DIPARTIMENTO DI GEOSCIENZE

UNIVERSITÀ DEGLI STUDI DI PADOVA

# Geophysics

# For

# Hydrological Risks

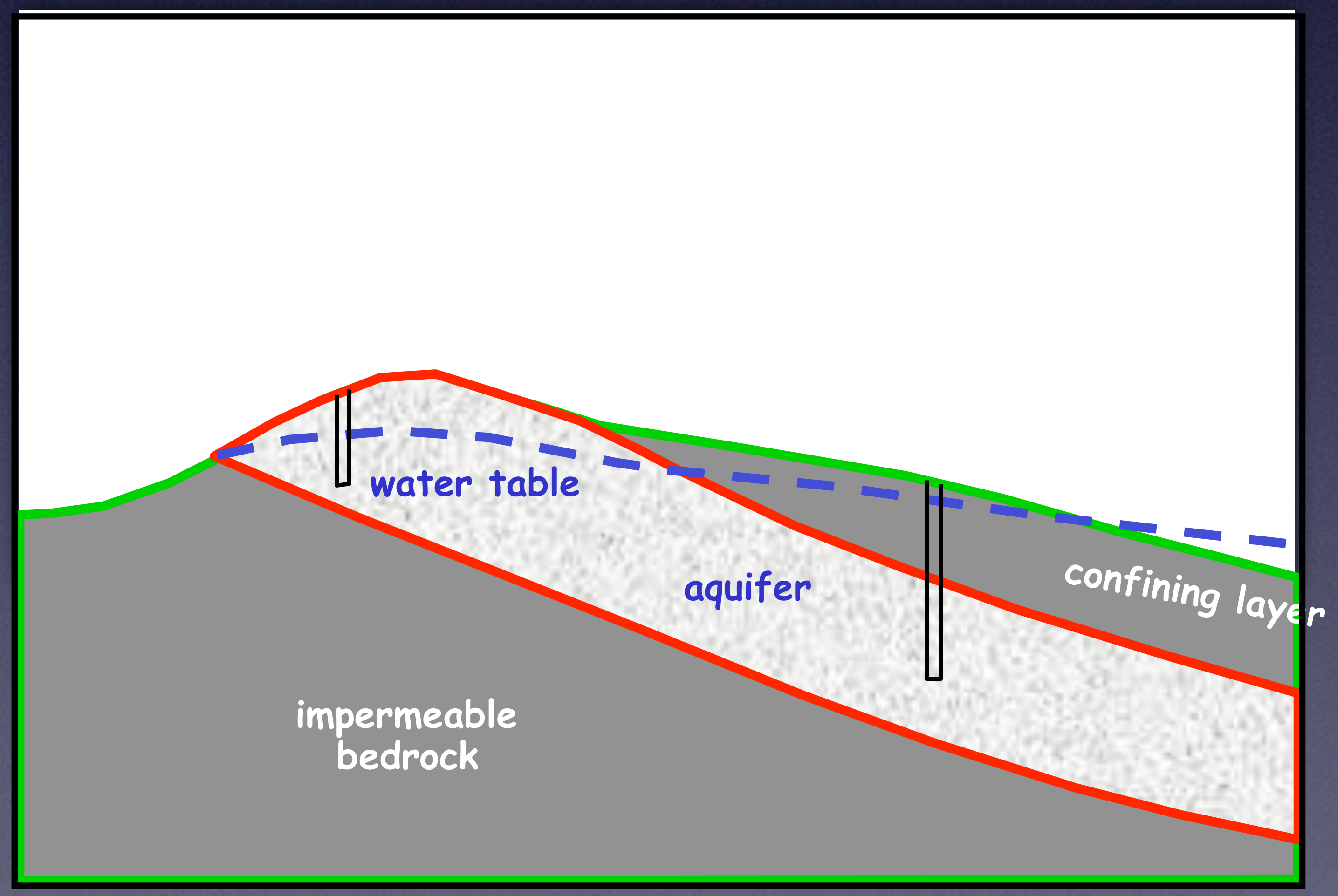
## Applied Examples

# Geophysical methods for the subsoil exploration

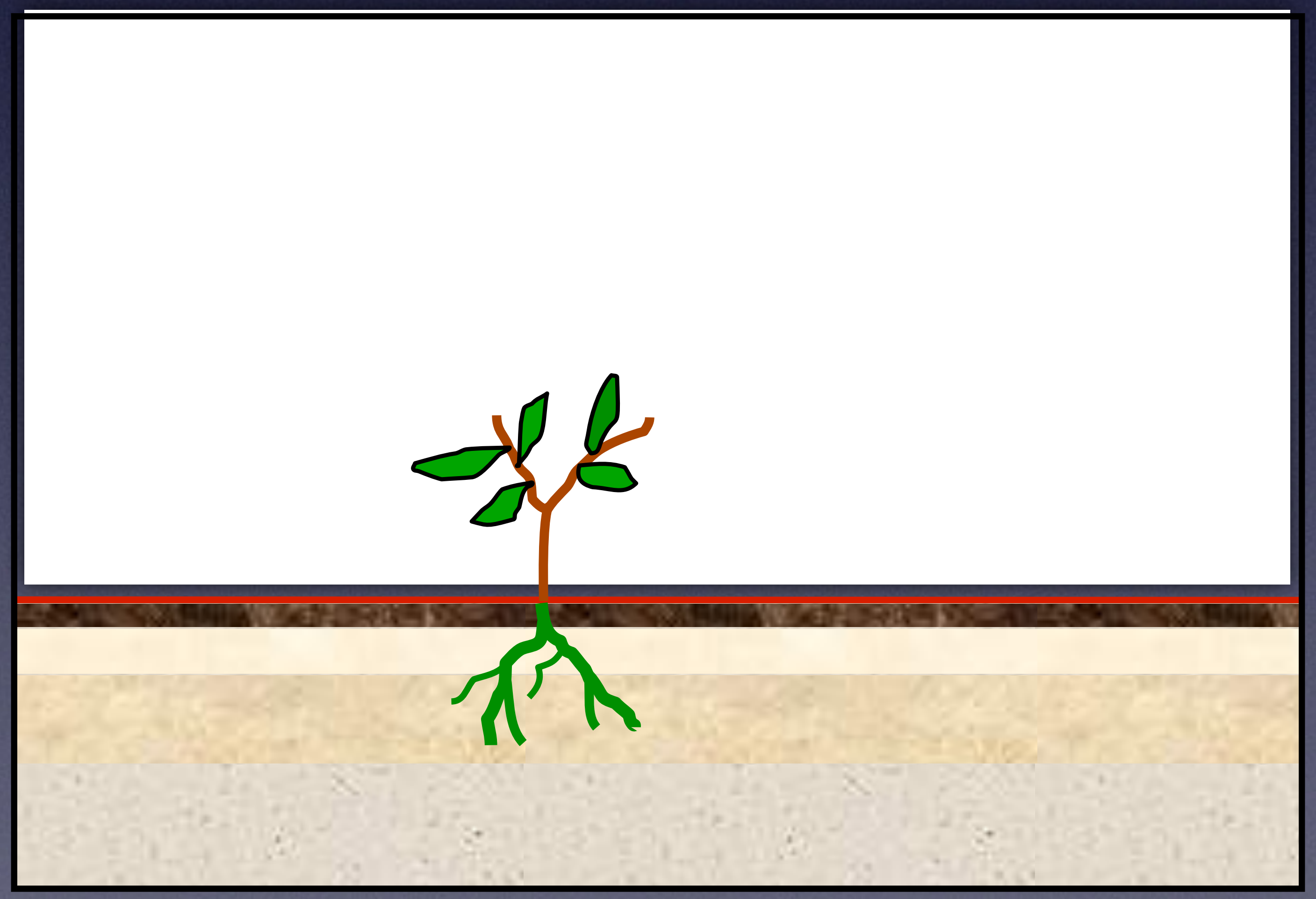
| Method | Structure | Dynamic |
|---|---|---|
| Seismic | + + | |
| Electro-Magnetic | + | ++ |
| DC resistivity methods | ++ | ++ |
| Ground Penetration Radar | ++ | + |
| Distributed Temp. Sensing | | ++ |
| Magnetics | + | |
| Gravimetry | + | + |
| Spectral Induced Polarization | + | |
| Self Potential | | + |
| Borehole logs | + + | + |

# What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)




large scale

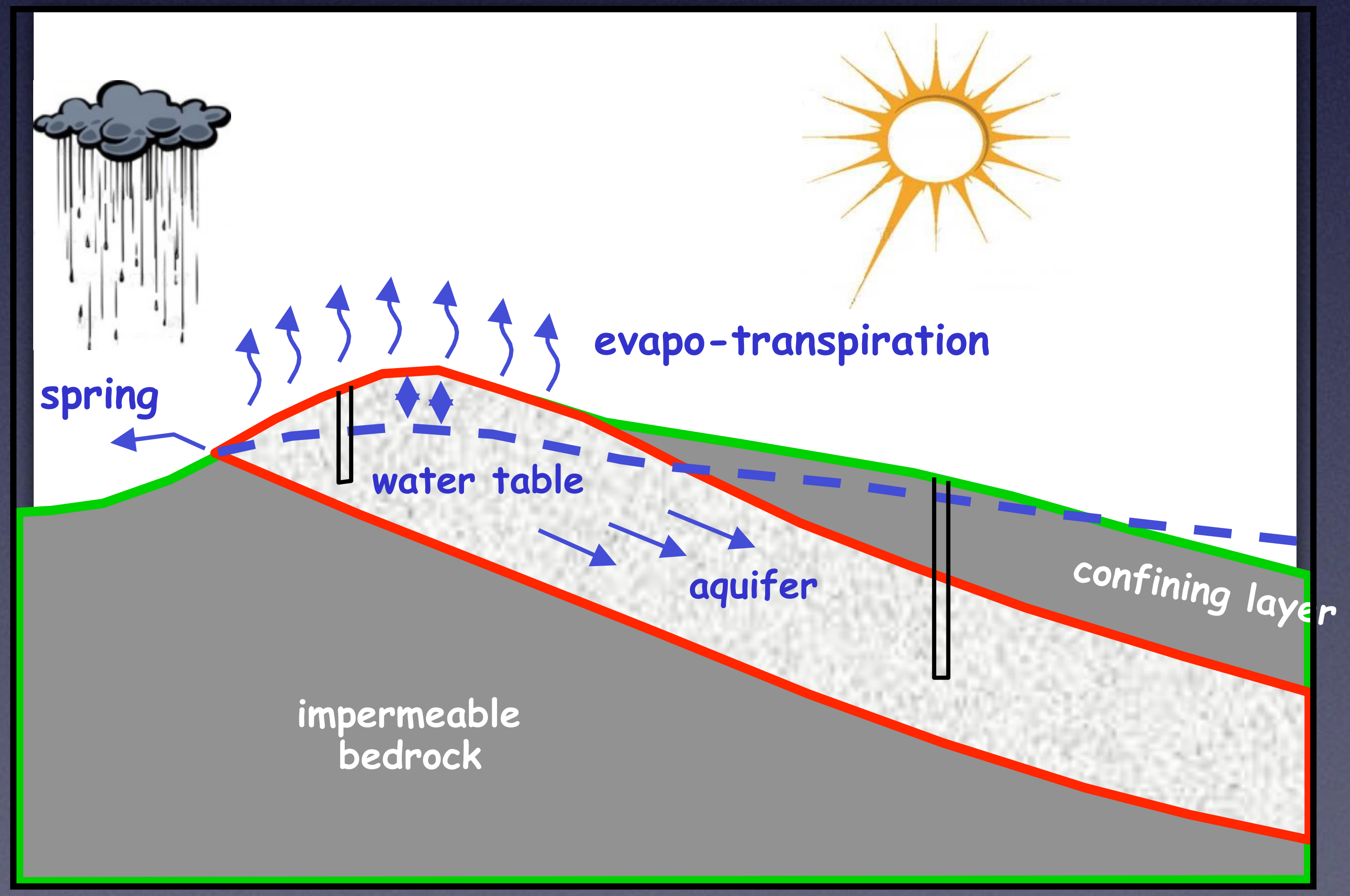


small scale

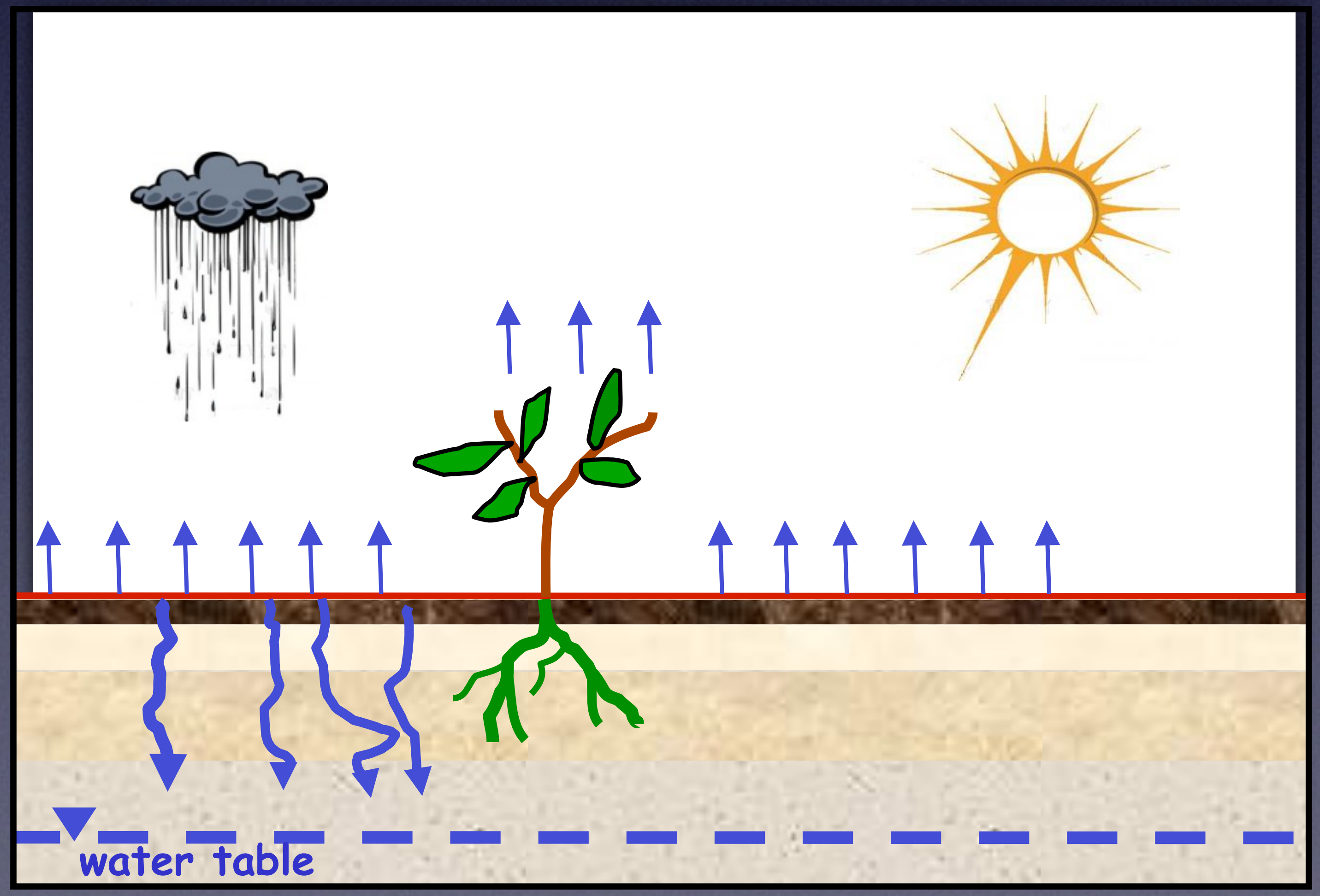
# What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)

- fluid-dynamics: e.g. time-lapse evolution of moisture content (DC resistivity methods, EM methods, GPR etc)




large scale



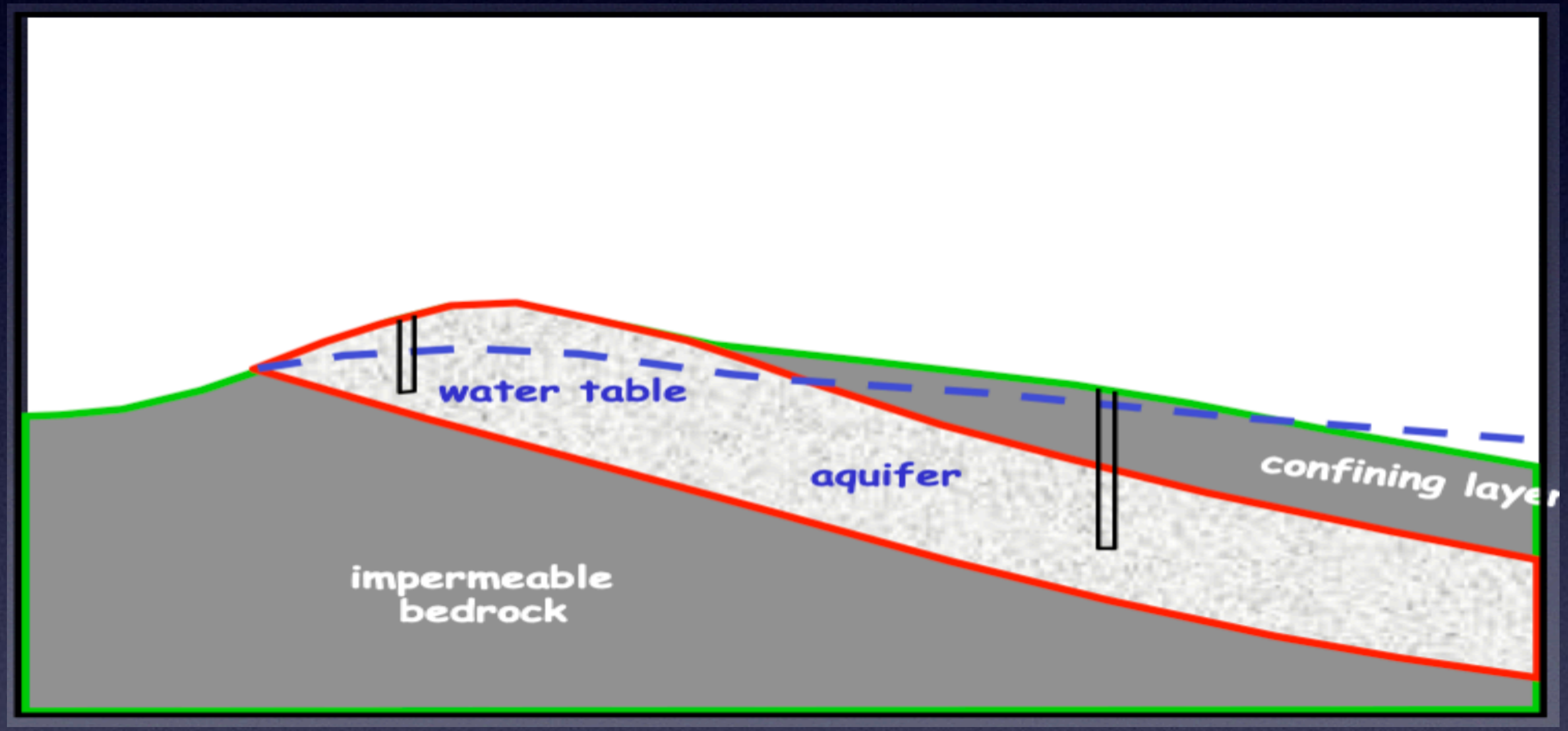

small scale

# Geophysical for the hydrological risks

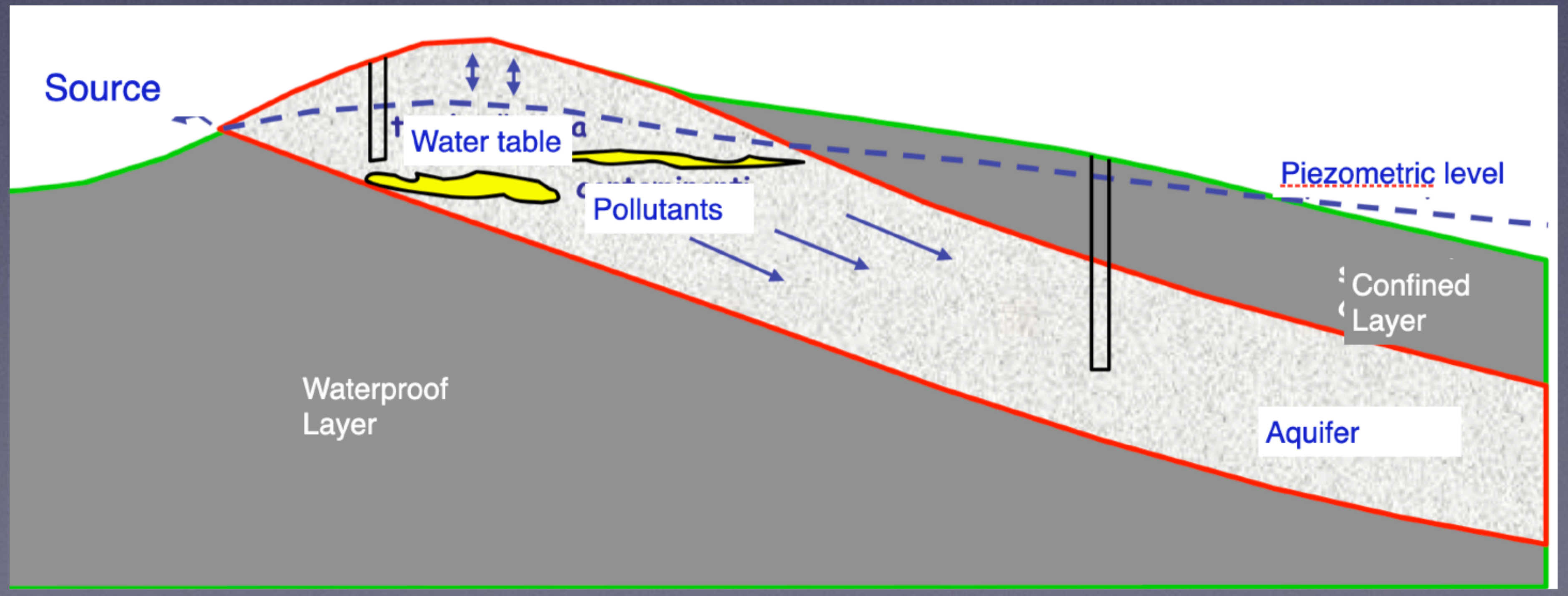


Geophysical prospecting to define:

Subsoil structure to physically constrain the problem




Subsoil dynamic in terms of changing parameters



The hydrological risk:

The hydrological risk involves the slope instability, rivers management, flood and drought occurrences due to particular environmental conditions (meteorological, geomorphological and geological conditions), pollutant diffusion in water resources and problems related to the hydrological cycle involving the population of a certain area.

# Geophysical for the hydrological risks (and resources)

Main applications of Geophysical methods for hydrological risk

1) Landslide characterisation

2) Rivers management

3) Water resources management

4) Polluted sites characterisations

## 1) Landslide characterisation

What Geophysical can help define ?

Methods

Slope subsoil structure → Electrical Resistivity Tomography, EM surveys

Slope subsoil structure → Seismic prospecting

Subsoil changes in water content → Electrical Resistivity Tomography, EM surveys

# 1) Landslide characterisation

Main surveys scopes:

- to define interface between solid ‘in place’ bedrock and landslide body (i.e. un-consolited materials prone to move under gravitational force)

→ *Landslide Thickness*

- to define the hydrological subsoil flows in order to evaluate preferential paths to be drawn or physically deviated.

→ *Landslide Hydrology*

# 1) Landslide characterisation

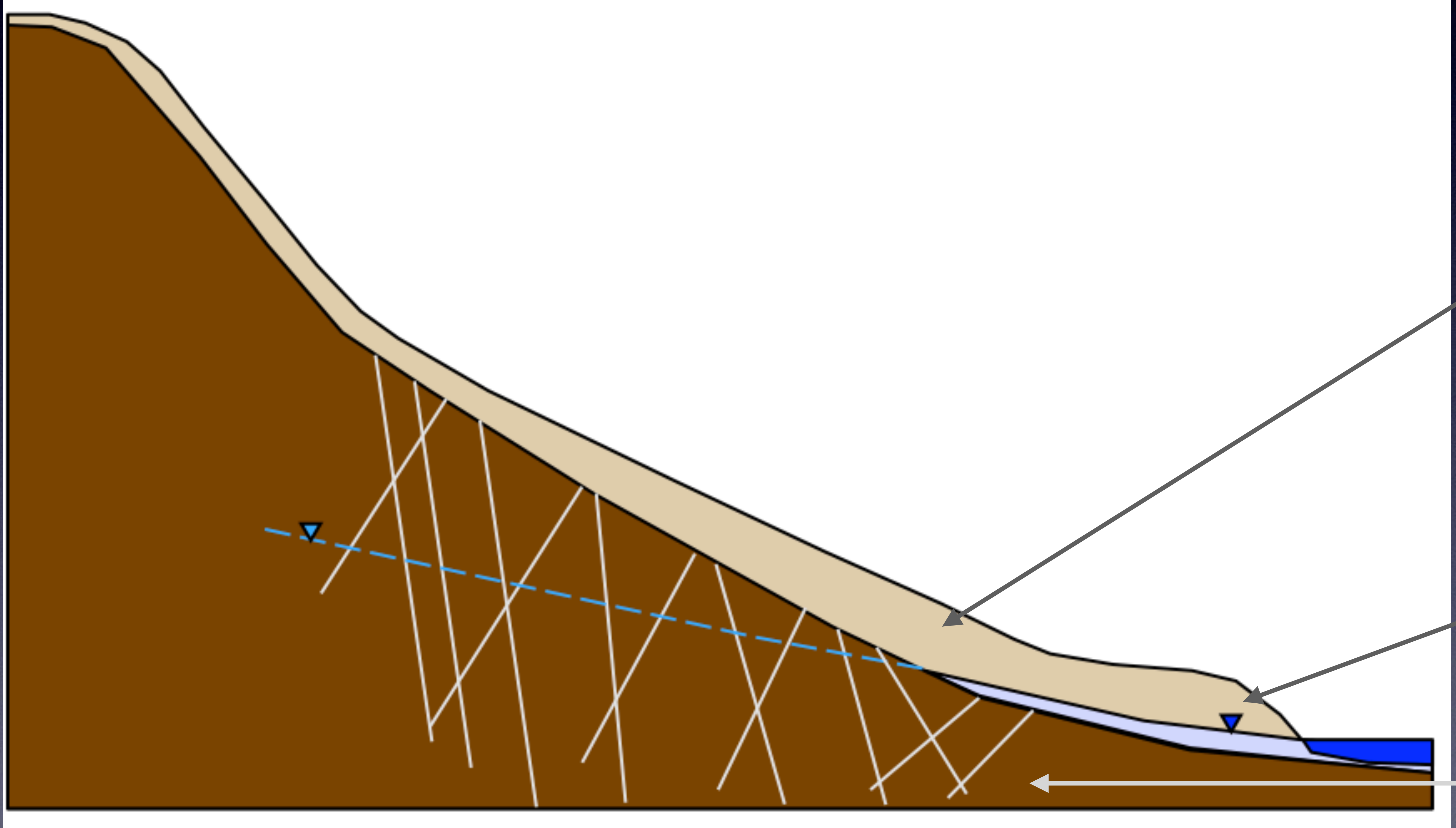
Main surveys scopes:

*Landslide Thickness* → Seismic prospecting (refraction, reflection, passive)
Electrical Resistivity Tomography

*Landslide Hydrology* → Electrical Resistivity Tomography
(EM in few cases)

# 1) Landslide characterisation

## Landslide characterisation



*Landslide body (materials in motion)*

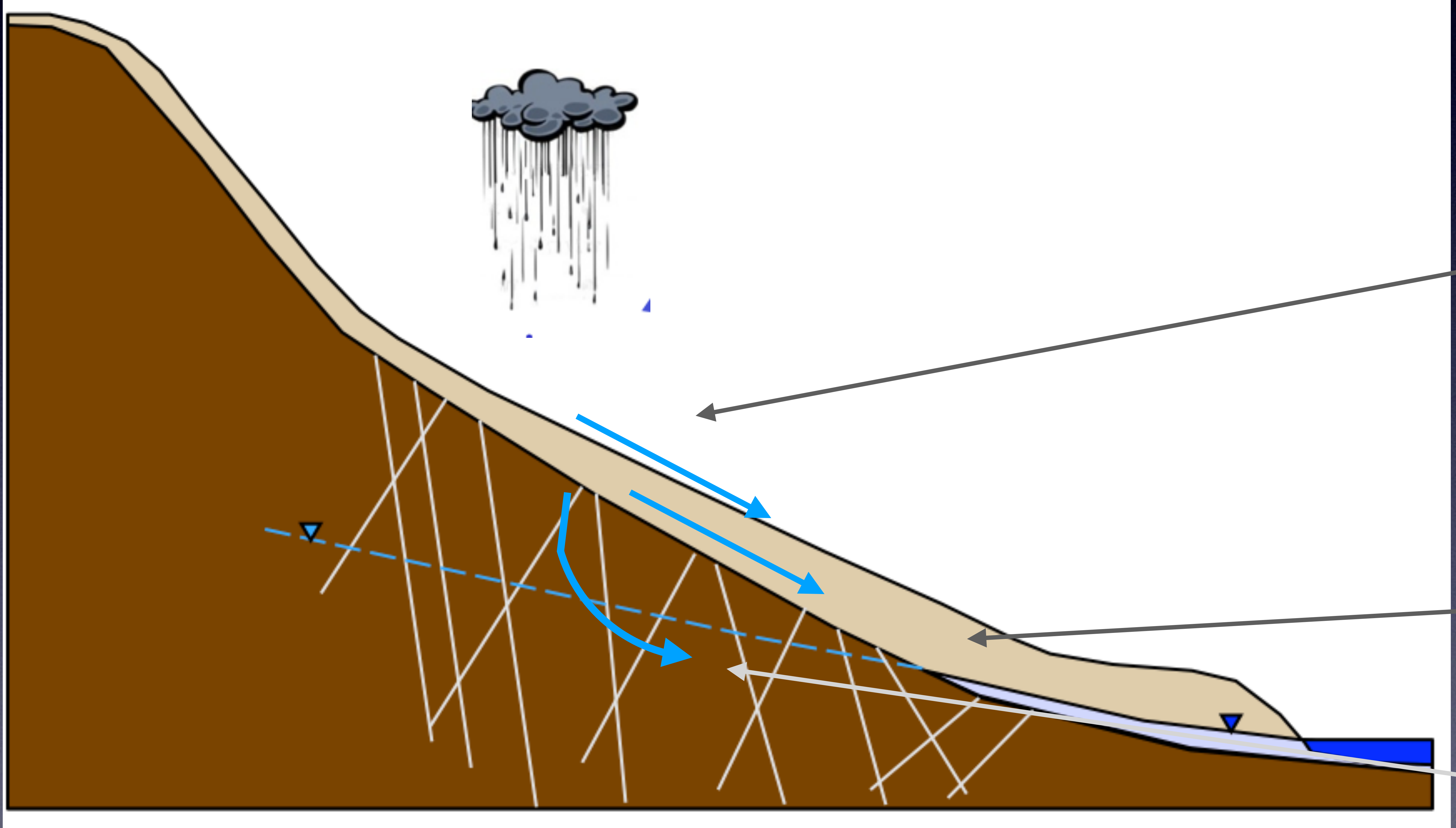
*Water table*

*Bedrock 'in place' rock*

Seismic prospecting / Electrical Resistivity Tomography

# 1) Landslide characterisation

## Landslide dynamic characterisation



*Water runoff*

*flow inside the landslide body*

*Flow in fractured bedrock*

Electrical Resistivity Tomography

## 1) Landslide characterisation

Connected to landslide characterisation is the geophysics applied to Permafrost sites

Methods

Electrical Resistivity Tomography

EM surveys, seismic

*To characterise the frozen/unfrozen Layers and monitor in time thawing evolution*

# 1) Landslide characterisation

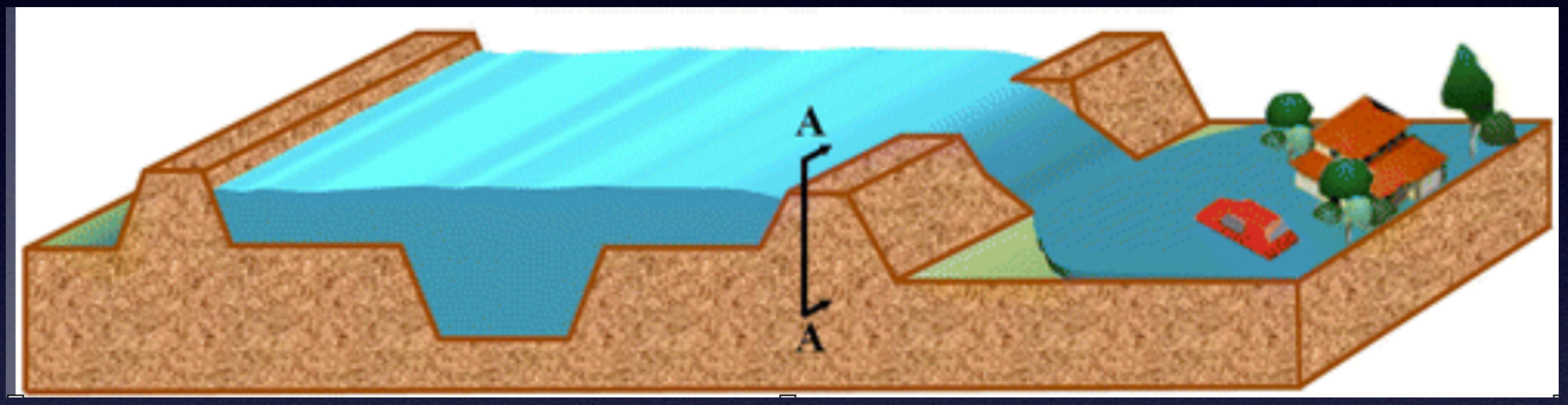
| Method | PRO | CONS |
|---|---|---|
| Electrical Resistivity Tomography | Easy to collect, sensible to water content and dynamic (Time lapse) | Depth of investigation (1/5 of array length) |
| Electro-magnetic Surveys | Contact less method, very easy to collect data, sensible to water content changes | Depth limited to few meters |
| Seismic method | Depth of investigation, sensible to soil density changes (e.g. very good for solid bedrock characterisation) | Logistic (installation, sources, etc), cost |

## 2) Rivers management

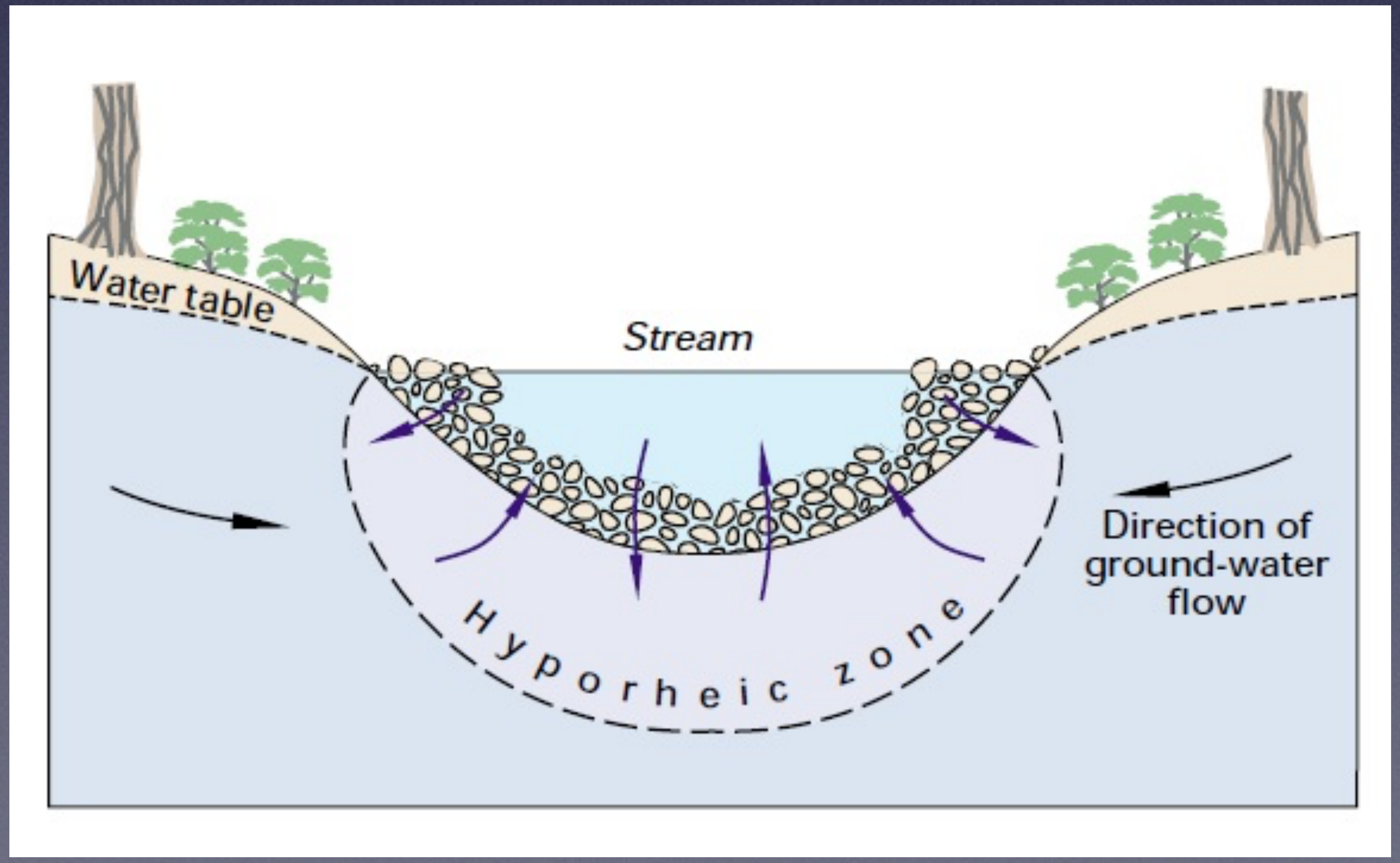
| What Geophysical can help define ? | | Methods |
|---|---|---|
| Levees structure | → | Electrical Resistivity Tomography<br>EM surveys<br>(Seismic prospecting) |
| Levees water content<br>Changes | → | Electrical Resistivity Tomography<br>EM surveys |
| Hyporheic exchanges | → | Electrical Resistivity Tomography |

## 2) Rivers management

Main surveys scopes:




- monitor levees structure, piping zones, leakages, presence of voids




- monitor subsoil/river water exchanges (hyphoreic zone)

The hyporheic zone (part of the critical zone) is the transition region where the interactions between surface water and groundwater take place

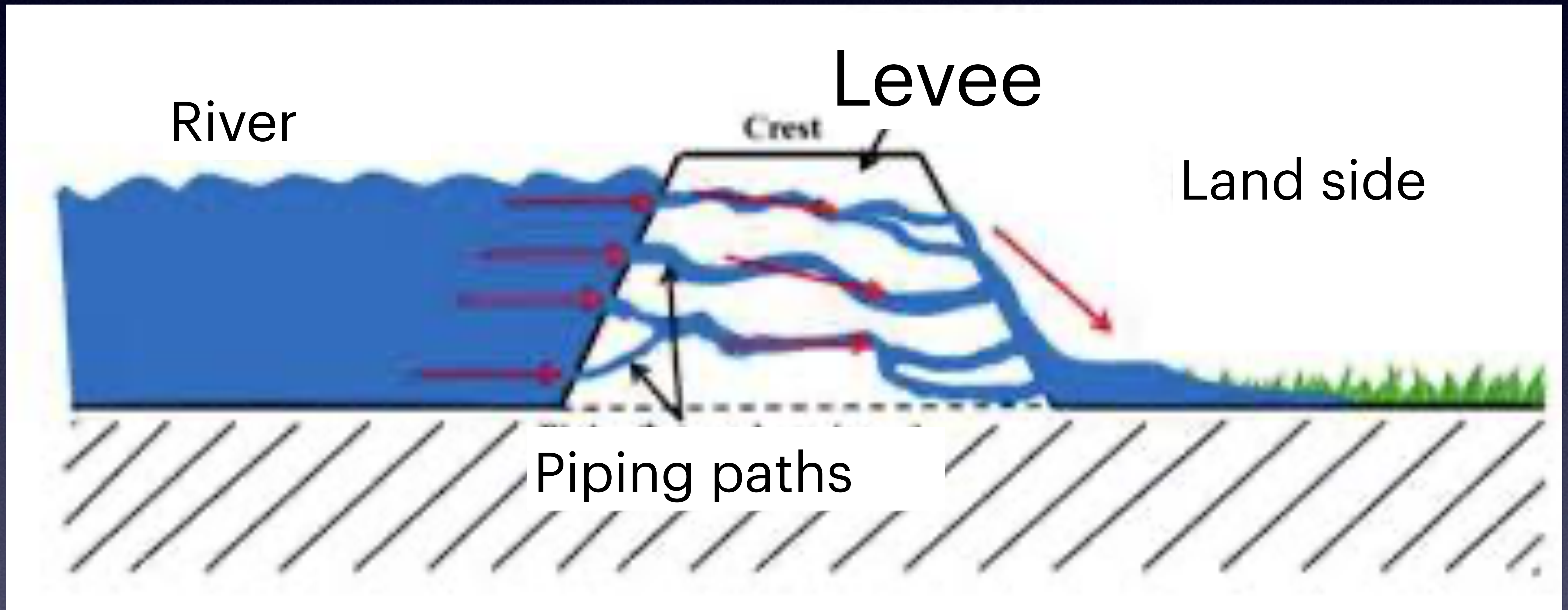
## 2) Rivers management

Main surveys scopes:

*Levees Structure* → Seismic prospecting (refraction, surface wave)
Electrical Resistivity Tomography
(EM in few cases)

*Water Exchanges monitoring* → Electrical Resistivity Tomography
Fiber Optic temperature monitoring
DTS Distributed Temperature sensing

## 2) Rivers management

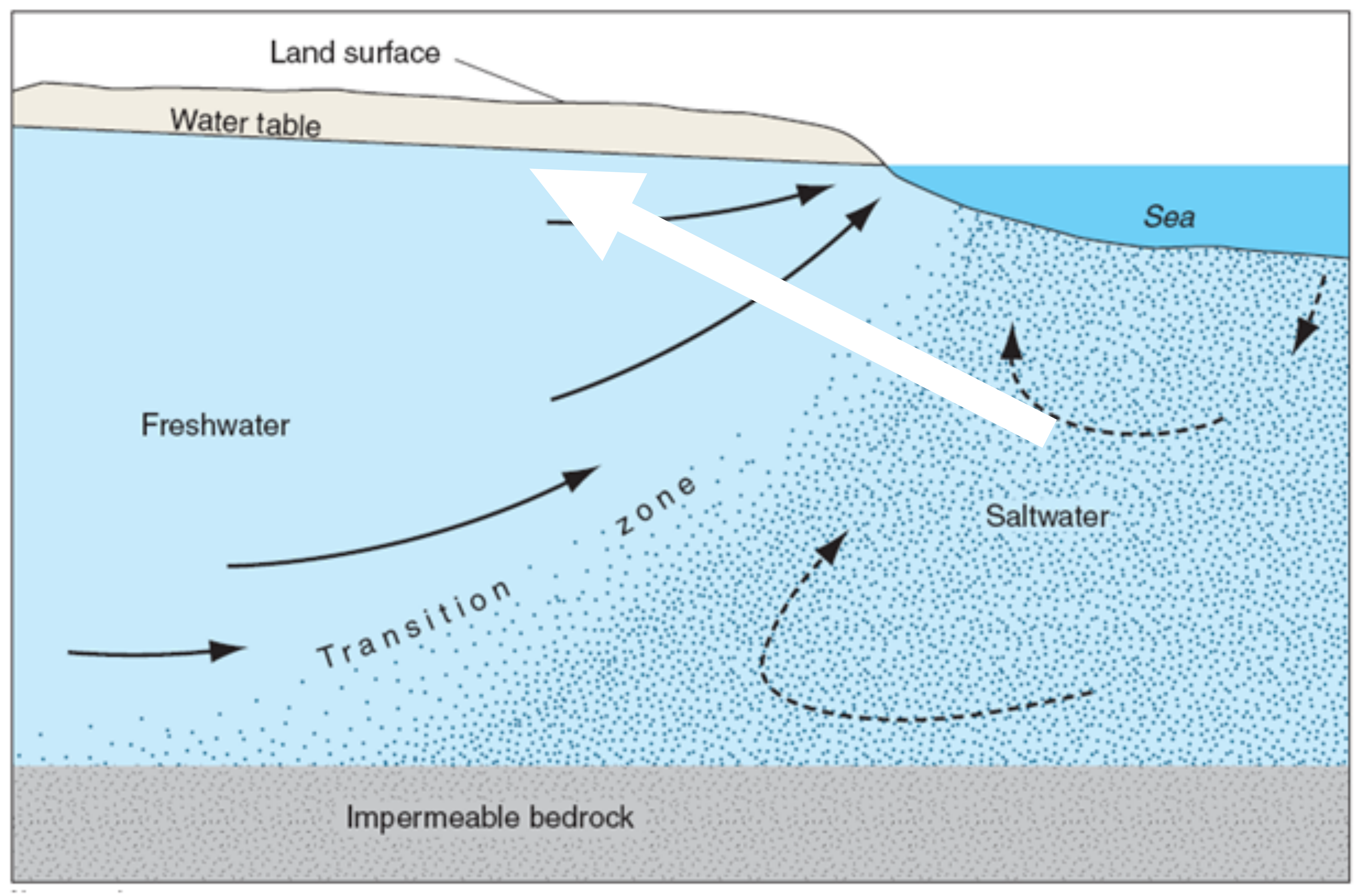



**Seismic prospecting** = rigidity and stability of the levee monitoring

**EM / ERT** = electrical properties of the levee, highlighting anomalous zones

Or high water content zone (piping monitoring)

## 2) Seawater management




Salt water intrusion

Big issue in coastal agriculture

Electrical Resistivity Tomography **ERT** = monitoring of salinity of subsoil water

## 2) Rivers management

| Method | PRO | CONS |
|---|---|---|
| Electrical Resistivity Tomography | sensible to water content and dynamic (good for Time lapse) | Ground contact method<br>Hard to deploy in long levee structure |
| Electro-magnetic Surveys | Contact less method, very easy to collect data, sensible to water content changes | Depth limited to few meters<br>Poor resolution respect to ERT |
| Seismic method | Depth of investigation, sensible to rigidity of the structure | Logistic (installation, sources, etc), |

## 3) Water resources management

What Geophysical can help define ?

