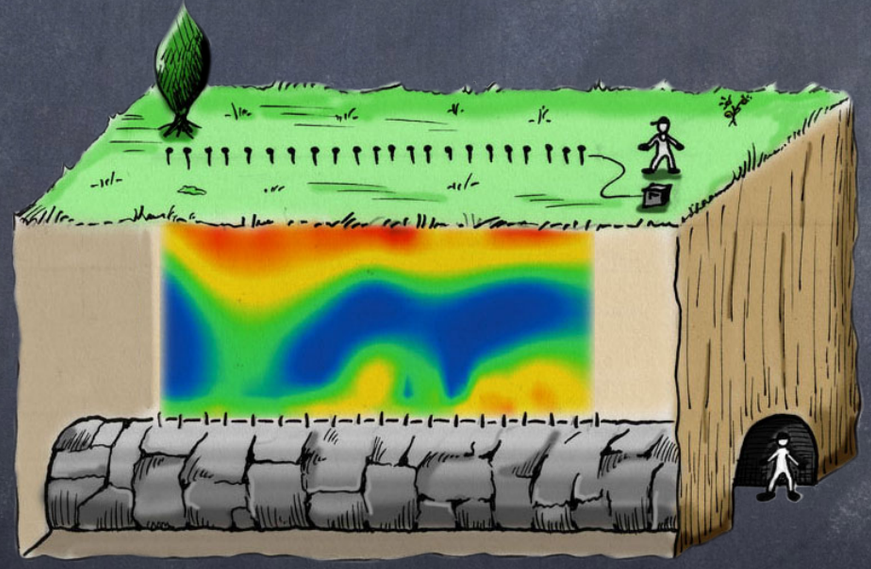
‘4D and HD Geophysics’ Workshop
5-16 /12 /2014

# Surface-to-Tunnel ERT measurements and a bench-scale application for monitoring of dense non-aqueous phase liquids

Simyrdanis Kleanthis. Tsourlos Panagiotis, Christopher Power



한국지질자원연구원 KIGAM Korea Institute of Geoscience and Mineral Resources

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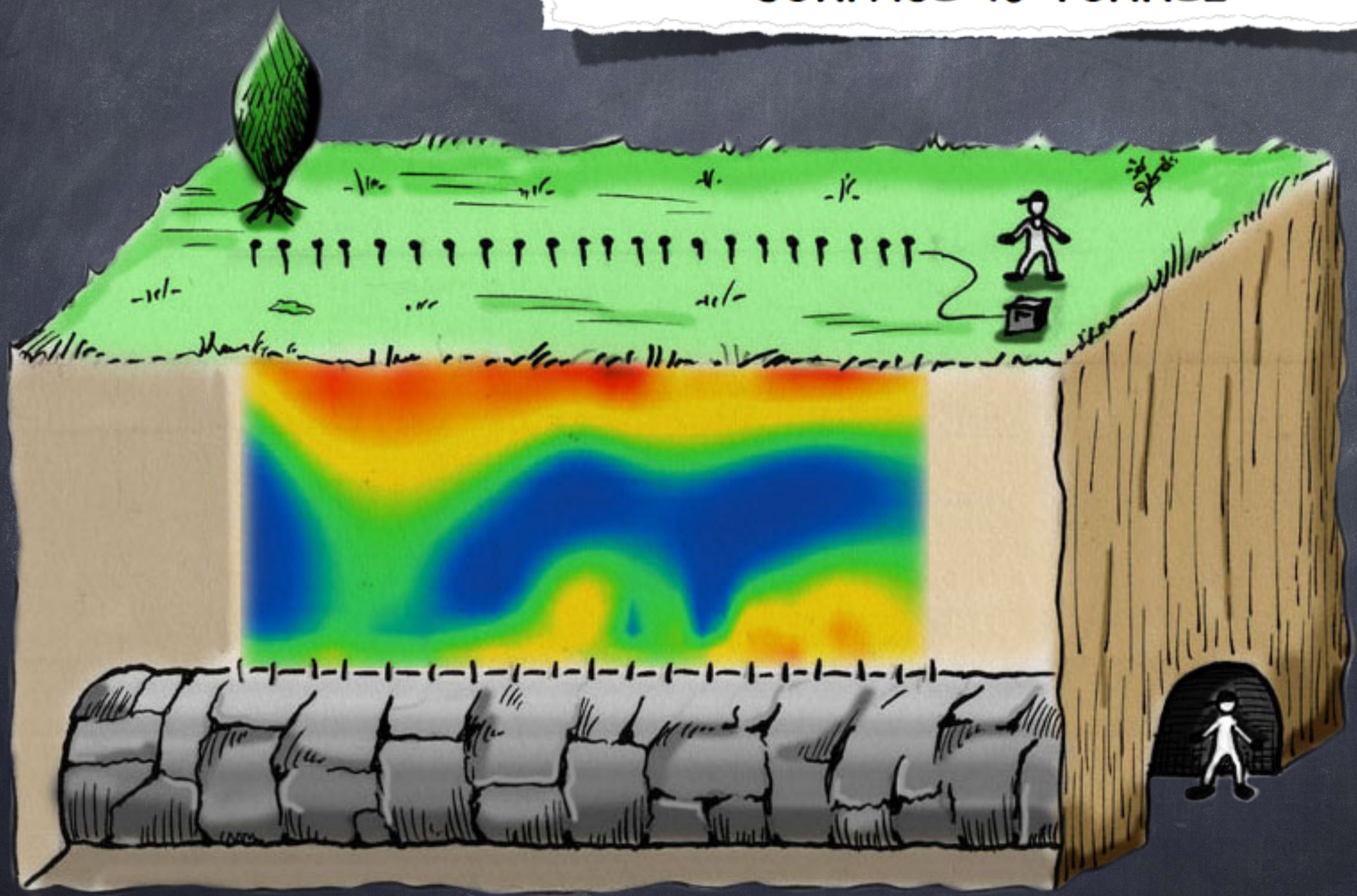
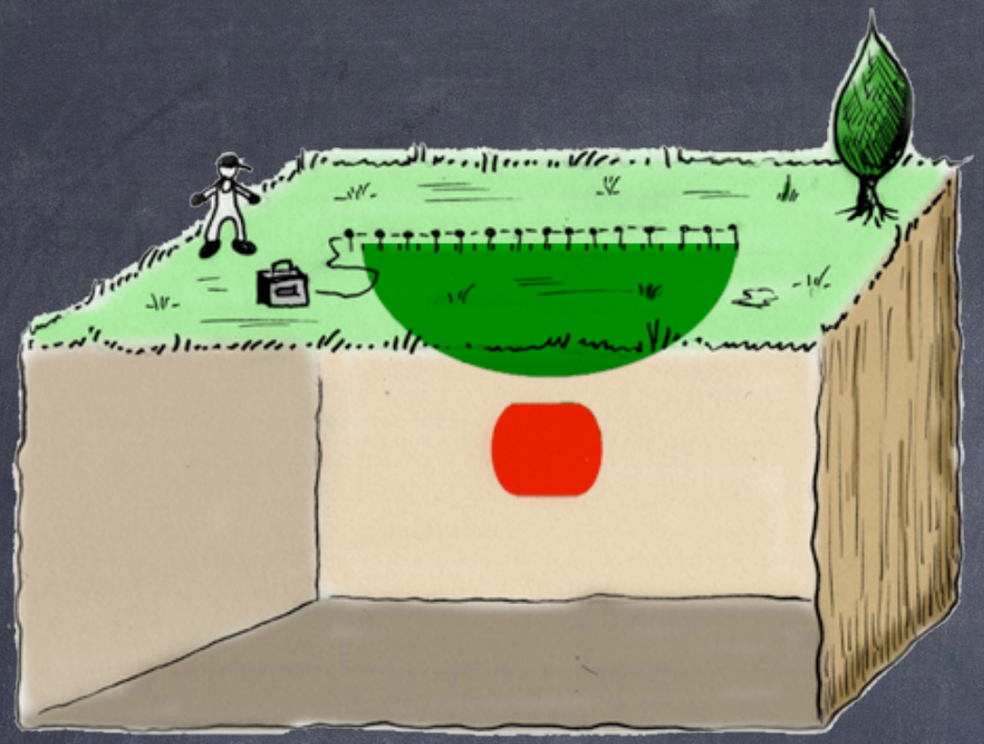
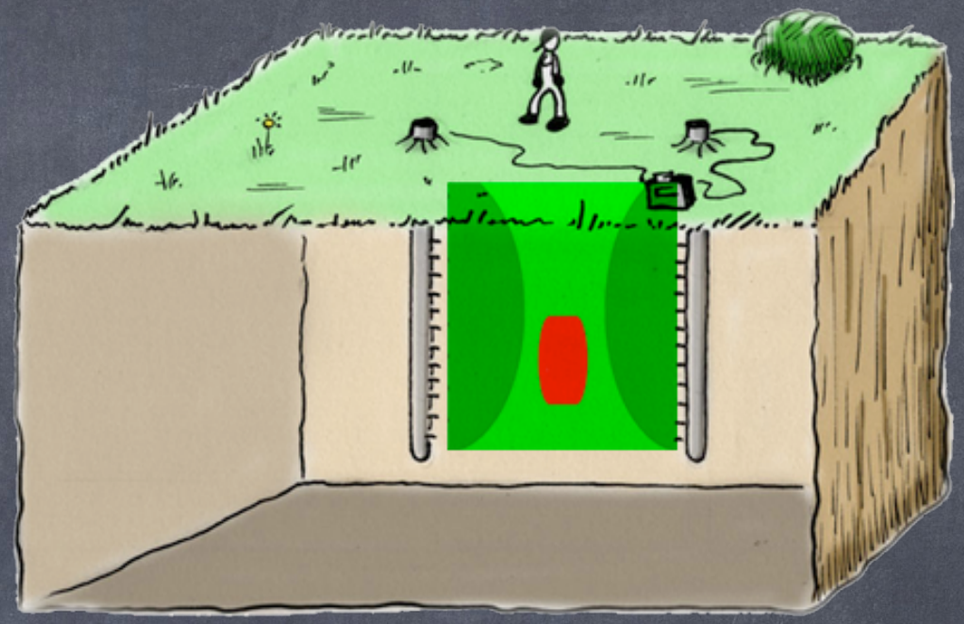
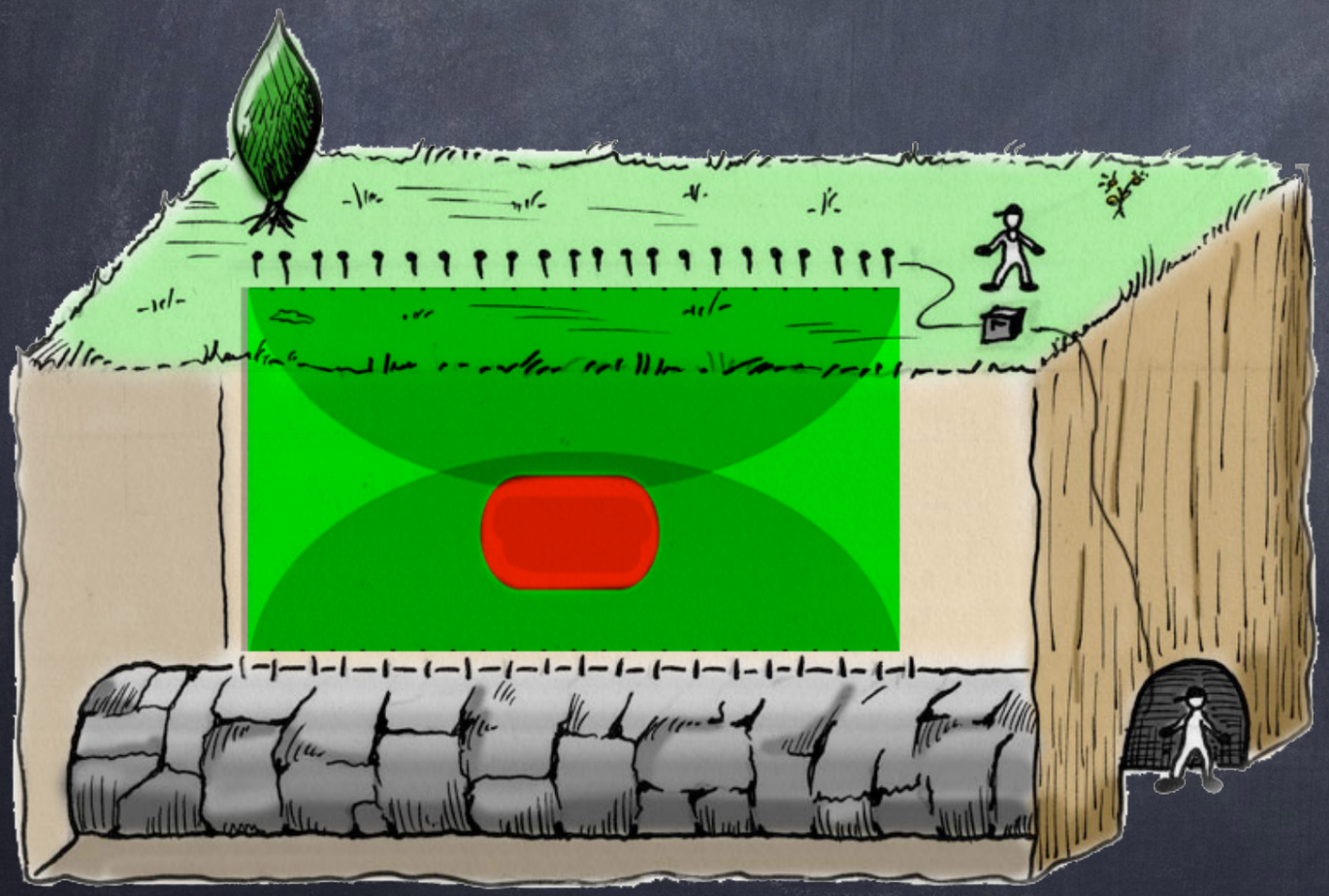
# GEOELECTRICAL MEASUREMENTS SURFACE-to-TUNNEL







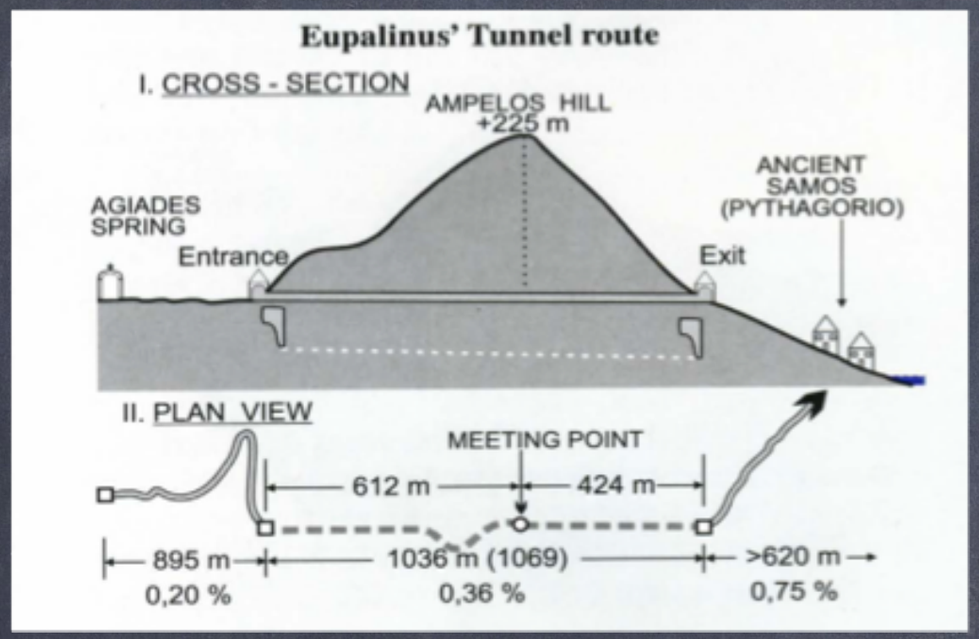


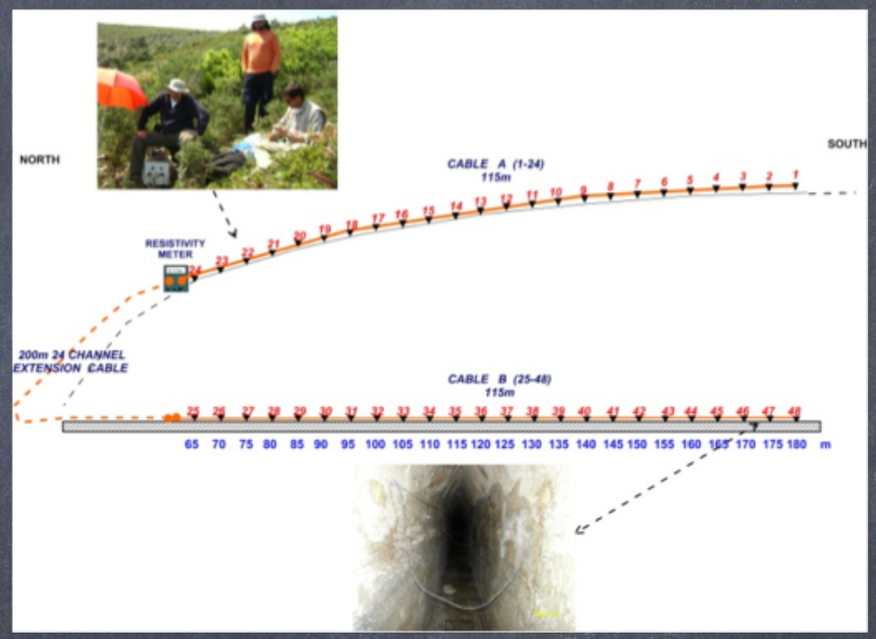
- BOREHOLE MEASUREMENTS
  - Special Installation
  - Dense Installation
  - Cost

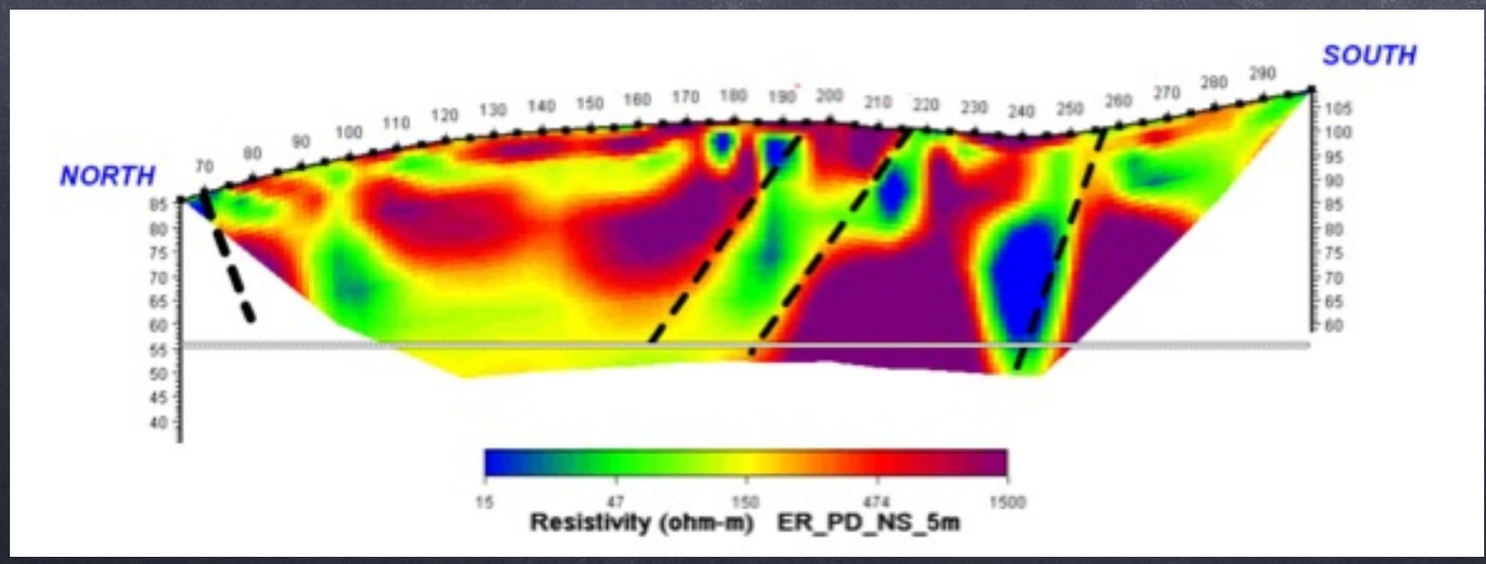
- USAGE of EXISTING STRUCTURES
  - Natural Caves
  - Artificial (Tunnels)


# The Cause

"Geophysical Survey in ancient tunnel of Efpalinio" (2009)
Prof. Tsokas Gregory



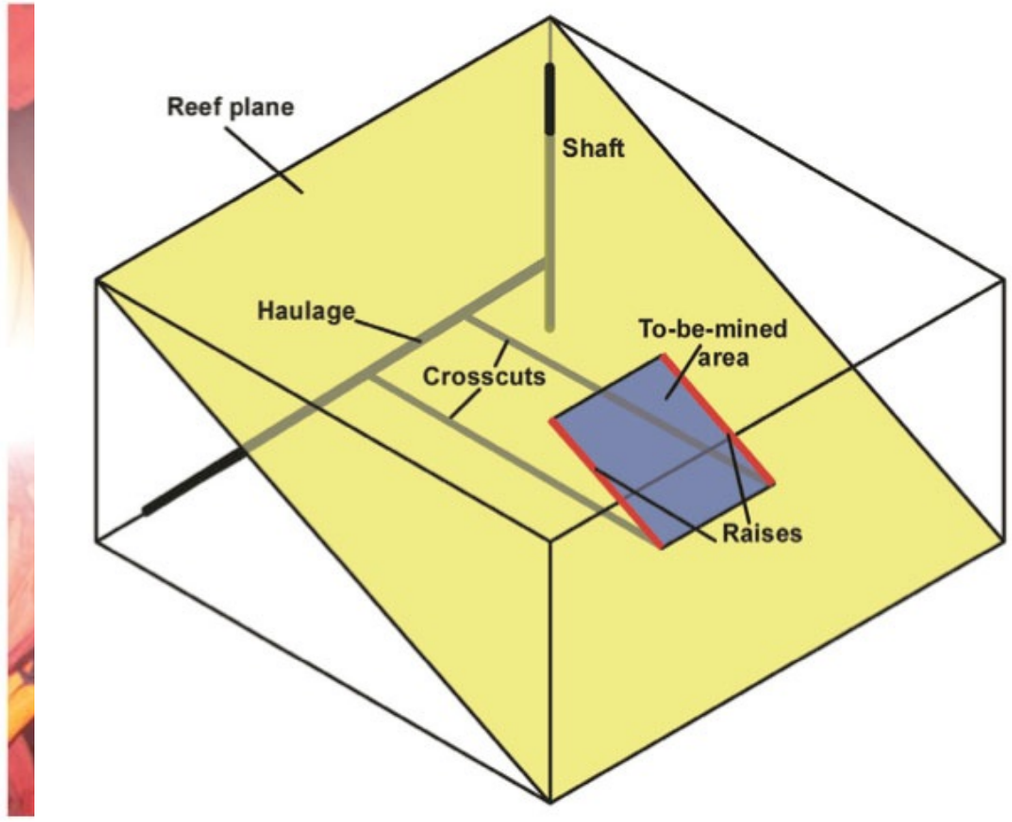



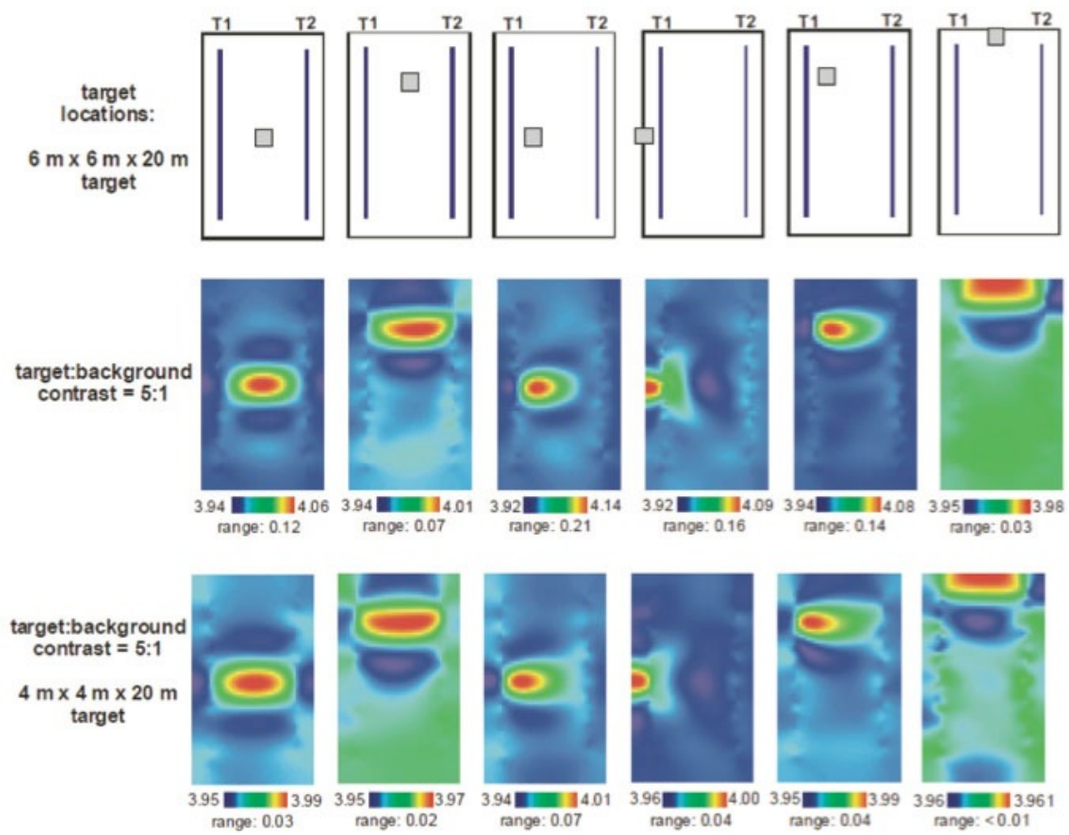
# Previous Studies

- SASAKI & MATSUO (1993)
  surface-to-tunnel application for very **deep mining**

- DANIELSEN & DAHLIN (2010)
  Horizontal boreholes examining the **geological conditions of the rock**
  in front of a tunnel bore machine

- VAN SCHOOR & BINLEY (2010)
  Applicability of tunnel-to-tunnel electrical resistance tomography for imaging
  **disruptive geological structures ahead of mining**,
  in an igneous platinum mining environment



- New type of measurements ... so new PROBLEMS !

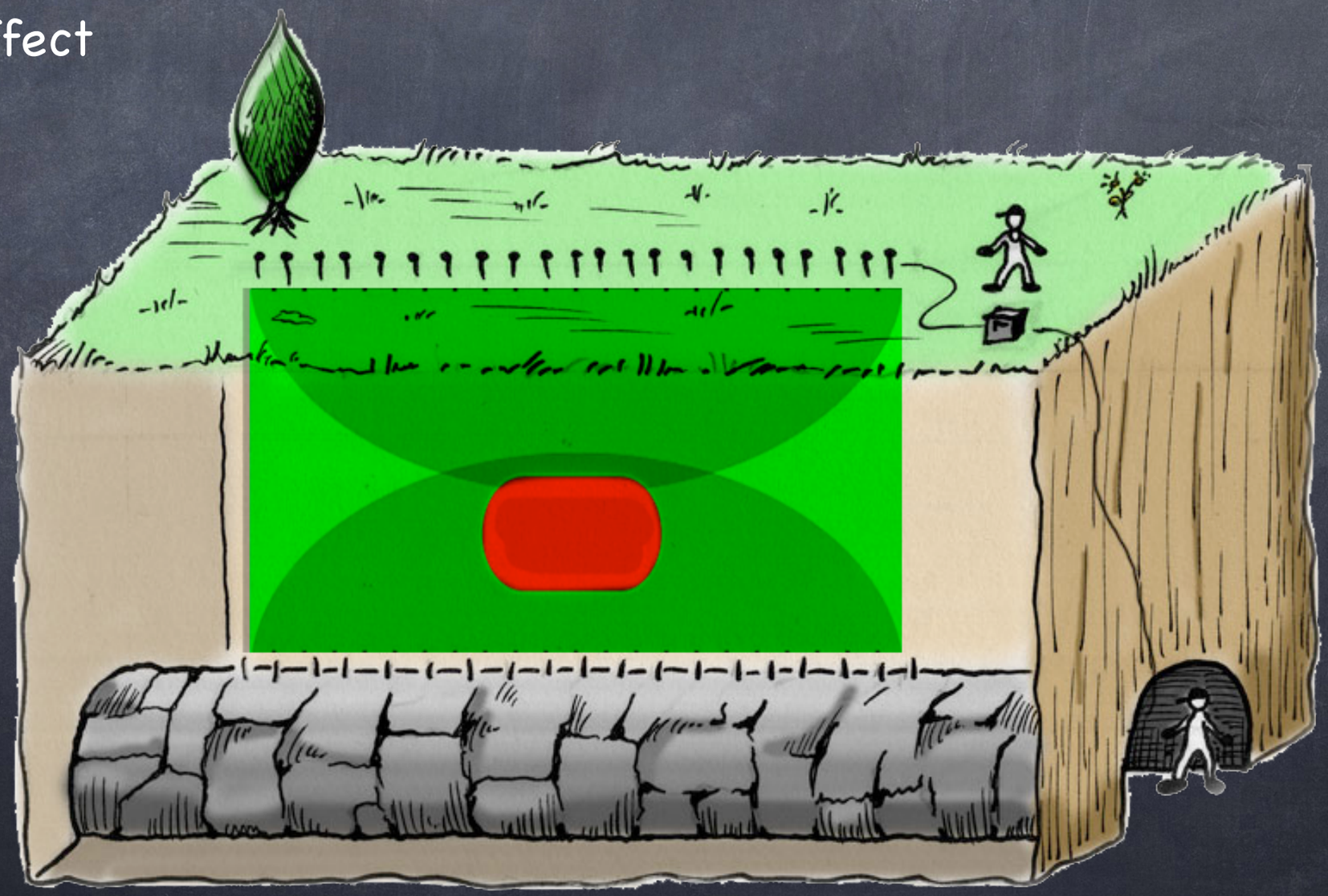
✓ How can we acquire measurements ?

✓ Can we optimize protocols used ?

✓ Tunnel Dimensions

✓ Distance between surface and interior electrodes

✓ Tunnel Effect



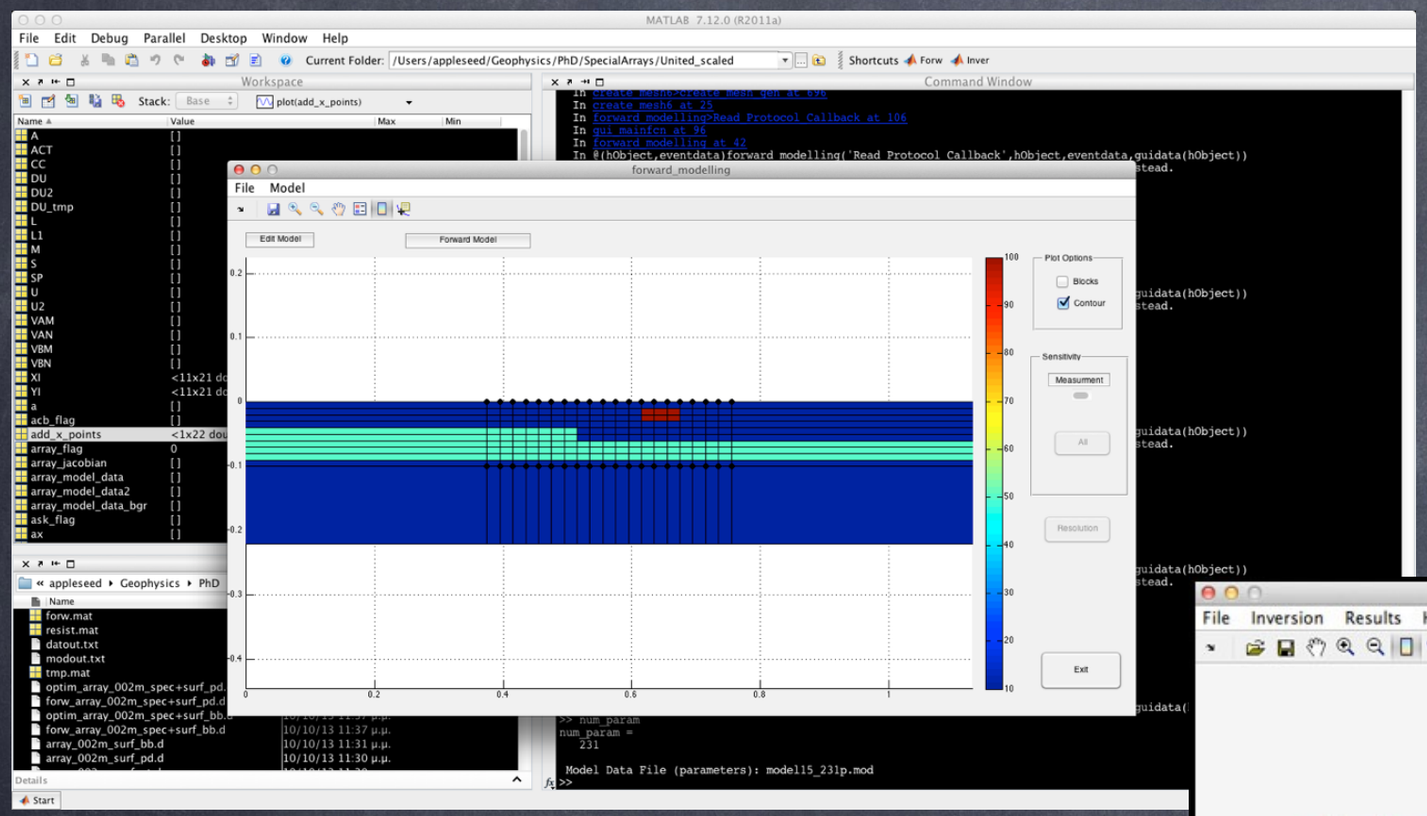
# STRUCTURE

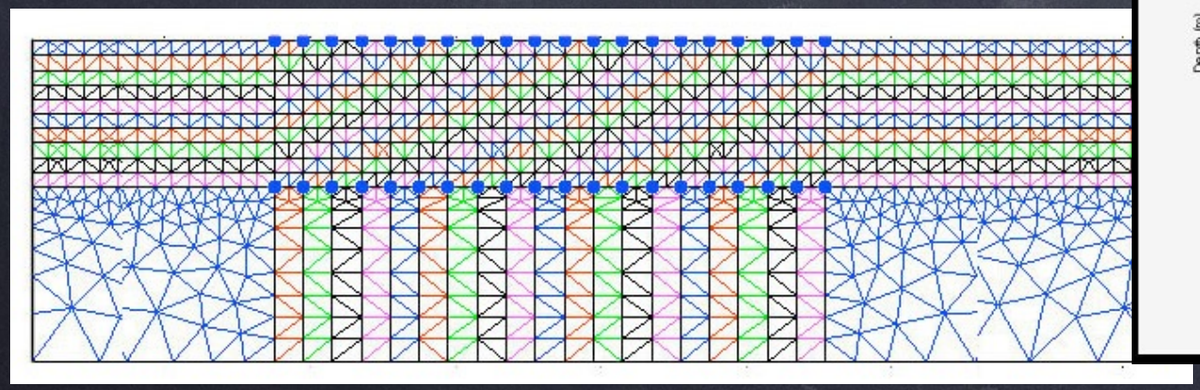
- Tools (algorithm, equipment)
- Arrays used
- Geometry
- Tunnel Effect - Corrections
- Protocols Optimization
- Real case study
- Bench-scale experimental application
- Conclusions

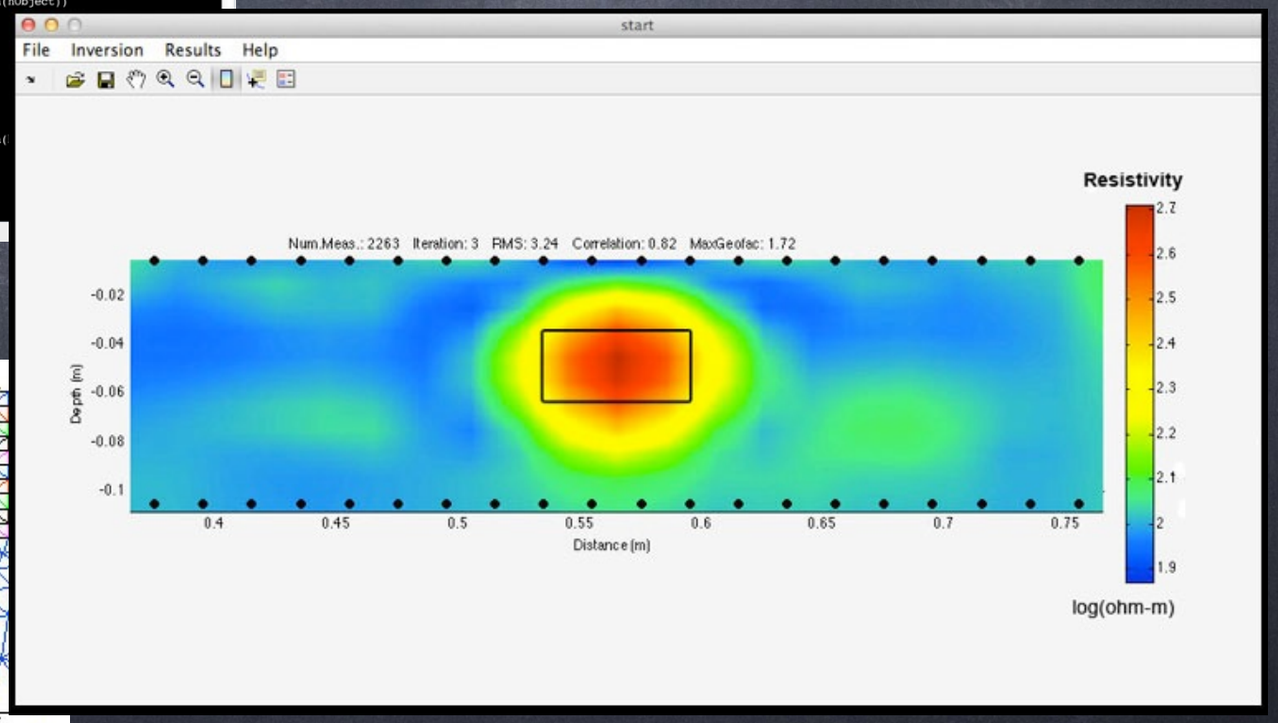
# Tools

# Inversion Algorithm ‘2D-InvCODE’

- Existing code in Matlab (Tsourlos, Karaoulis)
- Forward: Based on FEM
- Inversion: Occam



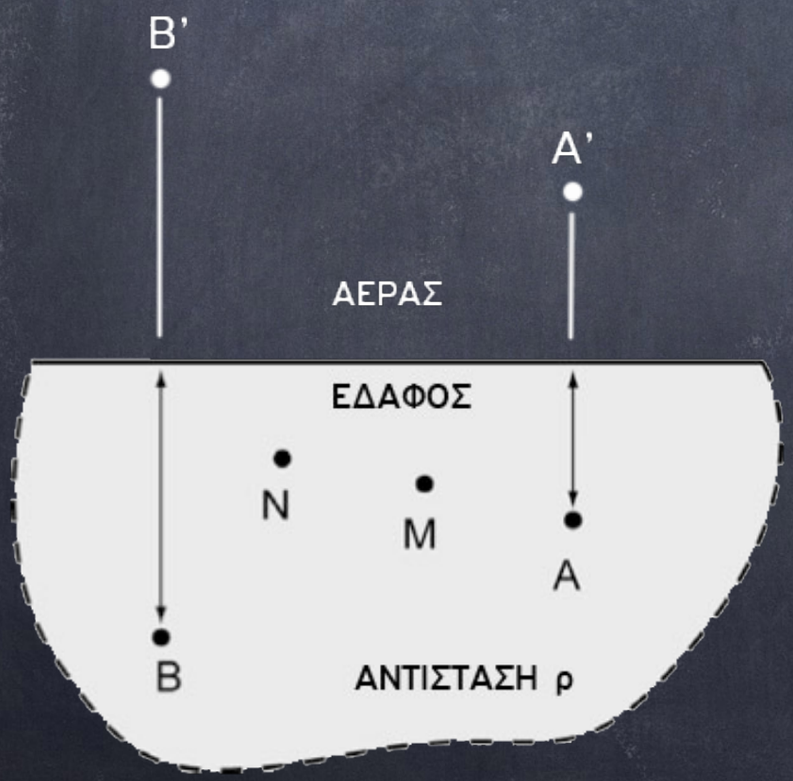



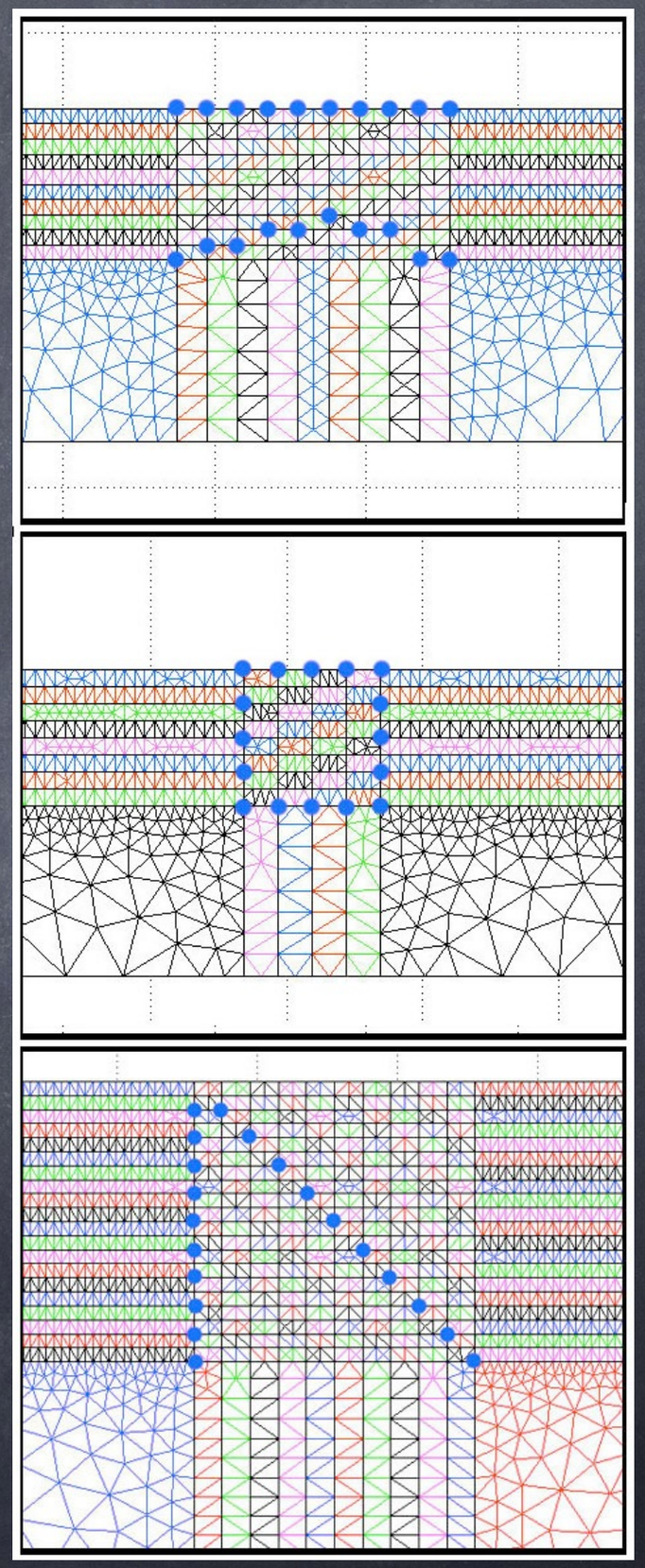


# Code Evolution

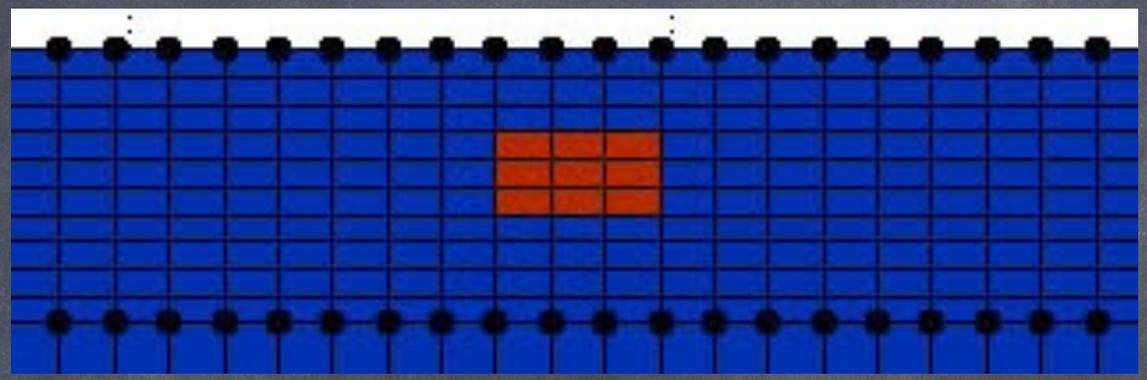
- New Protocols (2, 3 & 4 electrodes)
- Electrode Position
- Geometrical Factor Filter

$$K = \frac{4\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN} + \frac{1}{A'M} - \frac{1}{A'N} - \frac{1}{B'M} + \frac{1}{B'N}}$$

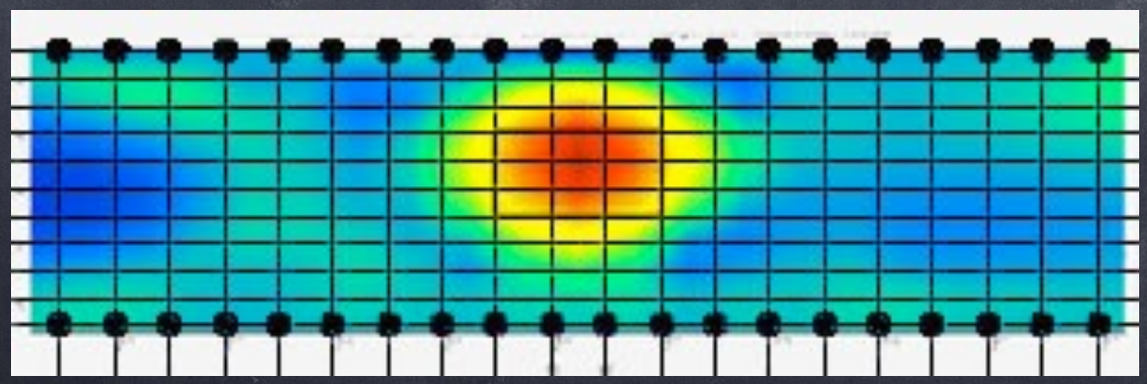


# CORRELATION FACTOR



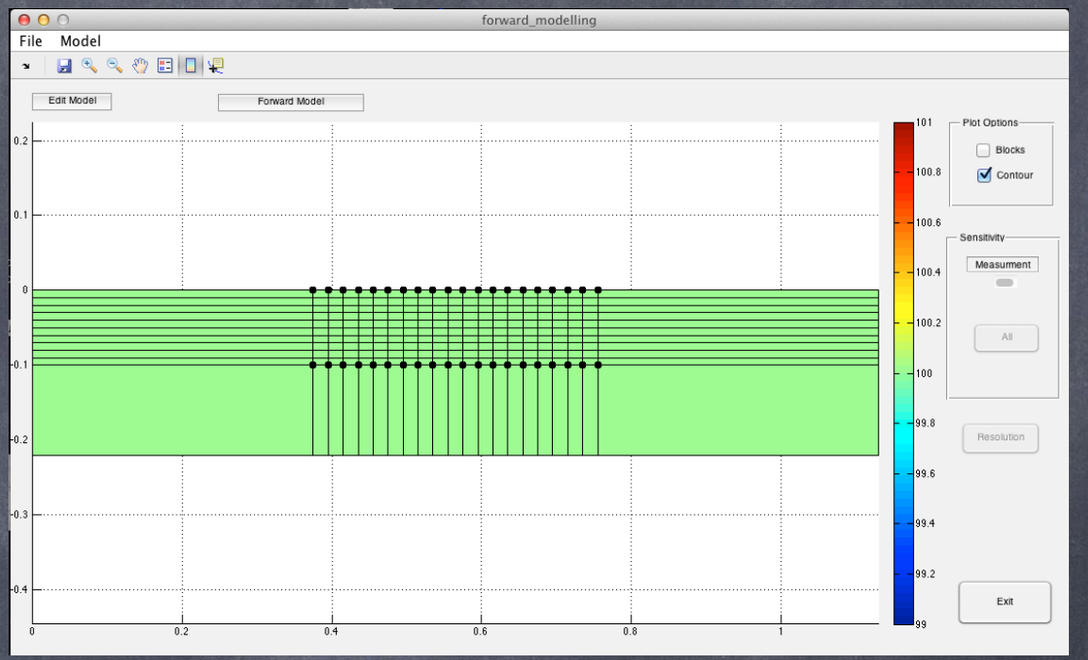
$$correlation = \frac{\overline{\rho_{inv} \cdot \rho_{\mathrm{mod}}} - \overline{\rho_{inv}} \cdot \overline{\rho_{\mathrm{mod}}}}{\left(\overline{\rho_{inv}^2} - \overline{\rho_{inv}}^2\right)^{1/2} \left(\overline{\rho_{\mathrm{mod}}^2} - \overline{\rho_{\mathrm{mod}}}^2\right)}$$

