fiva
International Research School of Water Resources

International PhD Course in

HYDROGEOPHYSICS

# Hydrogeophysical

# Data Fusion

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# Overview

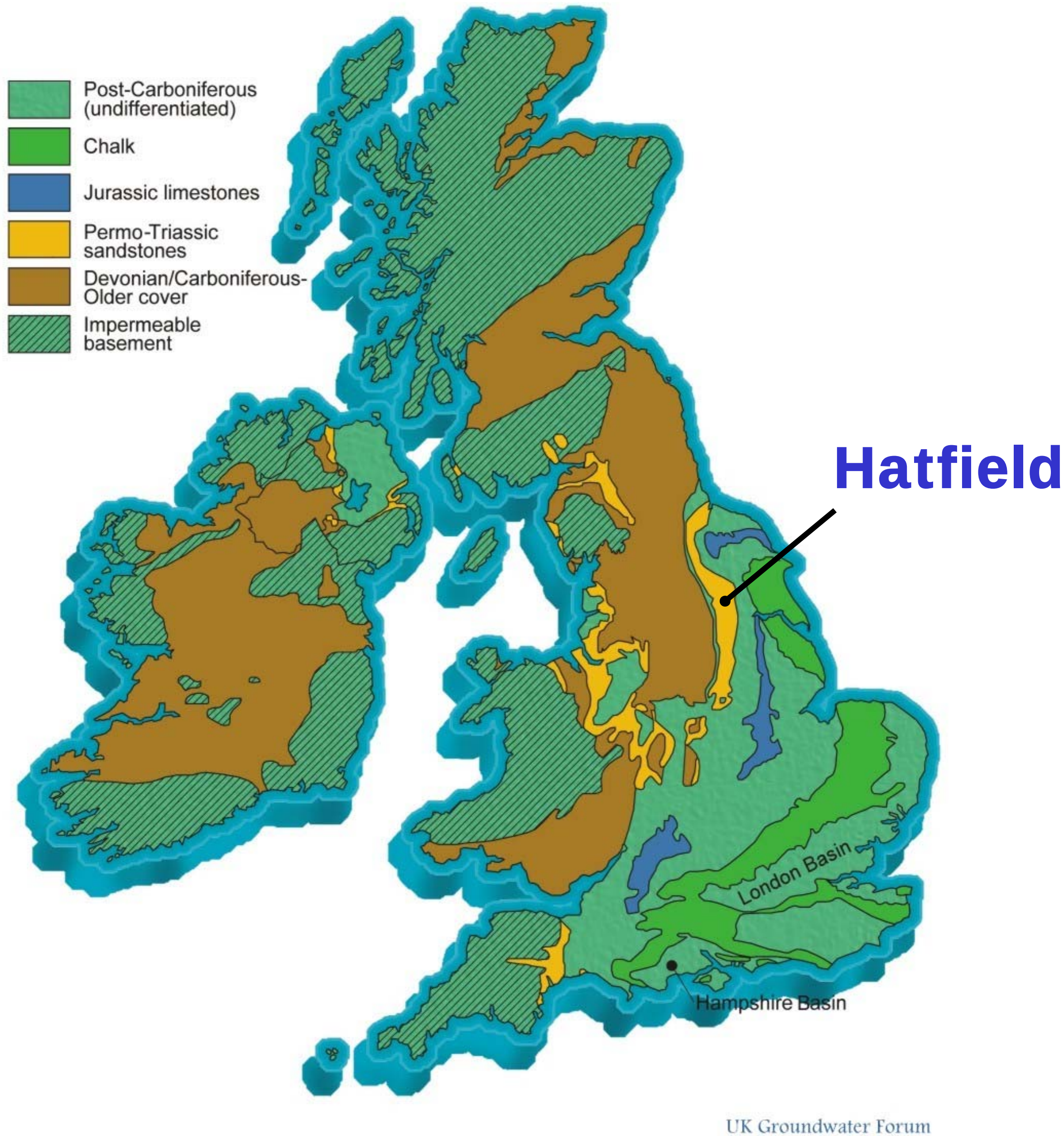
So far we have covered individual techniques but we need to think about how we can combine the geophysical results.

We also need to have a means of integrating the geophysical measurements with hydrological models.

We will illustrate approaches to these problems using two case studies.

# Case Study 1

Investigating flow and transport in unsaturated sandstone under natural and forced (tracer) loading

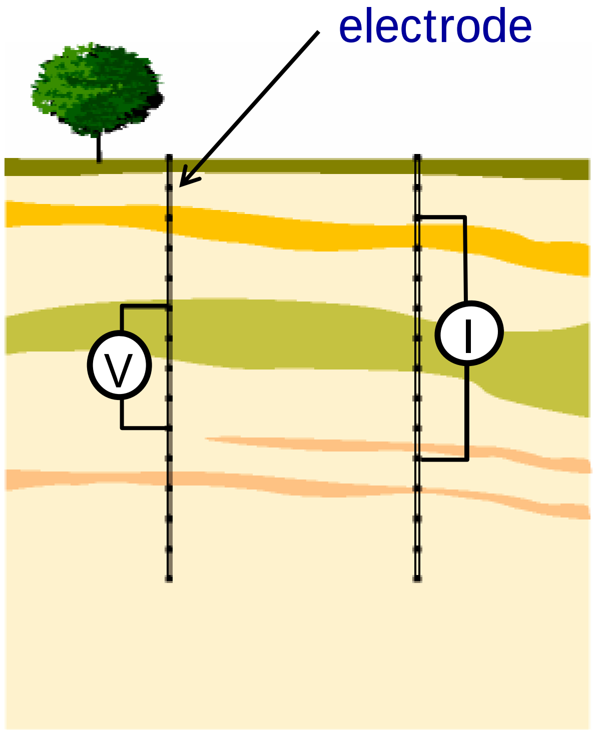


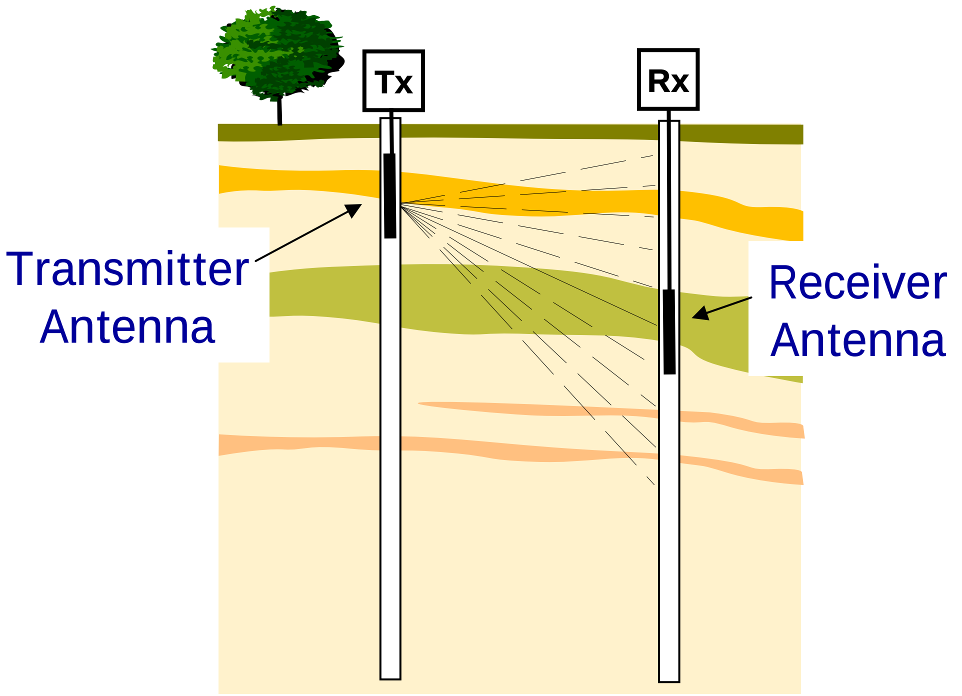
# Case Study - Objectives

Determination of effective hydraulic properties that control the transport of solutes in the unsaturated zone of the sandstone aquifer

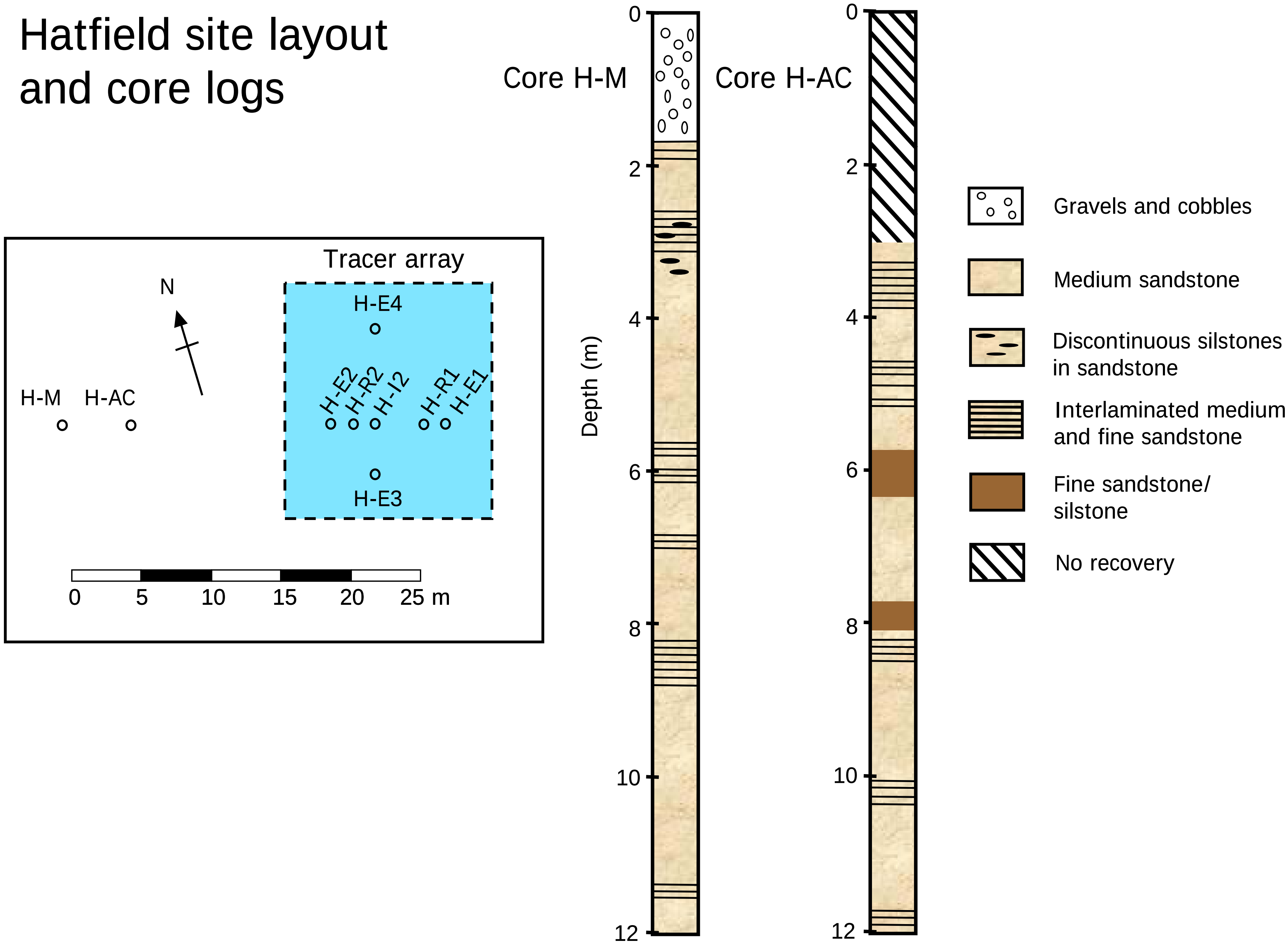
# Case Study - Methods

Combination of cross-borehole resistivity and radar tomography applied to monitor changes due to natural and forced (tracer) input

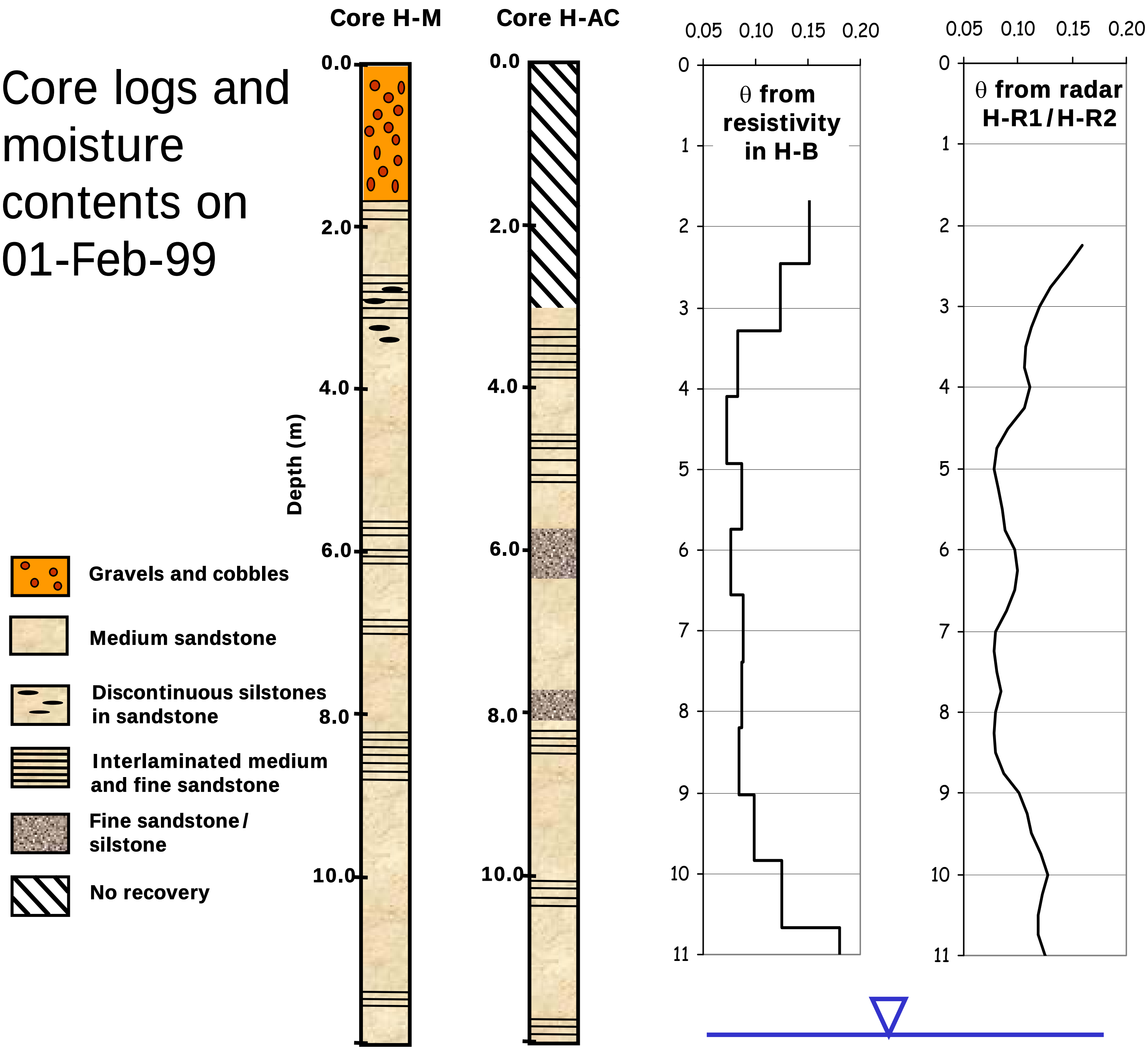


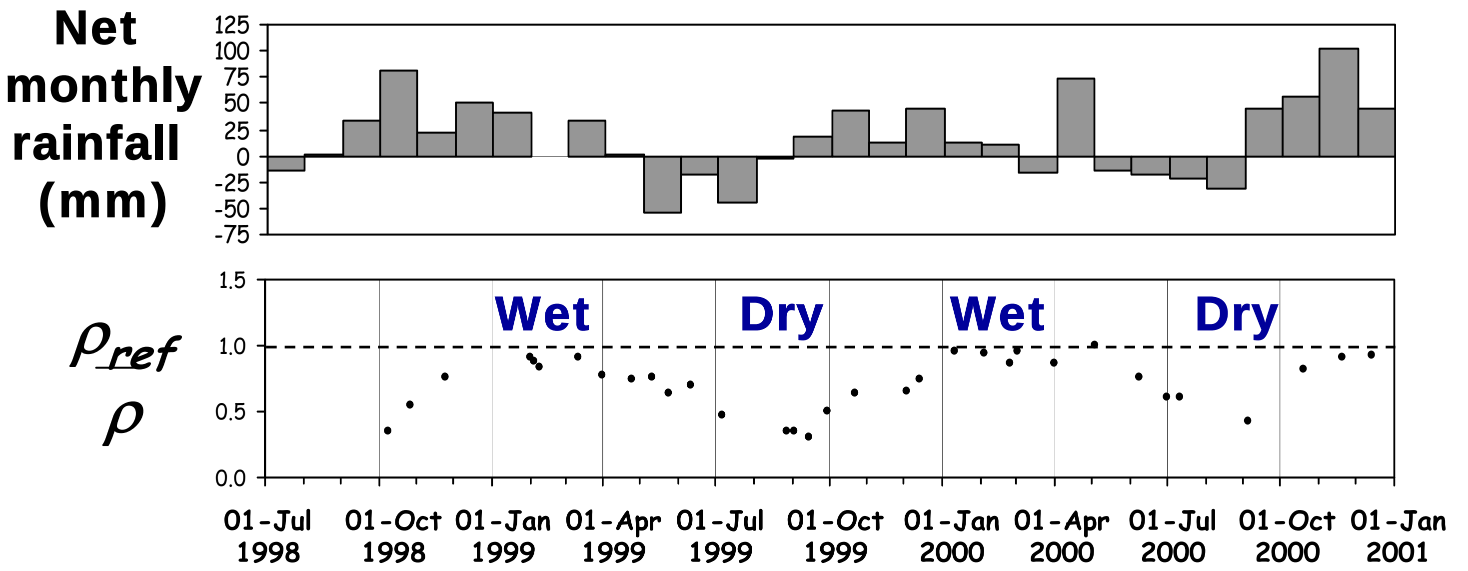
# Hatfield site layout and core logs



# Core logs and moisture contents on 01-Feb-99

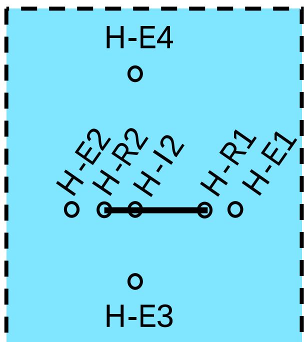


# Response to natural inputs – resistivity

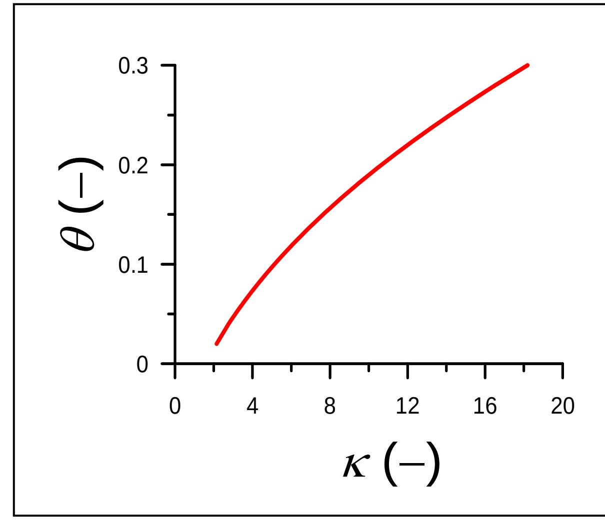



Comparison of net monthly rainfall and fractional change in 0 - 0.82 m depth ‘layer’ resistivity using 03-May-00 as reference

