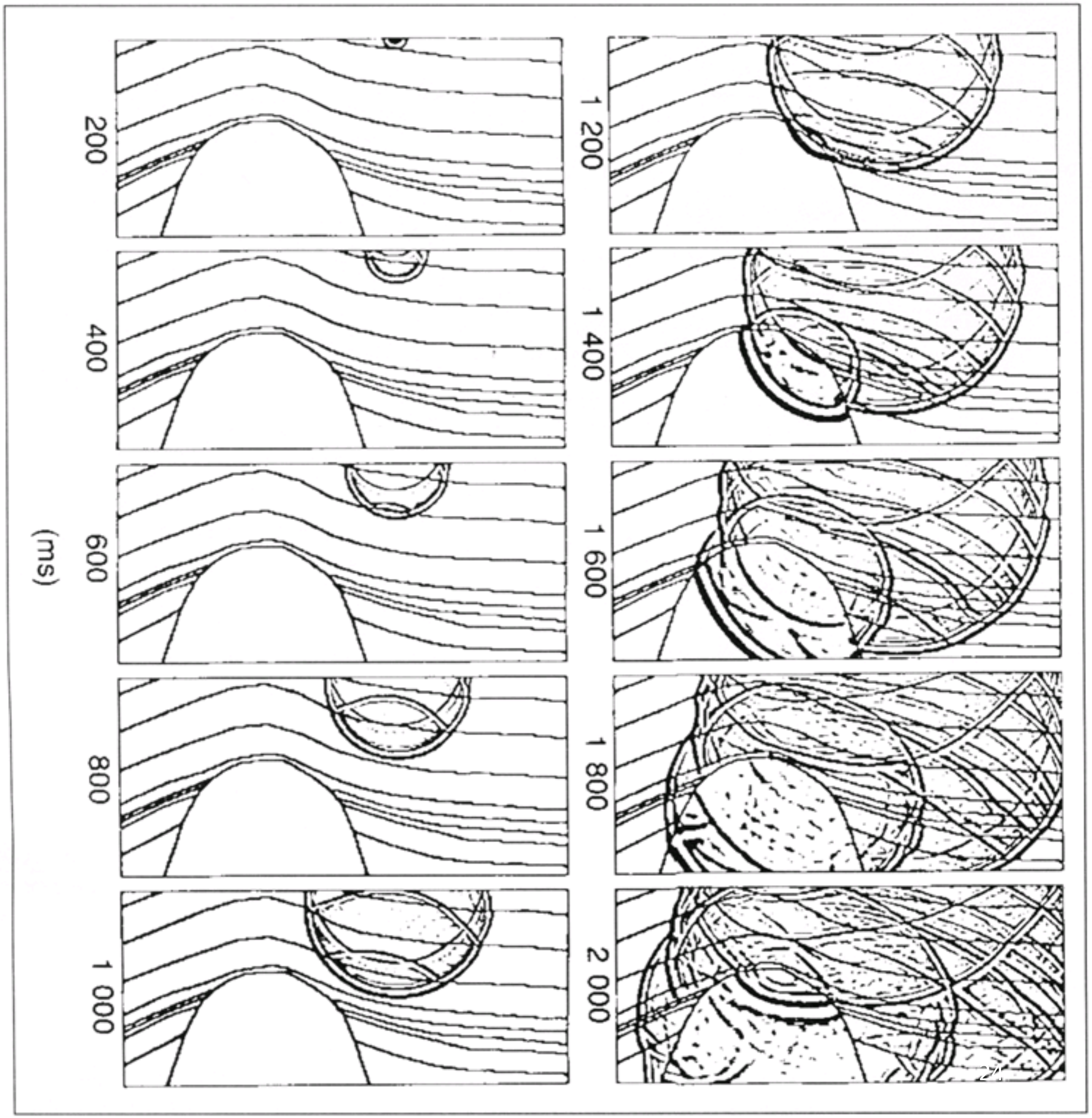
In synthesis:
recover true Earth response to stress applied at the surface



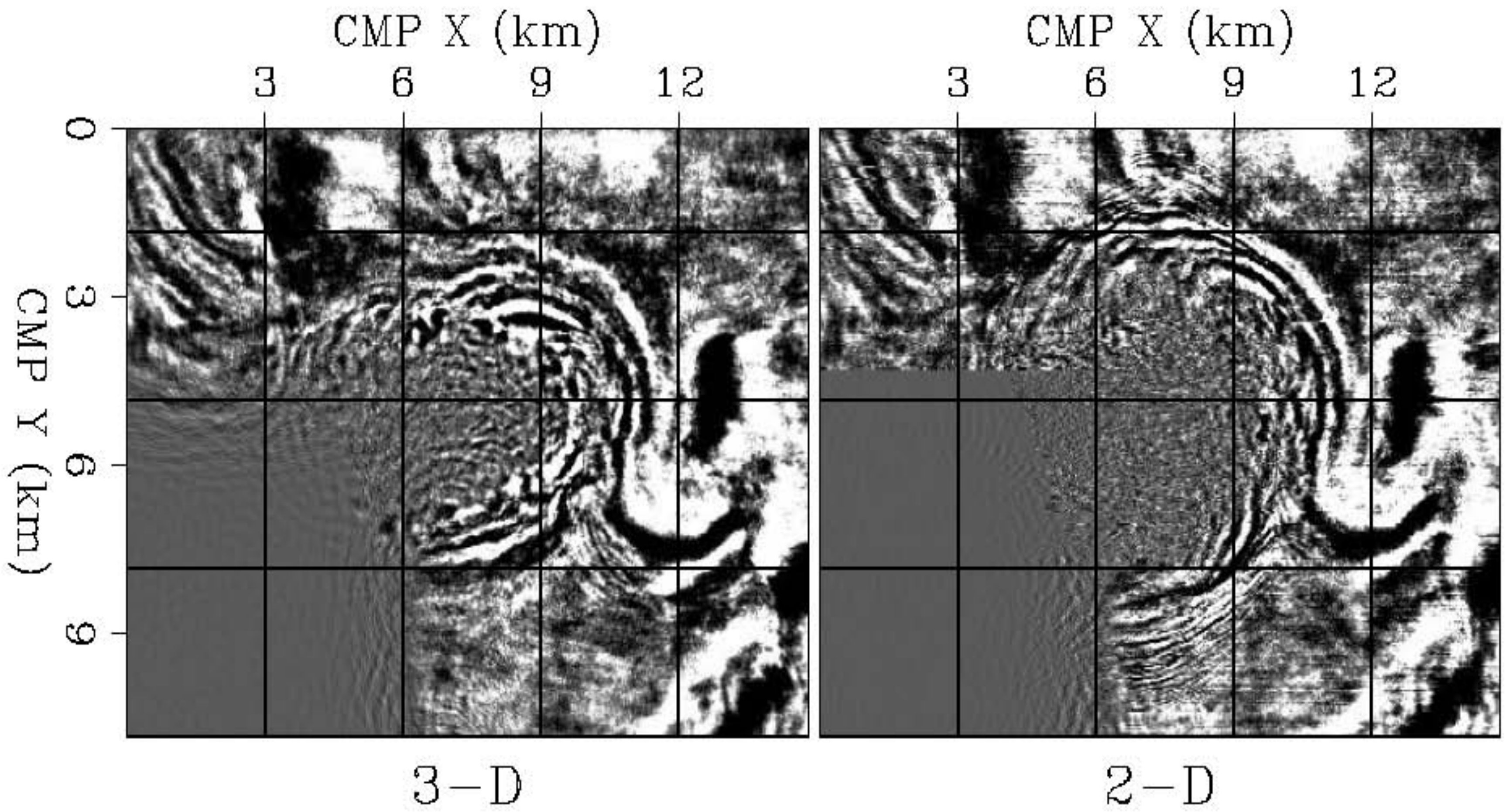
Geometric reasoning in 3-D



Seismic wavefield snaphots (simplified salt dome model)



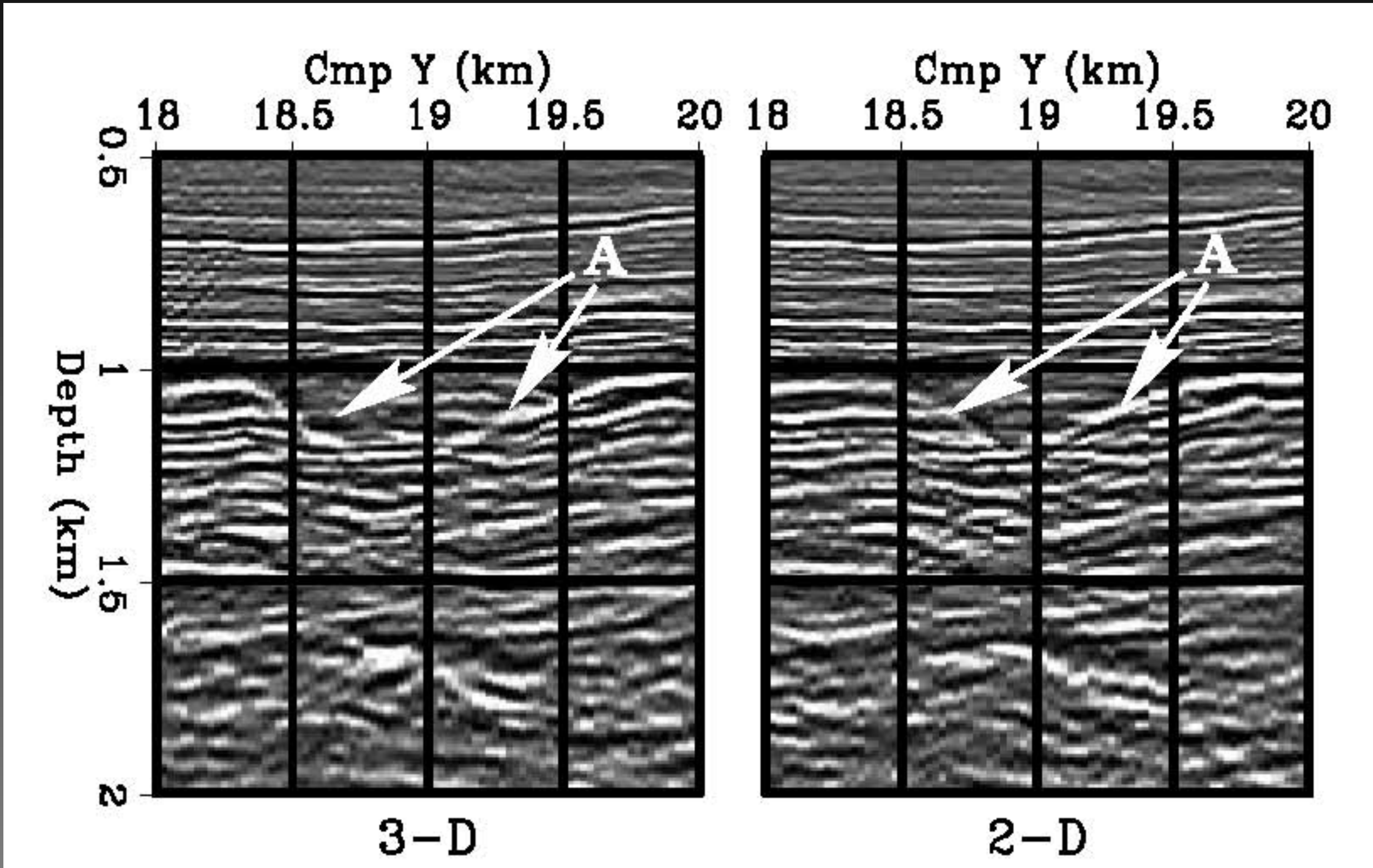
2-D imaging of a 3-D world: pitfalls and errors (1)
lateral mispositioning of structural boundaries



(Biondi, 2006)

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

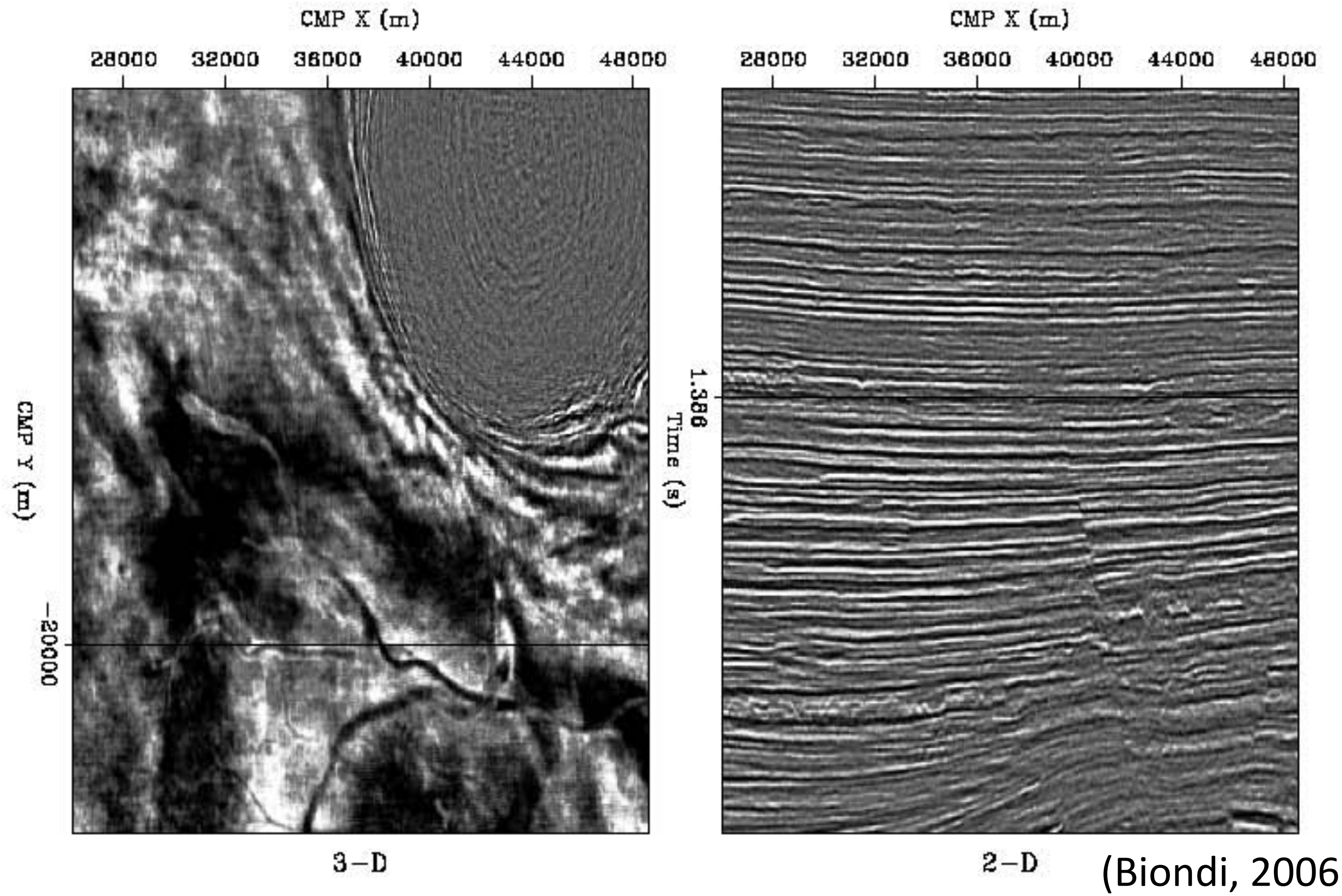
2-D imaging of a 3-D world: pitfalls and errors (2)



(Biondi, 2006)

