Characterisation of Structures and Transport Processes in Aquifers using Electrical Methods

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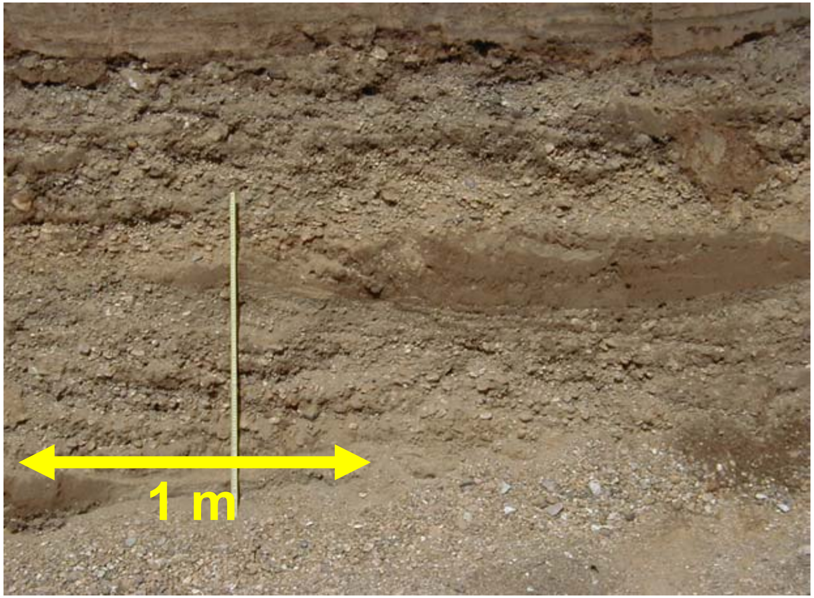
EAGE Near Surface 2005, Palermo, 4 September 2005

Outline

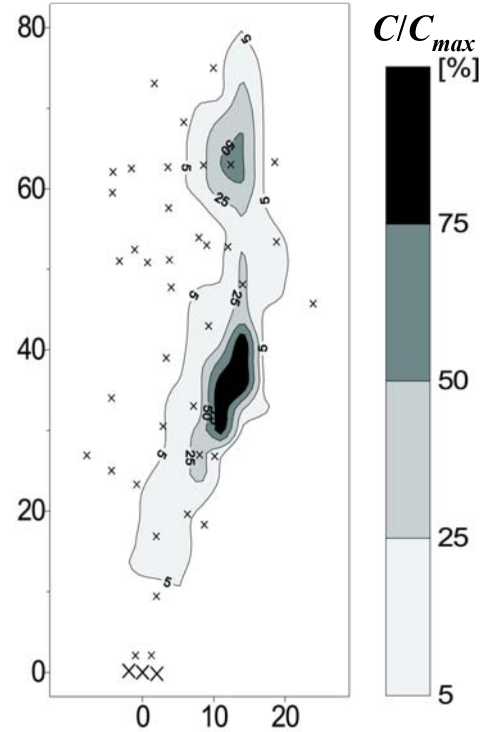
- Aquifer Structure and Processes
- Structural Characterisation
- Characterisation of Solute Transport
- Conclusions

Flow and Transport in Aquifers

- Flow and transport processes in aquifers are strongly determined by the aquifer structure



heterogeneous fluvial sediment
(variations in e.g. grain/pore size, clay content)



solute plume in a
heterogeneous aquifer
(variations in solute concentration)

Structure and Process Characterisation using Electrical Imaging

electrical imaging

petrophysical model

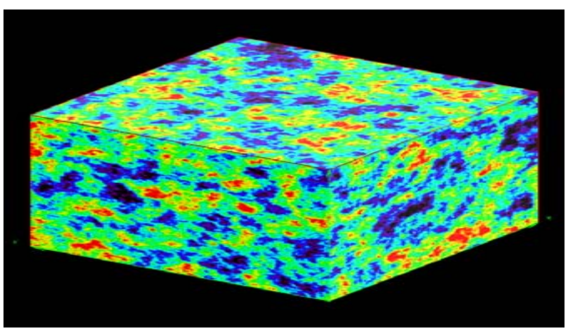
structure
(e.g. hydraulic conductivity)

