Geofisica per la caratterizzazione dei siti contaminati: limiti e applicazioni

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Outline

- Geophysics for contaminated sites
- Pathways: The Ferrara case
- The Decimomannu case
- The Trecate case
- Monitoring remediation: the Bologna case
- Conclusions and outlook

Aspects of the near surface to be highlighted using (also) geophysical methods

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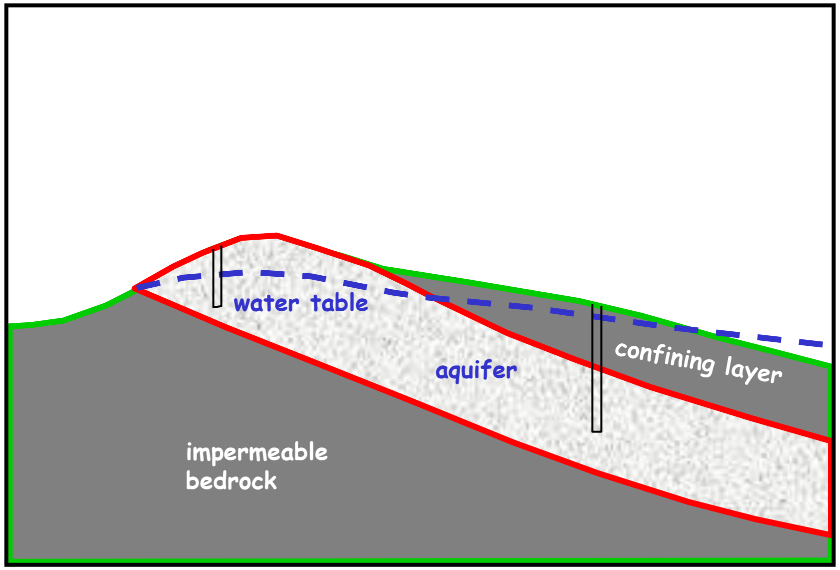
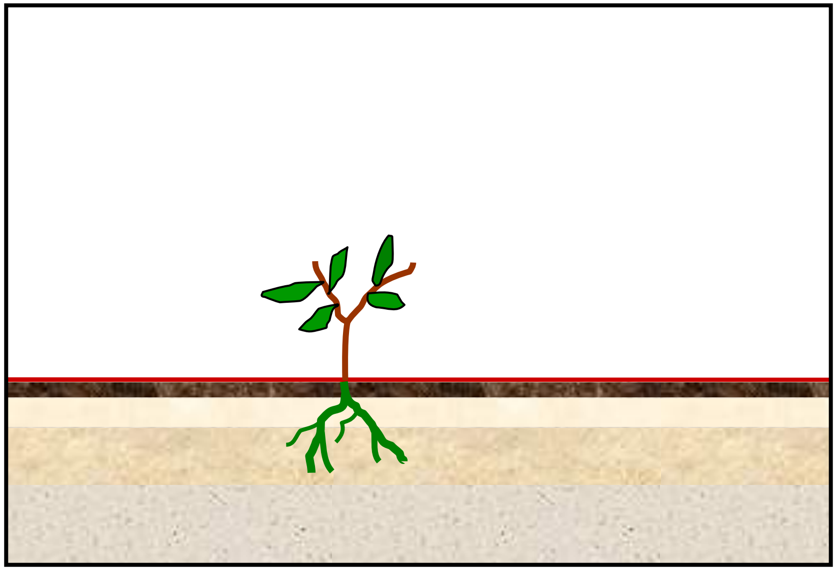
- structure / texture



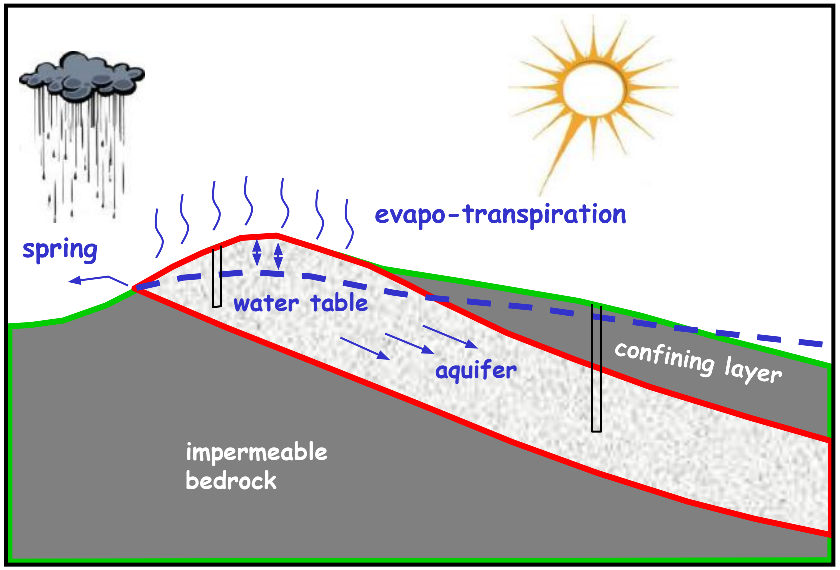
large scale



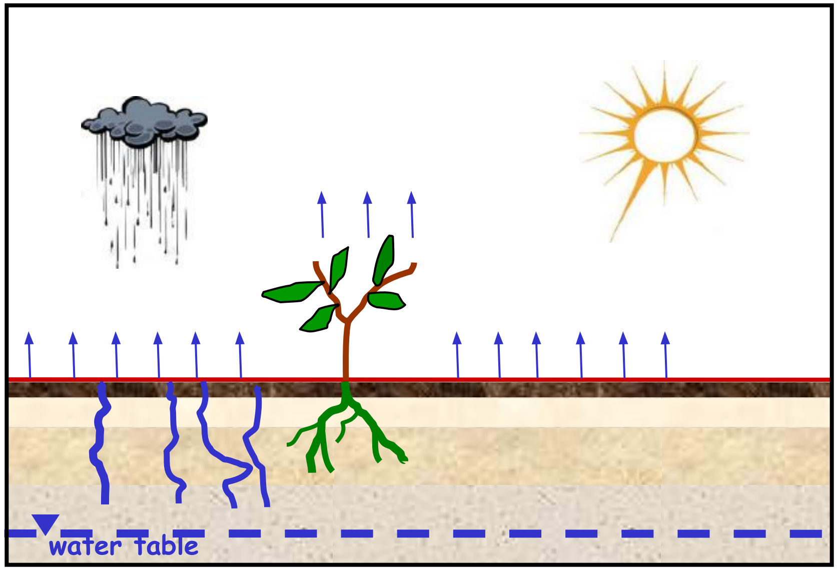
small scale

Aspects of the near surface to be highlighted using (also) geophysical methods

- structure / texture
- fluid-dynamics



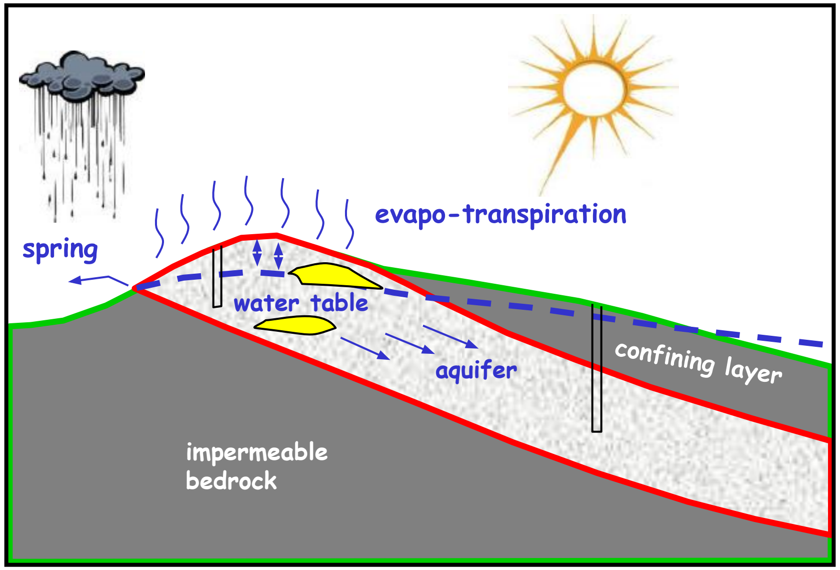
large scale



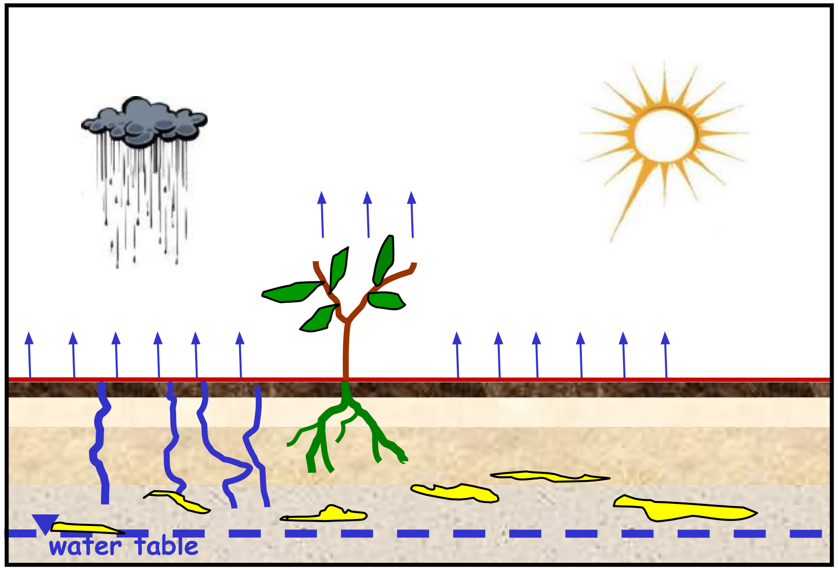
small scale

Aspects of the near surface to be highlighted using (also) geophysical methods

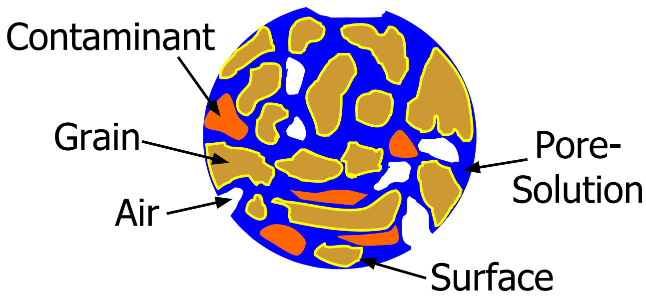
- structure / texture
- fluid-dynamics
- contamination



large scale



small scale



Generally speaking, contamination is only one, and not necessarily the most important, source of geophysical signal.

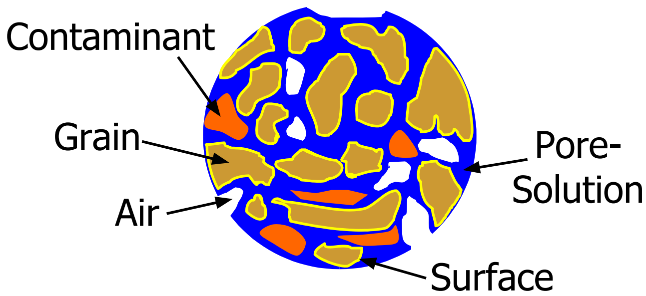
GEOPHYSICS

- electrical conductivity
- IP chargeability
- Dielectric constant
- ⋮

← **soil structure**: texture, porosity, mineralogy

← **contamination**: free-phase, dissolved, adsorbed

← **ambient dynamics**: moisture content, temperature



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- texture
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contamination
- free-phase
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- adsorbed

ambient dynamics
- moisture content
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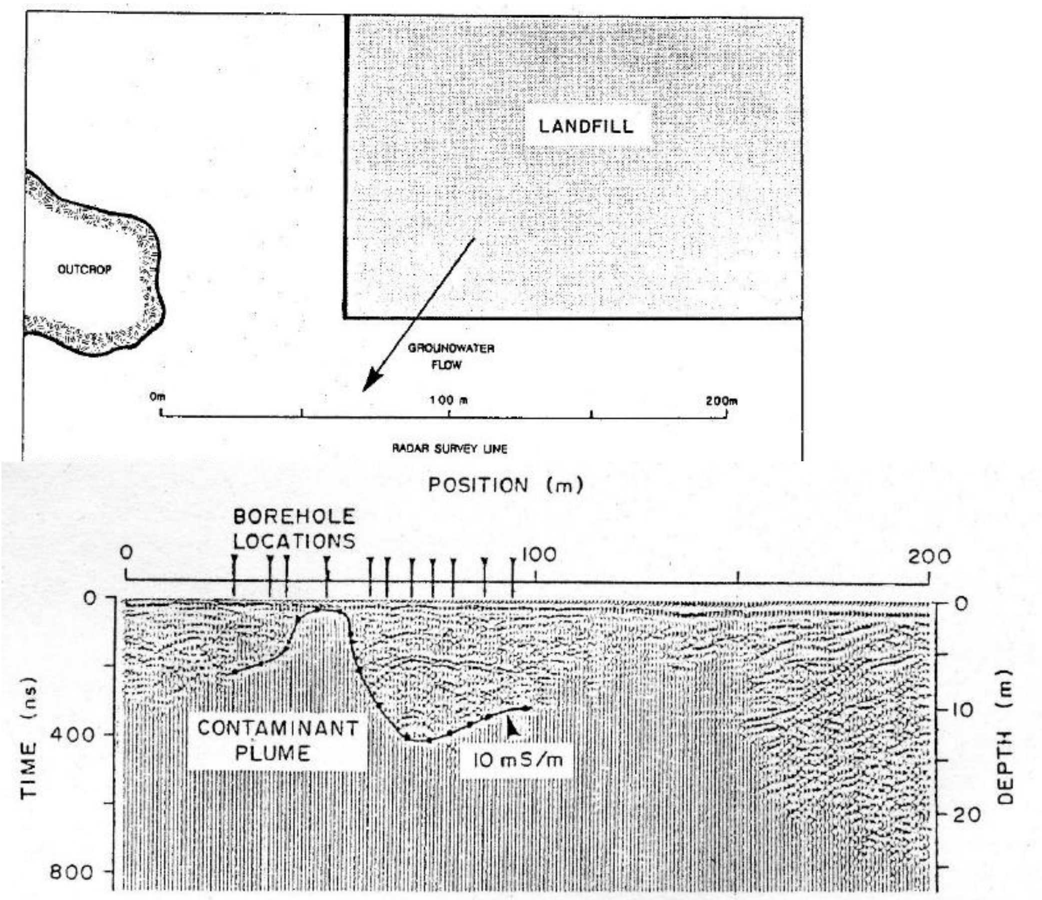
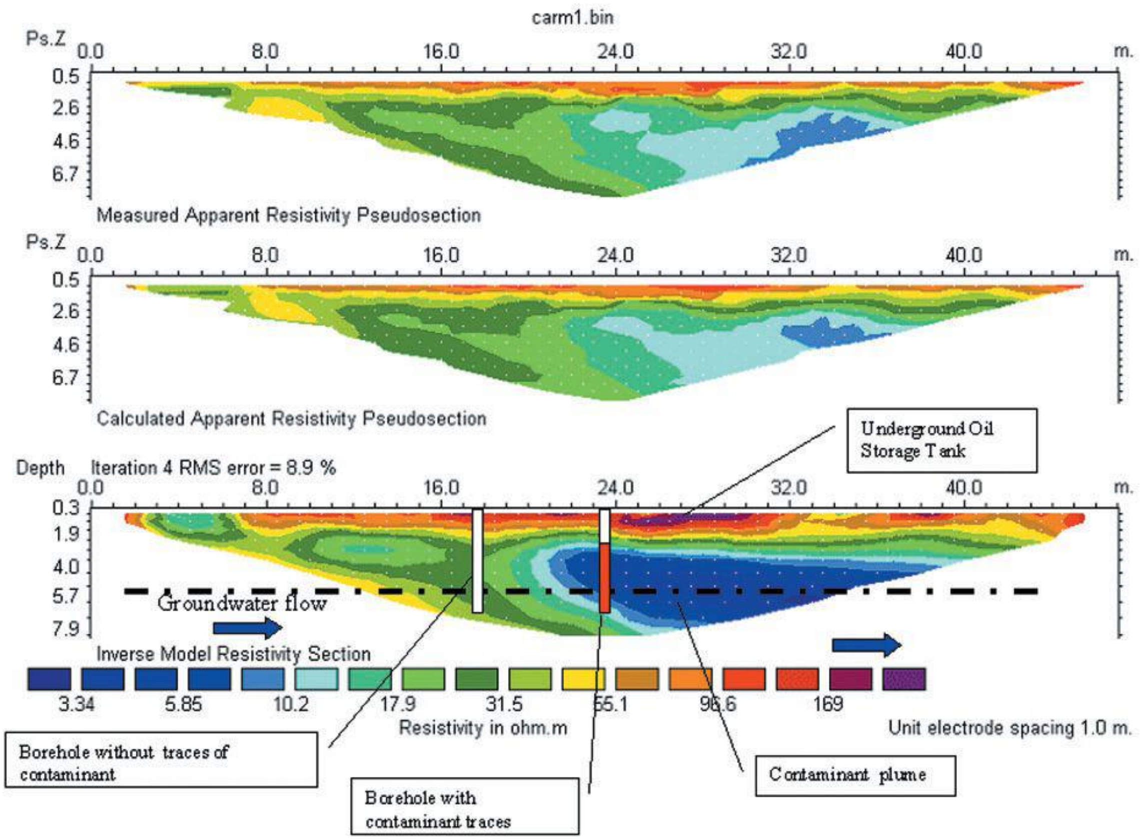
It has been often observed that "mature" hydrocarbon contamination increases the electrical conductivity of the host formation.

This causes the presence of signals in GPR (as attenuation)



It has been often observed that "mature" hydrocarbon contamination increases the electrical conductivity of the host formation.

… and of course in ERT

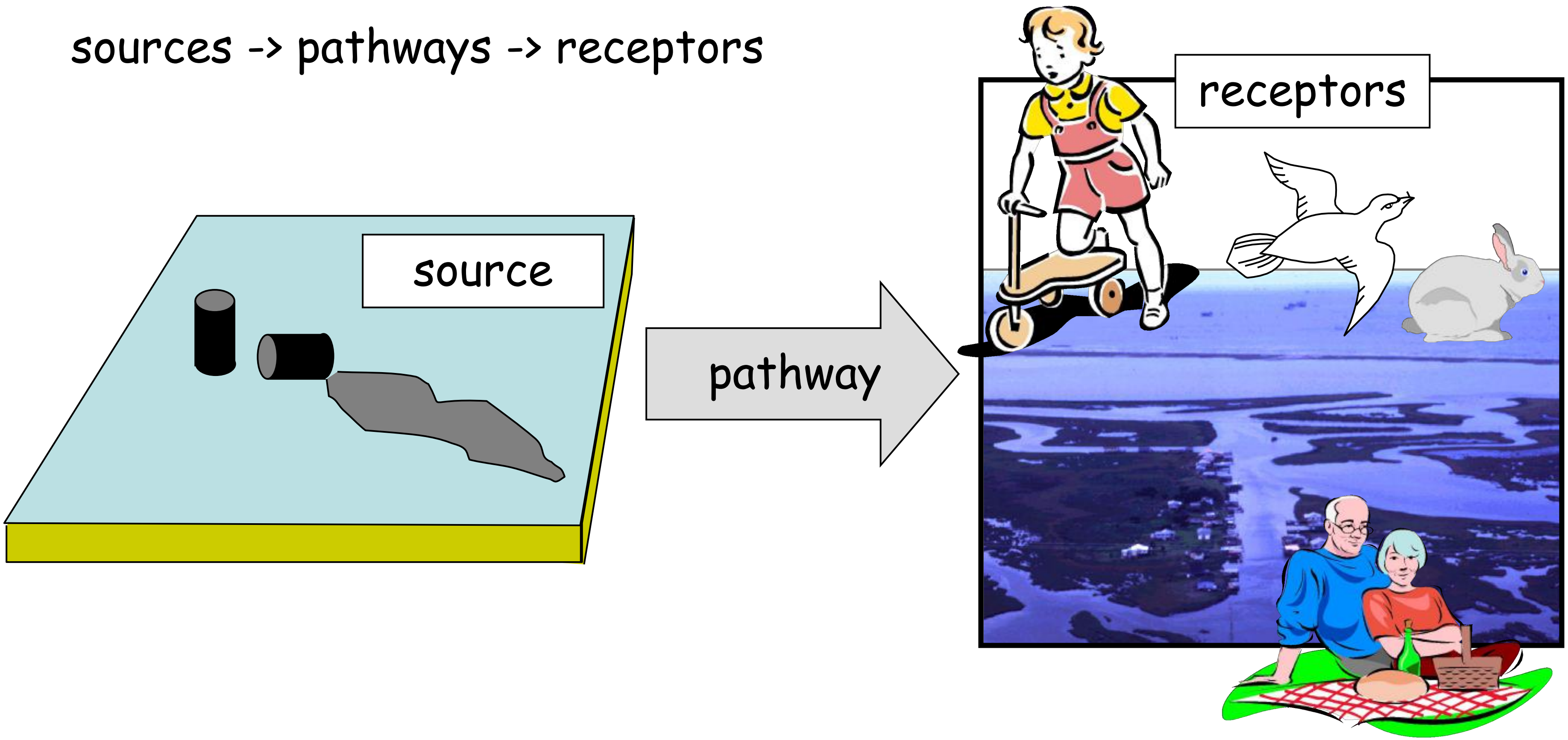


Godio and Naldi, NSG, 2003

SITE CHARACTERIZATION

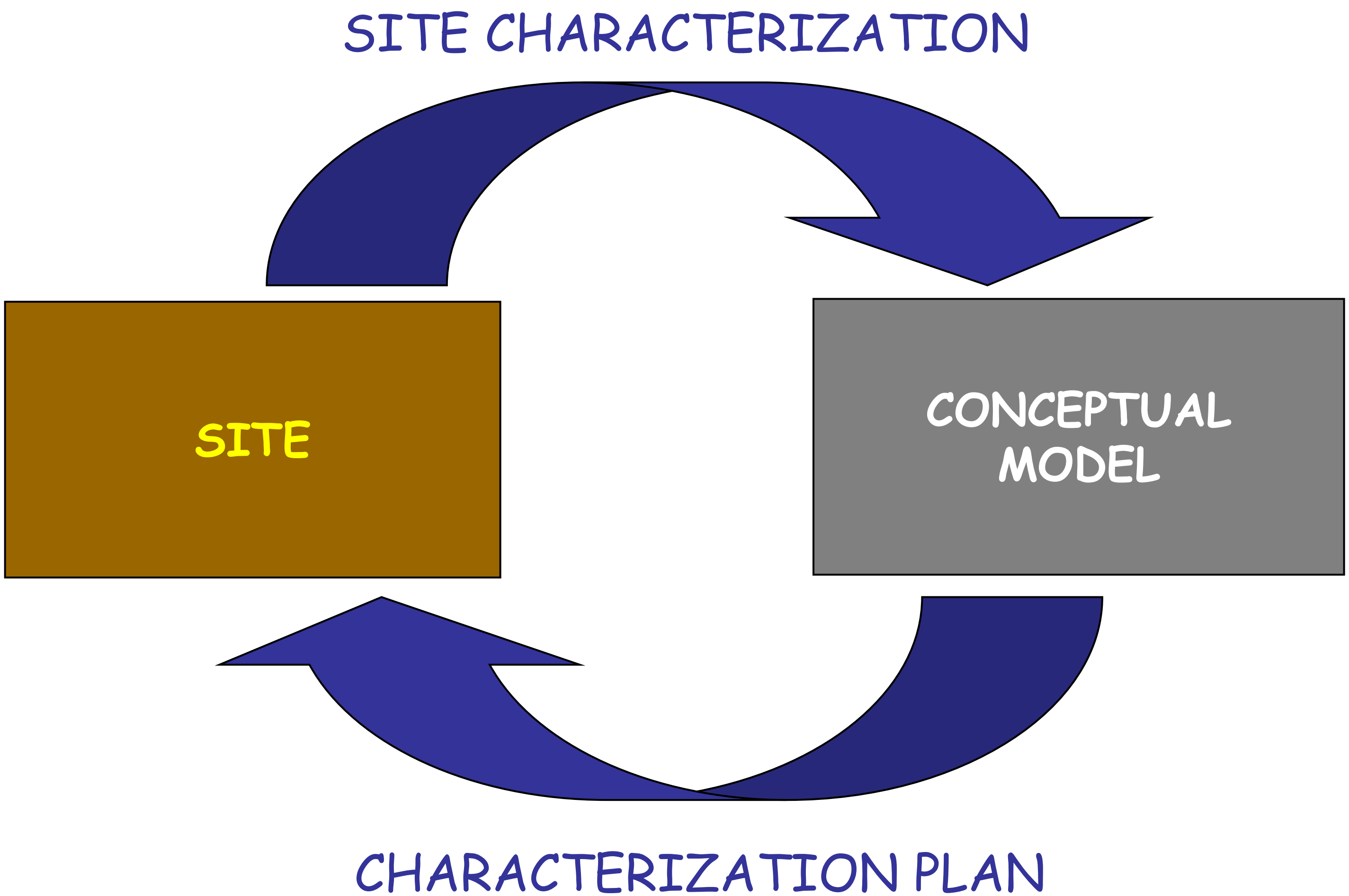
In the prospective of risk analysis, it should provide the necessary information to define the chain:

sources -> pathways -> receptors



The final product: A SITE CONCEPTUAL MODEL

(AN INSTANCE OF THE SCIENTIFIC METHOD)



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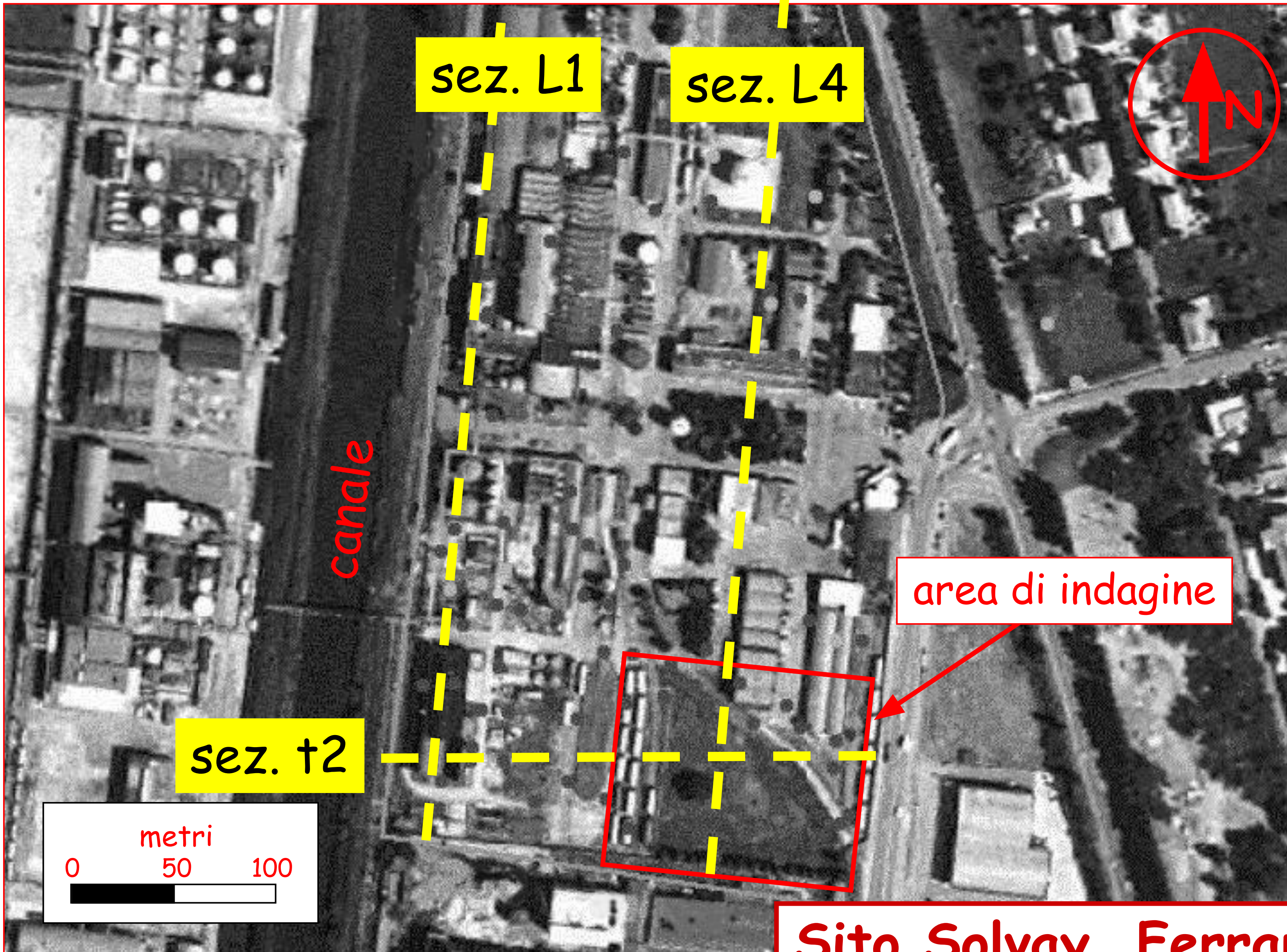
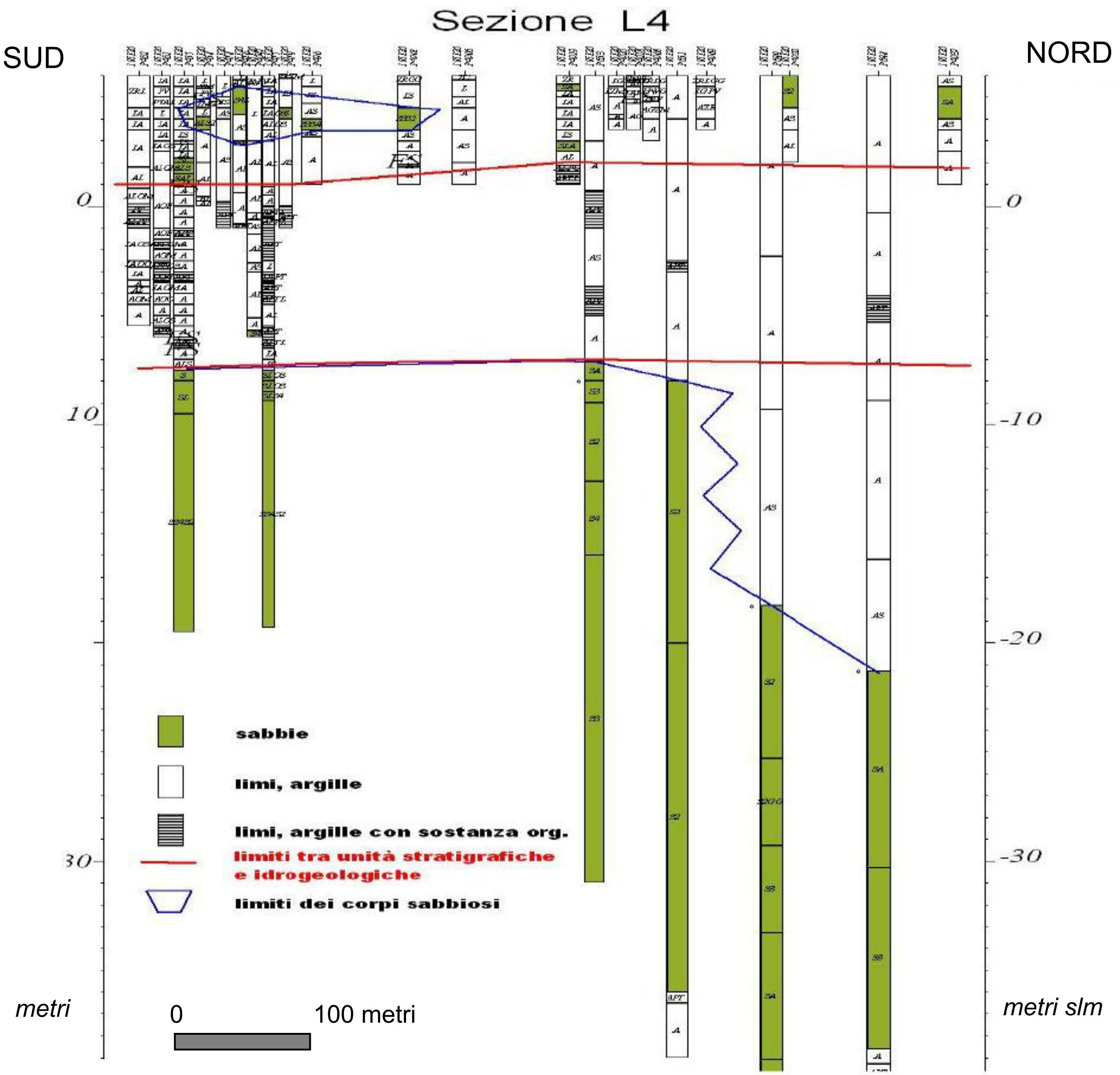
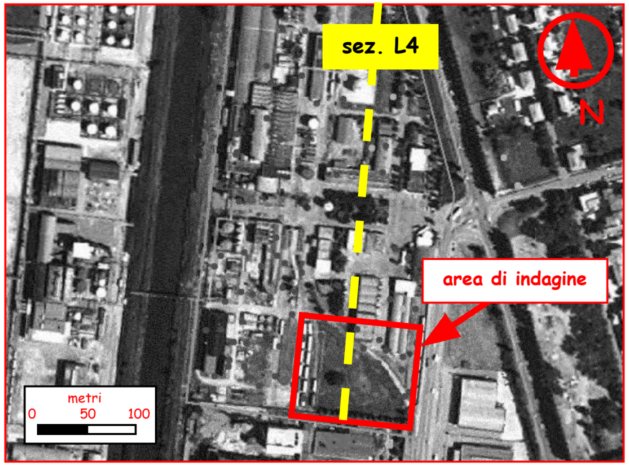
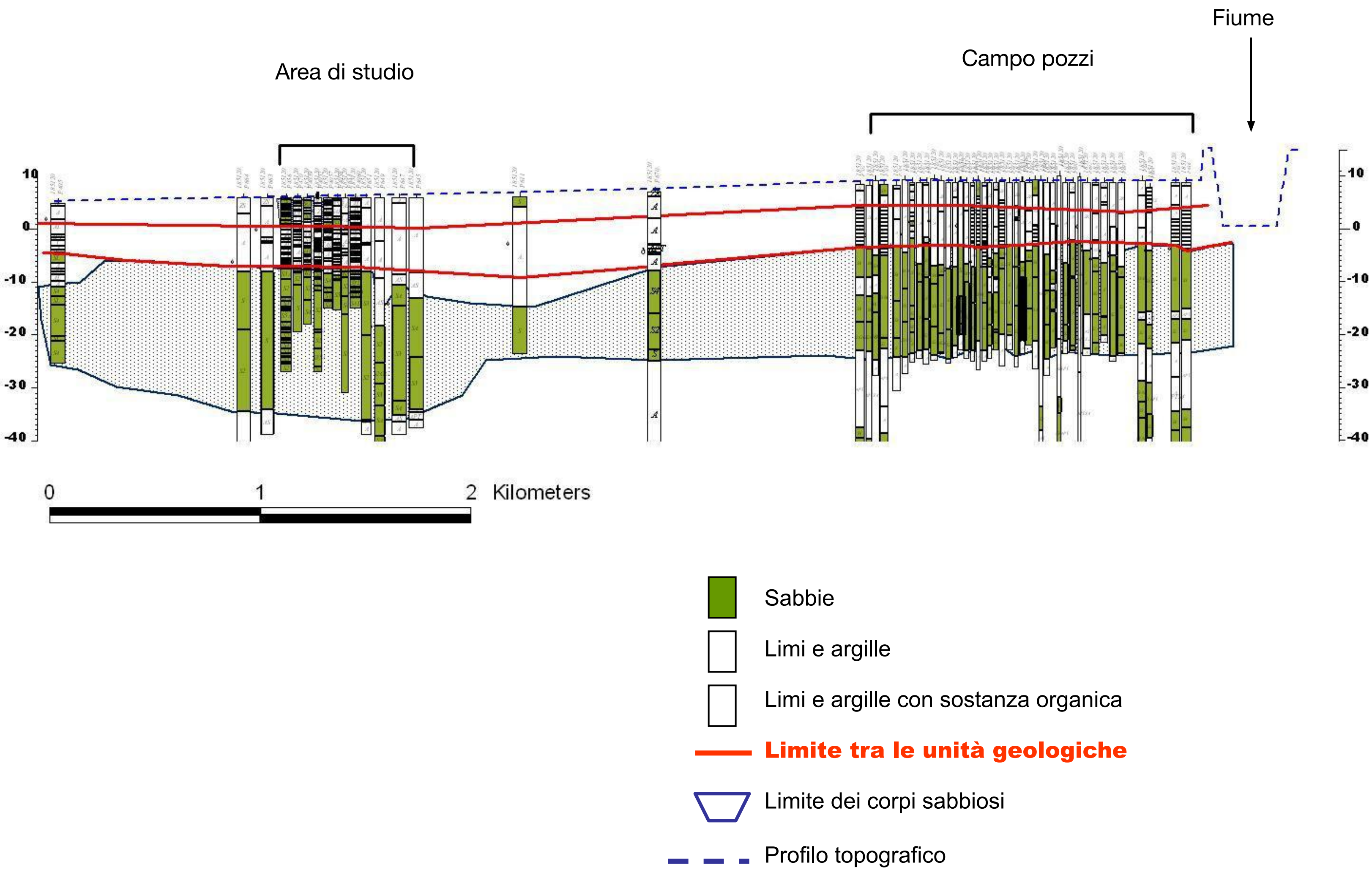


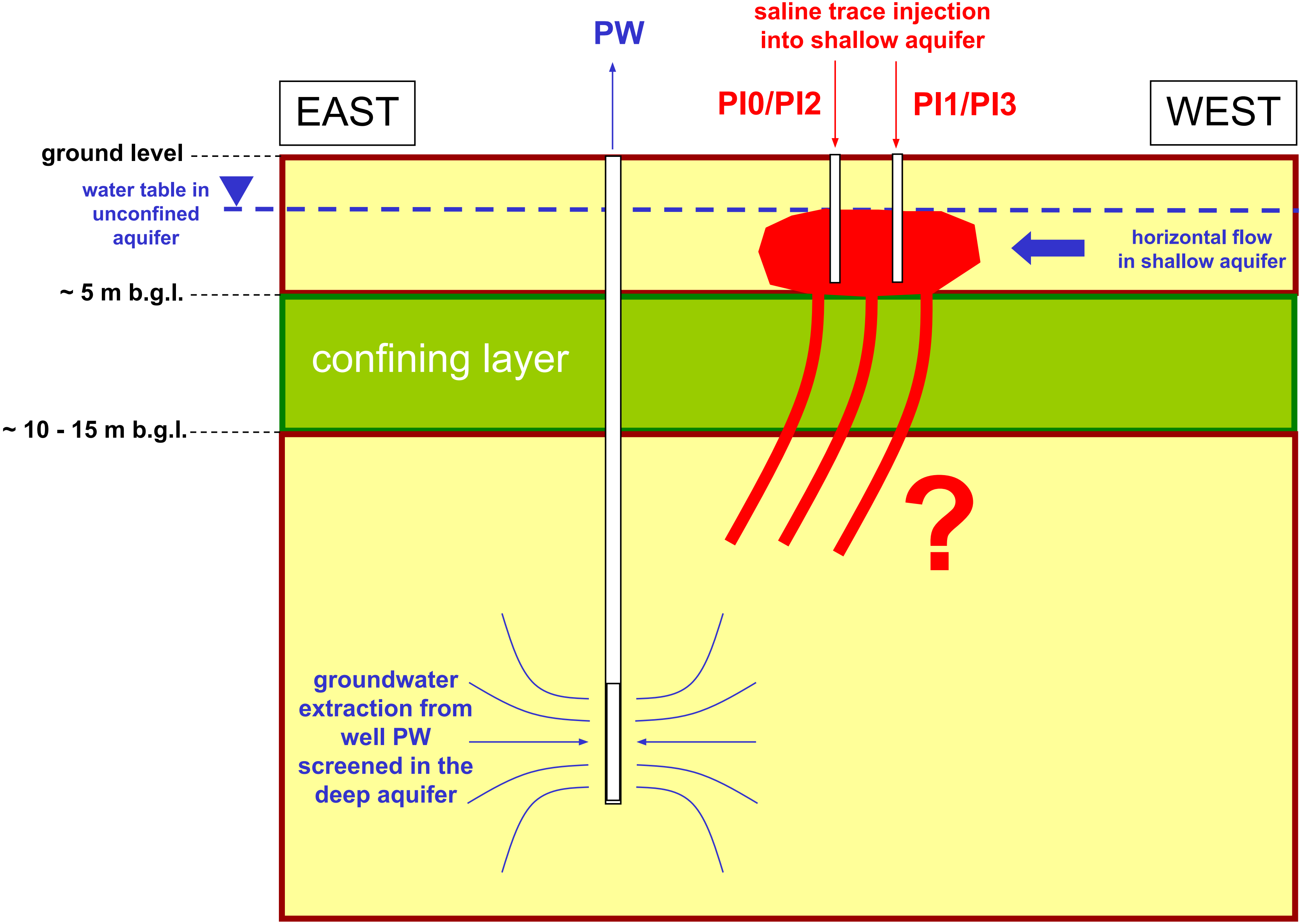
Sito Solvay, Ferrara


Sezione L4
SUD
NORD
0
10
30
0
-10
-20
-30
sabbie
limi, argille
limi, argille con sostanza org.
limiti tra unità stratigrafiche e idrogeologiche
limiti dei corpi sabbiosi
metri
0
100 metri
metri slm


sez. L4
N
area di indagine
metri
0
50
100

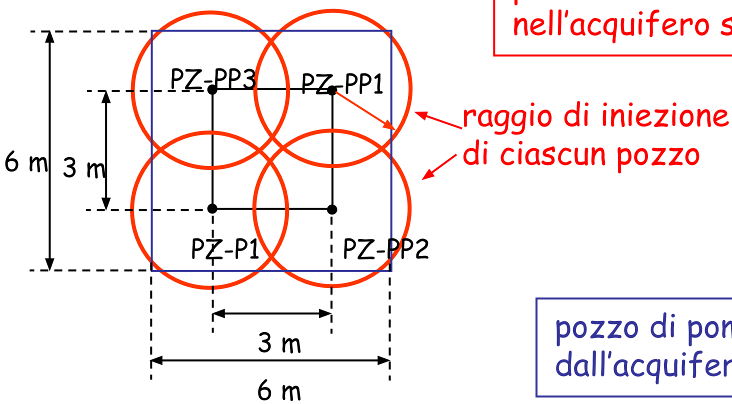
Estensione regionale delle formazioni di interesse

