

*High-resolution geophysics for  
porosity and fracture network  
assessment in shallow geothermal  
applications*

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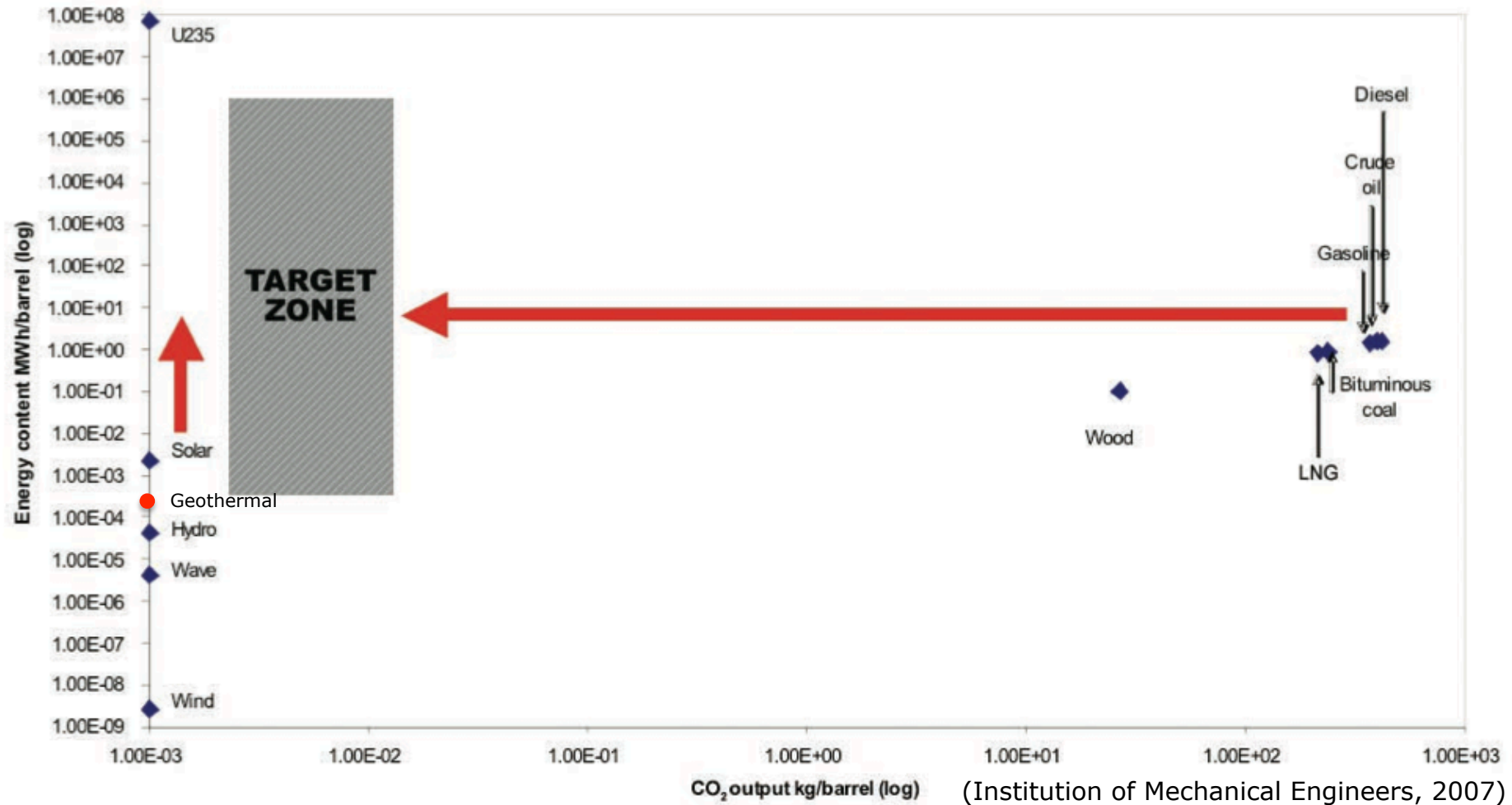
*University of Trieste*

*Dept. of Mathematics and Earth Sciences*

*Exploration Geophysics Group*

*Veli Losinj – XIV ECSAC Conference – July 25-37, 2014*

### Energy content vs CO<sub>2</sub> output



# OUTLINE

## *Objectives*

*FRACTURES and GEOTHERMAL SYSTEMS*

*The SCALE PROBLEM*

*The ENHANCEMENT CHALLENGE*

## *Methods*

*- SEISMICS: Reflection/Multi channel Analysis of Surface Waves – MASW*

*-2D and 2.5D Ground Penetrating Radar (GPR)*

*Electrical Resistivity Tomography (ERT) and magnetotellurics (MT)*

## *Examples of Results*

*1) Al – Lith geothermal area (SW Saudi Arabia) {MACRO}*

*2) Limestone outcrop (reservoir analogue) {MICRO}*

## *Concluding Remarks*

# *The role of Geophysics in Geothermal exploration*

Site Screening: downscaling workflow

Continental scale approach: Definition of interesting regions

Regional scale: broad-scale Geophysical studies

Local scale: Intermediate-scale Geophysical studies

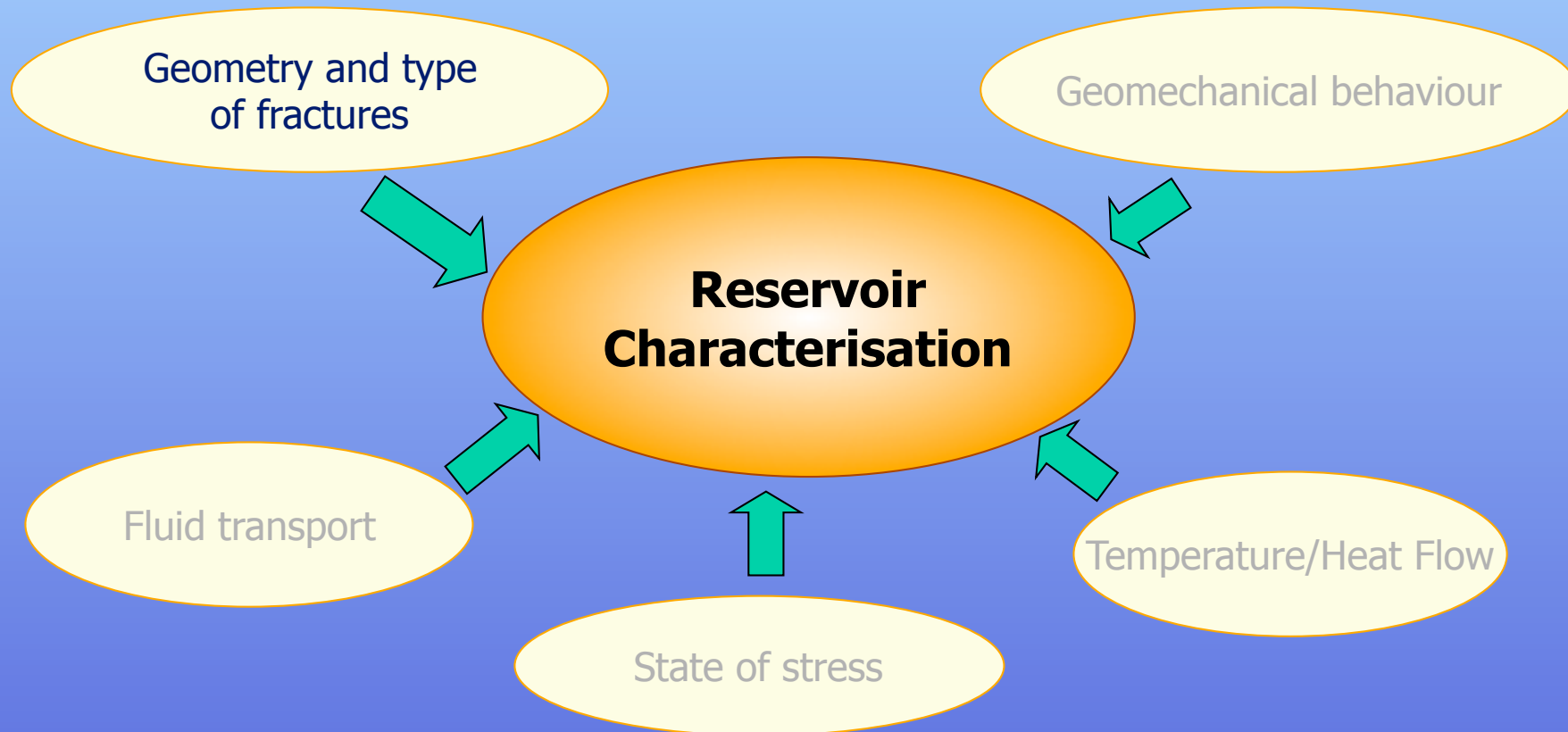
Reservoir scale: Well investigation and fine-scale geophysics



Different workflows in different geo-environments: volcanic, crystalline and sedimentary

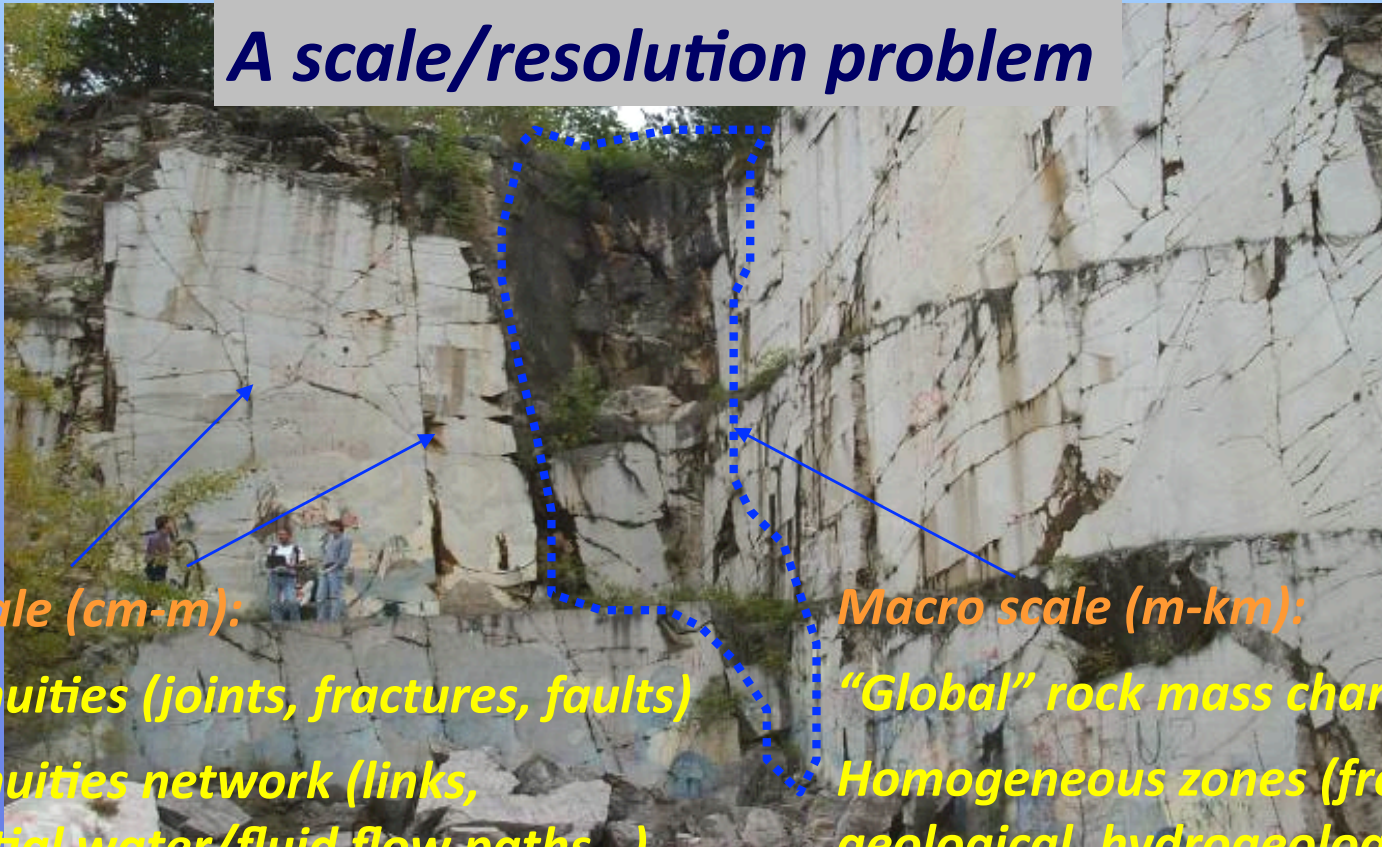


# Fracture detection



# Statement of the problem

## A scale/resolution problem



### *Micro scale (cm-m):*

*Discontinuities (joints, fractures, faults)*

*Discontinuities network (links, preferential water/fluid flow paths...)*

*Filling material*

*Voids (Karstic phenomena, open fractures)*

*Vertical and lateral lithological variations (layer/volume characteristics)*

### *Macro scale (m-km):*

*“Global” rock mass characteristics*

*Homogeneous zones (from geological, hydrogeological, geomechanical point of view)*

*Main discontinuities (large faults, main joints)*

*Voids (caves, tunnels)*

# **From the state of the art toward the future: Goals of exploration**

Characterization of host rock conditions: Mapping of permeability, temperature and stress

Data Integration

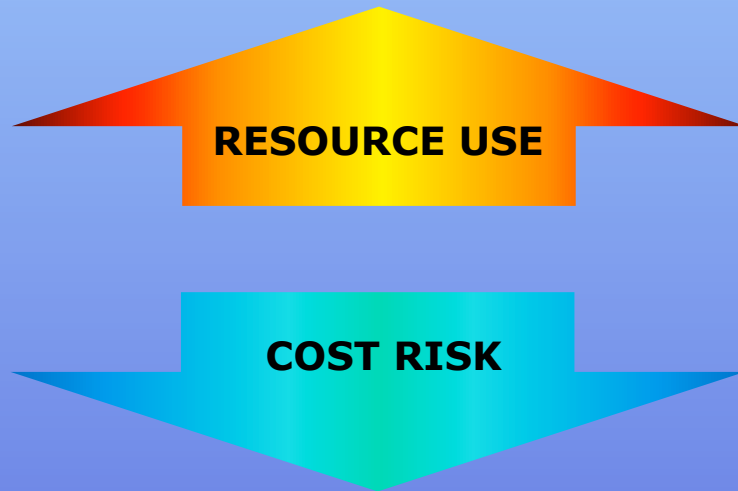
Improving imaging between wells

# The Enhancement challenge:

Extending the resources beyond a conventional use of geothermal resources requires the use of **non-conventional methods for exploring, developing and exploiting geothermal resources** that are not economically viable by conventional methods.

The final objective: development of a technology to produce electricity and/or heat from a basically ubiquitous resource - the internal heat of the Earth - in an economically viable manner relatively independent of site conditions.

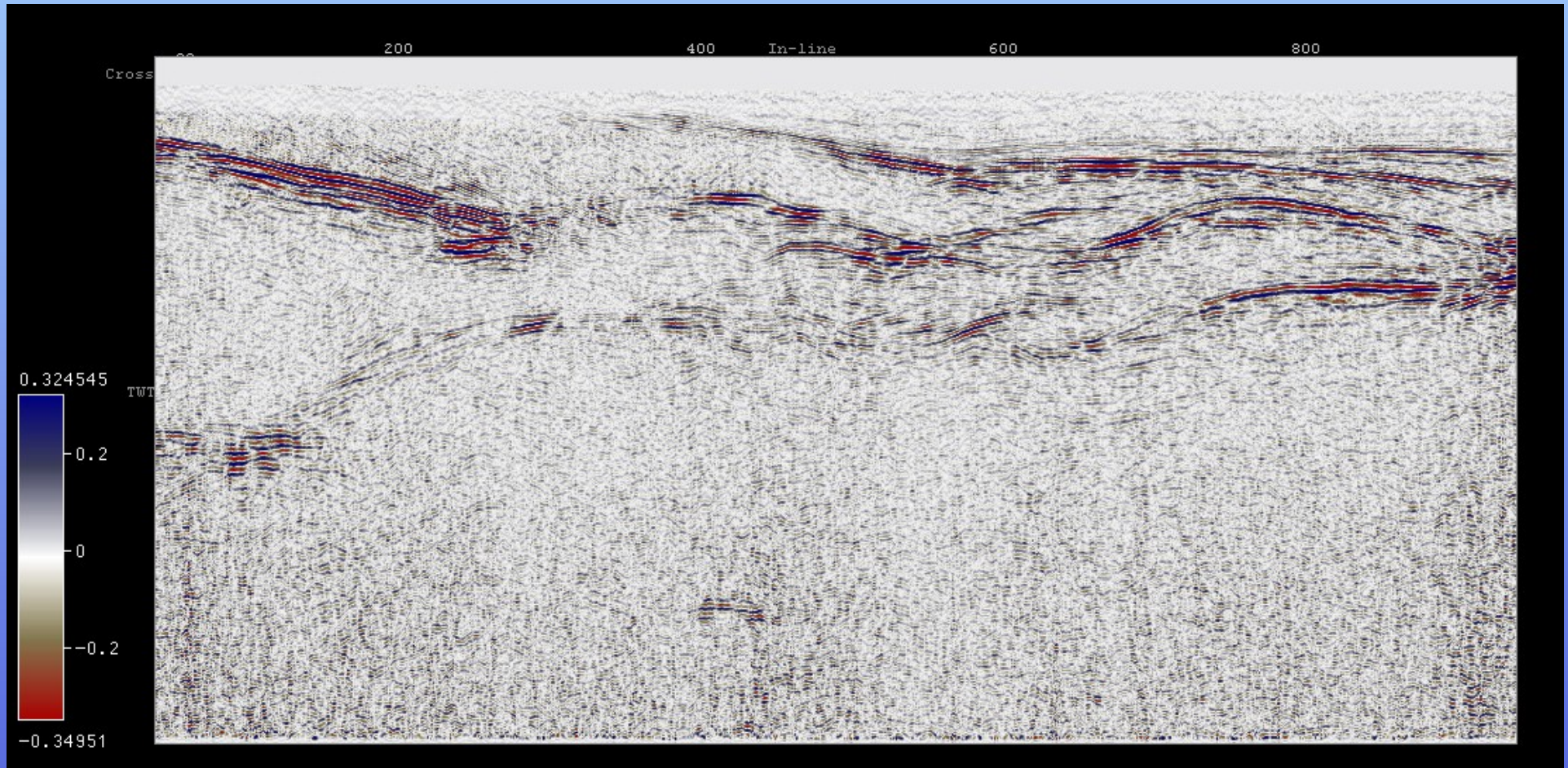
# The Enhancement challenge:



- exploration
- resource assessment
- resource management
- advanced drilling
- advanced stimulation
- efficient power cycles
- environmental impact



