Near Surface 2005
September 4-7, 2005, Palermo – Italy

WORKSHOP on Hydrogeophysics – a tool for sustainable use of groundwater resources

Integrated Seismic and GPR characterization of fractured rocks

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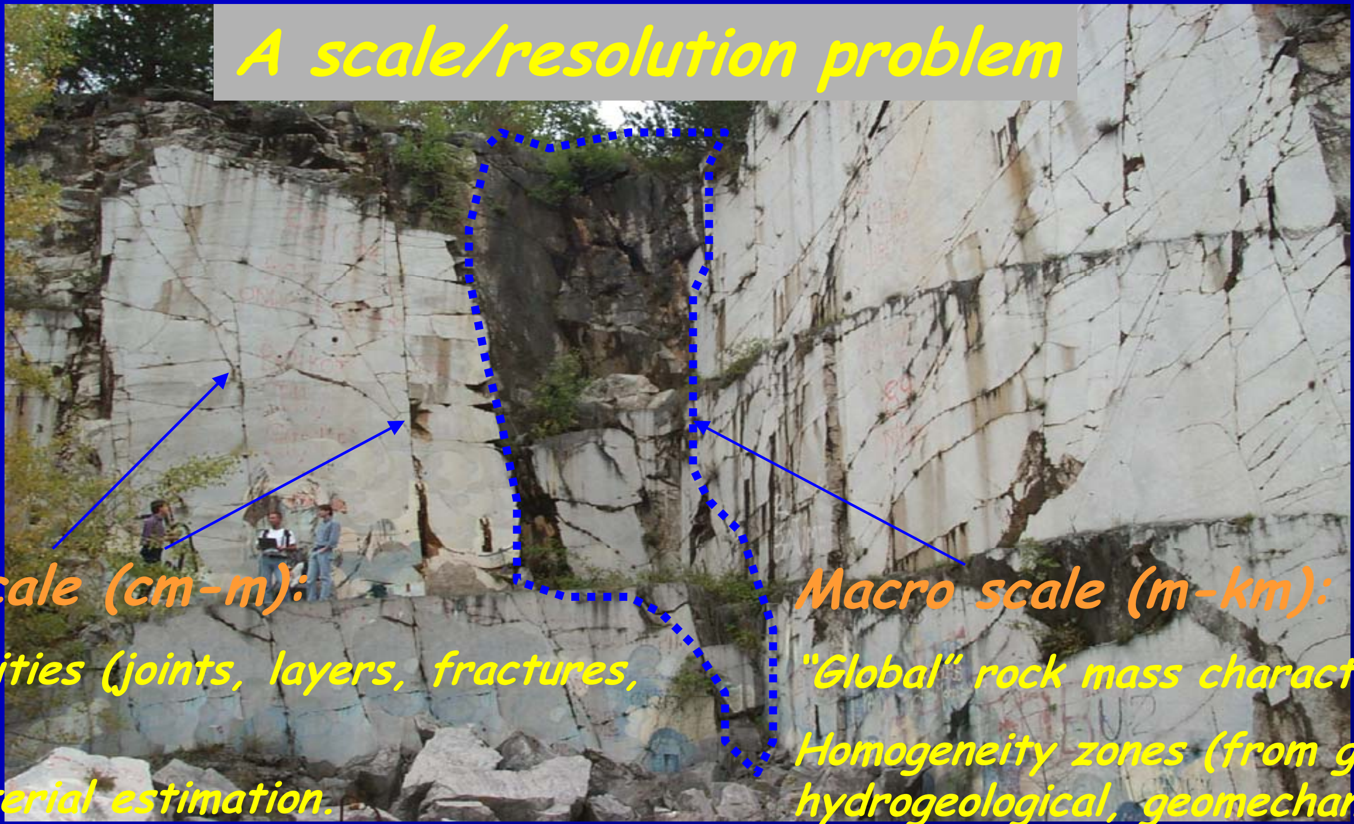
Statement of the problem



Micro scale (cm-m):

Discontinuities (joints, layers, fractures, faults).

Filling material estimation.

Discontinuities network (links, favourite water/fluid directions,…).

Voids (Karstic phenomena, open fractures,…).

Vertical and lateral lithological variations.

Macro scale (m-km):

"Global" rock mass characteristics.

Homogeneity zones (from geological, hydrogeological, geomechanical point of view).

Main discontinuities (large faults, bedrock).

Voids (caverns, tunnels).

Summary

Objectives

Imaging of rock mass characteristics (joints, fractures, voids, internal structures and heterogeneous volumes)

3D patterns reconstruction

Definition of rock mass homogeneity zones

Methods

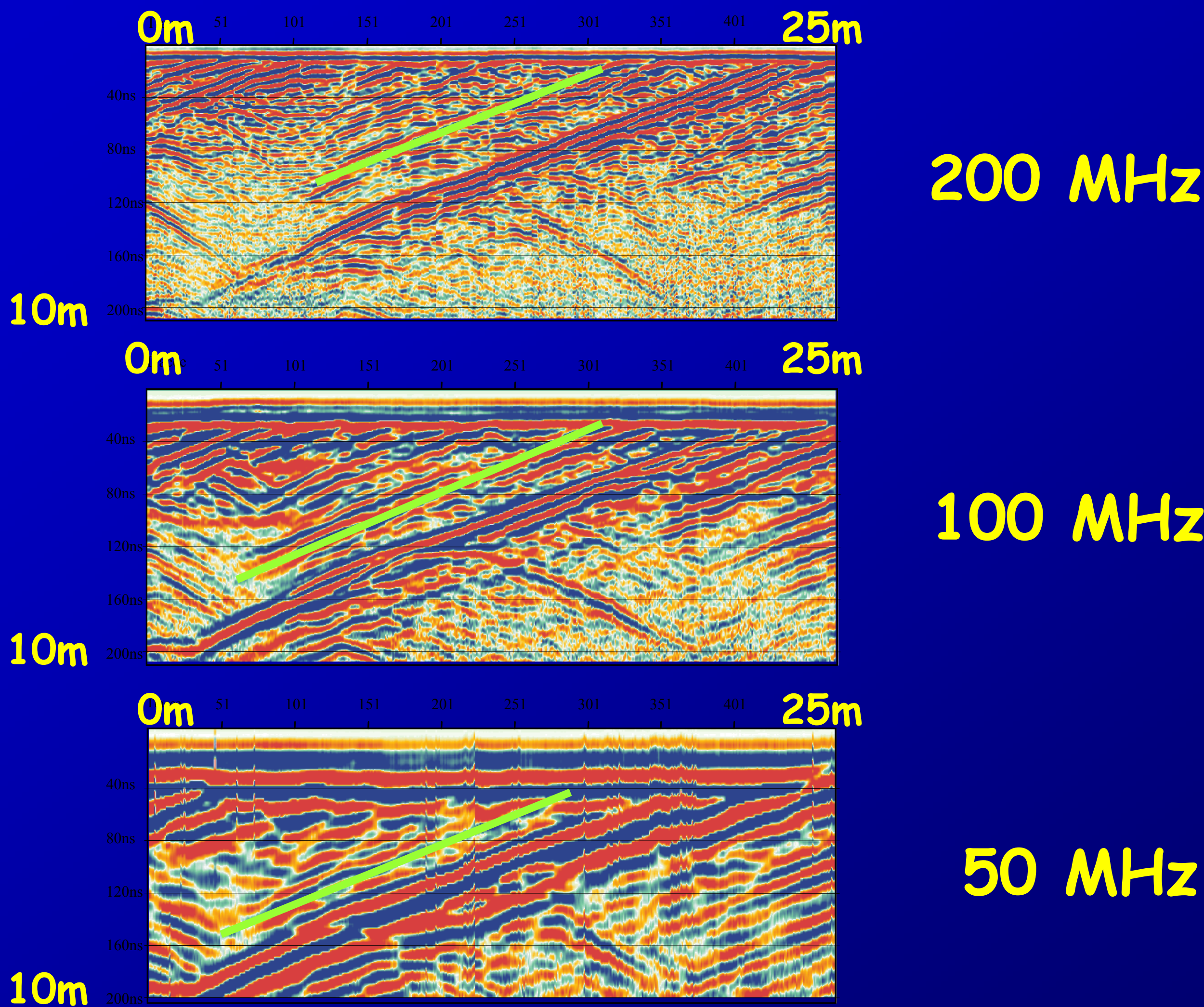
- SURFACE and BOREHOLE GPR
- SEISMICS: Multi channel Analysis of Surface Waves - MASW

Results

1) Imaging of rock discontinuities
2) Imaging of lithologic variation
3) Definition of different rock mass parameters
4) Geomechanical – hydrogeological problem assessment