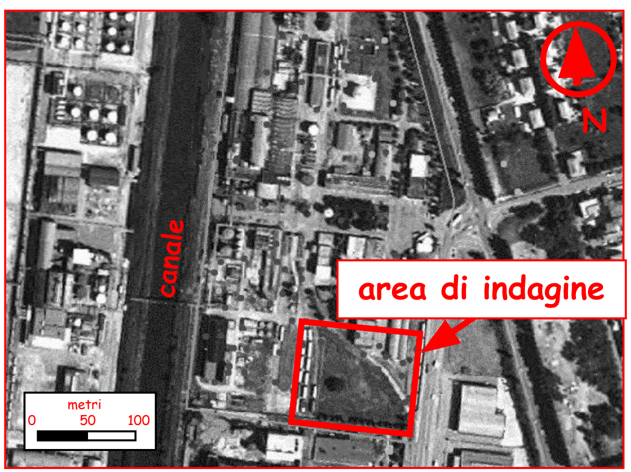


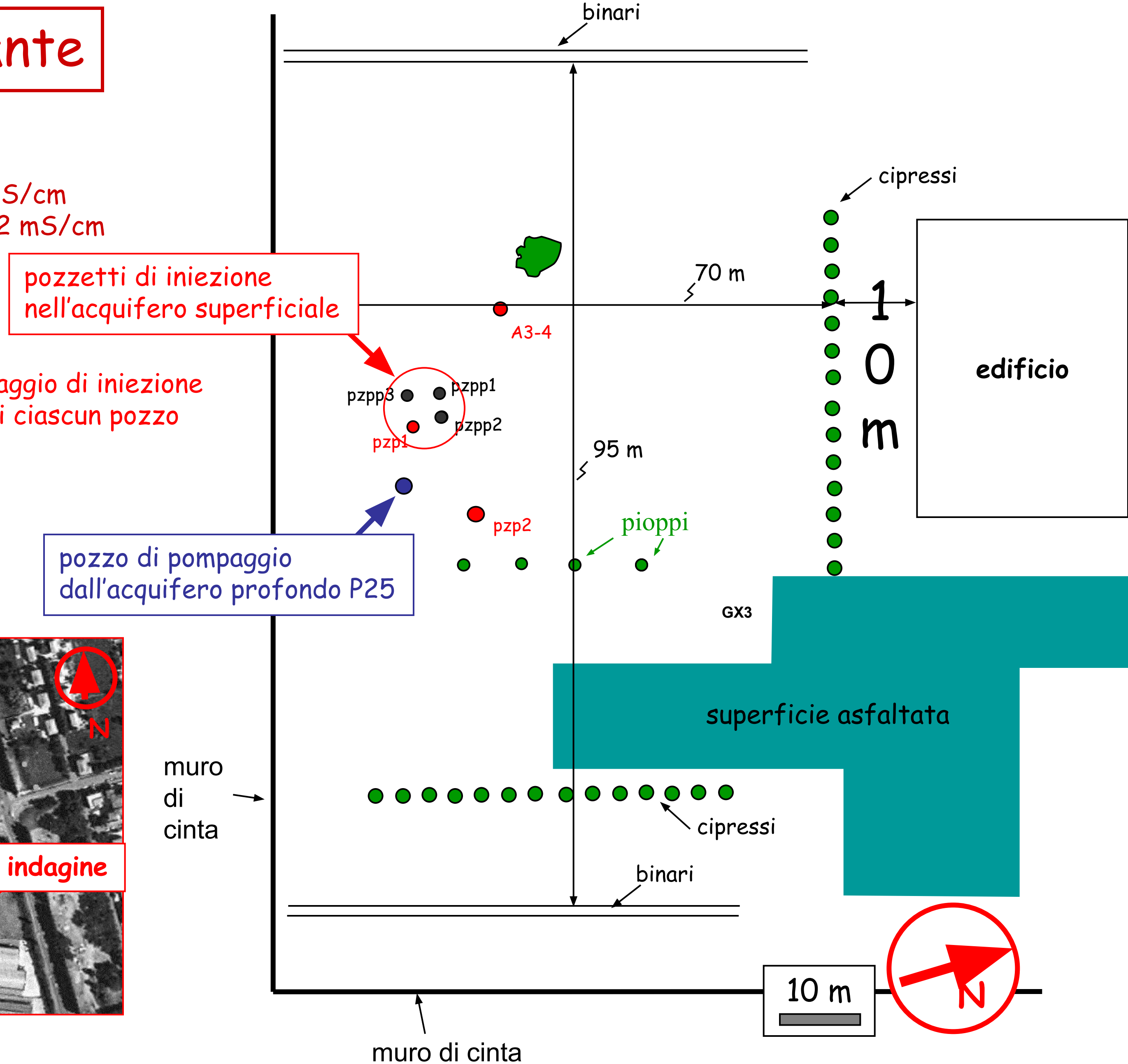

PW
saline trace injection
into shallow aquifer
PI0/PI2
PI1/PI3
EAST
WEST
ground level
water table in
unconfined
aquifer
horizontal flow
in shallow aquifer
~ 5 m b.g.l.
confining layer
~ 10 - 15 m b.g.l.
?
groundwater
extraction from
well PW
screened in the
deep aquifer

Test con tracciante

volume d'acqua iniettato = 20 m^3
concentrazione NaCl = 6 g/litro
conduttività della soluzione ≈ 11 mS/cm
conduttività dell'acqua in sito ≈ 1-2 mS/cm
durata dell'iniezione ≈ 22 ore








POZZO
25
380 VOLT


pozzetti di iniezione
pozzo P25

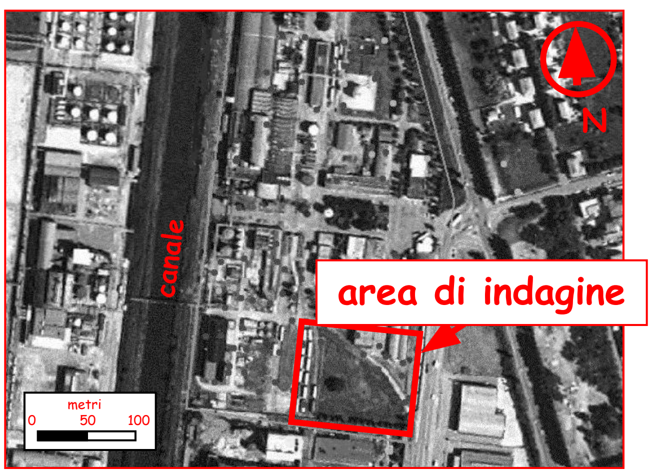
Monitoraggio geoelettrico

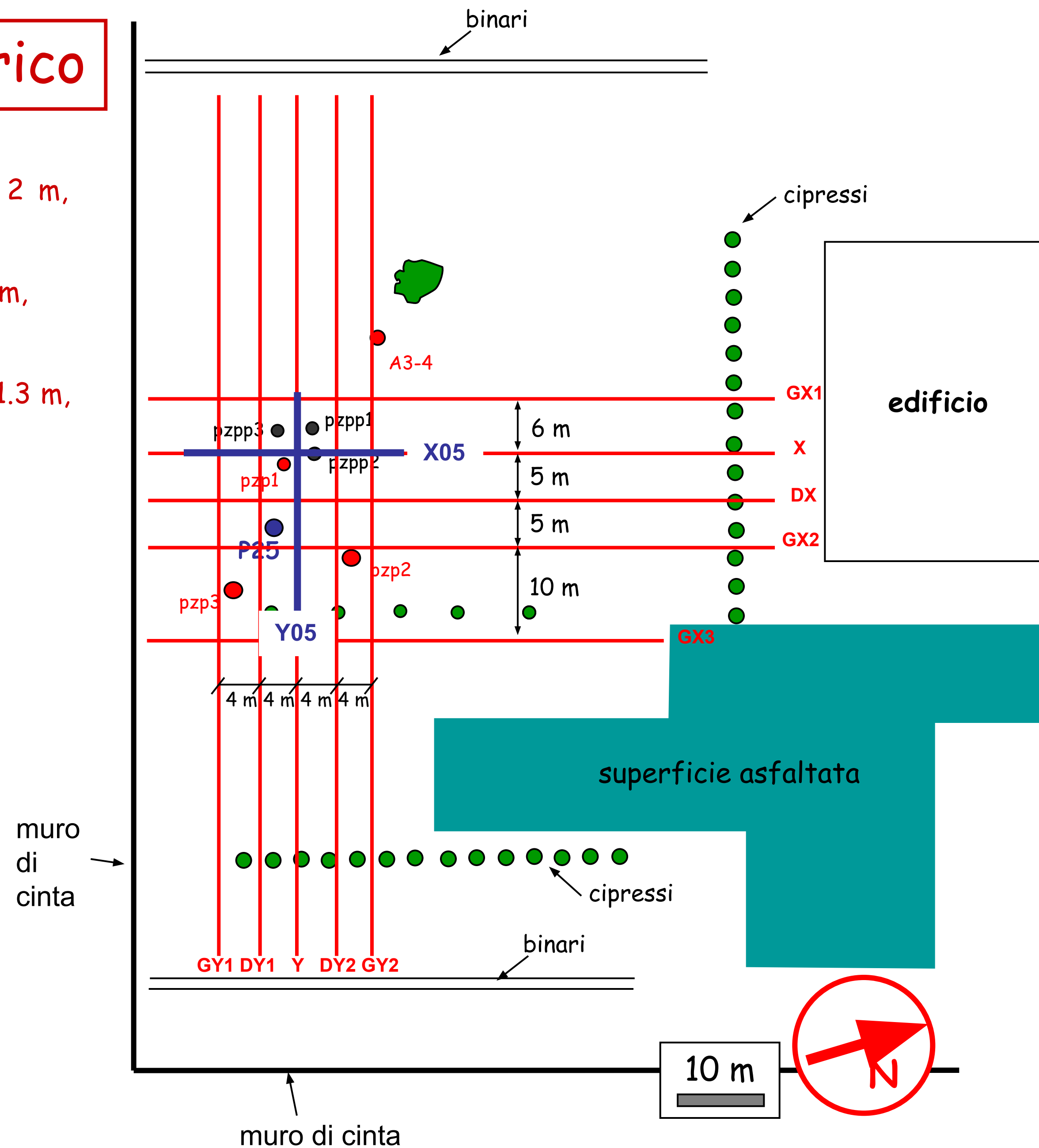
5 linee a 48 elettrodi E-W (Y) a spaziatura 2 m, lunghezza totale 94 m

4 linee a 48 elettrodi N-S (X) a spaziatura 1.5 m, lunghezza totale 70.5 m

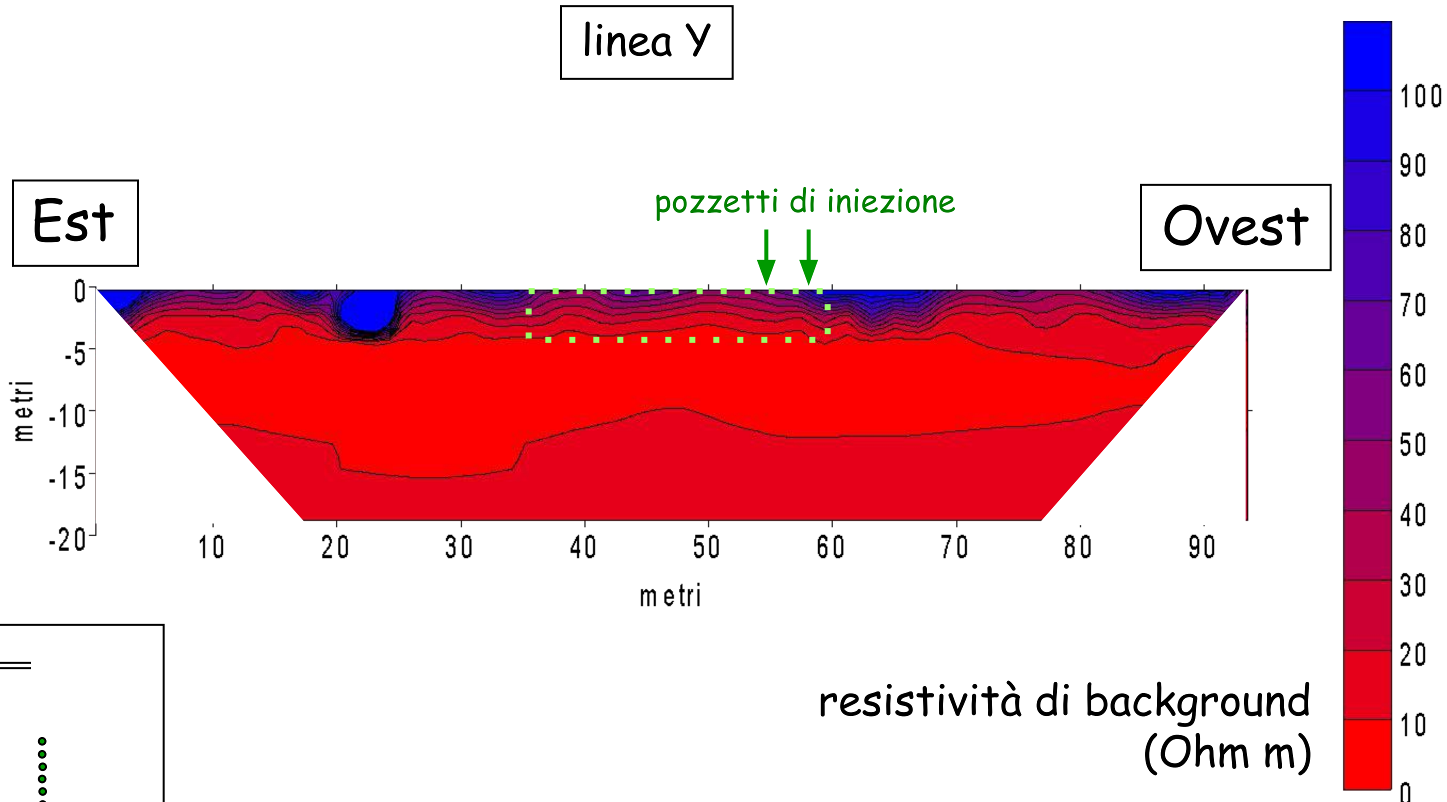
1 linee a 48 elettrodi N-S (GX3) a spaziatura 1.3 m, lunghezza totale 61.1 m

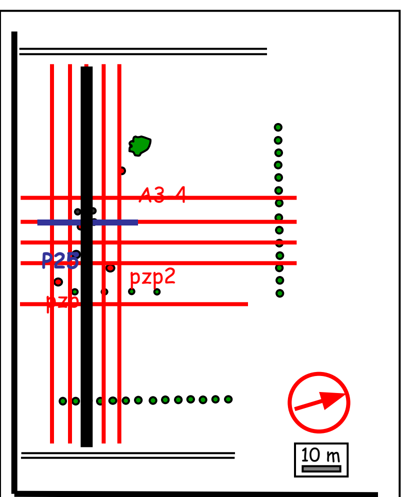
2 linee a 48 elettrodi ad alta risoluzione (X05 ed Y05) a spaziatura 0.5 m, lunghezza totale 23.5 m



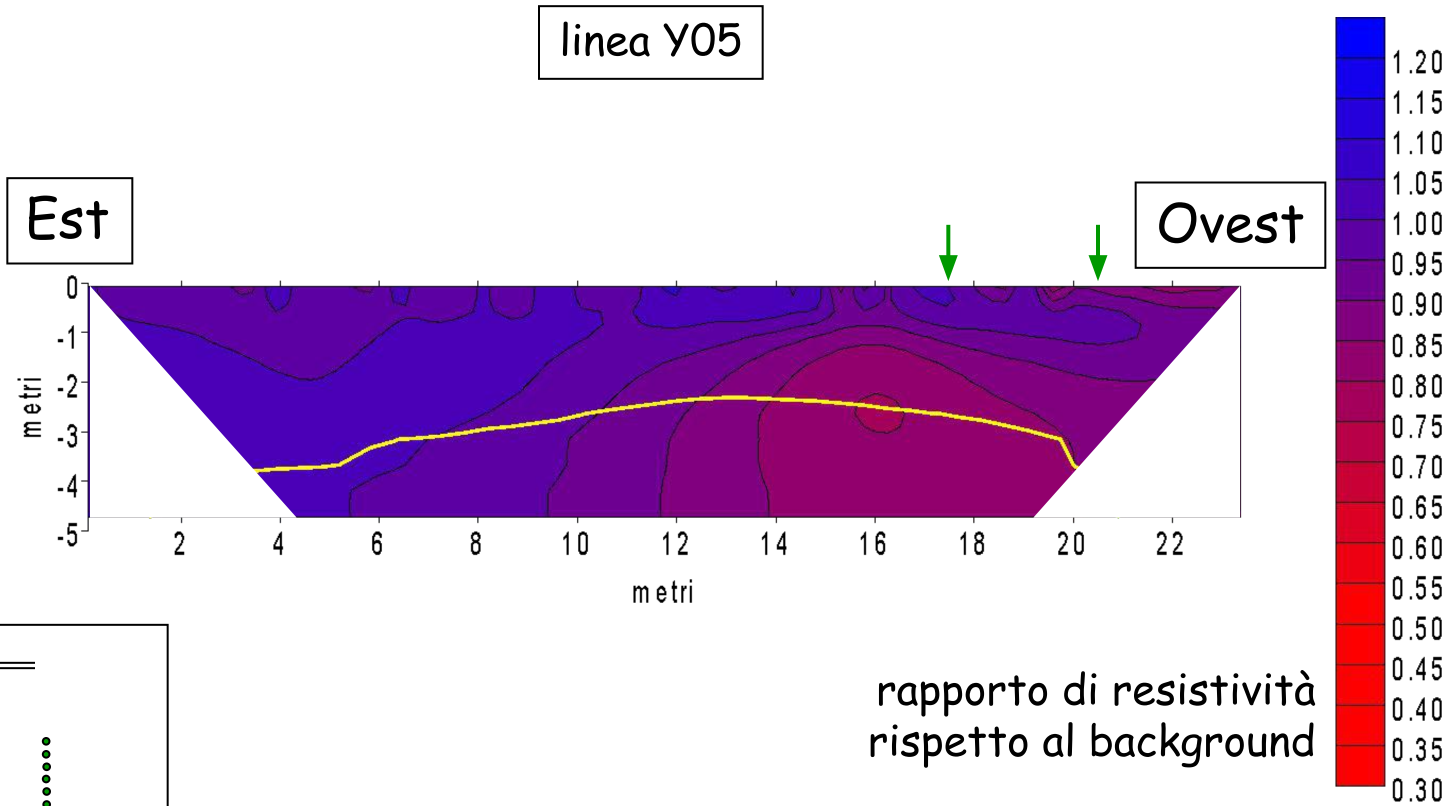


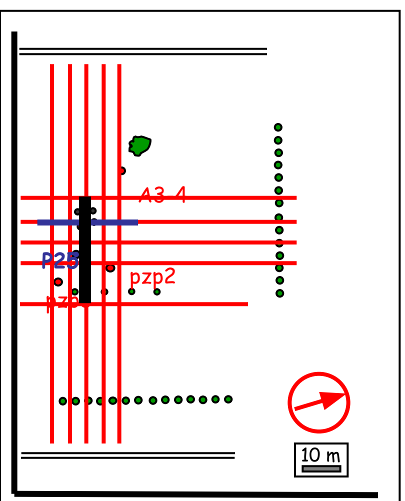
Survey di base (pre-iniezione)





Iniezione del tracciante





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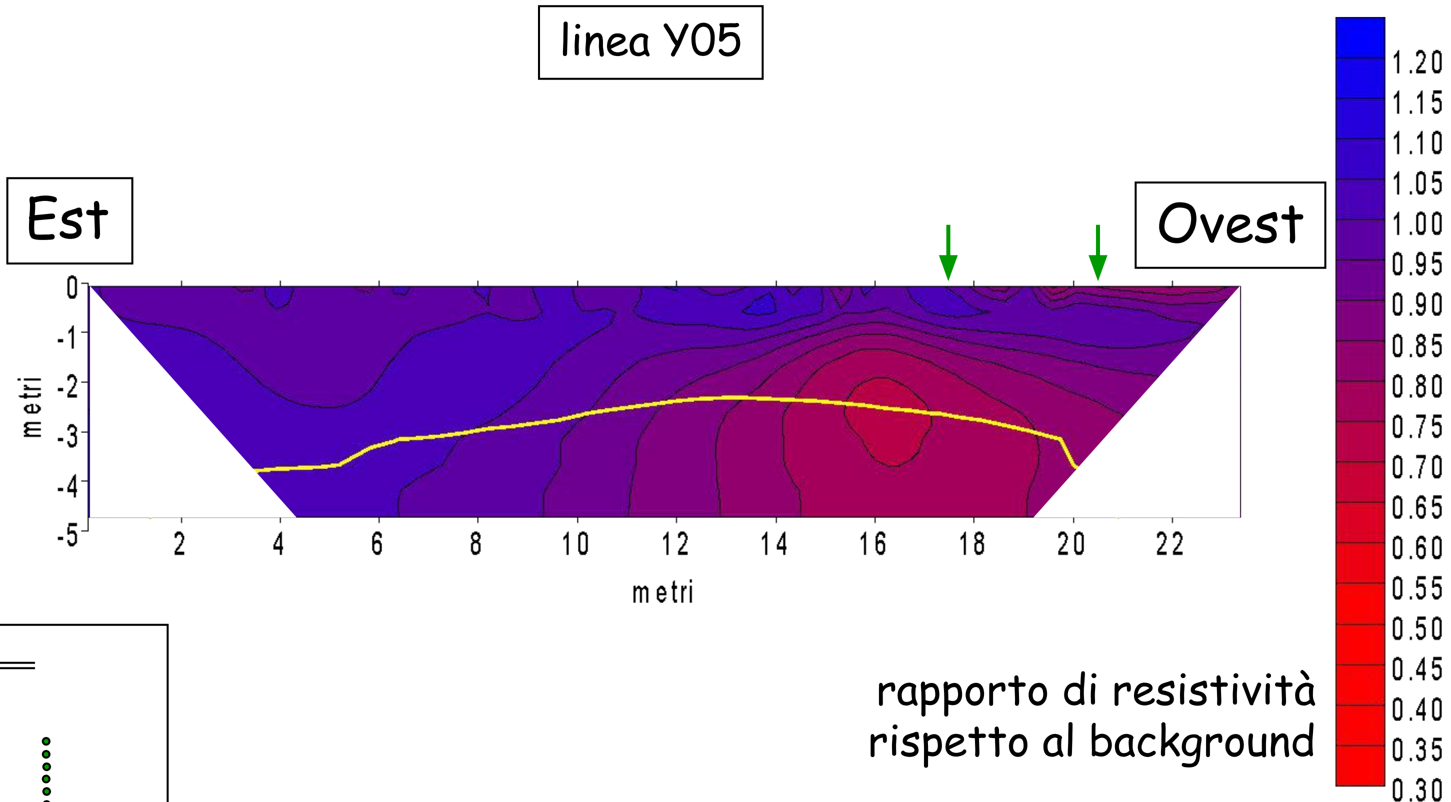

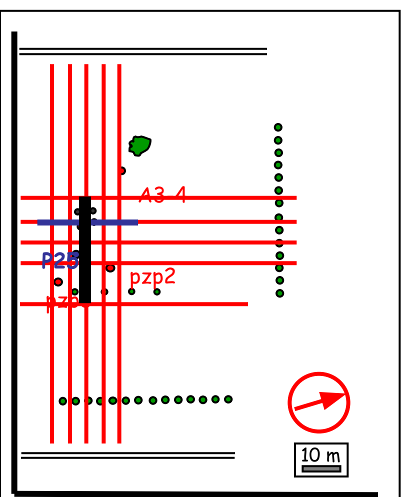

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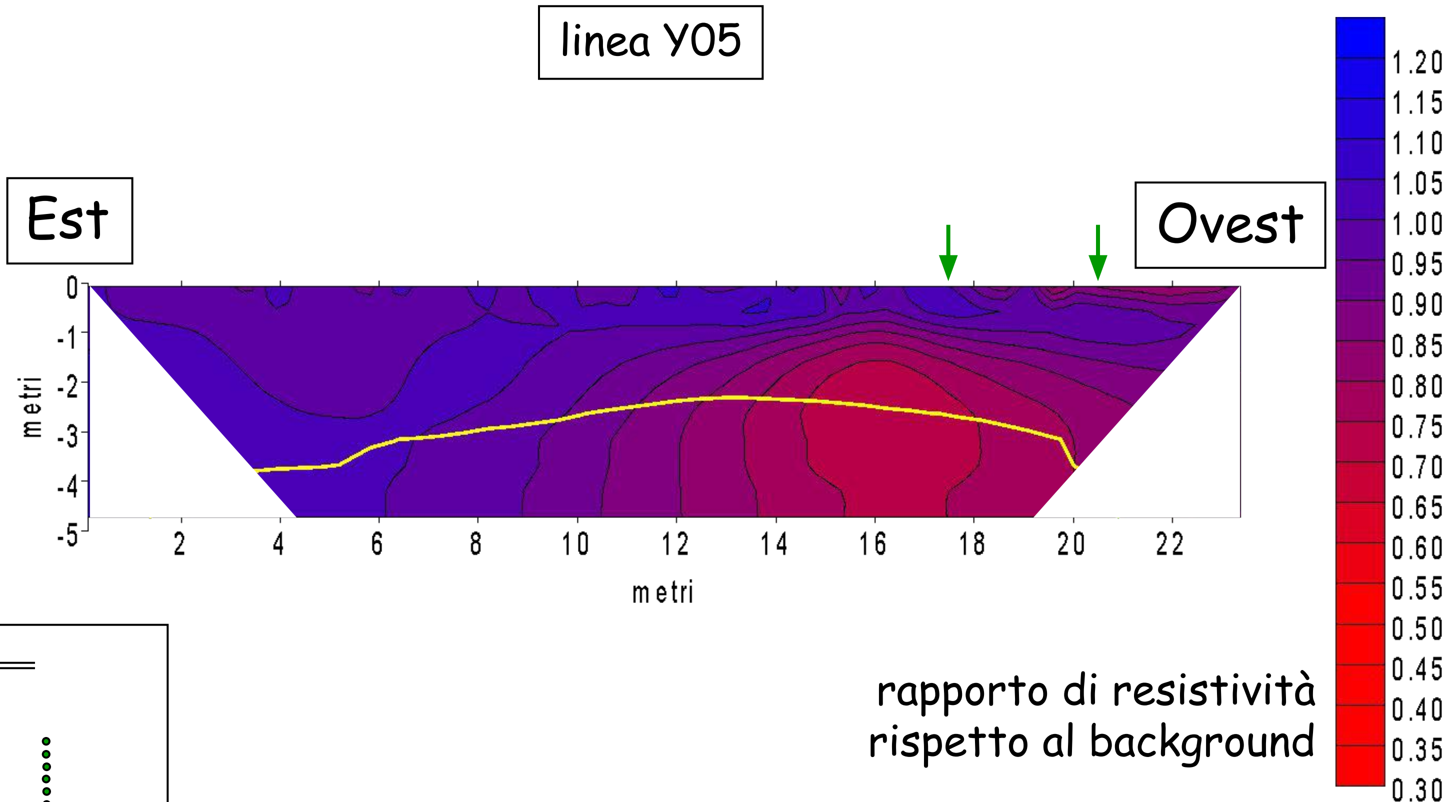

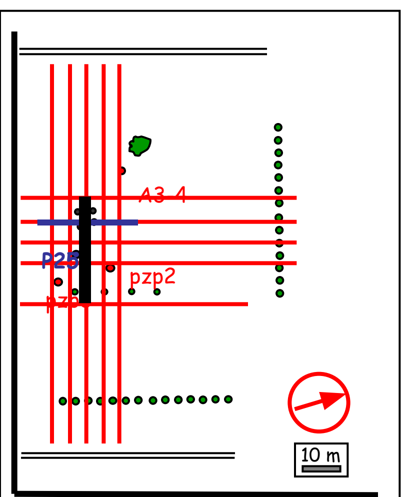

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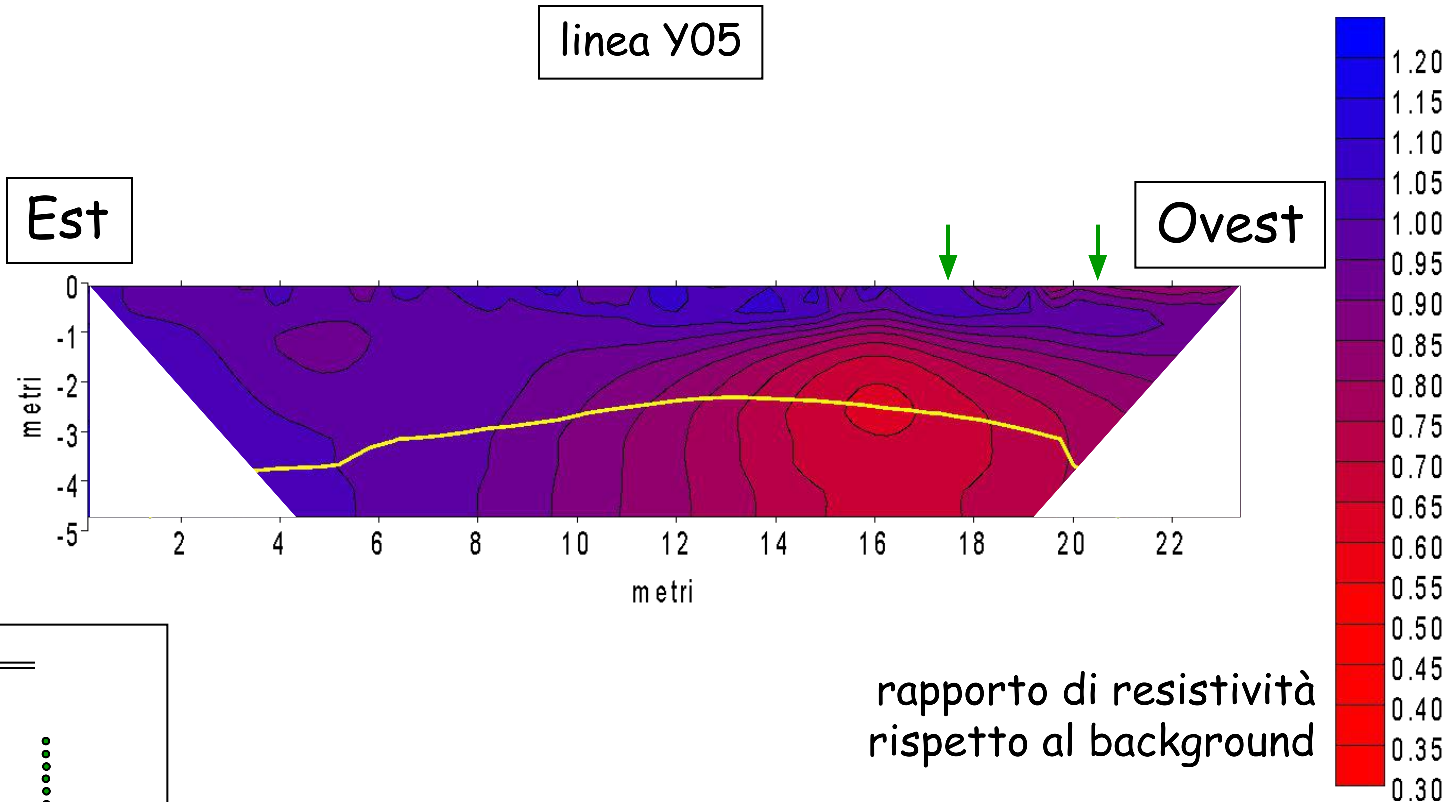

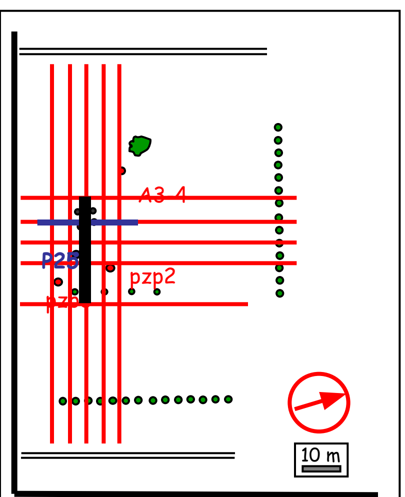

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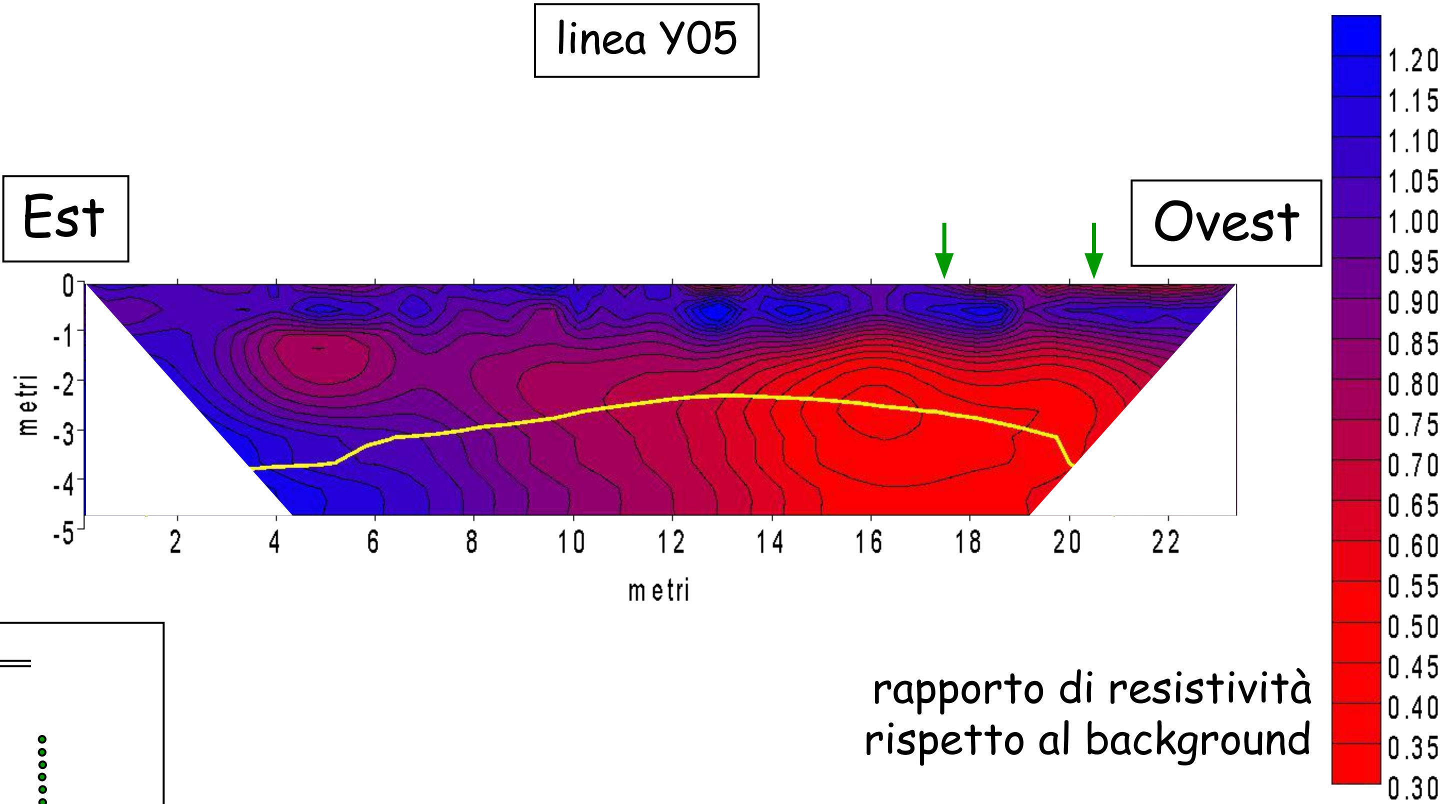

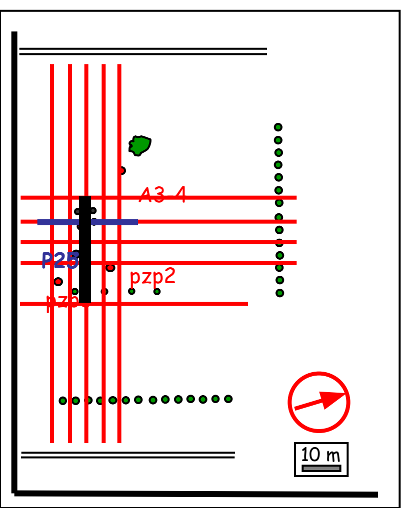

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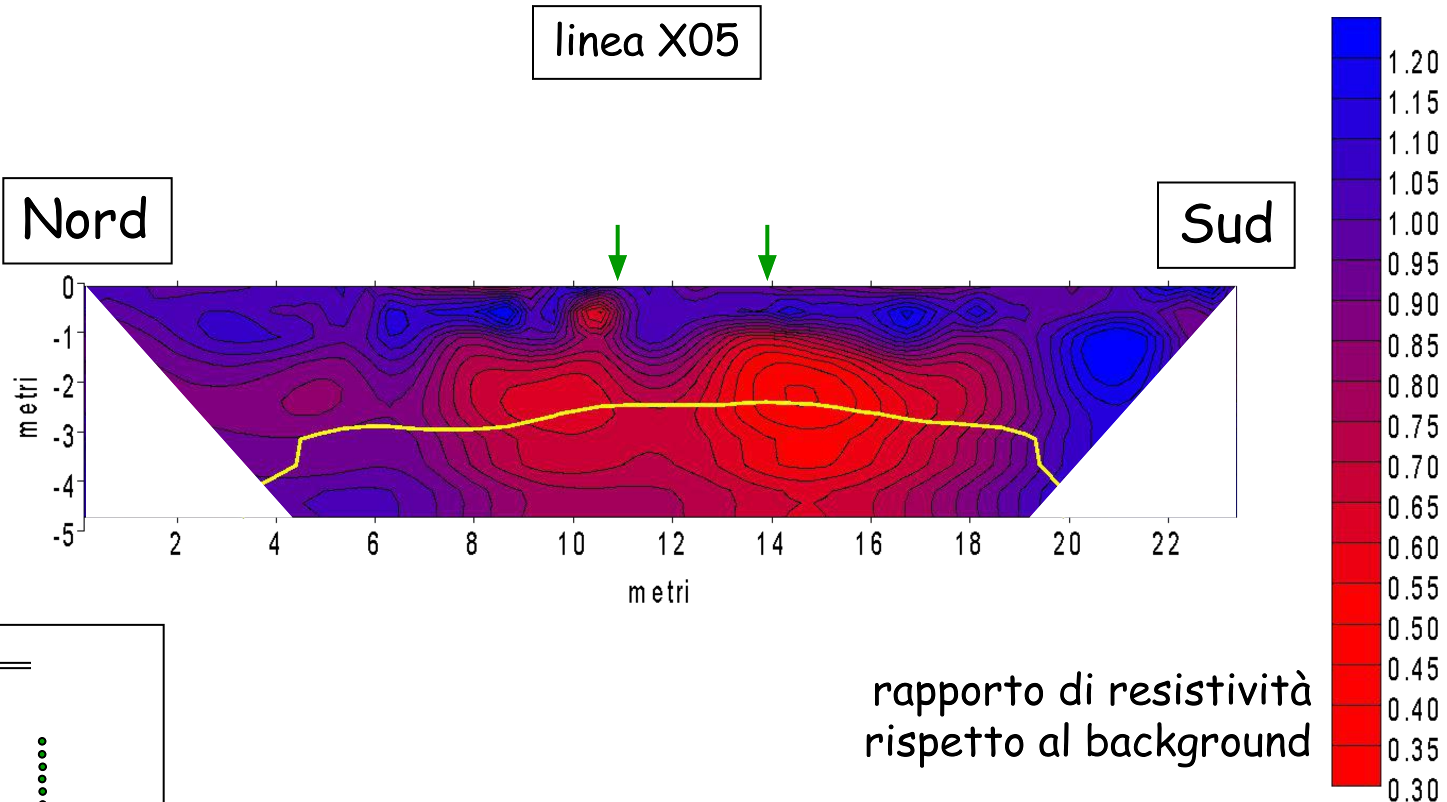

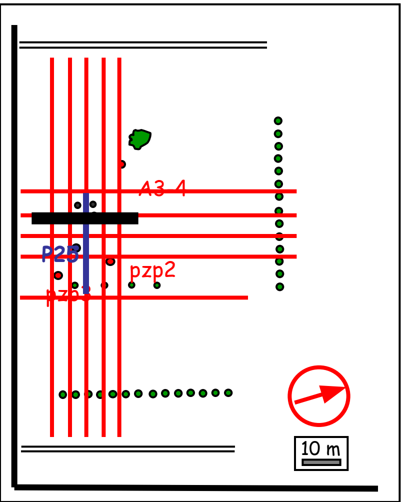

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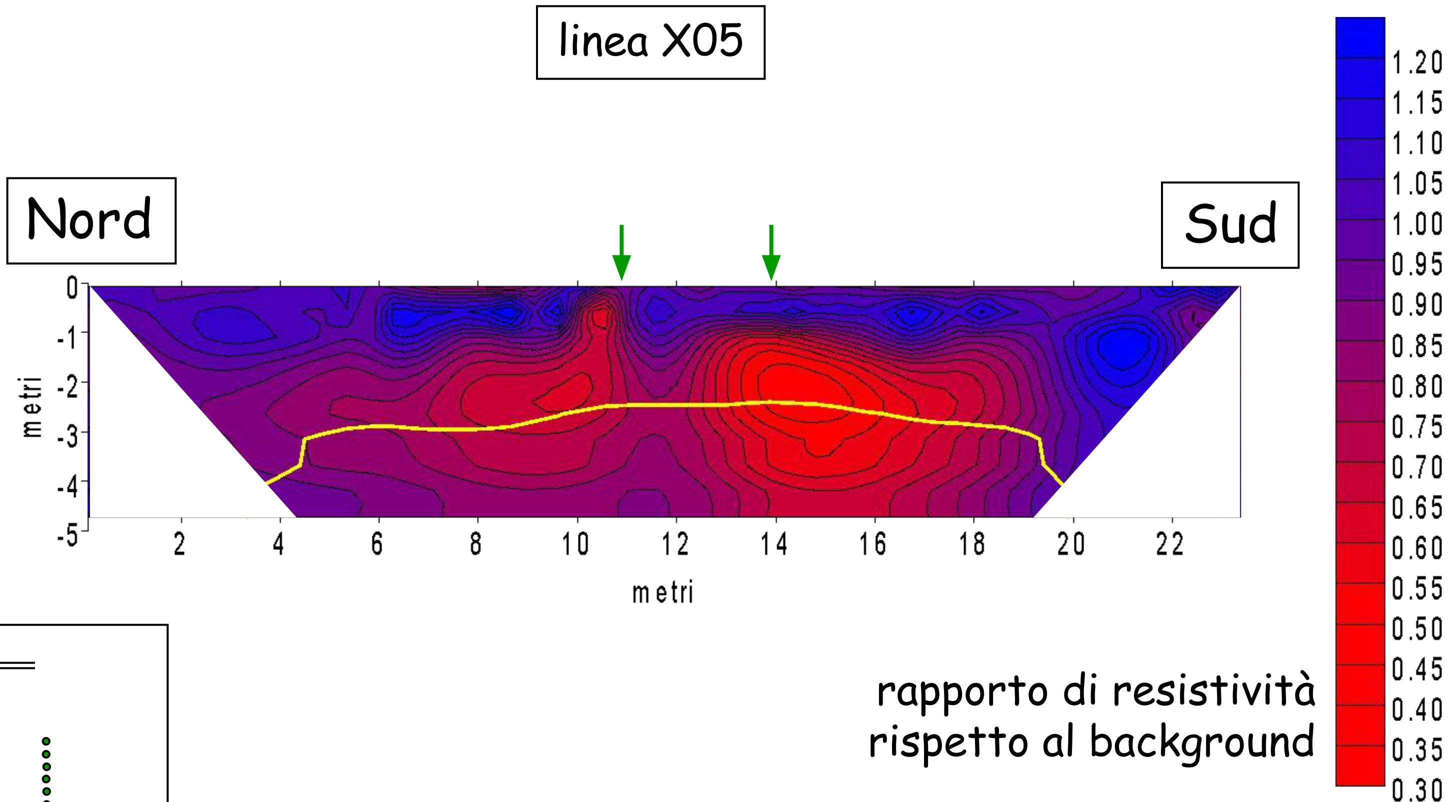