# Response to natural inputs – radar ZOP



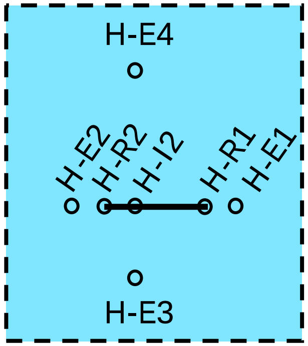

**CRIM model**

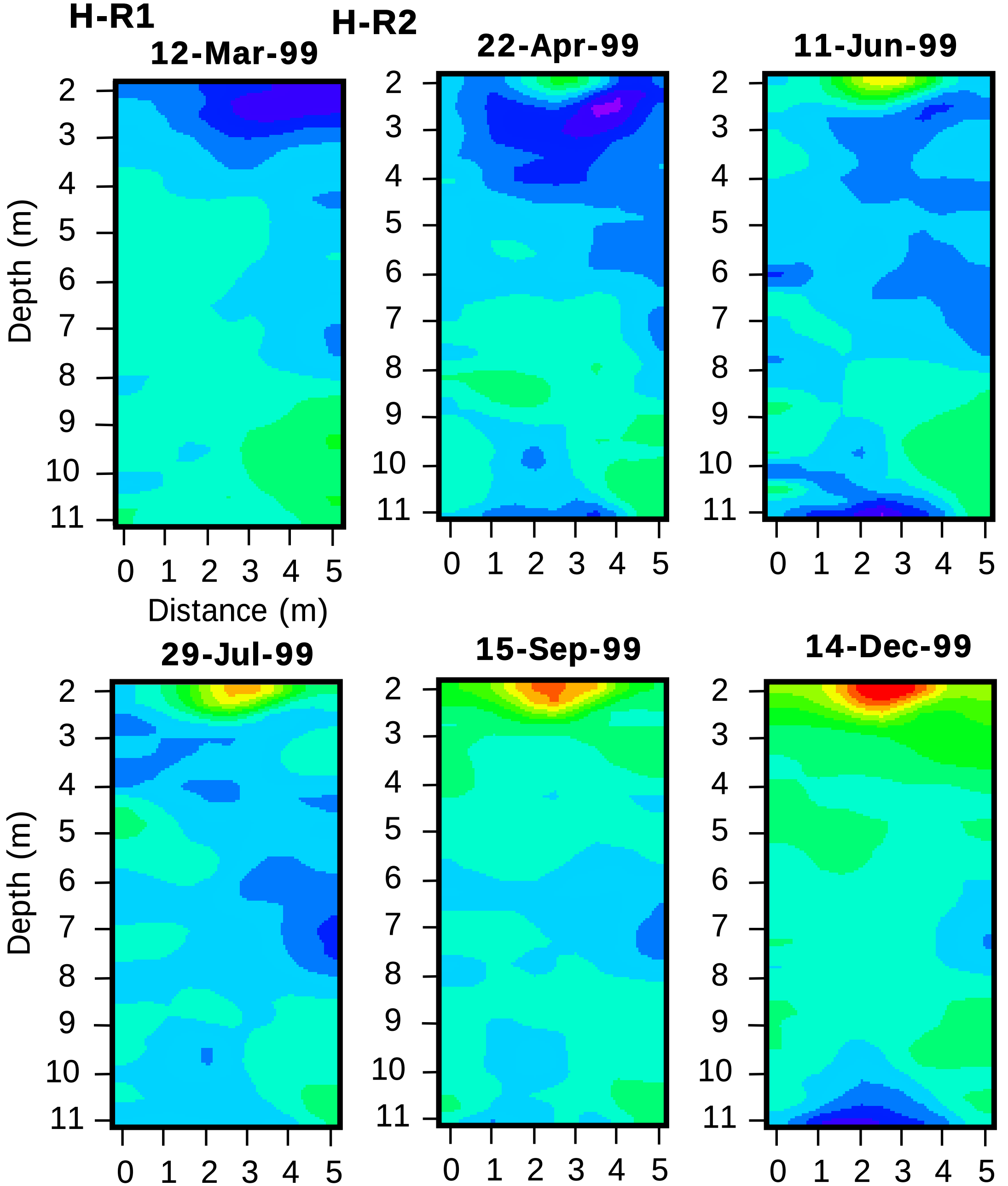



$$\sqrt{\kappa} = (1-\phi)\sqrt{\kappa_s} + \theta\sqrt{\kappa_w} + (\phi-\theta)\sqrt{\kappa_a}$$

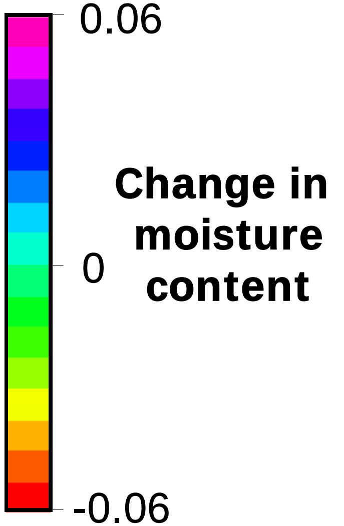
$$\Delta\theta = \Delta\left(\frac{1}{v}\right)\left(\frac{c}{\sqrt{\kappa_a} - \sqrt{\kappa_w}}\right) = 0.0375\Delta\left(\frac{1}{v}\right)$$

# Response to natural inputs – radar MOG




Changes from 01-Feb-99

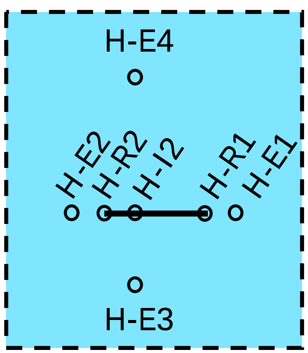


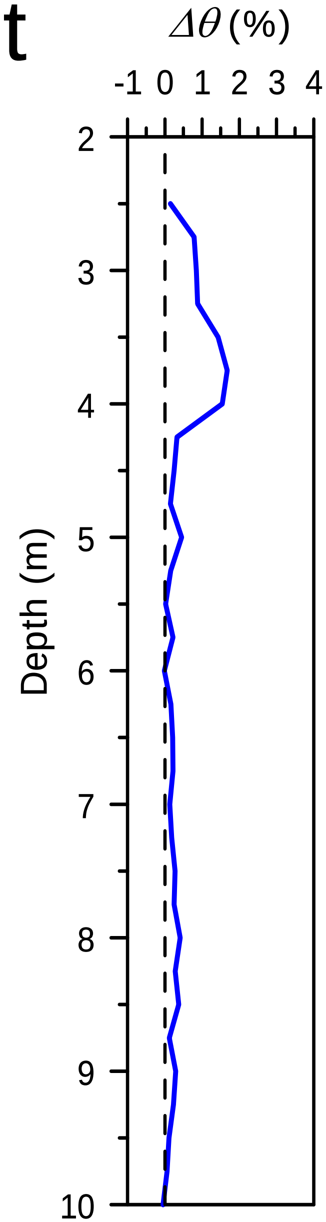
# Tracer Test

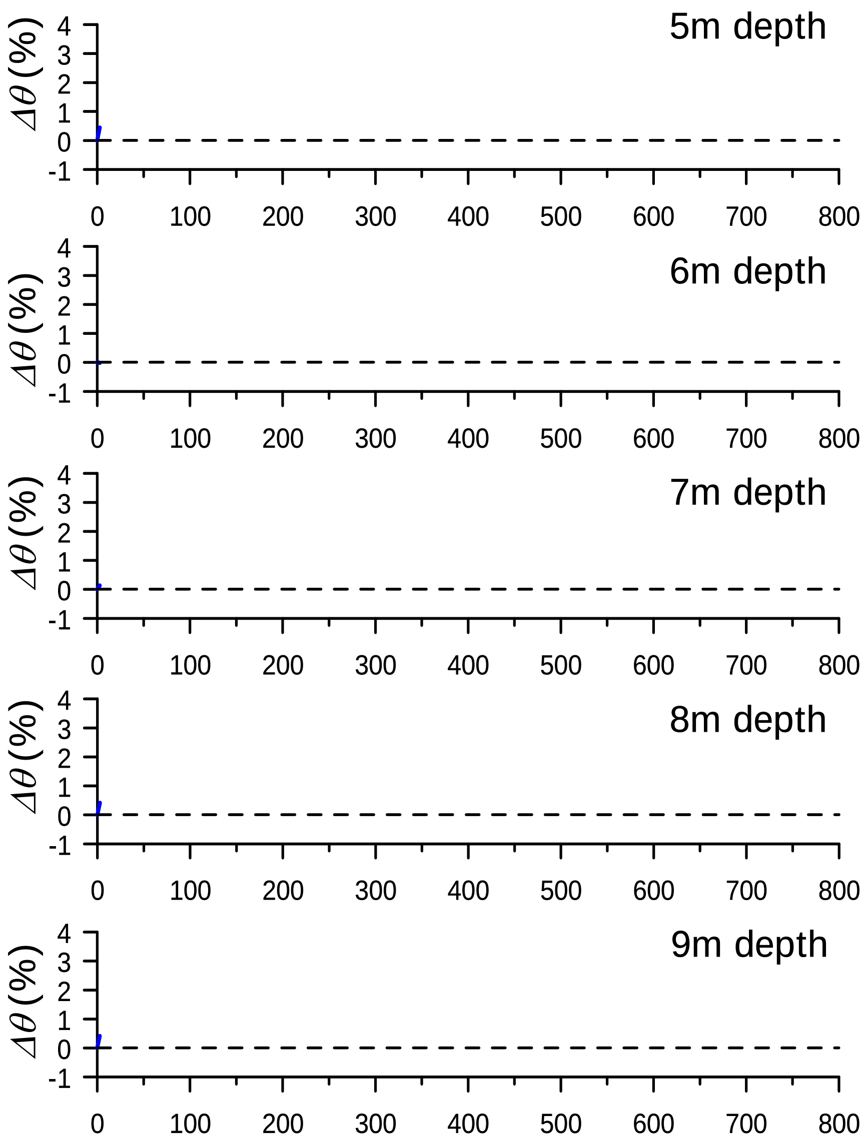
Changes in moisture content from radar surveys

14-Mar-03

Tracer array



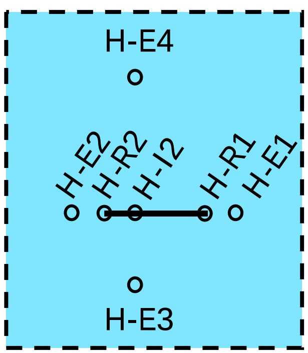



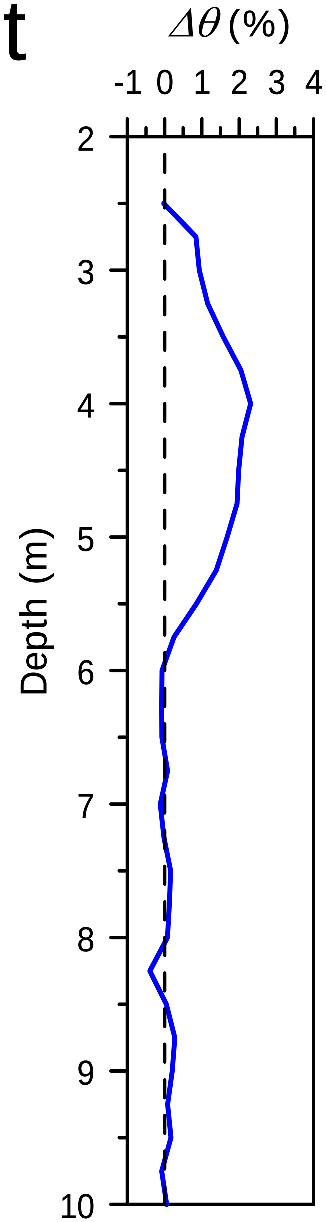
# Tracer Test

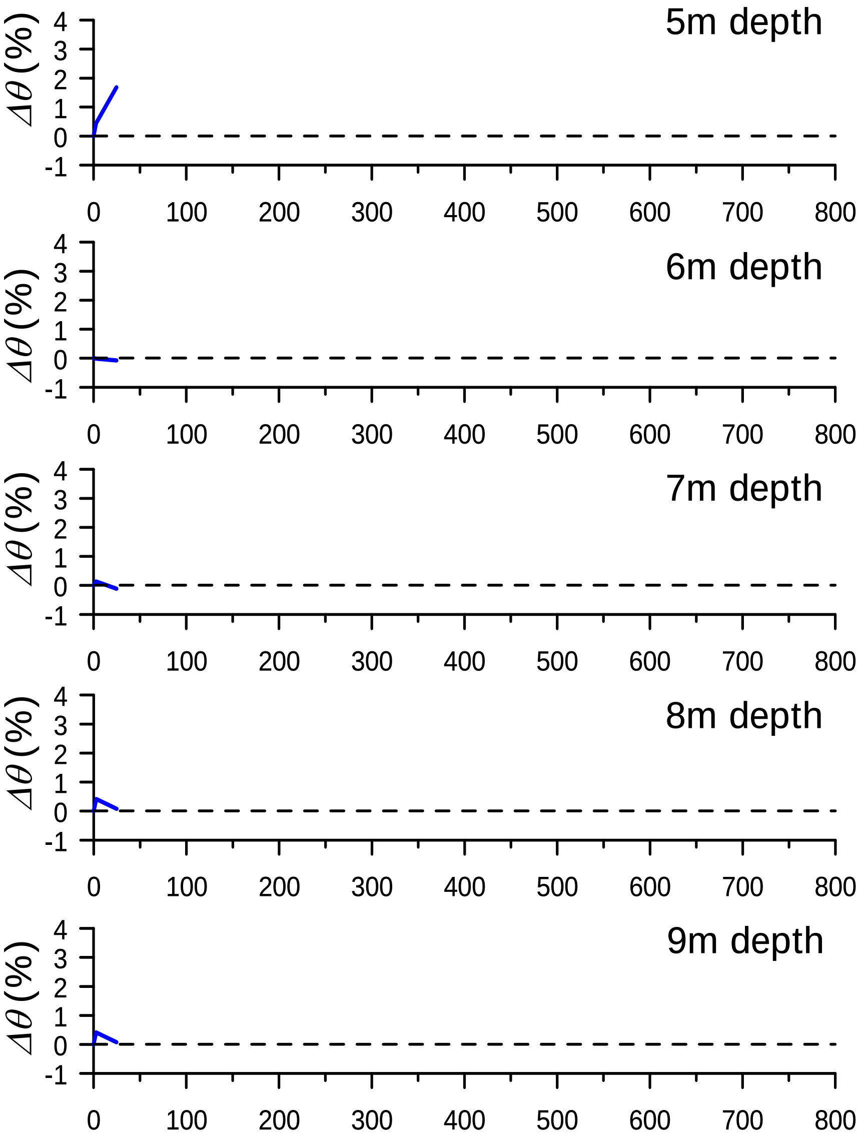
Changes in moisture content from radar surveys