# MACRO SCALE (Km) Reflection Seismic



# Conventional indicator of fracturing/faulting at MACRO SCALE:

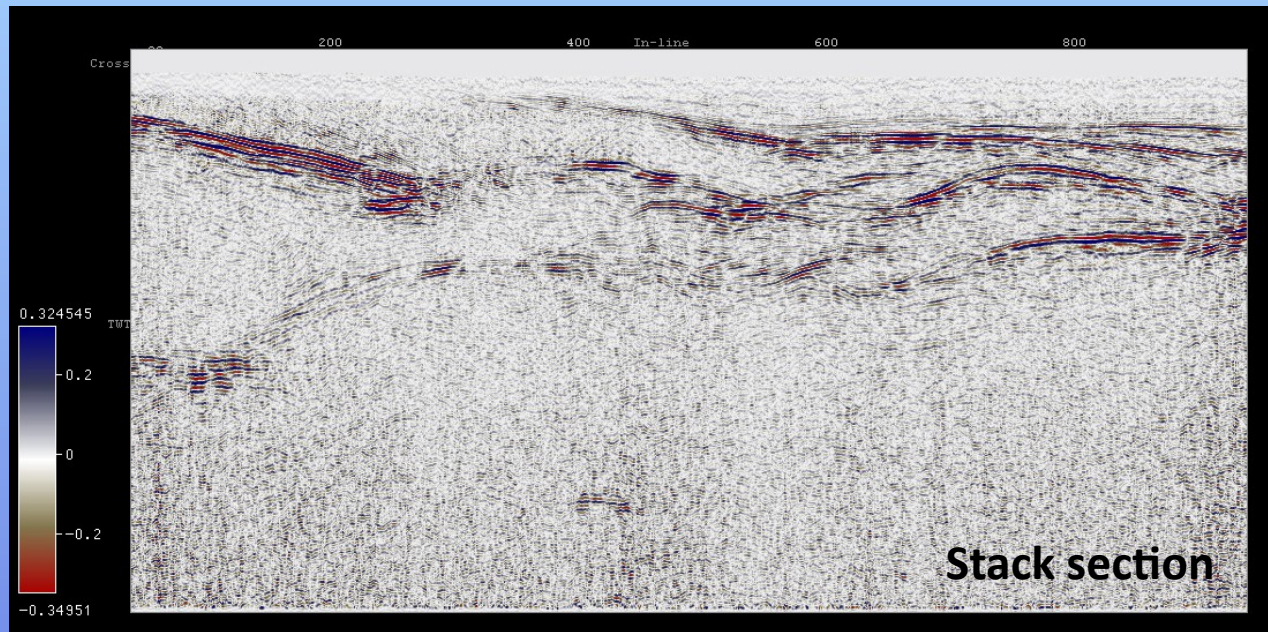
>> Level of seismicity

Drawbacks:

- Poor localization
- Poor characterization of fracture systems

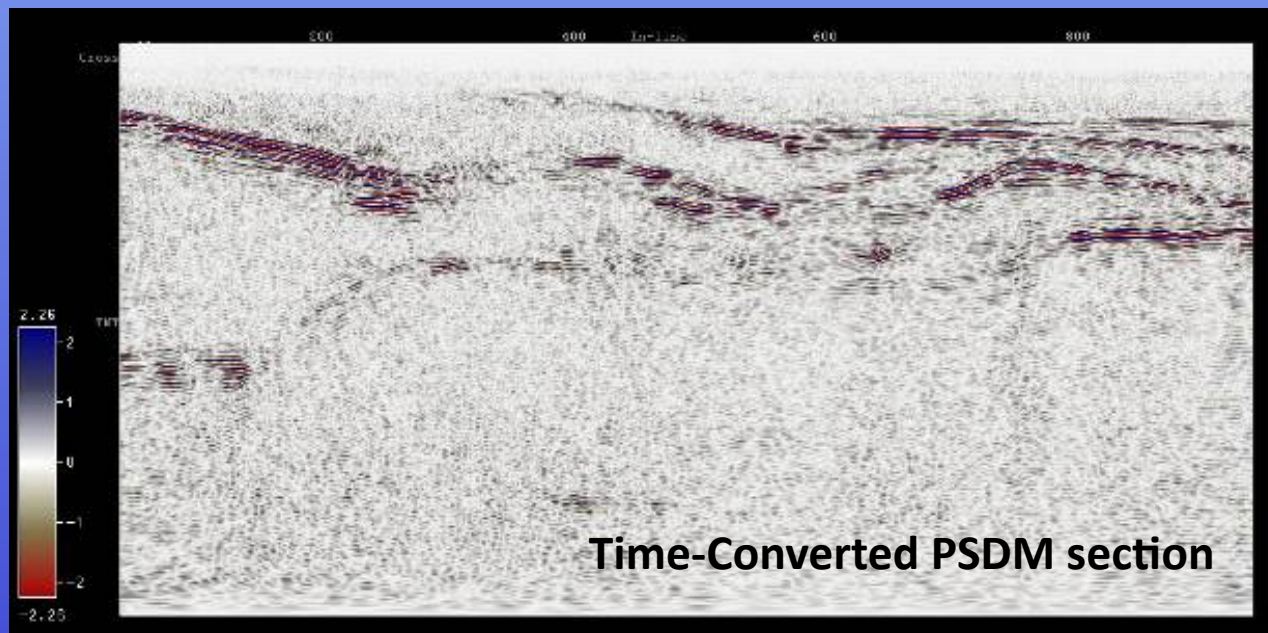


# MACRO SCALE (Km) Reflection Seismic



**EXAMPLE: 5Km 2D land  
seismic survey**

**Standard Processing**



**PSDM + Attributes + AVO**

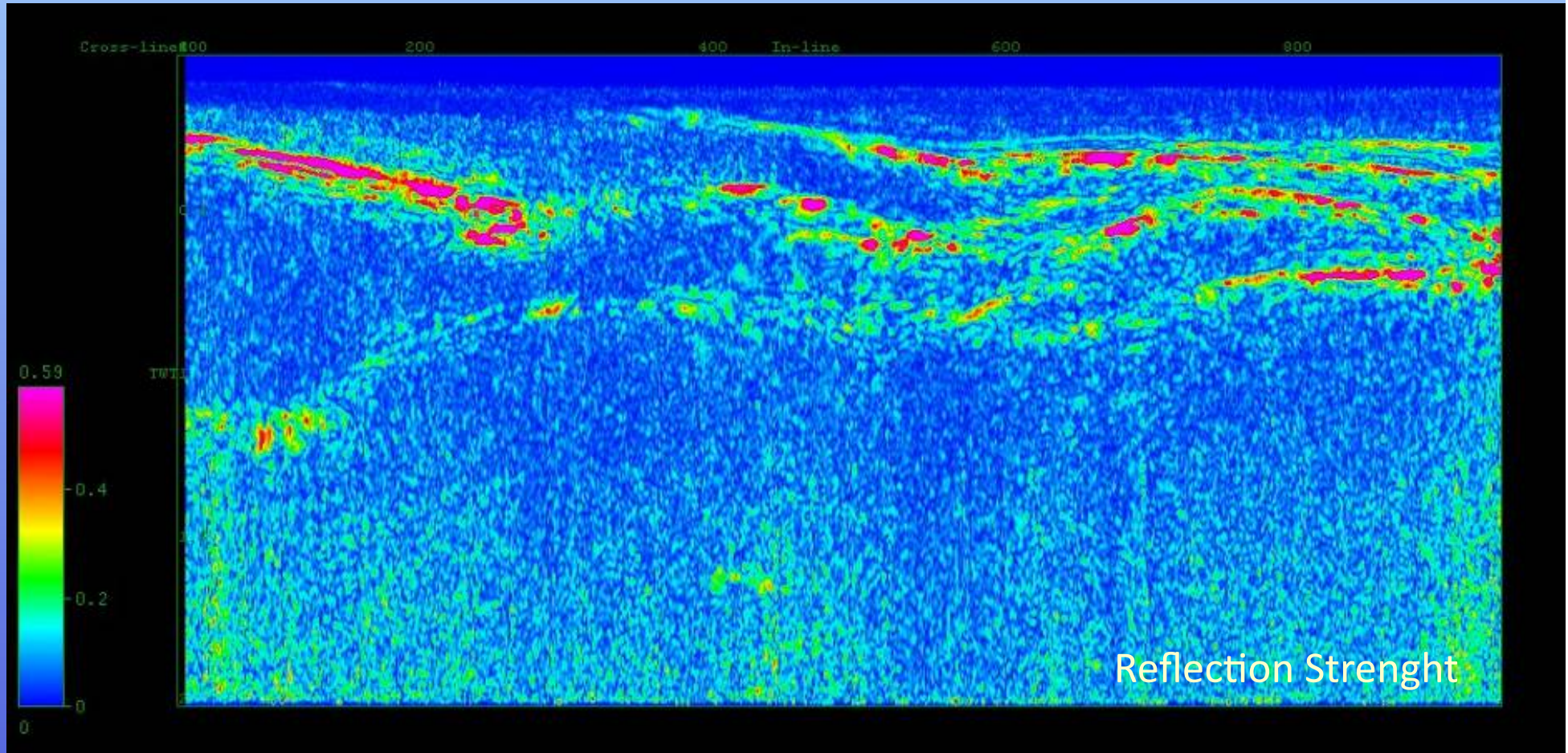
**1) Migration velocity  
analysis**

**2) Attribute Analysis**

**3) AVO/AVA**

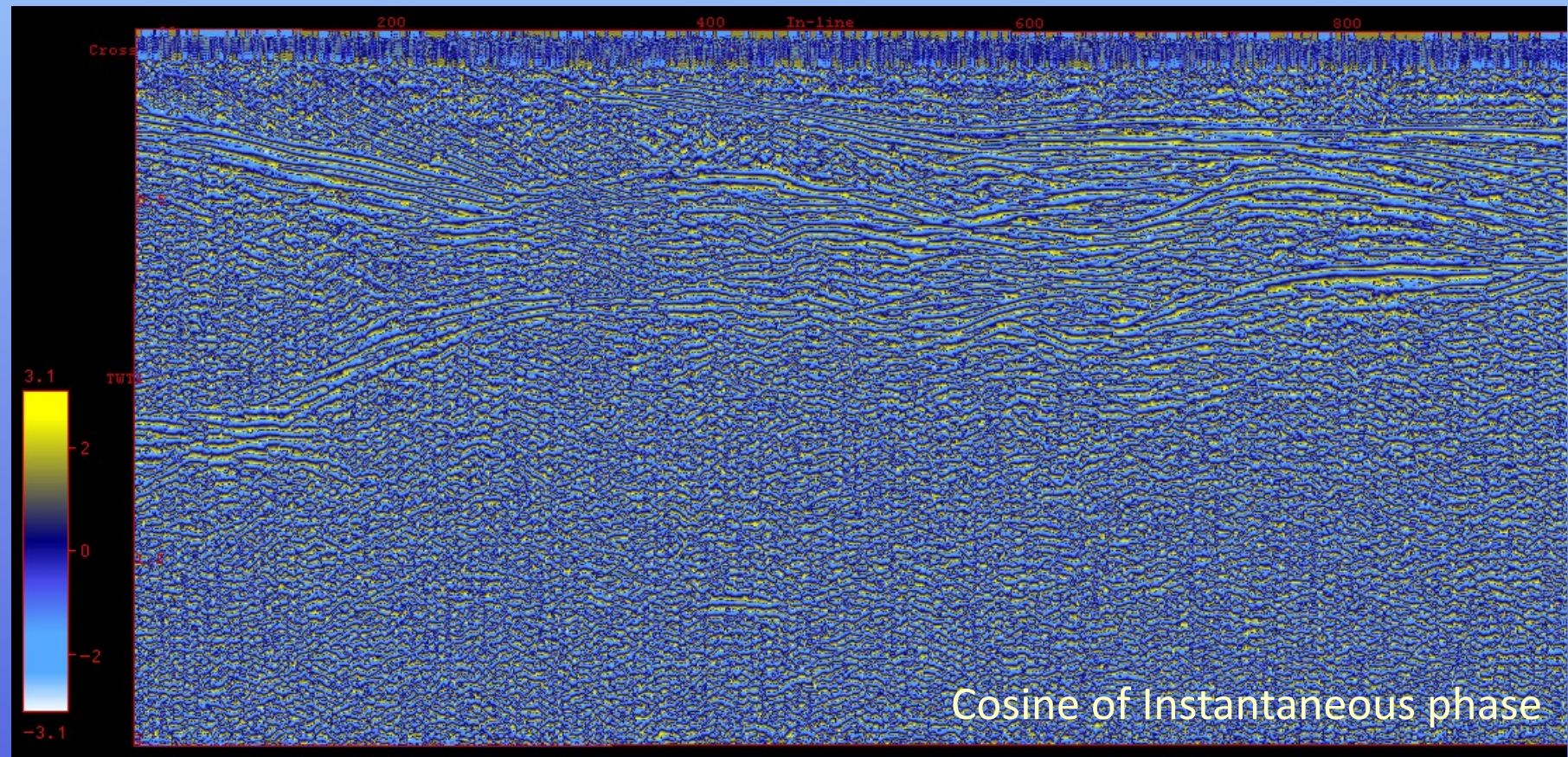


# MACRO SCALE (Km) Reflection Seismic



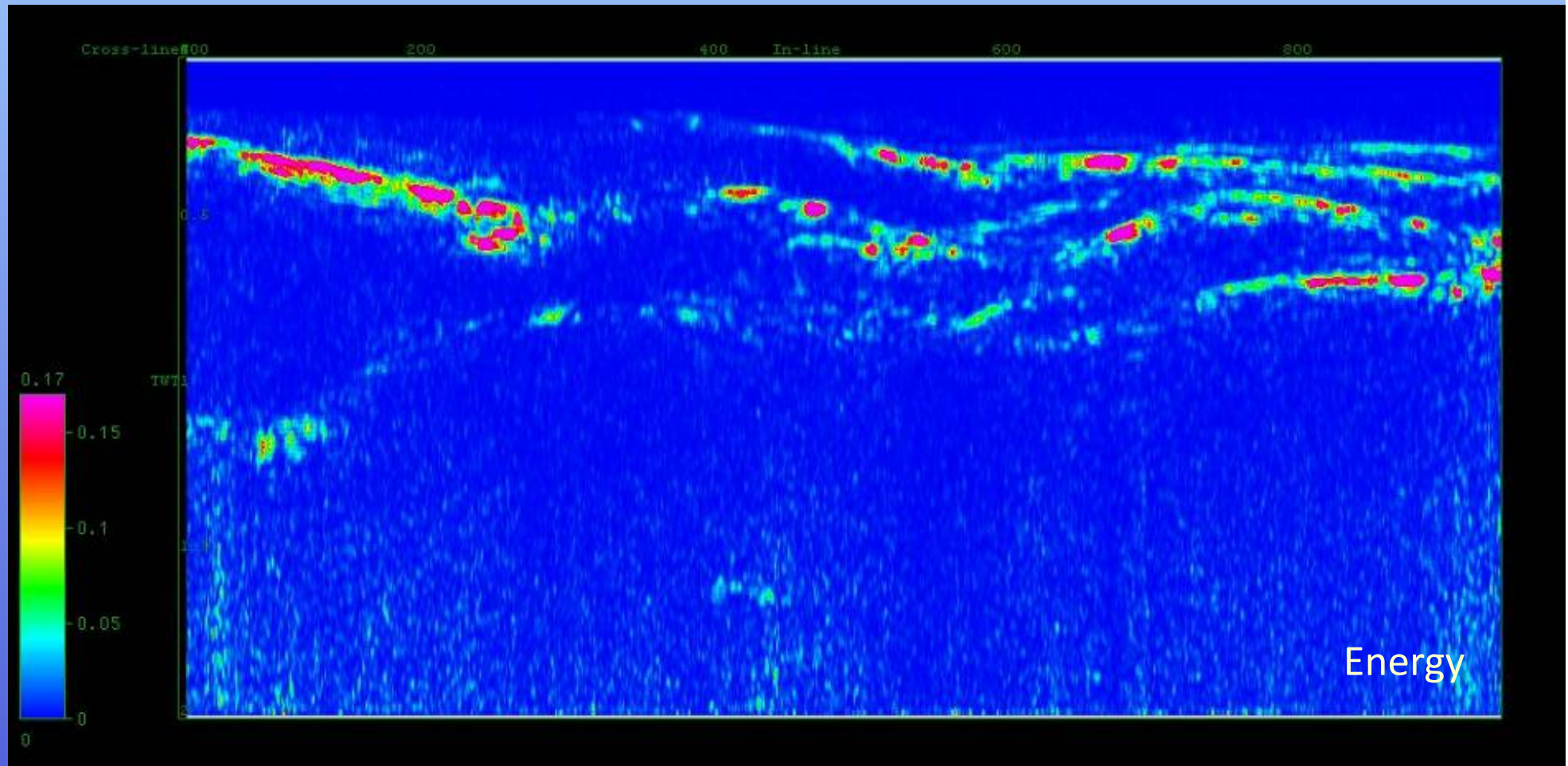


# MACRO SCALE (Km) Reflection Seismic



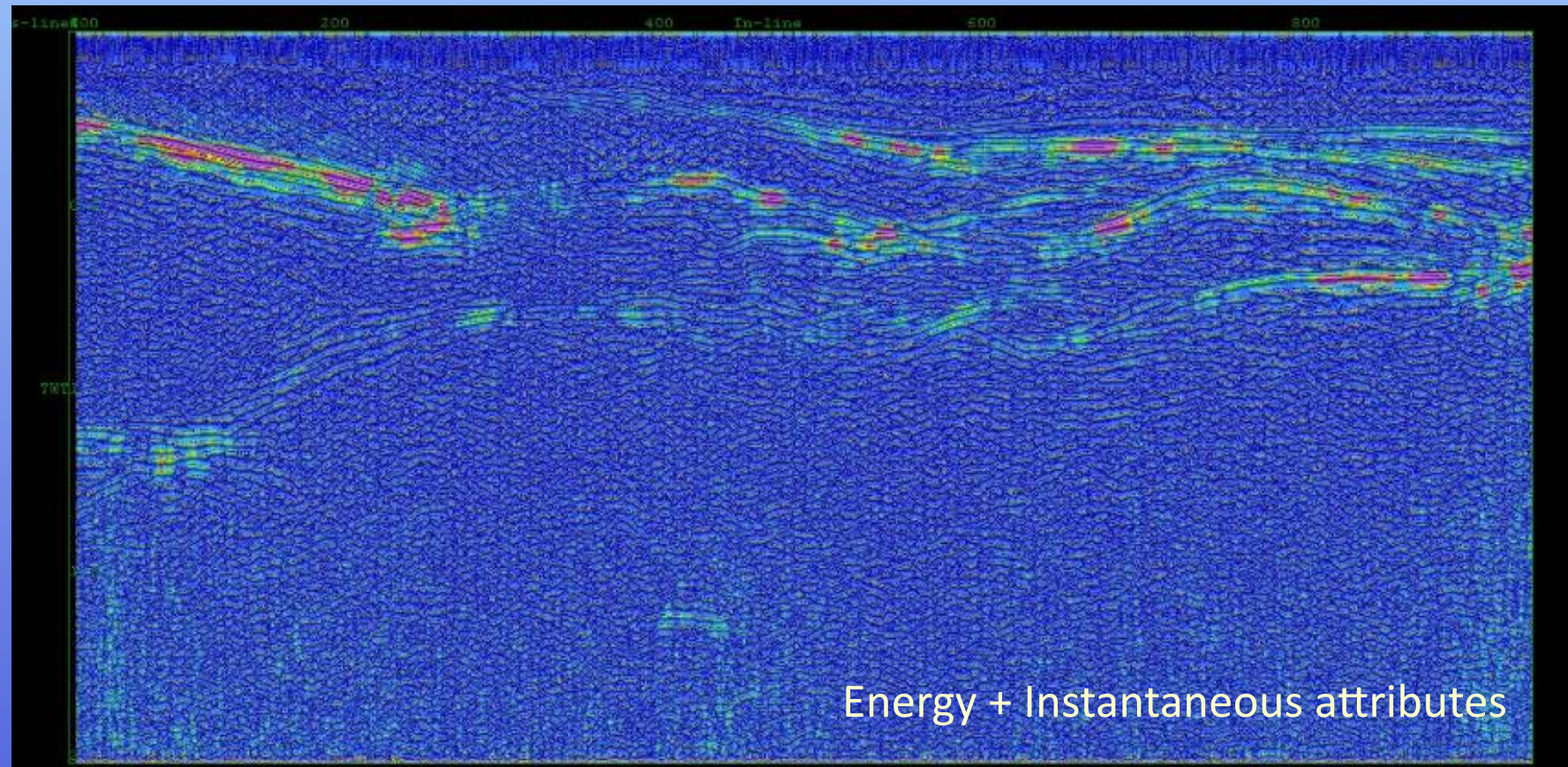


# MACRO SCALE (Km) Reflection Seismic



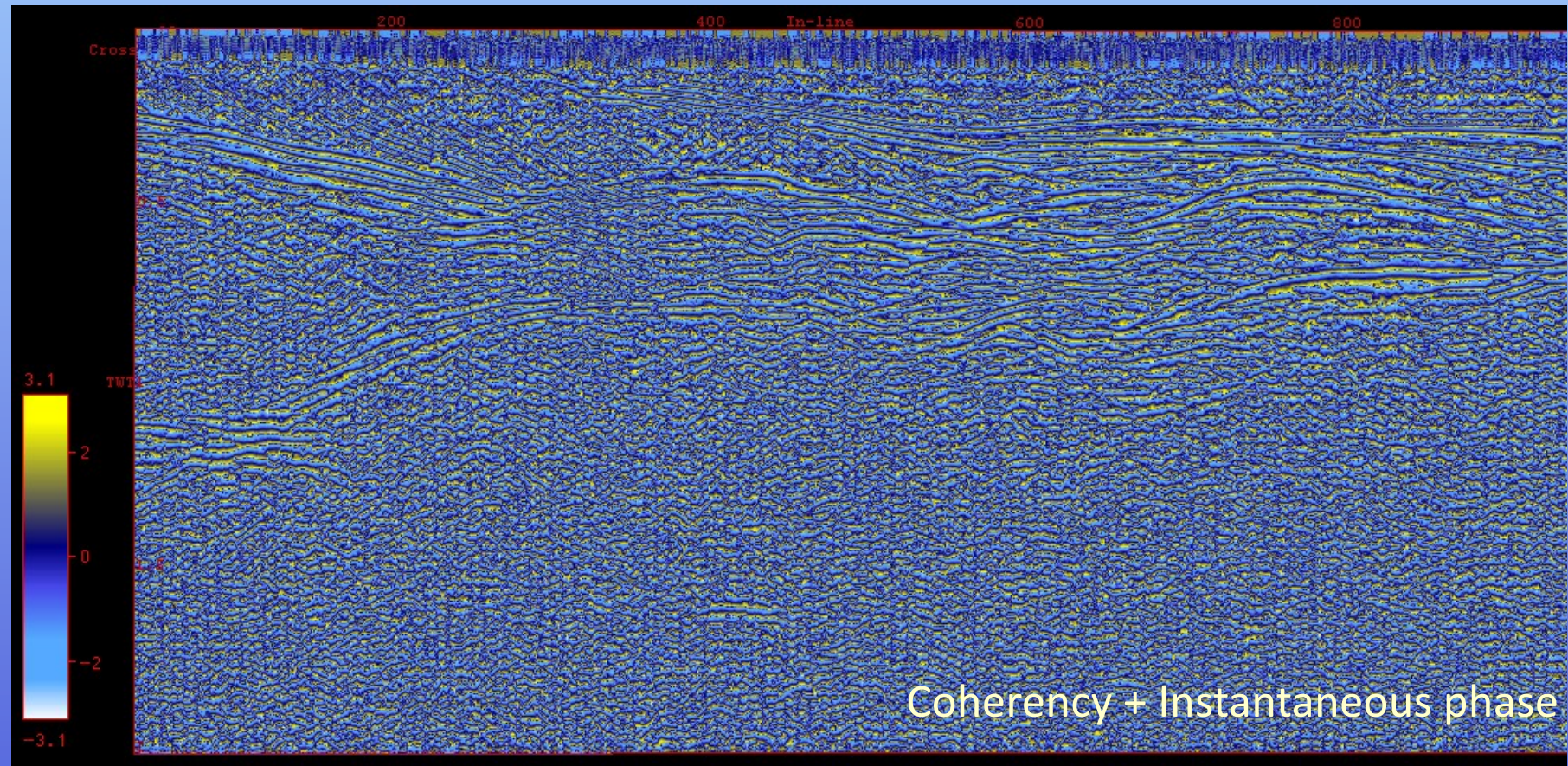


# MACRO SCALE (Km) Reflection Seismic





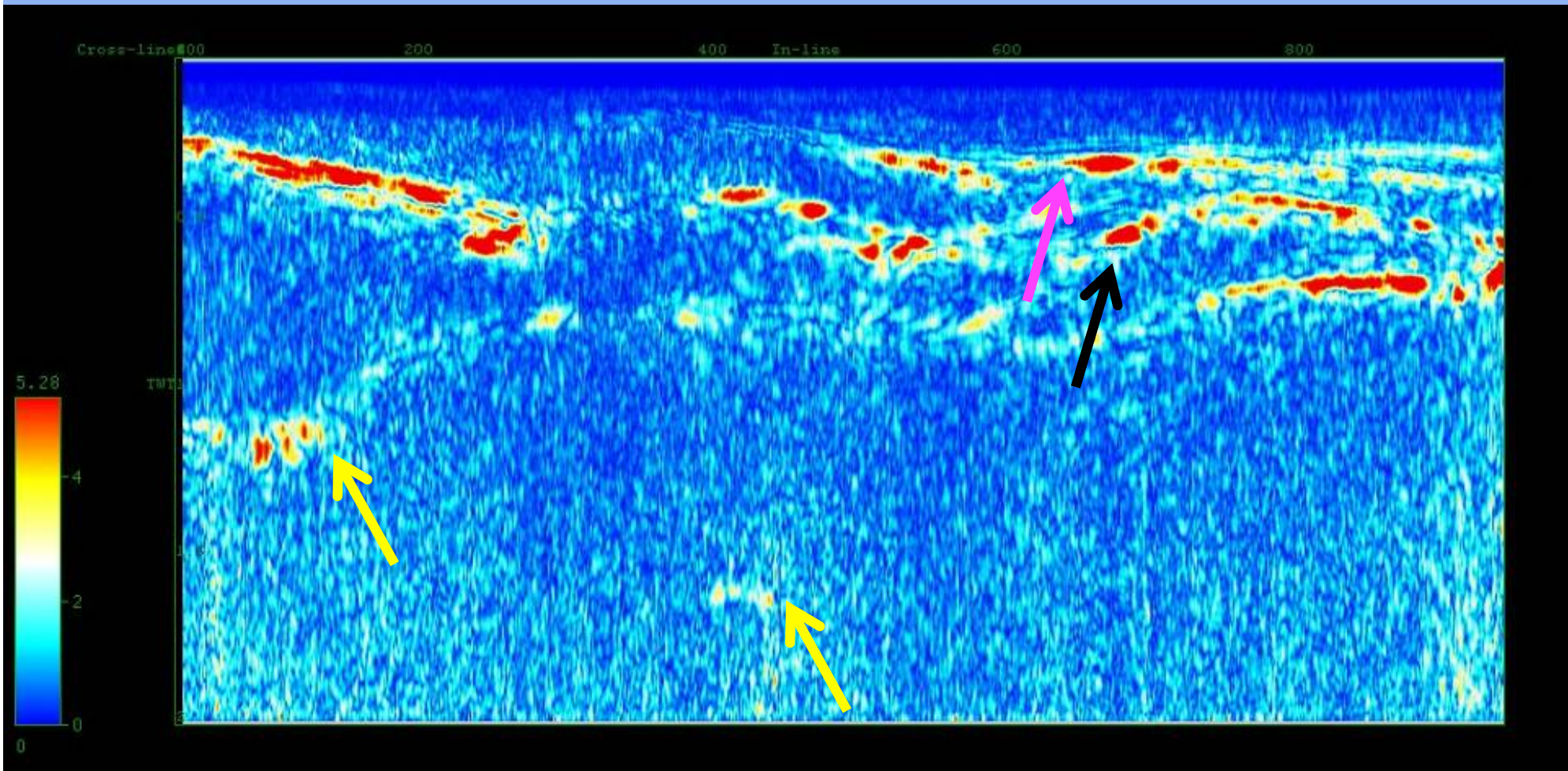
# MACRO SCALE (Km) Reflection Seismic





# MACRO SCALE (Km) Reflection Seismic: Exploiting spectral characteristics

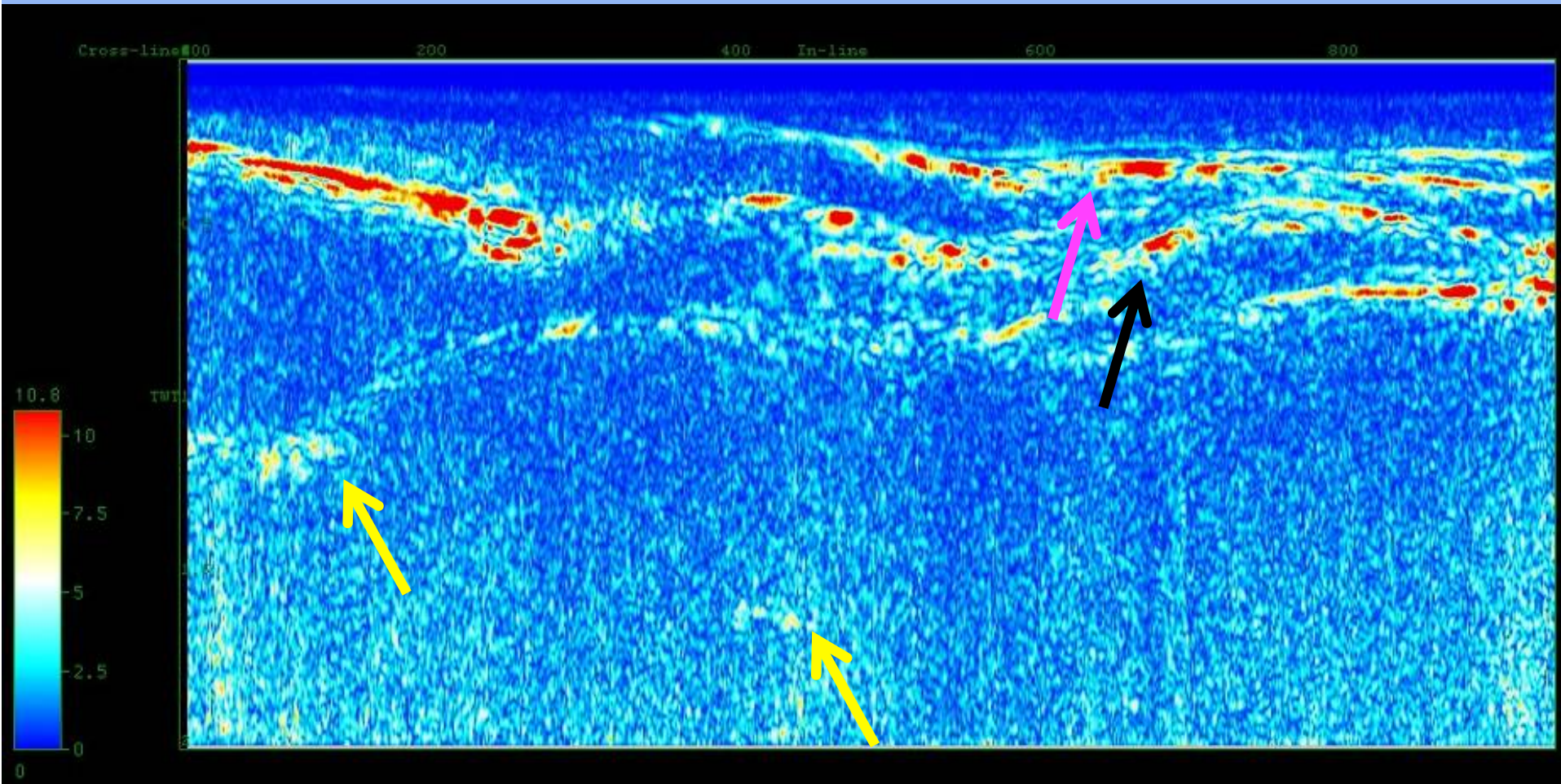
20Hz Spectral content





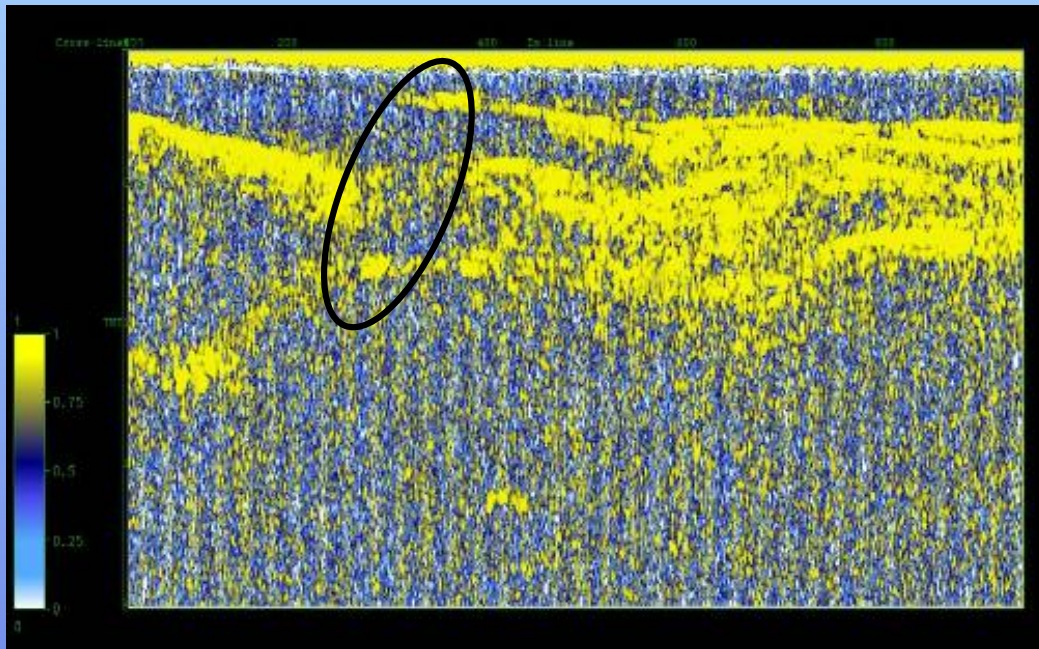
# MACRO SCALE (Km) Reflection Seismic

## 50Hz Spectral content



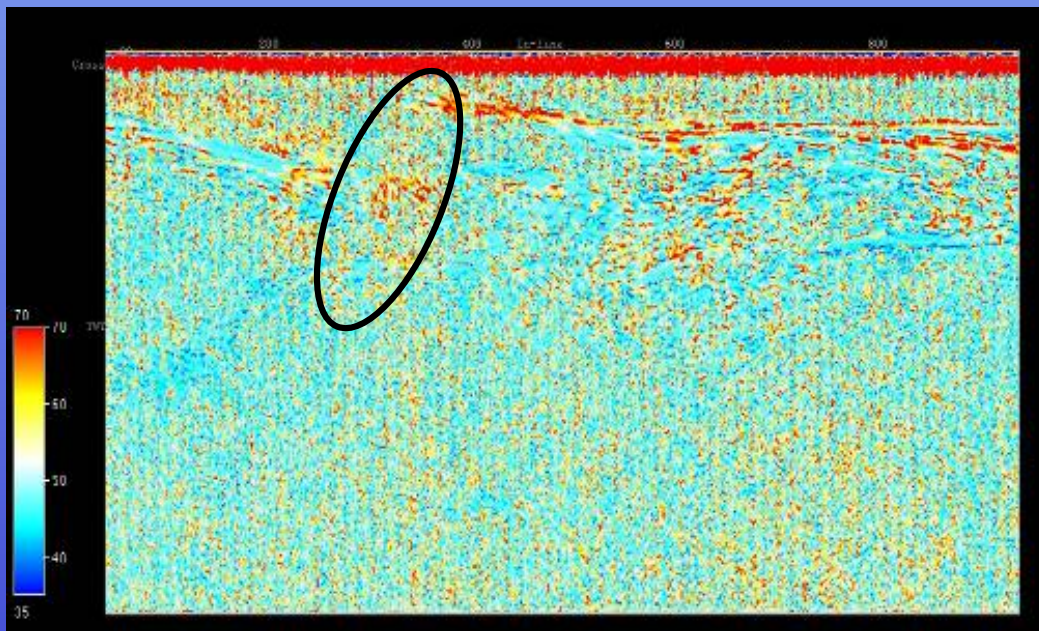


# MACRO SCALE (Km) Reflection Seismic



*COHERENCY*  