Conclusions - Remarks

GPR VERTICAL RESOLUTION and PENETRATION



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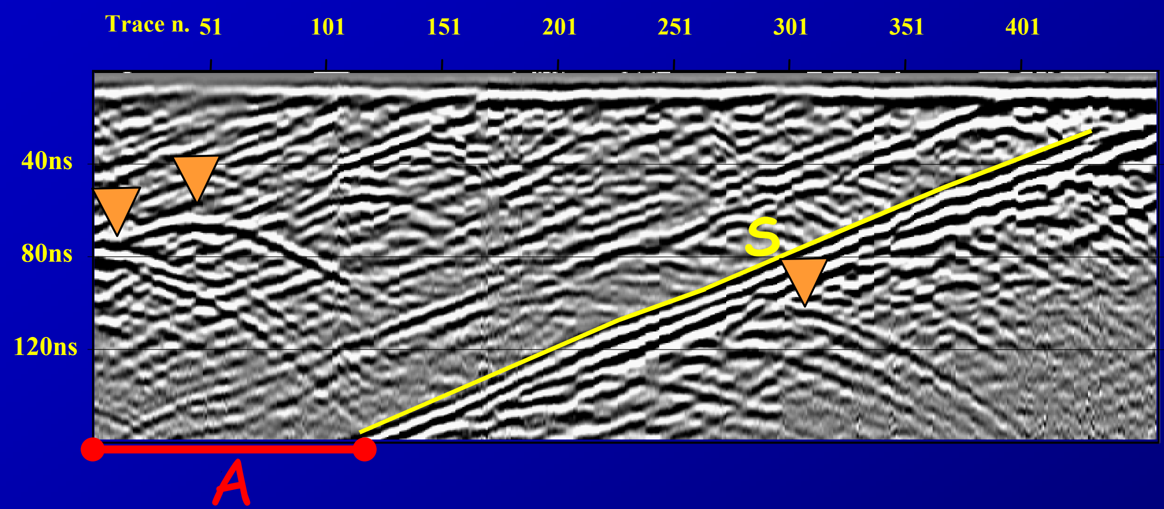
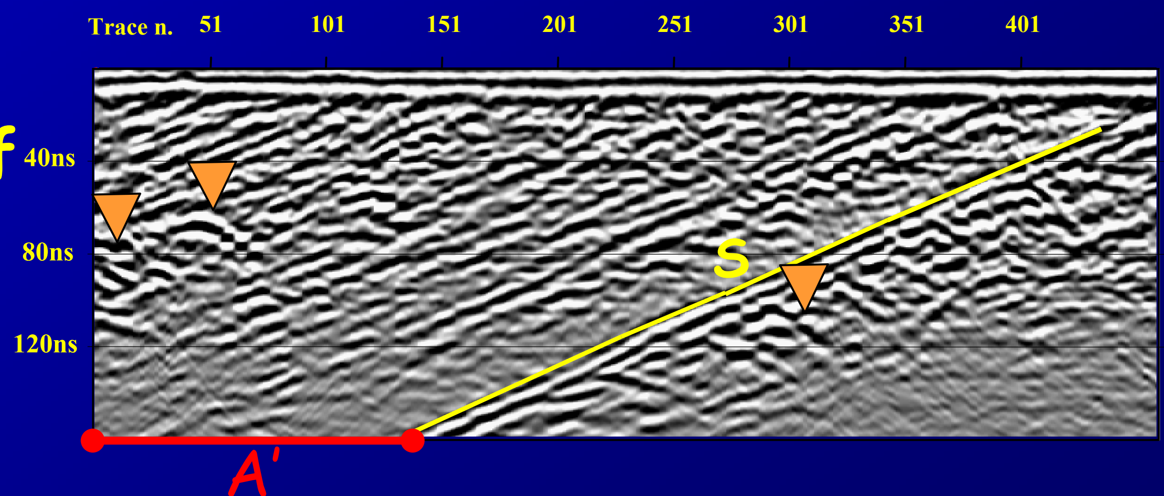
GPR processing: 200 MHz STACK and MIGRATION

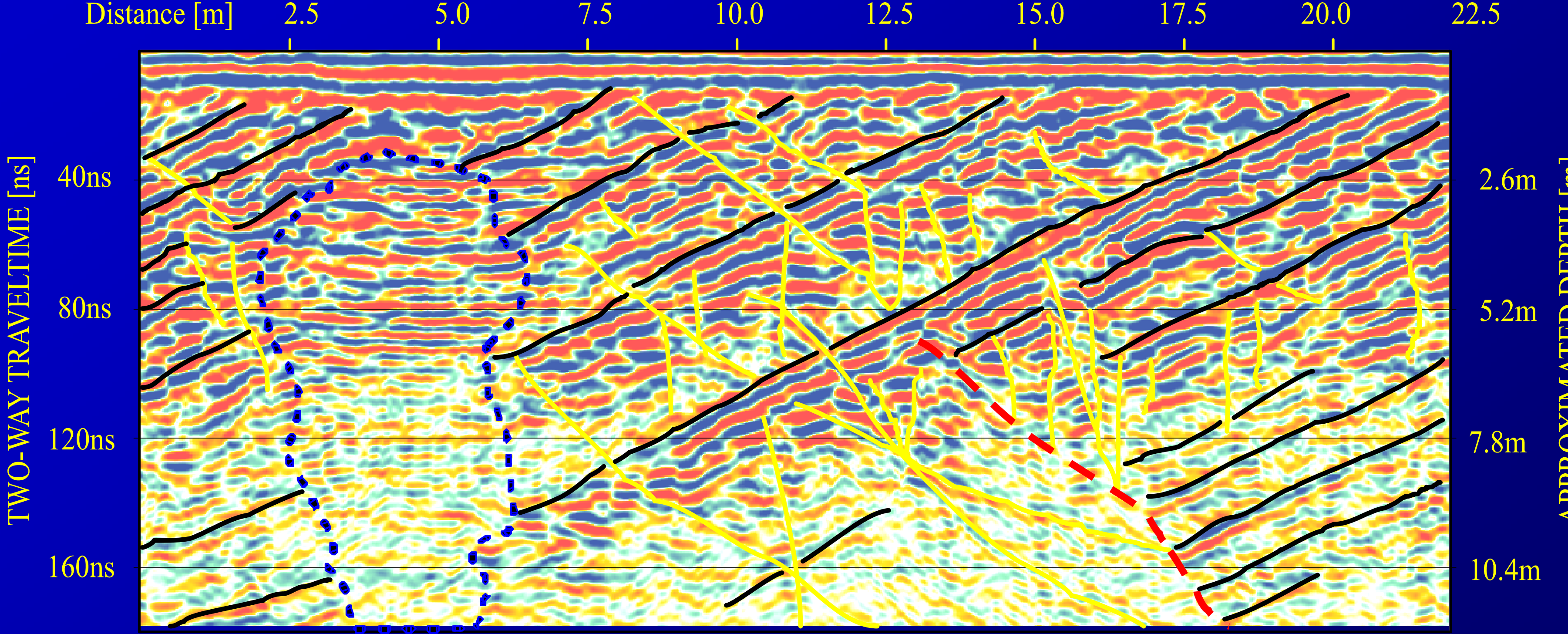
Stack section



Pre-stack Kirchhoff depth migrated (time converted) section



GPR INTERPRETATION:
Layering, fractures, faults and cavities



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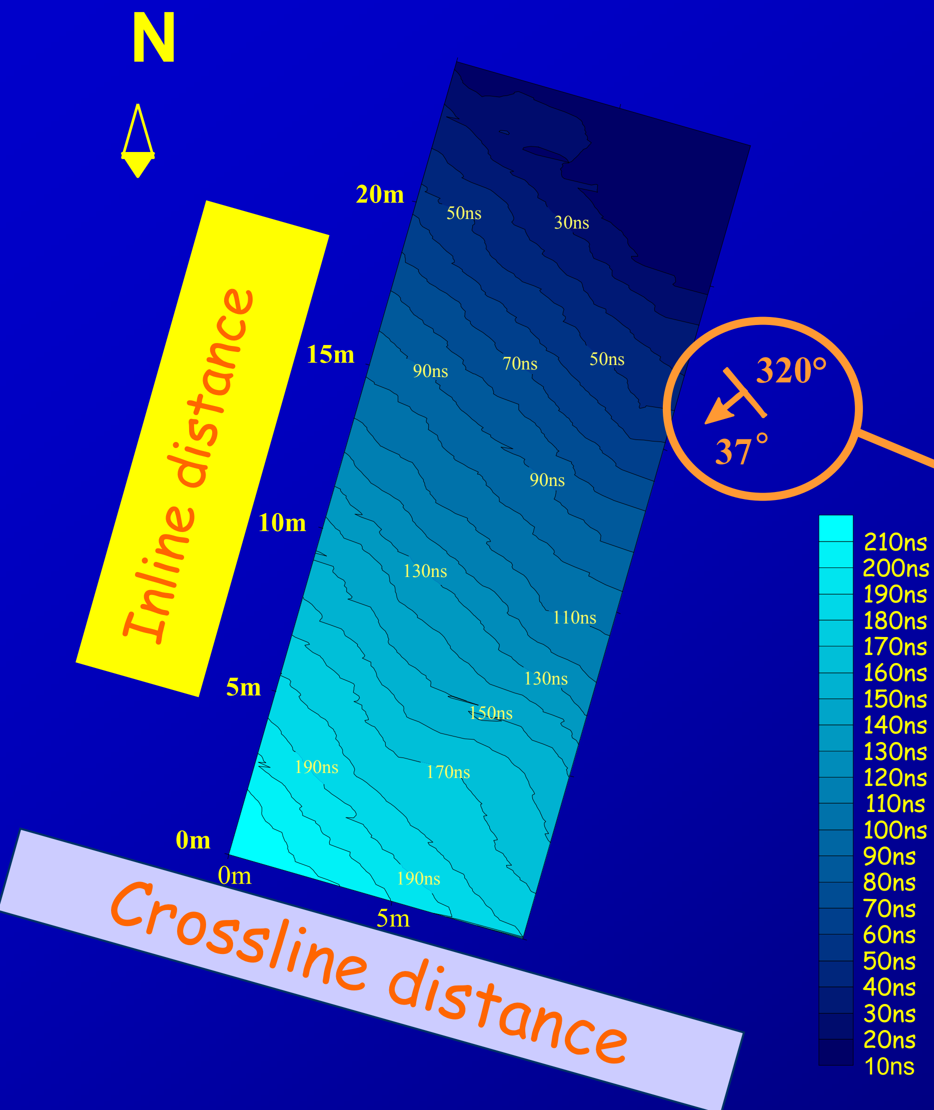
3D reconstruction and interpretation