15-Mar-03

Tracer array



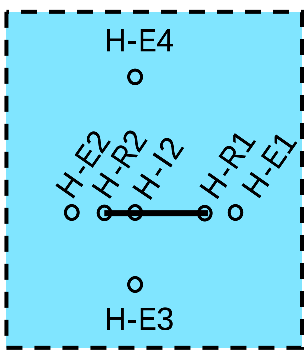



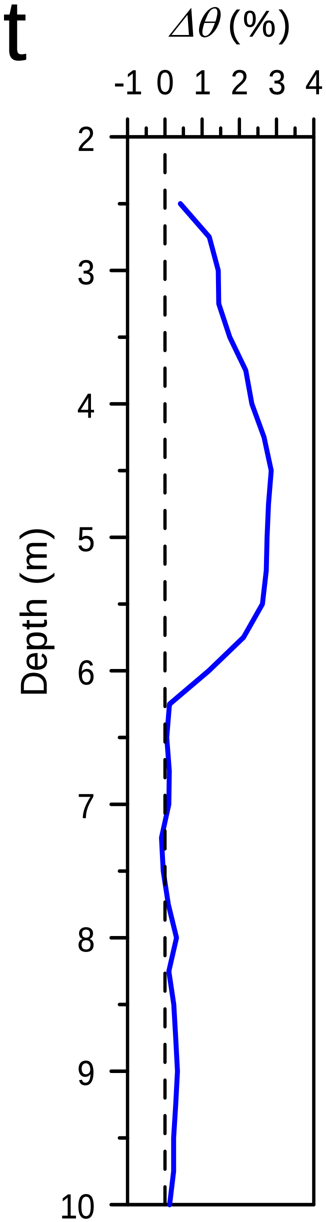
# Tracer Test

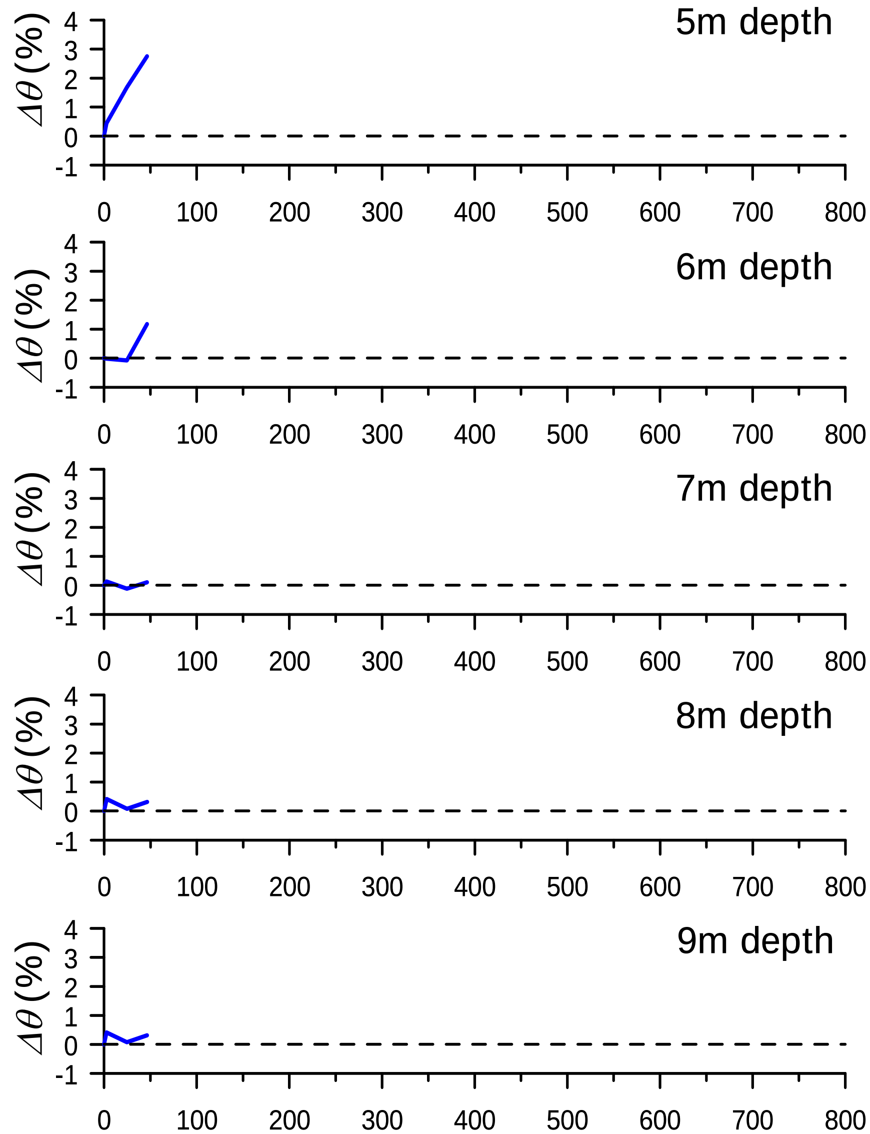
Changes in moisture content from radar surveys

16-Mar-03

Tracer array



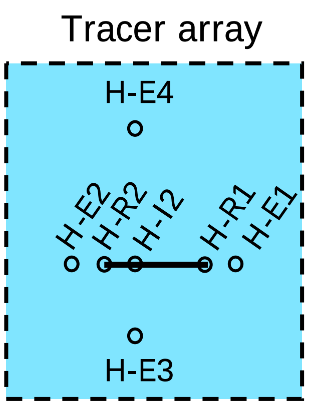



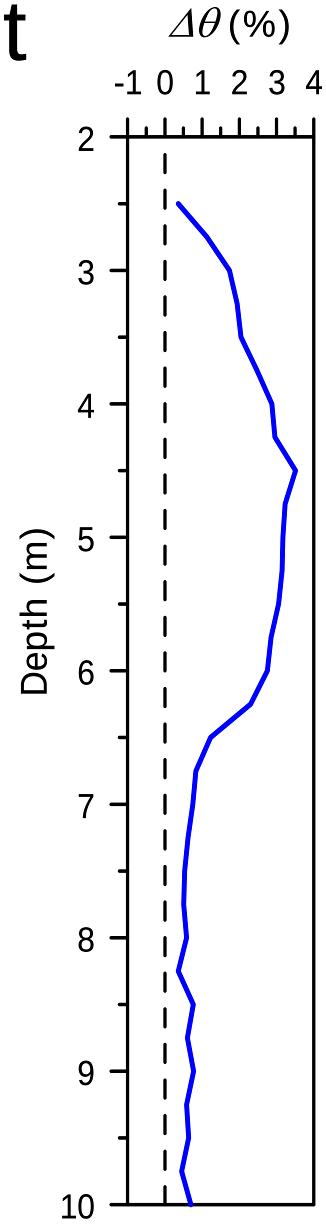



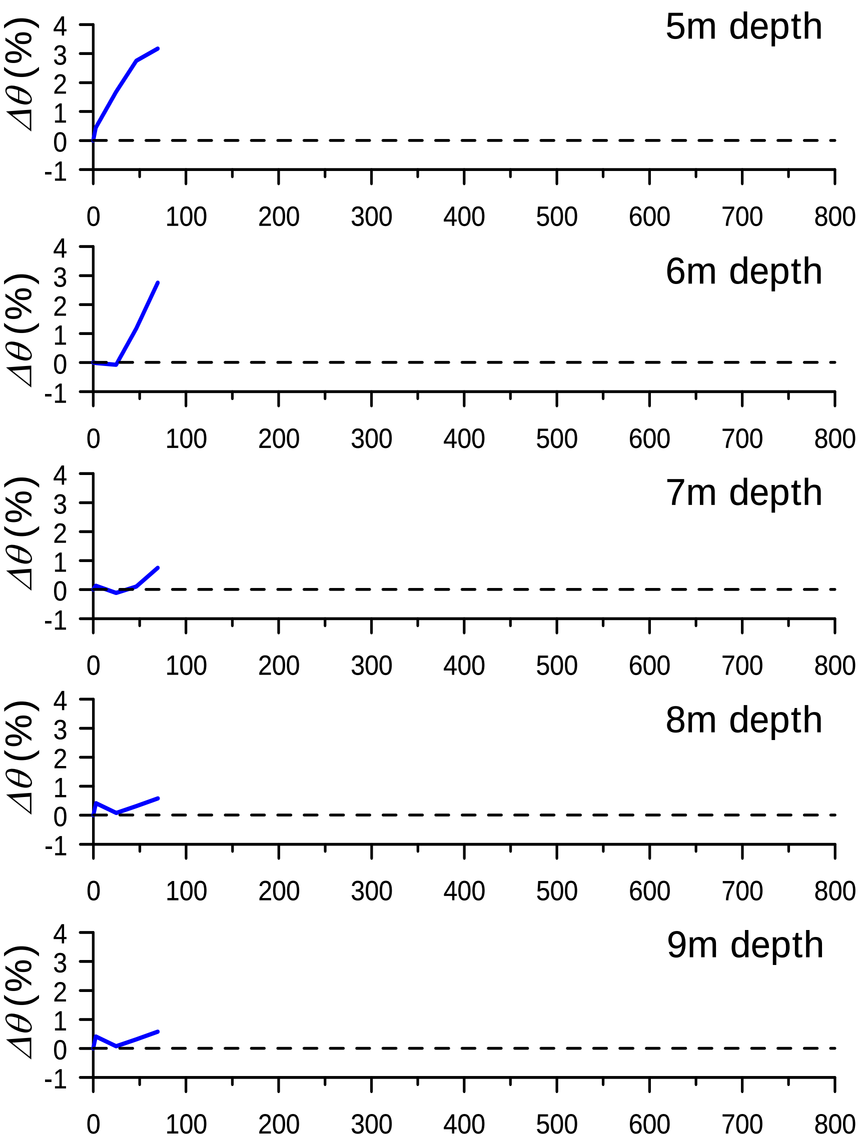
# Tracer Test

Changes in moisture content from radar surveys

17-Mar-03



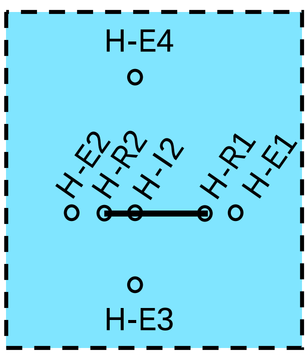



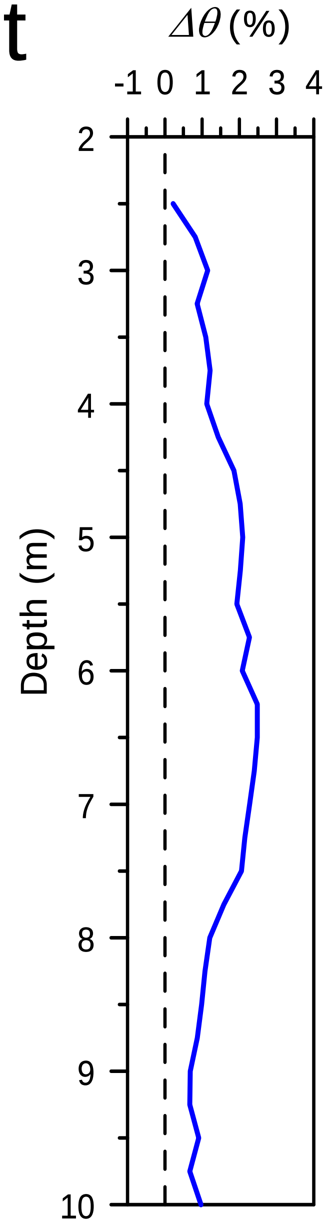
# Tracer Test

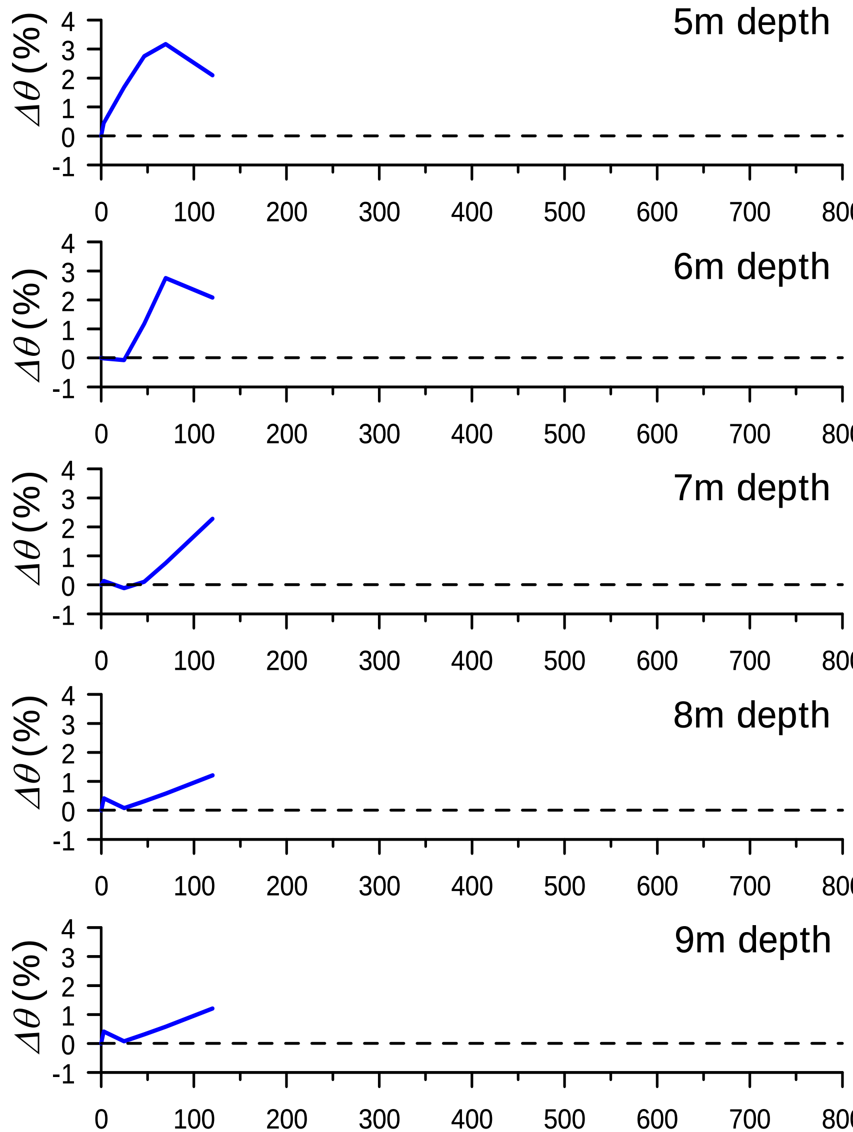
Changes in moisture content from radar surveys

19-Mar-03

Tracer array



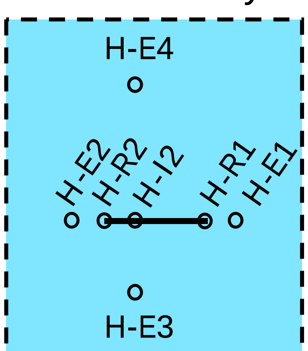



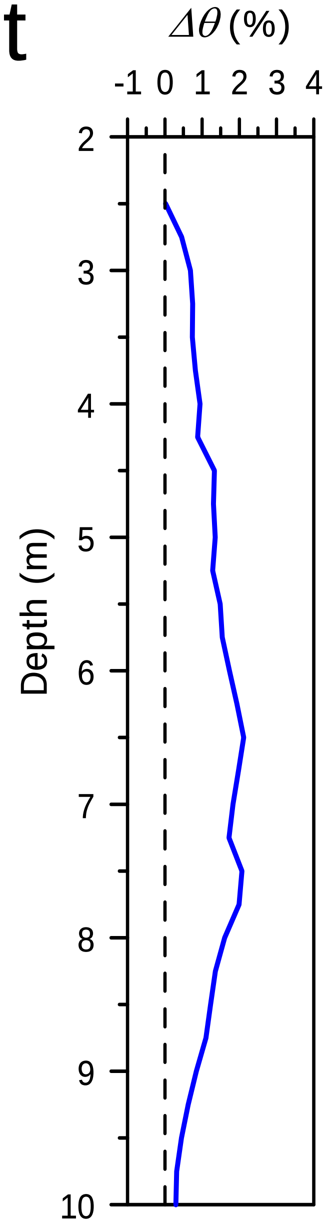
# Tracer Test

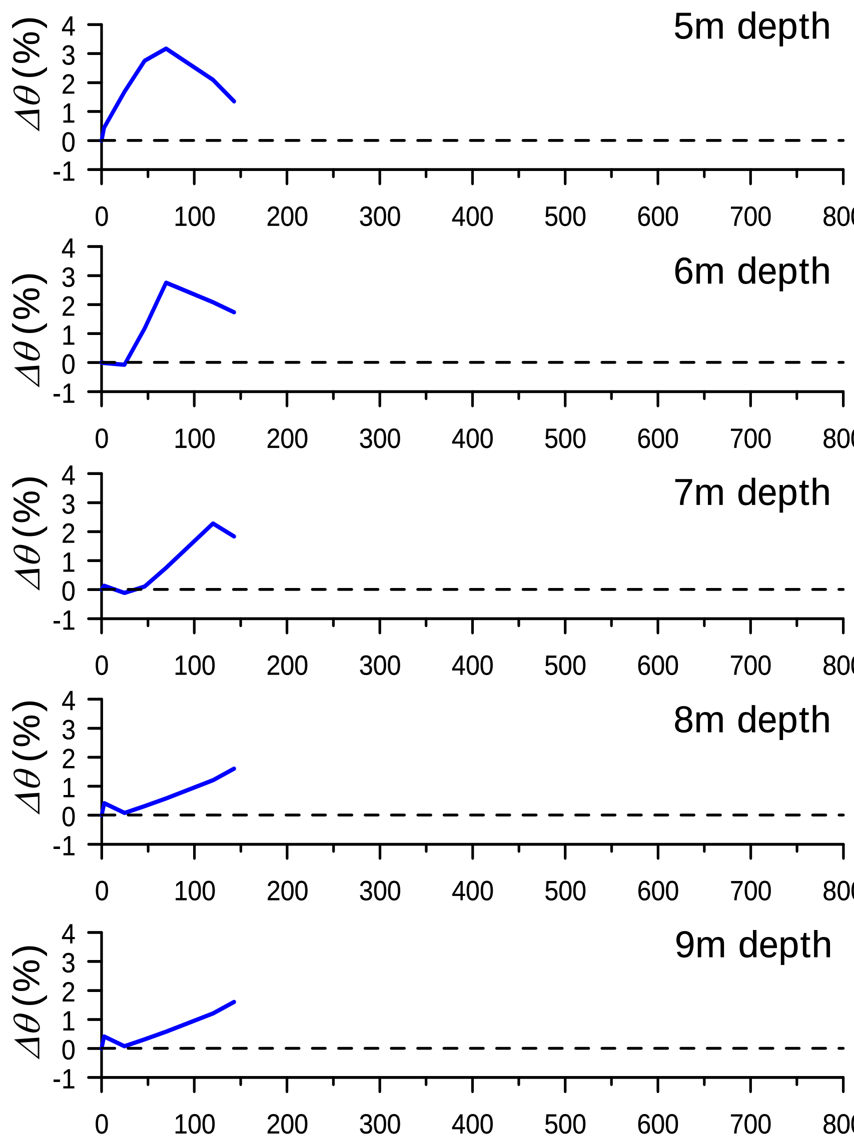
Changes in moisture content from radar surveys