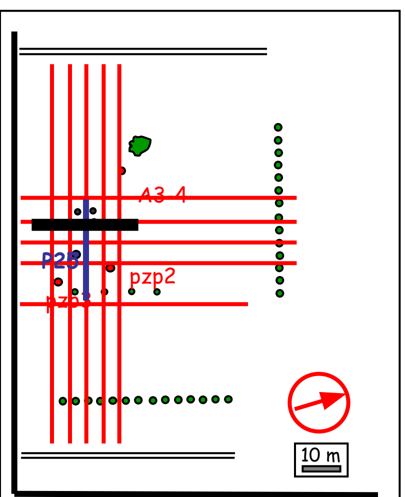

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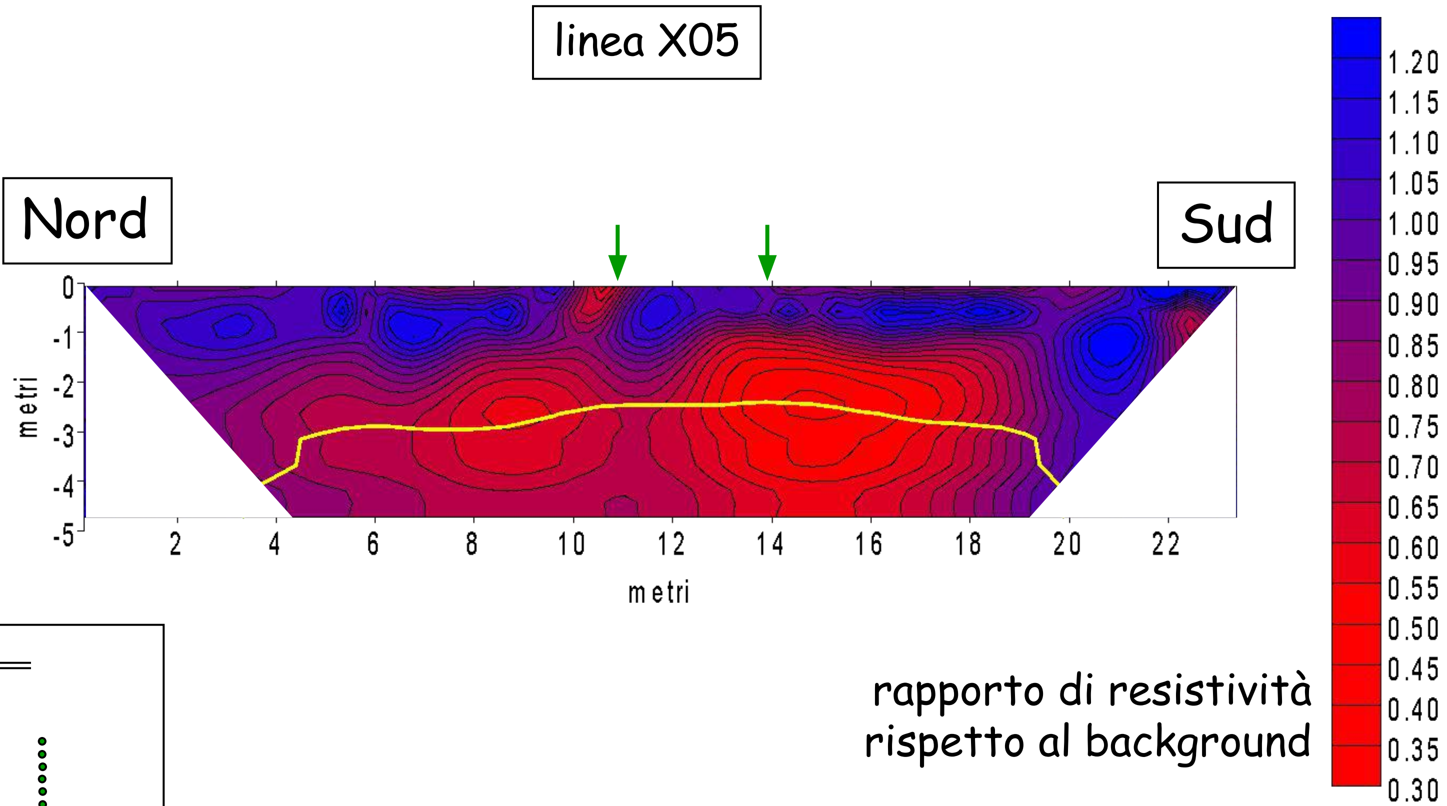
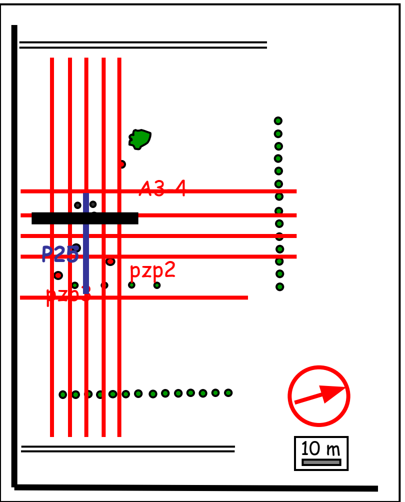
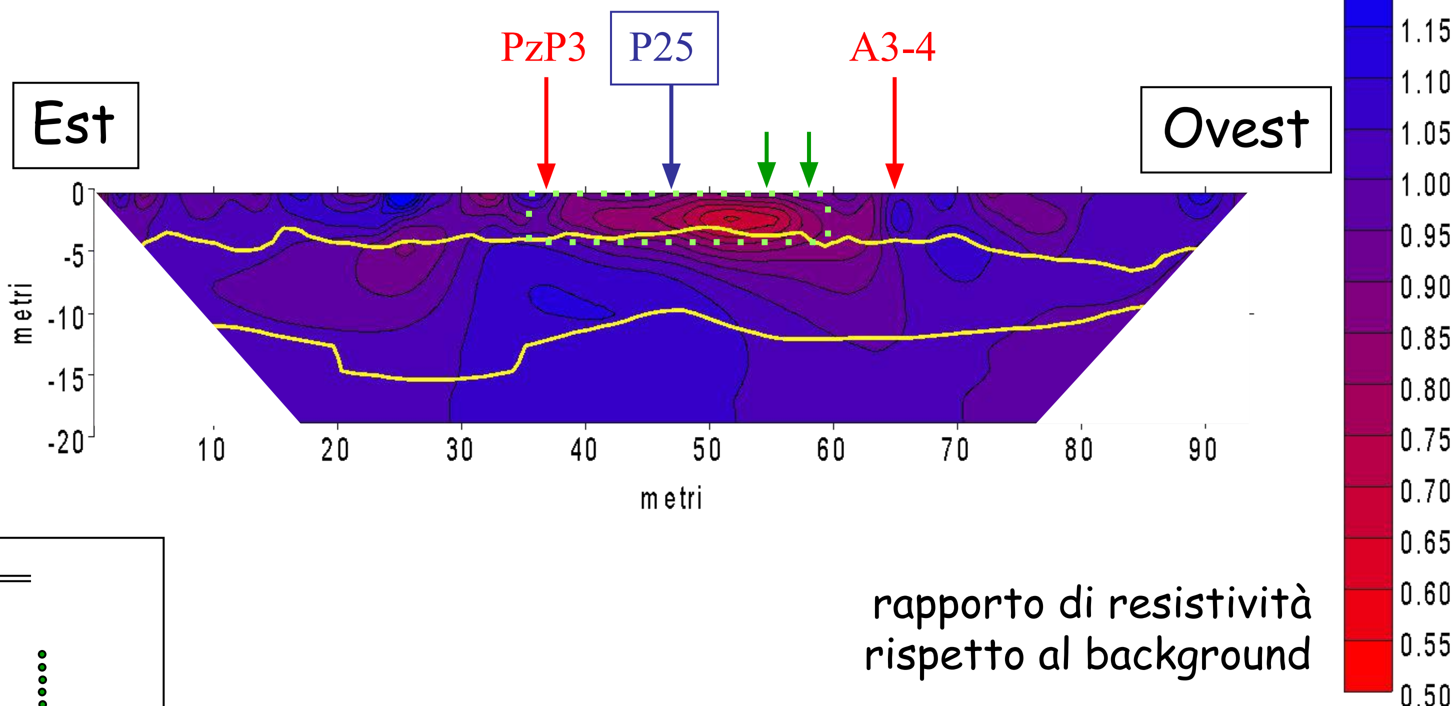
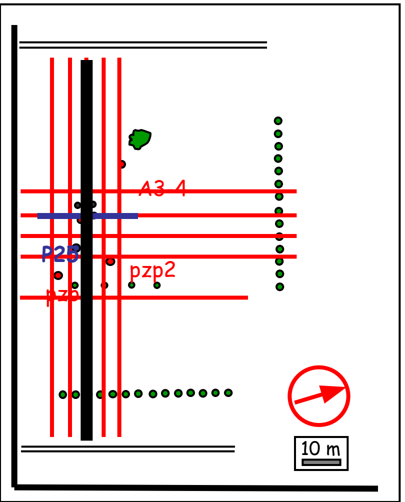




Surveys post-iniezione

linea Y – 8 agosto

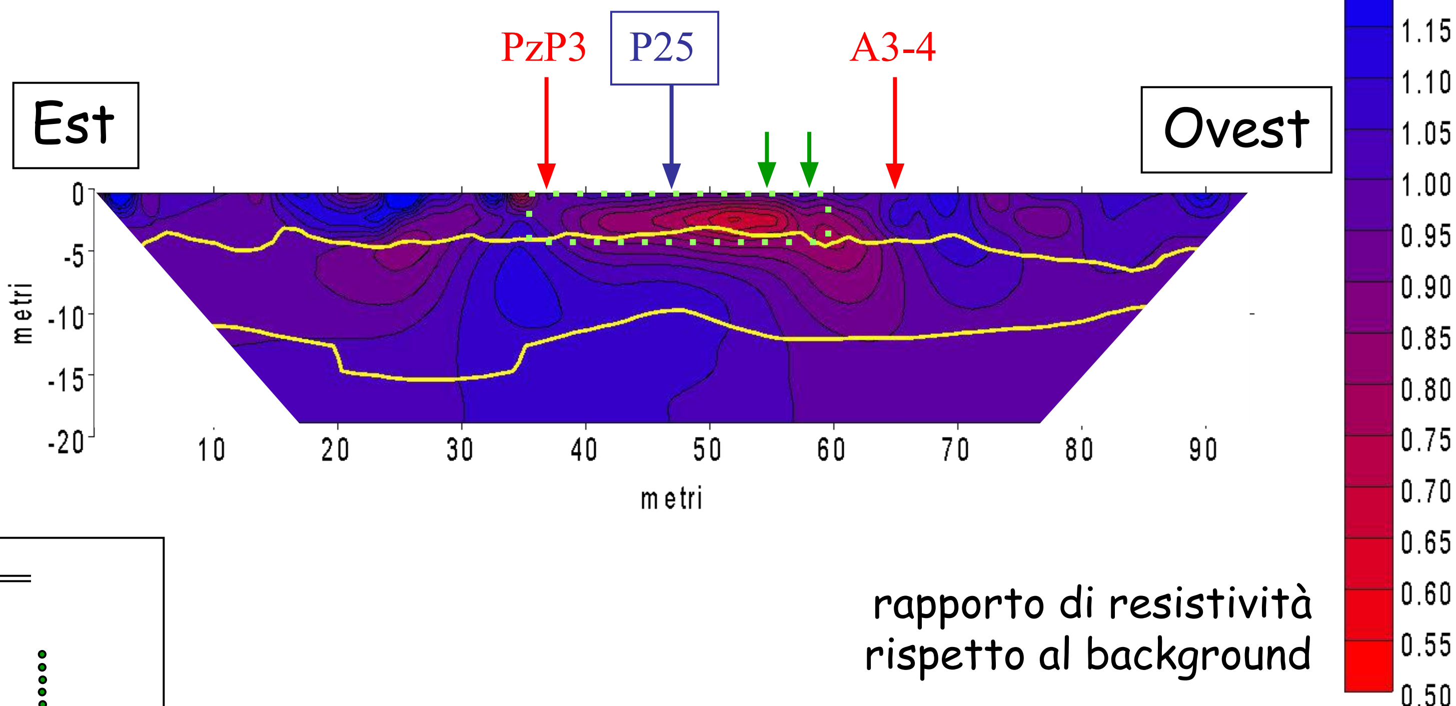




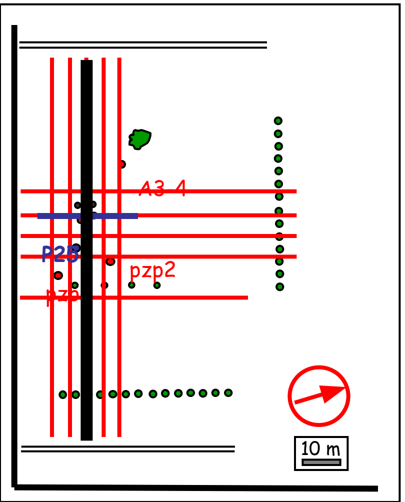
direzione prevalente della faldina superficiale

Surveys post-iniezione

linea Y - 12 agosto

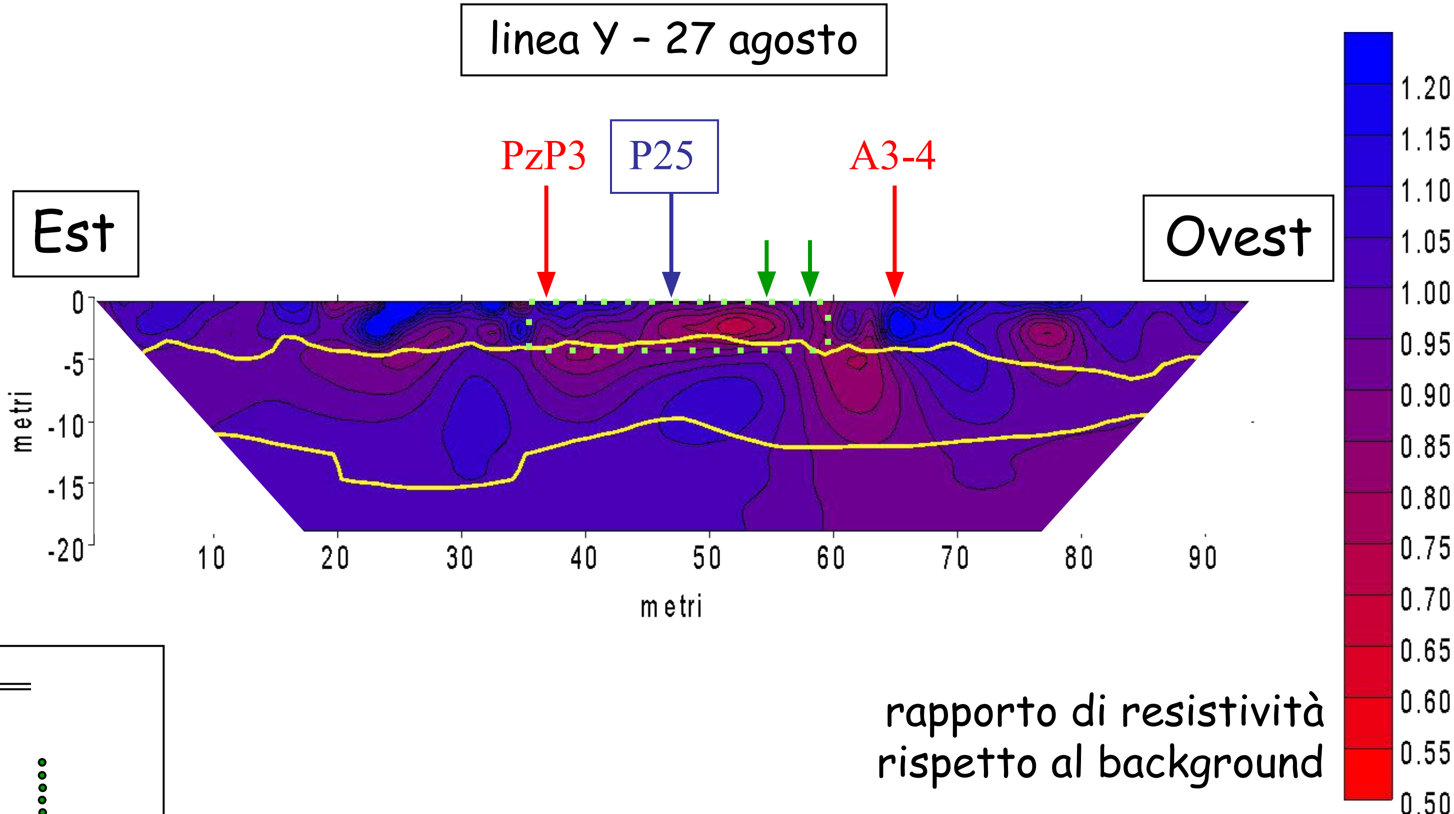


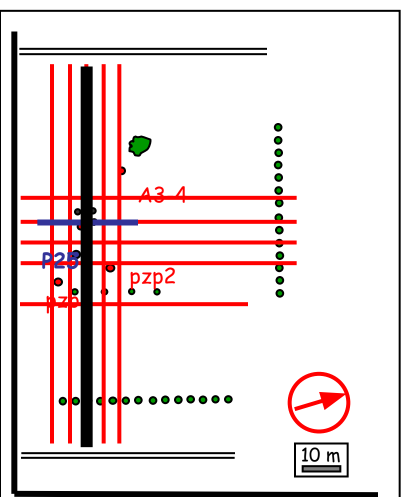
rapporto di resistività rispetto al background



direzione prevalente della faldina superficiale

Surveys post-iniezione

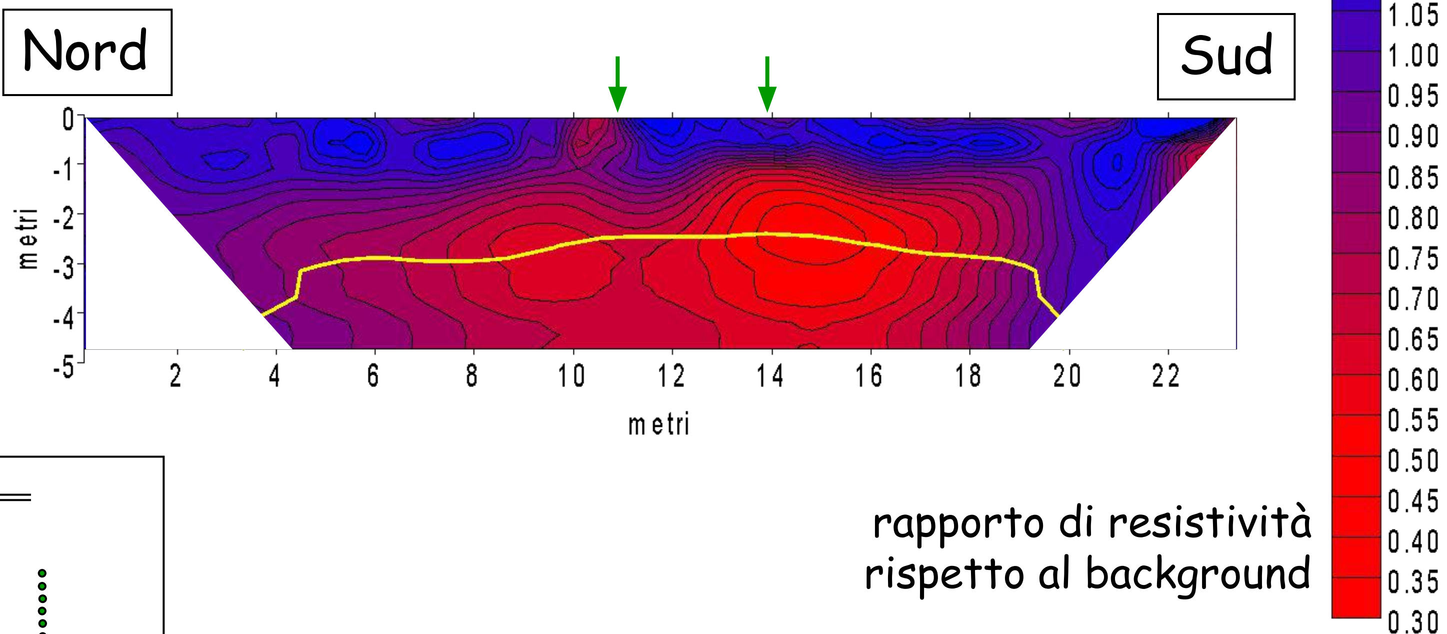


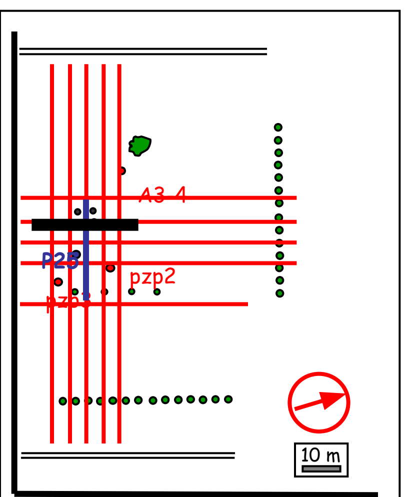


direzione prevalente della faldina superficiale

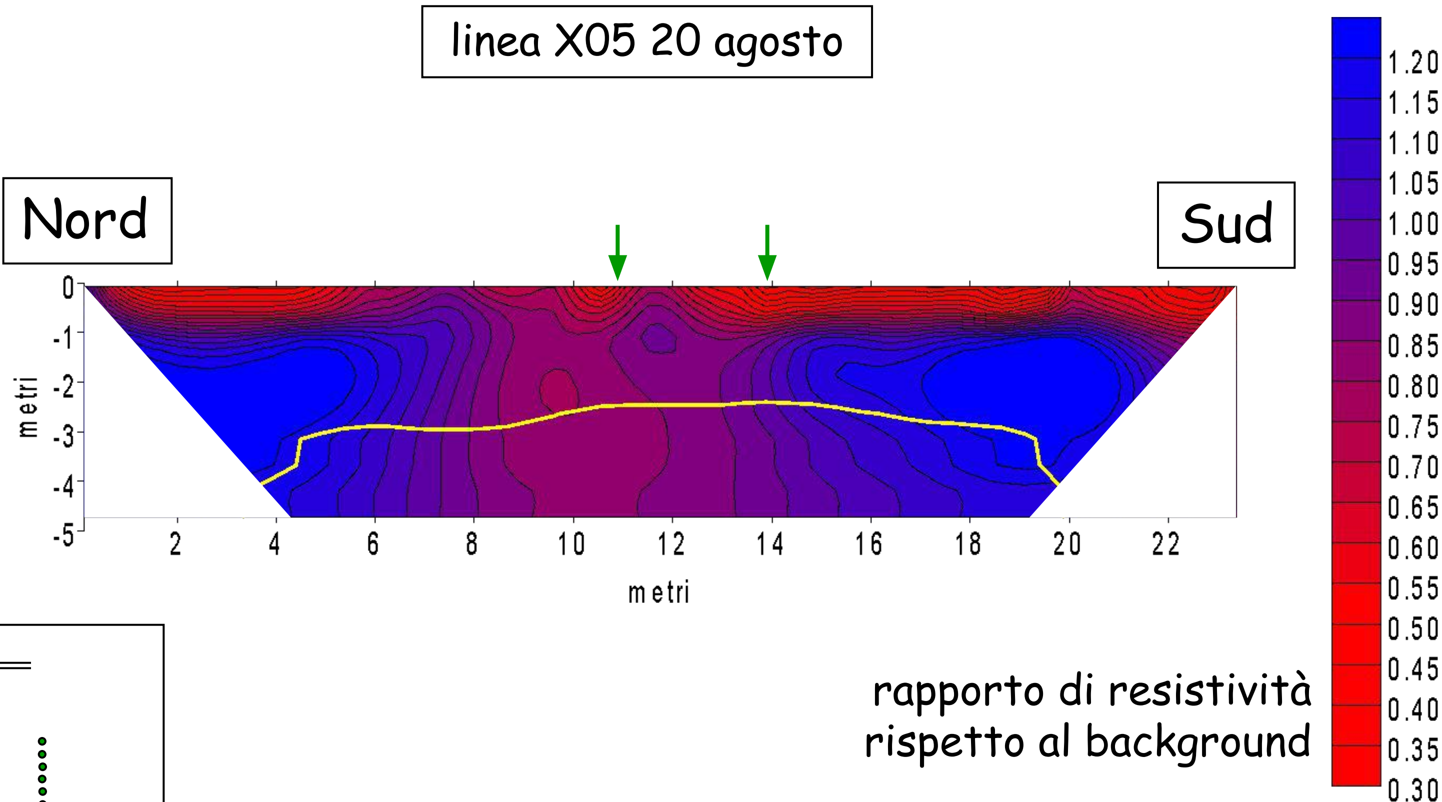
Surveys post-iniezione

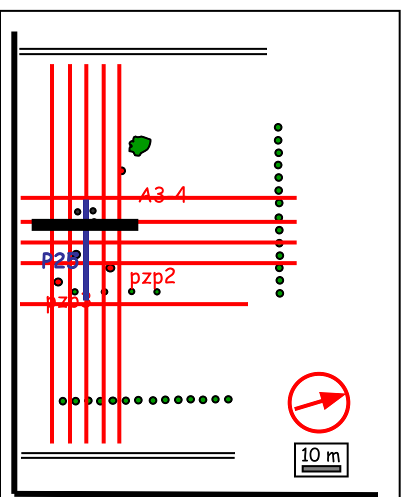
linea X05 13 agosto





Surveys post-iniezione

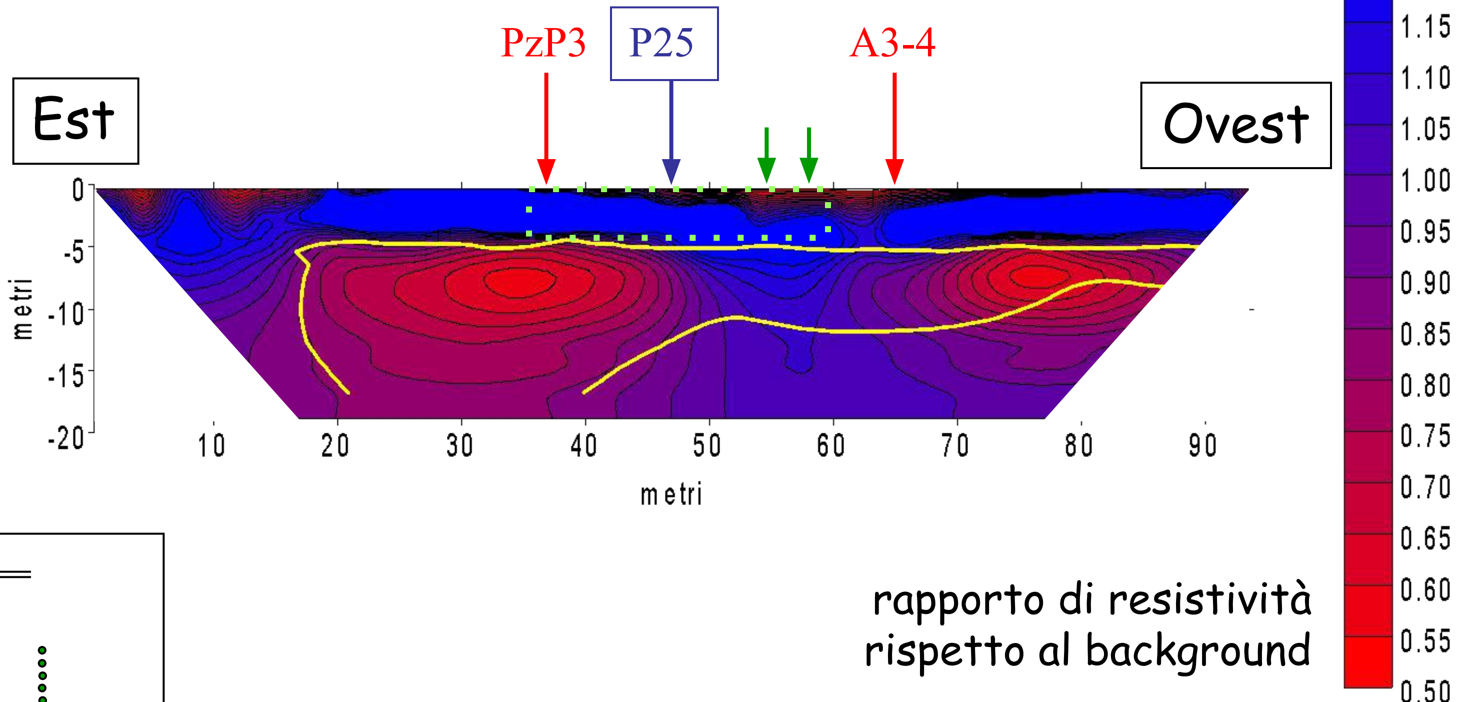




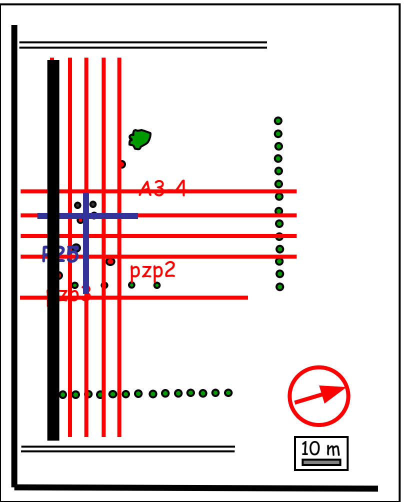
dopo un intenso evento di pioggia il 15 agosto

Surveys post-iniezione

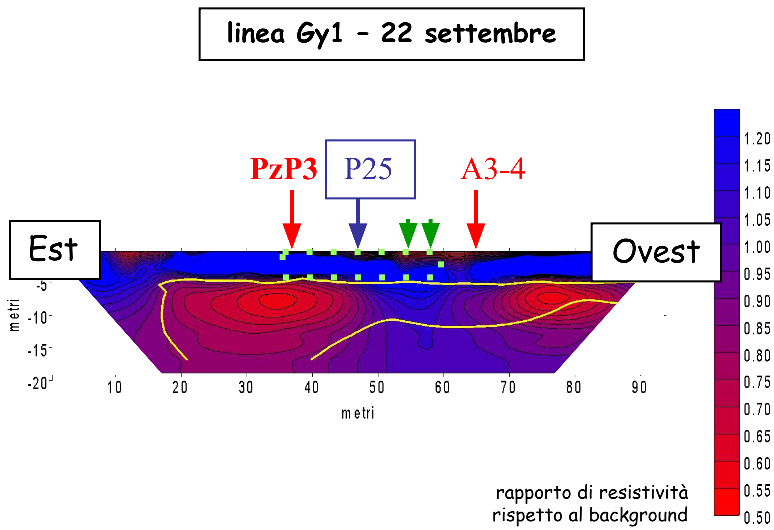
linea Gy1 - 22 settembre

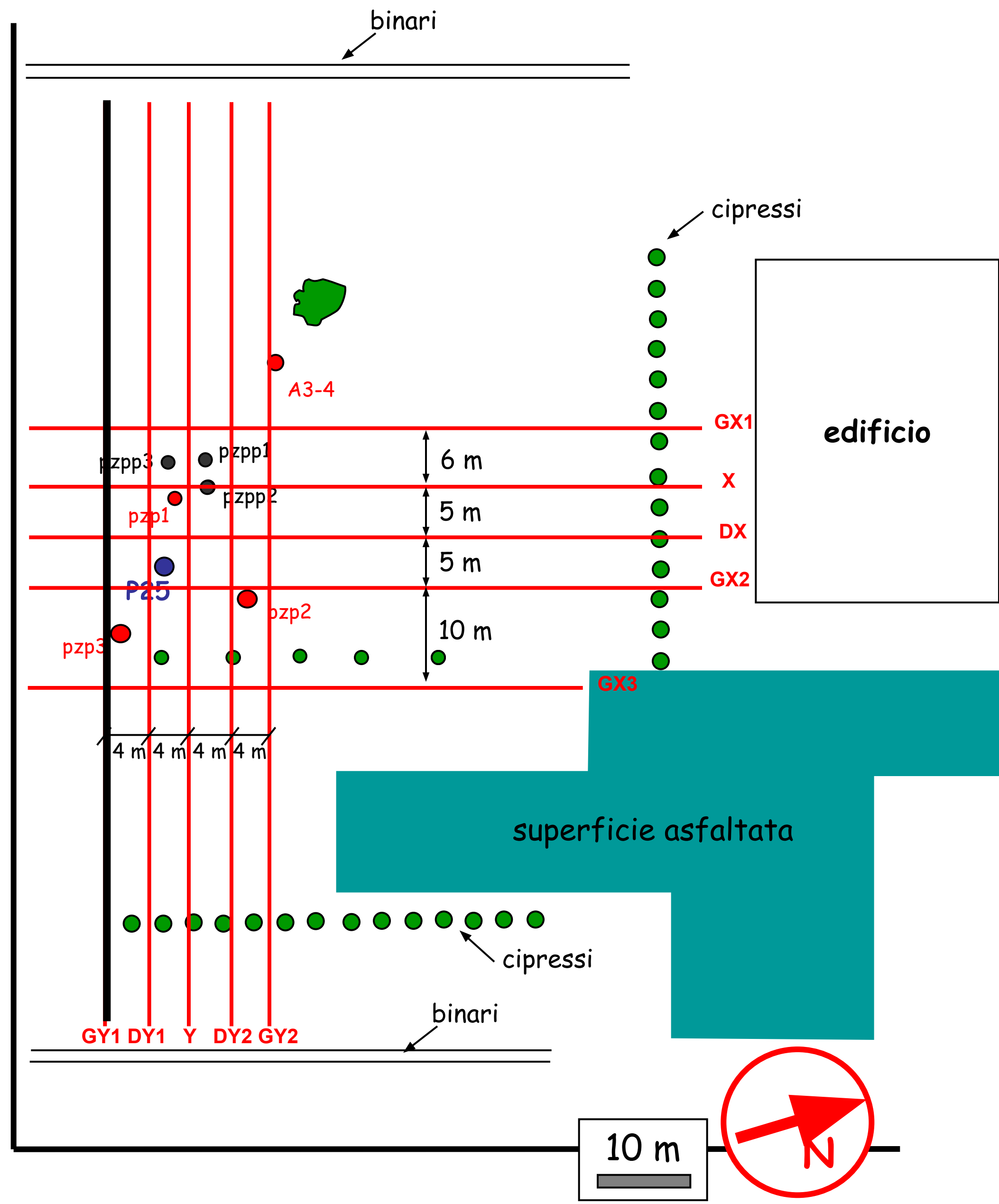


rapporto di resistività
rispetto al background

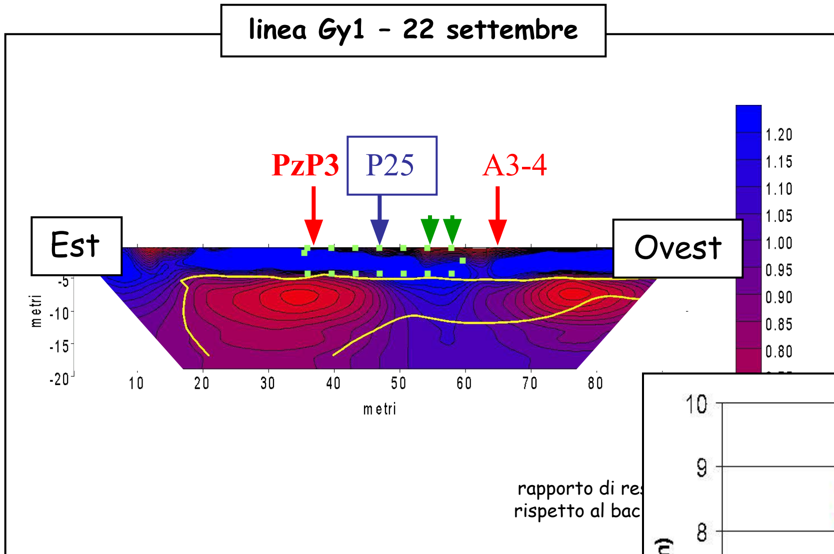


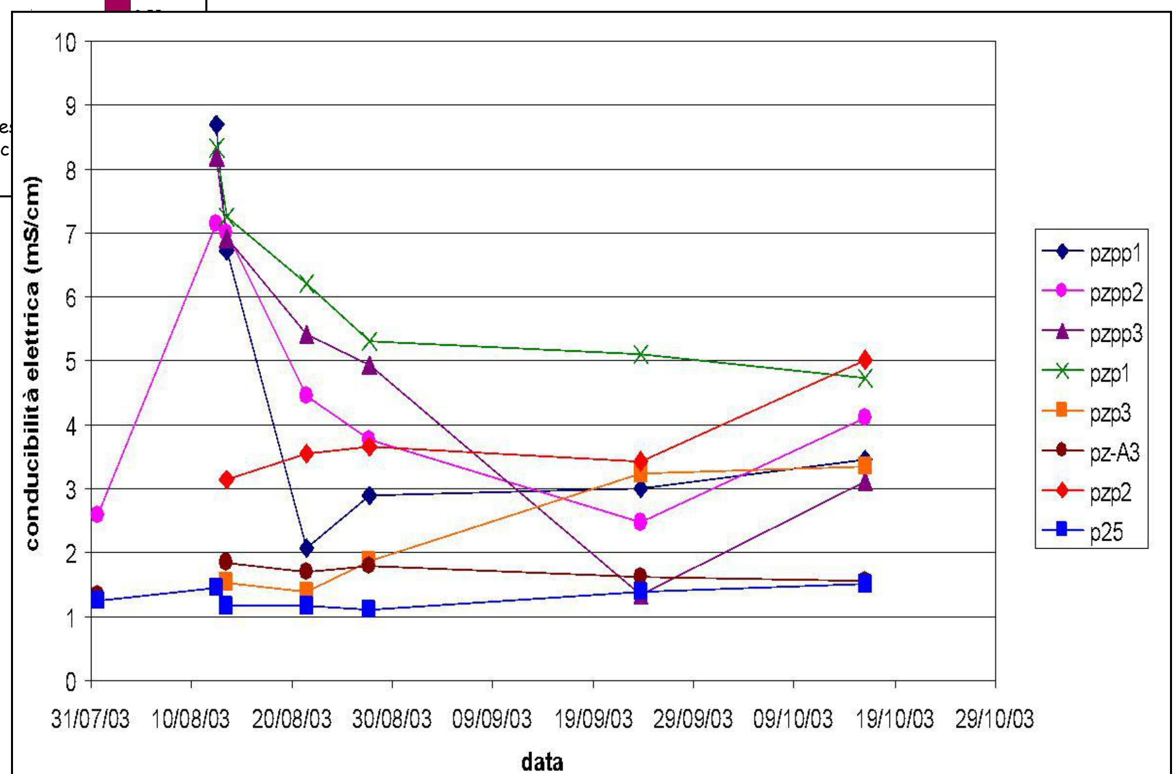
Surveys post-iniezione





misure dirette di conducibilità elettrica





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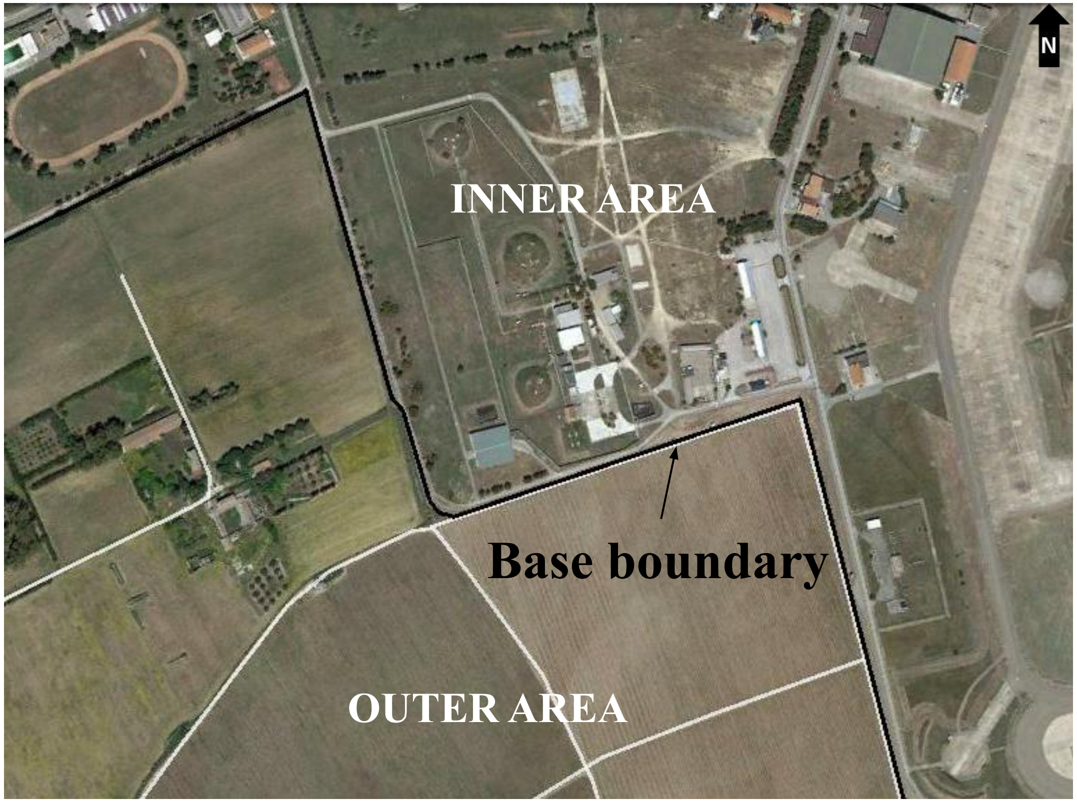
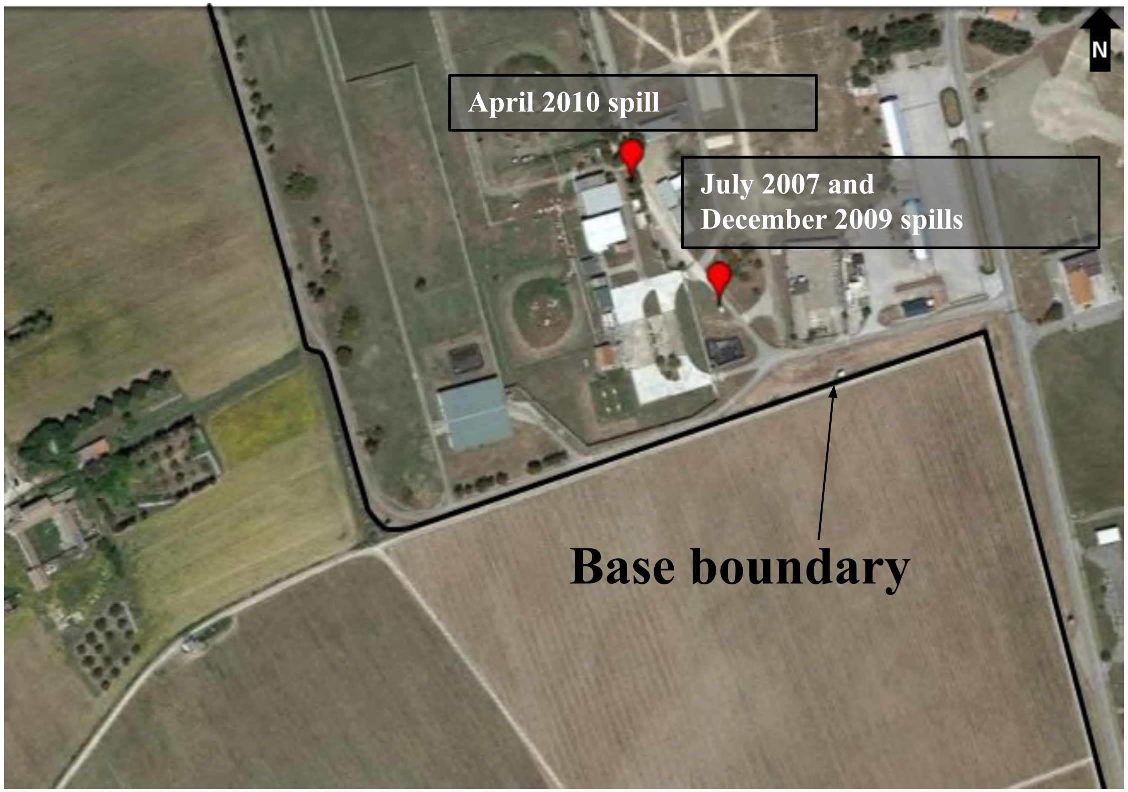
STUDY AREA
The NATO air base in Decimomannu, Sardinia (Italy)