Methods

Water presence → Electrical Resistivity Tomography ERT; Vertical Electrical Survey VES

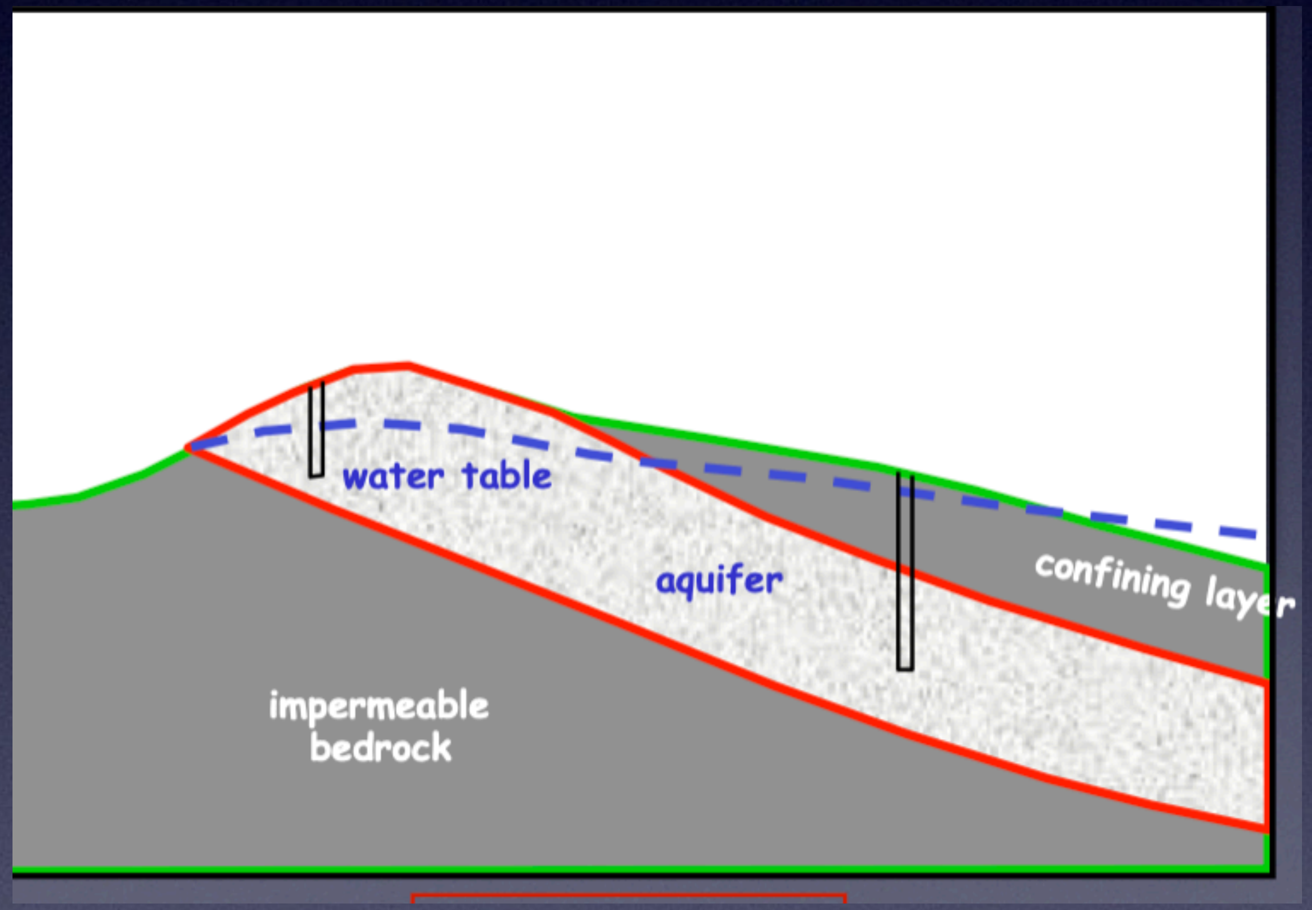
Water dynamic

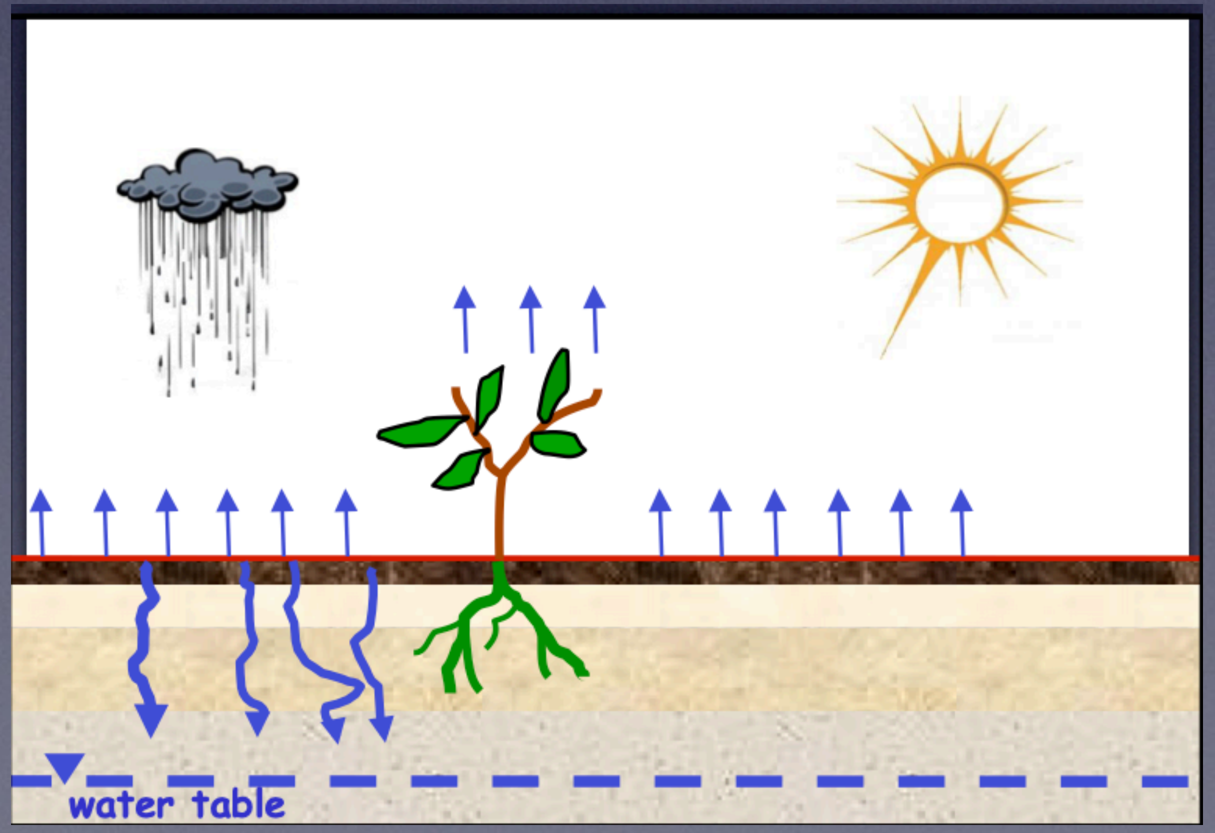
e.g. phreatic oscillations → Electrical Resistivity Tomography ERT

Precision Agriculture

# 3) Water resources management

Main surveys scopes:




- Hydrological bodies characterisation
- Subsoil water dynamic
- Plants/soil interactions

→ Electrical Resistivity Tomography

# 3) Water resources management

| Method | PRO | CONS |
|---|---|---|
| Electrical Resistivity Tomography | sensible to water content and dynamic (flow dynamic in Time lapse) | Depth of investigation / resolution in depth |
| Vertical Electrical Sounding VES | Very quick and easy collecting logistic Depth of investigation | Poor resolution respect to ERT |

# 4) Polluted sites characterisations

| What Geophysical can help define ? | | Methods |
|---|---|---|
| Presence of Pollutants | → | Electrical Resistivity Tomography<br>EM surveys<br>RADAR surveys |
| Dynamic of Pollutants in the subsoil | → | Electrical Resistivity Tomography<br>RADAR surveys |

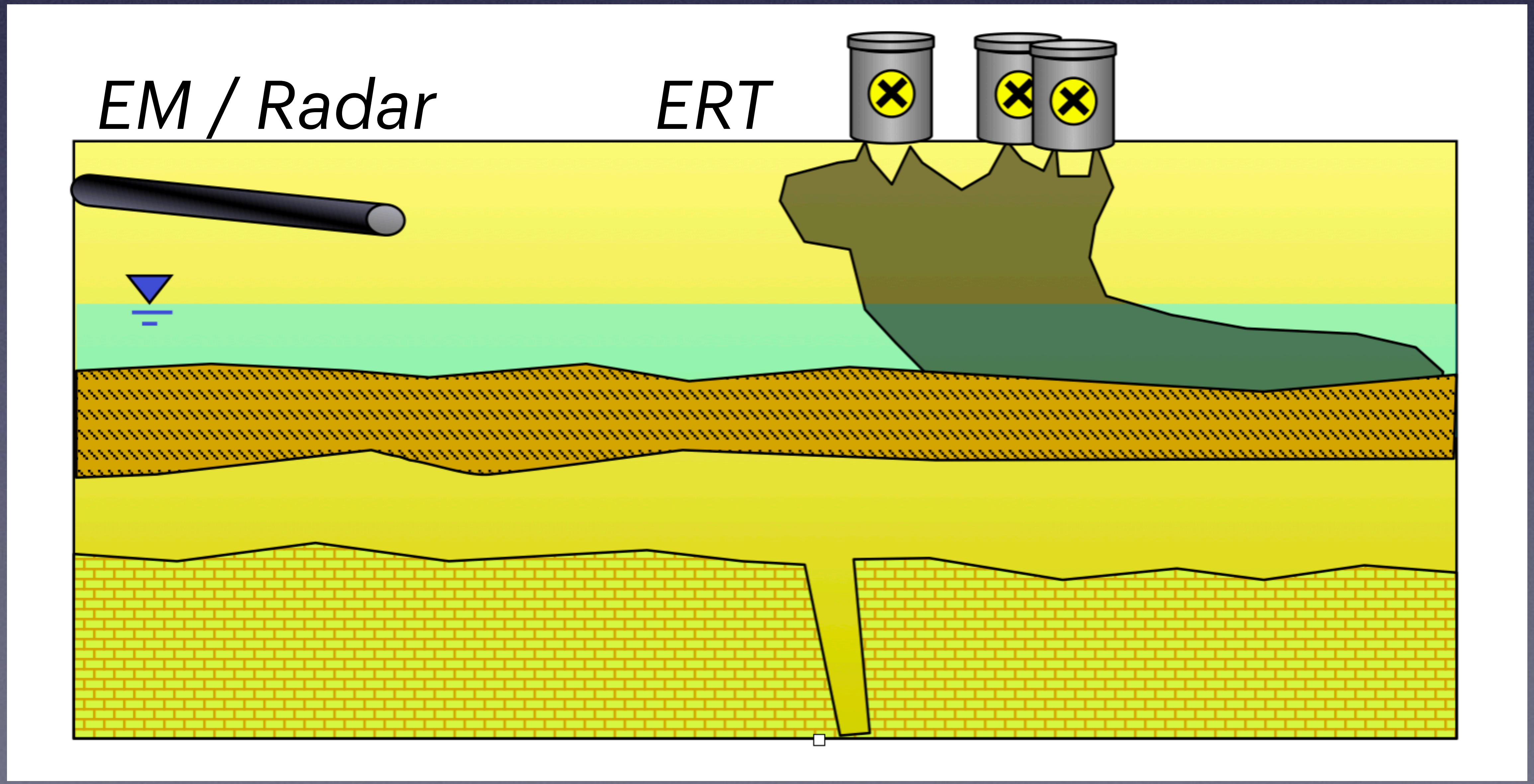
# 4) Polluted sites characterisations

Main surveys scopes:

*Polluants*

*In the subsoil* → Electrical Resistivity Tomography

Electro-magnetic survey



# 4) Polluted sites characterisations

| Method | PRO | CONS |
|---|---|---|
| Electrical Resistivity Tomography | sensible to water content and pollutants presence<br>Good in borehole | Logistic in big polluted area |
| Electro-magnetic Surveys | Contact less method, very easy to collect data map, sensible to water content changes and pollutants | Depth limited to few meters<br>Resolution |
| GEO-RADAR methods | Quick logistic, very high resolution especially in borehole | Depth of penetration |

## Geophysical for the hydrological risks (and resources)

- The seismic methods
- The Electric methods
- The Electro-magnetic methods (in frequency domain)
- The Radar methods

for the hydrological risks

# The seismic methods

# for Hydrological Risks

# Geophysical for the hydrological risks (and resources)

| Method | Structure | Dynamic |
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| Distributed Temp. Sensing | | ++ |
| Magnetics | + | |
| Gravimetry | + | + |
| Spectral Induced Polarization | + | |
| Self Potential | | + |
| Borehole logs | + + | + |

# Geophysical for the hydrological risks (and resources)



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| Self Potential | | + |
| Borehole logs | + + | + |

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# PHYSICAL PROPERTIES (P)

- **Seismic** : *elastic moduli and density*
- **Gravimetry** : *density*
- **Magnetic Methods** : *magnetic susceptibility*
- **GeoElectrics** : *electric conductivity*
- **Electro-Magnetic methods** : *electric conductivity*
- **Induced polarization** : *electric complex conductivity*
- **Spontaneous potential** : *electric conductivity sources*
- **Ground penetrating radar** : *dielectric constant*

# *PHYSICAL PROPERTIES (P)*

- ***Seismic** : elastic moduli and density*
- ***Gravimetry** : density*
- ***Magnetic Methods** : magnetic susceptibility*
- ***GeoElectrics** : electric conductivity*
- ***Electro-Magnetic methods** : electric conductivity*
- ***Induced polarization** : electric complex conductivity*
- ***Spontaneous potential** : electric conductivity sources*
- ***Ground penetrating radar** : dielectric constant*

## Near Surface Geophysics

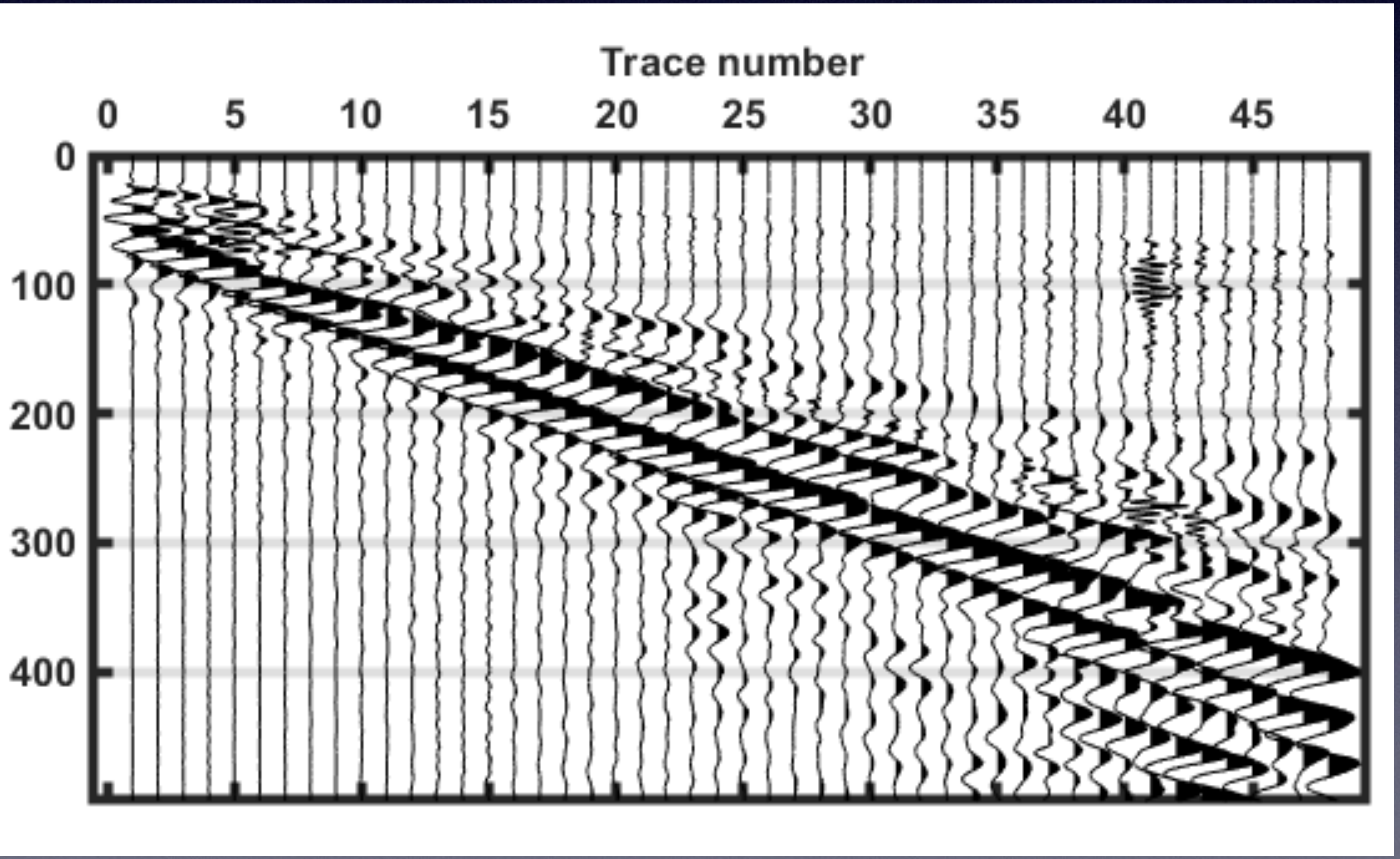
Seismic → Refraction seismic (both SH or P waves )

Seismic → Surface wave methods (to retrieve Vs structure)

# Geophysical for the hydrological risks (and resources)

## Near Surface Seismic for hydrological risks

Study propagation of elastic waves ti retrieve the elastic moduli of the subsoil




Physics parameter P
=
*Elastic properties*

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# Geophysical for the hydrological risks (and resources)

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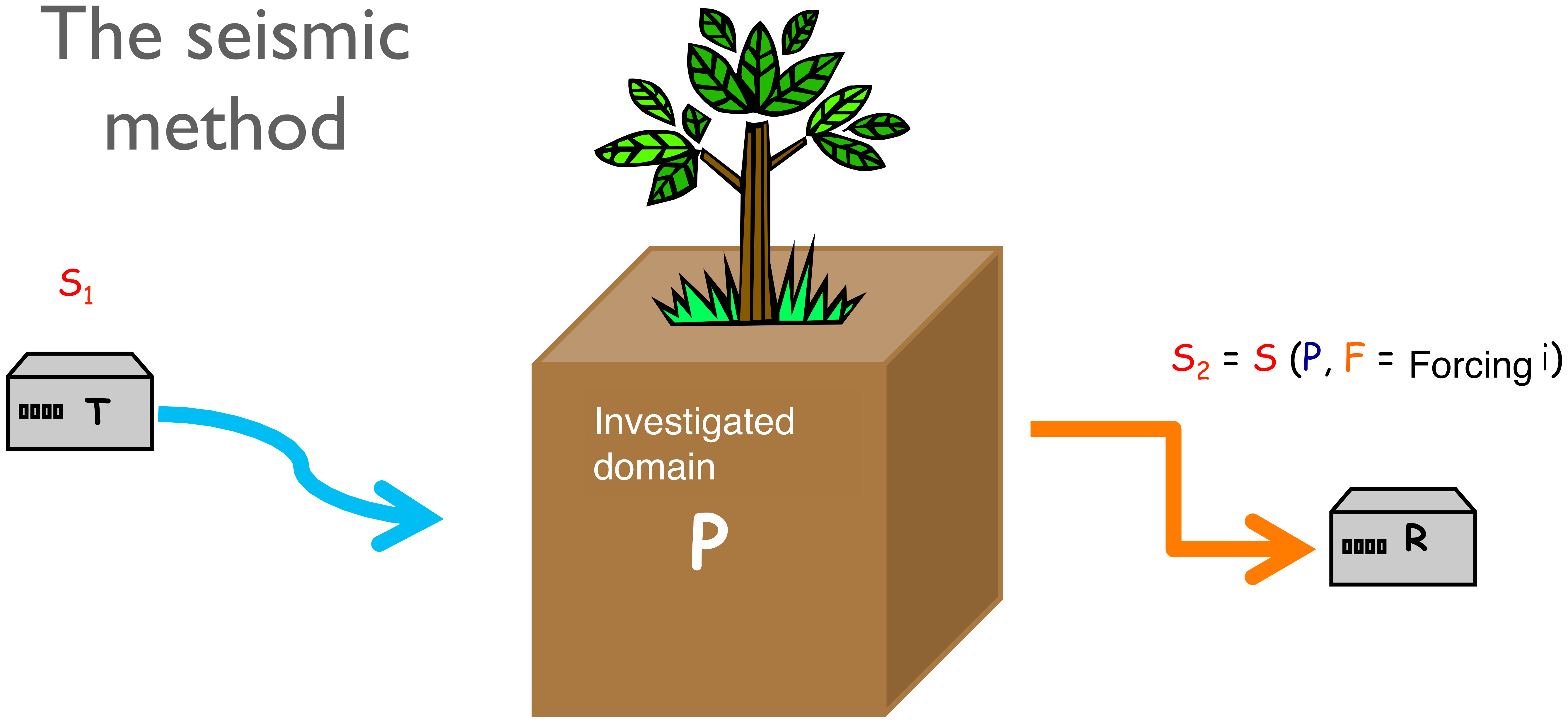
## The seismic method



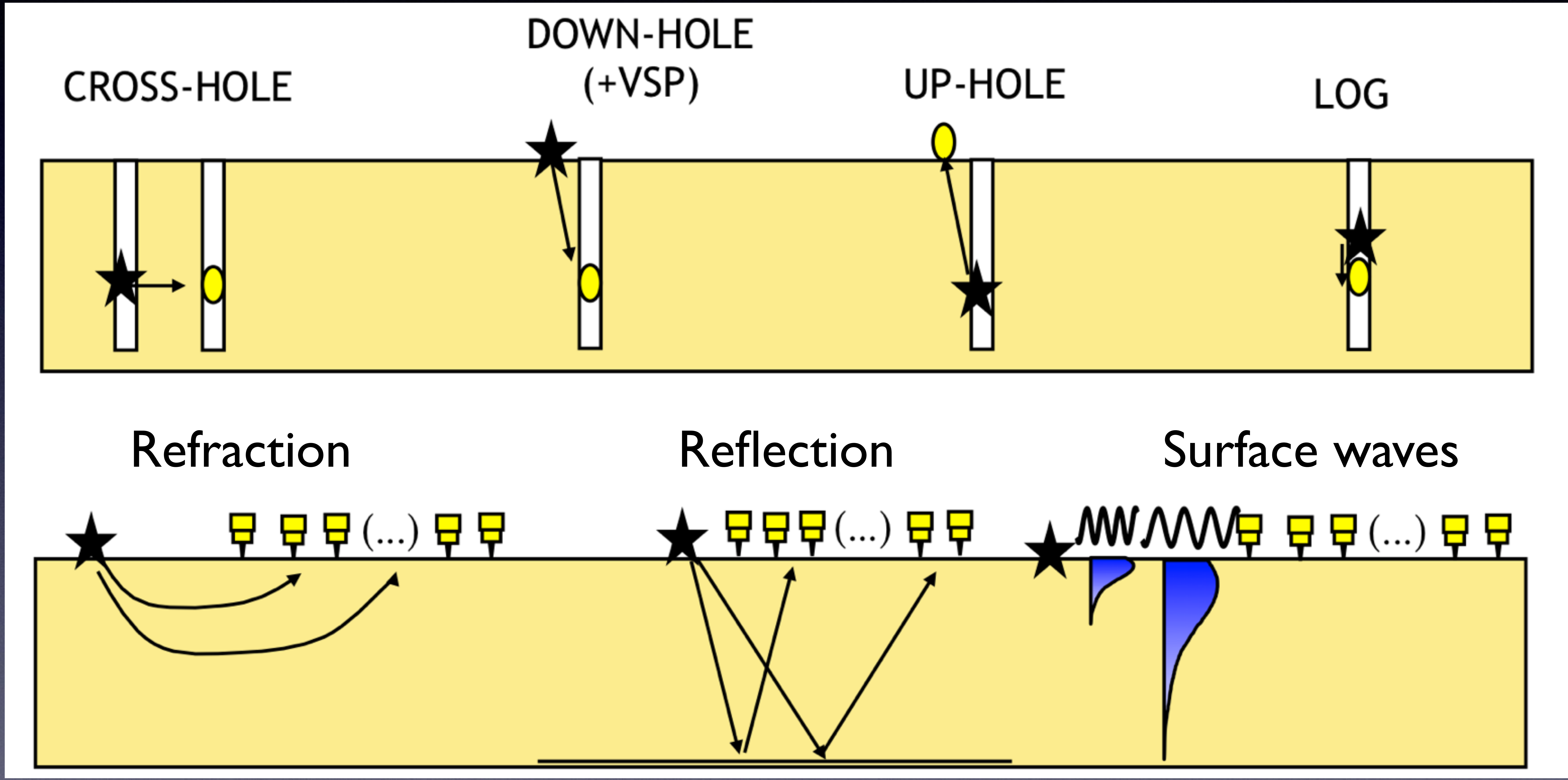

$S_1$ = Signal = Elastic wave source

$S_2$ = Signal = Induced vibration

**P** = Physical parameter Elastic moduli/ density

Seismic Methods
- Borehole seismic
- Surface seismic
  - ~~Reflection seismic~~
  - Refraction seismic
  - Surface wave seismic

## Borehole Seismic

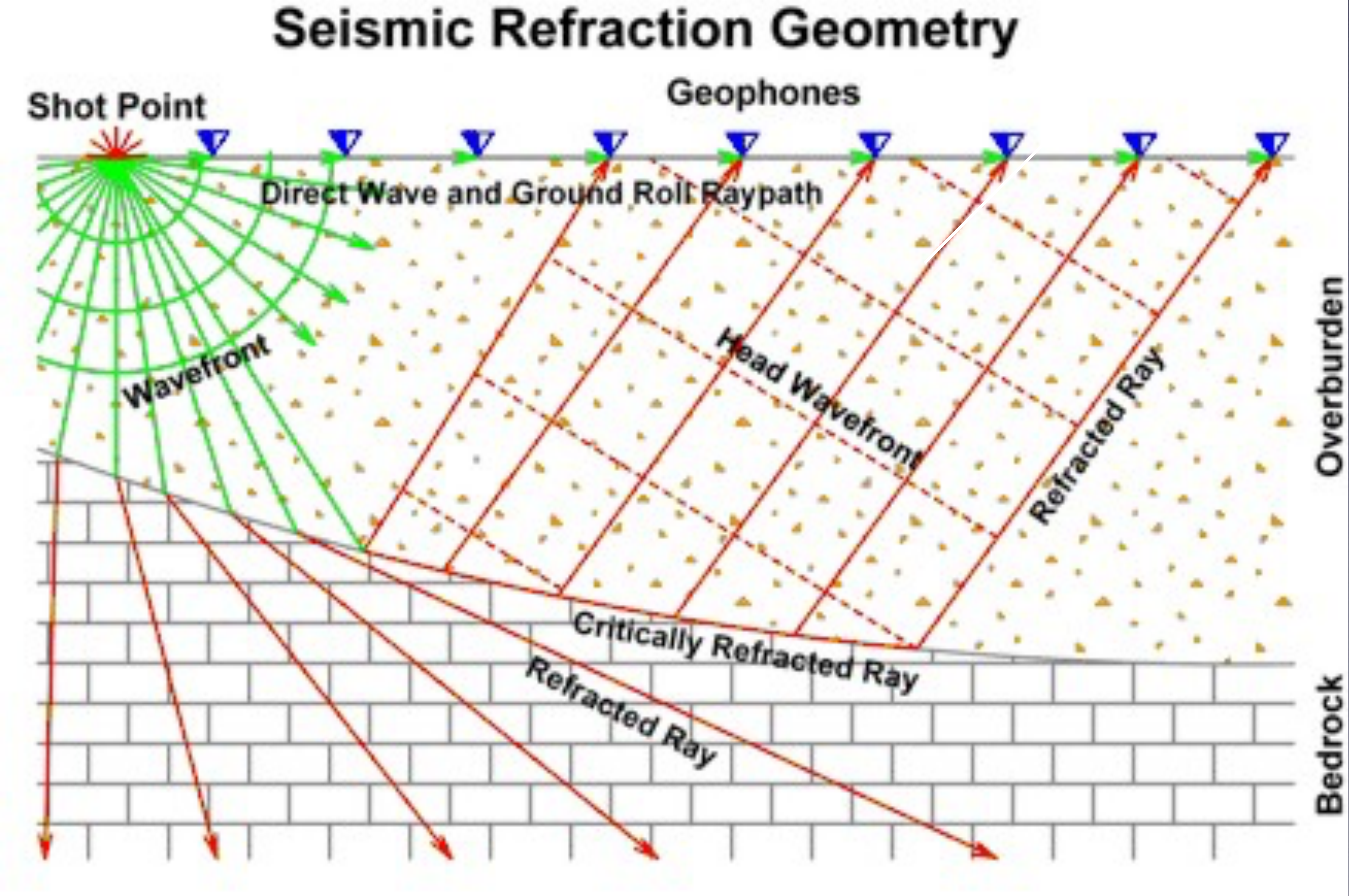



## Surface seismic

## *REFRACTION SEISMIC*

*Refracted waves study to evaluate* → *Thickness of the deposits*

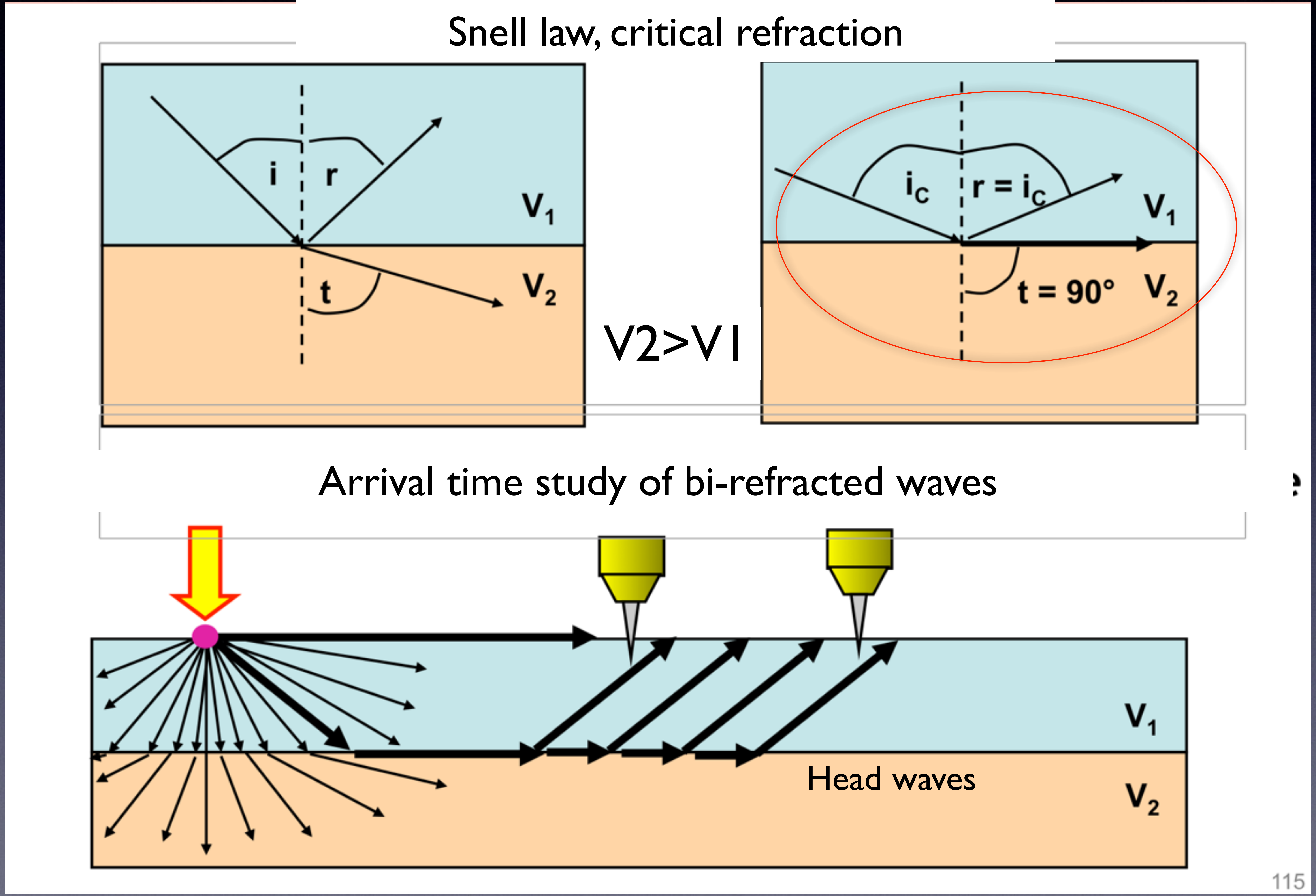
→ *Characteristic of the deposits*



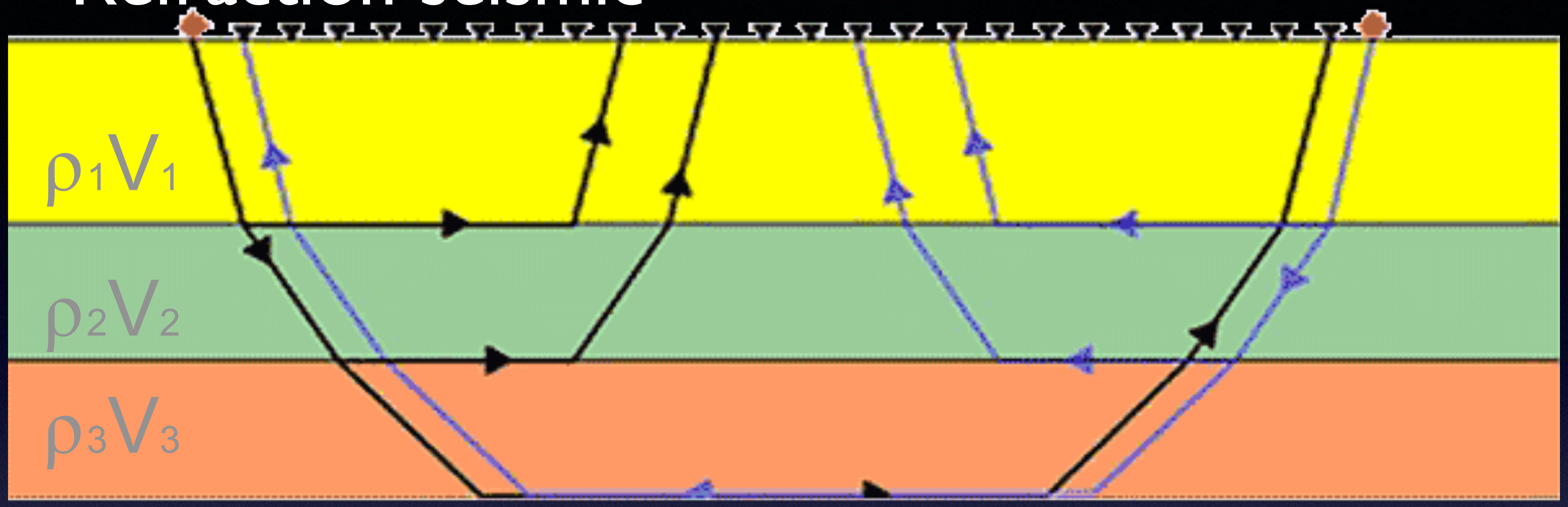

*Critically refracted waves*

*Head-waves*

# Refraction seismic



# Refraction seismic




Impedance Contrast $= \frac{\rho_2 V_2}{\rho_1 V_1} > 1$ → REFRACTION

If V2 < V1 No refracted

→ Method is BLIND to velocity inversion in depth

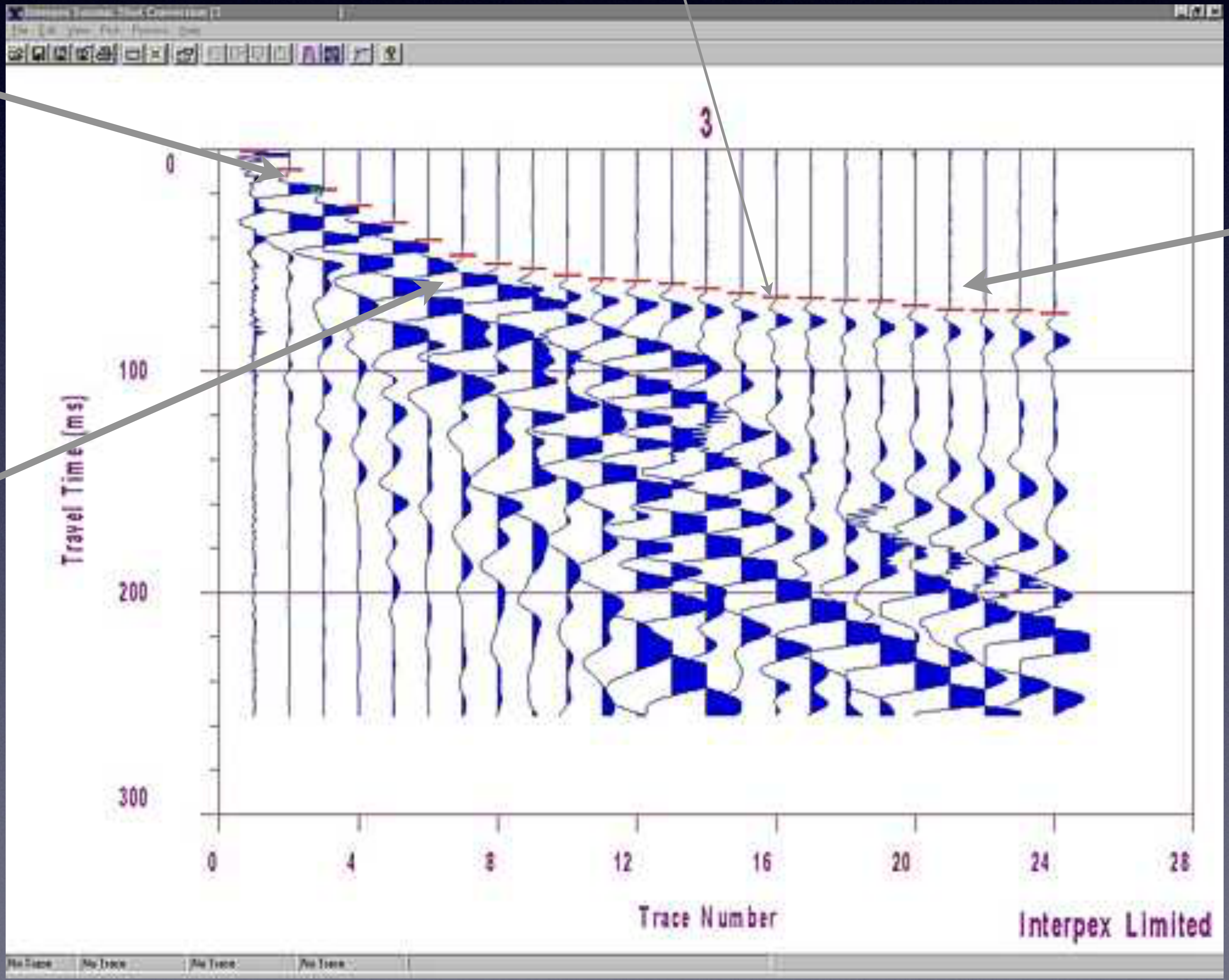
# Principles of REFRACTION SEISMIC

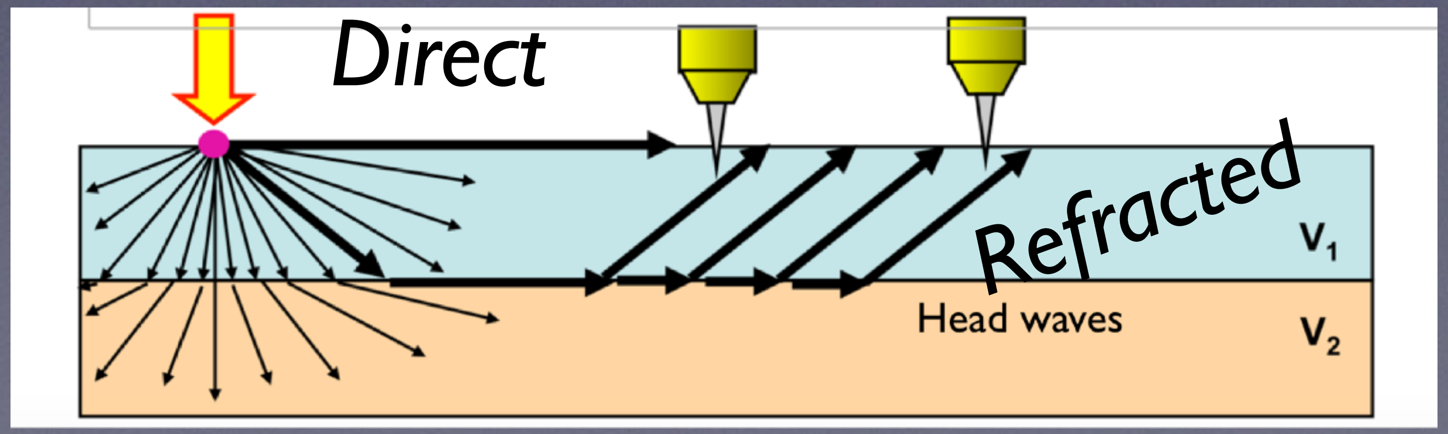
## First break Picking of the time arrivals