+  
*SPECTRAL*

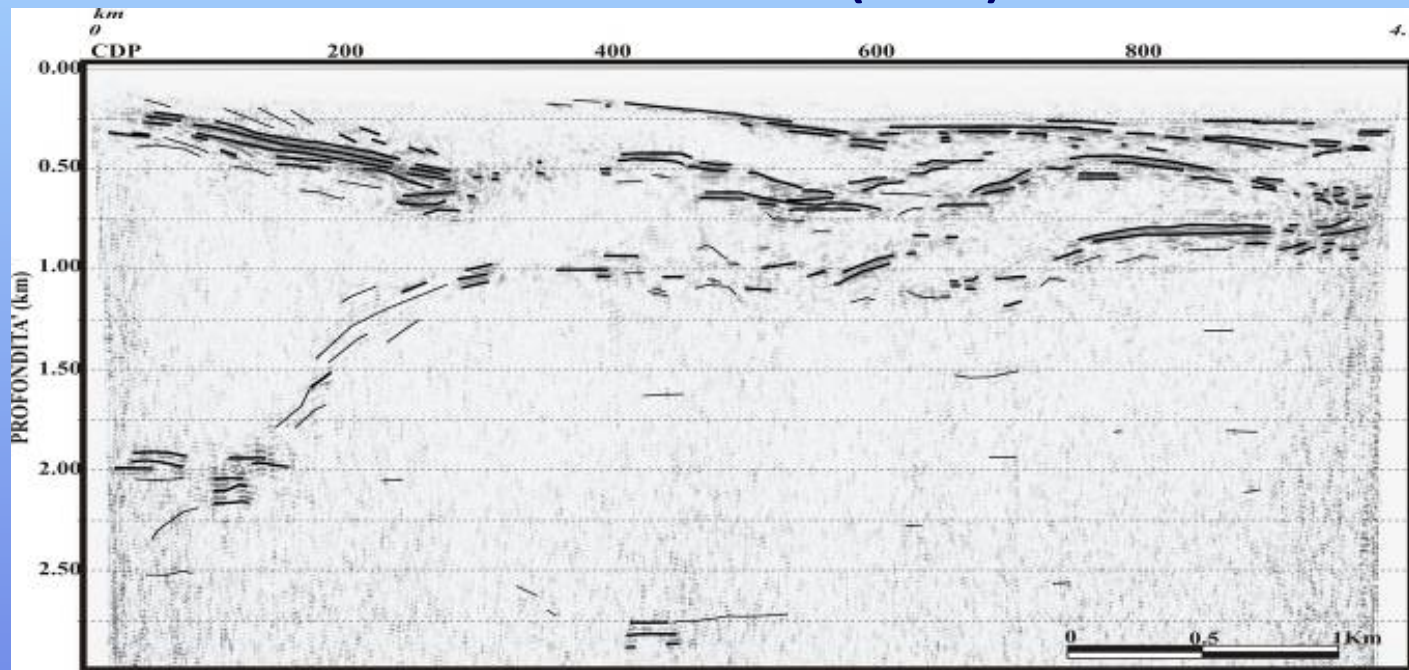
**Similarity**



**Dominant Freq.**

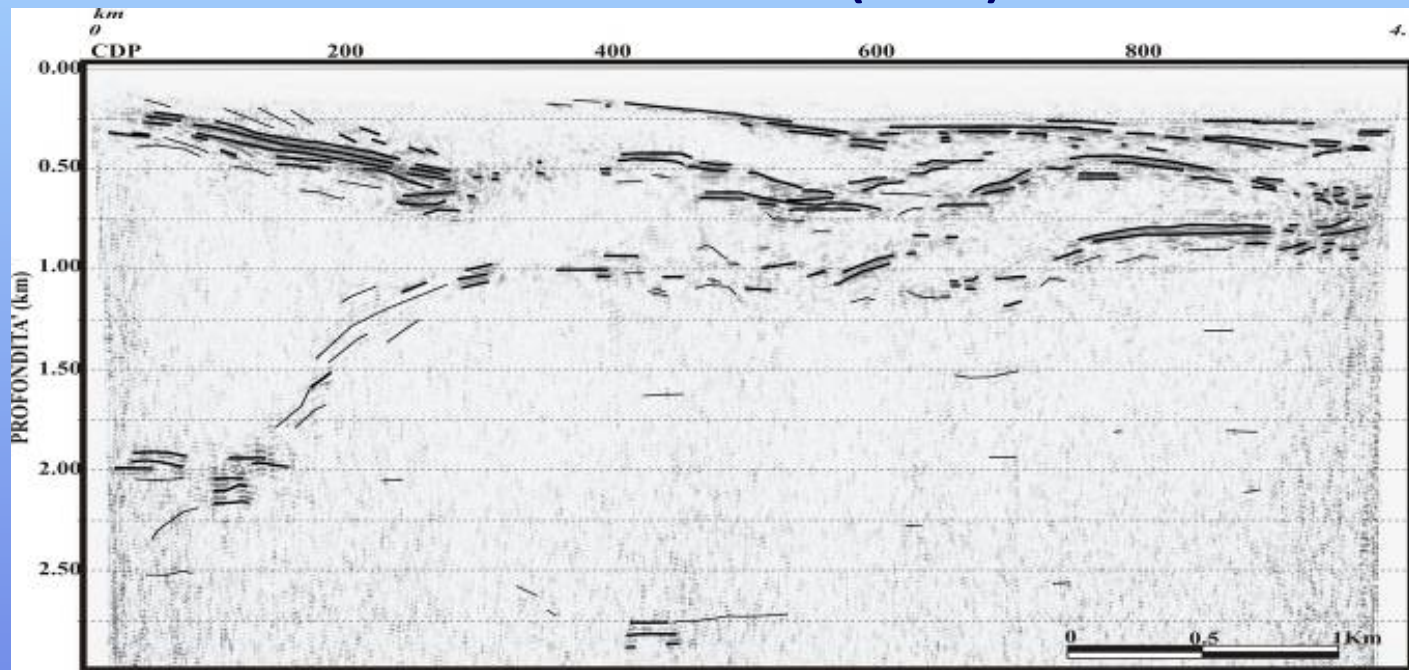


# MACRO SCALE (Km) Reflection Seismic

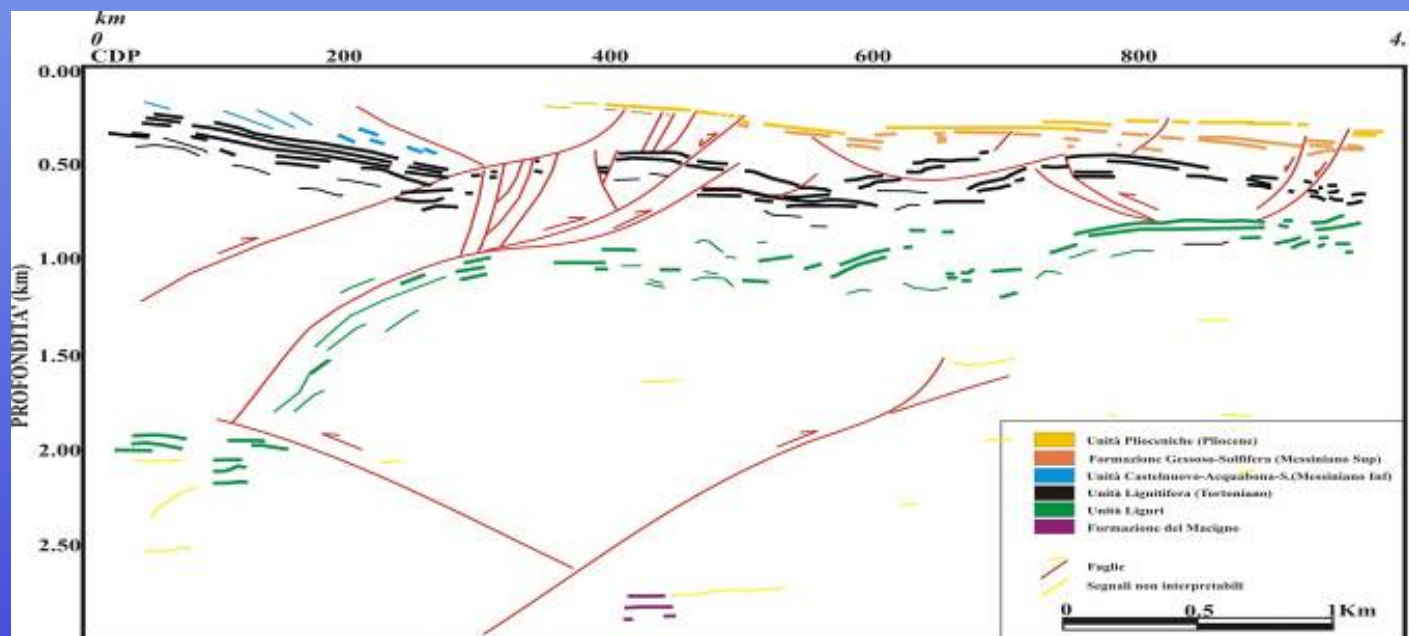


Line drawing on  
depth section

# MACRO SCALE (Km) Reflection Seismic



Line drawing on  
depth section

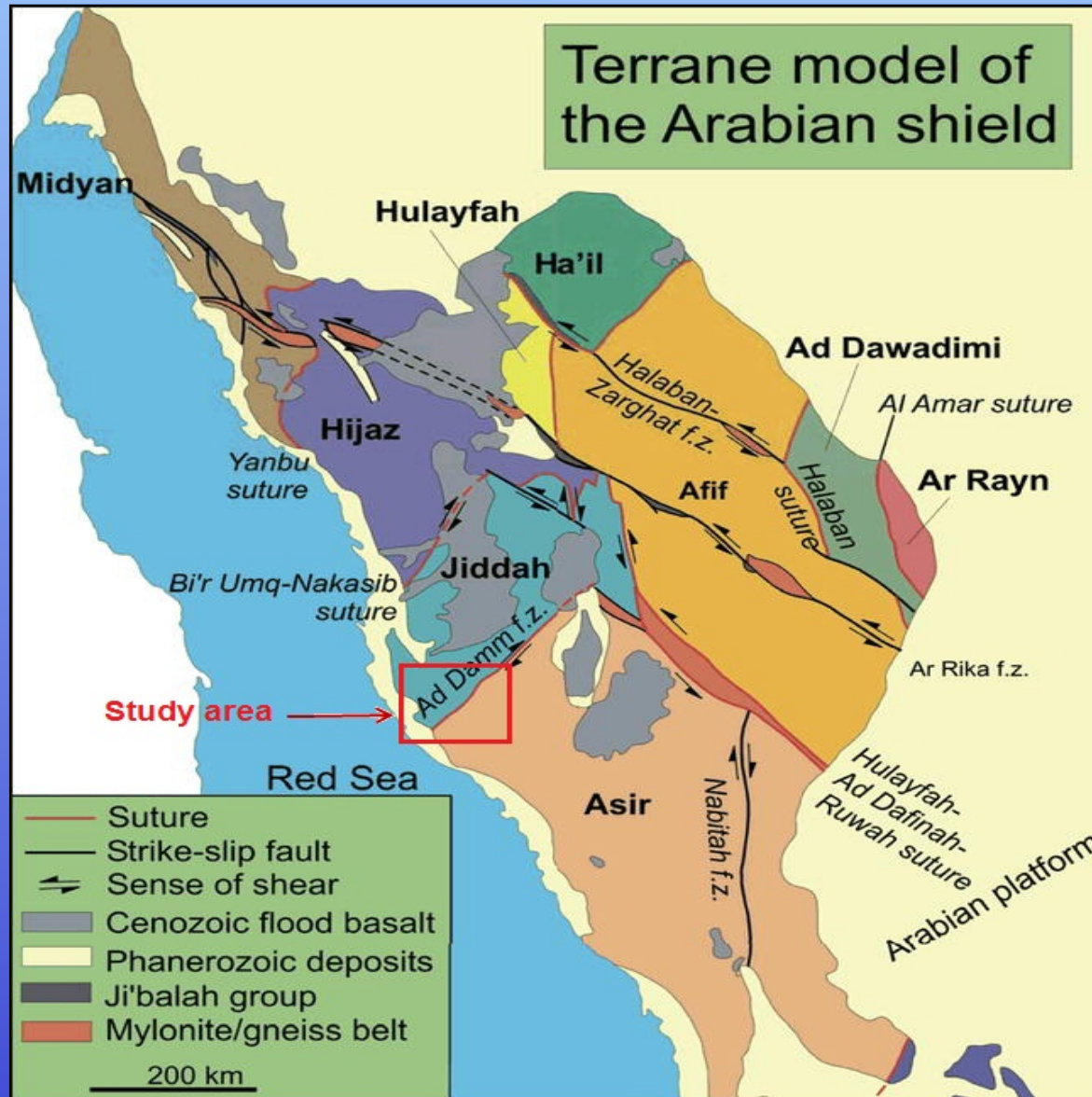


“Final”

Interpretation

# Study of SW Saudi Arabia geothermal systems: Al-Lith area

Geologic-  
Tectonic setting



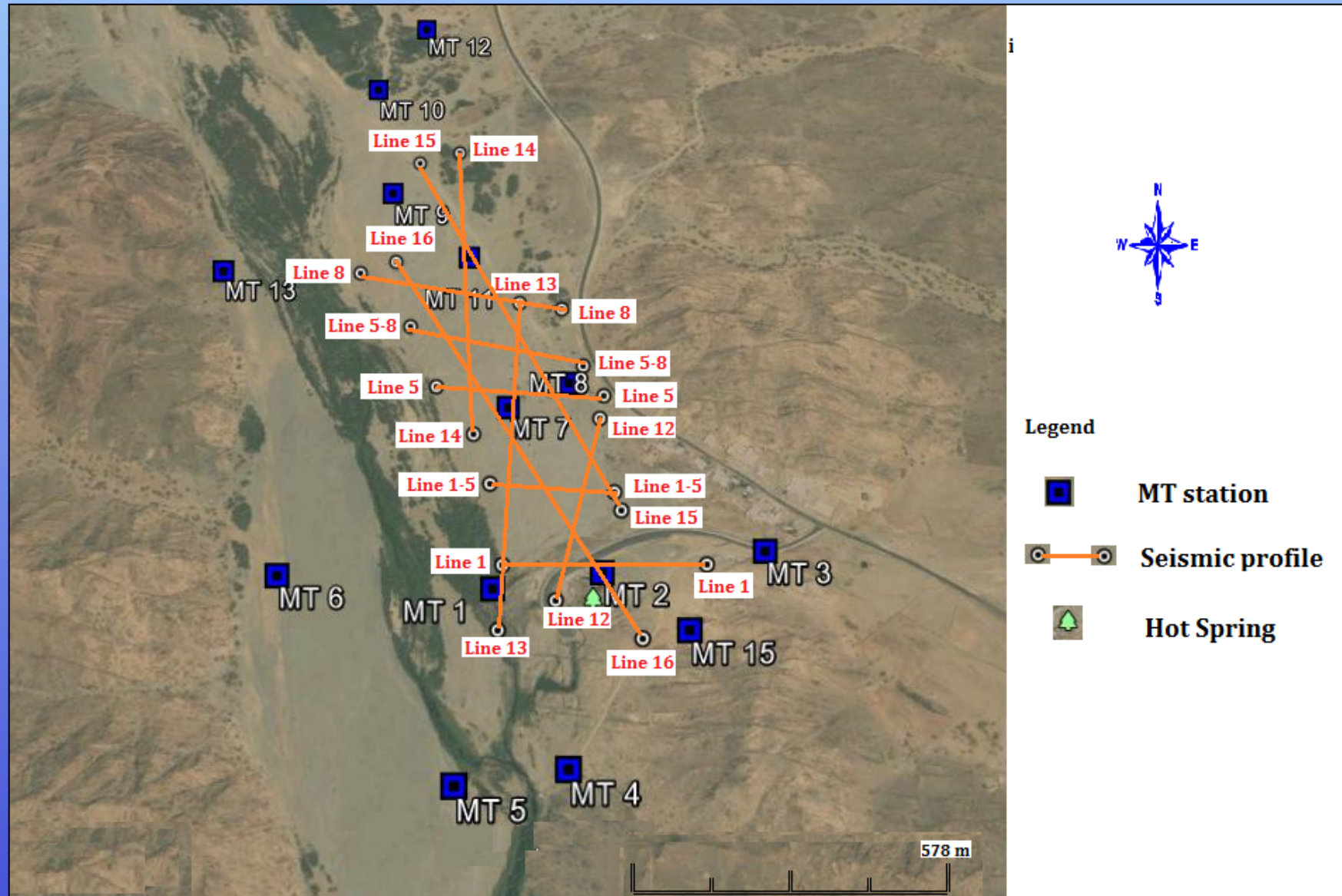
# Field measurements at the main four hot springs in the Wadi Al-Lith area

Hot Spring	Surface Temp. (°C)	Elevation (m)	PH	TDS (ppm)	EC ( $\mu\text{Scm}^{-1}$ )
Ain Al Harrah	Up to 95	167.0	7.8	2180	3633
Wadi Markub	56	136.0	6.85	2960	4933
Al Darakah	41	151.0	7.6	2900	4825
Bani Hilal	45	170.0	7.5	2426	4043

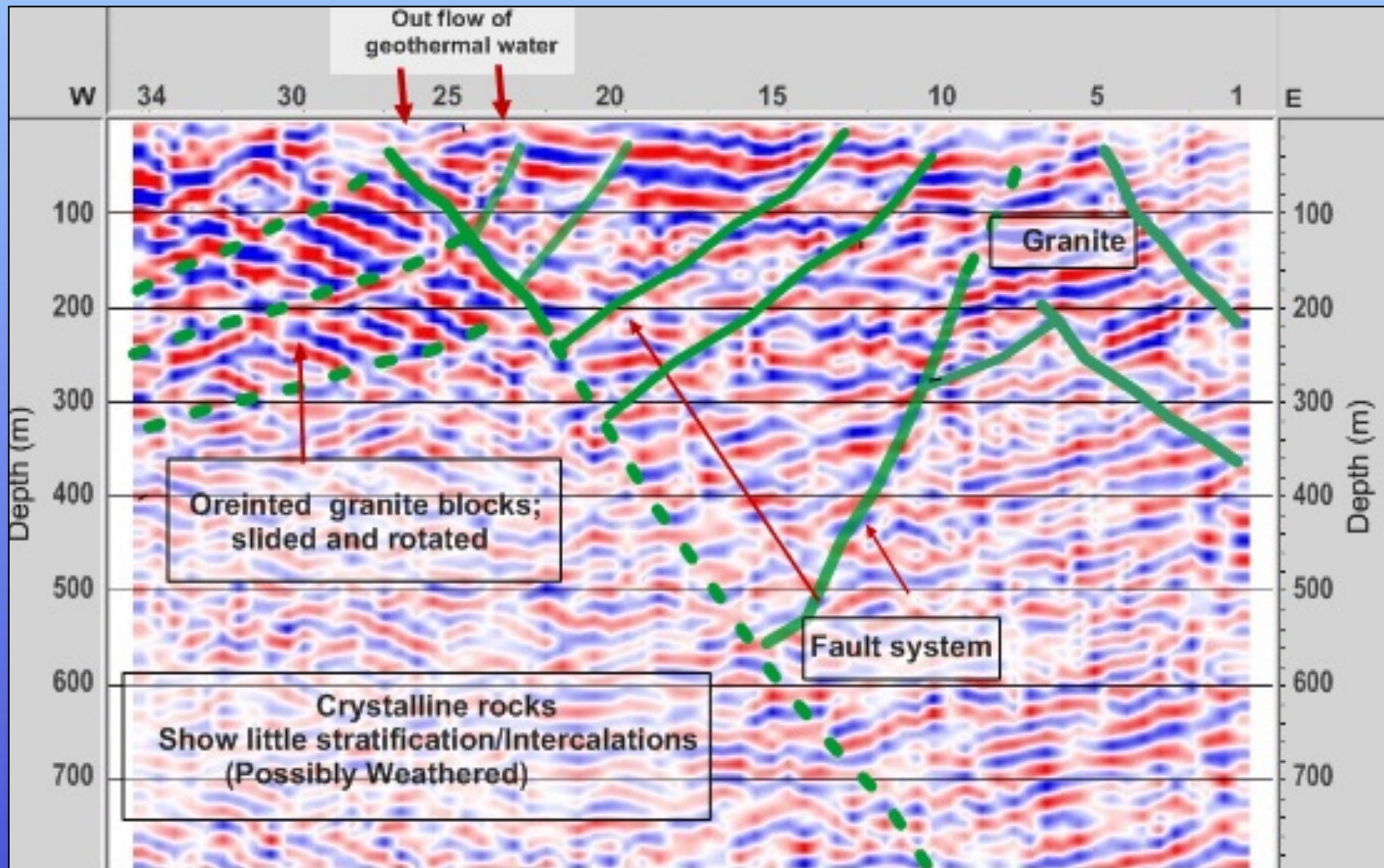
Hot Spring	Subsurface Temp. (°C)	Discharge Enthalpy (Kj/Kg)	Heat Flow ( $\text{mW}/\text{M}^2$ )
Ain Al Harrah	136.00	218.96	182.79
Wadi Markoub	120.06	193.30	159.23
Al Darakah	105.10	169.21	136.93
Bani Hilal	120.34	193.74	159.63