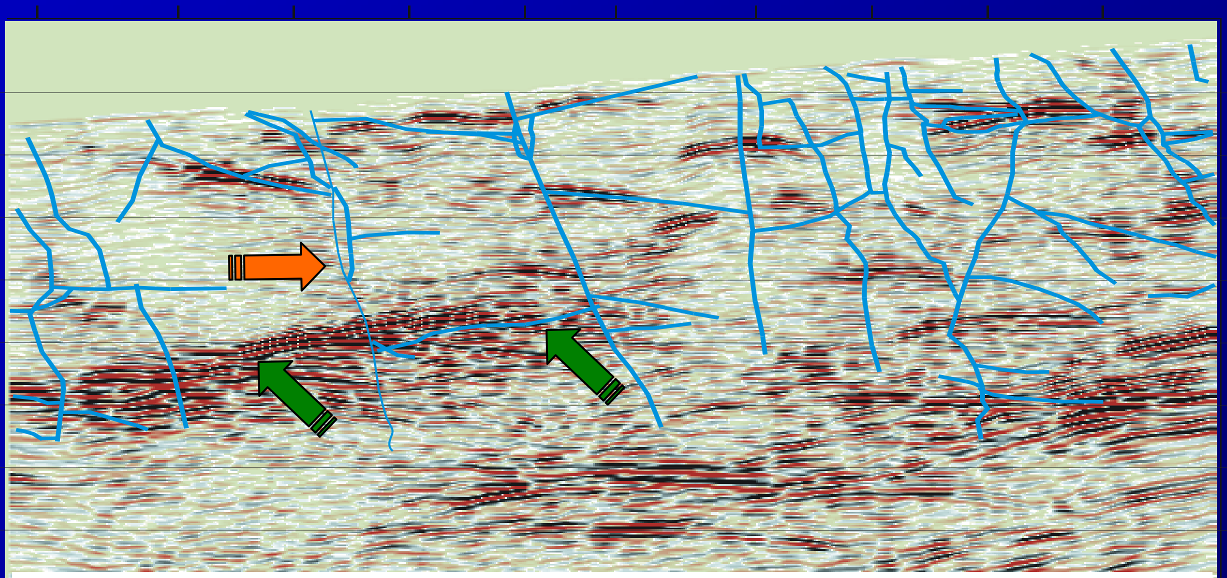
Example of ISOPACH SURFACE reconstruction (TWT in ns)

Precise geological attitude determination:

- strike
- dip
- direction of dip

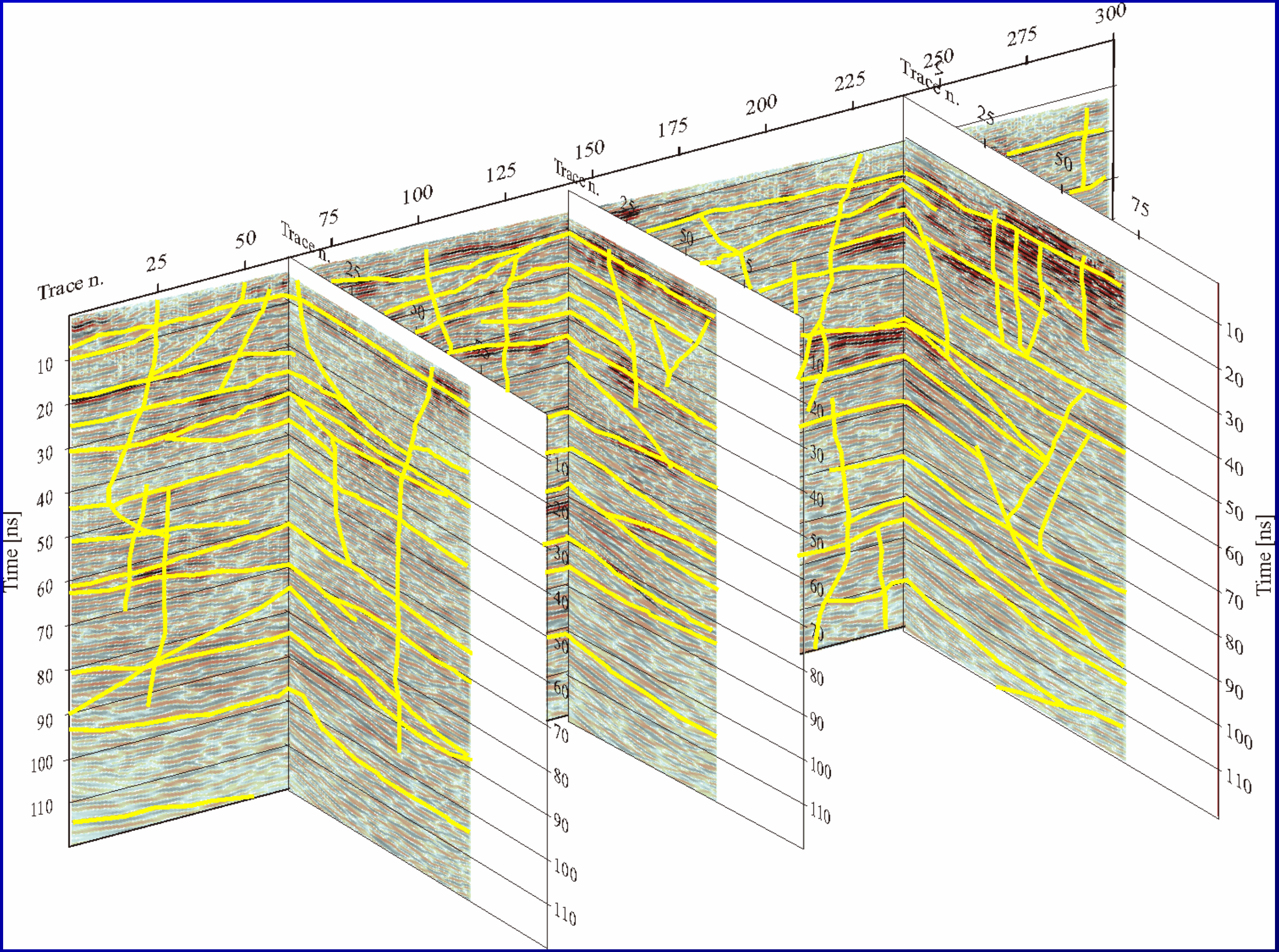
… and local variations

GPR interpretation and validation



Interpreted migrated section – 800 MHz

3D discontinuities reconstruction



Surface GPR Constrains and Limits

1. Maximum reachable penetration depth (high conductivity sediments on surface)

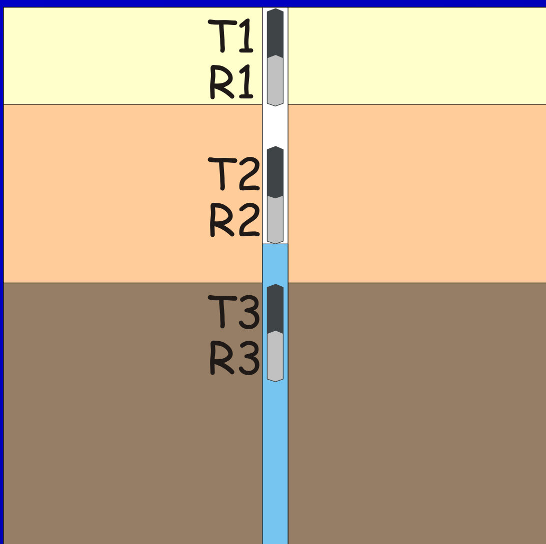
2. Good definition of single rock discontinuities but poor information on "global" rock mass characteristics

3. Resolution and imaging limits for:
   - very thin fractures (virtually no electromagnetic contrast)
   - vertical/sub-vertical discontinuities