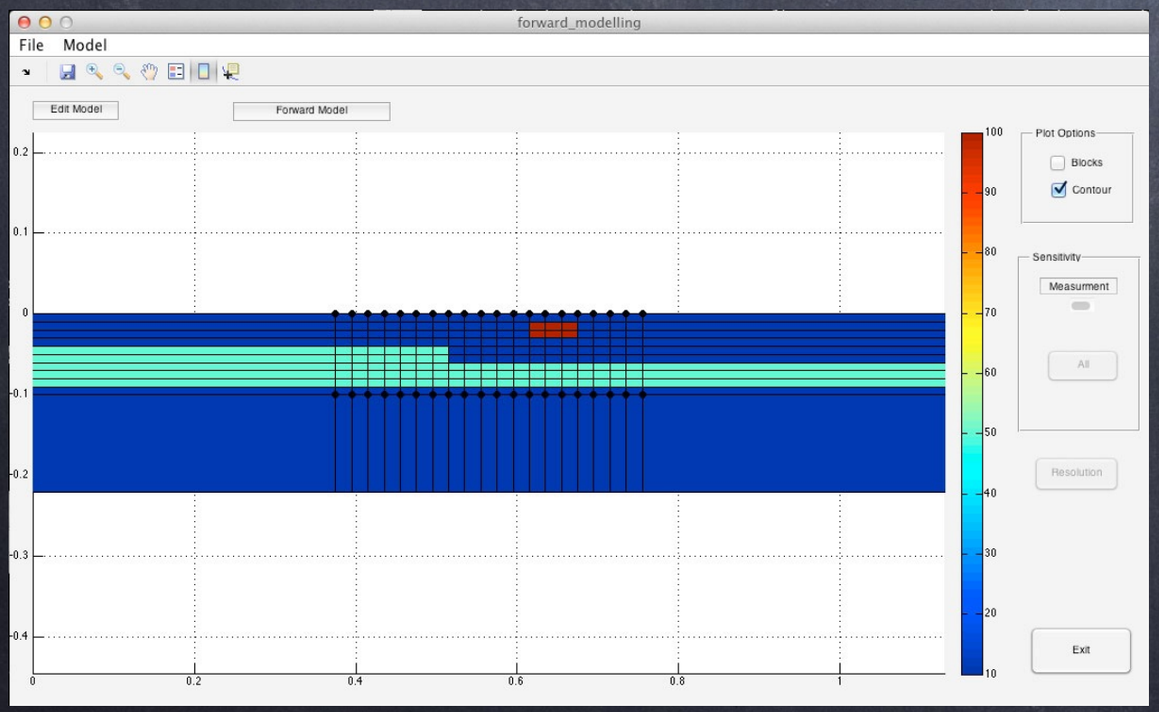


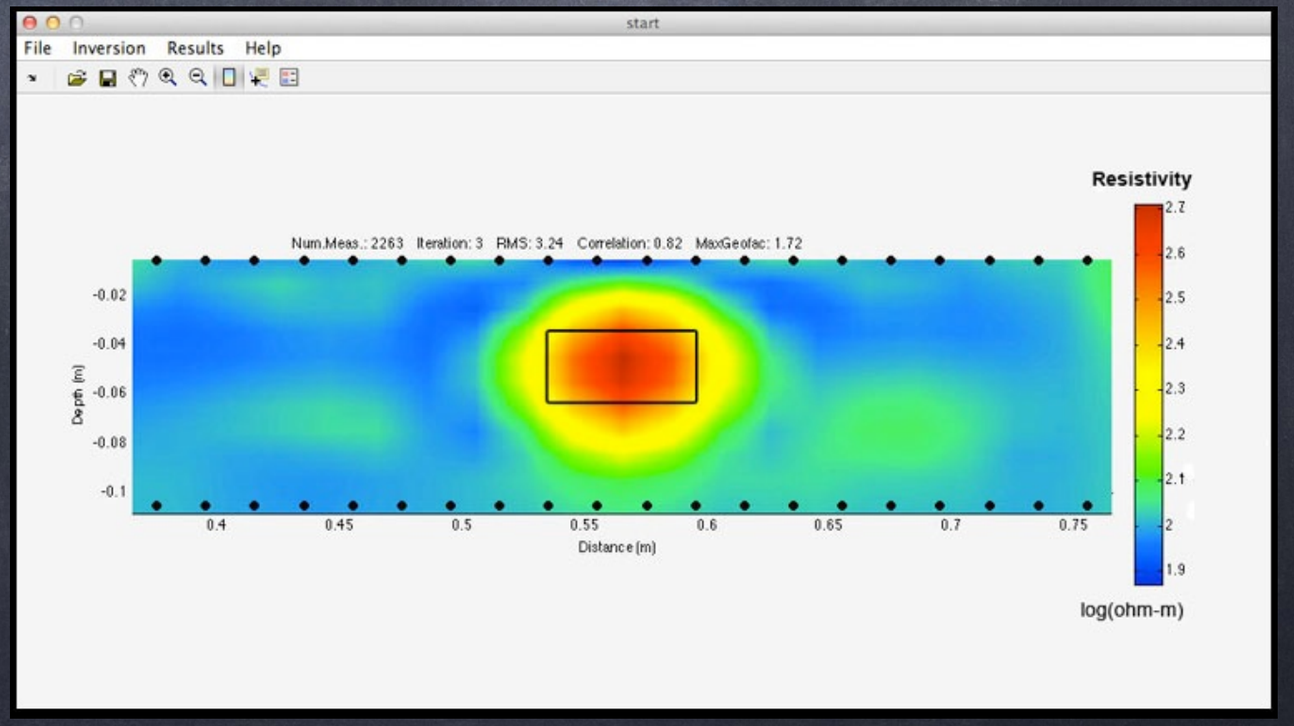
$0 < C < 1$

# ALGORITHM DESCRIPTION

- Electrode Position
  - Creating Parameters
  - Resistance Distribution
- Inversion Results
  - % RMS
  - Correlation
  - Precise Target Position (black line)



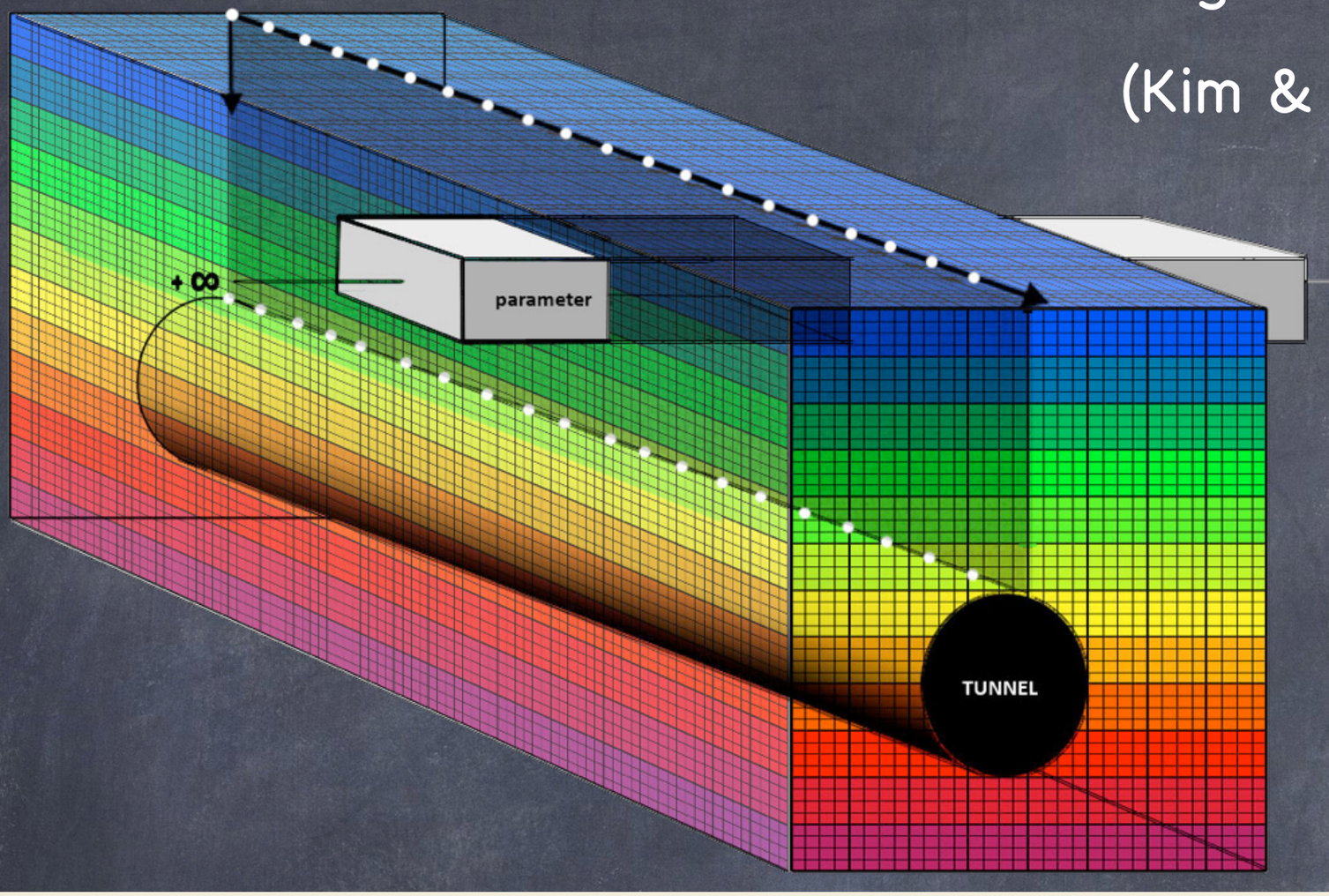



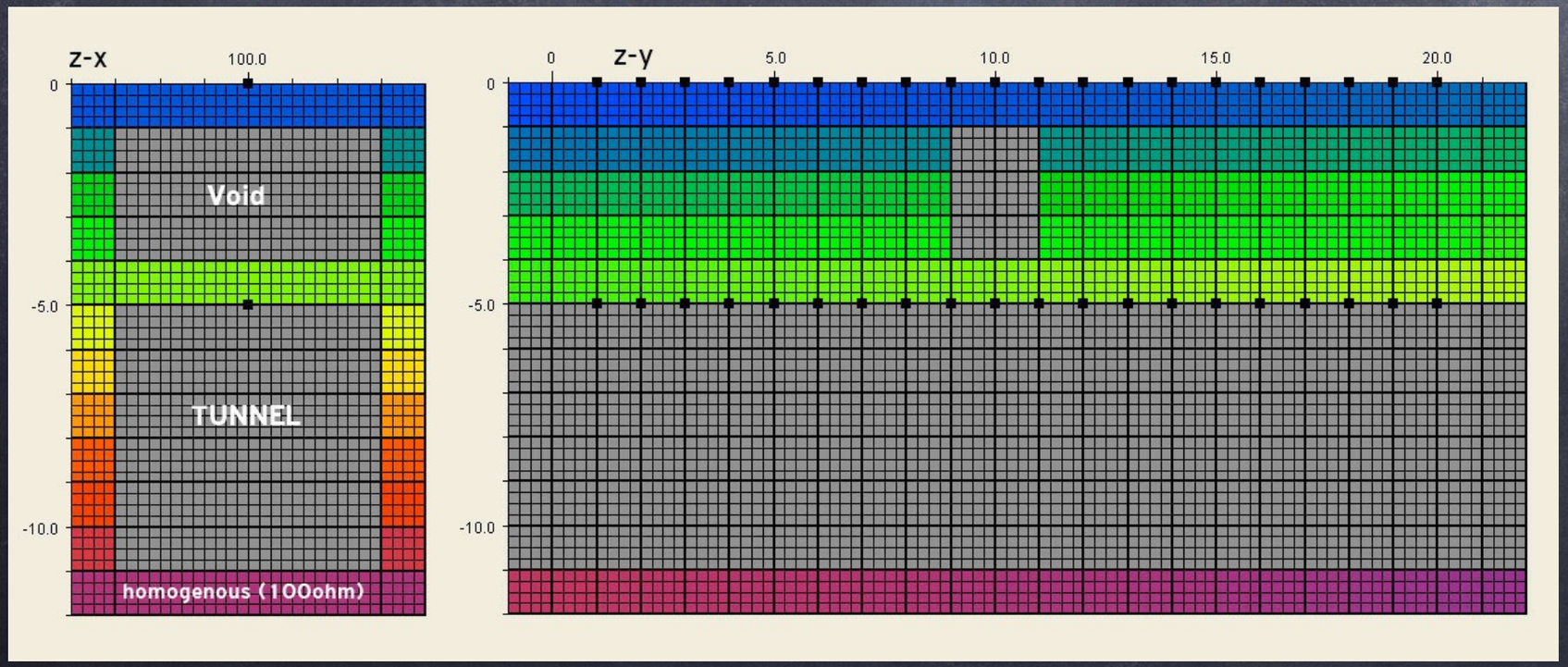



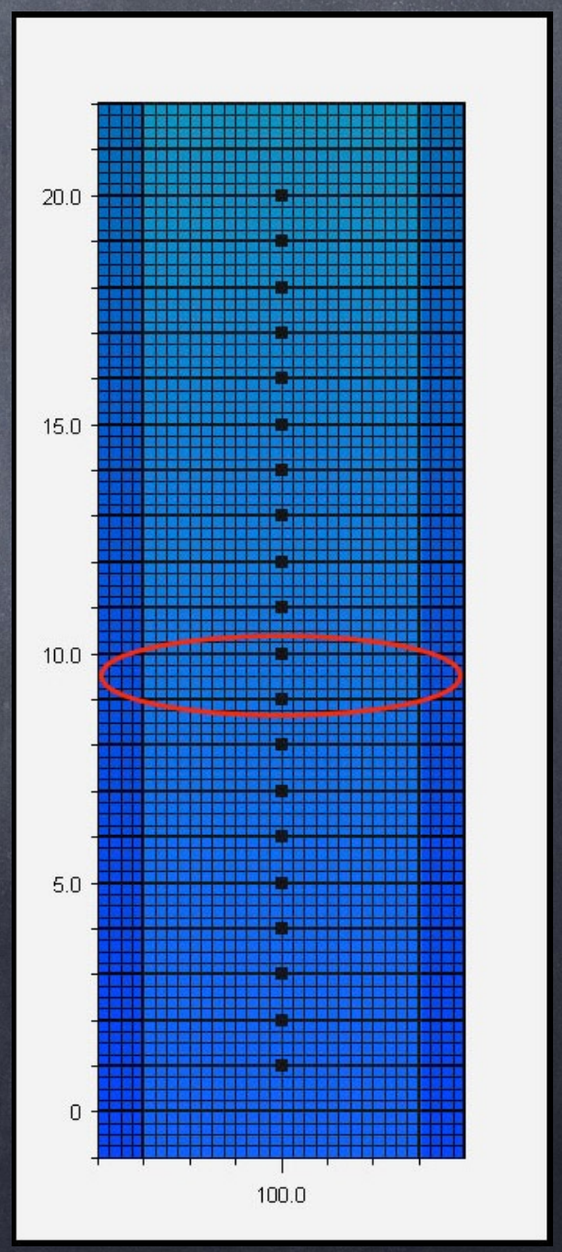
# 3D Inversion Algorithm 'DC-3DPro'

## (Kim & Yi)

- 3D Simulation Data for 2.5D Inversion
- Inversion



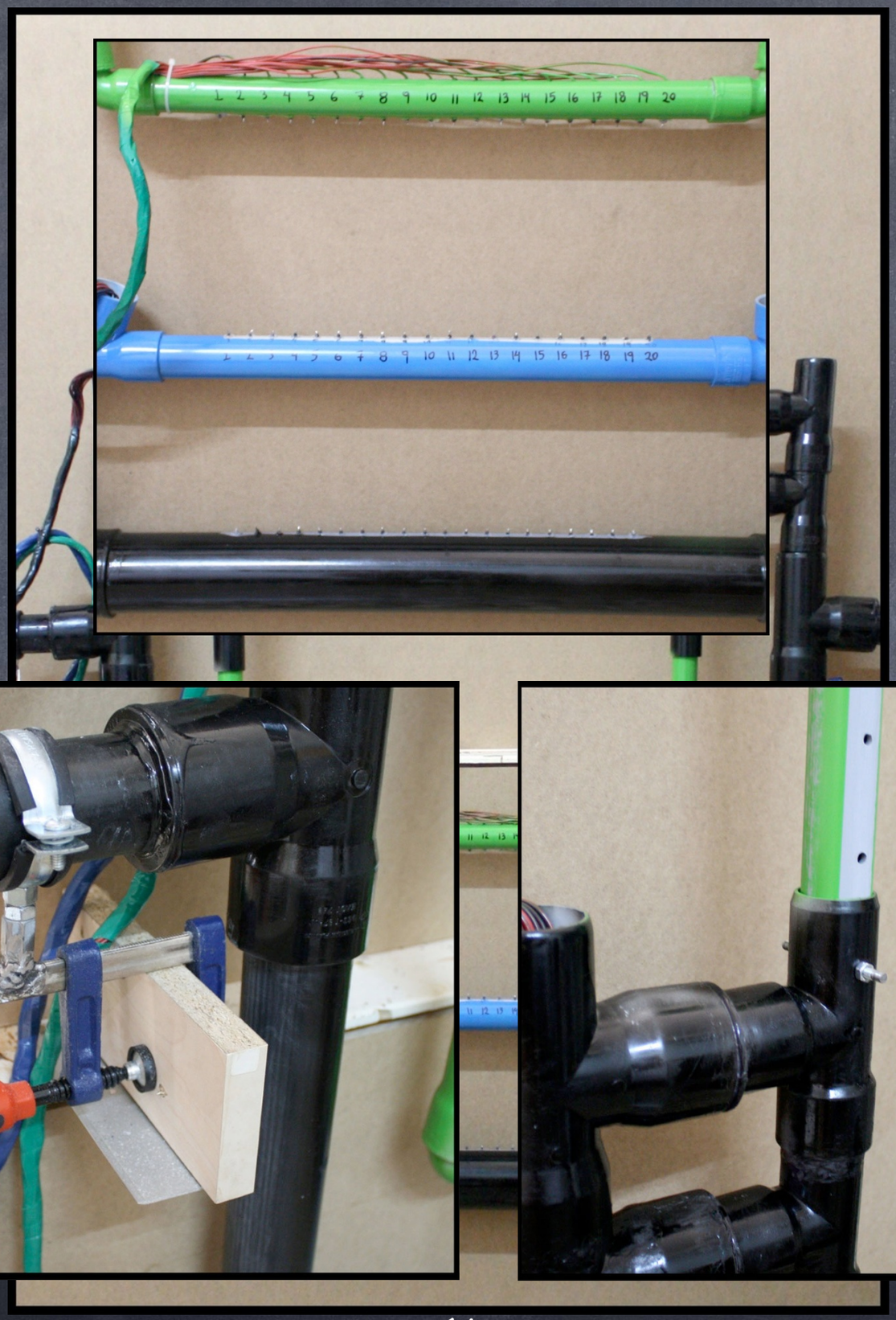
## Equipment

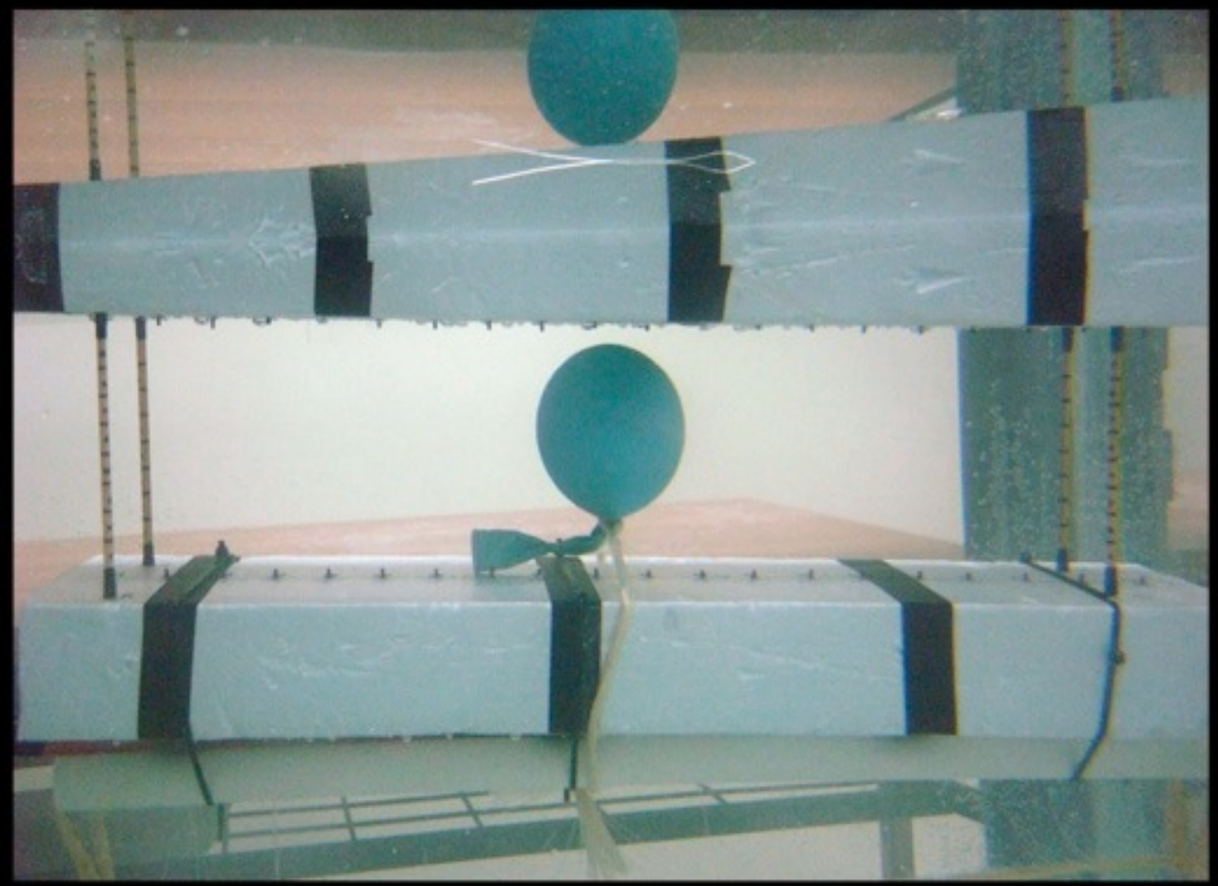
# TANK

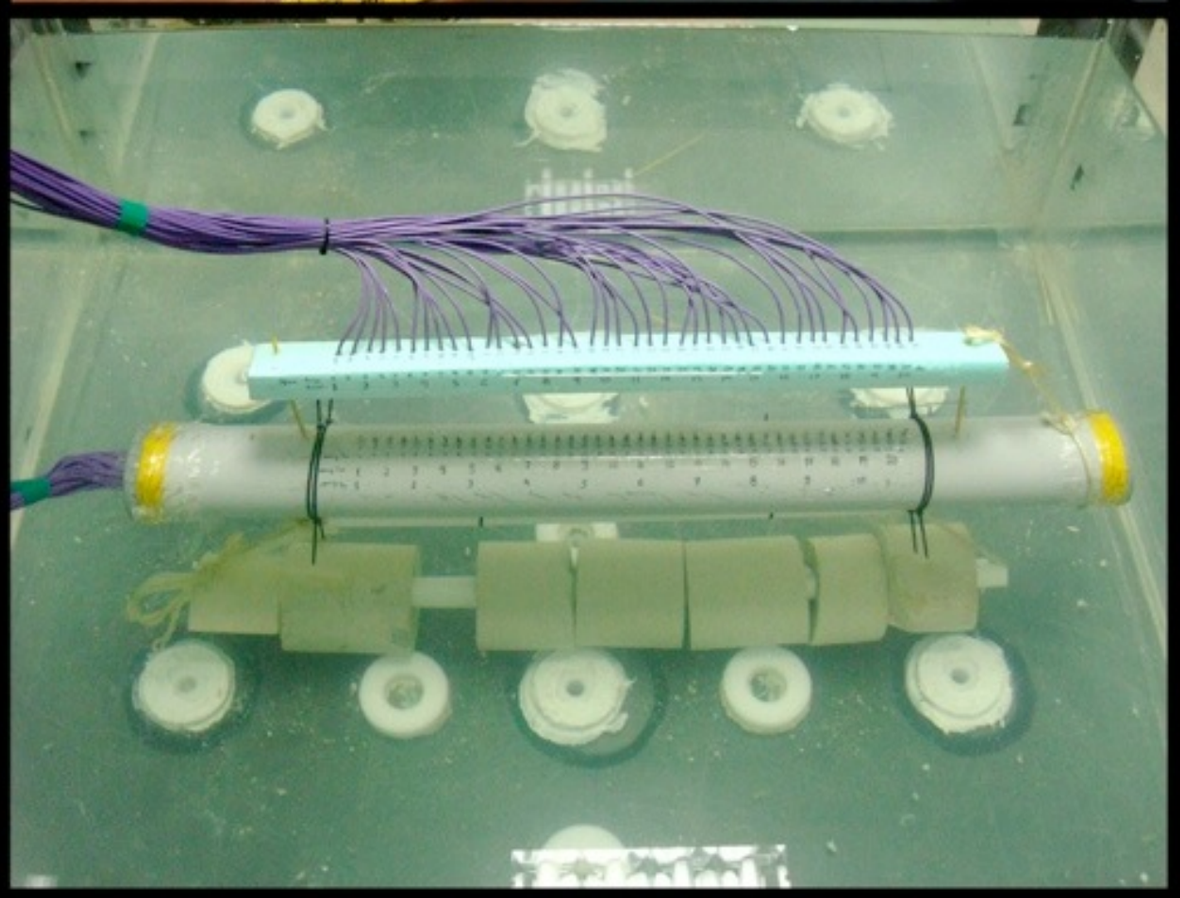
- Experimental Data
  - Fully Controlled Environment
  - Verification of Basic Inversion Code
  - Array Evaluation
  - Study of Tunnel Effect, Electrode Displacement etc

Laboratory of Geophysics & Seismology
Department of Natural Resources & Environment
Technological Educational Institute of Crete

# Apparatus

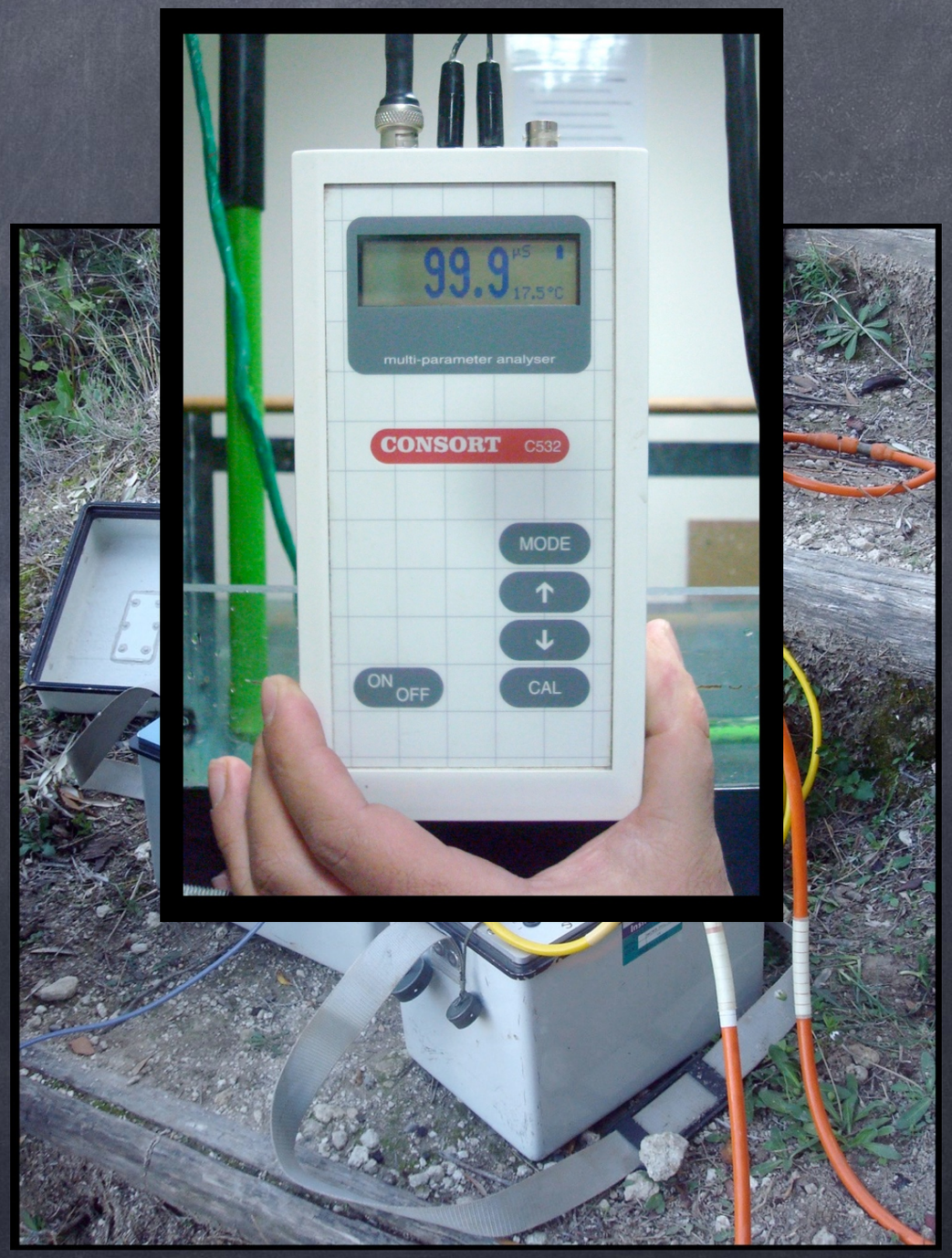






# Instruments

- Electrical Resistivity Meter
- Conductivity Meter

# Arrays

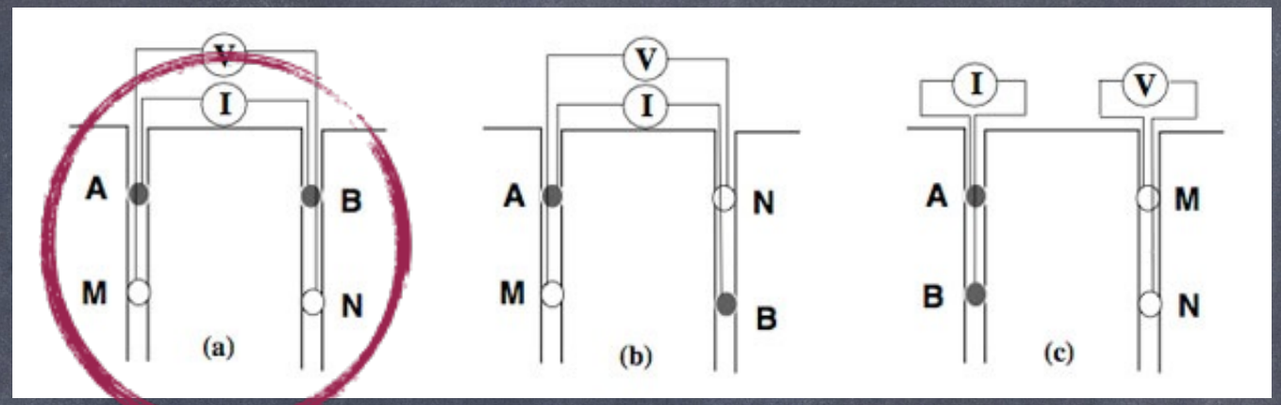
- Why I should make new Protocols ?

  - Different Arrays between boreholes and surface-to-tunnel

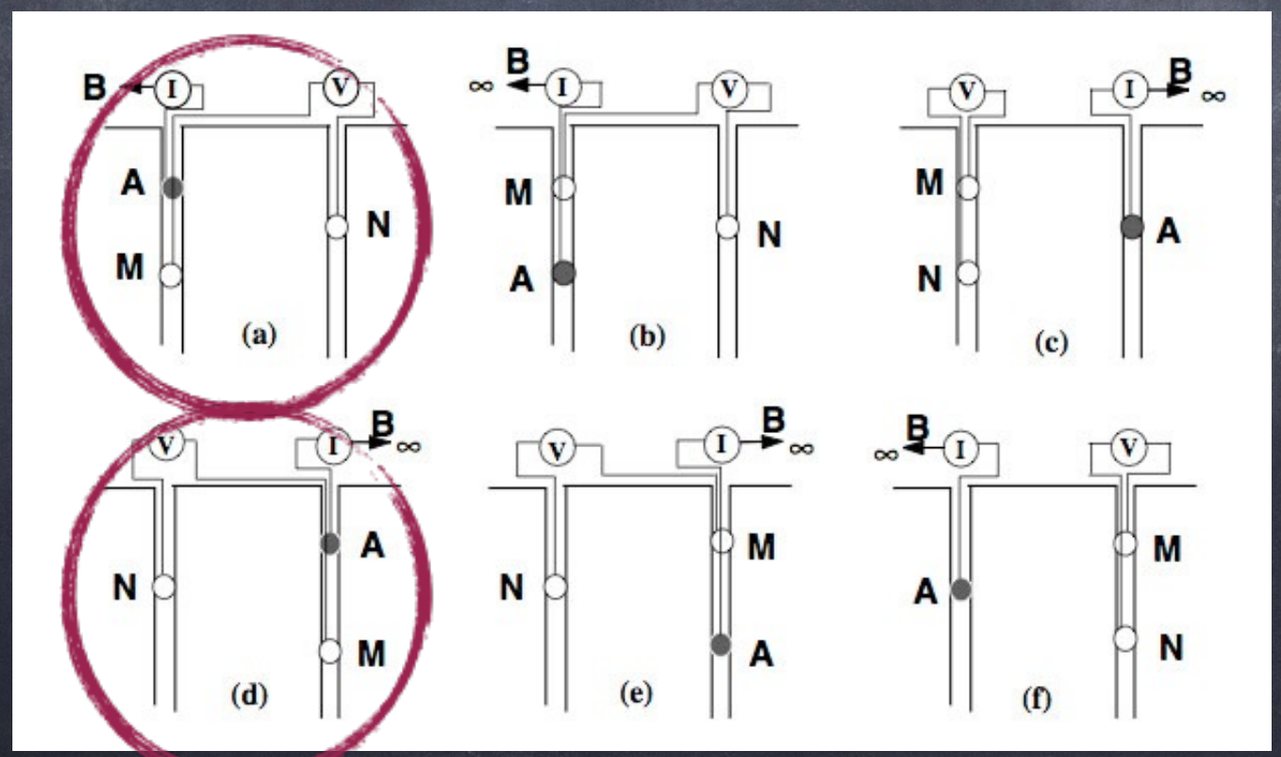
    => Asymmetrical Sensitivity

# Algorithm to generate Protocols (MATLAB)

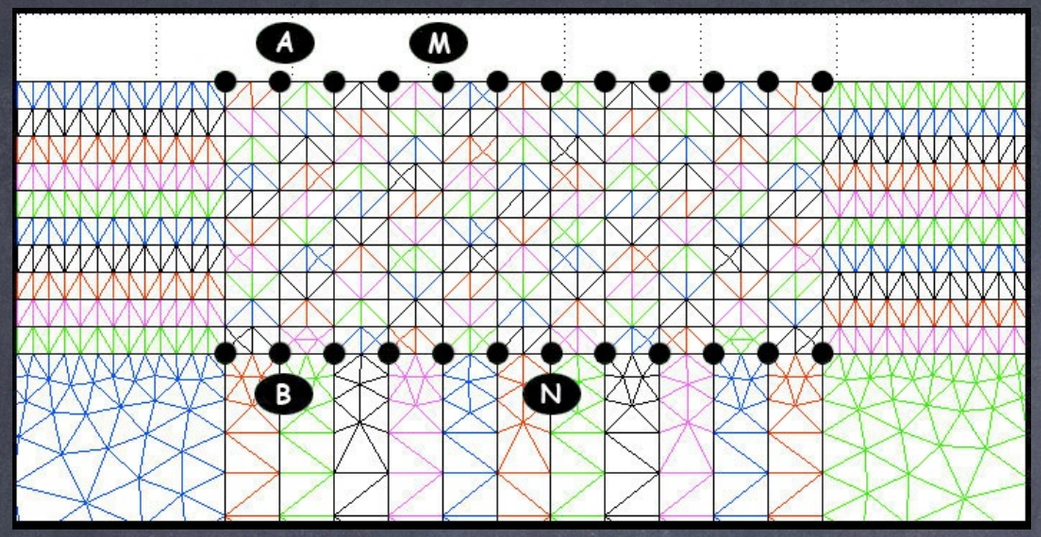
Electrode combinations based on Crosshole Arrays

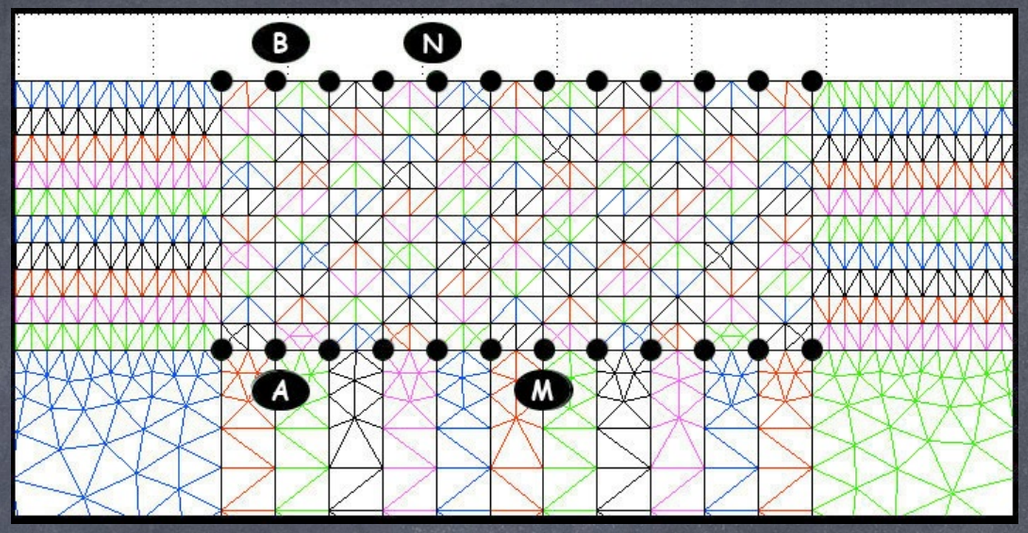



Greenhalgh & Bing (2000)

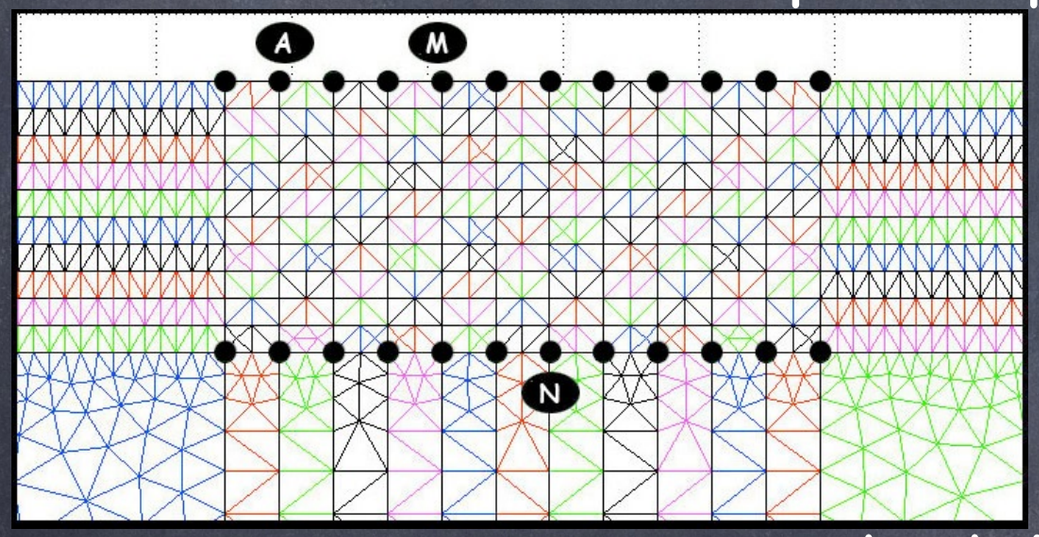


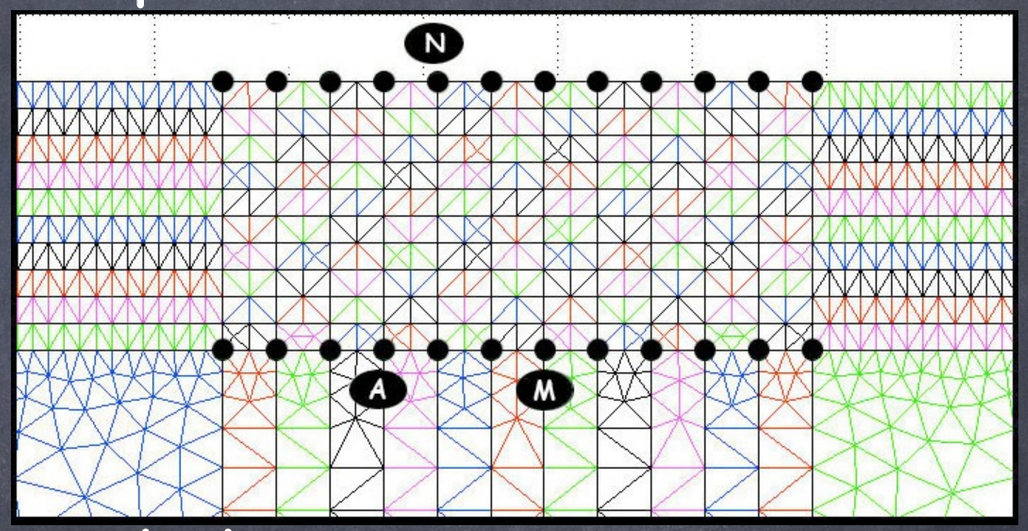
## bipole-bipole (bb)