# Seismic sections and MT stations location map, Wadi Al Lith area

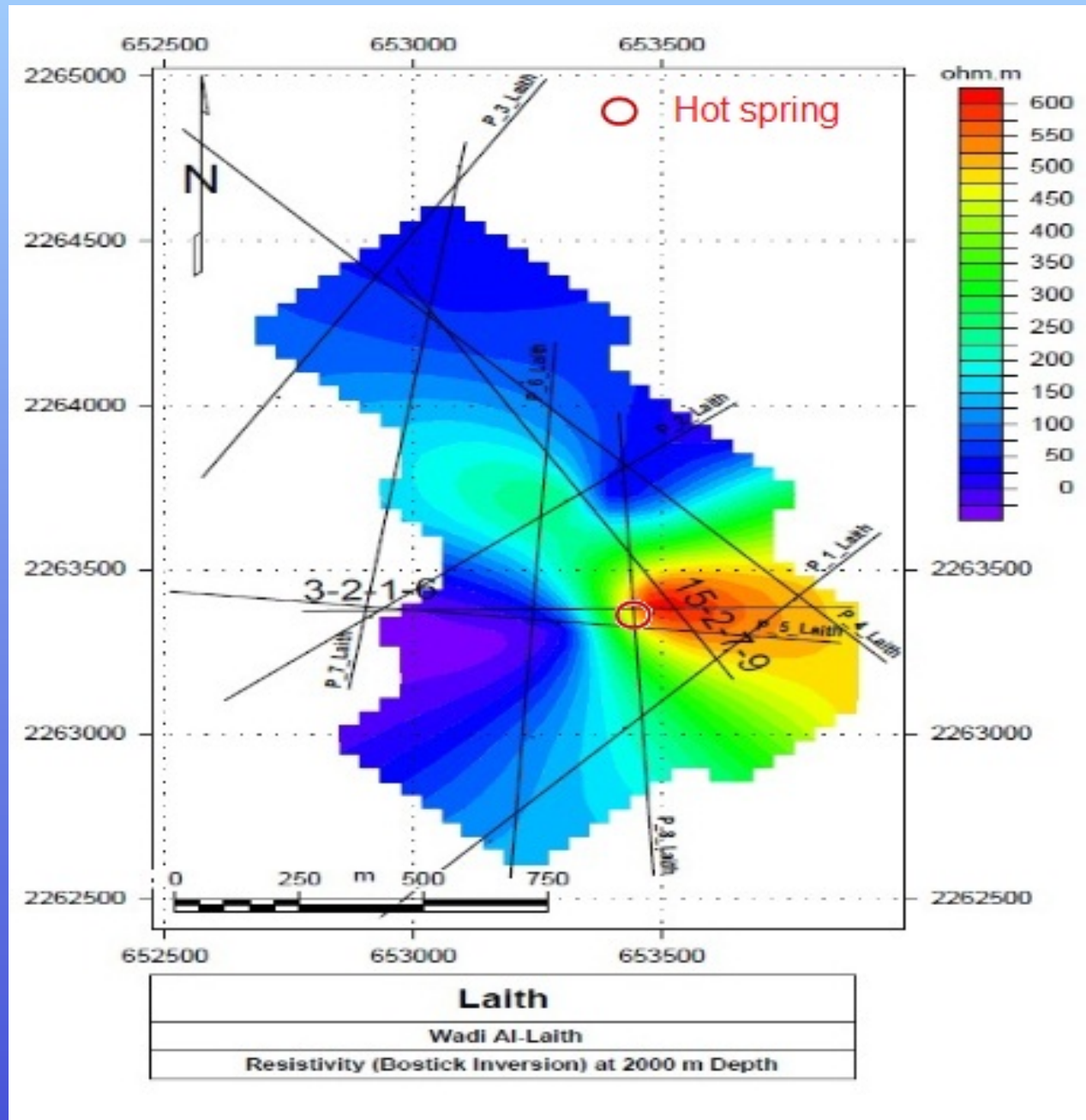


# Interpreted seismic section-1 passing Ain Al Harrah hot spring, Al Lith area





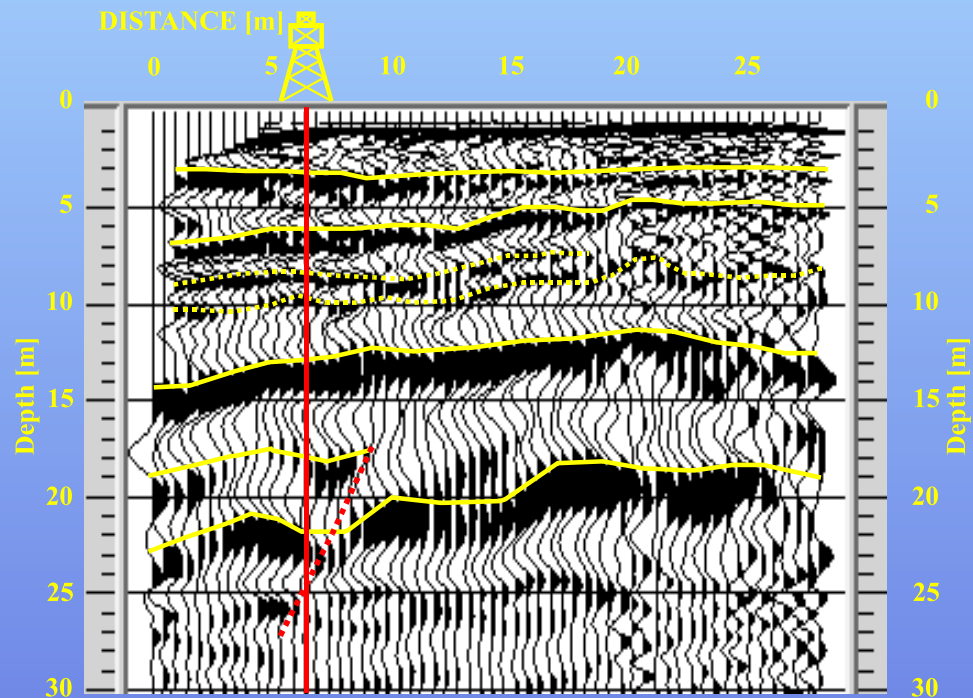
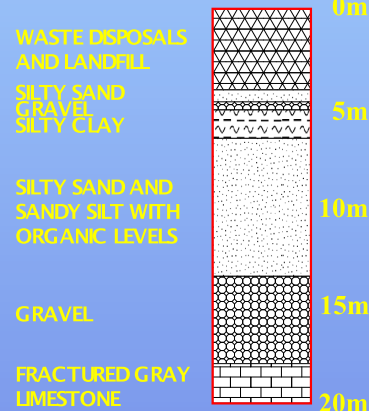
# MT slice map at a depth level of 2000 m, Al Laith area



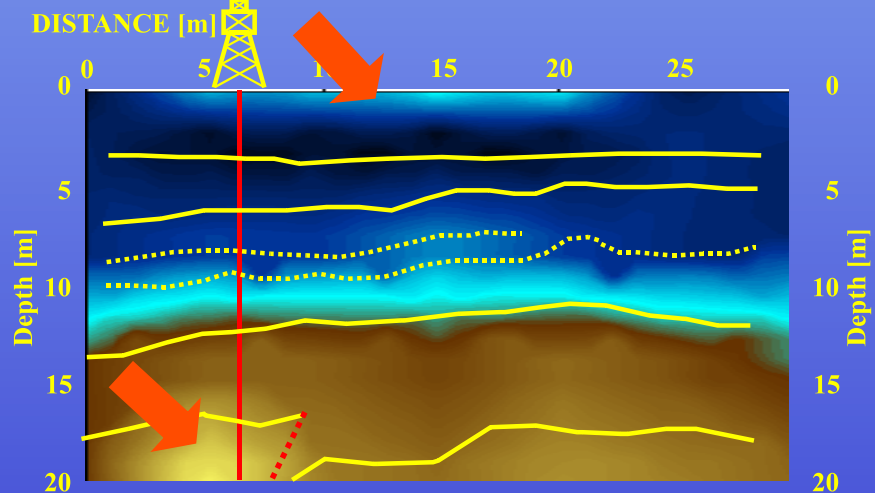
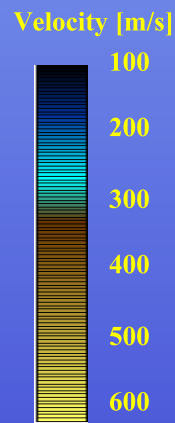
...increasing resolution:  
*Imaging + characterization*



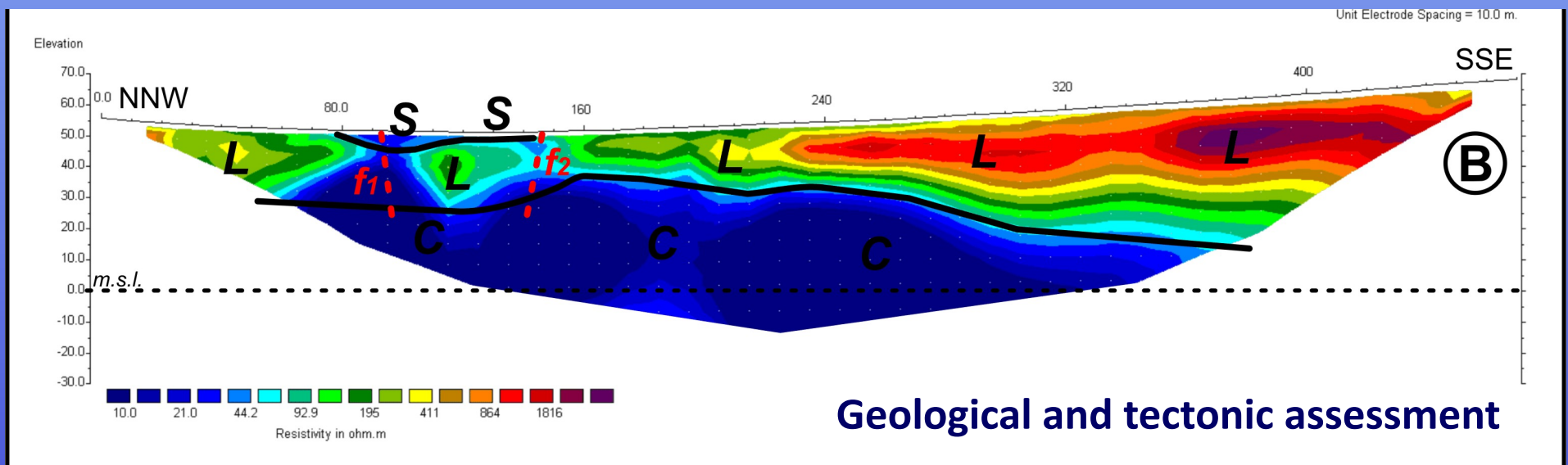
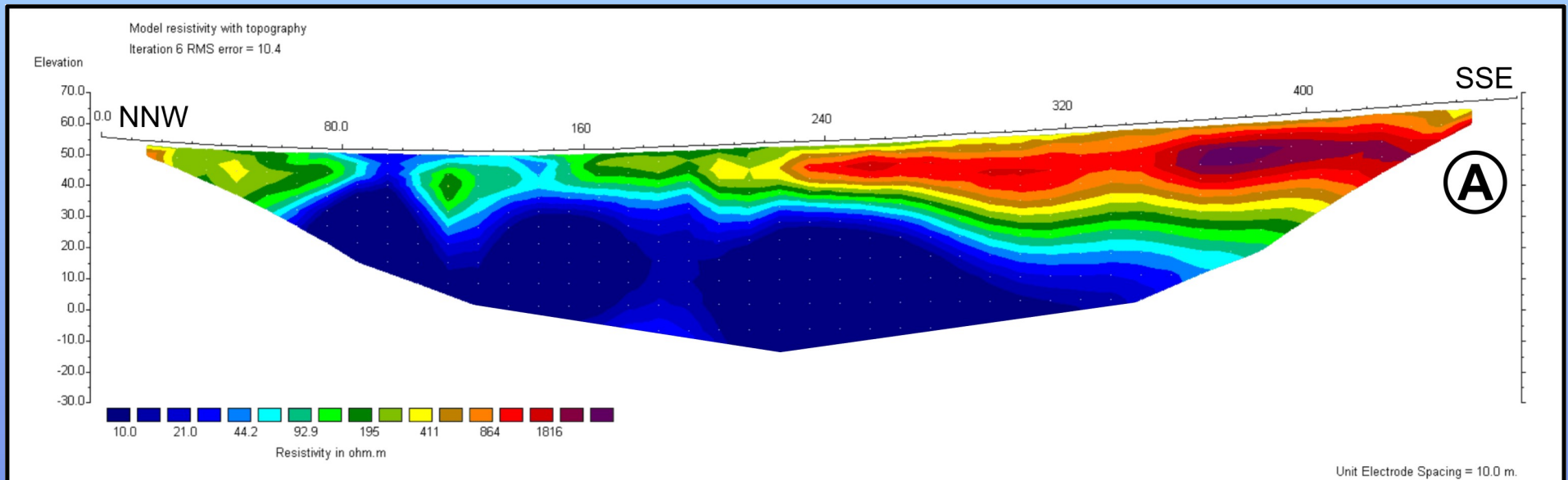
# MICRO SCALE (m) Reflection Seismic/MASW



**MASW**  
2D Velocity  
profile  
Obtained by  
inversion of  
several 1D  
dispersion curves

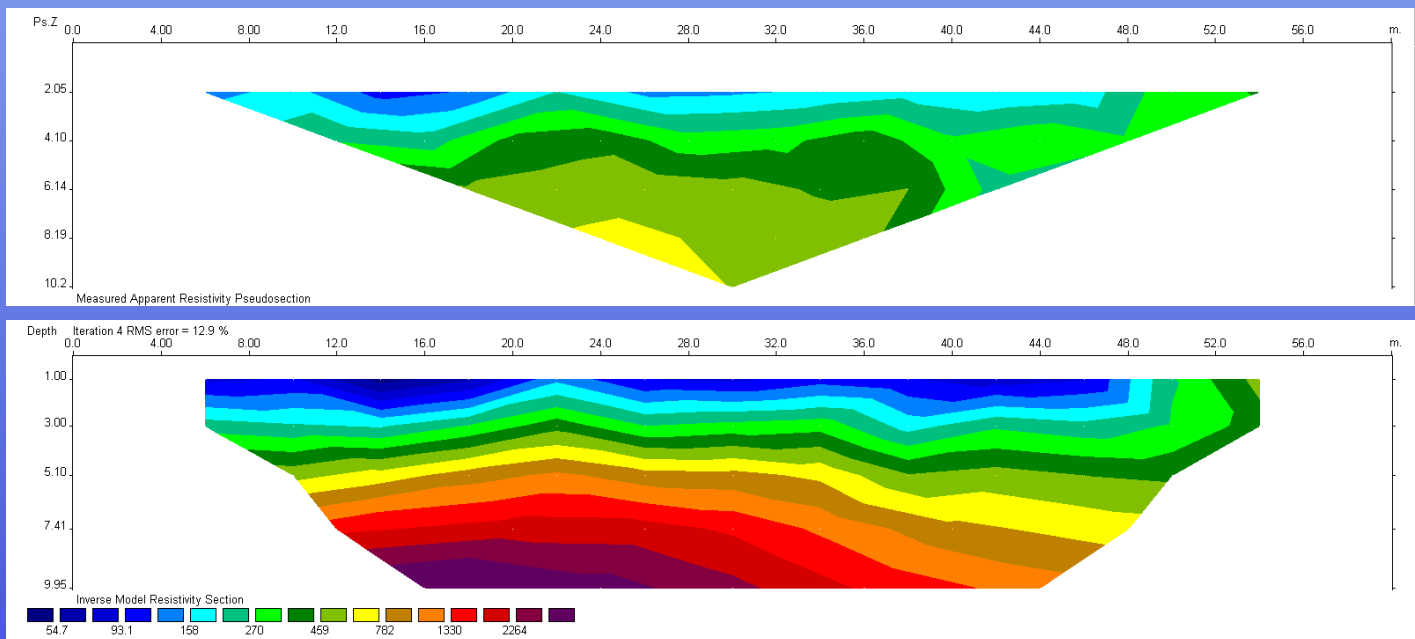
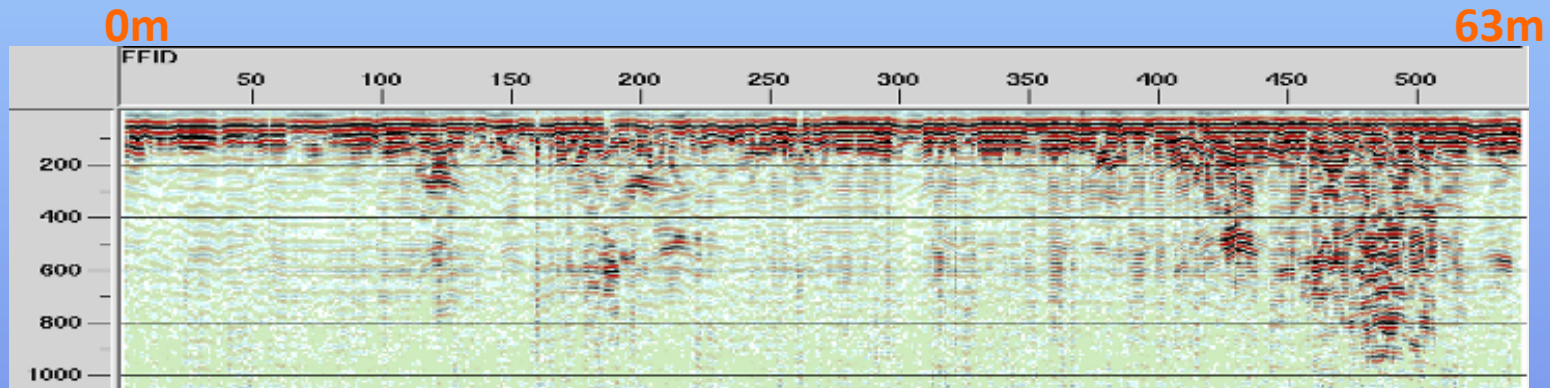