20-Mar-03

Tracer array



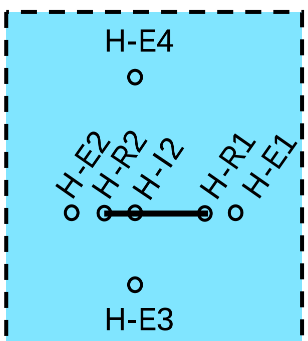



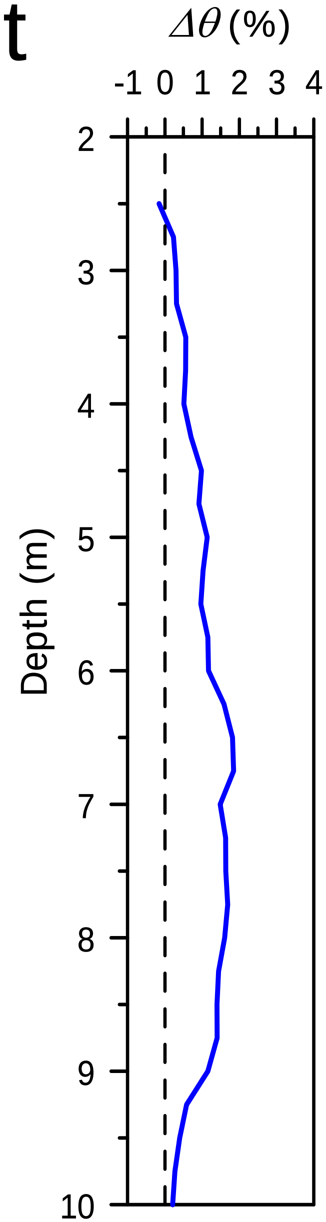
# Tracer Test

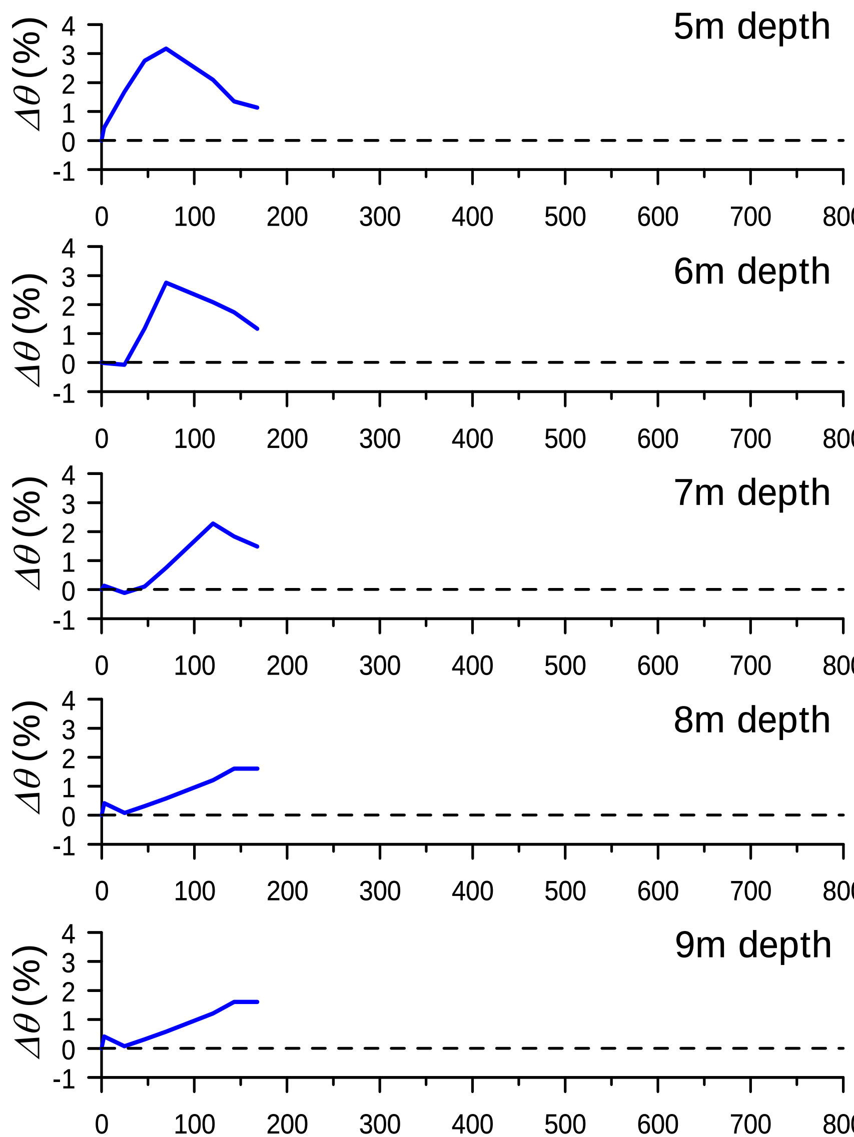
Changes in moisture content from radar surveys

21-Mar-03

Tracer array



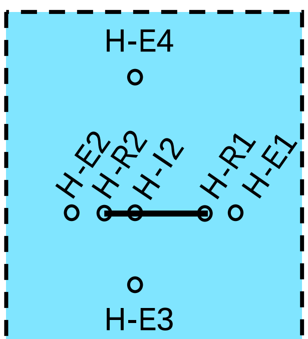



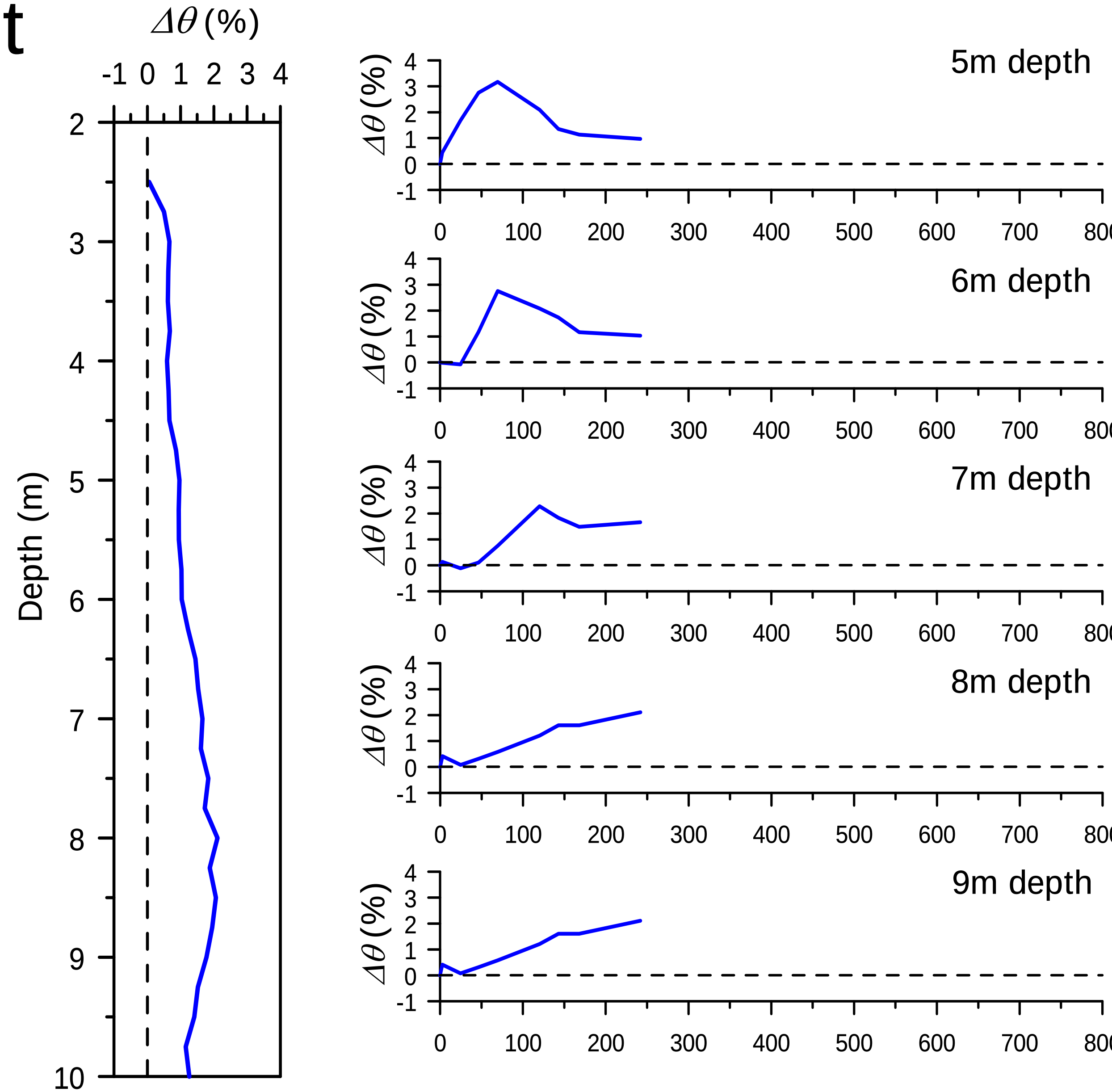
# Tracer Test

Changes in moisture content from radar surveys

24-Mar-03

Tracer array

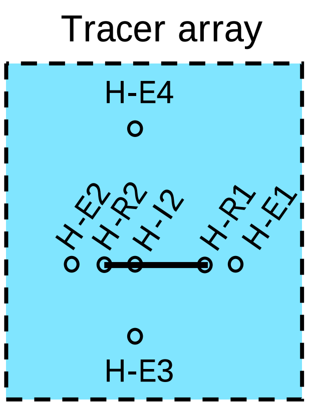


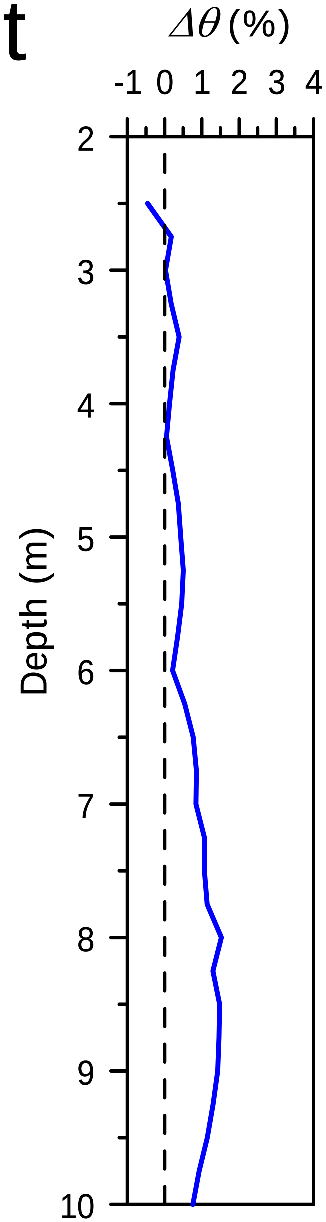



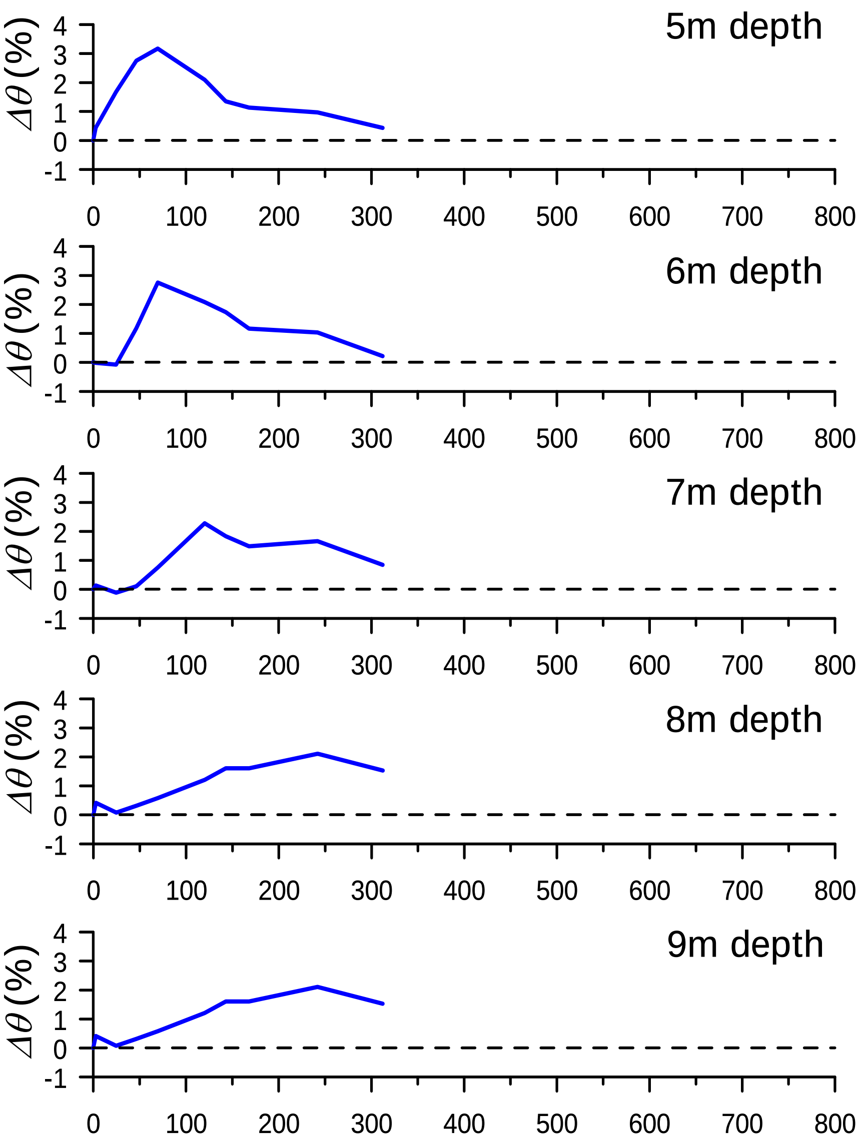
# Tracer Test

Changes in moisture content from radar surveys

27-Mar-03



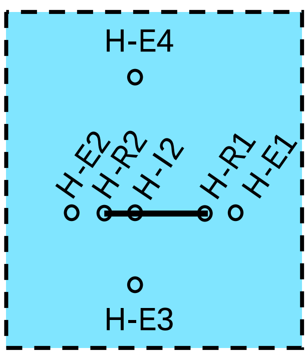



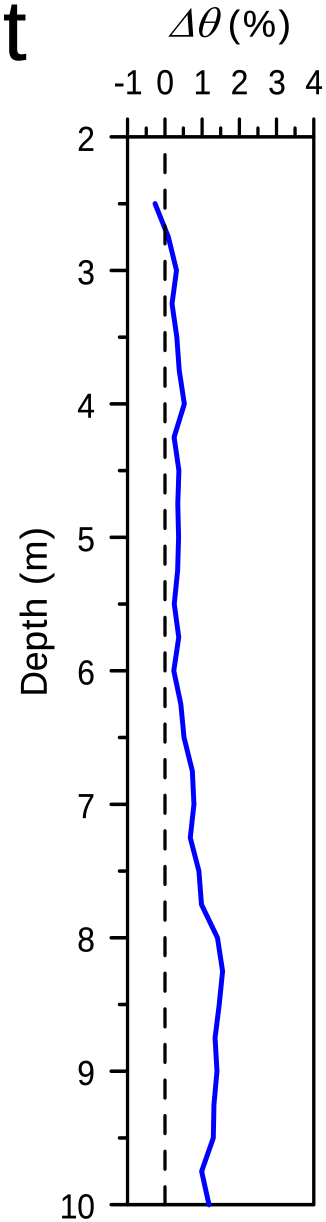
# Tracer Test

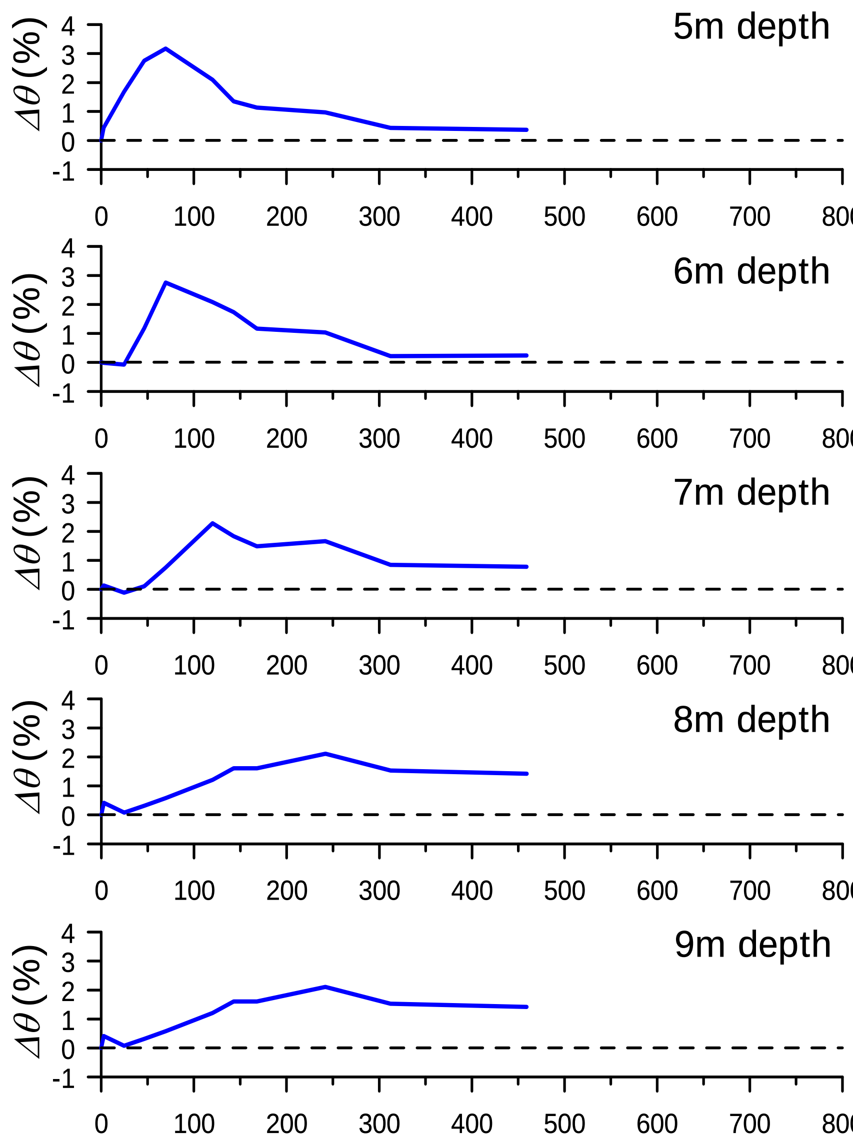
Changes in moisture content from radar surveys

