Monitoring of flow in the vadose zone

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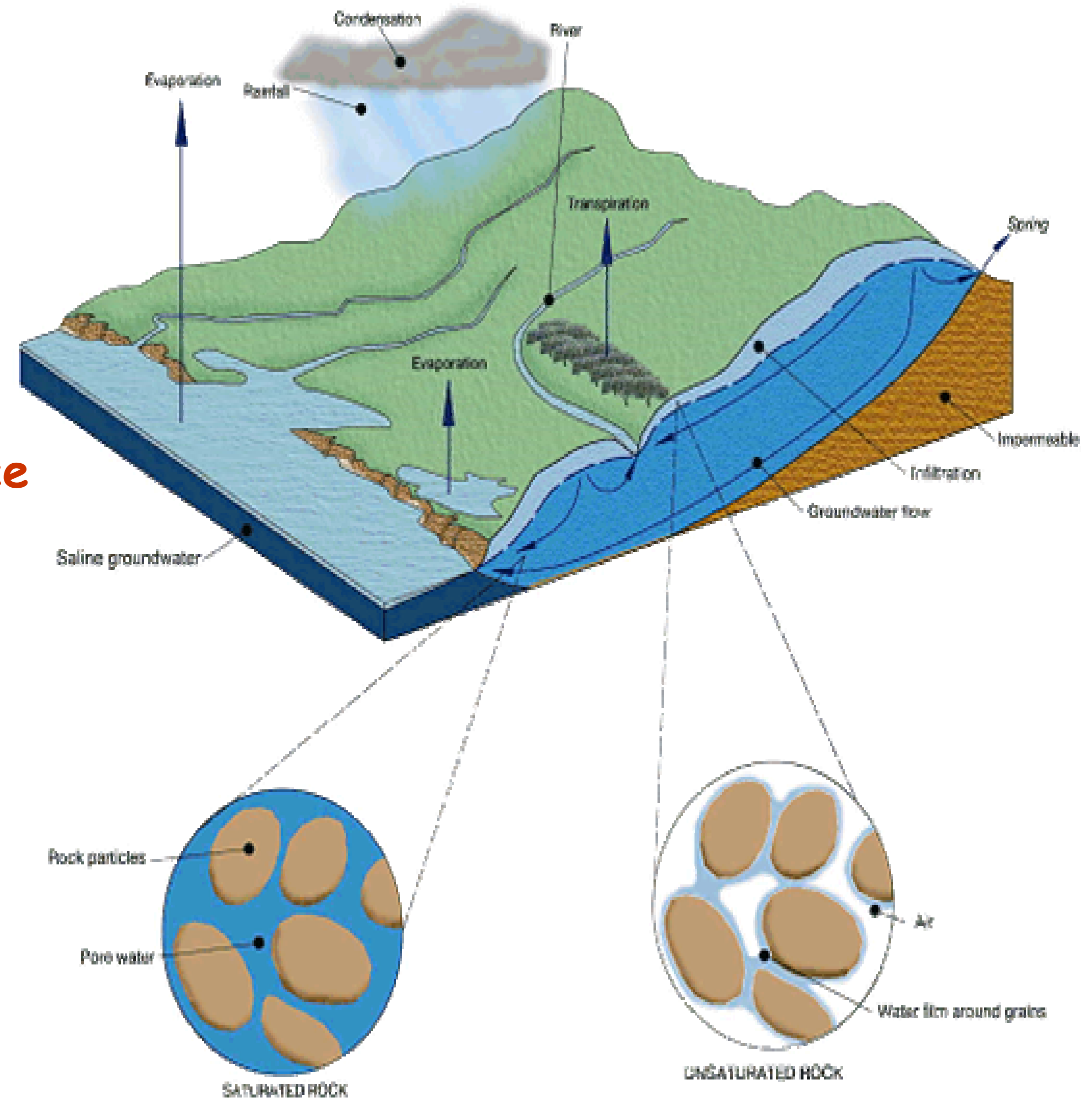
Outline

- Environmental issues: the role of water and the vadose zone
- The tools of hydro-geophysics for the vadose zone
- Estimation of hydraulic parameters in the vadose zone: a water injection experiment monitored via borehole GPR and ERT
- Conclusions and outlook

Environmental problems

Floods
Mountain slope stability
Soil/groundwater contamination



Water in the shallow subsurface
carries energy
modifies the state of stress
carries contaminants

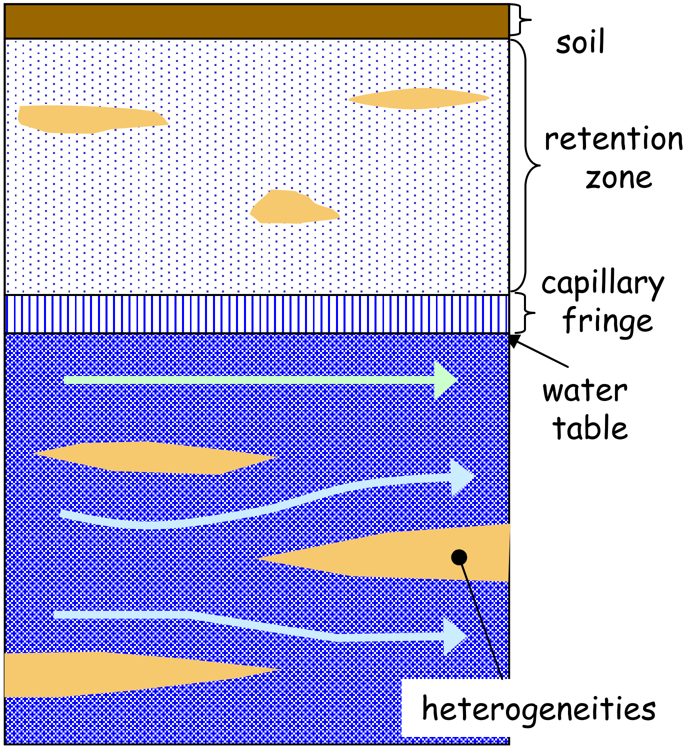
Environmental fluid-dynamics
(hydrology)

Shallow geophysics
(hydro-geophysics)

The saturated zone

Water migration ~ horizontal

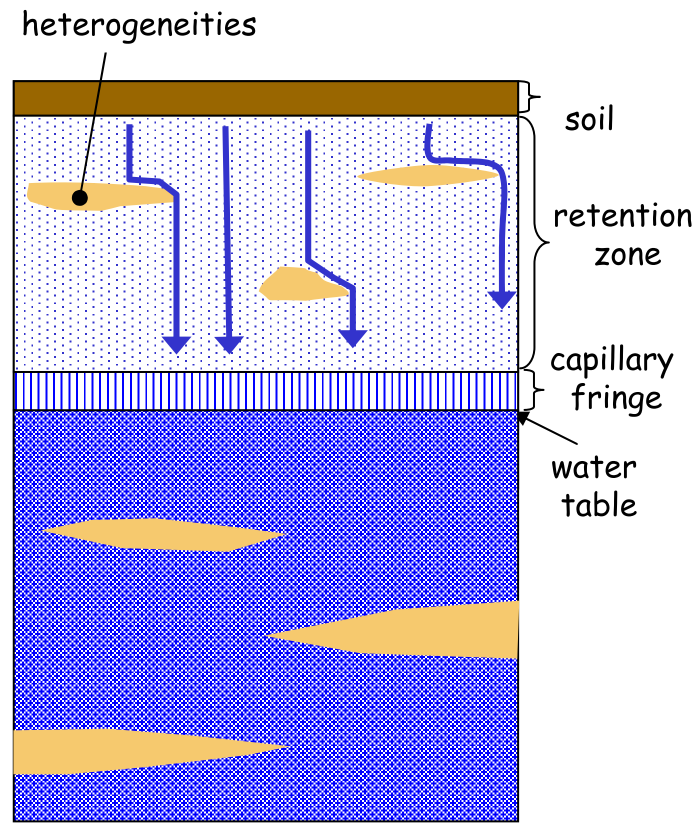
- surface stream baseflow
- changes in state of stress
- transport of contaminants
- water resources



The unsaturated (vadose) zone

Water migration ~ vertical

- downward transport of contaminants
- boundary with atmosphere
- soil mechanics and capillary forces
- floods and soil moisture content



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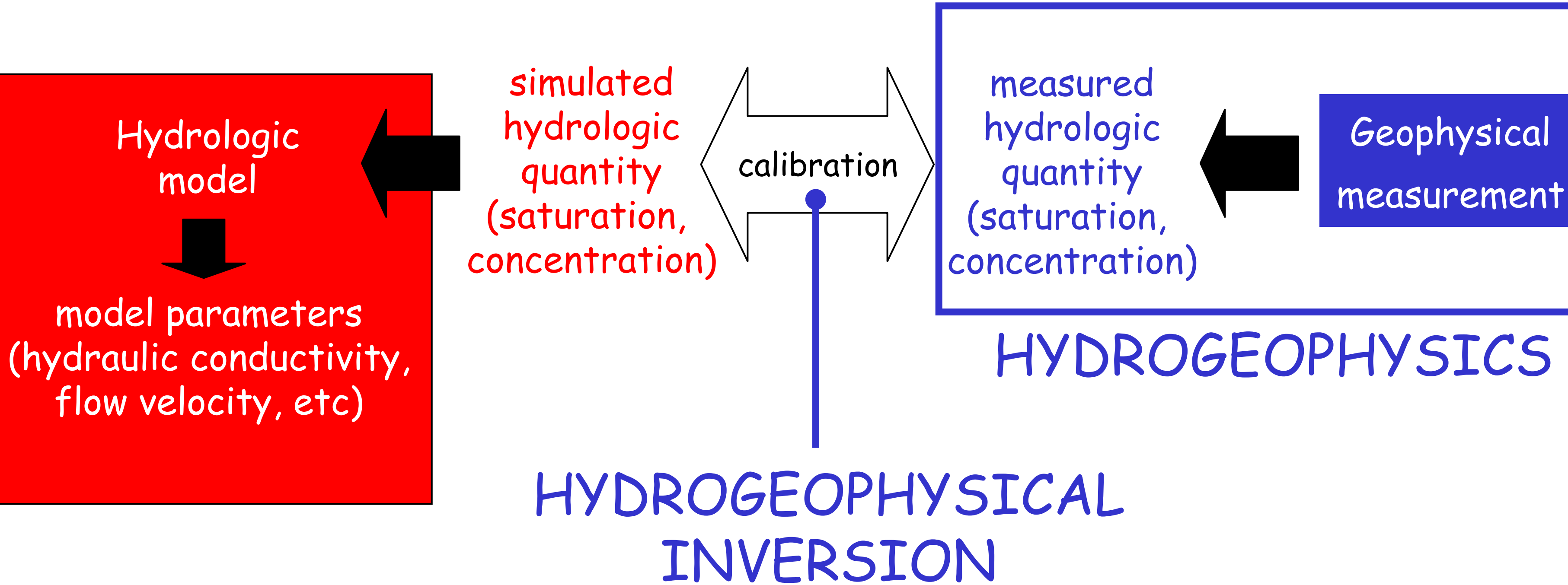
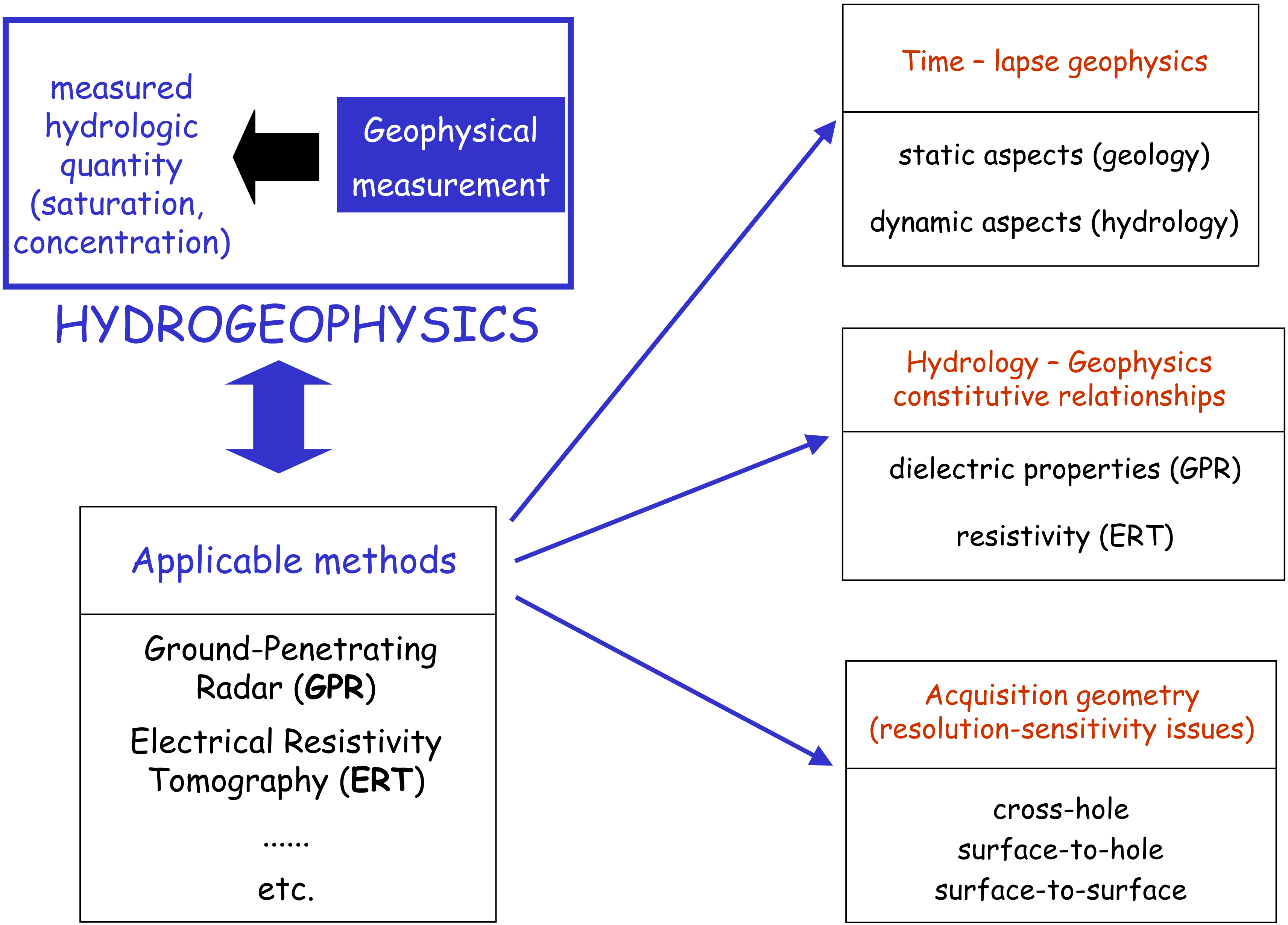
GENERAL APPROACH



Geophysical data must be translated into *quantitative* estimates of hydrological parameters.



measured hydrologic quantity (saturation, concentration)
Geophysical measurement
HYDROGEOPHYSICS
Applicable methods
Ground-Penetrating Radar (GPR)
Electrical Resistivity Tomography (ERT)
......
etc.
Time – lapse geophysics
static aspects (geology)
dynamic aspects (hydrology)
Hydrology – Geophysics constitutive relationships
dielectric properties (GPR)
resistivity (ERT)
Acquisition geometry (resolution-sensitivity issues)
cross-hole
surface-to-hole
surface-to-surface

Ground-Penetrating Radar (GPR)

Electro-magnetic waves with frequencies in the 10 MHz -1 GHz range.

The propagation velocity v depends only on the **dielectric constant** of the medium κ:

$$\boxed{v = \frac{c}{\sqrt{\kappa}}} \qquad c \cong 0.3 \text{ m/ns}$$

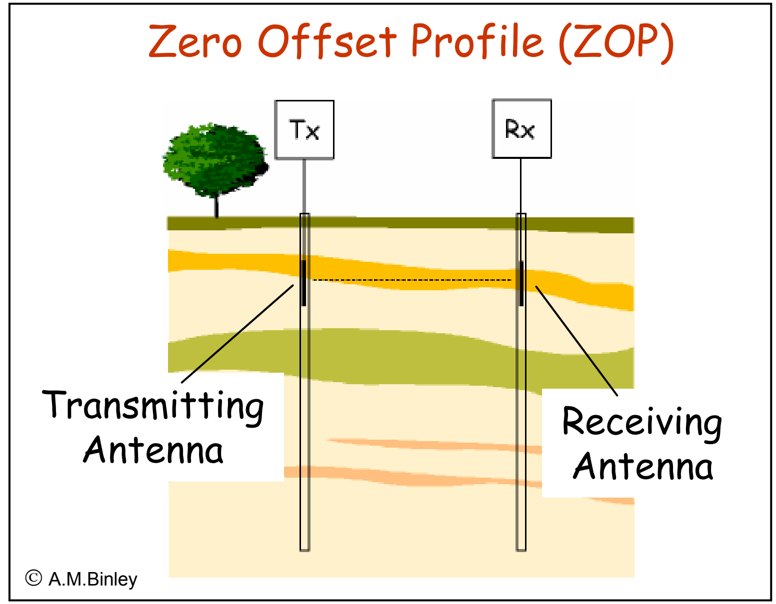
***Topp et al.*, [1980]:**

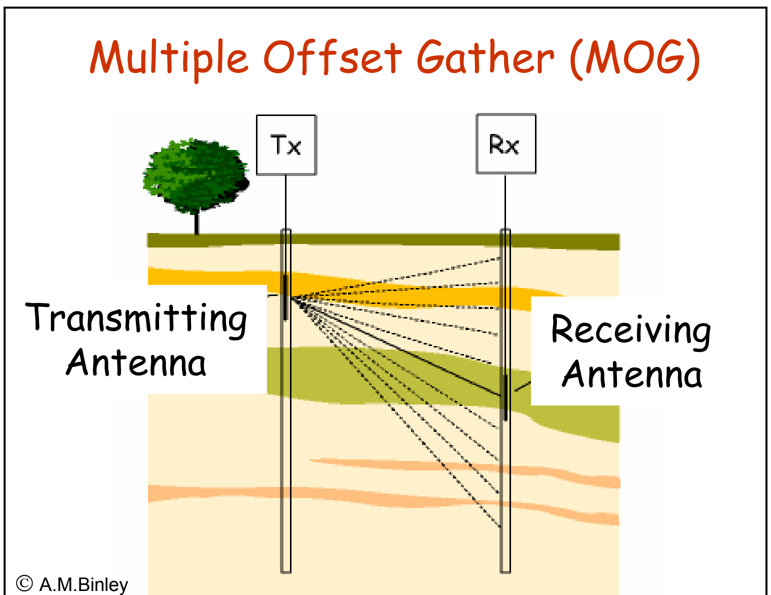
$$\boxed{\theta = \left(-530 + 292\,\kappa - 5.5\kappa^2 + 0.043\,\kappa^3\right) \times 0.0001}$$