CONTAMINATION HISTORY



Three jet fuel (JP8) spills from pipelines have been identified during the past decade:

- July 2007, 40000 liters at 2 m depth;
- December 2009, 5000 liters (same location as in 2007);
- April 2010, 5000 liters

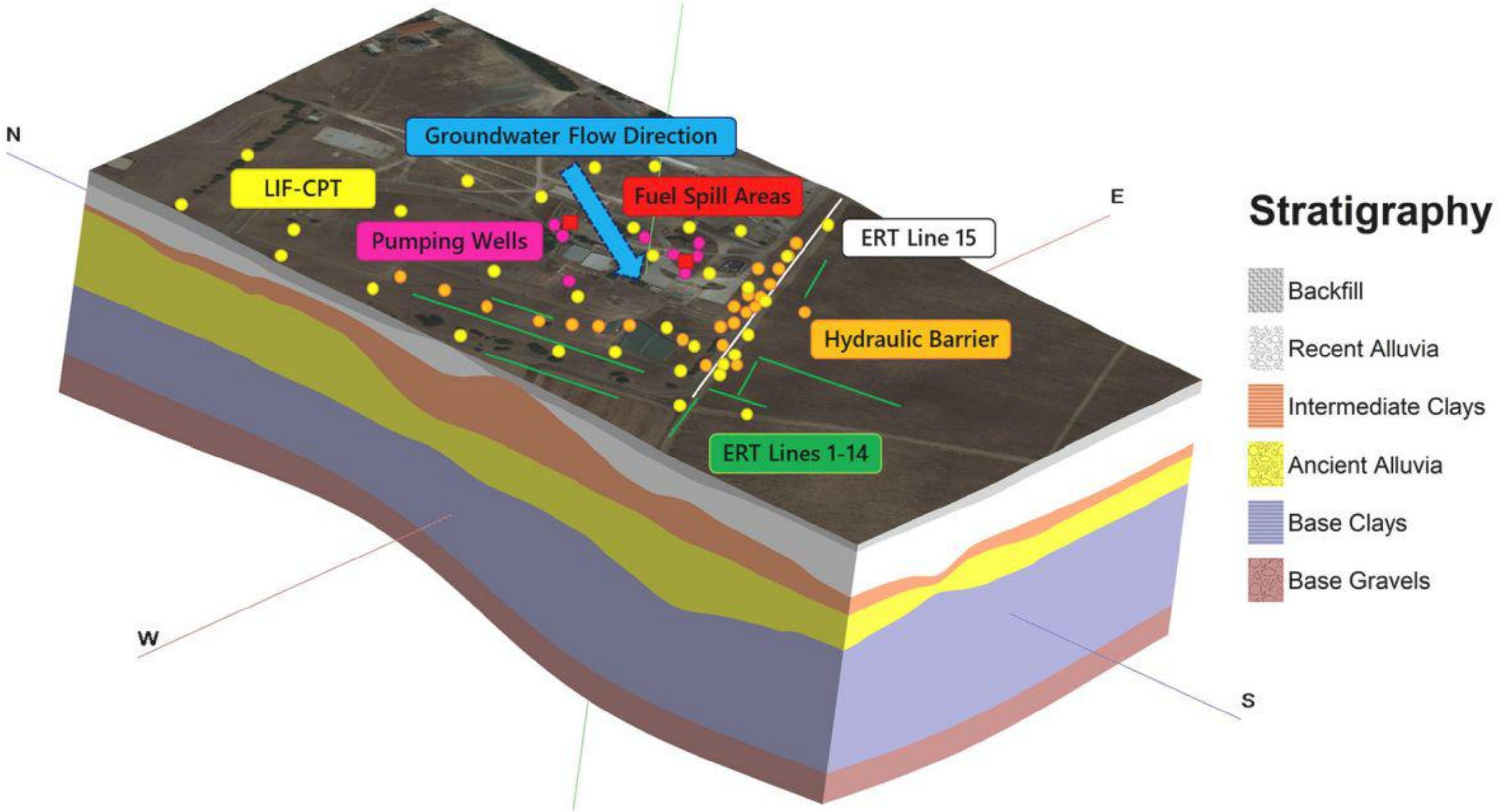
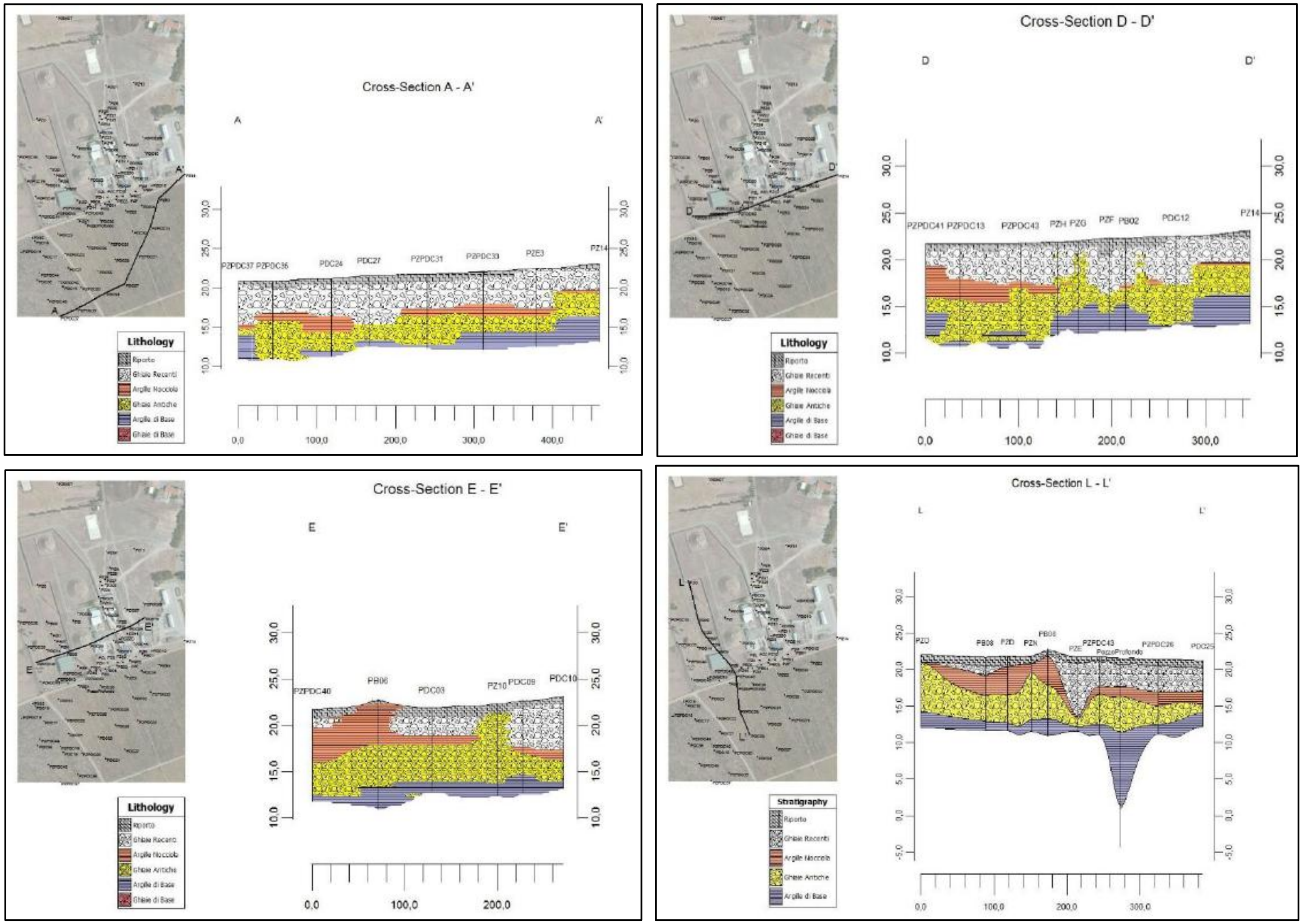
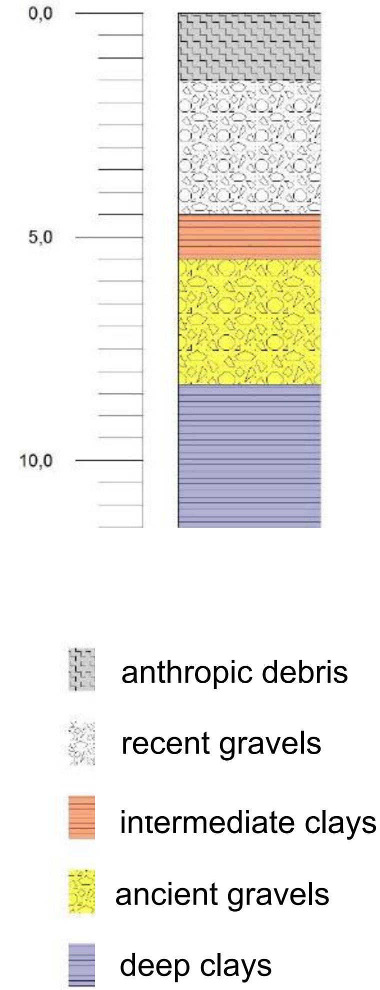


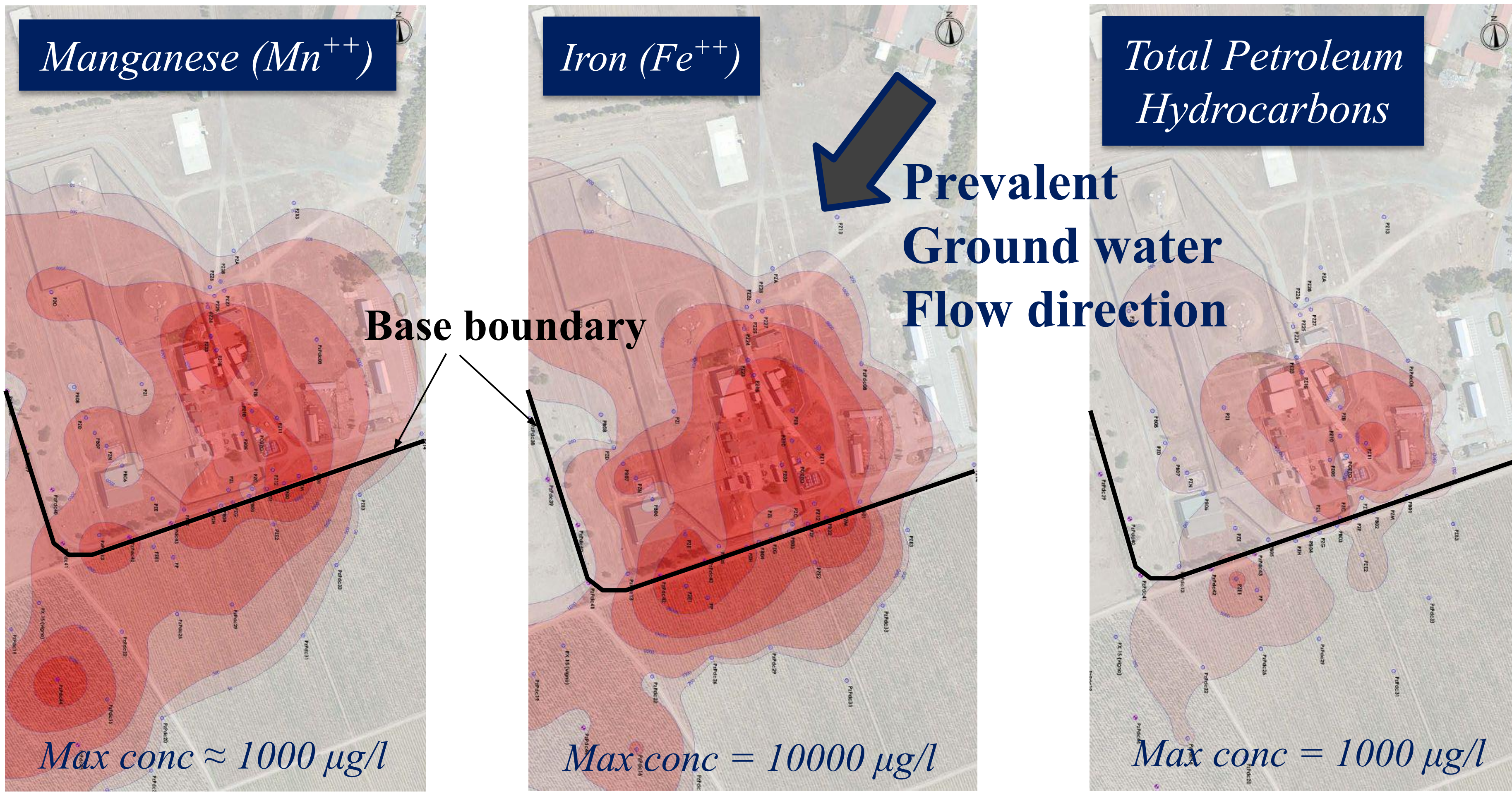
Fig. 1. Three-dimensional geological model of the Decimomannu military airbase depicting the stratigraphic relationships. Position of the fuel spill areas, pumping wells, hydraulic barrier, LIF-CPT investigations, and ERT lines inside the military domain.

GEOLOGICAL CONTEXT



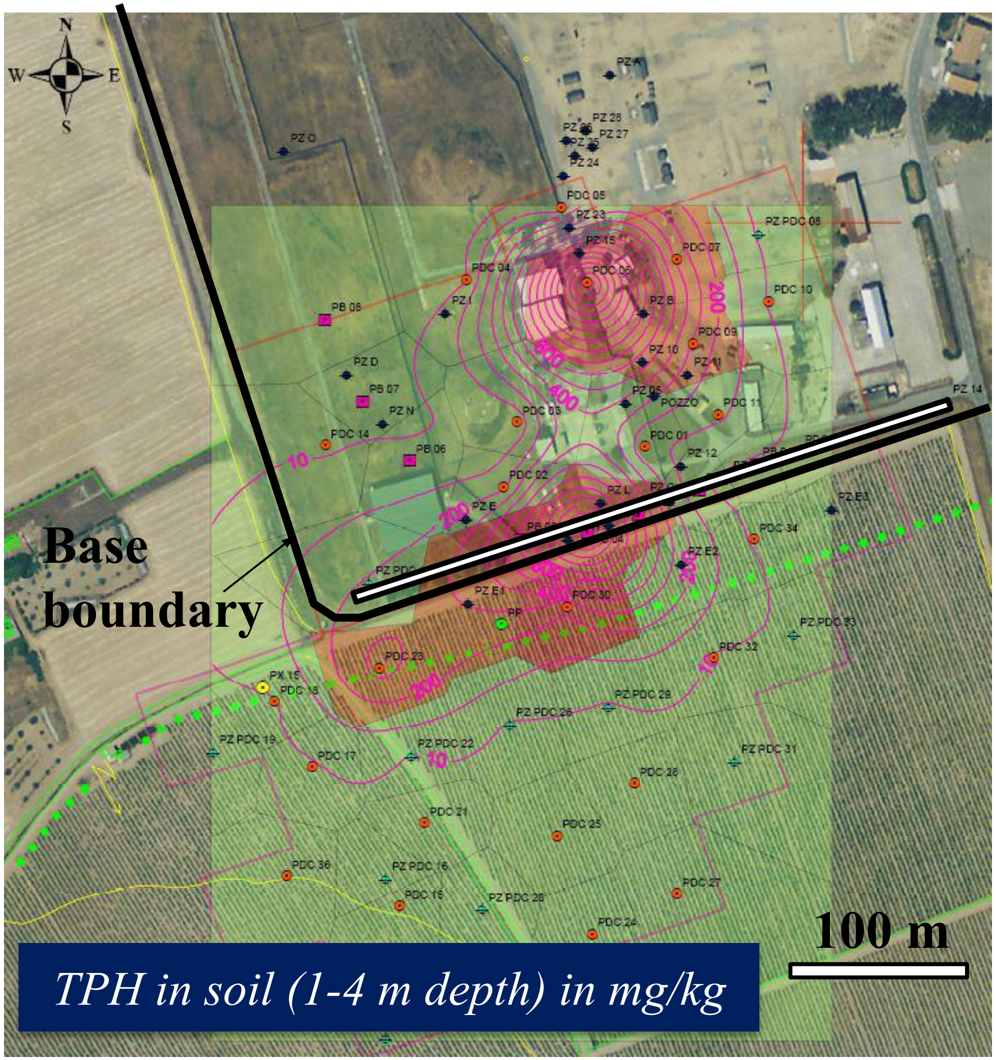


GROUNDWATER CONTAMINATION

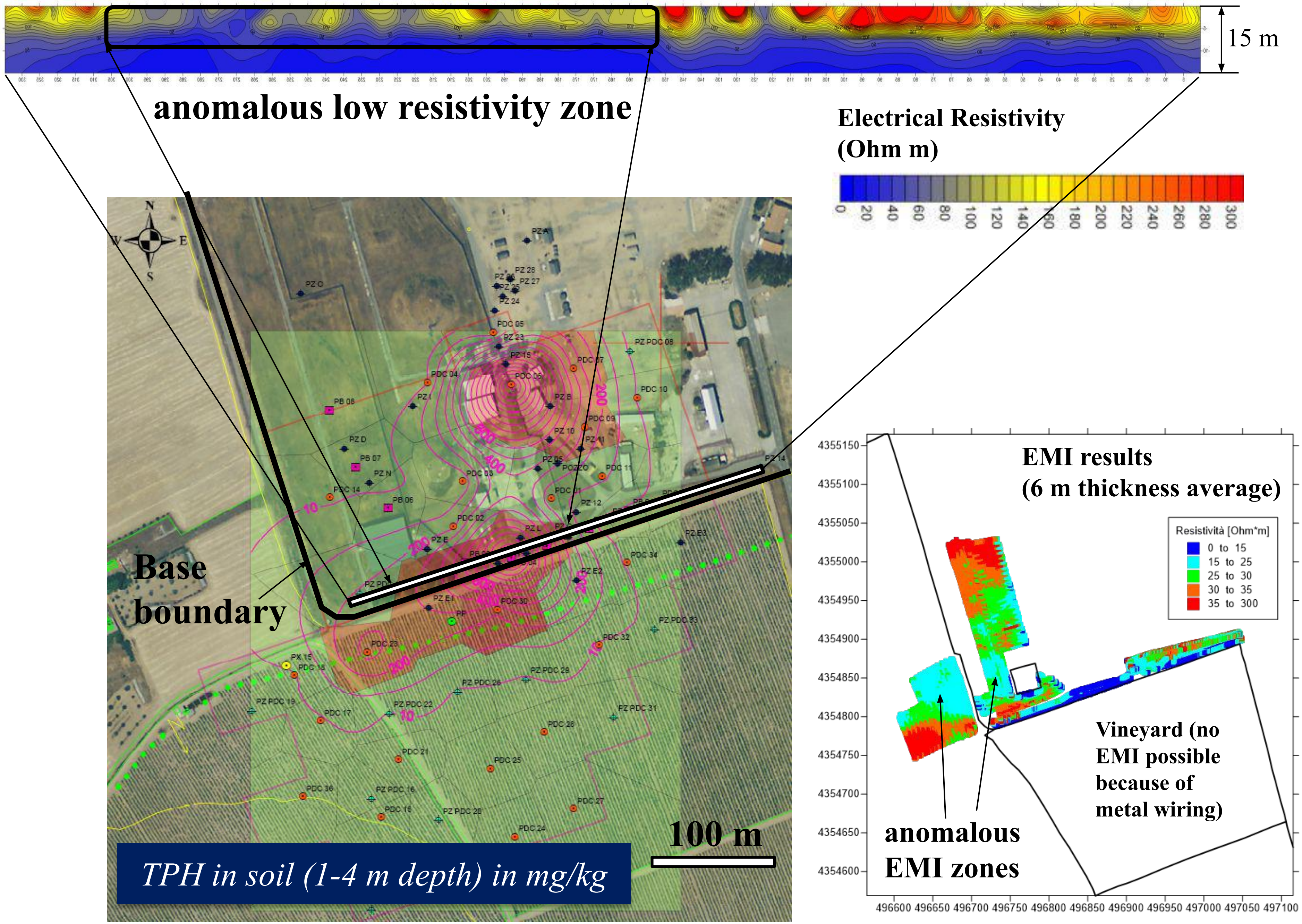


The water table oscillates (+/- 2 m) around 5 m below ground

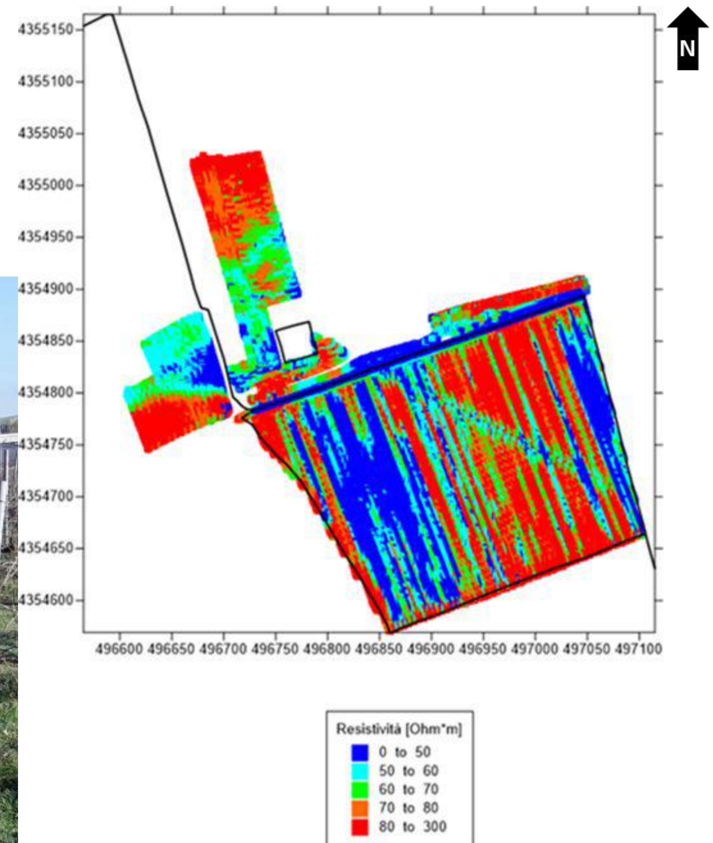
SOIL CONTAMINATION

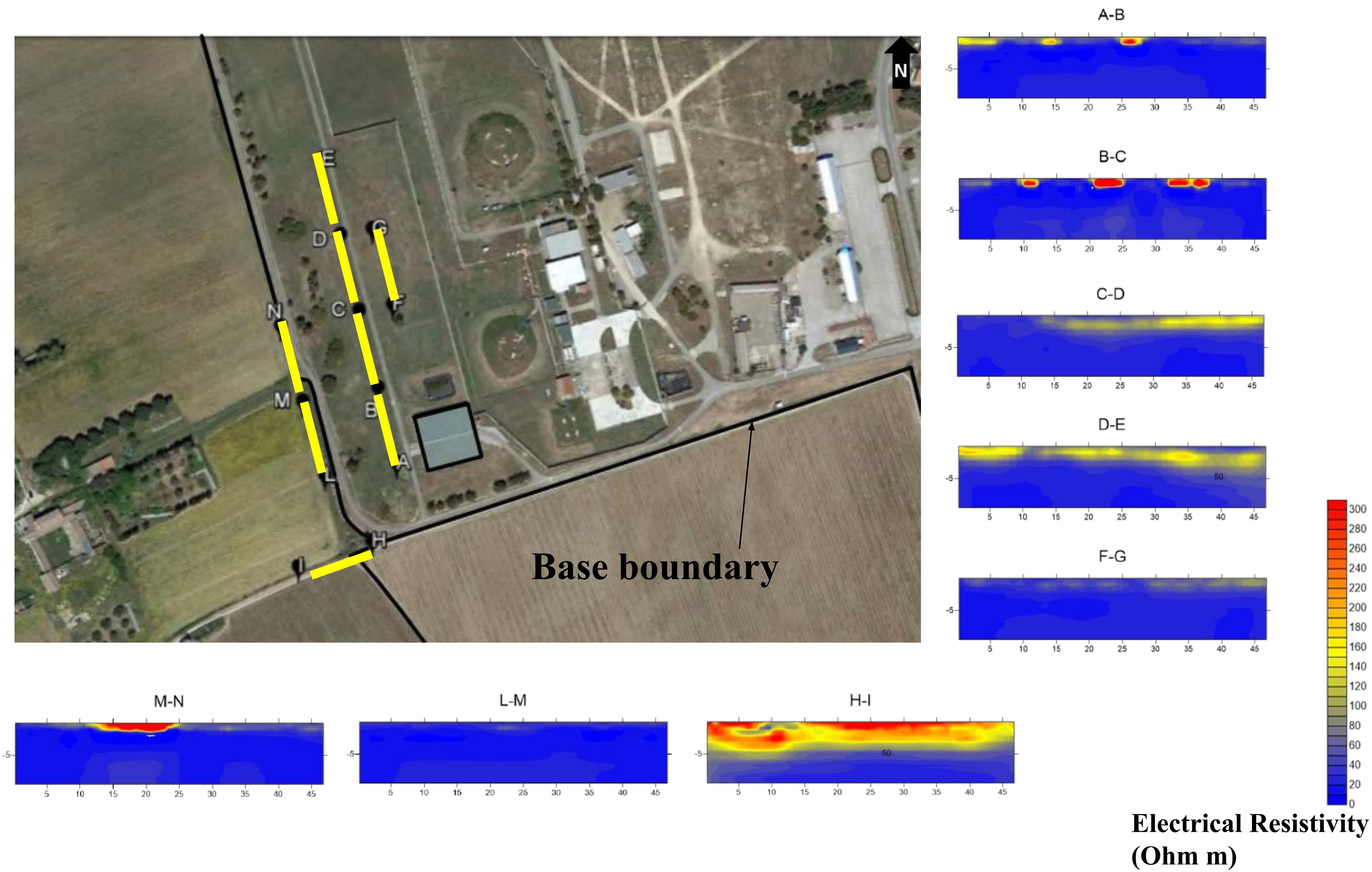


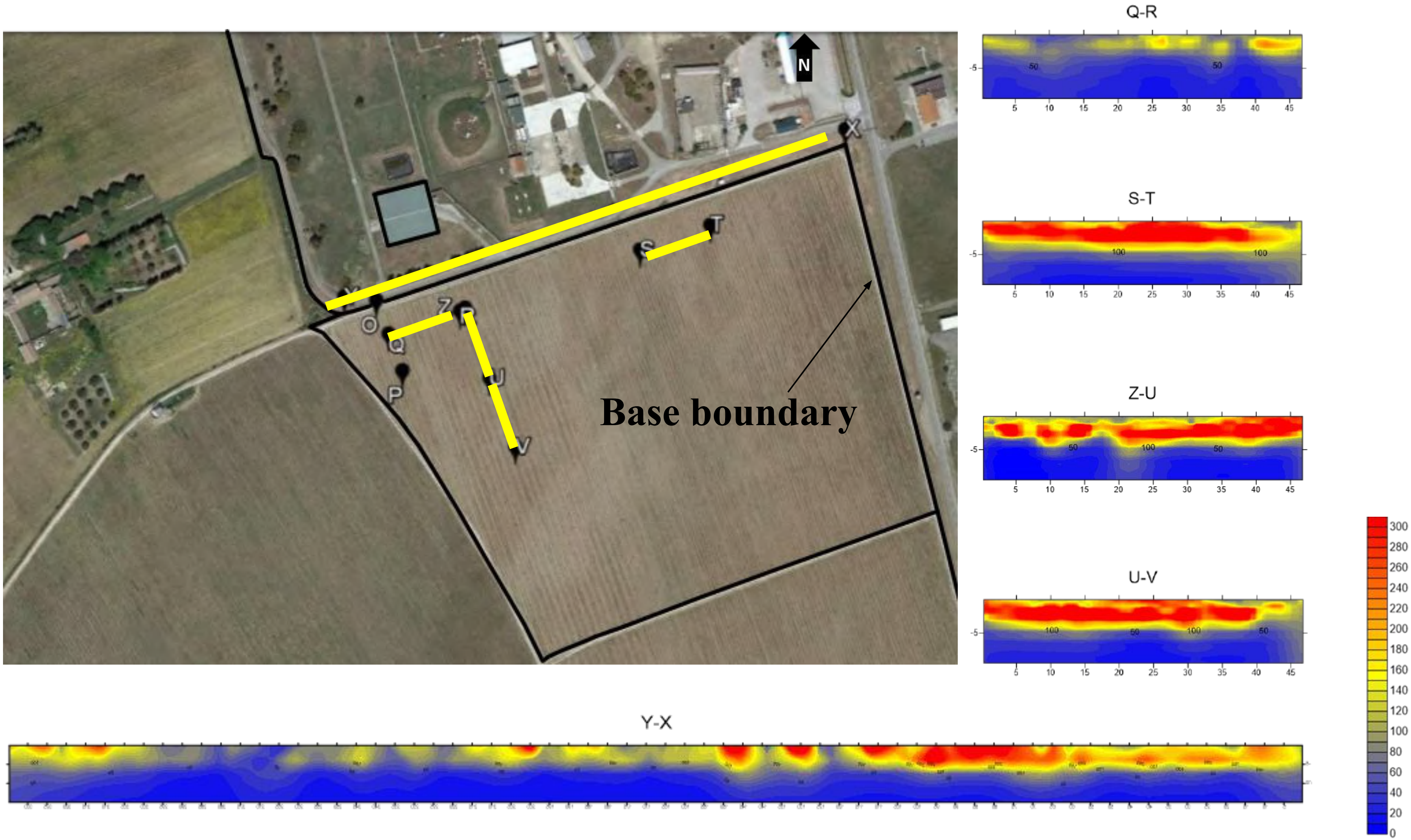
GEOPHYSICAL INVESTIGATIONS (ERT / EMI)


15 m
anomalous low resistivity zone
Electrical Resistivity
(Ohm m)
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
N
W
E
S
Base
boundary
100 m
TPH in soil (1-4 m depth) in mg/kg
EMI results
(6 m thickness average)
Resistività [Ohm*m]
0 to 15
15 to 25
25 to 30
30 to 35
35 to 300
Vineyard (no
EMI possible
because of
metal wiring)
anomalous
EMI zones
4355150
4355100
4355050
4355000
4354950
4354900
4354850
4354800
4354750
4354700
4354650
4354600
496600 496650 496700 496750 496800 496850 496900 496950 497000 497050 497100

Vineyard (no EMI possible because of metal wiring)




N
E
D
G
C
F
N
M
B
A
L
H
I
Base boundary
A-B
B-C
C-D
D-E
F-G
M-N
L-M
H-I
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
Electrical Resistivity
(Ohm m)

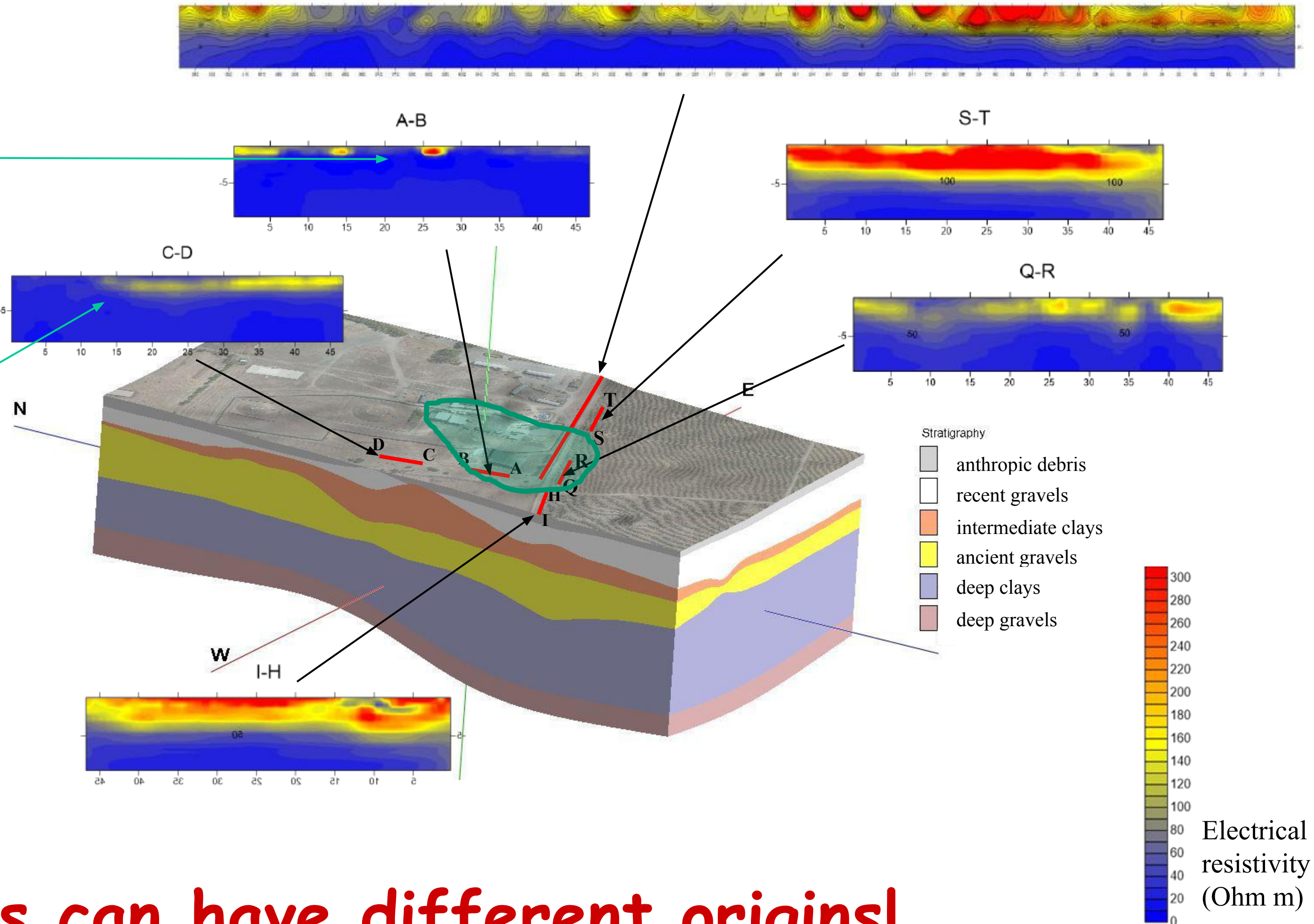


Electrical Resistivity (Ohm m)

Overall interpretation of resistivity anomalies

Low resistivity of contamination/ biodegradation origin

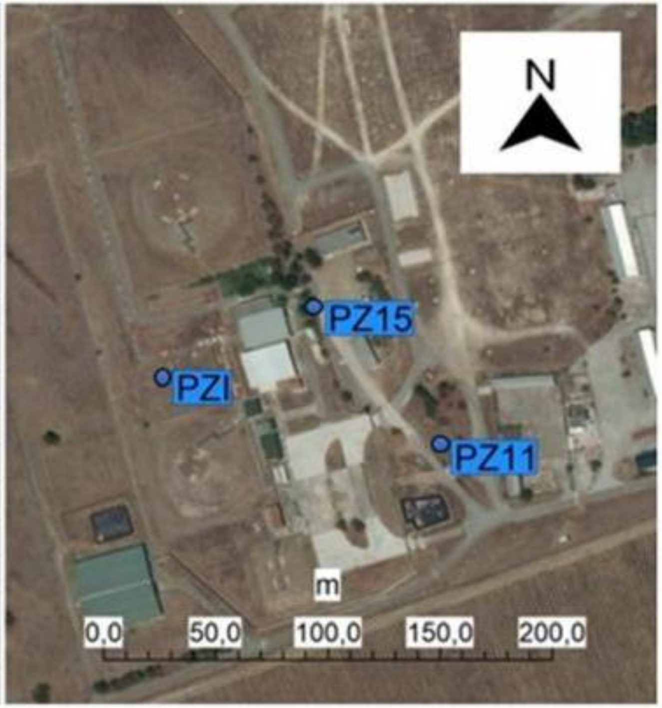
Low resistivity of lithological origin (hazelnut clays)



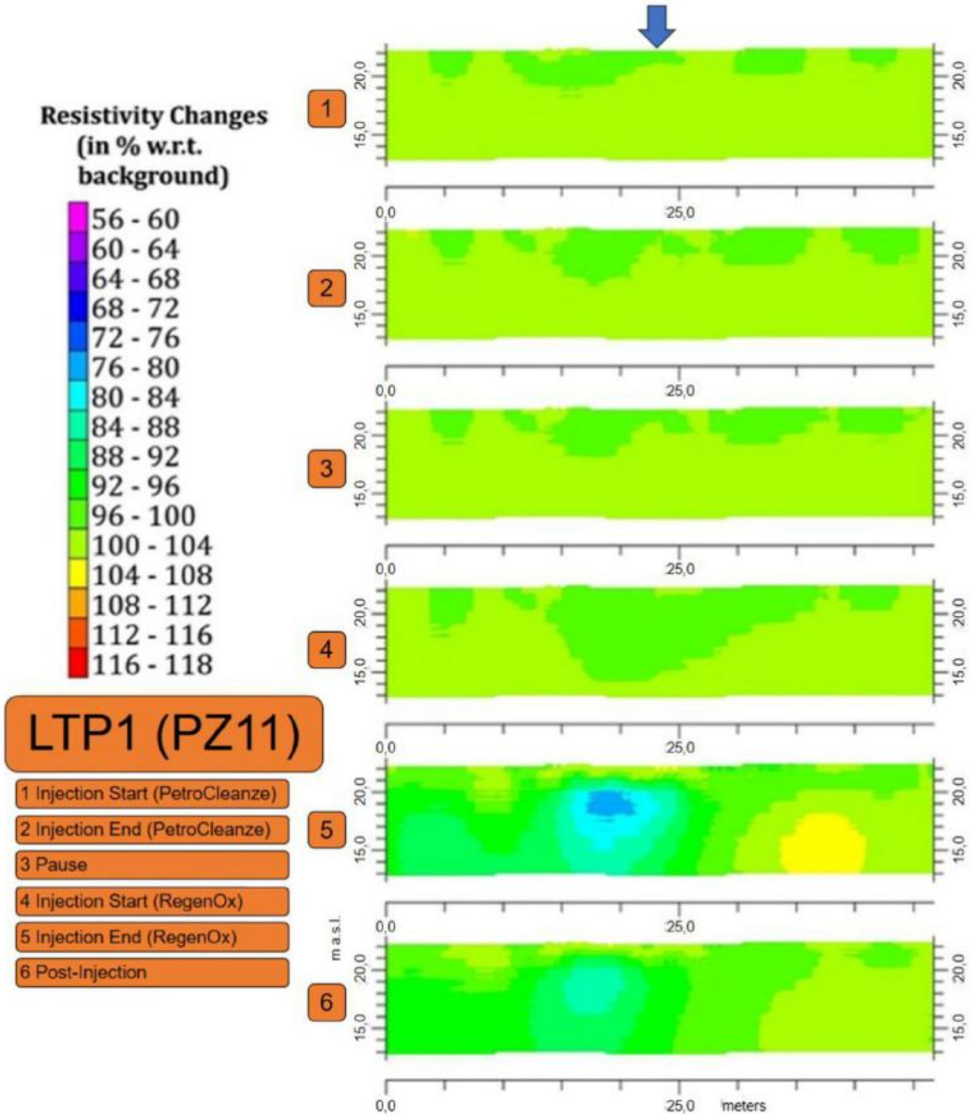
Similar signals can have different origins!