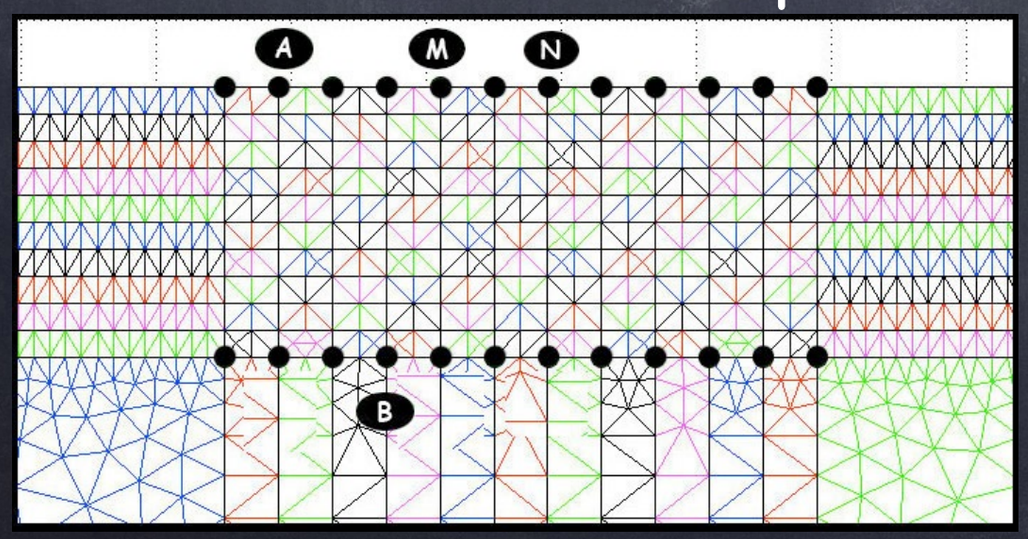



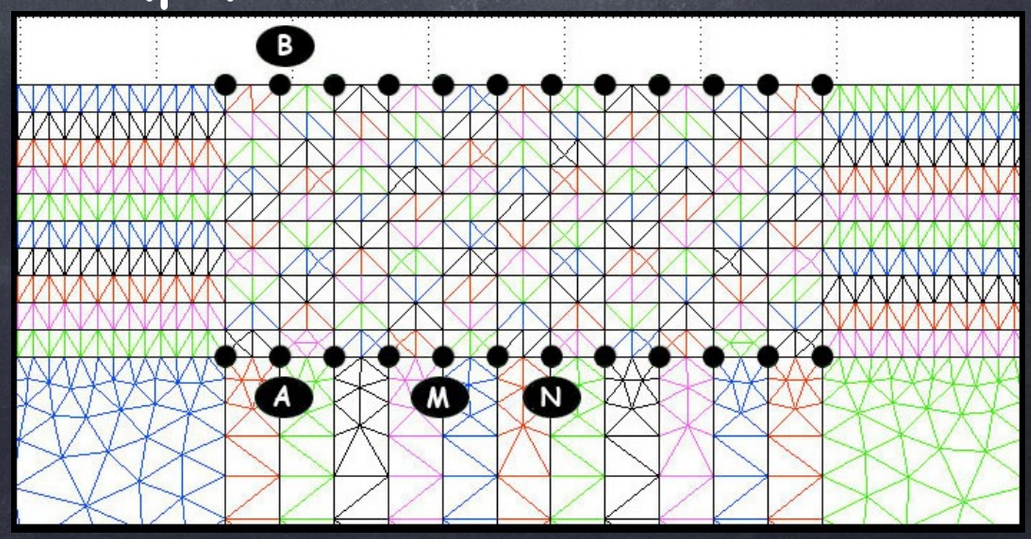

## pole-dipole (pd)




## pole-tripole (pt)



MATLAB

ektypwsh

protocol_bb_o

mod15_bb

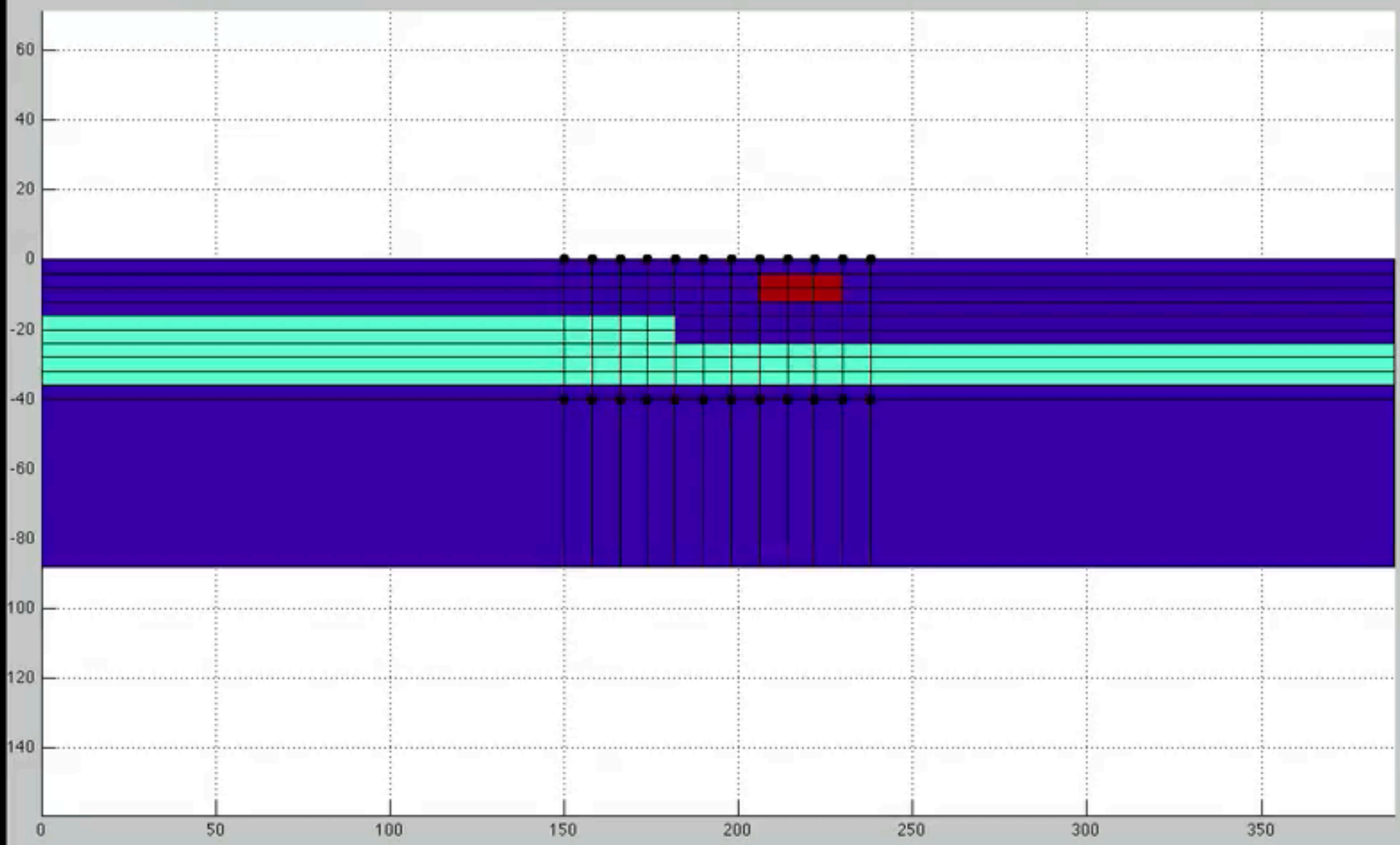
mod15_bb_opt

forward_modelling

File Model

Edit Model

Forward Model





Plot Options

Blocks

Contour

Sensitivity

Measurment

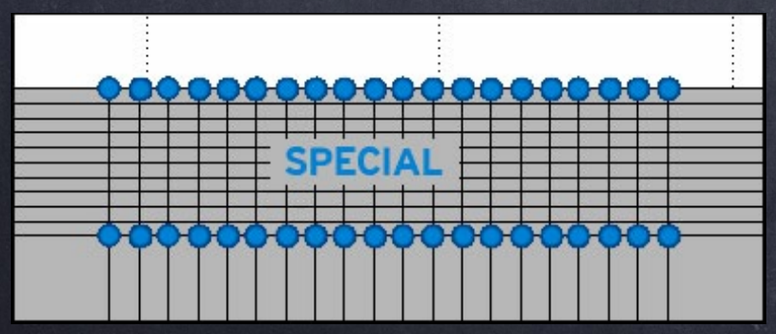
All

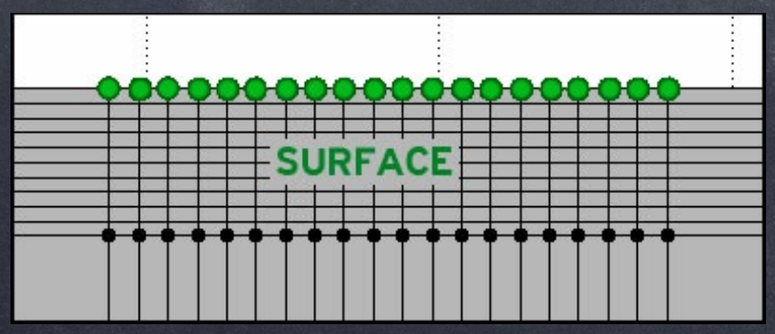
Resolution

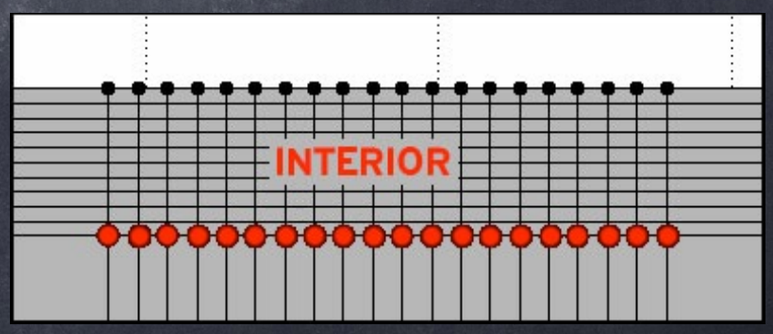
Exit

# FINAL PROTOCOLS

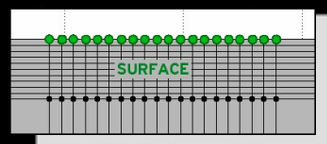
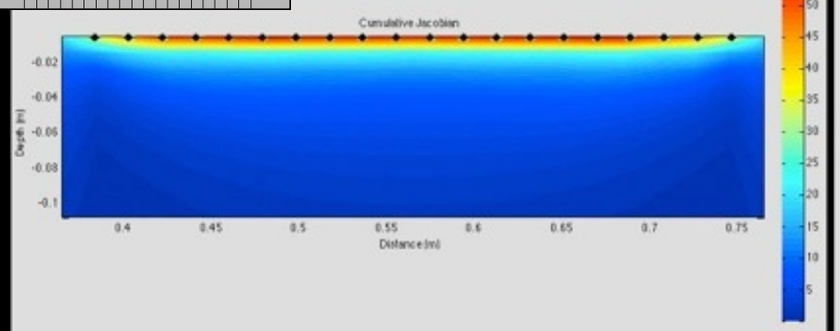
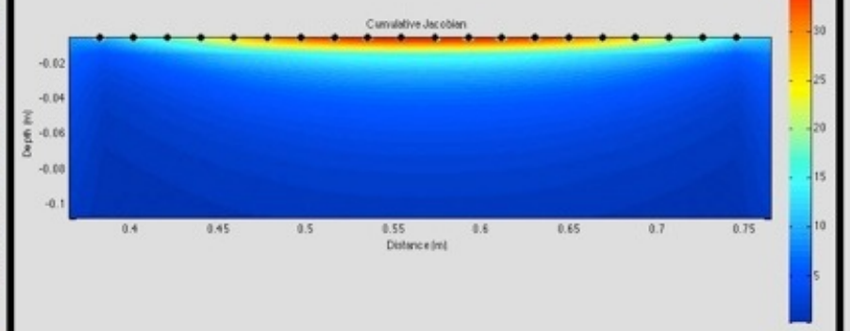
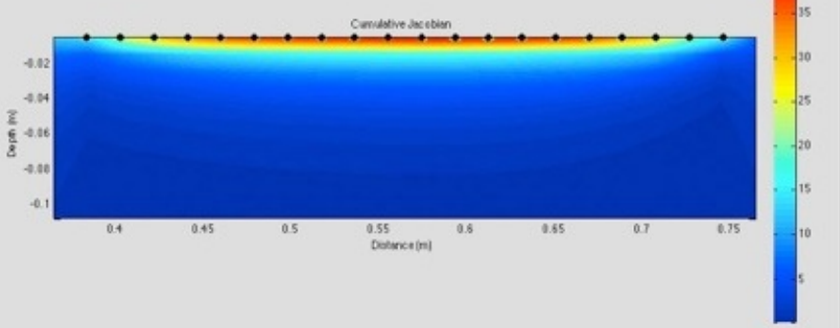
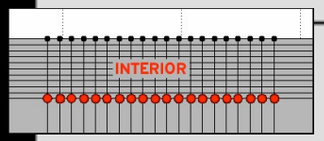
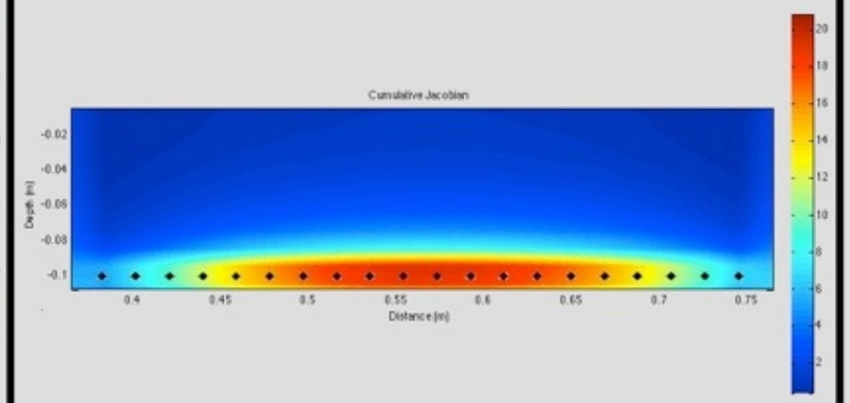
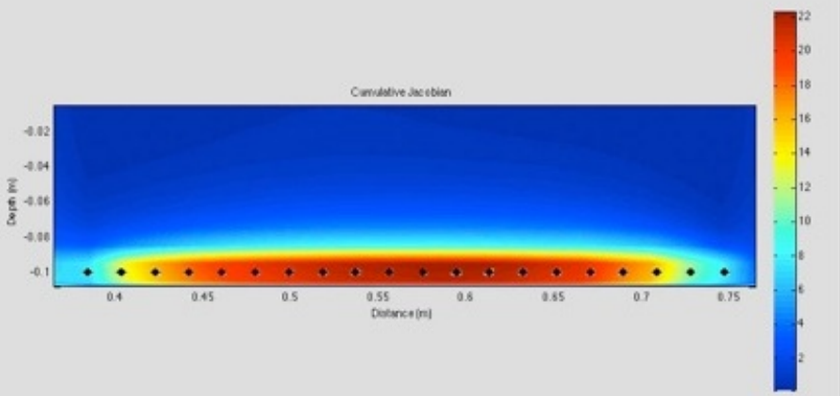
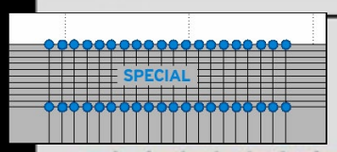
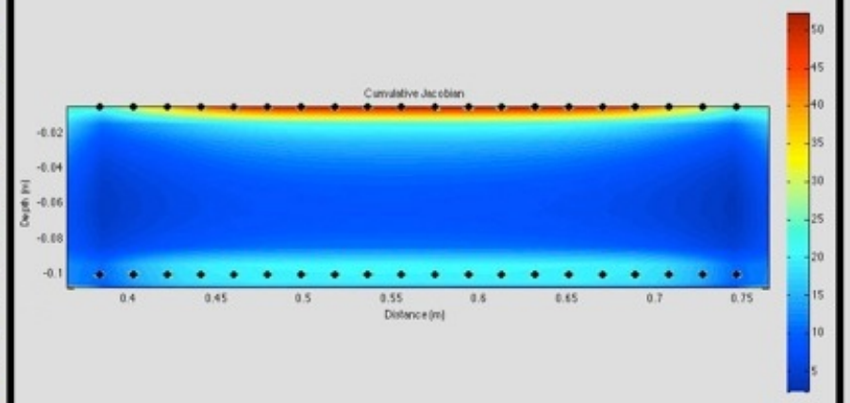
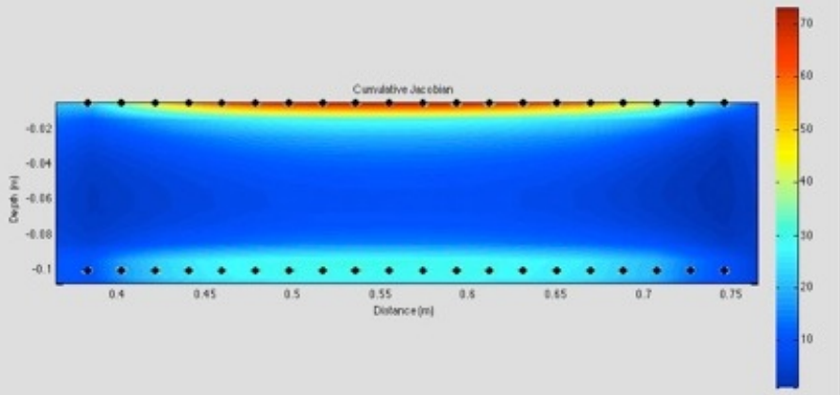
| | Protocol | Combination |
|---|---|---|
| Special | special-bb | AM-BN |
| | special-pd | AM-N + N-AM |
| | special-pt | AMN-B + B-AMN |
| Surface | surf-bb, pd, pt | AMBN, AMN+NAM, AMNB+BAMN |
| Interior | inter-bb, pd, pt | |

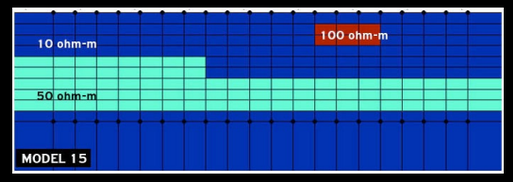


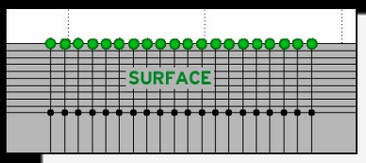
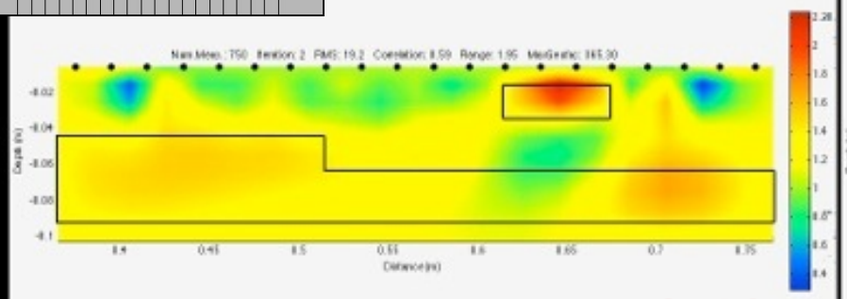
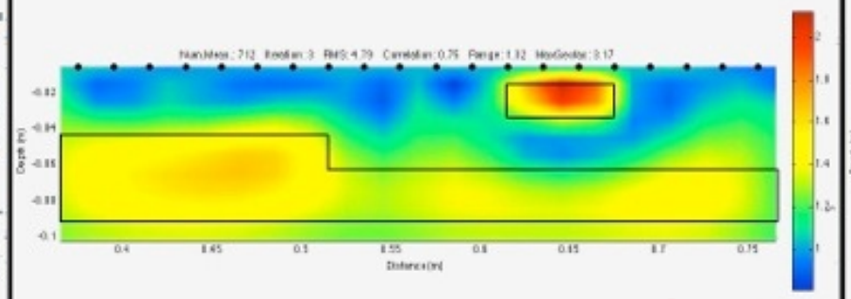
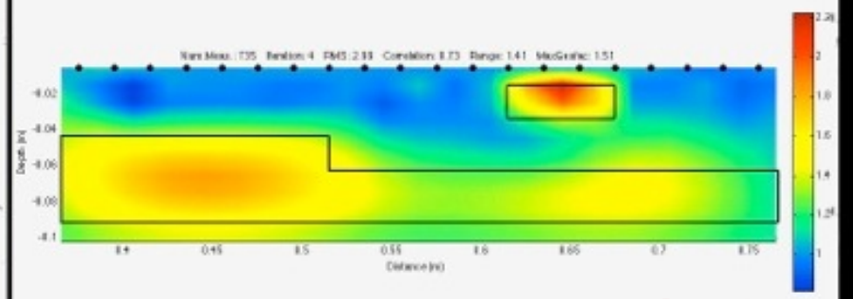
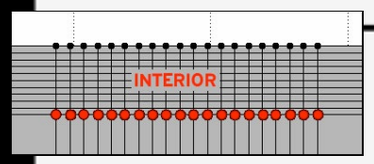
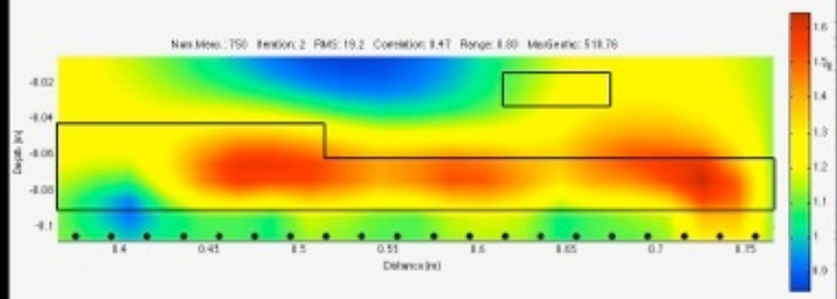
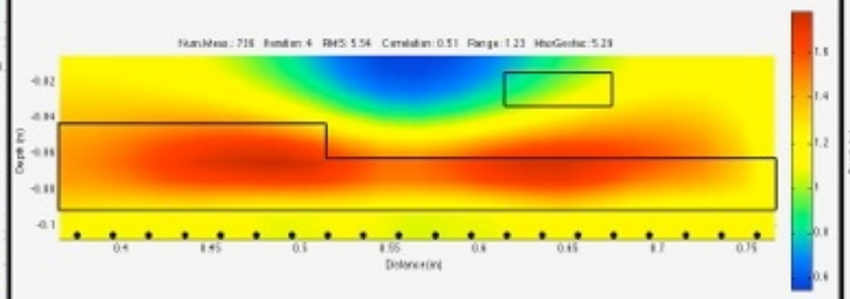
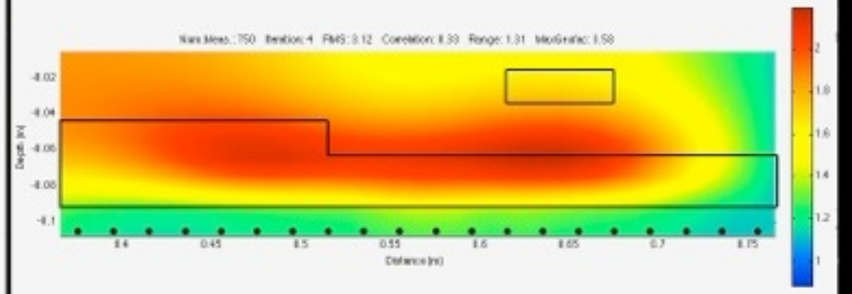
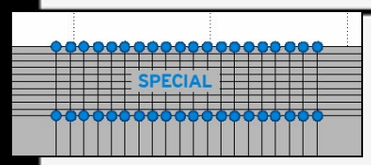
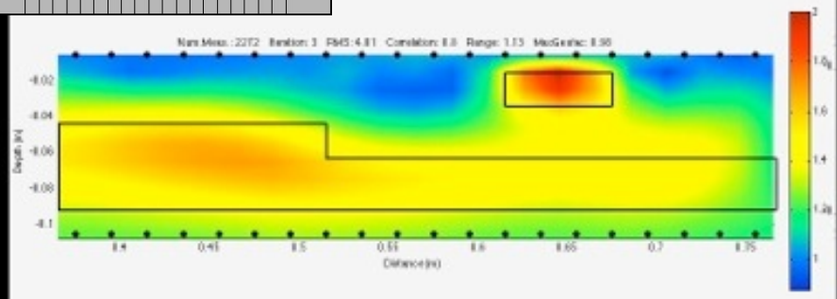
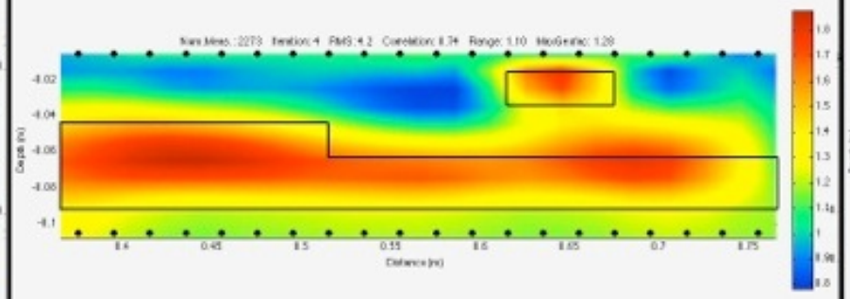
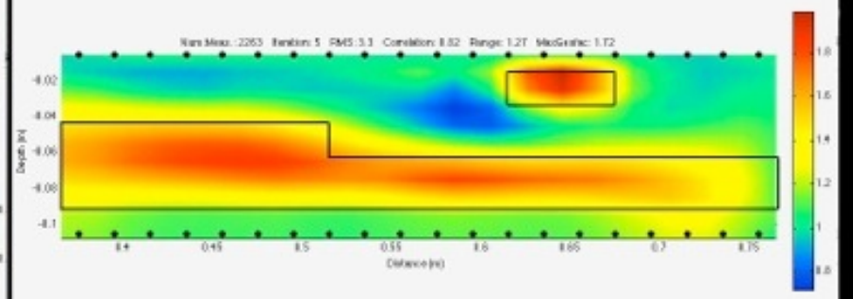



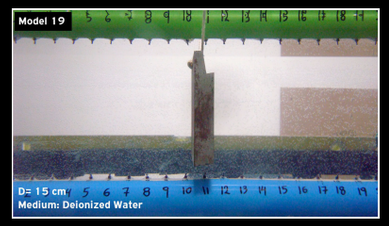
# Cumulative Jacobian Matrix

| | bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|---|
|   SURFACE |   |   |   |
|   INTERIOR |   |   |   |
|   SPECIAL |   |   |   |




| | bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|---|
|  SURFACE |  cor=0.59 |  cor=0.75 |  cor=0.73 |
|  INTERIOR |  cor=0.47 |  cor=0.51 |  cor=0.33 |
|  SPECIAL |  cor=0.8 |  cor=0.74 |  cor=0.82 |

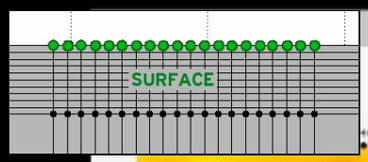
Conductive target



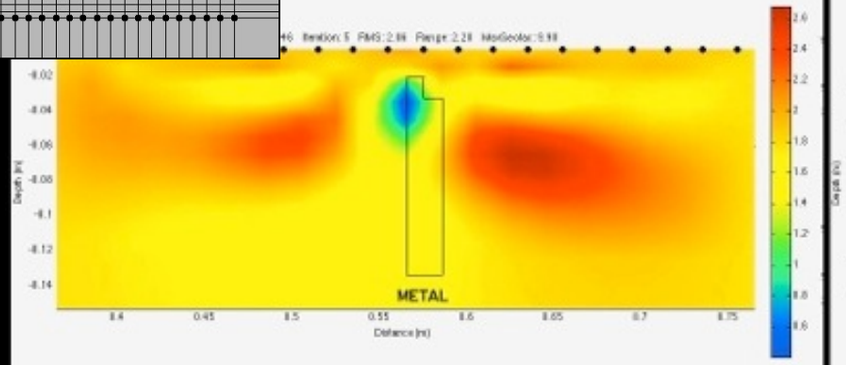

bipole-bipole

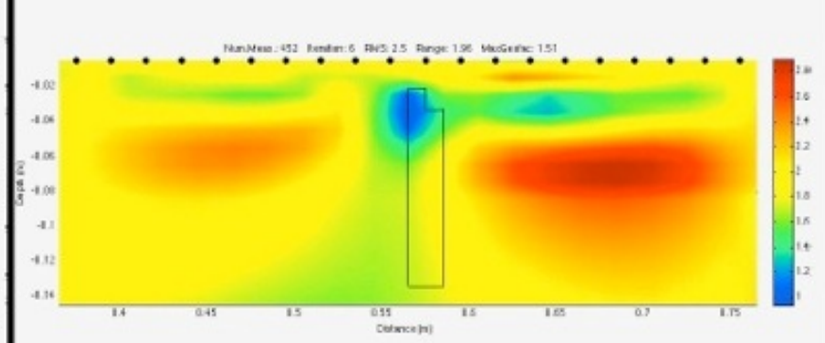
pole-dipole

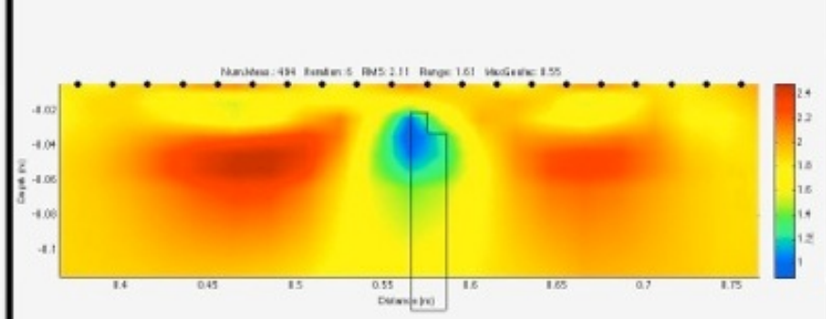
pole-tripole

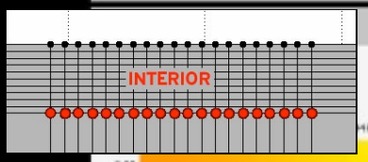



SURFACE

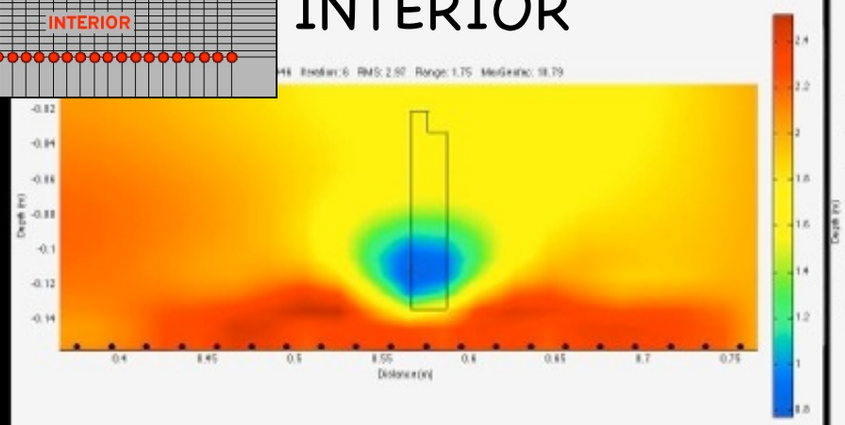


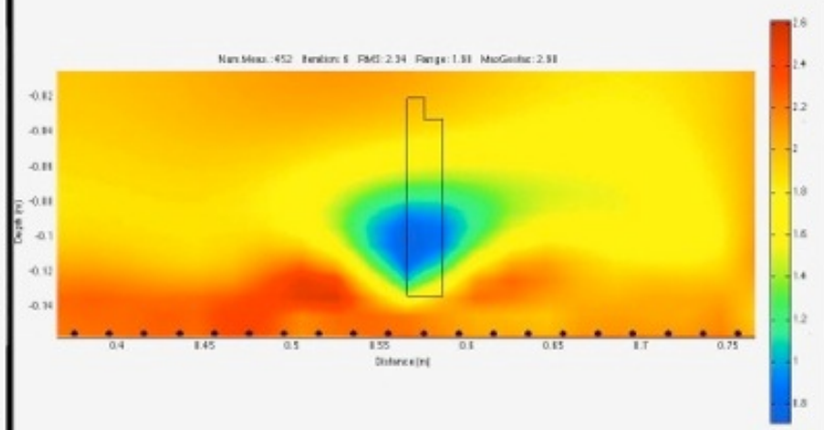



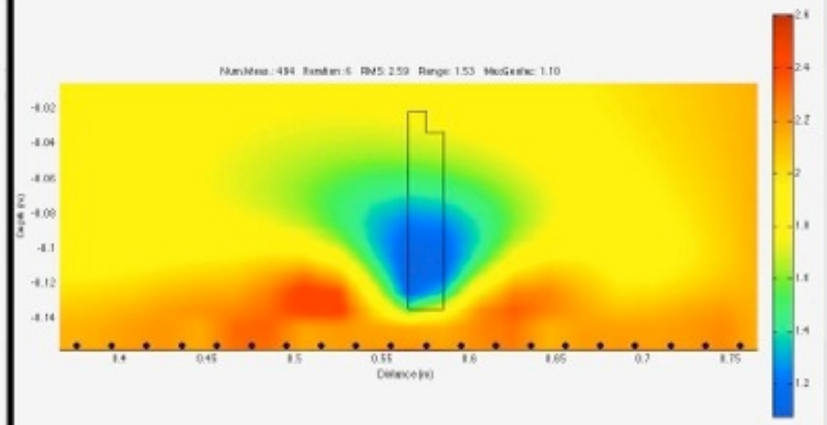



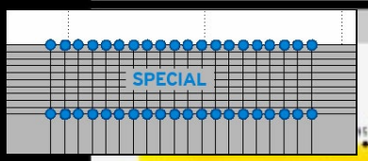



INTERIOR

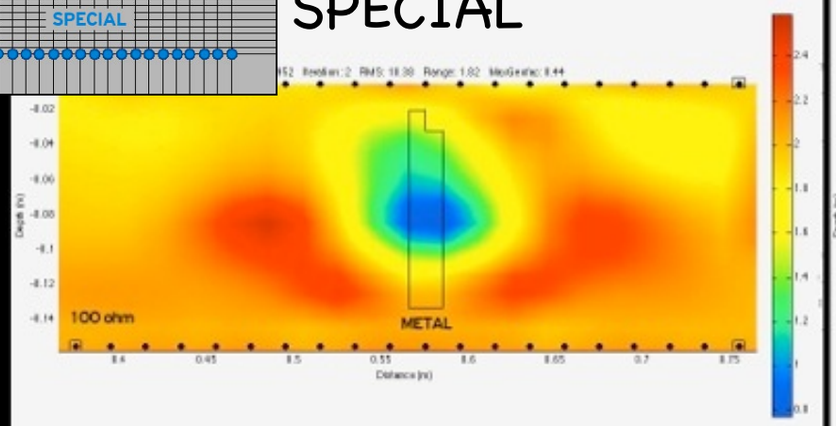


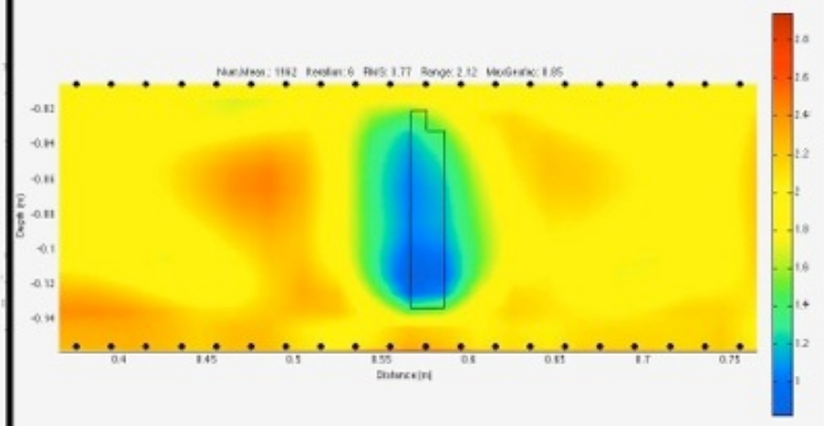



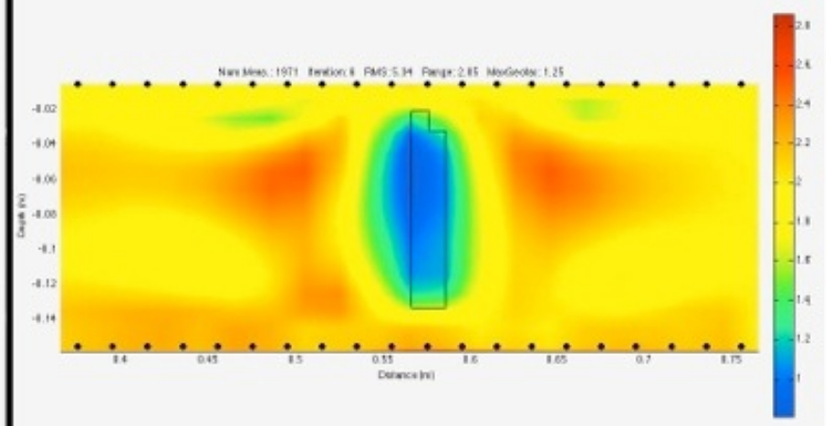



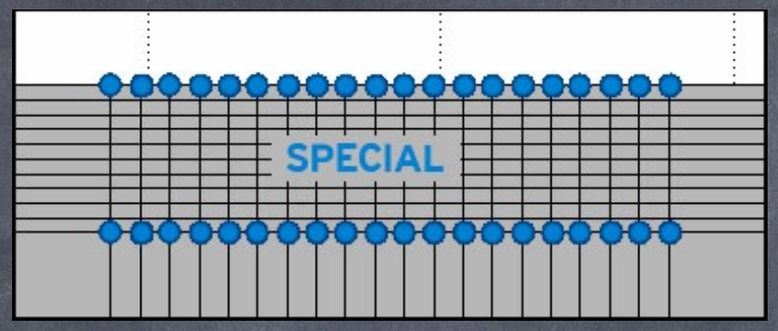

SPECIAL



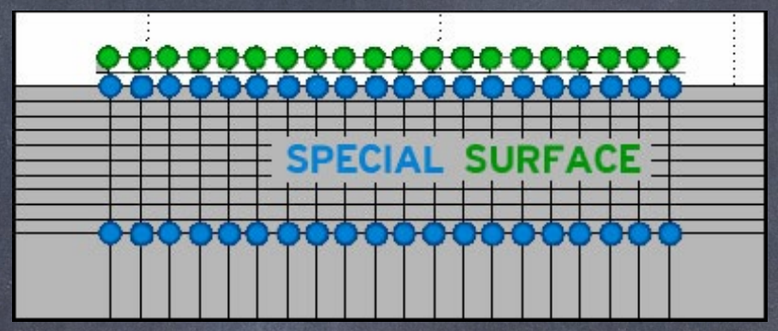



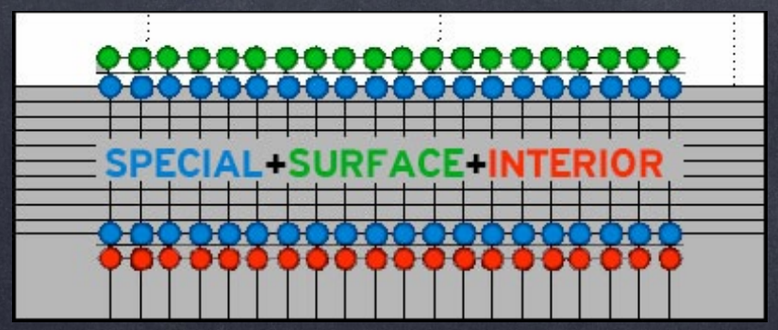
# SPECIAL

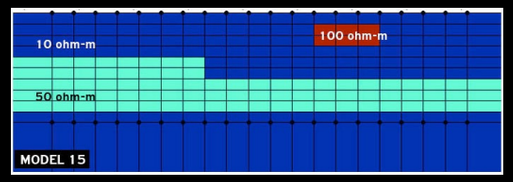


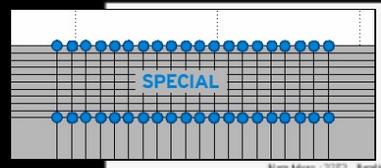
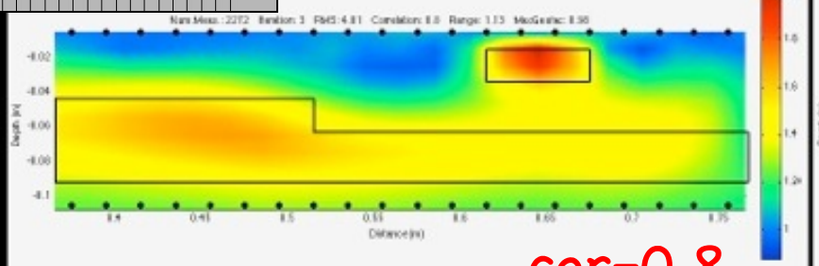
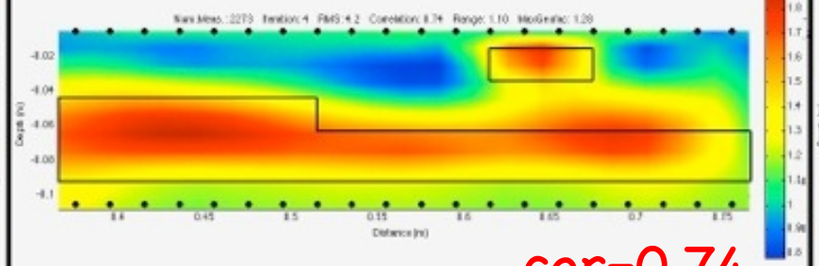
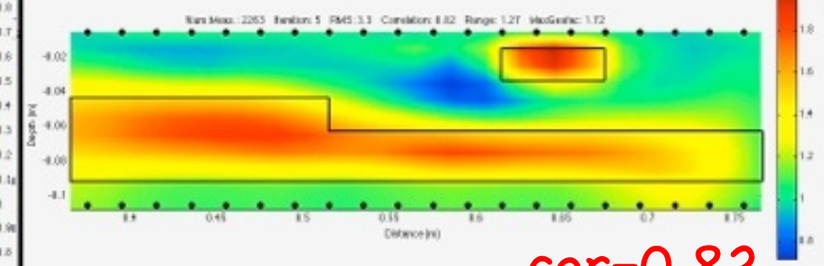
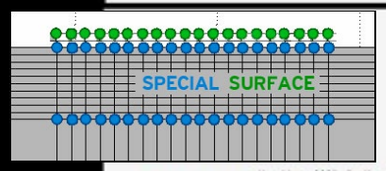
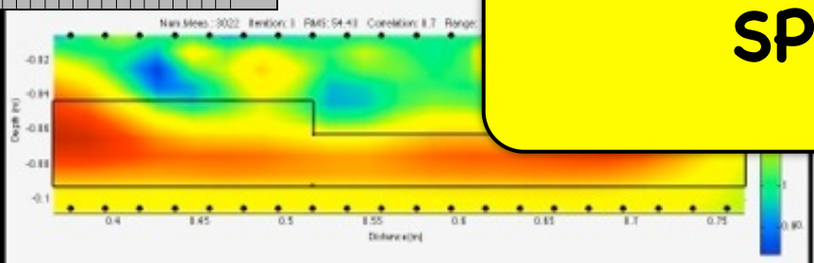
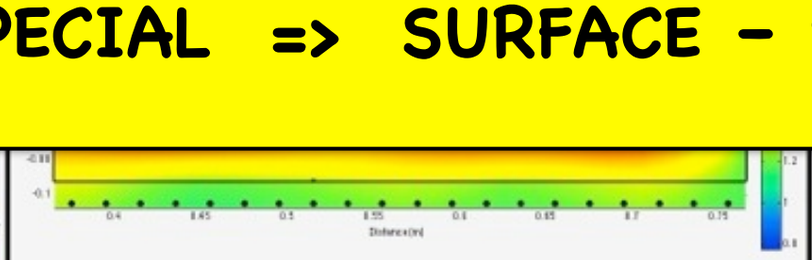
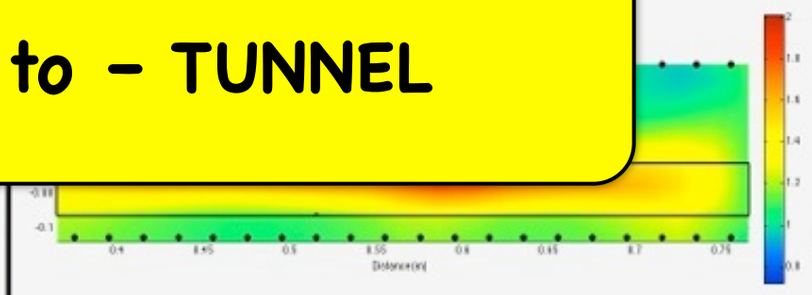
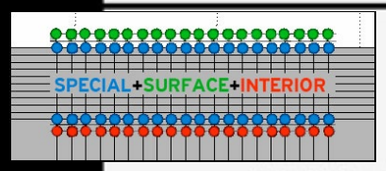
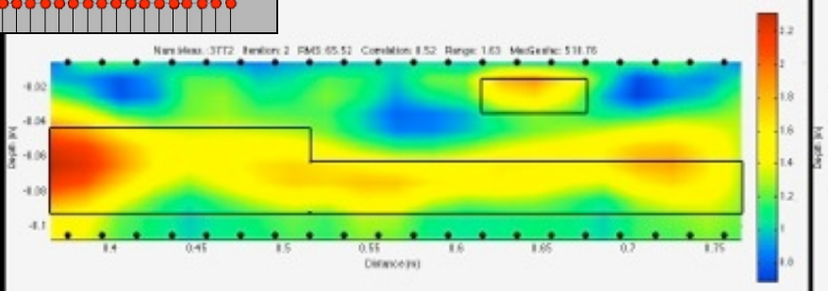
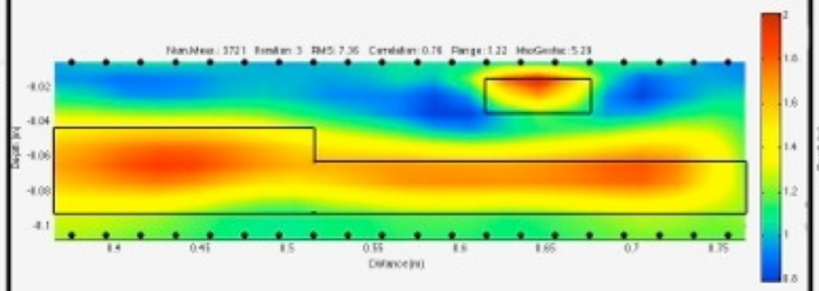
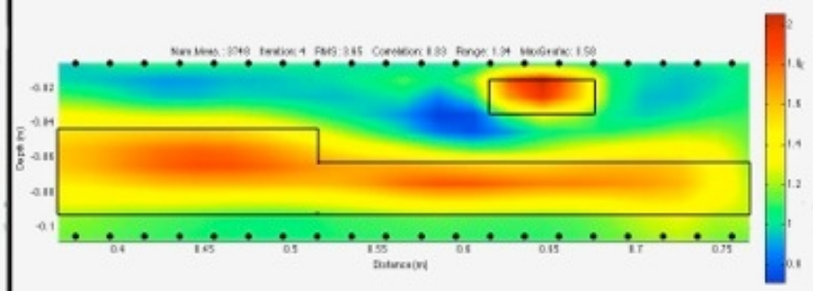

# SPECIAL + SURFACE




# SPECIAL + SURFACE + INTERIOR

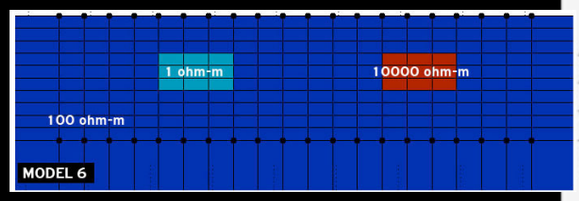
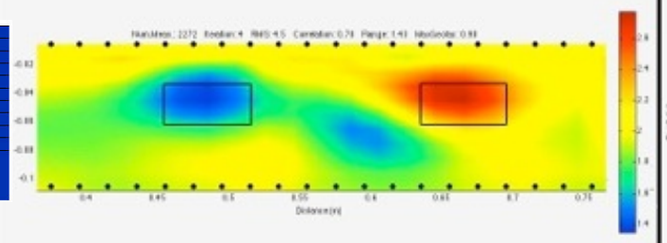
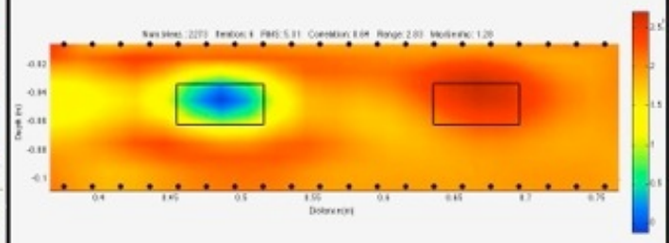
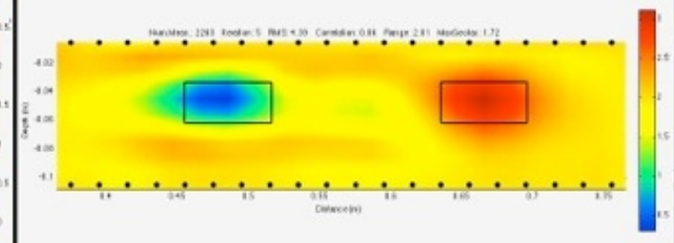
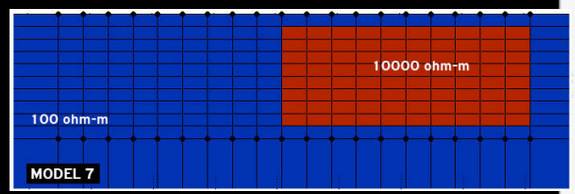
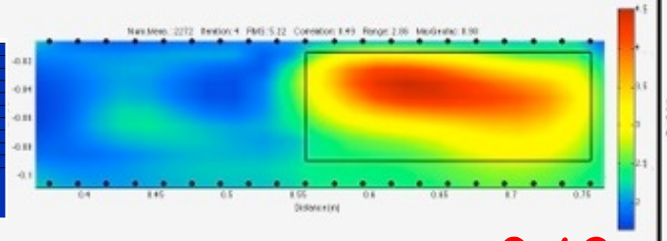
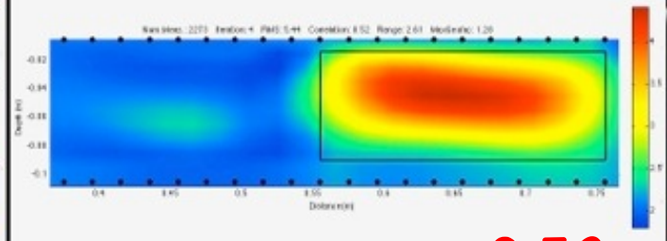
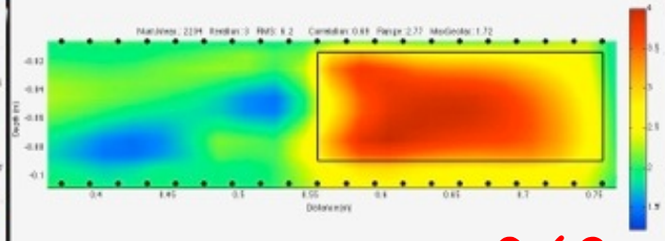
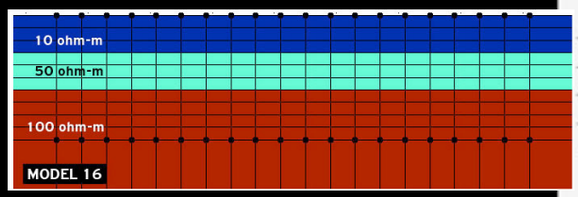
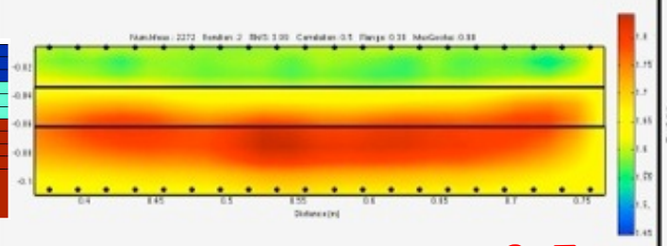
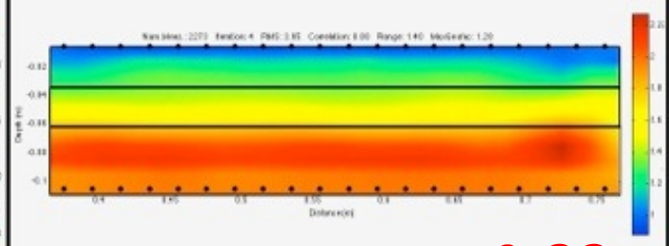
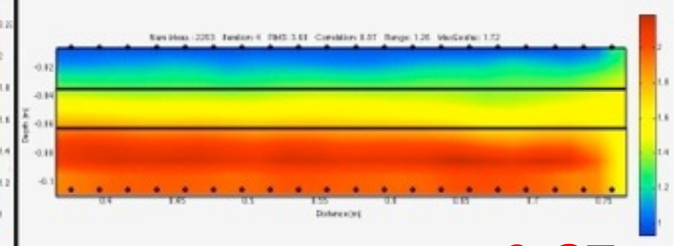
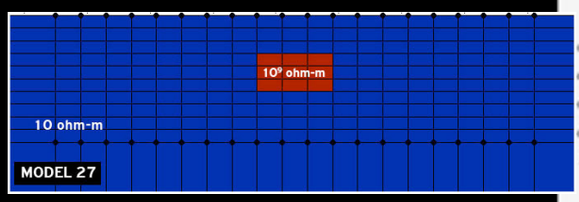
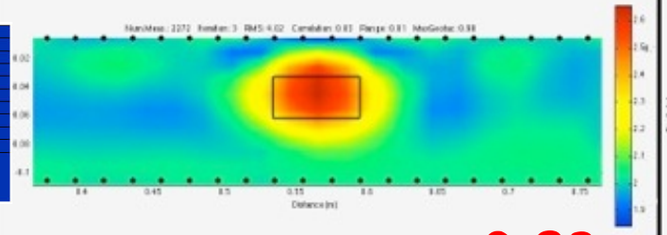
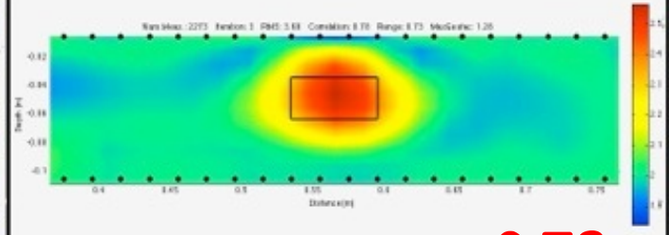
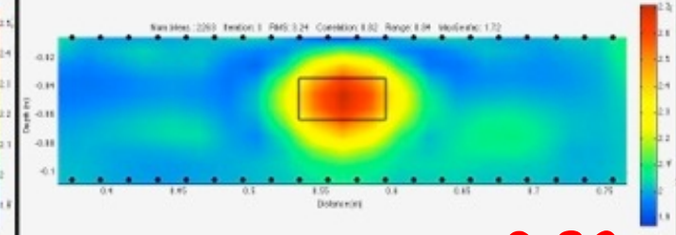





| | bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|---|
|  SPECIAL |  cor=0.8 |  cor=0.74 |  cor=0.82 |
|  SPECIAL SURFACE |  cor=0.7 |  cor=0.8 |  cor=0.83 |
|  SPECIAL+SURFACE+INTERIOR |  cor=0.52 |  cor=0.76 |  cor=0.83 |