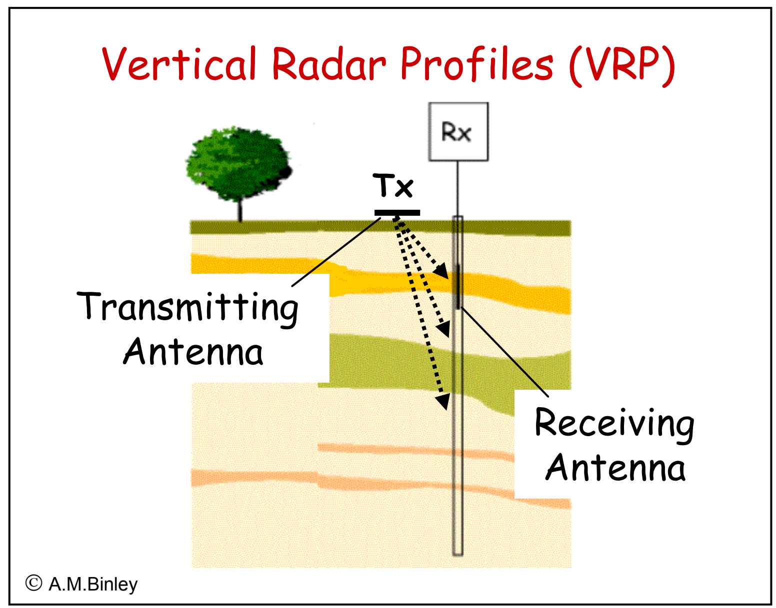
radar velocity (v) → $\kappa = \left(\frac{c}{v}\right)^2$ → dielectric constant (κ) → Topp et al. CRIM .... → moisture content (θ)

Cross-Hole GPR

- conductive surface layers are by-passed: penetration is increased
- velocity is determined easily







GEOELECTRICS

Resistivity relationship with moisture content and water salinity

The classical empirical relationship linking electrical resistivity (conductivity) to the soil moisture content is Archie's law [1942]:

$$\boxed{\sigma_b = \sigma_w \phi^m S_w^n + \sigma_s}$$

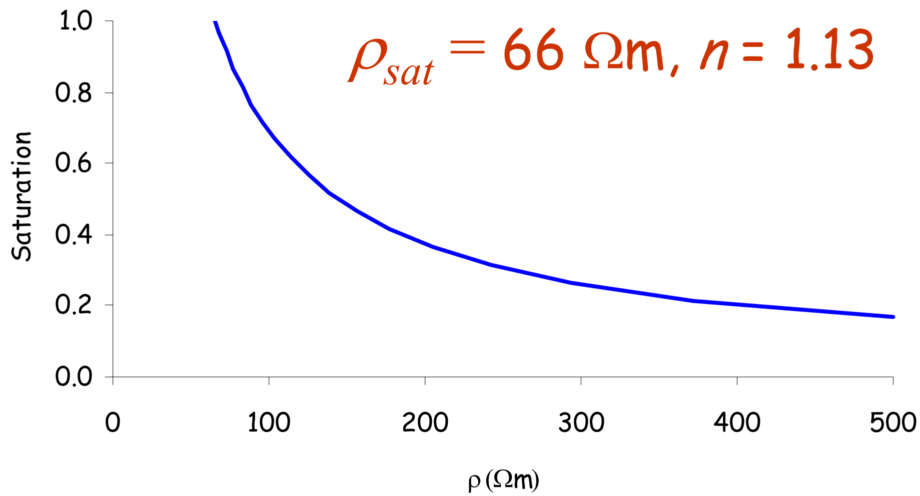
σ_b = bulk conductivity

σ_w = conductivity of water saturating the pores,

ϕ = porosity

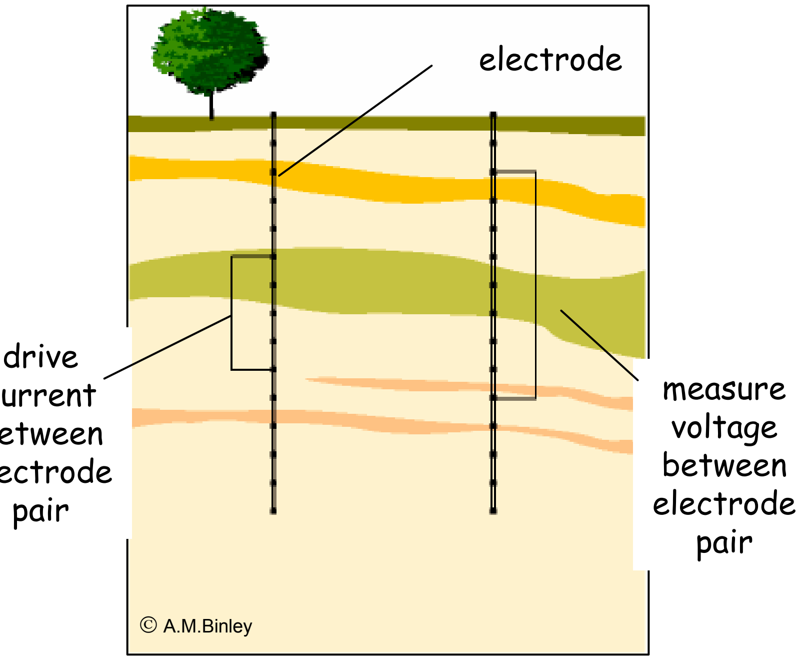
S_w = water saturation.

σ_s = grain surface conductivity.



n and *m* are formation parameters

Cross-Hole
Electrical Resistivity Tomography (ERT)

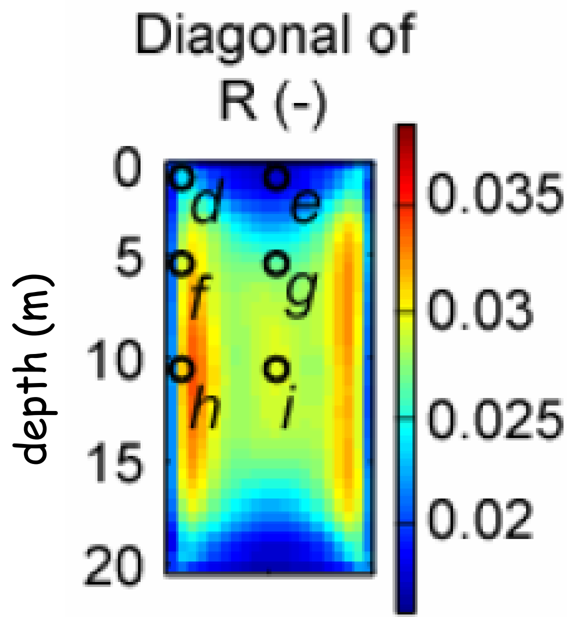


- resolution is not lost with depth
- resistivity distribution is determined accurately in 2D or 3D
- local conditions around the hole are less critical than e.g. in well logs

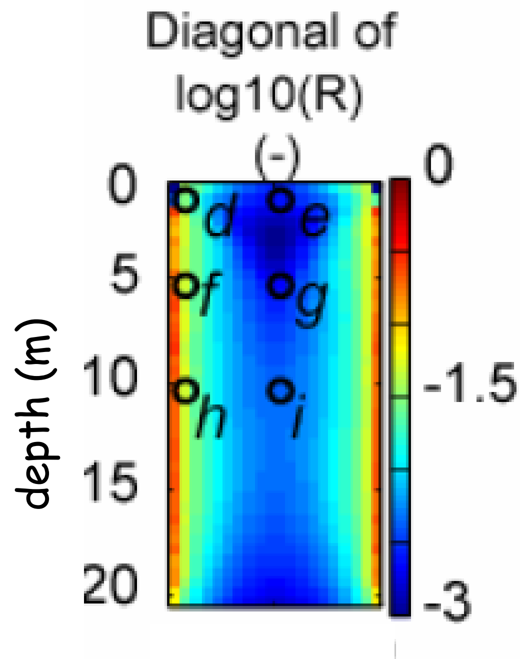
- a tomographic inversion is needed

Resolution issues for cross-hole GPR and ERT

(after Day-Lewis, Singha and Binley, JGR, 2005)



GPR



ERT

R = model resolution matrix

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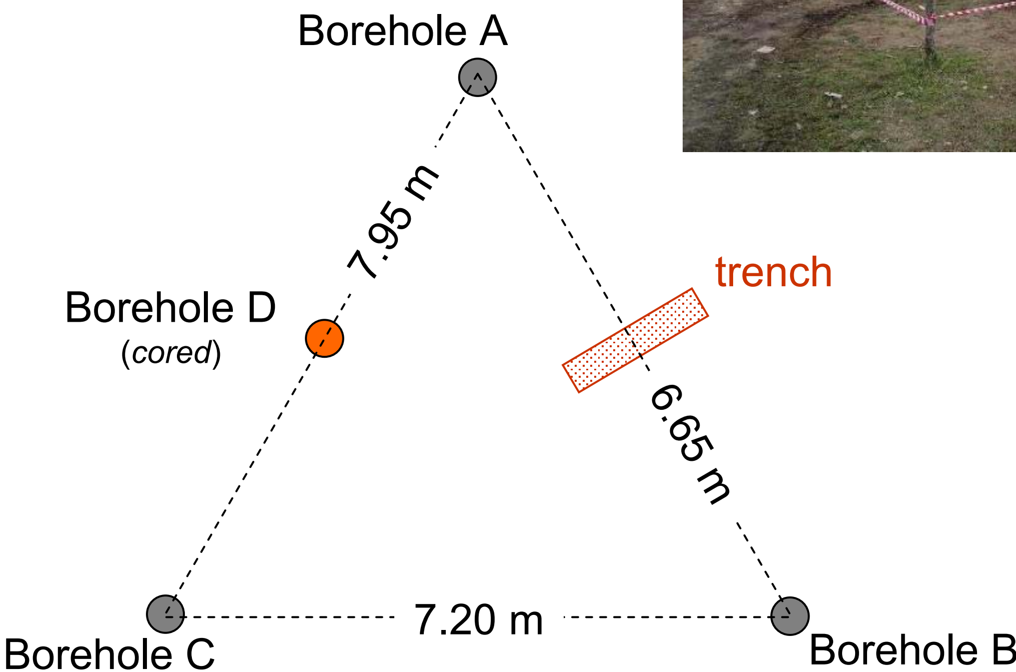
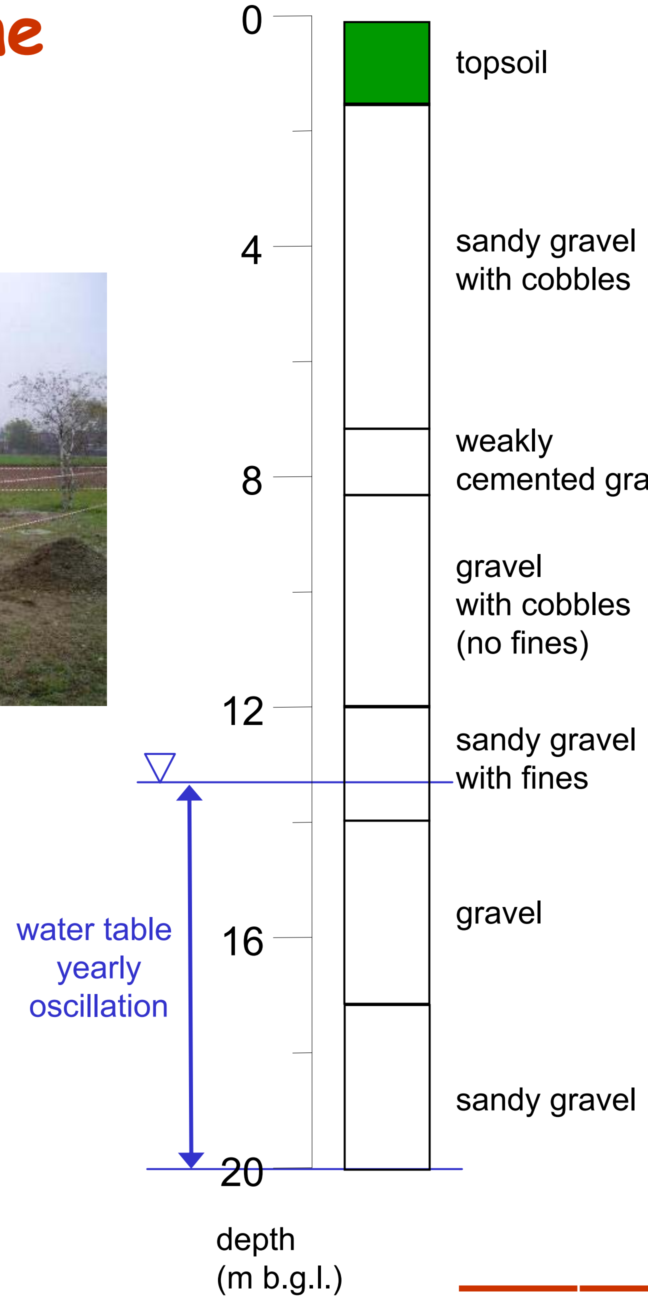
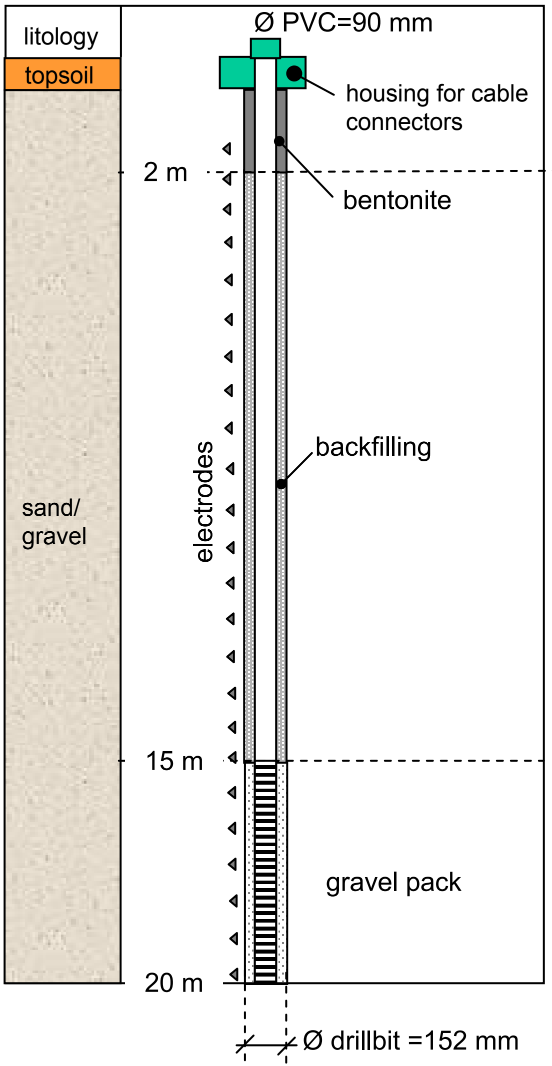
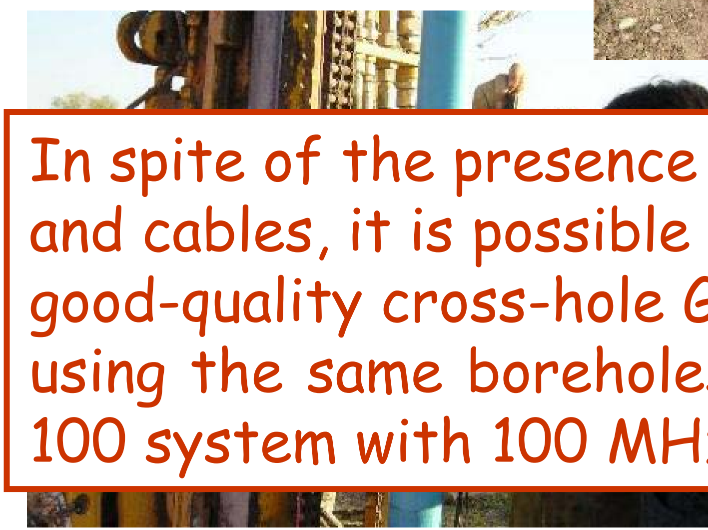
Characterisation of the vadose zone of the Po river plain sediments: the Gorgonzola test site