To overcome some of these limits… GPR tomography

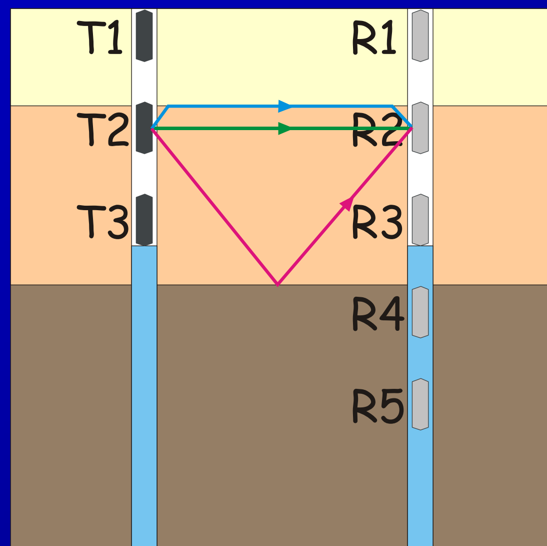
Borehole GPR Data acquisition methods

Reflection



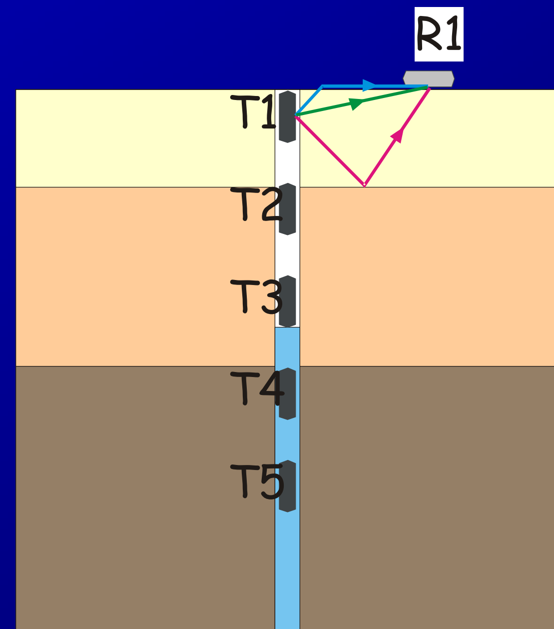
T and R into the same borehole

Tomography



T and R into different boreholes

VRP

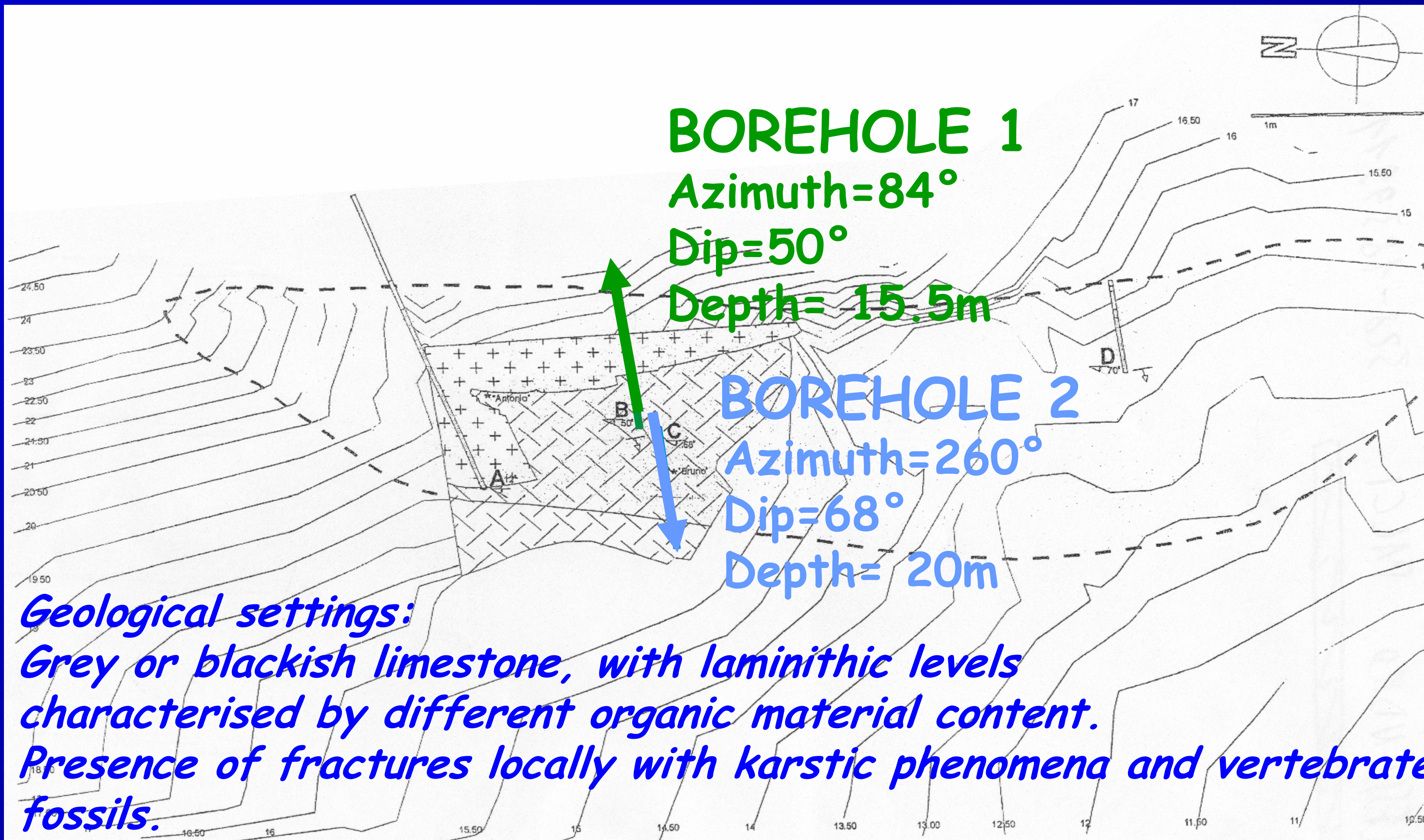


T into a borehole
R on the surface

Borehole GPR measurements: Tomography

A Borehole GPR Tomography example

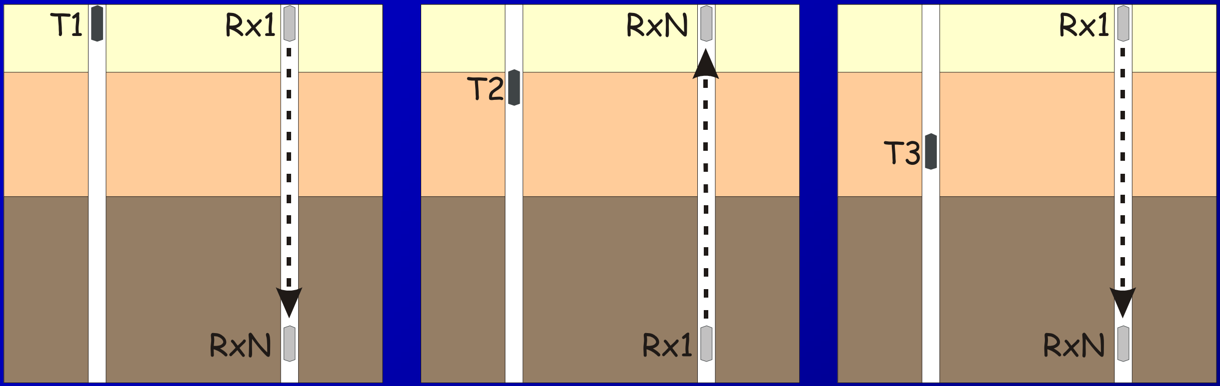
Boreholes Location Map

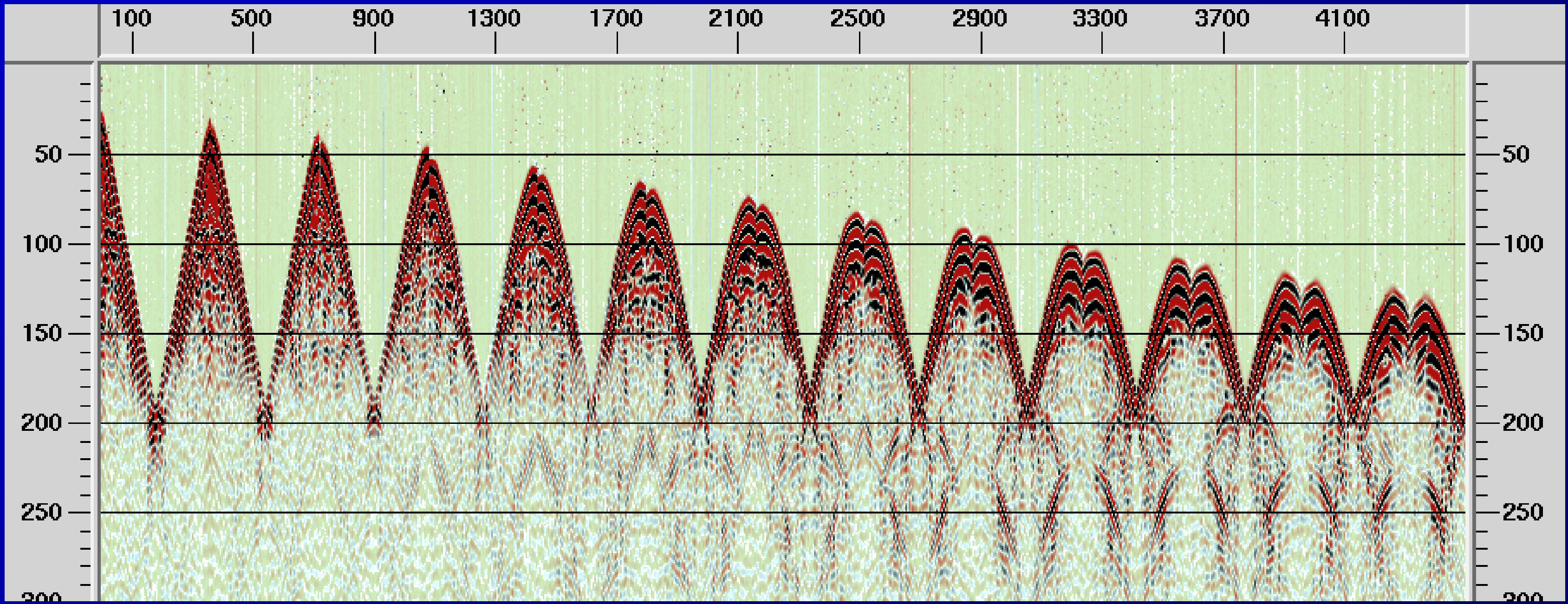


Geological settings:
Grey or blackish limestone, with laminithic levels characterised by different organic material content.
Presence of fractures locally with karstic phenomena and vertebrate fossils.