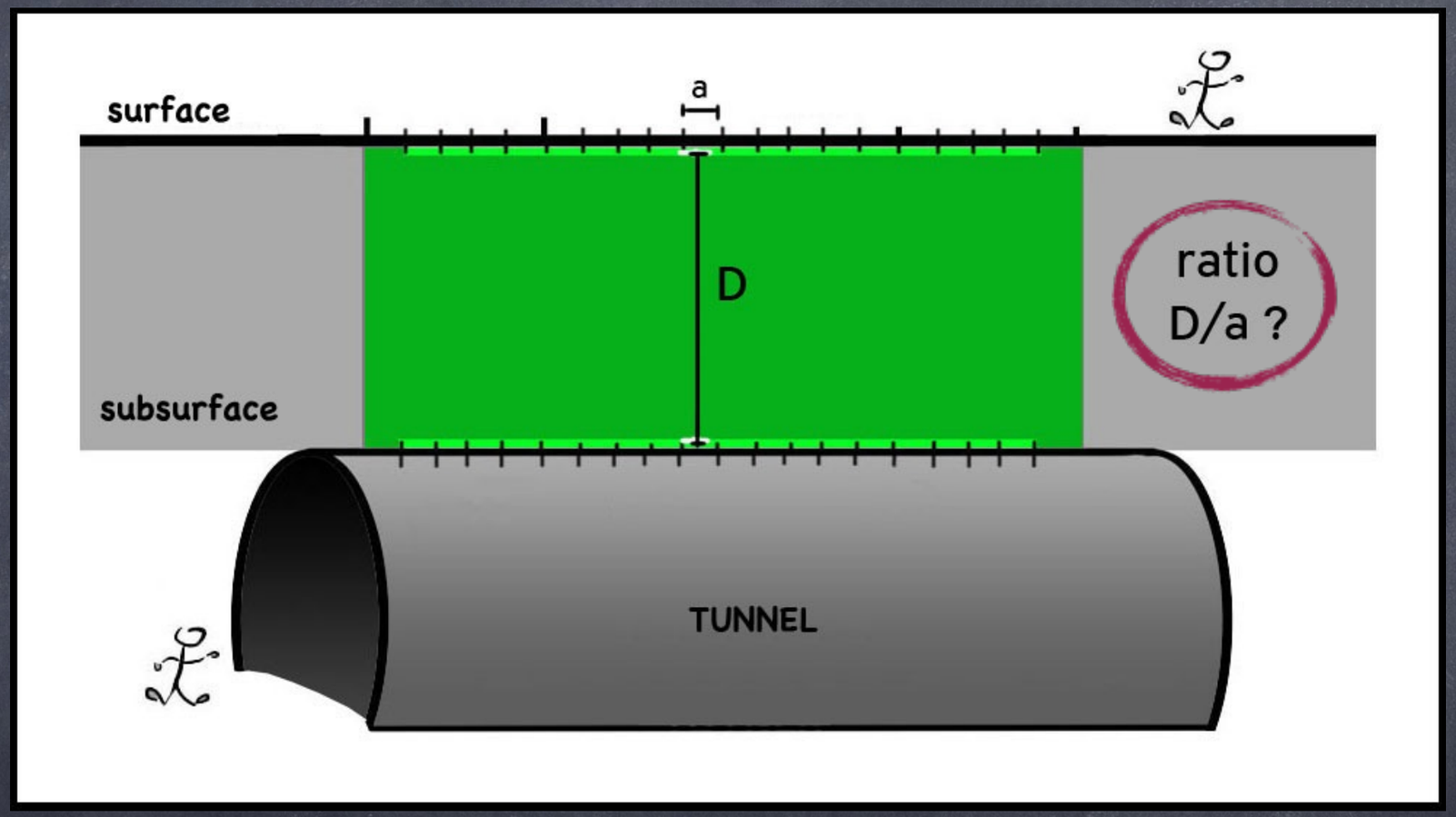
**SPECIAL => SURFACE - to - TUNNEL**

# Array Comparison

| | bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|---|
|  |  cor=0.78 |  cor=0.64 |  cor=0.86 |
|  |  cor=0.49 |  cor=0.52 |  cor=0.69 |
|  |  cor=0.5 |  cor=0.88 |  cor=0.87 |
|  |  cor=0.83 |  cor=0.78 |  cor=0.82 |

# GEOMETRY

## TUNNEL DISTANCE FROM SURFACE (D)



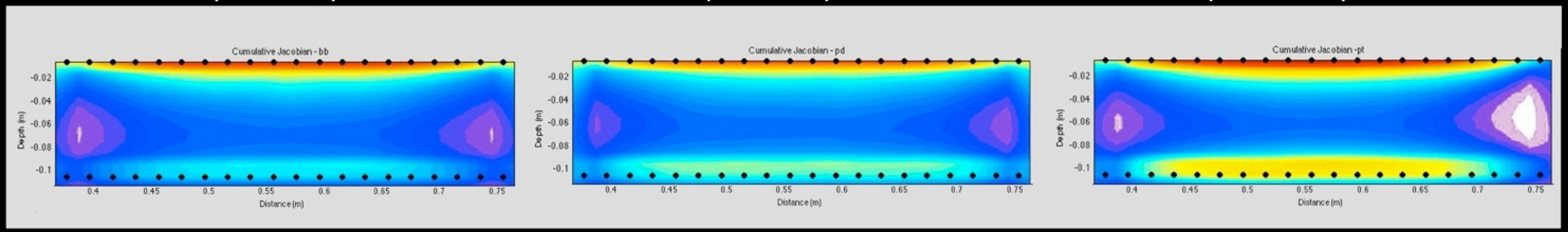

NO EXPERIMENTAL DATA due to TANK LIMITATIONS

# Cumulative Jacobian Matrix

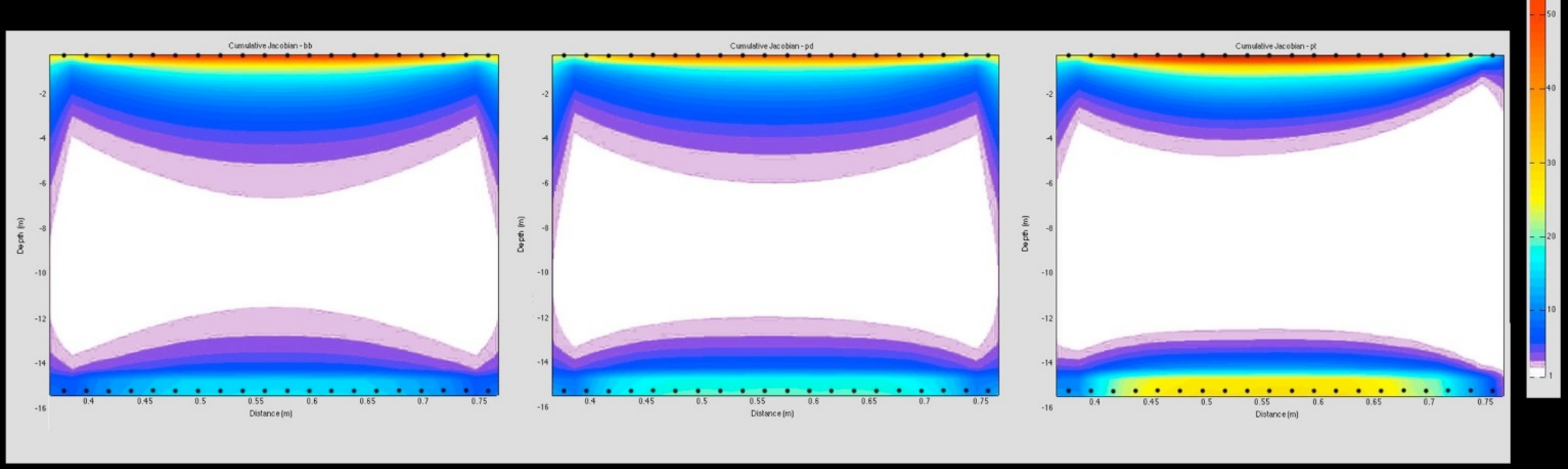
bipole-bipole

pole-dipole

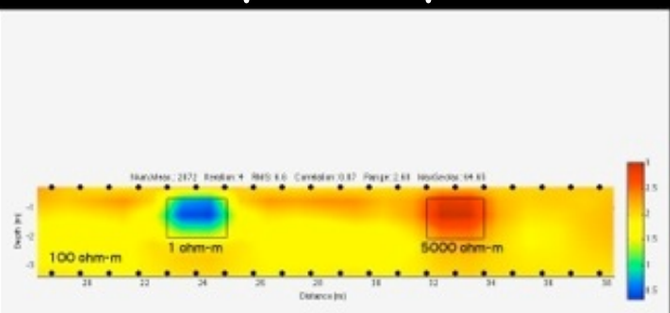
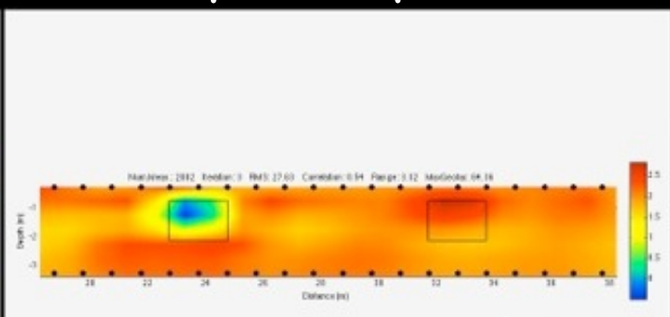
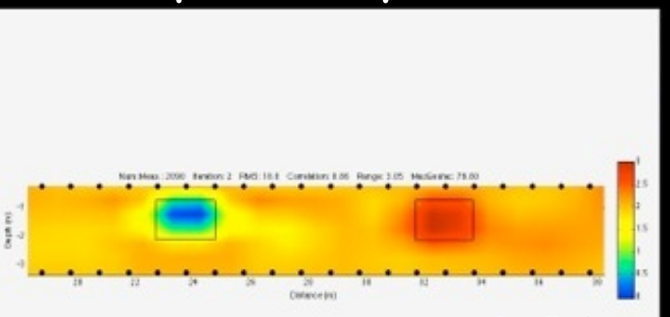
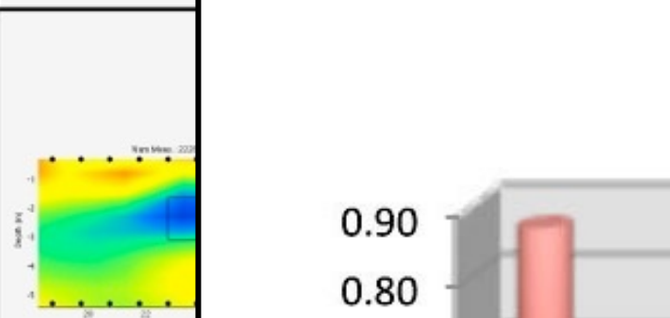
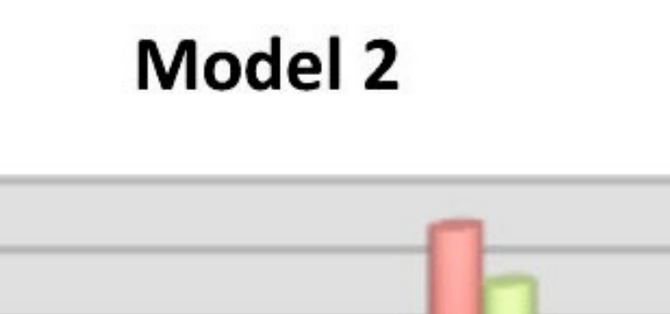
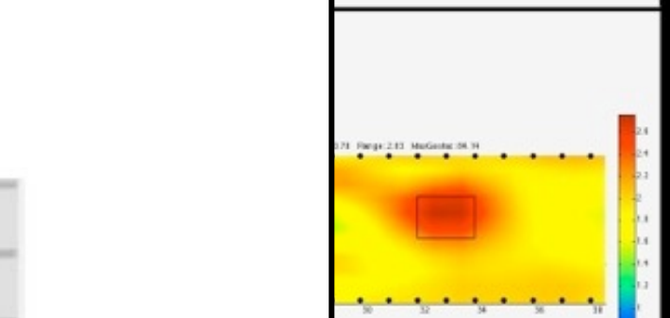
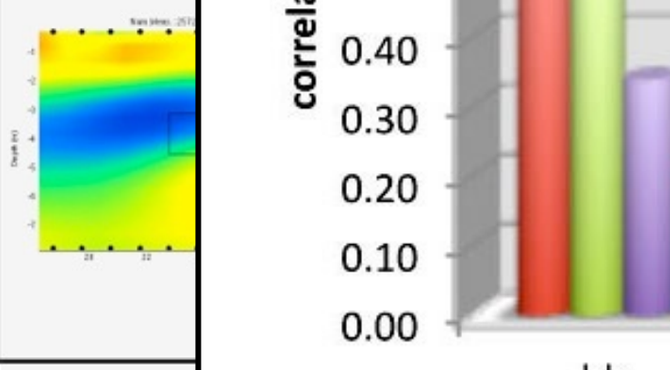
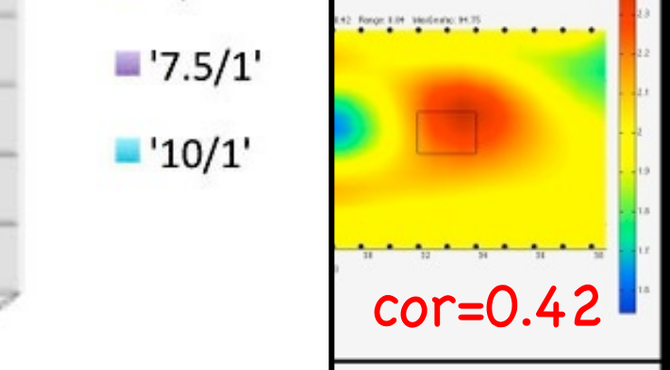
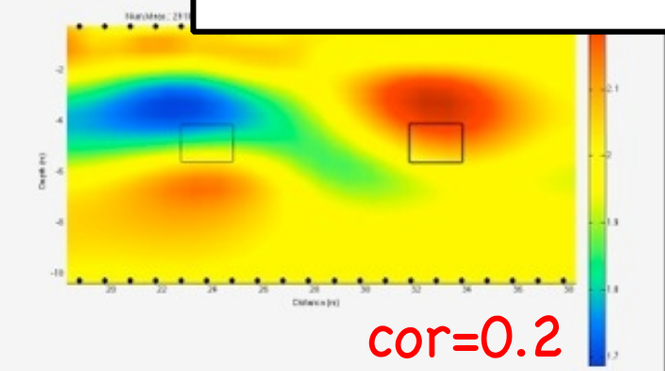
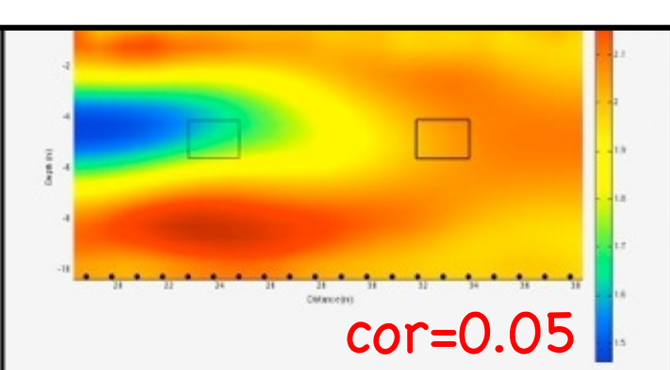
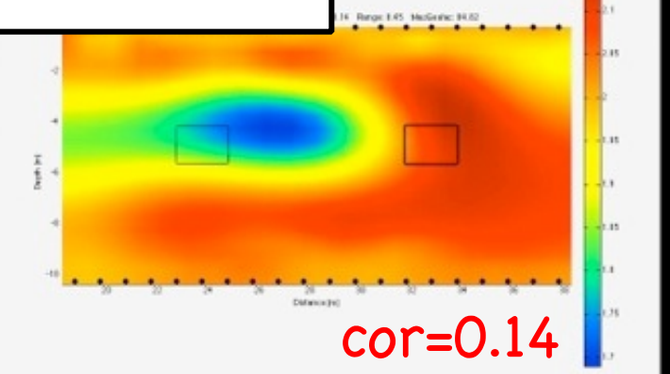
pole-tripole




ratio 5/1

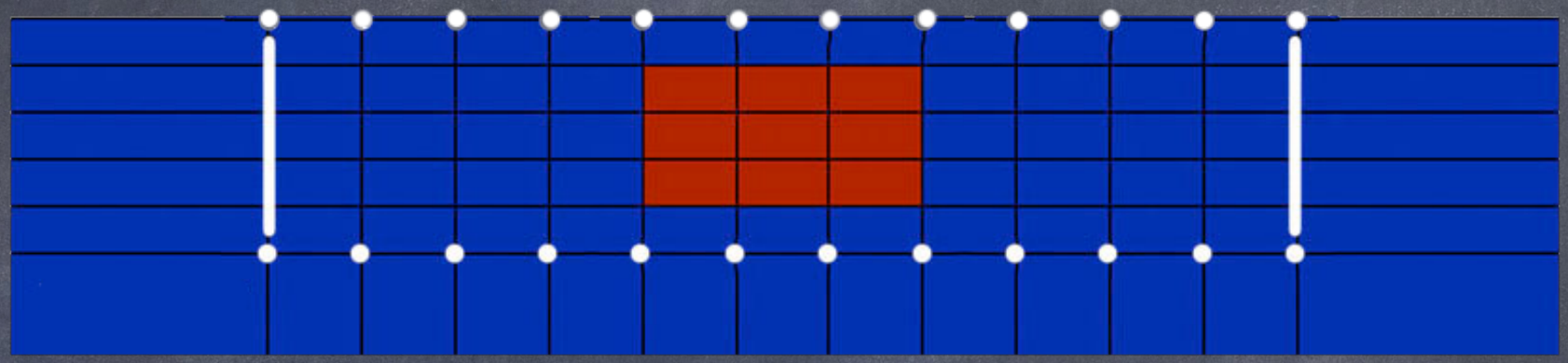



ratio 15/1

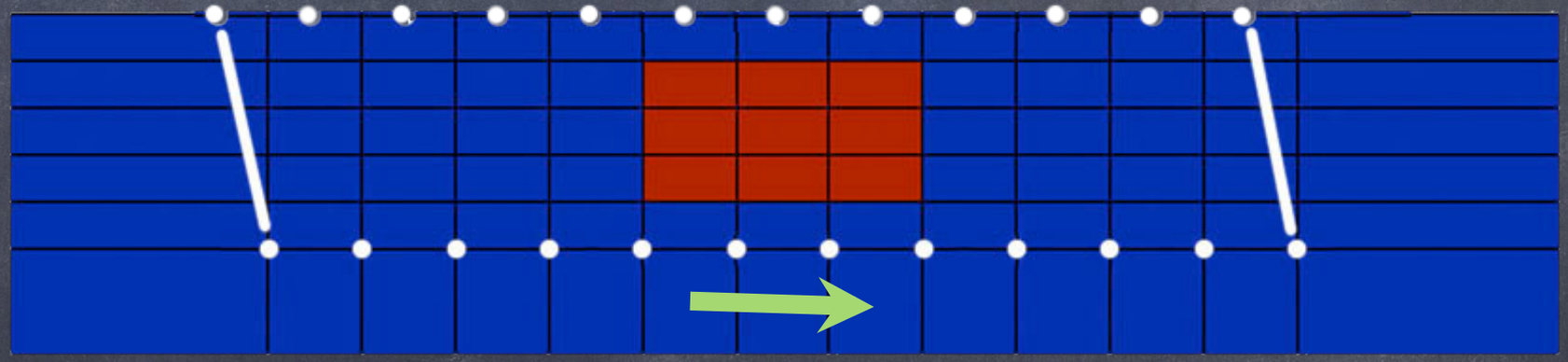
| DISTANCE RATIOS | bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|---|
| ratio 3/1 |   cor=0.87 |  cor=0.54 |  cor=0.86 |
| ratio 5/1 |  |  |  cor=0.78 |
| ratio 7.5/1 |  |  |  cor=0.42 |
| ratio 10/1 |  cor=0.2 |  cor=0.05 |  cor=0.14 |

# ELECTRODE HORIZONTAL DISPLACEMENT

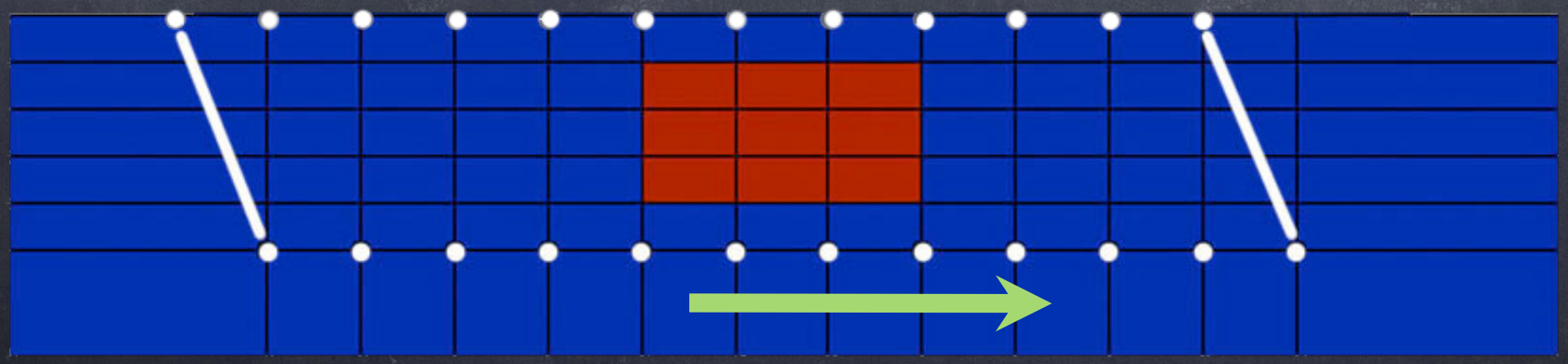
K1



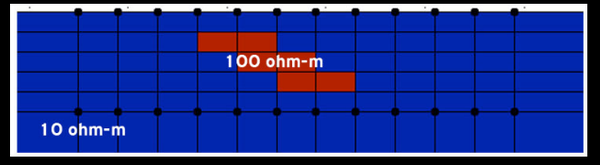
K2

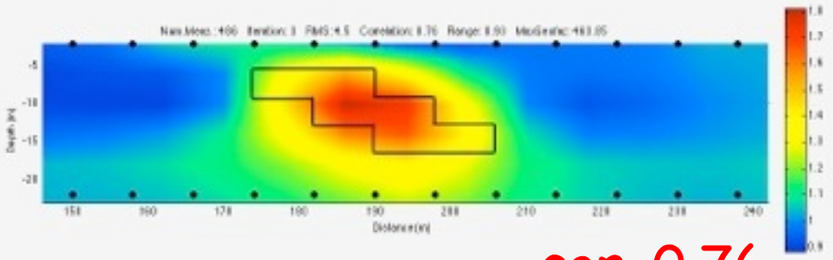
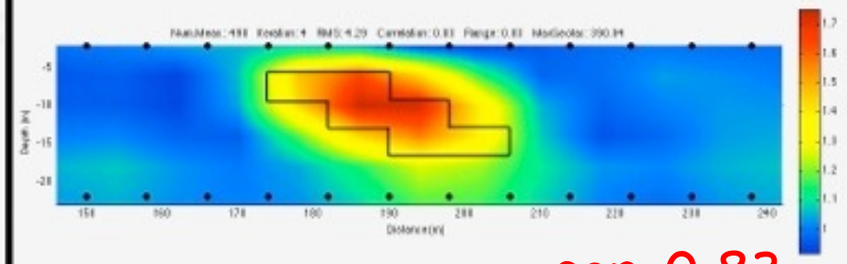
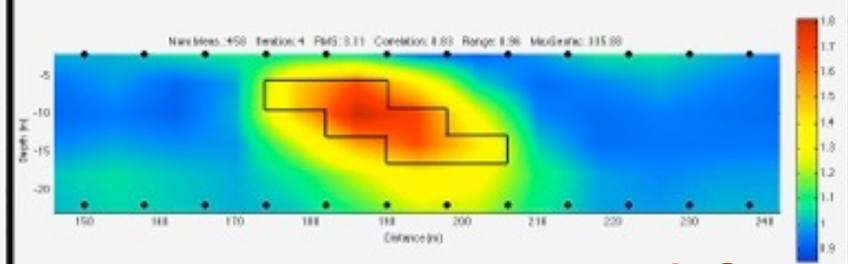
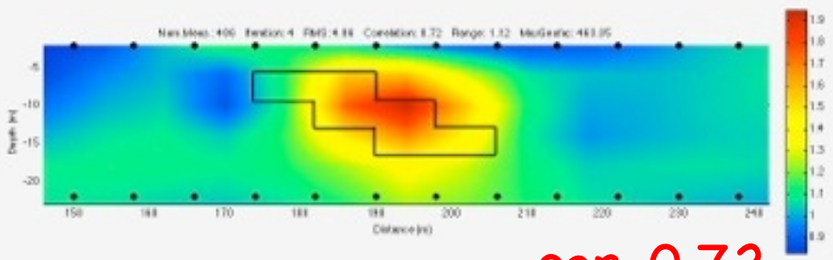
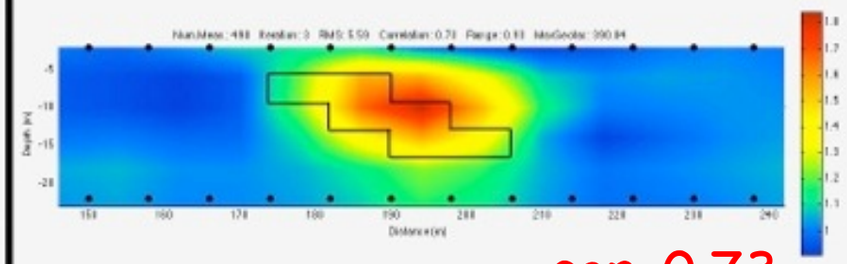
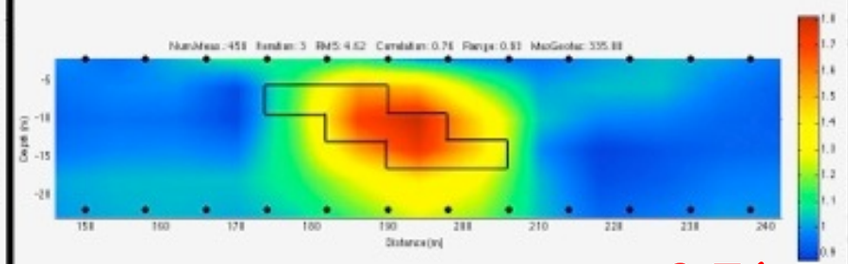
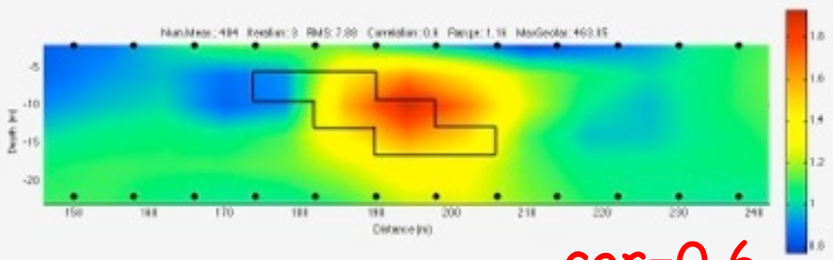
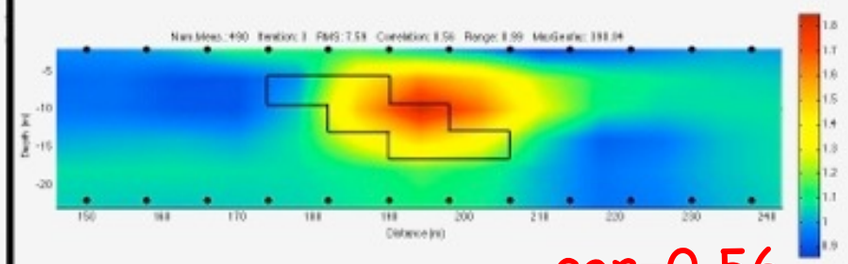
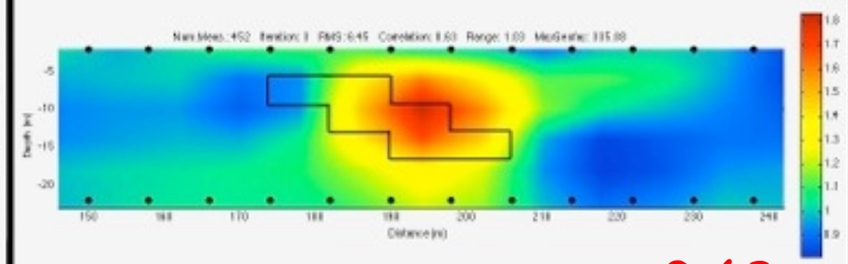


K3

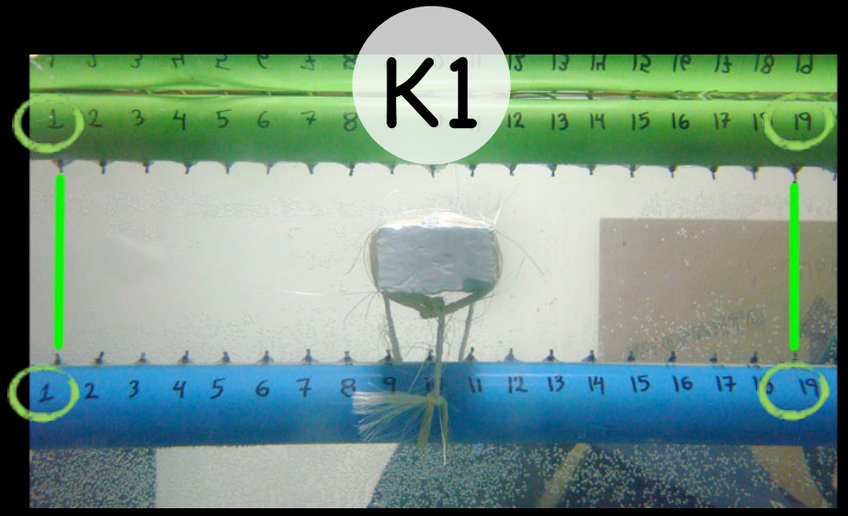


RESISTIVE
'crack'

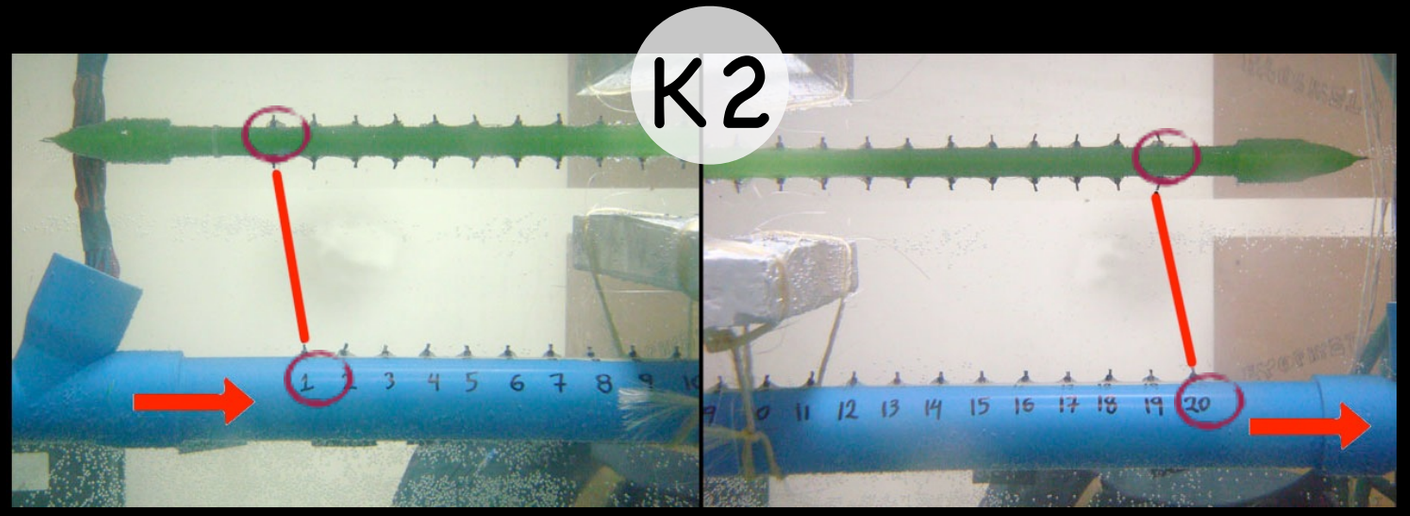



| | bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|---|
| K 1 |  cor=0.76 |  cor=0.83 |  cor=0.83 |
| K 2 |  cor=0.72 |  cor=0.73 |  cor=0.76 |
| K 3 |  cor=0.6 |  cor=0.56 |  cor=0.63 |