02-Apr-03

Tracer array



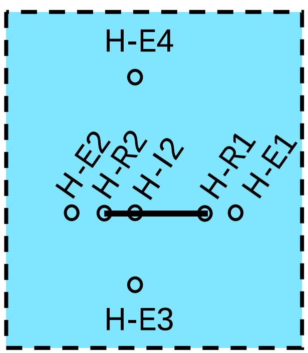



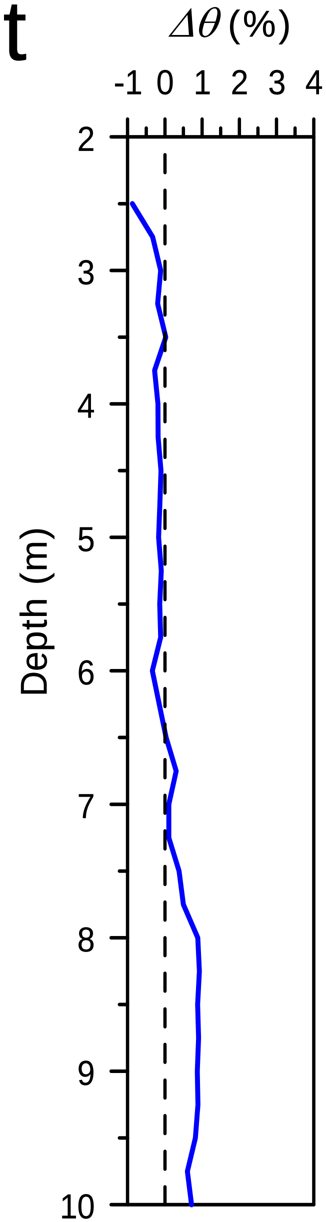
# Tracer Test

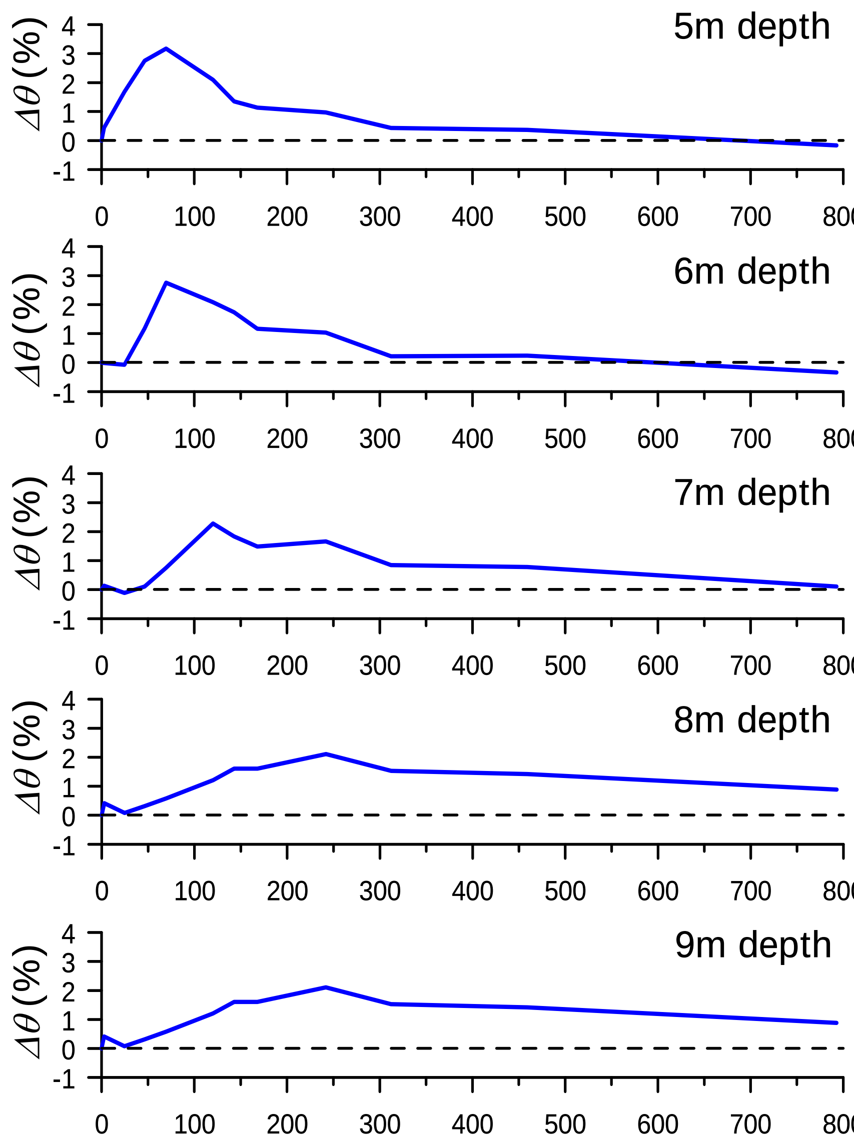
Changes in moisture content from radar surveys

16-Apr-03

Tracer array



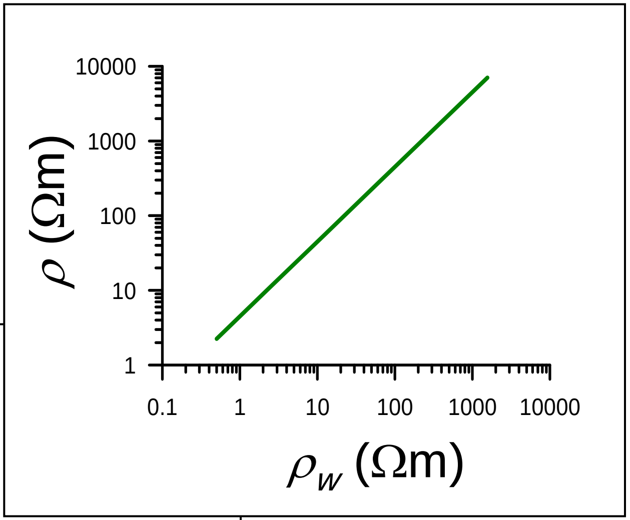



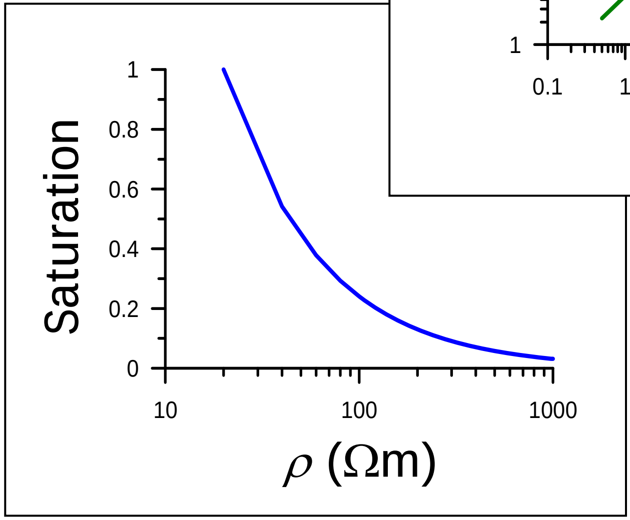
# Tracer Test

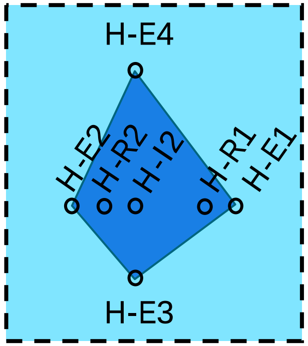
Changes in resistivity from 3-D ERT surveys

$$\rho = a\varphi^{-m}\left(\frac{\theta}{\phi}\right)^{-n}\rho_w$$




- results from change in moisture content and pore water conductivity

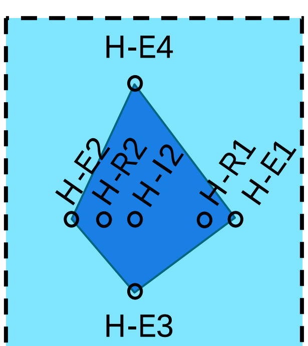


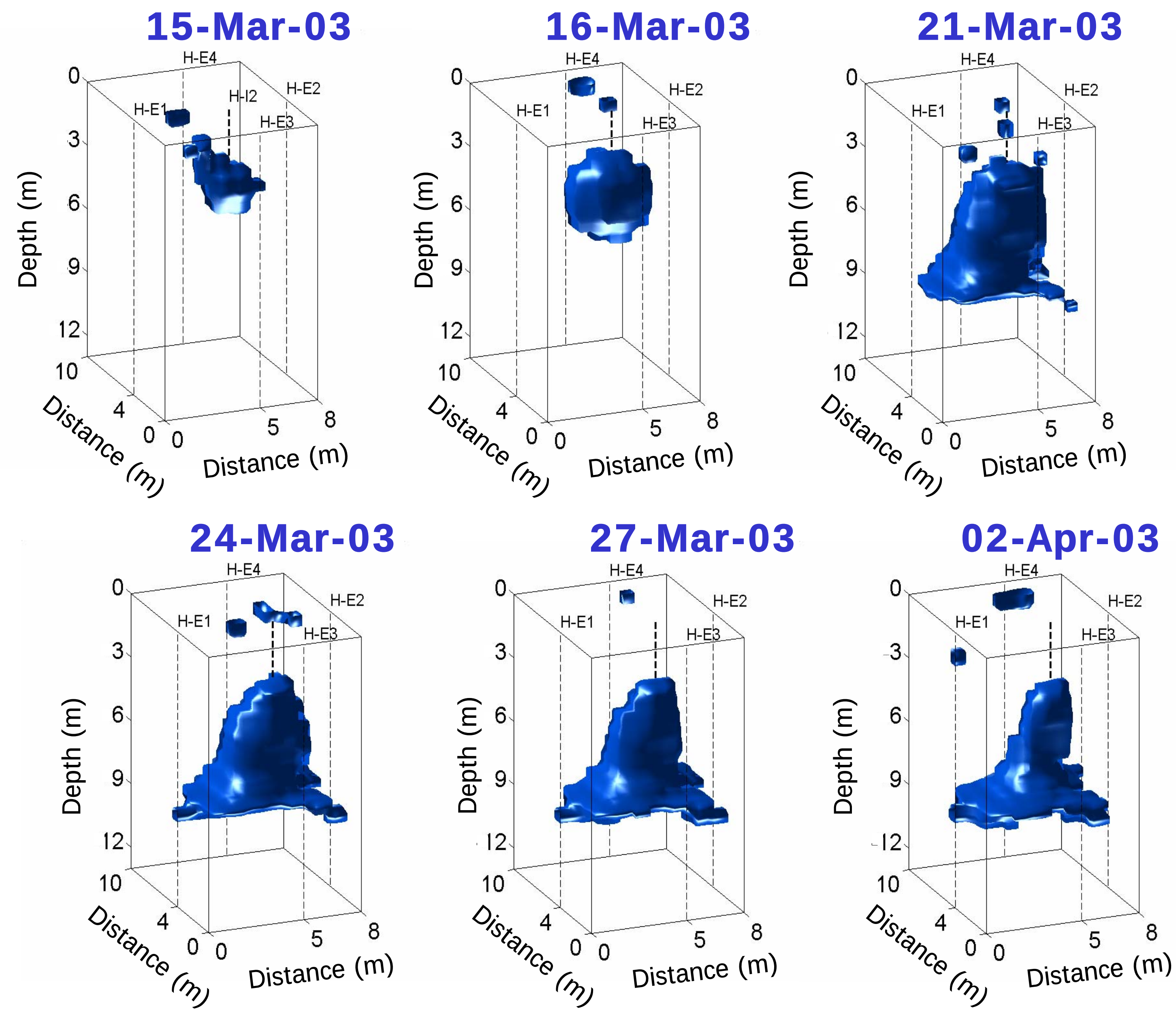




$$\boxed{\frac{\rho_t}{\rho_0} = \frac{\theta_t^{-n}}{\theta_0^{-n}}\,\frac{\rho_{w,t}}{\rho_{w,0}}}$$

# Tracer Test – 3D ERT response

Changes shown as isosurface of 7.5% change from background ERT image



# Tracer Test – changes in solute concentration

Changes in concentration from 3-D ERT and 2-D radar surveys

Resistivity:

$$\rho = a\varphi^{-m}\left(\frac{\theta}{\phi}\right)^{-n}\rho_w$$

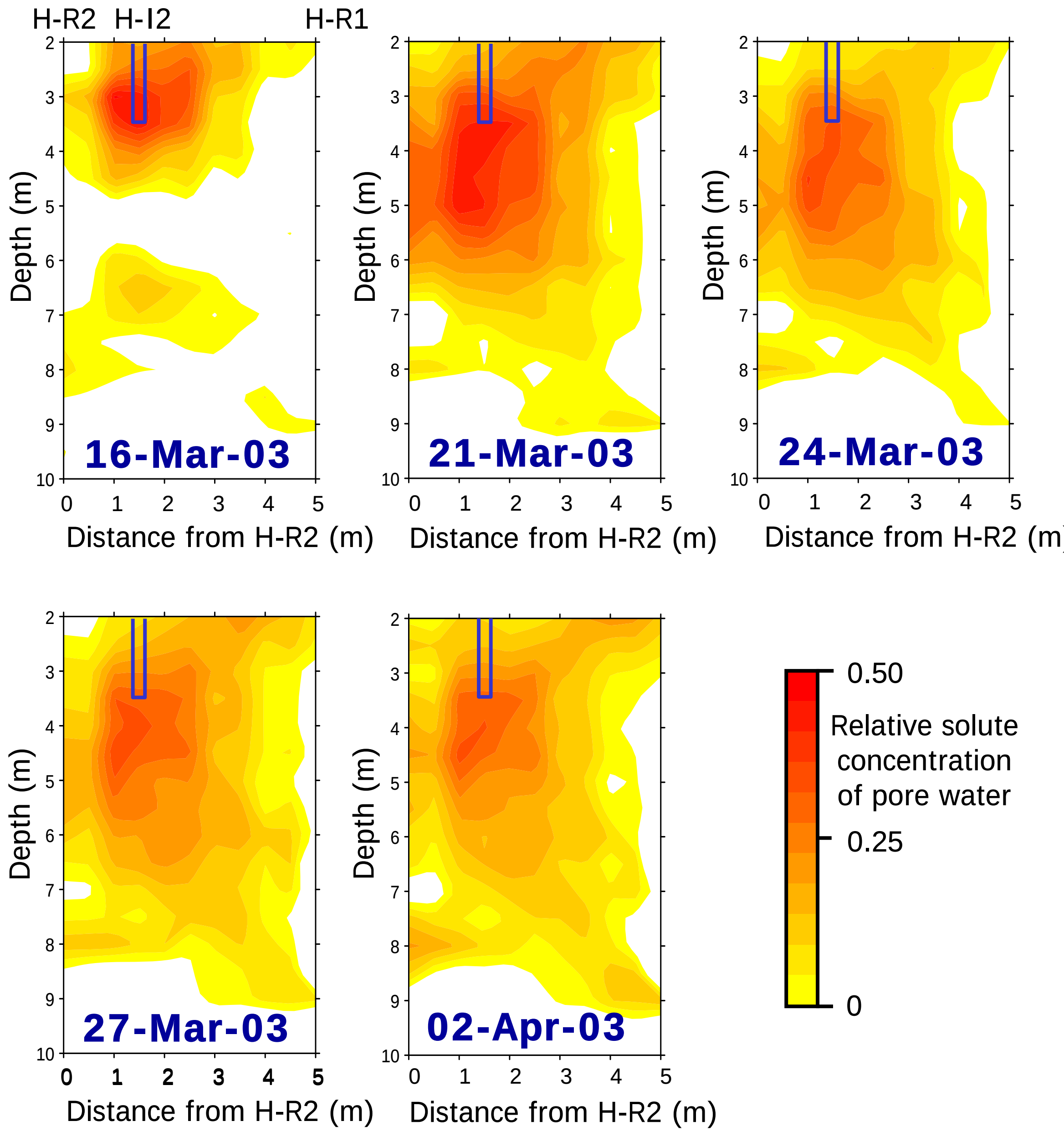
Dielectric constant:

$$\sqrt{\kappa} = (1-\phi)\sqrt{\kappa_s} + \theta\sqrt{\kappa_w} + (\phi-\theta)\sqrt{\kappa_a}$$

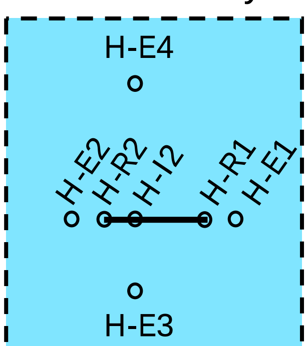
$$\boxed{\frac{C_t}{C_0} = \frac{\rho_0}{\rho_t}\left(\frac{\sqrt{\kappa_0} + \phi(\sqrt{\kappa_s} - \sqrt{\kappa_a}) - \sqrt{\kappa_s}}{\sqrt{\kappa_t} + \phi(\sqrt{\kappa_s} - \sqrt{\kappa_a}) - \sqrt{\kappa_s}}\right)^n}$$