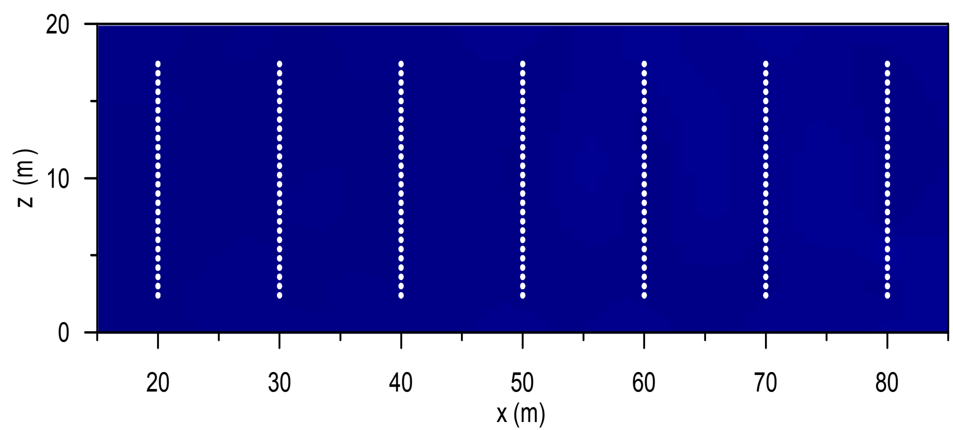
hydrological model

time-lapse electrical imaging

petrophysical model

process
(e.g. solute transport)





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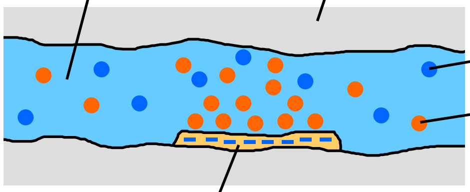
Electrical Properties of Porous Rocks

- Electrolytic conductivity σ_{el}

$$\sigma_{\mathrm{el}} = a\,\sigma_{\mathrm{w}}\,\Phi^{m} S^{n}$$

- Surface (interface) conductivity $\sigma^{*}_{\mathrm{surf}}$



→ complex, frequency-dependent electrical conductivity

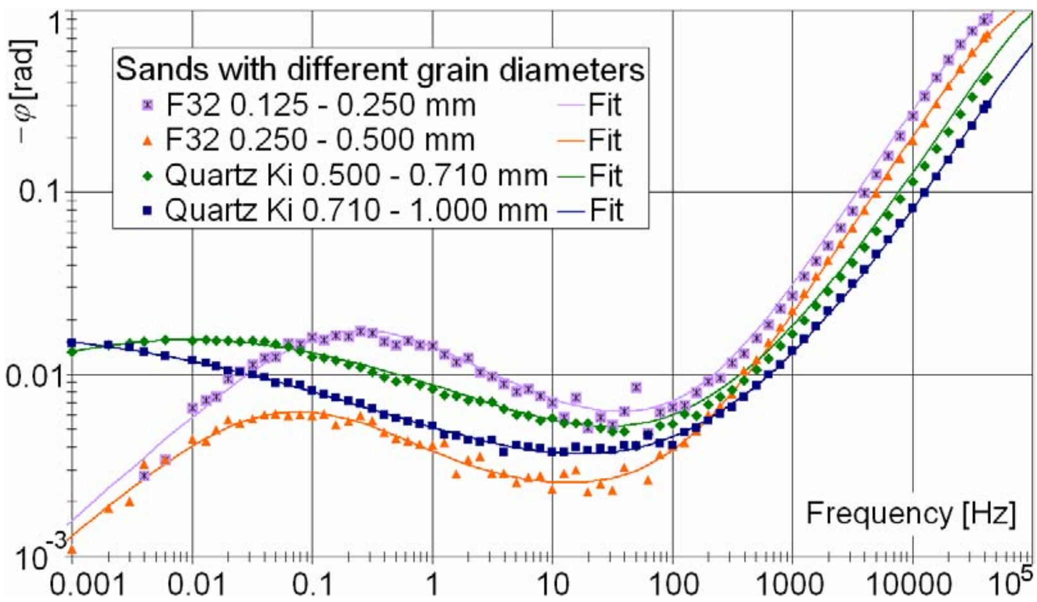
$$\sigma^{*} = |\sigma|\,\mathrm{e}^{\mathrm{i}\varphi} = \left[\sigma_{\mathrm{el}} + \sigma'_{\mathrm{surf}}(\omega)\right] + \mathrm{i}\,\sigma''_{\mathrm{surf}}(\omega)$$

contains information on:

e.g. salinity, water content, clay content, pore space topology, hydraulic conductivity