Dipping reflectors: mispositioning in 2-D

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

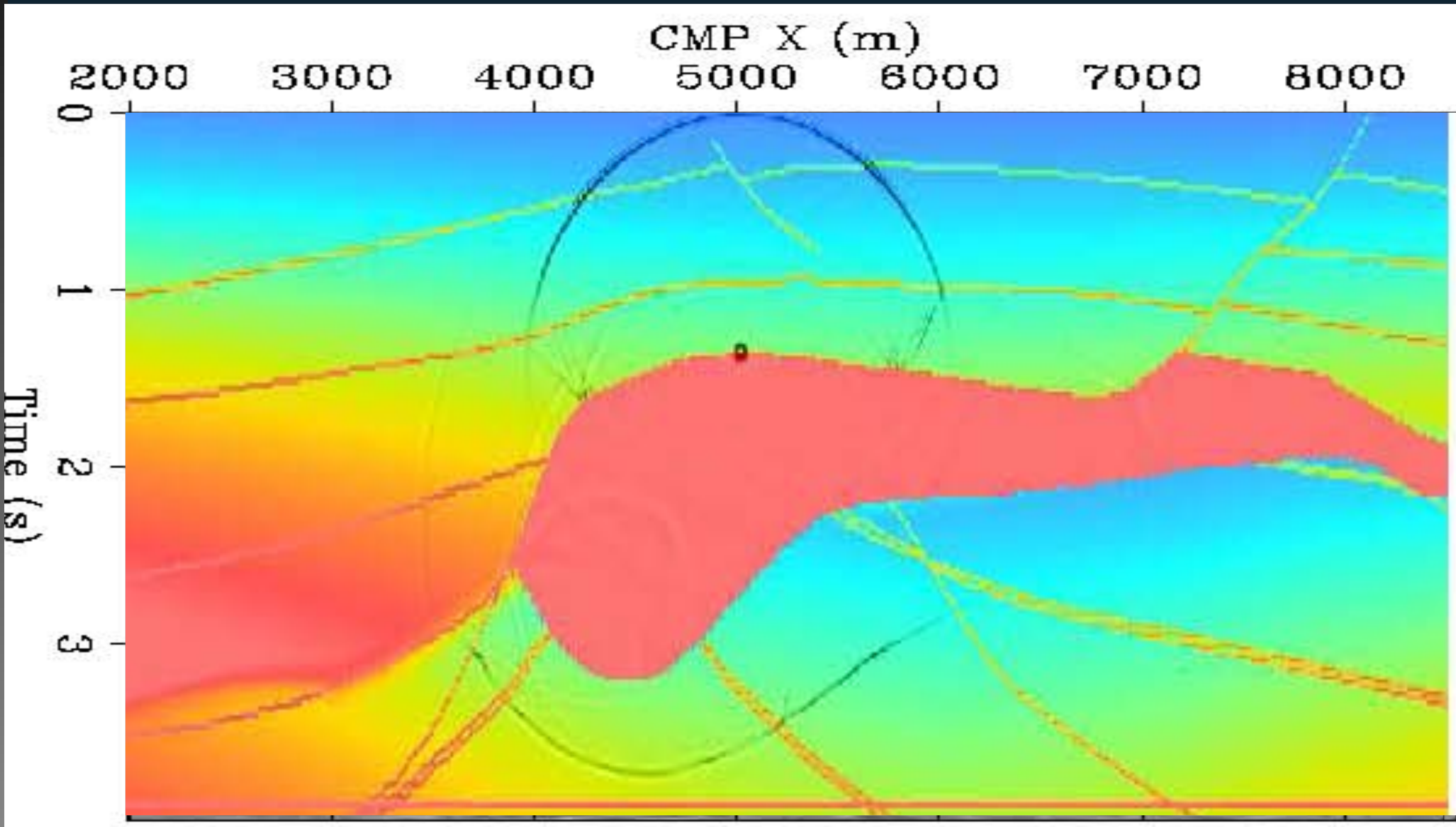


(Biondi, 2006)

Time-slice 1.3 s

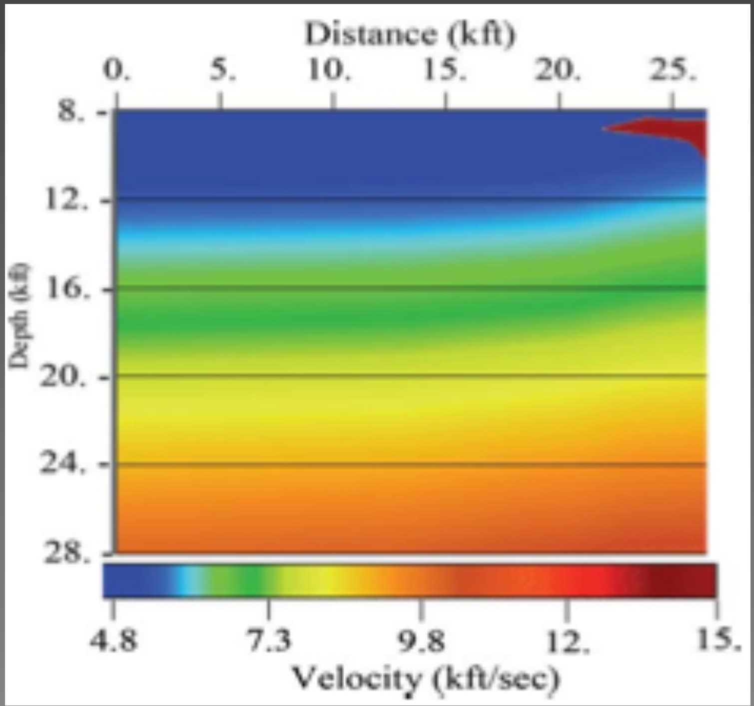
In-line cross-section

Structural model enhancement from 3-D imaging

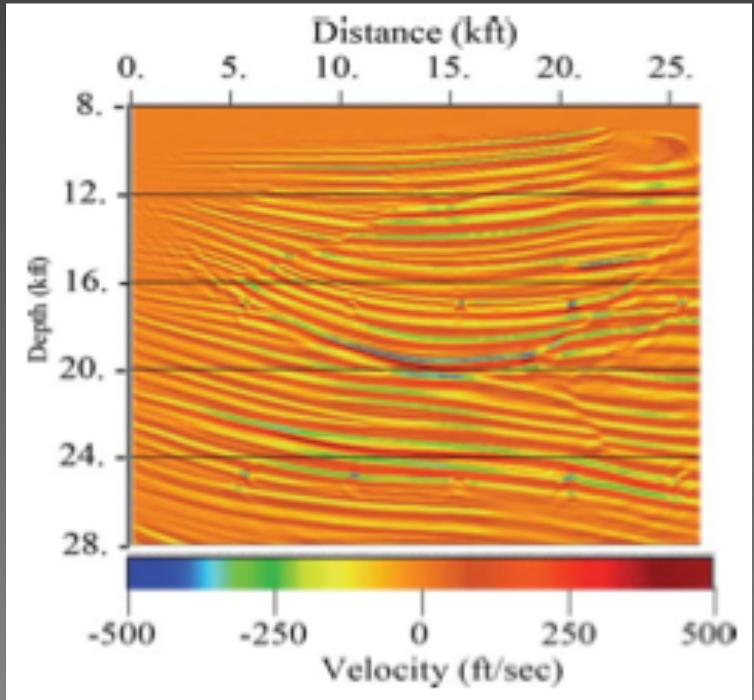


Velocity model enhancement from Full Waveform Inversion (FWI)

FWI is an automated method for refining a velocity model by iteratively attempting to match modelled data with recorded data.
Each iteration represents a linearization of the non-linear problem by the Born-approximation (see Tarantola, 1984).



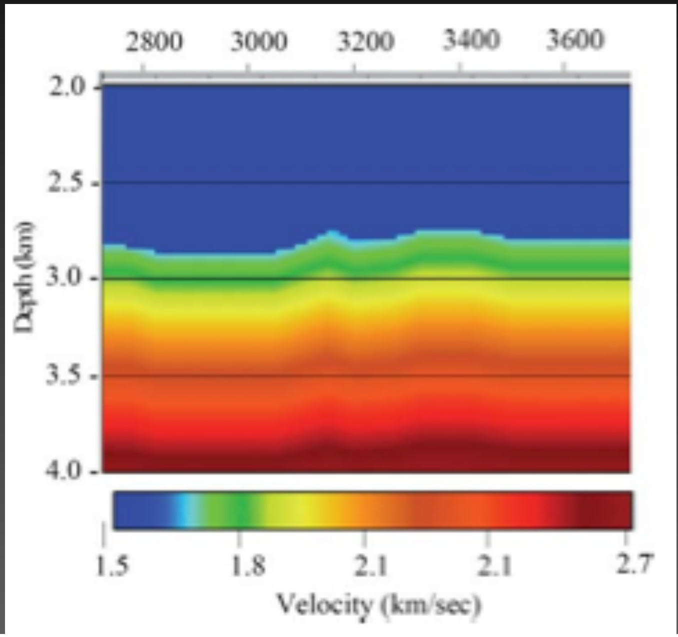
Starting velocity model

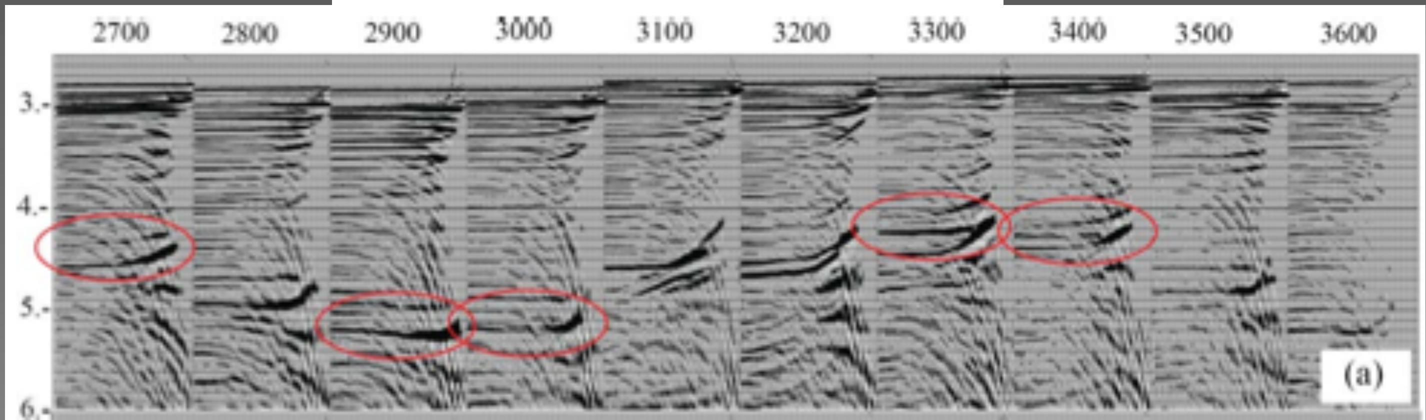


Difference between inverted and starting velocity model

Full Waveform Inversion example from offshore Cyprus

Starting velocity model

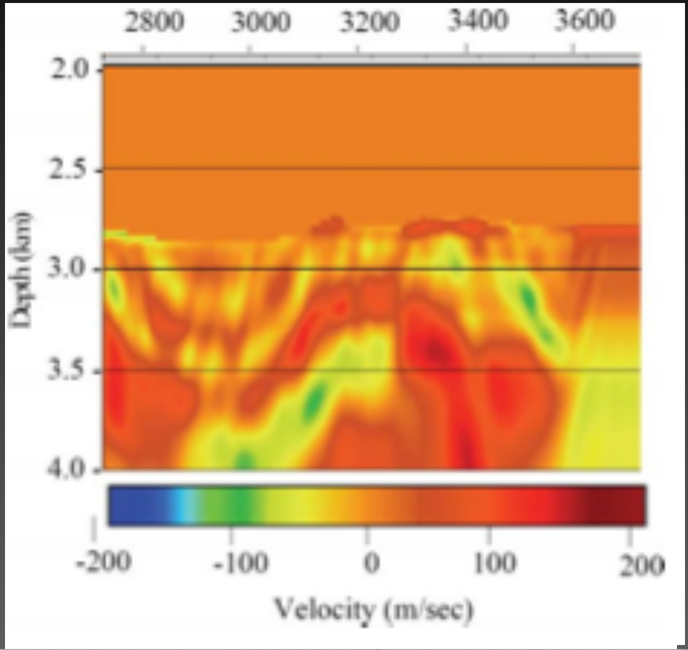


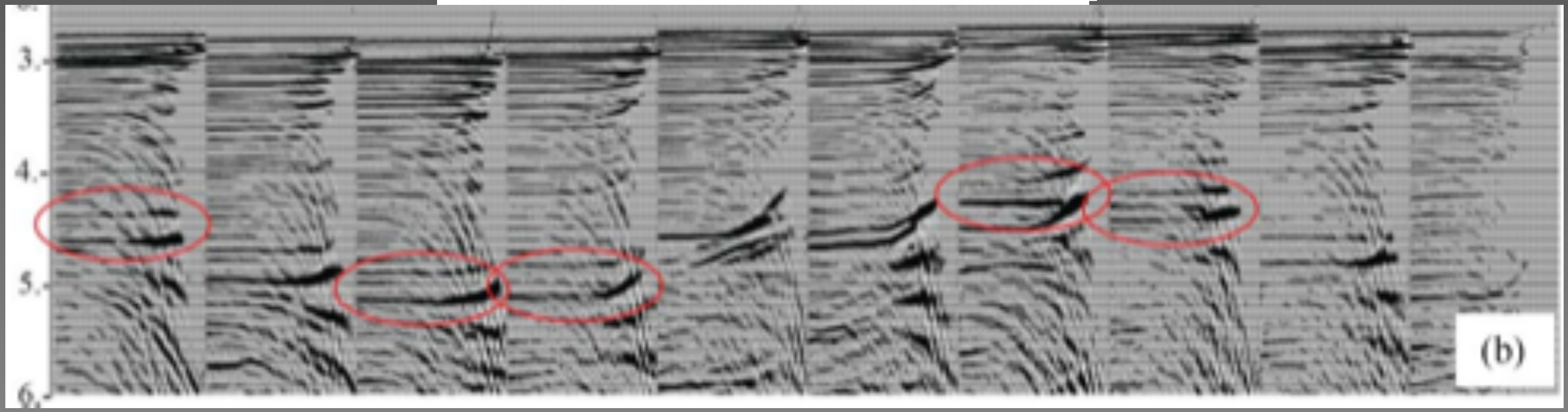


Kirchhoff migrated CMP gathers

Full Waveform Inversion example from offshore Cyprus

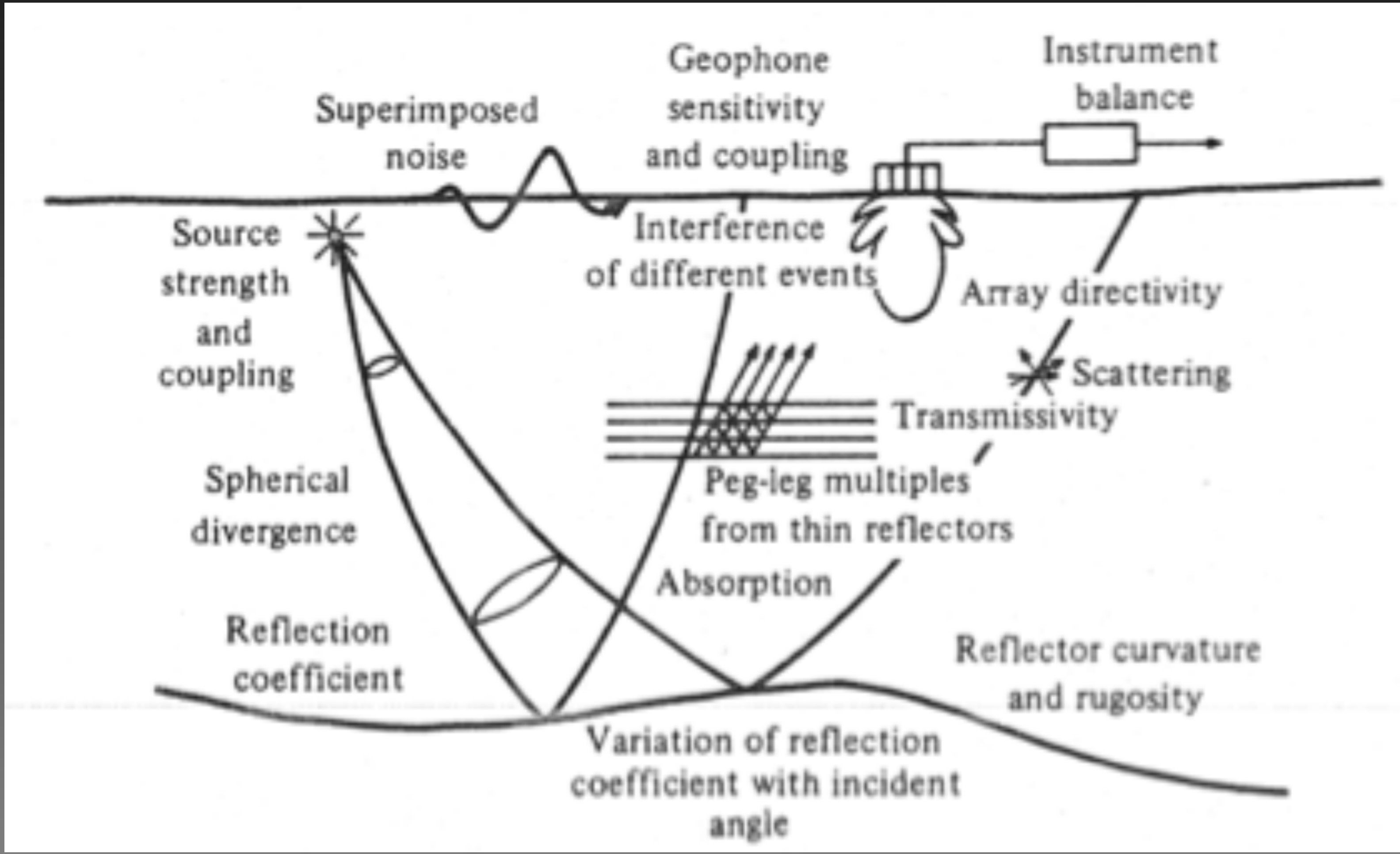
Difference between Inverted and starting models