# Tracer Test – changes in solute concentration

Changes in concentration from 3-D ERT and 2-D radar surveys




Tracer array

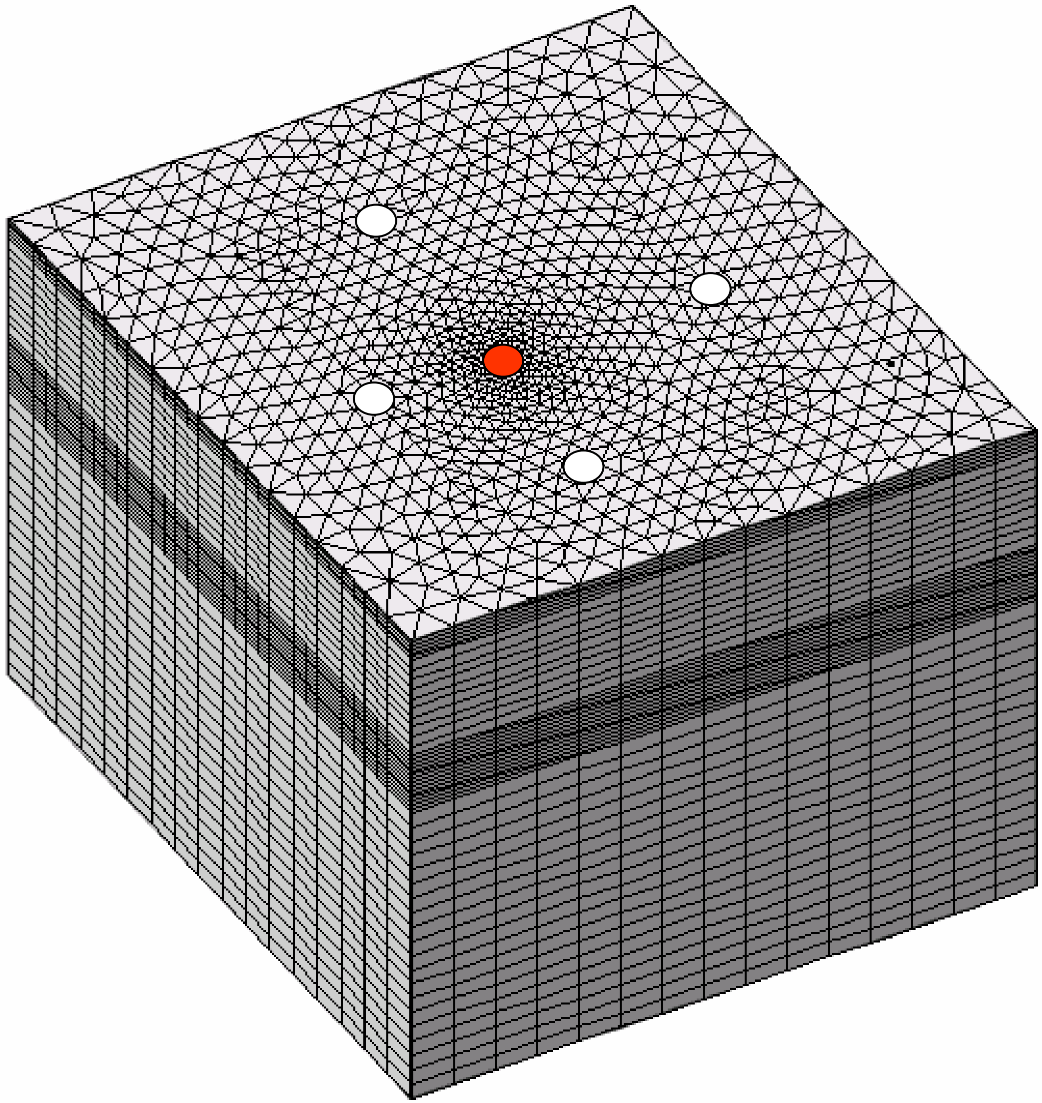


# Tracer Test – modelling tracer response

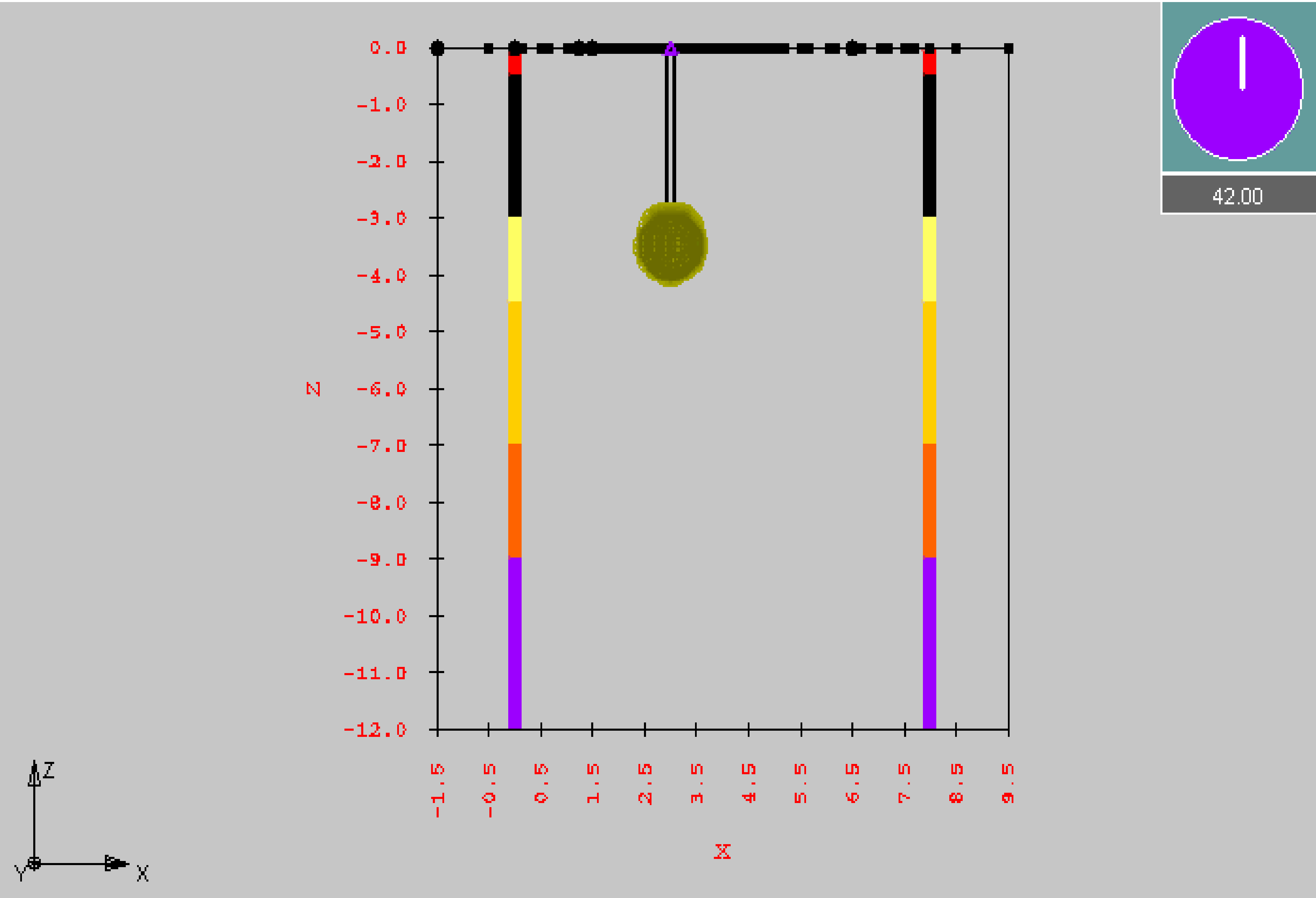
Approximately
66,000 nodes

3-D solution of the
Richards Equation

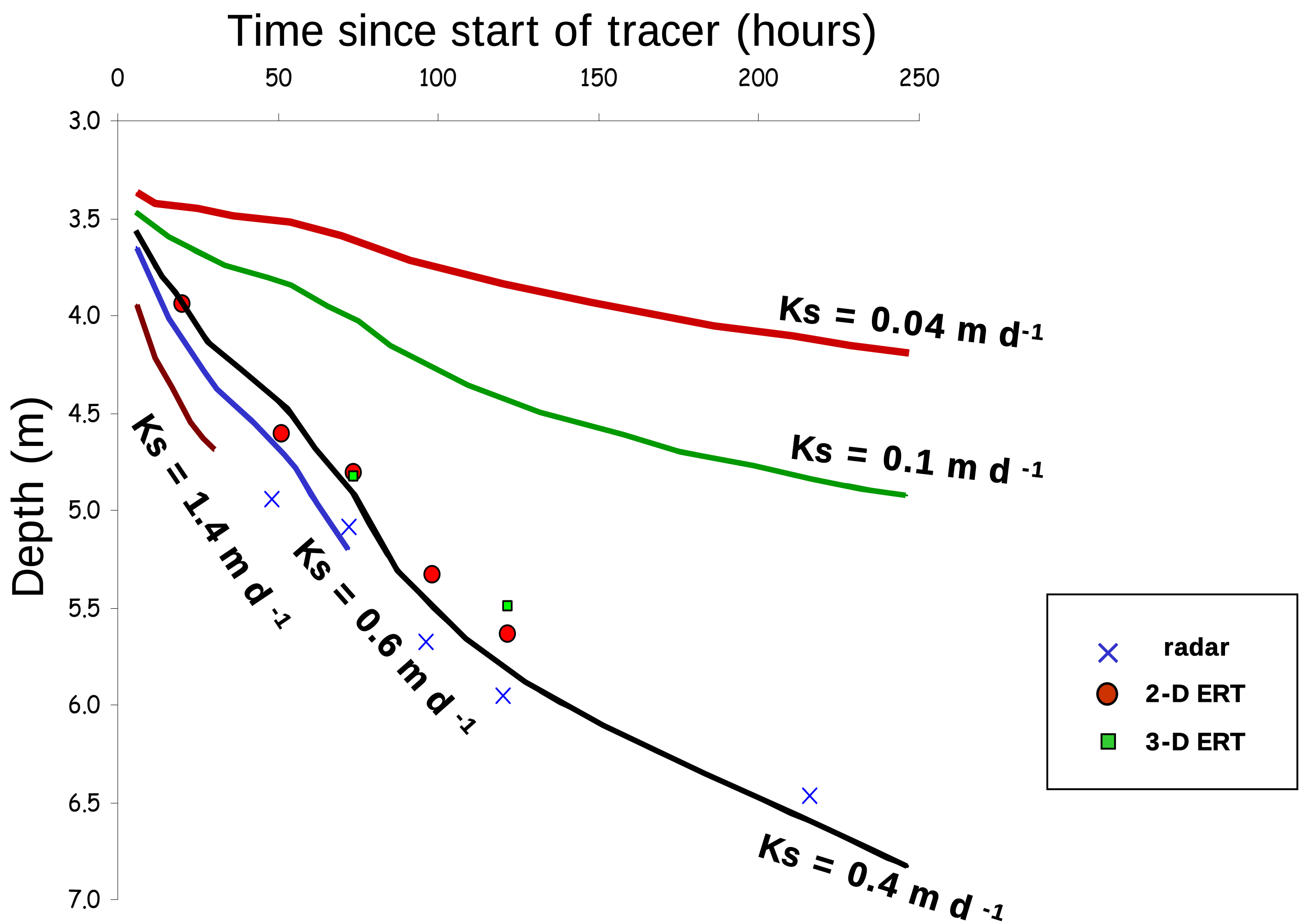
Comparison of
model
response with the
geophysical data



# Tracer Test – modelling tracer response



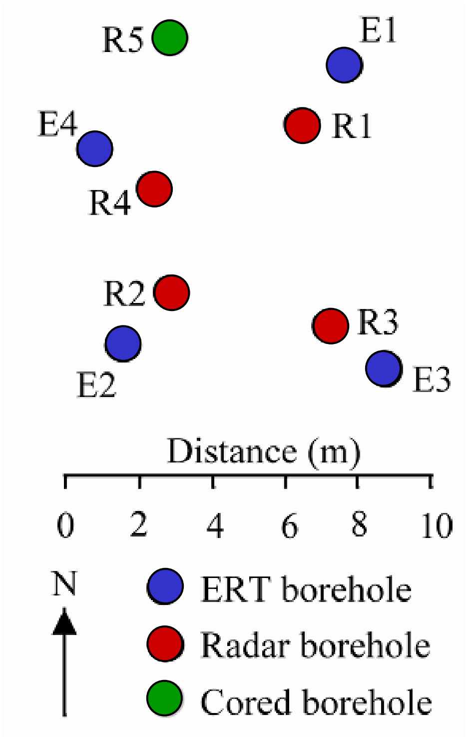
# Tracer Test – modelling tracer response

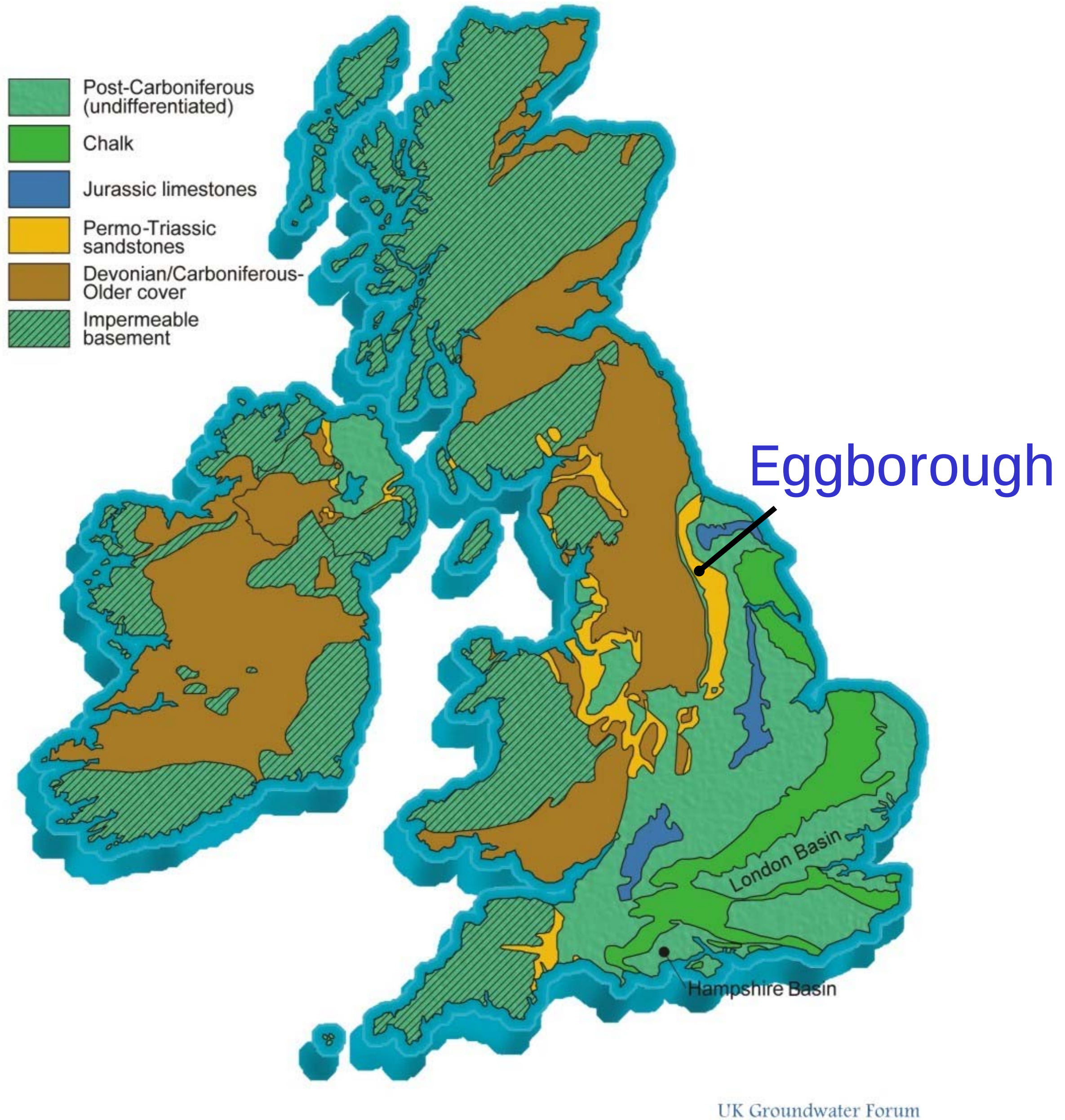



Comparison of simulated and measured tracer movement - comparing movement of the centre of mass