Direct waves front

Refracted waves front

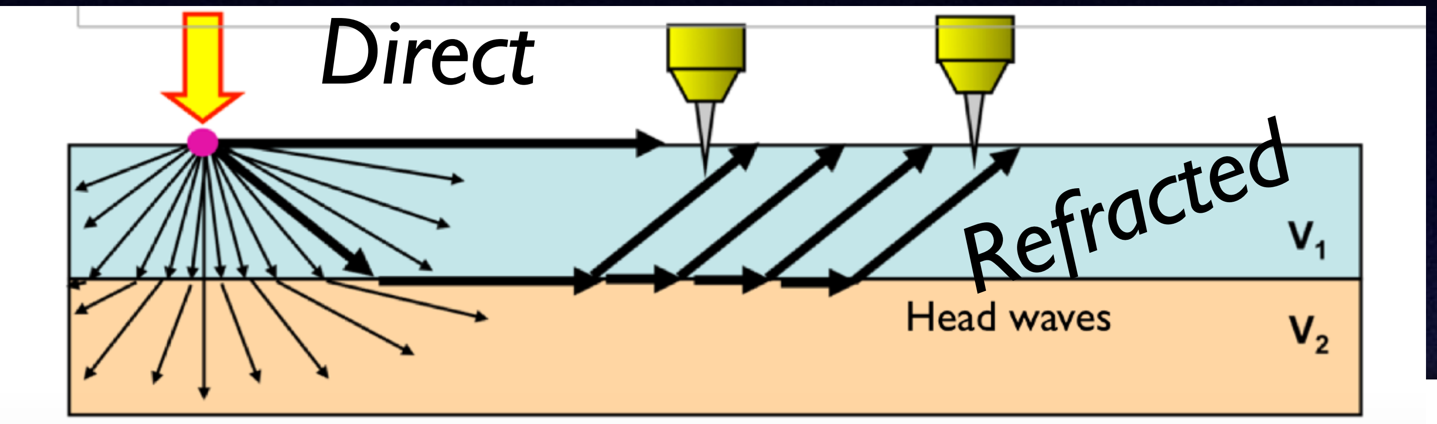
Cross point



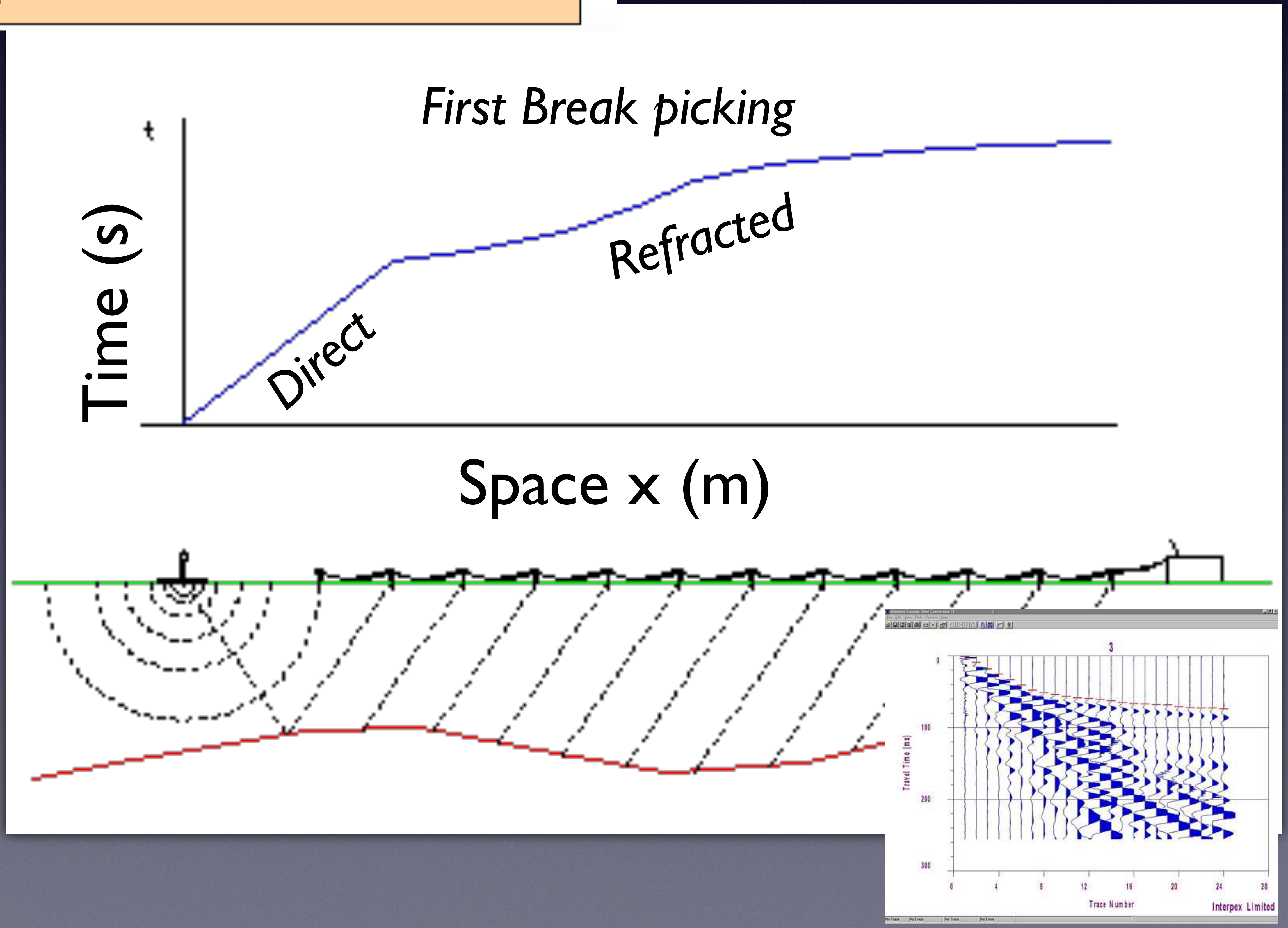



# Principles of REFRACTION SEISMIC

## First break Picking of the time arrivals

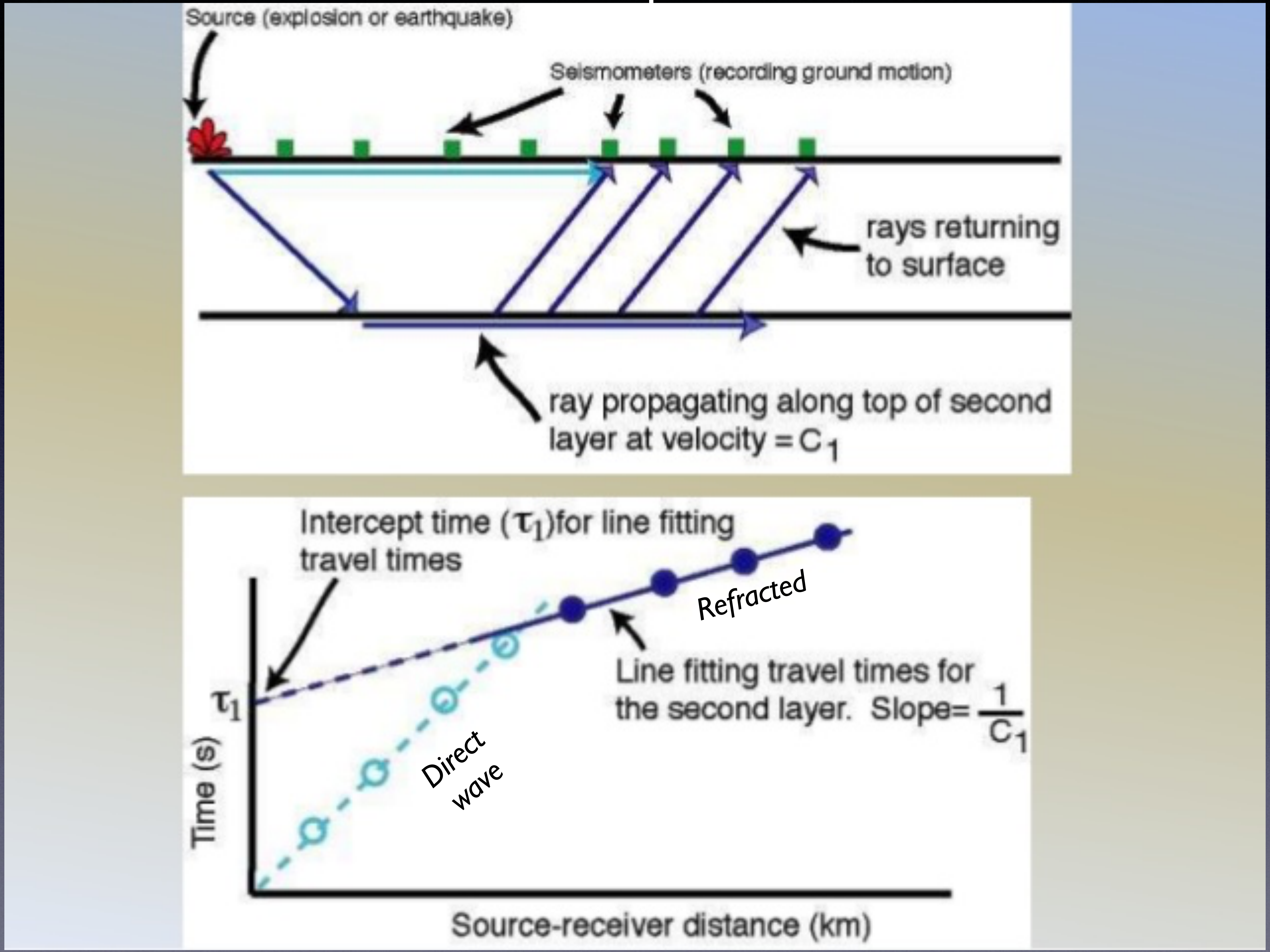



Space/Time diagram




Travel-Time curves

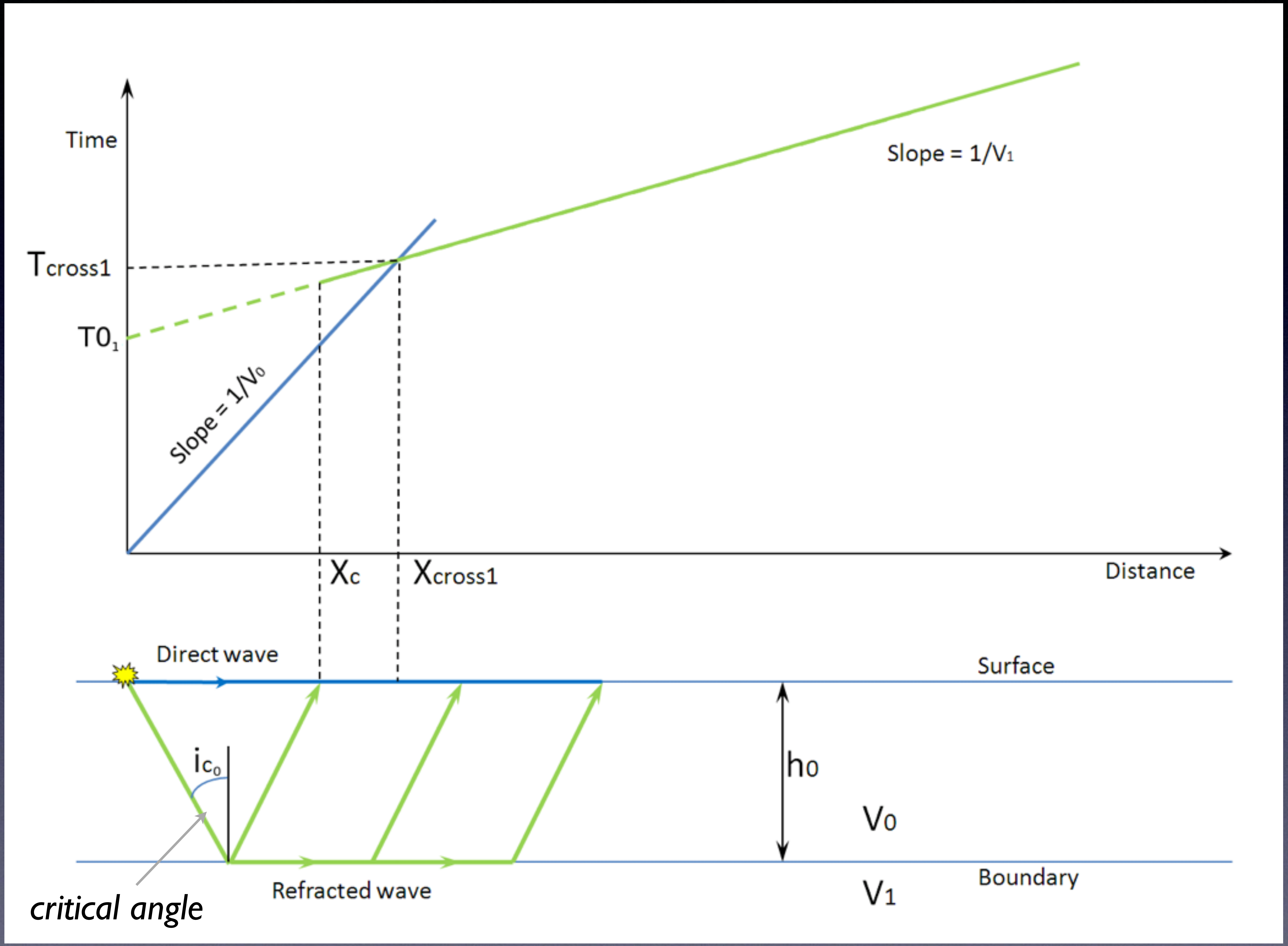
# Principles of REFRACTION SEISMIC




Velocity of the layer (c) Is proportional to the slope of the arrival time line

Thichness of the layer Is proportional to the Cross point distance

# Principles of REFRACTION SEISMIC



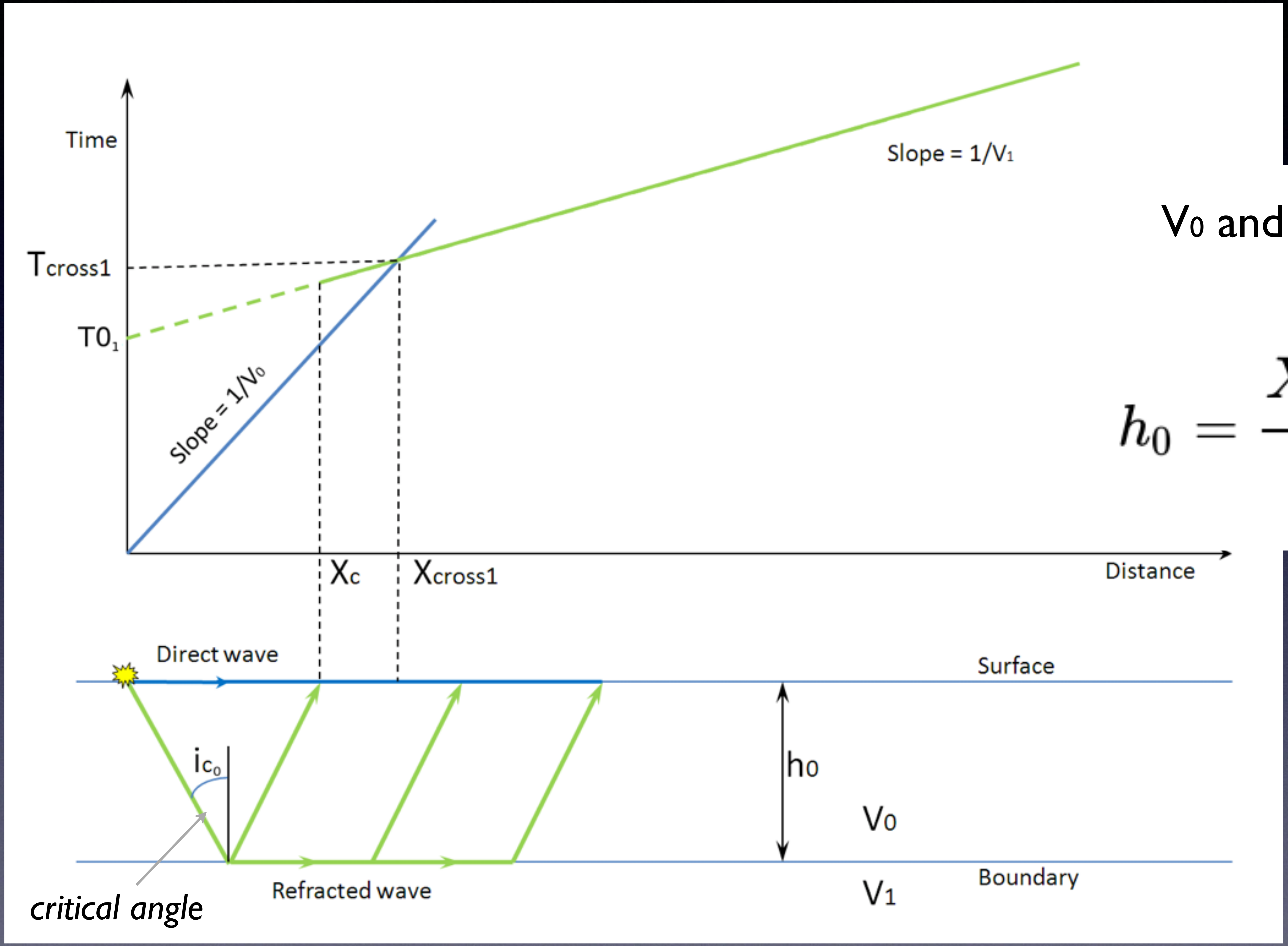

1) Slope of the dromochrone

2) Xcross Crossover point distance

3) $T_0$ Intercept time

# Near Surface Seismic for hydrological risks

## Principles of REFRACTION SEISMIC

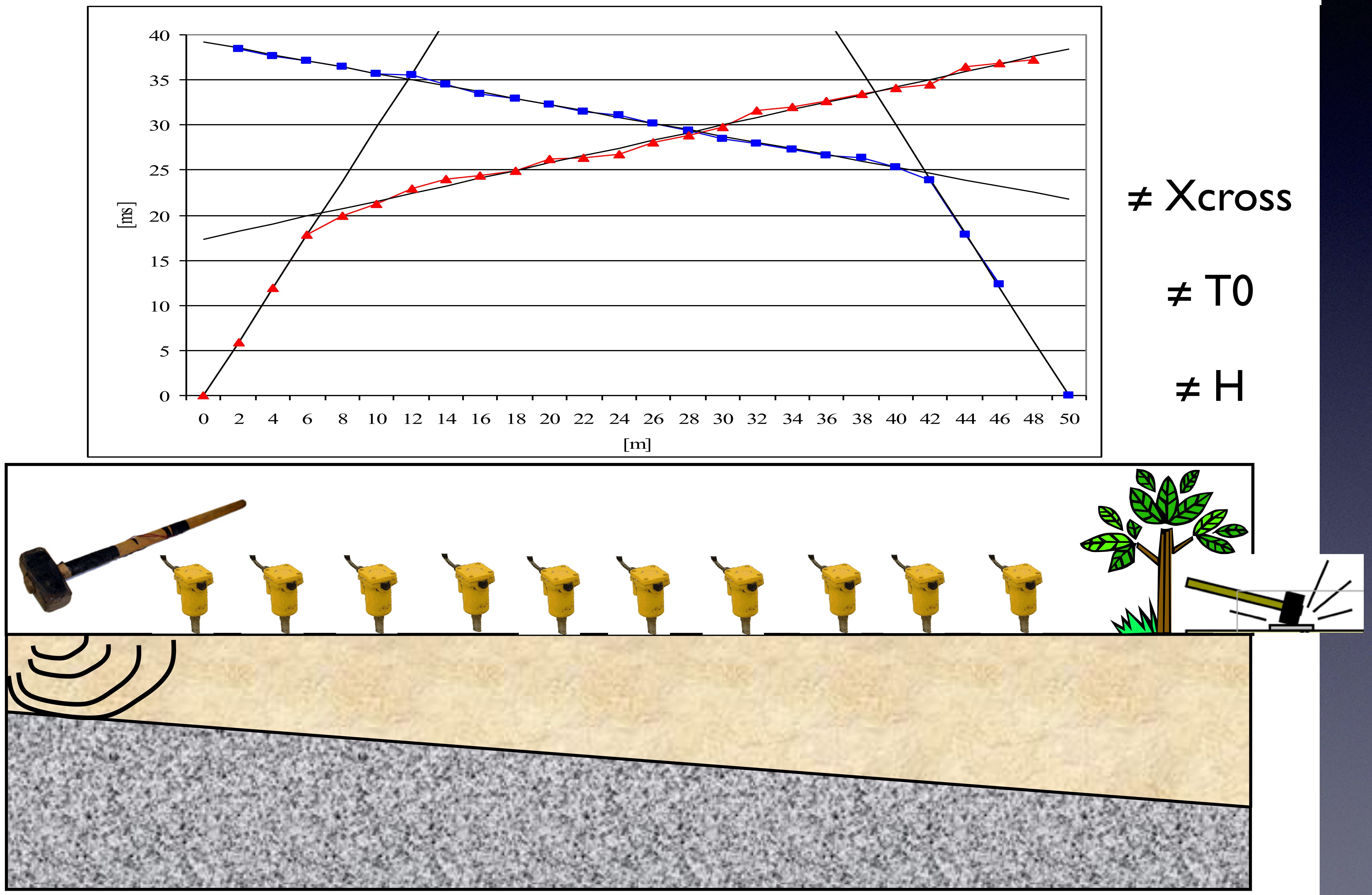



V0 and V1 from the slope

$$h_0 = \frac{X_{cross_1}}{2}\sqrt{\frac{V_1 - V_0}{V_1 + V_0}}$$

Velocity and thickness of the layers !

# Principles of REFRACTION SEISMIC




≠ Xcross

≠ T0

≠ H

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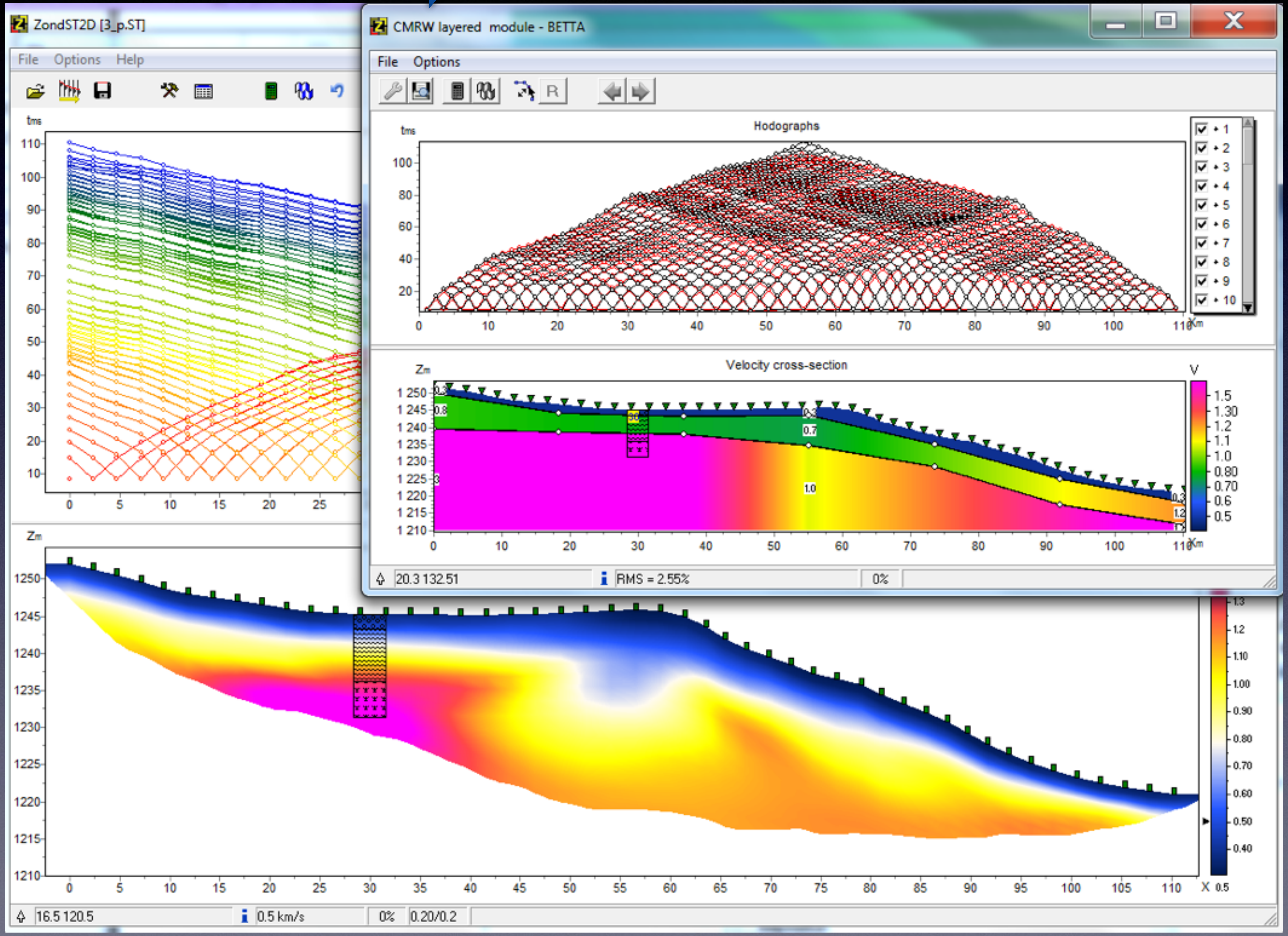
*N travel times* → *Seismic tomography*

Refraction seismic

Refraction seismic Model



REFRACTION Seismic

P Wave (compressional source)

Vp Model

Sledgehammer

SH Wave (shear source)

Vs Model

Shear Polarised Sources

*seismic method*

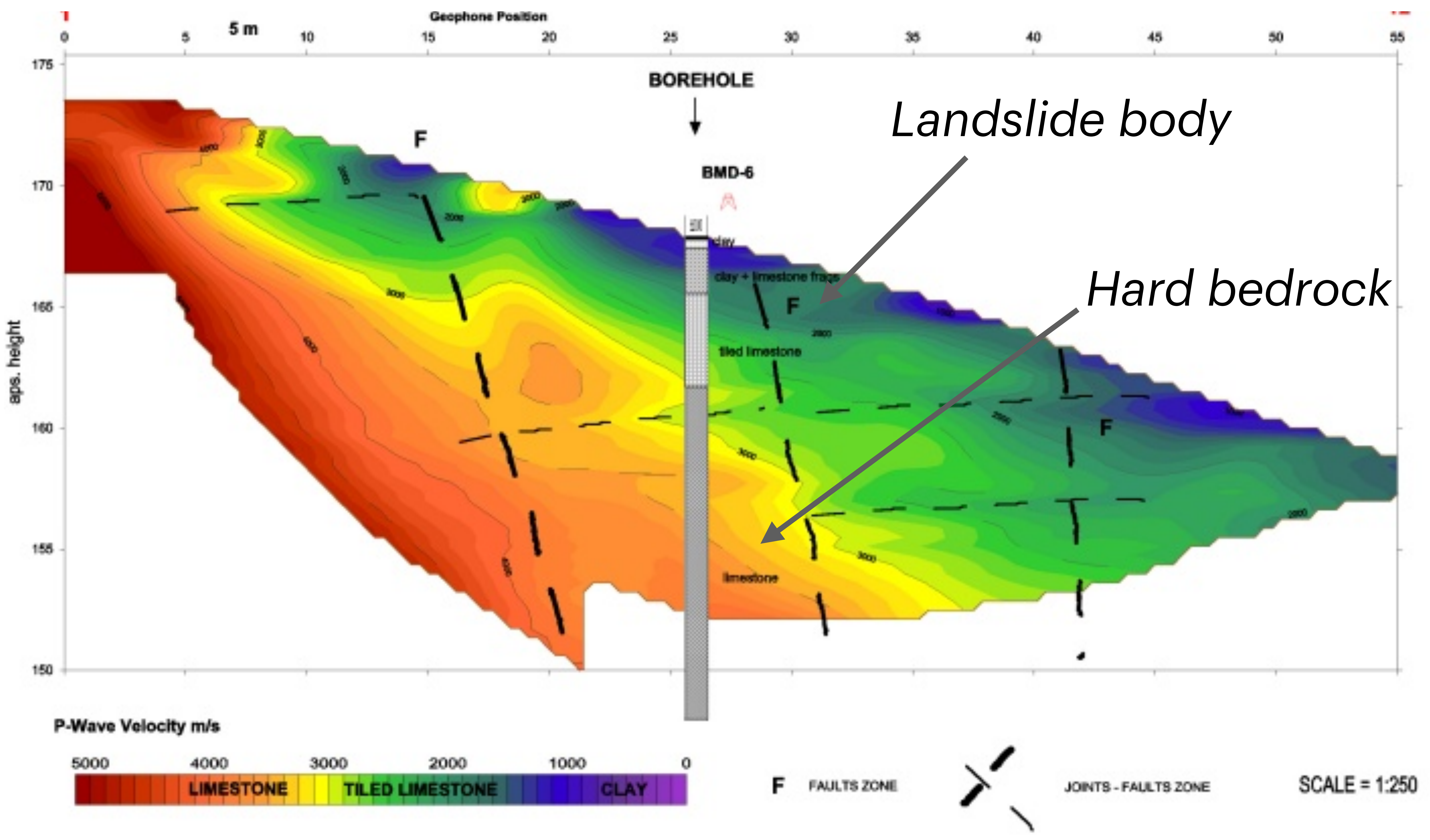


# I) LANDSLIDE CHARACTERISATION

Refraction seismic

Both in P and S waves

## *Tomographic Refraction in P wave*

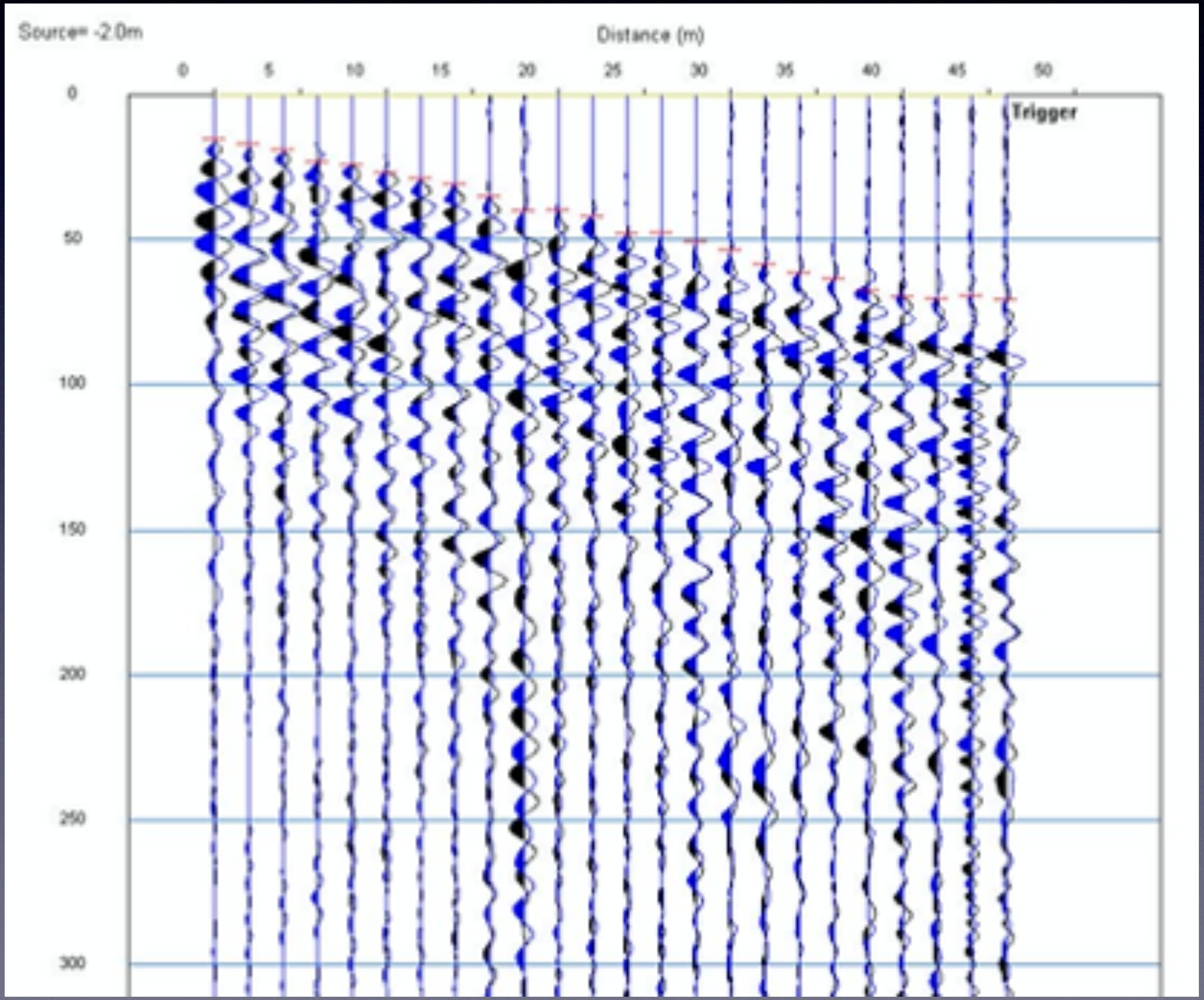


*seismic method*

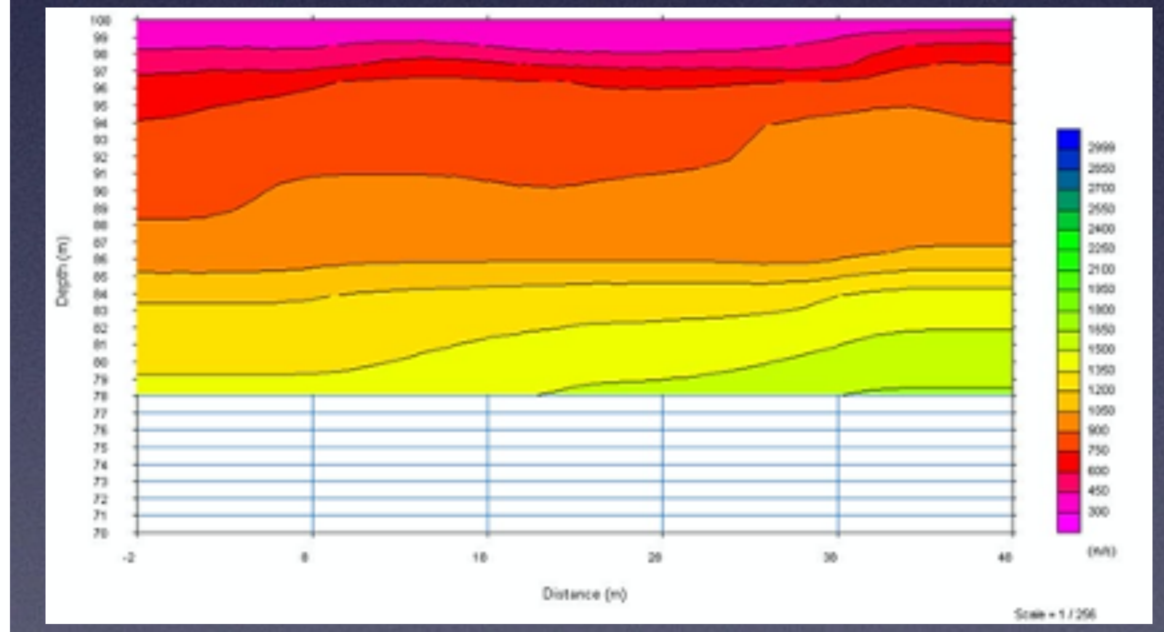
# I) LANDSLIDE CHARACTERISATION

Example of SH WAVE REFRACTION
For landslide

## Anti-phase double horizontal shear shot to help SH picking




Vs model



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# Near Surface Seismic for hydrological risks

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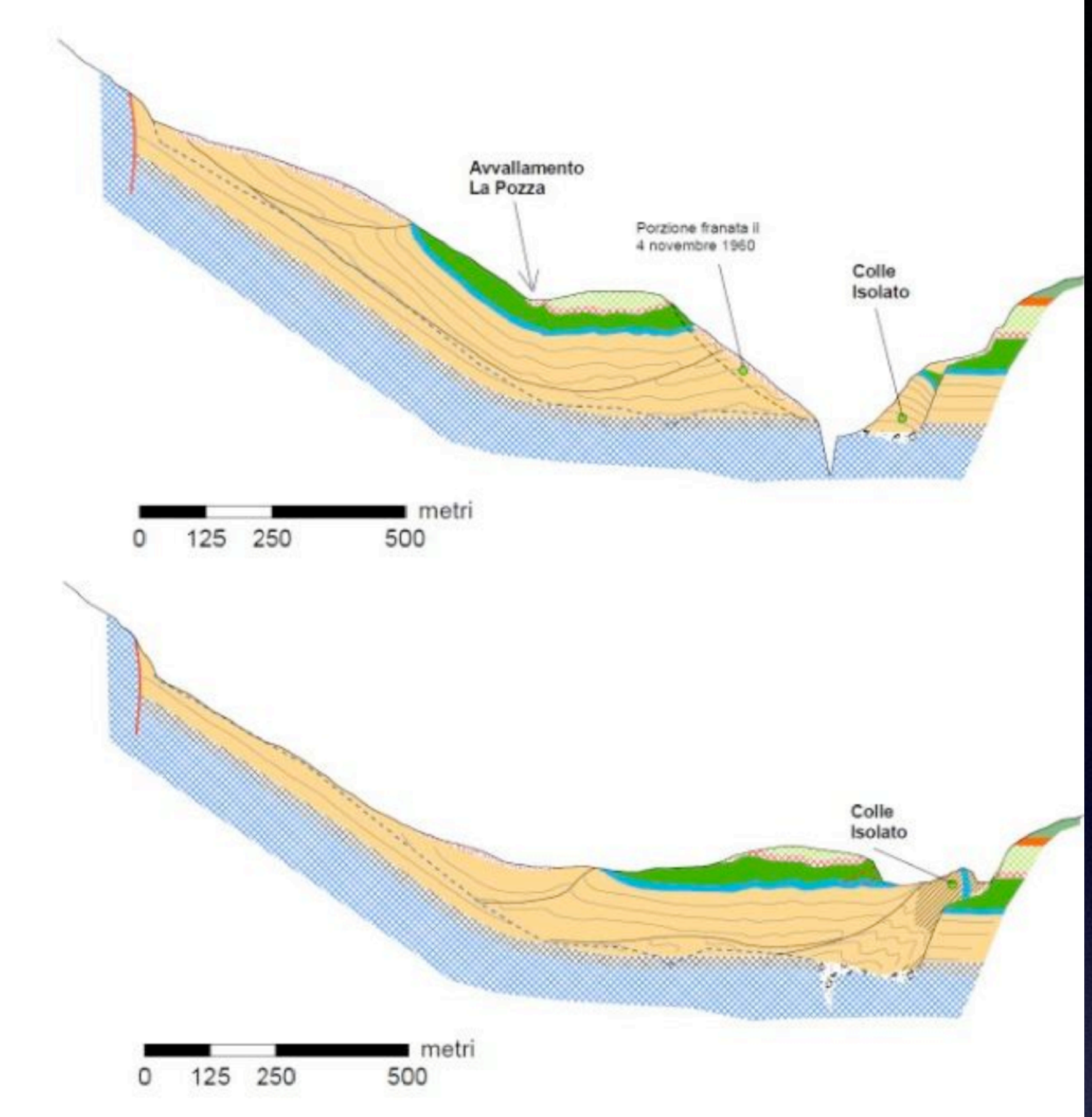
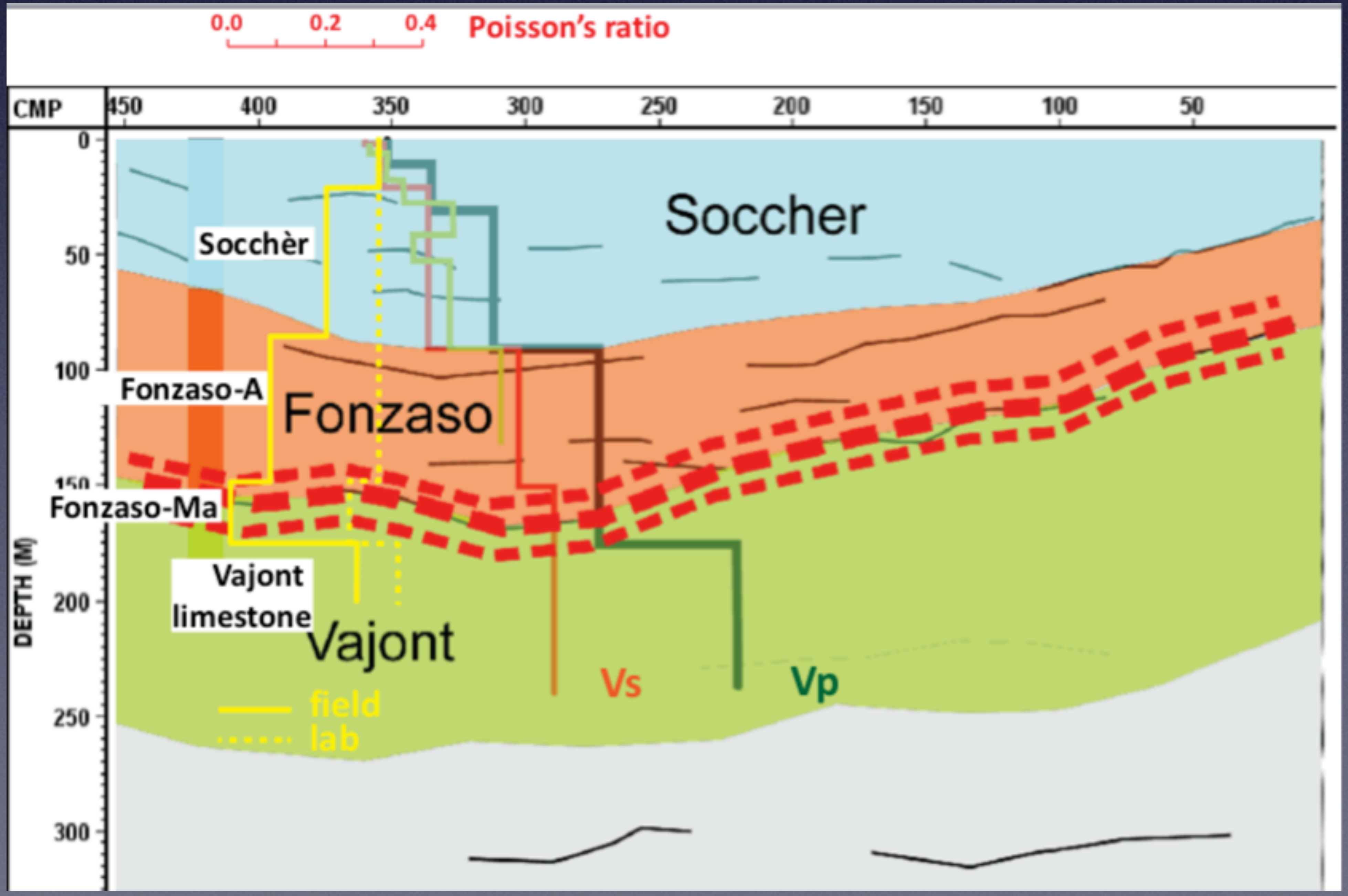
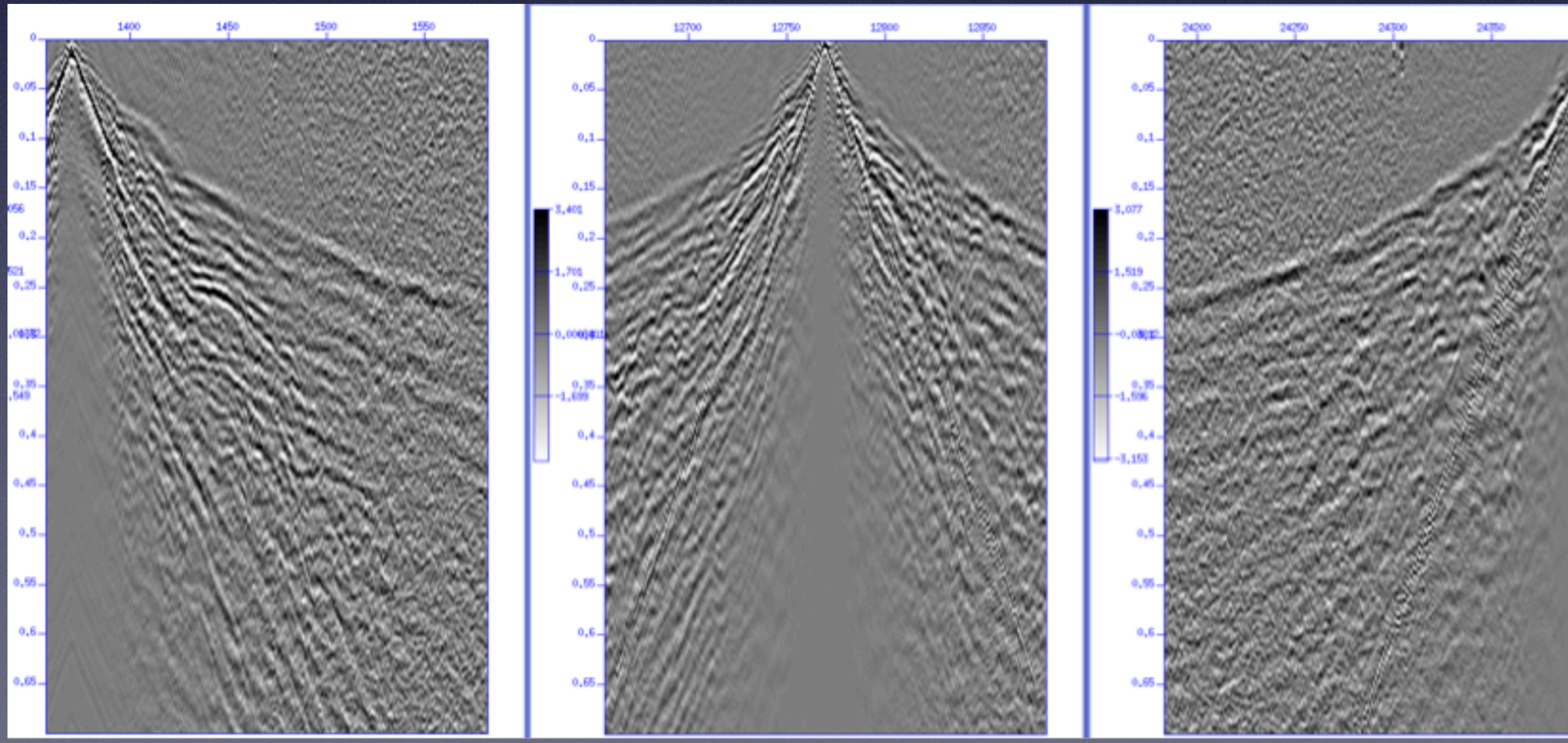
*seismic method*