# EXPERIMENTAL DATA



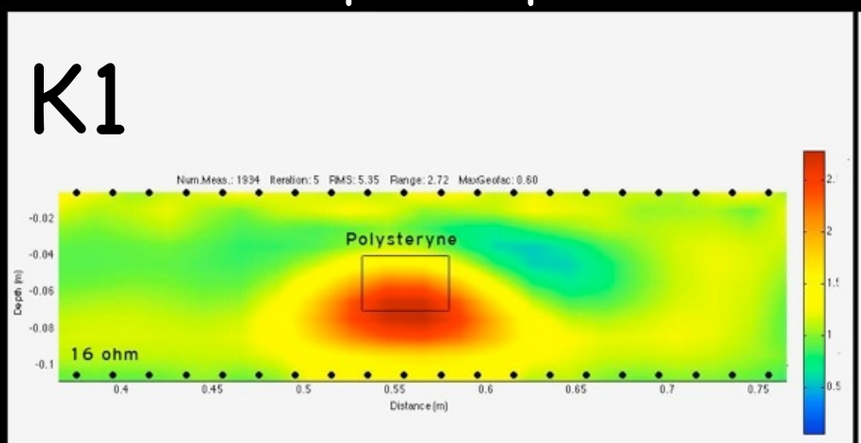

bipole-bipole

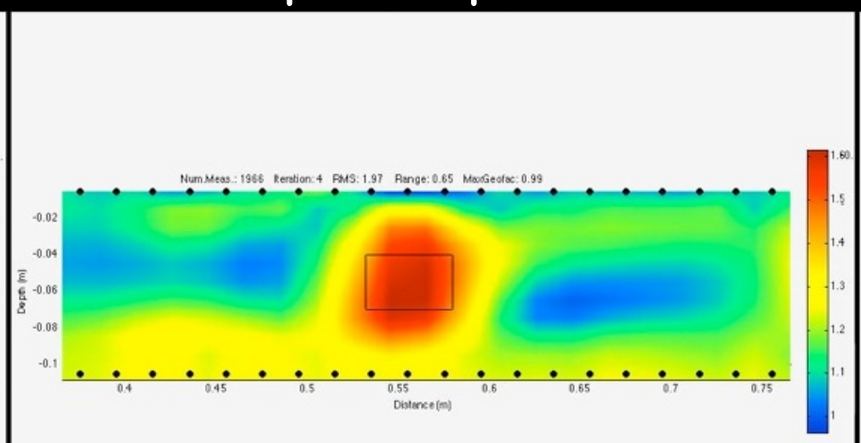


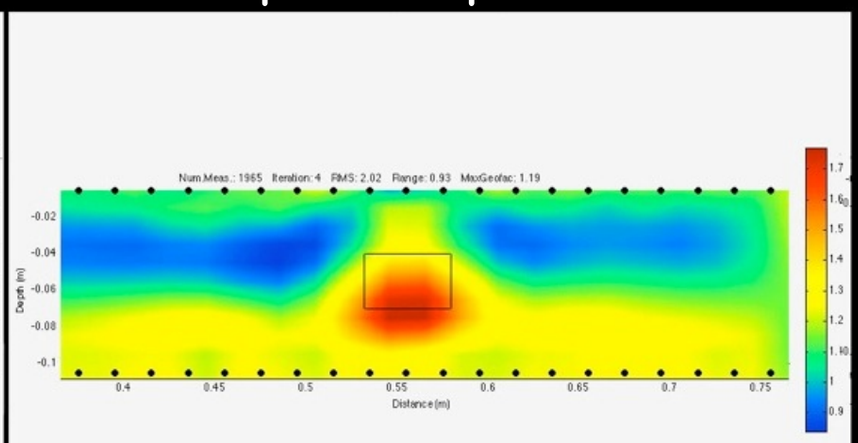

pole-dipole

pole-tripole

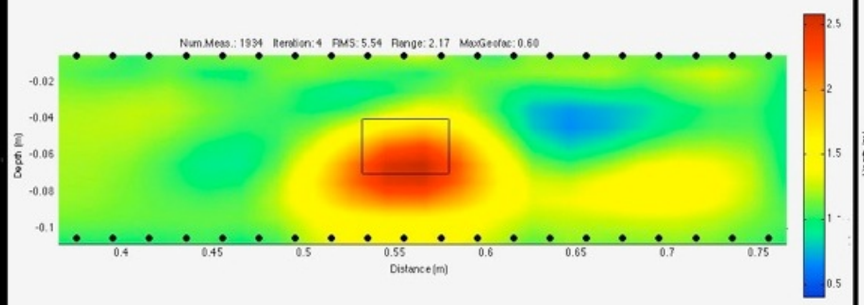
K1

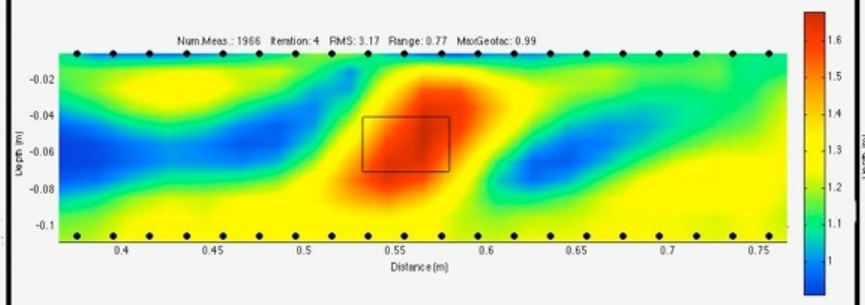


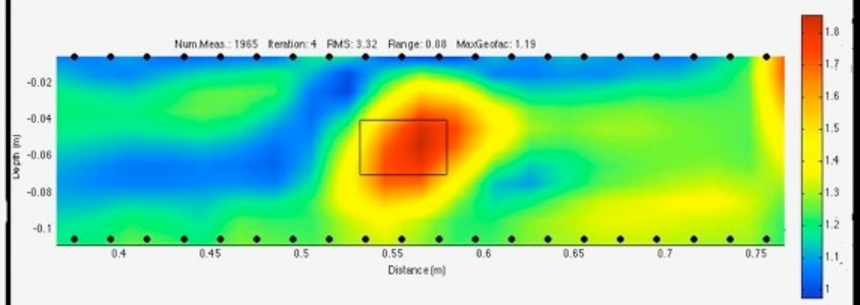




K2

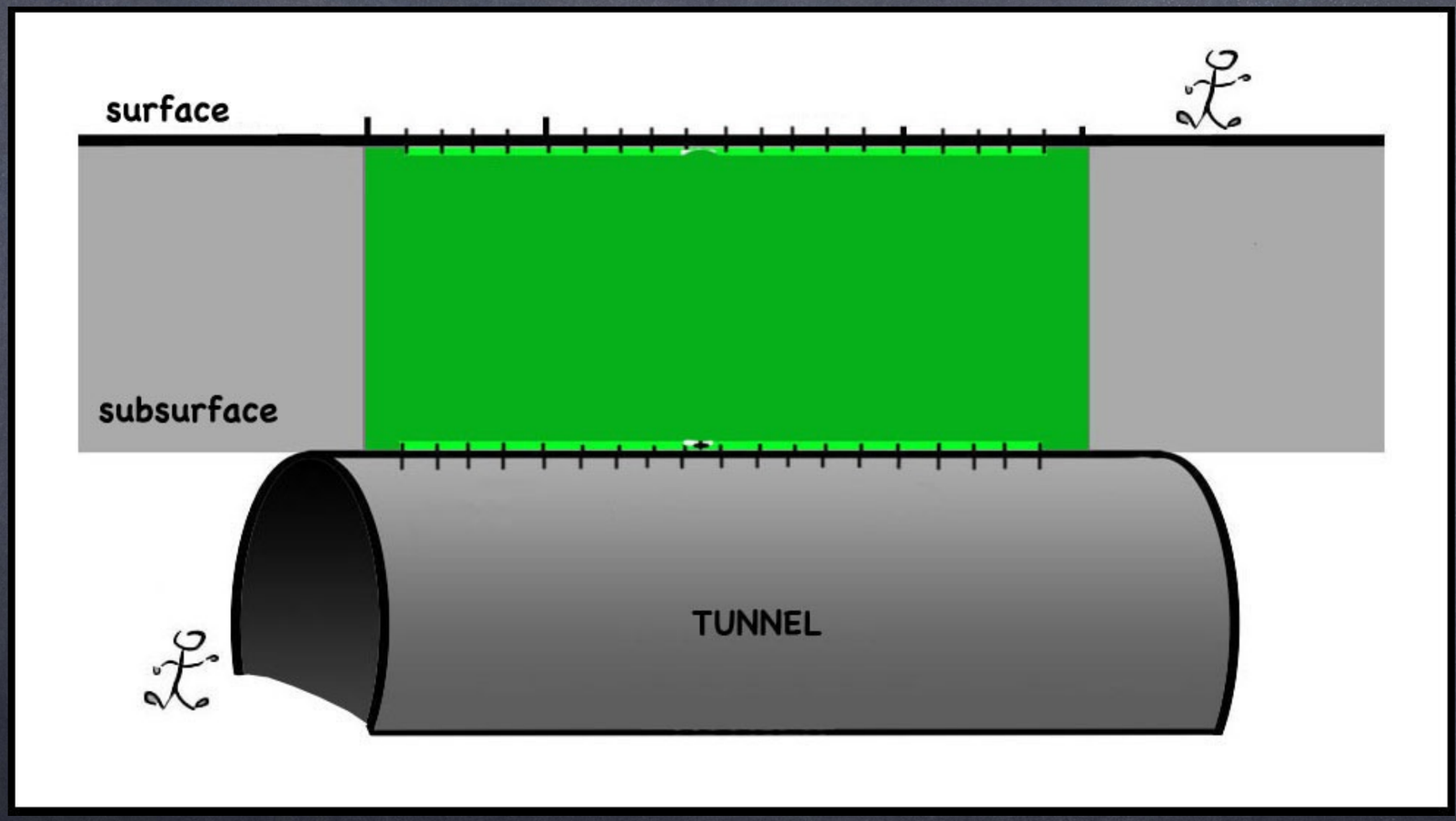


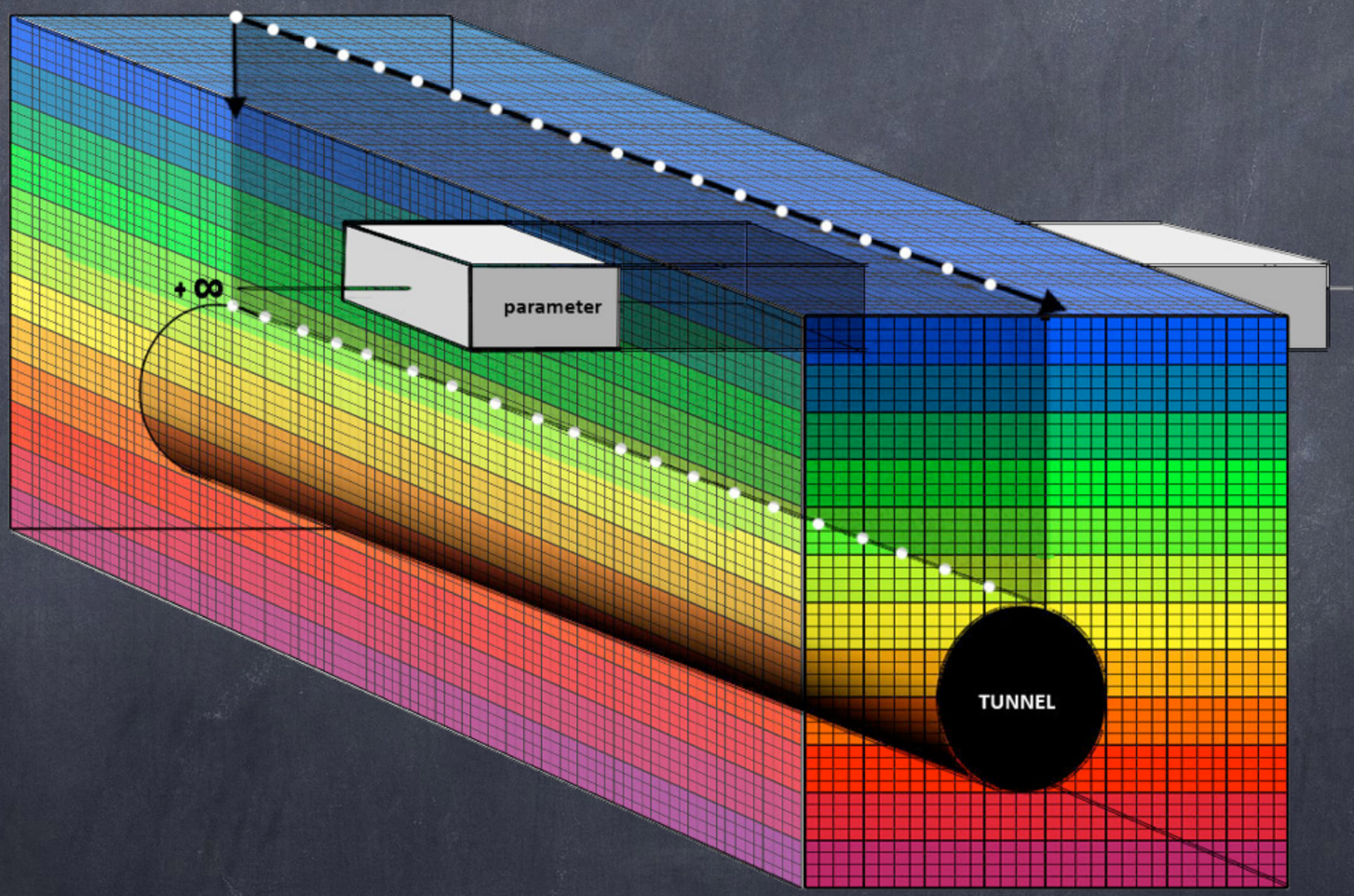
# TUNNEL EFFECT

## DIMENSIONS

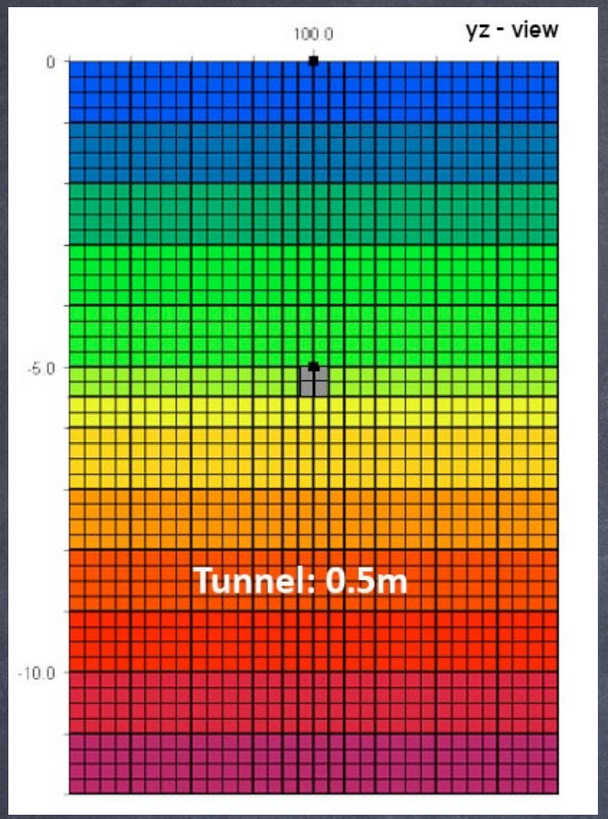


# PROGRAM ‘DC-3DPRO’

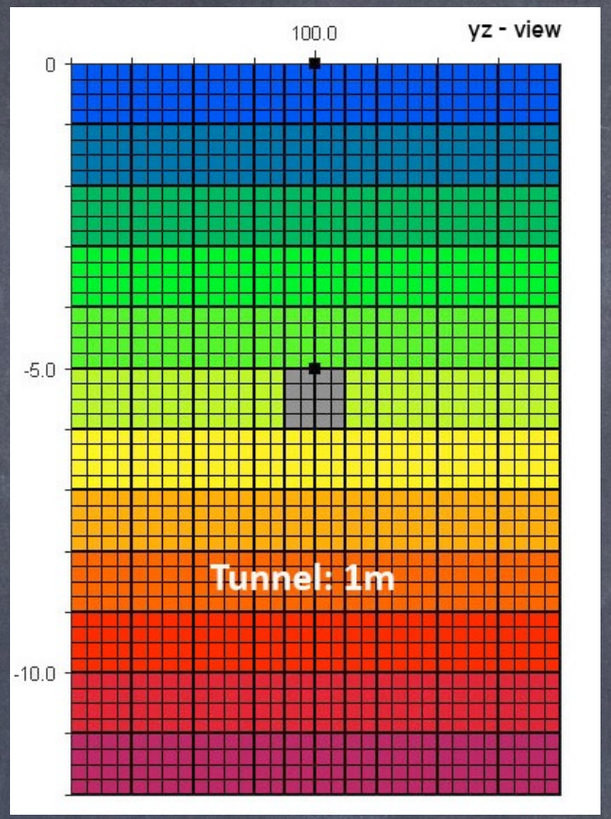
## TUNNEL SIMULATION IN 3D DIMENSIONS



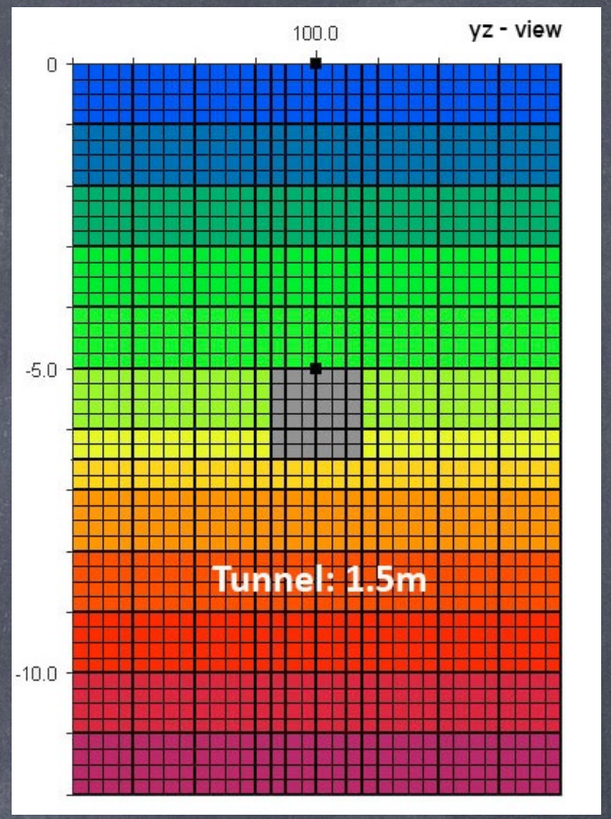
tunnel d=0.5m



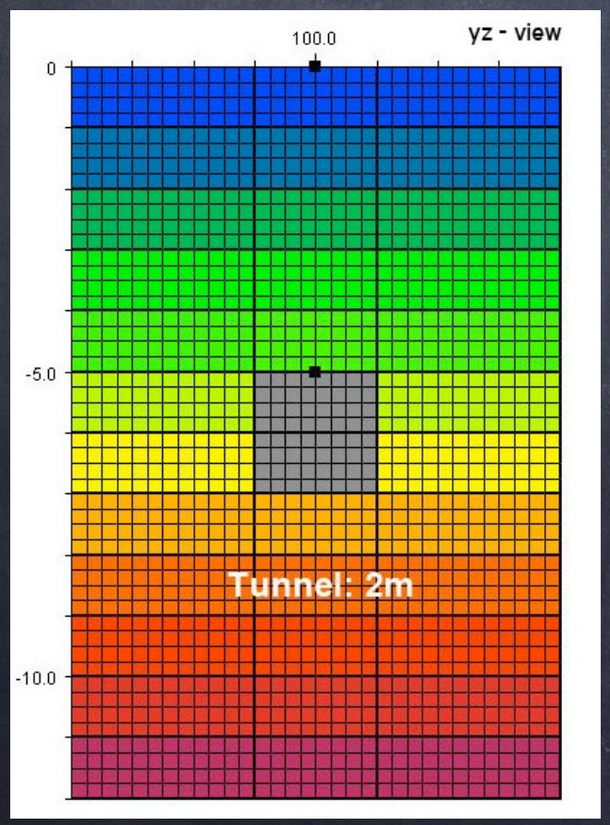

tunnel d=1m



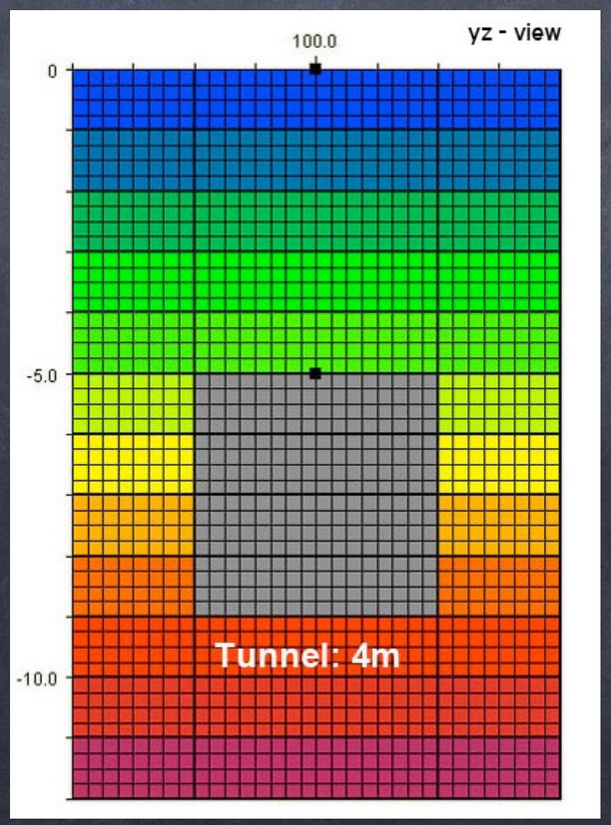

tunnel d=1.5m



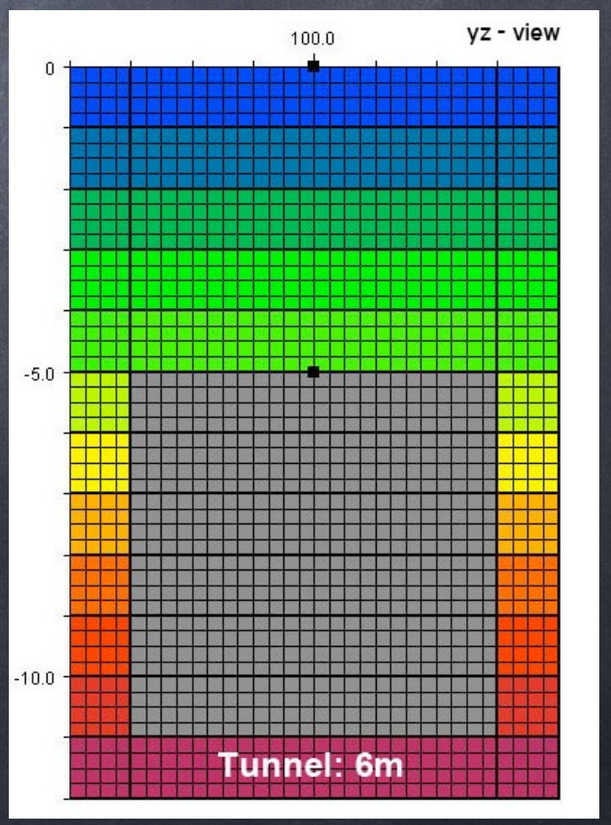

tunnel d=2m



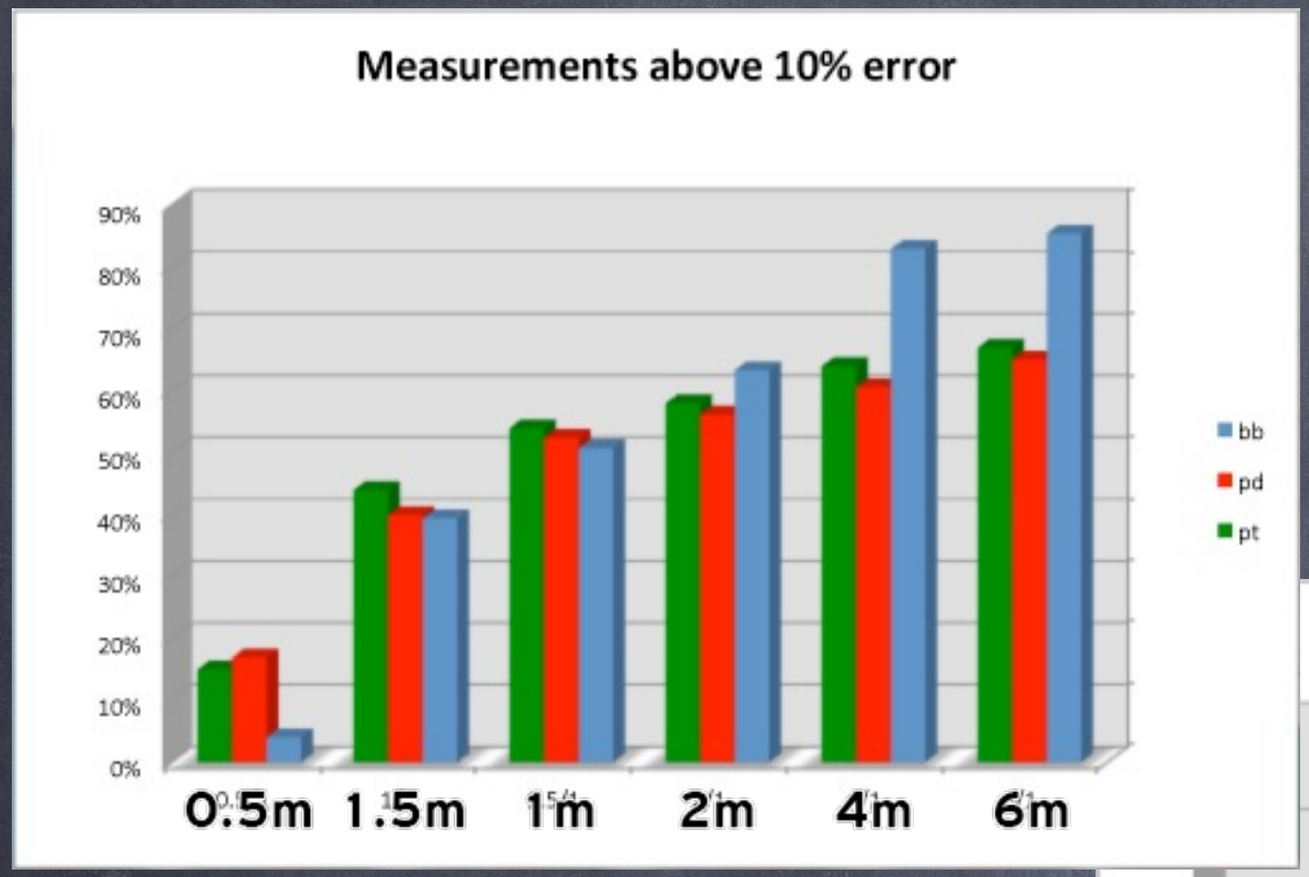

tunnel d=4m



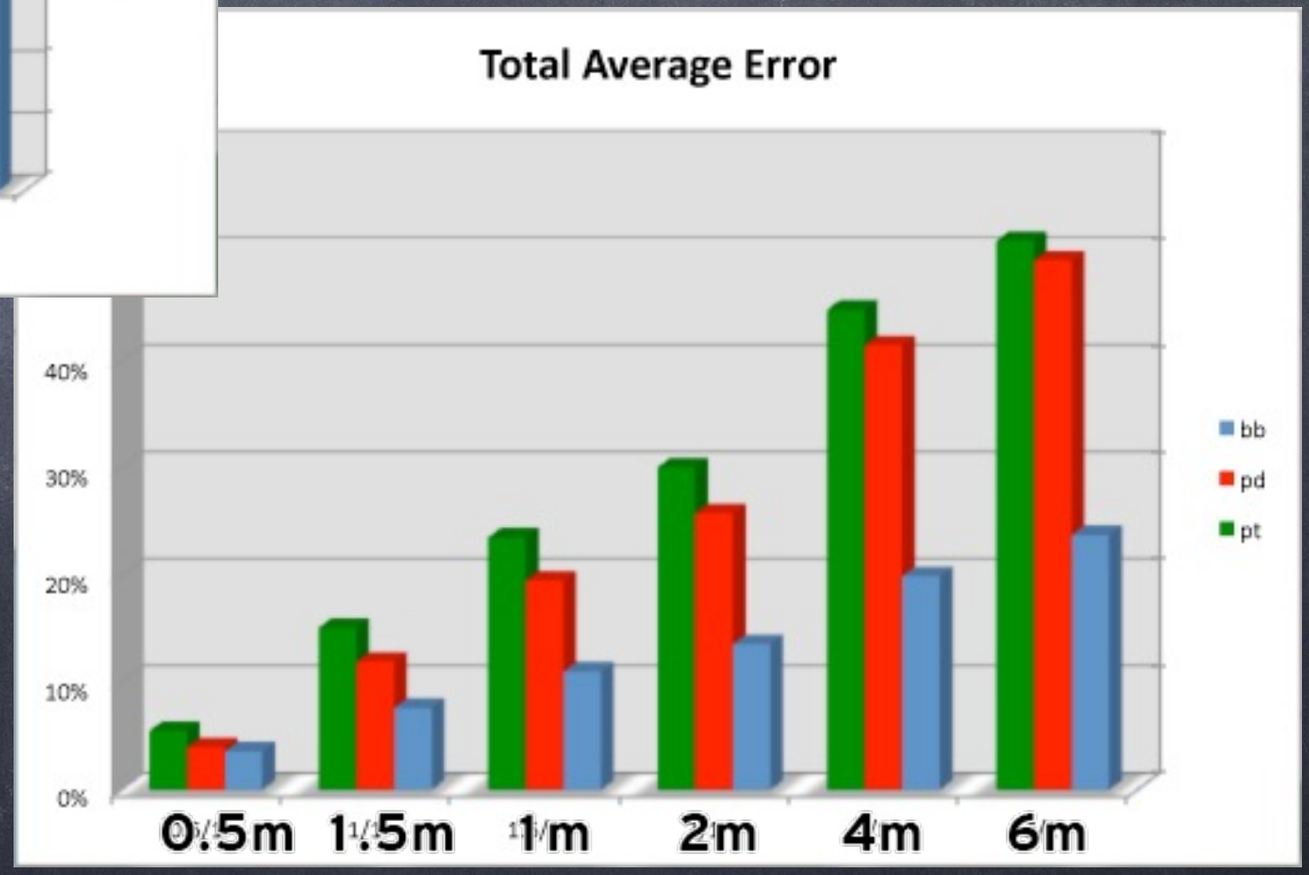

tunnel d=6m

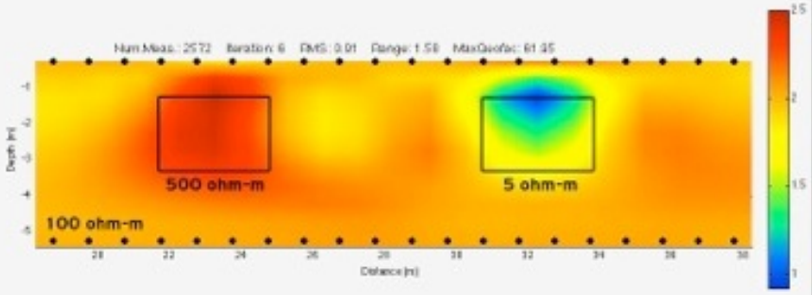
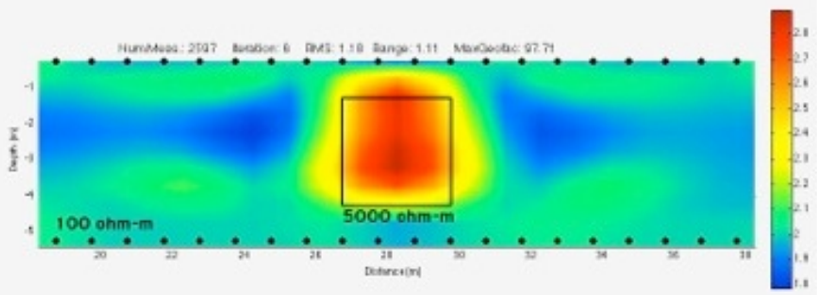
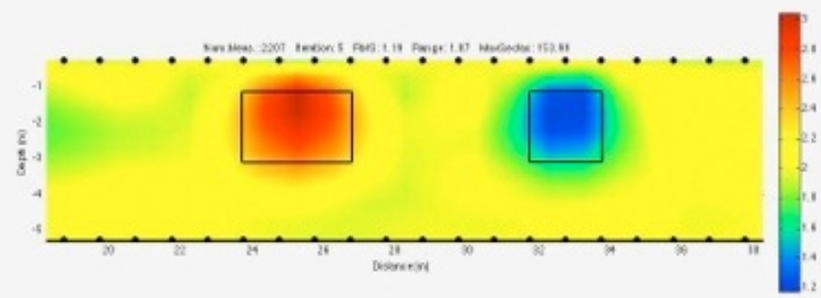
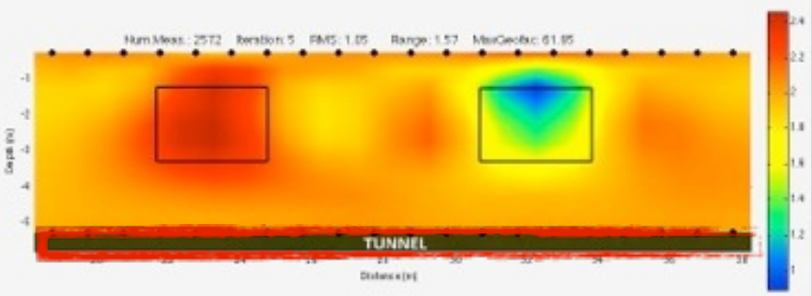
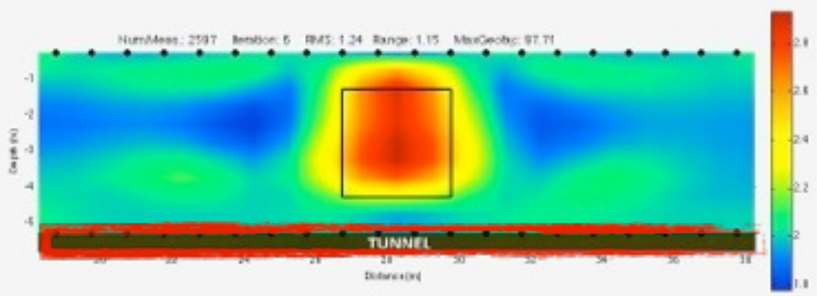
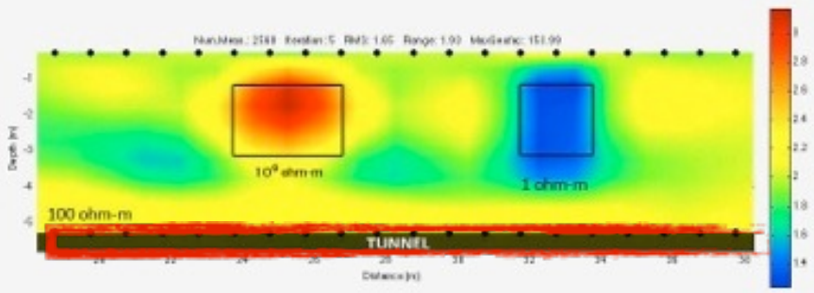
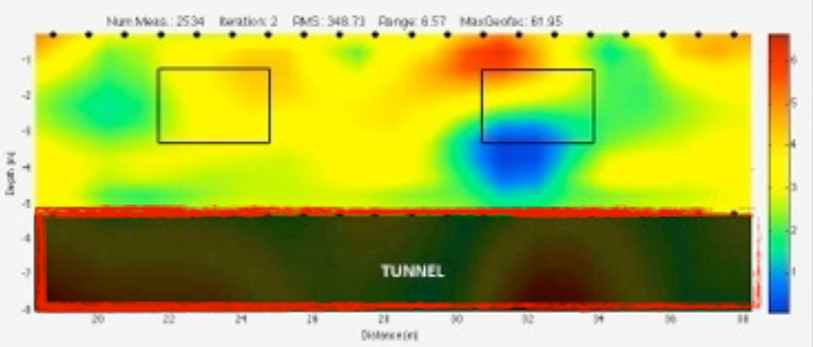
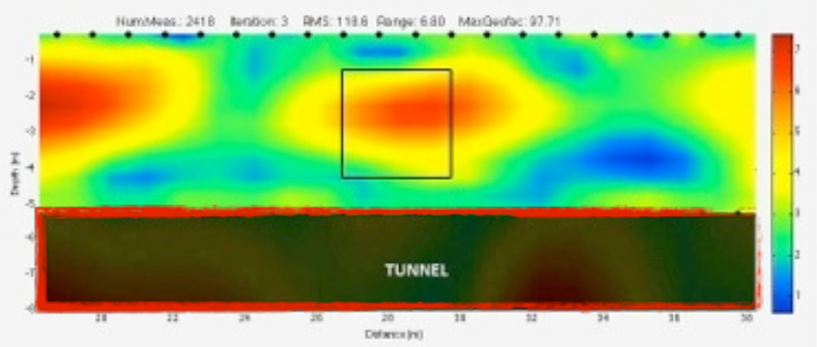
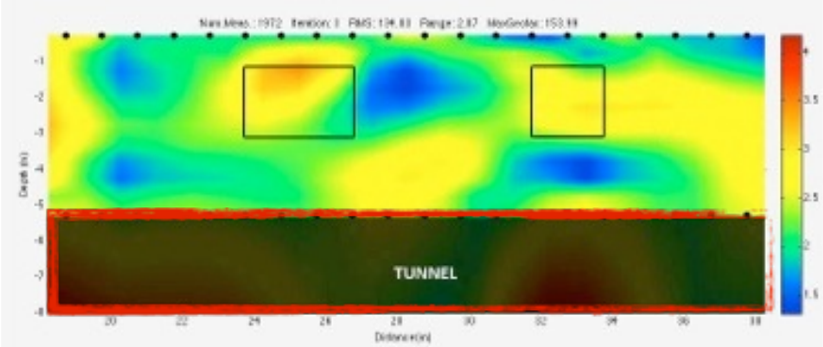


# NOISE




$$\%noise(i) = \frac{\rho_h - \rho_i}{\rho_h}$$



| | bb - Target 1 | pd - Target 2 | pt - Target 3 |
|---|---|---|---|
| No tunnel |  |  |  |
| Tunnel d=0.5m |  |  |  |
| Tunnel d=6m |  |  |  |

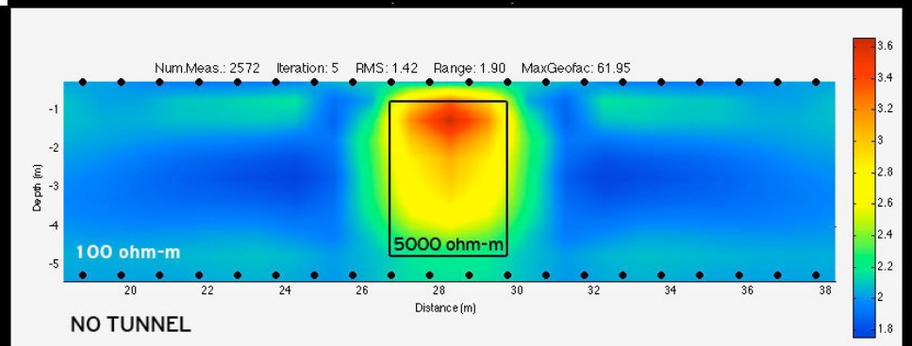
# DIMENSION TUNNEL LIMIT



Tunnel diameter

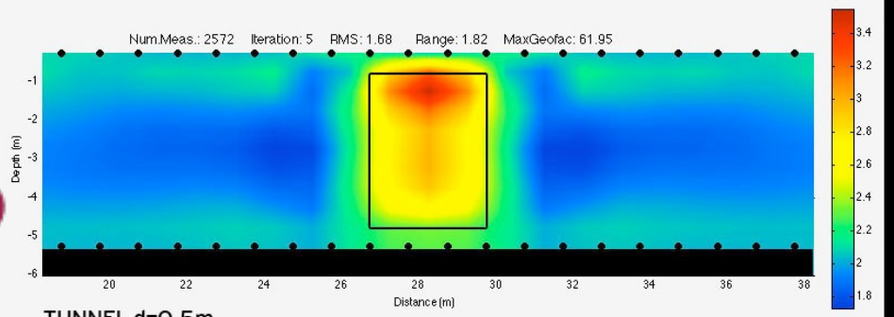
## bipole-bipole

d=0 m



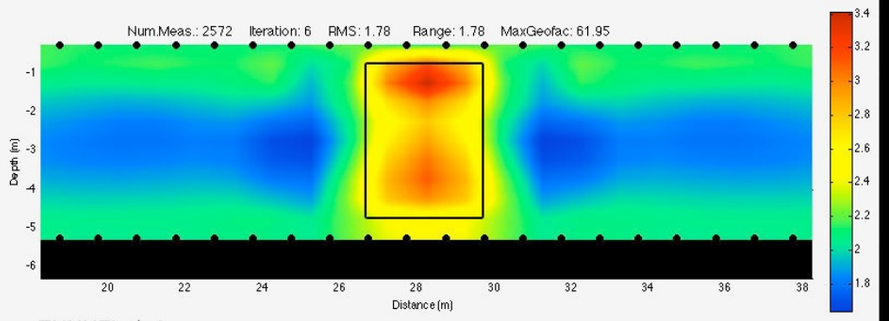

NO TUNNEL

d=0.5 m



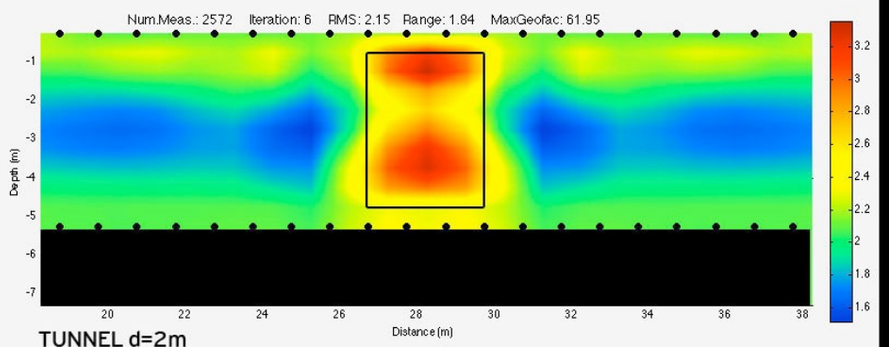

TUNNEL d=0.5m

d=1 m




TUNNEL d=1m

d=2 m

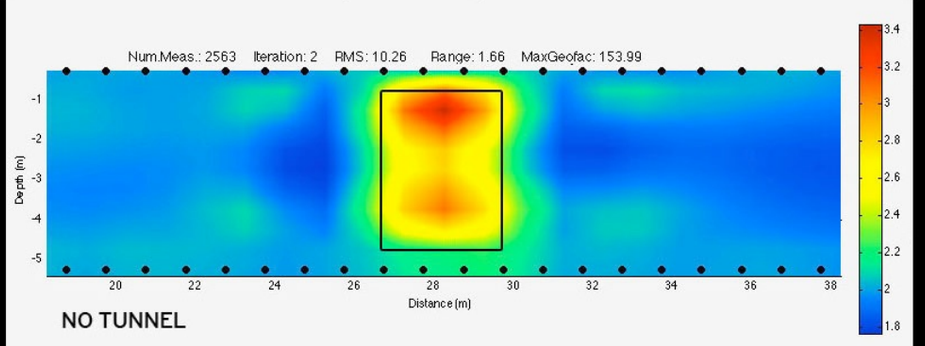



TUNNEL d=2m

Tunnel diameter

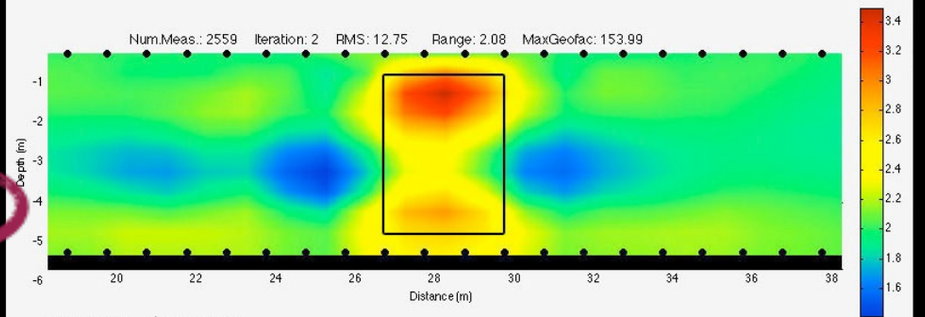
## pole-tripole

d=0 m



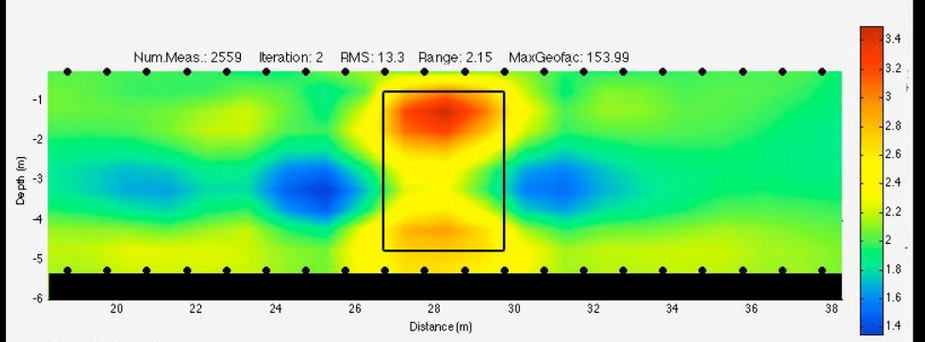

NO TUNNEL

d=0.25 m



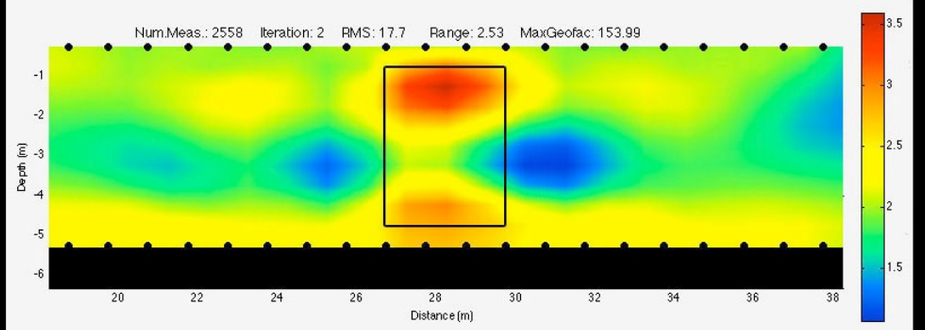

TUNNEL d=0.25m

d=0.5 m



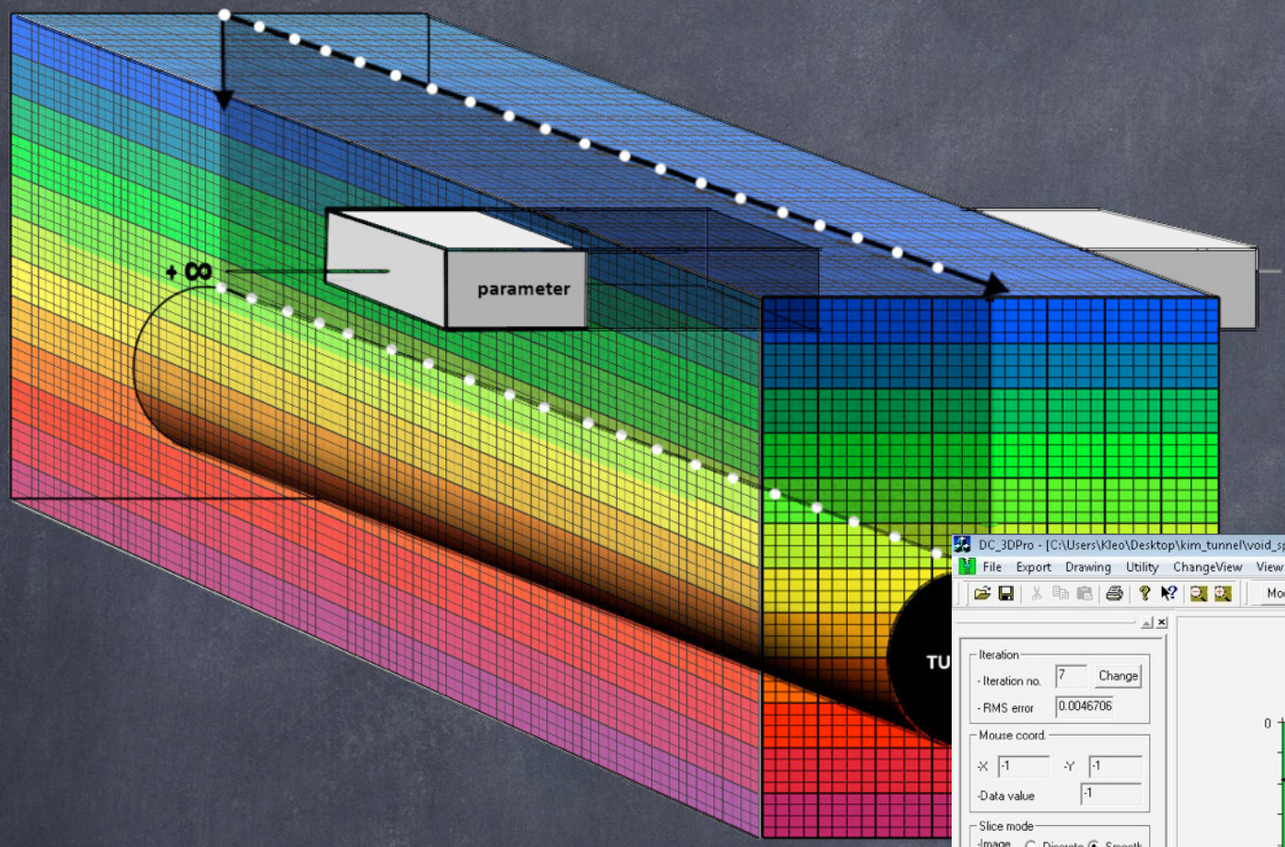

TUNNEL d=0.5m

d=1 m

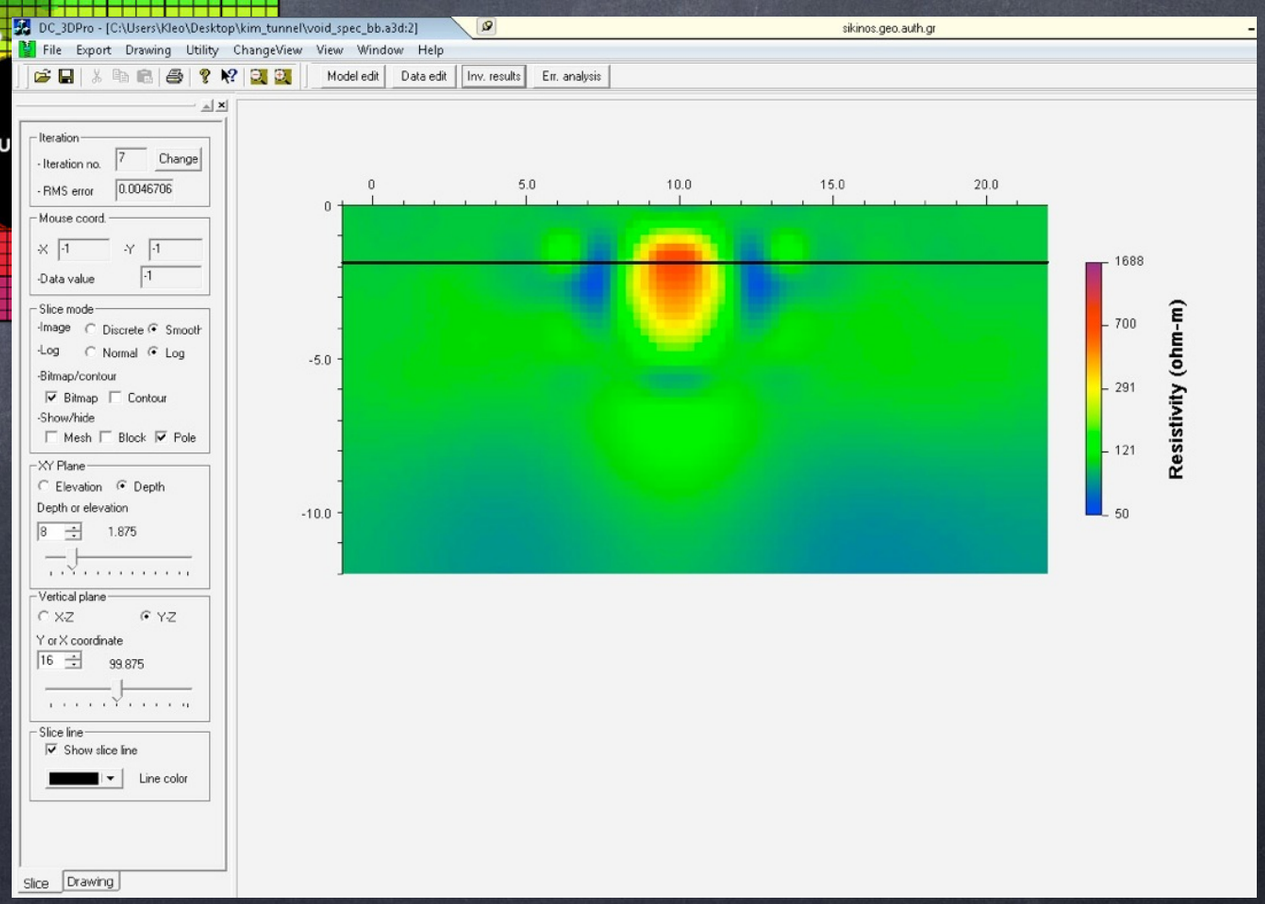



TUNNEL d=1m

# TUNNEL EFFECT CORRECTION




DC3D-Pro




## Corrections …

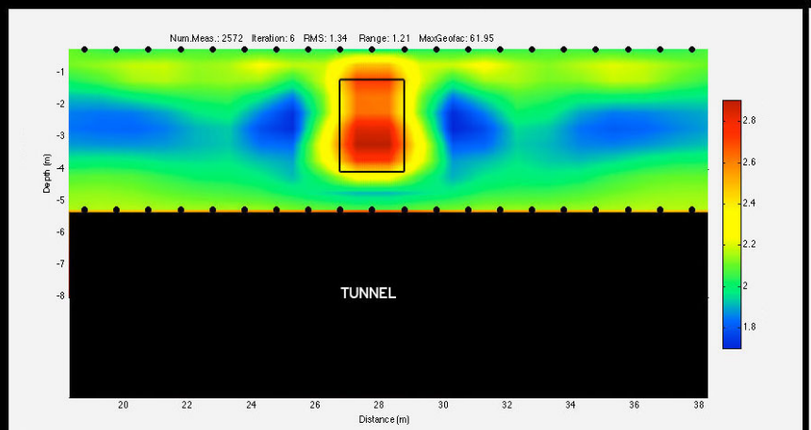
- 3D TUNNEL SIMULATION

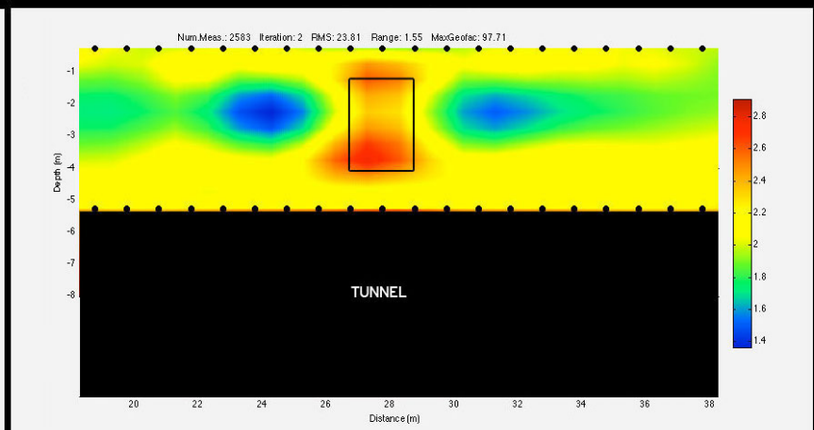
bipole-bipole

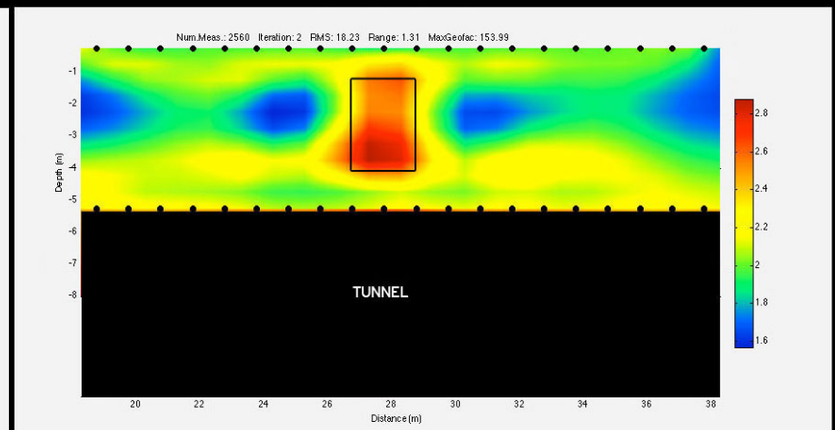
pole-dipole

pole-tripole

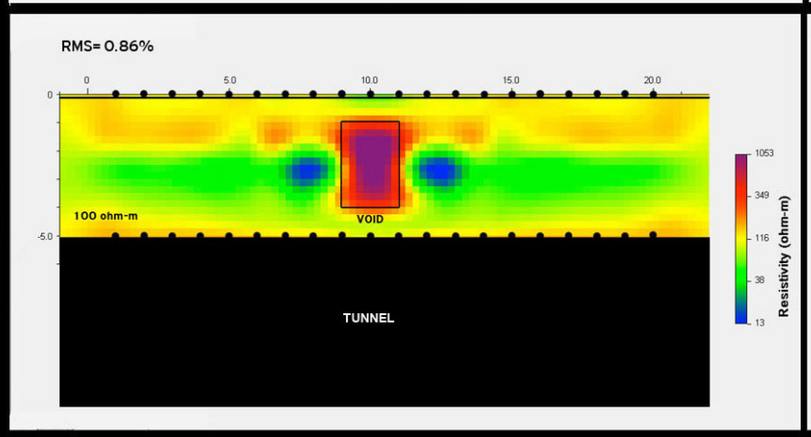
Raw

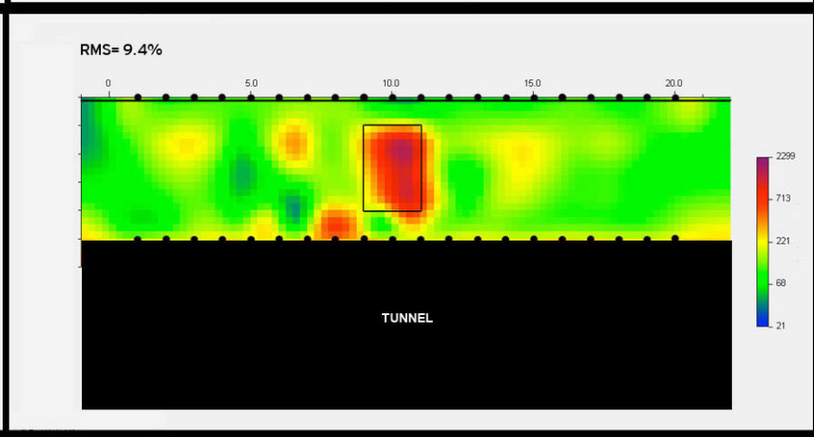


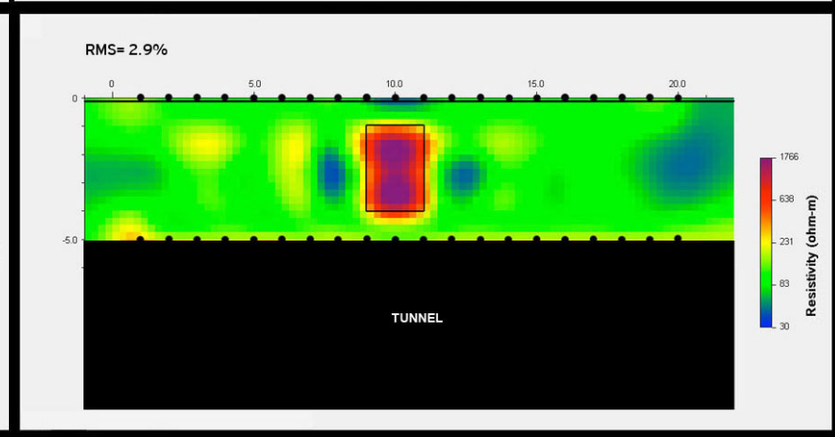




3D INVERSION



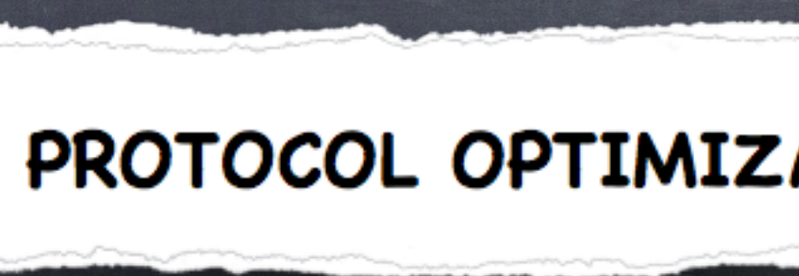



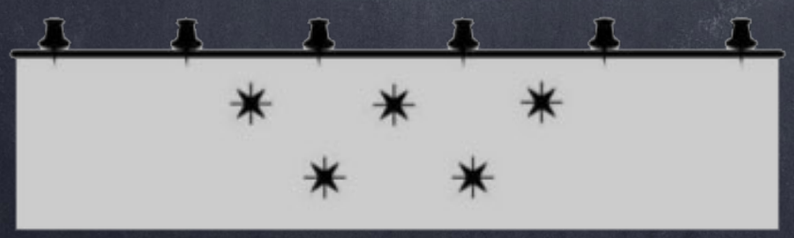
# PROTOCOL OPTIMIZATION

- ATHANASIOU ET AL., 2007
- BASIC CODE MODIFICATION ('2D-InvCODE')