# Case study 2

Combined resistivity/ radar investigation of lithology



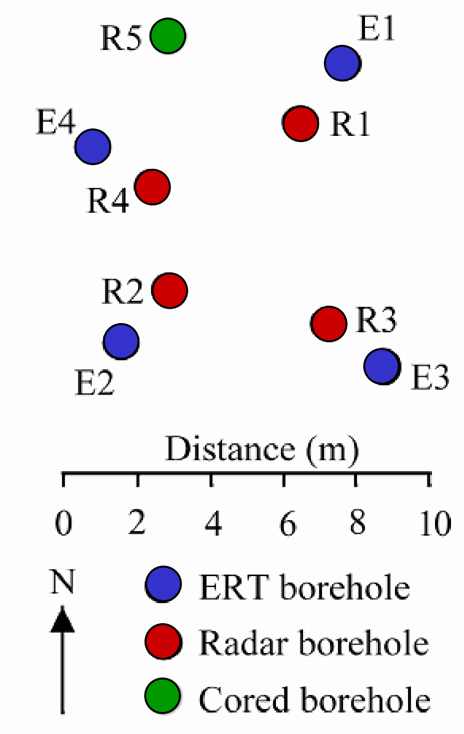
# Using other data sources

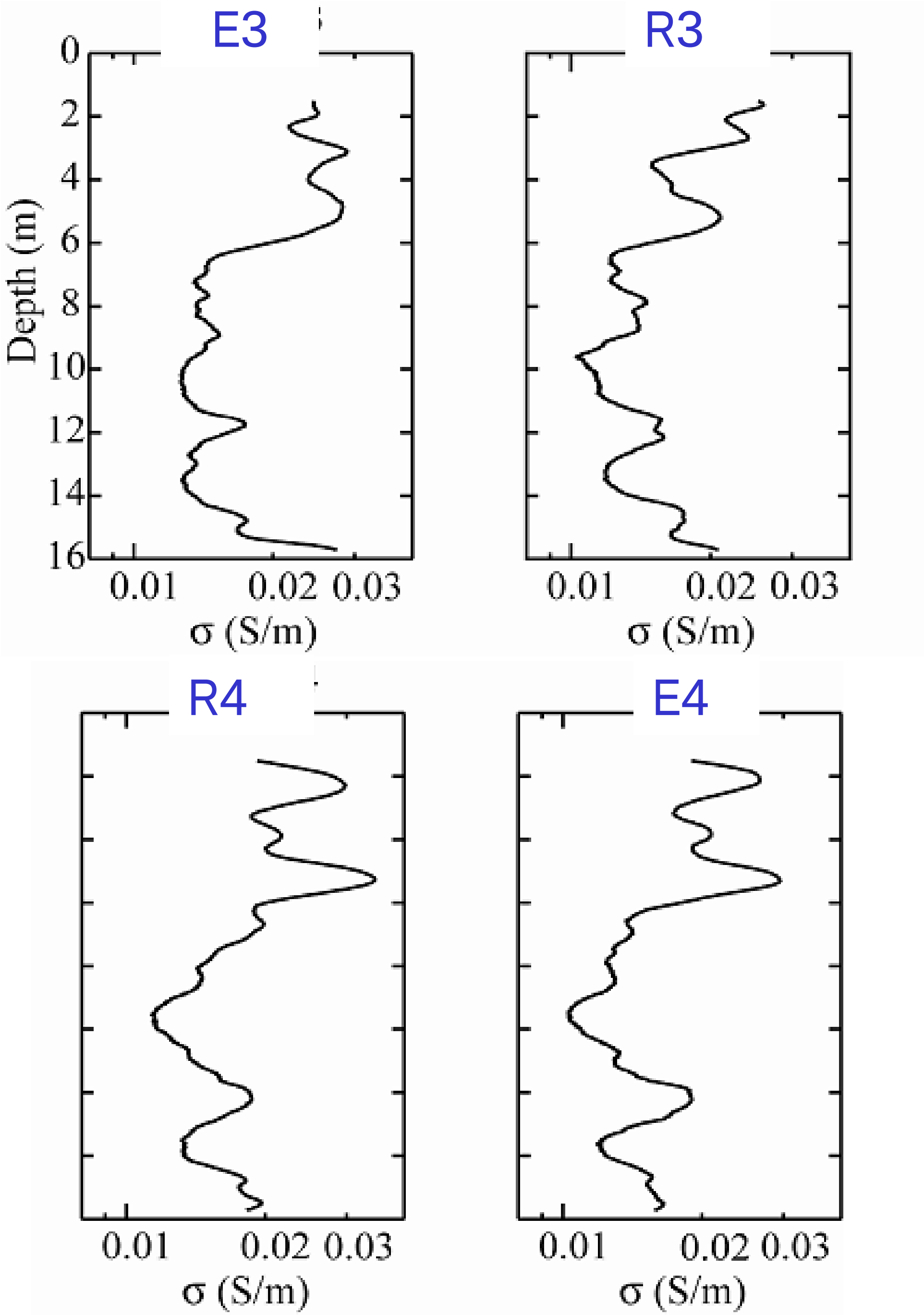
Our inversions often need a regularisation operator, e.g.

$$\Psi = \Psi_d + \Psi_m$$
$$= \left\| W_d \left( F(\mathbf{m}) - d \right) \right\|^2 + \alpha \left\| W_m (m - m_0) \right\|^2$$

Can we use existing information to help set $W_m$ ?

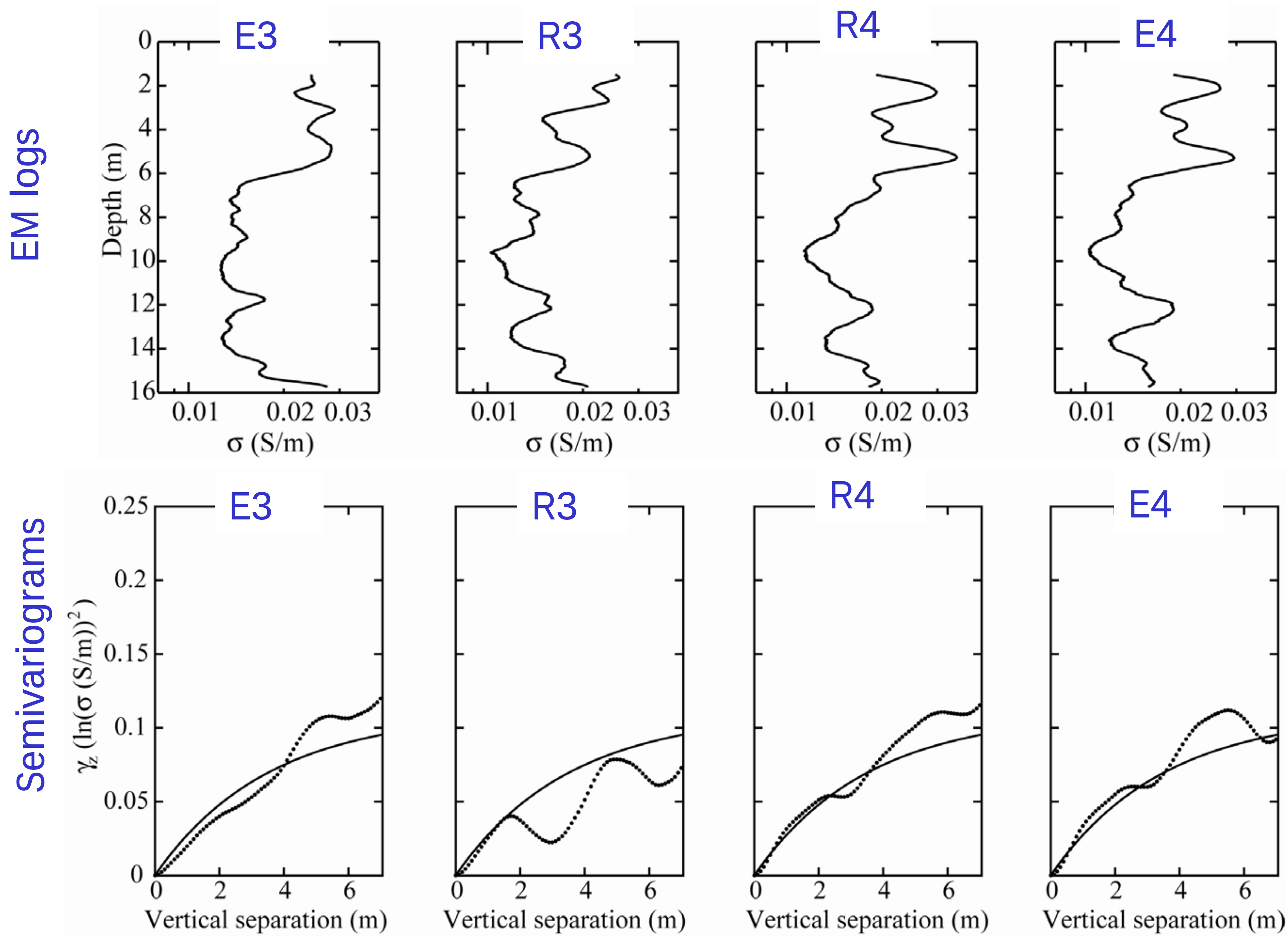
Can we use the covariance matrix based on well log data?



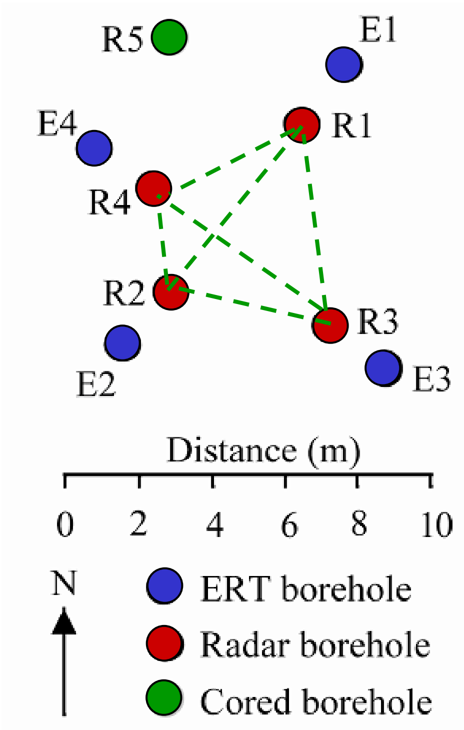



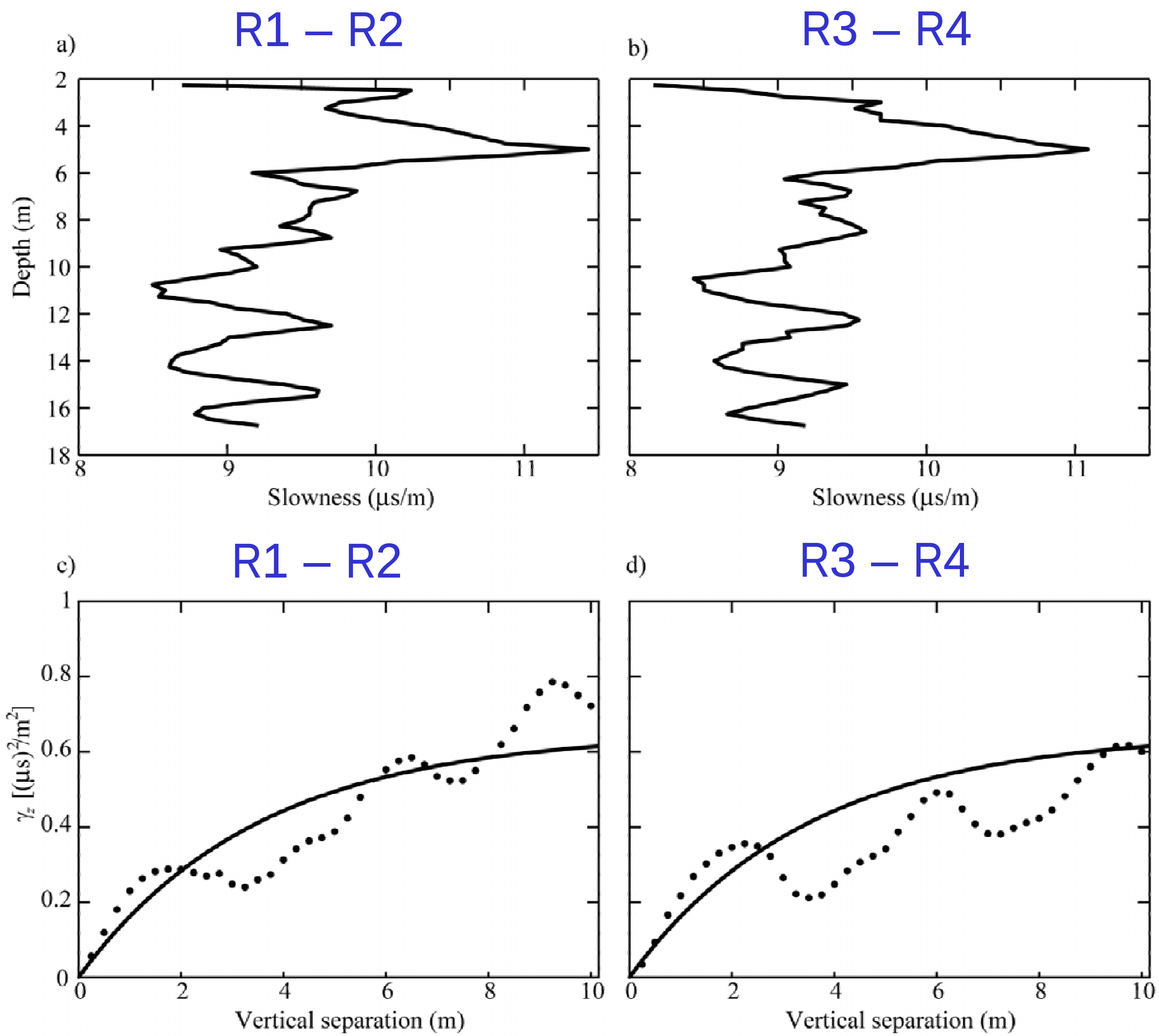

*Linde, Binley, Tryggvason, Pedersen and Revil (under review)*

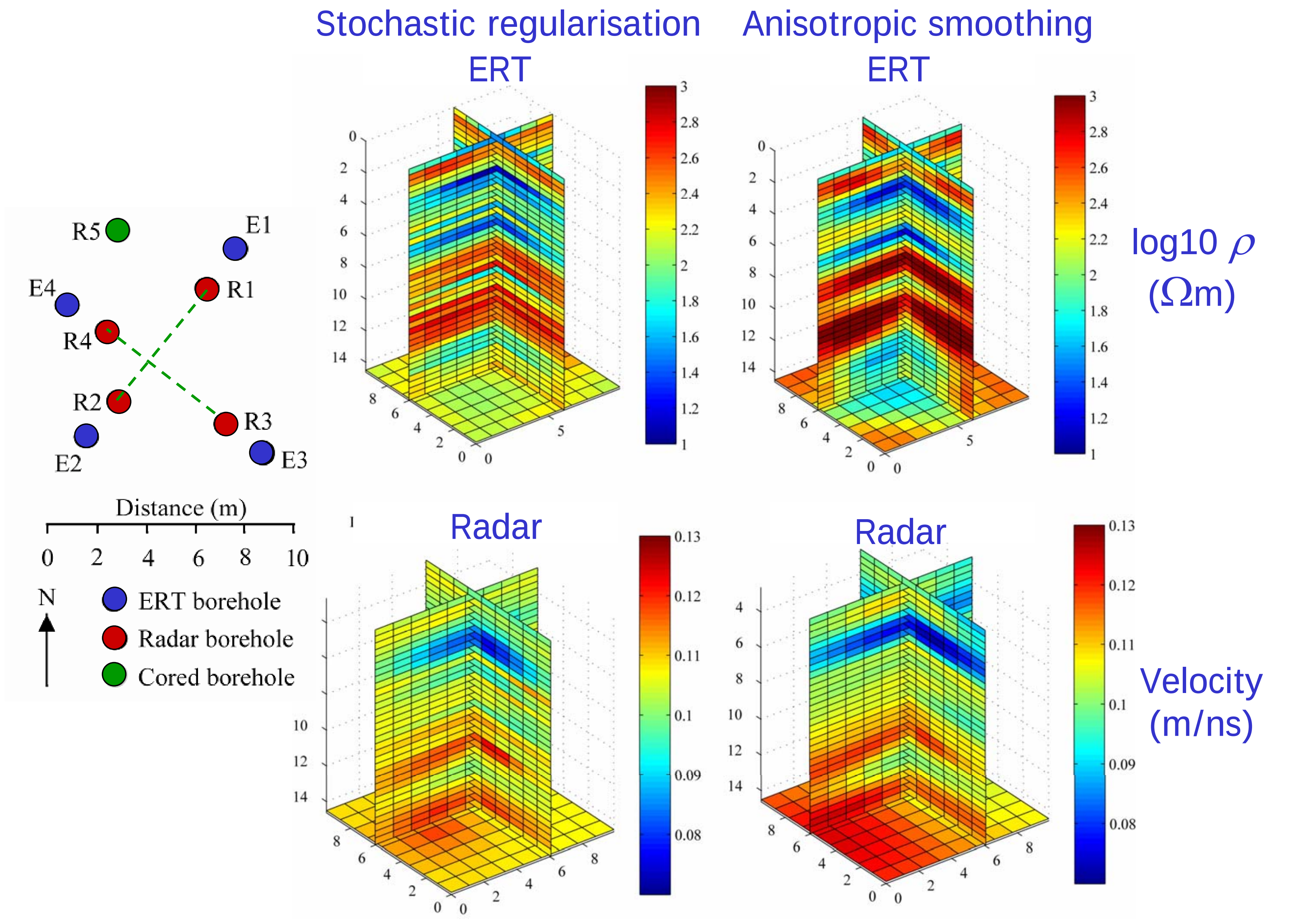
# EM logs – geostatistics for ERT constraints



# ZOP profiles – geostatistics for radar constraints





Stochastic regularisation
ERT
Anisotropic smoothing
ERT
log10 ρ
(Ωm)
Radar
Radar
Velocity
(m/ns)
R5
E1
E4
R1
R4
R2
R3
E2
E3
Distance (m)
0 2 4 6 8 10
N
ERT borehole
Radar borehole
Cored borehole

# Combining multiple data sources

We could try formulate the inverse problem in terms of our hydrological variable, e.g. moisture content $\theta$

$$
\begin{aligned}
\Psi &= \Psi_d + \Psi_m \\
&= \left\| W_d \left( F(\theta) - d \right) \right\|^2 + \alpha \left\| W_m \left( \theta - \theta_0 \right) \right\|^2
\end{aligned}
$$

Now the forward model would produce the equivalent radar velocity and/or transfer resistance for a given moisture content