Monitoring of pilot tests for reagent injections

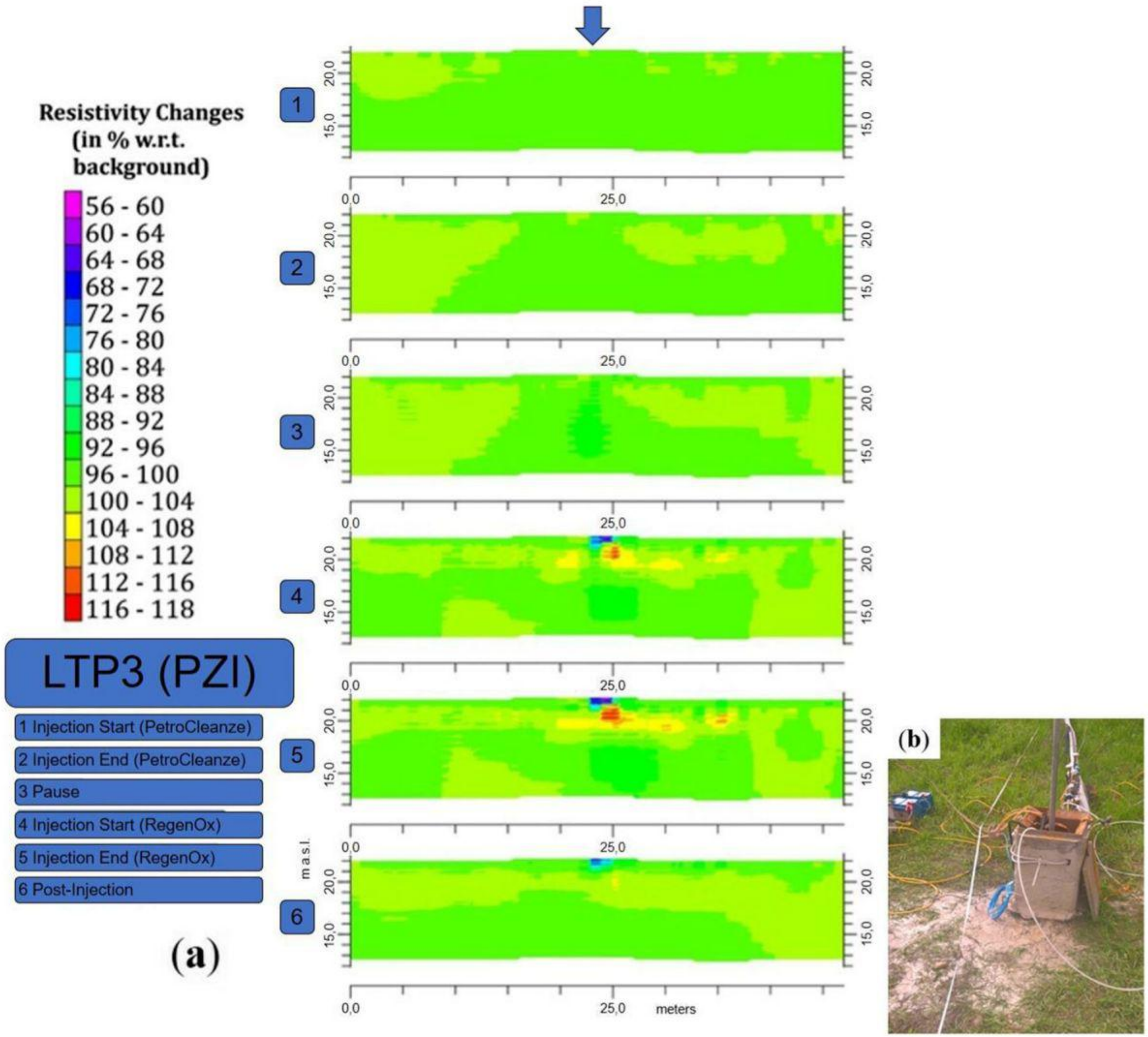
PHASE	DATUM	PZ11	PZ15	PZI
Preliminary activities	Water Depth (m b.g.l.)	5,02	4,72	4,97
	Groundwater pH	6,72	6,73	6,84
Petrocleanze Injection 36 Kg of Petrocleanze 725 L of solution (5% dilution)	Injection Pressure (bar)	0	0	0
	Injection Rate (L/min)	26	21	20
	Injection Time (min)	35	36	40
Wash	Washing Volume (L)	100	100	100
	Injection Pressure (bar)	0	0	0
	Injection Rate (L/min)	26	25	20
	Injection Time (min)	4	4	5
Regenox Injection 36 Kg of Regenox 725 L of solution (5% dilution)	Injection Pressure (bar)	0	0	0
	Injection Rate (L/min)	25	15	11
	Injection Time (min)	45	55	*
Wash	Washing Volume (L)	100	100	100
	Injection Pressure (bar)	0	0	0-0,2*
	Injection Rate (L/min)	25	15	11-6*
	Injection Time (min)	4	7	*
Final activities	Water Depth (m b.g.l.)	2,32	3,53	3,55
	Groundwater pH	10-11	11-12	12



Monitoring of pilot tests for reagent injections



Monitoring of pilot tests for reagent injections



Presence of free phase from fluorescence logs

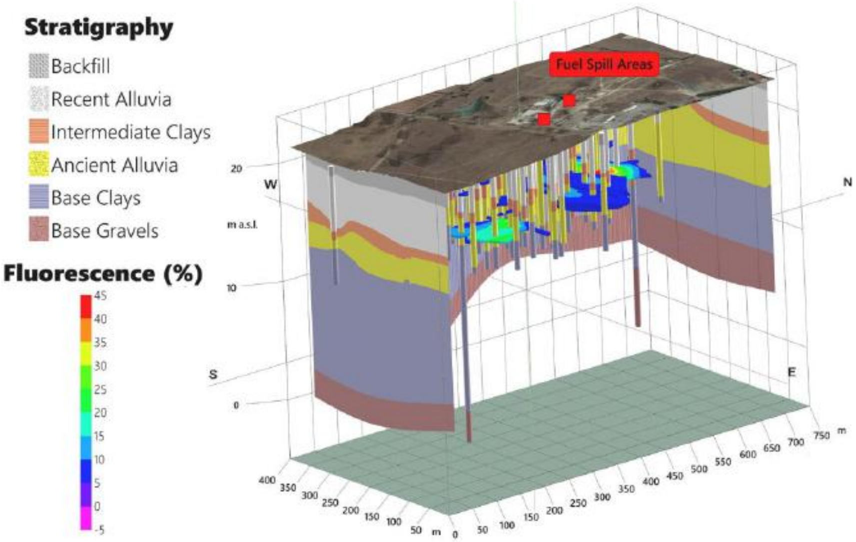


Fig. 11. 3D model of fluorescence measured by LIF-UVOST probes in the geological framework of the site. The executed stratigraphic boreholes are p three-dimensional solid and multi-source picture.

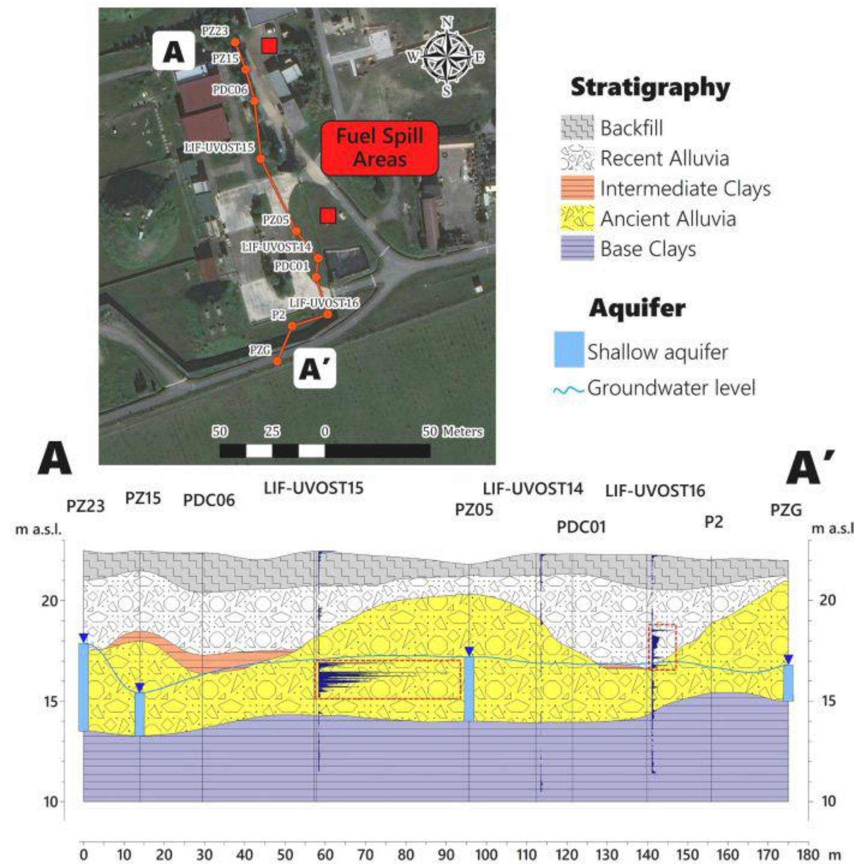


Fig. 12. Stratigraphic section, piezometric level, and fluorescence peaks detected along the track reported in the map.

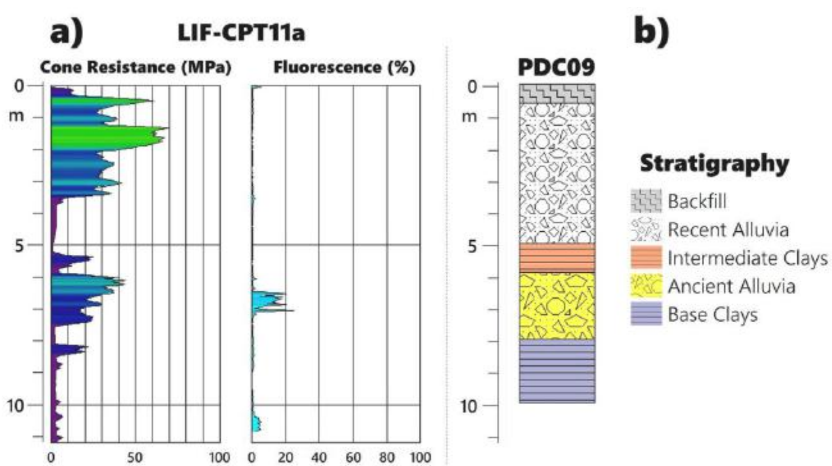


Fig. 9. Resistance to penetration of the cone resulting from CPT and fluorescence signals detected by LIF-UVOST technology along with a vertical profile (a). Adjacent stratigraphic log representing the calibration borehole (b).

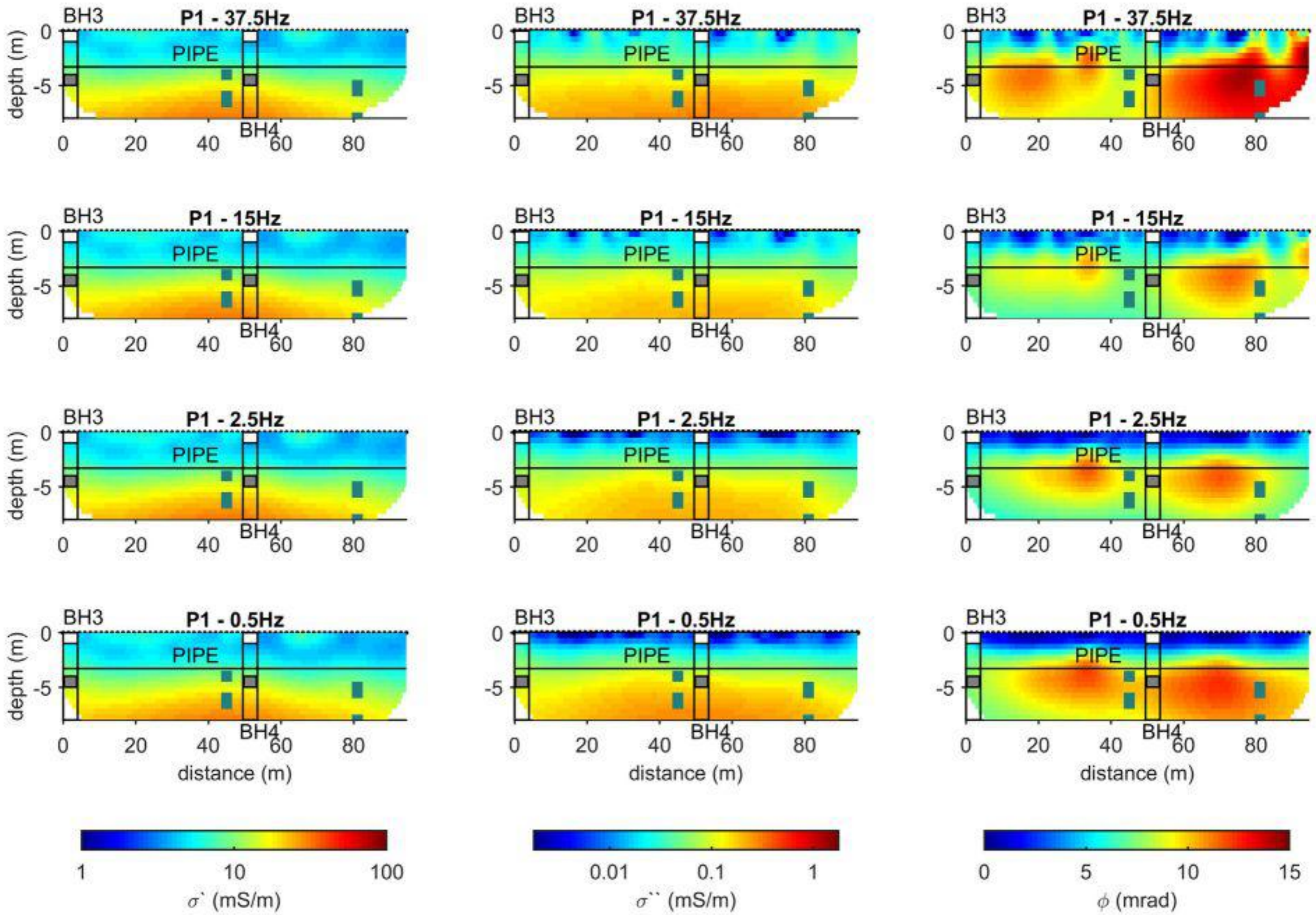
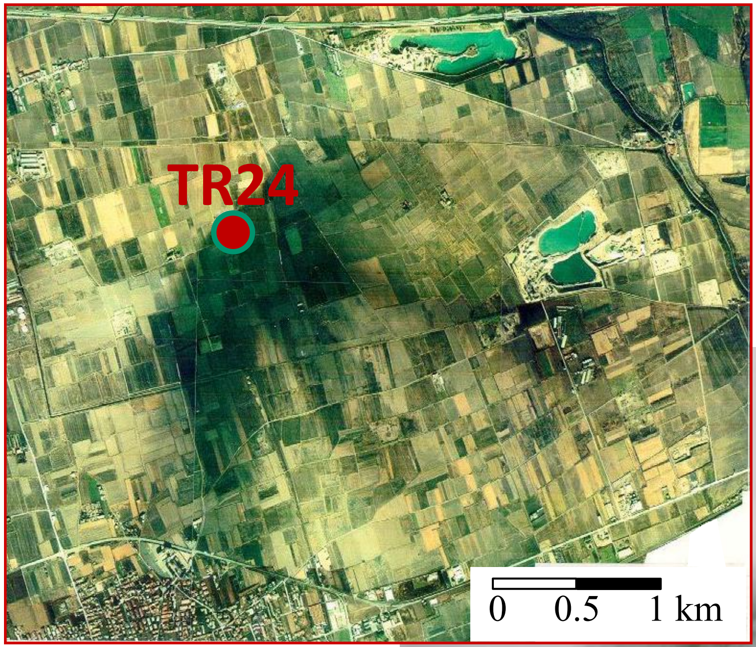


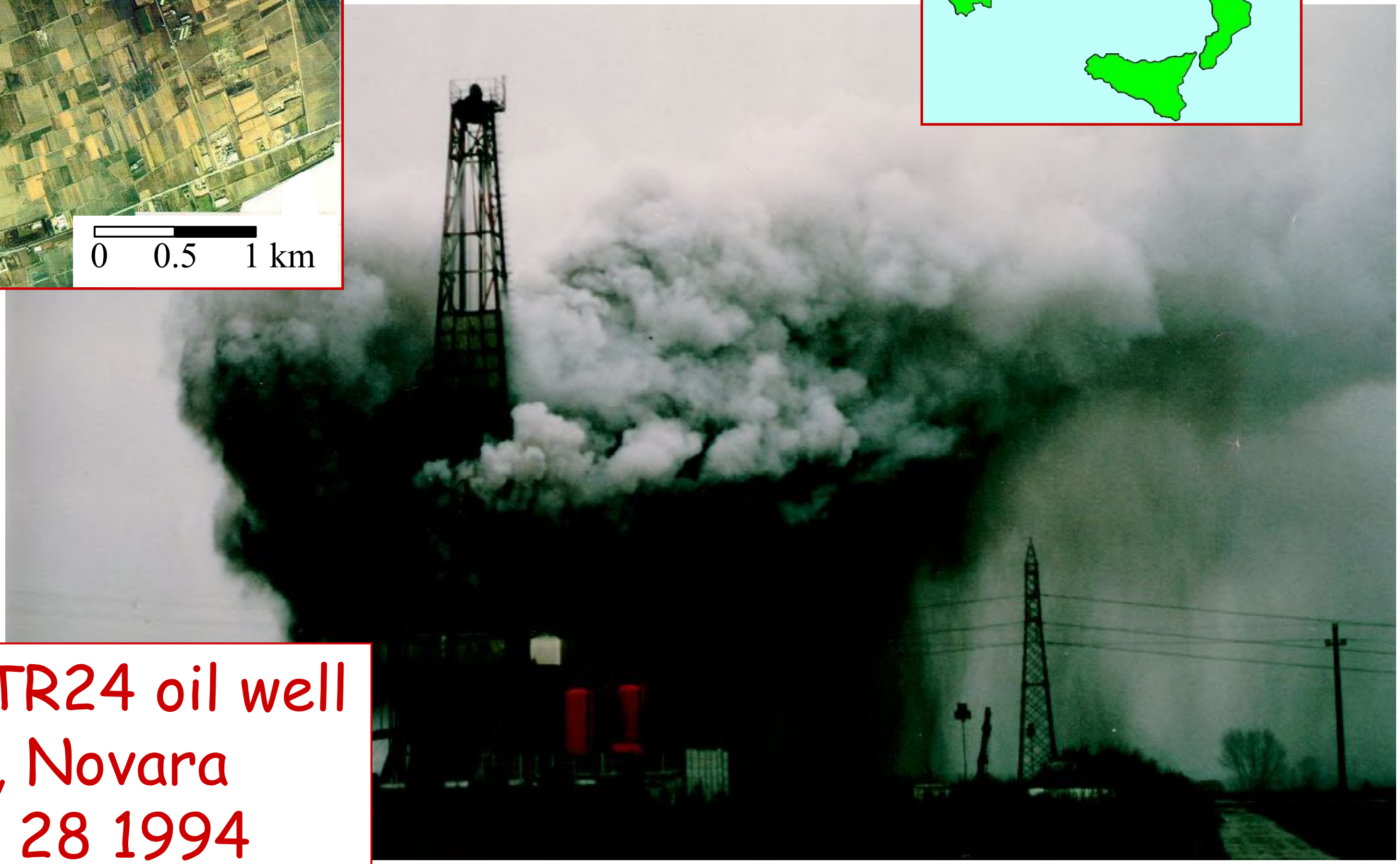
Fig. 3. CCI results for data collected along profile P1 where the presence of LNAPL in free-phase has been reported by means of LIF logging (indicated by the blue rectangles at ca. 45 and 80 m of the profile distance). The CCI are presented in terms of the real, imaginary and phase of the complex conductivity. The dots at the surface show the position of the electrodes, while the continuous horizontal line at 3.3 m depth indicates the position of the groundwater table during our measurements. Lithological information obtained from boreholes BH6 and BH7 is imposed on the electrical model, with the boxes, indicating: the backfill materials on the top (white), the recent alluvial (no color), the Hazelnut clays (gray) and the ancient alluvial sediments (no color).

Outline

- Geophysics for contaminated sites
- Pathways: The Ferrara case
- The Decimomannu case
- **The Trecate case**
- Monitoring remediation: the Bologna case
- Conclusions and outlook

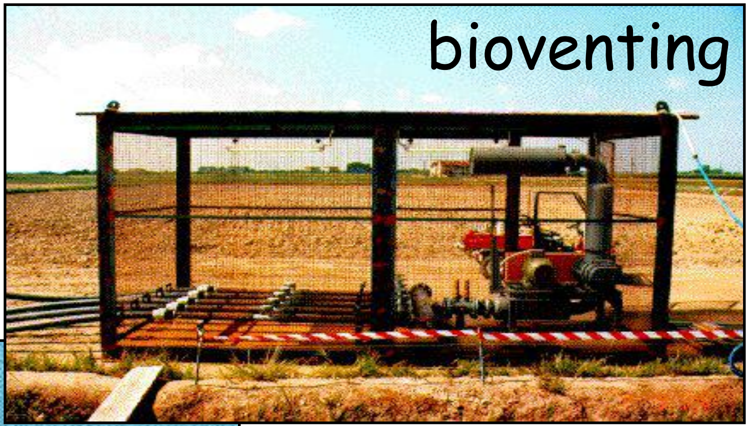

Trecate, NW Italy
February 28 1994



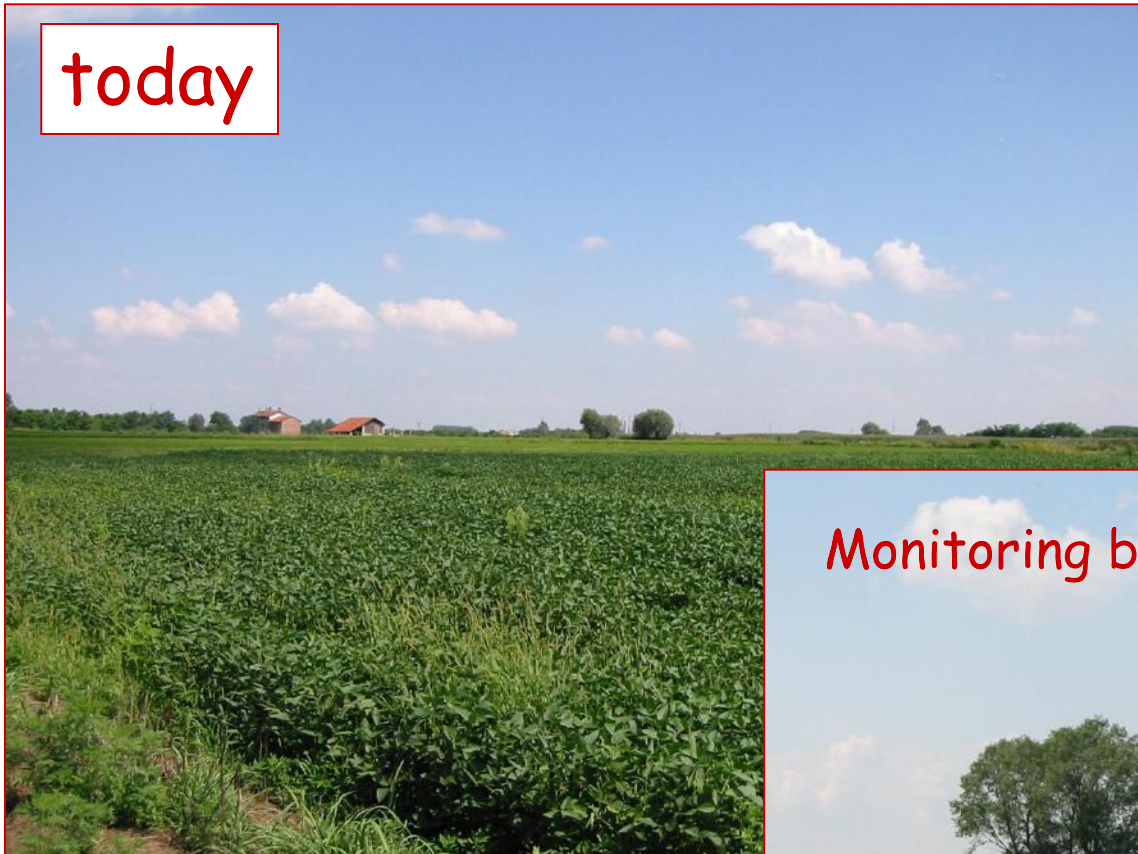


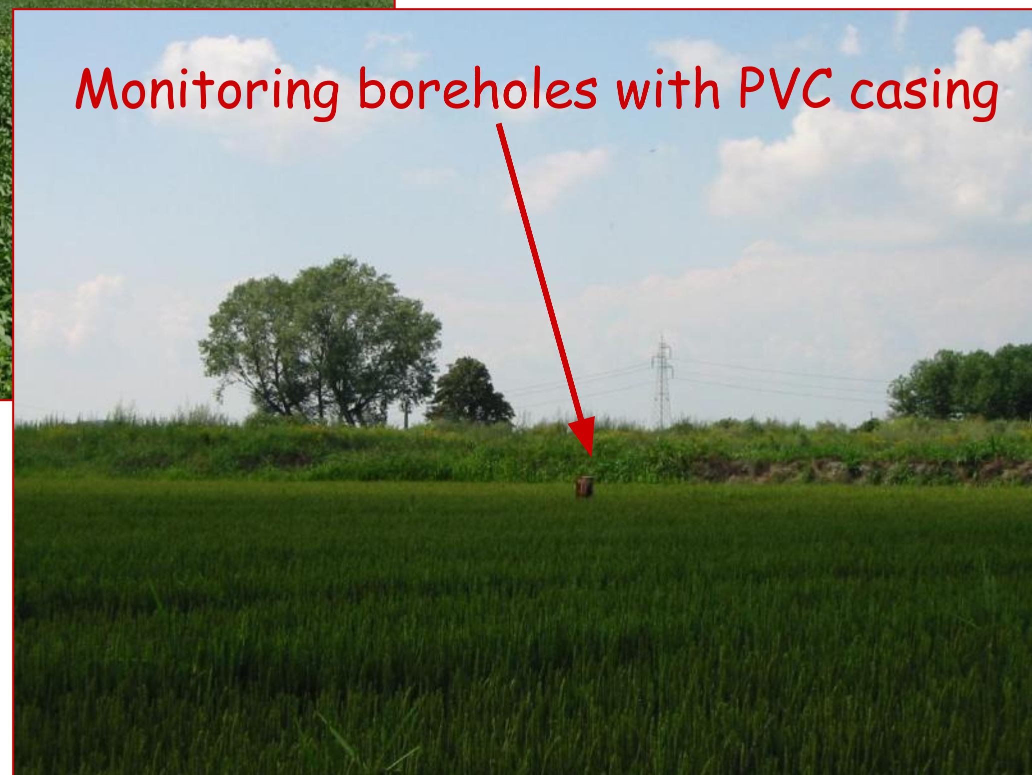
Blow out of TR24 oil well
Trecate, Novara
February 28 1994

Remediation




today

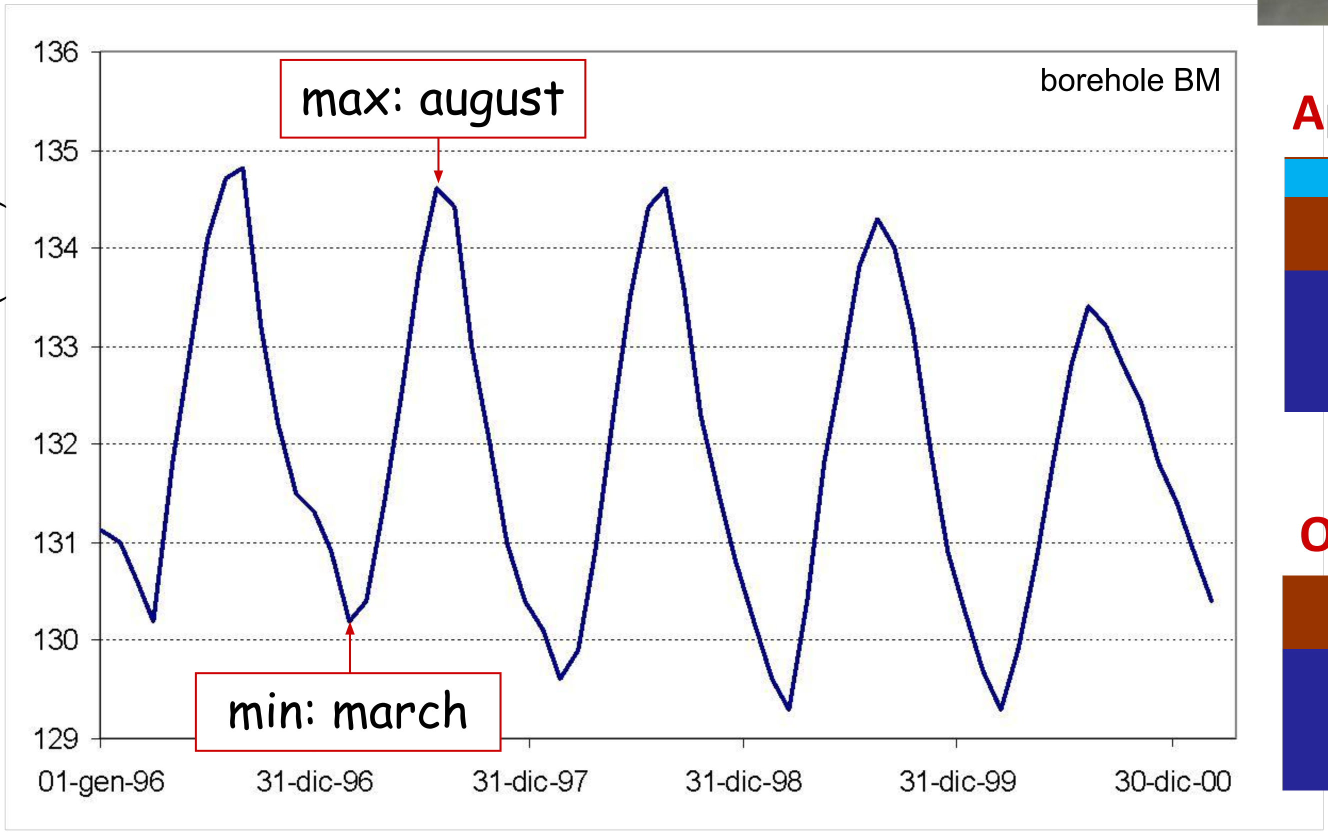


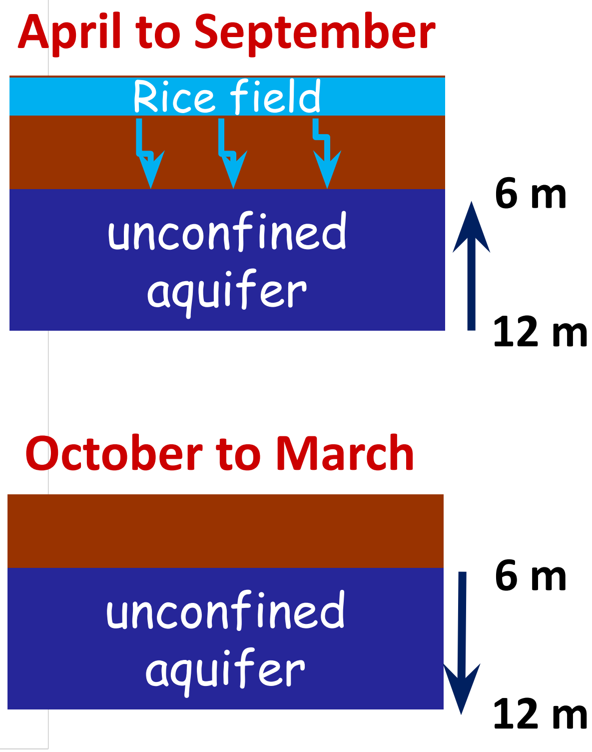


Rice, soy and corn fields

Water table oscillations

Caused by extensive rice field irrigation.
The water table rises and falls at a rate of about 1 m/month.

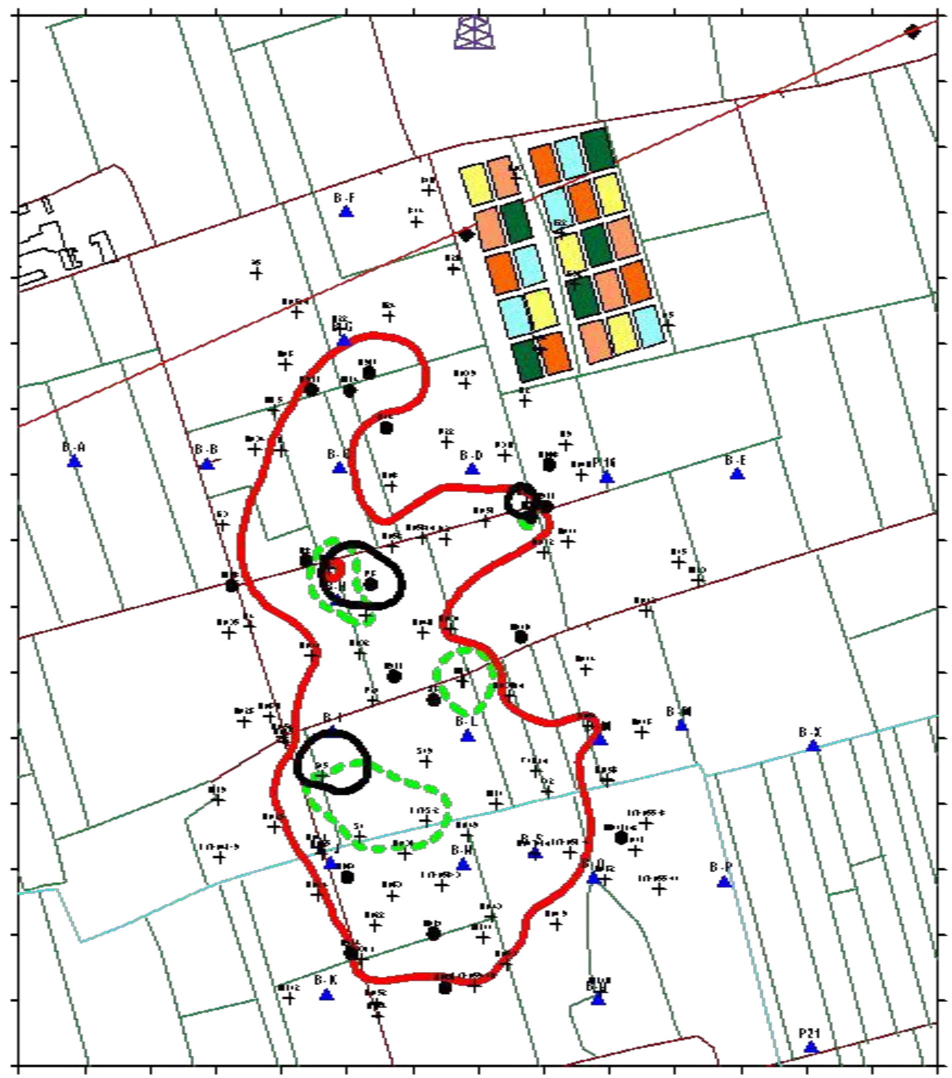




The subsoil is made of silty and sandy gravel (fluvio-glacial deposits)

Oil contamination in the Trecate subsoil

(from Geoprobe samples)

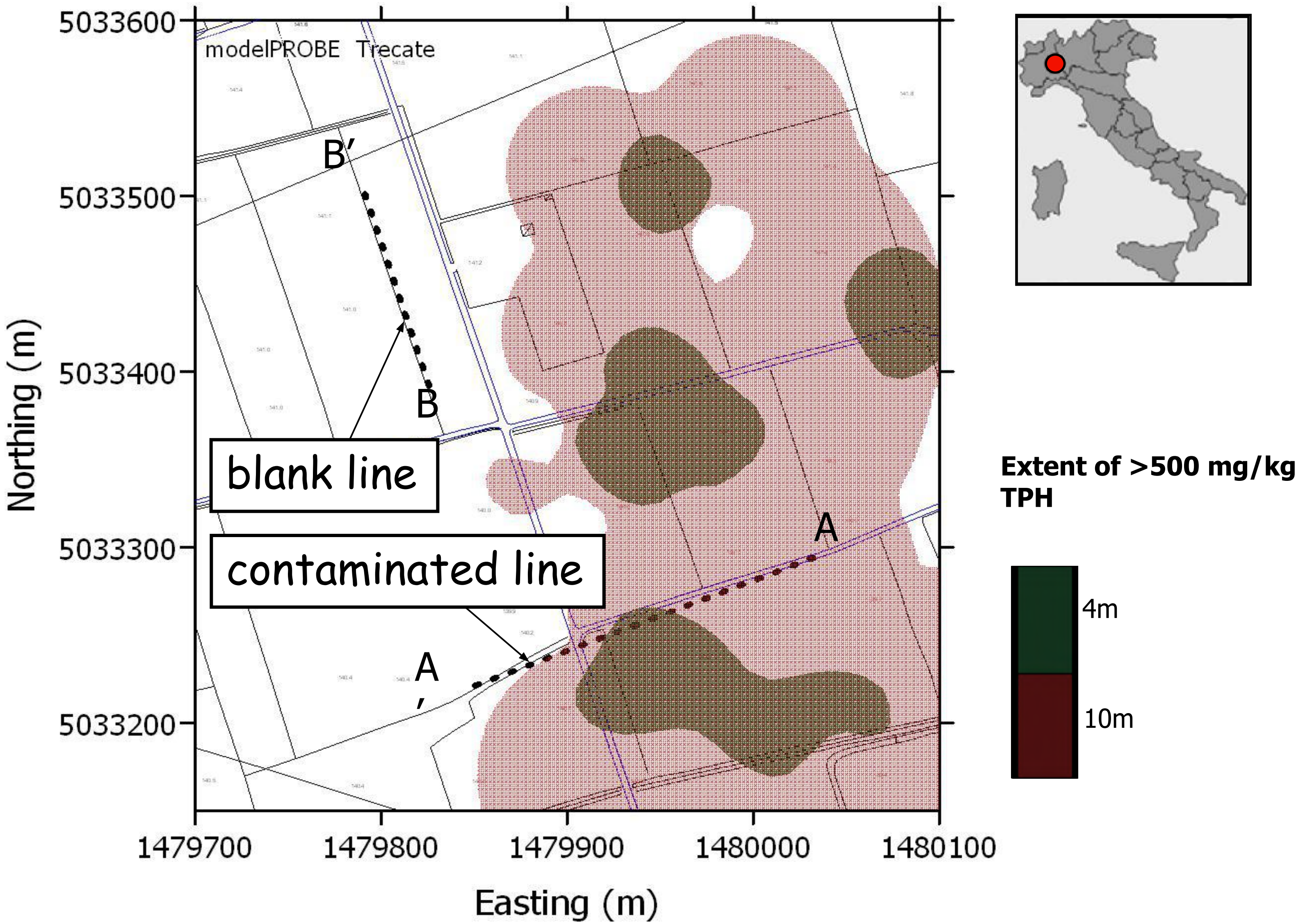


Extent of >500 mg/kg TPH 4 m 6 m 10 m

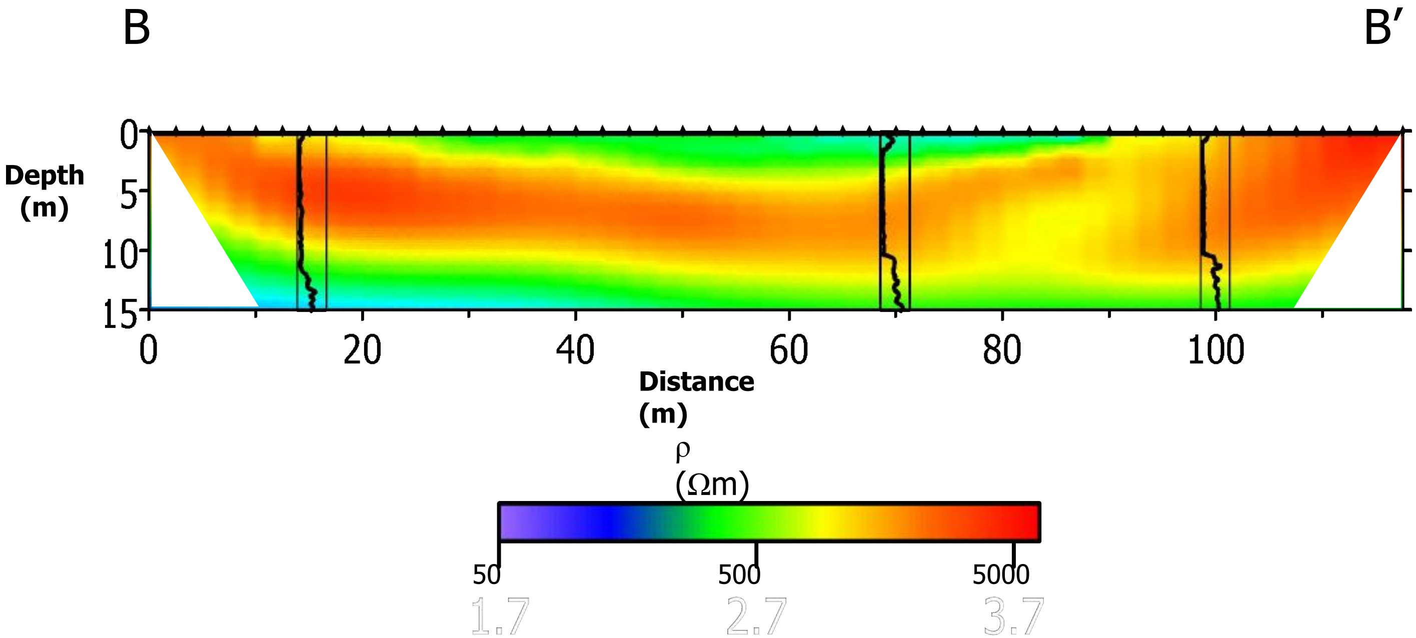
Outline

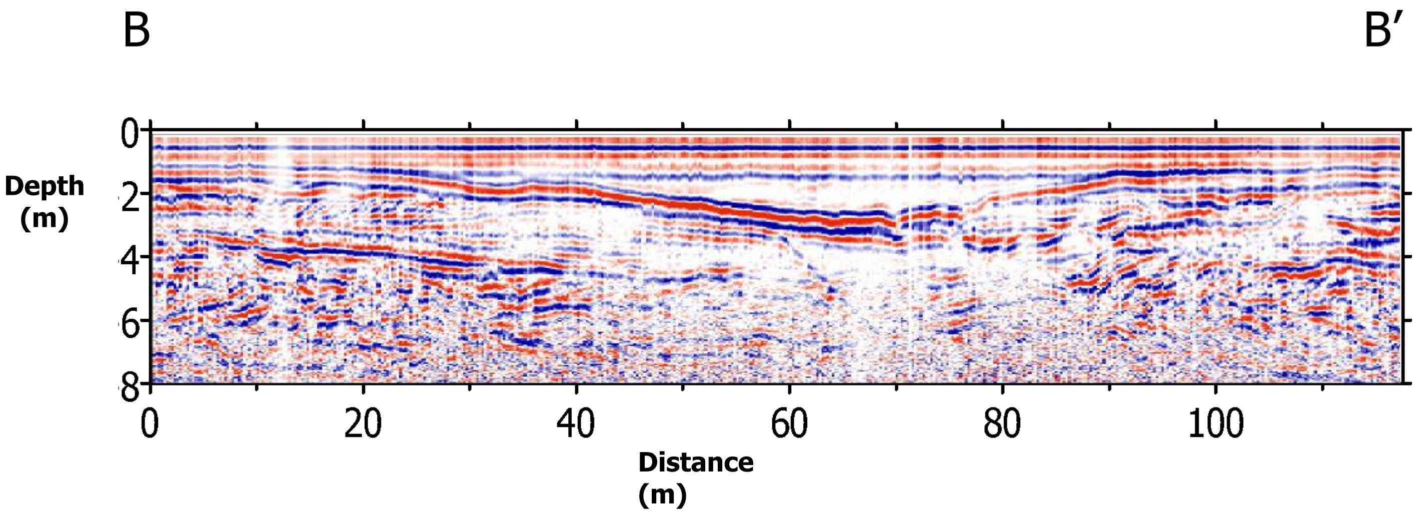
- ❑ Geophysical detection of contaminants
- ❑ The Trecate case
- ❑ **Geophysics at the Trecate site: structure**
- ❑ Geophysics at the Trecate site: contamination
- ❑ Conclusions and outlook