A Borehole GPR Tomography example

Example of borehole GPR tomography acquisition scheme:
Tx increment = 50cm
Rx increment = 10cm





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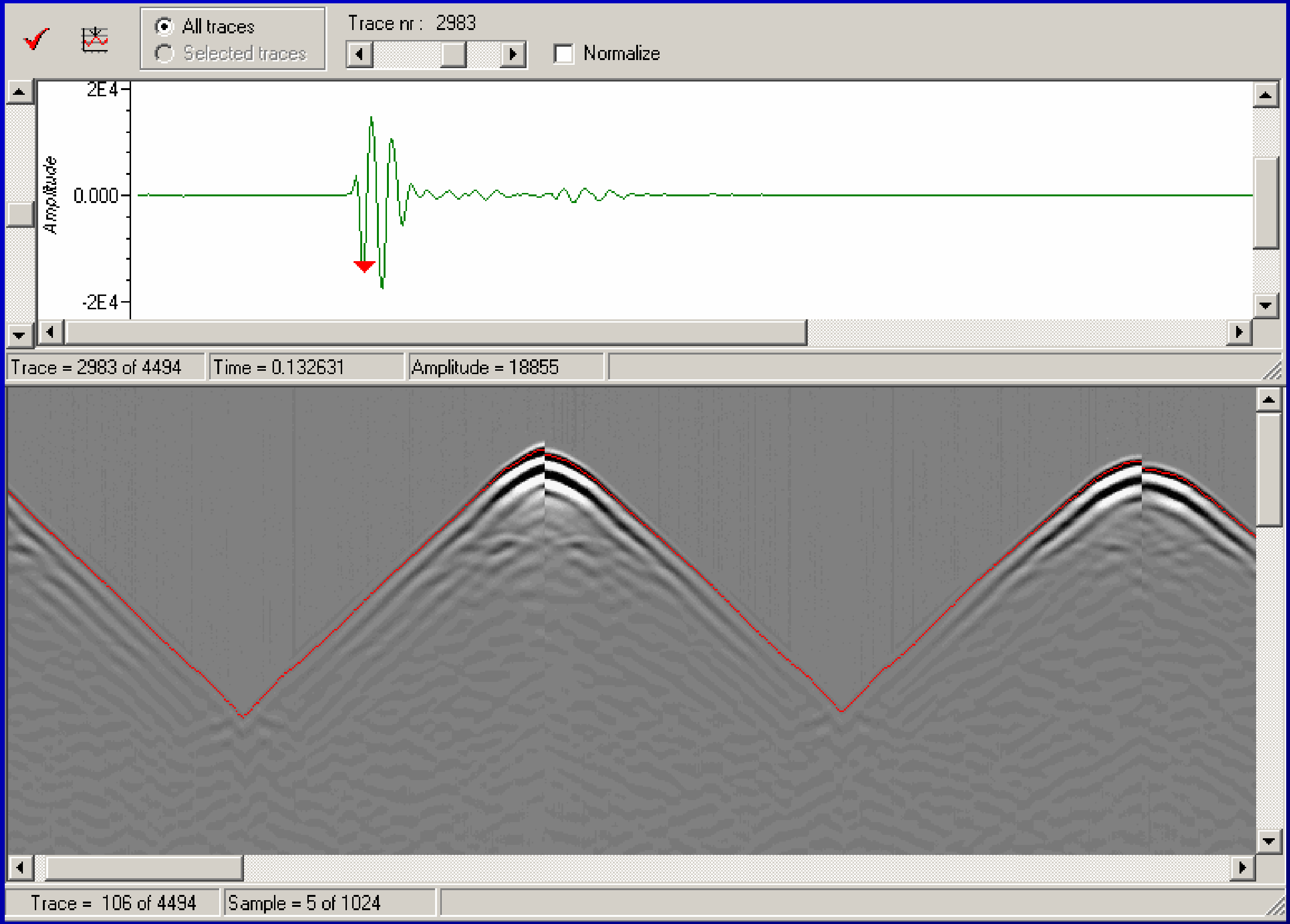
A Borehole GPR Tomography example



First break picking

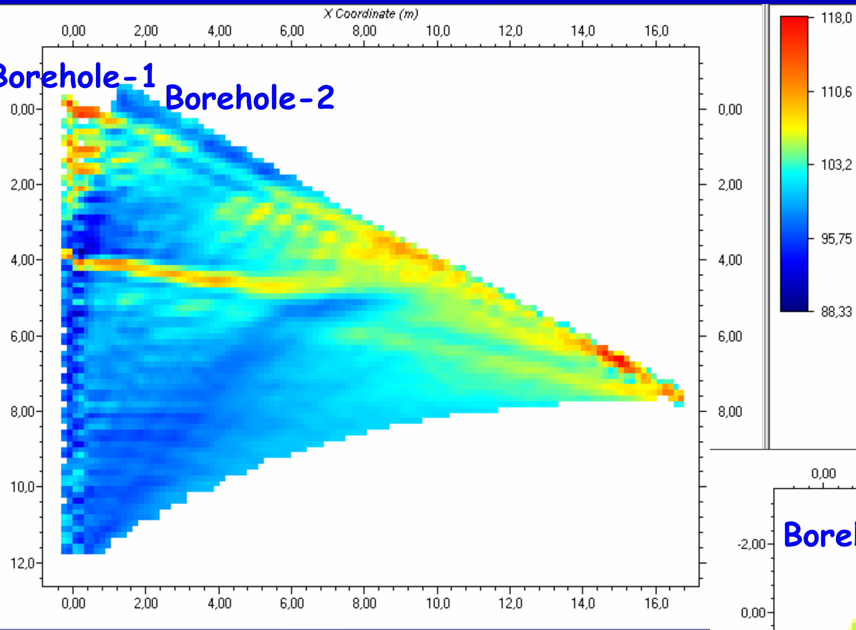
Traveltime inversion → velocity

Amplitude inversion → attenuation

A Borehole GPR Tomography example

Velocity Field

Velocity
[mm/ns]