The Gorgonzola test site: borehole completion

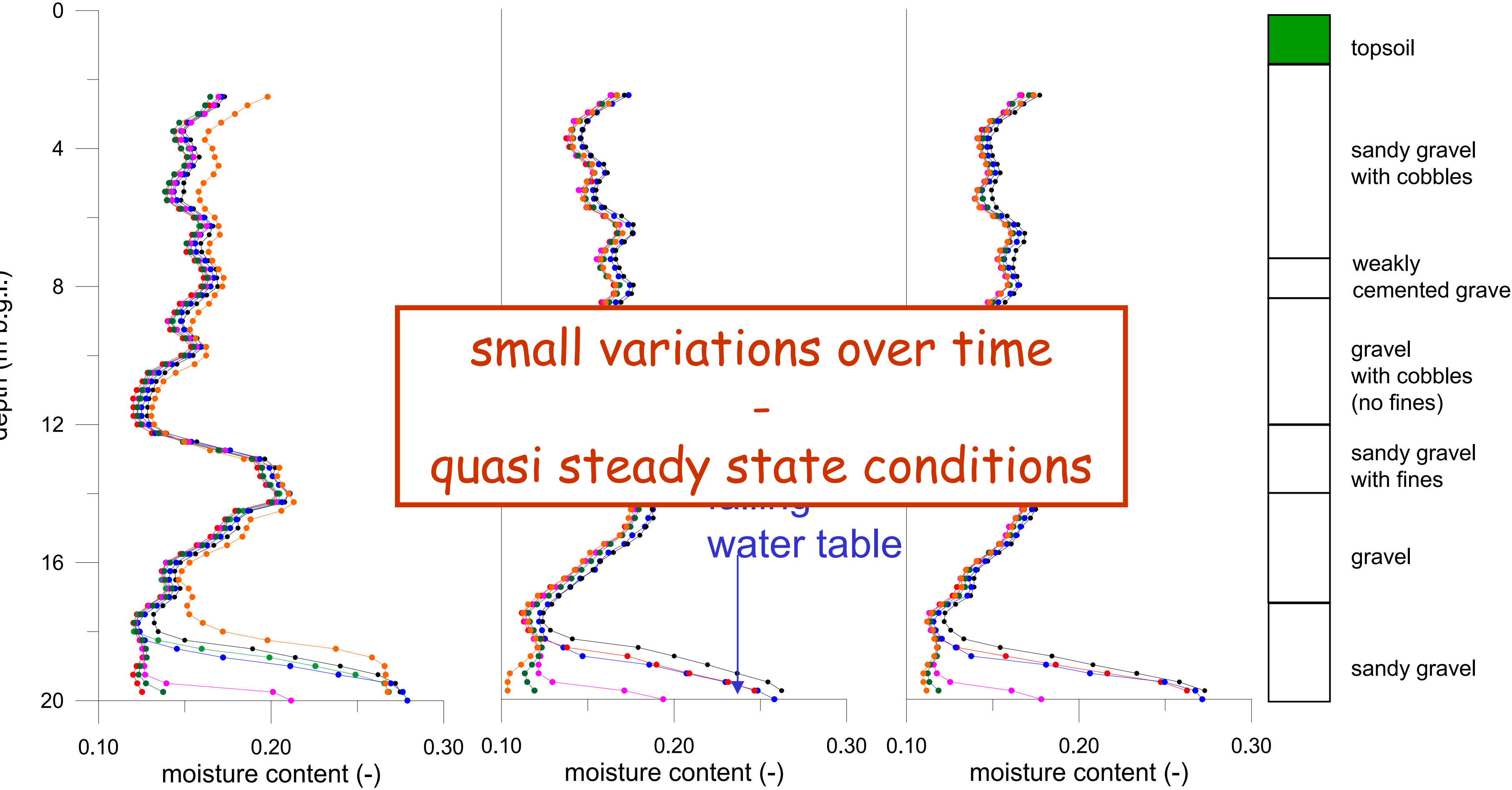




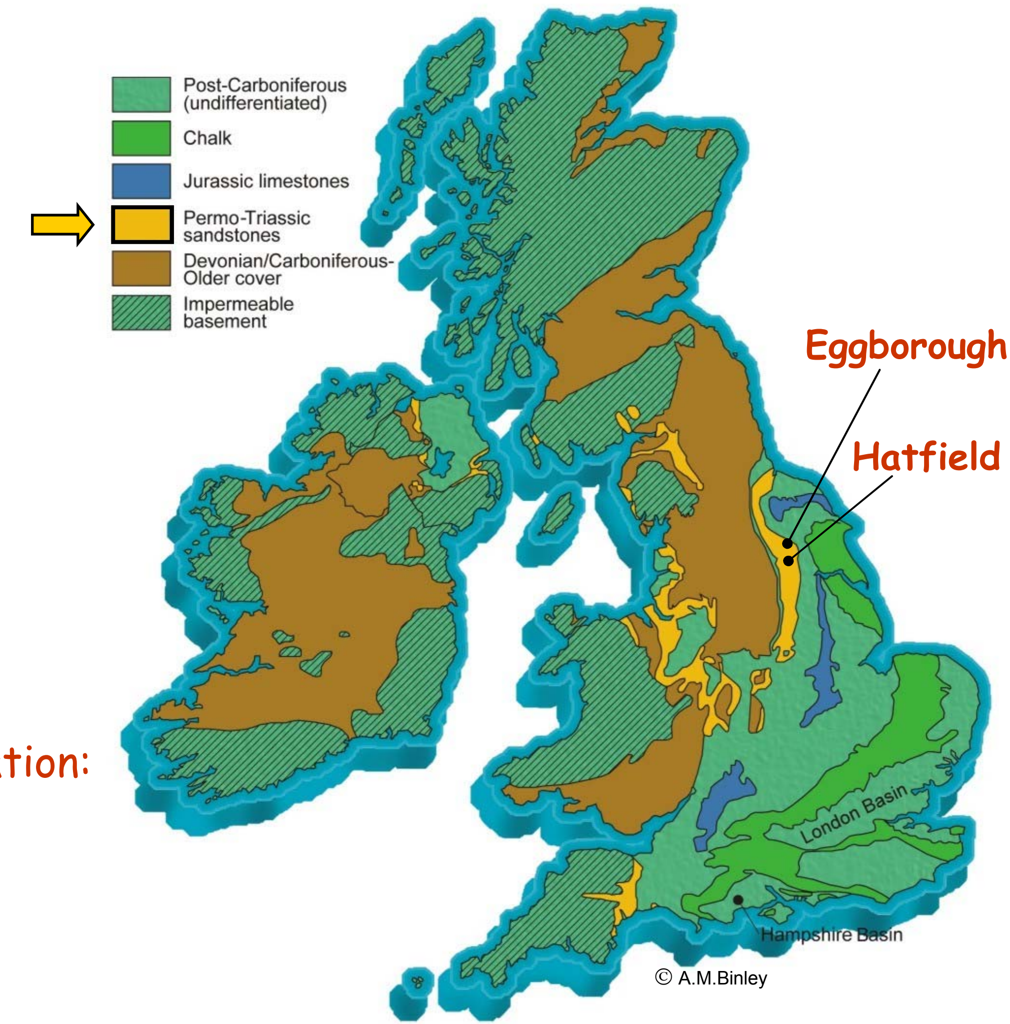
In spite of the presence of electrodes and cables, it is possible to acquire good-quality cross-hole GPR data using the same boreholes and a PulseEkko 100 system with 100 MHz antennas

Moisture content data from ZOP radar

100 MHz antennas - bi-weekly measurements January-April 2005



Characterisation of the unsaturated zone in the Sherwood Sandstone Aquifer



Project Aims

Practical

- ❑ To assess aquifer vulnerability
- ❑ Characterize unsaturated hydraulic properties of the sandstone

Methodological

To assess the value of non invasive methods in vadose zone characterization:

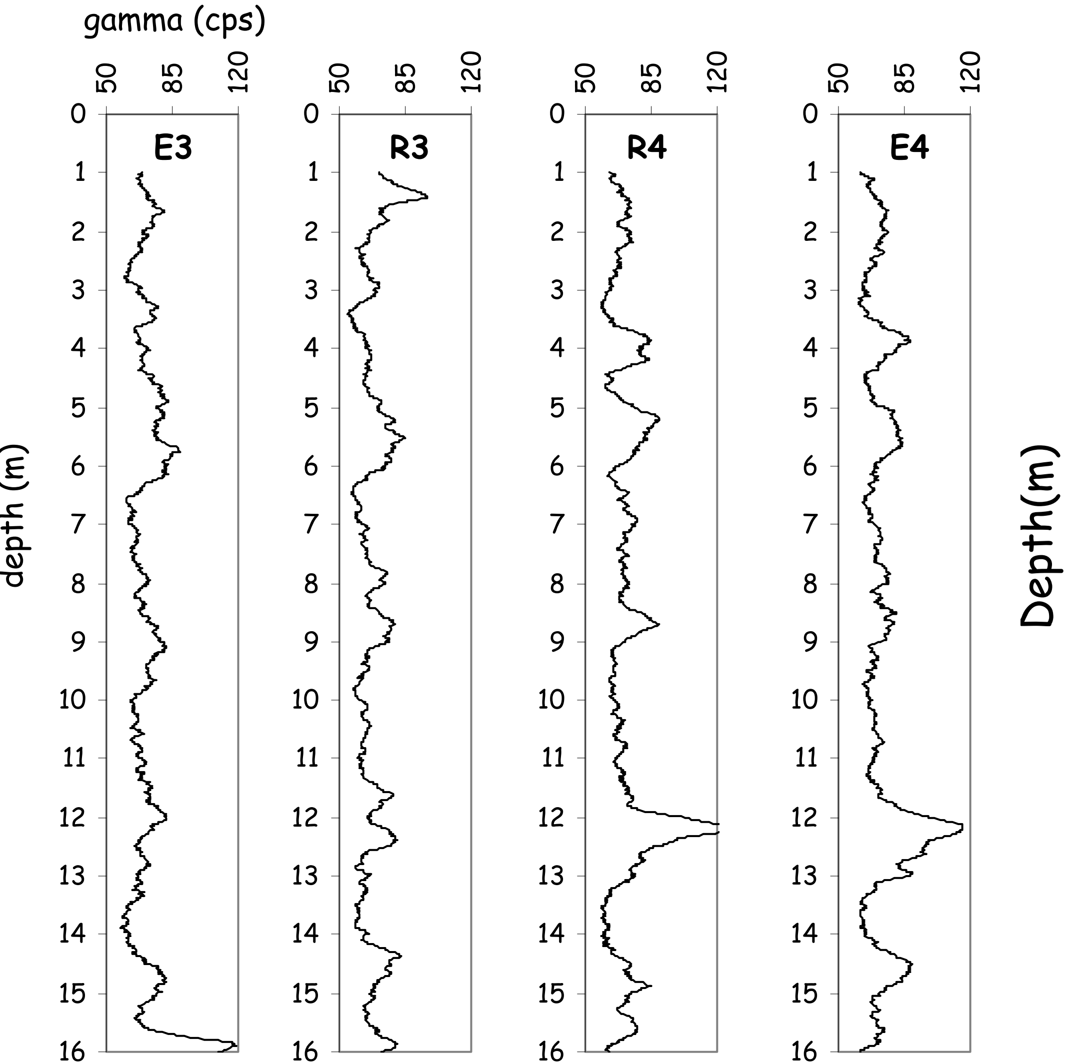
- ❑ cross borehole radar
- ❑ electrical resistivity tomography

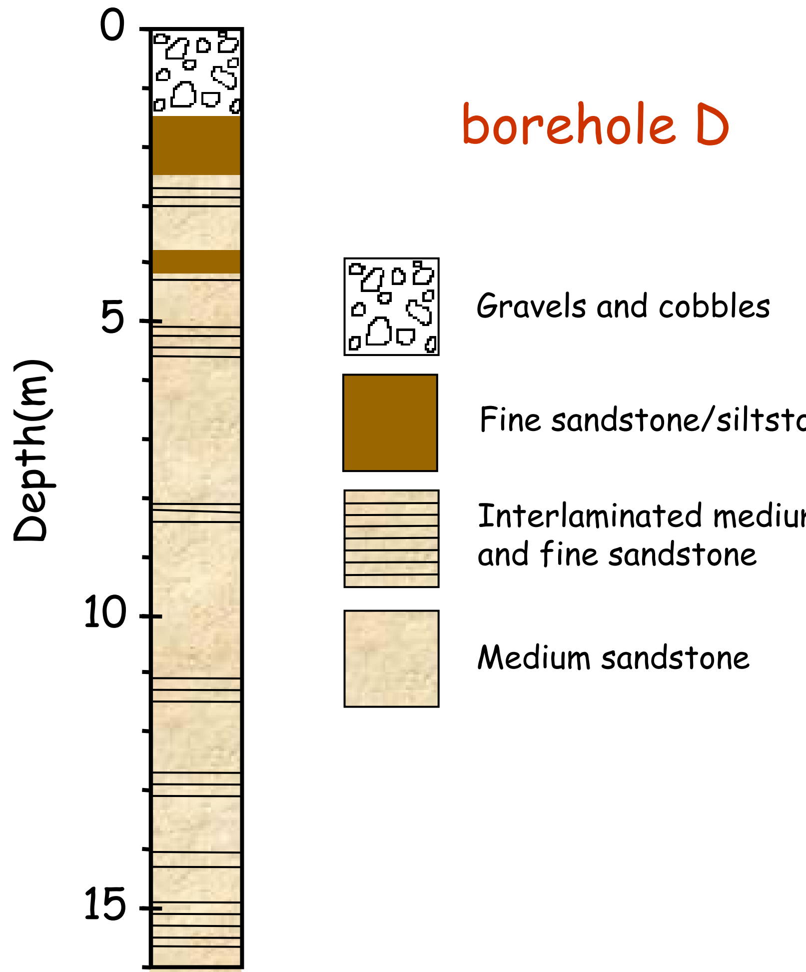
P.I. **Andrew Binley**, Lancaster University

Partners: University of Leeds

Funded by: Natural Environment Research Council, UK

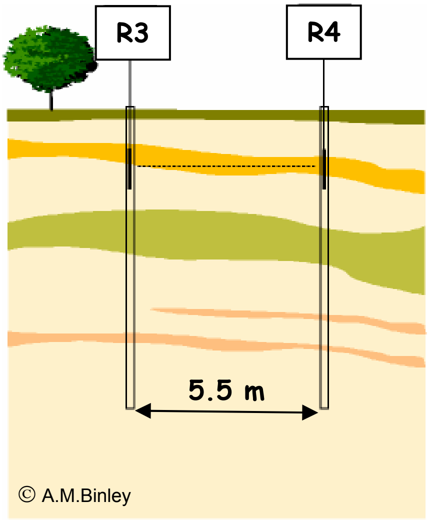
Eggborough site: lithology information from cores and gamma logs

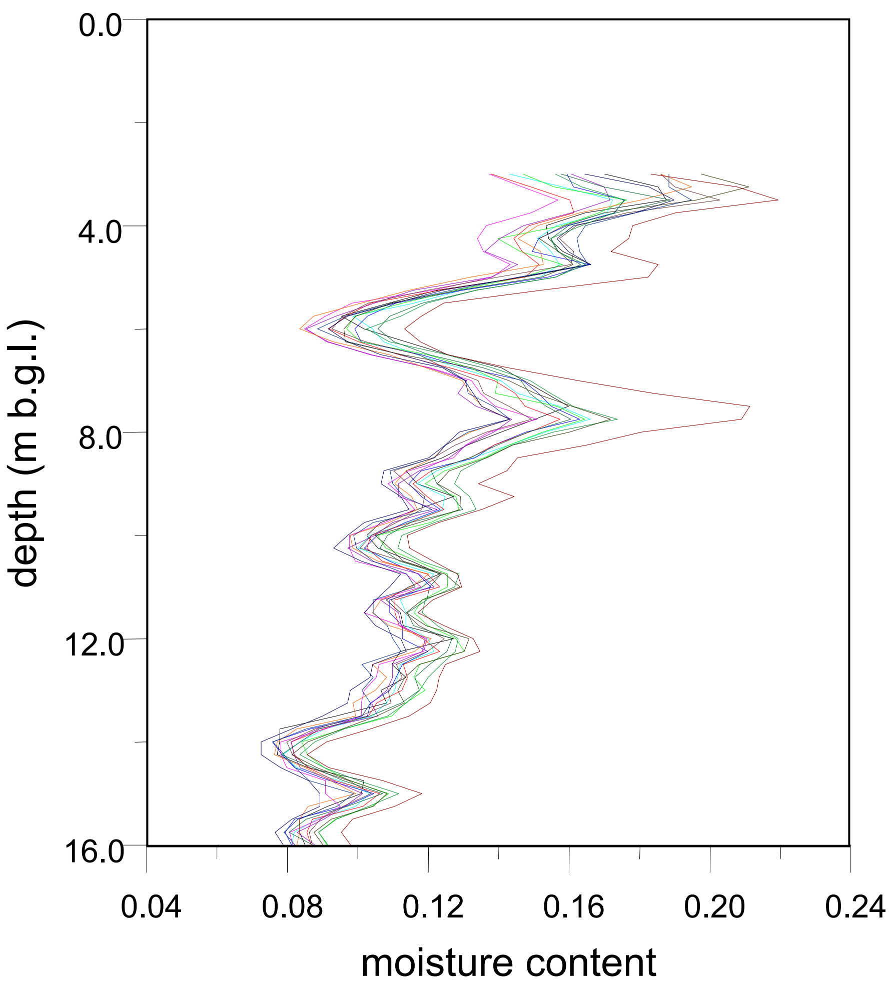




Moisture content data from ZOP radar

50 MHz antennas
monthly measurements
August 1999 - September 2000





Nearly **steady state conditions**

- small variations in time
- large variations in depth

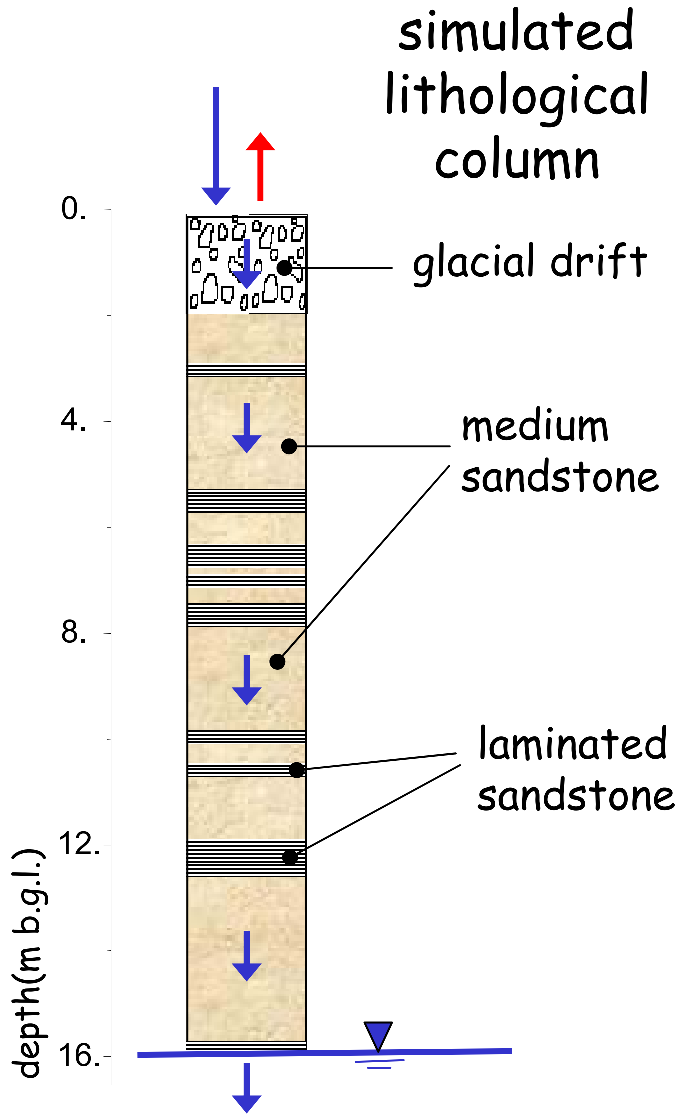
Hydrological model calibration using geophysical data