Reflection seismic for very big Landslide

1963 Vajont Landslide



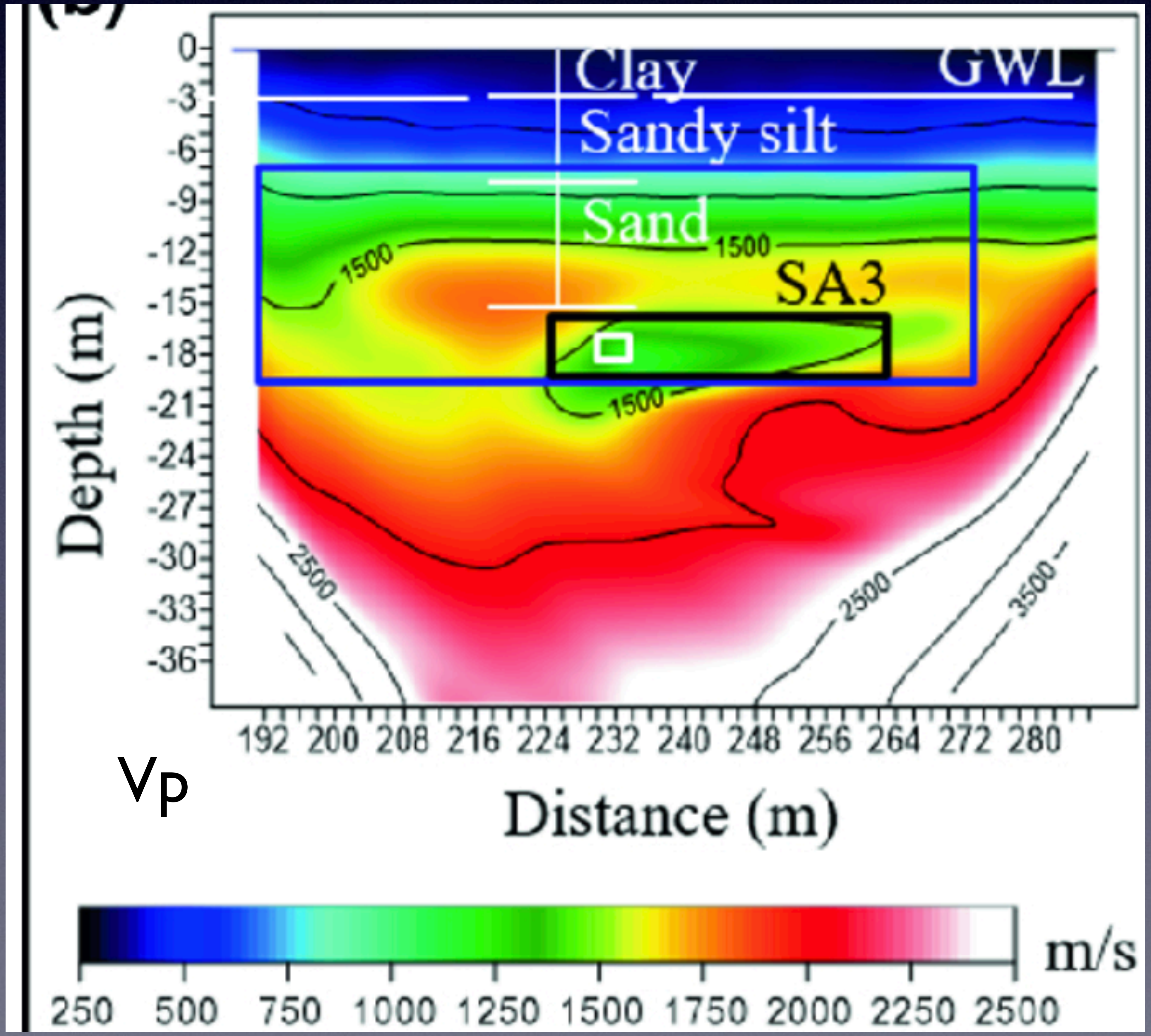
*seismic method*

# 2) Rivers management

- Levee

Structure

Seismic
REFRACTION



*seismic method*

# 2) Rivers management

- Levee

Structure

Seismic STREAMER

Efficient tool to collect data quickly for Elongated structure as the levee

PRO logistic
CONS. bad coupling with soil

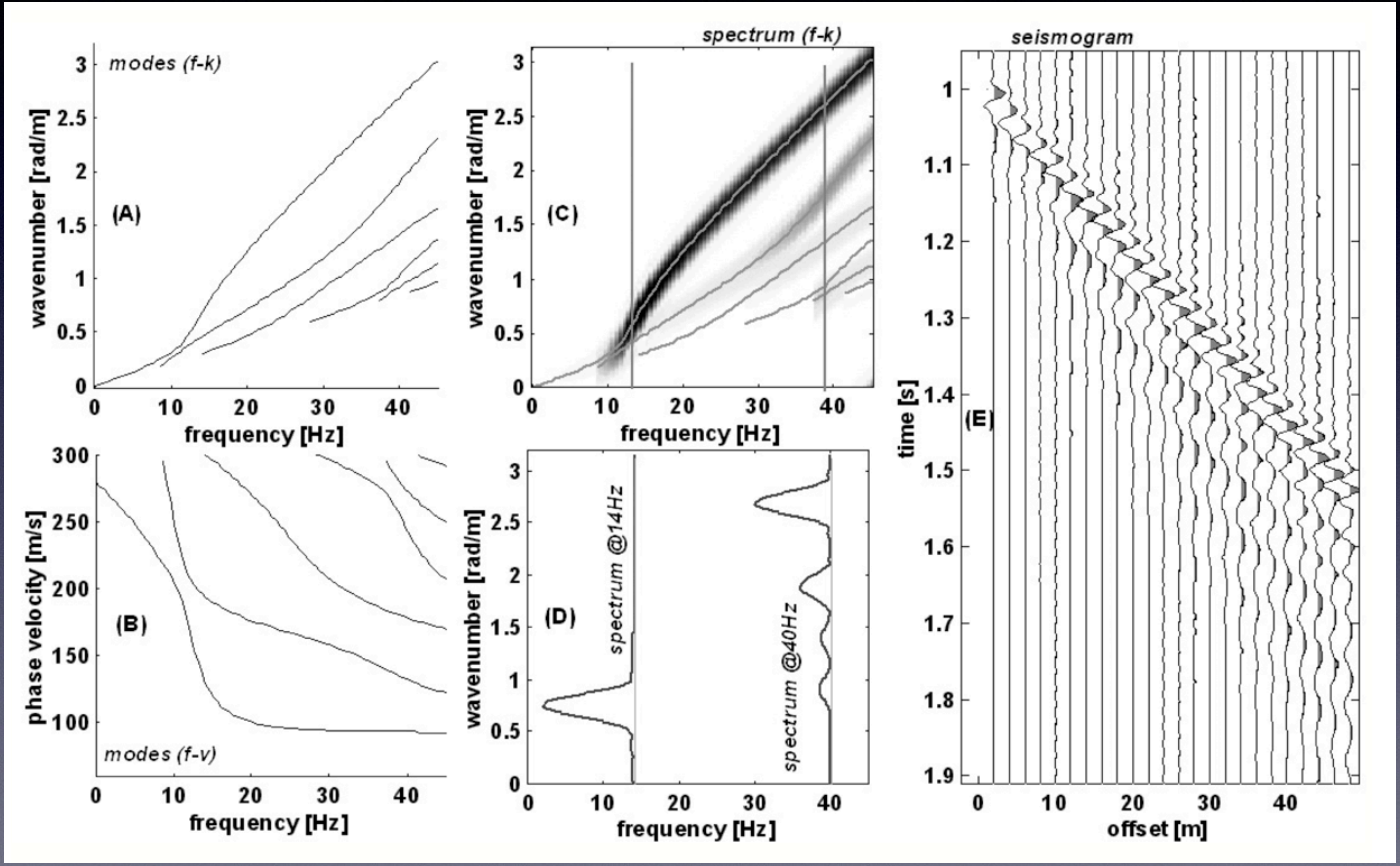
*seismic method*

# 2) Rivers management

## SURFACE WAVES

- Levee

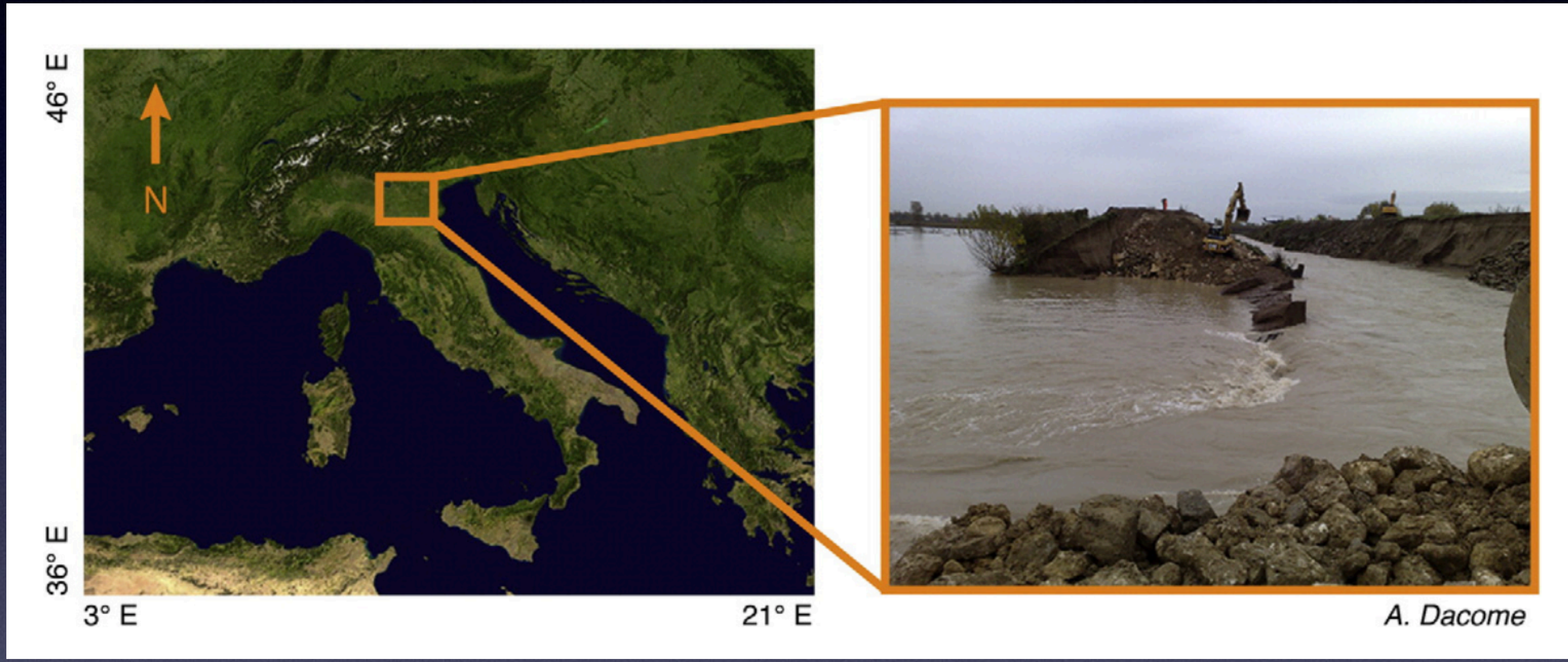
Structure

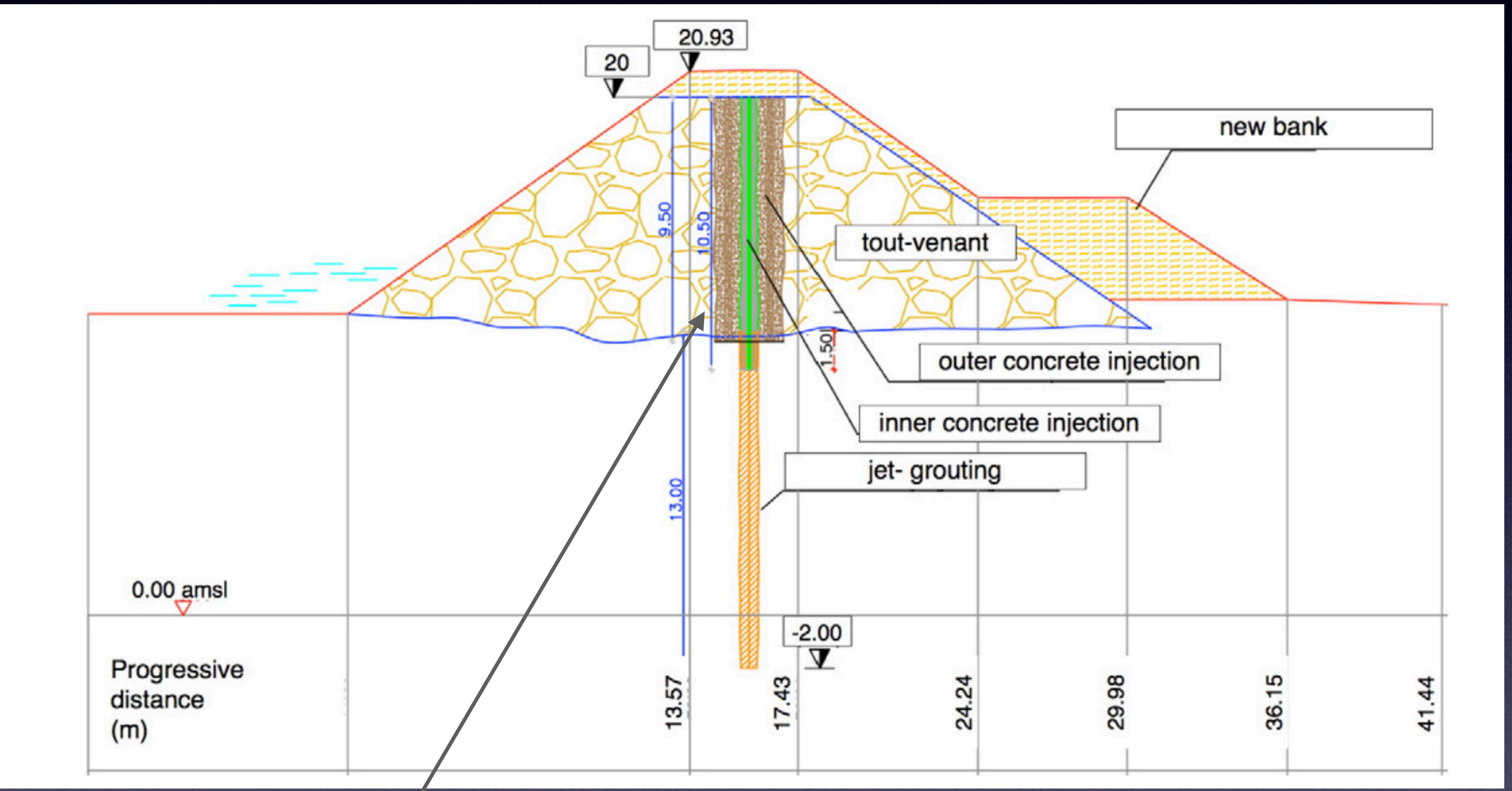


*seismic method*

# 2) Rivers management

## Example the FRASSINE Reconstructed levee




Jet grouting concrete septum

Seismic streamer dragged over the levee to check the presence continuity of hydraulic septum

*seismic method*

# 2) Rivers management

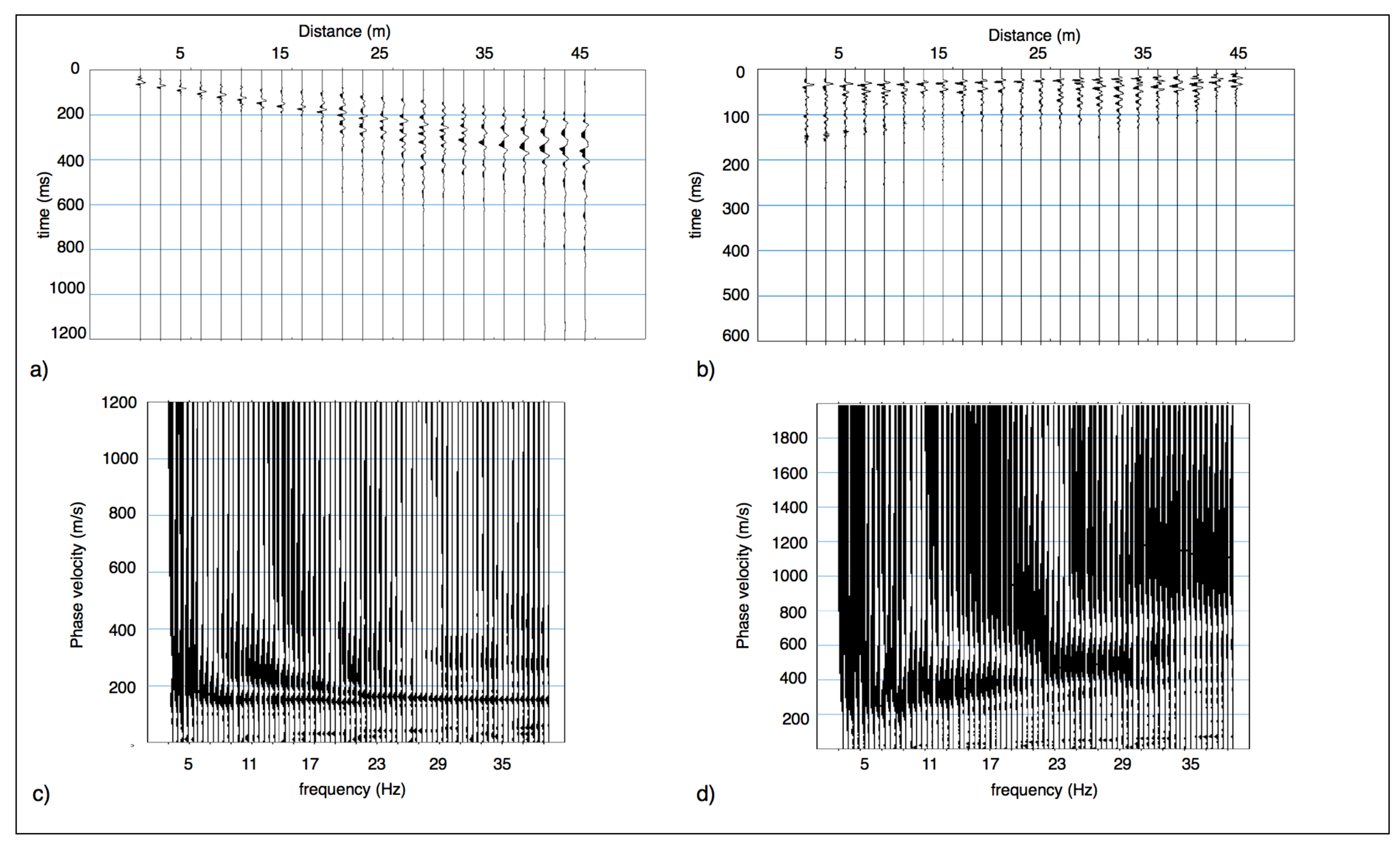
- Levee

Structure

Surface WAVE

## Natural Levee

## Reconstructed Levee



3) Water resources management

4) Polluted sites characterisations

~~Seismic Methods~~

*Seismic methods are poorly used for scope where water content / solute content are more important (i.e. electrical properties rule over density)*

## *The electric methods*

1) LANDSLIDE CHARACTERISATION

2) Rivers management

3) Water resources management

4) Polluted sites characterisations

## *The electric methods*

I) LANDSLIDE CHARACTERISATION

*How much material in motion?*

Lamosano (BL Italy)

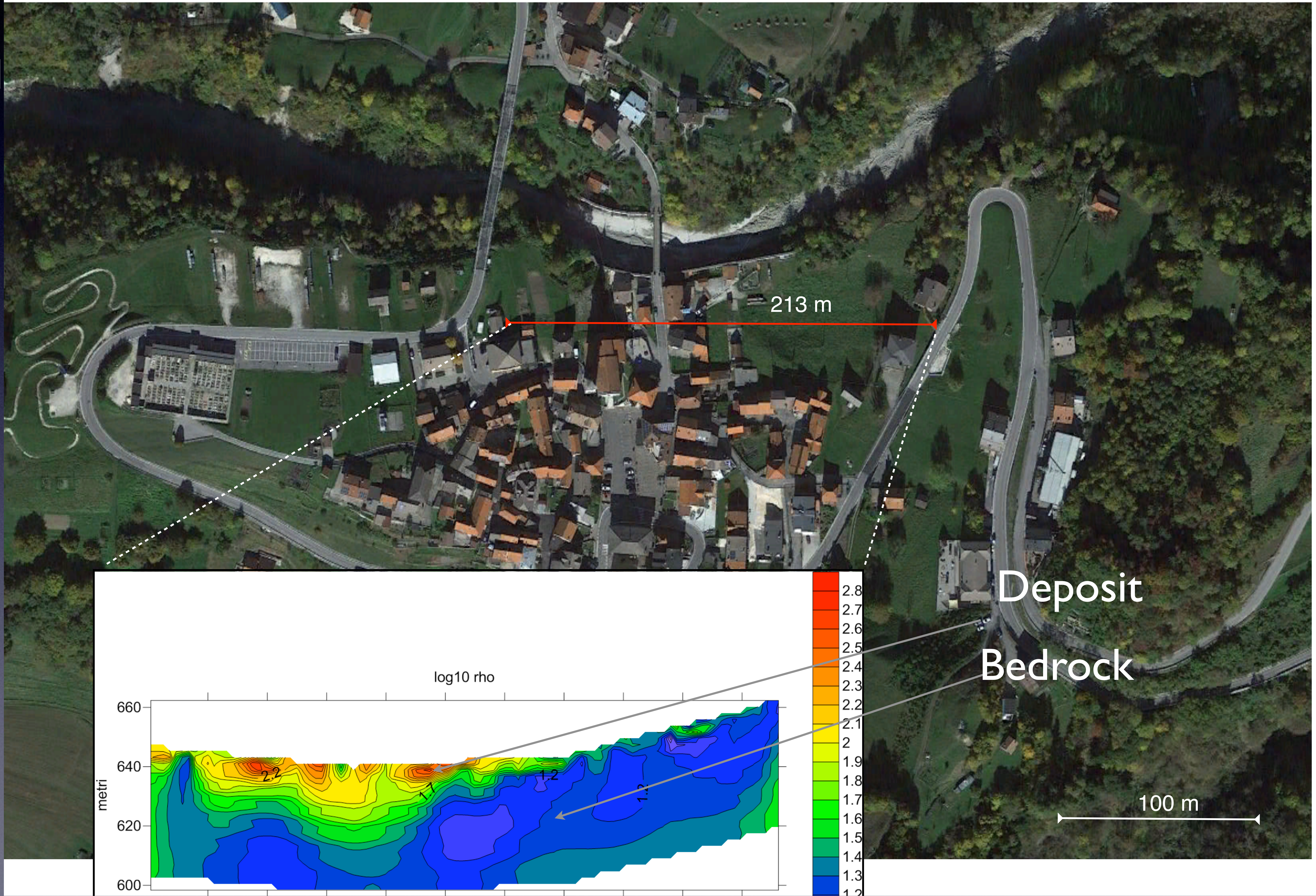
ERT Lines

# ERT for landslide



*The electric methods*

I) LANDSLIDE CHARACTERISATION



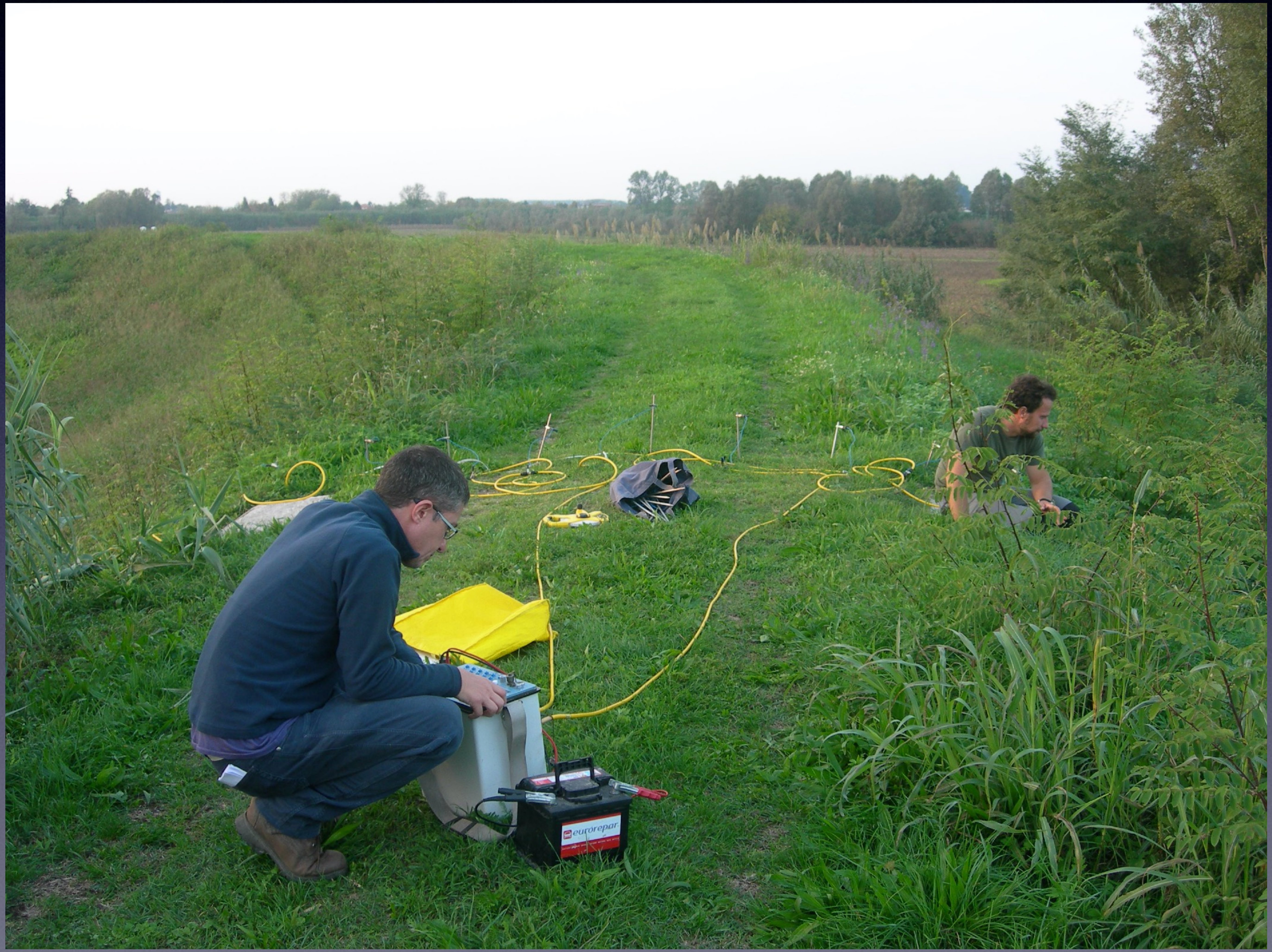

25 m thick!

# ERT for levee studies



*The electric methods*

2) Rivers management



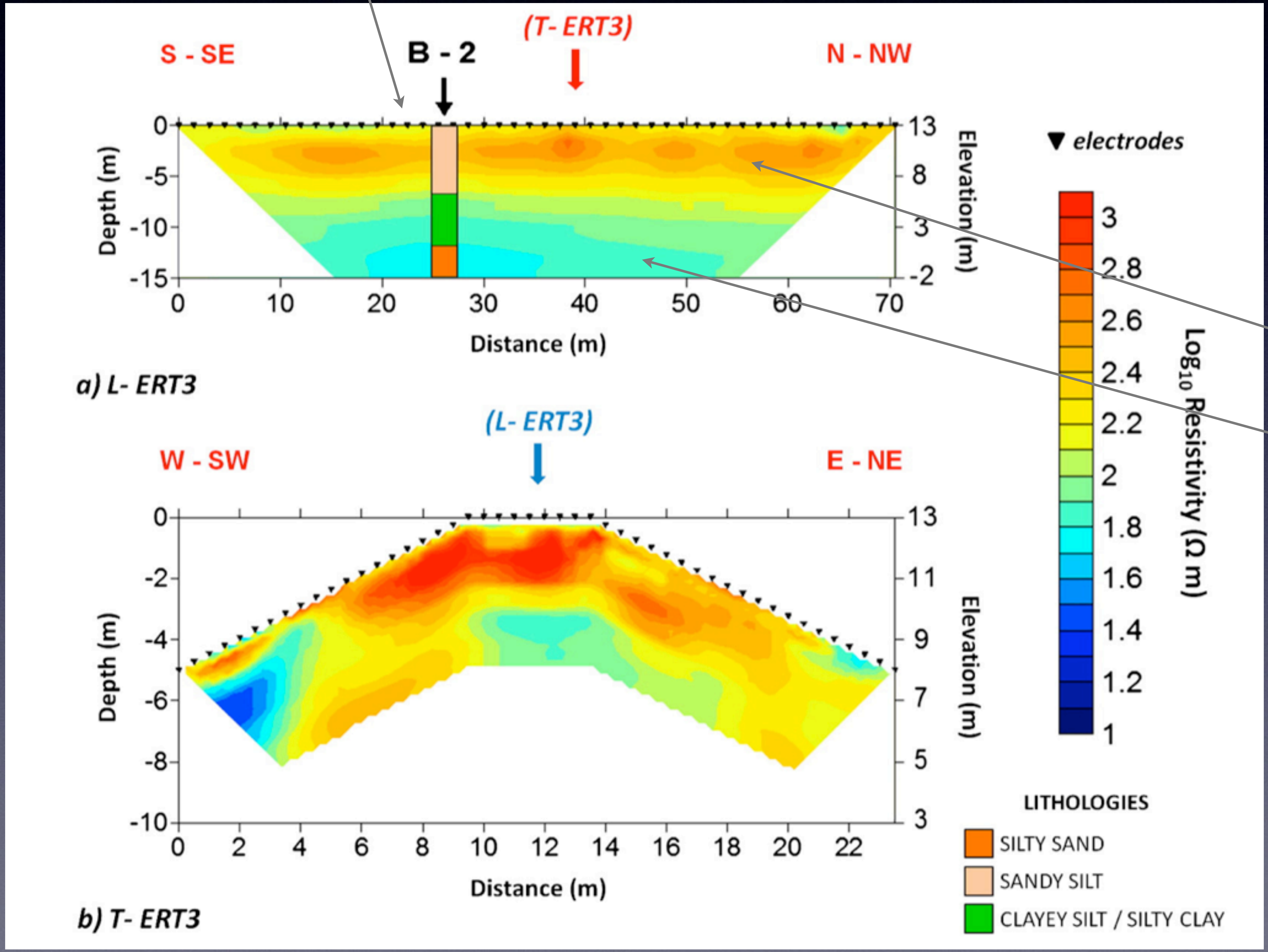
# ERT for levee studies

*The electric methods*

## 2) Rivers management

Fluvial levees monitoring

Borehole




Sand

silt/clay

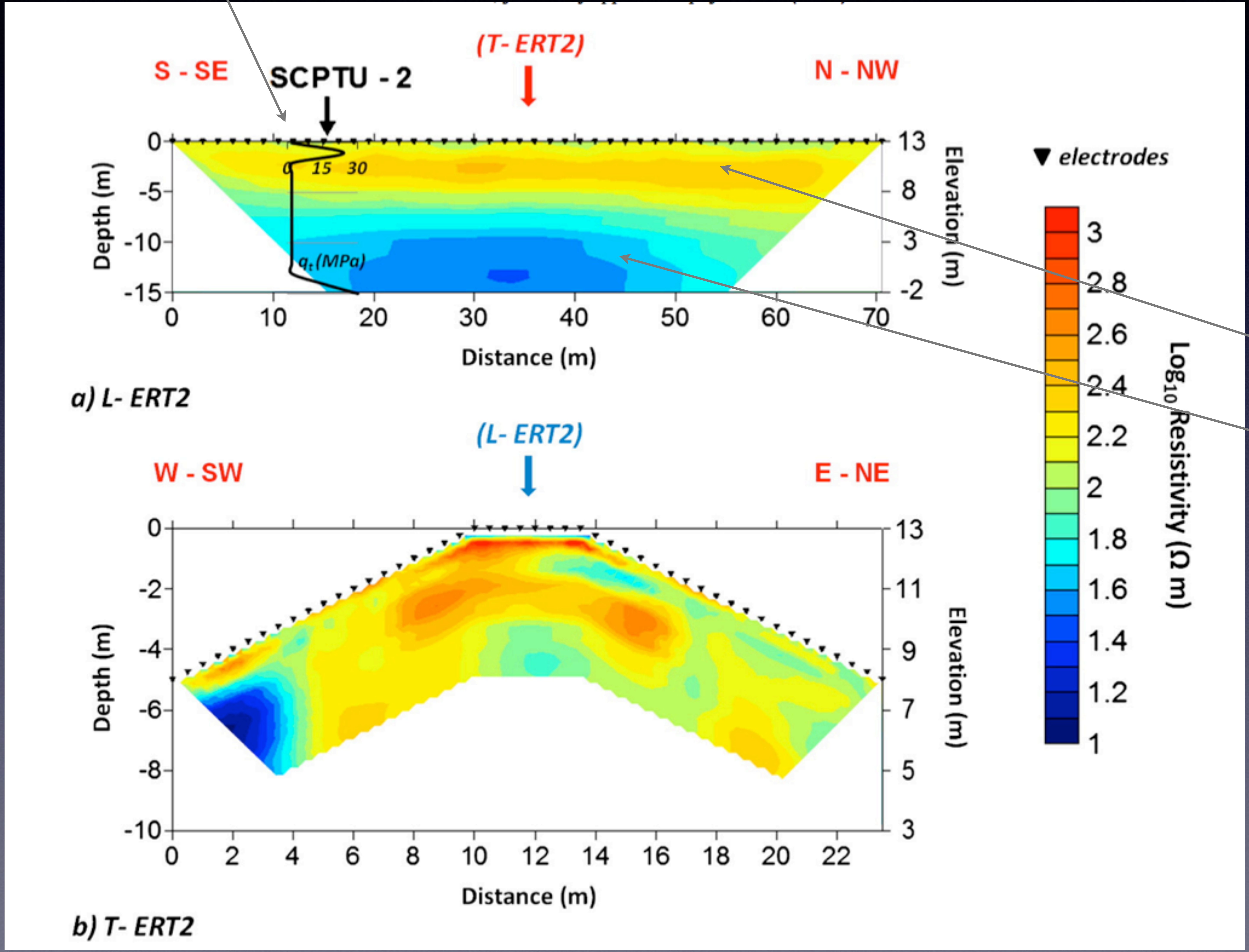
# ERT for levee studies

*The electric methods*

2) Rivers management

CPTU test

Fluvial levees monitoring




Sand

silt/clay

Good agreement with geotechnical Info

DIPARTIMENTO DI GEOSCIENZE

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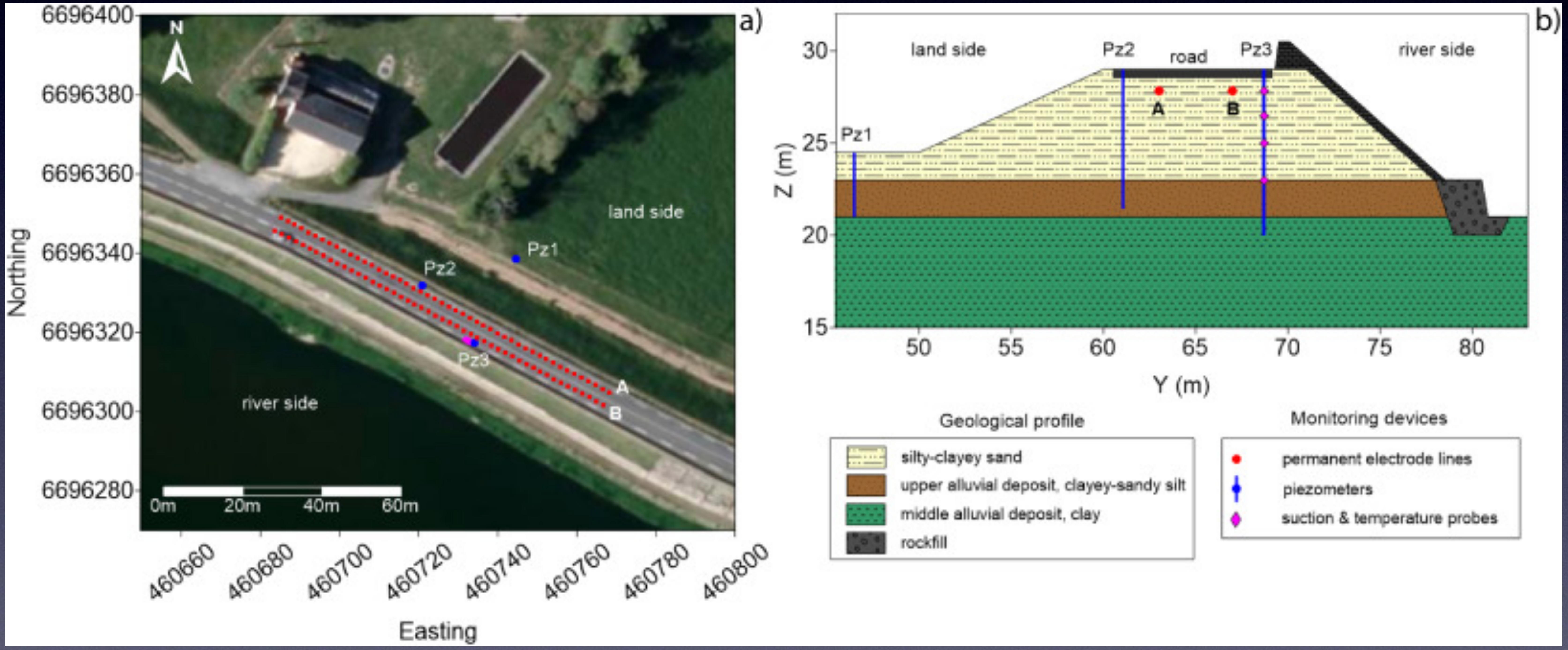
# *The electric methods*

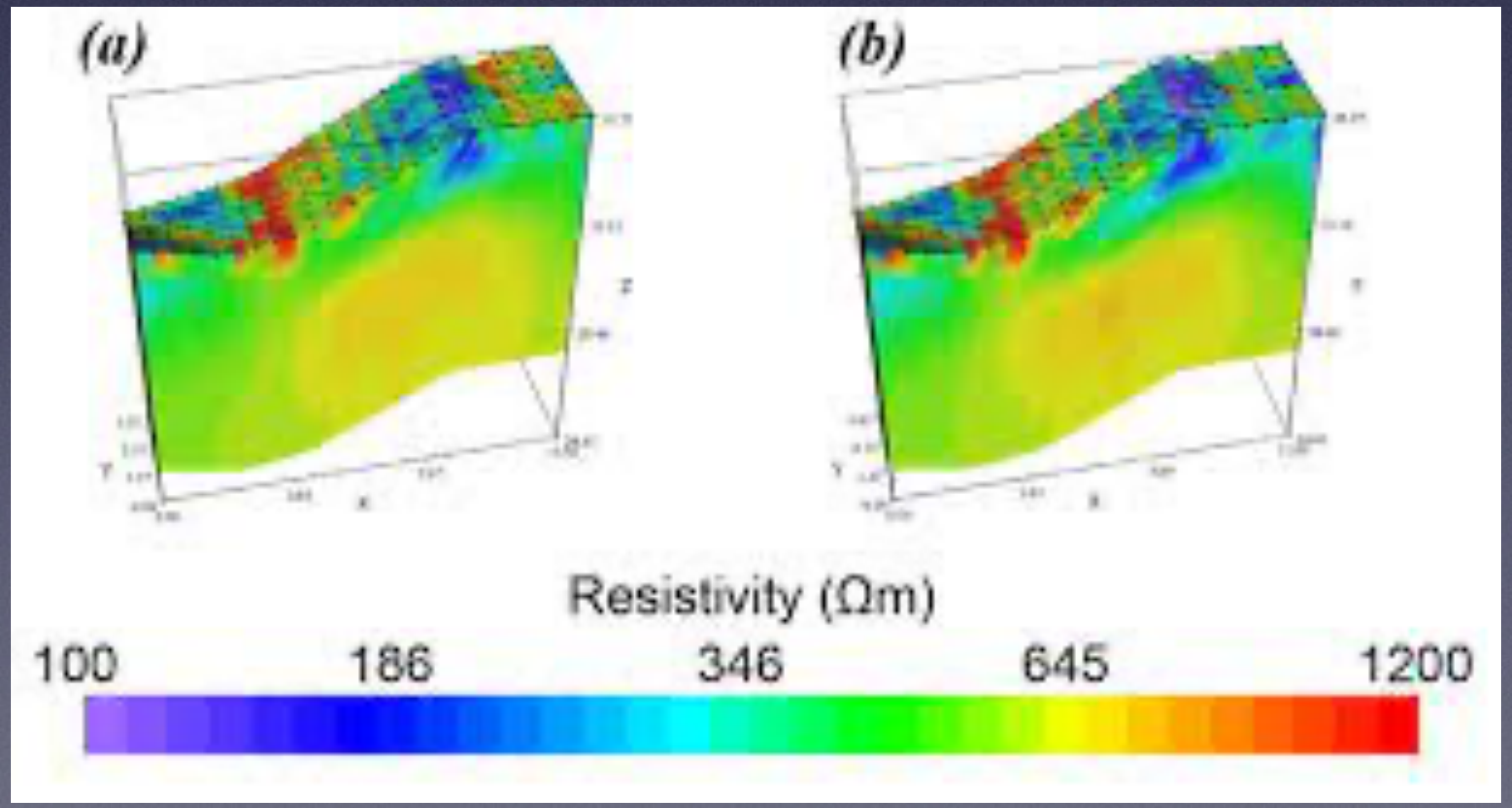
## 2) Rivers management

3d ERT

Looking for

Nutria (RAT) Nests....