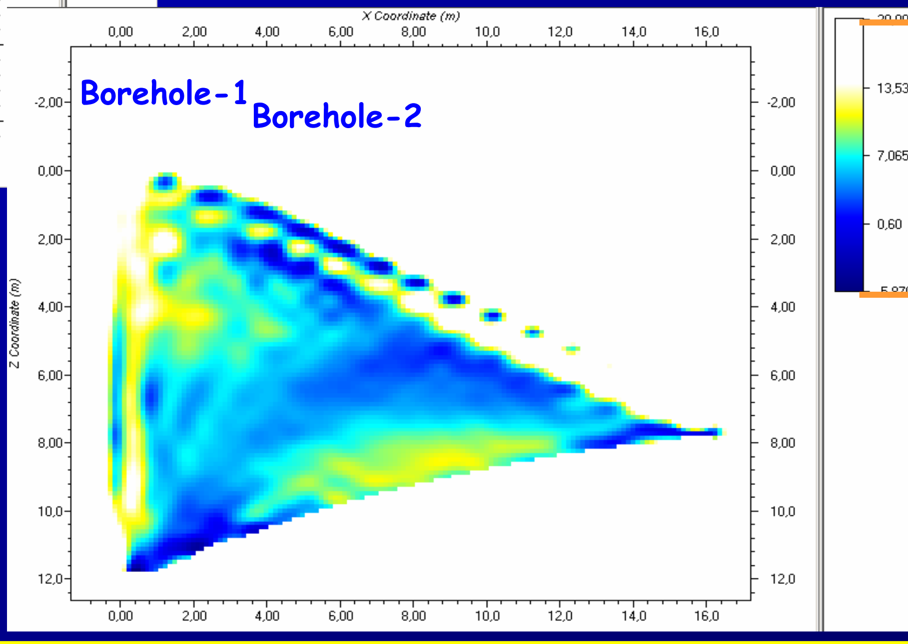


~12cm/ns

~9cm/ns

Attenuation field

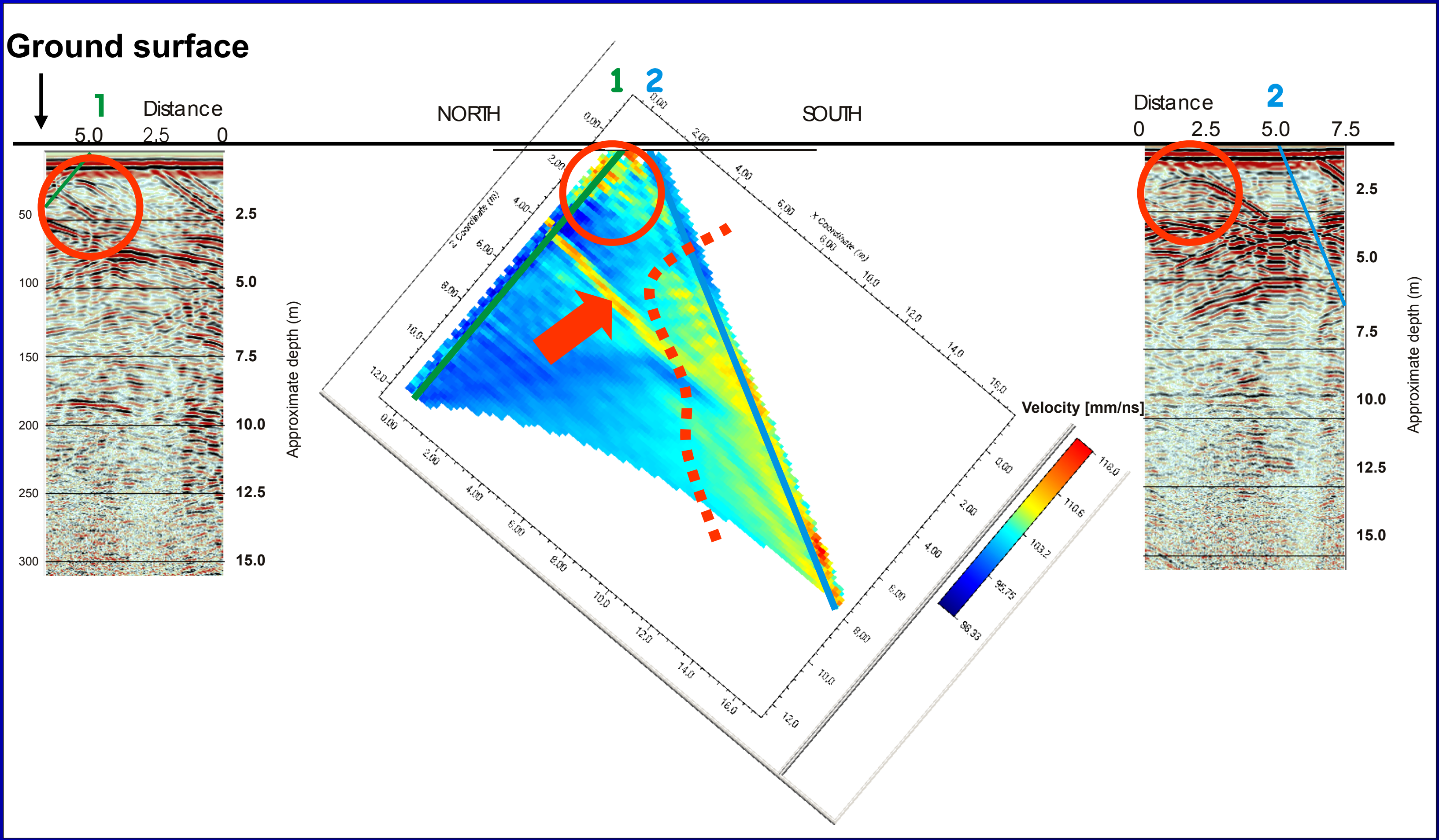
Attenuation
Db/m



~20Db

~6Db

A Borehole GPR Tomography example



An integrated approach: seismic

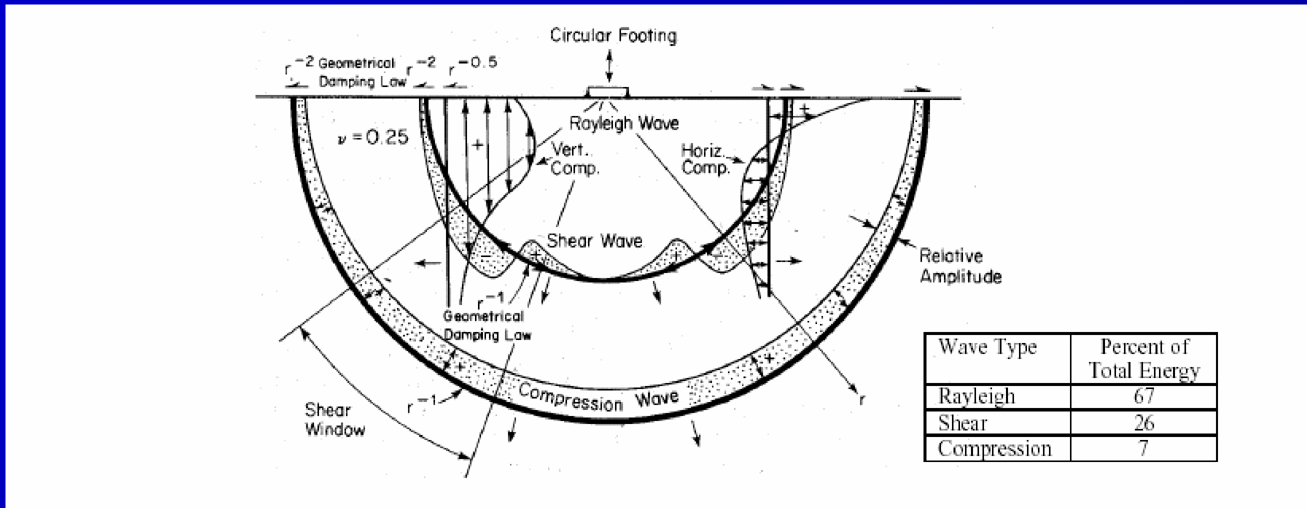
MAIN OBJECTIVE:

**Definition of “global” rock mass parameters useful for geologica
hydrogeological, geomechanical, environmental problems**

Which method?
Refraction – Reflection
Borehole – Tomography – 2D – 3D – P waves – S waves

…or more?

Why surface waves?



Wave Type	Percent of Total Energy
Rayleigh	67
Shear	26
Compression	7

1. The percentage of energy converted into Rayleigh waves is by far higher (67%) with respect to the energy involved in the P (7%) and S (26%) wave generation

2. *Surface wave* amplitude depends on $\sqrt{r}$ and not on ***r*** (*body waves*)

Why surface waves?

3. Differently than the refraction method, surface wave analysis does not suffer for limitations due to the presence of possible velocity inversions

4. Rayleigh wave velocity is mainly influenced by the shear wave velocity – fundamental parameter for many geomechanical/geotechnical analyses