Steady state Richards' equation (1-D)
(flow in variably saturated medium)

$$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z}-1\right)\right]=0$$

ψ is pressure head (suction)
θ is moisture content
K is hydraulic conductivity

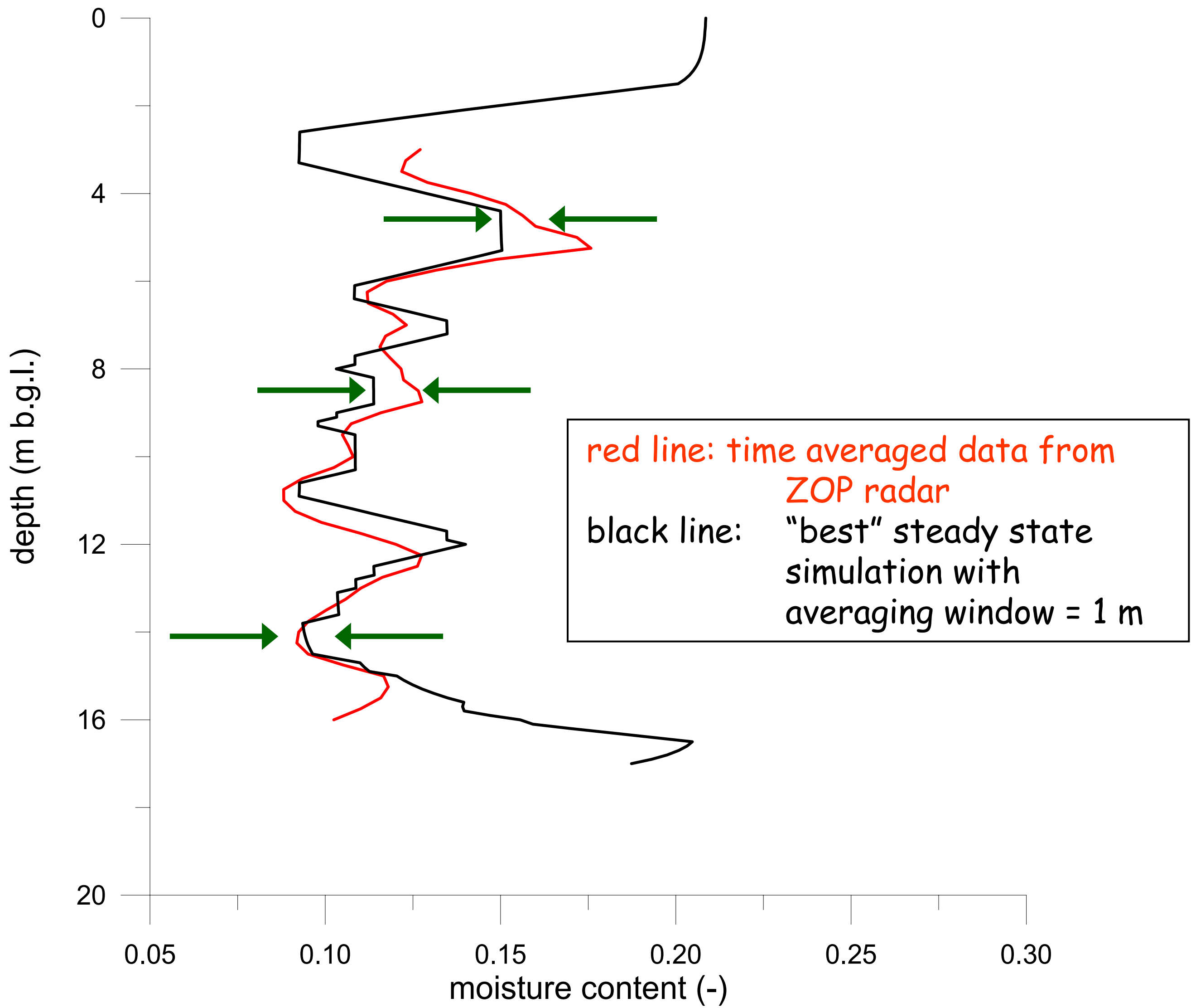
carry out repeated
(**Monte Carlo**) simulations



Results: matching moisture content θ

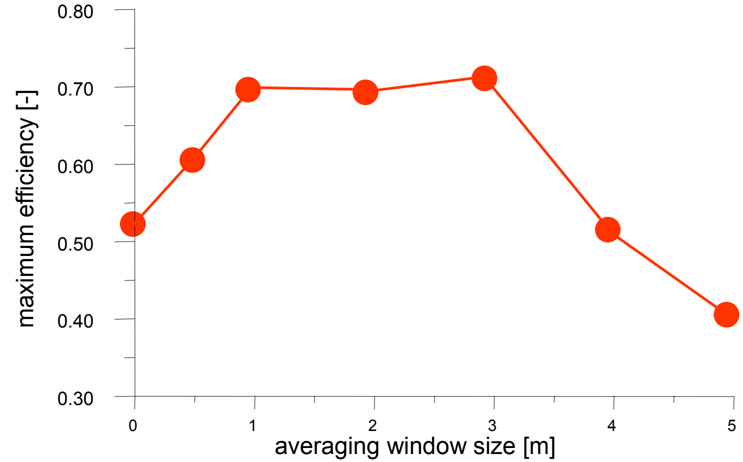
define efficiency:

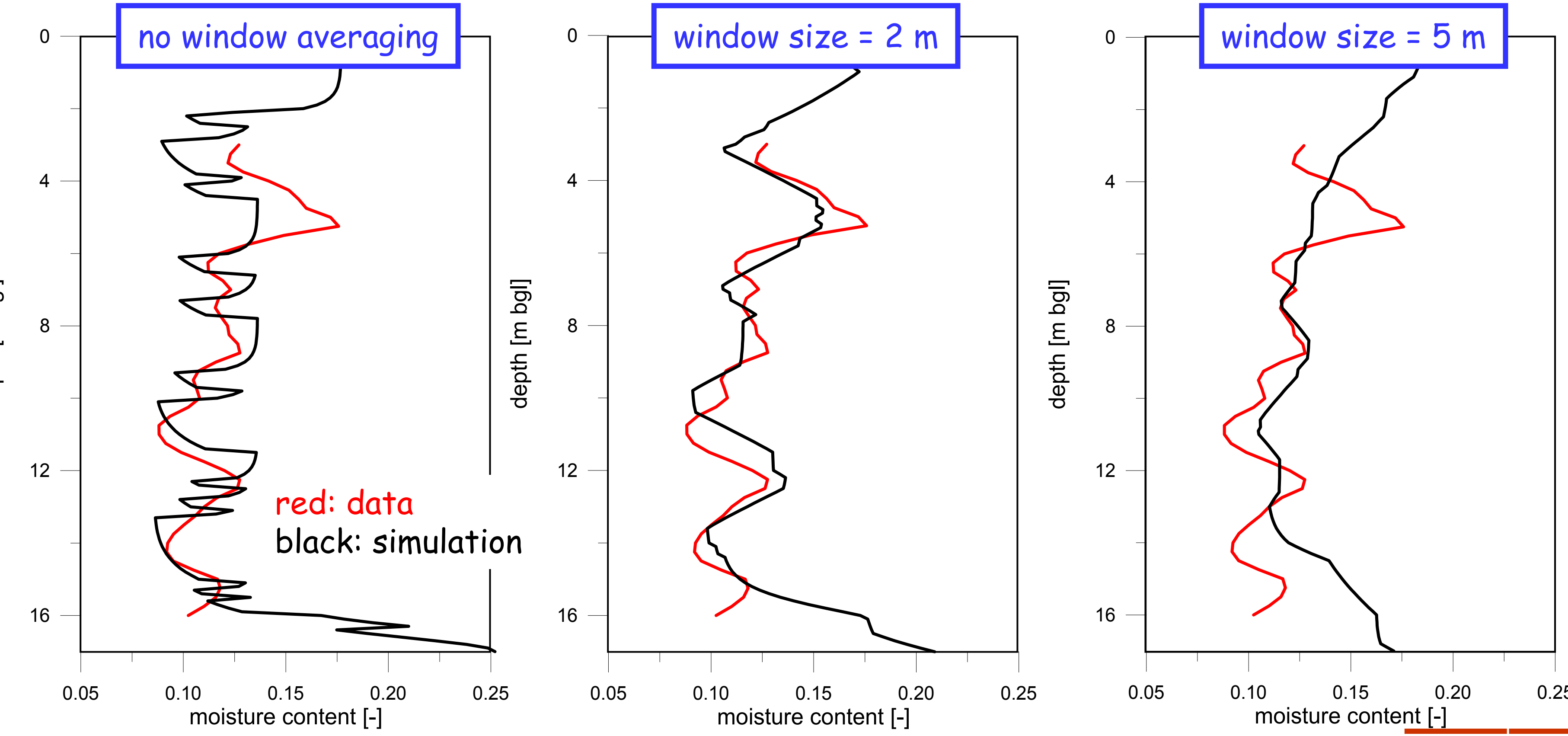
$$\eta = 1 - \frac{\sigma_{error}^2}{\sigma_{data}^2}$$



BUT: in order to match moisture content we must account for **scale effects**

This is done by taking **moving window averages** of the simulated curves.





Scale effects in ZOP cross-hole radar are a combination of

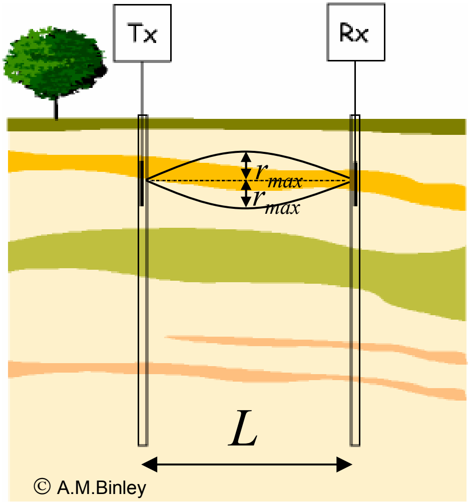
(1) Fresnel zone

$$r_{\max} = \sqrt{VL/f}\,/2$$

V = propagation velocity

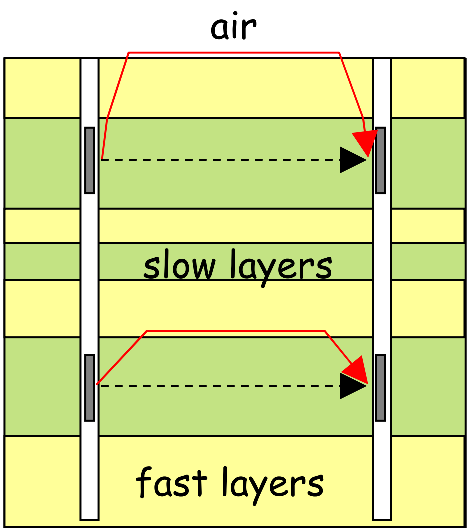
f = central frequency

r_{max} = maximum radius of Fresnel zone (in our case about 3 m)



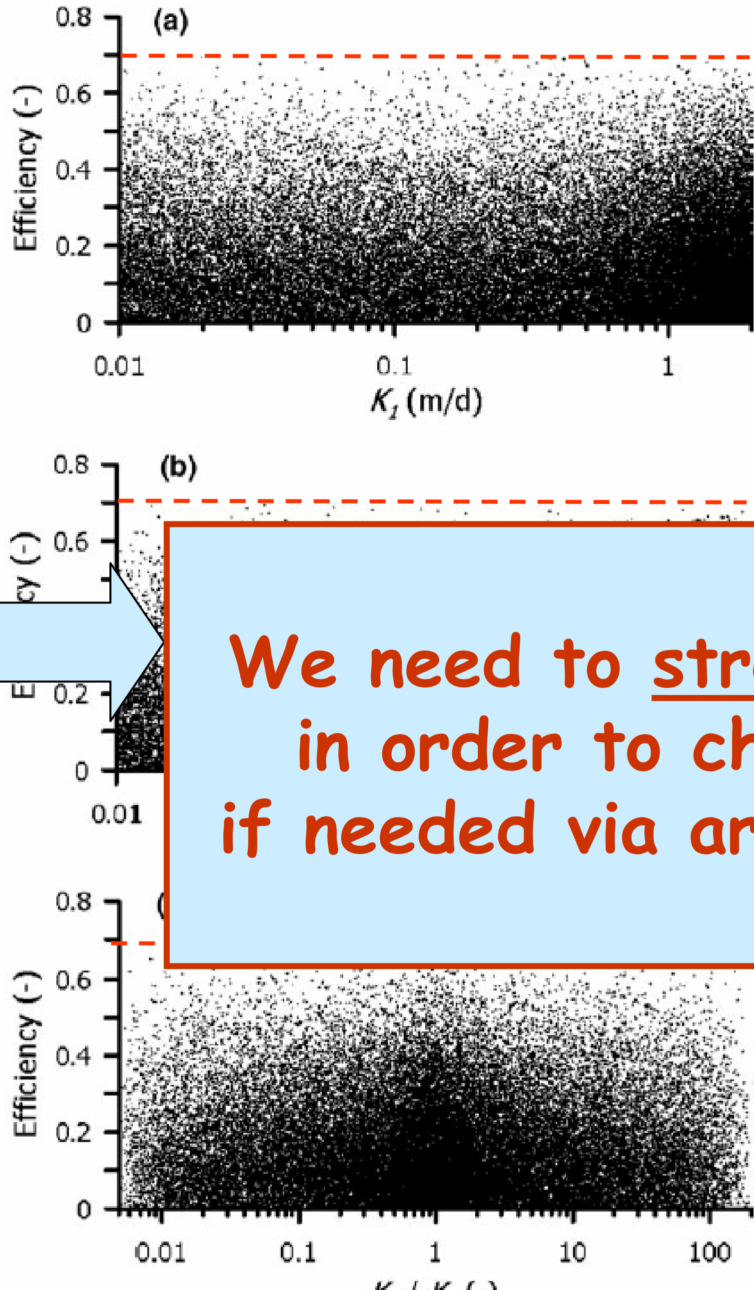
(2) Critically refracted arrivals

first arrivals can be critically refracted energy along neighbouring "fast" layers



(3) Antenna size

2 m for 50 MHz antennas



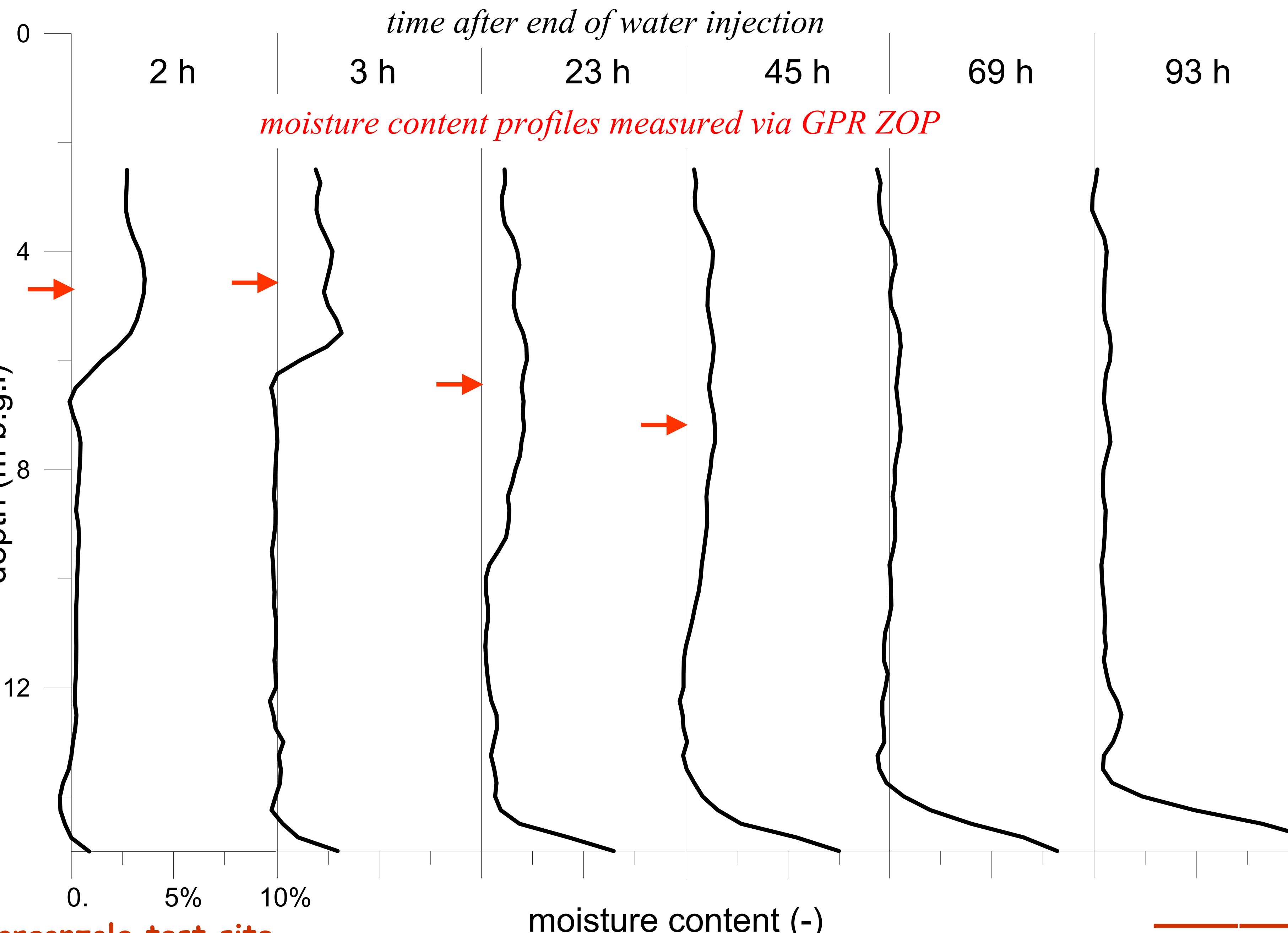
There is no
such thing as
an "optimal"
parameter set !