3d ERT, borehole ERT Looking for  Voids

# ERT for levee studies



## *The electric methods*

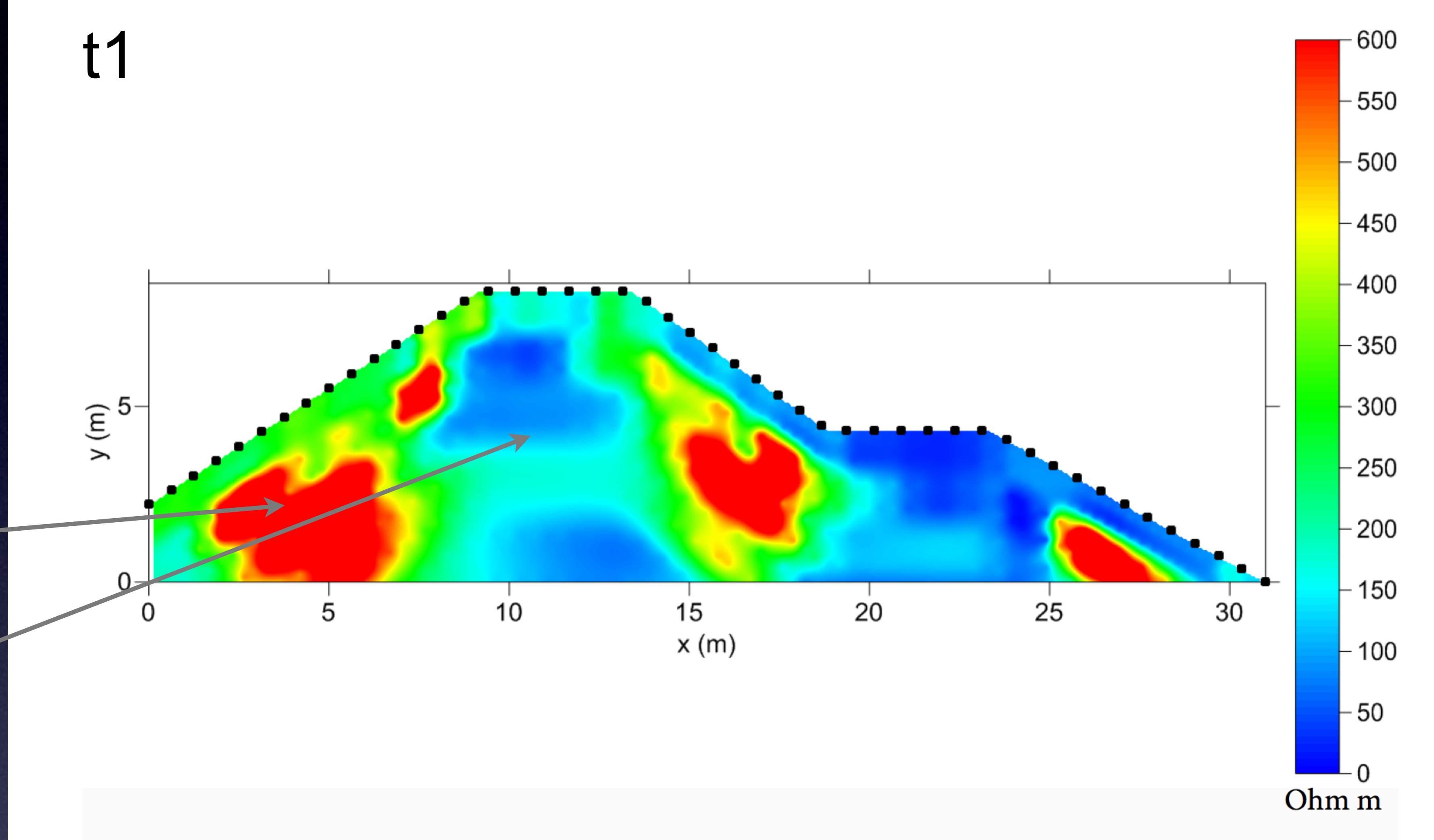
*A. Binley R2 code*

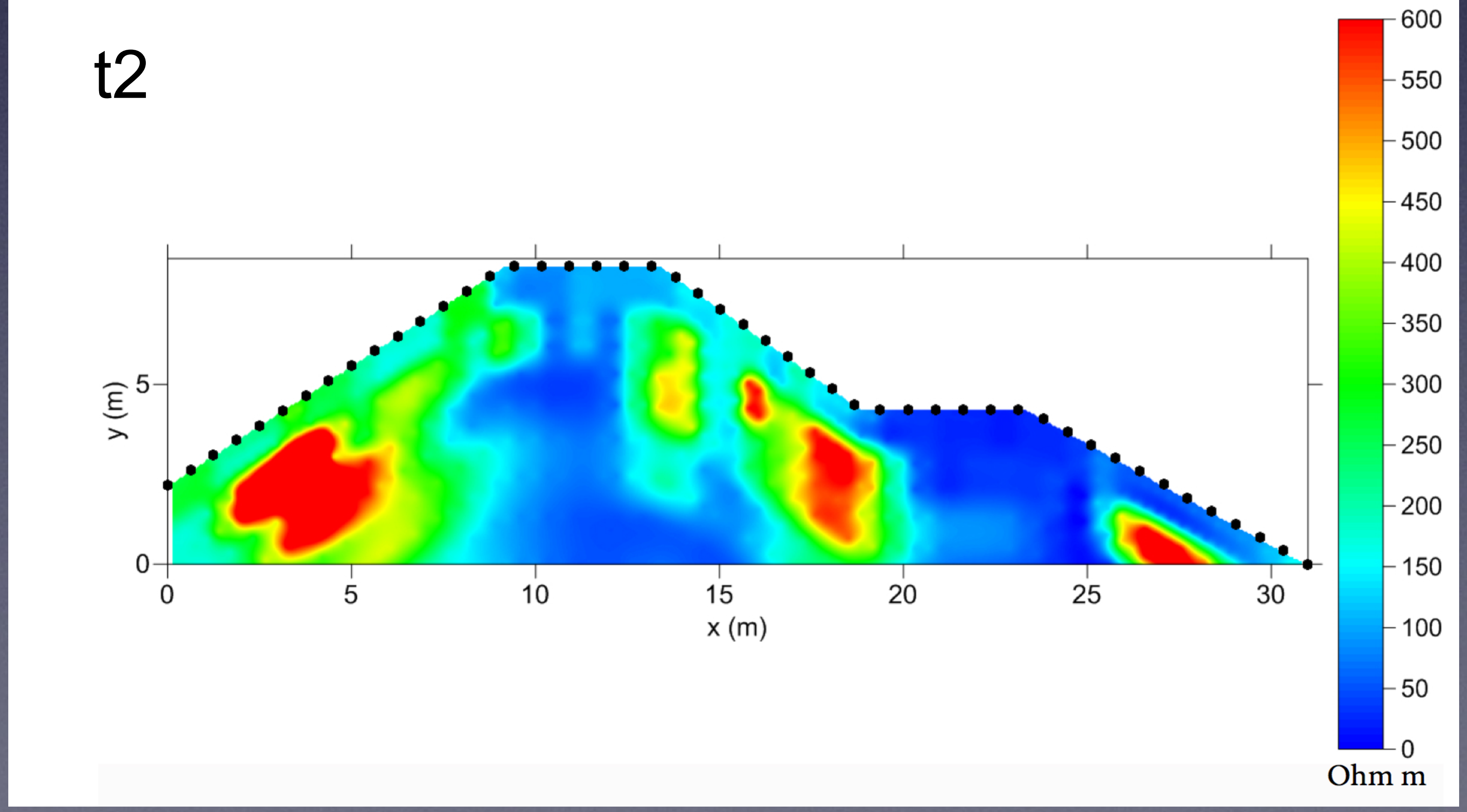
### 2) Rivers management

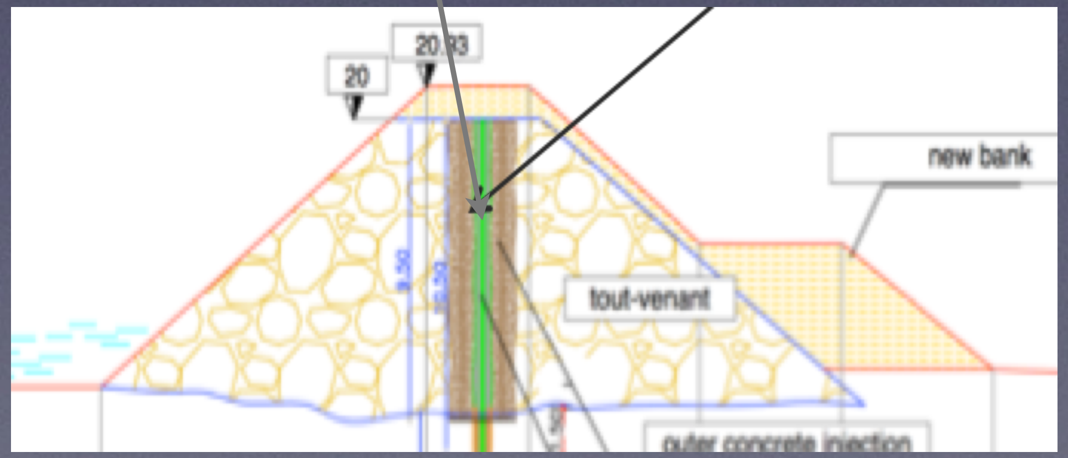
ERT transverse
- Top resolution
  - Ok for laterally extension

Tout Venant

Jet grouting Septum



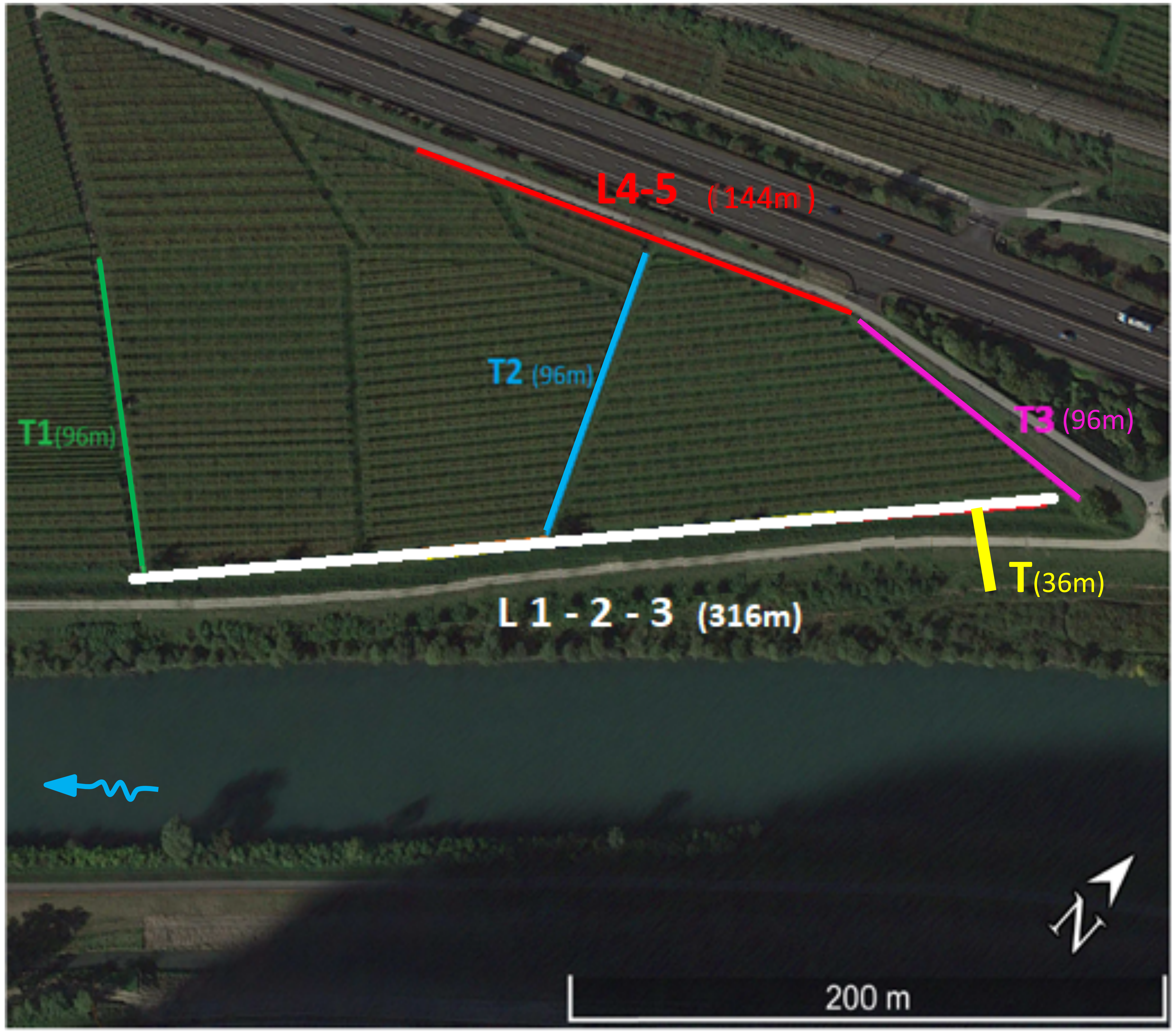



# TOMOGRAFIE DI RESISTIVITÀ ELETTRICA (ERT)

*The electric methods*

2) Rivers management




**Configurazione elettrodica:**

- Dipolo dipolo;
- skip 4;
- 72 canali;
- spaziatura elettrodica 2m;

**Camagne di misura:**

- 5 Maggio 2017:
  Misure preliminari; T;
- 30 Agosto 2017:
  L1-2-3; T1; T2;
- 20 Ottobre 2017:
  L4-5; T3;

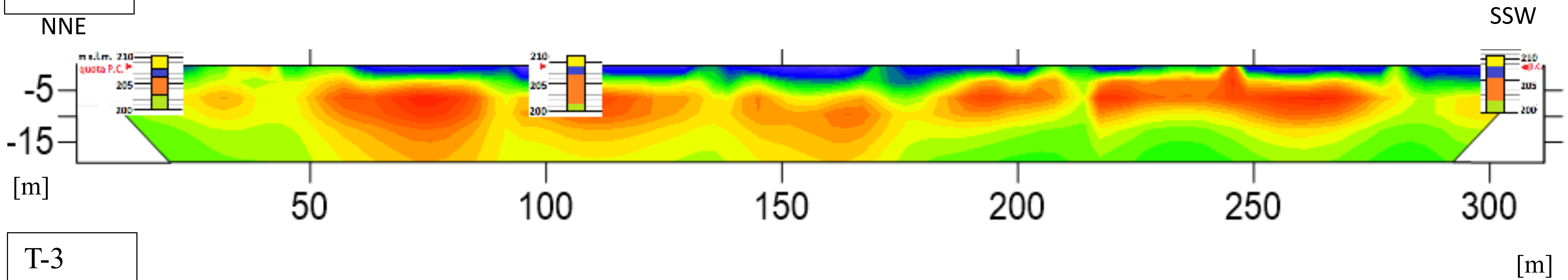
**Codici di inversione:**

- ProfilerR ;
- R2;

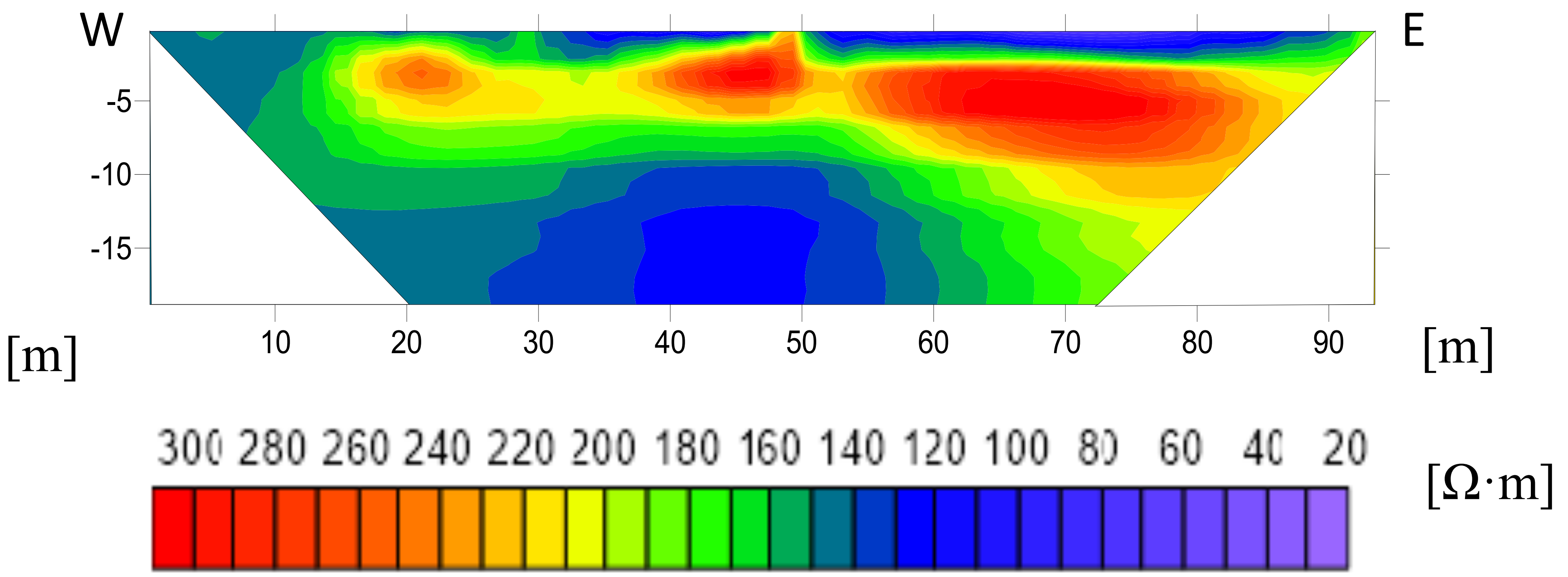
Sviluppati e distribuiti da Prof. A. Binley, Lancaster University (UK)

# SEZIONI ERT

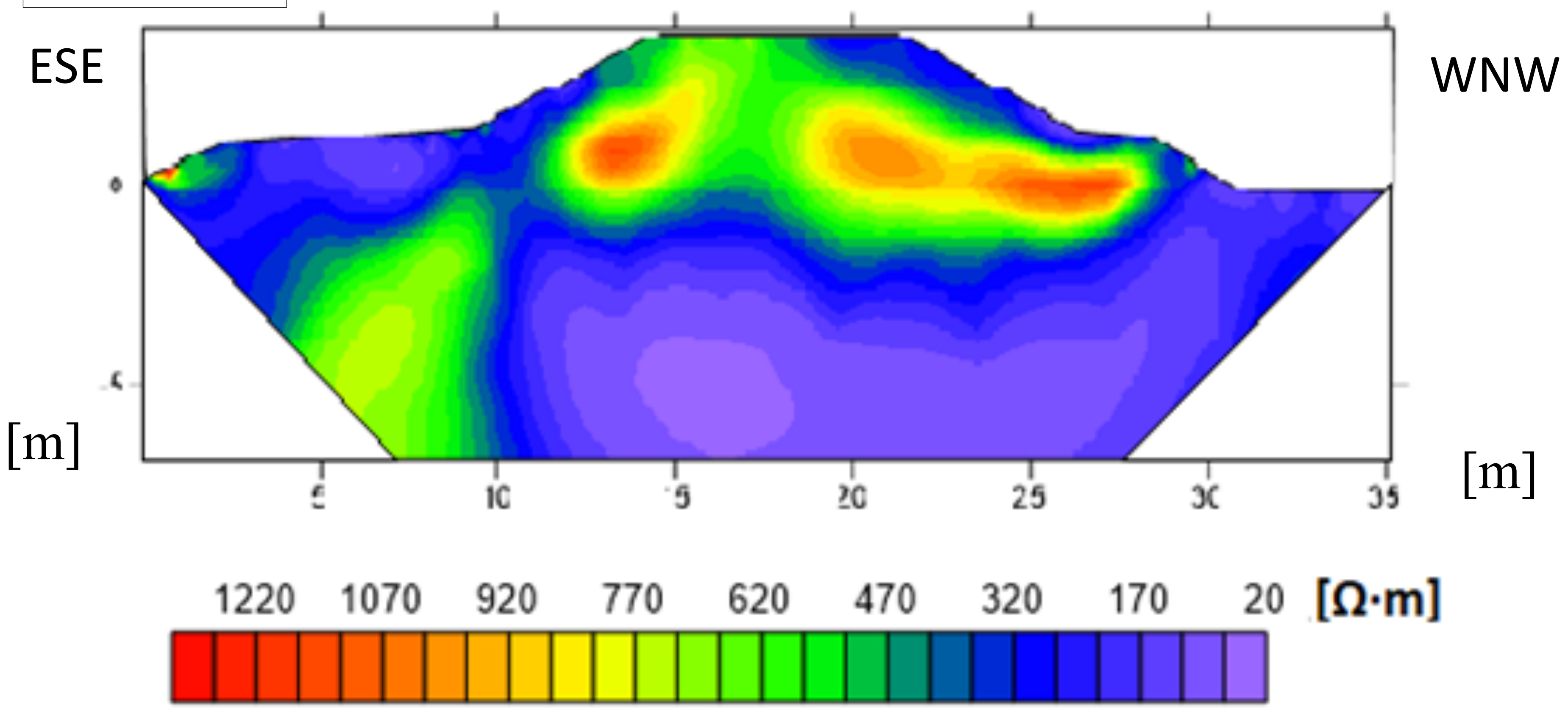
L 1-2-3

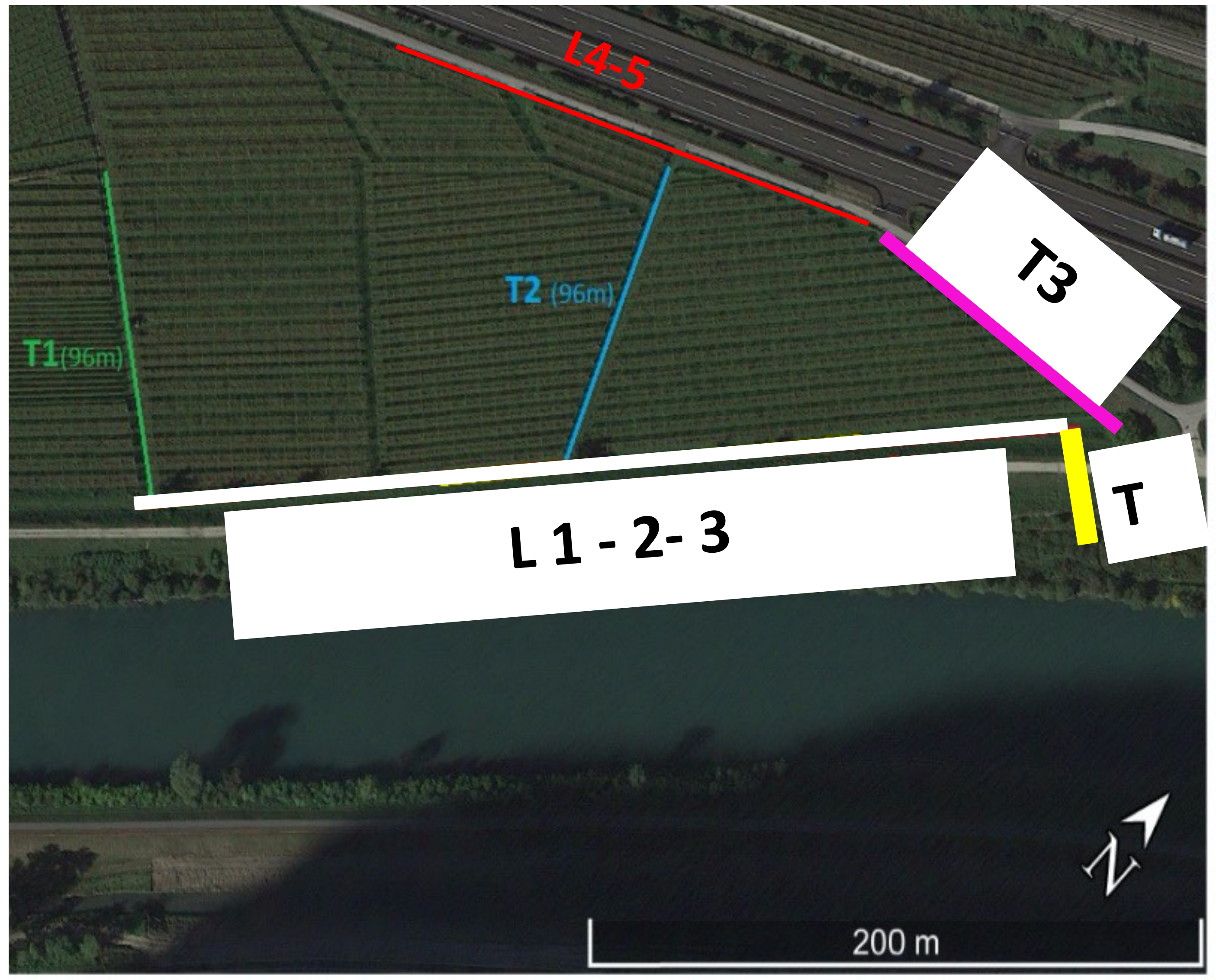



T-3



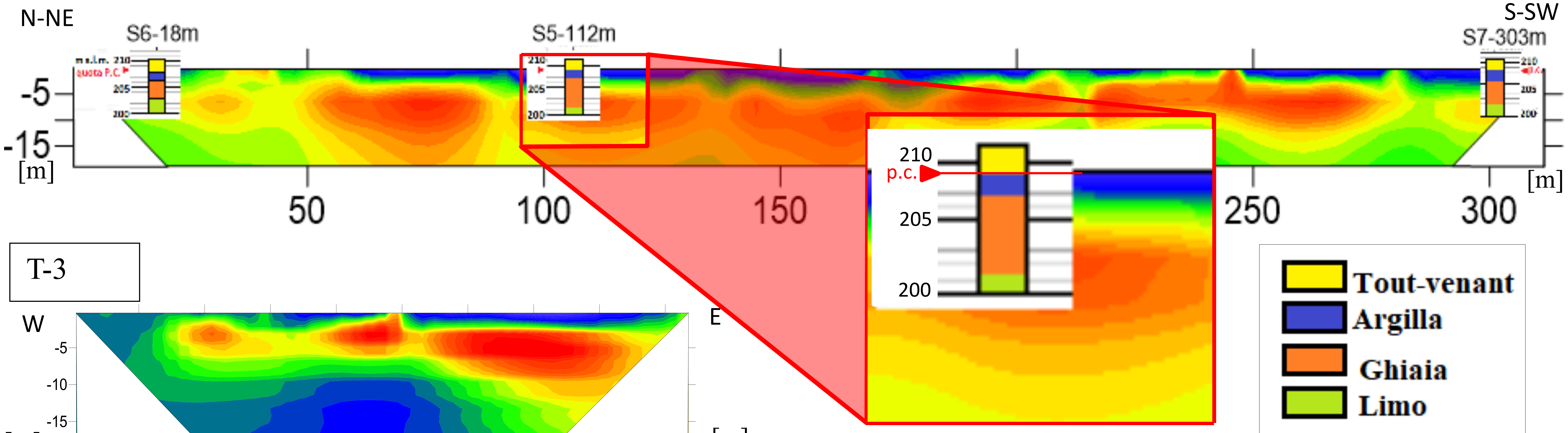

T



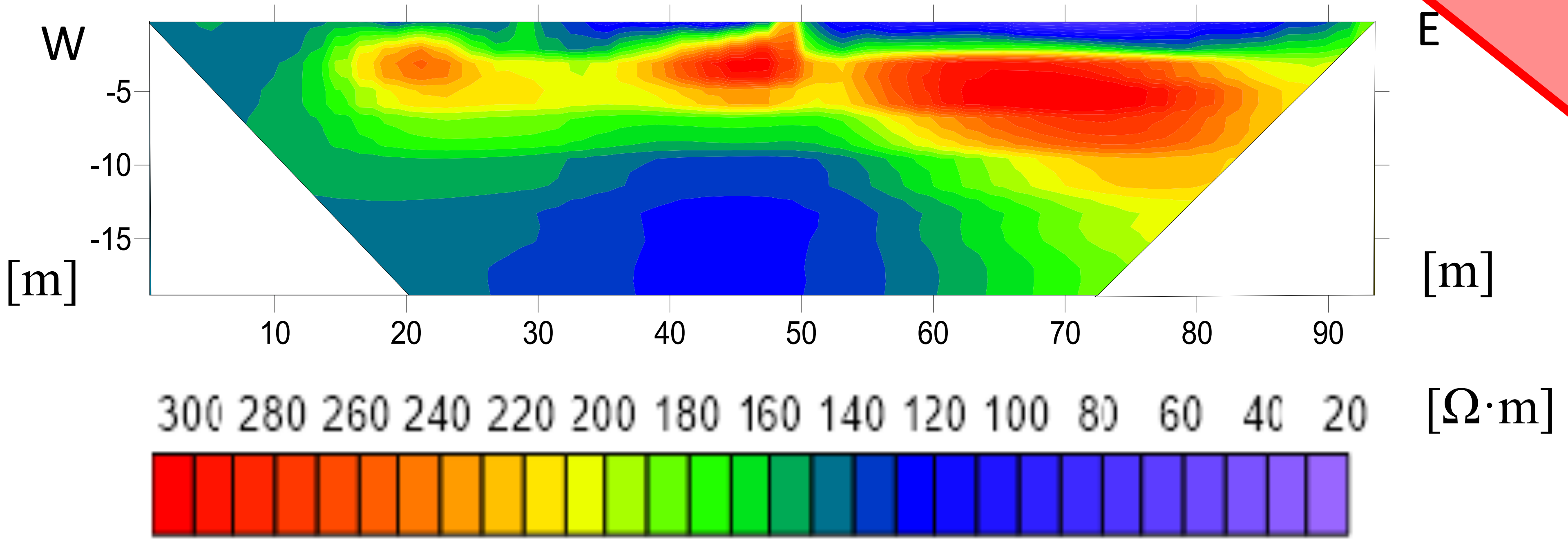



# SEZIONI ERT

L 1-2-3




T-3

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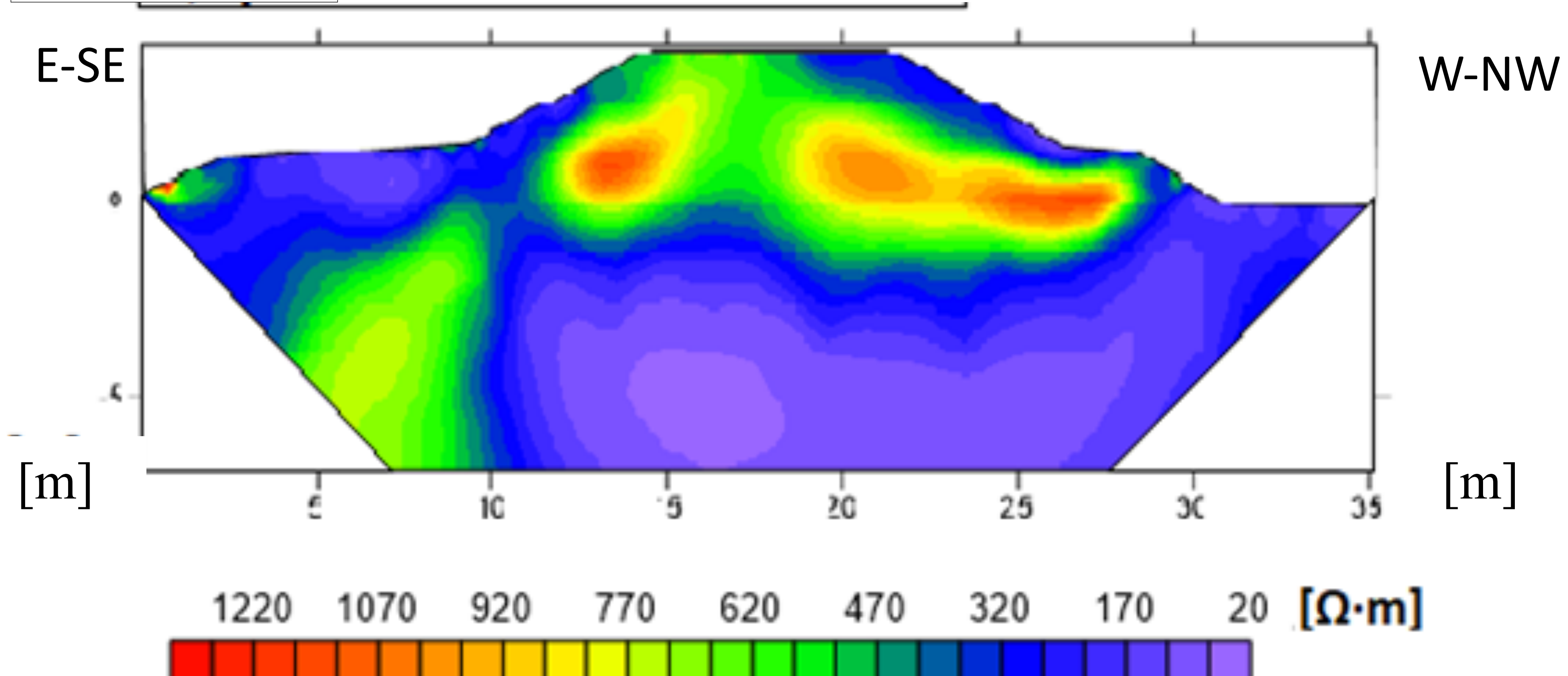
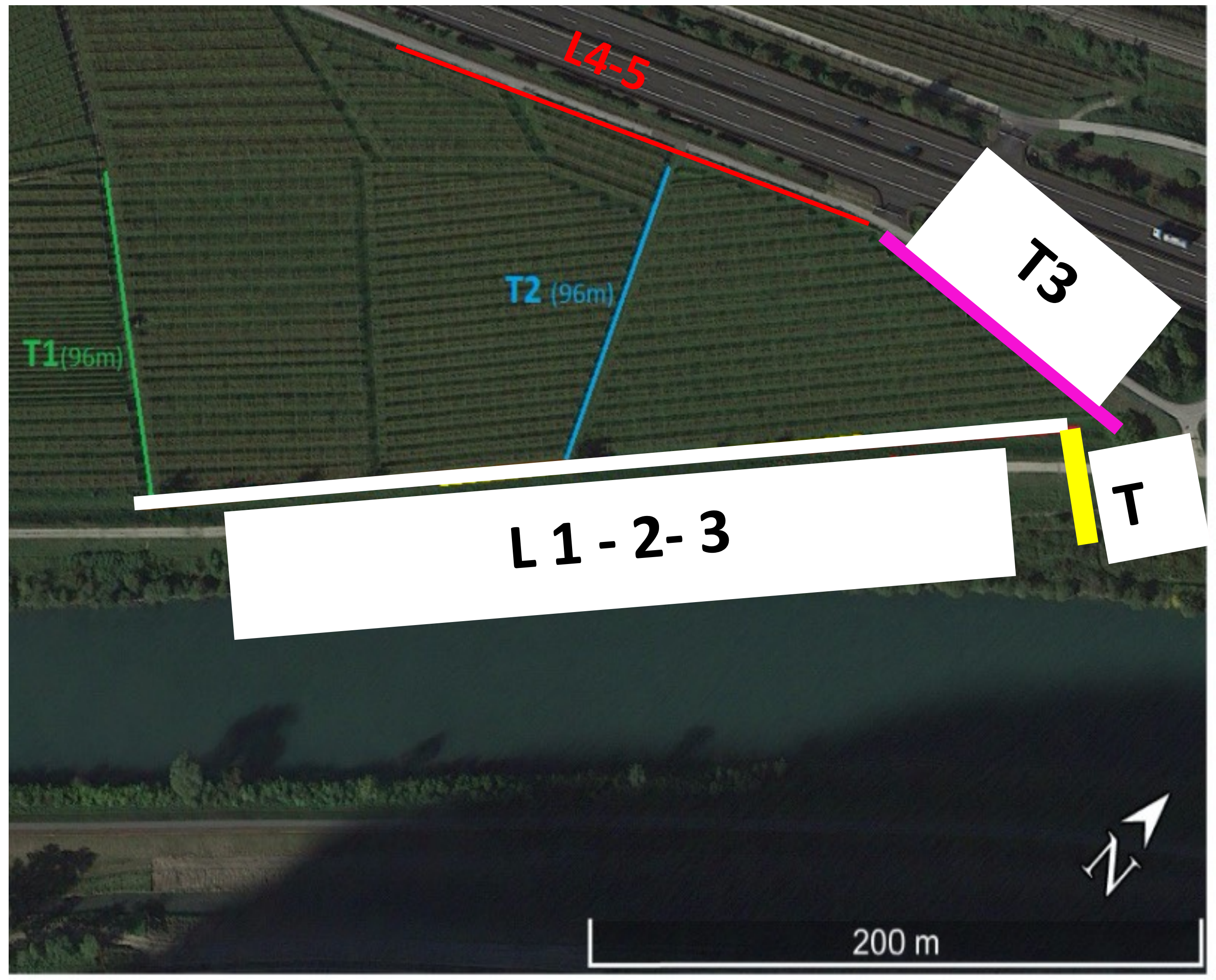
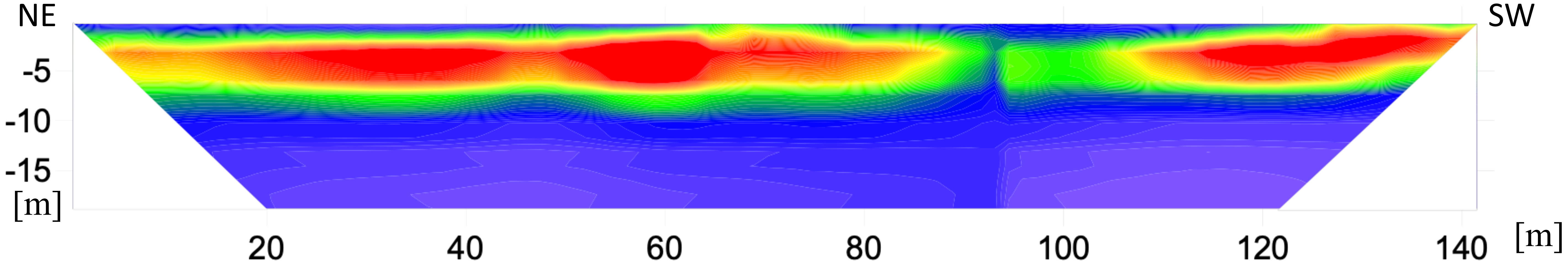