5. Applicable also with low impedance contrasts

6. Very simple acquisition and pre-processing required

7. Low overall costs

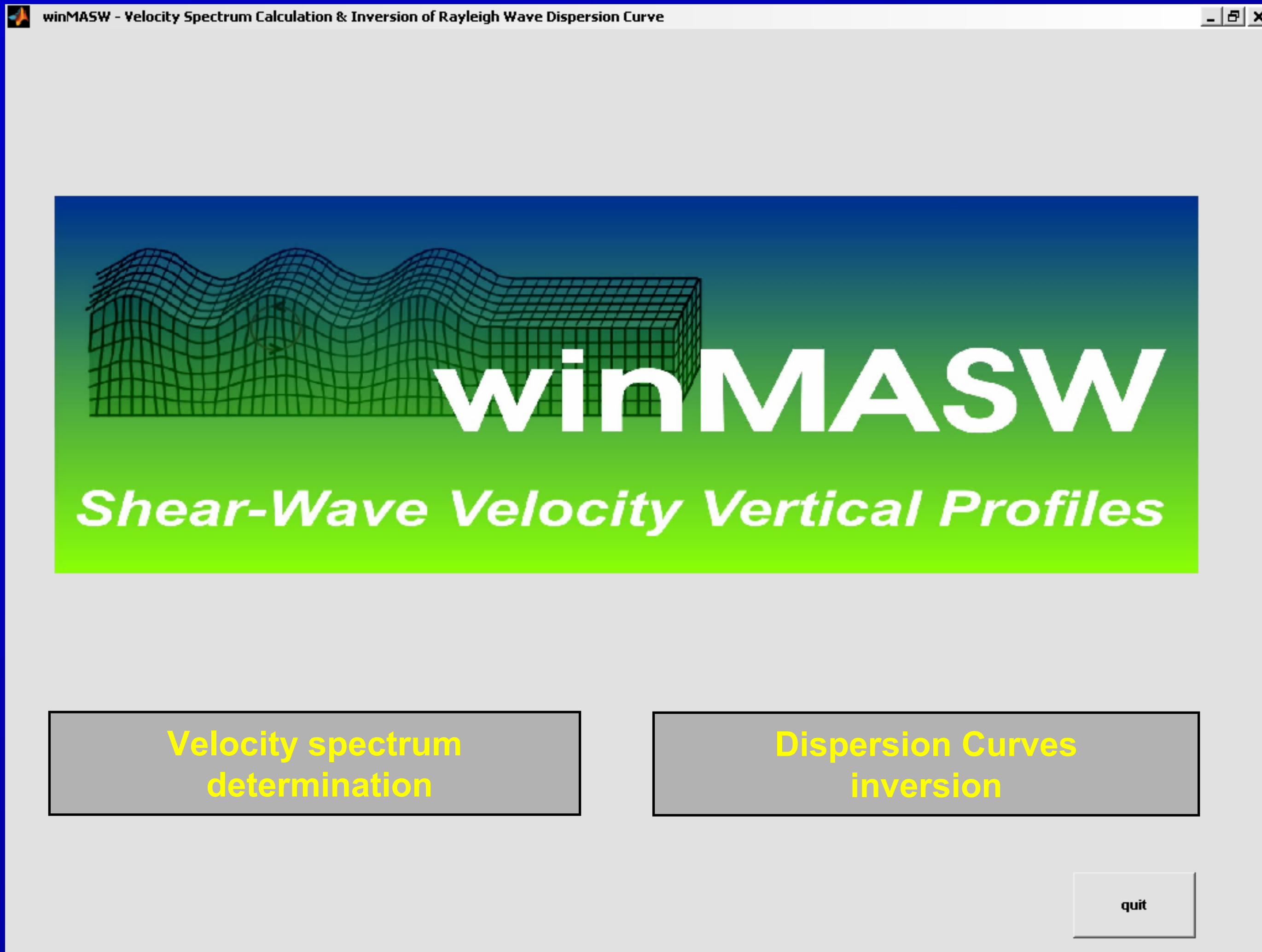
8. No "a-priori" constrains

MASW: Two steps

1. Dispersion curve picking

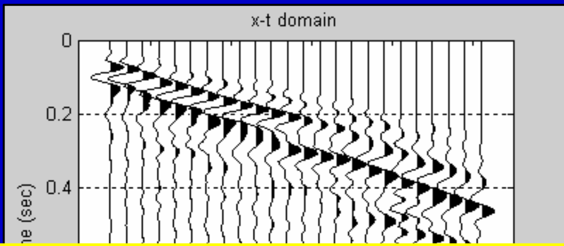
2. Dispersion curve inversion

A new implemented program

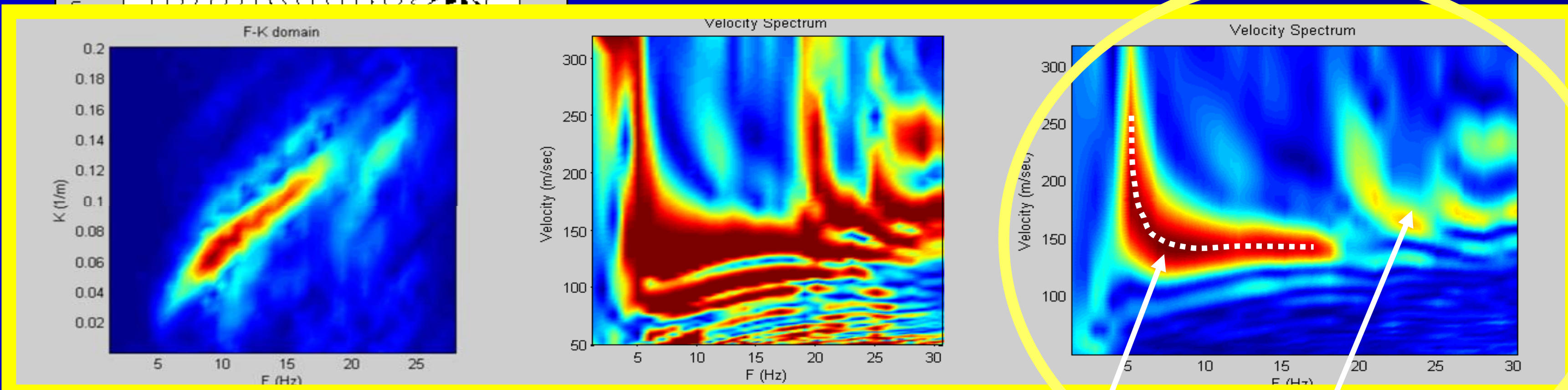


Dispersion curves determination and picking

24 traces, bandpass filtered (0-3-50-70 Hz) and offset balanced



Common-shot gather



F-K

τ-p

Principal mode

Phase Shift

Higher modes

A Phase Shift method was selected and applied to data according to an adopted velocit
A sum is then performed for each considered frequency
(see e. g. Park et al., 1998, SEG, Expanded Abstracts, 1377-1380)

Dispersion curves inversion

<u>Main problem</u>: it is a multi-modal problem and common linear methods typically strongly depend on the initial model

Genetic Algorithms for Surface Wave Inversion

It is a *global search tool* able to *explore* a **<u>wide search space</u>** and *exploit* the obtained information starting with very low constrains and required assumptions.

The algorithm can identify a mean model (and not only the "last" model) and calculates the standard deviations for each considered variable.

For further details see e.g.:

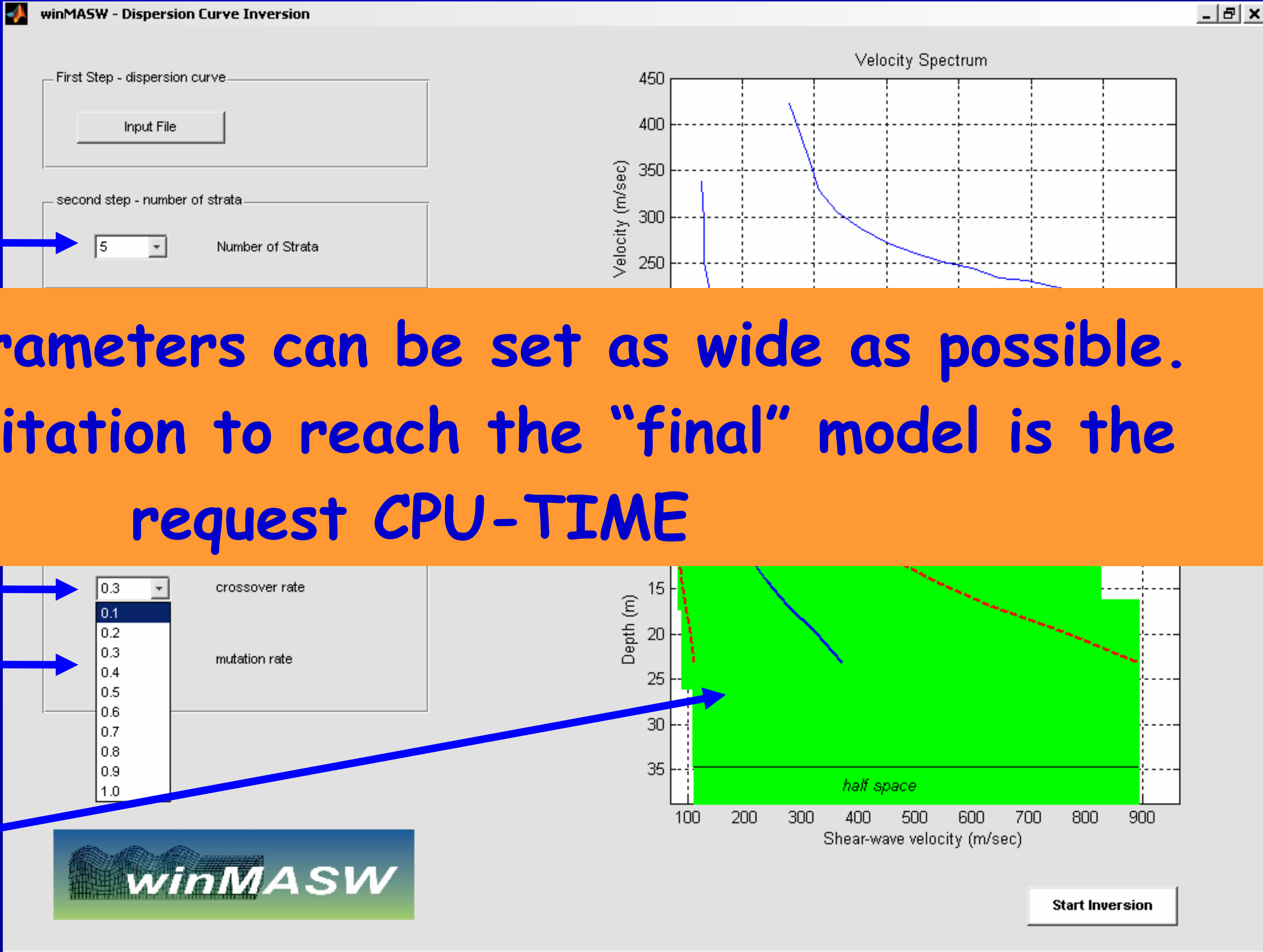
Xia J., et al., 2004. Utilization of High-Frequency Rayleigh Waves in Near-Surface Geophysics, The Leading Edge, Vol. 23, No. 8, 753-759.

Dal Moro G., et al., 2005. Rayleigh Wave Dispersion Curve Inversion via Genetic Algorithms and Marginal Posterior Probability Density Estimation, submitted to the Journal of Applied Geophysics.

Dispersion curves inversion: parameters

Fixing boundaries of the search space for all the chosen variables

Number of strata



All these parameters can be set as wide as possible. The only limitation to reach the "final" model is the request CPU-TIME