We need to stress hydraulically the system in order to characterize its parameters if needed via artificial water injection tests

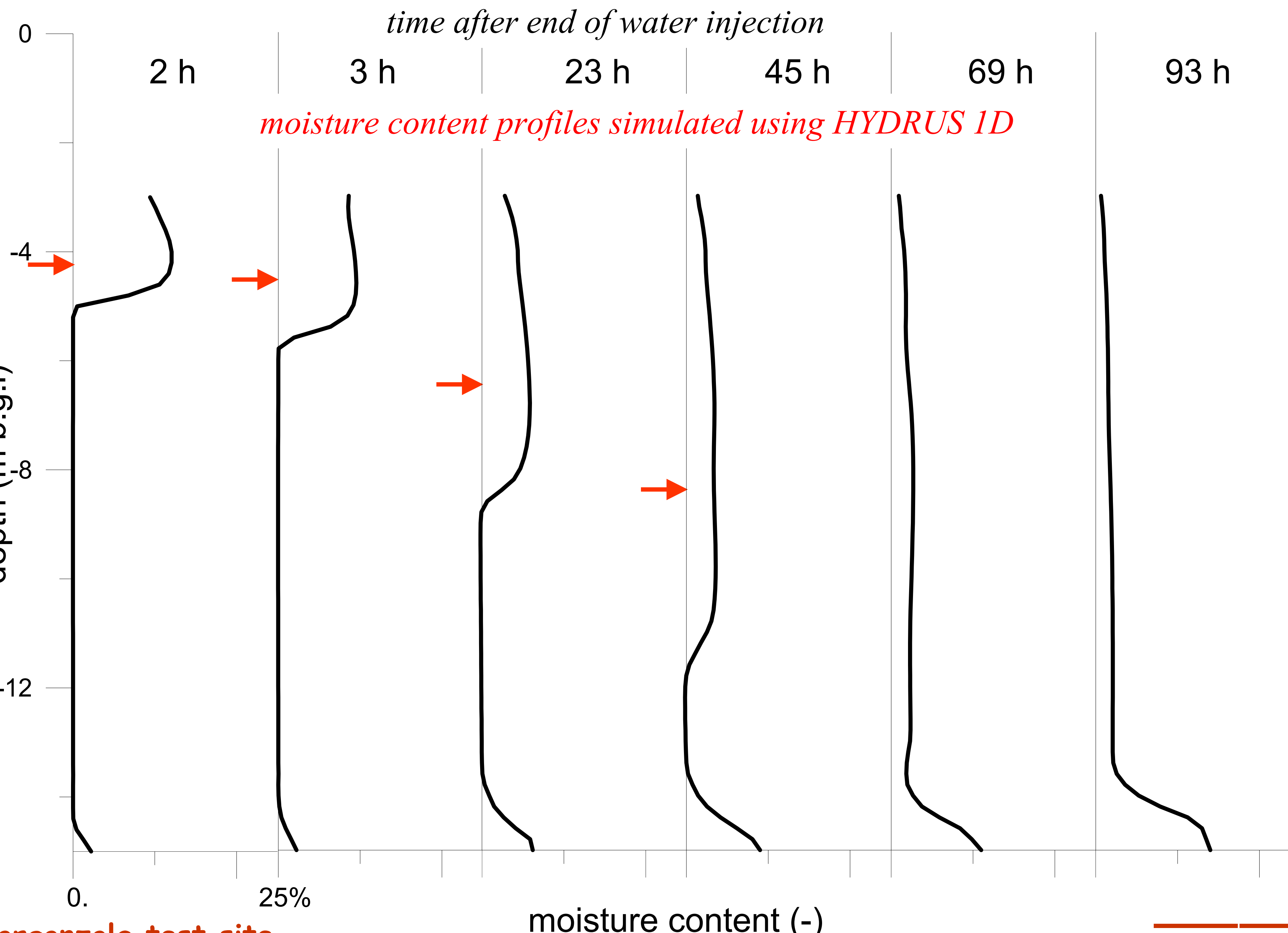
Gorgonzola test site

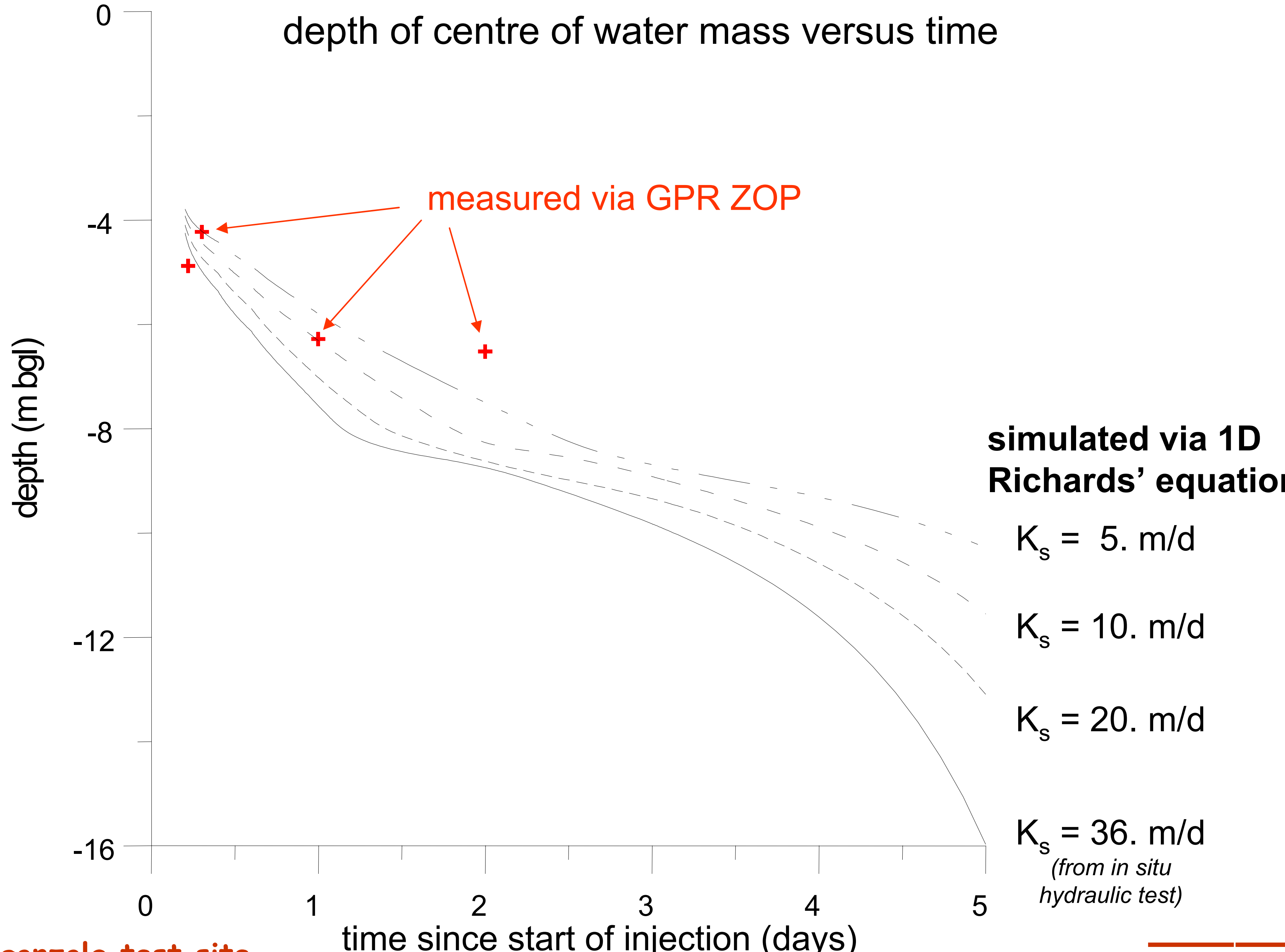
Gorgonzola test site

Gorgonzola test site



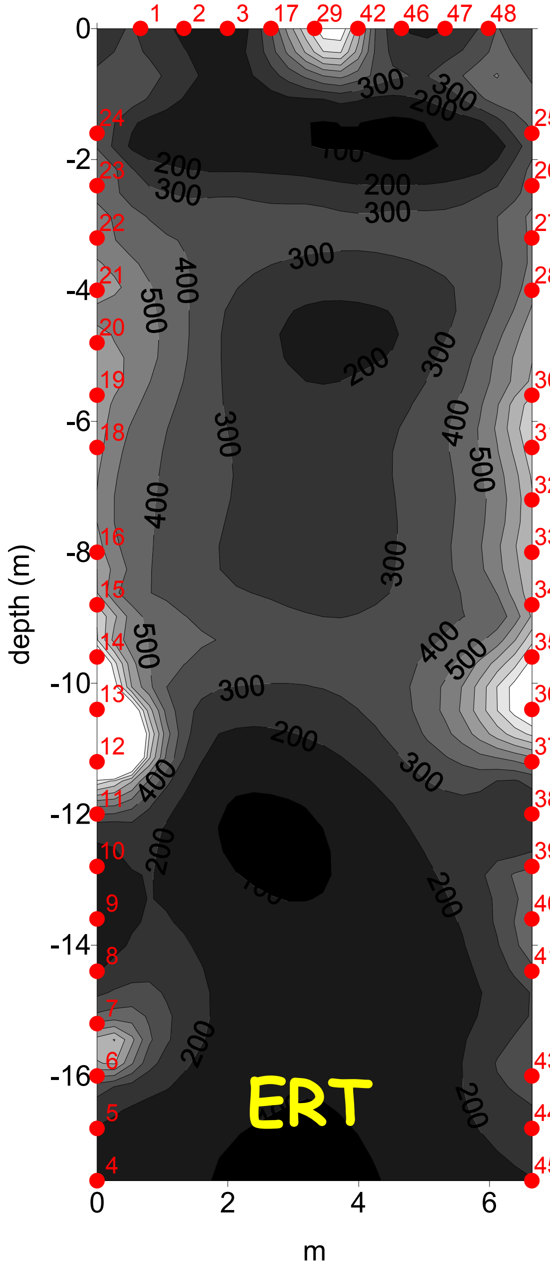
time after end of water injection
2 h
3 h
23 h
45 h
69 h
93 h
moisture content profiles measured via GPR ZOP
0
4
8
12
0.
5%
10%
moisture content (-)


time after end of water injection
2 h
3 h
23 h
45 h
69 h
93 h
moisture content profiles simulated using HYDRUS 1D
0
-4
-8
-12
0.
25%
moisture content (-)

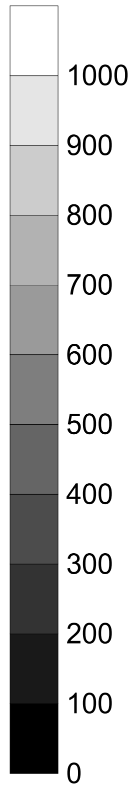


depth of centre of water mass versus time
measured via GPR ZOP
simulated via 1D Richards' equation
K_s = 5. m/d
K_s = 10. m/d
K_s = 20. m/d
K_s = 36. m/d
(from in situ hydraulic test)
depth (m bgl)
time since start of injection (days)
0
-4
-8
-12
-16
0
1
2
3
4
5

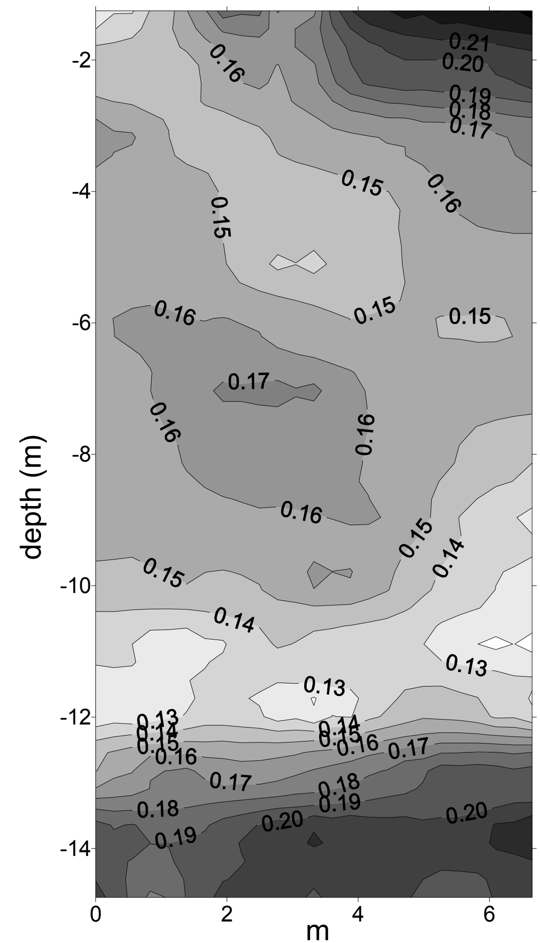
BACKGROUND



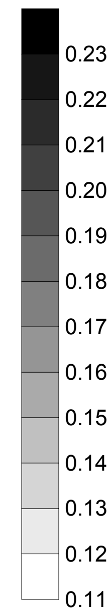
resistivity (Ωm)

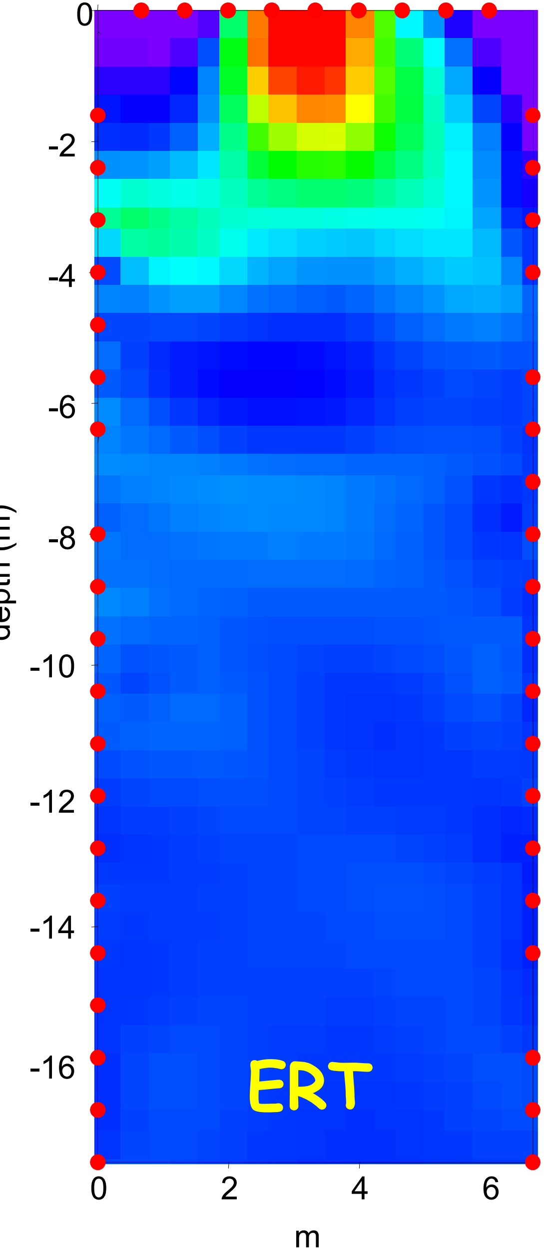


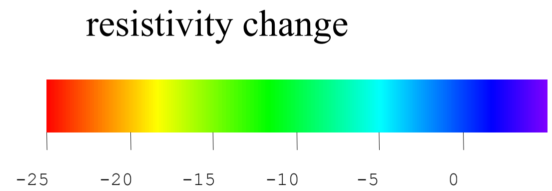
July 5, 2005
10:00 a.m.