Spectral Induced Polarisation (SIP)

- Phase spectra on sands with different grain size



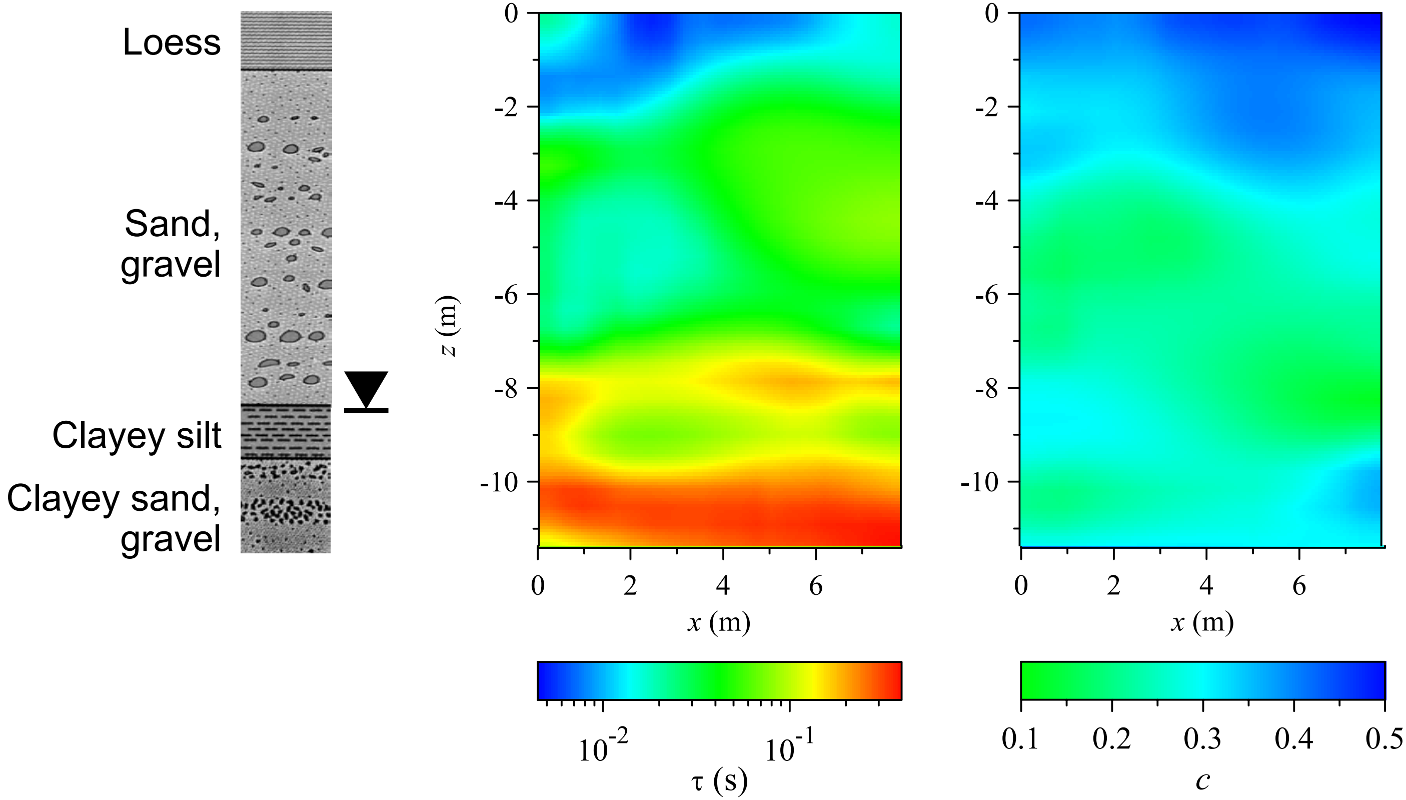
$$Z(\omega) = R_0 - R_0 m + R_0 m \int_0^\infty \frac{g(\tau')}{1+(i\omega\tau')^c} d\tau'$$

→ inverse modelling of relaxation time distribution

→ pore size distribution (relaxation diffusion length $L \sim \sqrt{\tau}$)

SIP Imaging

- Improved textural characterisation by analysing the spectral response



relaxation time
➢ dominant pore/grain size

spectral dispersion
➢ pore/grain size distribution (sorting)