Parameters




Measurements



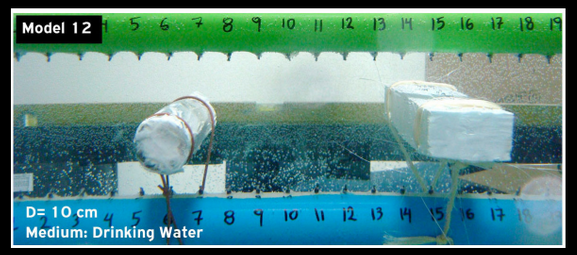
## USING JACOBIAN MATRIX

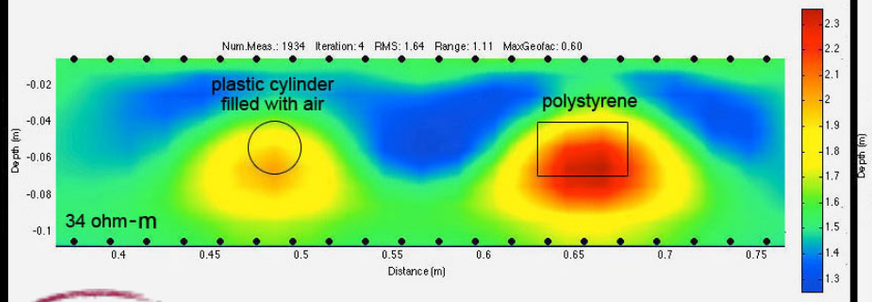
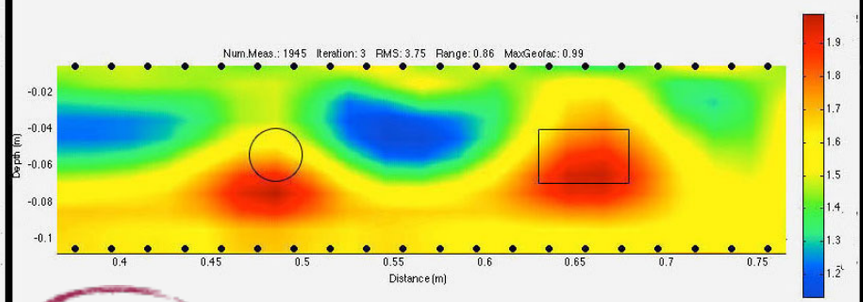
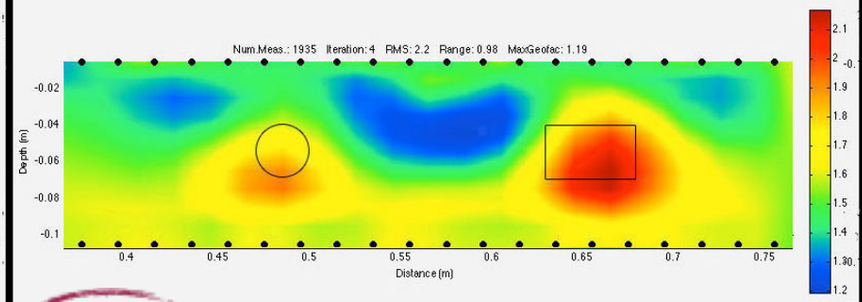
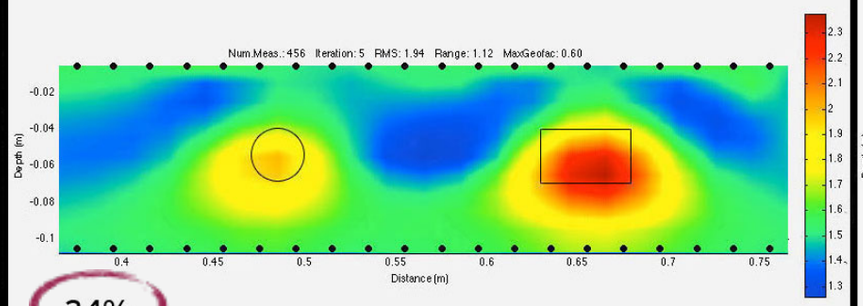
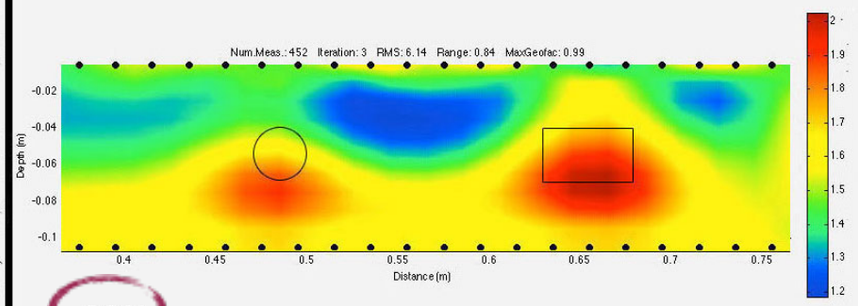
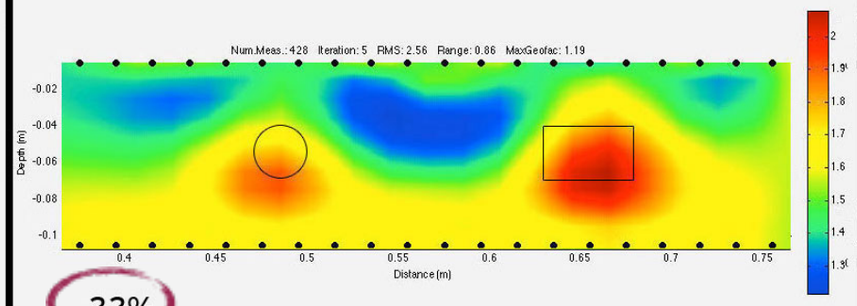
$$J_{ij} = \frac{d\rho_{ai}}{d\rho_j}$$

| | P1 | P2 | P3 | P4 |
|---|---|---|---|---|
| M1 | 0.798 | 0.226 | -0.025 | 0.128 |
| M2 | 0.625 | -0.276 | 0.22 | -0.028 |
| M3 | -0.356 | 0.856 | -0.986 | ~~0.935~~ |
| M4 | 0.832 | -0.347 | 0.856 | ~~0.658~~ |
| M5 | 0.556 | 0.885 | 0.659 | ~~0.663~~ |

+ EXTRA MEASUREMENTS FOR 'WEAK' PARAMETERS

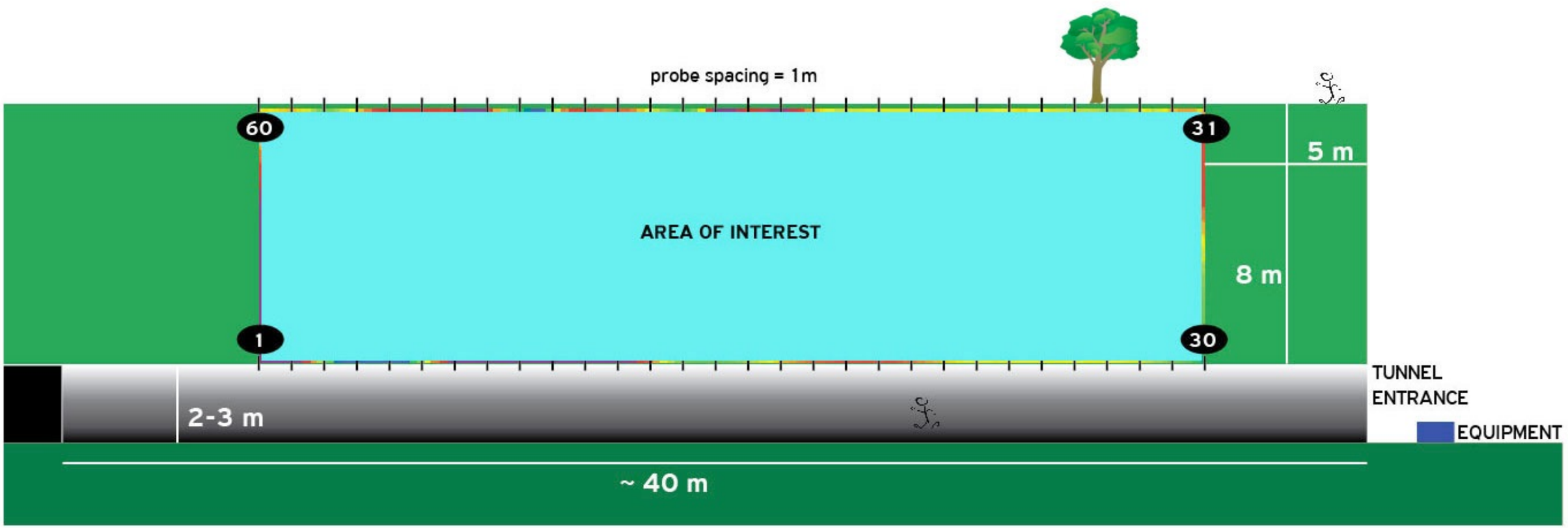
RESISTIVE TARGETS




| bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|
| INITIAL DATA | | |
|  |  |  |
|  |  |  |
| 100% measurements | 100% | 100% |
| JACOBIAN | | |
|  |  |  |
|  |  |  |
| 24% | 23% | 22% |

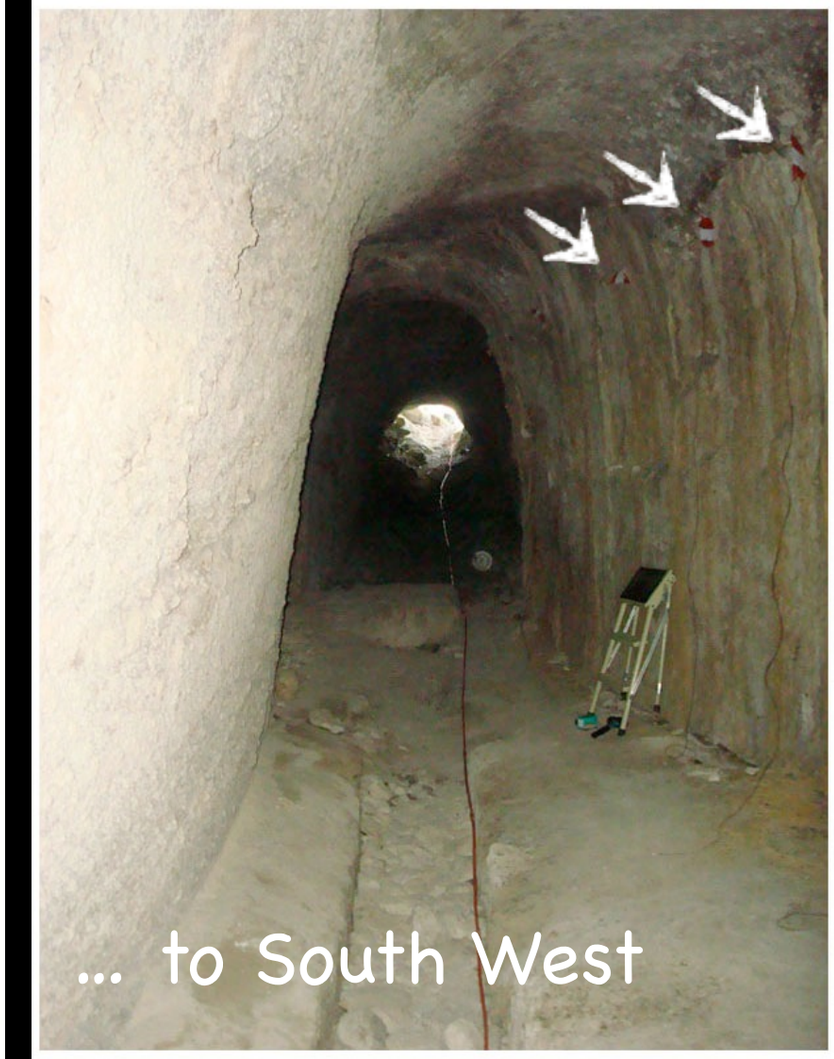
# FIELD DATA

## STUDY AREA





... to North East

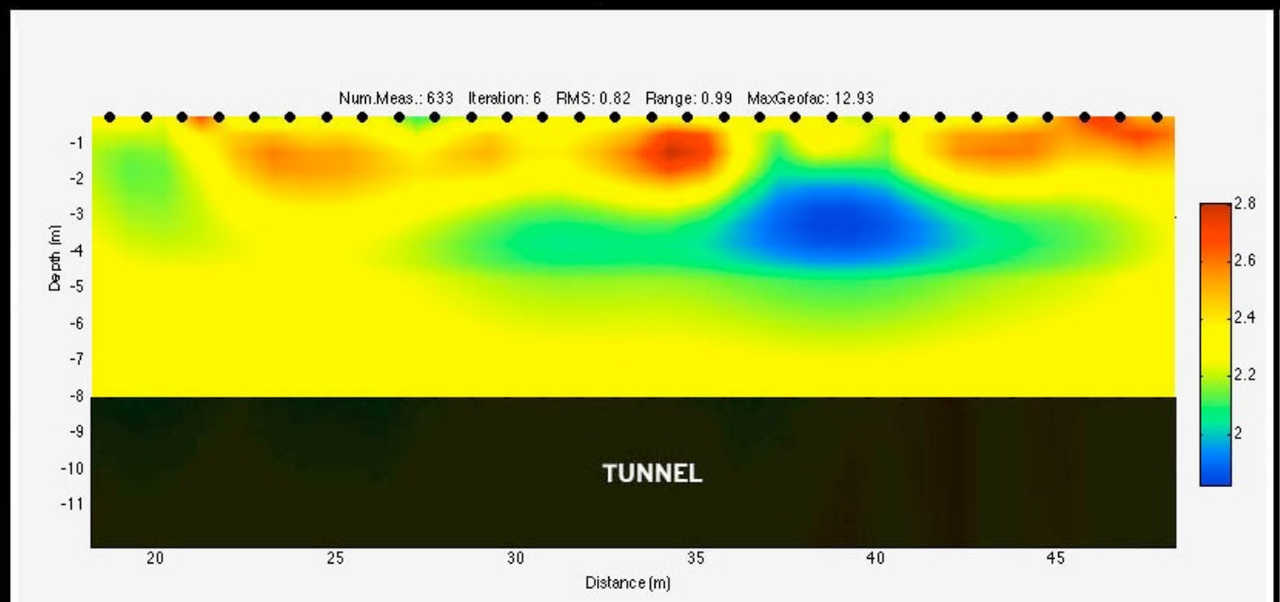


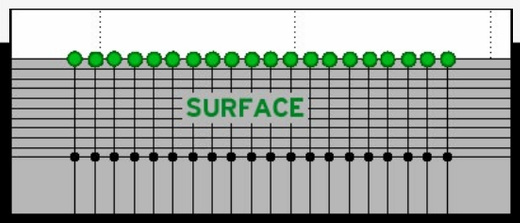
... to South West

# ELECTRODE POSITIONING USING TOPOGRAPHICAL SURVEY

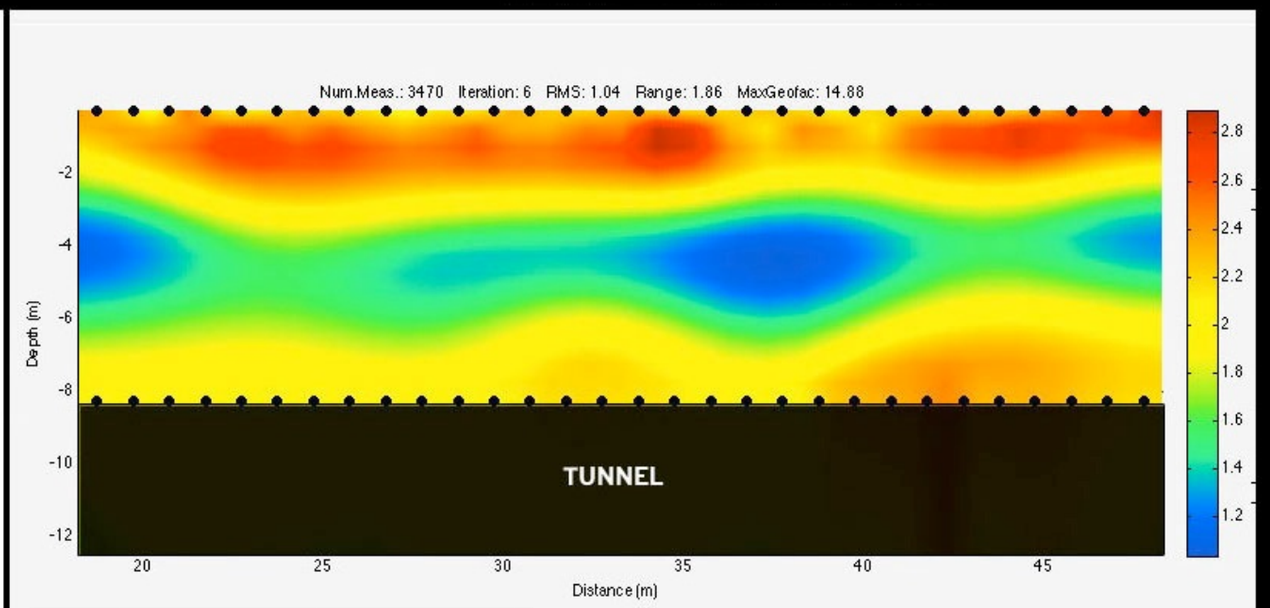


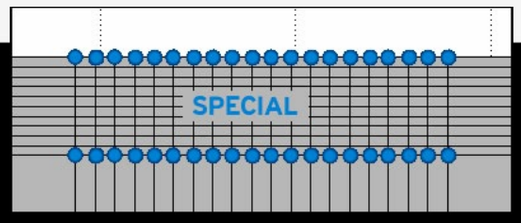

# SURFACE vs. SURFACE-TO-TUNNEL



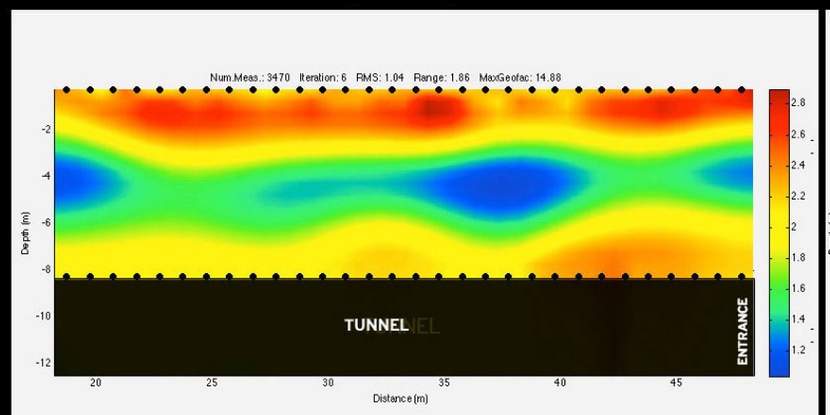
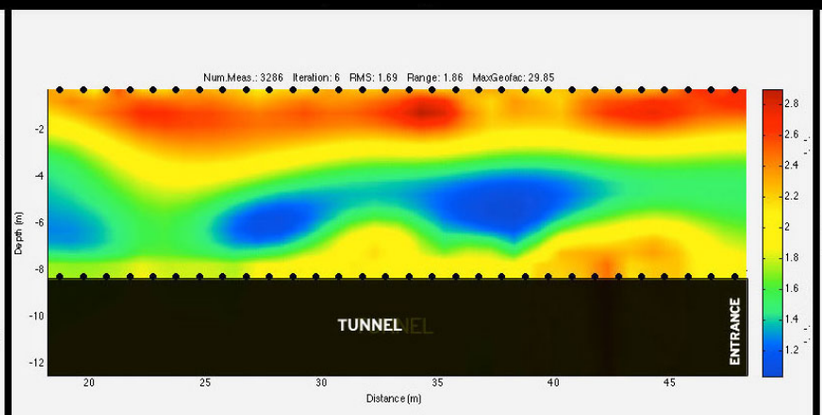
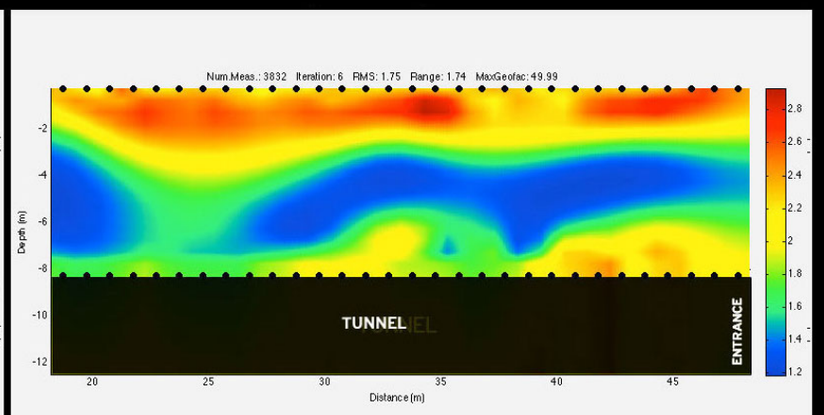
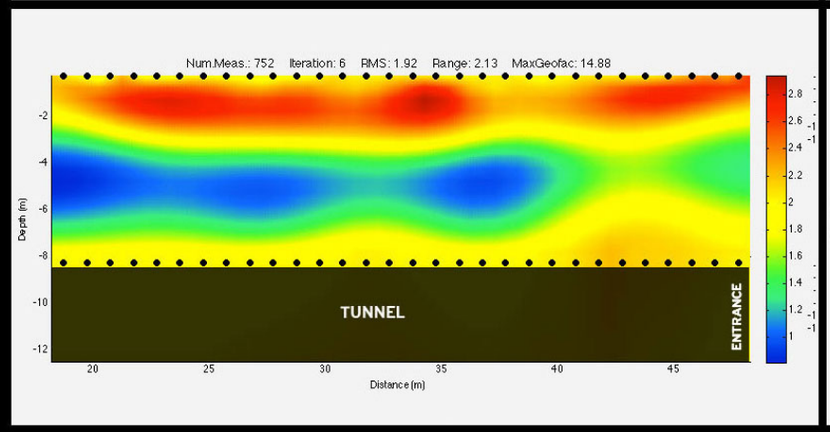
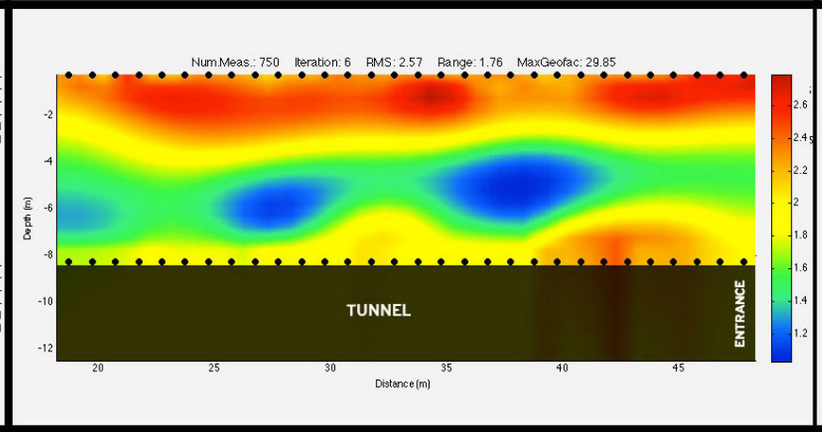
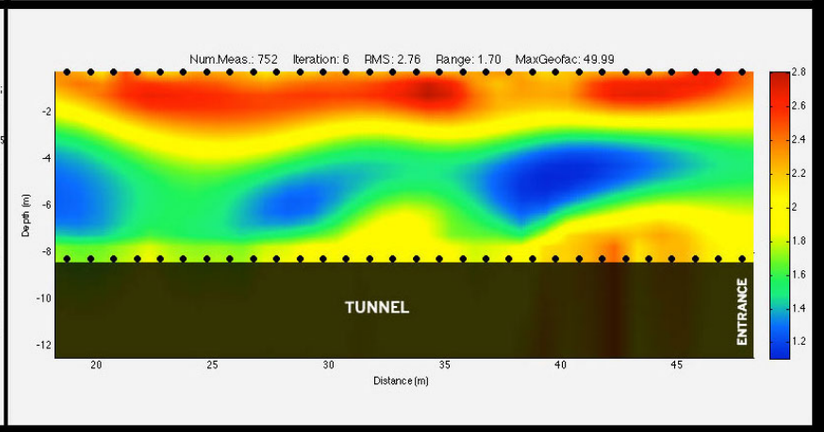

SURFACE




SURFACE-TO-TUNNEL

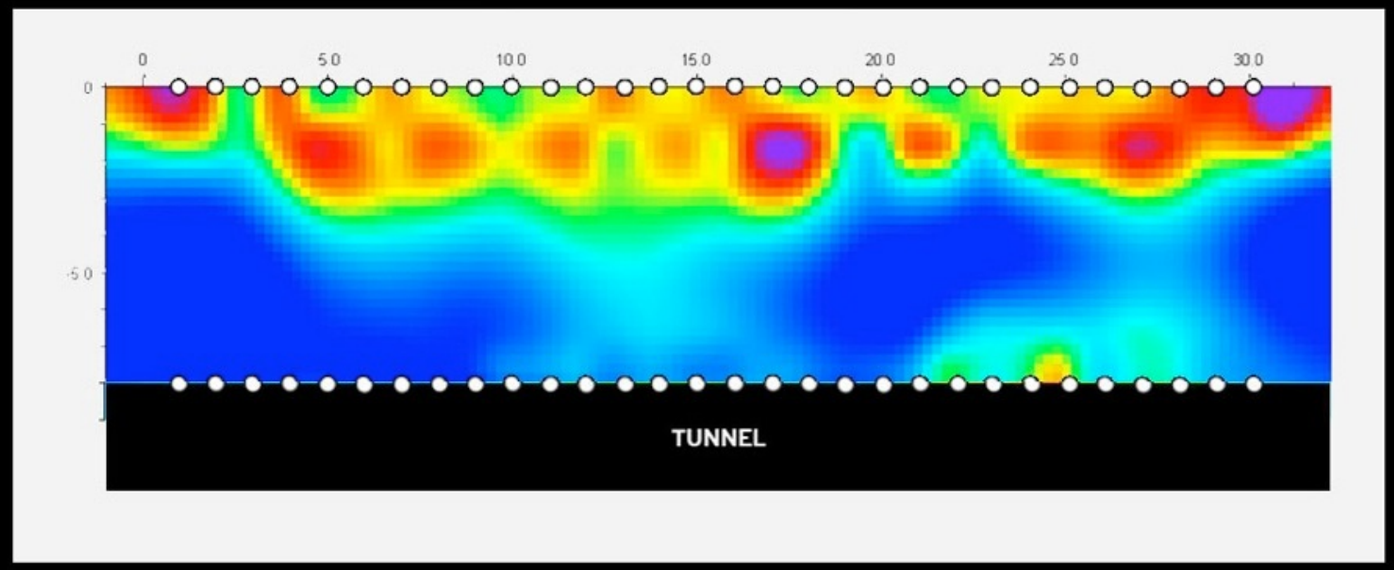
# - PROTOCOL OPTIMIZATION

| | bipole-bipole | pole-dipole | pole-tripole |
|---|---|---|---|
| Raw Data |  |  |  |
| Jacobian Optimum |  |  |  |

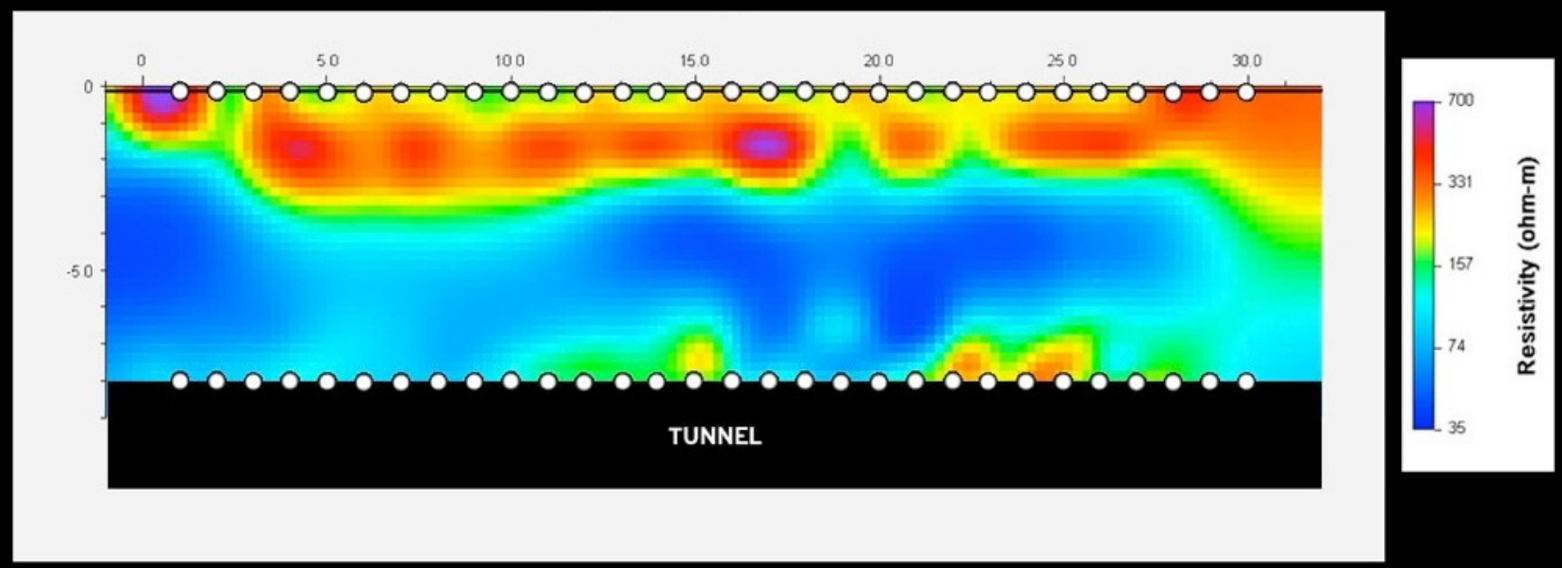
# - TUNNEL EFFECT CORRECTION

FIELD DATA

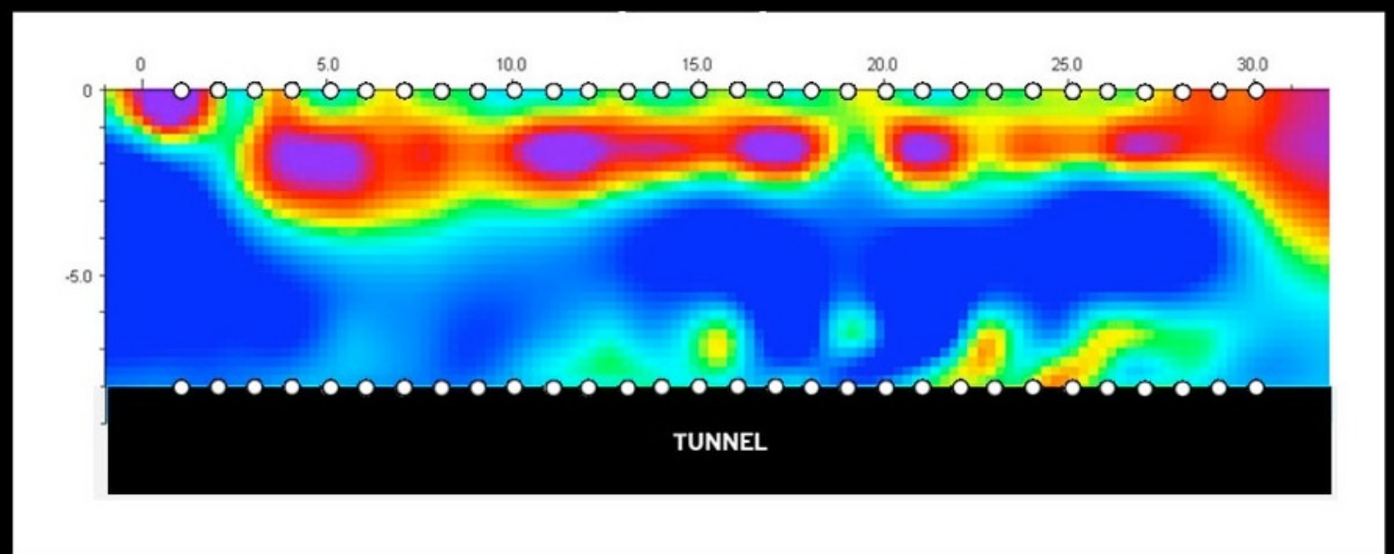
bipole-bipole




pole-dipole

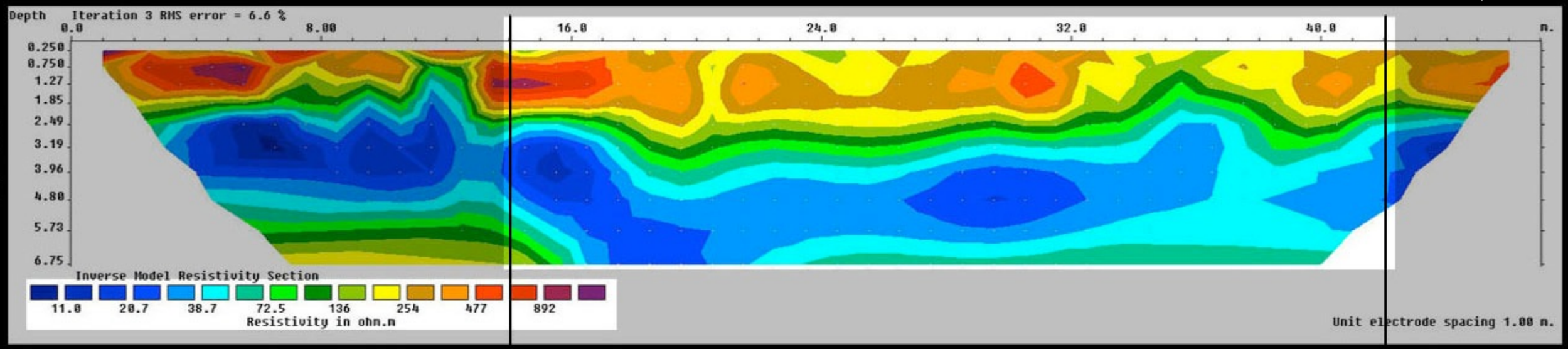



pole-tripole

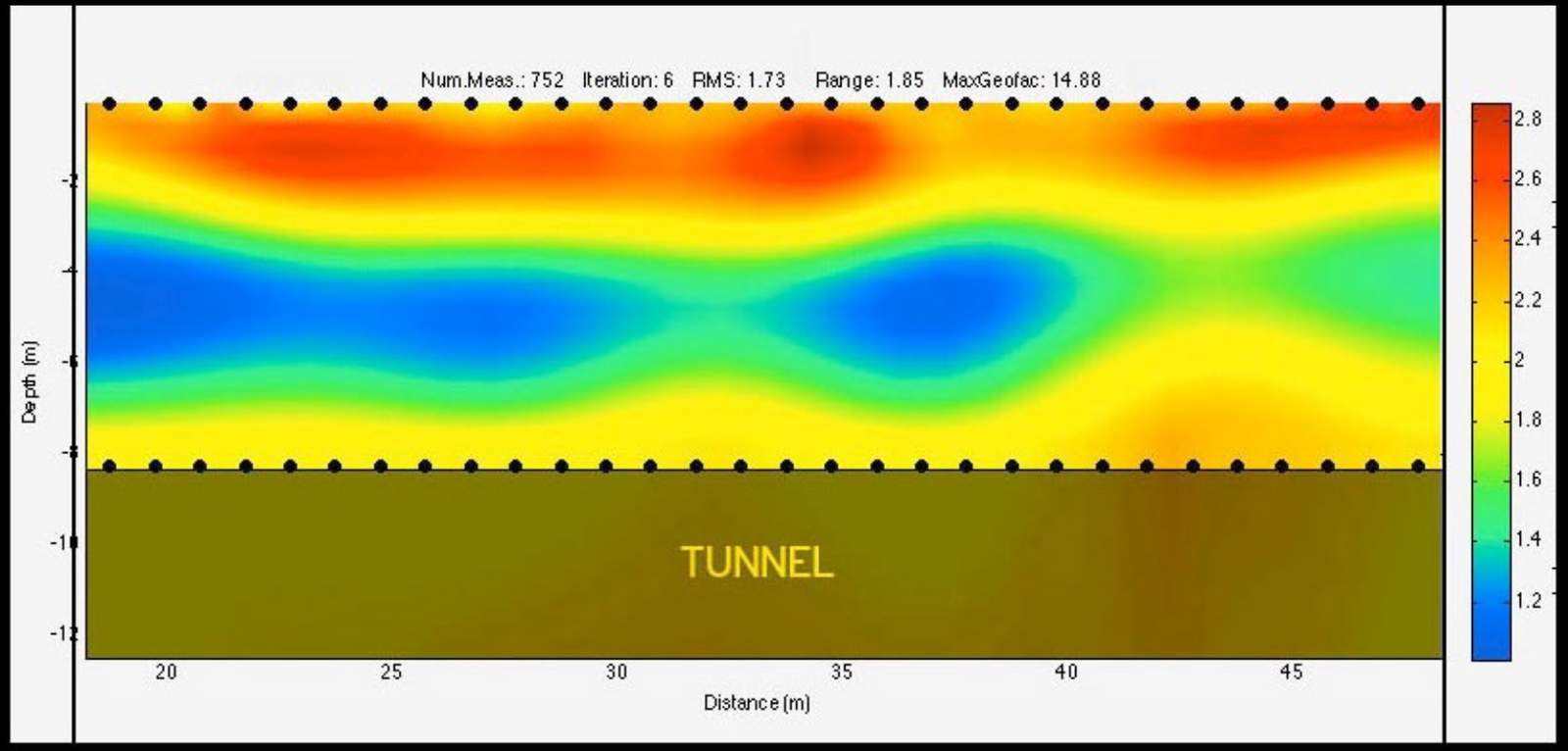


# Comparison with Previous Data

PAPADOPOULOS N., 2012







# TIME LAPSE

Improved time-lapse electrical resistivity tomography monitoring of dense non-aqueous phase liquids with surface-to horizontal borehole arrays

Christopher Power

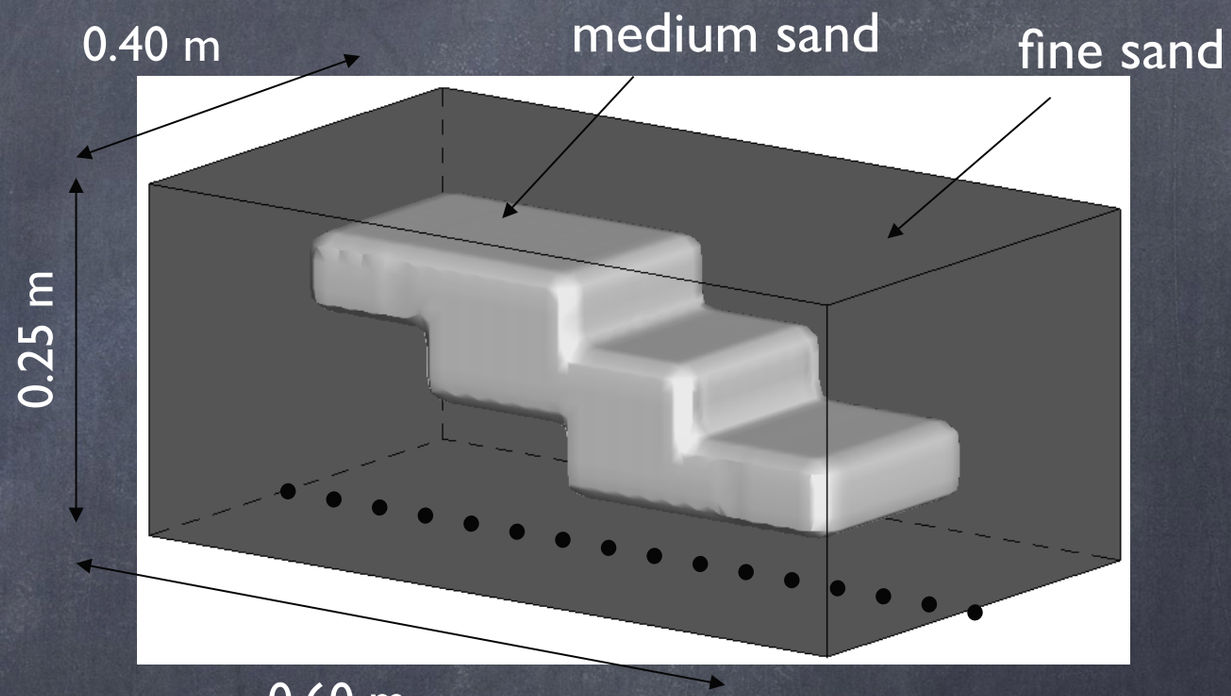
(*Power et al.,* 2015, Journal of Applied Geophysics)

# Bench-Scale Experiments - Set up

tank

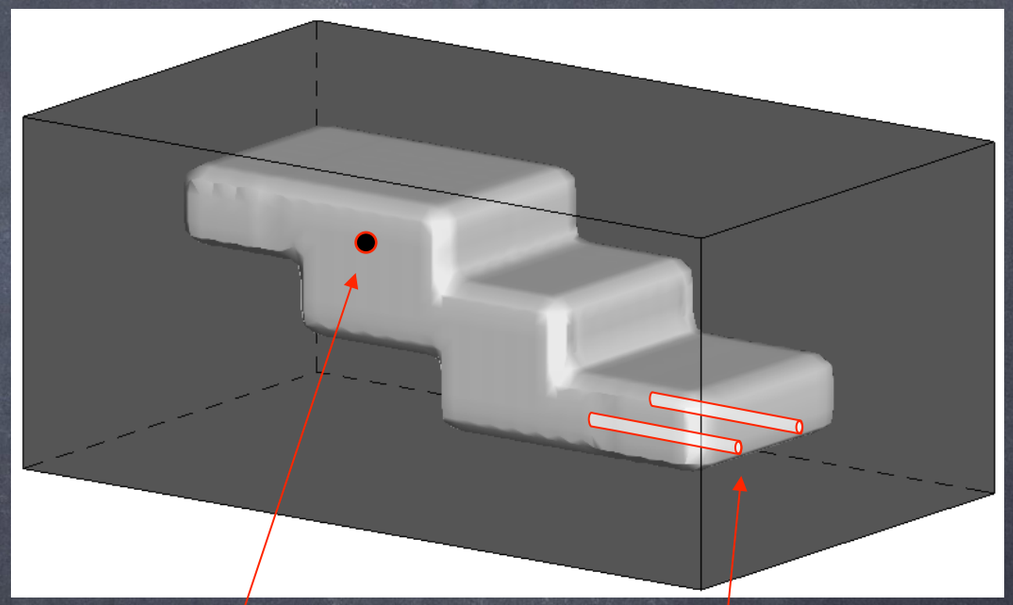

1 x 1 x 1 m

3D Visualization/Simulation




(Technological Educational Institute of Crete)