# MACRO SCALE (n100m) ERT: complementary geological/tectonical information

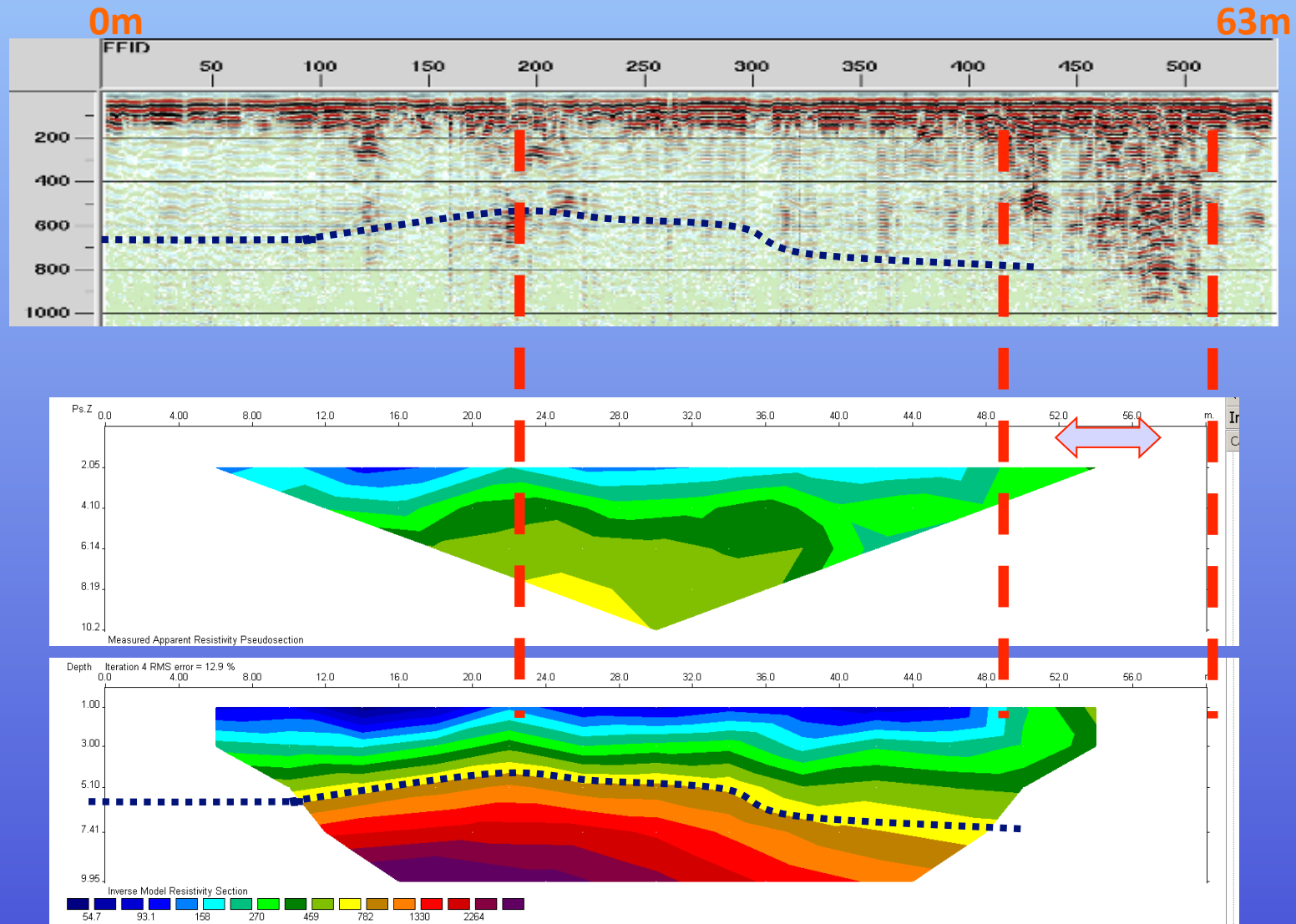


S=Weathering L=Limestones C=Clay f=Main faults

# MESO SCALE (10m) ERT + GPR

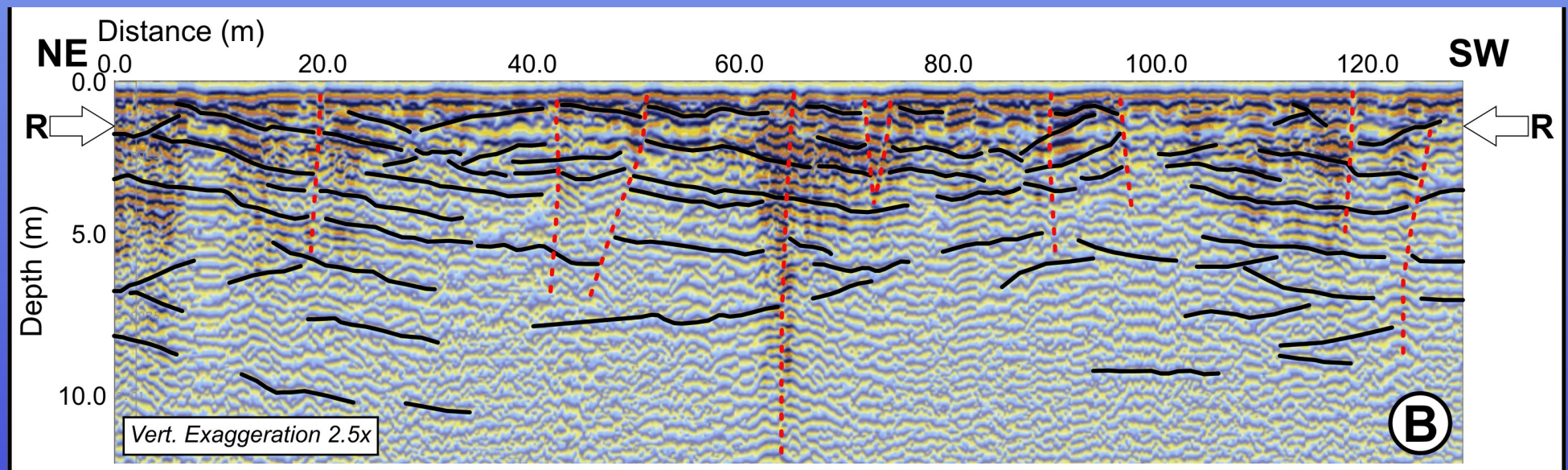
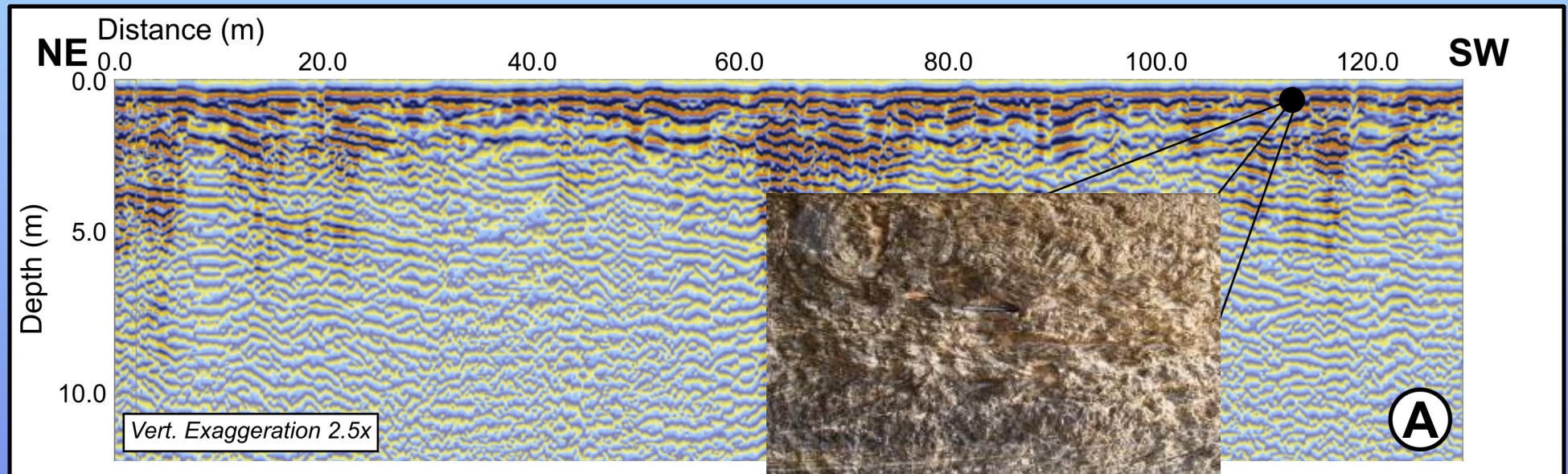


# MESO SCALE (10m) ERT + GPR





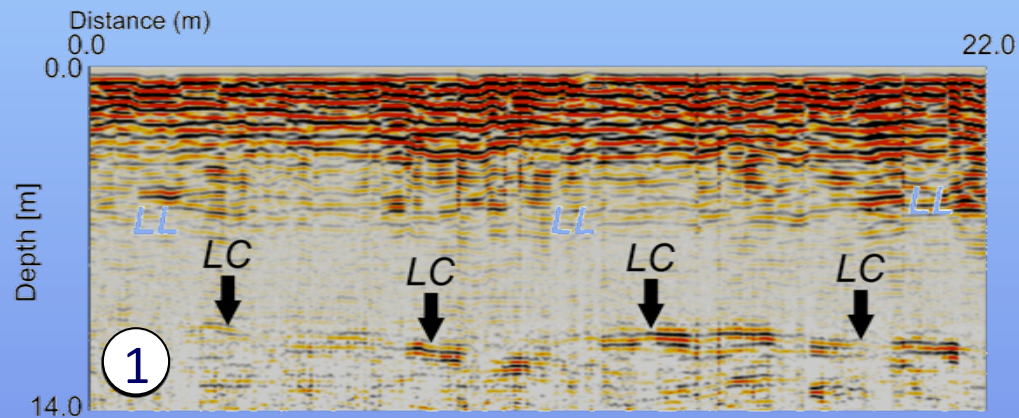
# MACRO/MICRO SCALE (10m-0.1m) GPR



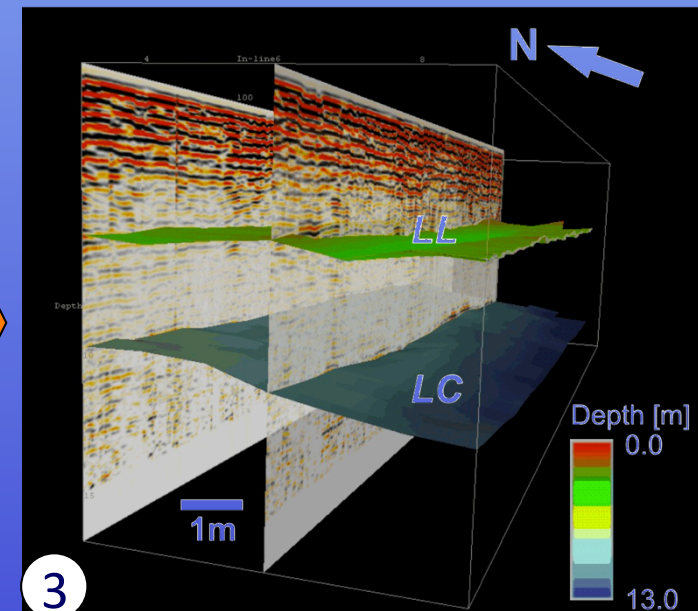
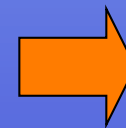
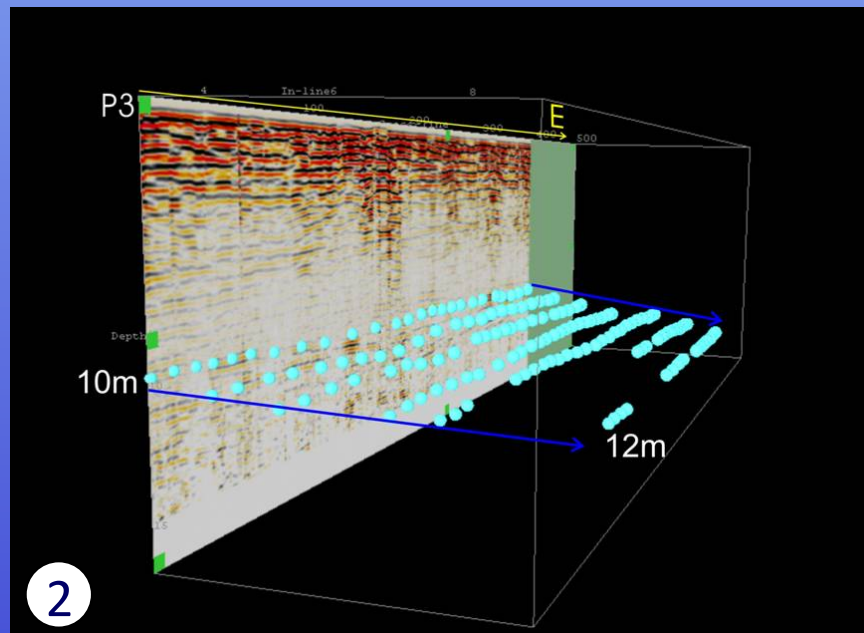


# MICRO SCALE (1m-0.1m) GPR

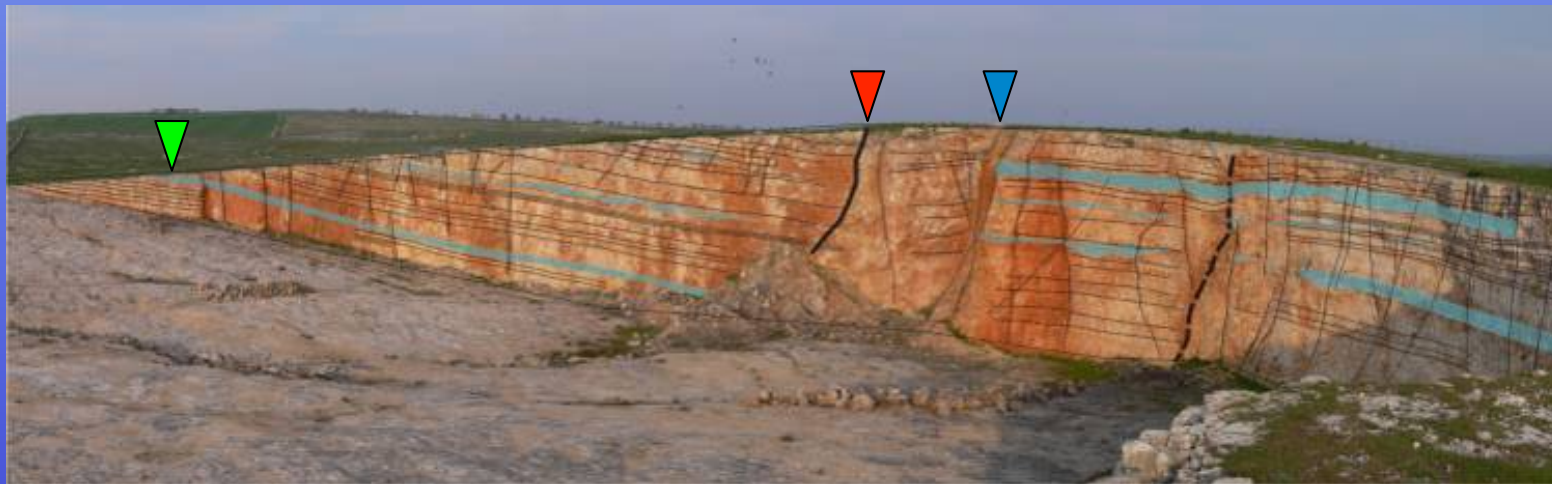
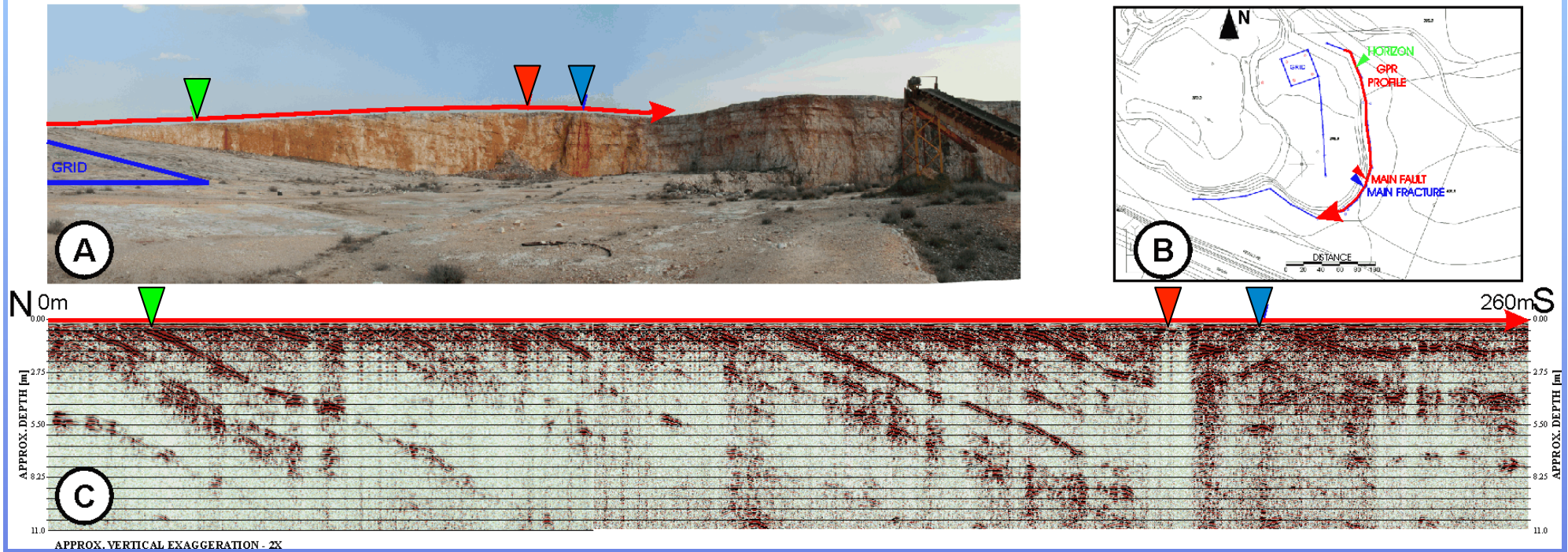
## 3-D GPR fractures/horizons imaging