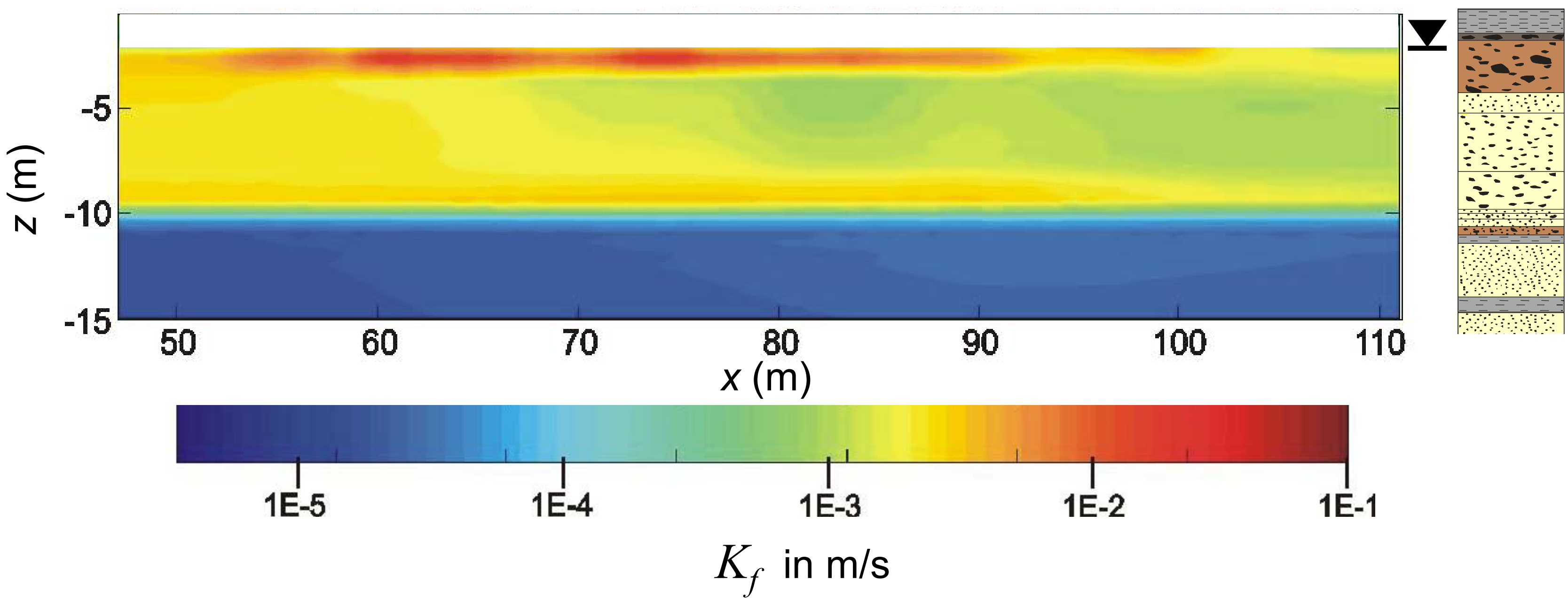
Hydraulic Permeability Estimation

- Surface imaging result

$$S_{\text{por}} = a\sigma'', \quad K \approx \frac{b}{F\,S_{\text{por}}^{c}}$$

Börner el al. (1996)