Residual soil contamination

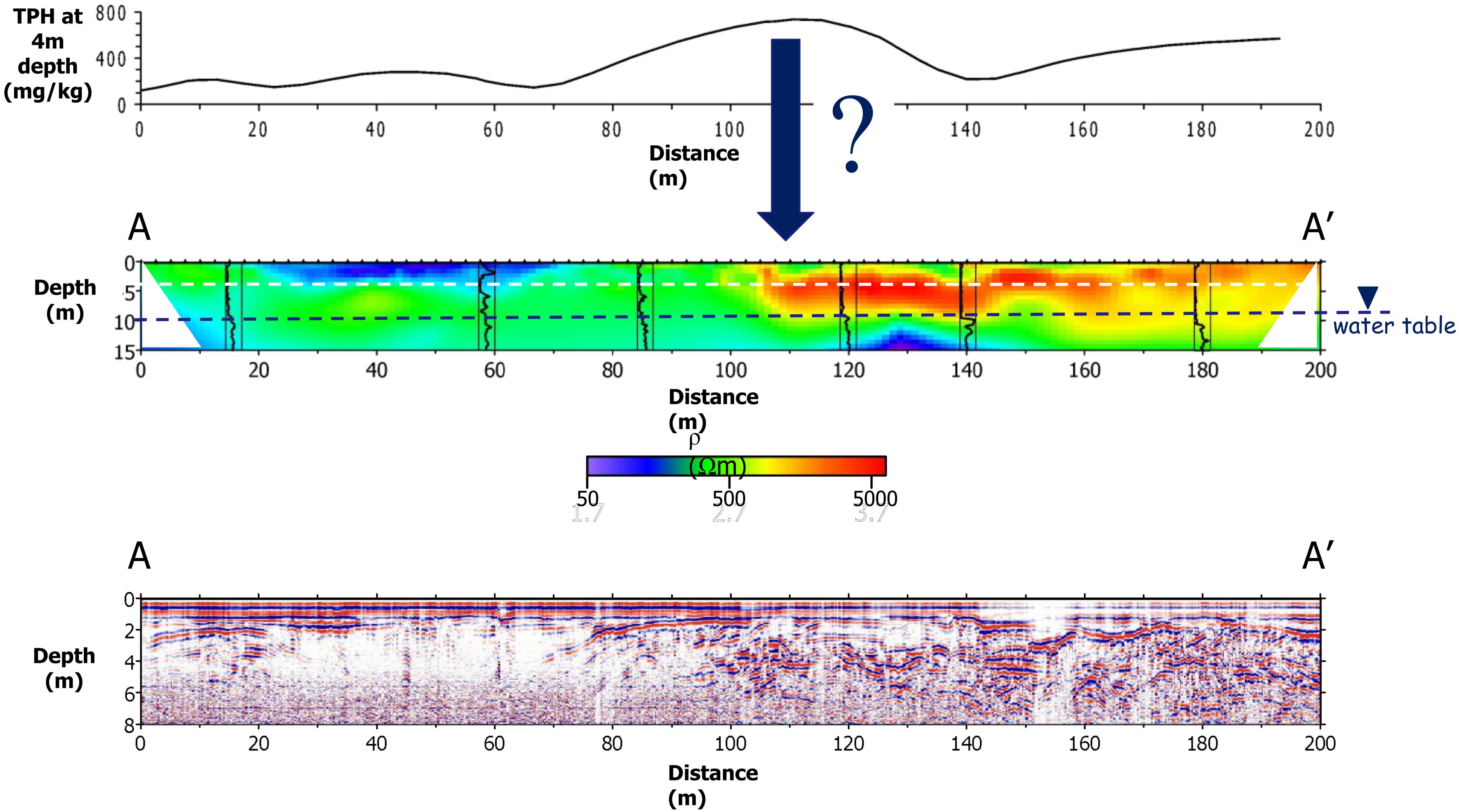


ERT and GPR on blank line B

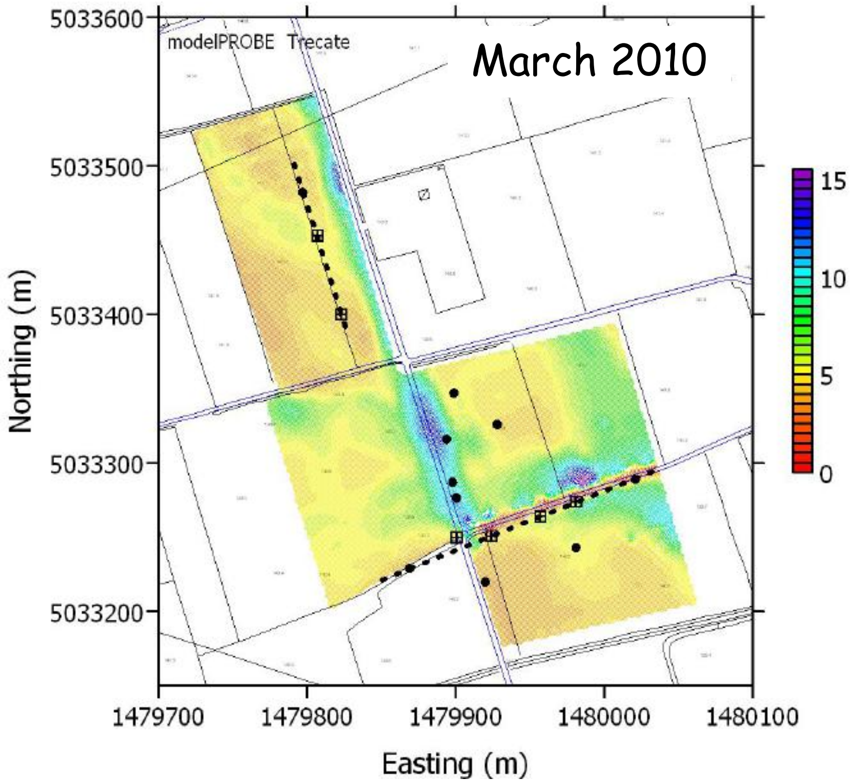


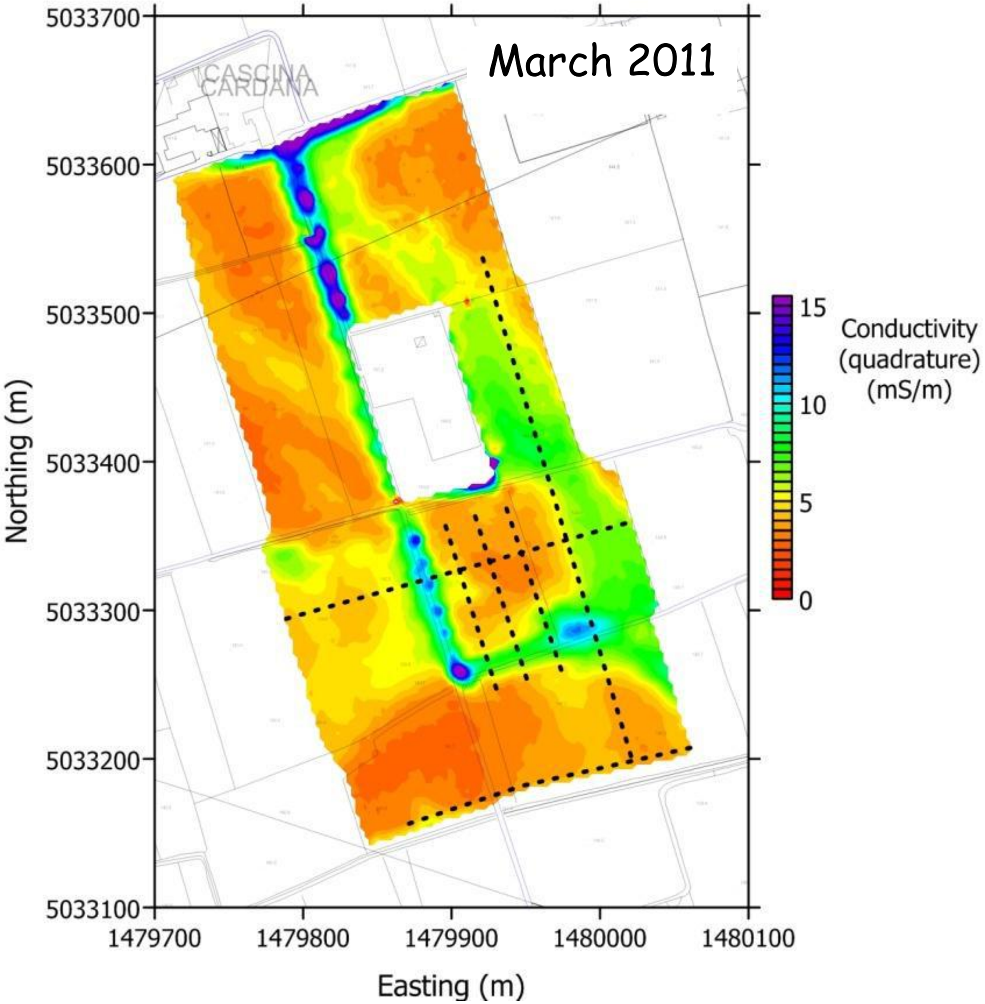


ERT and GPR on contaminated line A

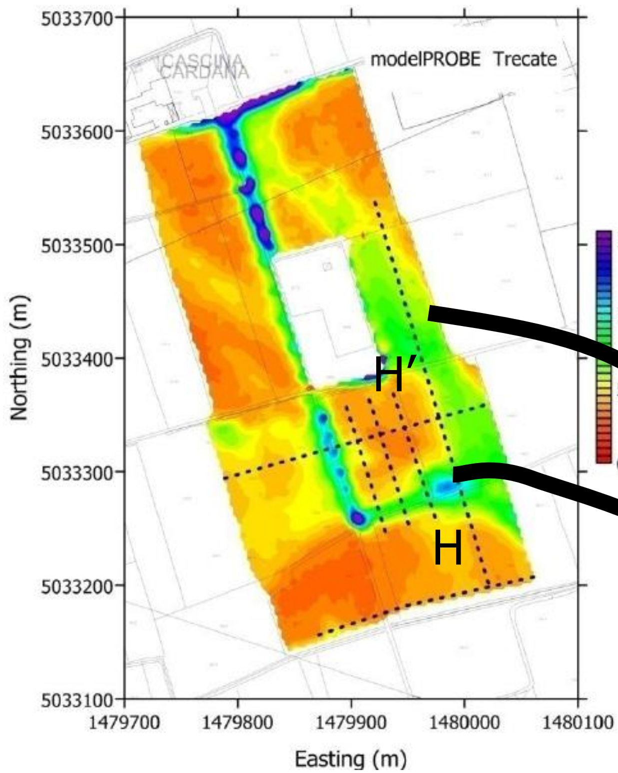


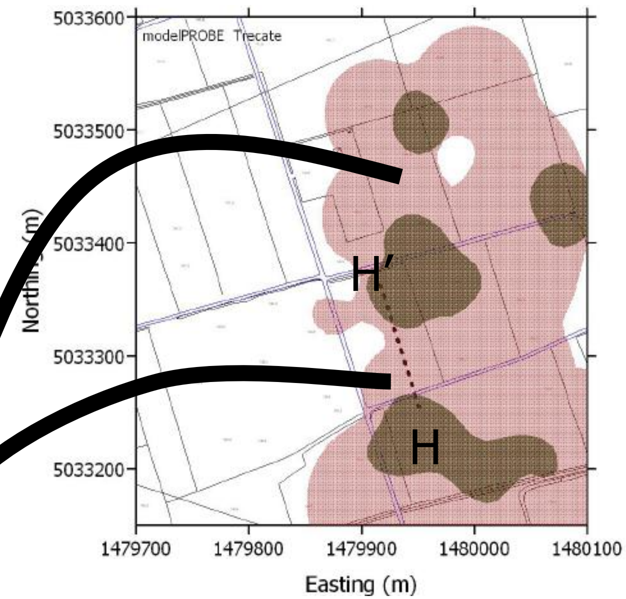
FDEM electrical conductivity maps (6 m depth)



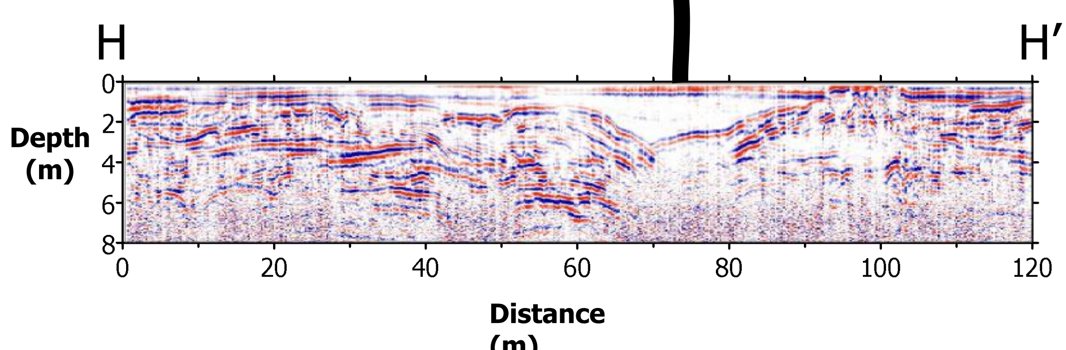


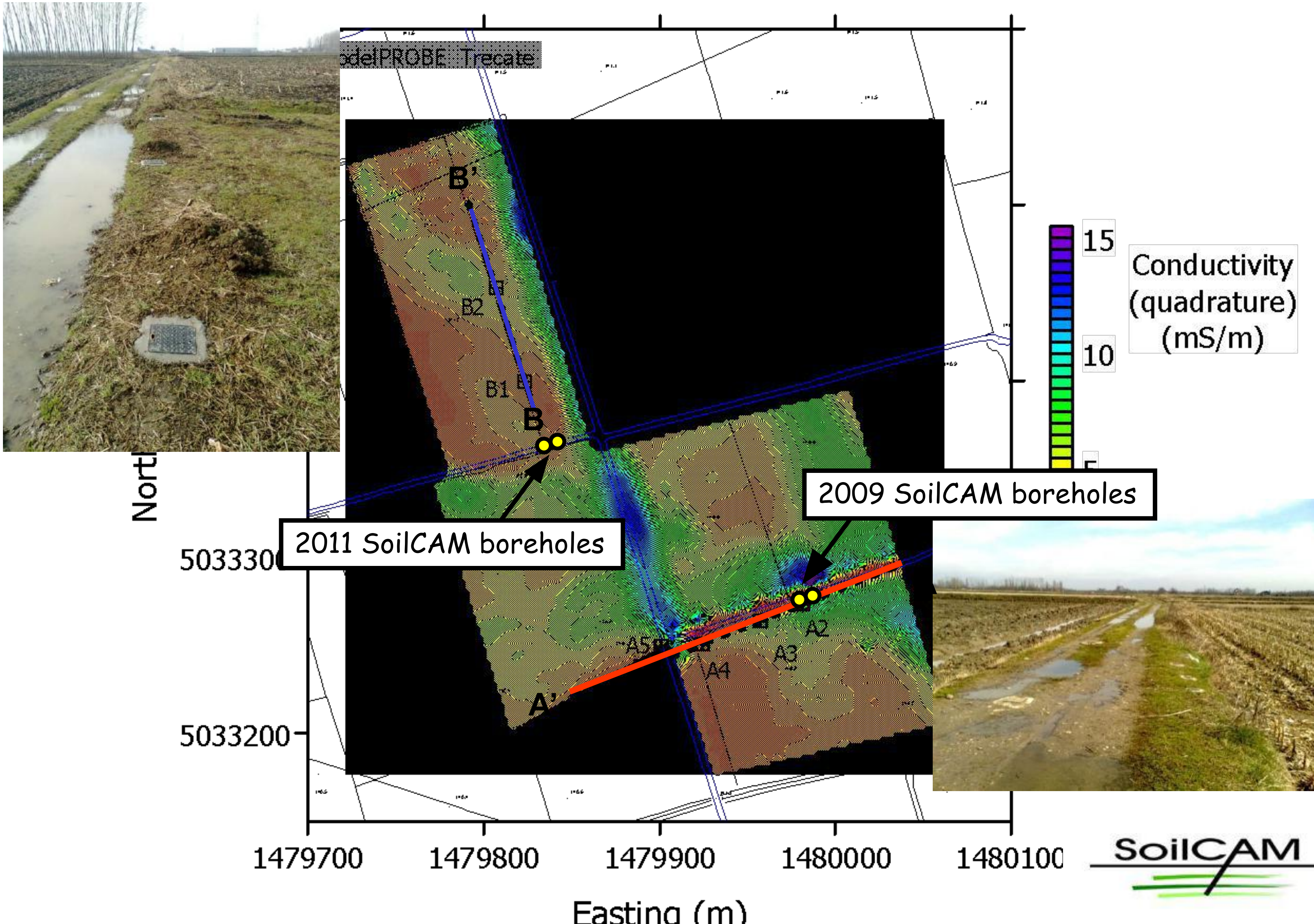
Structural control on contamination





High conductivity (low permeability?) channels acting as barriers for oil vertical migration

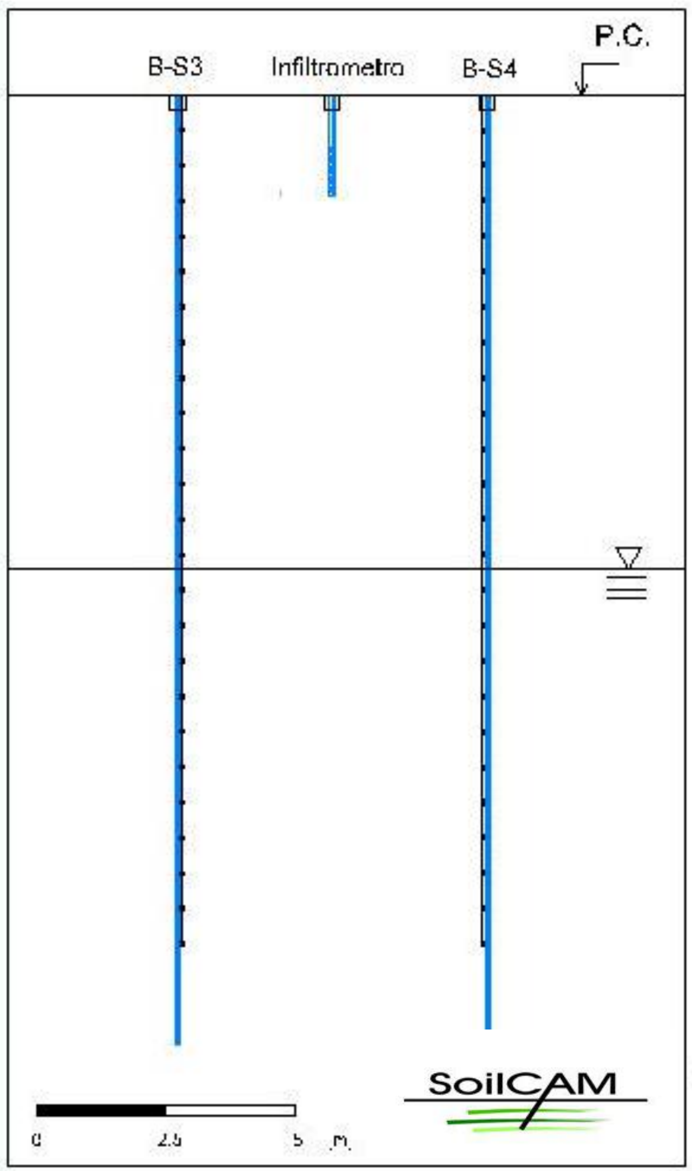


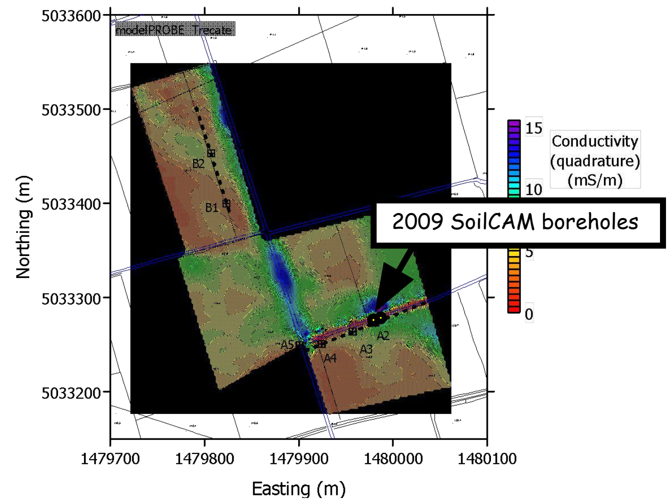

delPROBE Trecate
B'
B2
B1
B
2011 SoilCAM boreholes
2009 SoilCAM boreholes
A5
A4
A3
A2
A'
15
10
5
Conductivity (quadrature) (mS/m)
North
5033300
5033200
1479700
1479800
1479900
1480000
1480100
Easting (m)

SoilCAM

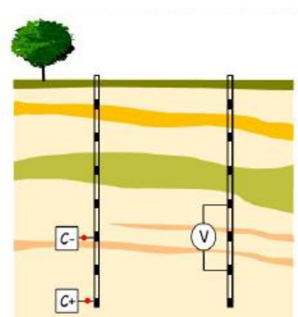
Boreholes permanently equipped with electrodes for ERT,

Used also for cross-hole GPR

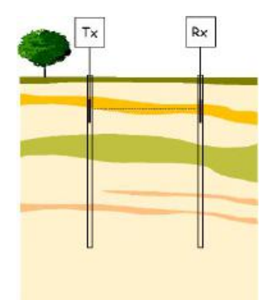




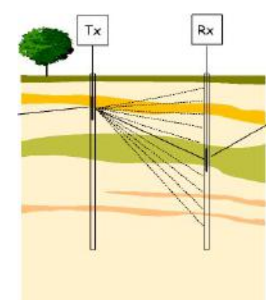
ERT



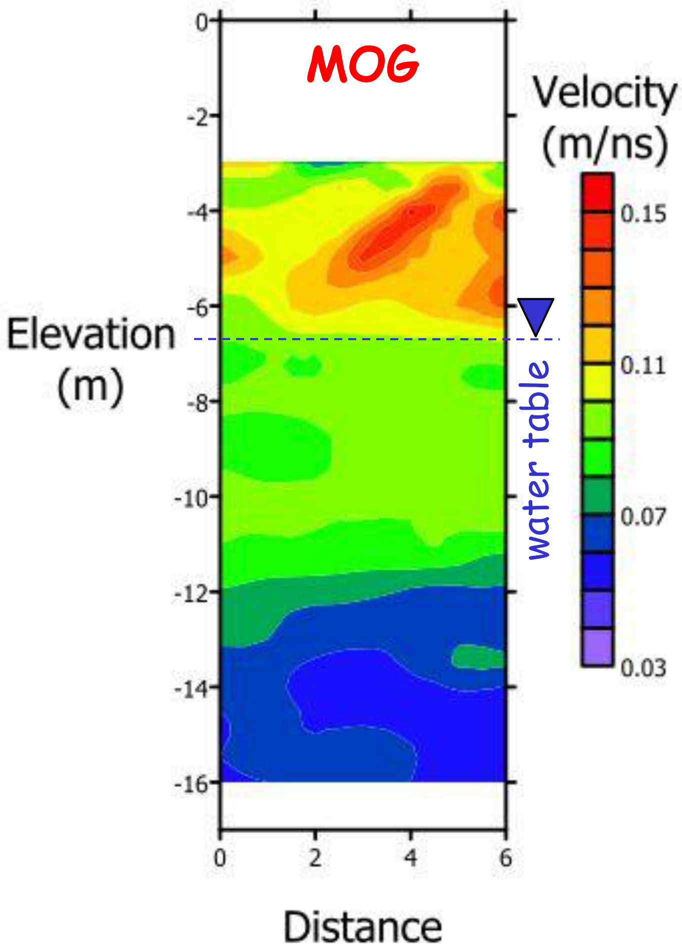
ZOP GPR

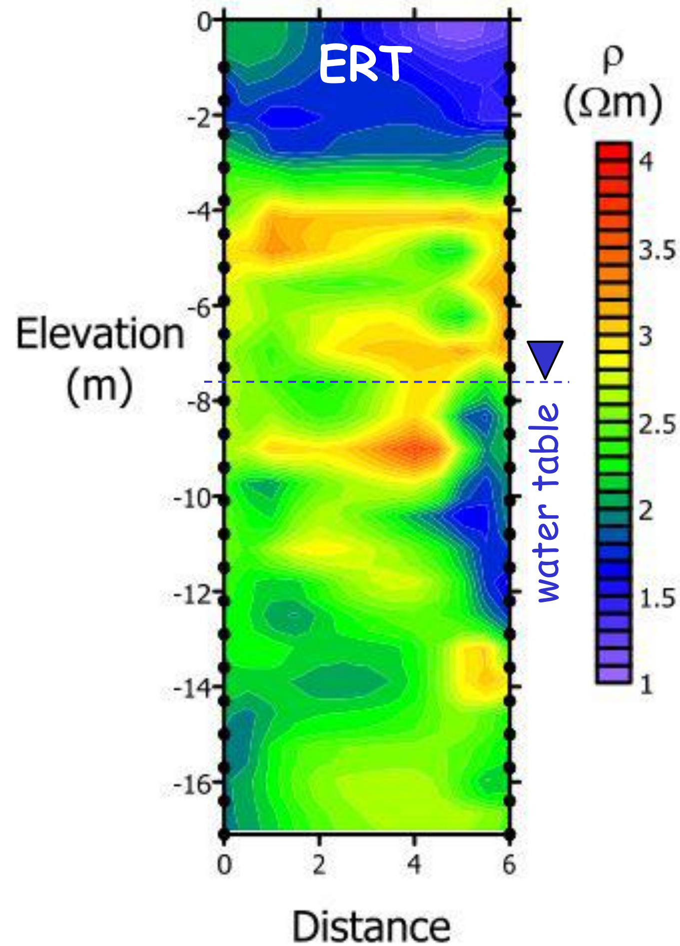


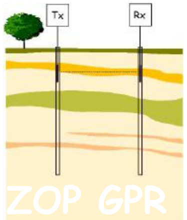
MOG GPR



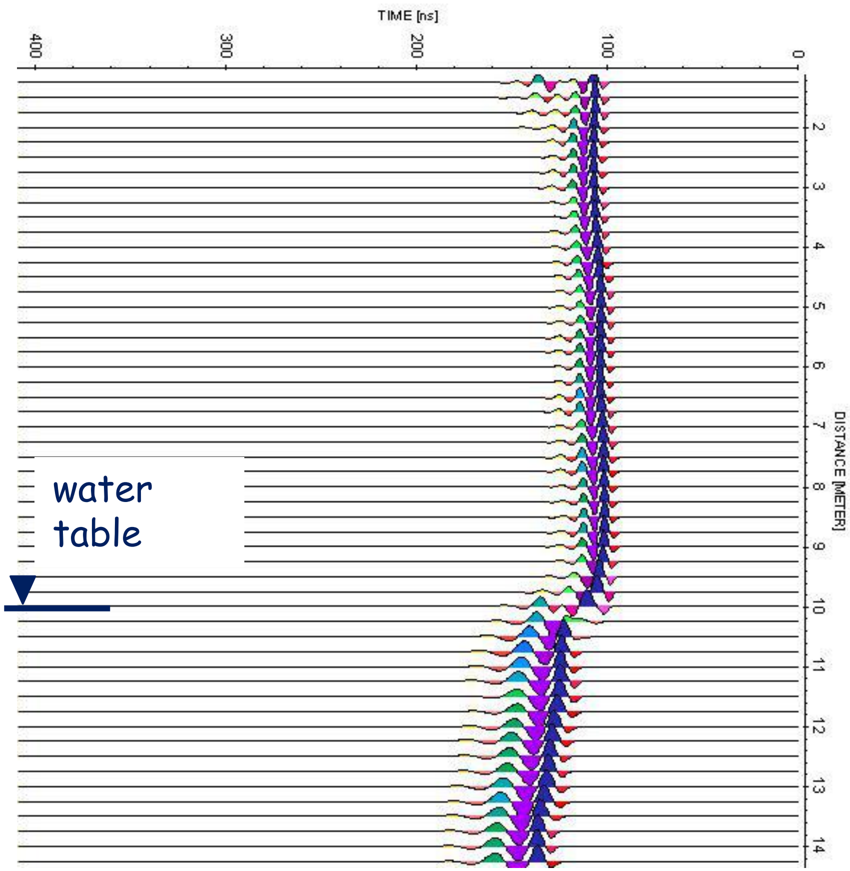
2009 Soilcam boreholes
Cross borehole radar (Sep 2009) and ERT (June 2009)



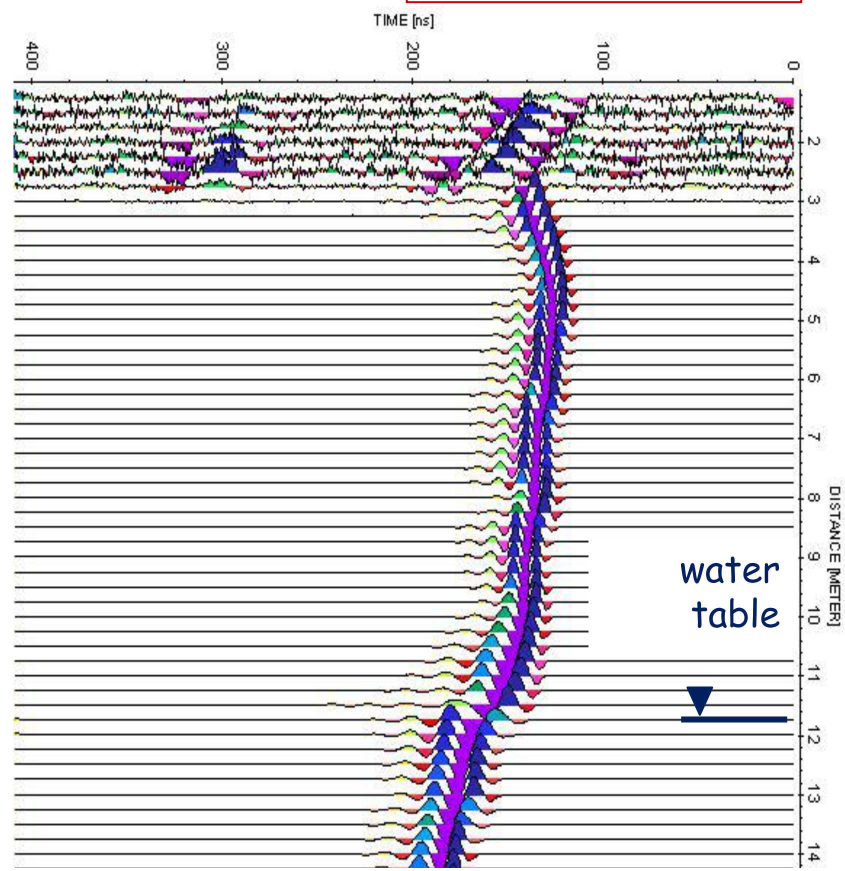




2011 Soilcam boreholes (uncontaminated)



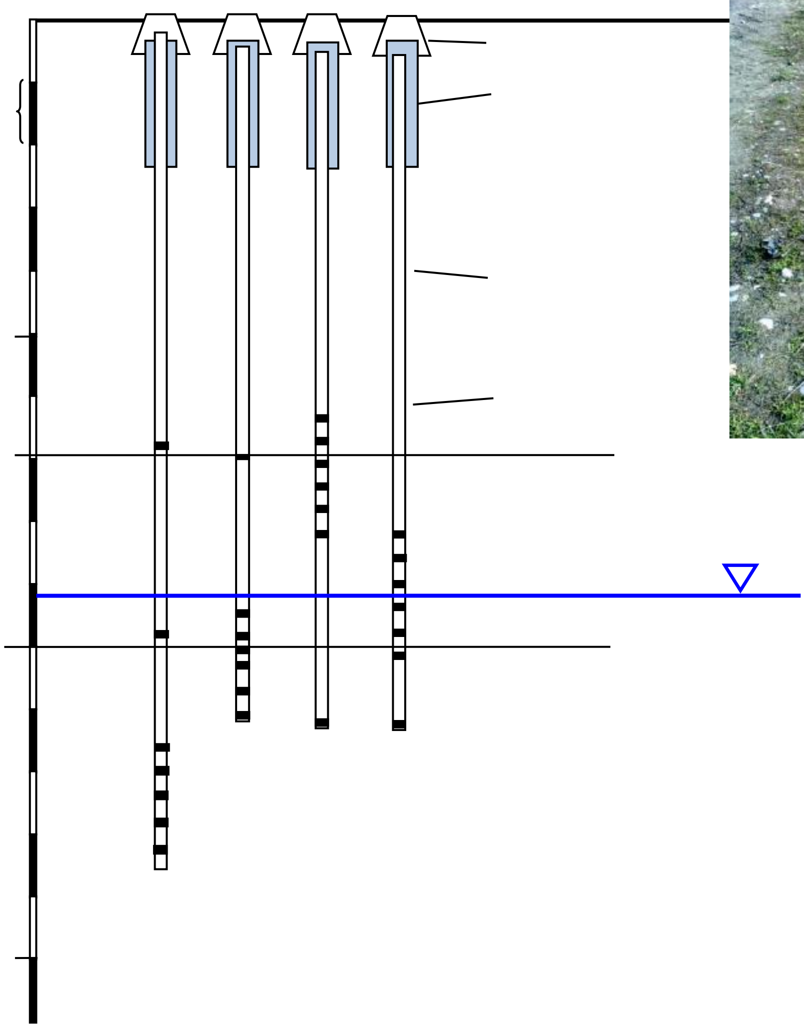
2009 Soilcam boreholes (contaminated)

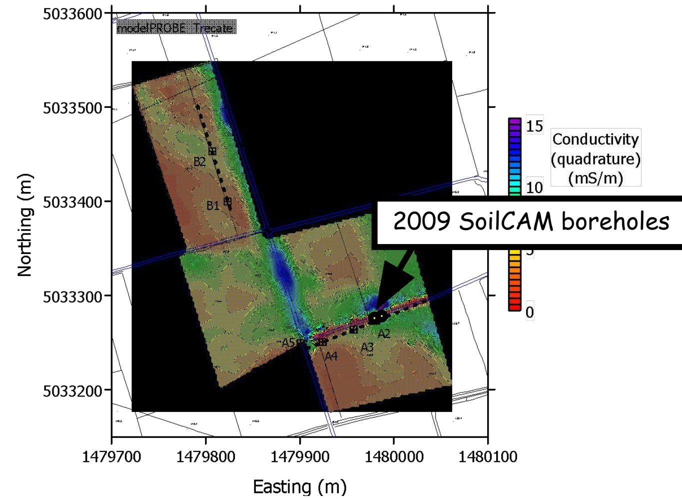


MARCH 2011

SoilCAM multilevel samplers

(Markus Wehrer - Univ of Jena)





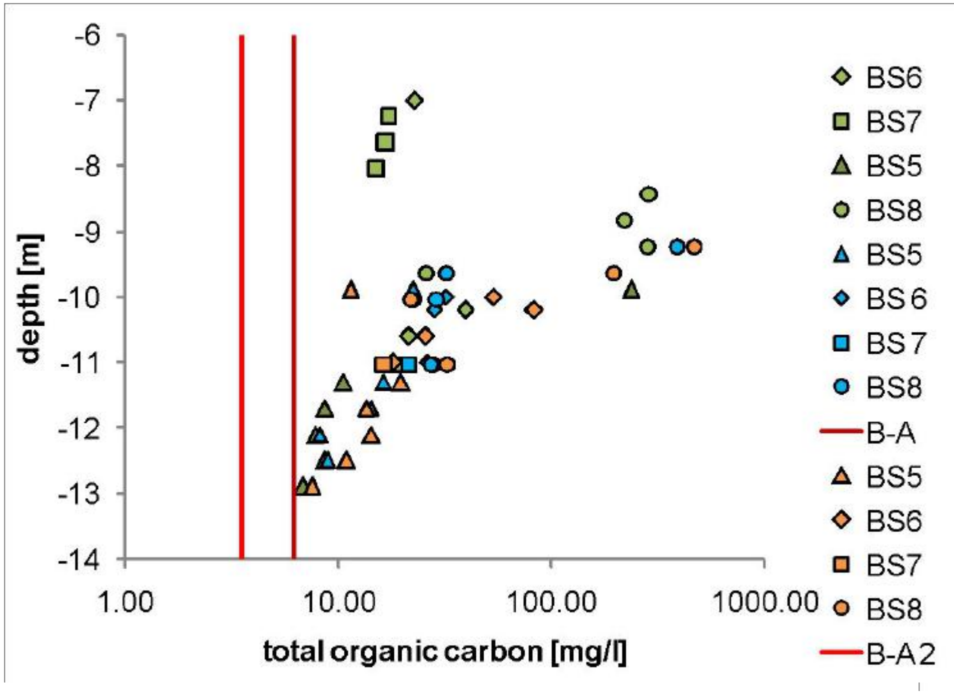
SoilCAM

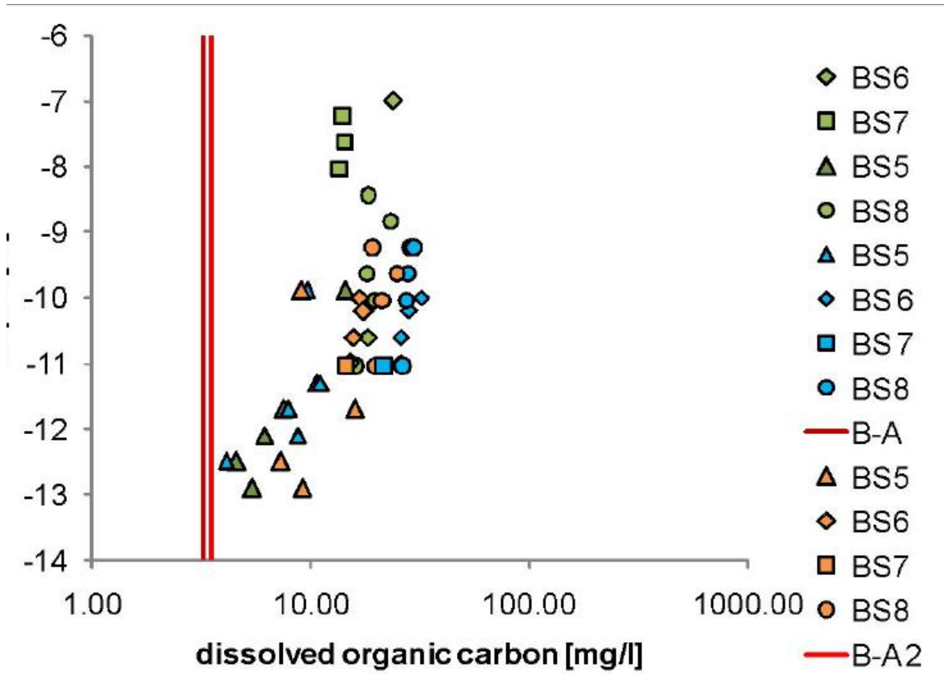
SoilCAM multilevel samplers

Green 1st campaign: 30.08.-04.09.2010: water table ≈ - 6.5 m bgl

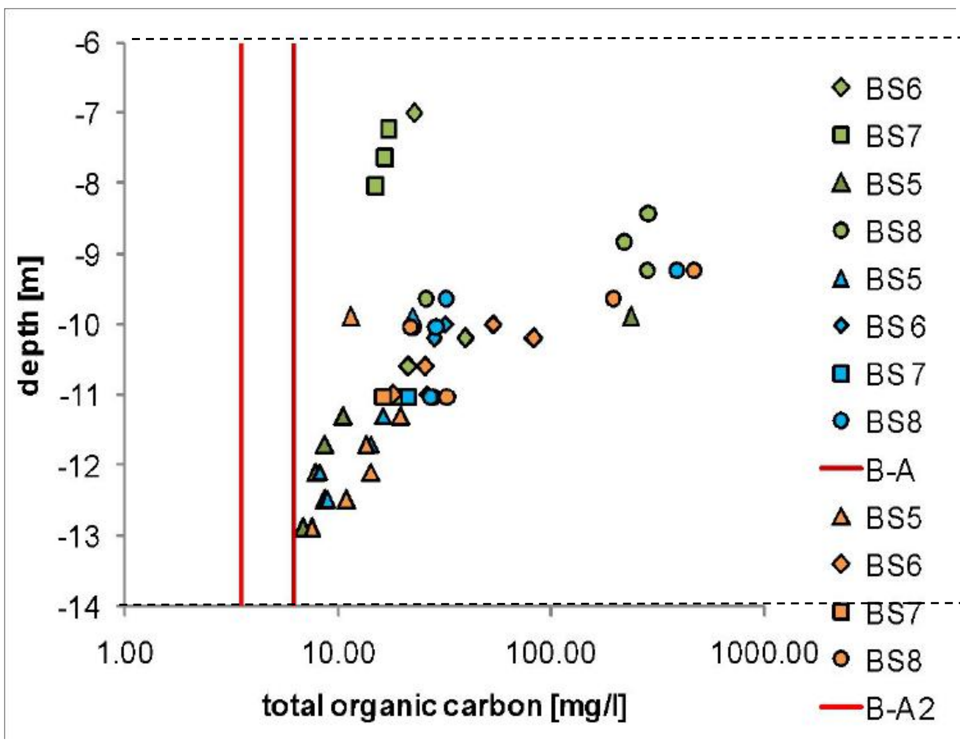
Blue 2nd campaign: 11.10-15.10.2010: water table ≈ - 8.5 m bgl

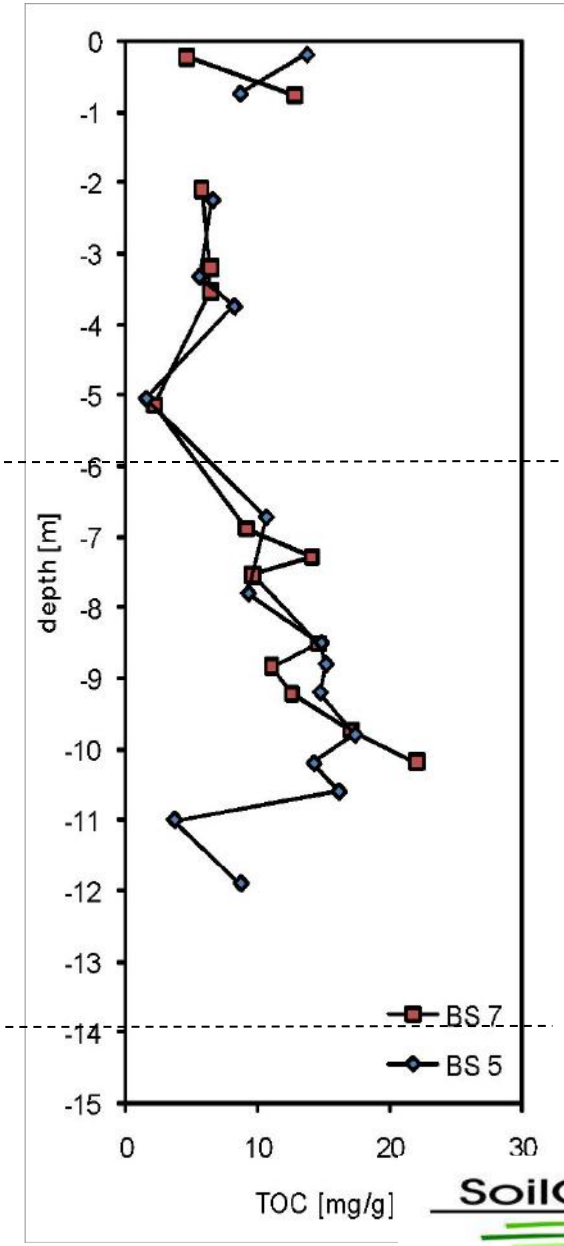
Yellow: 3rd campaign: 10.05.-12.05.2011: water table ≈ - 8.5 m bgl