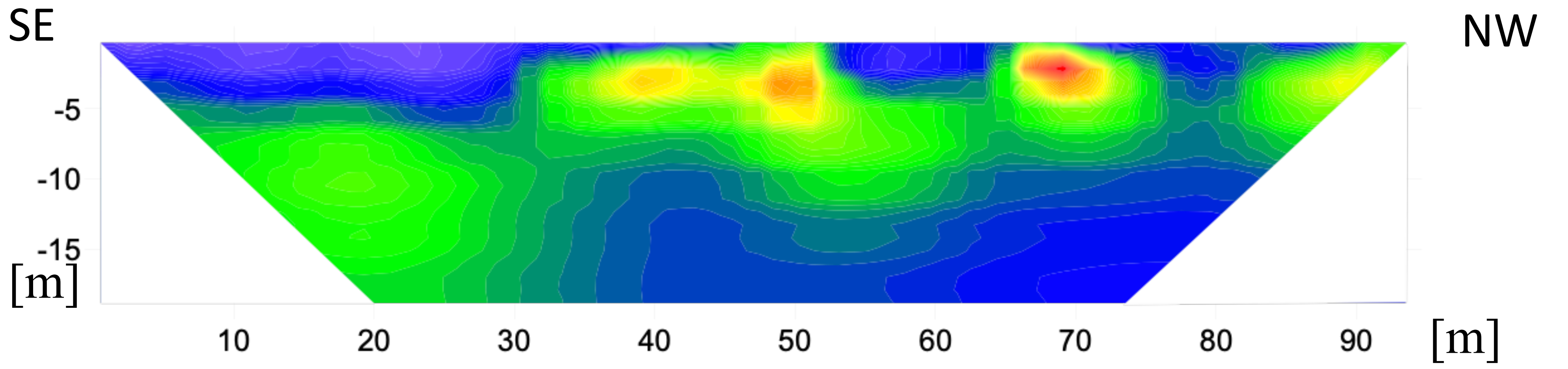



# SEZIONI ERT

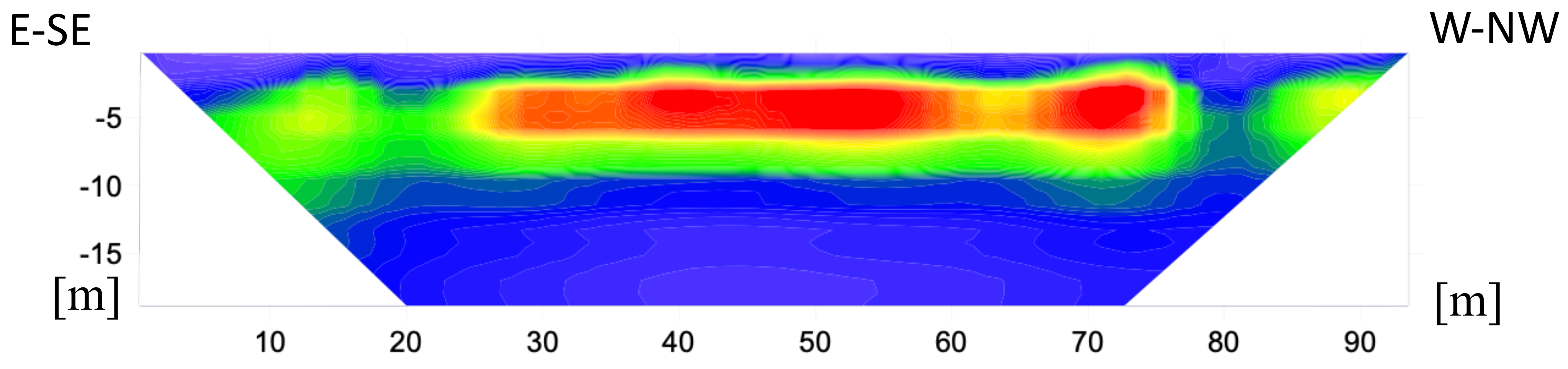
L 4-5

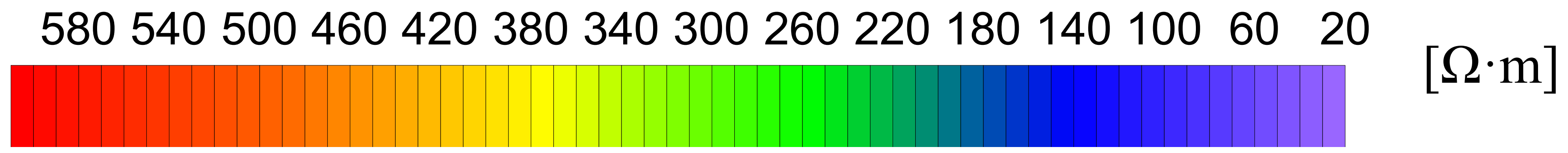


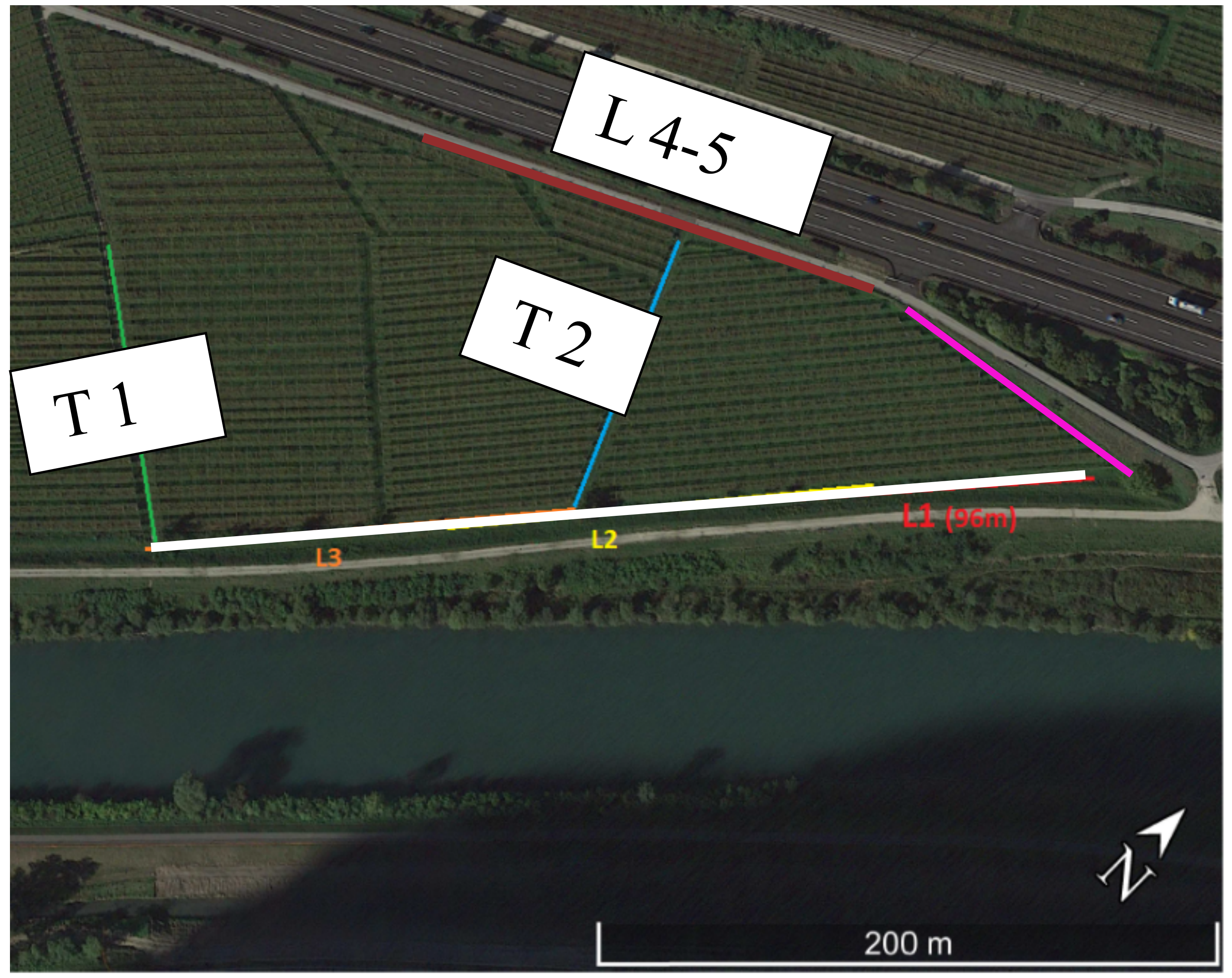

T 2



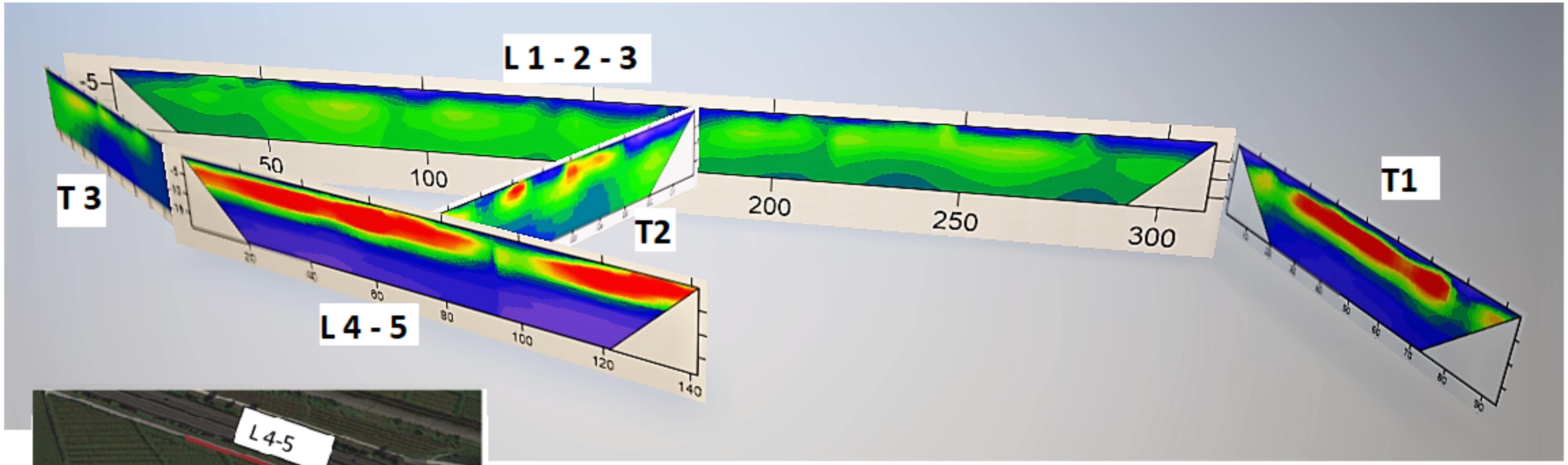

T 1

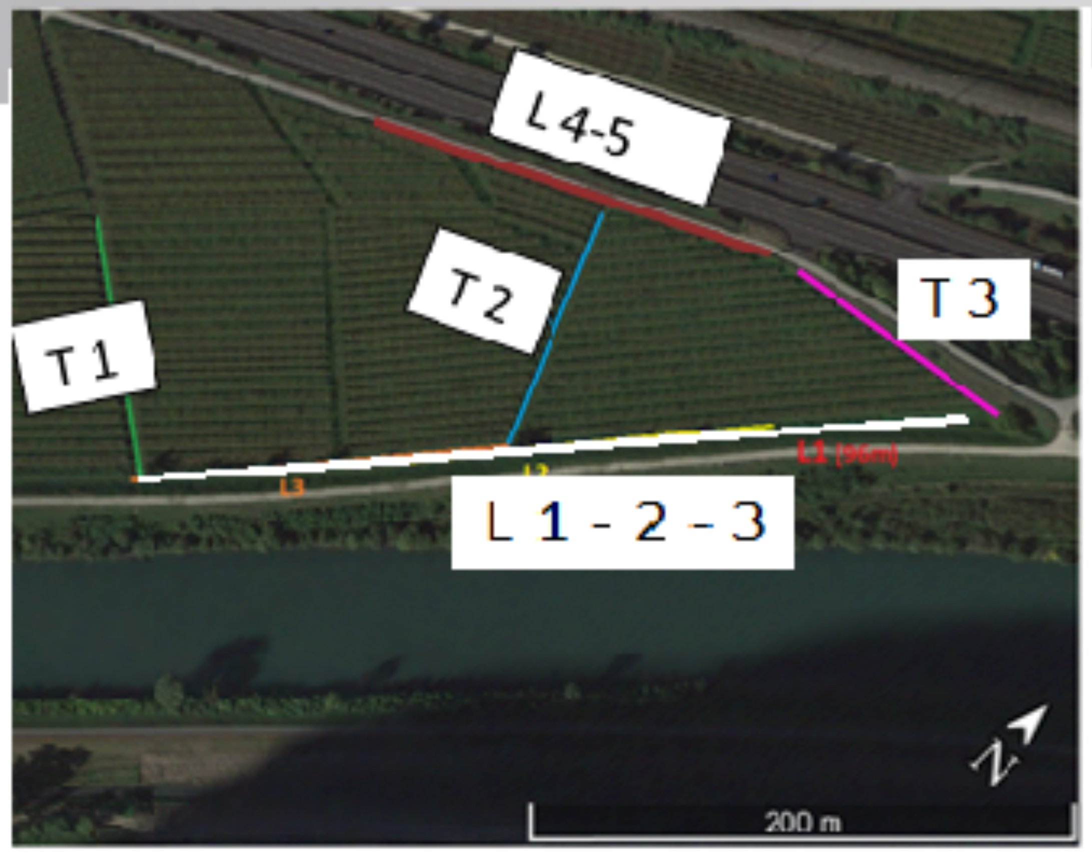


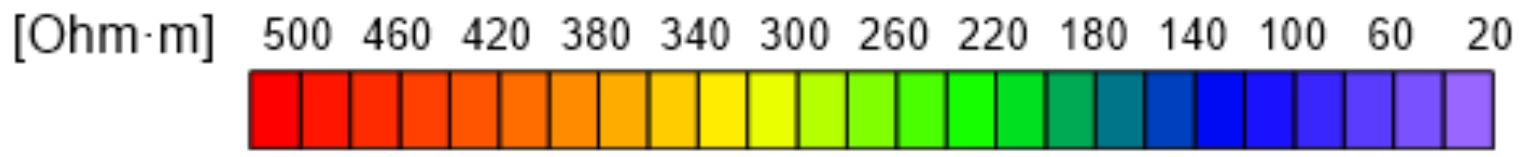



# VISTE 3D DELLA DISTRIBUZIONE DELLE SEZIONI ERT

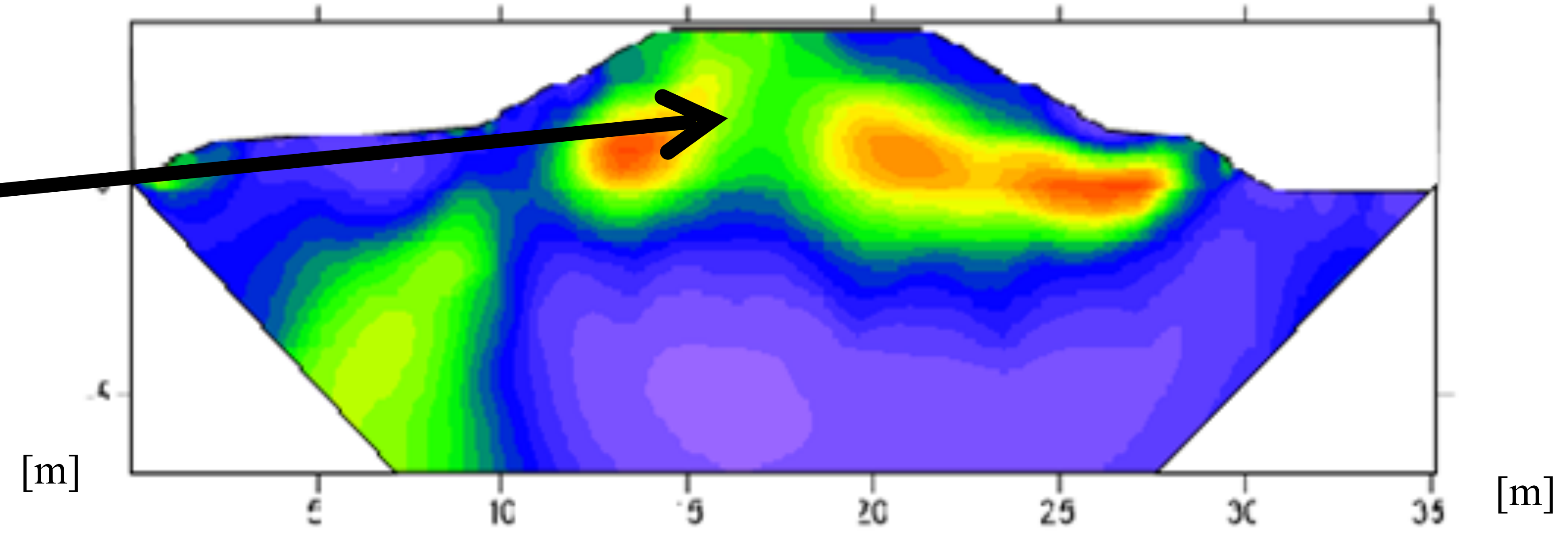


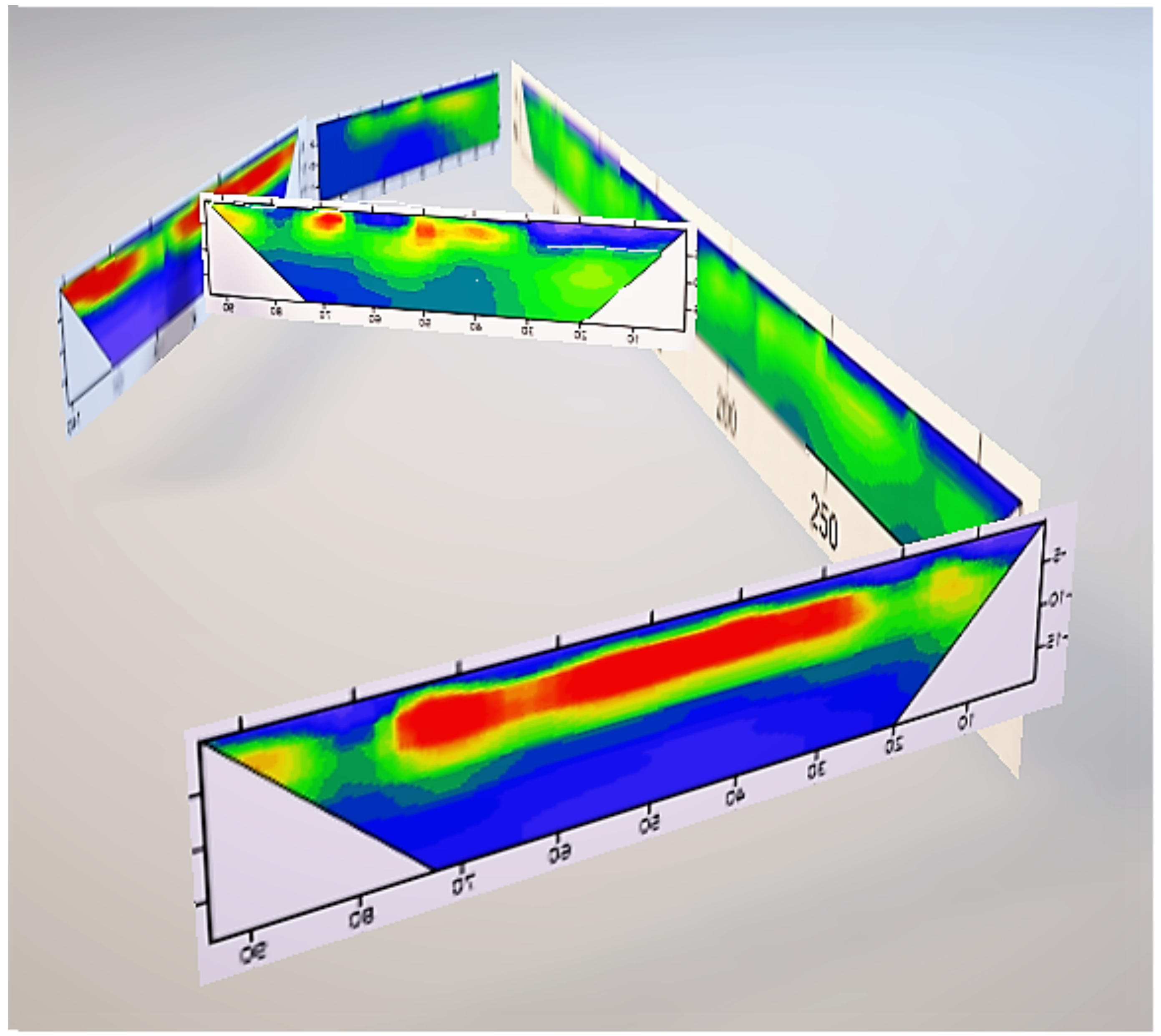



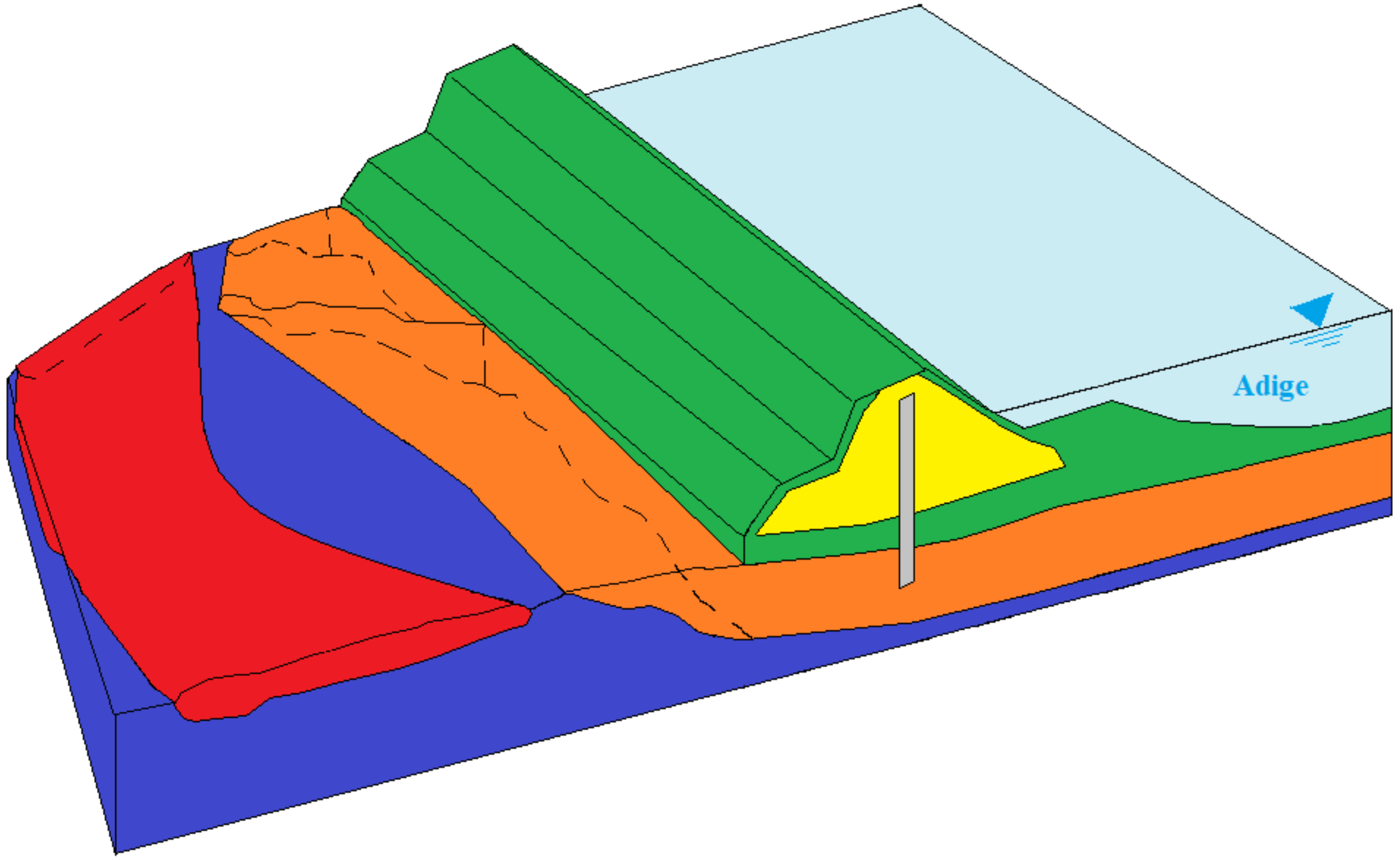
# LAVORI FUTURI

- Monitoraggio delle condizioni del setto.



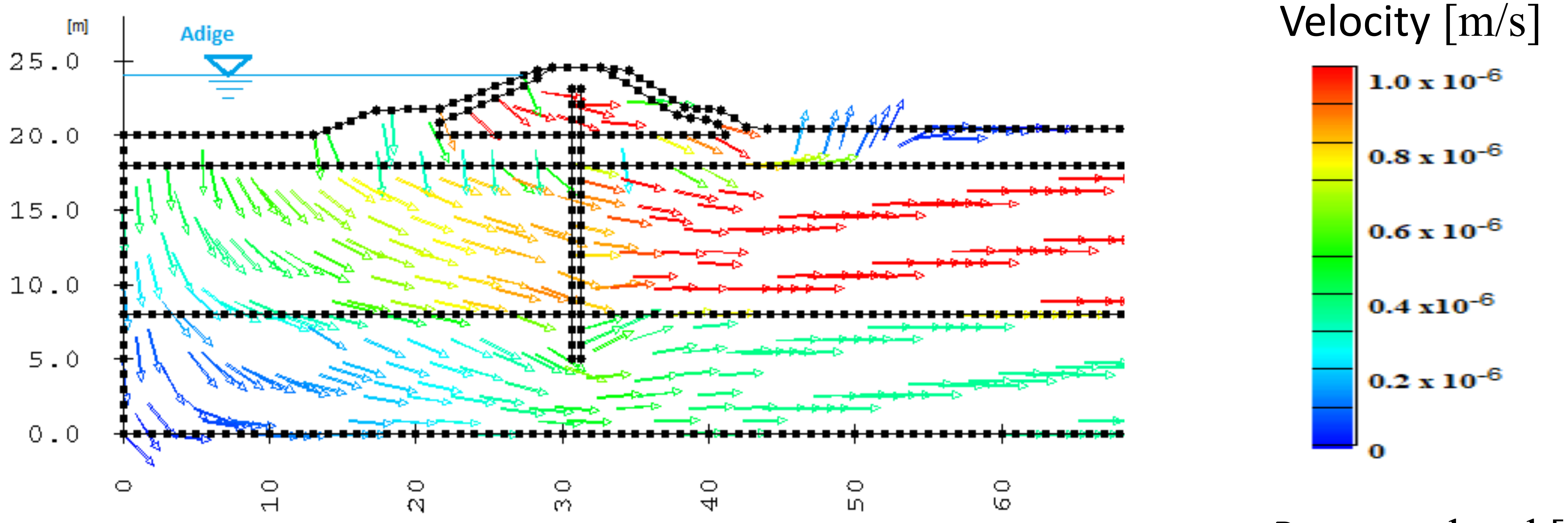

- Modellazione idrologica 3D

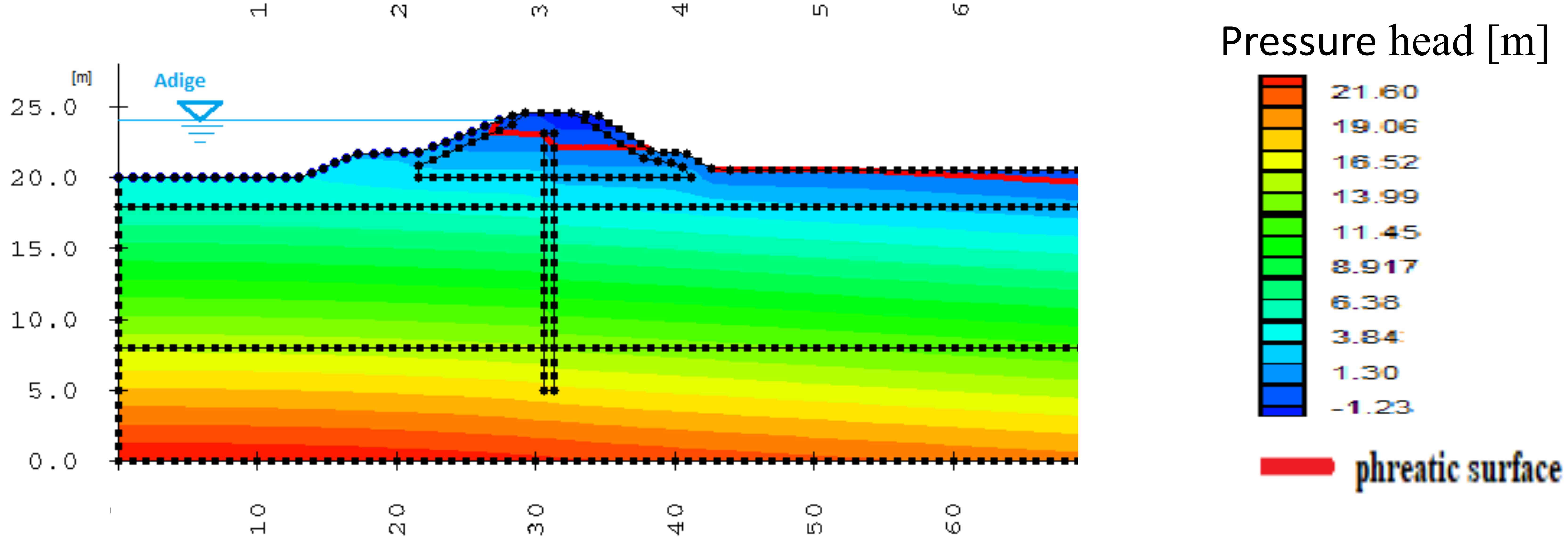




# CASO DI UN DIAFRAMMA DISCONTINUO

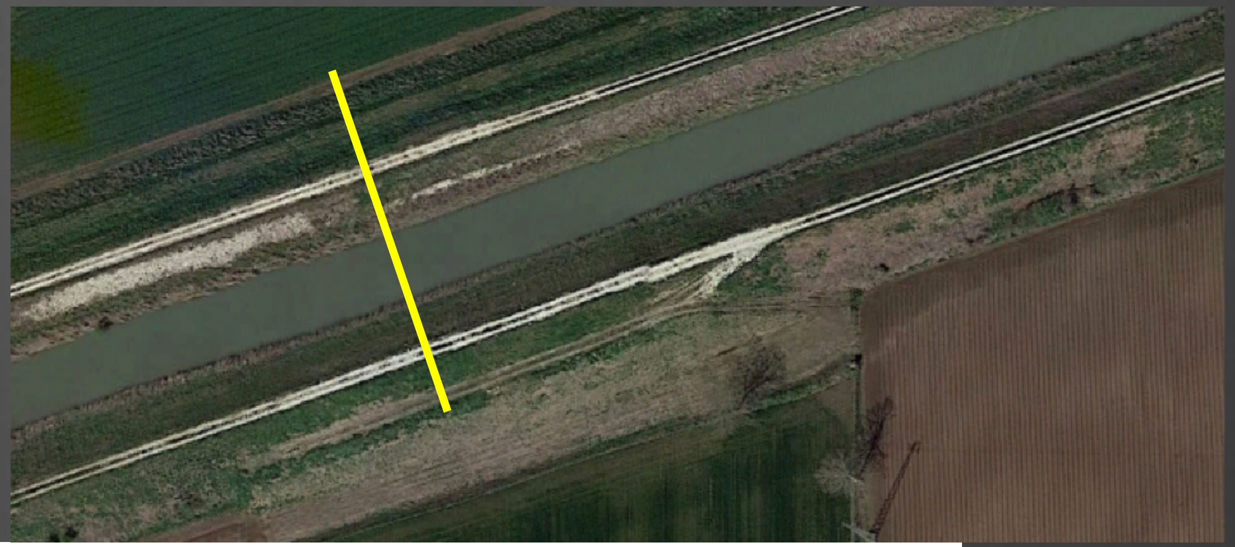
Carico idraulico imposto in alveo = 4 m; Conducibilità idraulica del setto = $1 \times 10^{-6}$ m/s



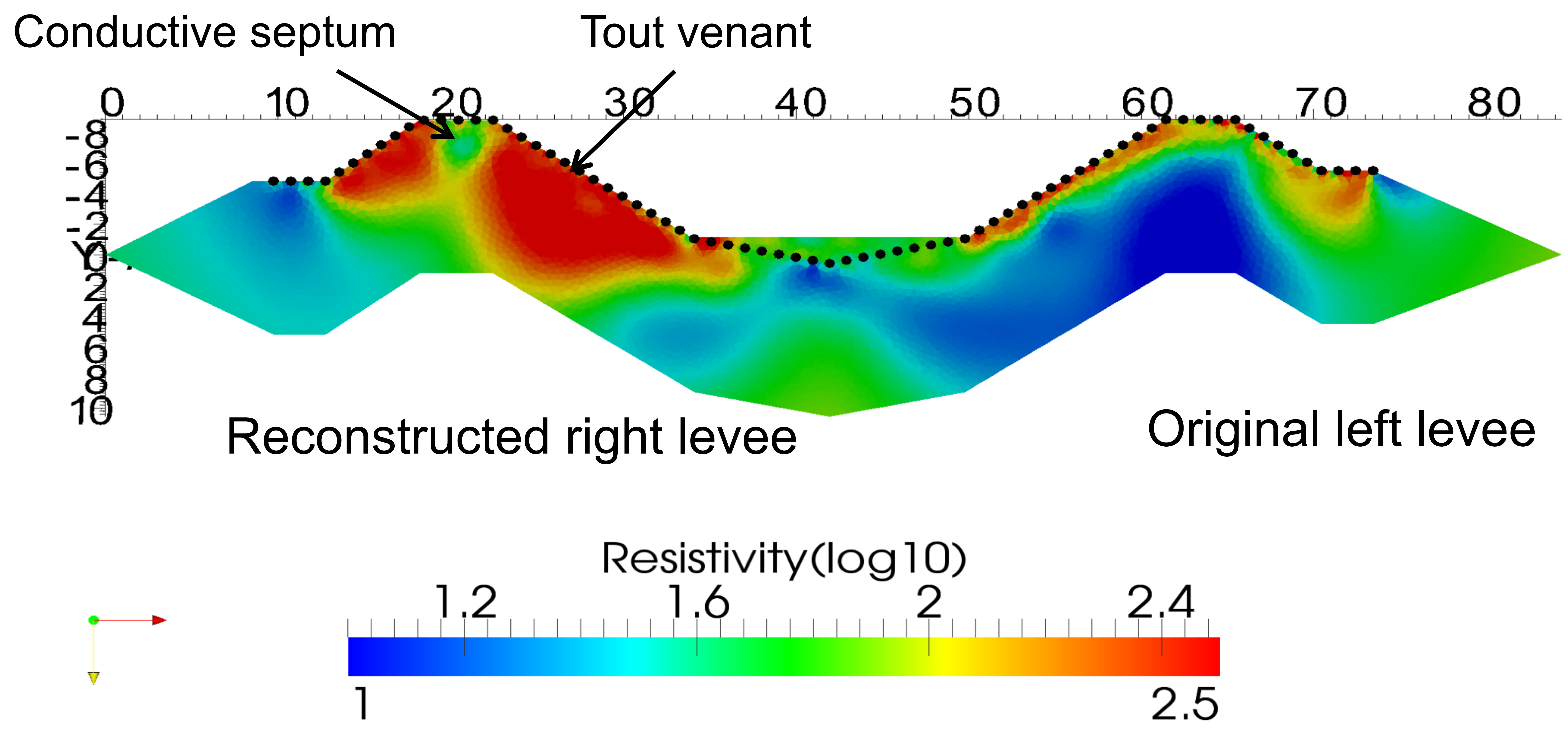



# 3. Electrical Resistivity Tomography results

## Cross-river profile



Cross-river profile, 72 elec., 1 m sp., dip-dip



## *The electric methods*

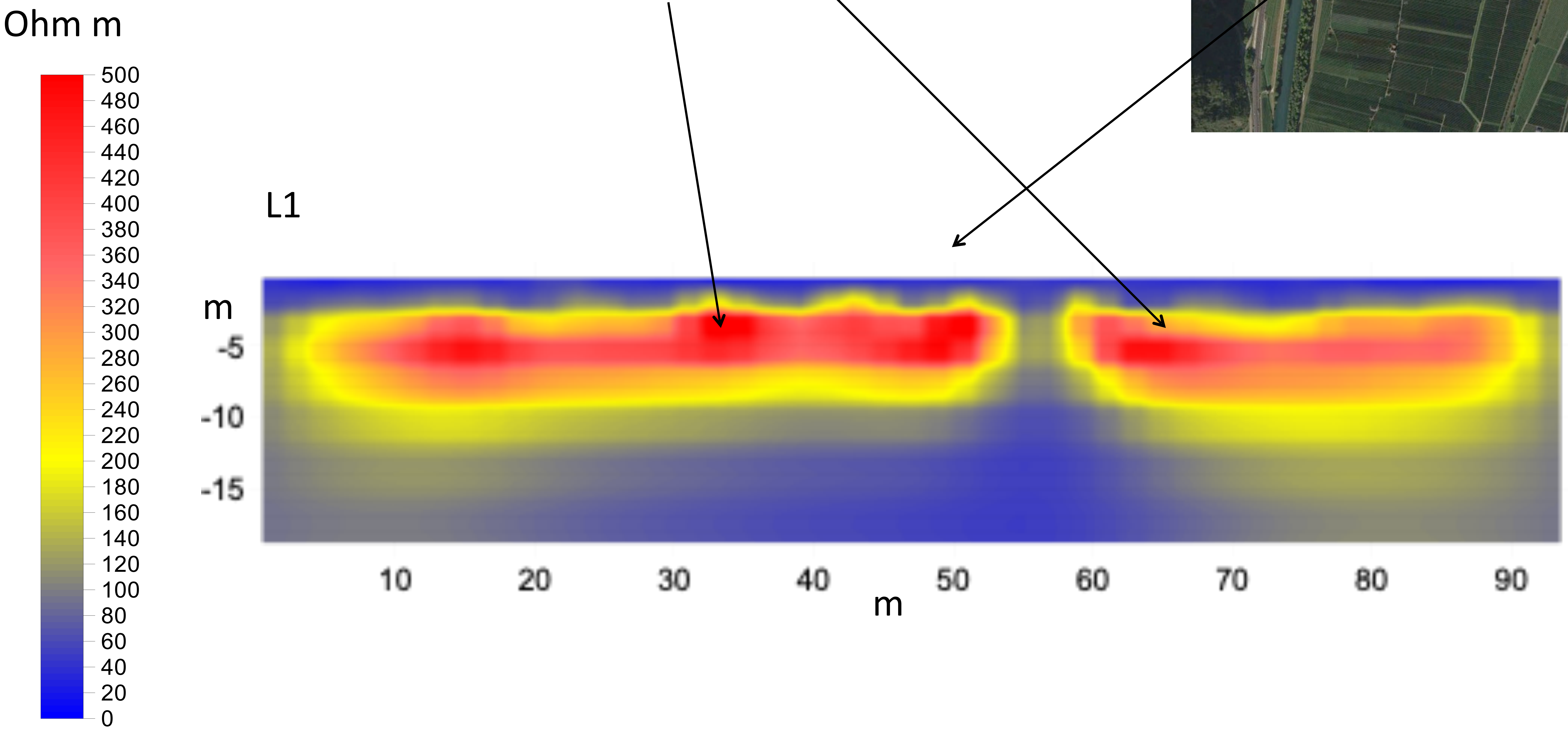
3) Water resources management

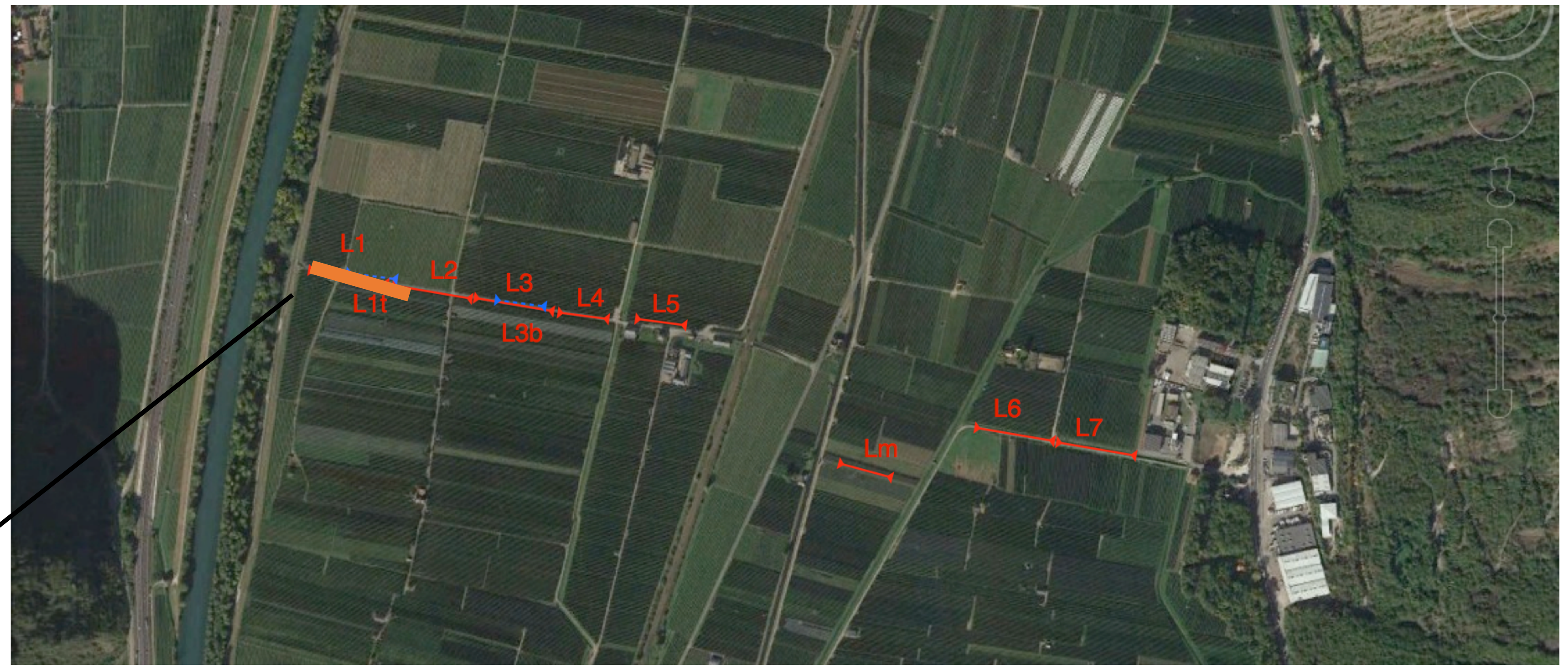
-Water table exploration….

-Water reservoir (e.g. sandy-bodies)

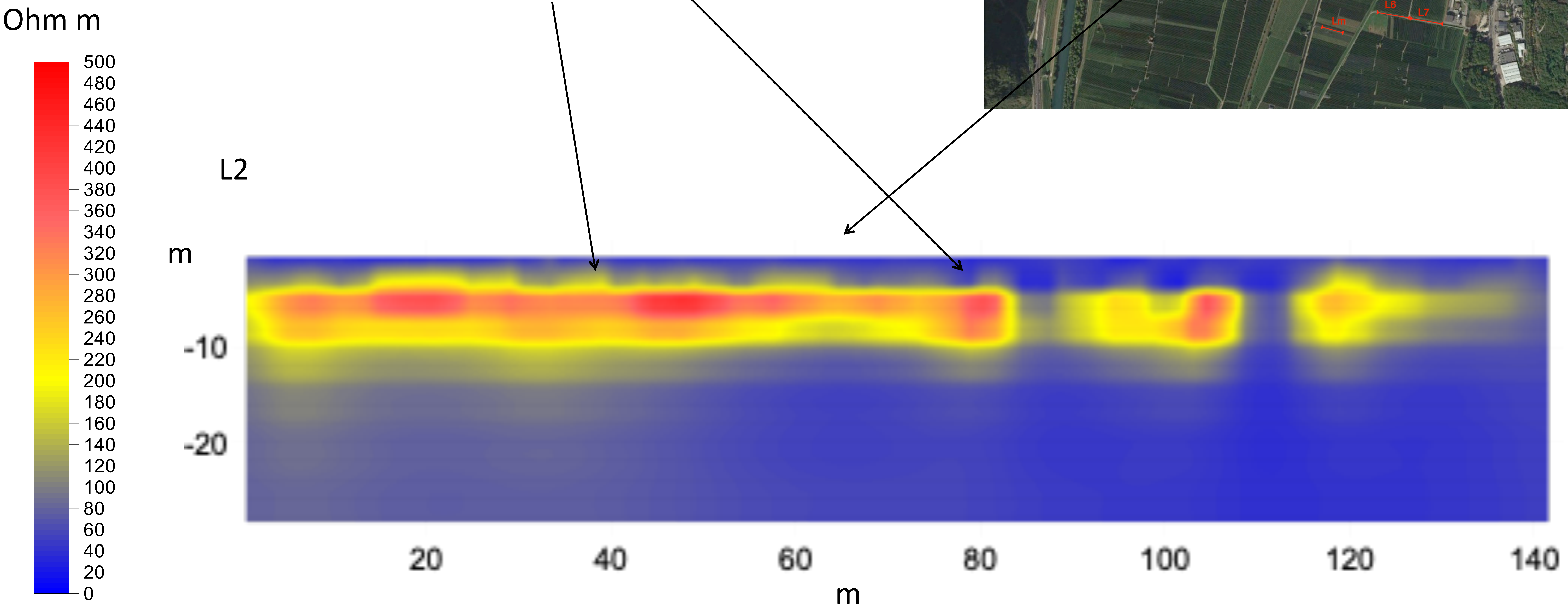
# ERT – Sourh Tyrol looking to paleo-channels of Adige River
# Ora - Auer

Sandy paleo -channel



Sandy paleo -channel



*The electric methods*

# 4) Polluted sites characterisations

Polluted site (Bologna Railway station)

Organic-clorurate concentrations > 10 norms

Level

*The electric methods*

# 4) Polluted sites characterisations

Injection of active carbon solution

Helping remediation

Monitored by geophysics

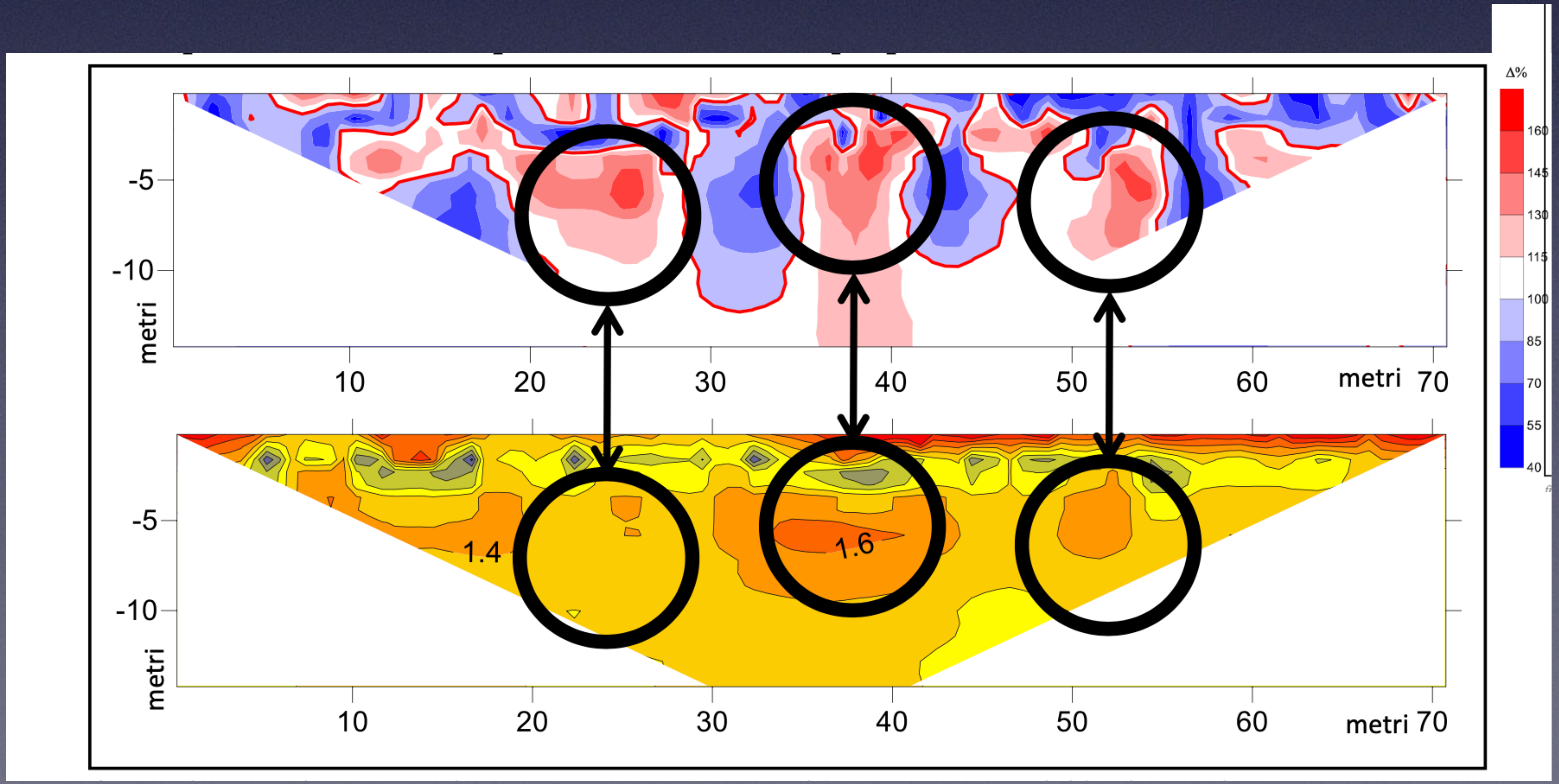
*The electric methods*

# 4) Polluted sites characterisations

Injection of active carbon solution

Helping remediation

Monitored by geophysics




Time lapse ERT showing higher Resistivity

Due to bacteria activity after the injection

ERT

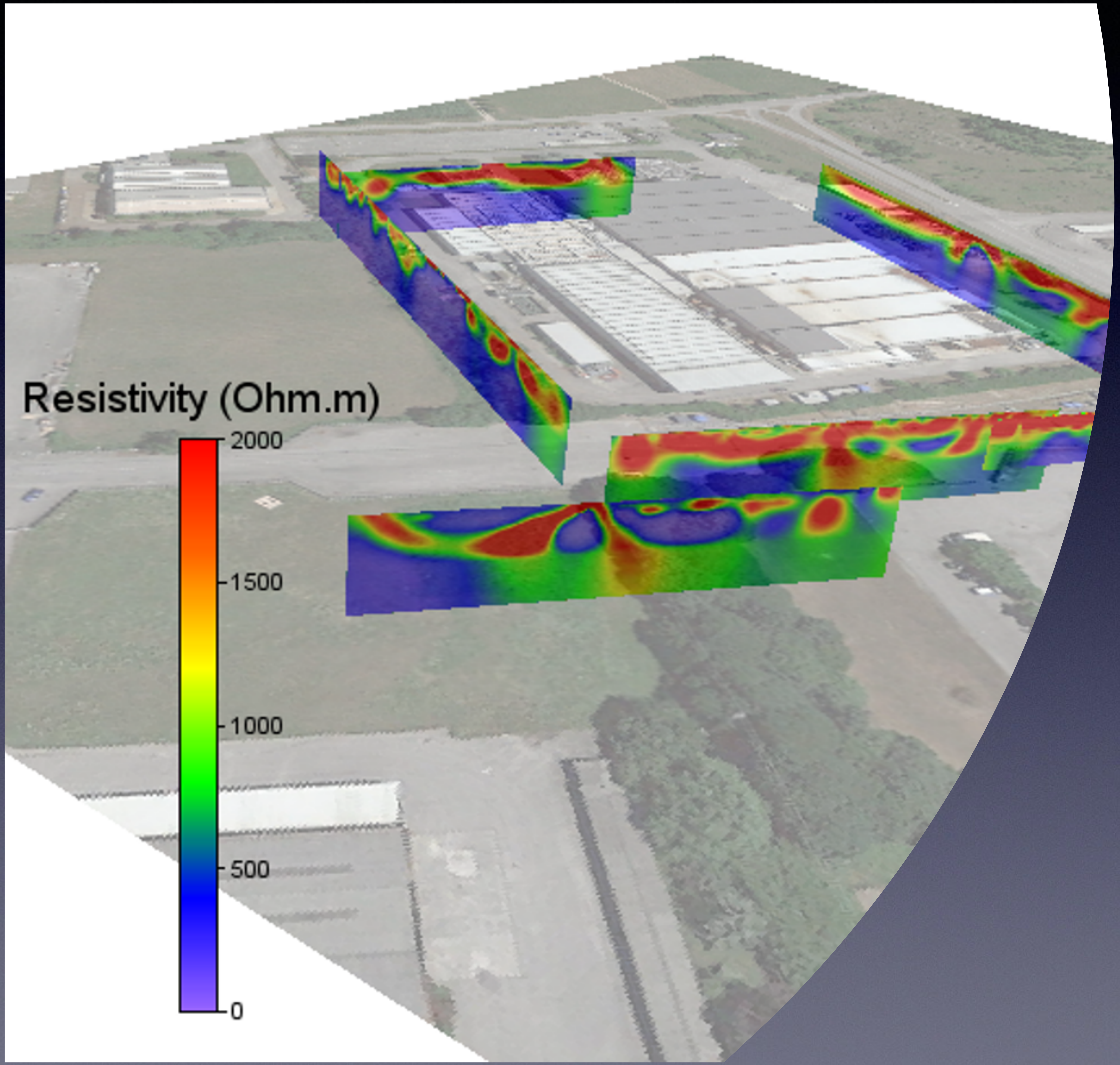
Log 10 Ohm m

*The electric methods*

4) Polluted sites characterisations

Polluted industrial site

Looking to clay level able to stop polluted water infiltration…



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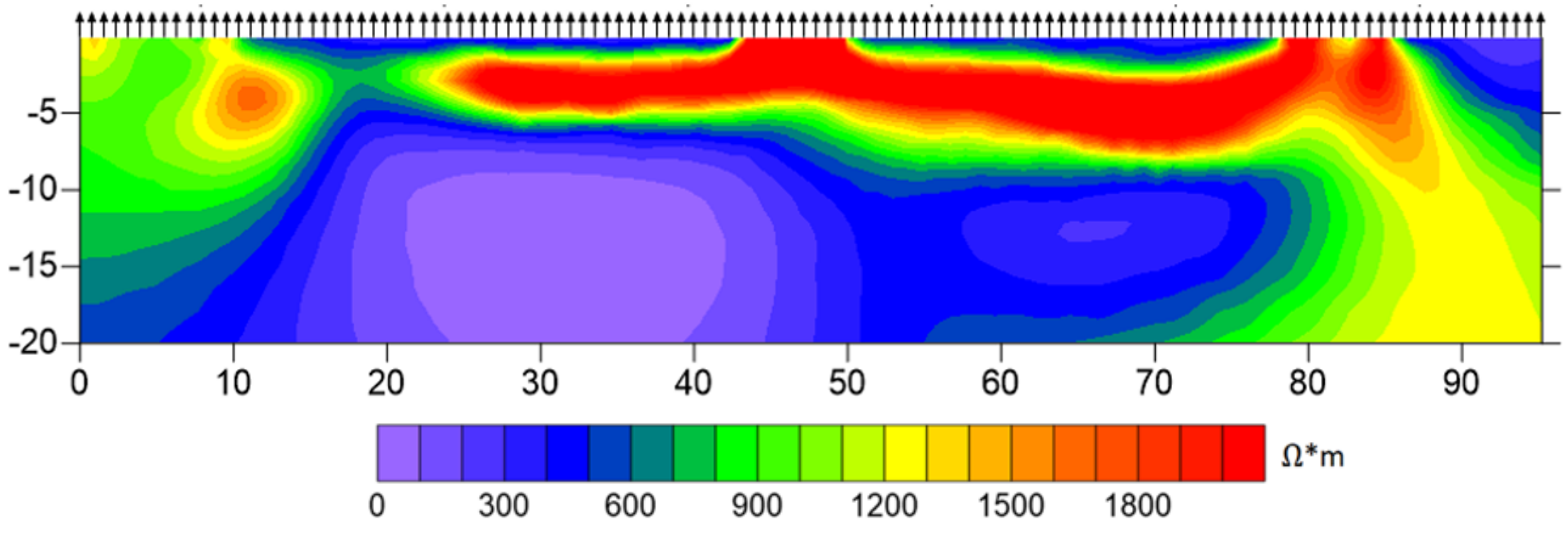
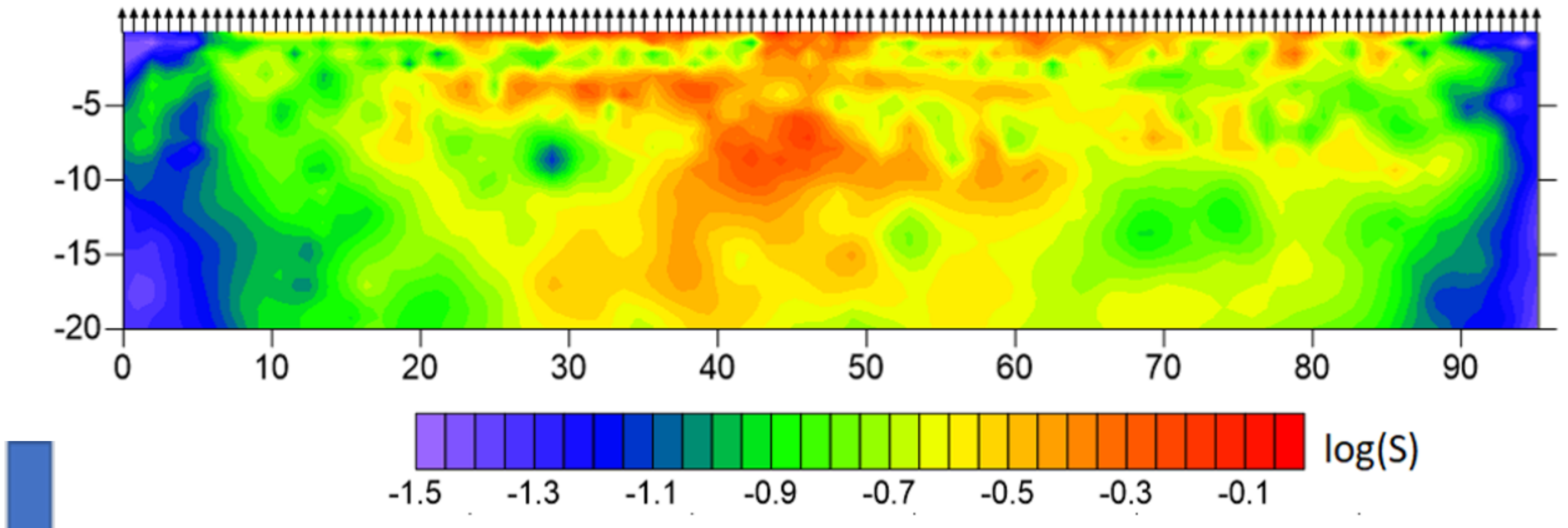
DIPARTIMENTO DI GEOSCIENZE