Krauthausen test site with monitoring wells



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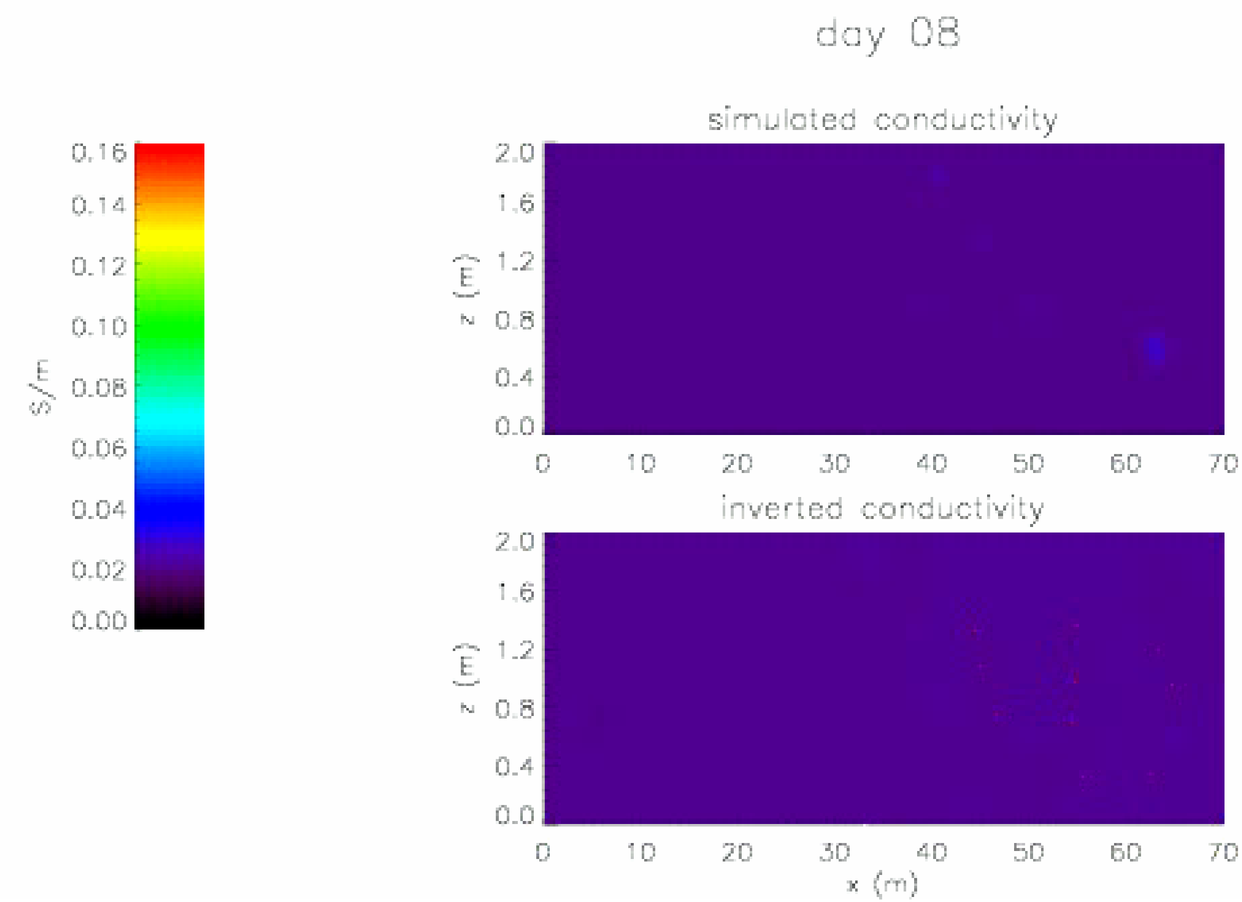
Electrical Imaging of Solute Transport

- Synthetic experiment



3D input model

2D electrical imaging

Vanderborght et al., 2005, WRR

Solute Transport in Heterogeneous Porous Media

- Flow equation
  (sink/source free region)

$$\nabla \cdot [K(\mathbf{x}) \nabla \psi(\mathbf{x})] = 0 \qquad \mathbf{q}(\mathbf{x}) = -K(\mathbf{x}) \nabla \psi(\mathbf{x})$$

- Convection dispersion equation (CDE)
  (non-reactive solute)

$$\theta(\mathbf{x}) \frac{\partial C(\mathbf{x},t)}{\partial t} = -\mathbf{q}(\mathbf{x}) \nabla C(\mathbf{x},t) + \nabla \cdot [\theta(\mathbf{x}) \mathbf{D}(\mathbf{x}) \nabla C(\mathbf{x},t)]$$