Kirchhoff migrated CMP gathers

AVO and attributes: factors that influence amplitudes



Fundamentals equations for reflection coefficients

Zoeppritz's equations

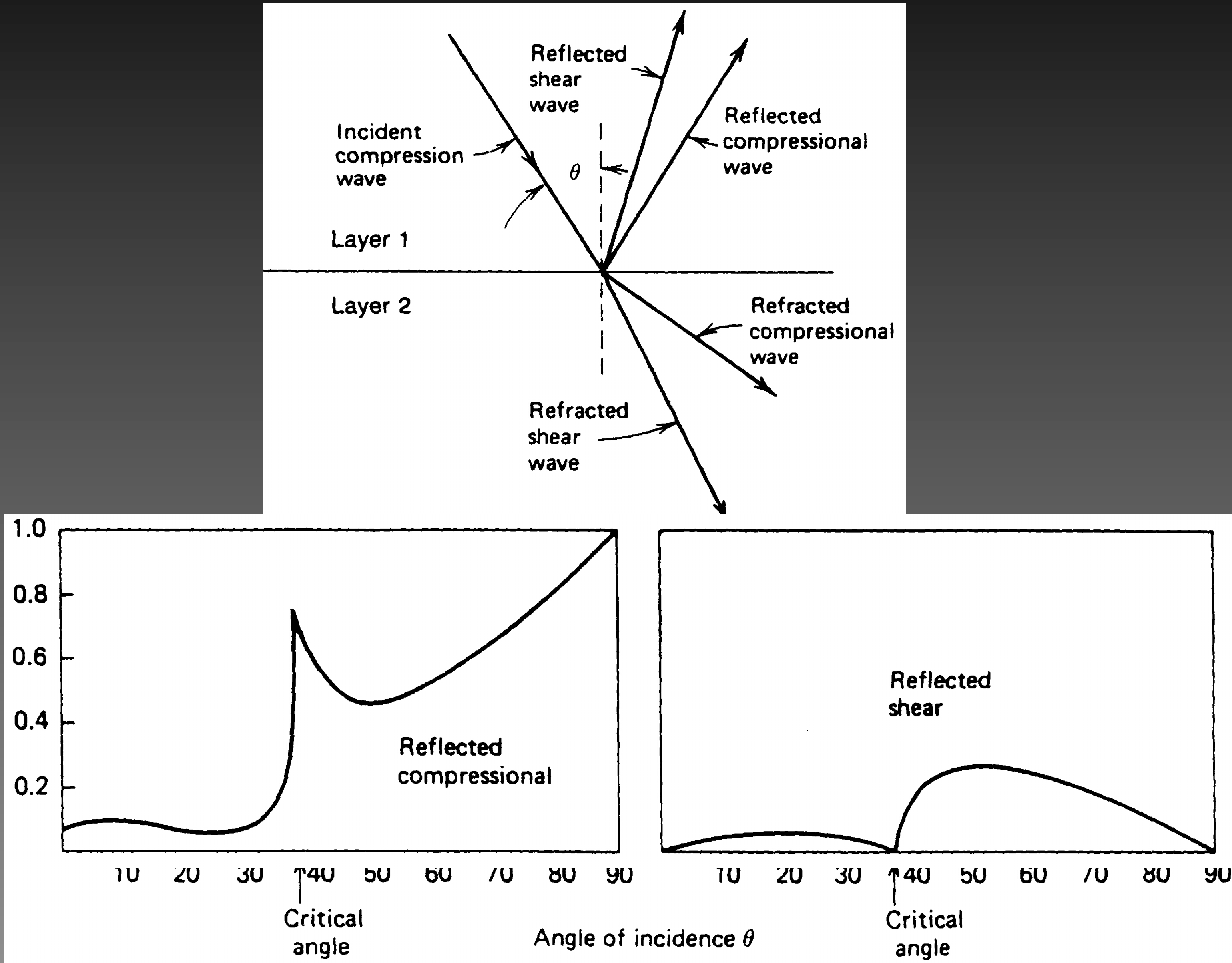
Aki & Richards (1980)
(P,S reflectivity)

$$R(\theta) = \frac{A_1}{A_0} = + \left[\frac{1}{2}\left(1 + \tan^2\theta\right)\right]\frac{\Delta V_P}{\overline{V}_P} - \left[4\frac{\overline{V}_S^2}{\overline{V}_P^2}\sin^2\theta\right]\frac{\Delta V_S}{\overline{V}_S} + \left[\frac{1}{2}\left(1 - 4\frac{\overline{V}_S^2}{\overline{V}_P^2}\sin^2\theta\right)\right]\frac{\Delta\rho}{\overline{\rho}}$$

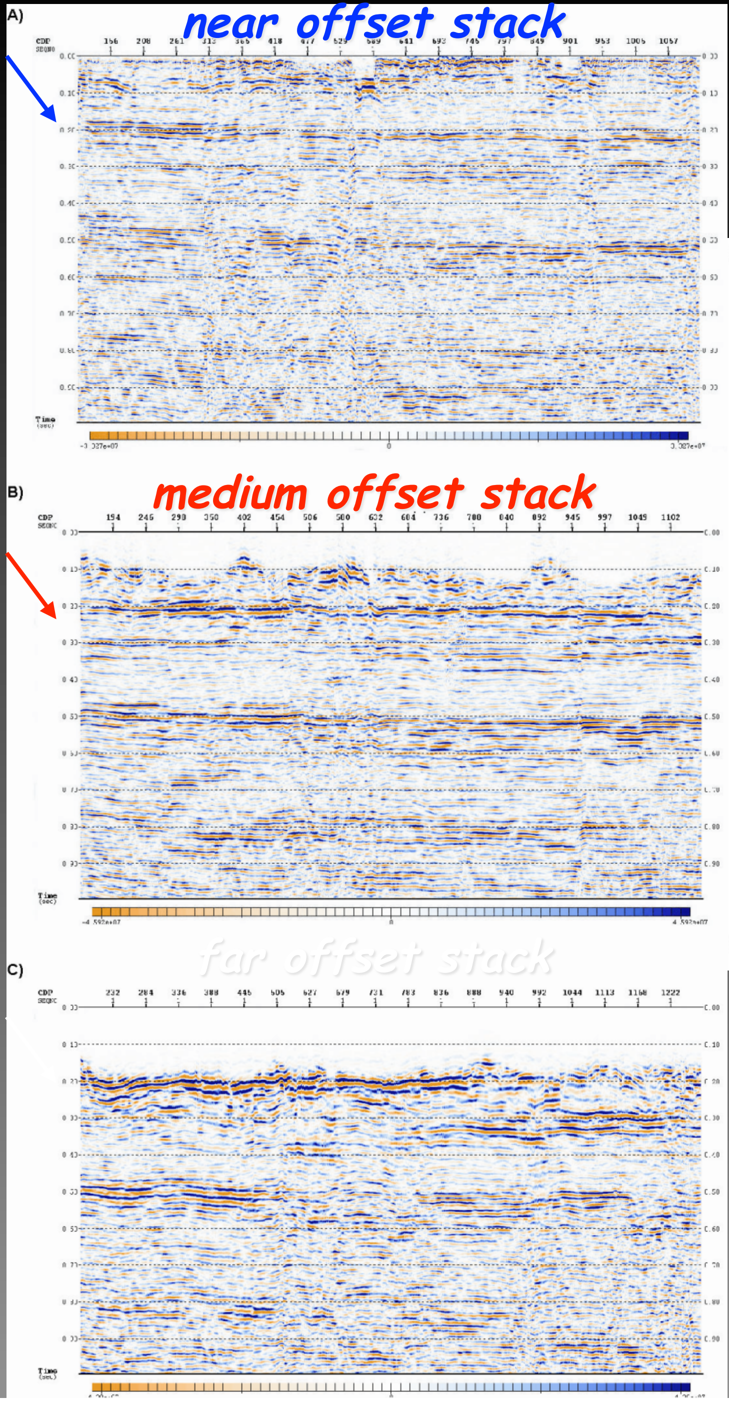
Shuey (1985)
(reflectivity at normal incidence)

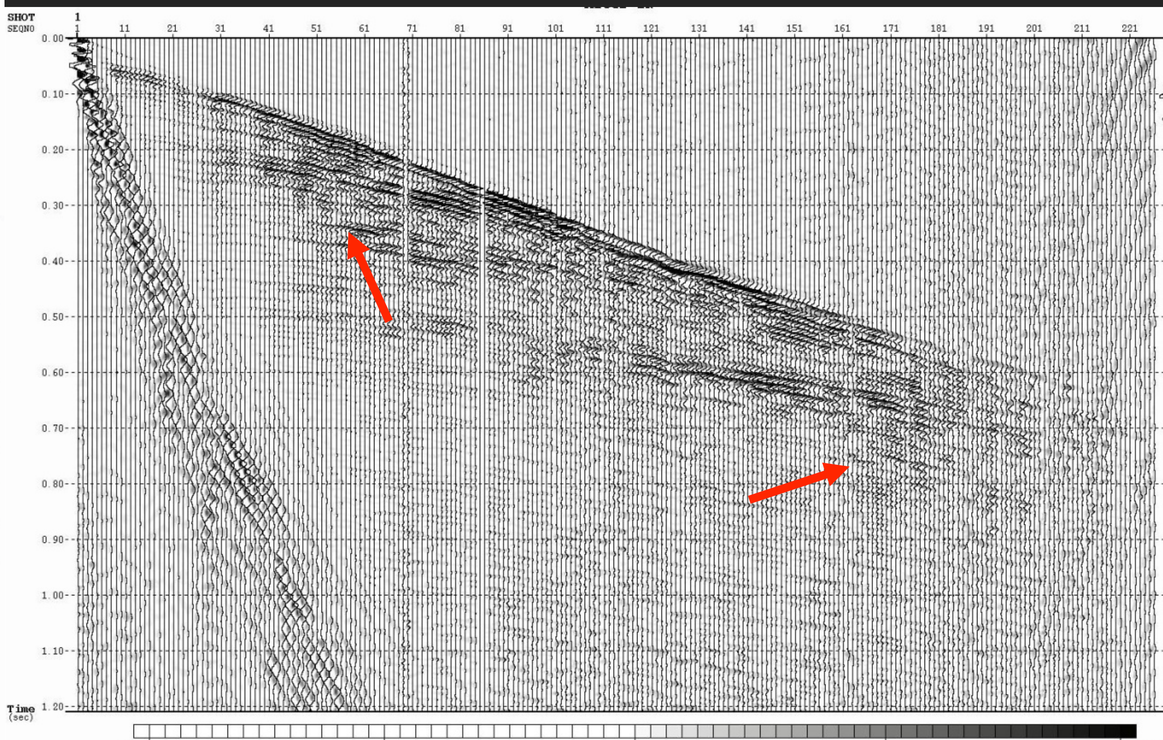
$$R(\theta) = R(0) + \left[R(0)\,H_0 + \frac{\Delta\sigma}{\left(1-\overline{\sigma}\right)^2}\right]\sin^2\theta + \left[\frac{1}{2}\,\frac{\Delta V_P}{\overline{V}_P}\right]\left(\tan^2\theta - \sin^2\theta\right)$$

AVO : Zoeppritz's equations



STRONG AVO effects: aquifer example

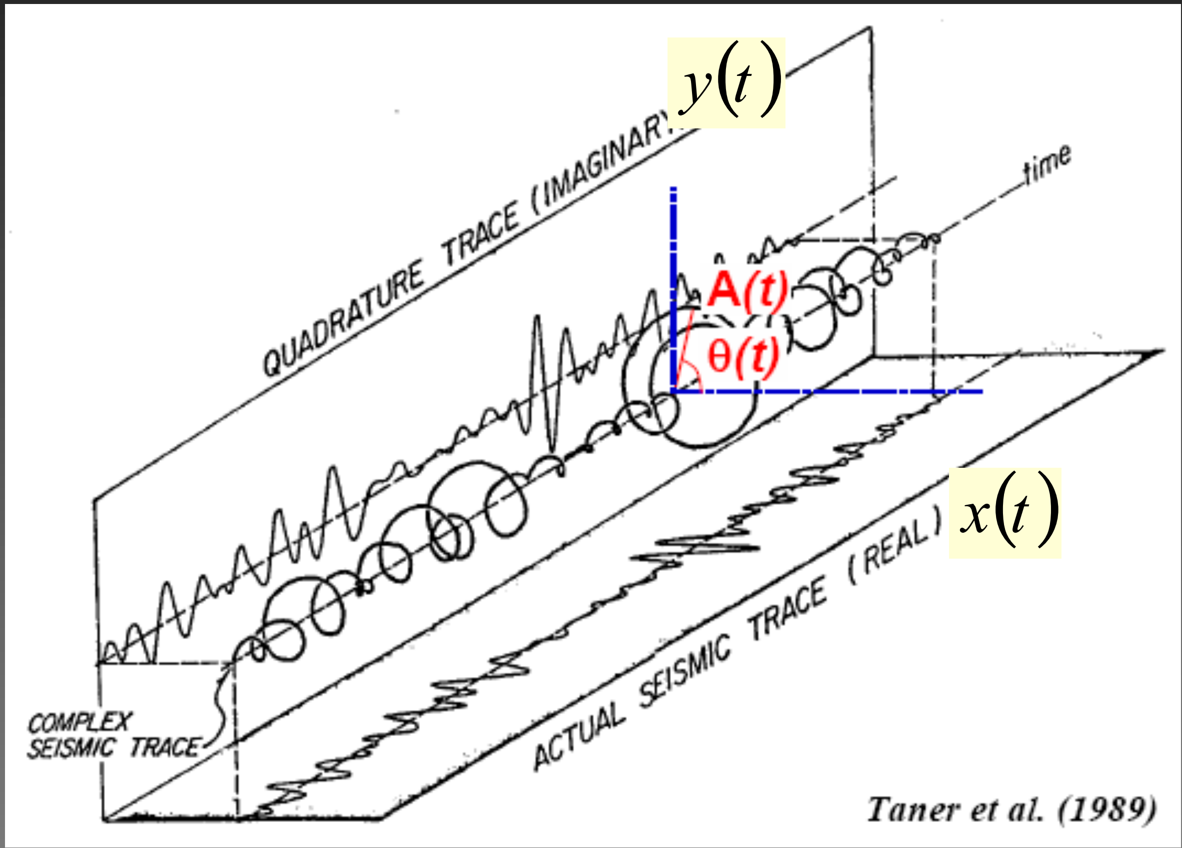




(Giustiniani et al., 2008)

Hilbert transform and instantaneous attributes

HILBERT TRANFORM (HT) and INSTANTANEOUS ATTRIBUTES



AMPLITUDE

$$A(t) = \sqrt{x^2(t) + y^2(t)}$$

PHASE

$$\phi(t) = arctg\left(\frac{y(t)}{x(t)}\right)$$

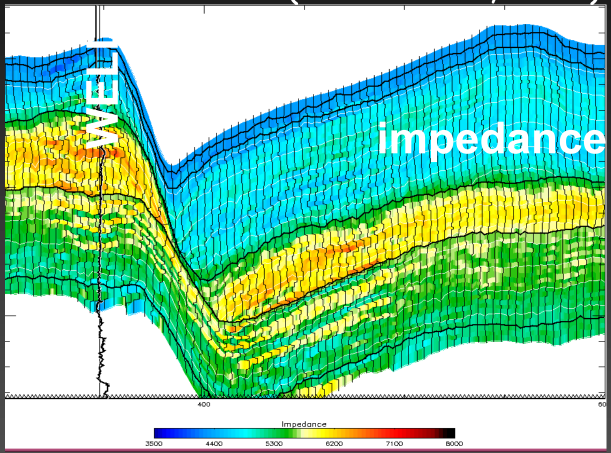
FREQUENCY

$$\omega(t) = \frac{d\phi(t)}{dt}$$

The use of attributes

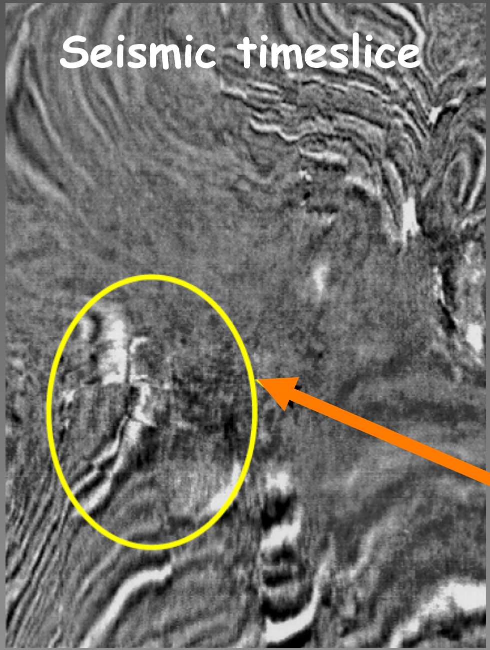
HILBERT TRANFORM (HT) and INSTANTANEOUS ATTRIBUTES

(Veekan et al, 2002)



1. Extrapolate well logs to the reservoir

2. Identify/image tectonic/stratigraphyc structures → Improved INTERPRETATION



Tectonically complex zone, difficult to interpret on the original data

(Gersztenkorn et al, 1999)

4D-Time Lapse: "Looking for Image Changes over Time"

Example: 2 images

Are they the same?

What are the differences between them?

What other subtle changes do you observe or can you explain?

Are the observations related?