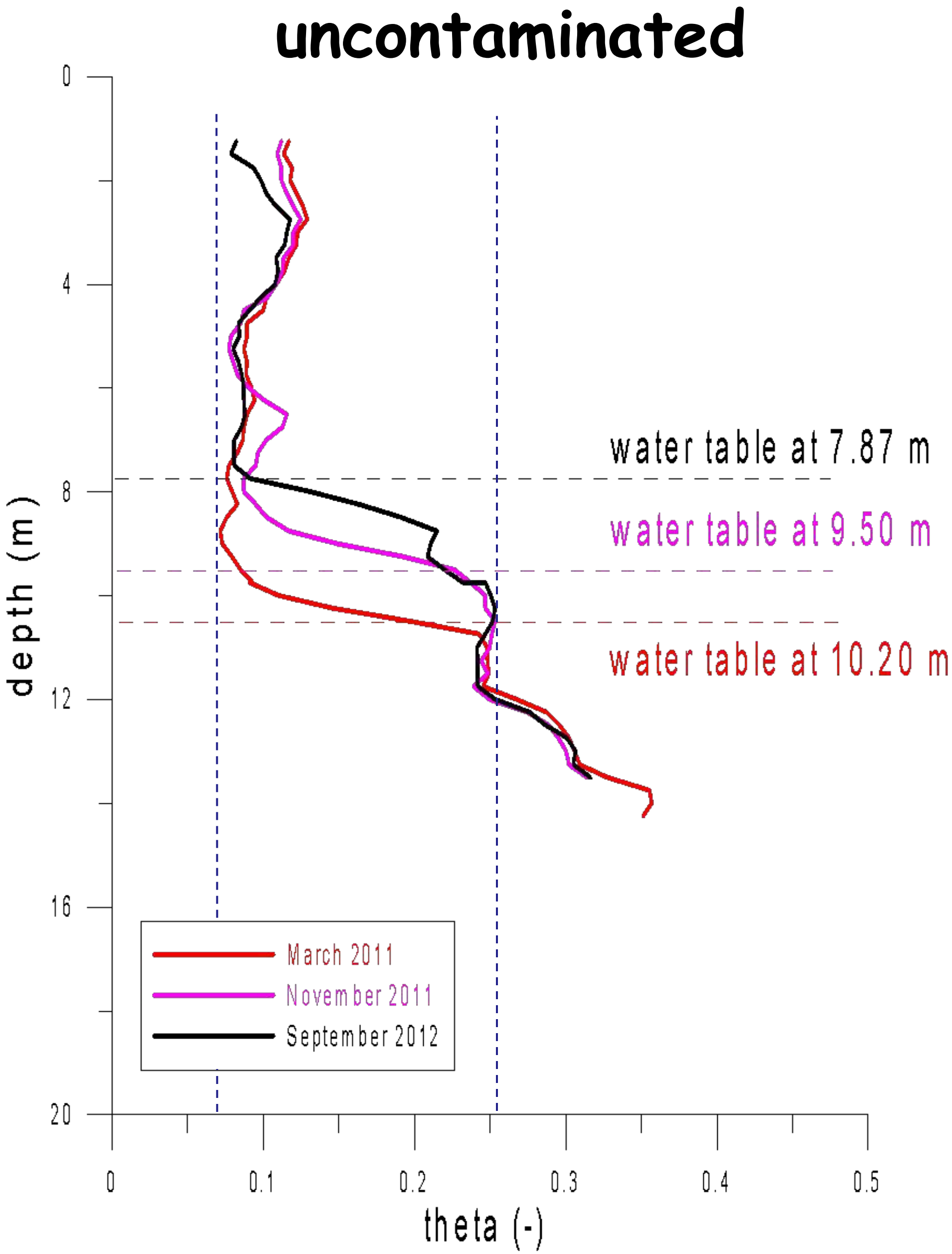


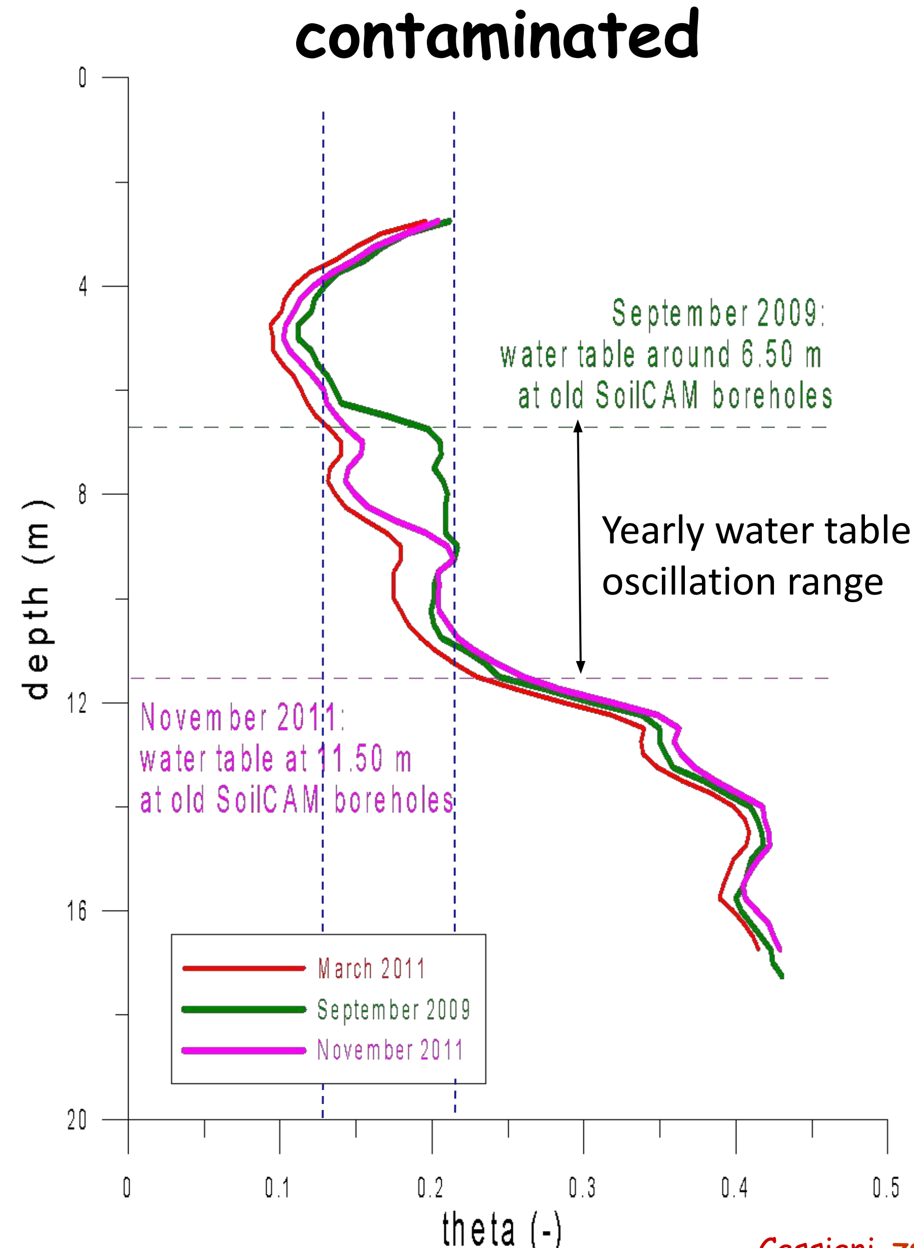


SoilCAM multilevel samplers
vs
concentration in soil (liners)






uncontaminated
depth (m)
theta (-)
0
4
8
12
16
20
0
0.1
0.2
0.3
0.4
0.5
water table at 7.87 m
water table at 9.50 m
water table at 10.20 m
March 2011
November 2011
September 2012


contaminated
depth (m)
theta (-)
0
4
8
12
16
20
0
0.1
0.2
0.3
0.4
0.5
September 2009:
water table around 6.50 m
at old SoilCAM boreholes
Yearly water table
oscillation range
November 2011:
water table at 11.50 m
at old SoilCAM boreholes
March 2011
September 2009
November 2011

Contamination at 2009 Soilcam boreholes

UNIVERSITÀ DEGLI STUDI DI PADOVA

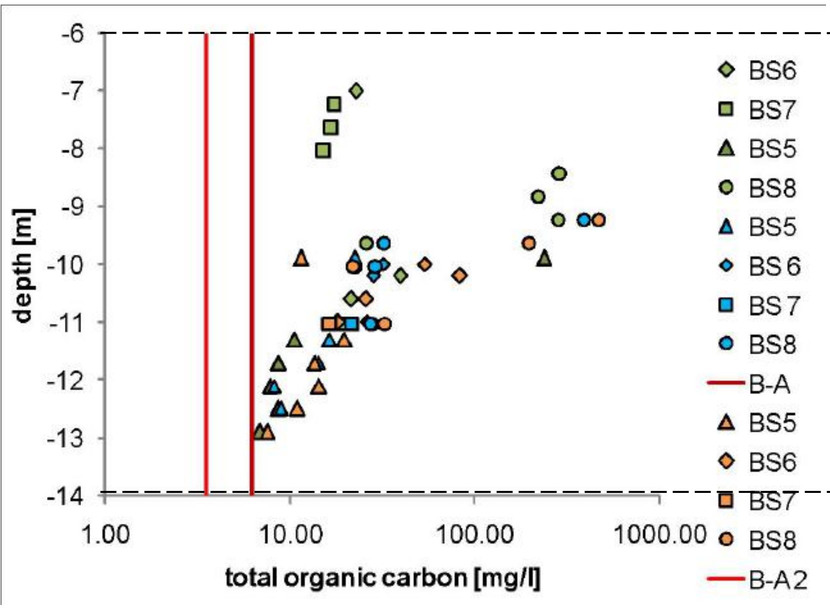
DIPARTIMENTO DI GEOSCIENZE

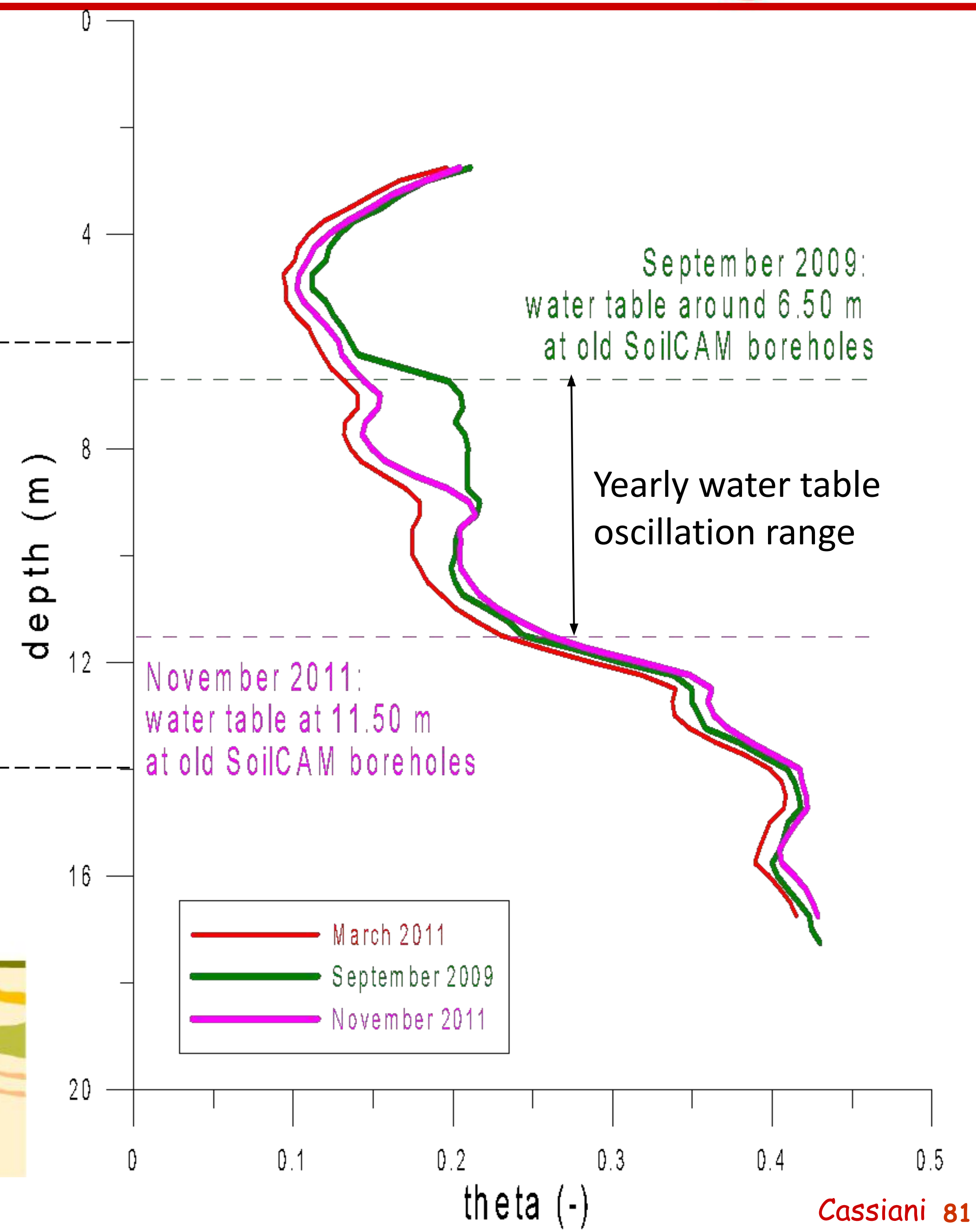
Contamination from multilevel samplers

The sample in the plastic bottle left is not filtered, it has a thin floating oilphase and the brown aqueous phase below is an emulsion.

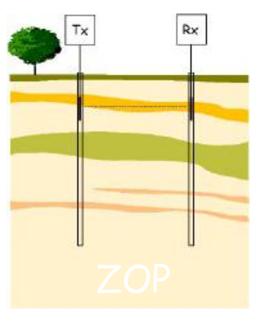
The sample in the tube on the right (which is the same sample but filtered at 0.45 μm), is tranparent

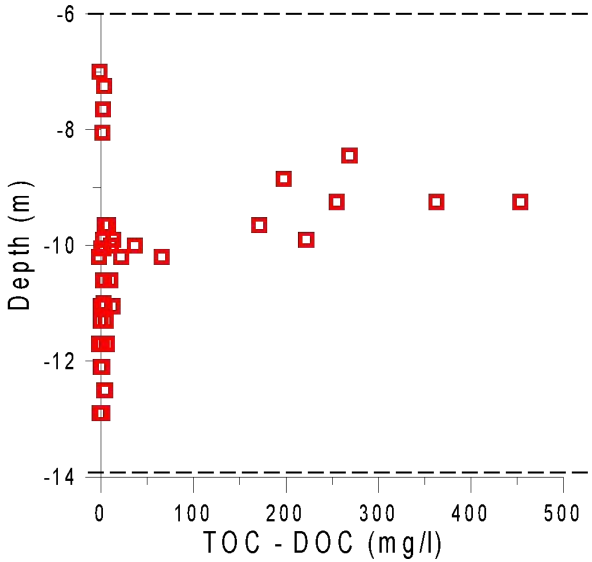
SoilCAM

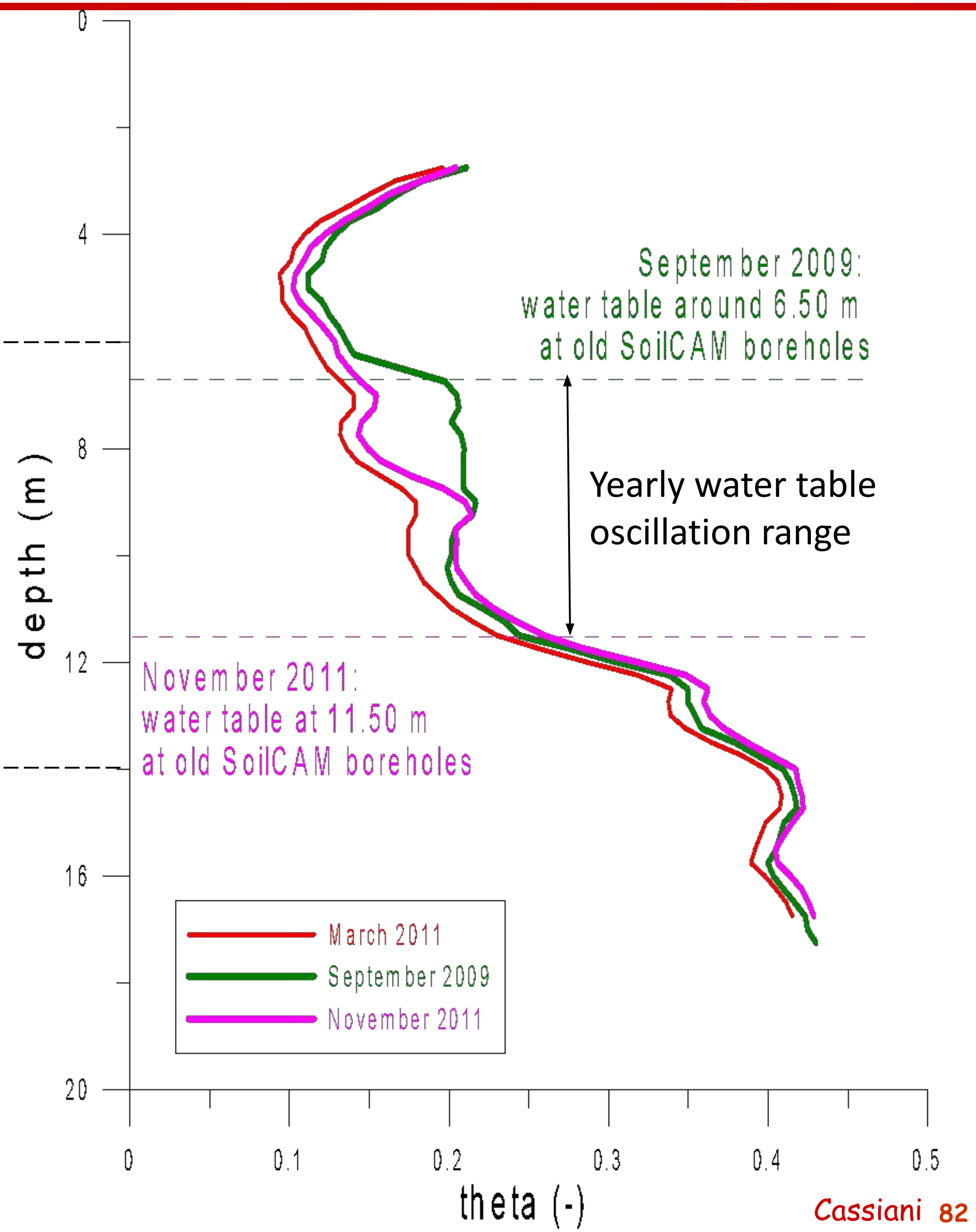




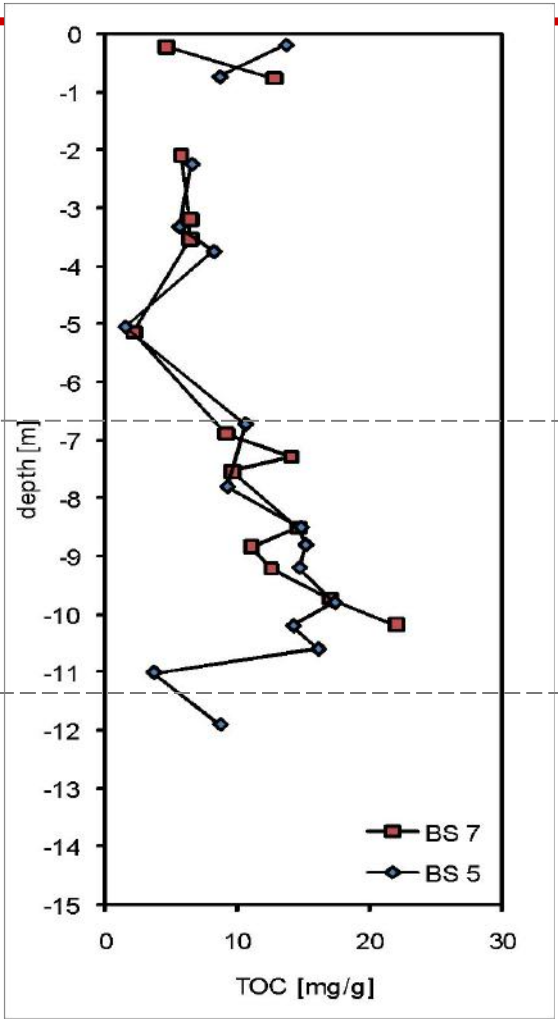
ZOP GPR
vs
multilevel samplers

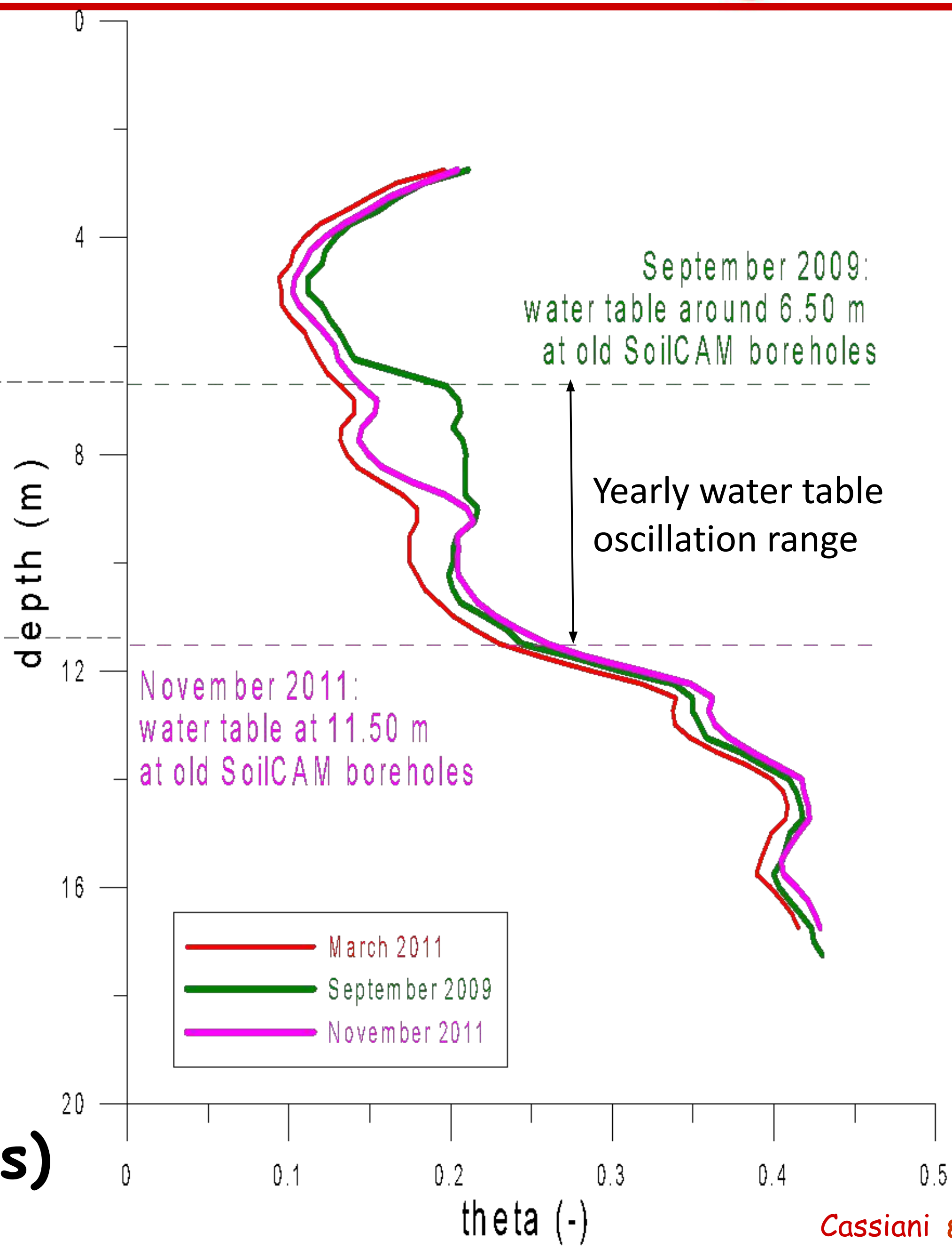






ZOP GPR
vs
multilevel samplers

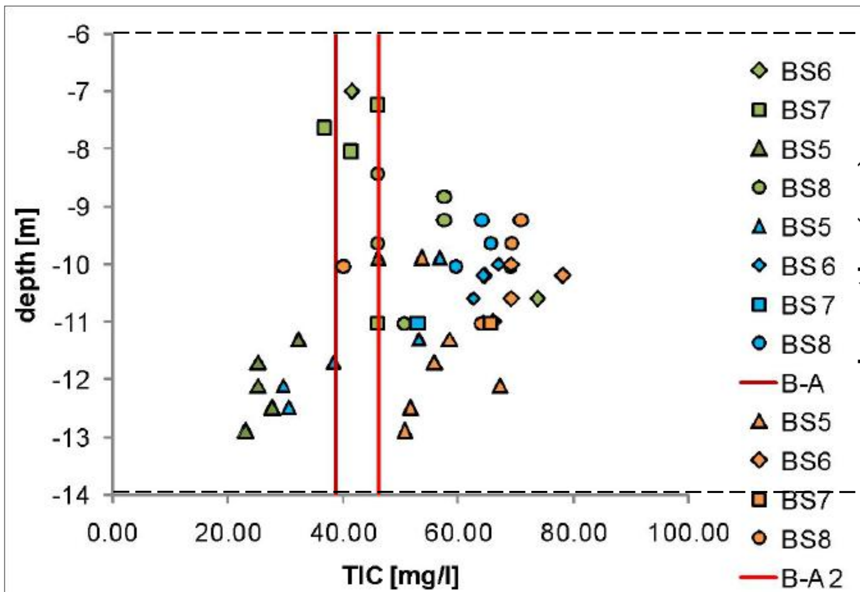


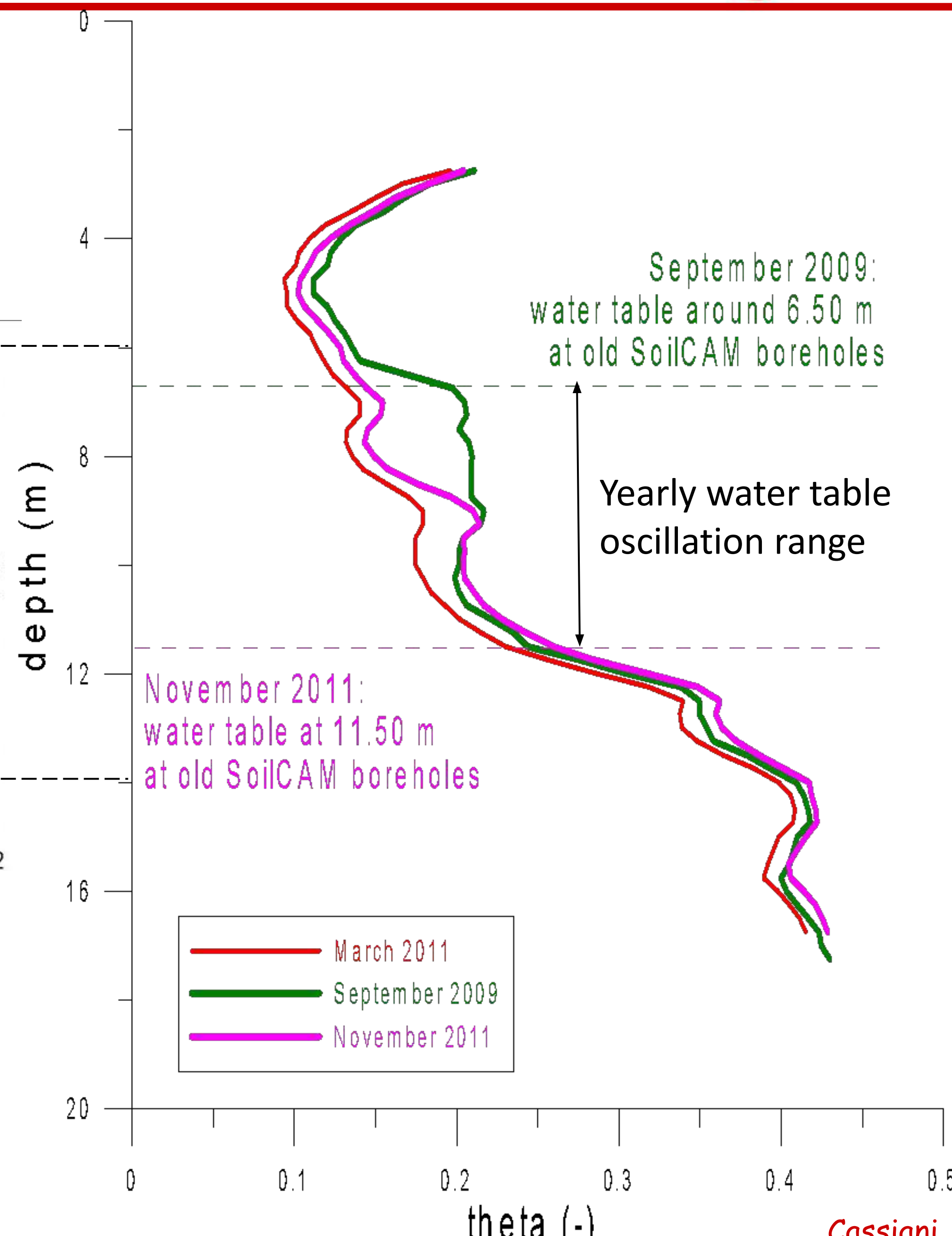


ZOP GPR

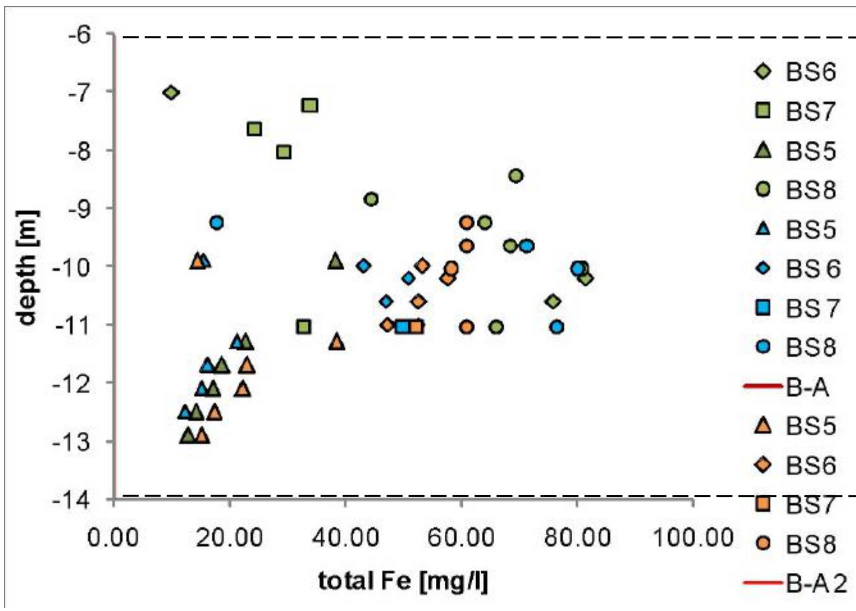
vs

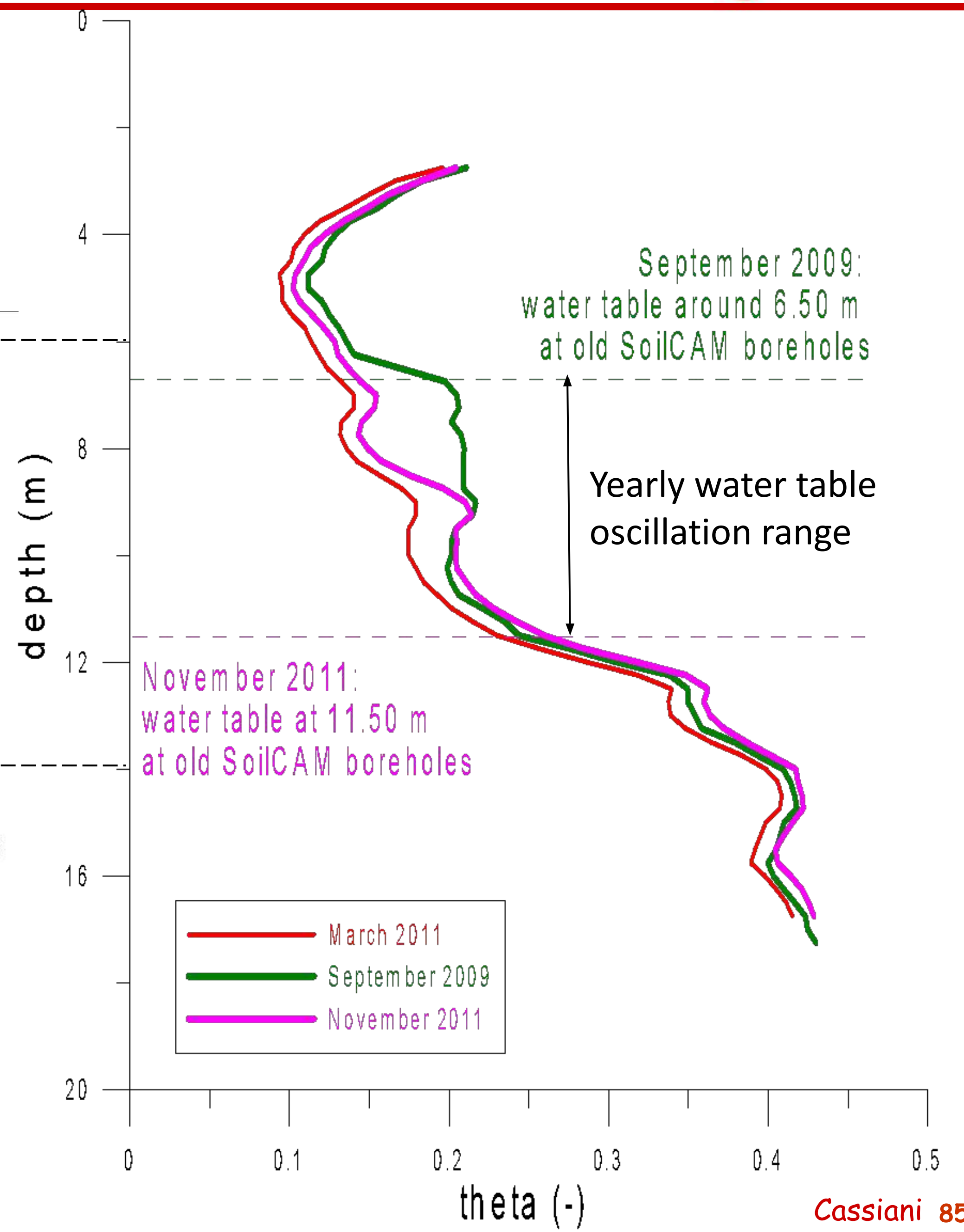
concentration in soil (liners)