From 2D to 3D imaging and detailed geometry reconstruction

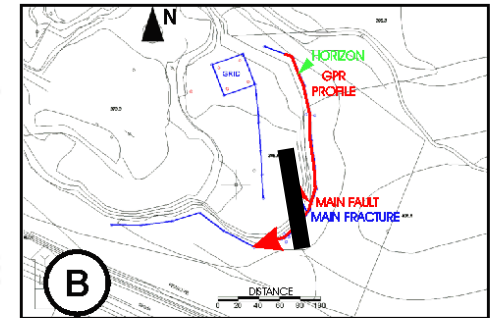
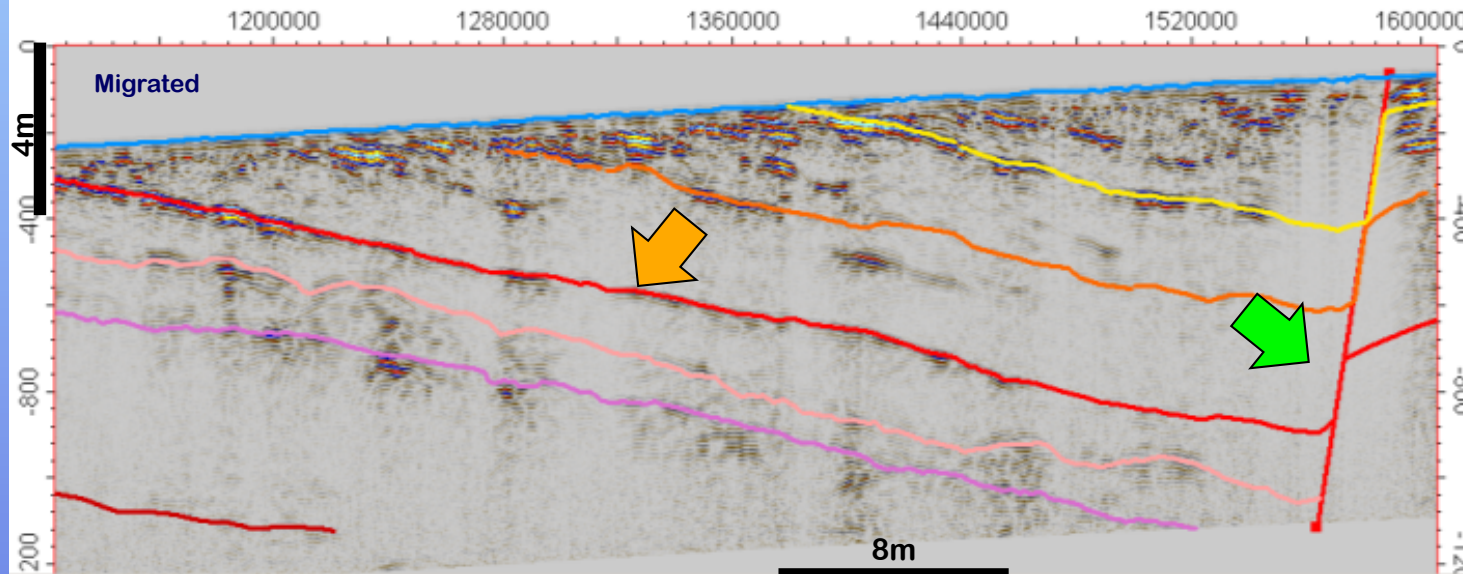


# MESO-MICRO SCALE (1m-0.1m) GPR INTEGRATED 2D and 2.5D SURVEYS





# MESO-MICRO SCALE (1m-0.1m) GPR INTEGRATED 2D and 2.5D SURVEYS

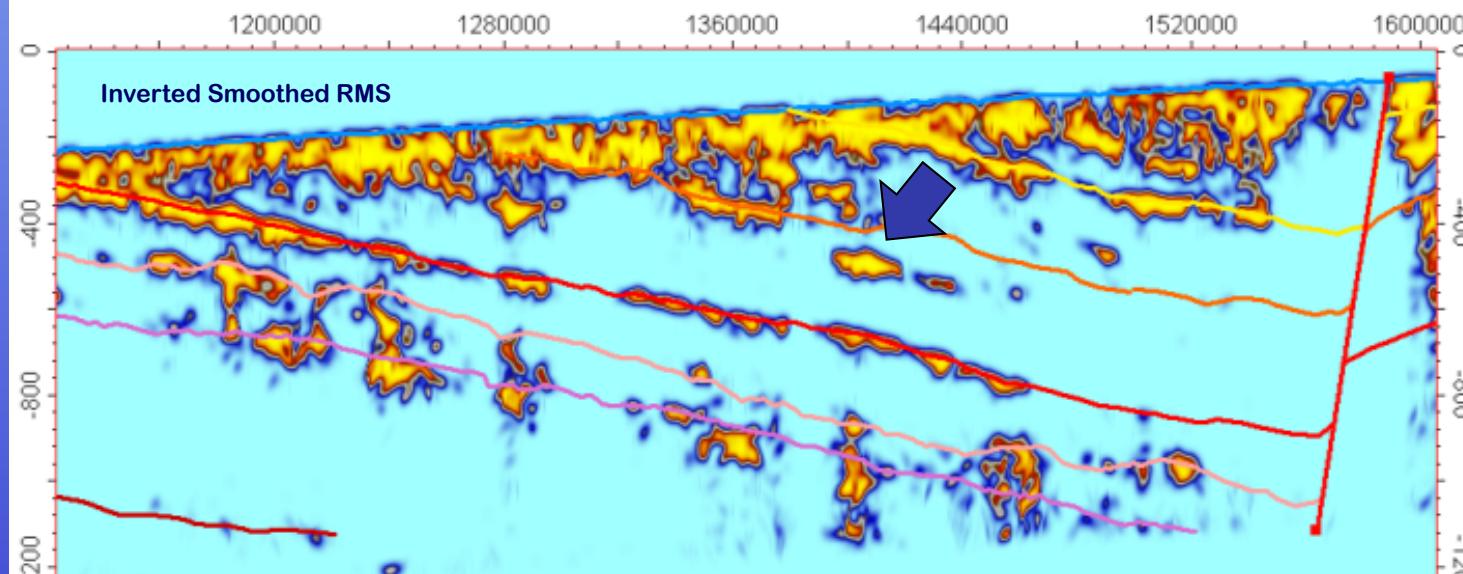


**FAULTS INTERPRETED BY  
IDENTIFYING MAJOR  
LOSS OF COHERENCY**

**BEDDING MAPPED BY  
INTERPOLATING  
SPATIALLY COHERENT  
EVENTS**

**KARSTS FEATURES  
INFERRED FROM  
CHANGES IN AMPLITUDES**

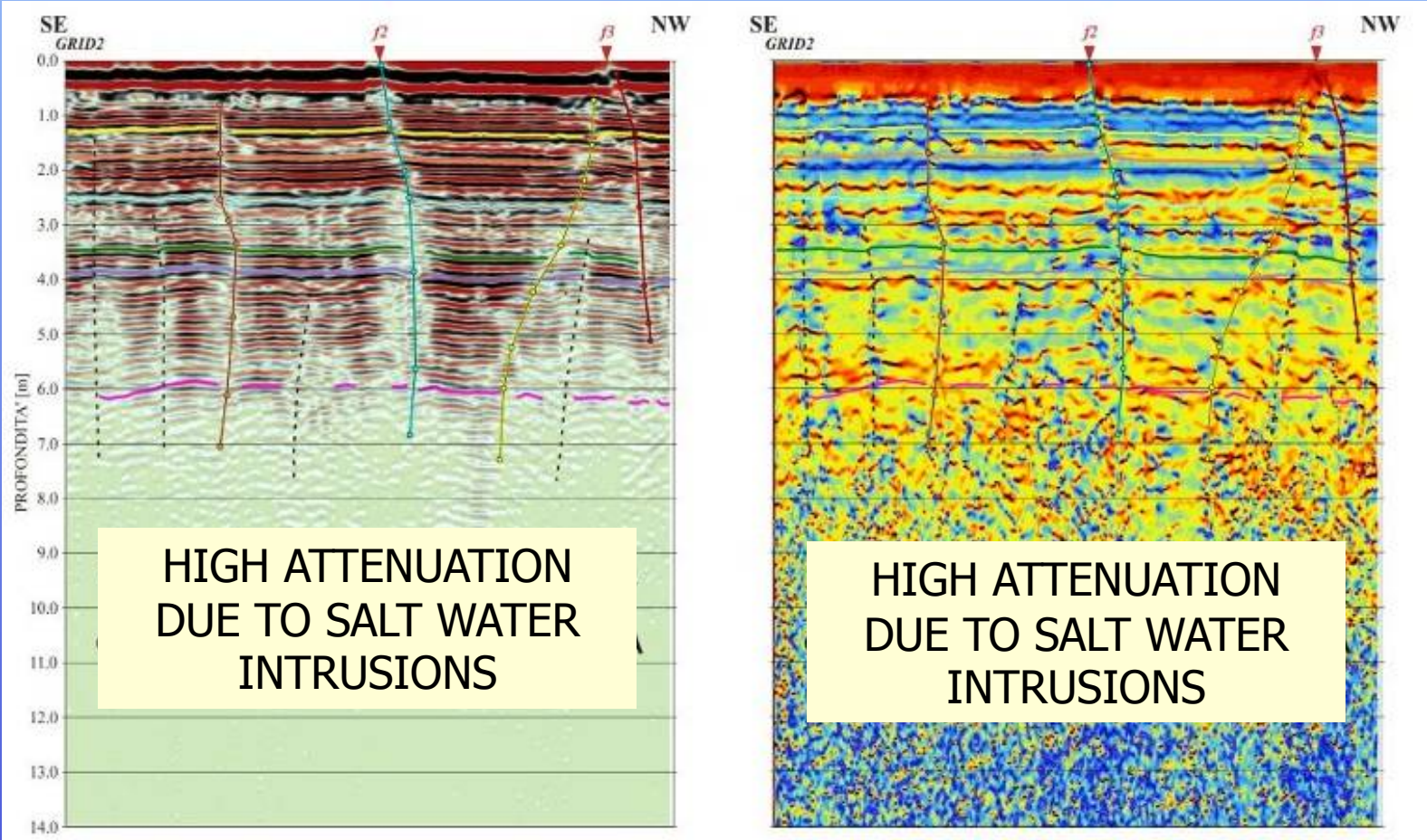
**But also:  
GPR ATTRIBUTES  
and VELOCITY FIELD  
RECONSTRUCTION**





# MESO-MICRO SCALE (1m-0.1m) GPR INTEGRATED 2D and 2.5D SURVEYS

## DETAILED DISCONTINUITY NETWORK IMAGING

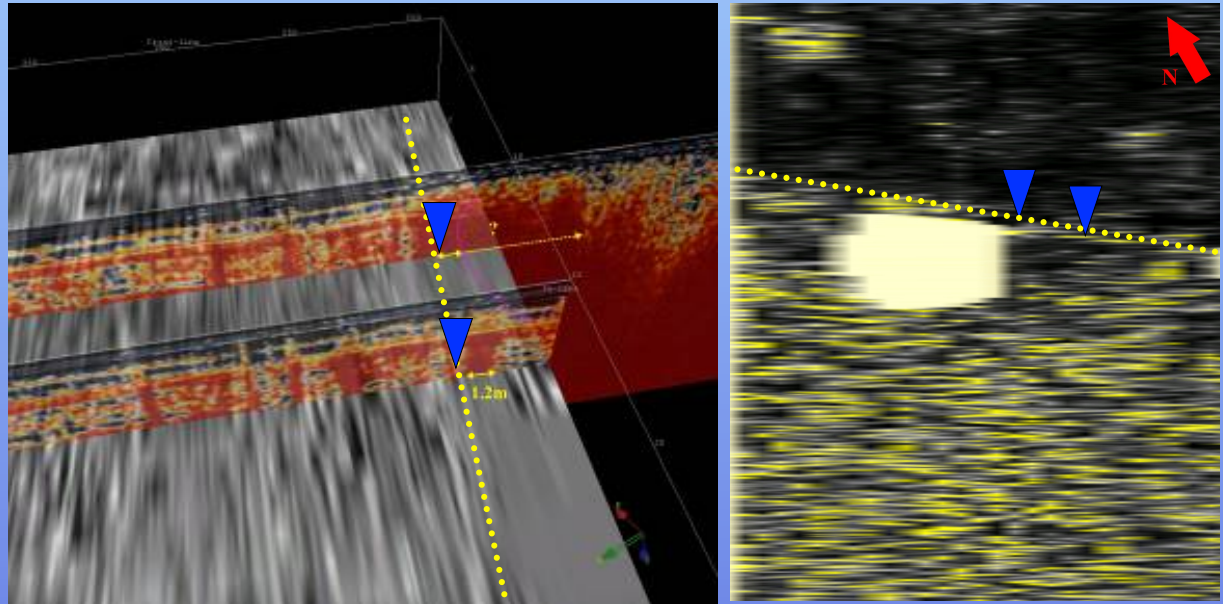


AMPLITUDE SECTION

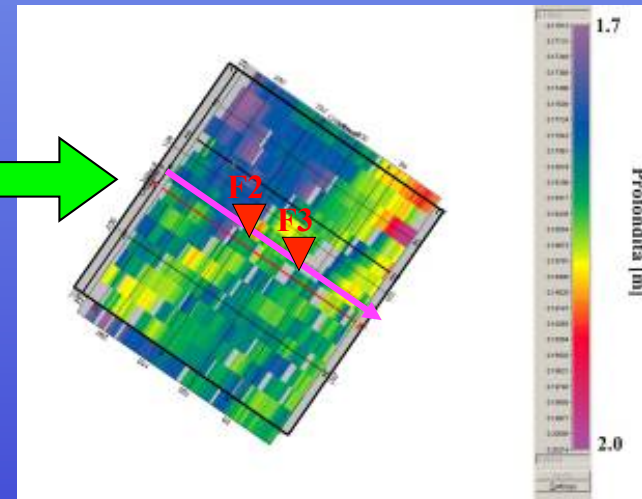
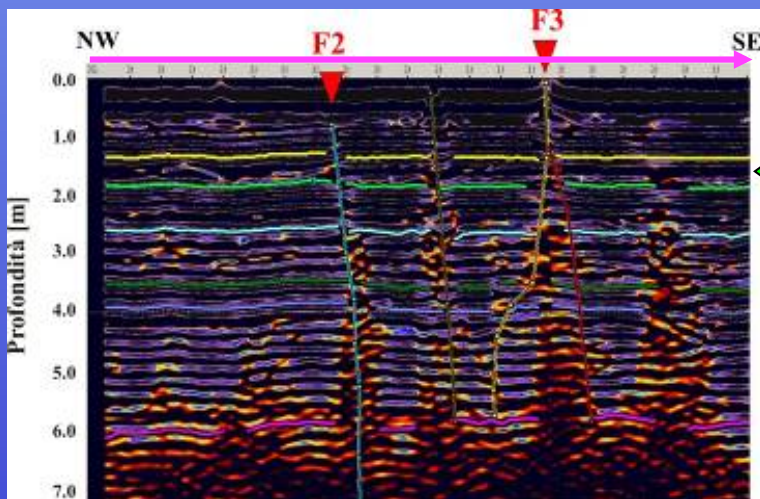
DOMINANT FREQUENCY