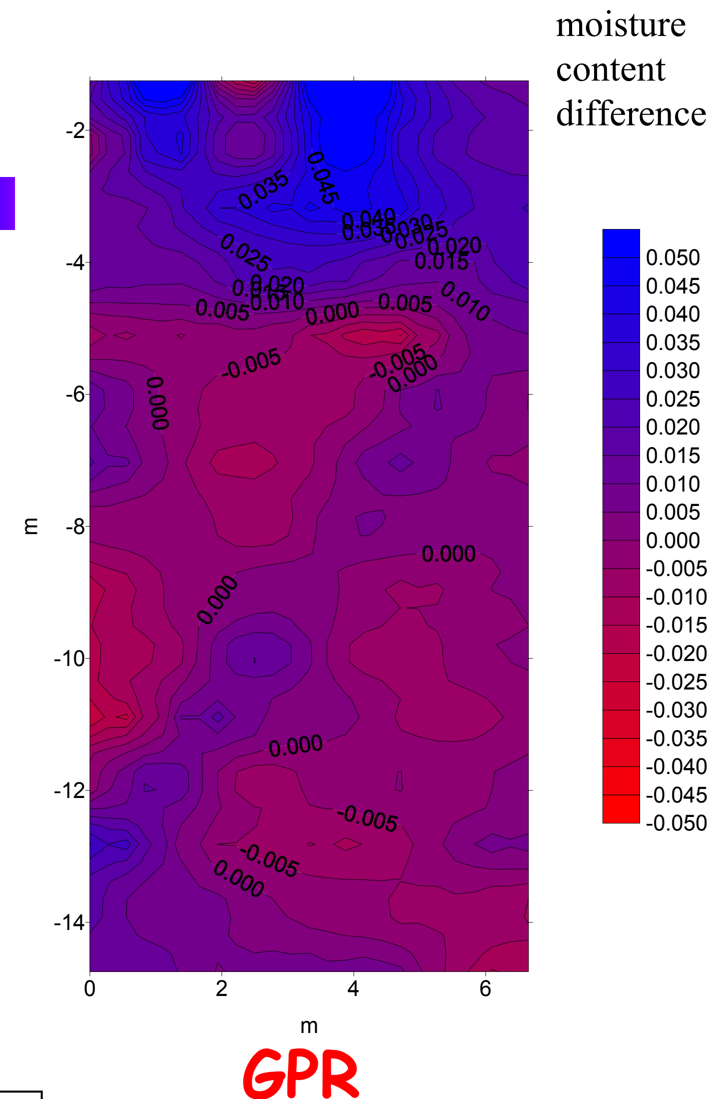


moisture content (

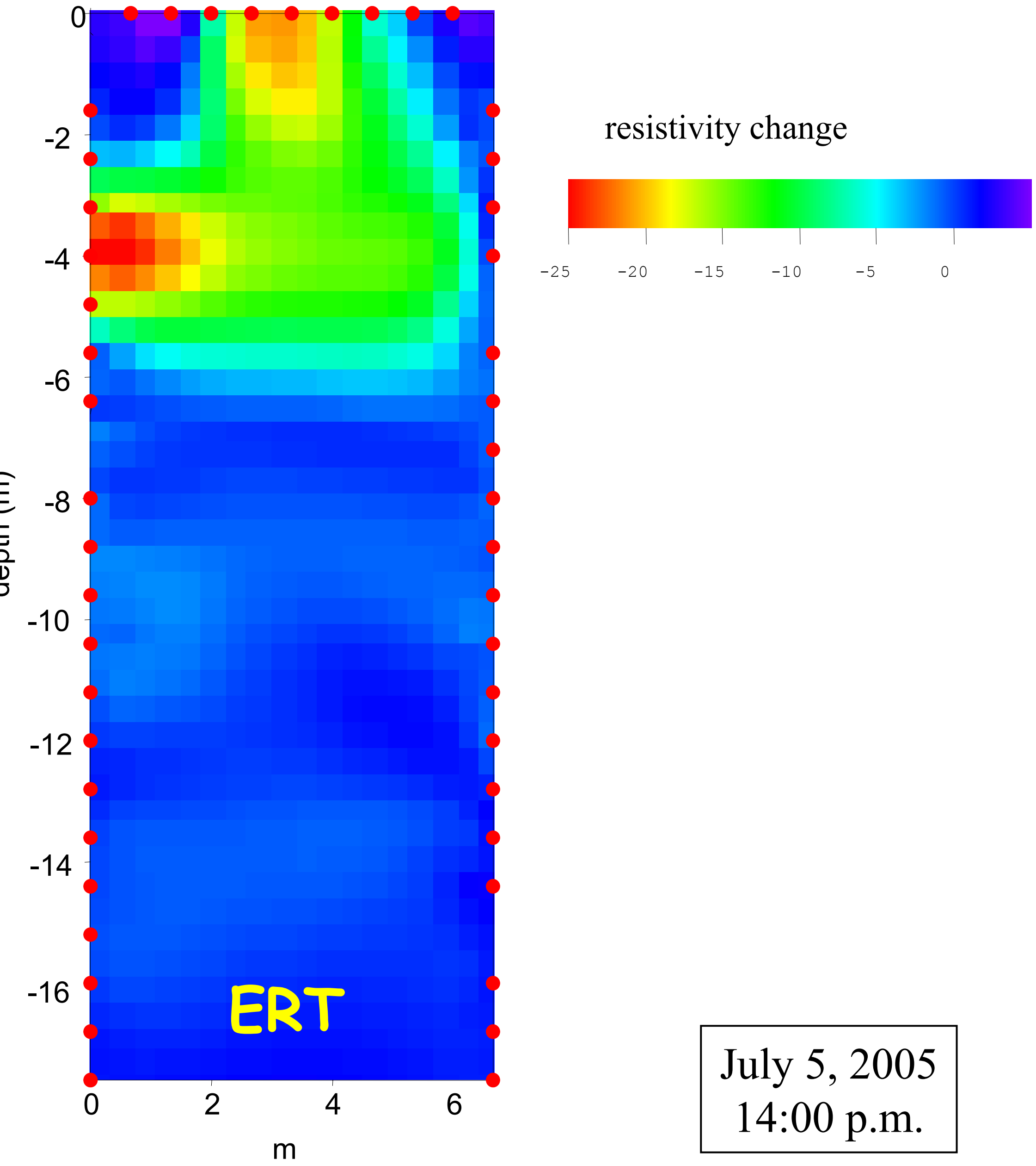






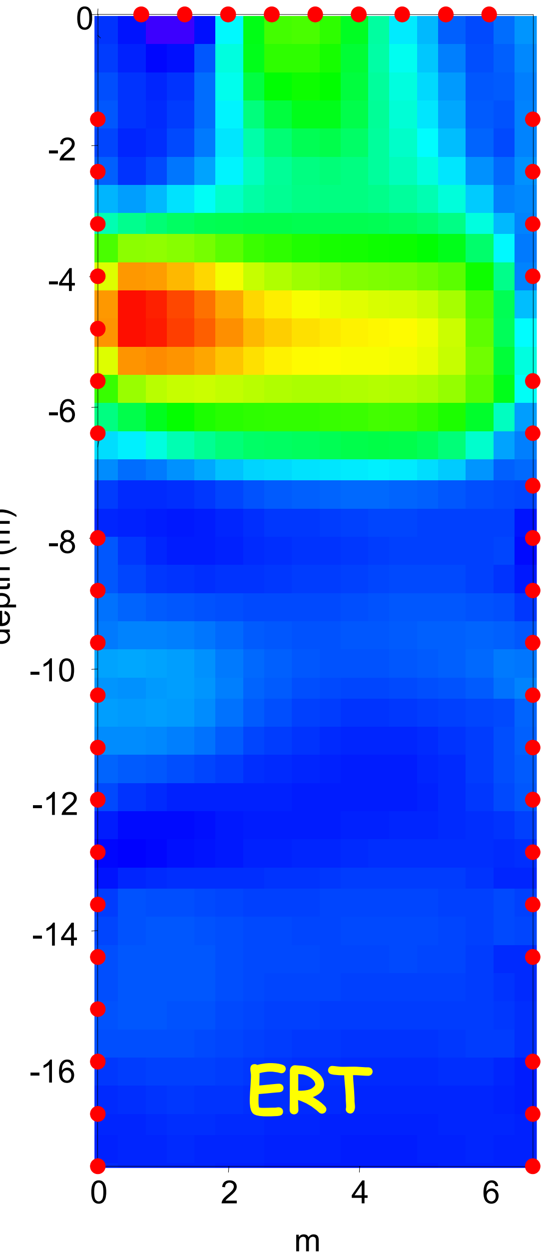


July 5, 2005
12:00 noon
(end of water injection)

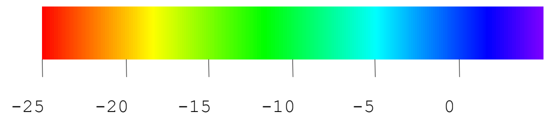


no corresponding GPR MOG

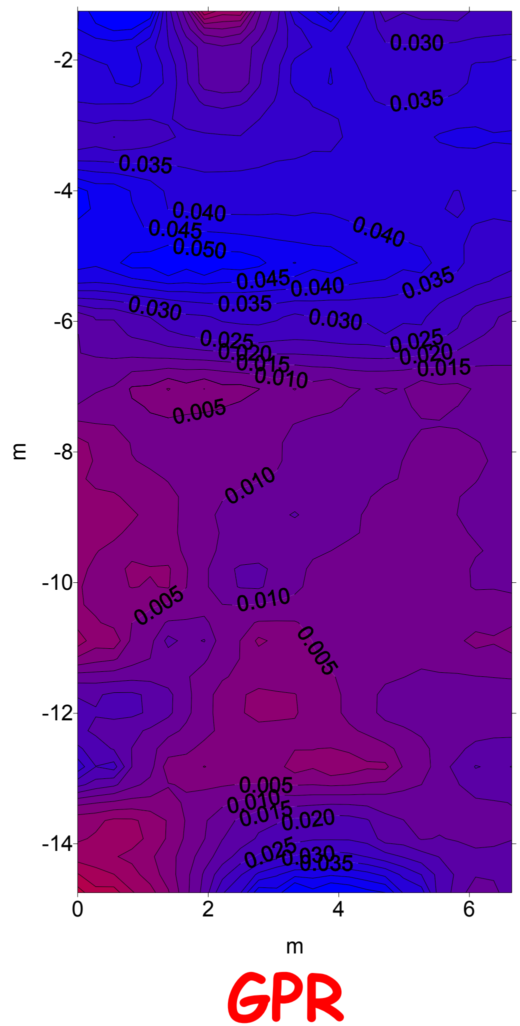
July 5, 2005
14:00 p.m.

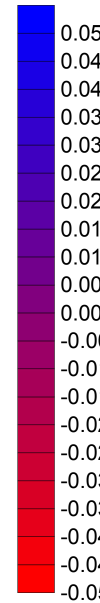


resistivity change

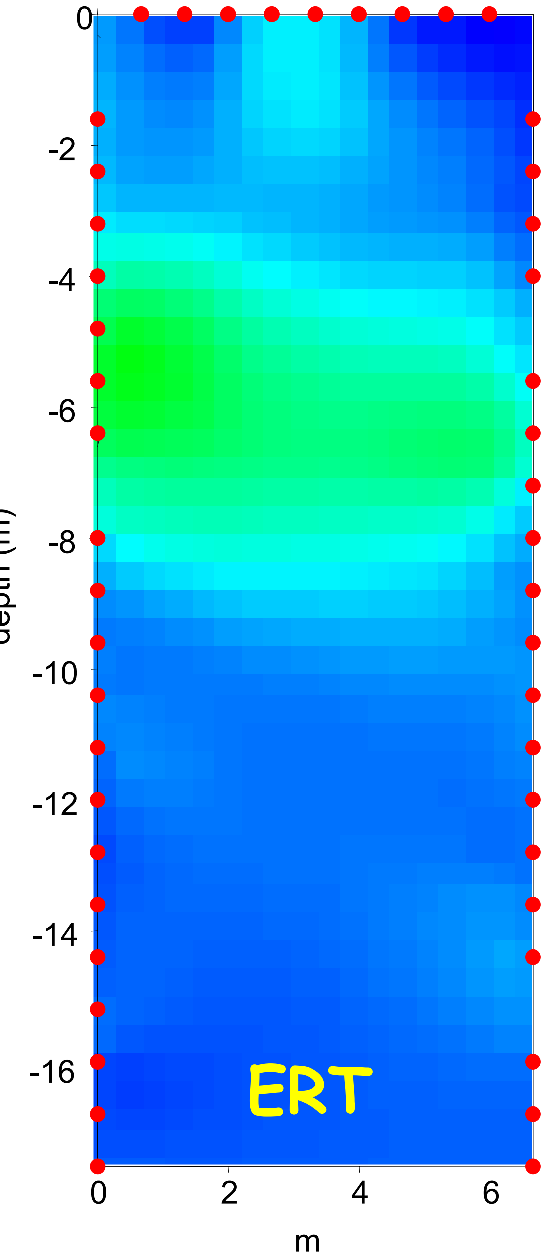


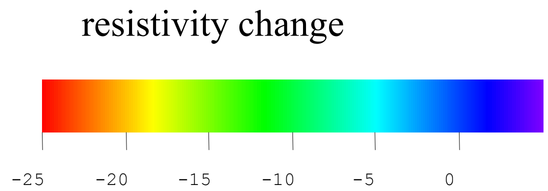
moisture content difference

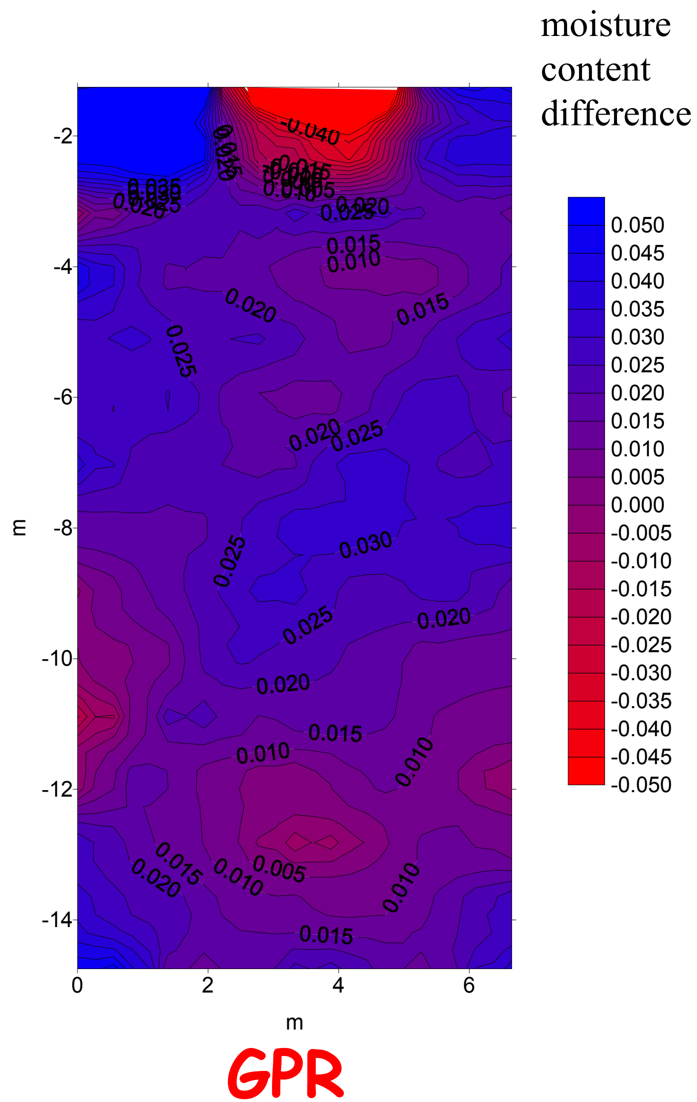




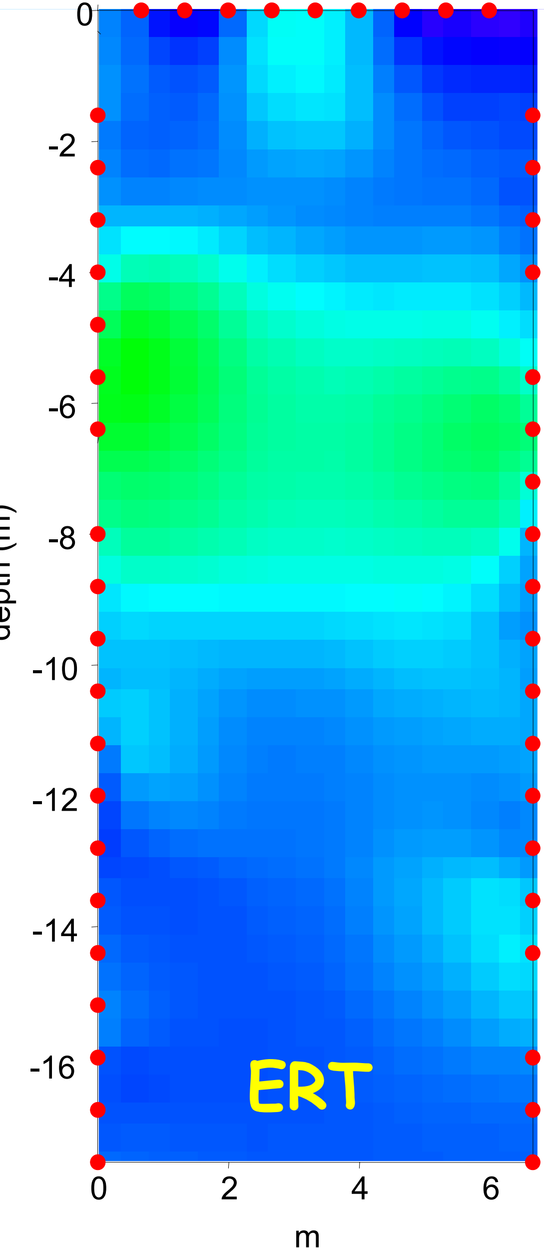
July 5, 2005
15:00 p.m.