# Injection Sources

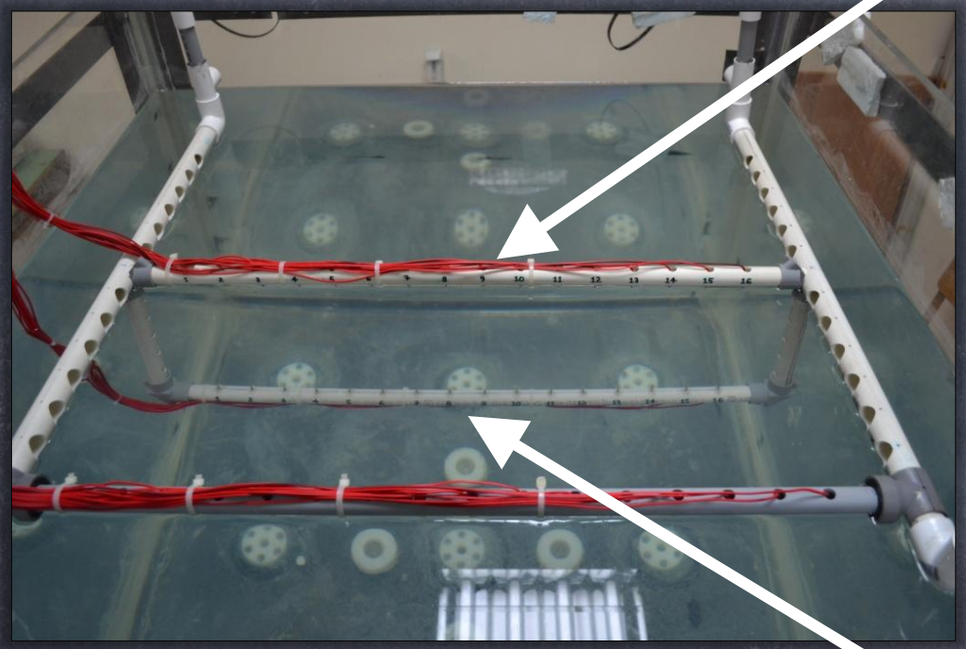



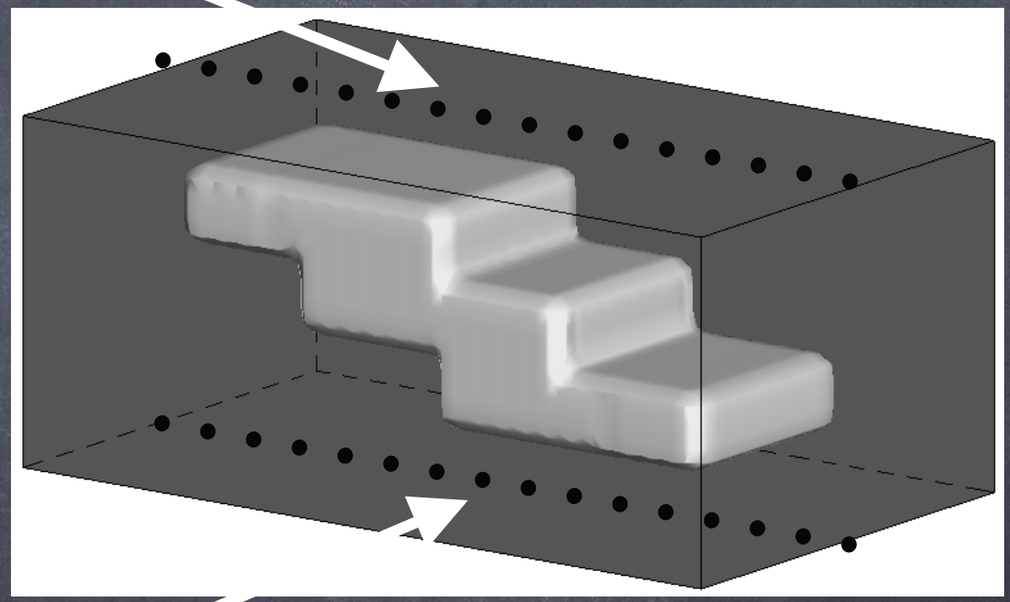
point
injection well

horizontal
injection wells

# Surface to horizontal borehole ERT frame

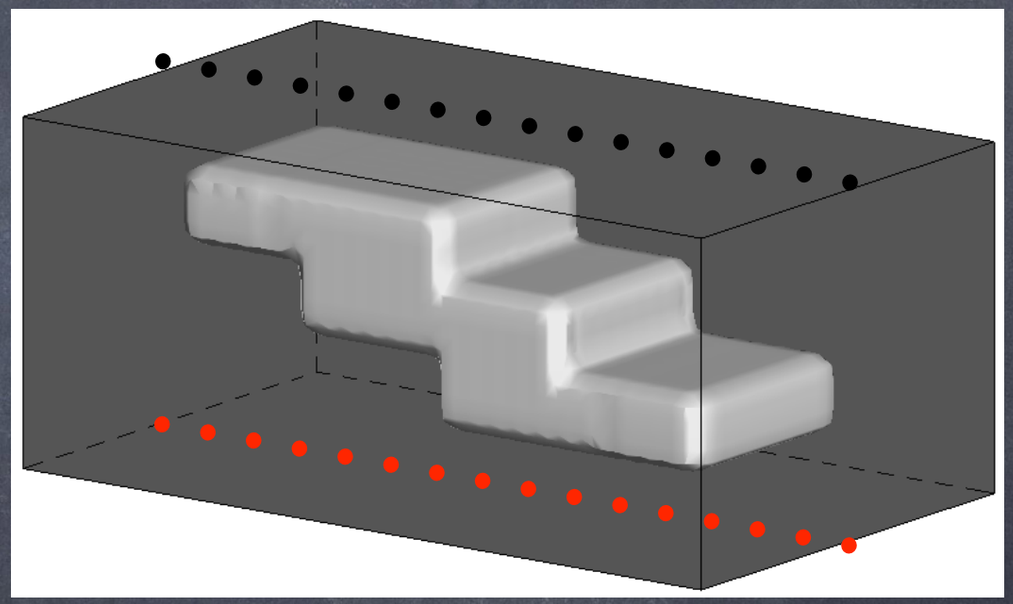
Surface electrodes



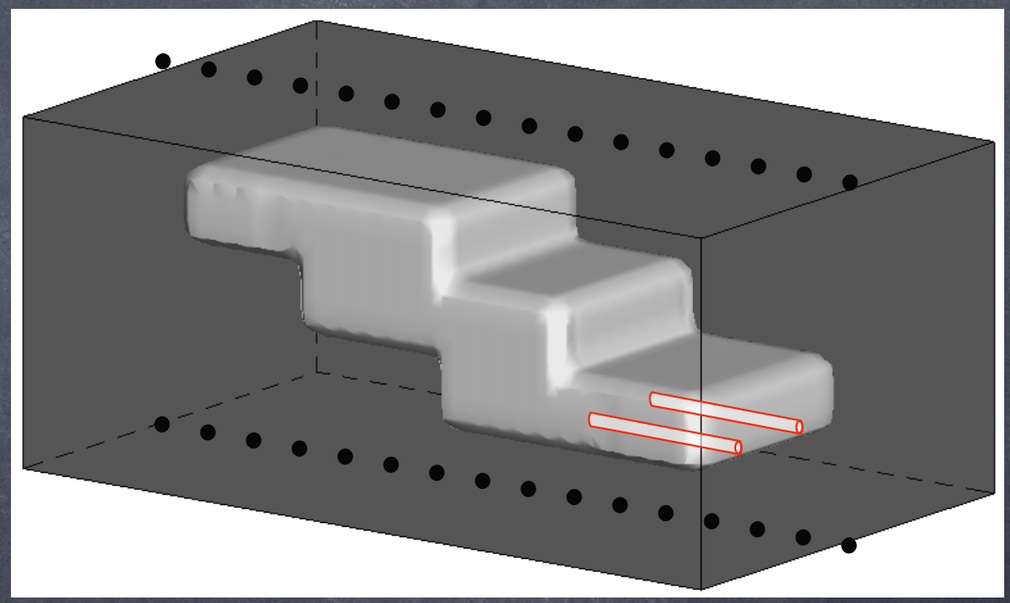


horizontal borehole electrodes

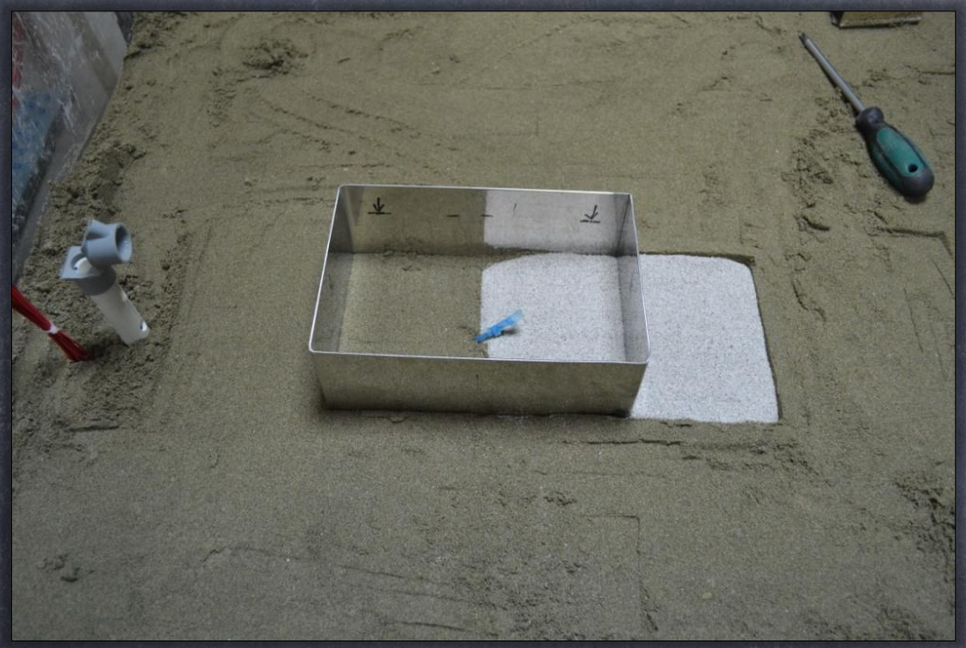
# Horizontal borehole installation

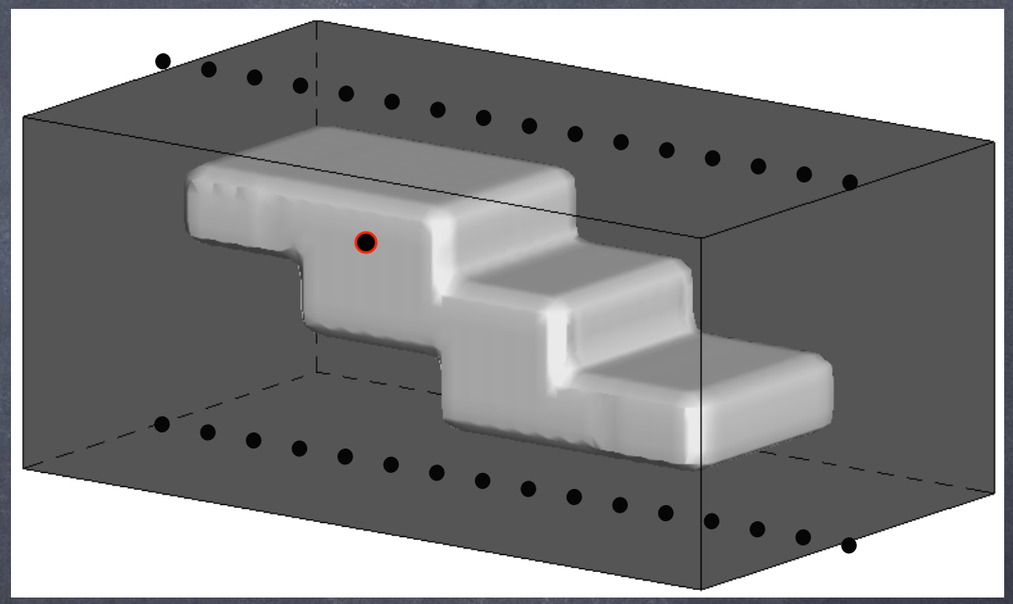


# Installation of horizontal injection wells

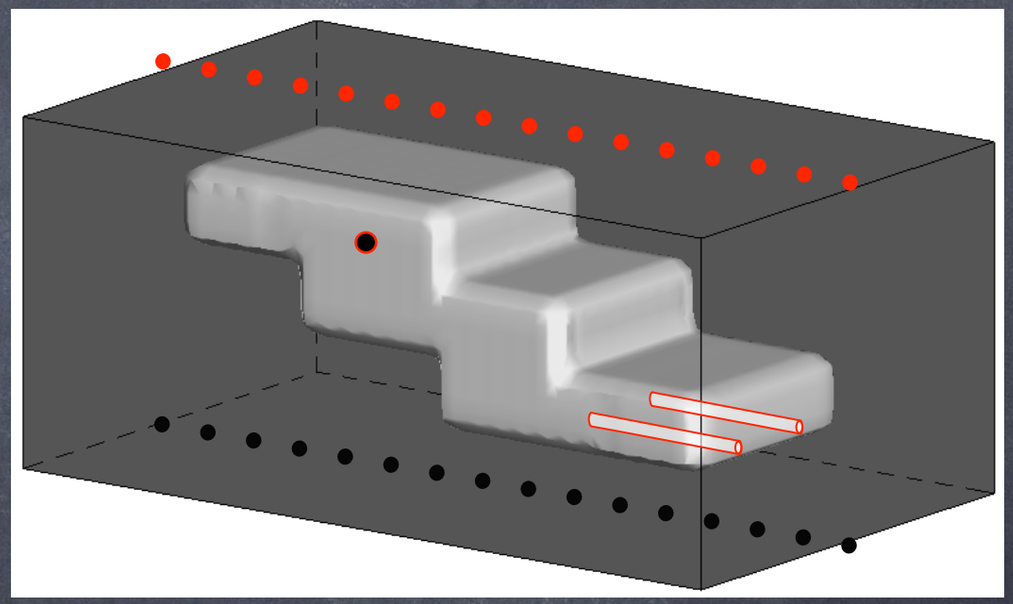


# Installation of point injection well

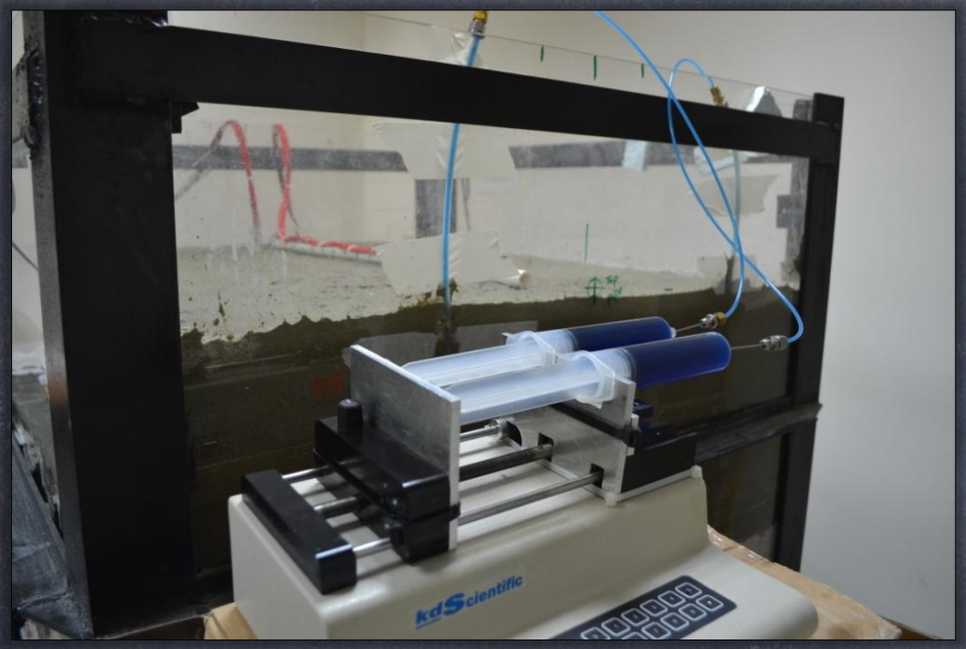


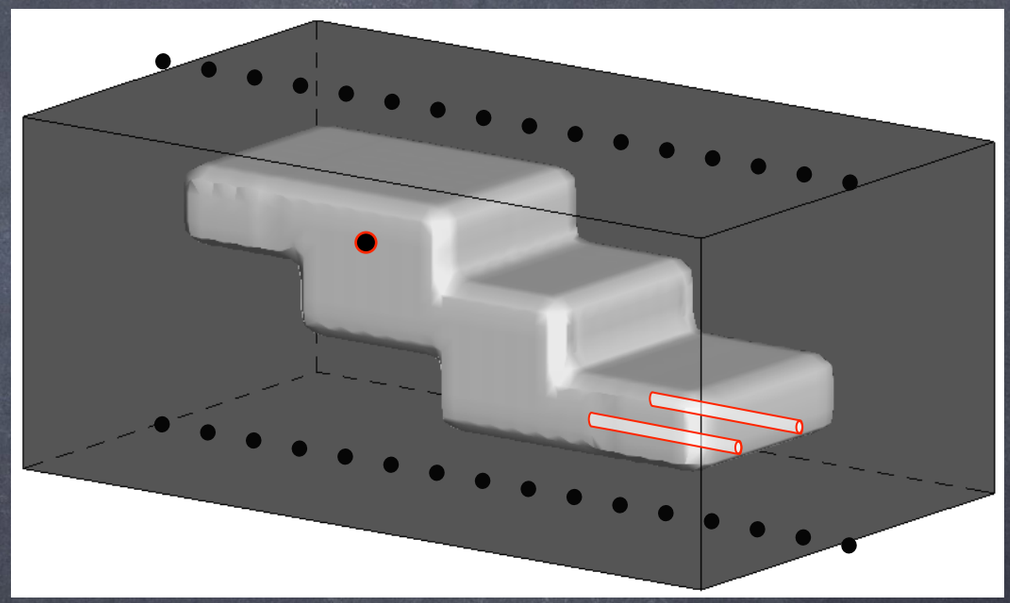


# Surface ERT electrodes

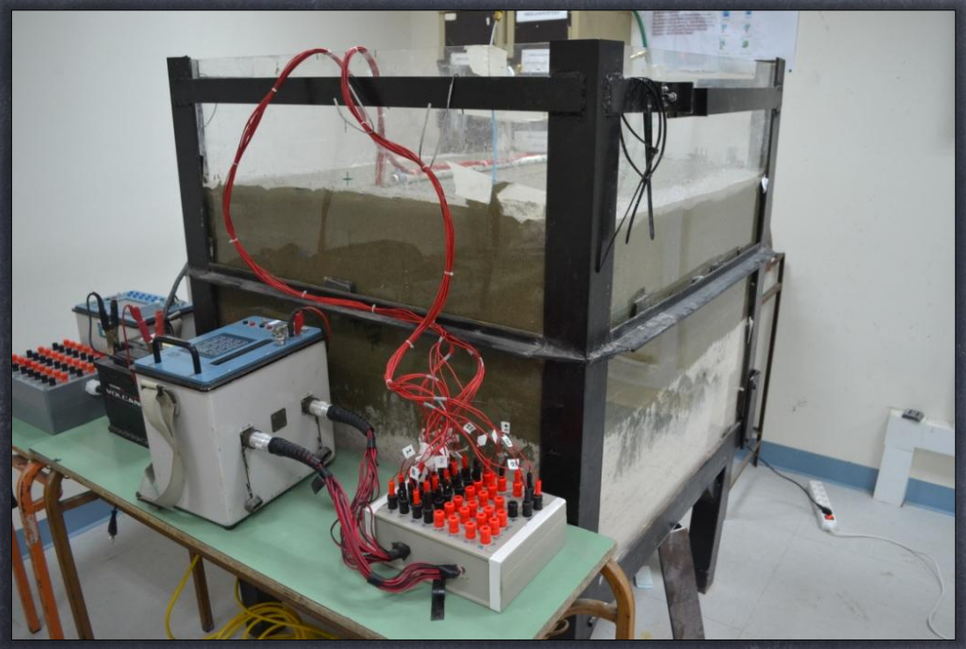


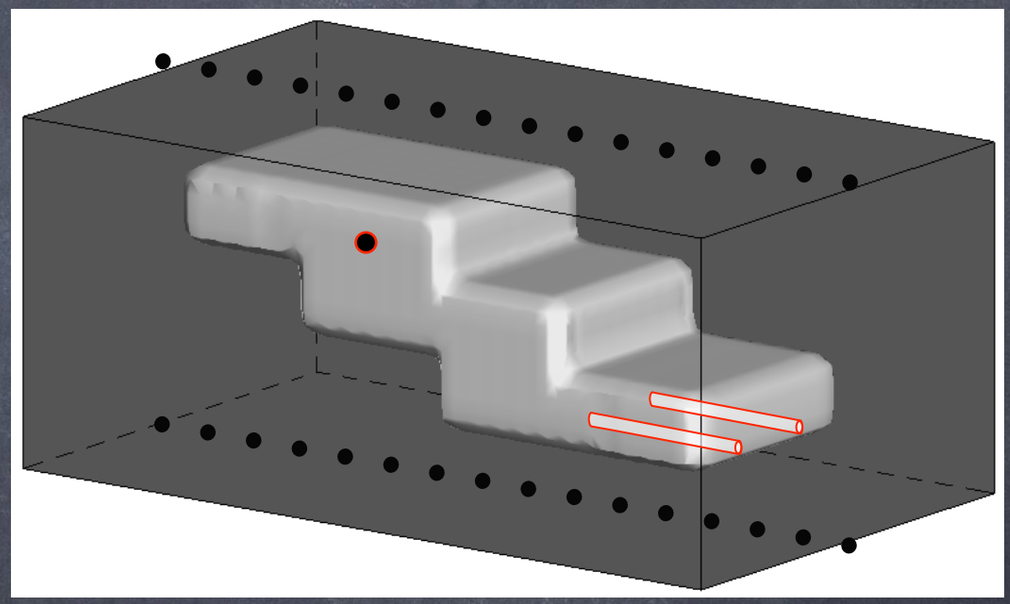
# NAPL injection
# through syringe pumps