heterogeneous flow field and local dispersion

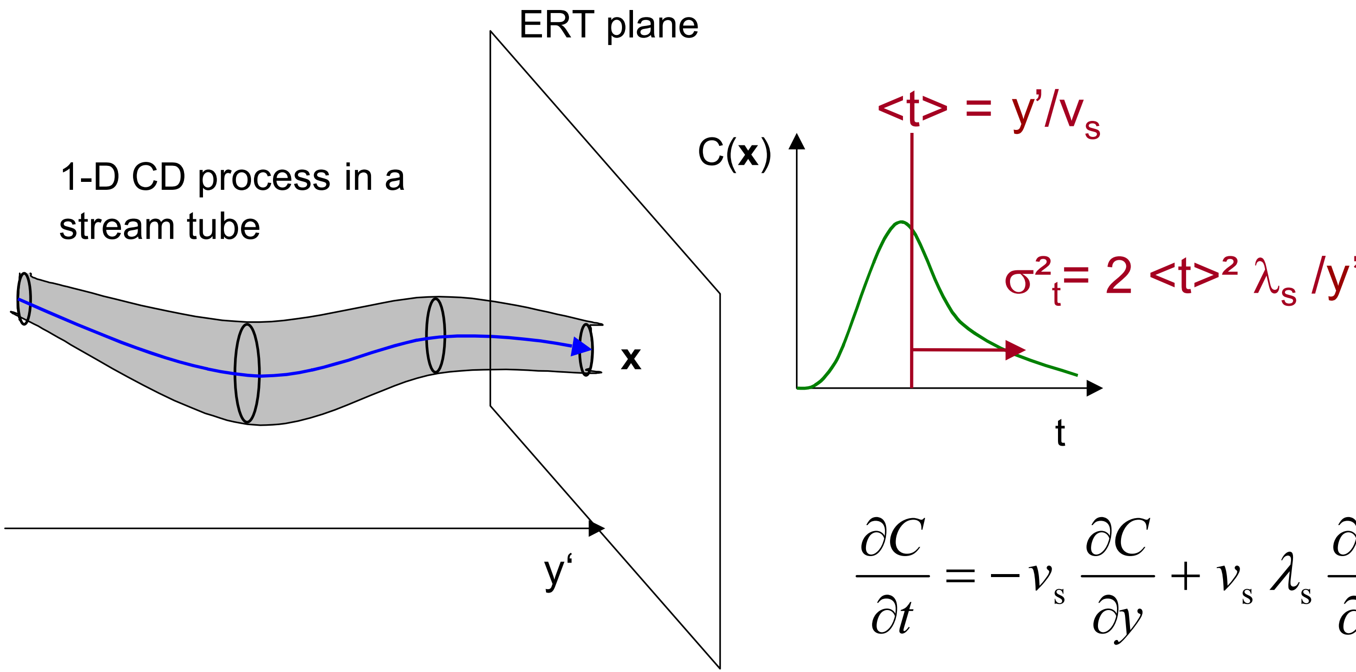
homogeneous flow field and local dispersion

heterogeneous flow field without local dispersion

Englert, 2004

Quantification of Transport Properties

- Conversion of electrical conductivity changes in concentrations
- Fitting an equivalent 1D (“stream tube”) convection dispersion model to the local breakthrough curves (BTCs)



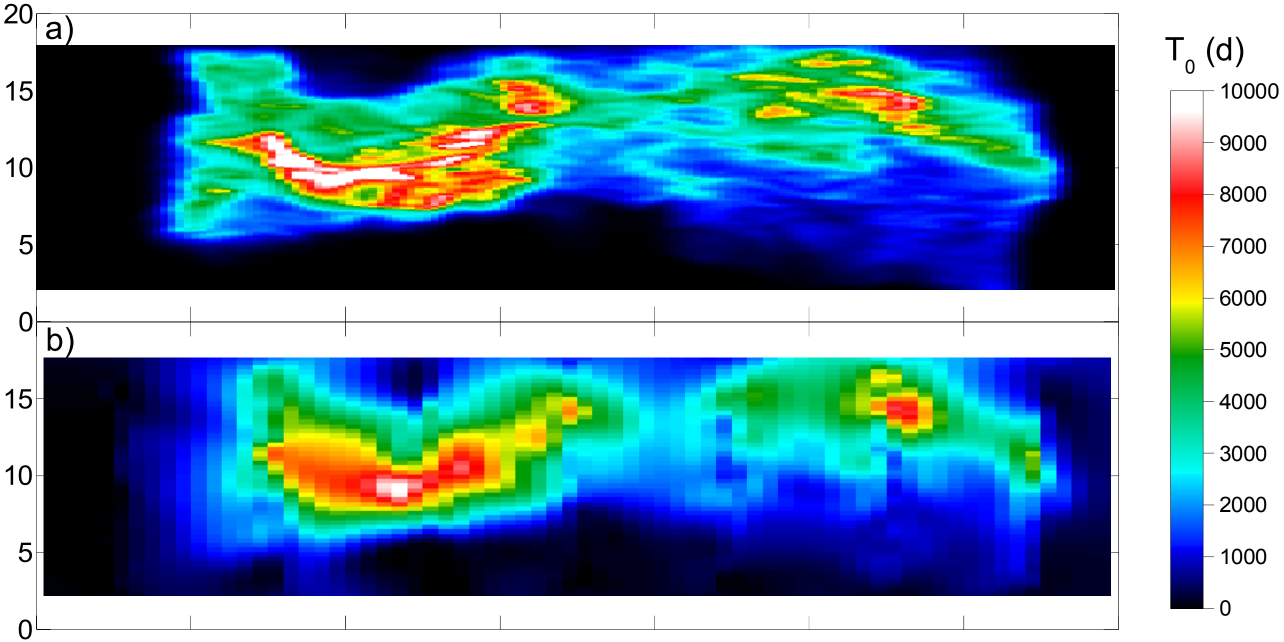
$$\frac{\partial C}{\partial t} = -v_s \frac{\partial C}{\partial y} + v_s \lambda_s \frac{\partial^2 C}{\partial y^2}$$