(R. Detomo, 2012)

4D-Time Lapse: Examining the Differences in the Images

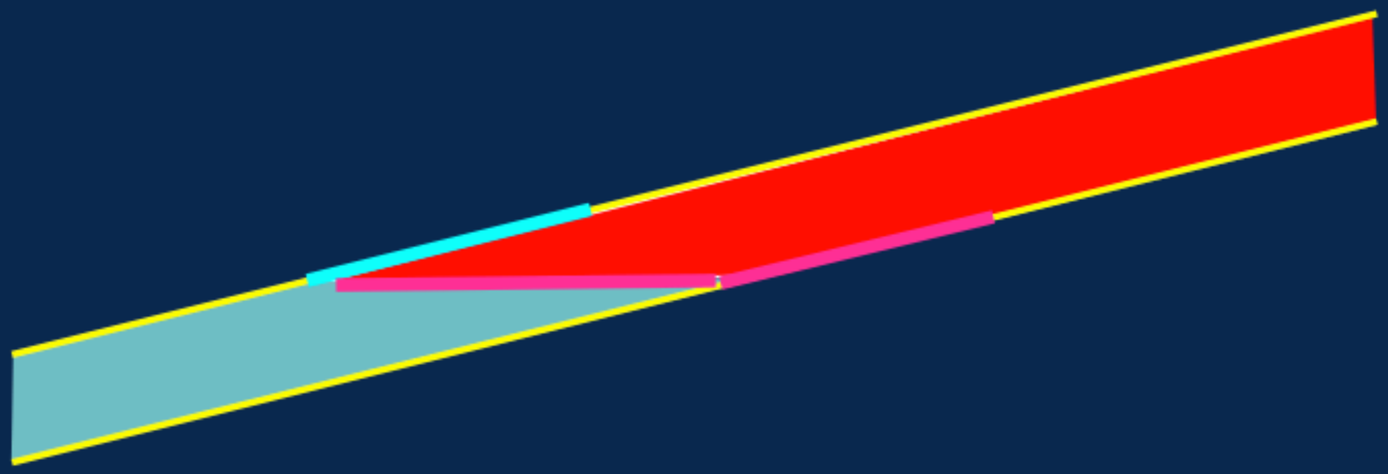
Subtracting the two images (in gray-scale) immediately highlights the differences.

(R. Detomo, 2012)

However, note that the "source-receiver" (object-camera) positions are not "accurately" recreated making subtraction of the two datasets valuable, but less accurate or "crisp".

WHAT SORT OF TME-LAPSE CHANGES MAY WE EXPECT IN GEOTHERMAL EXPLORATION AND RESERVOIR MONITORING?

Effects due to Fluid Saturation Changes in Reservoirs – Density, Velocity, Temperature, Pressure



Acoustic Changes at Reservoir Top and Base are different for different Fluids, and the Fluid Contact itself has a contrast, as well.

(R. Detomo, 2012)

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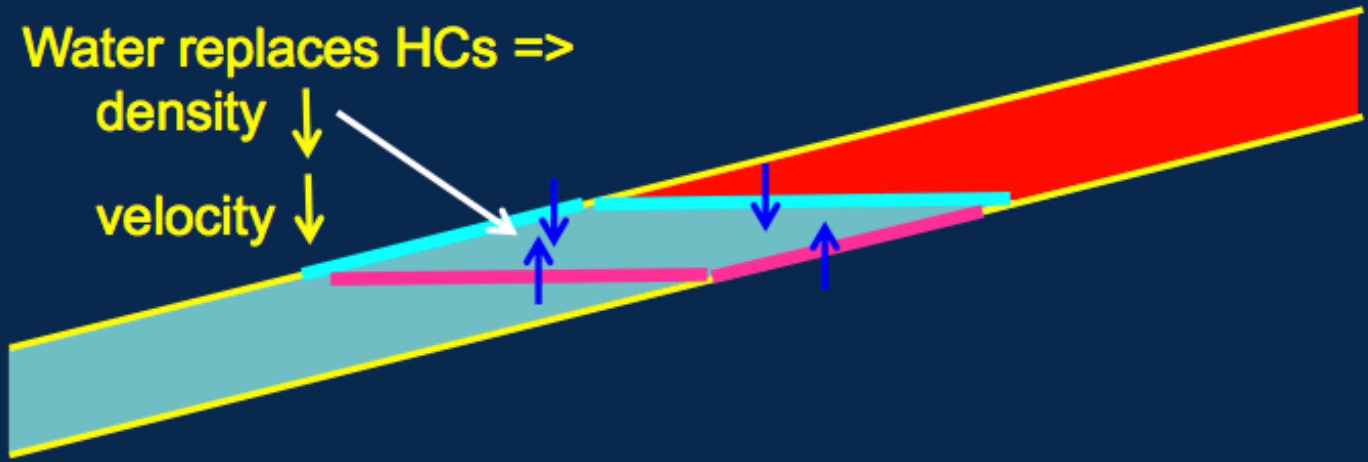


Fluid Saturation Changes in Reservoirs changes the Reflection Coefficient at the Top and Base of the Reservoir and at the Fluid Contact! This results in changes in the Seismic Amplitudes and Time Thickness!

WHAT SORT OF TME-LAPSE CHANGES MAY WE EXPECT IN GEOTHERMAL EXPLORATION AND RESERVOIR MONITORING?

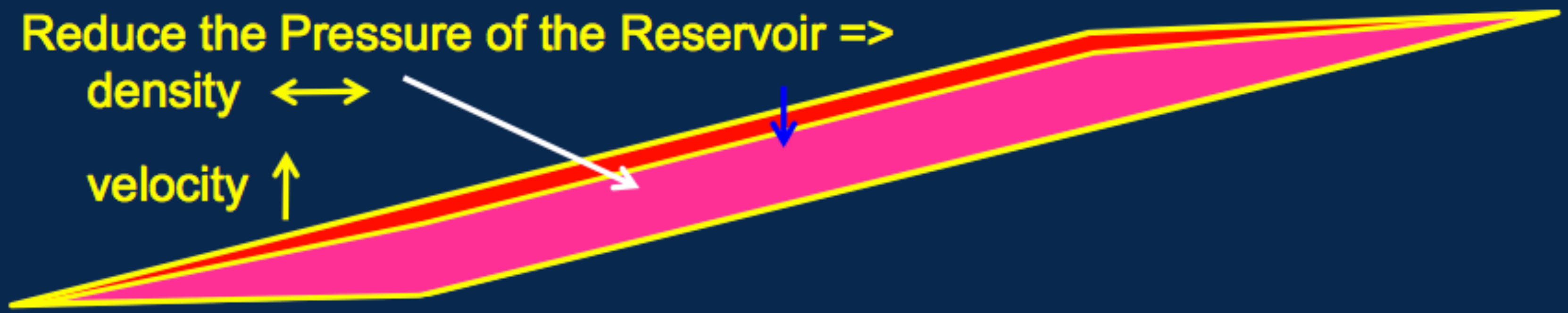
Effects due to Reservoir Thickness Changes – Compaction, Subsidence, Density, Velocity

The Time-Thickness of the Reservoir is determined by the Reservoir Thickness and its Velocity. How well it can be measured is determined by the Seismic Bandwidth

(R. Detomo, 2012)

WHAT SORT OF TME-LAPSE CHANGES MAY WE EXPECT IN GEOTHERMAL EXPLORATION AND RESERVOIR MONITORING?

Effects due to Reservoir Thickness Changes – Compaction, Subsidence, Density, Velocity



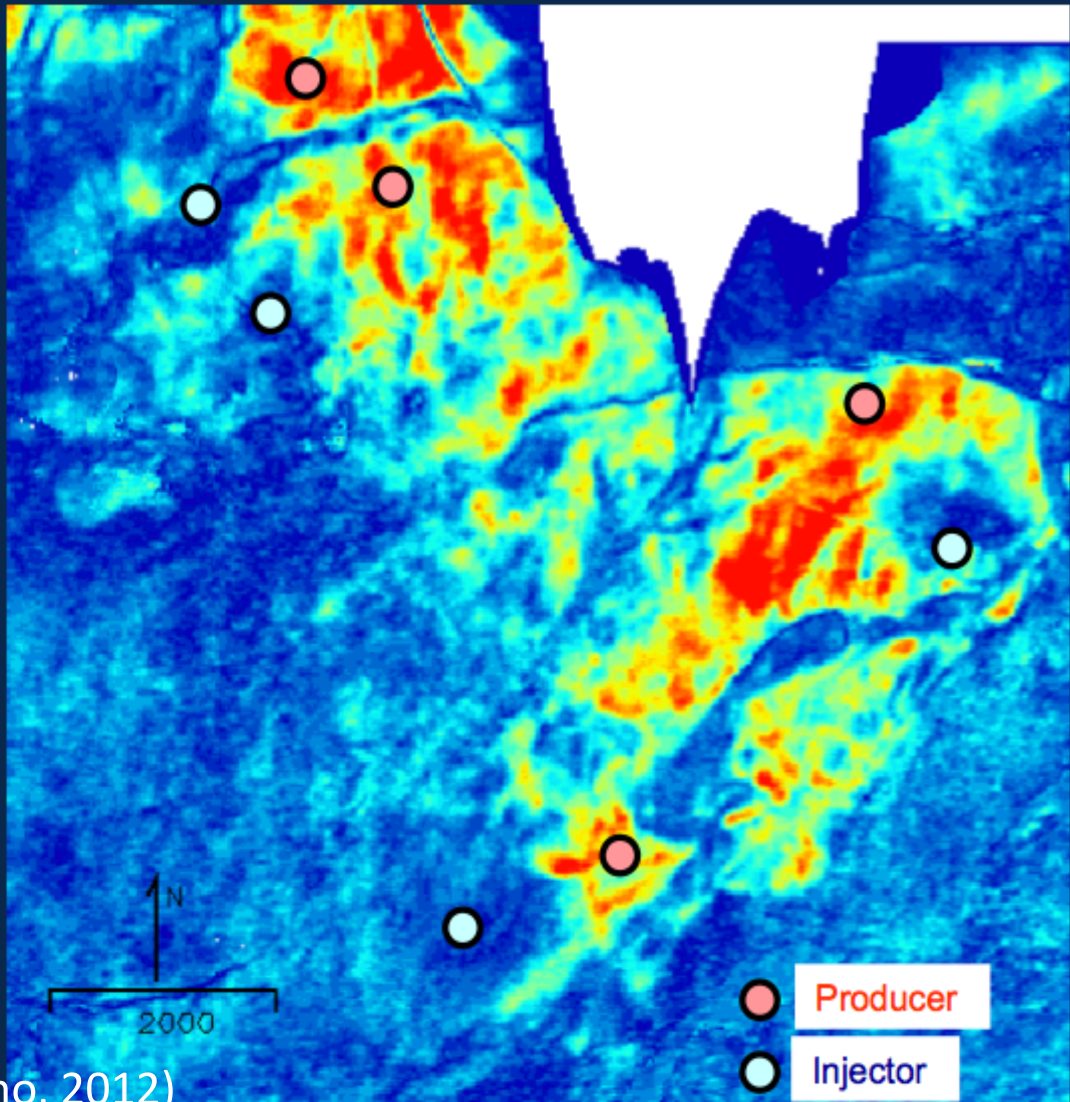
Pressure Changes in Reservoirs changes the Reflection Coefficient at the Top and Base of the Reservoir and changes the velocity of the reservoir! This results in changes in the Time Thickness & Seismic Amplitudes!

(R. Detomo, 2012)

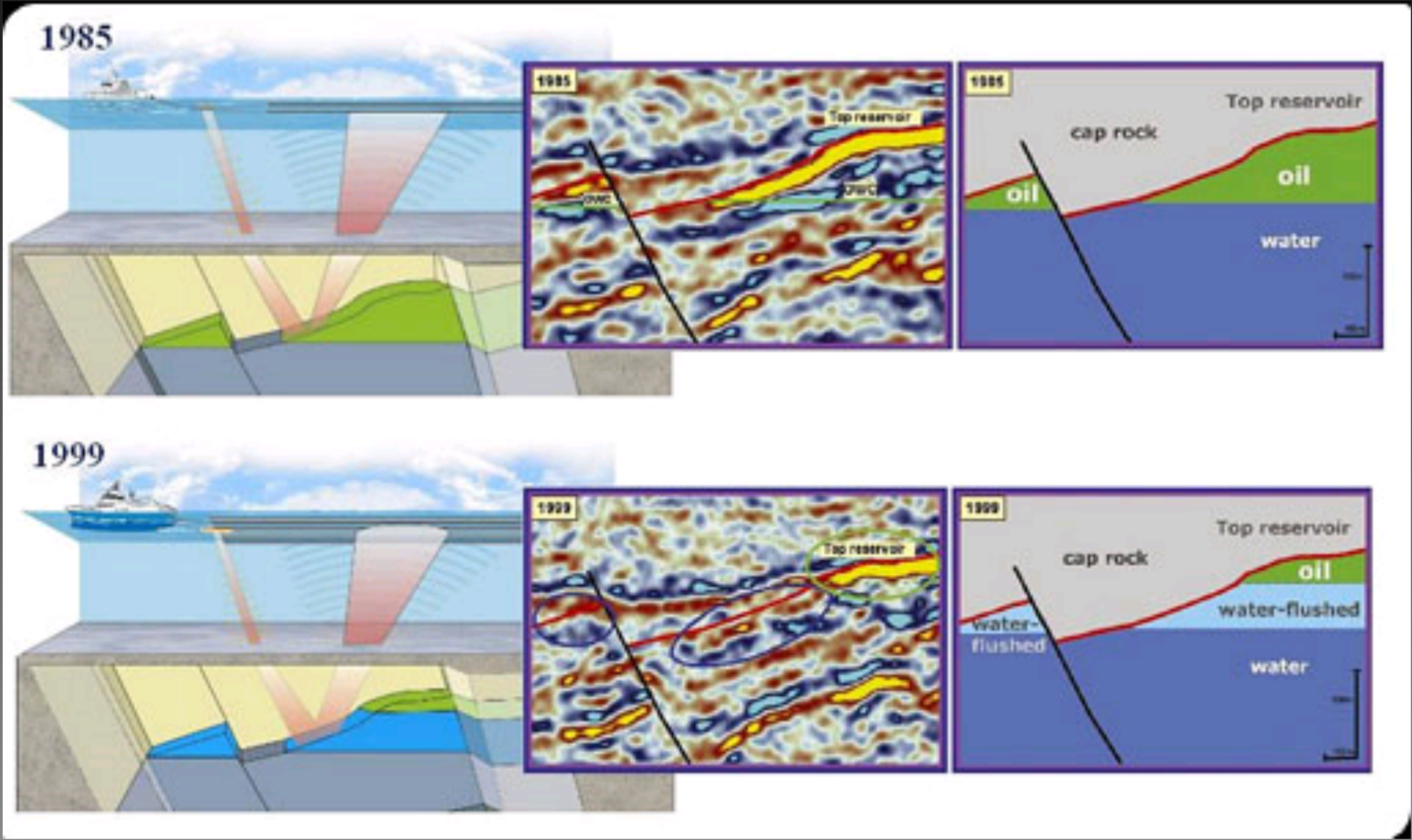
Example 1

2008 Monitor Streamer

3 years of Oil Production with Water Injection Pressure Maintenance
Note areas of difference where Water has Replaced Oil



(R. Detomo, 2012)


1985
1985
Top reservoir
owc
1985
Top reservoir
cap rock
oil
oil
water
1999
1999
Top reservoir
1999
Top reservoir
cap rock
oil
water-flushed
water-flushed
water