**First surface line "S1" with 120 electrodes spaced 0.80 m and measurements performed with a Dipole-Dipole configuration skip 8**

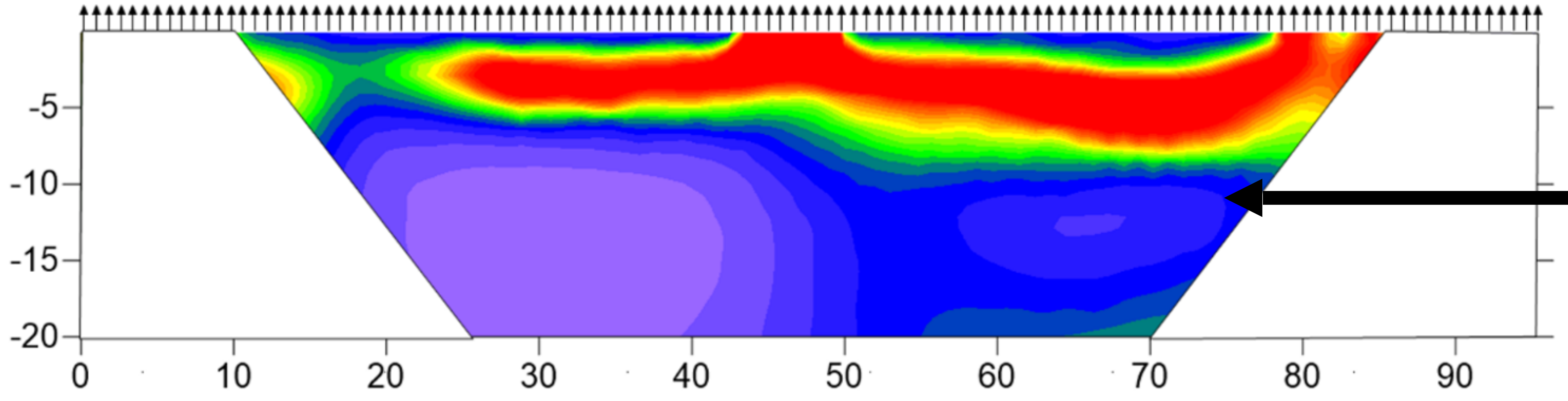
**RESISTIVITY SECTION**




**SENSITIVITY SECTION**




**FINAL RESISTIVITY SECTION**




**The conductive layer of clay is continuous but we cannot correctly define its thickness**

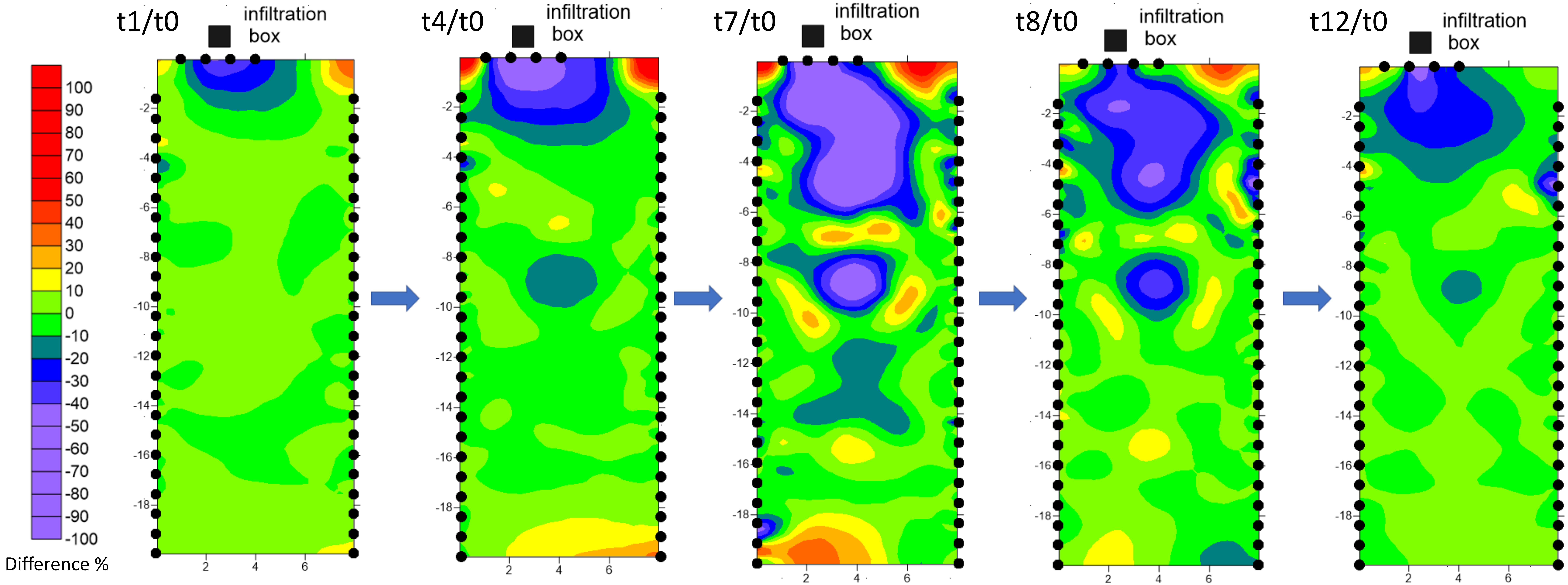
## *The electric methods*

4) Polluted sites characterisations

Polluted industrial site

Infiltration test and Borehole ERT to measure vertical permittivity…

# Using a ratio inversion approach we are able to highlight the resistivity changes from one-time frame to the next and therefore it is possible to study the infiltration process



## *The electro-magnetic methods*

1) LANDSLIDE CHARACTERISATION ??

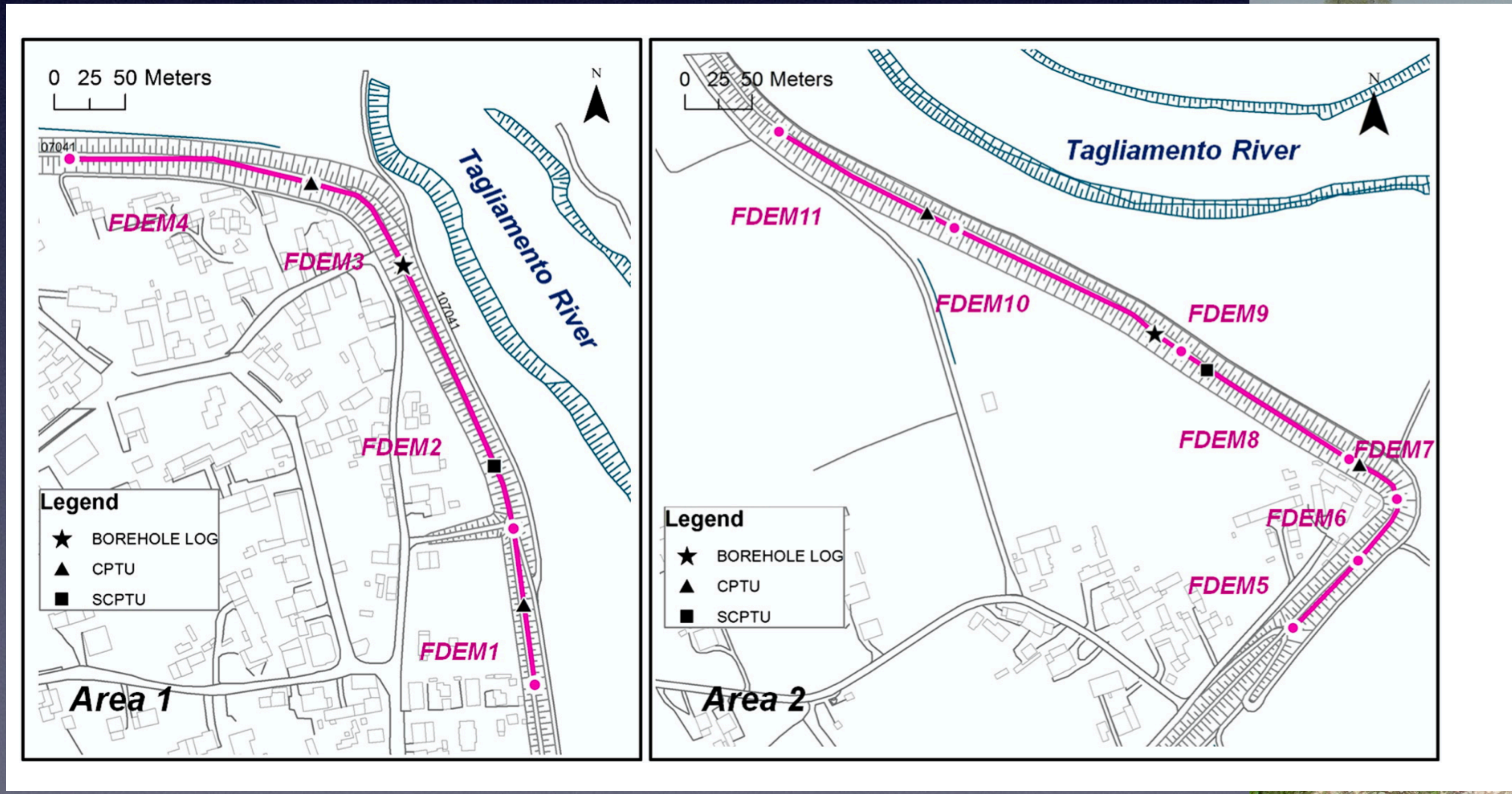
2) Rivers management

3) Water resources management

4) Polluted sites characterisations

# *The electro-magnetic methods*

## 2) Rivers management




## *The electro-magnetic methods*

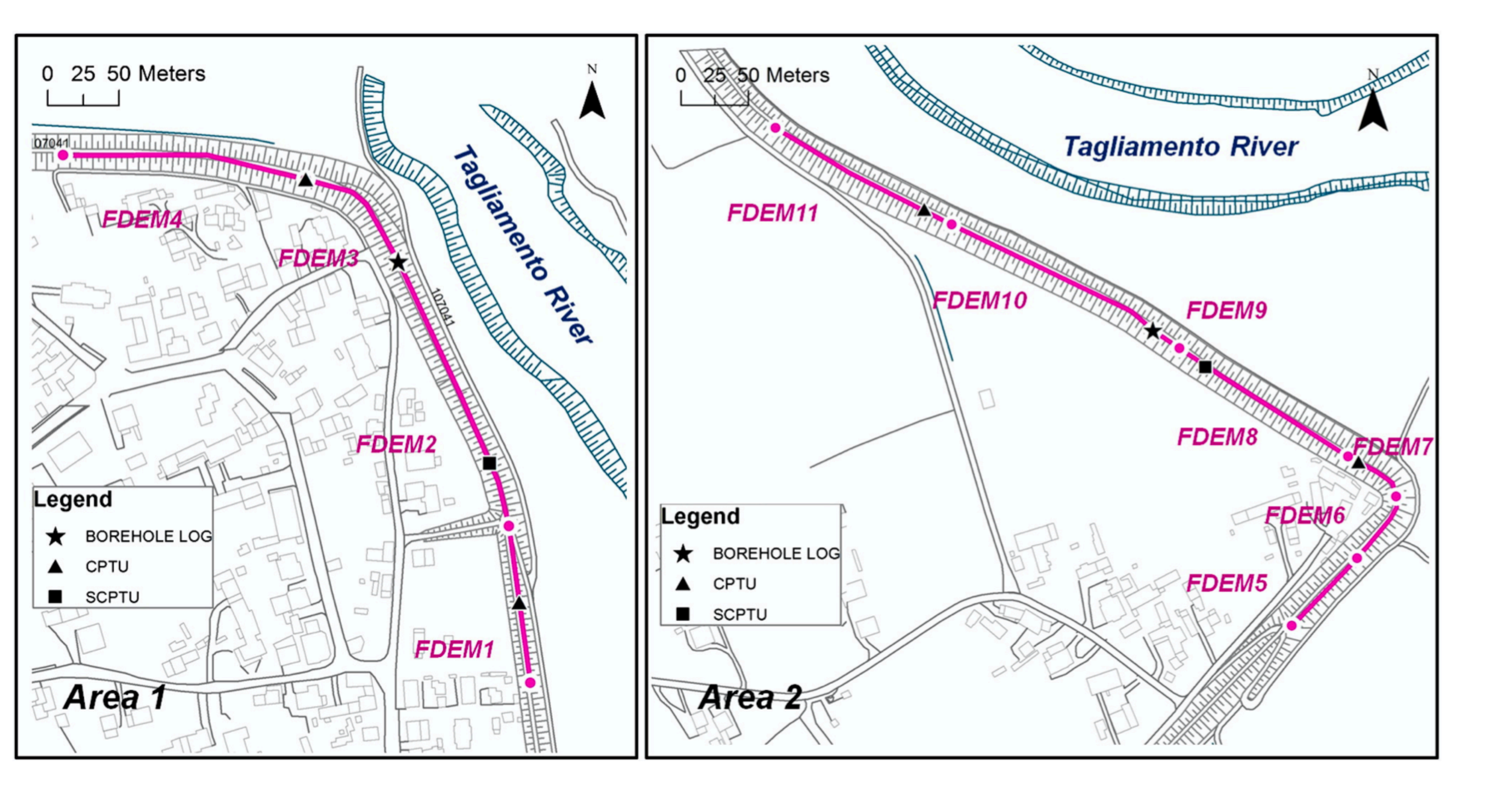
# 2) Rivers management

FDEM monitoring

Of Levee

Looking for buried

irregularities



*The electro-magnetic methods*

2) Rivers management

FDEM monitoring

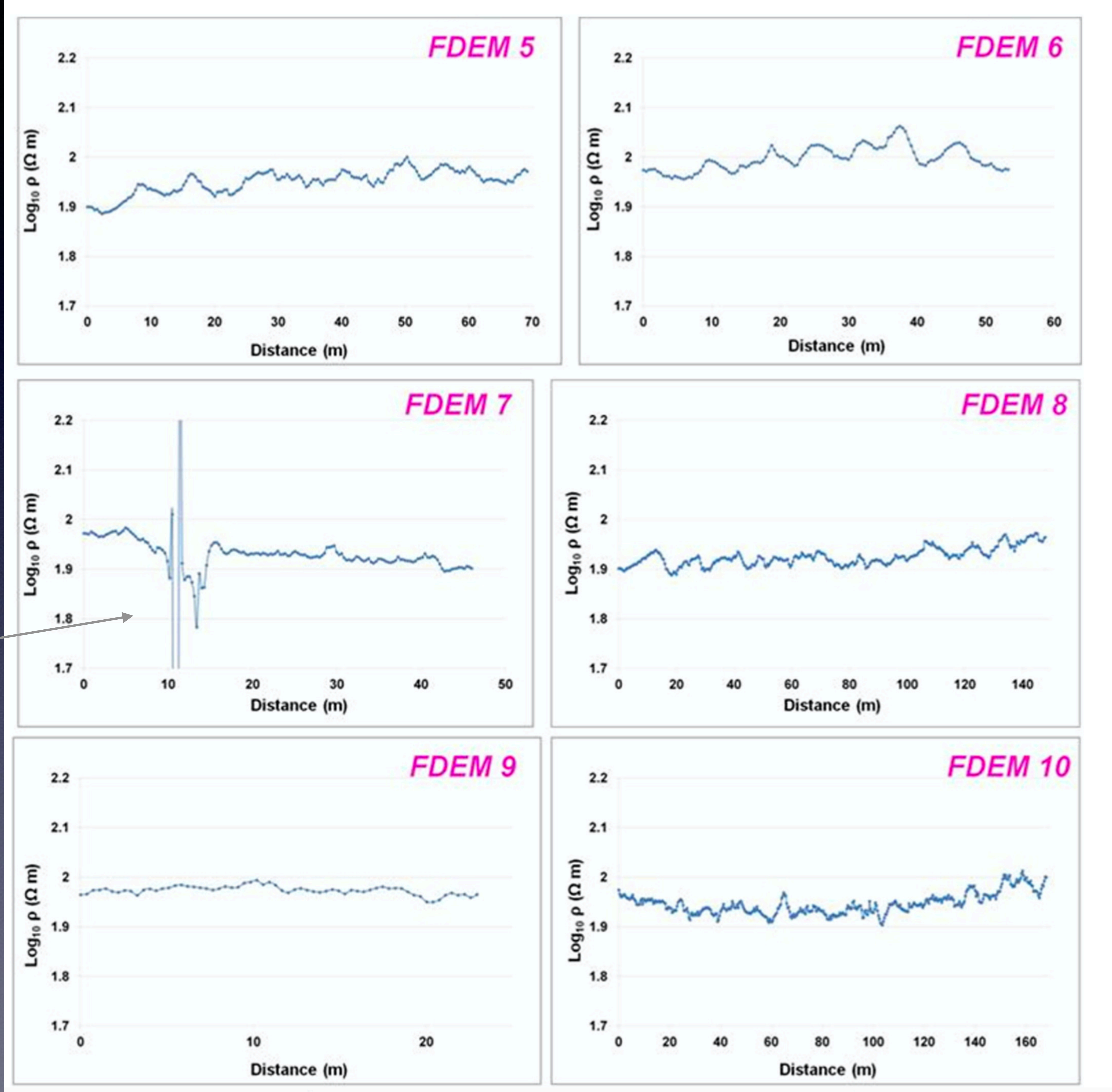
Of Levee

Looking for buried

irregularities

Metallic tunnel

Partially buried

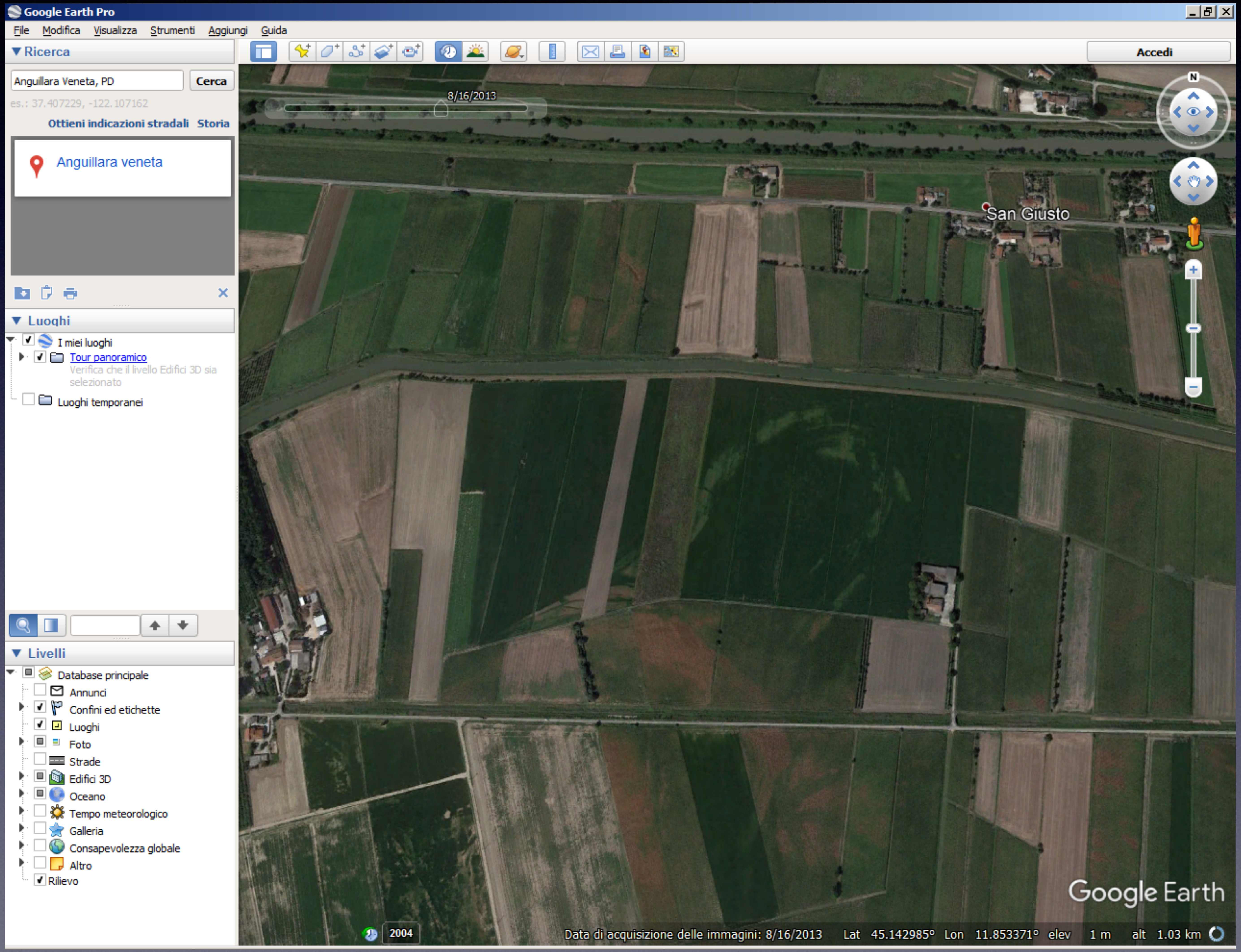


# *The electro-magnetic methods*

## 3) Water resources management

Studying fine deposits for

Agriculture



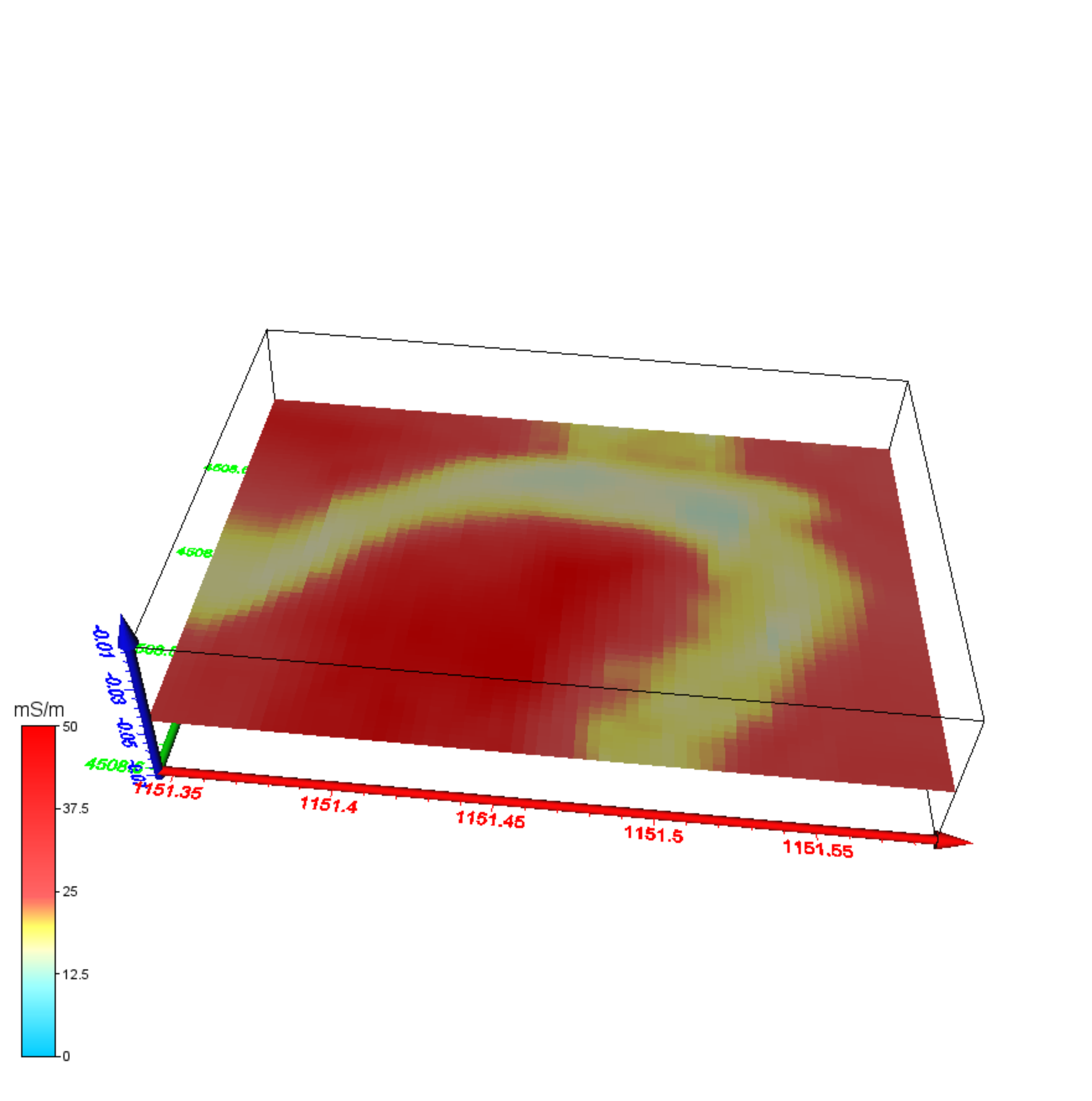
*The electro-magnetic methods*

3) Water resources management

Sandy bodies (Paleo-channel)

Retrieved with CMD EXPLORER

10kHz, 3 coils

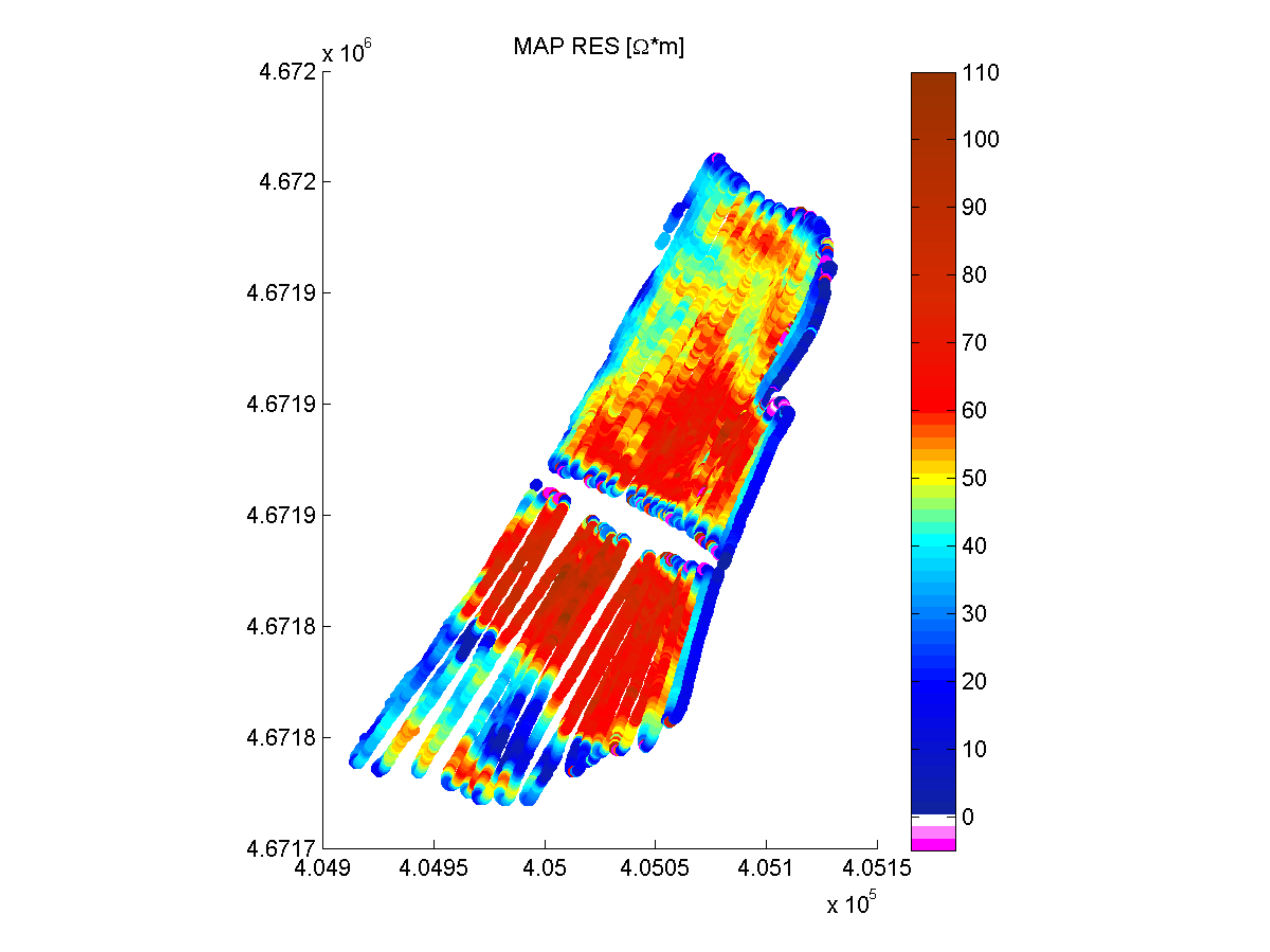


# *The electro-magnetic methods*

## 4) Polluted sites characterisations

Metallic materials in

Illegal waste



## *The electro-magnetic methods*

### 4) Polluted sites characterisations

Characterisation of waste deposit

In Wien

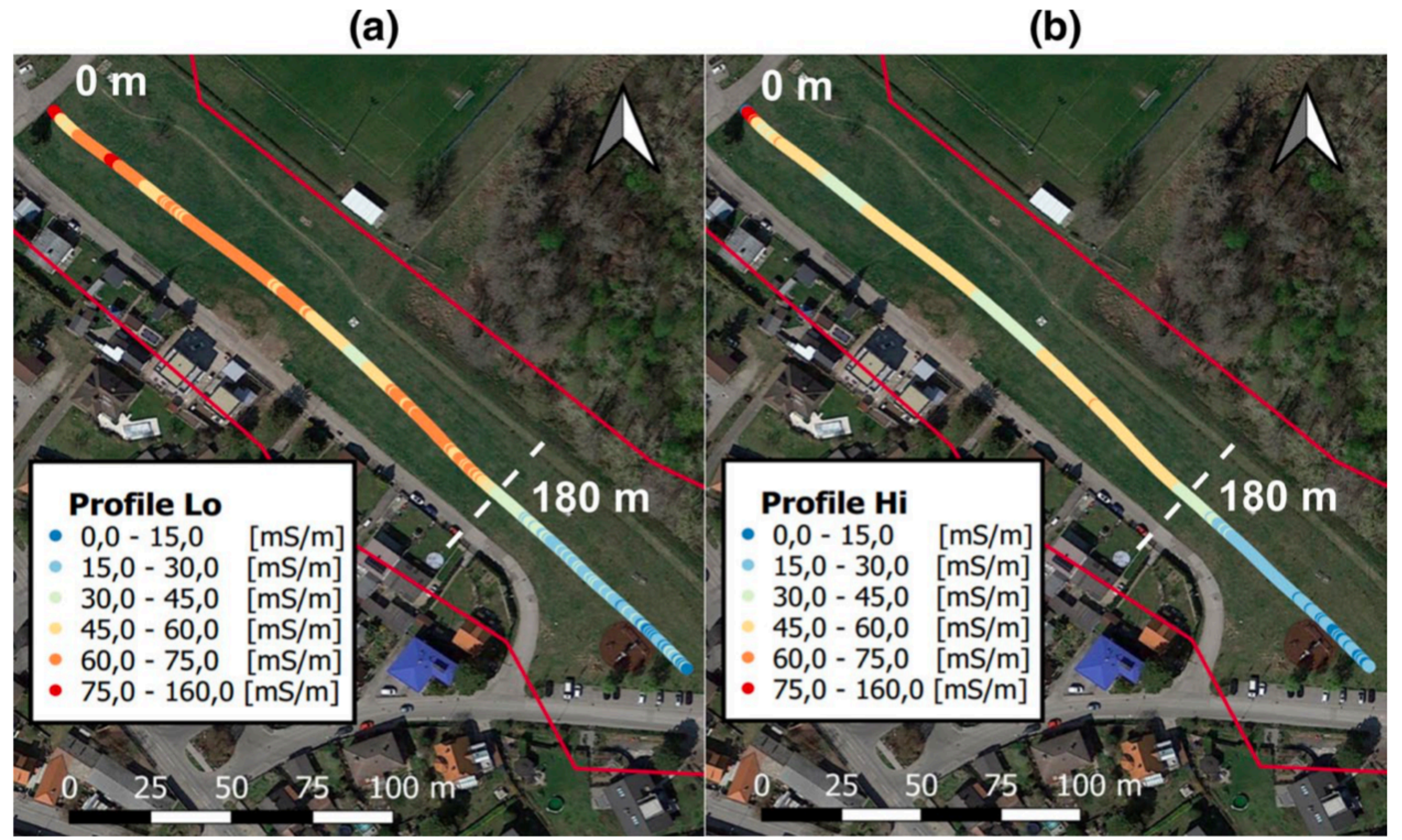



**Fig. 9** Apparent conductivity values from the EMI acquisition. EMI data were collected with a GF-Explorer probe using both possible coil orientations (Low and High modes, see Table 2). Results from the probe coil 3 (coil separation of 4.49 m and transmitter frequency of 10 kHz) collected in the **a** low-VMD mode (3.3 m nominal depth) and in the **b** high-HMD mode (6.7 m nominal depth). The white dotted line indicates the beginning of the lateral variation identified through the surface wave analysis. The red line defines the presumed perimeter of the landfill