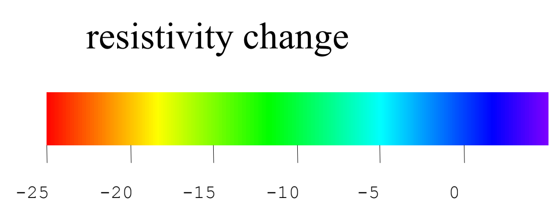


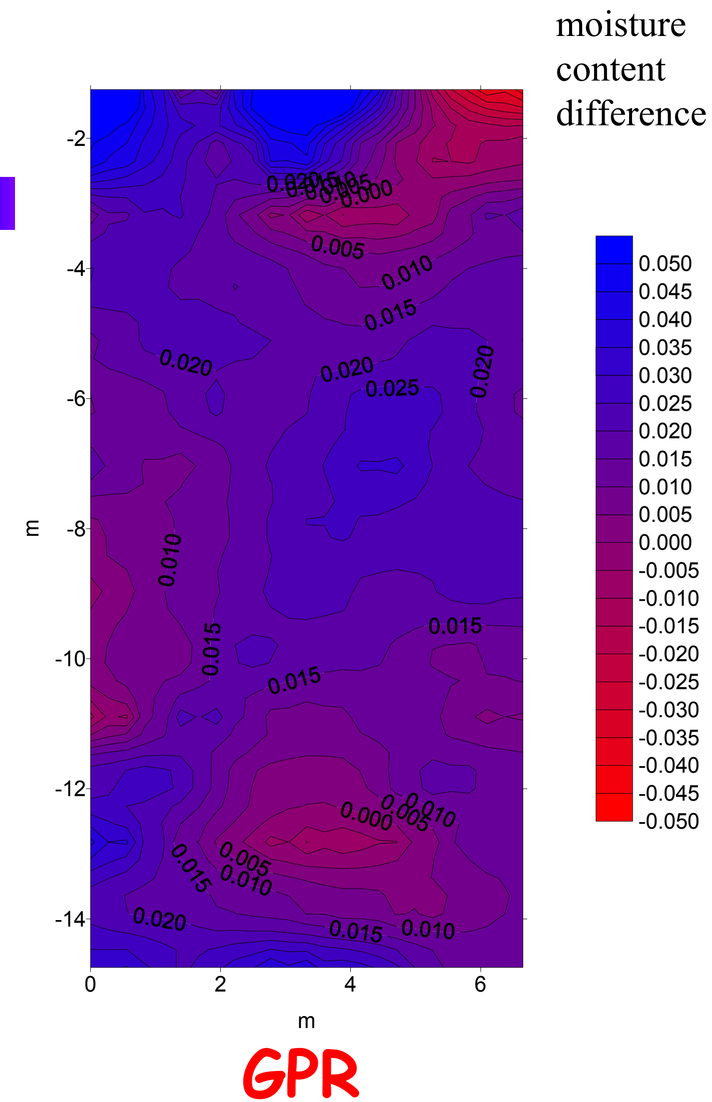




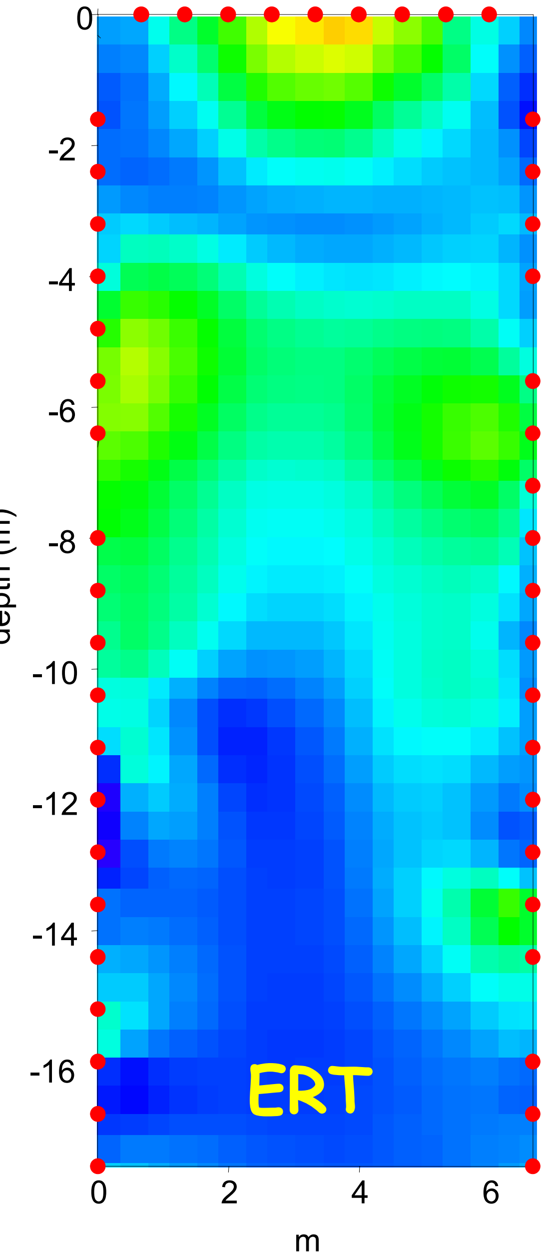
July 6, 2005
11:00 a.m.

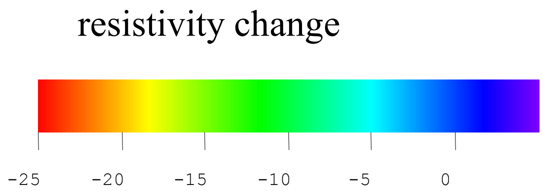


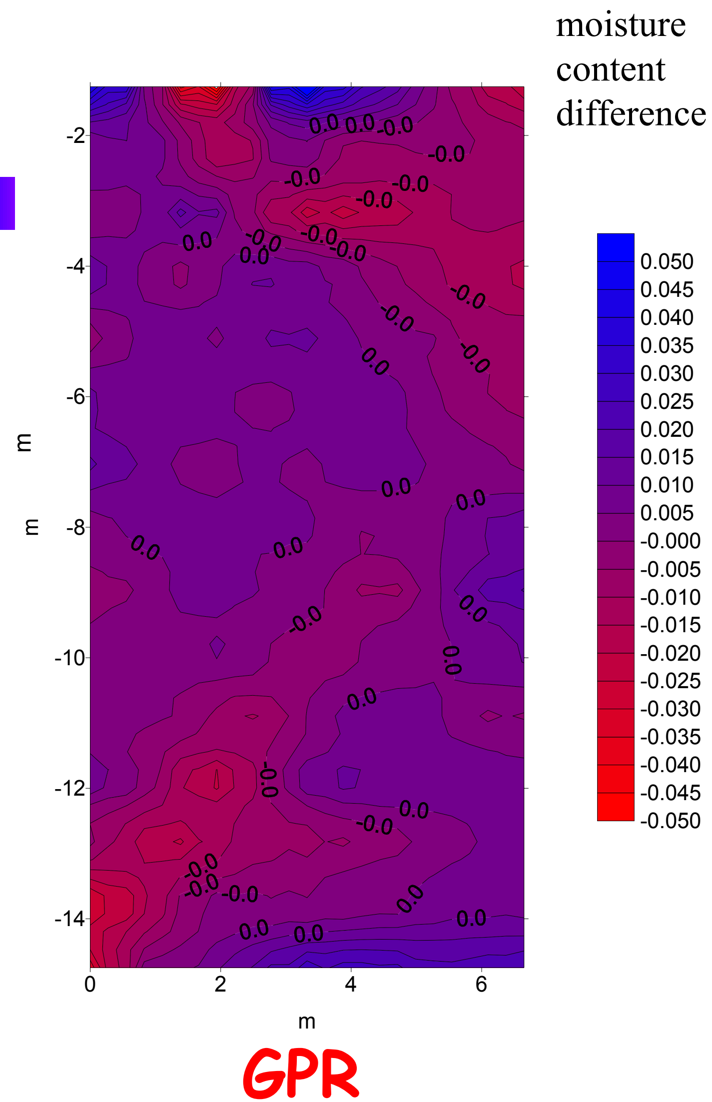




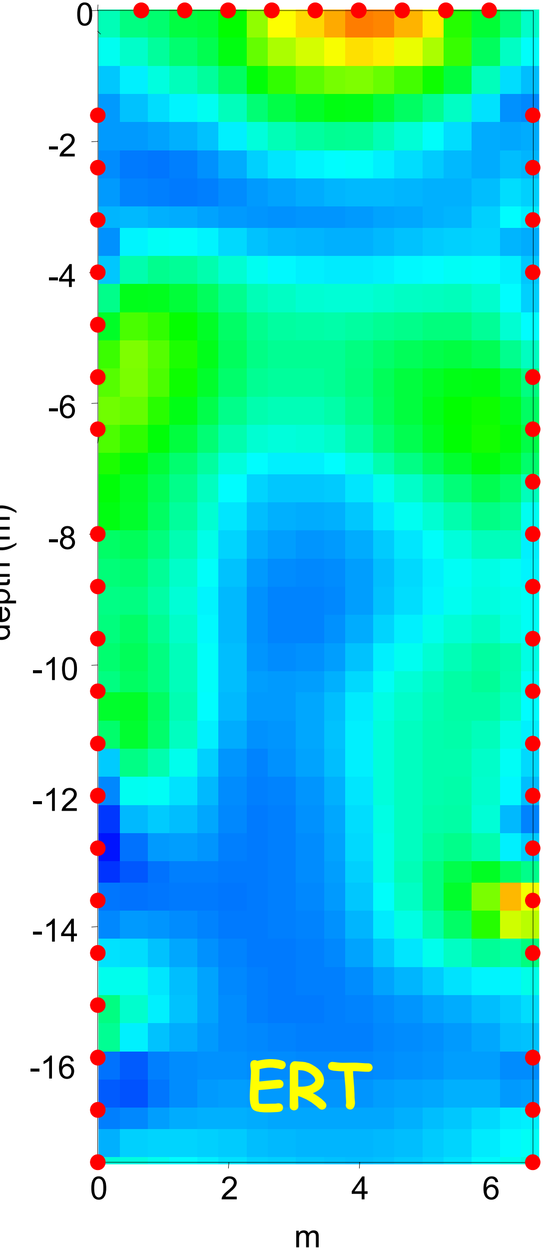
July 7, 2005
9:30 a.m.

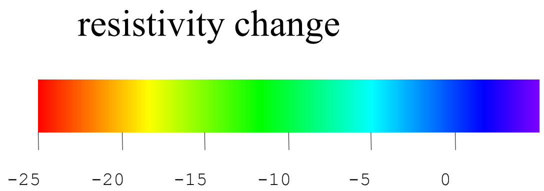


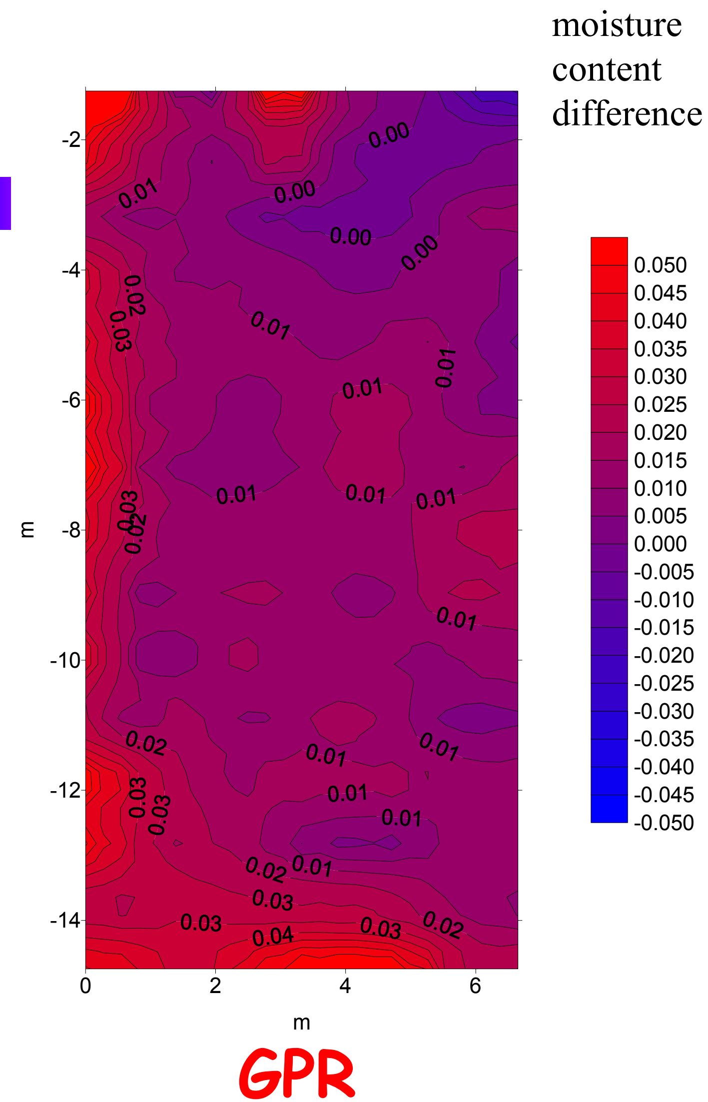




July 8, 2005
9:00 a.m.



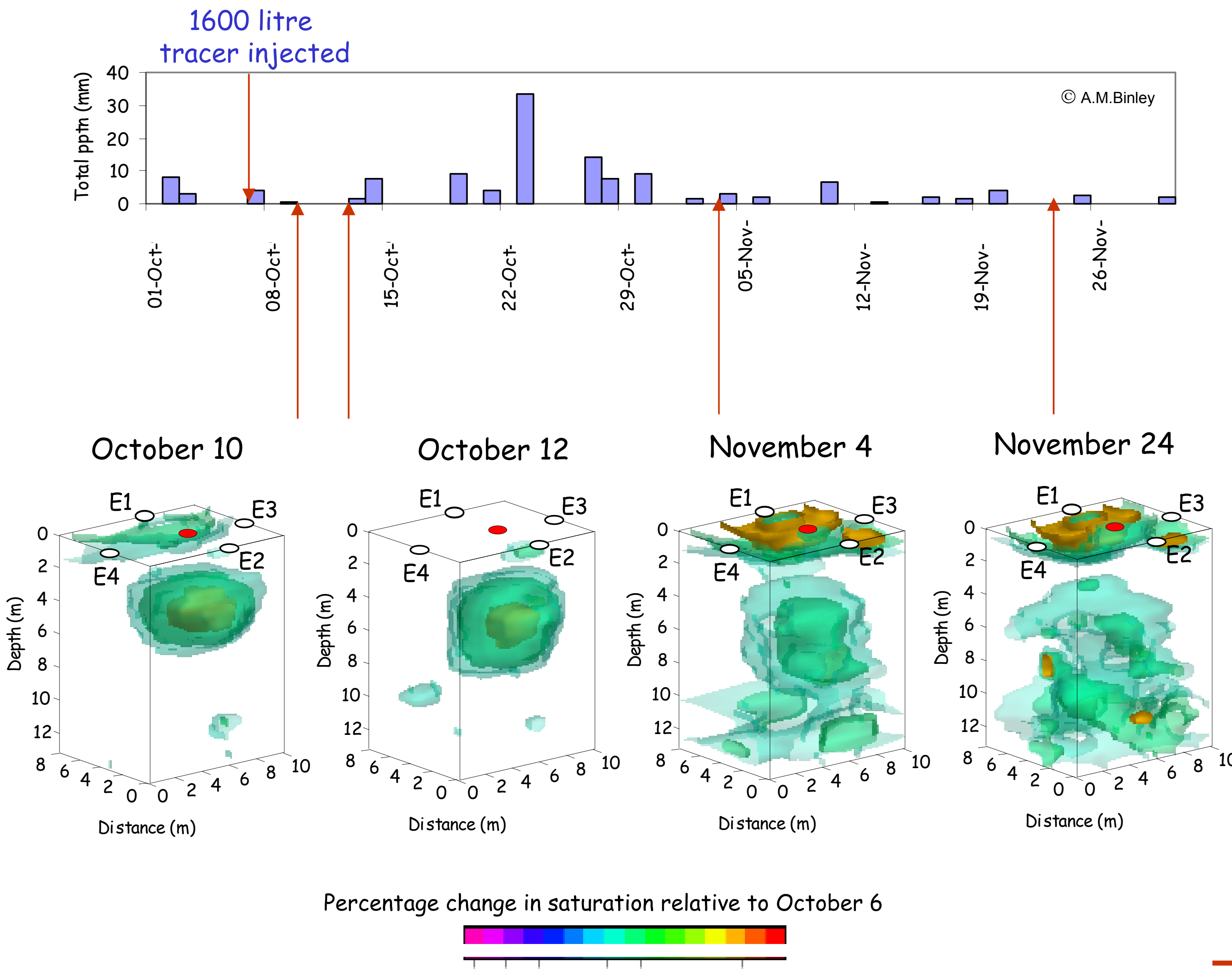




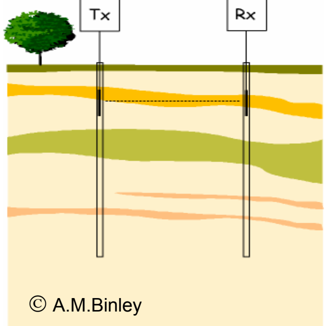
July 11, 2005
9:00 a.m.

Hatfield site, UK

3-D ERT on a controlled injection experiment



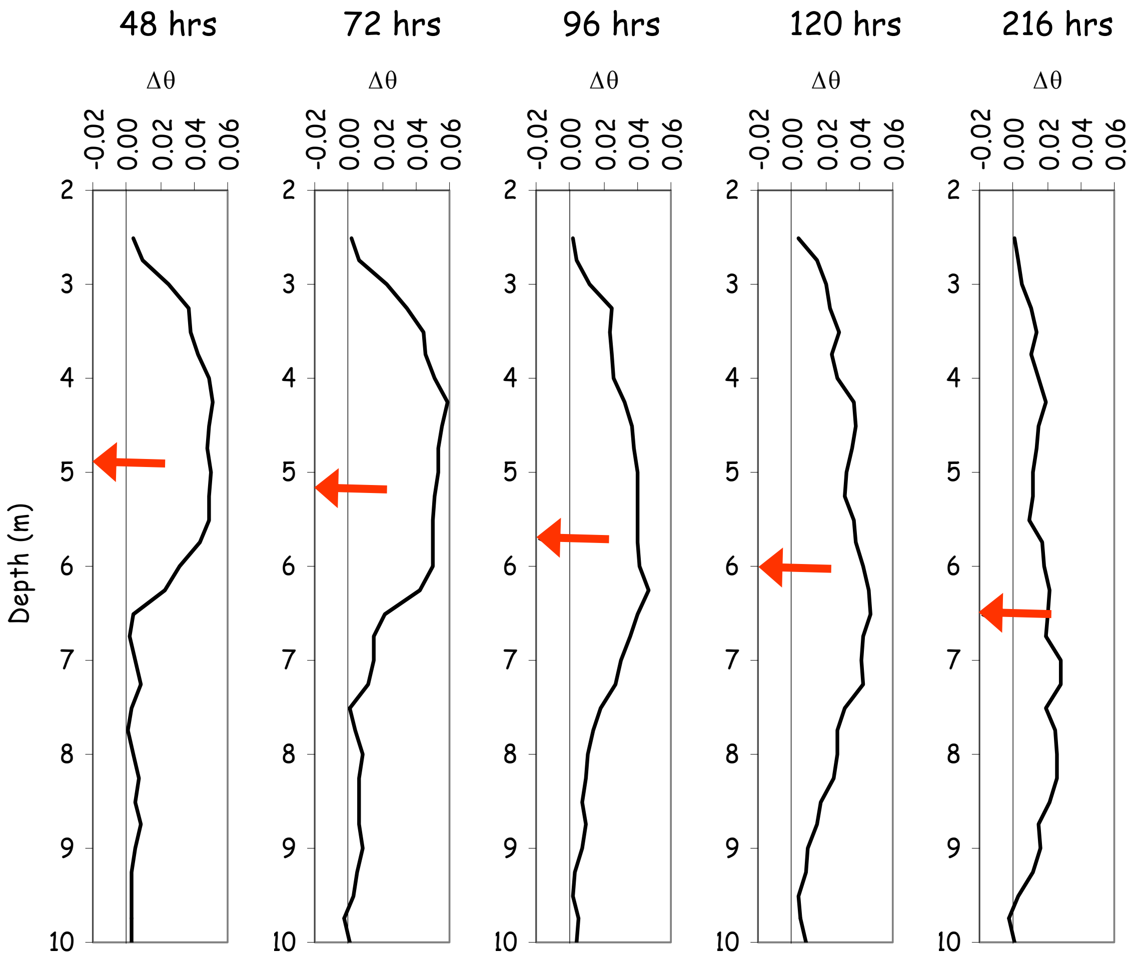
Percentage change in saturation relative to October 6