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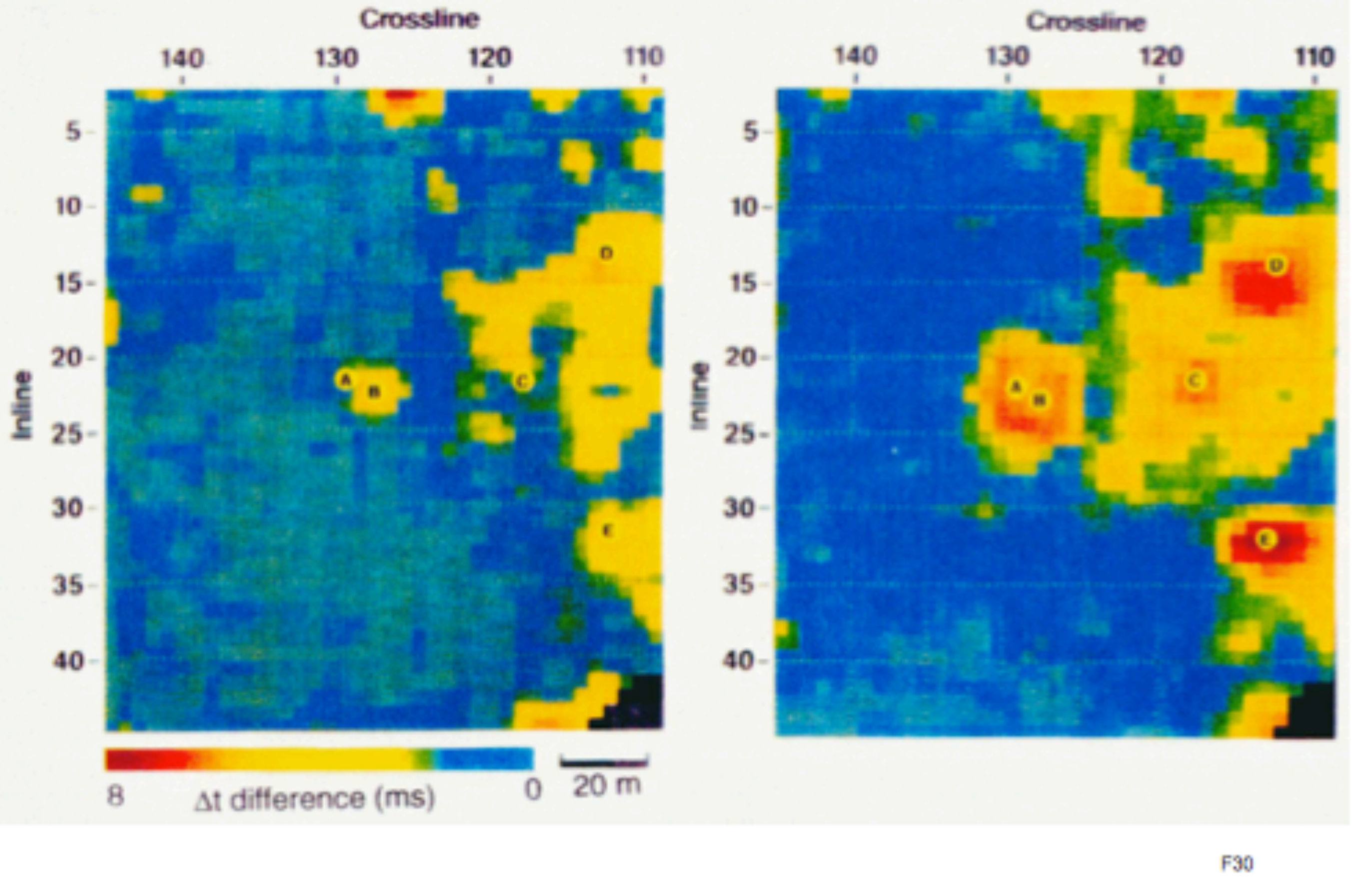
An Early, Successful 4D Field Study
Thermal Signature of Steam Flood

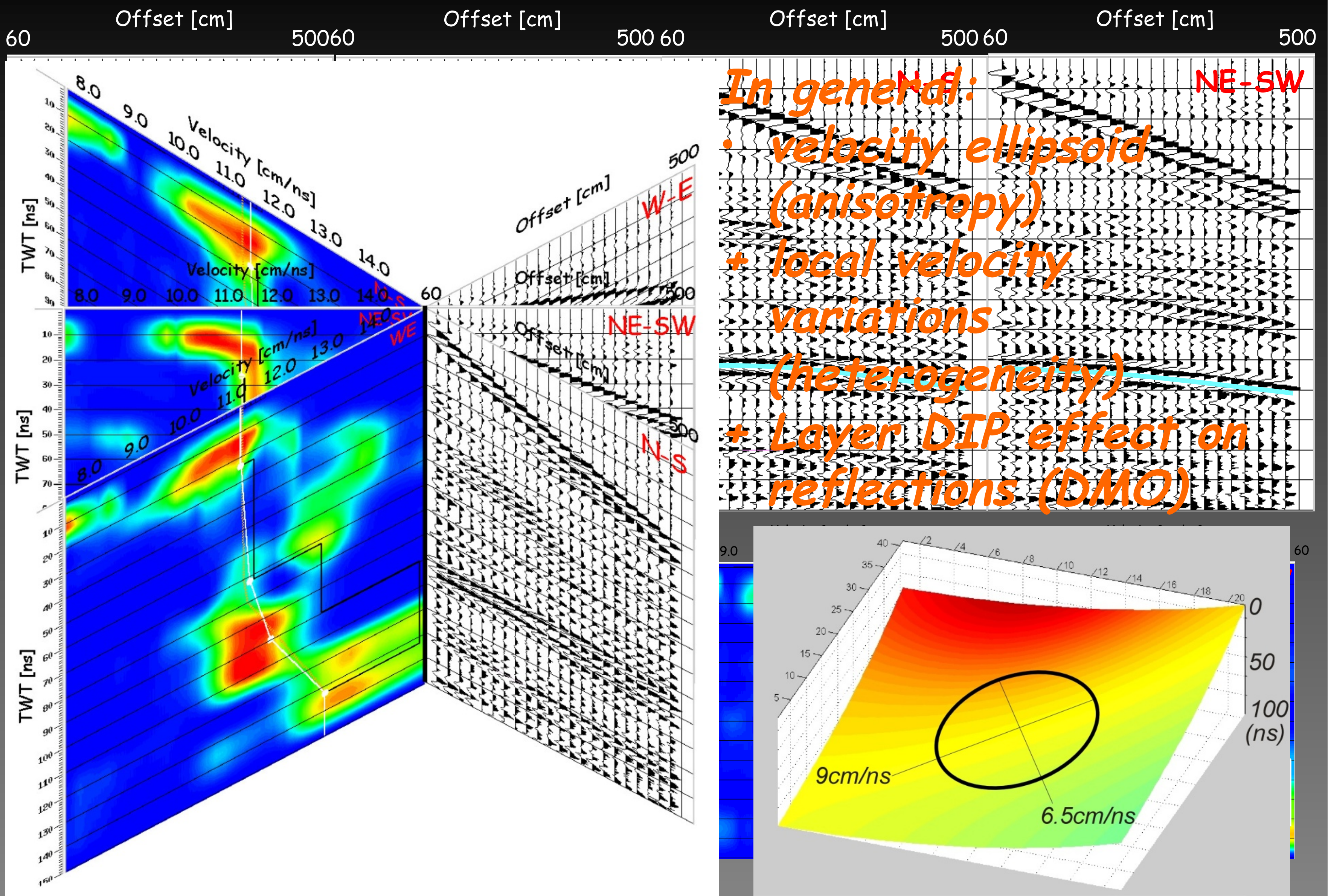


Traveltime increase in steamed interval after a few months of steam injection.

After a few more months, the anomaly spreads.

(From DeBuyl, 1989)

Velocity analysis

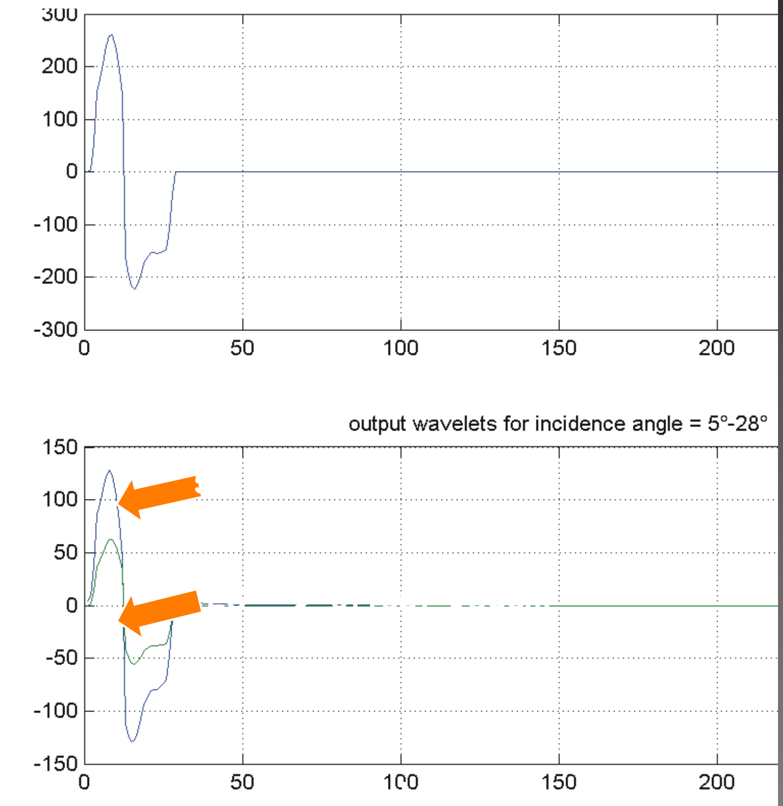


In general:
- *velocity ellipsoid (anisotropy)*
- *+ local velocity variations (heterogeneity)*
- *+ Layer DIP effect on reflections (DMO)*

Migration velocity analysis for enhanced material characterization

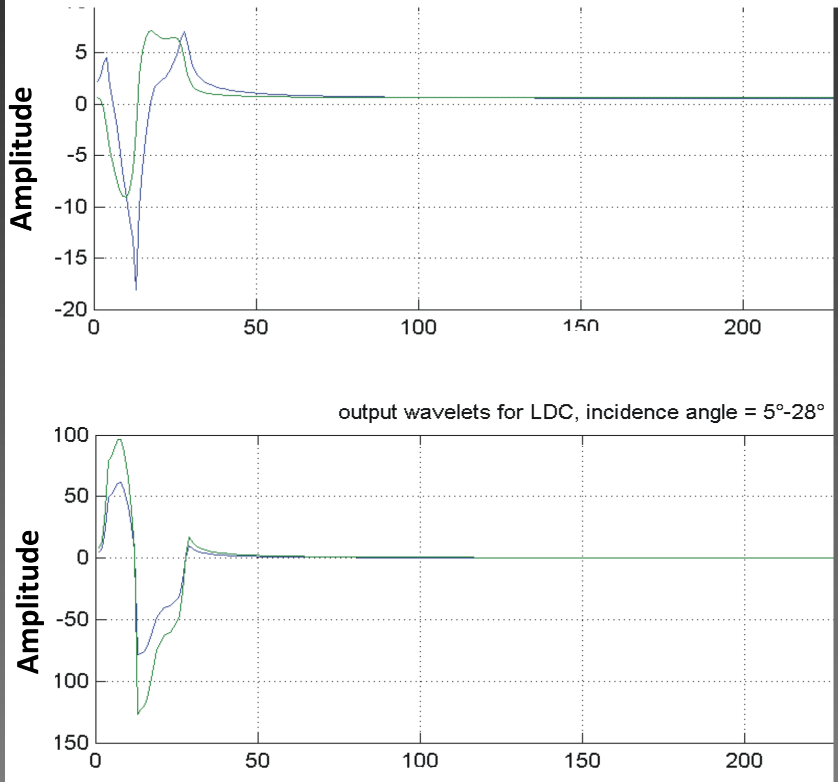
Characterization of materials and fractures (numerical simulation and Comparison with field data)

Synthetic data for different materials and incidence angles



Limestone-air contact

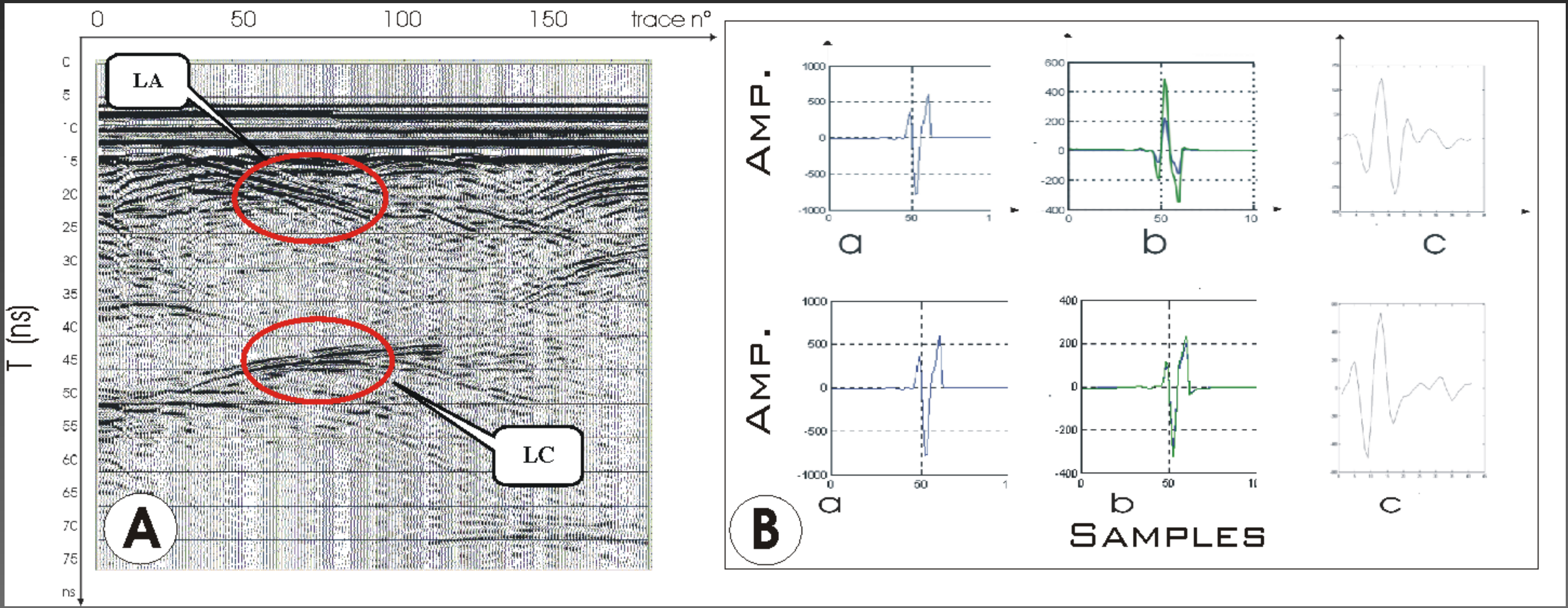
Limestone-wet clay contact



Limestone-water contact

Discontinuities characterization using MODELING

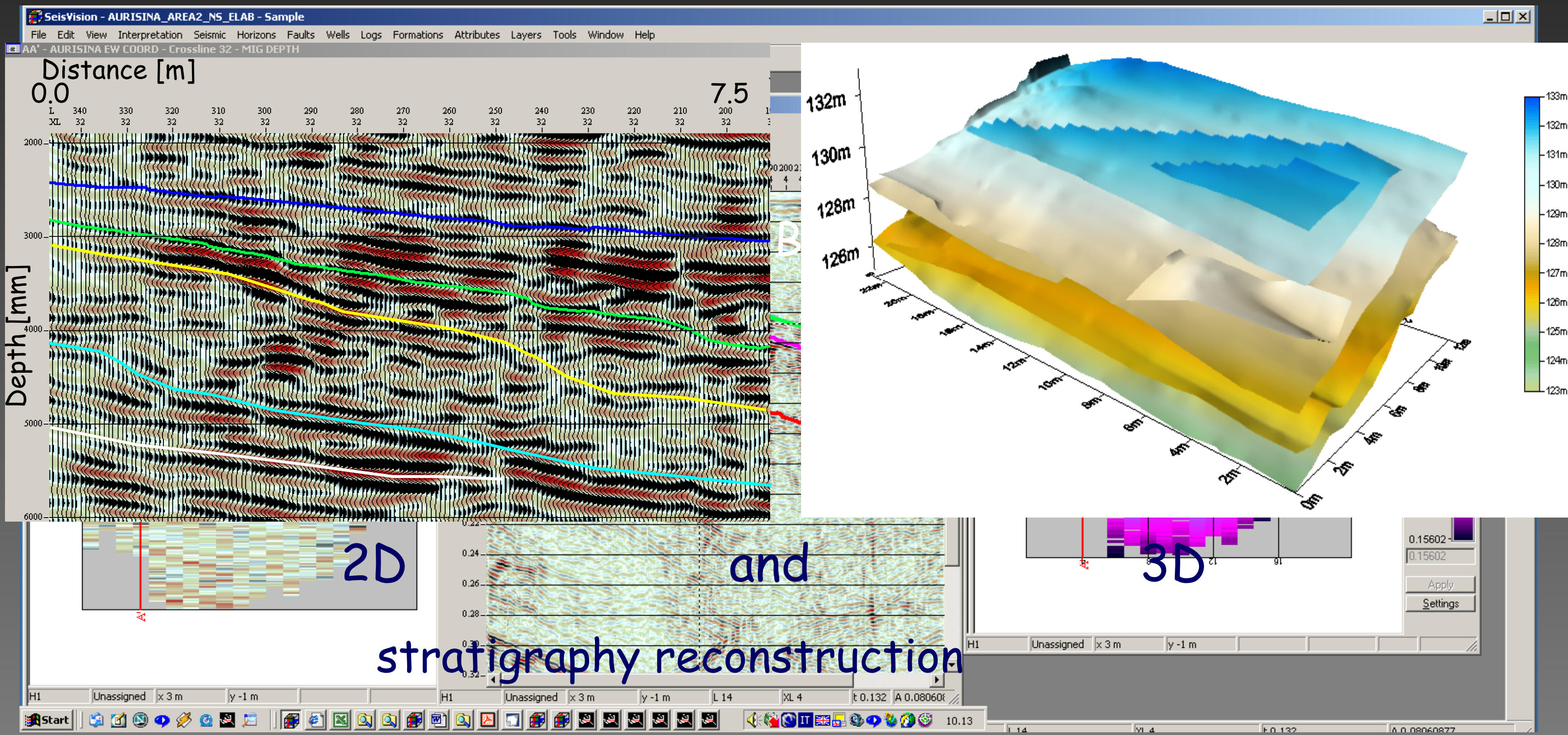
Comparison between field and synthetic data