## *The Radar methods*

1) LANDSLIDE CHARACTERISATION

2) Rivers management

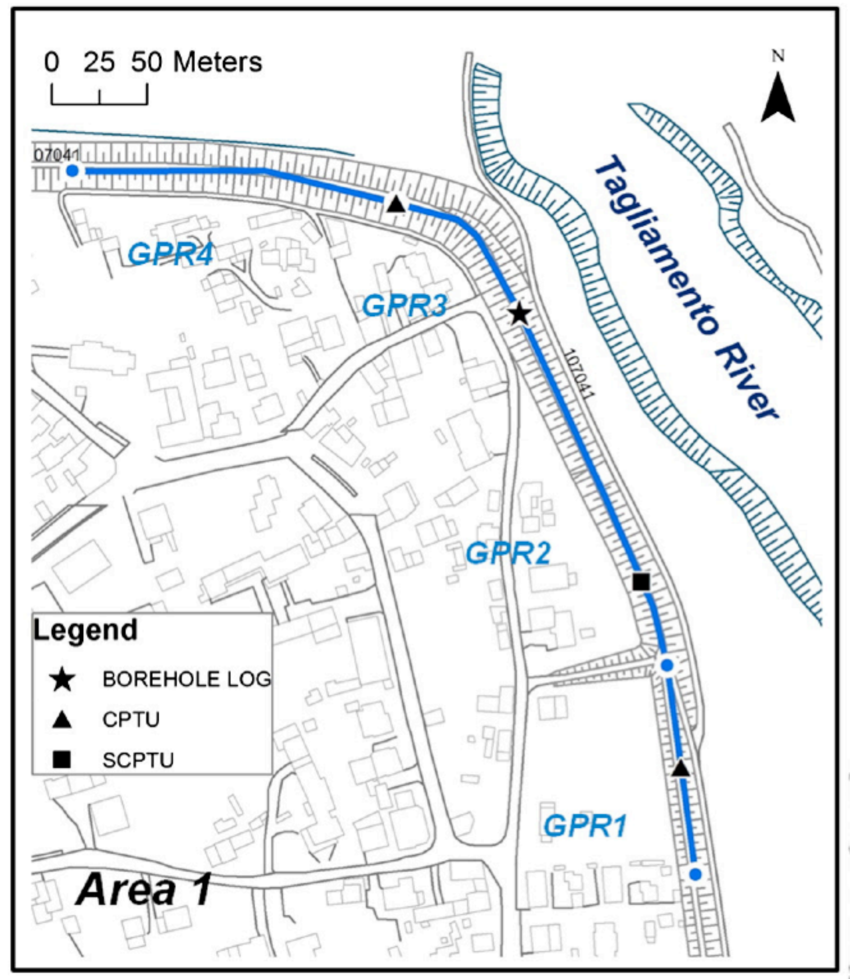
3) Water resources management

4) Polluted sites characterisations

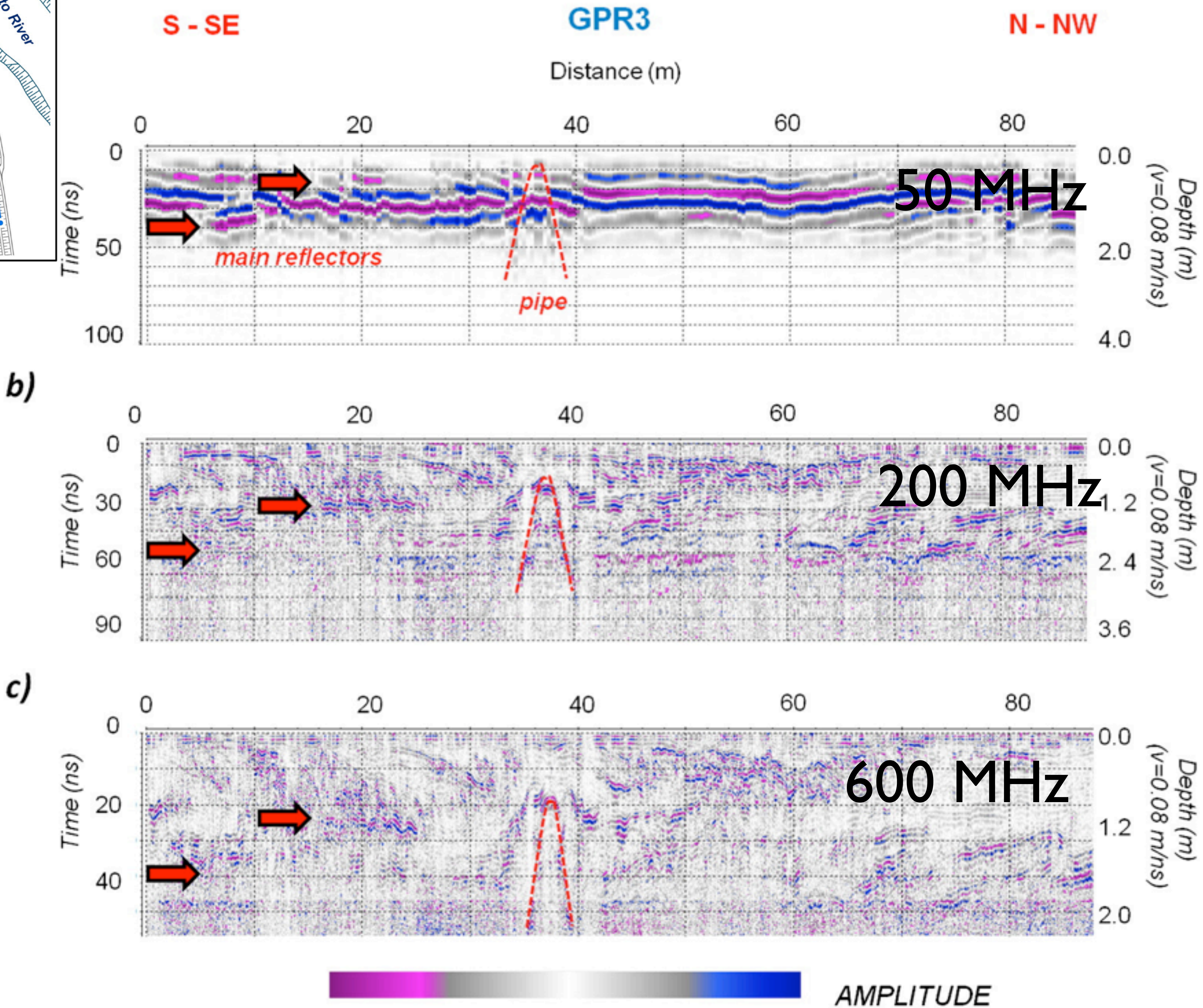
*The Radar methods*

2) Rivers management

Characterisation of levee



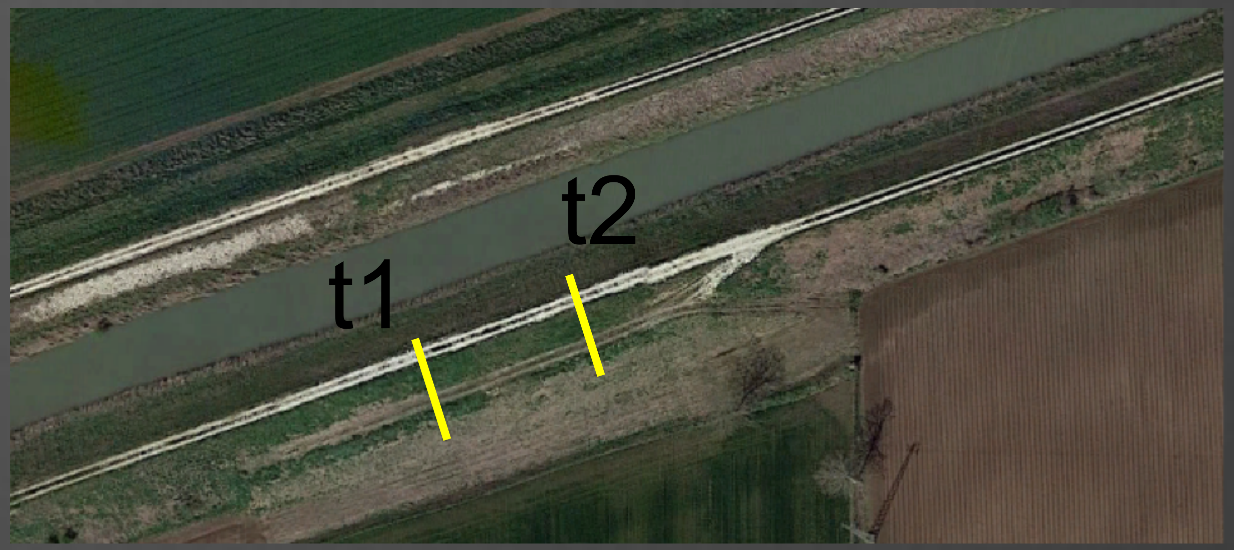

Buried tunnel




Perri et al
2014

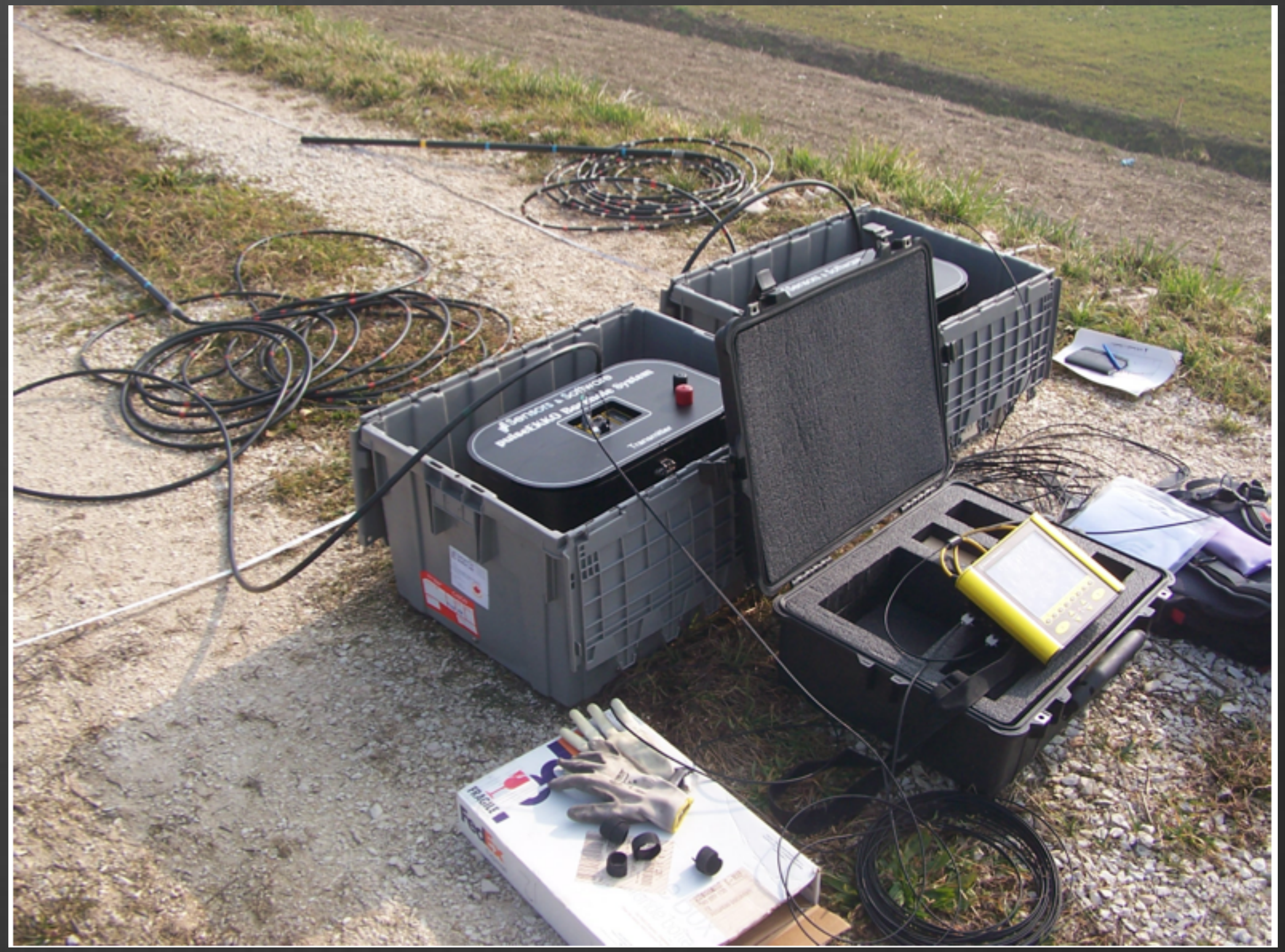
## 4. GPR results

Same position of
transversal ERT sections T1 and T2





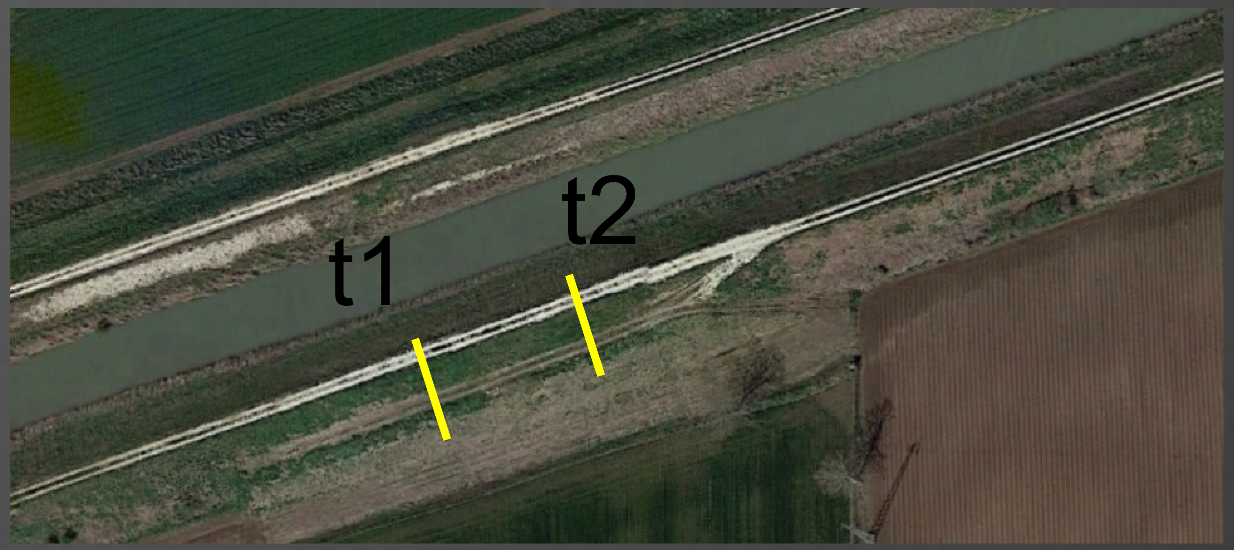
- Bi-static profile
- Tx and Rx on internal and external sides of the levee (ZOP)
- 100 Mhz antennas

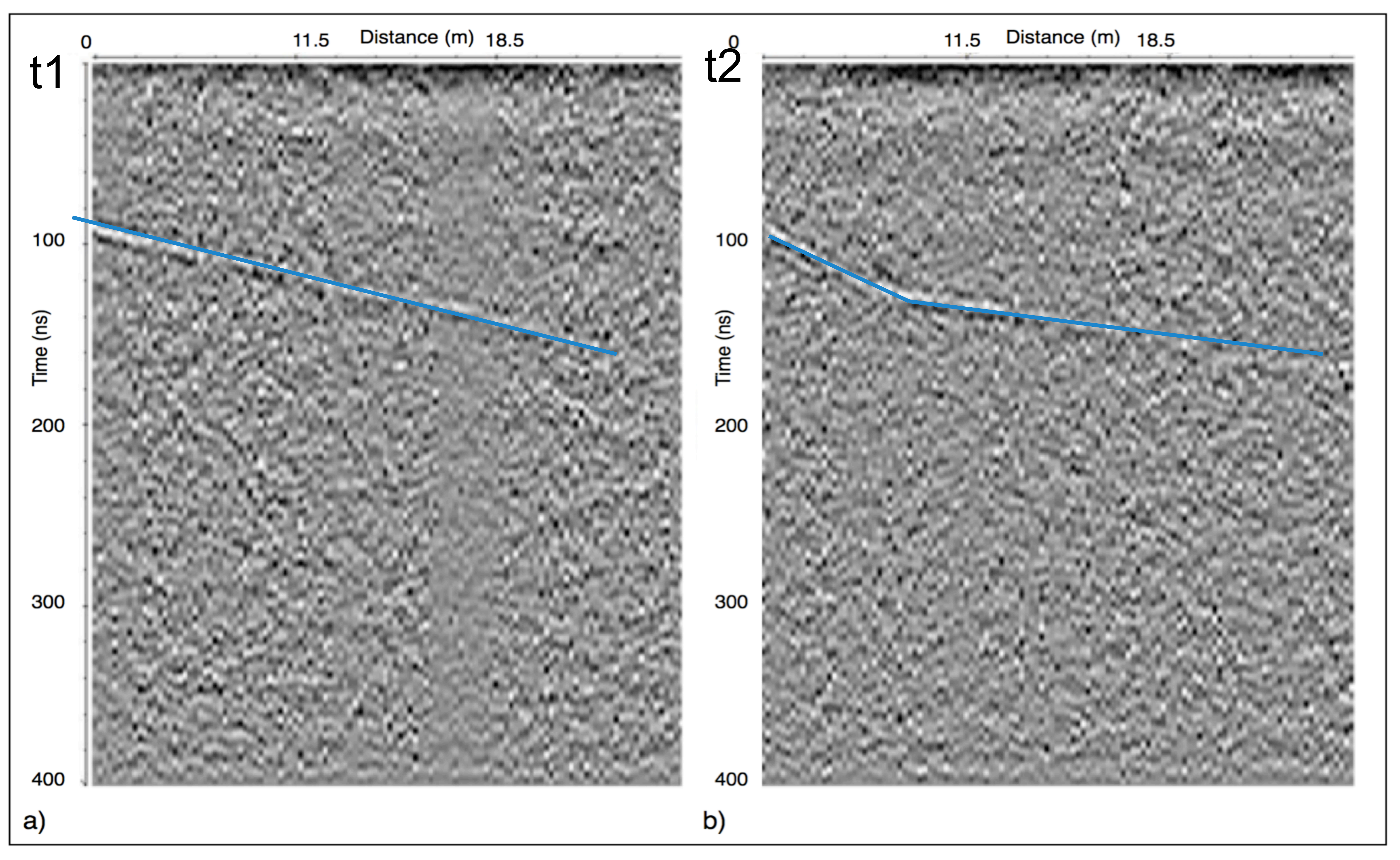


## 4. GPR results

Conductive core - noisy data

First pick arrival for (ε) estimation

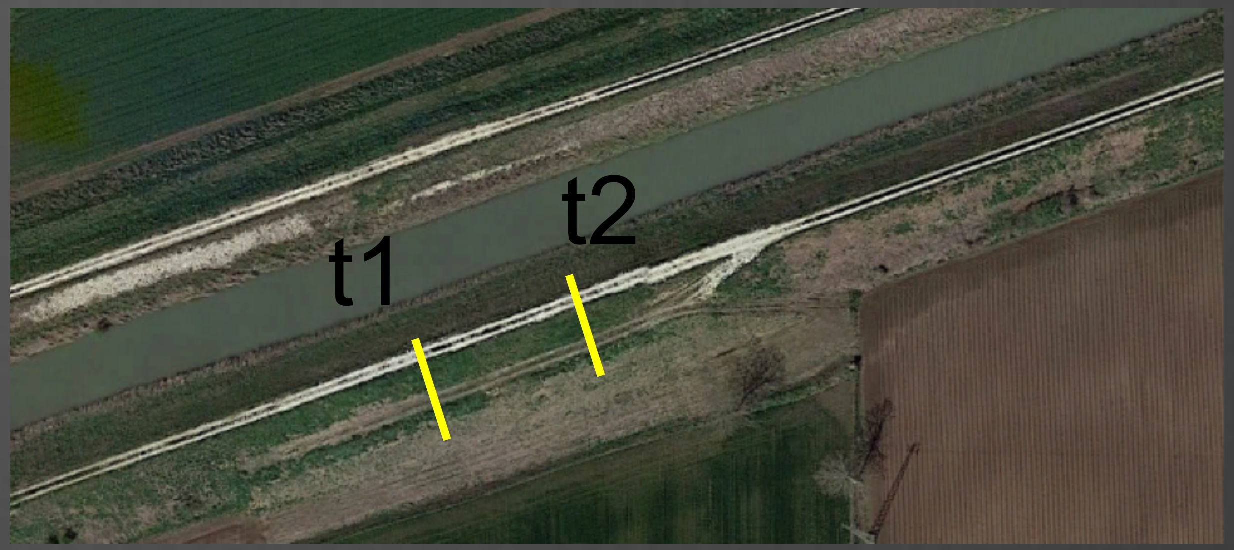


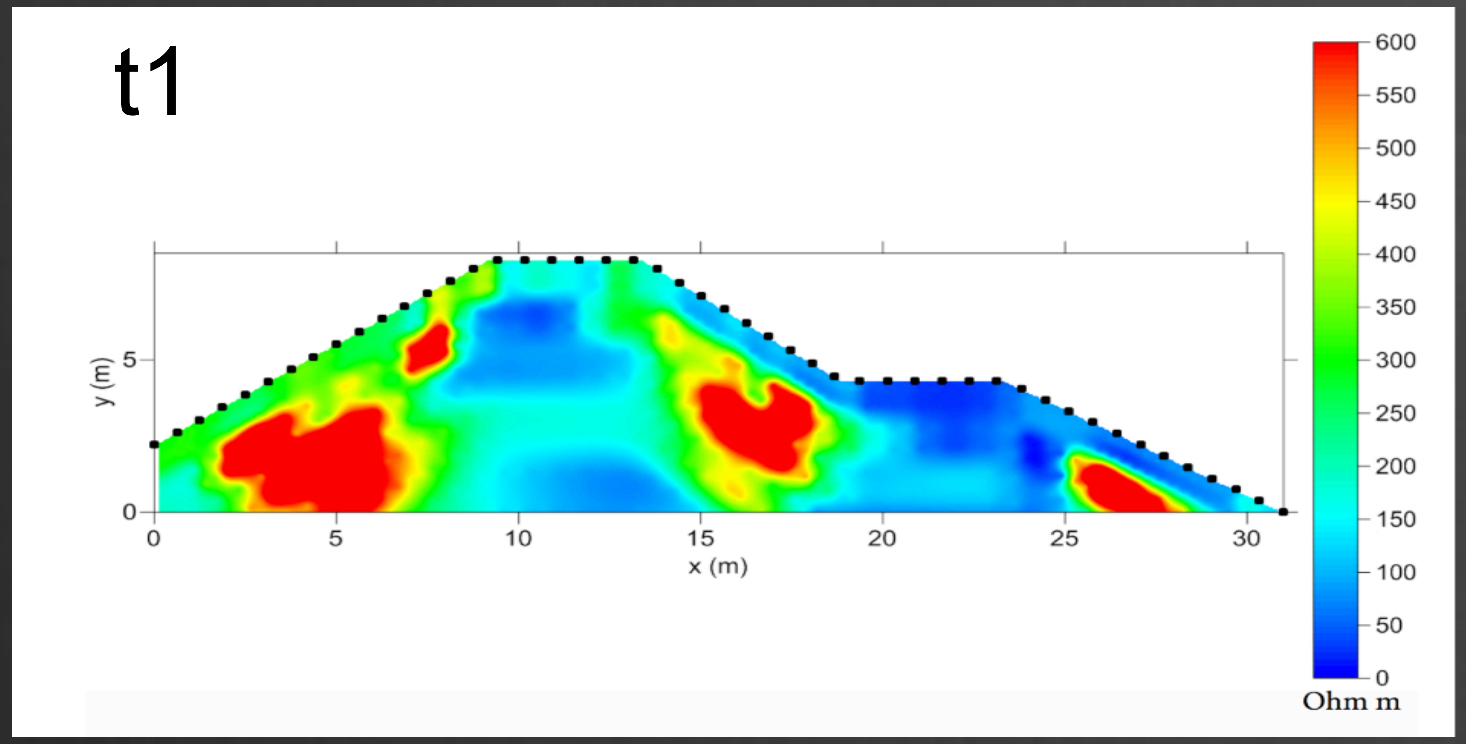
# 4. GPR results

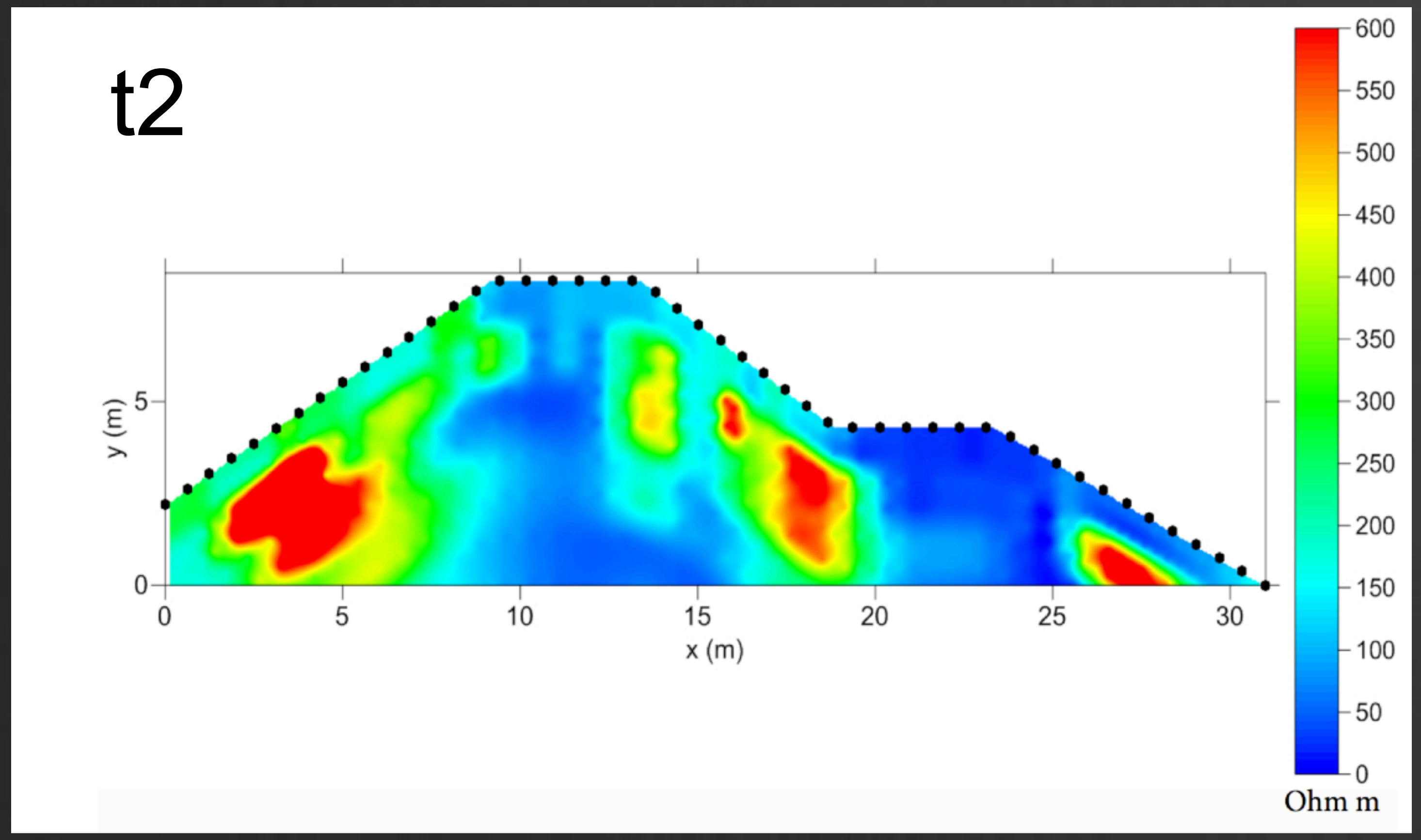
Theta from Topp (1980)

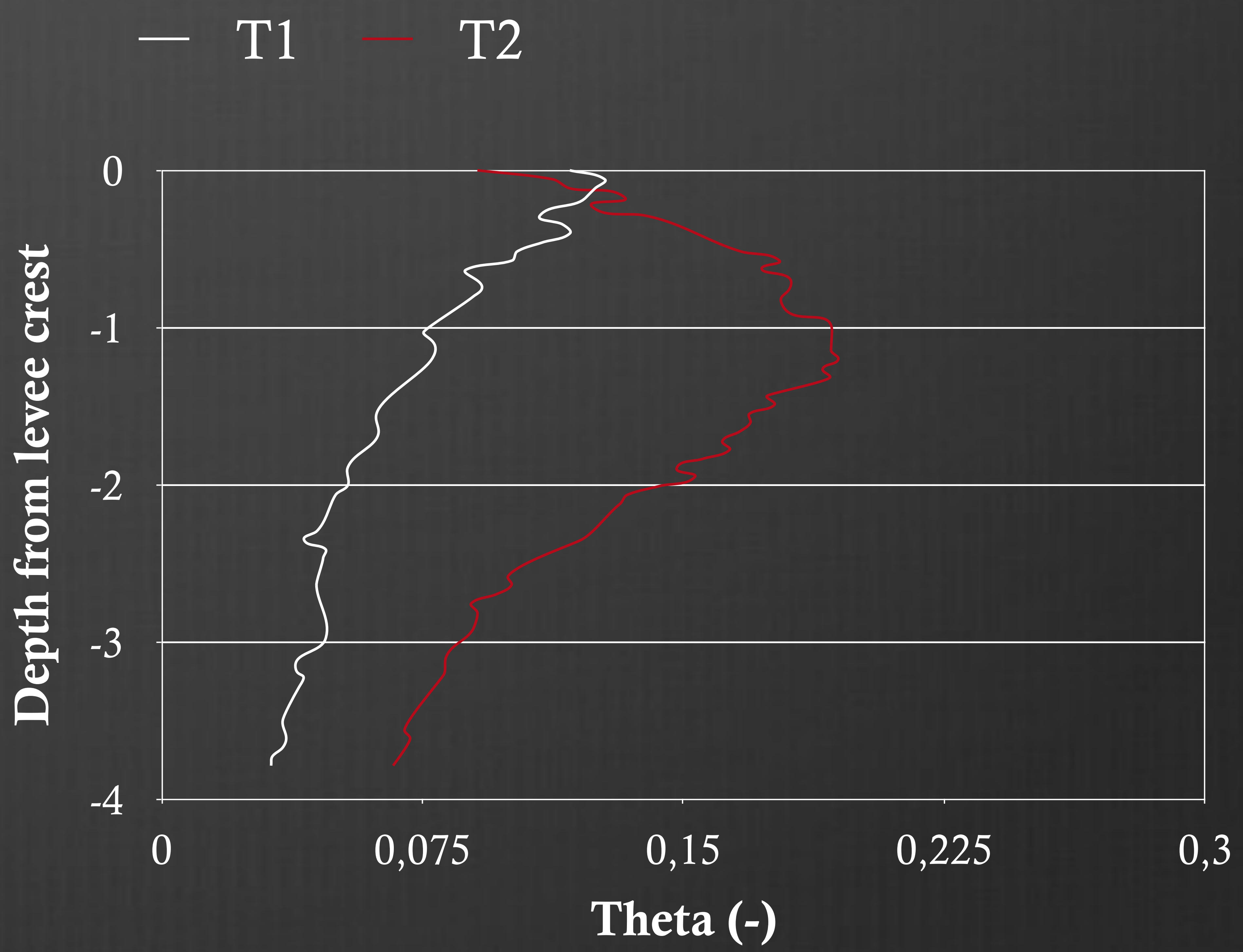
$$\vartheta = 0,053\varepsilon + 0,0292\varepsilon^2\ 0,00055\varepsilon^3 + 0,0000043\varepsilon^3$$




> Theta in stronger concrete septum



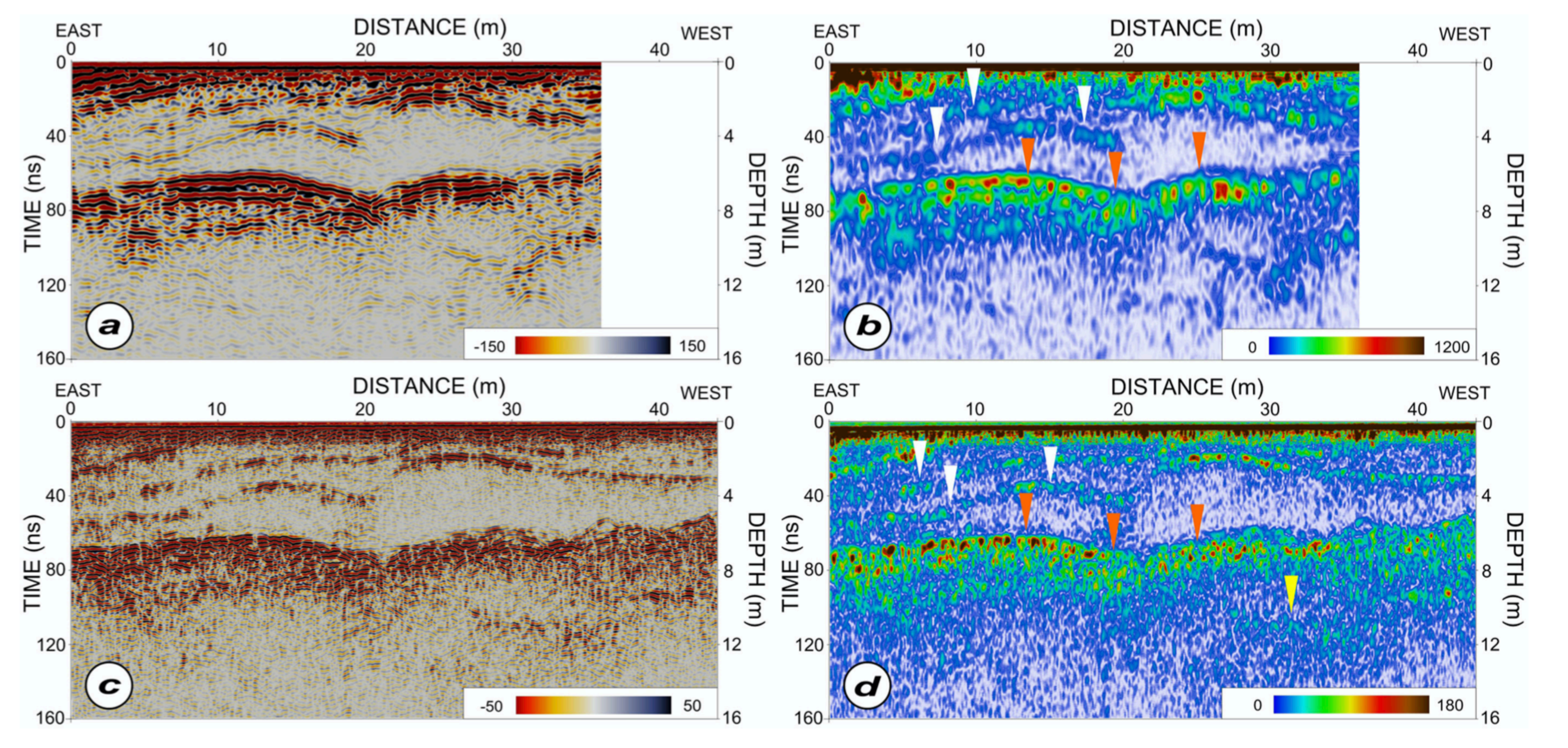



# *The Radar methods*

## 3) Water resources management

Optimal for restive bodies investigation, e.g.

**Glaciers Characterisation**

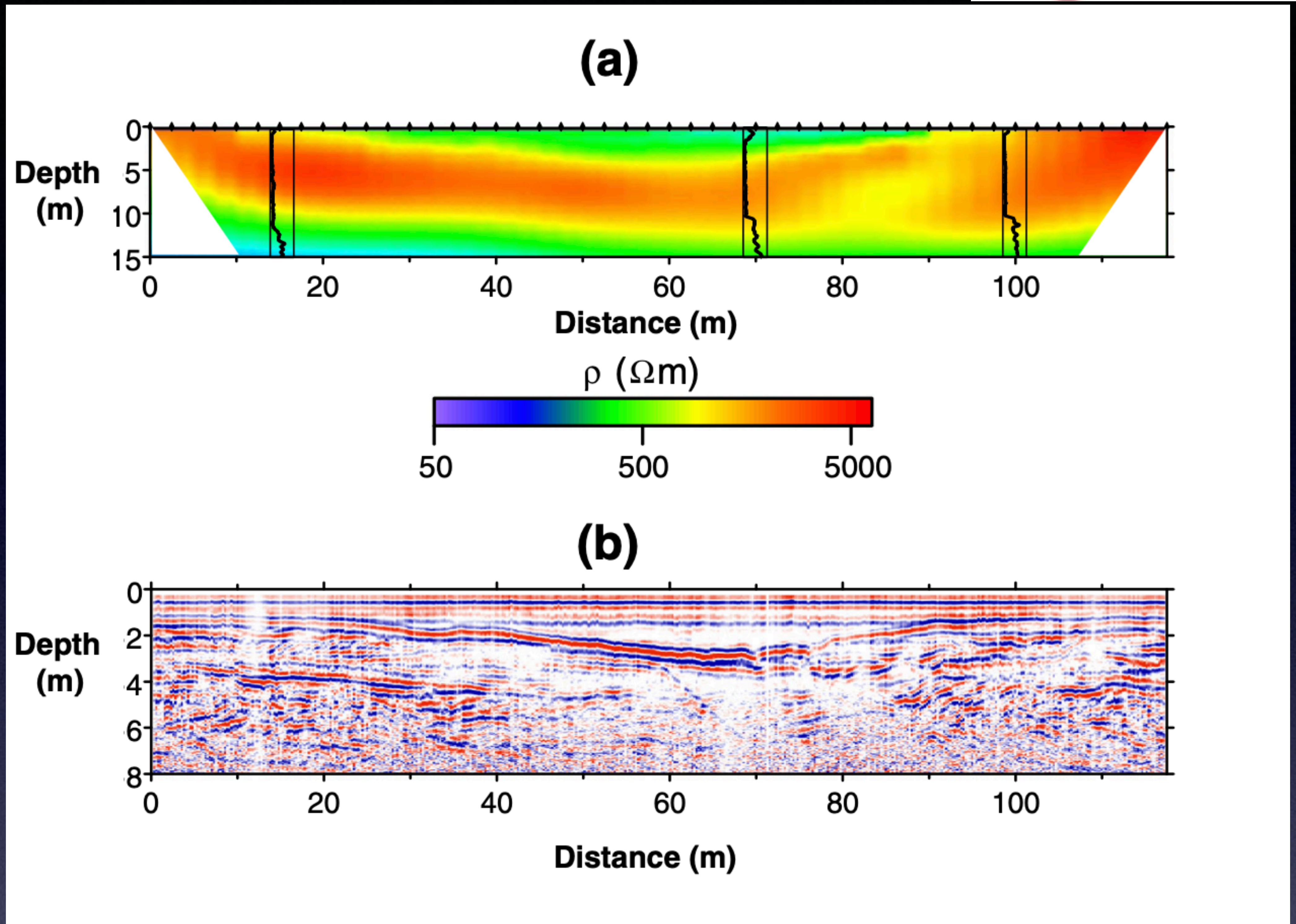


## *The Radar methods*

# 4) Polluted site characterisation

Unpolluted

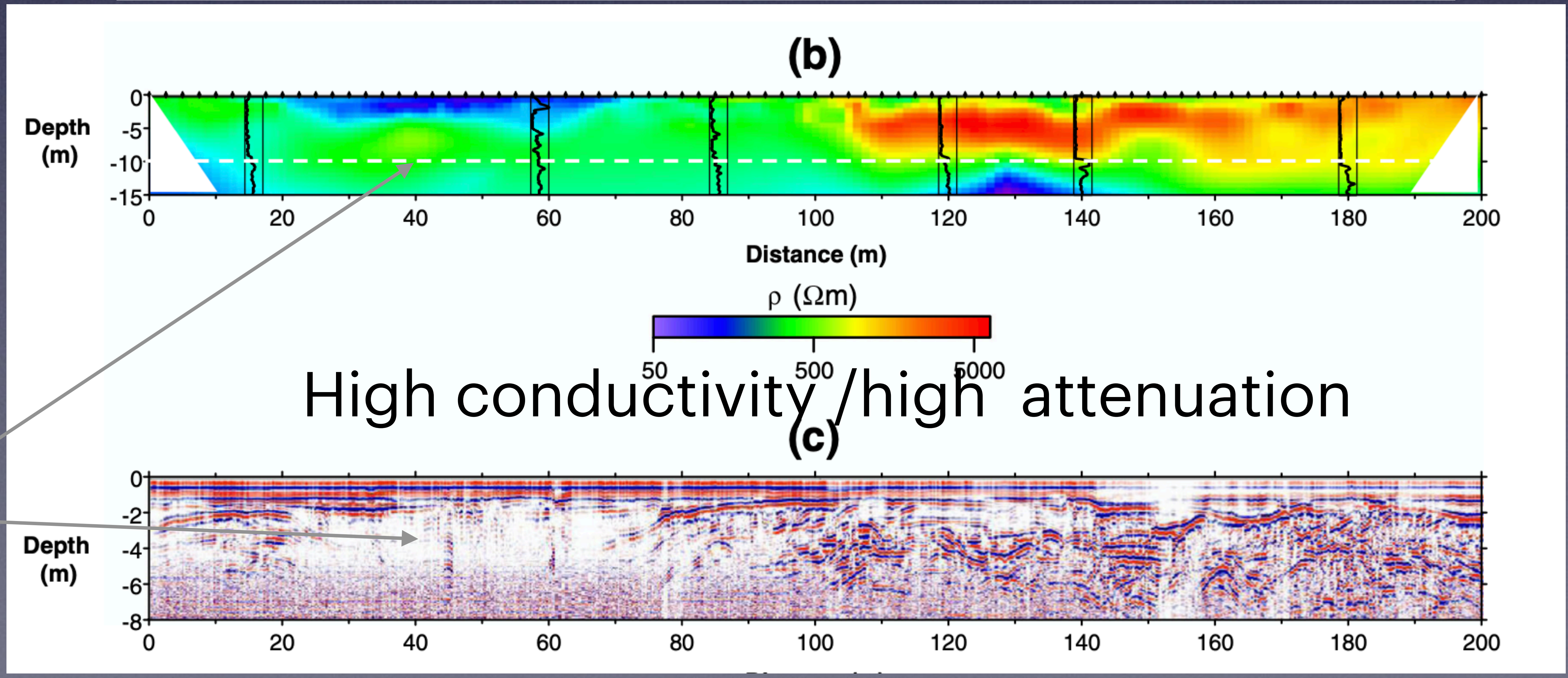
Area




Hydrocarbon

Polluted

Zones




High conductivity /high attenuation

*The Radar methods*

# 4) Polluted site characterisation

Borehole Radar

Zero Offset Profile

zop

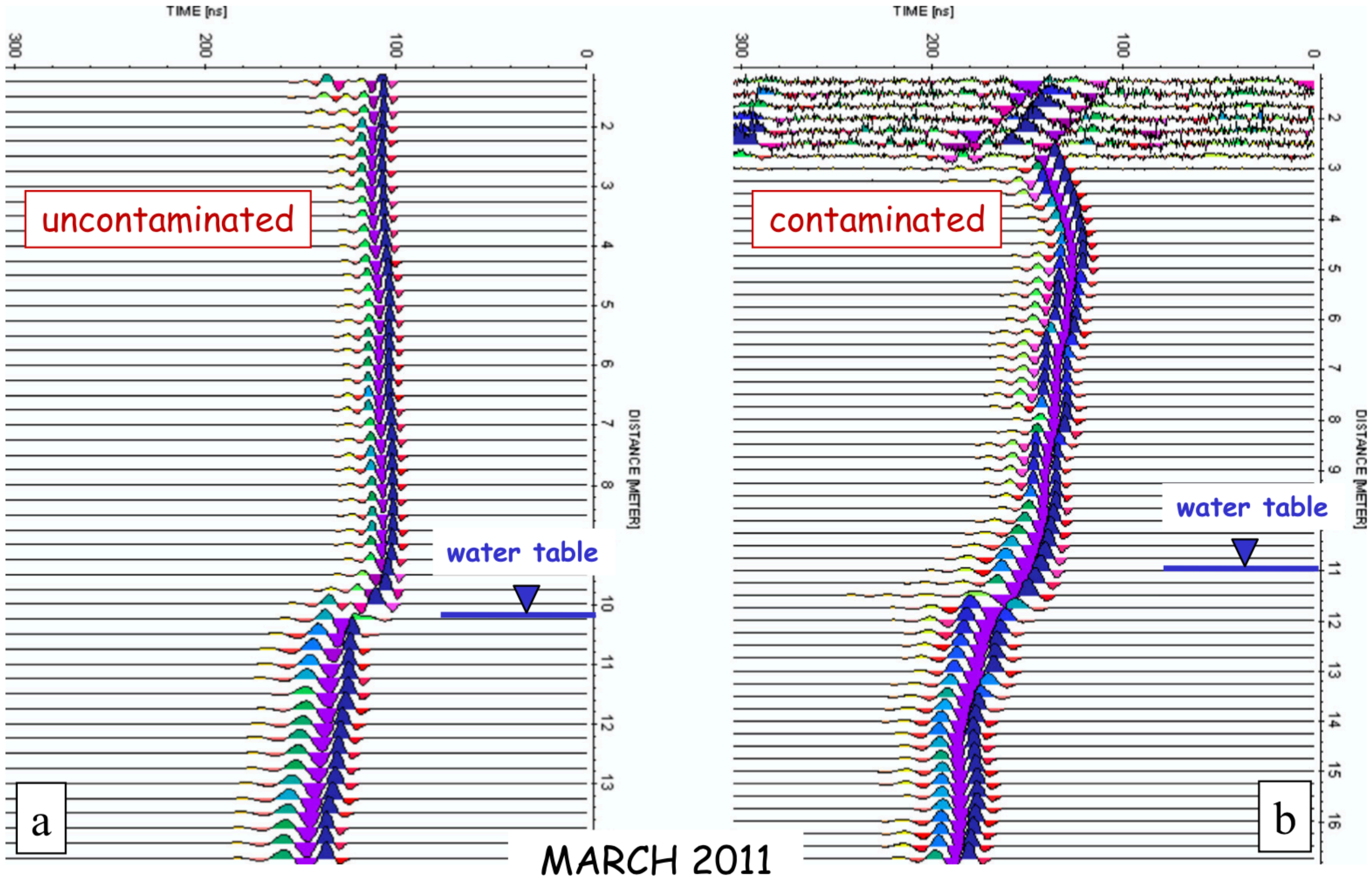


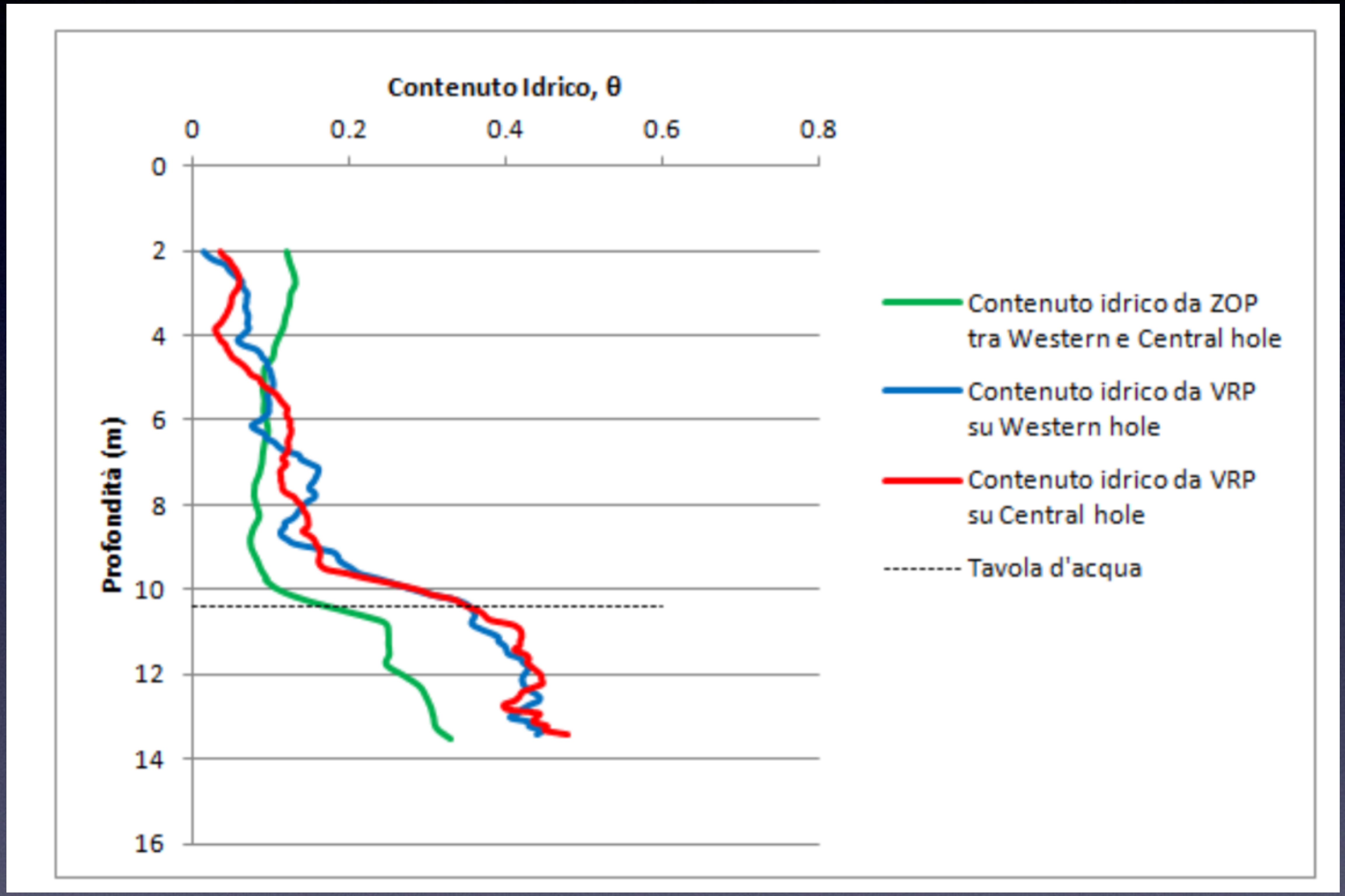

**Fig. 9** Cross-hole GPR zero offset profile (ZOP) radargrams collected in March 2011 on **a** the 2011 SoilCAM boreholes in the uncontaminated zone and **b** the 2009 SoilCAM boreholes in the contaminated zone

## es. Trecate (No)

$\varepsilon_r = f\ (saturation)$

$\varepsilon_r = f\ (fluid)$

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$




Watertable

Pollutant