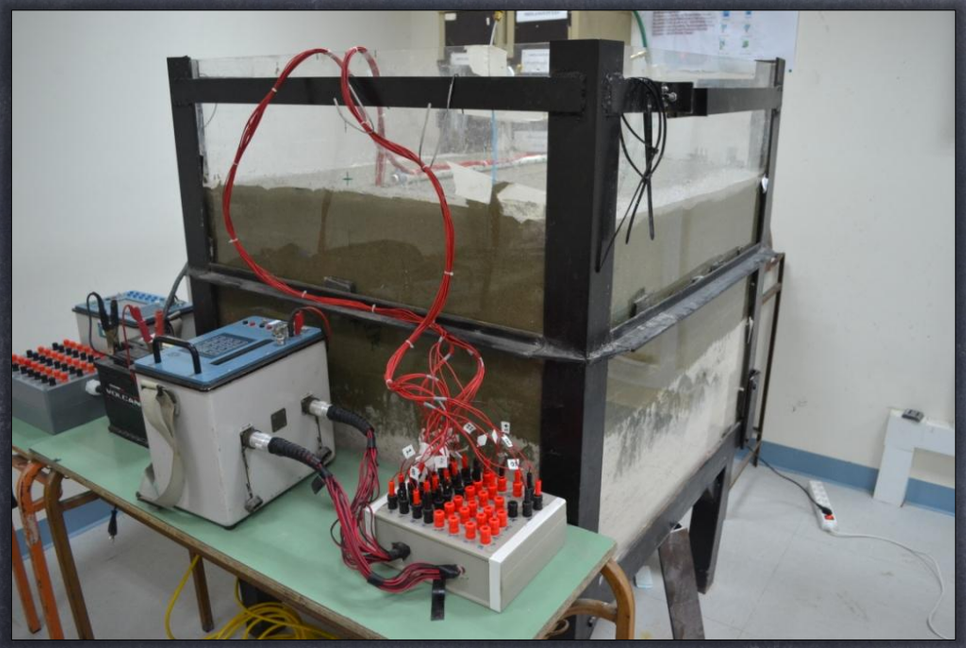



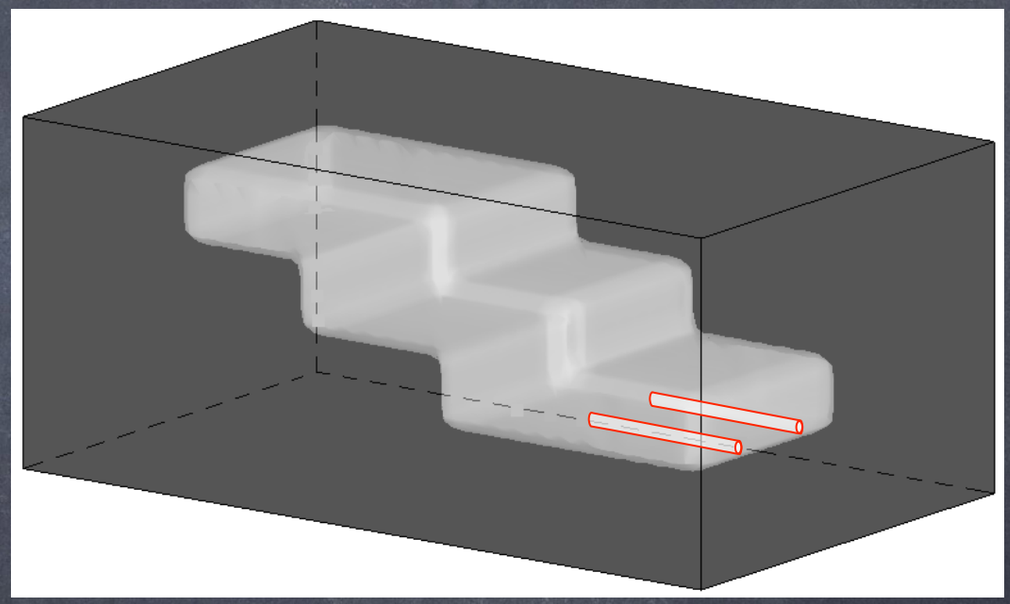
# ERT measurement system



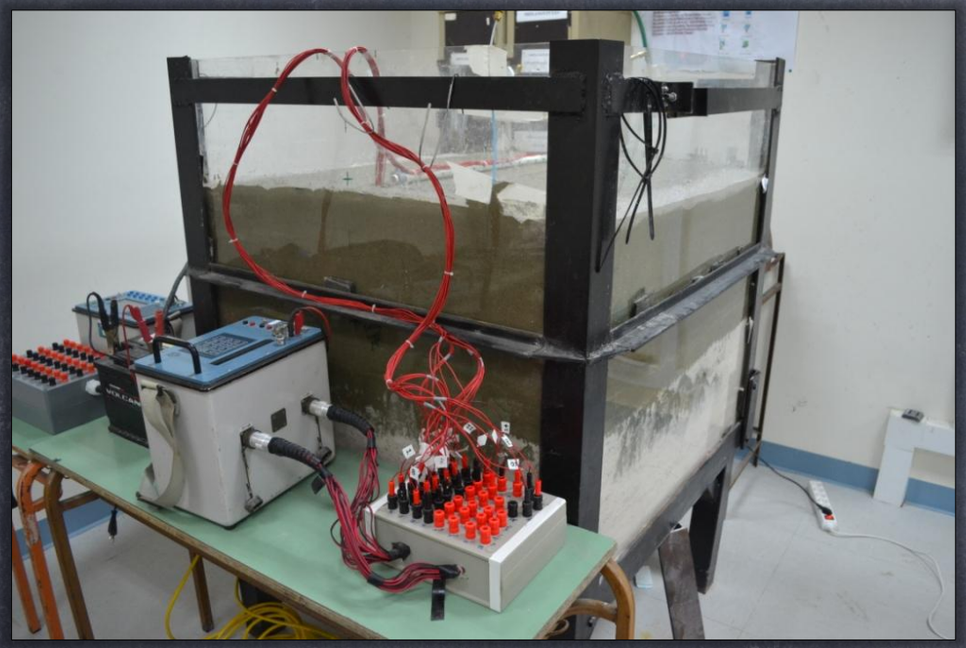


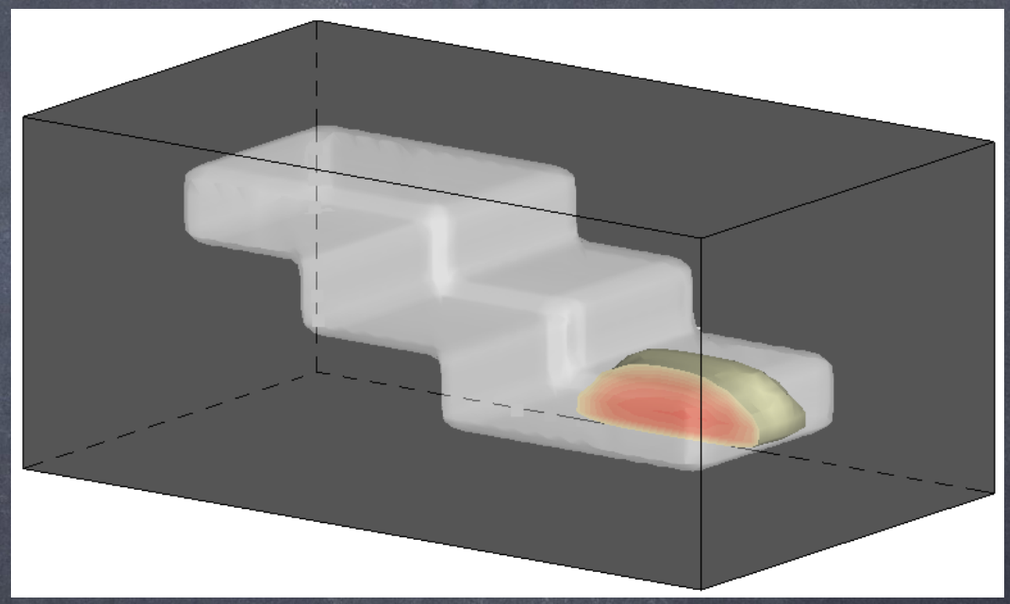
# 0 mL NAPL



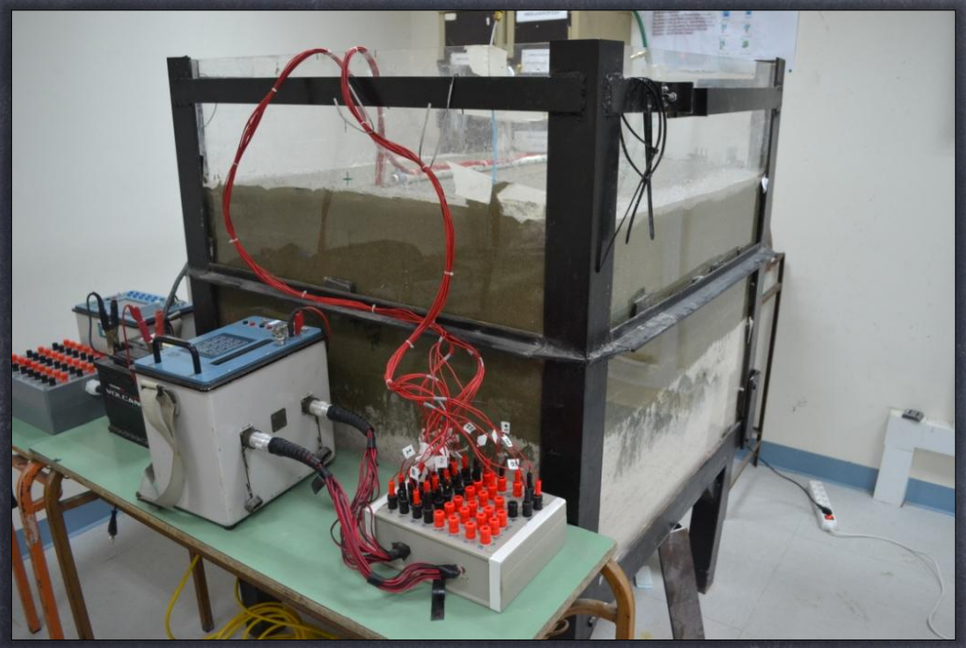


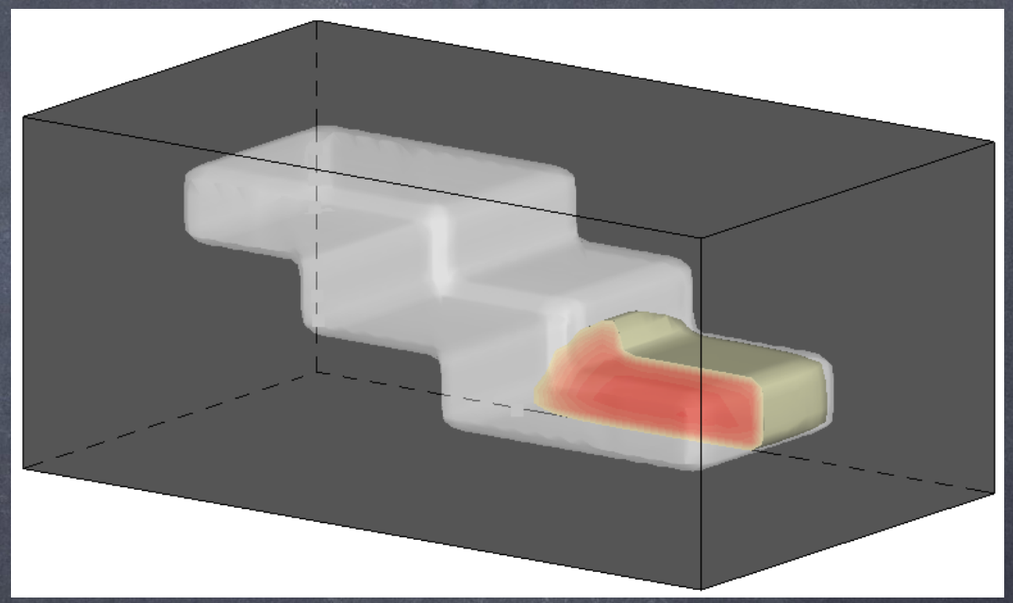
# 200 mL NAPL



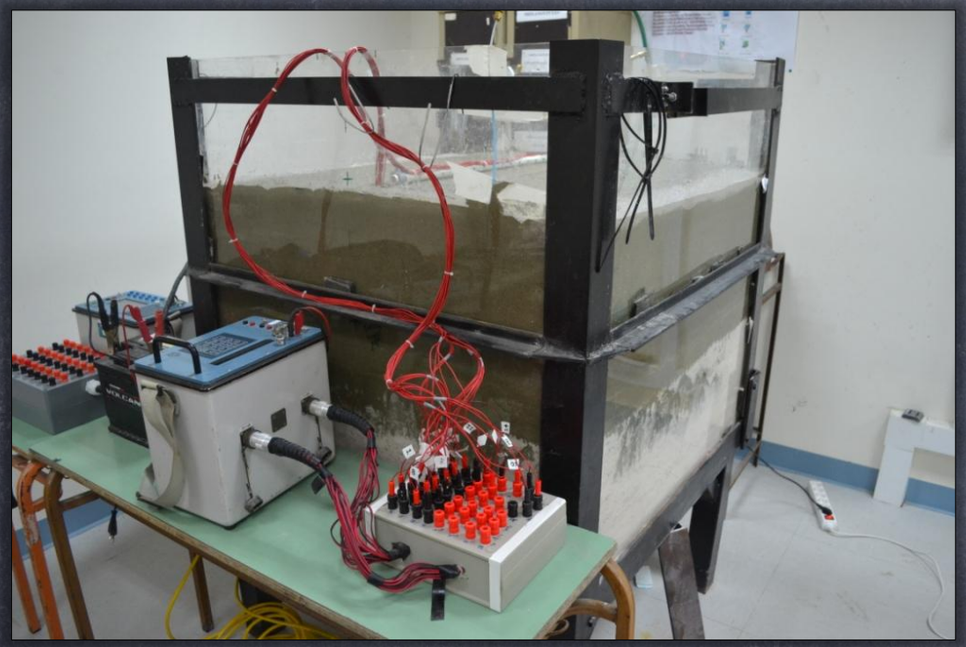


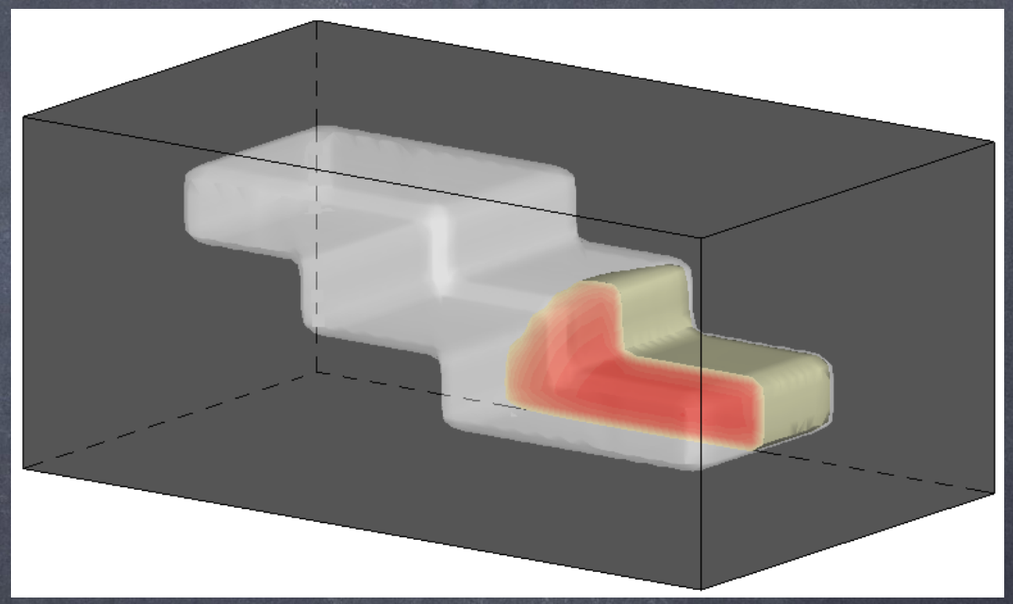
# 400 mL NAPL



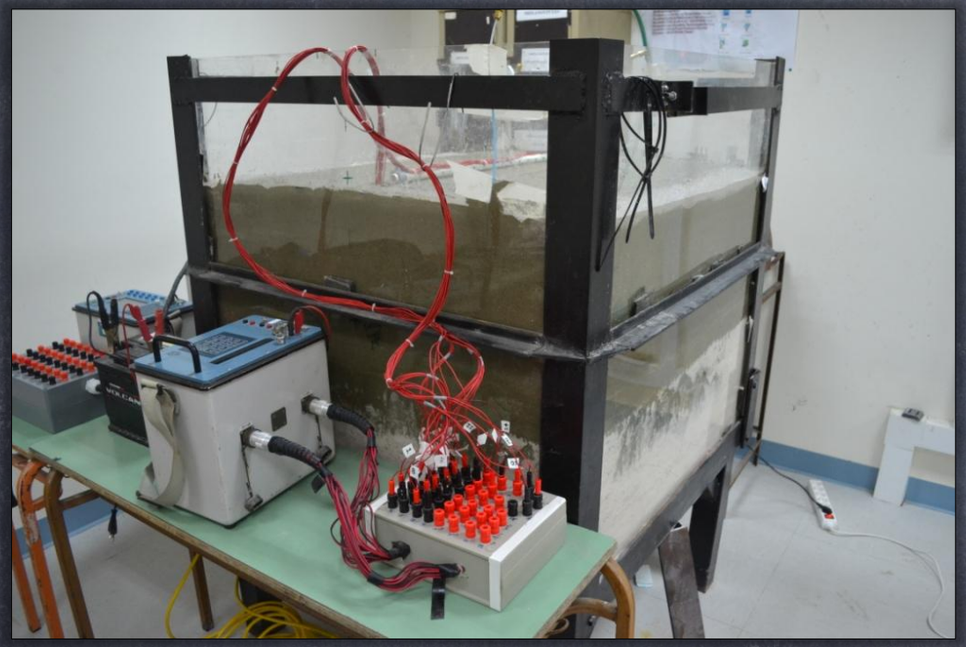


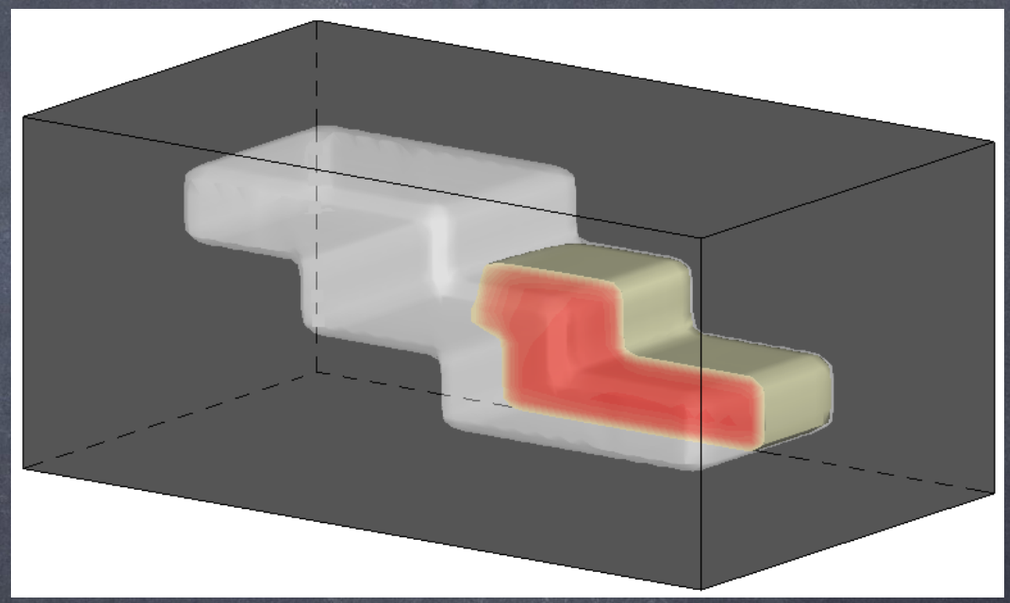
# 600 mL NAPL



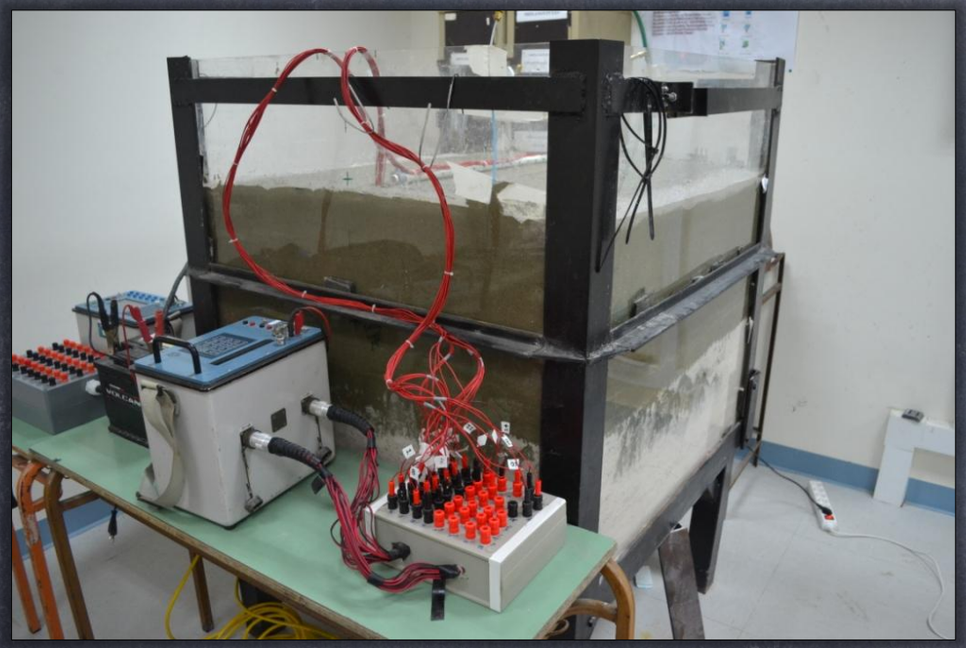


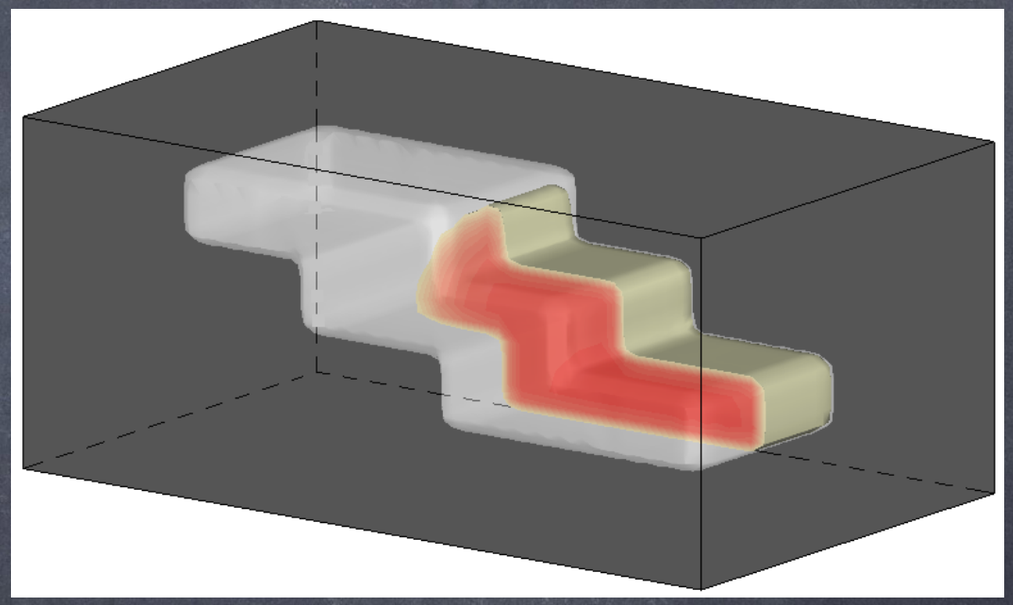
# 800 mL NAPL



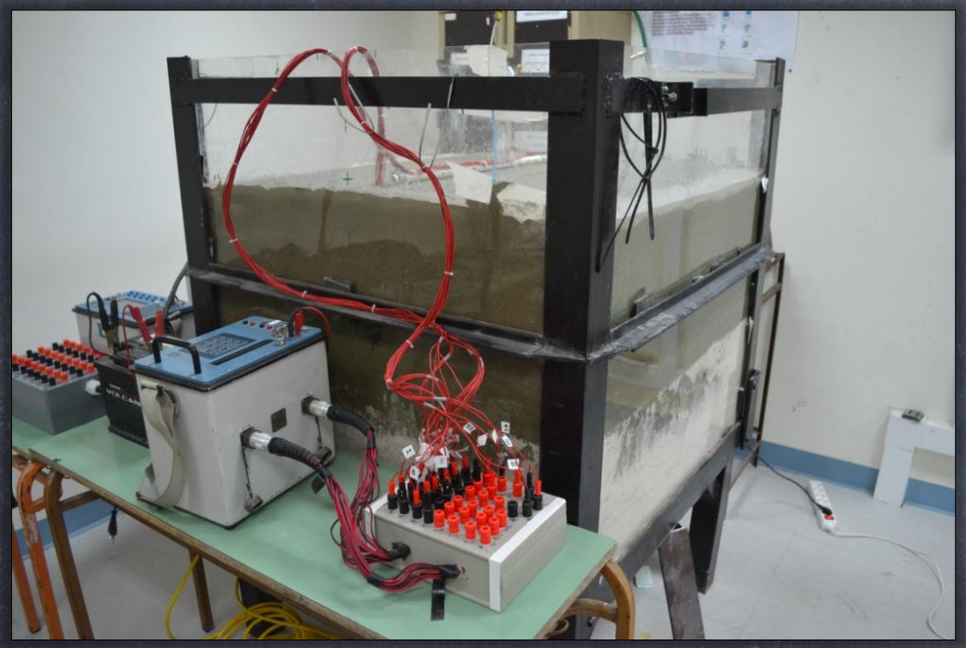


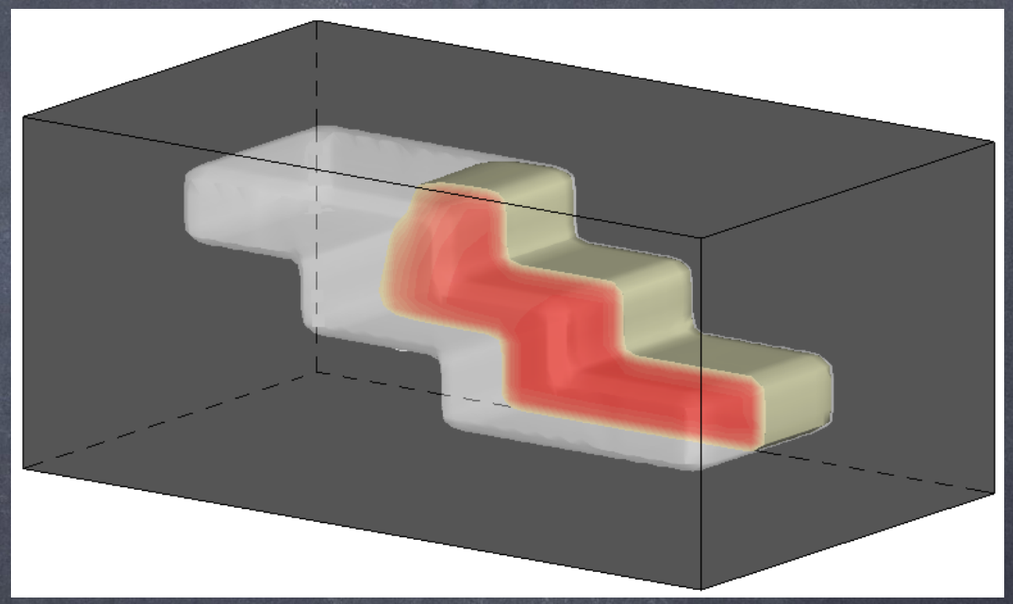
# 1000 mL NAPL



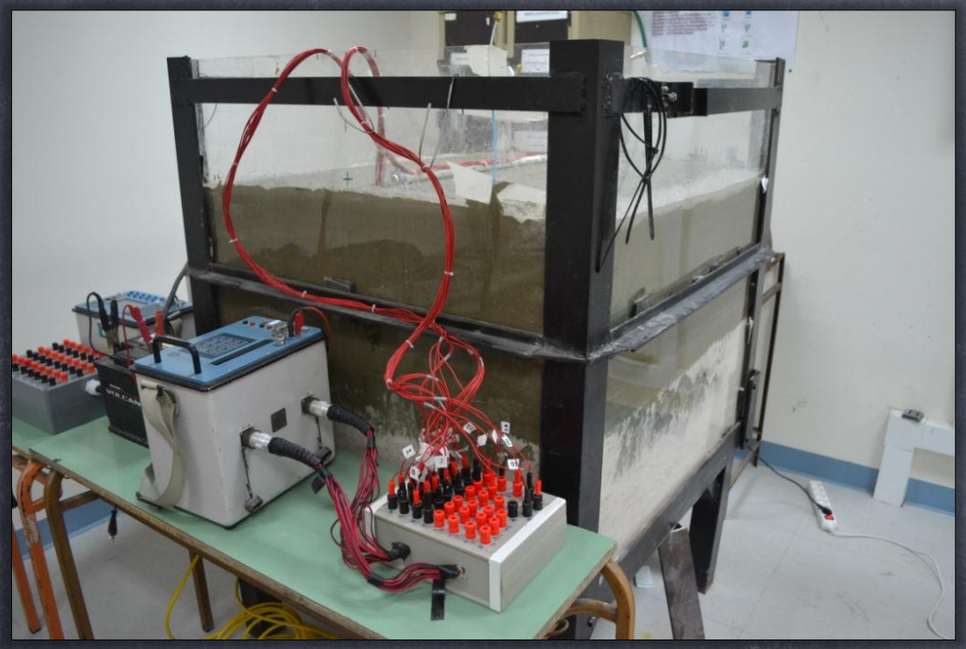


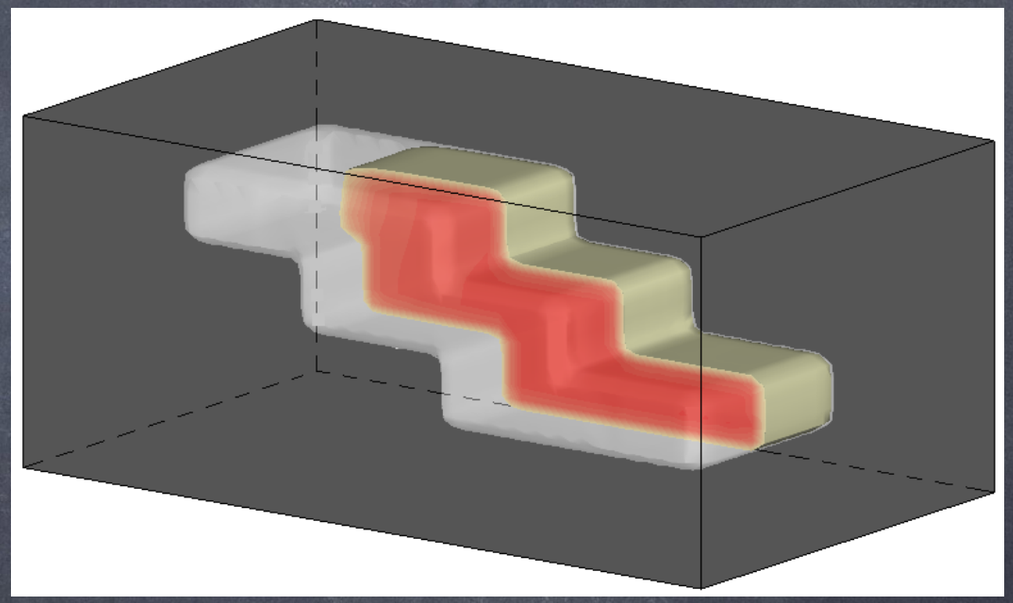
# 1200 mL NAPL



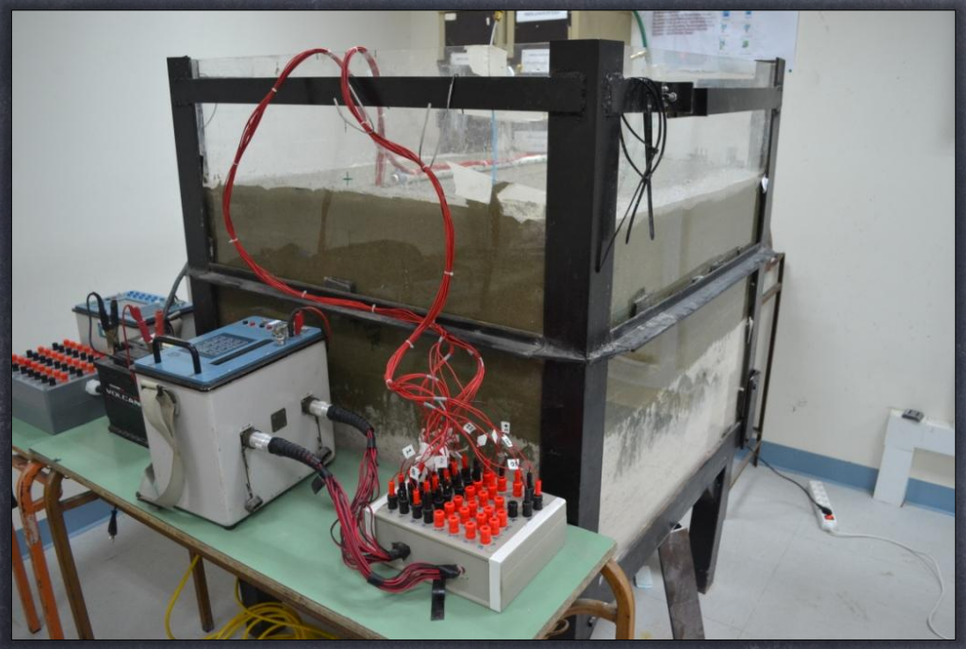


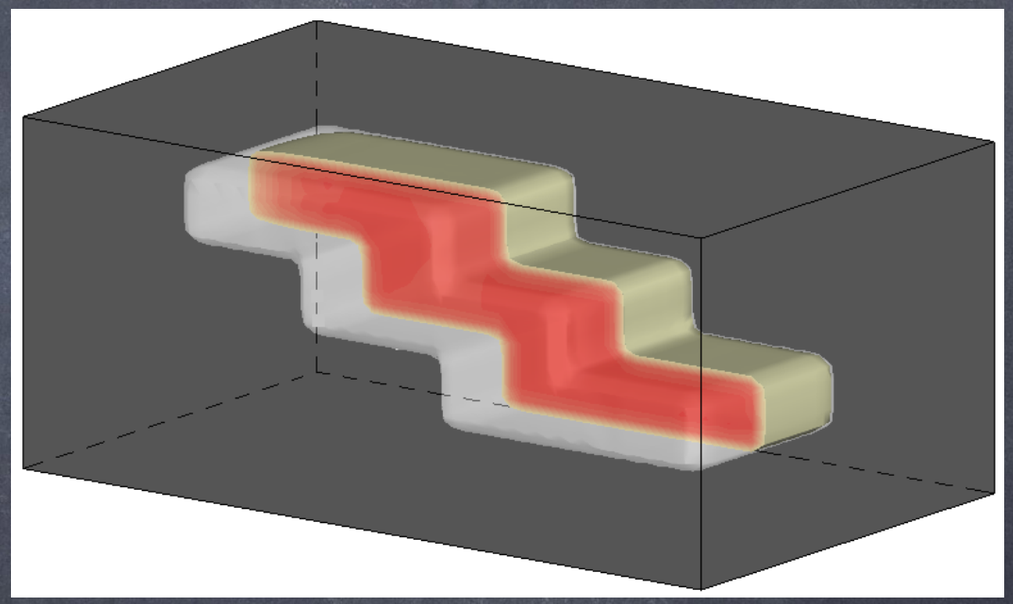
# 1400 mL NAPL





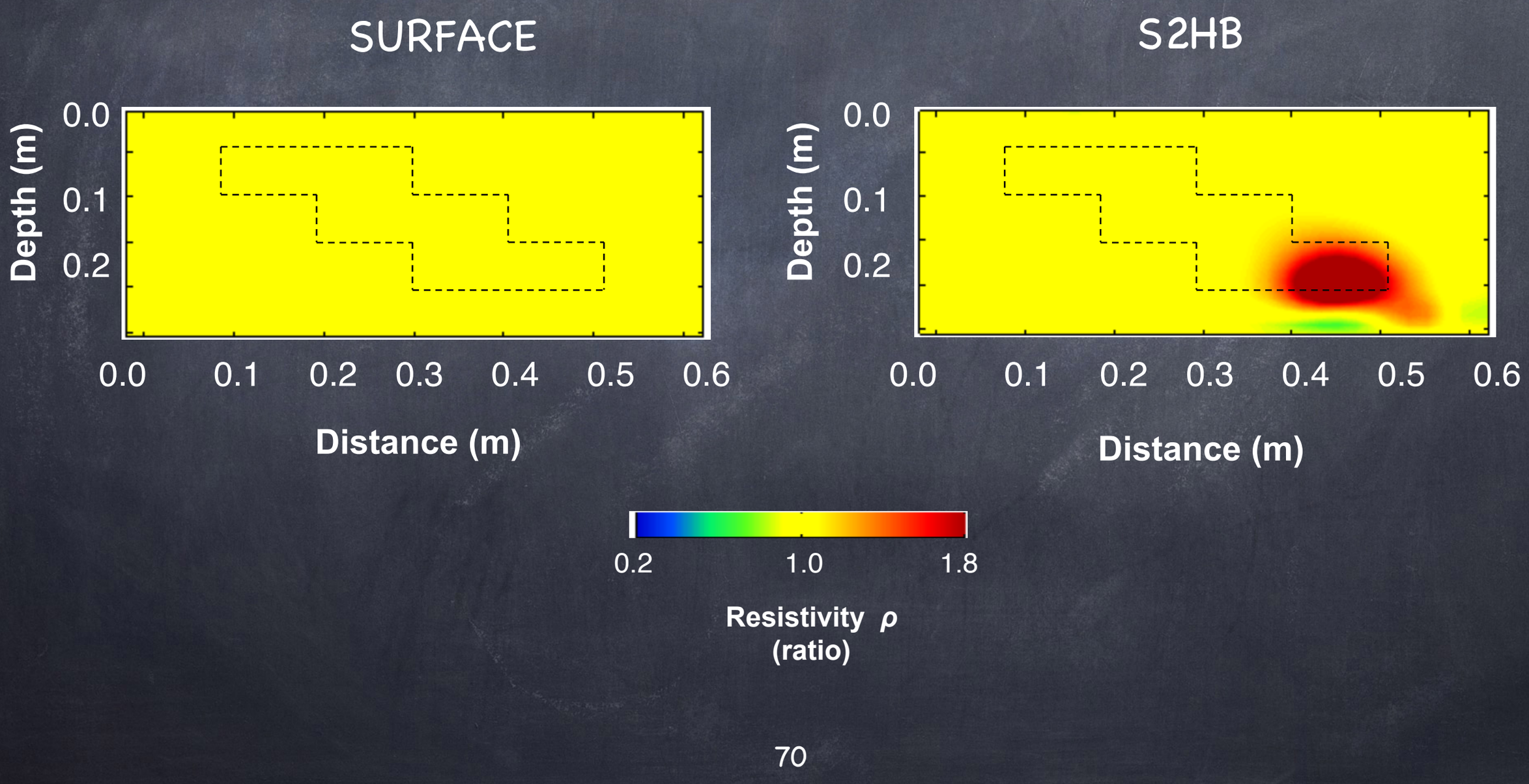
# 1600 mL NAPL



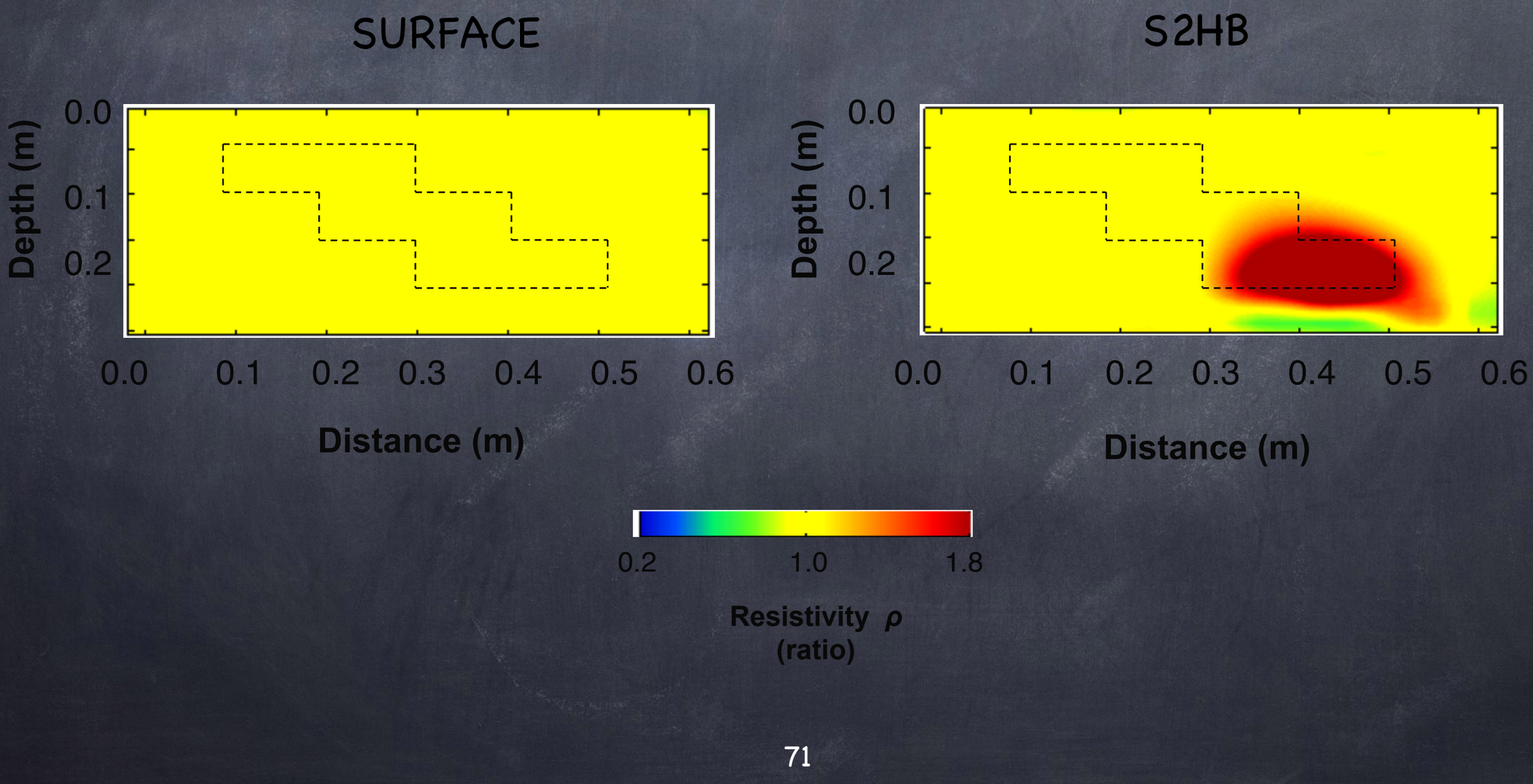


# Results - Time lapse monitoring

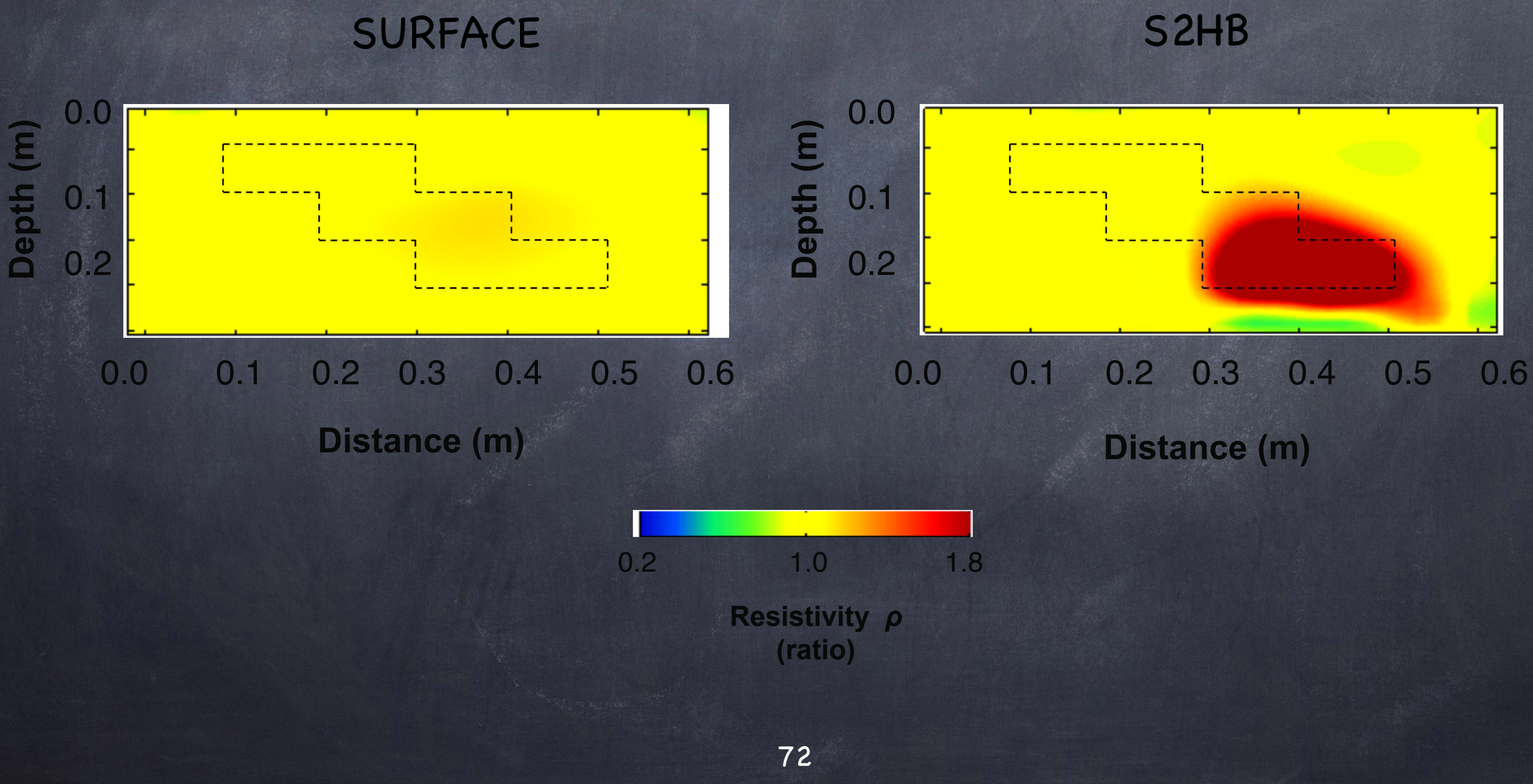
**200 mL / 0 mL**



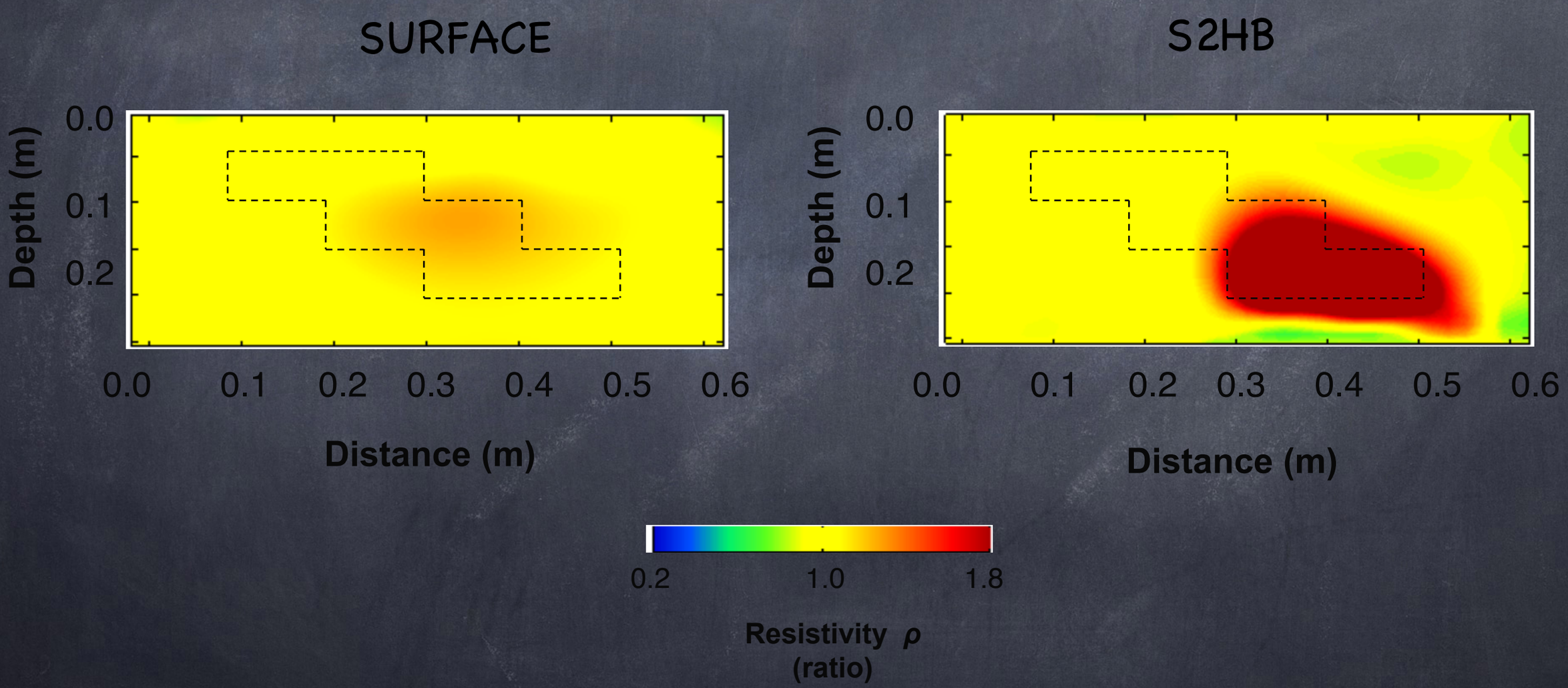
**400 mL / 0 mL**


SURFACE
S2HB
Depth (m)
0.0
0.1
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Distance (m)
0.2
1.0
1.8
Resistivity ρ
(ratio)

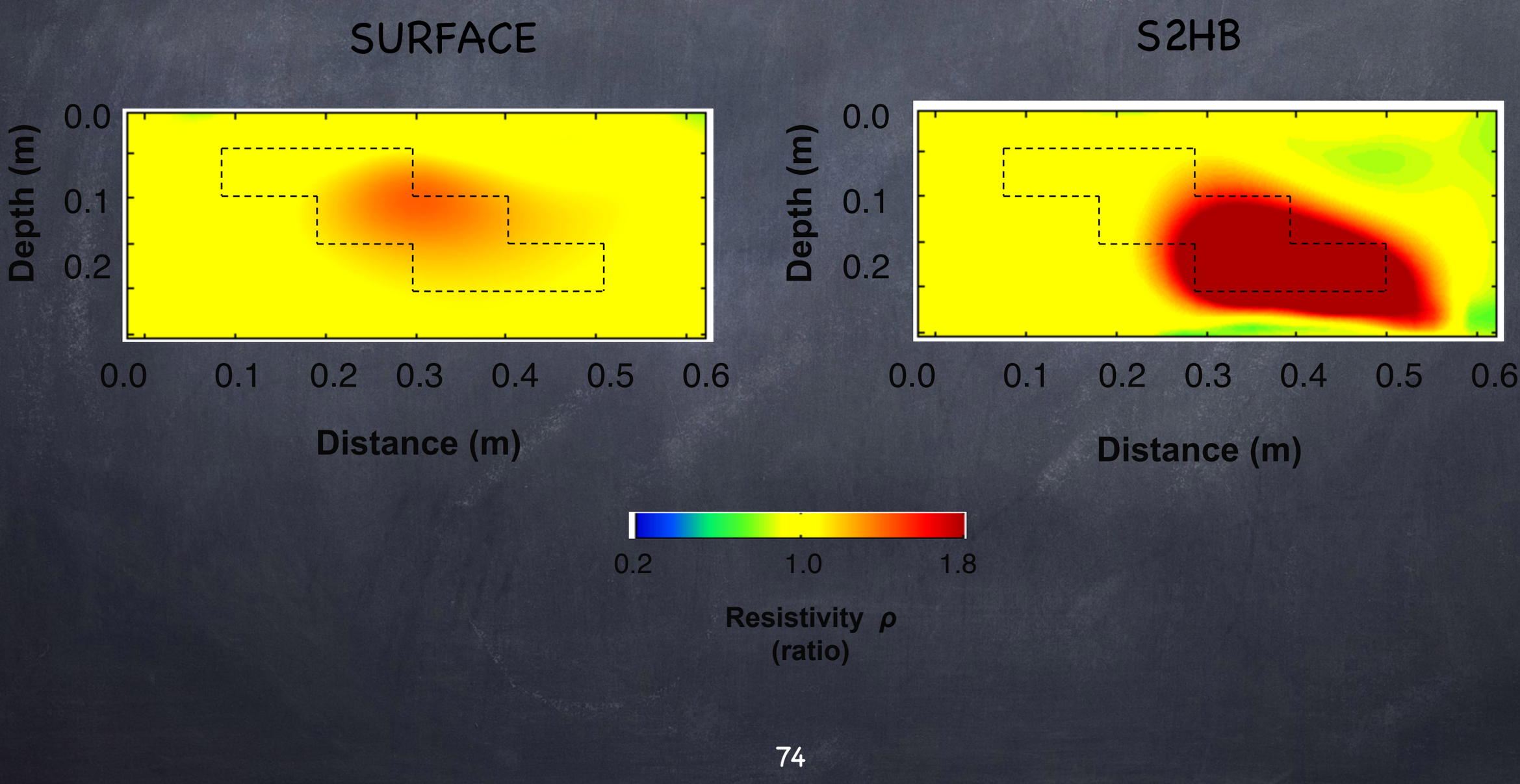
**600 mL / 0 mL**


SURFACE
S2HB
Depth (m)
0.0
0.1
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Distance (m)
0.2
1.0
1.8
Resistivity ρ
(ratio)

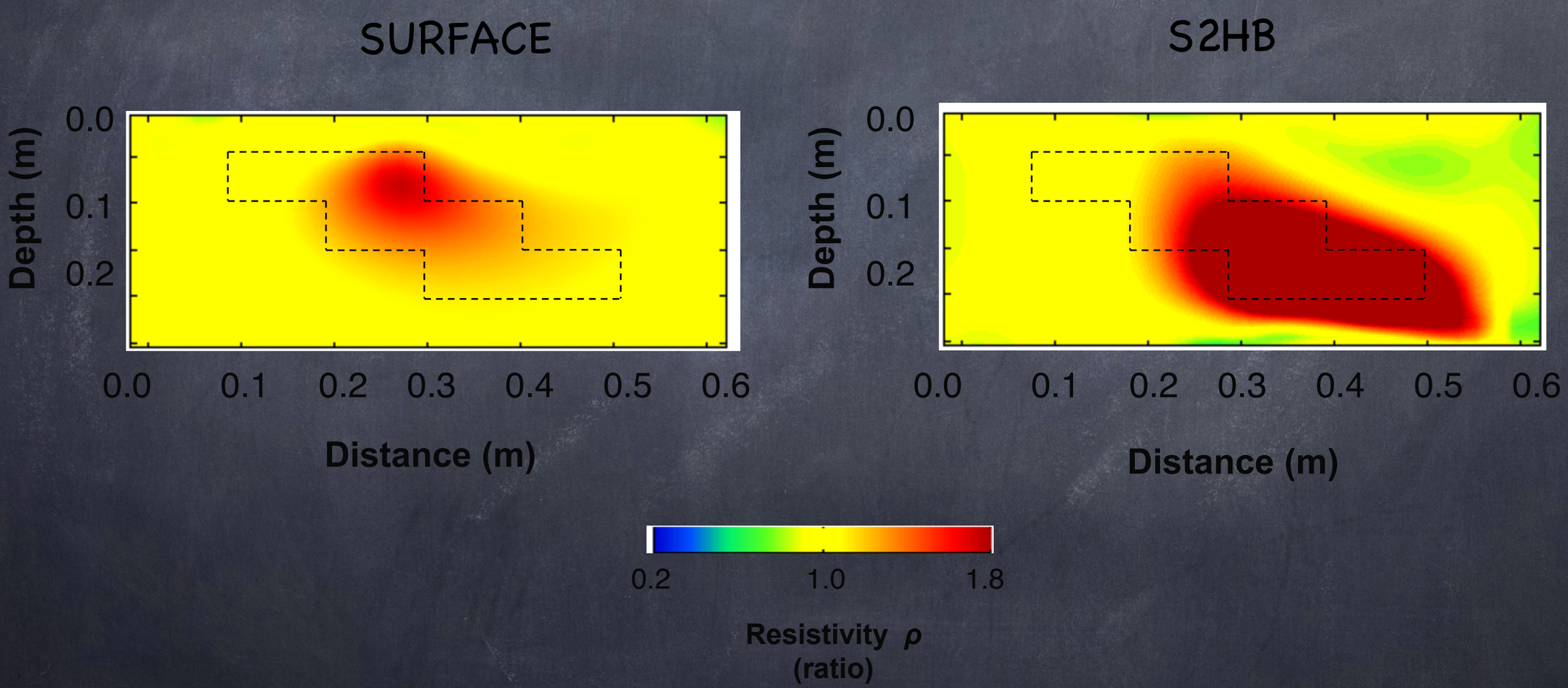
**800 mL / 0 mL**


SURFACE
S2HB
Depth (m)
0.0
0.1
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Distance (m)
0.2
1.0
1.8
Resistivity ρ
(ratio)

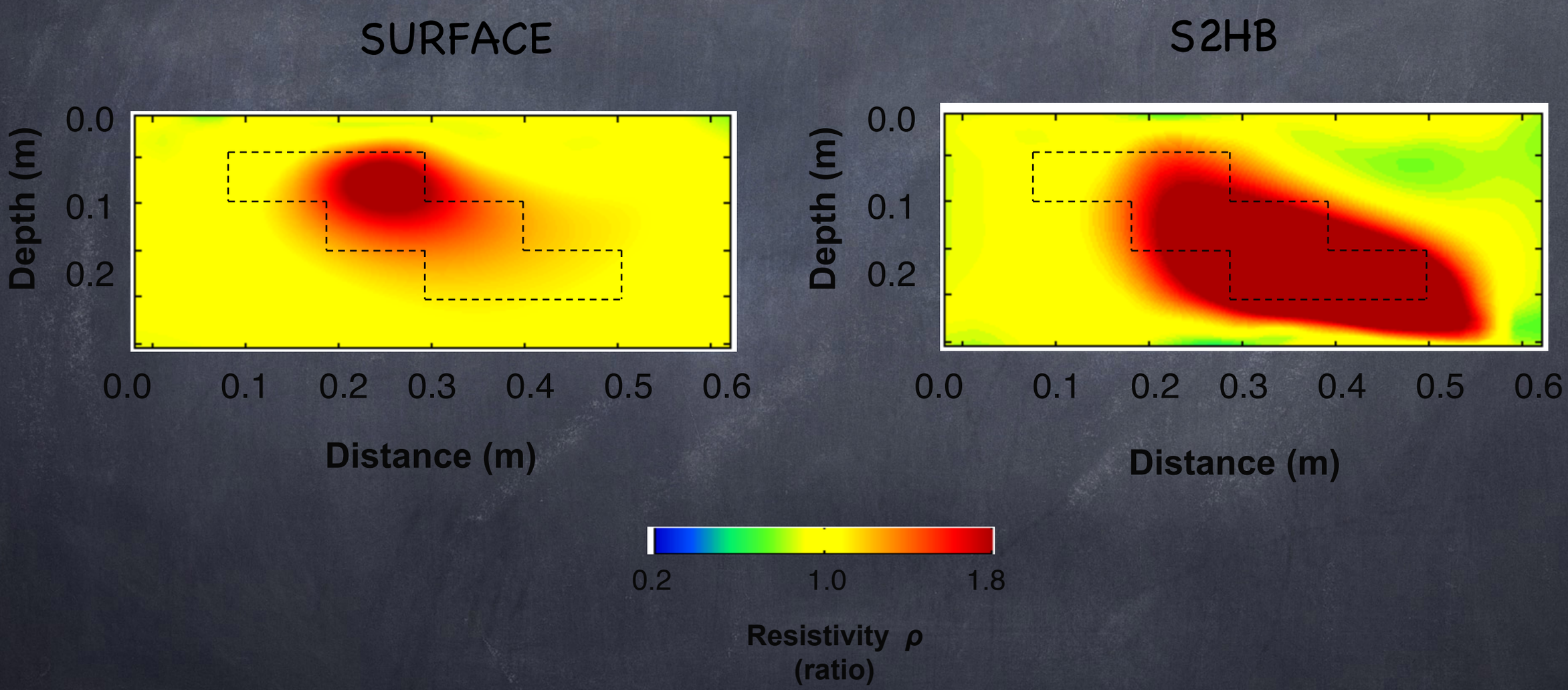
**1000 mL / 0 mL**


SURFACE
S2HB
Depth (m)
0.0
0.1
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Distance (m)
0.2
1.0
1.8
Resistivity ρ
(ratio)

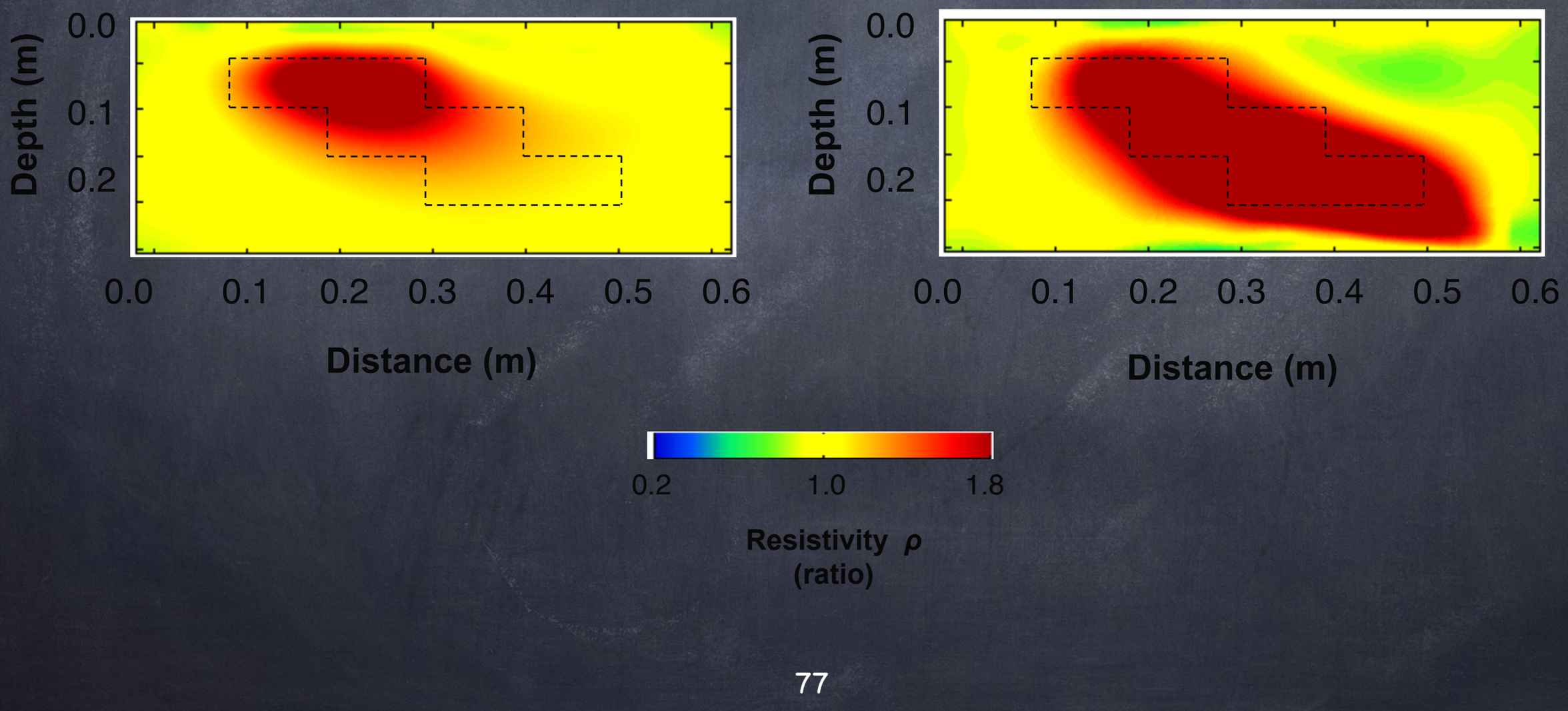
# 1200 mL / 0 mL


SURFACE
S2HB
Depth (m)
0.0
0.1
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Distance (m)
0.2
1.0
1.8
Resistivity ρ
(ratio)

**1400 mL / 0 mL**

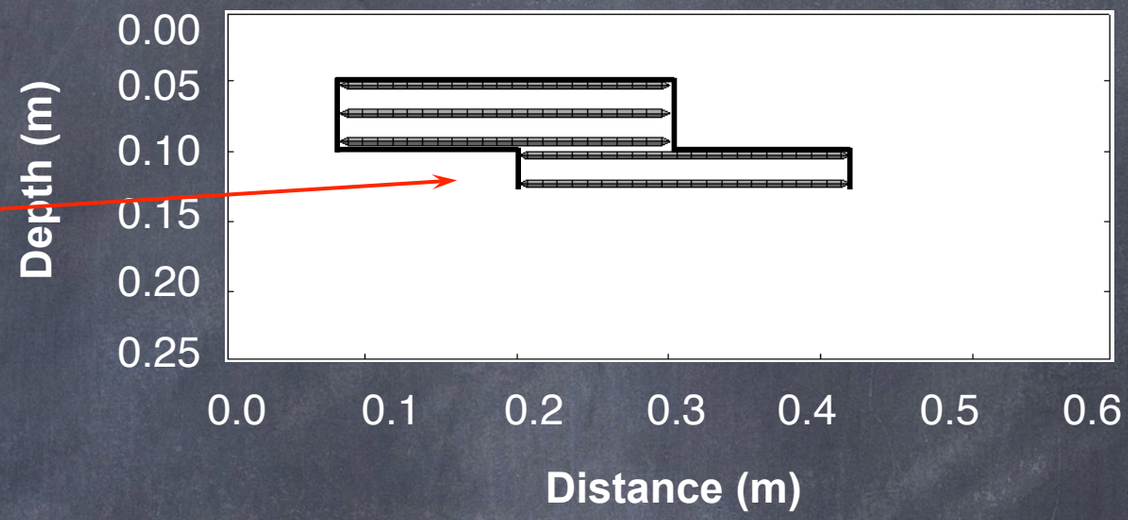

SURFACE
S2HB
Depth (m)
0.0
0.1
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Distance (m)
0.2
1.0
1.8
Resistivity ρ
(ratio)

# 1600 mL / 0 mL

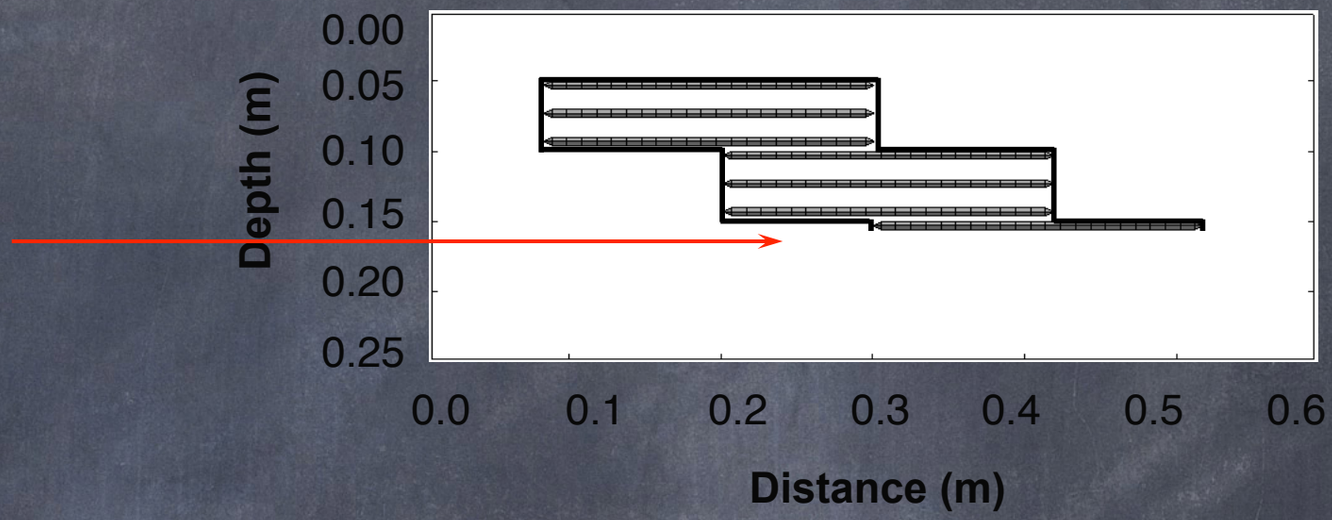

SURFACE
S2HB
Depth (m)
0.0
0.1
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Distance (m)
0.2
1.0
1.8
Resistivity ρ
(ratio)

- Excavation of tank at the end of experiment

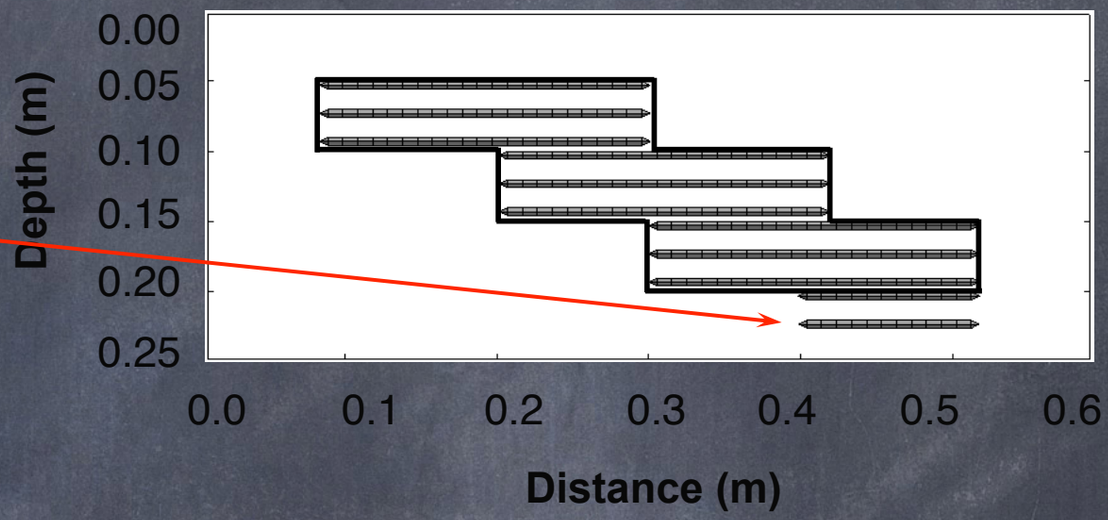
12 cm depth



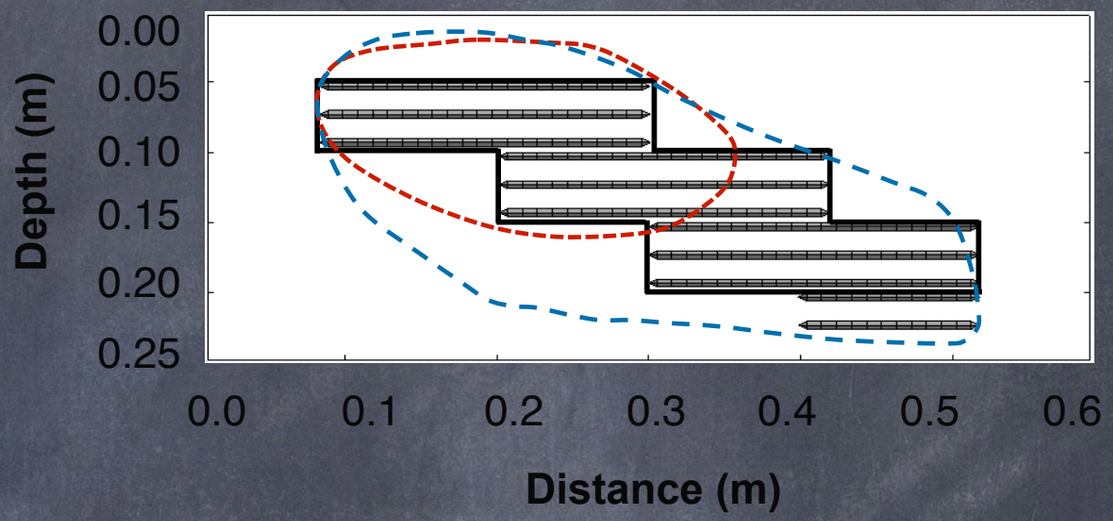
## 17 cm depth



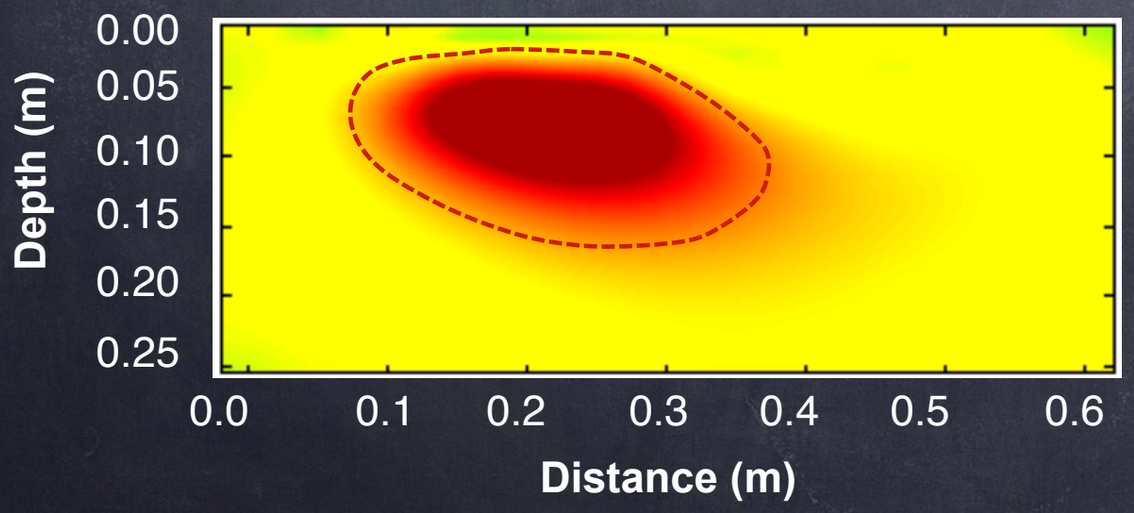
## 22 cm depth



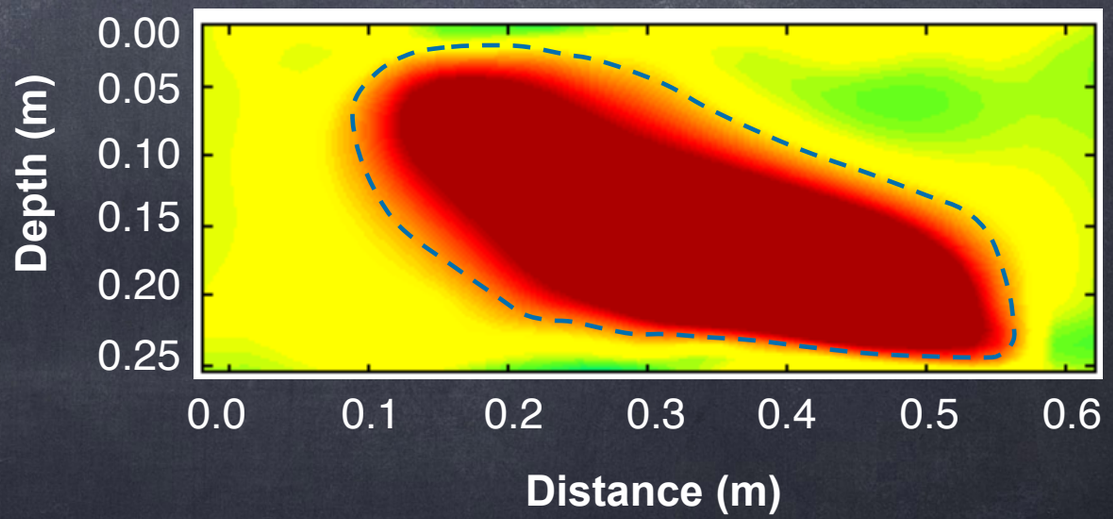
## 22 cm depth




SURFACE



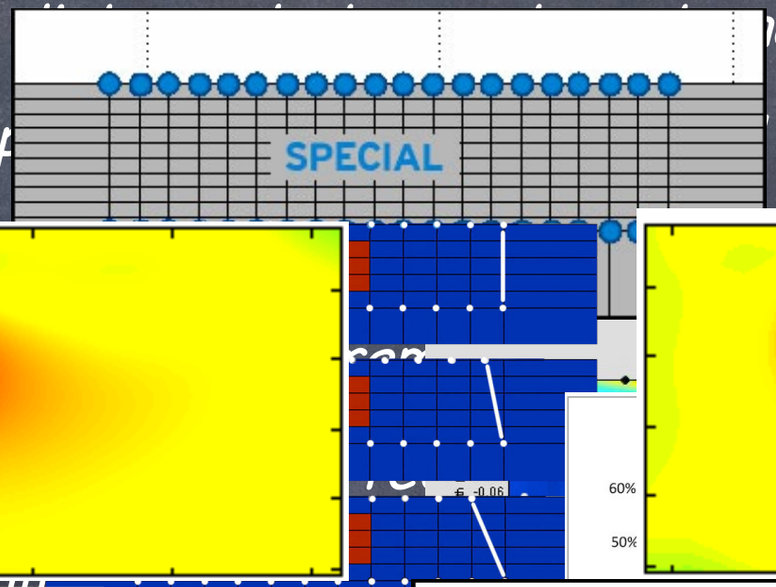

S2HB

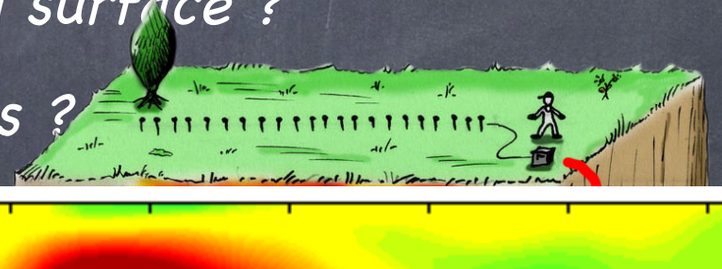


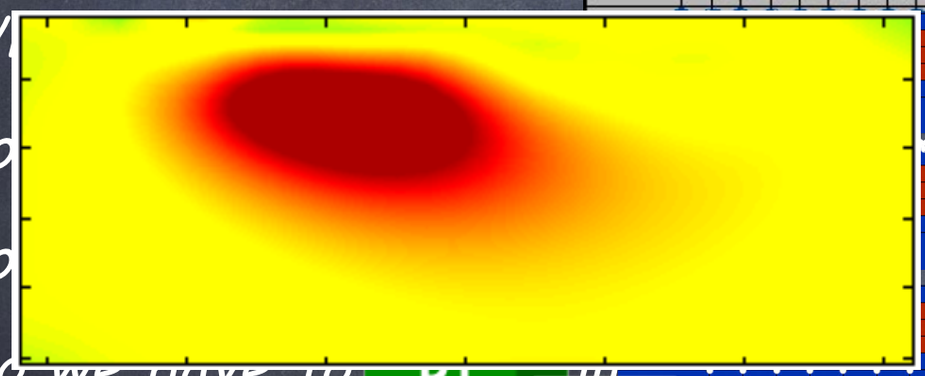
# CONCLUSIONS

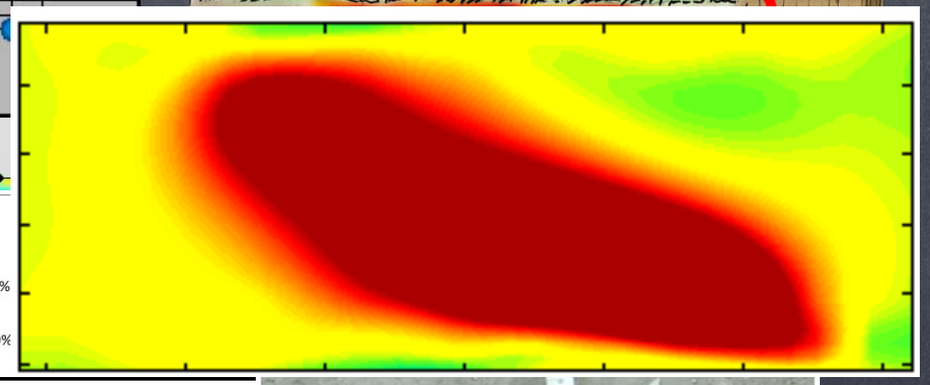
... with questions

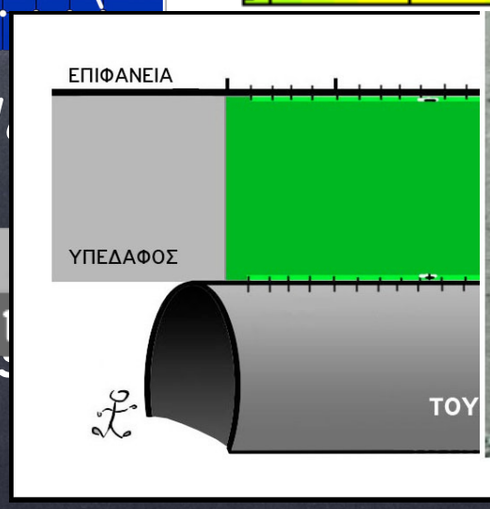
1. *Why to use "surface-to-tunnel" measurements and which array is the 'best'?*
2. *Which is the maximum* [illegible] *surface ?*
3. *How the horizontal disp* [illegible] *ts ?*
4. *W* [illegible]
5. *Do* [illegible]
6. *Ho* [illegible]
7. *Do we have to* [illegible]
8. *Can I avo* [illegible] *trode* [illegible]
9. *Do I nee* [illegible] *nt* [illegible]
10. *Is it* [illegible]








# Acknowledgements

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European Union
European Regional Development Fund

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Ministry of Education and Religious Affairs
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OPERATIONAL PROGRAMME
OPC II
NSRF 2007-2013

NSRF 2007-2013
programme for development

regions at the centre of development

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... 양해 해 주셔서 감사합니다!