This would need a reliable petrophysical model, which we may not have

# Combining multiple data sources

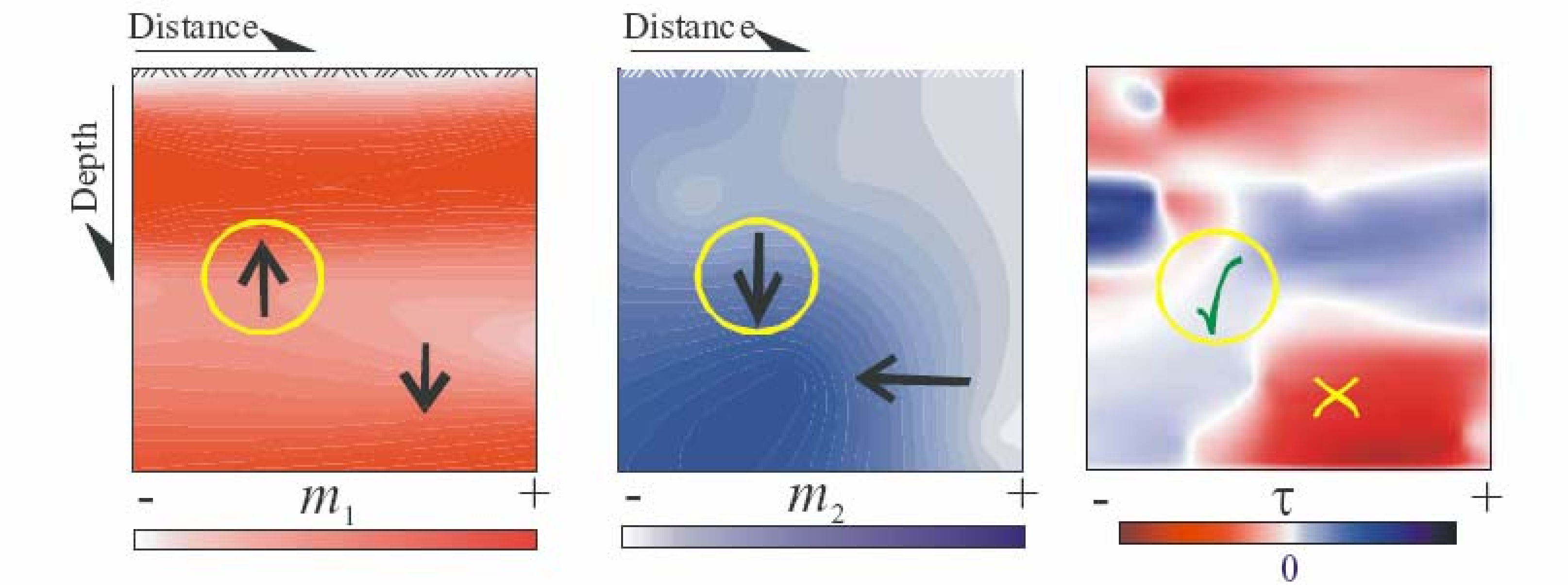
Alternatively we could try to run a joint inversion so that the different geophysical images are *structurally similar*

Gallardo & Meju (2003) proposed a cross gradient approach for combining DC resistivity and seismic data

# Combining multiple data sources

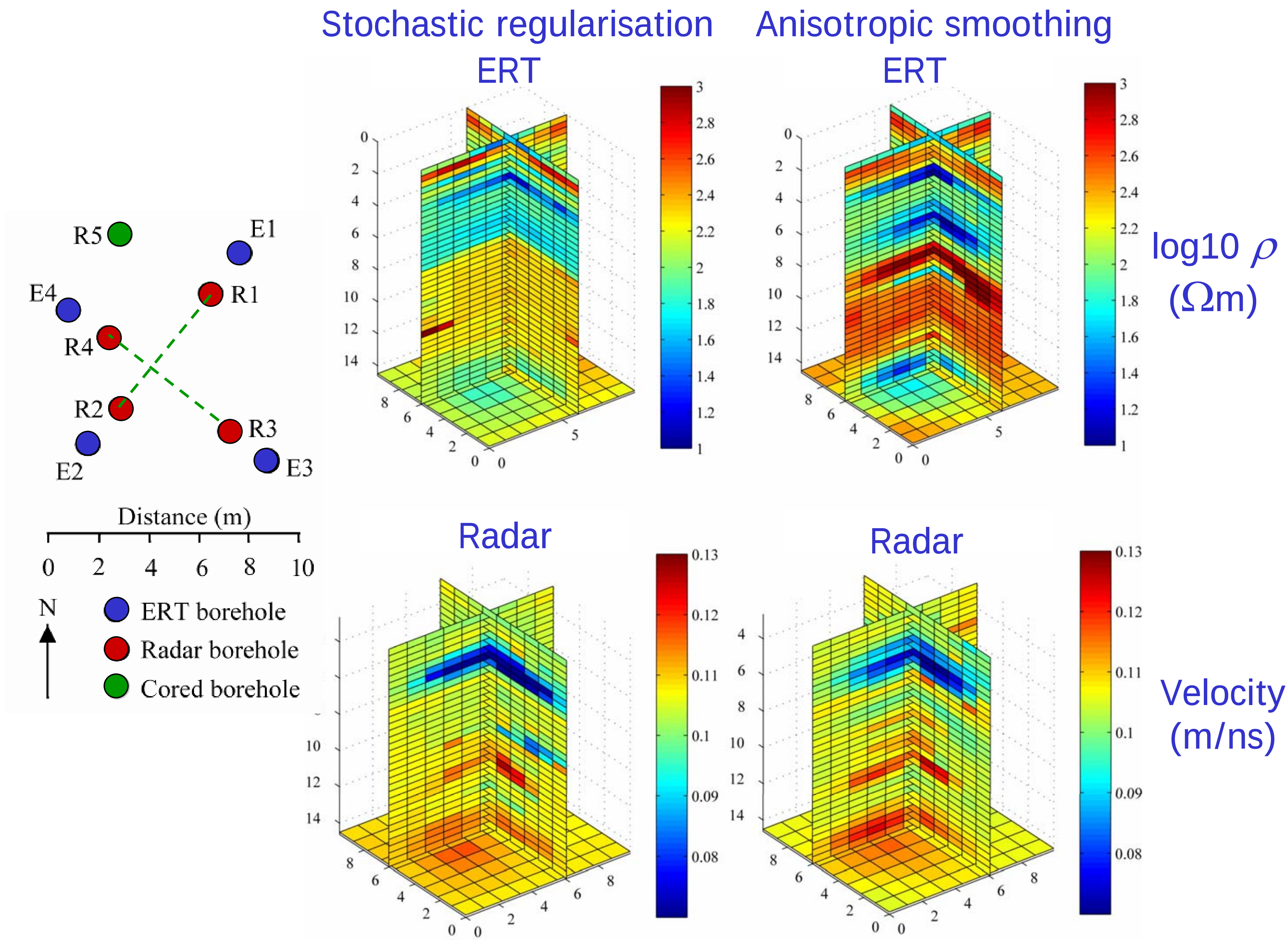
In their approach we try to minimise the operator

$$\vec{\tau}(m_1, m_2) = \nabla m_1 \times \nabla m_2$$



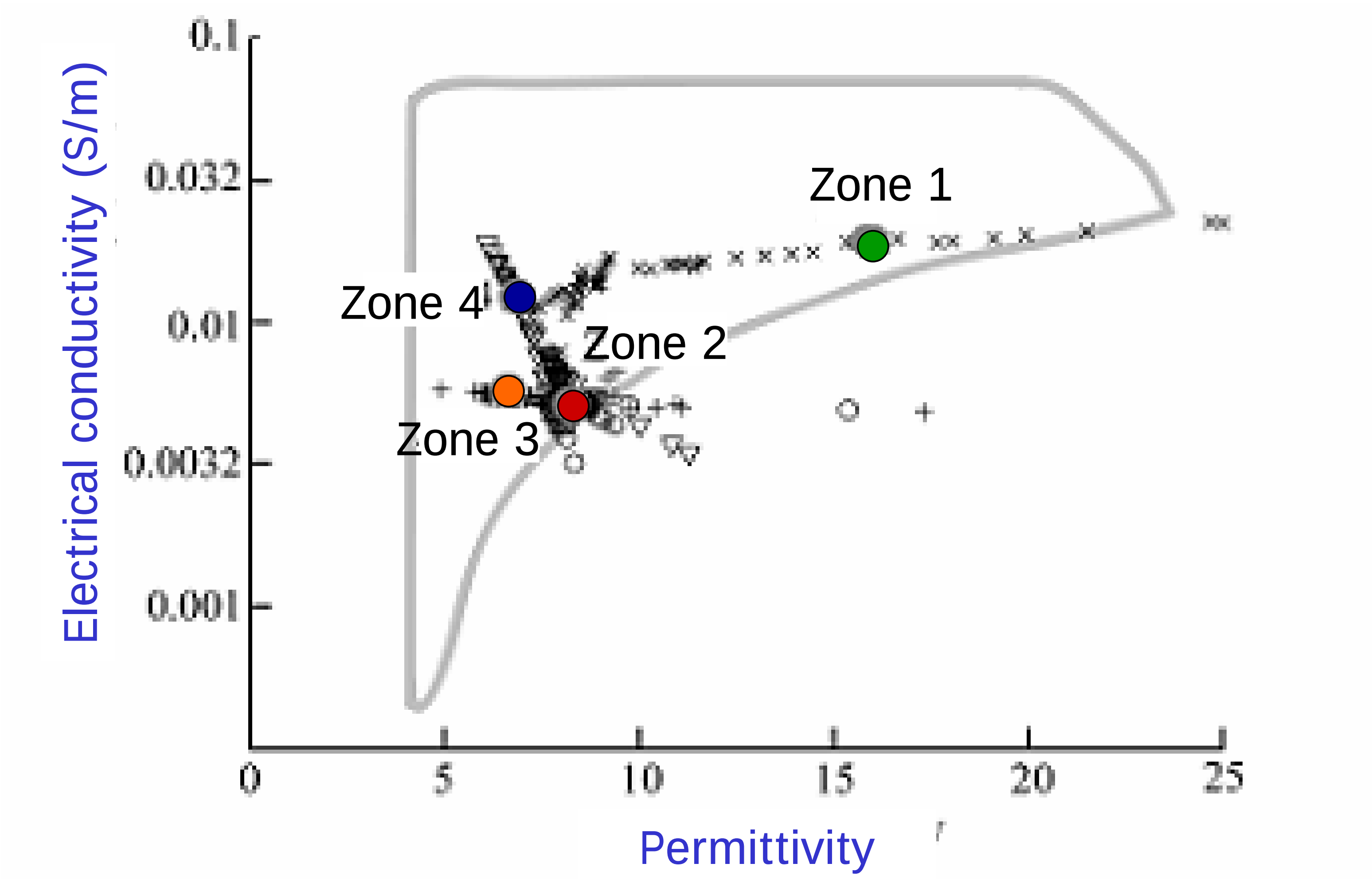

In areas where the gradients are in the same or opposite direction (or where one of the gradients is zero) $\tau$ will be zero (and the pixels structurally similar)

*Gallardo (2006)*



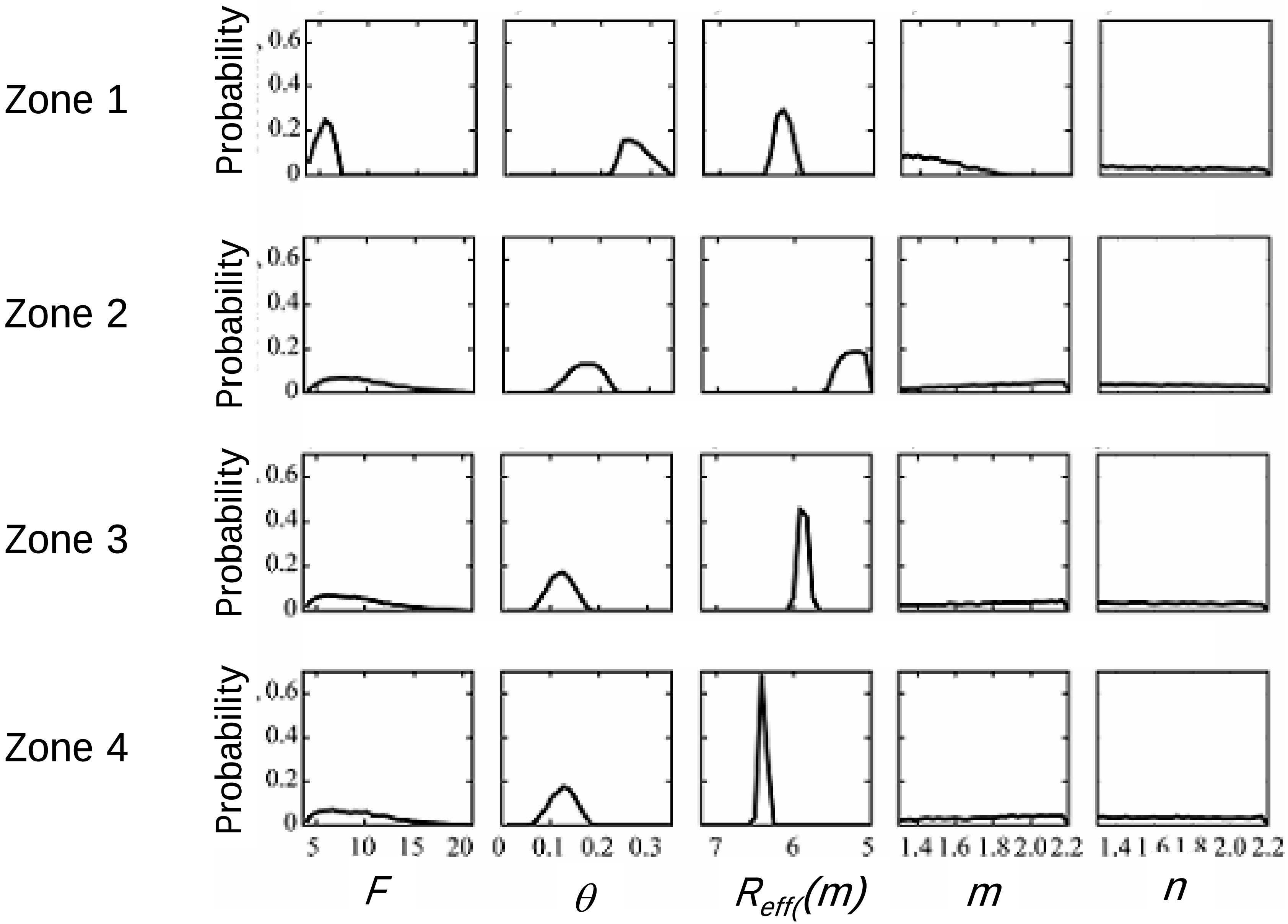
Stochastic regularisation
ERT
Anisotropic smoothing
ERT
log10 $\rho$ ($\Omega$m)
Radar
Radar
Velocity (m/ns)
R5
E1
E4
R1
R4
R2
R3
E2
E3
Distance (m)
0 2 4 6 8 10
N
ERT borehole
Radar borehole
Cored borehole

The stochastic regularisation reveals four zones with different behaviour of the ERT – radar parameters

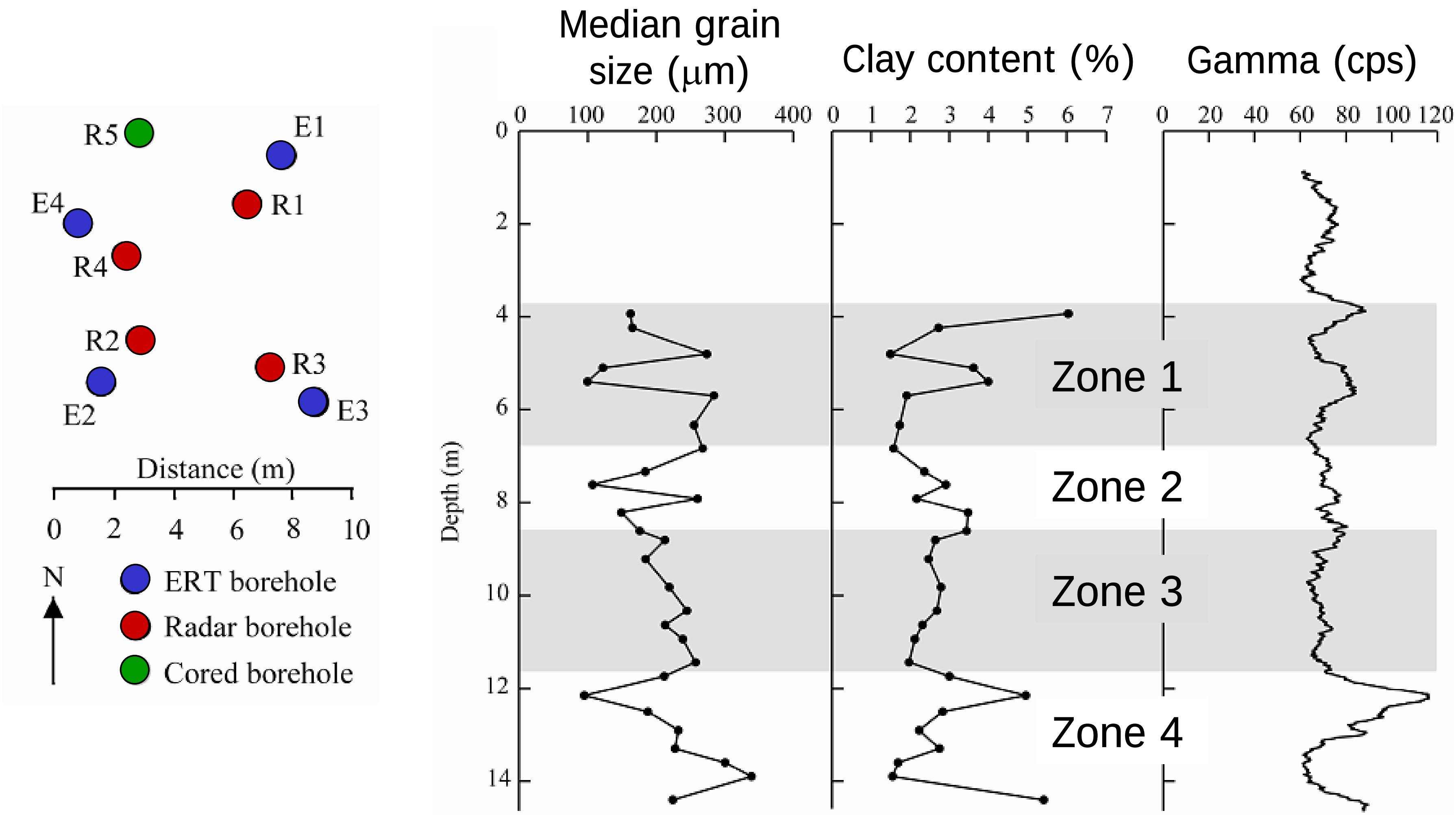



*Linde, Binley, Tryggvason, Pedersen and Revil (under review)*

Taking petrophysical models for conductivity and permittivity we can look at what ranges of parameters of these models are valid



We can then compare this zonation with the independent core log data



# Summary

We can use geophysical data with hydrological models to explore possible hydrological properties that are consistent with the geophysical response.

So far this kind of approach has only been done as independent operations but joint operations are likely to appear.

We can improve our regularisation operators with a priori information, e.g. well logs.

Methods are now available to jointly invert datasets to ensure structural of petrophysical similarity.