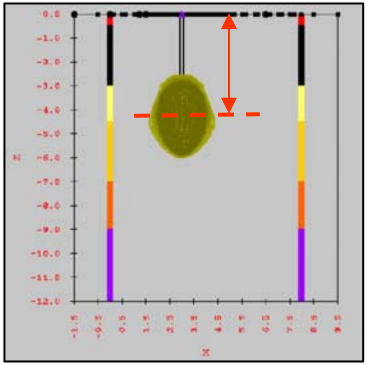
ZOP radar between R1 and R2 boreholes during the controlled water injection

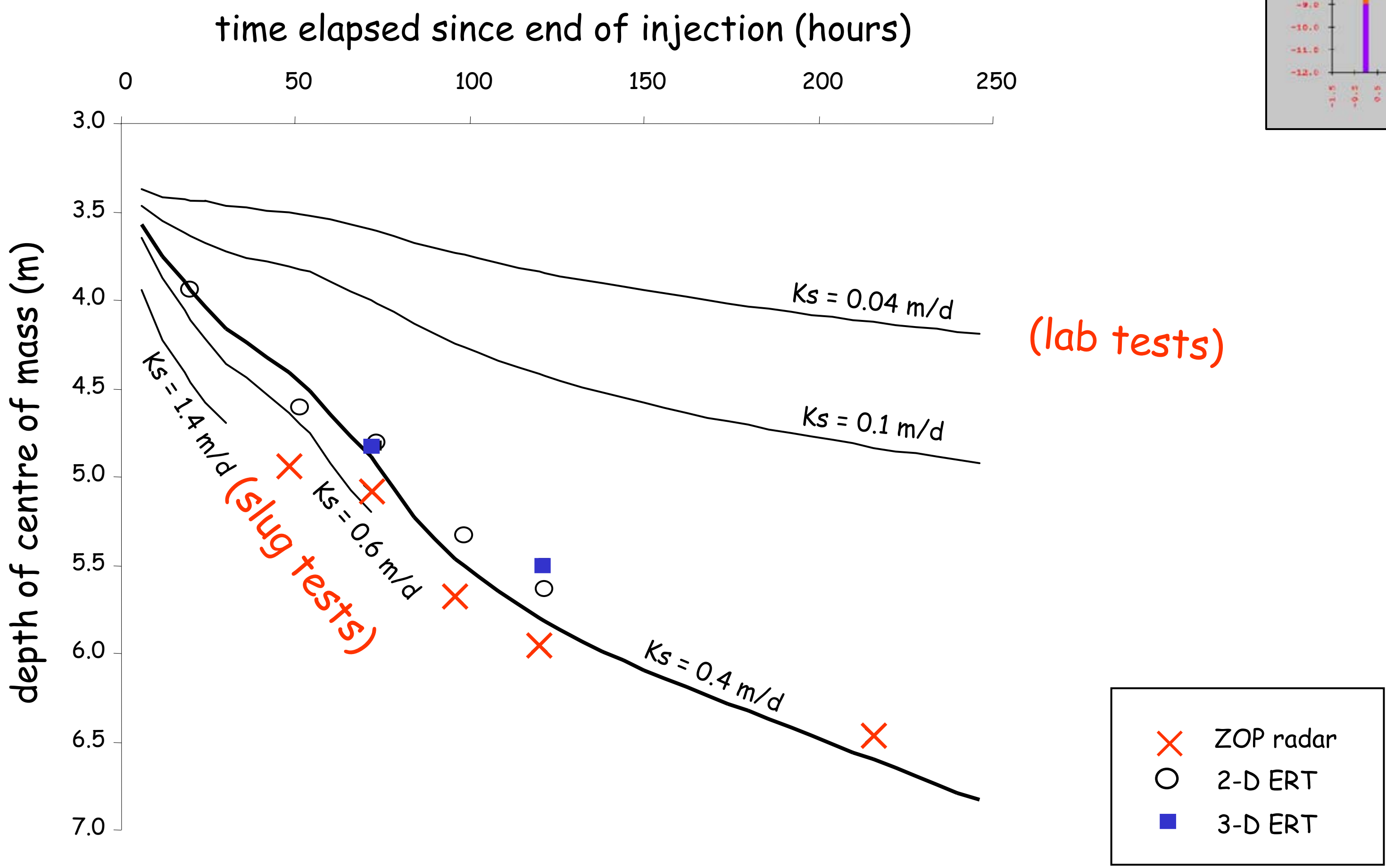
moisture content changes with respect to the pre-injection situation

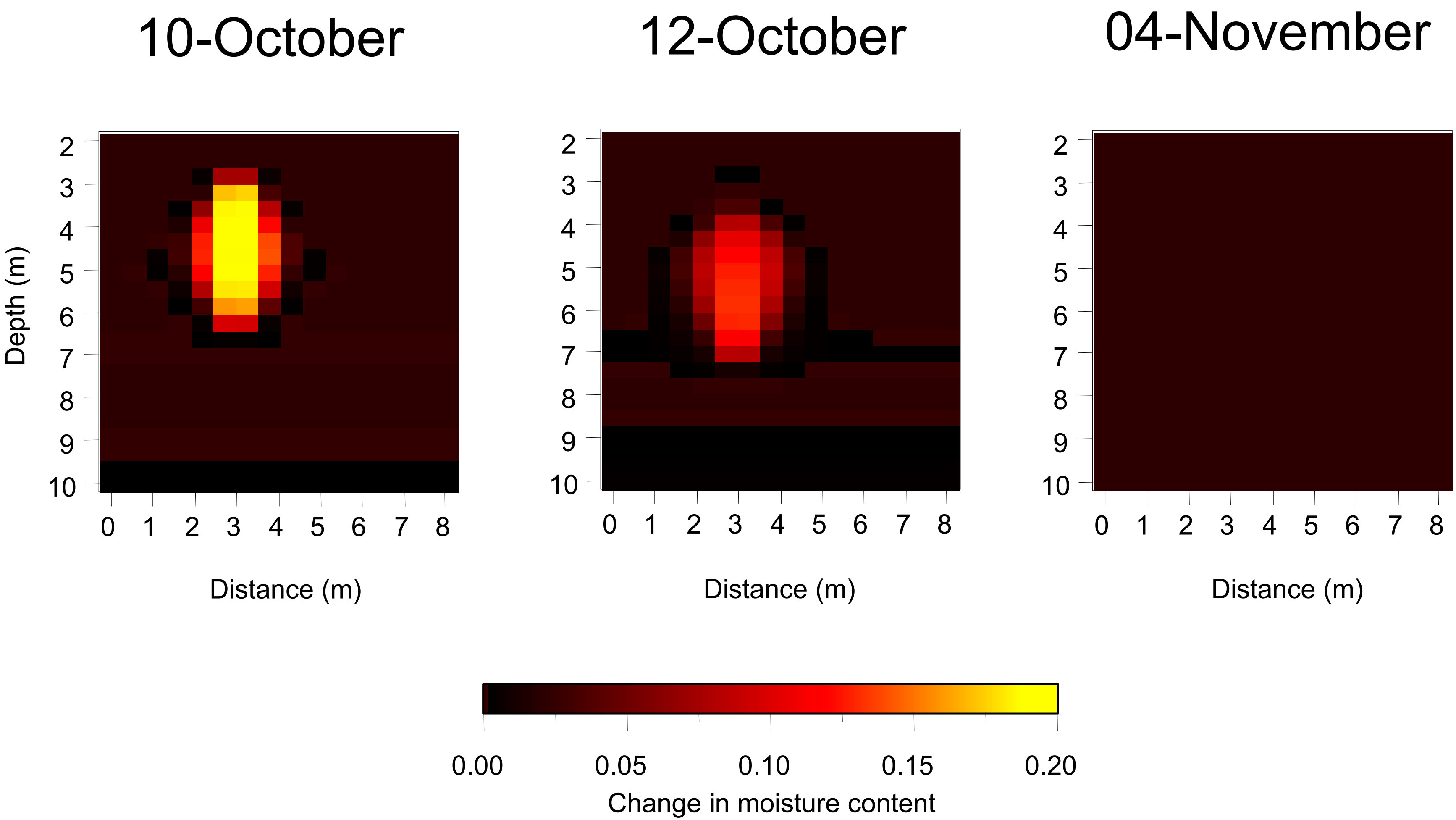
red arrows show position of the centre of mass



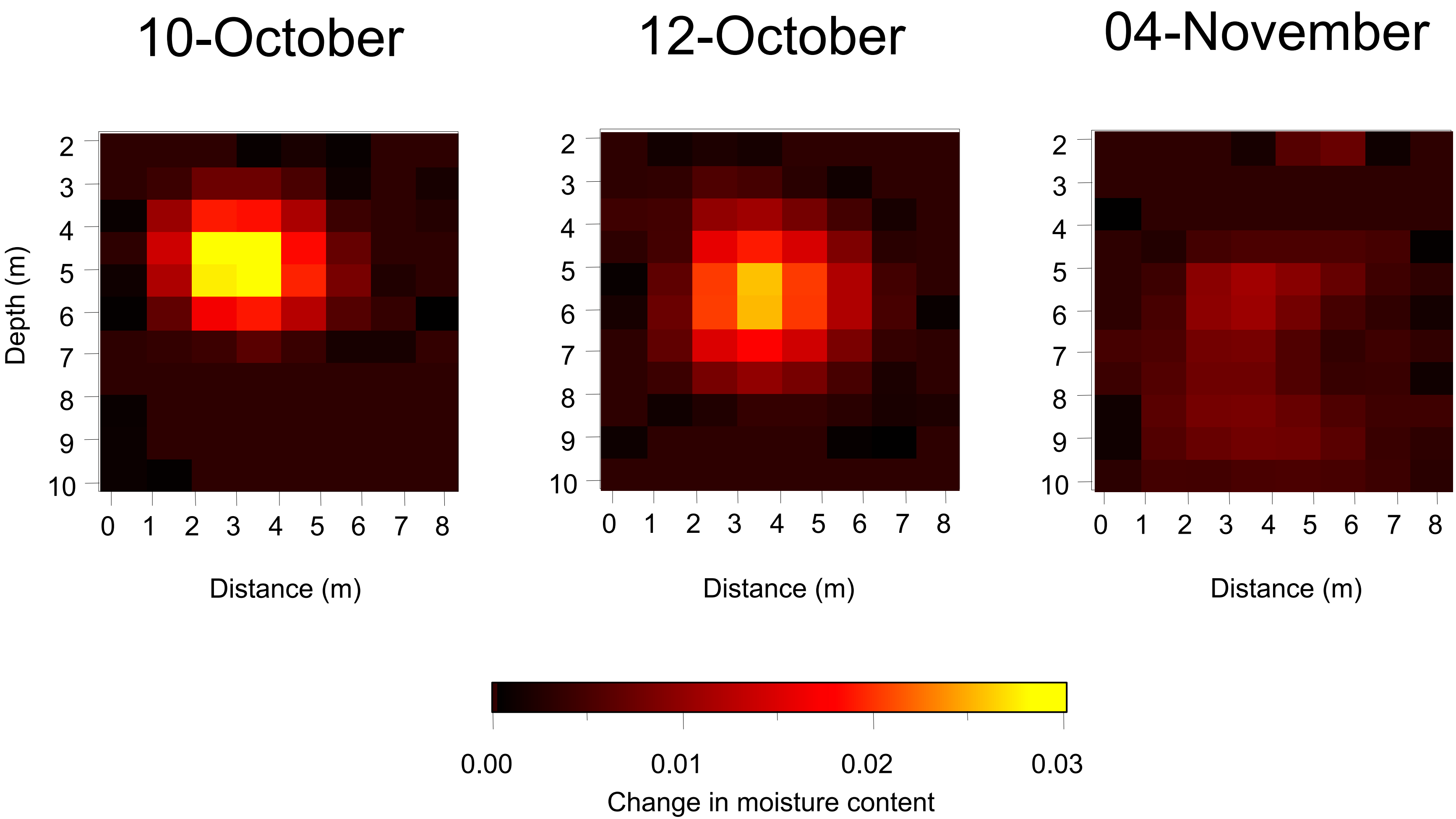
Vertical motion of tracer centre of mass comparison between field data and simulations



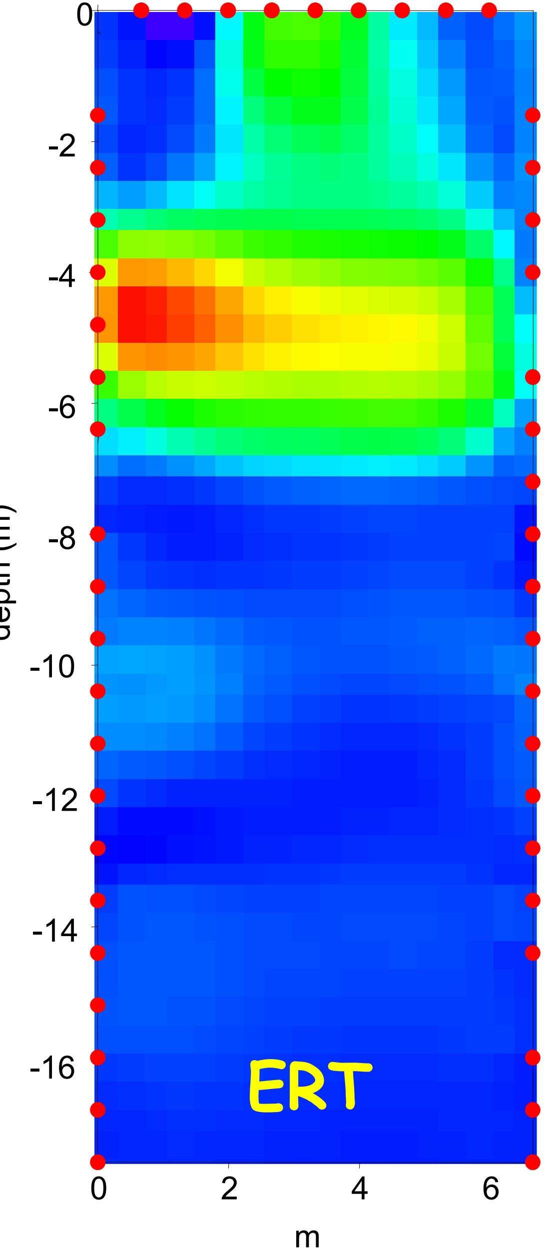


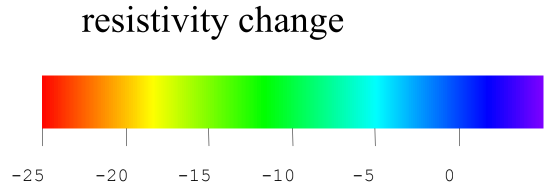


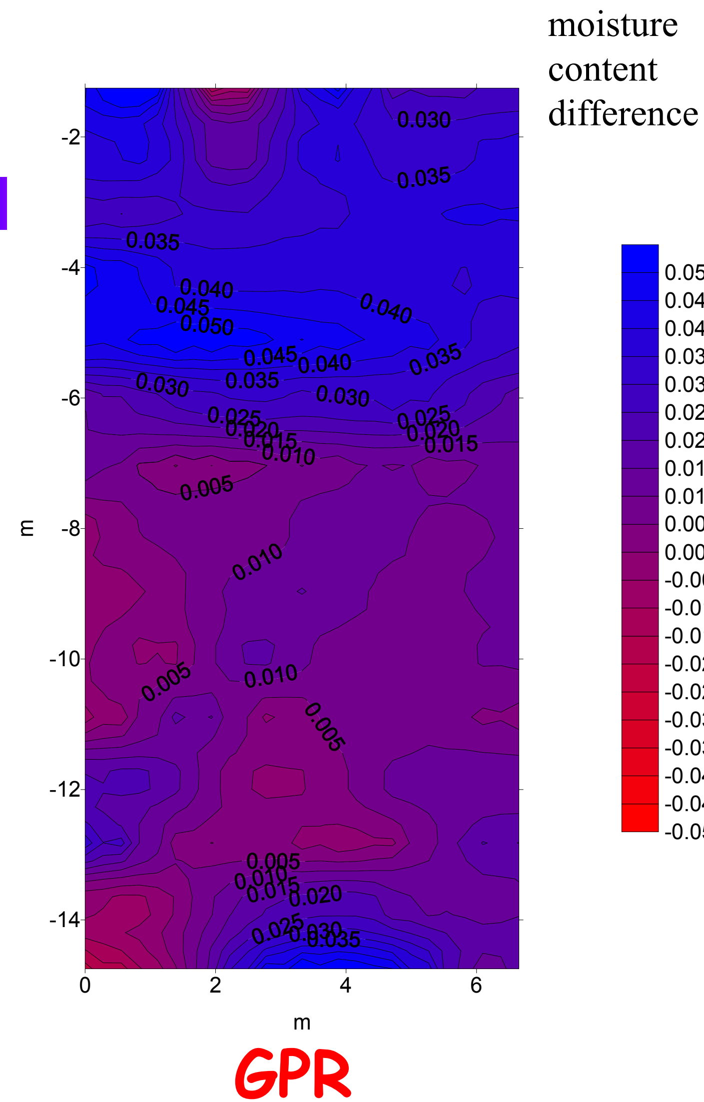
SIMULATION WITH K_z=0.4 m/d, K_x/K_z=1.5
(~ hydraulic conductivity value from slug tests)


10-October
12-October
04-November
Depth (m)
2
3
4
5
6
7
8
9
10
0 1 2 3 4 5 6 7 8
Distance (m)
0.00
0.01
0.02
0.03
Change in moisture content

ERT DATA







July 5, 2005
15:00 p.m.

General conclusions

- The hydrologic behavior of the vadose zone can be pictured with accuracy and completeness
- The information is maximized by time-lapse measurements and strong changes in moisture content
- The acquisition and inversion characteristics of the adopted hydro-geophysical methods have critical impact (e.g., scale effect): better to use cross-hole methods
- The resolution characteristics of the adopted methods must be understood and accounted for

Outlook

- Hydraulic tests should be designed to be optimally imaged by hydro-geophysics
- Joint inversion of different methods (e.g. ERT and GPR) shall be sought
- Integration with borehole logs shall be strengthened
- More synergies shall be established with hydrologists (the end users)

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