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

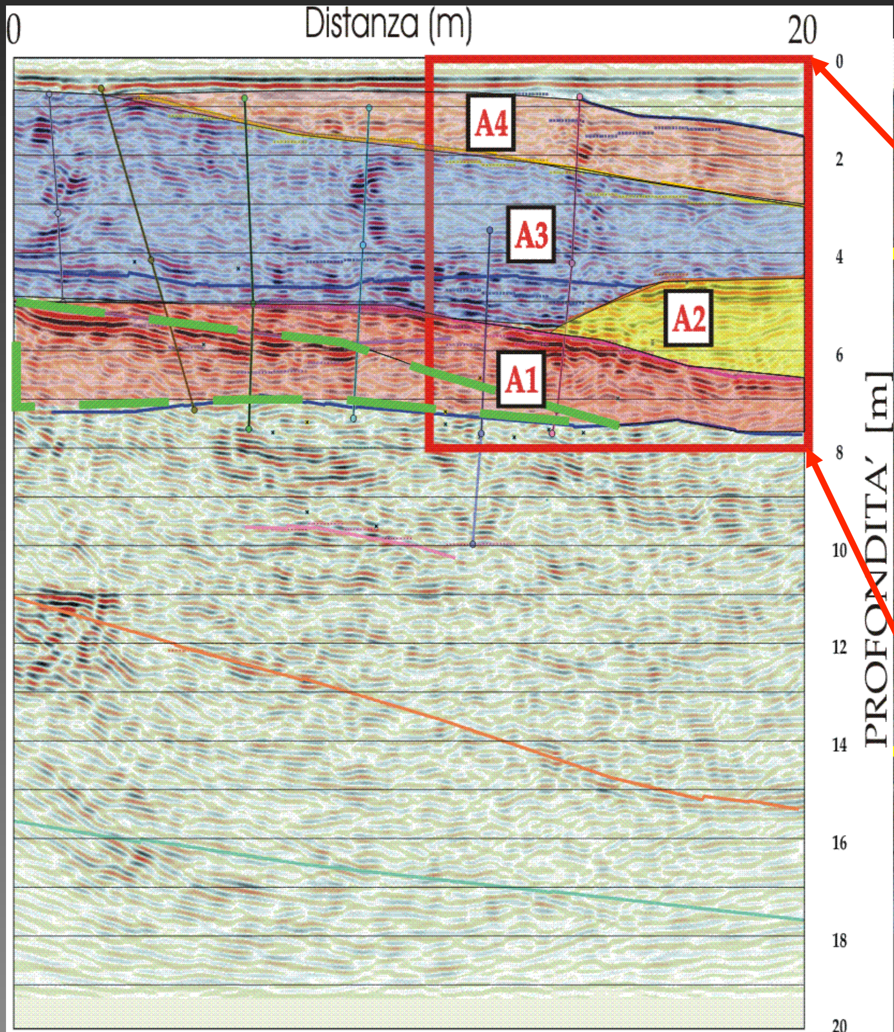
Data integration-interpretation

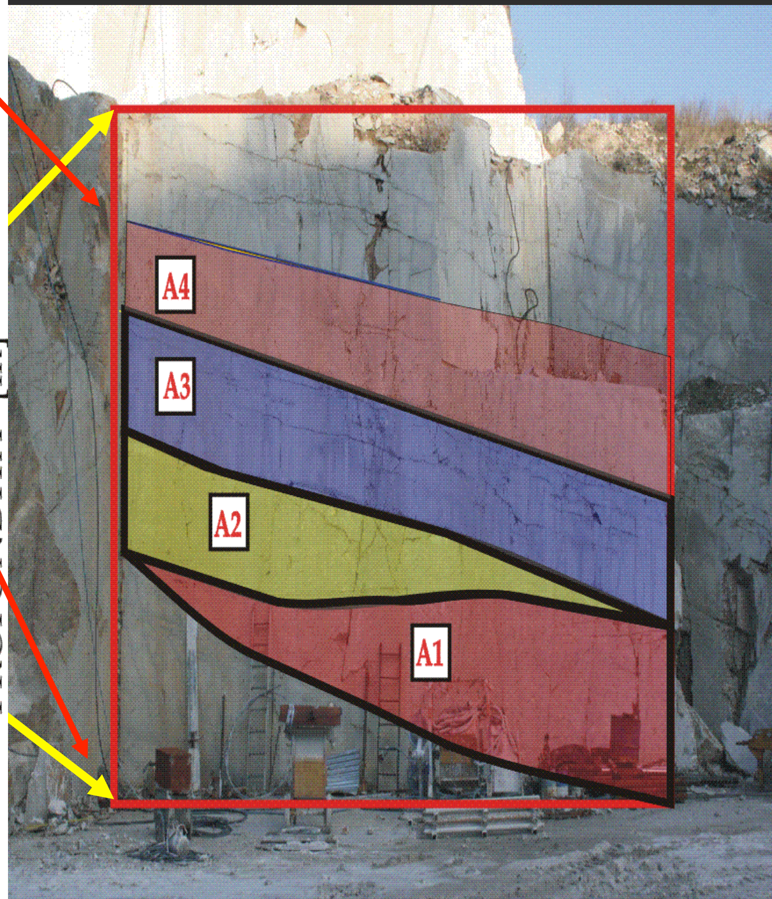
From 2D interpretation to 3D stratigraphy reconstruction



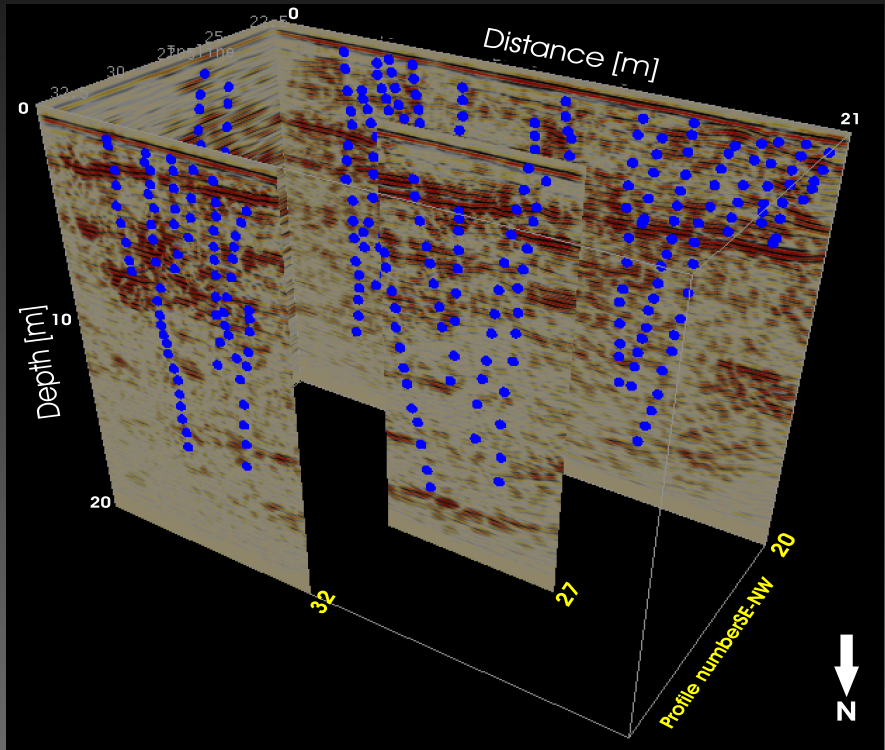
Data integration-interpretation

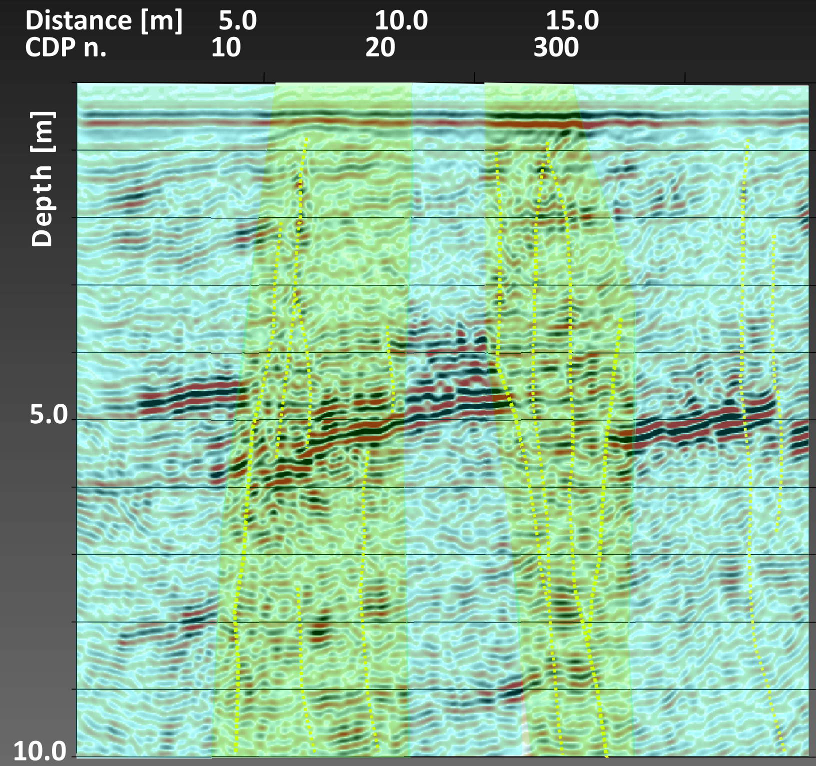
Correlation, calibration and validation with outcrops