# MICRO SCALE (0.1-0.05m) GPR INTEGRATED 2D and 2.5D IMAGING DETAILED DISCONTINUITY NETWORK IMAGING

IMAGING OF ONE MAIN FAULT  
AND SEVERAL  
INTERCONNECTED  
DISCONTINUITIES



Detailed mapping and CENTIMETRIC HEAVE DEFINITION





# MICRO SCALE (0.1-0.05m) GPR INTEGRATED 2D and 2.5D IMAGING DETAILED DISCONTINUITY NETWORK IMAGING





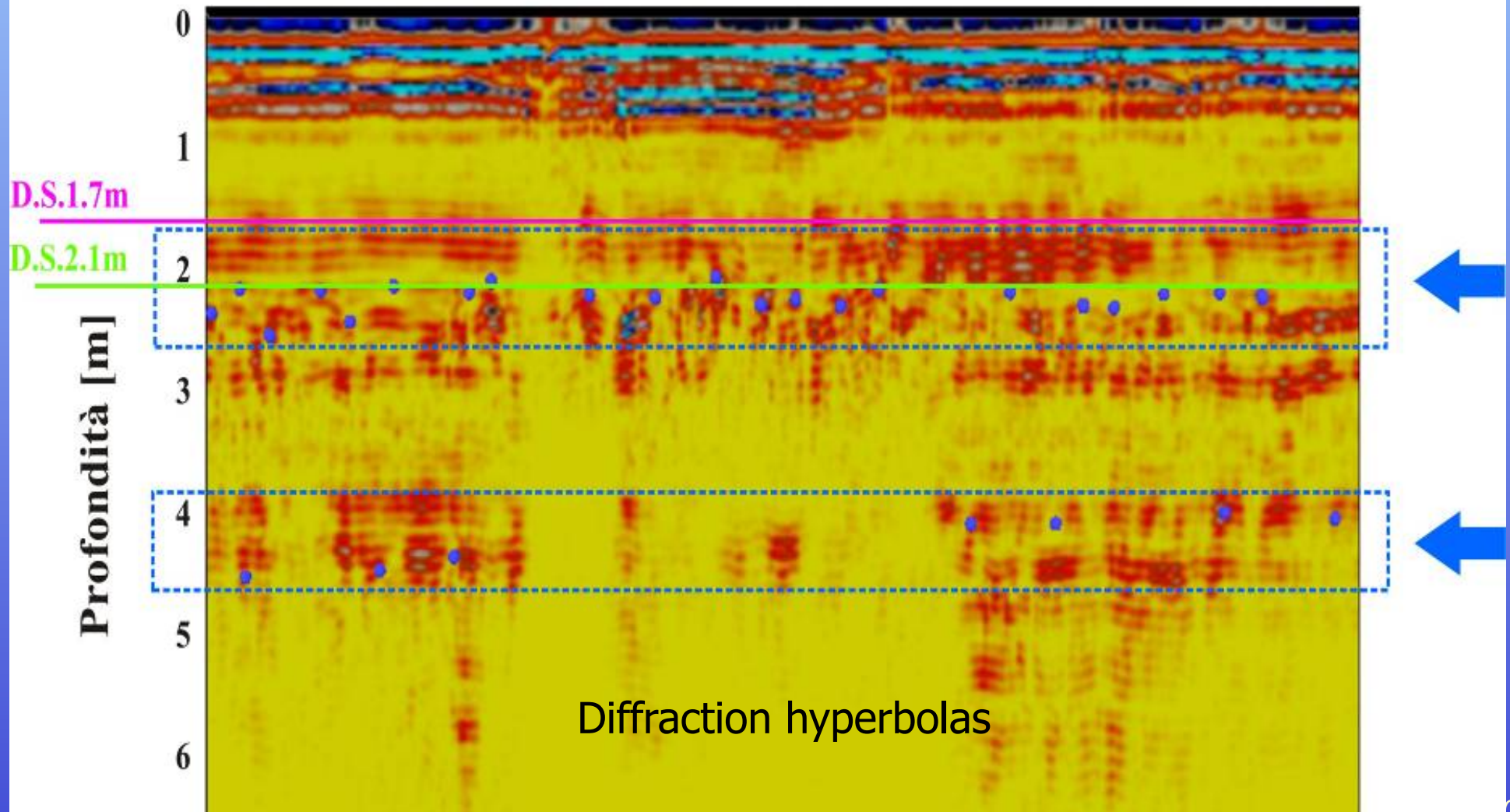
# MICRO SCALE (0.1-0.05m) GPR

## INTEGRATED 2D and 2.5D IMAGING

Validation: dissolution caves located along specific layers

Relation between Karstic phenomena and the discontinuity network

ESE Identification based on integrated criteria WNW



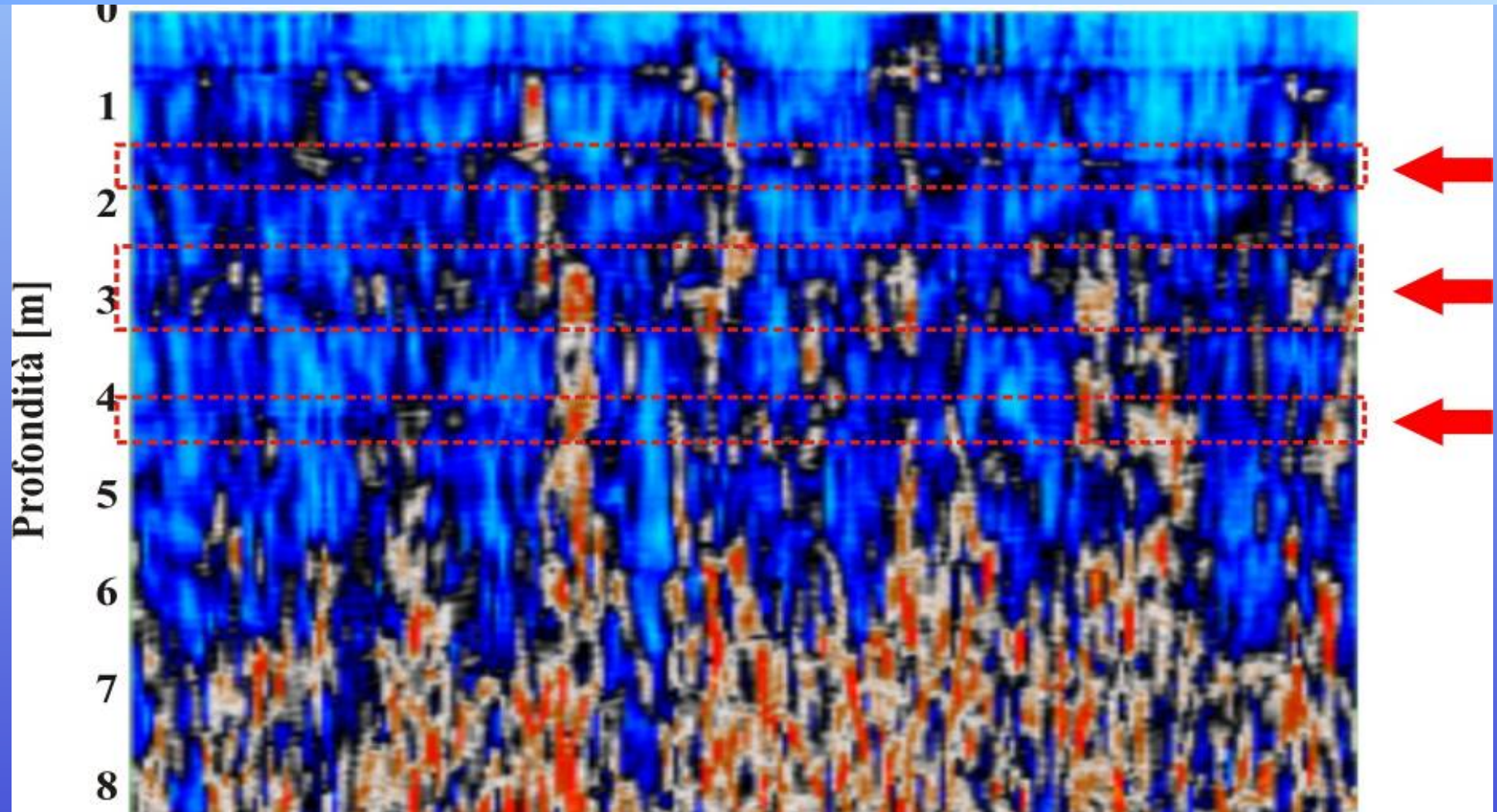


# MICRO SCALE (0.1-0.05m) GPR

## INTEGRATED 2D and 2.5D IMAGING

Validation: dissolution caves located along specific layers

Relation between Karstic phenomena and the discontinuity network





# MICRO SCALE (0.1-0.05m) GPR

## INTEGRATED 2D and 2.5D IMAGING

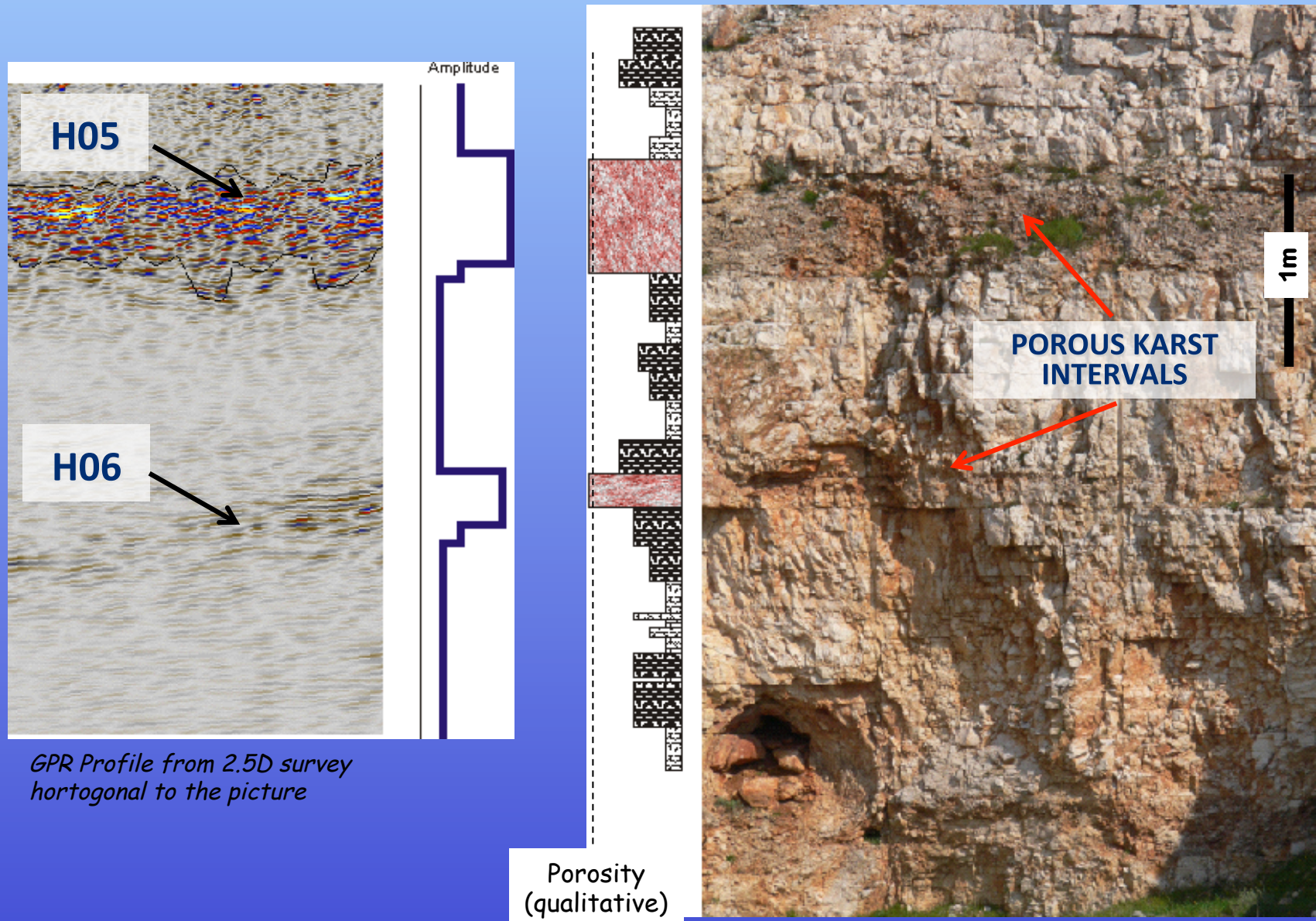
Validation: dissolution caves located along specific layers





# MESO-MICRO SCALE (1m-0.1m) GPR

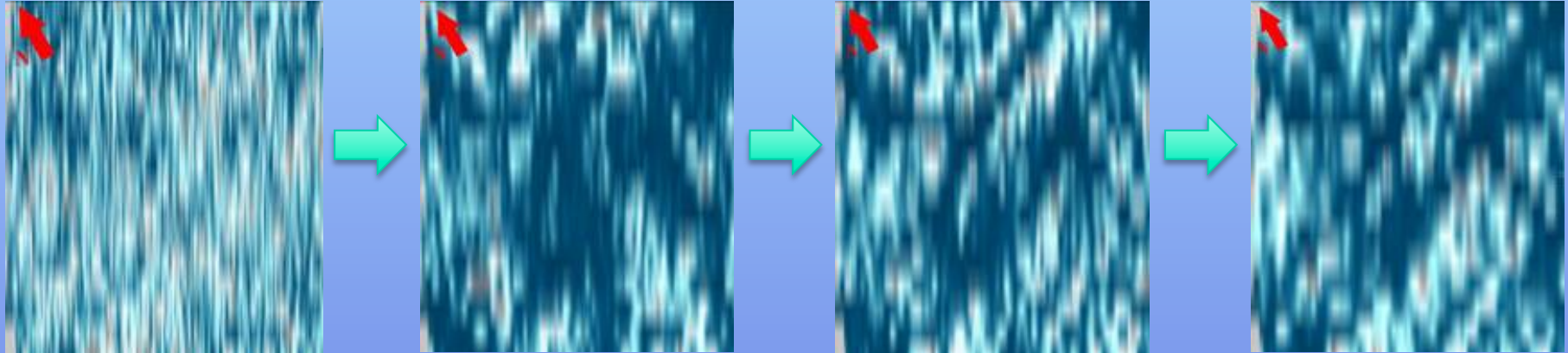
## GEOLOGICAL/STRATIGRAPHICAL/TECTONICAL INTERPRETATION



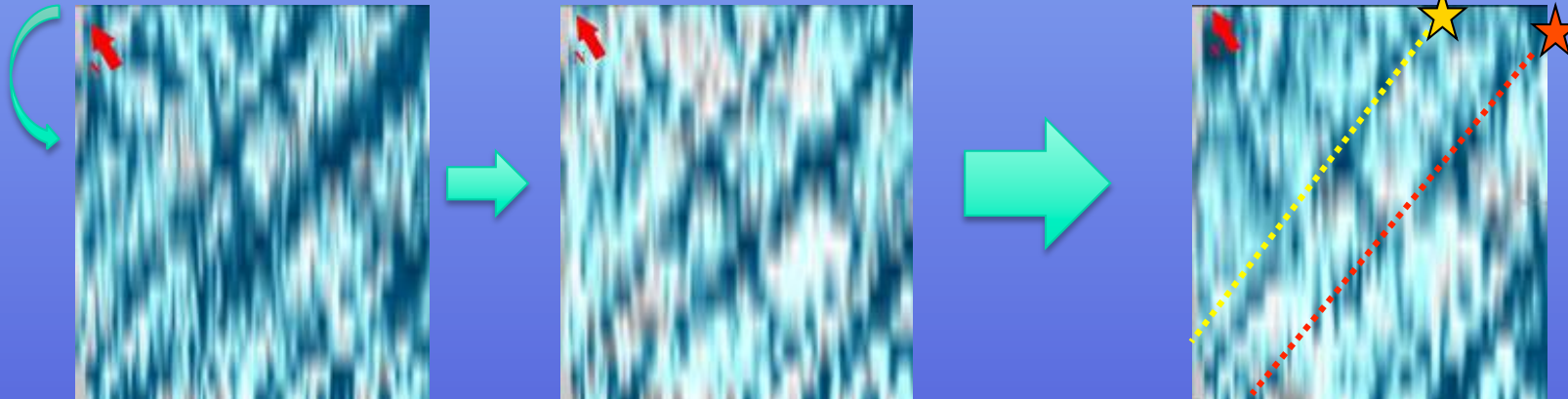
# MESO-MICRO SCALE (1m-0.1m) GPR

## GEOLOGICAL/STRATIGRAPHICAL/TECTONICAL INTERPRETATION

Shallow (.5 m)



ANALYSIS OF SERIES OF DEPTH SLICES

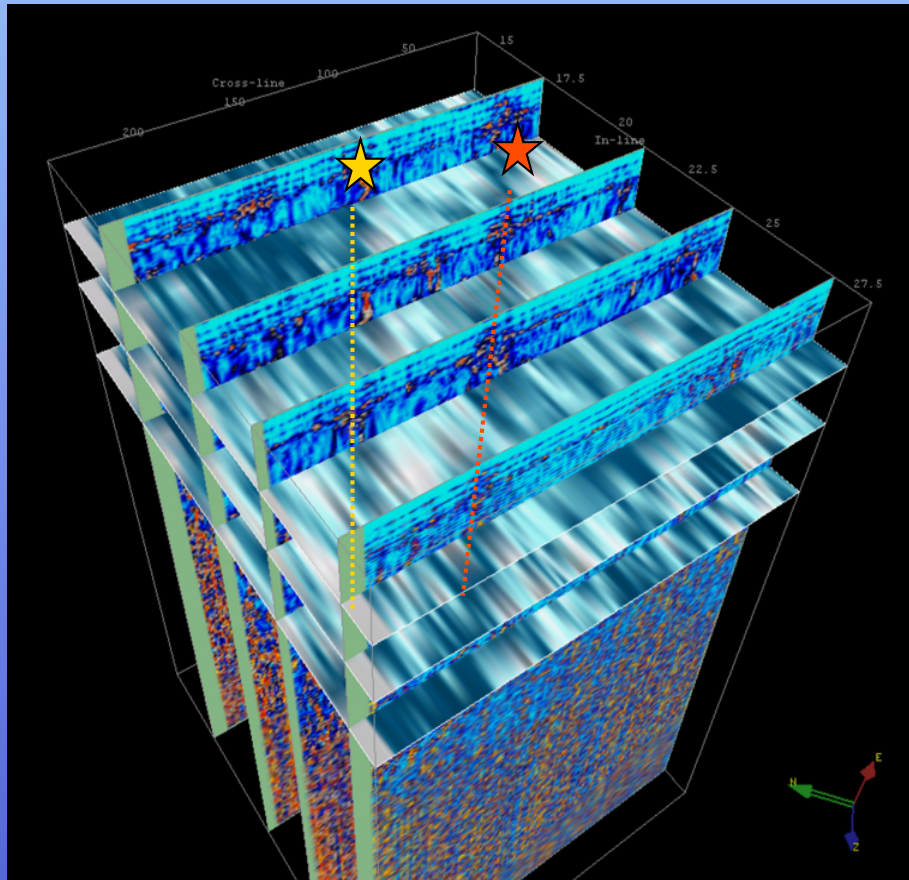


Deep (7 m)

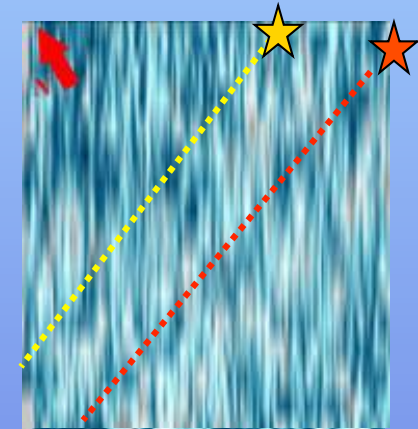


# MESO-MICRO SCALE (1m-0.1m) GPR

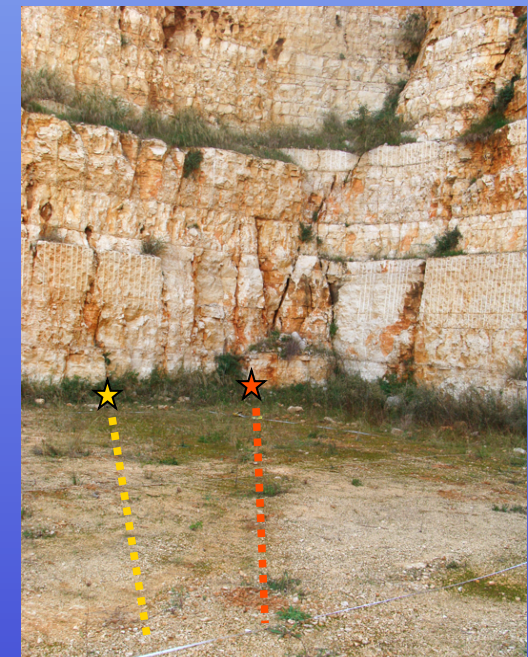
## GEOLOGICAL/STRATIGRAPHICAL/TECTONICAL INTERPRETATION



Use of Integrated attributes to extract all the information embedded within the dataset



ANALYSIS OF SERIES OF DEPTH SLICES



Validation with outcrops





**Thank you for the attention!**