Crossover rate

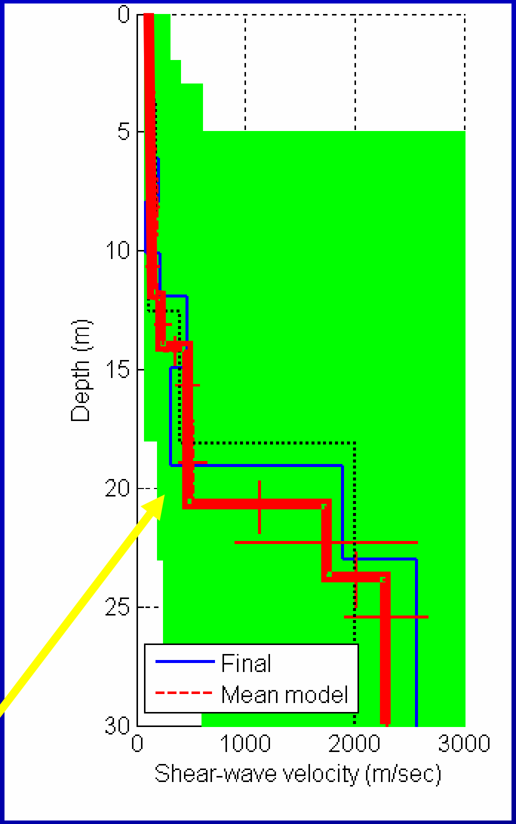
Mutation rate

Velocity range

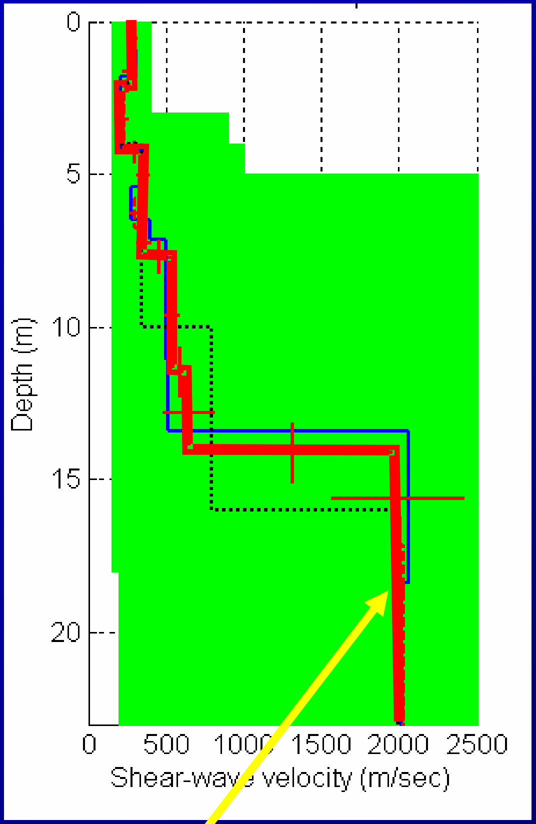
Dispersion curves inversion

The inversion procedure is performed on several close seismic shots

SHOT 1



SHOT 12

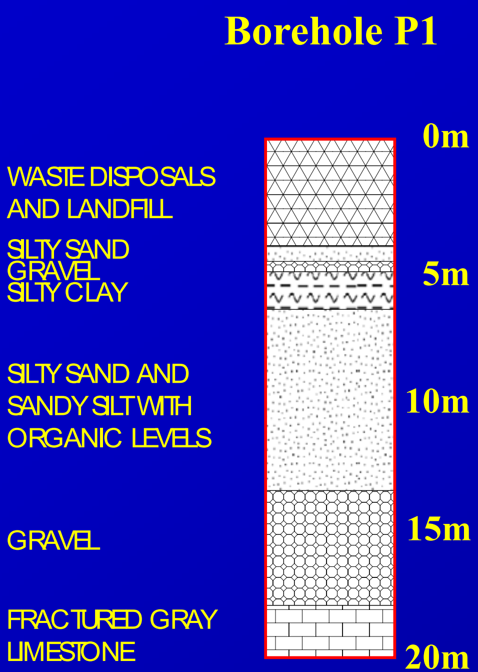


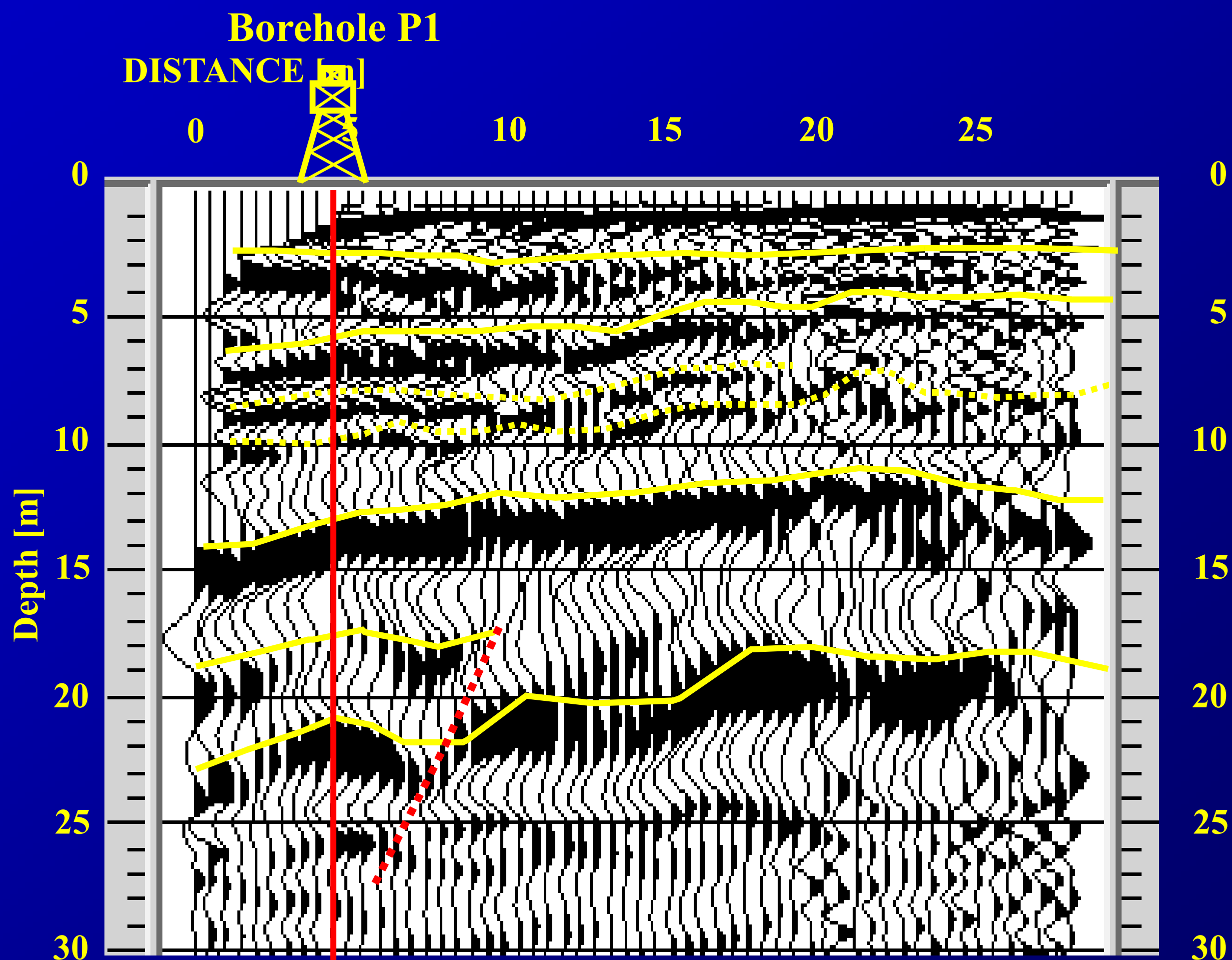
Search space

Mean (best reliable) velocity model for Shot-1

Mean (best reliable) velocity model for Shot-12

MASW-reflection seismic comparison and validatio





Shear-wave depth converted reflection seismic section

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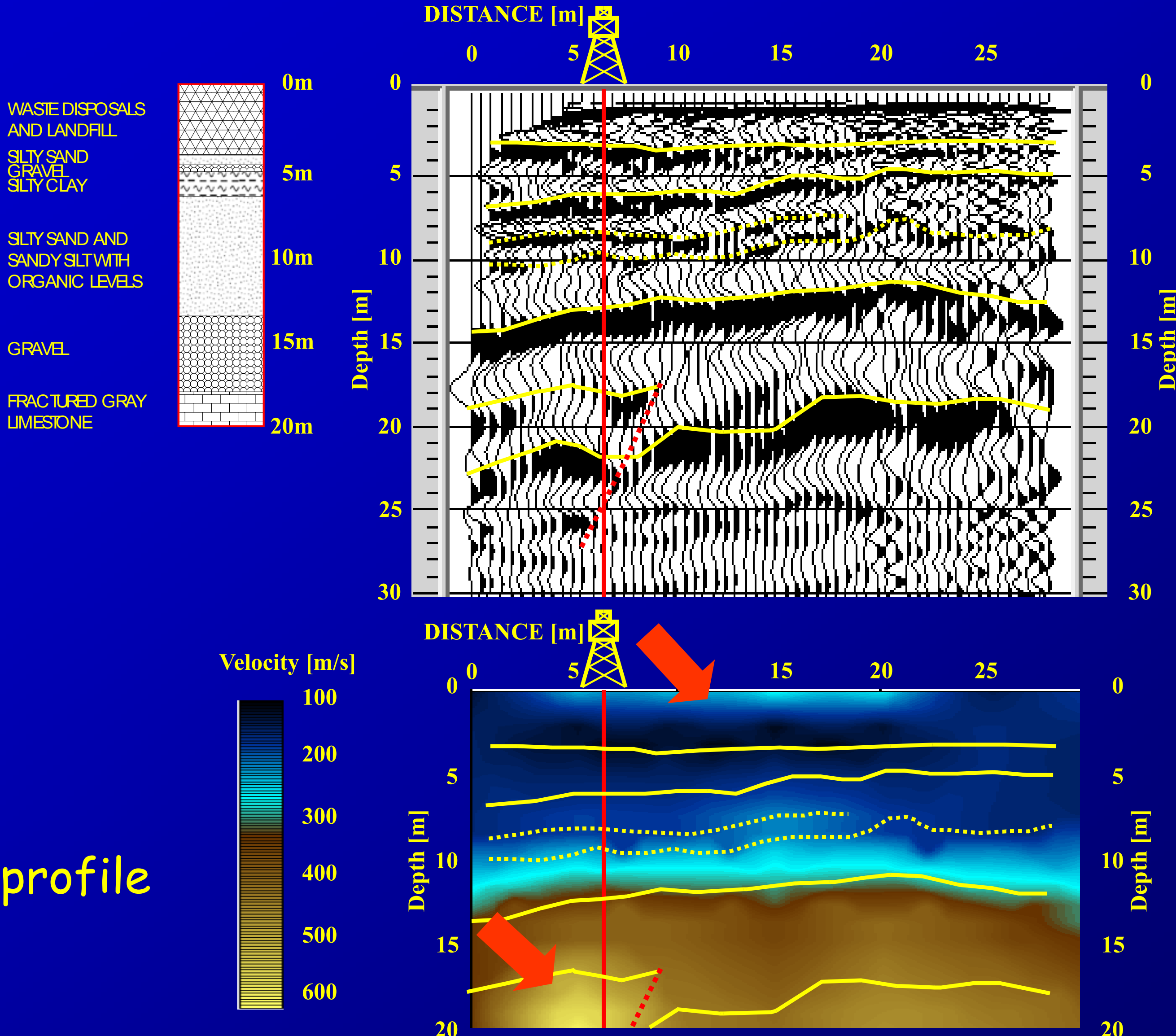

MASW
Velocity profile

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Conclusions - Remarks

Geophysisics can give important information with different scale levels that are very difficult to achieve with direct methods.

GPR profiles and borehole tomography allow unambiguous high resolution 2D and 3D imaging of bedding planes, fractures, joints and cavities also in complex environments.

This techniques are particularly efficient if performed with antennas directly coupled with the rock surface and with a required penetration depth not exceeding 20-30m or a similar distance between boreholes.

In order to overcome this constrain, and to assess some "global" rock mass parameters Seismic MASW techniques can be very useful in terms of costs and reliability of results.

Further efforts are required to obtain more detailed quantitative information.

Thank you for the attention!

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