Data integration-interpretation





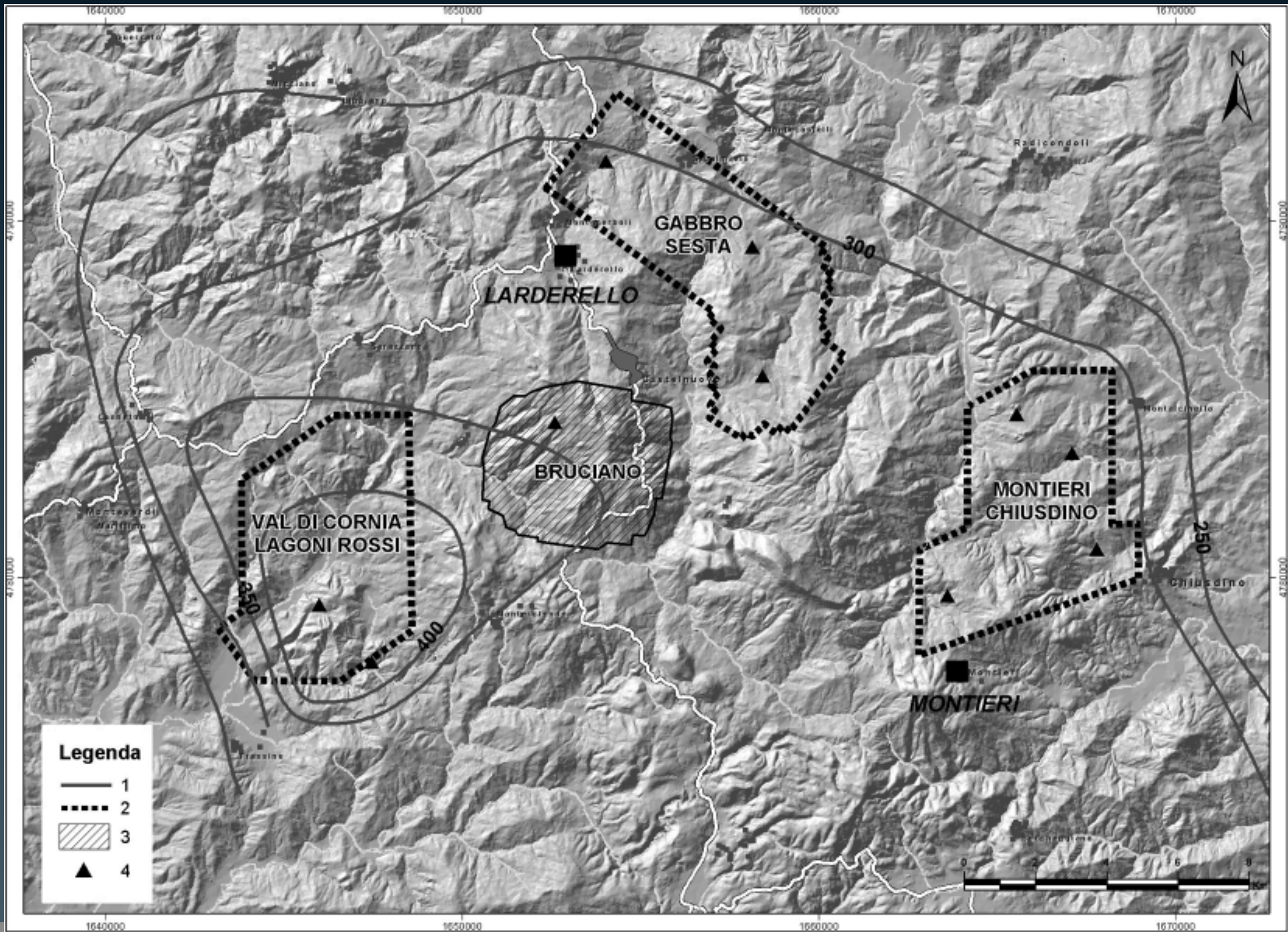
3D Discontinuities mapping and

HIGH fractures density

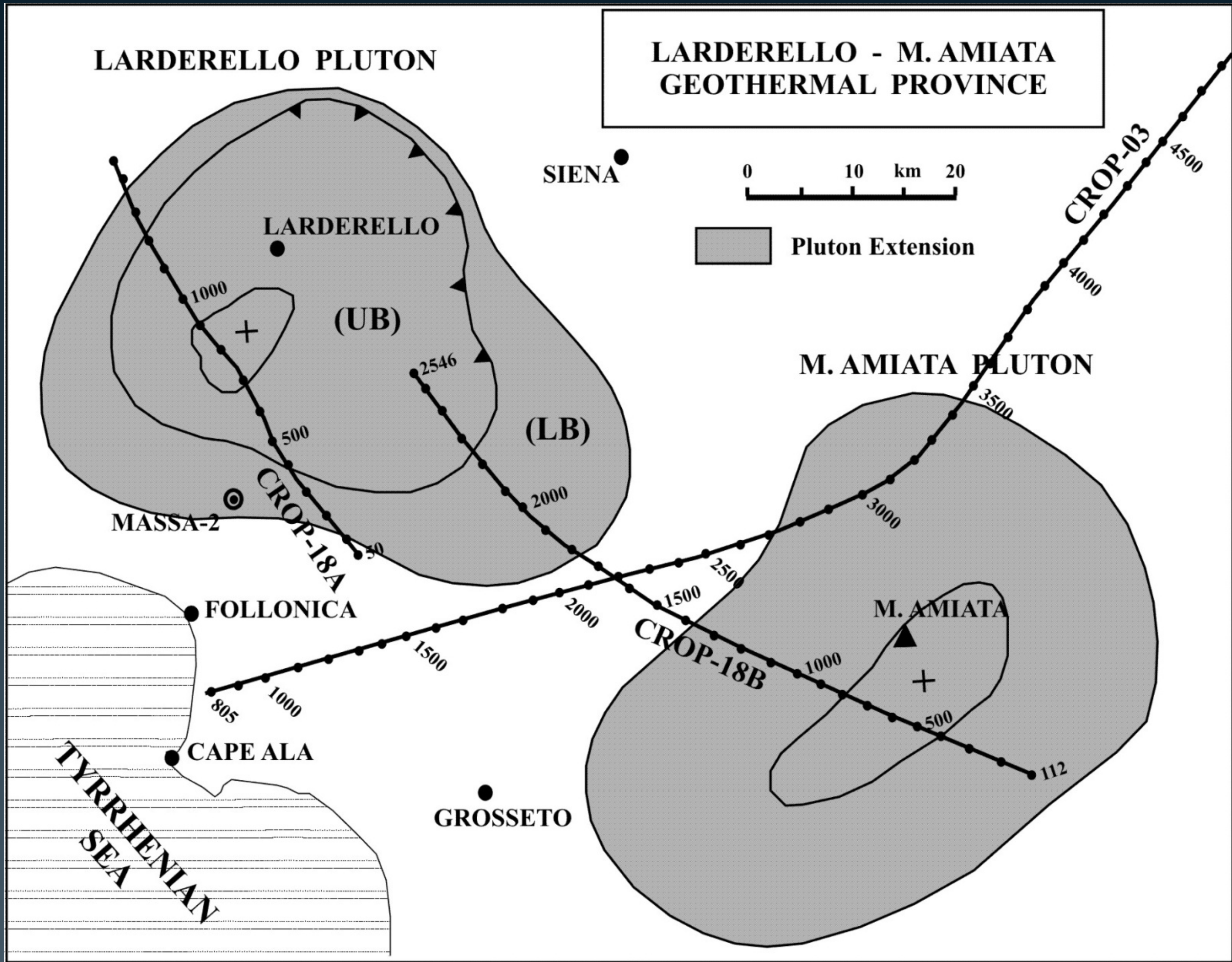
LOW fractures density

Homogeneous zones definition ➔ geomechanic rock characterization

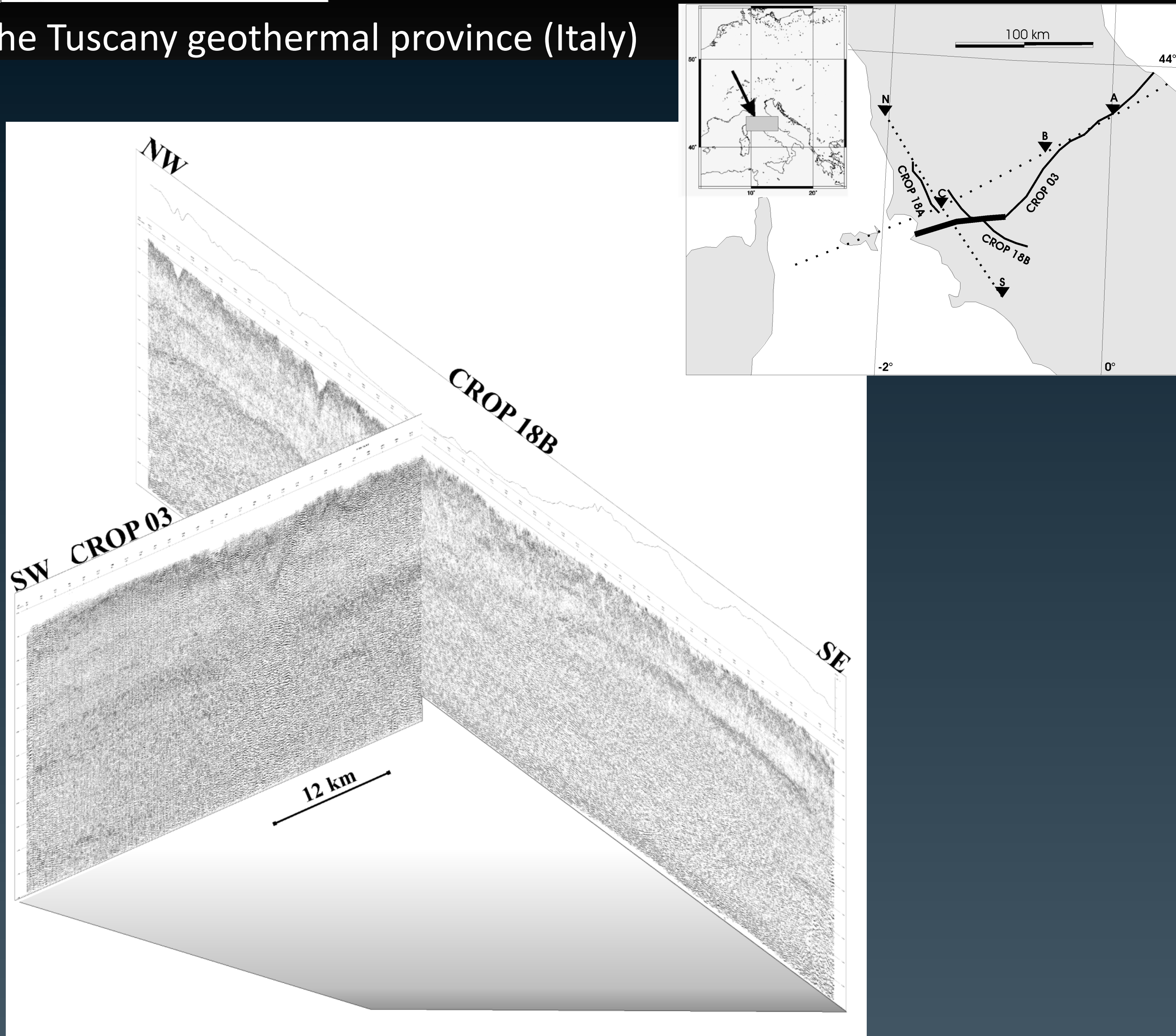
3-D exploration of the Tuscany geothermal province (Italy)



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

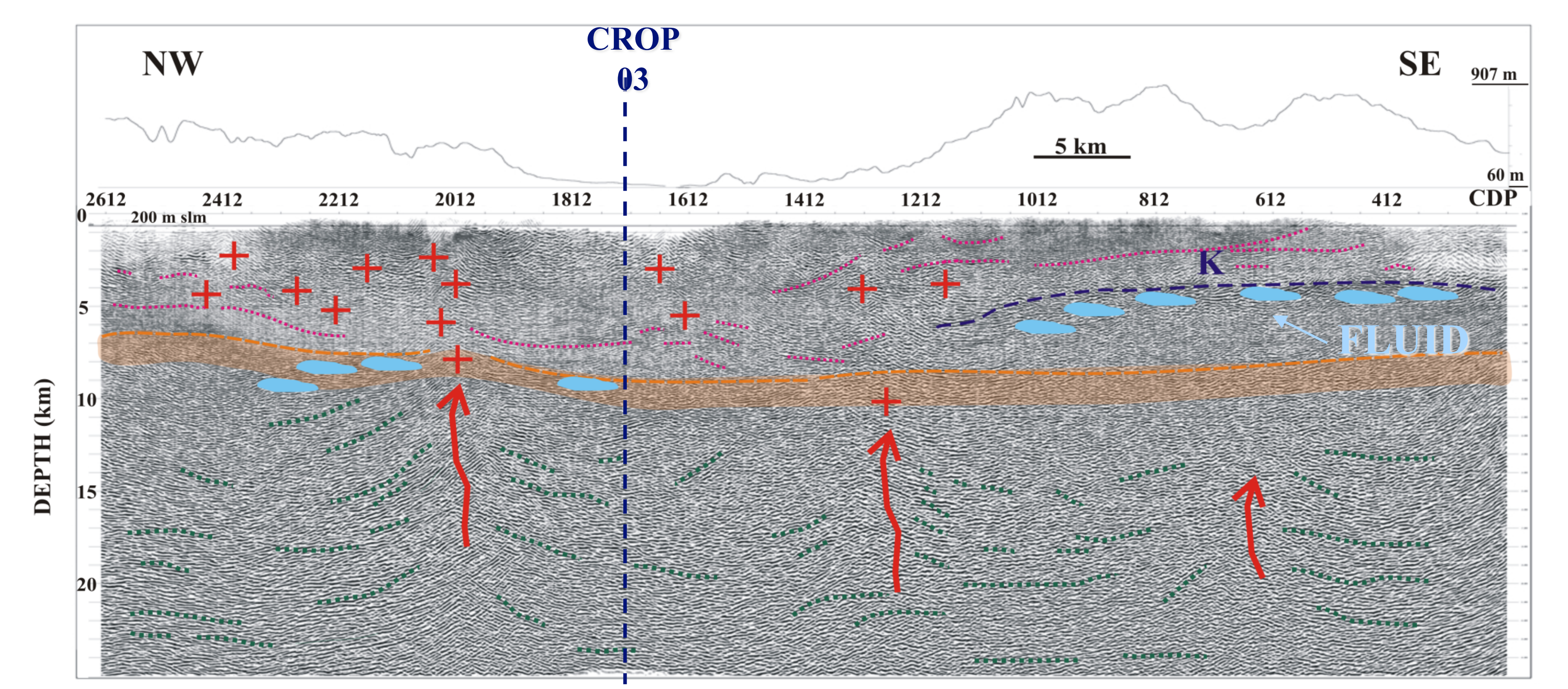


3-D exploration of the Tuscany geothermal province (Italy)



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

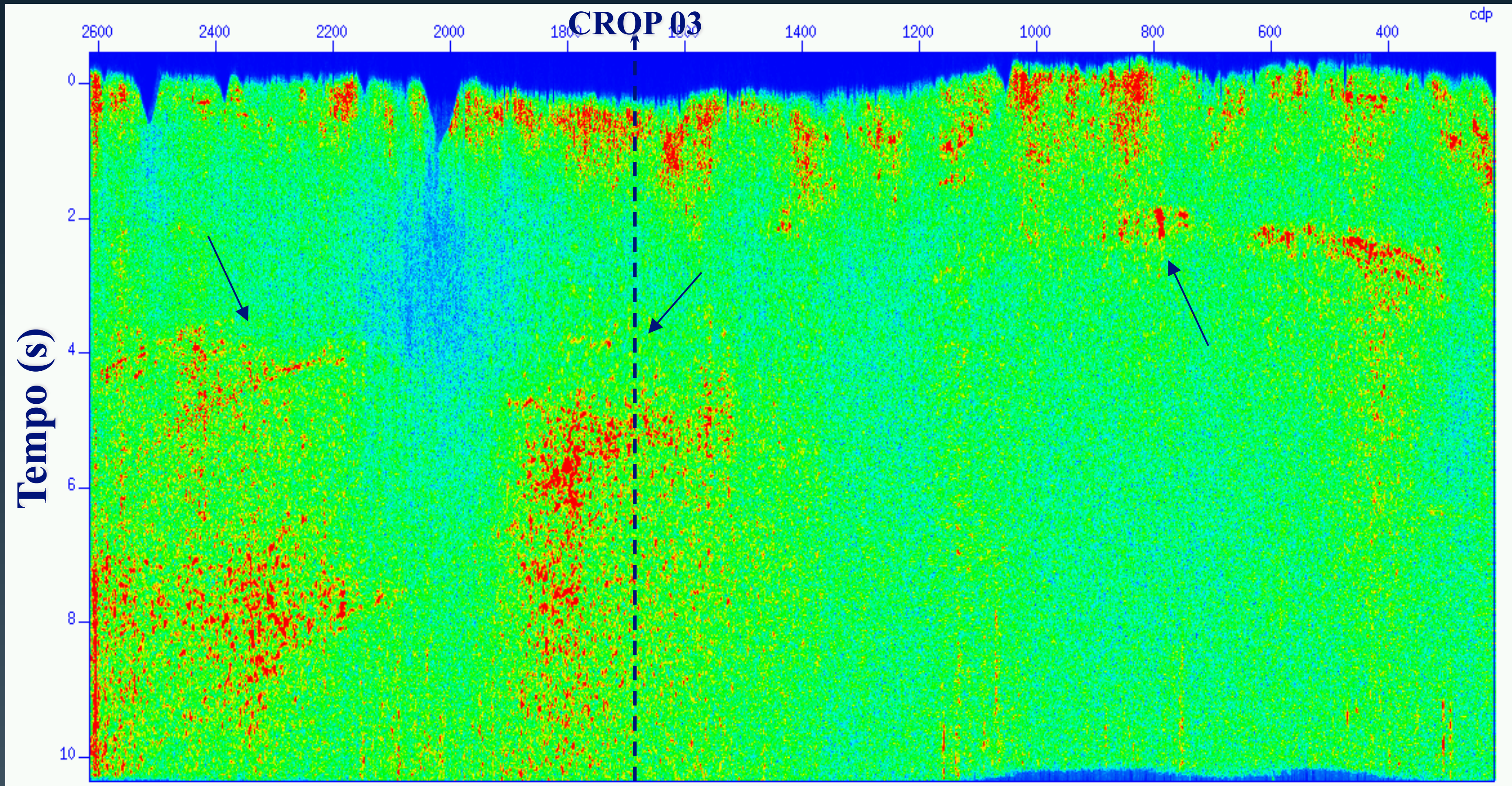
SEISMIC LINE CROP 18B



(From AVO analysis) (Tinivella et al., 2003)

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

SEISMIC LINE CROP 18B

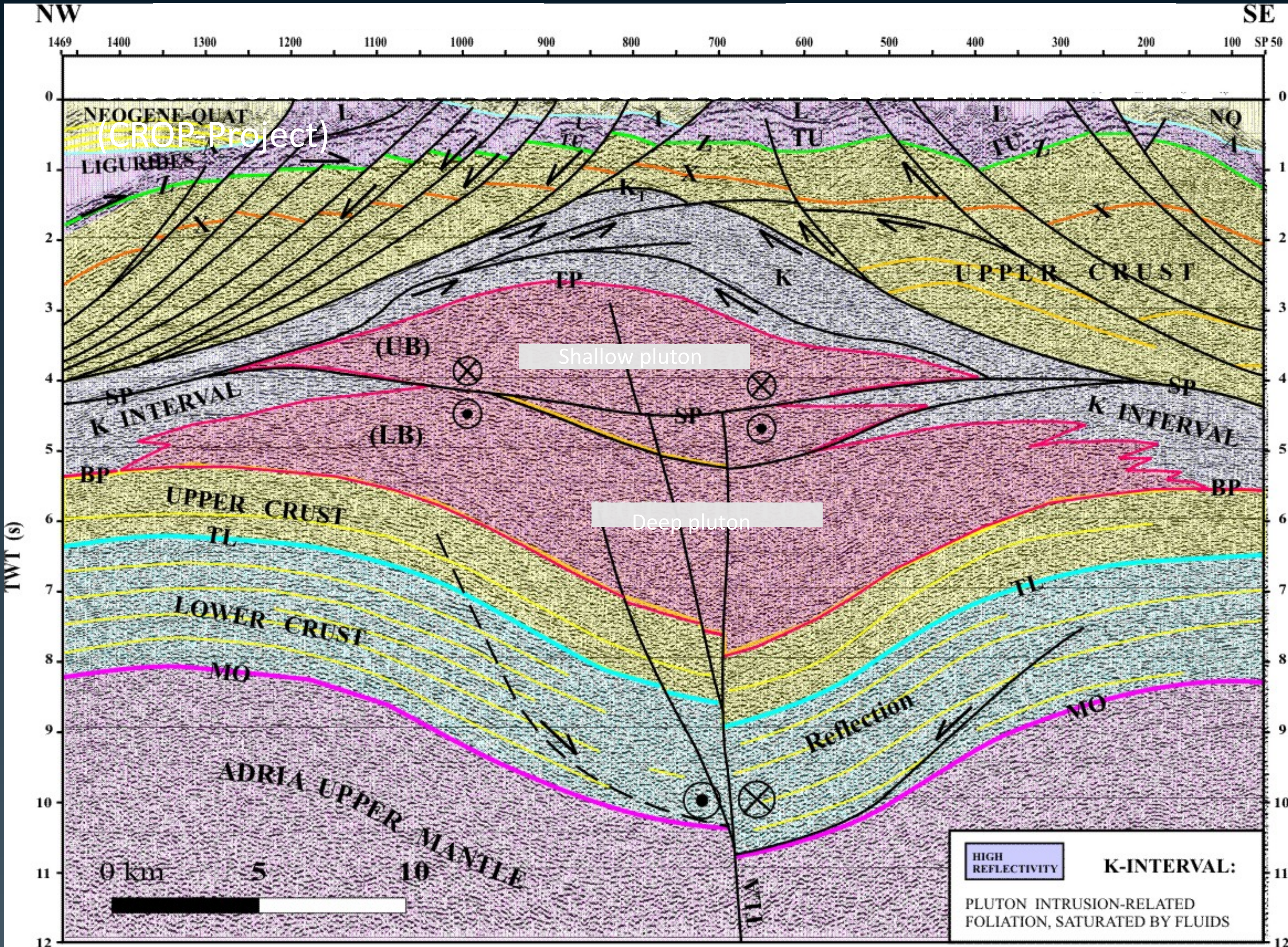


[redacted]

Instantaneous amplitude analysis (Tinivella et al., 2004)