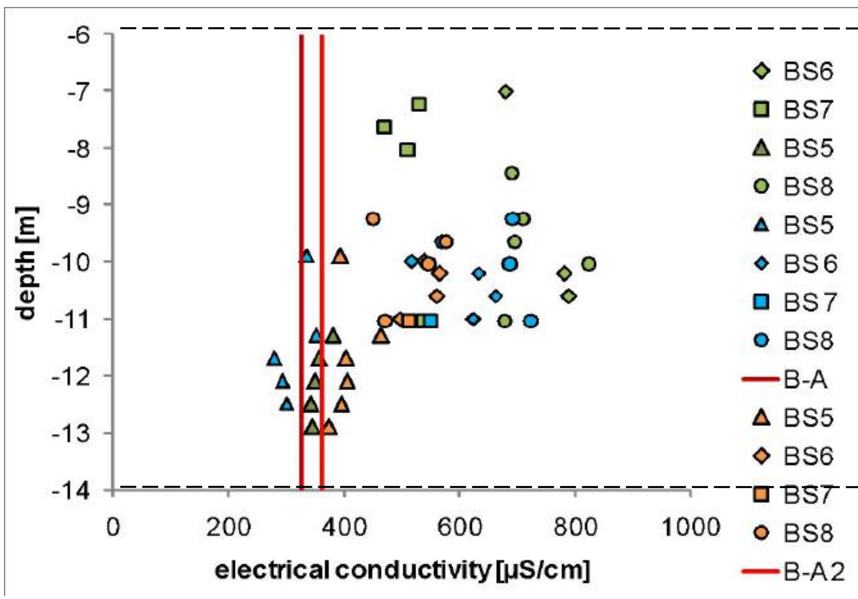


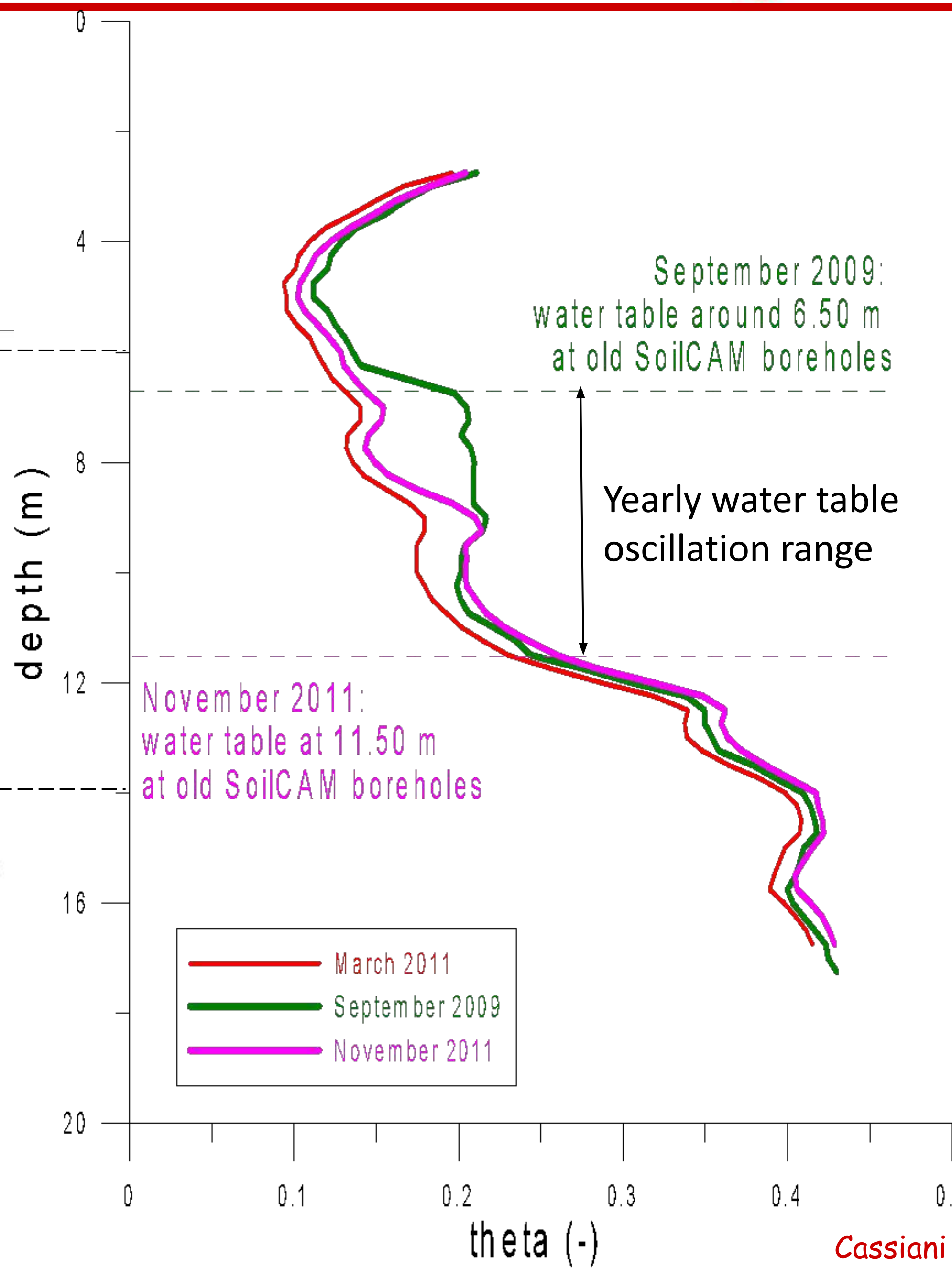
ZOP GPR
vs
multilevel samplers





ZOP GPR
vs
multilevel samplers





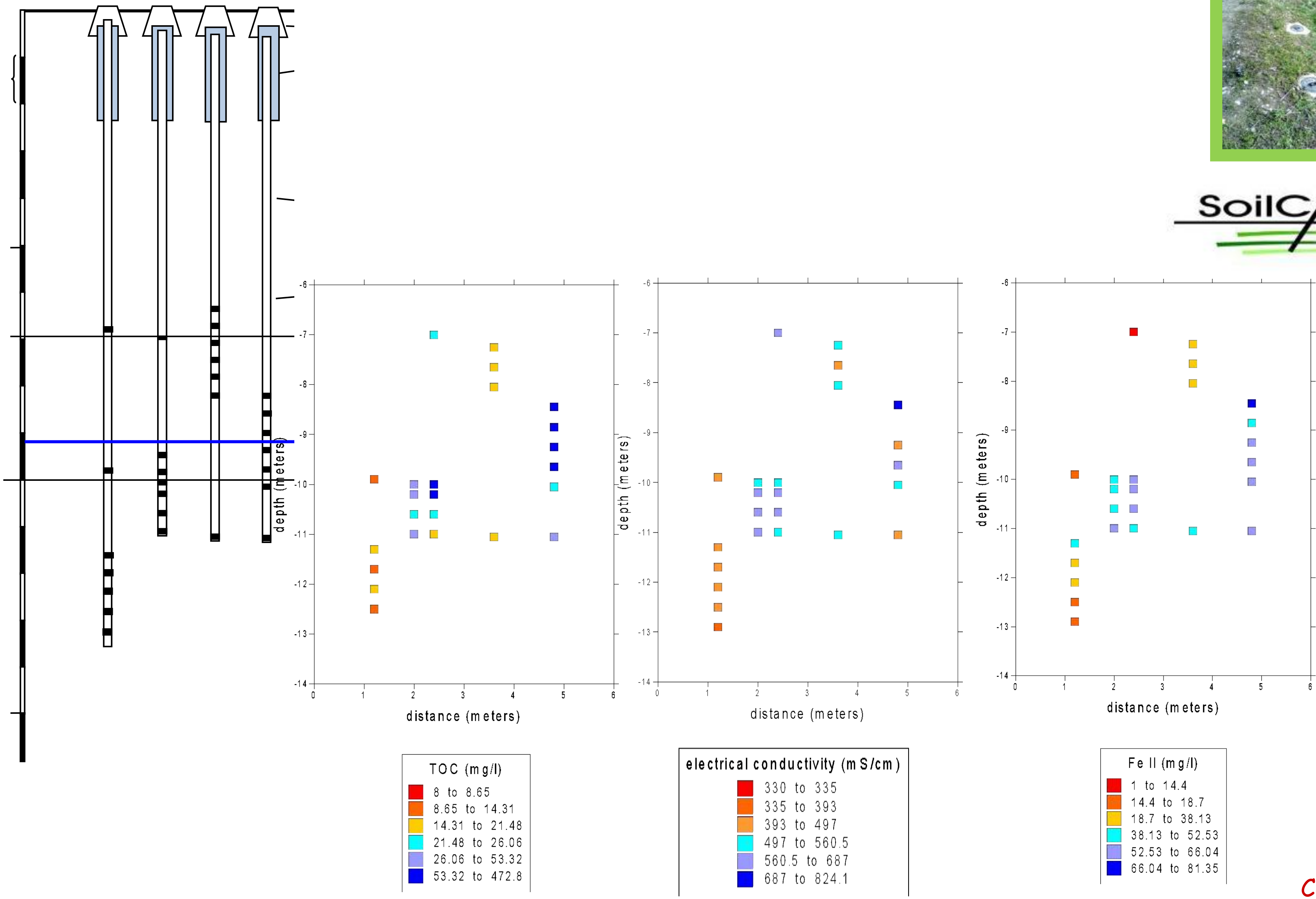
ZOP GPR

vs

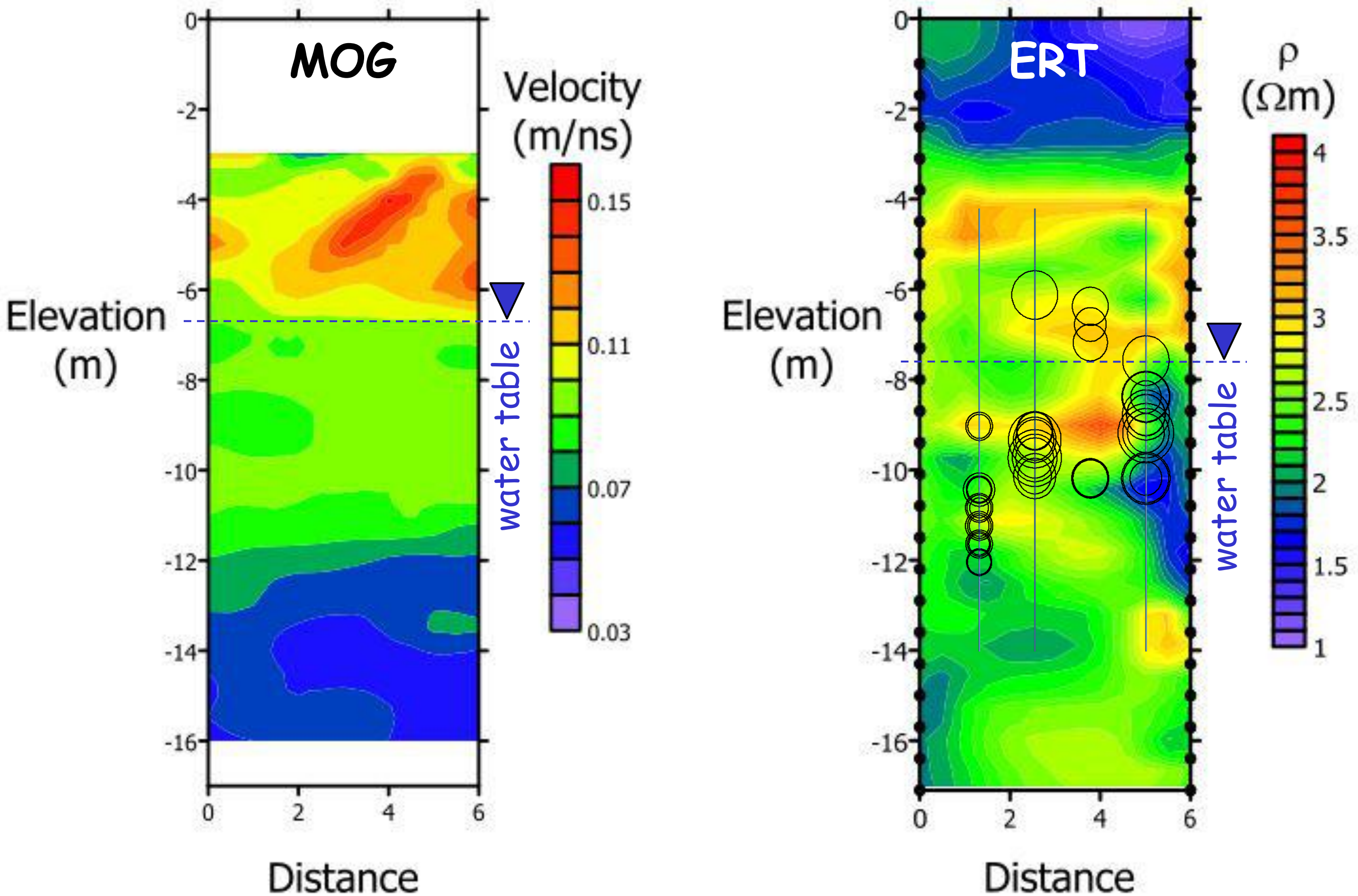
multilevel samplers

Multilevel samplers

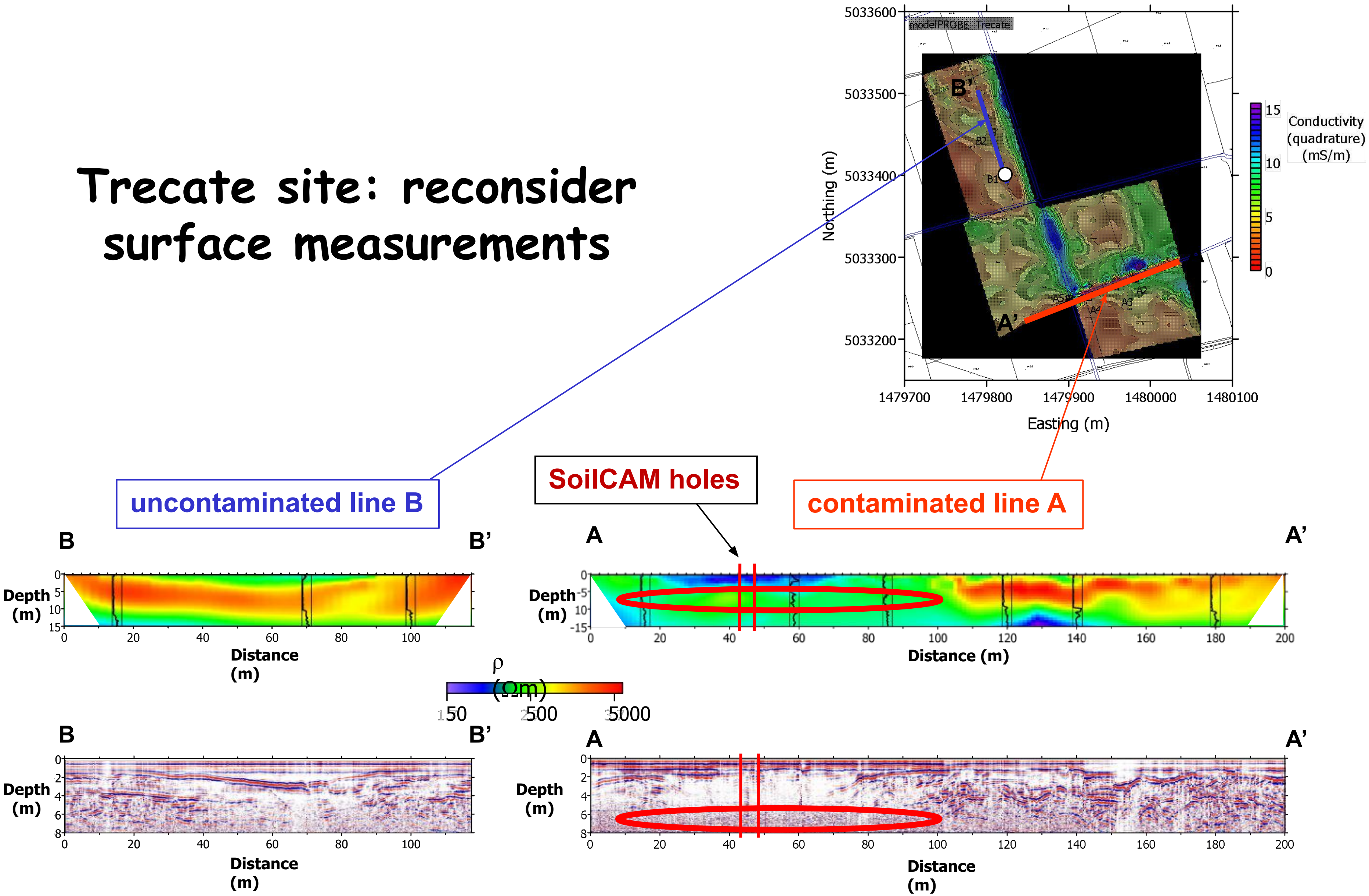
SoilCAM



Cross borehole radar (Sep 2009) and ERT (June 2009)



Trecate site: reconsider surface measurements



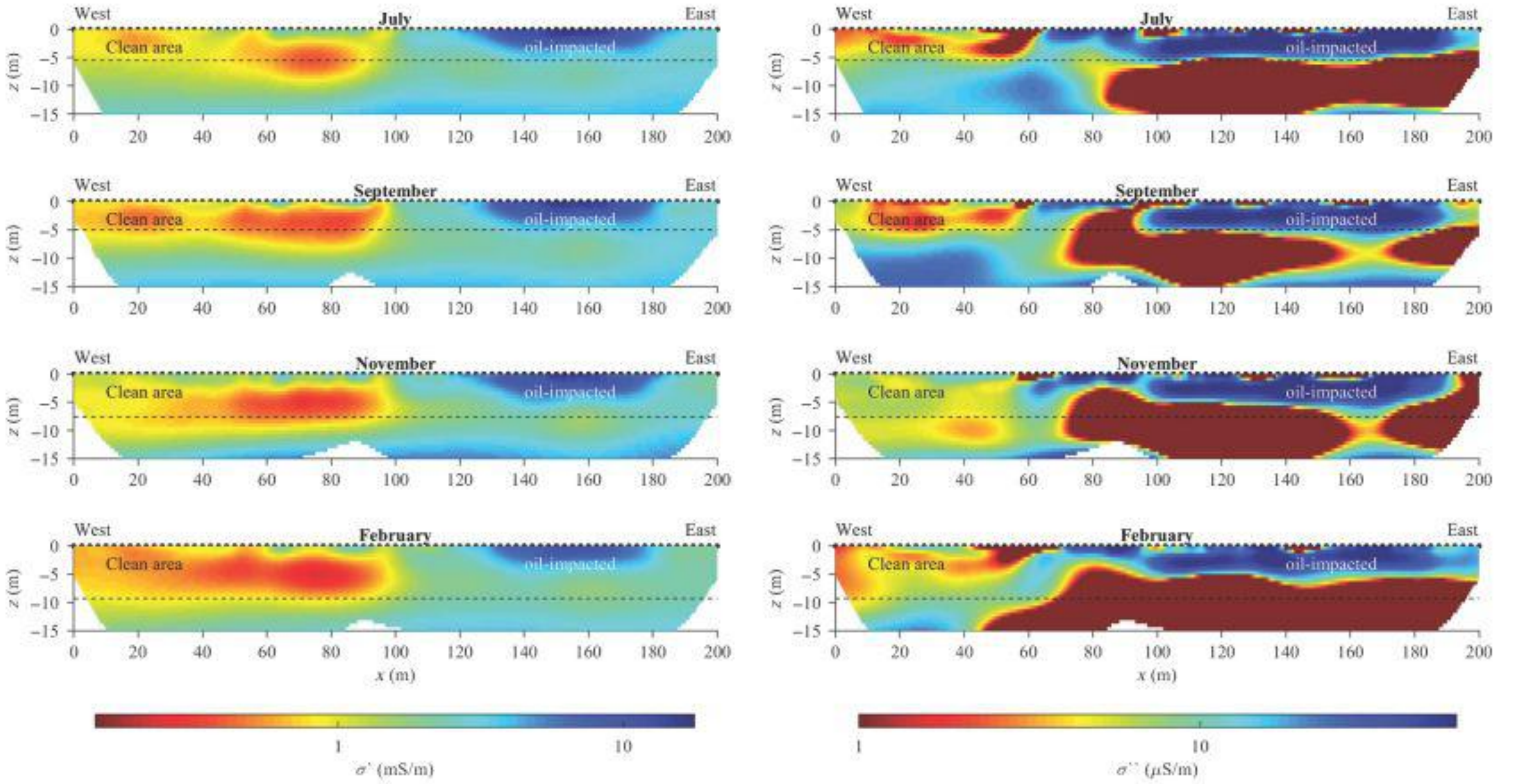


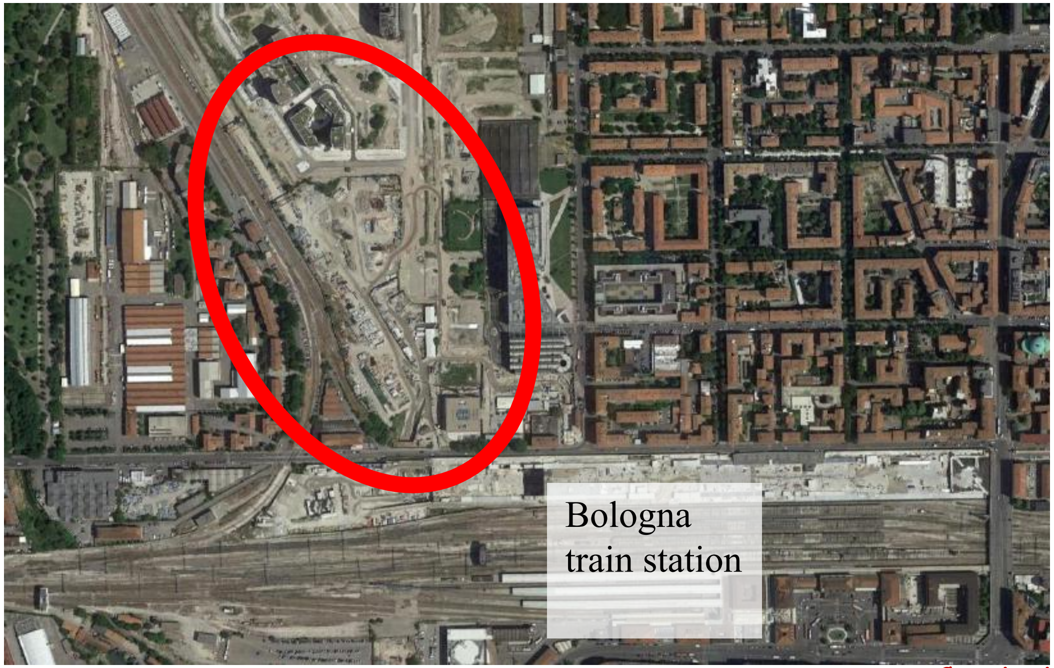
Figure A-1. The CCI results obtained for monitoring data collected at the Trecate site. Each data set was processed independently following the analysis of the misfit between direct and reciprocal readings described in Flores Orozco et al. (2012a). Accordingly, outliers and error parameters were defined independently for each data set. Imaging results are presented in terms of the real and imaginary component of the CC. The dashed line represents the position of the groundwater level at each monitoring period. The position of the electrodes is indicated at the surface by the black points.

Outline

- Geophysics for contaminated sites
- Pathways: The Ferrara case
- The Decimomannu case
- The Trecate case
- **Monitoring remediation: the Bologna case**
- Conclusions and outlook

Bologna railway station site: contamination

- PCE and TCE about 10-15 times the maximum allowed concentrations in groundwater.
- Origin: degreasing of railway coaches.
- Contamination known since early 2000's.



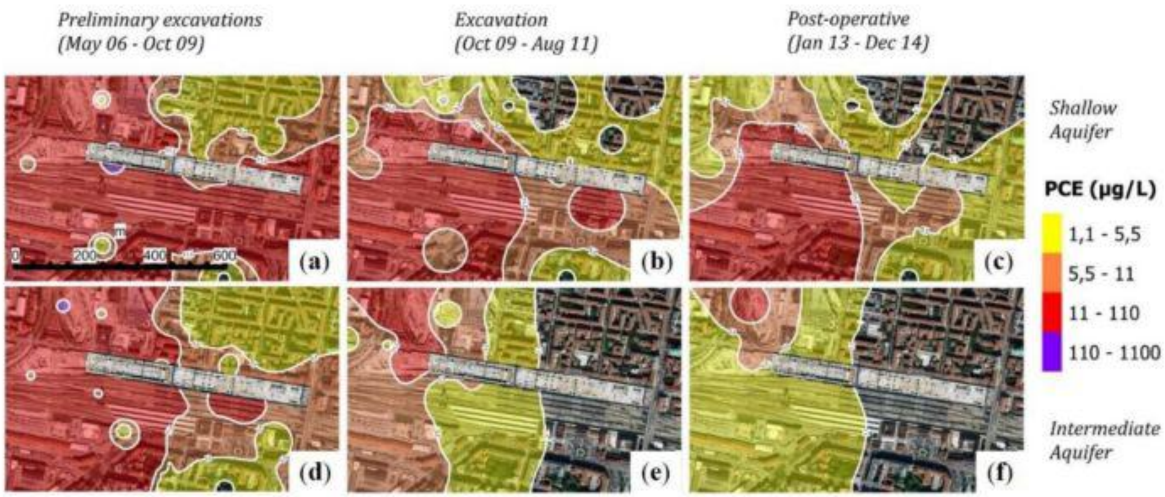


Figure 6. Contour maps representing values of tetrachloroethylene (PCE) concentration in the (**a–c**) shallow and (**d–f**) intermediate aquifers at three time instants.

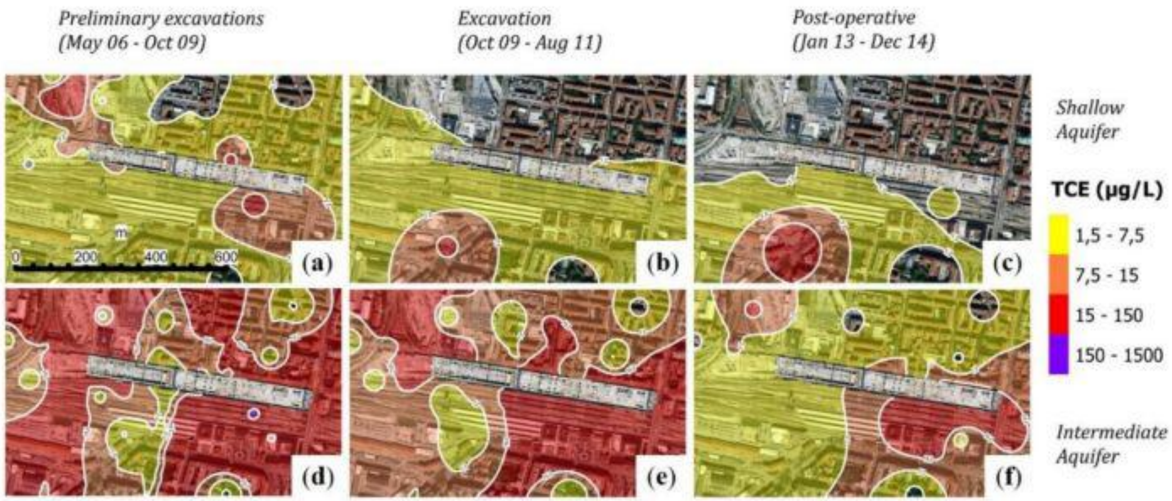
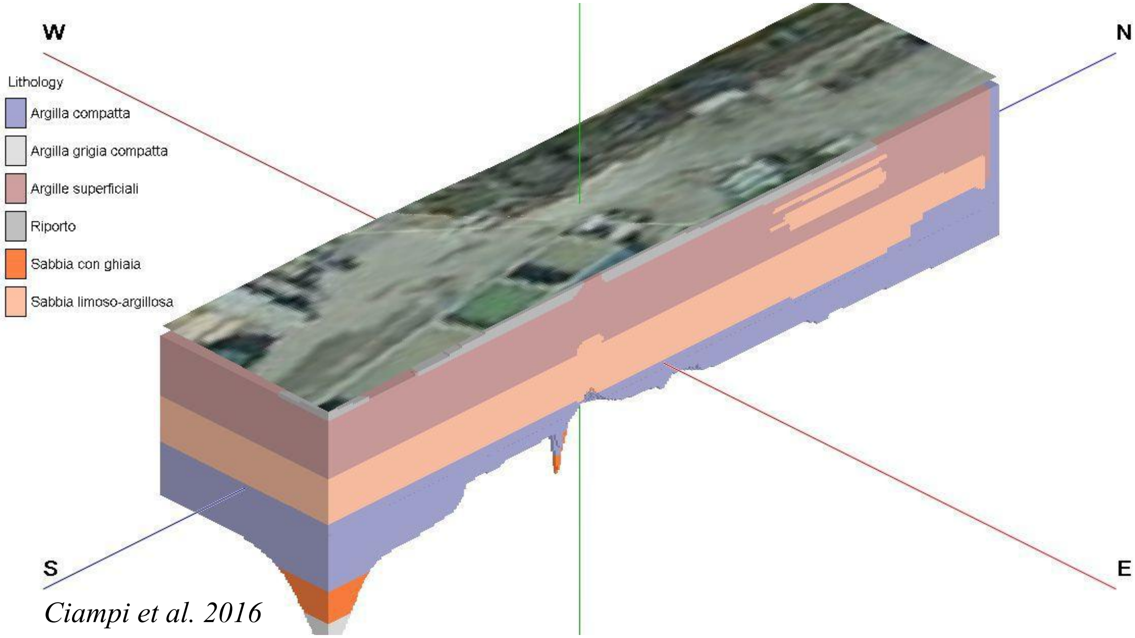
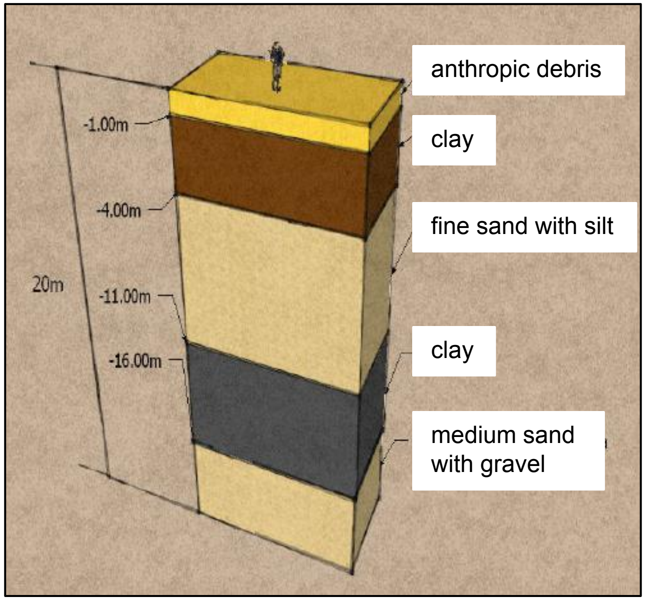


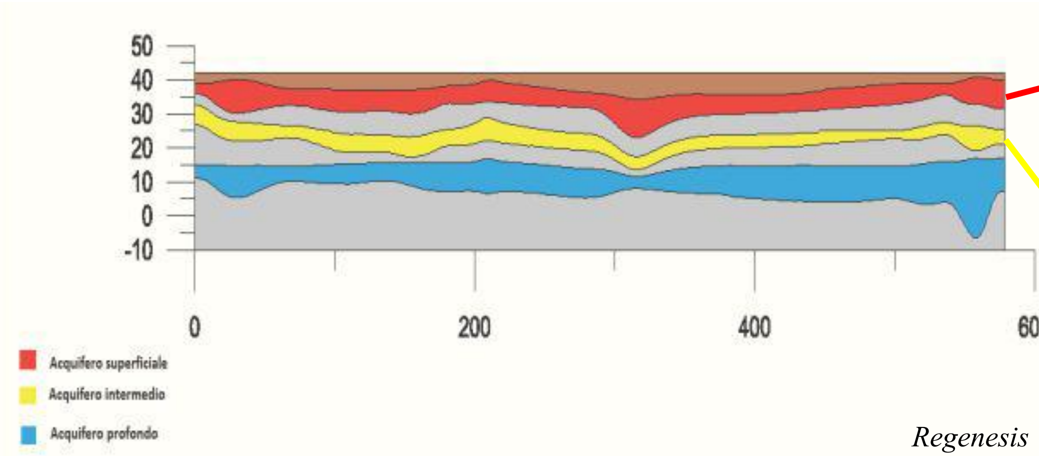
Figure 7. Contour maps representing values of trichloroethylene (TCE) concentration in (**a–c**) shallow and (**d–f**) intermediate aquifers at three time instants.

Bologna railway station site: stratigraphy



Ciampi et al. 2016



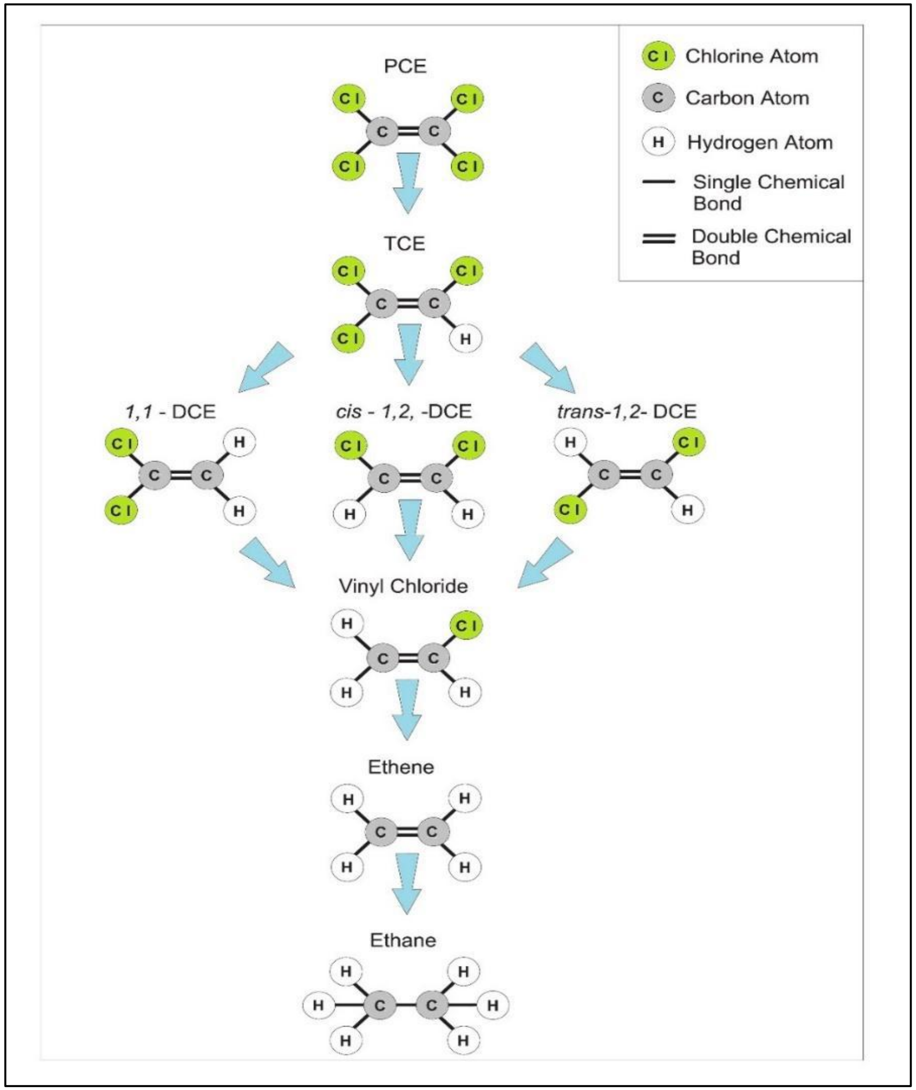


Regenesis

Shallow acquifer hydraulic conductivity = $5x10^{-6}$-$1x10^{-4}$ [m/s]

Intermediate acquifer hydraulic conductivity = $5x10^{-5}$-$1x10^{-4}$ [m/s]

Bologna railway station site: remediation



PCE and TCE can be degraded using **reductive dechlorination**.

This is mediated by *Dehalococcoides* bacteria under reducing conditions.

However, at the Bologna site the concentrations are too low to trigger natural attenuation.

Bologna railway station site: remediation

- **The strategy involves injecting substances that can help activate the natural attenuation. In particular two substances are needed:**

1. **Colloidal activated carbon** (PLUMESTOP® by REGENESIS) with ≈ 1-2 µm particle size in water suspension, to help immobilize and concentrate the PCE for microbial uptake.
2. Sugar amendment as an electron donor to reduce Redox conditions and activate anaerobic conditions.

Bologna railway station site: remediation

- Laboratory column experiments have demonstrated the effectiveness of the approach

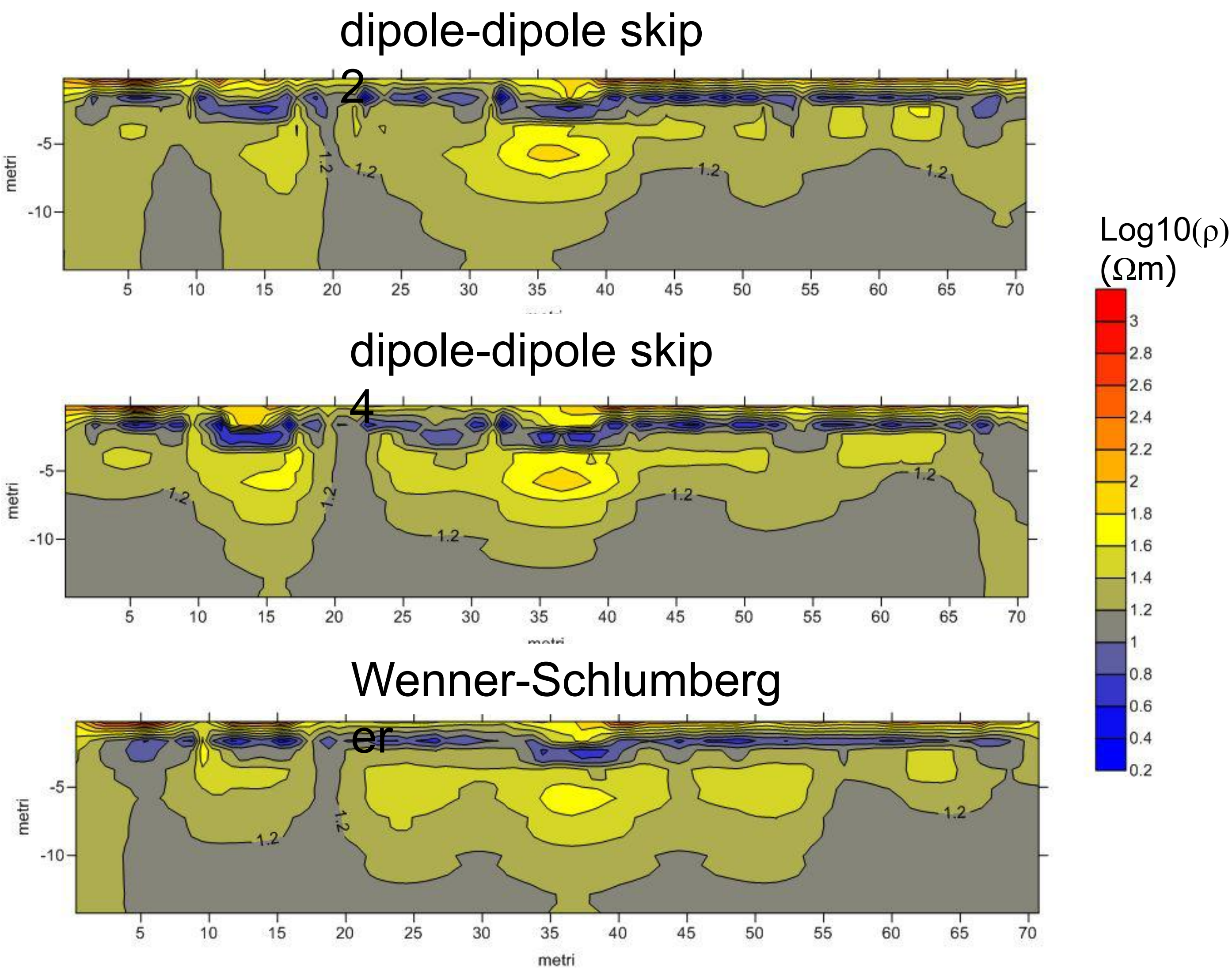
- Field-scale application has followed: injection has taken place from 13 wells, injecting at low pressure 4m^3 per well.

Geophysical monitoring

As both the colloidal activated carbon and the sugar amendment increase the electrical conductivity of groundwater, we used time-lapse ERT as a monitoring technique.

Logistics is not easy at all…

Geophysical monitoring: the logistical difficulties required optimal ERT design. Both dipole-dipole and WS tested.



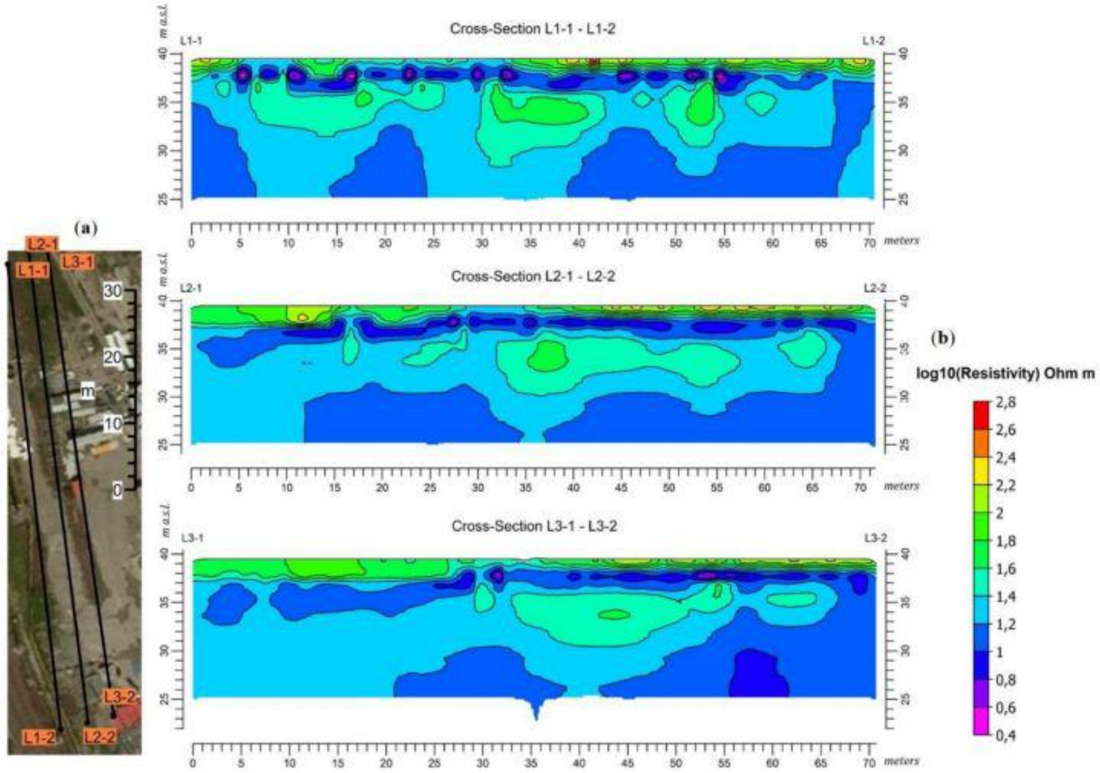


Figure 4. (**a**) Arrangement of electrodes in the soil in the pilot test area and (**b**) resulting in electrical resistivity tomography (ERT) profiles.

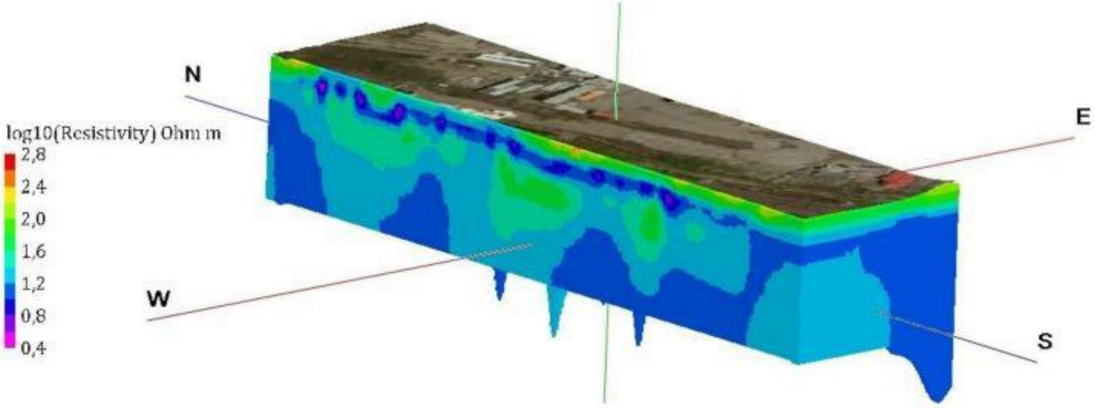


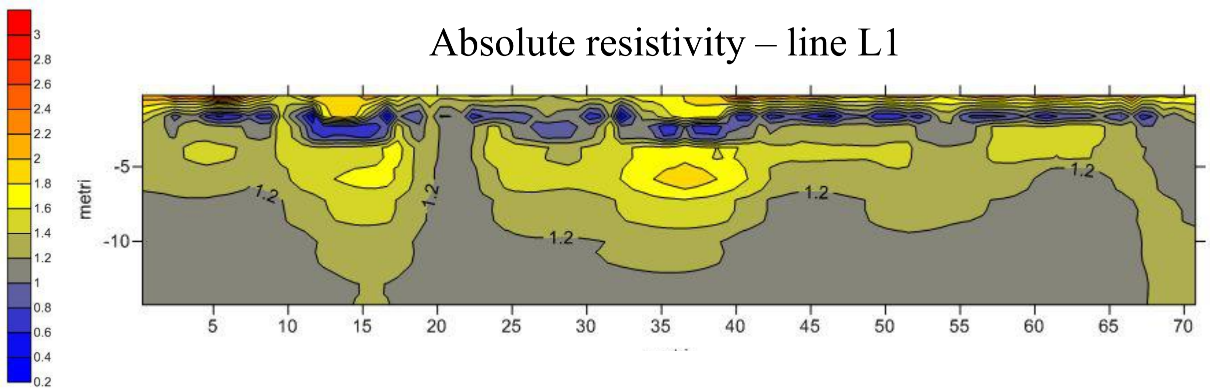
Figure 5. 3D resistivity model covering the pilot test area.

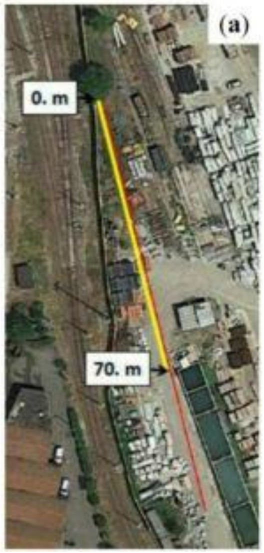
Geophysical monitoring:

1) background ERT images show palae-channels that control fluid migration.
(2) time-lapse ERT images show the heterogeneous distribution of injected fluid.

Log10(ρ) (Ωm)

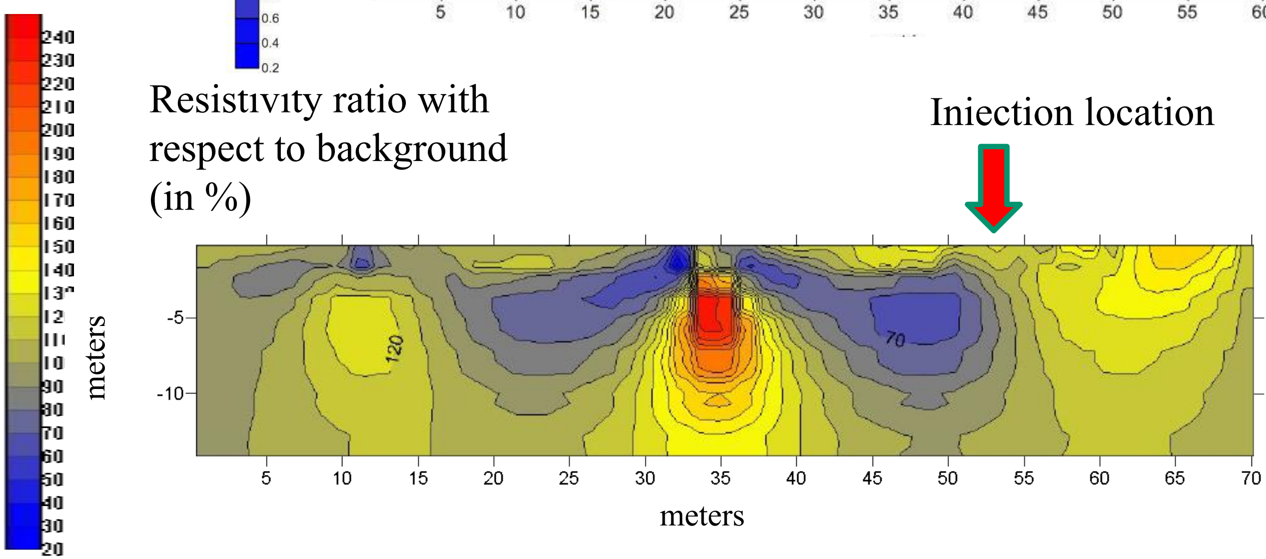
Absolute resistivity – line L1





Resistivity ratio with respect to background (in %)

Iniection location



Variation of resistivity caused by the november 2015 injection

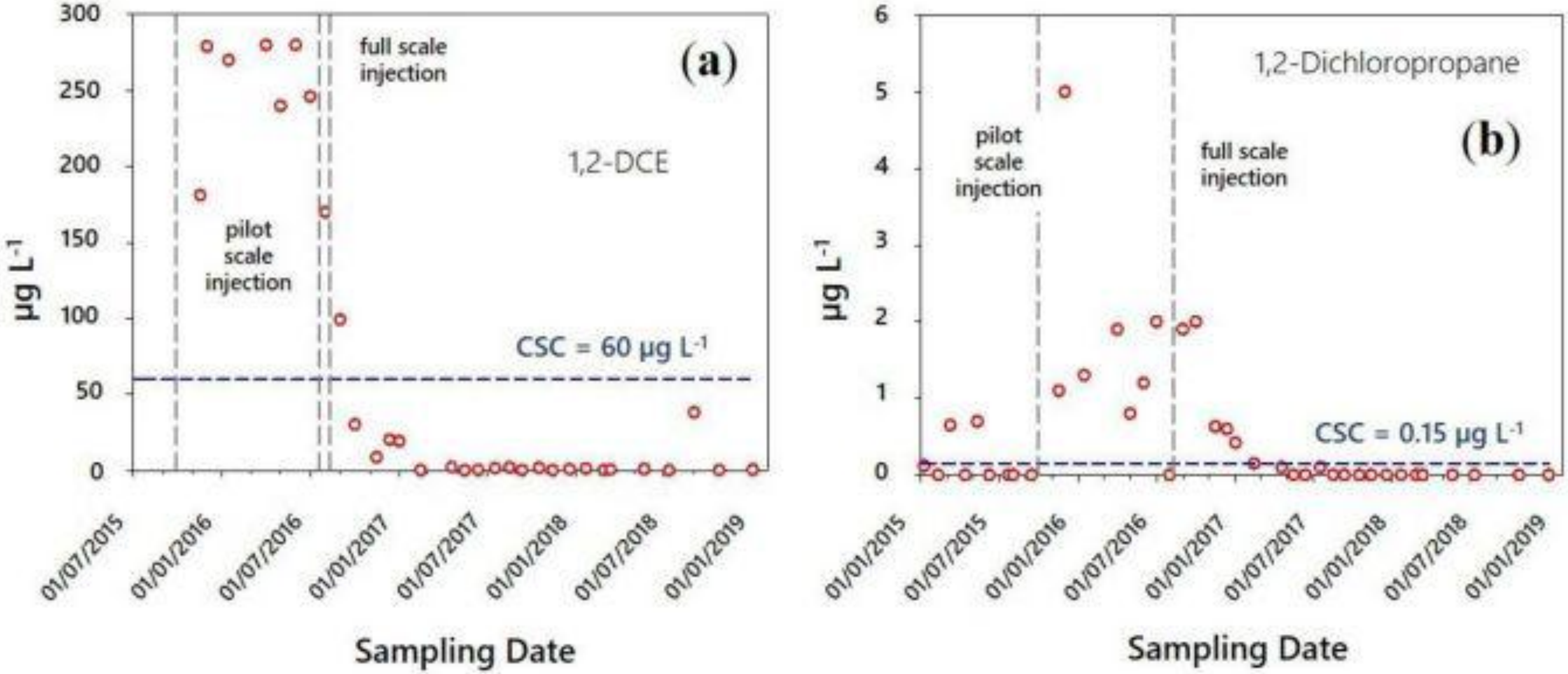


Figure 10. Concentrations of (**a**) 1,2 dichloroethene (1,2-DCE) and (**b**) 1,2-dichloropropane detected in a piezometer installed in the pilot test area.

General conclusions

- The use of geophysical measurements for hydrocarbon contamination studies can reveal:

(a) structural information /pathways

(b) contamination mapping

- For structure and even more for contamination assessment from geophysics, independent information is essential.

- In all cases the resolution and penetration capabilities of geophysical methods must be assessed carefully

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6. UFZ Leipzig, Germany
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12. Dipartimento di Scienze della Terra, Università di Roma La Sapienza, Rome, Italy

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SEVENTH FRAMEWORK PROGRAMME

ModelPROBE

Model driven Soil Probing, Site Assessment and Evaluation

SoilCAM