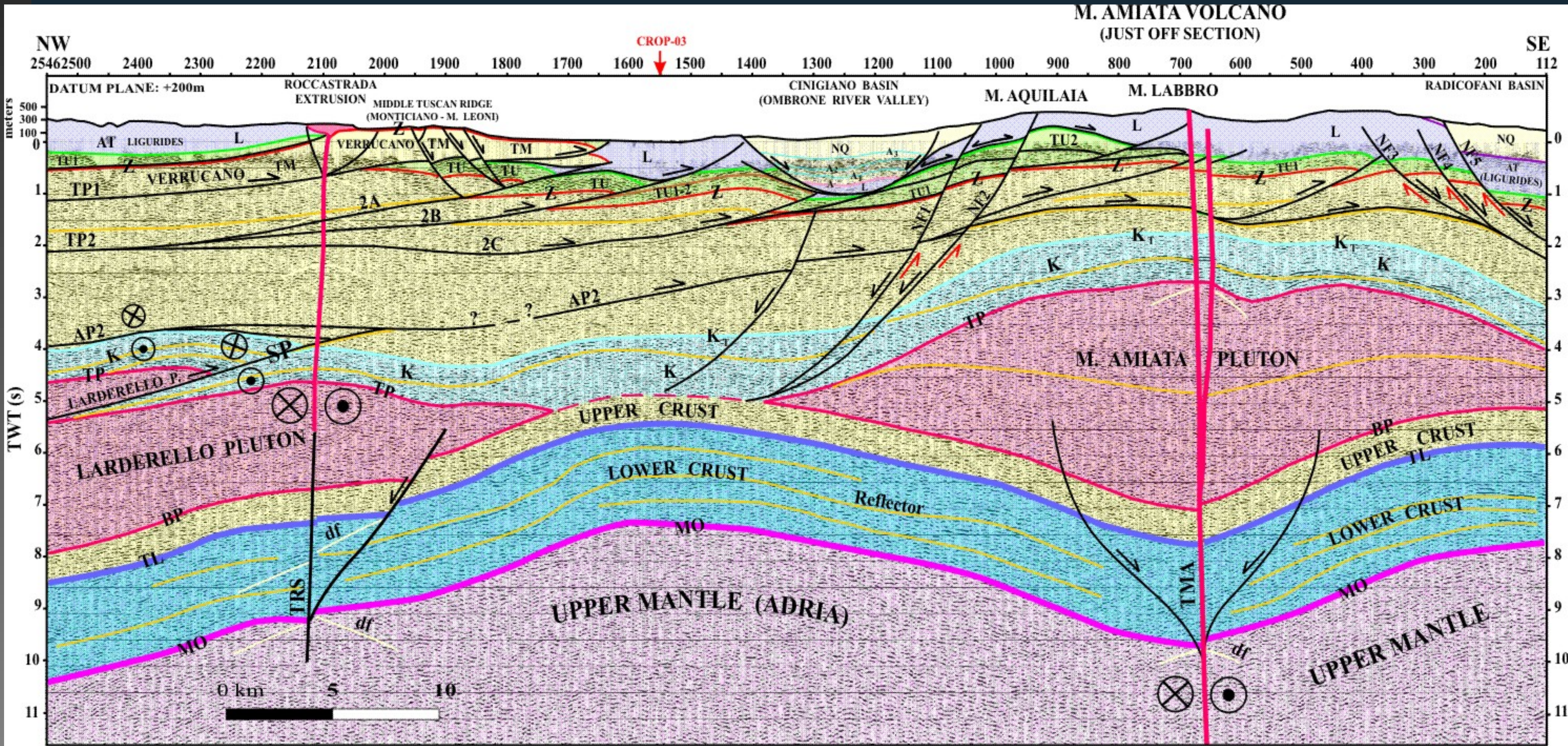
3-D exploration of the Tuscany geothermal province (Italy) (Finetti et al., 2001)

(CROP Project)



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

(Finetti et al., 2001)



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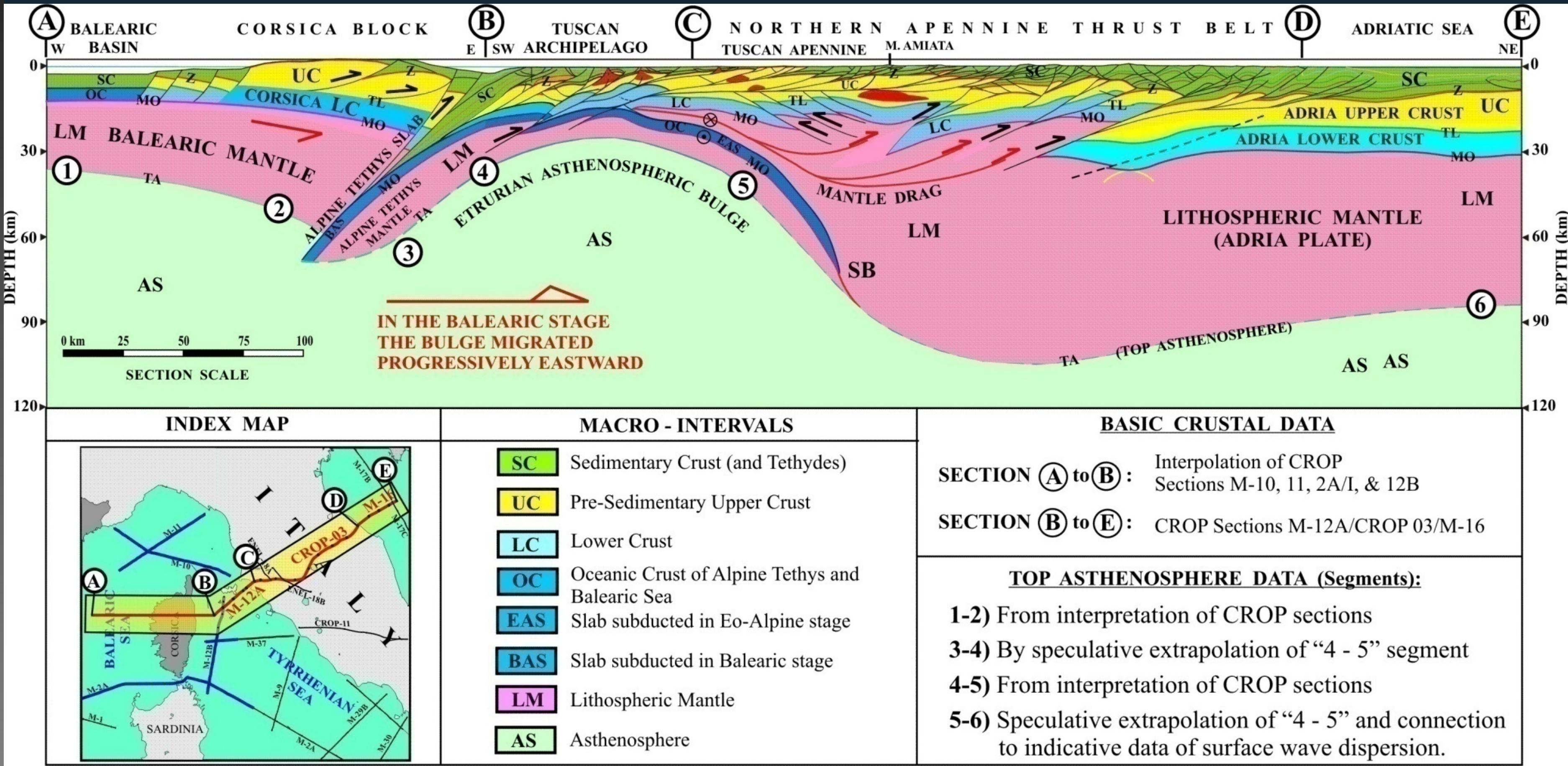
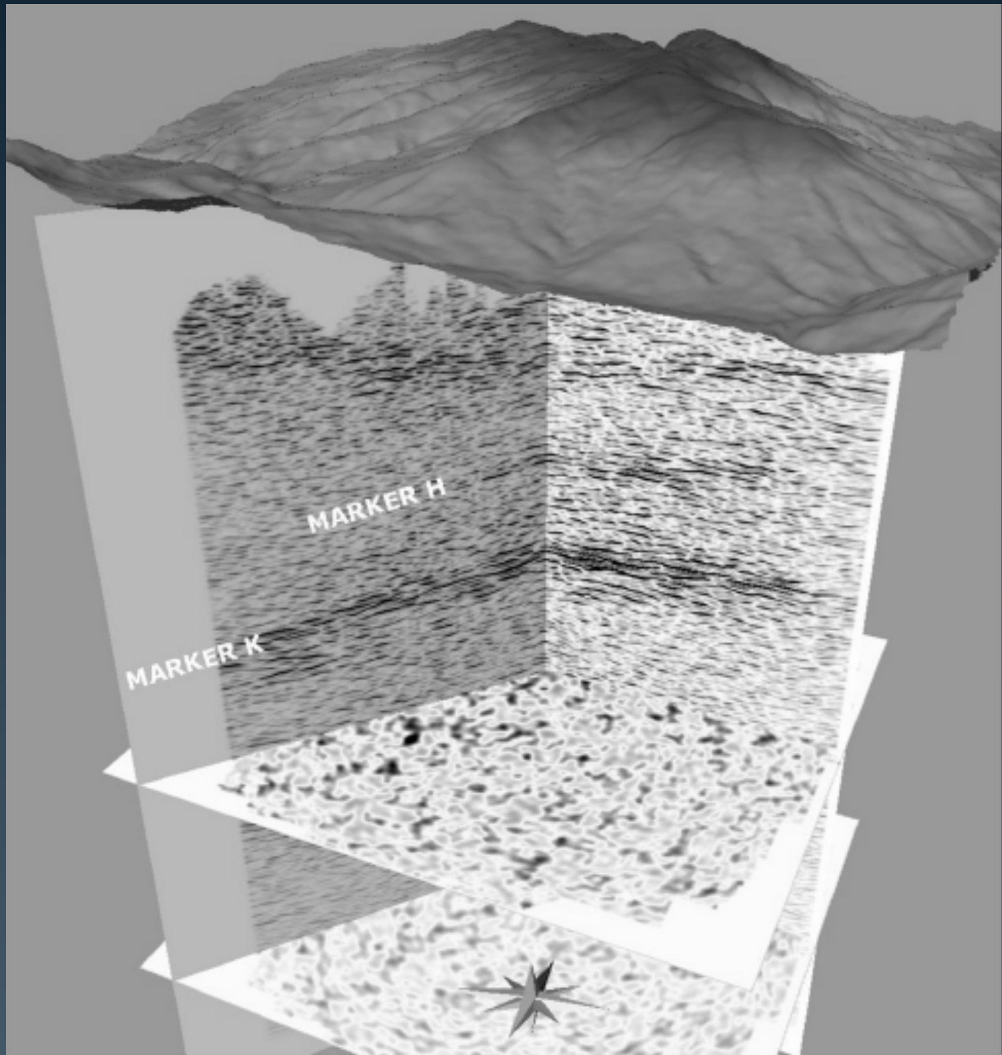
3-D exploration of the Tuscany geothermal province (Italy)

(Finetti et al., 2001)



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



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

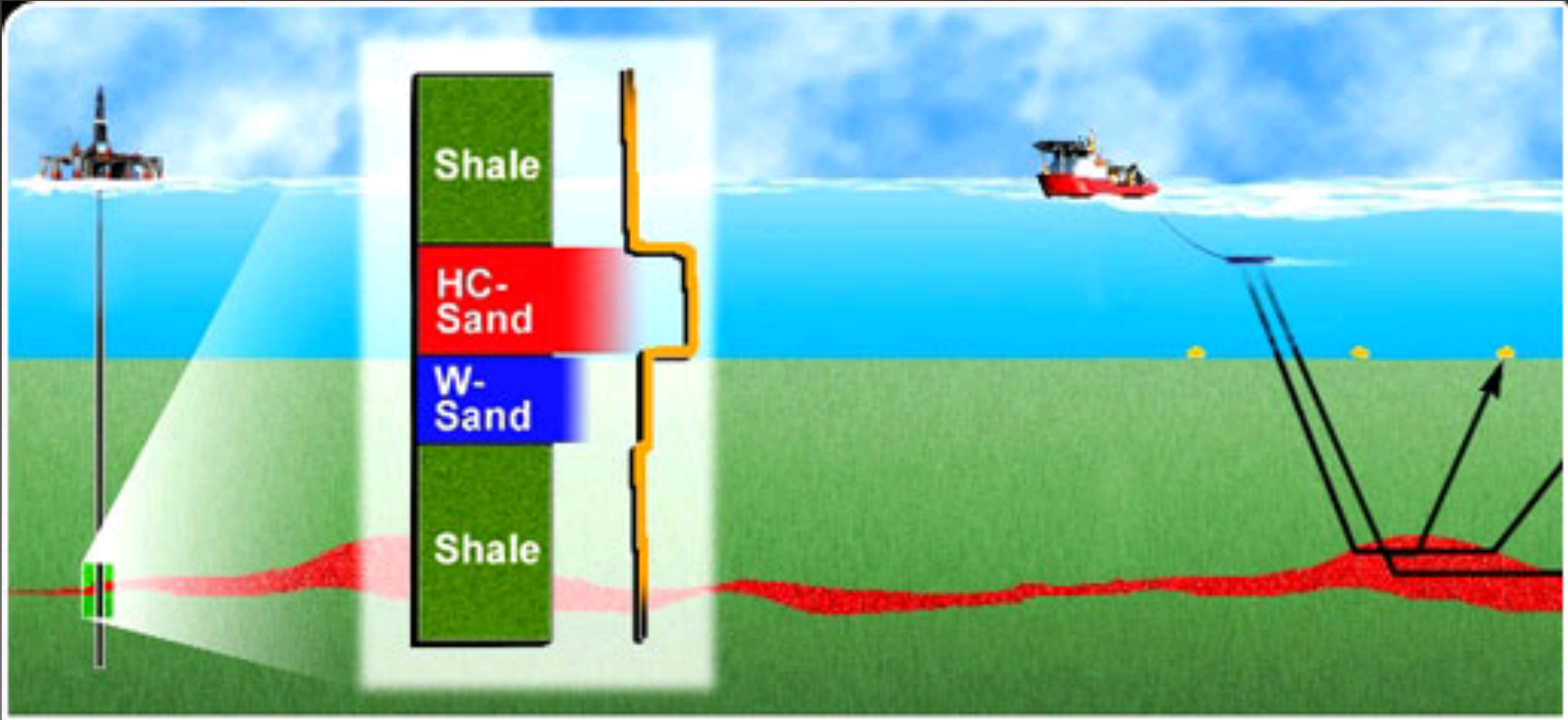
NONETHELESS…

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: electric and elastic properties

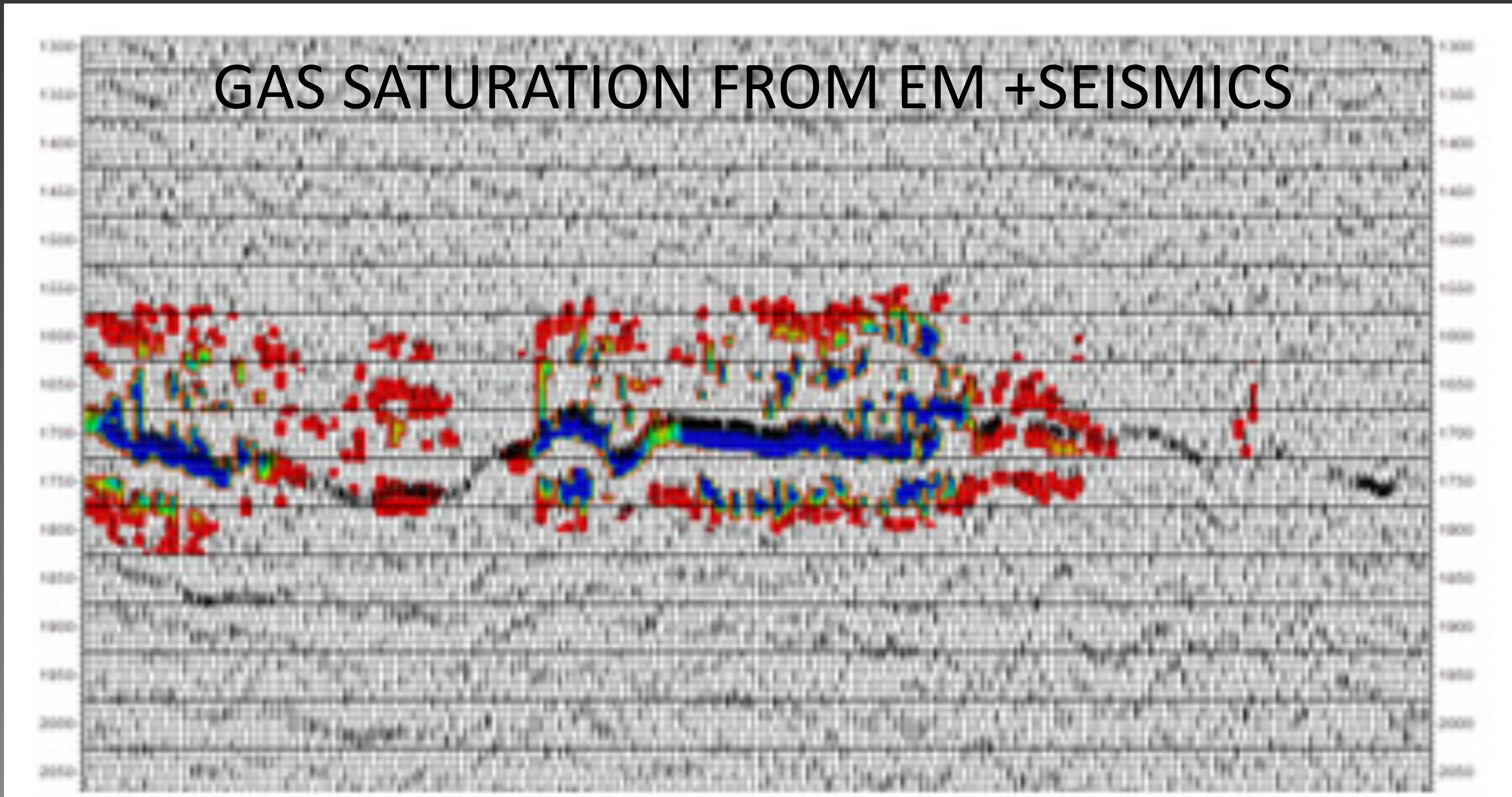


Borehole principle

Shale – very low resistivity; Water-bearing sandstone – low resistivity; Hydrocarbon-bearing sandstone – high resistivity

…THE ROAD AHEAD IN GEOTHERMAL EXPLORATION:

Joint Seismic/EM imaging and inversion



!!!! Thanks !!!!