→ Spatial variability of flow velocity and (longitudinal) dispersivity

Synthetic Experiment

- Spatial variability of 0th moment of local BTCs

3D input model



2D imaging

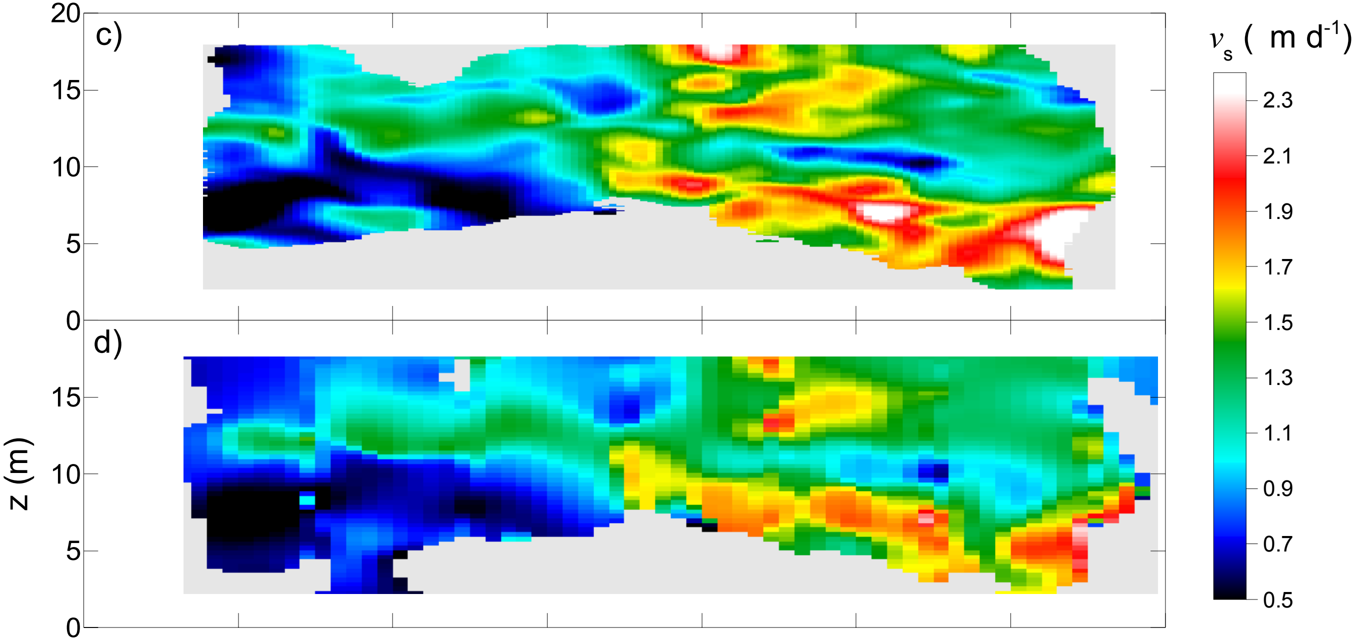
Synthetic Experiment

- Spatial variability of equivalent velocity

3D input model

$<v_s> = 1.15$ m/d

$\sigma^2_{v_s} = 0.13$ (m/d)²



2D imaging

$<v_s> = 1.13$ m/d

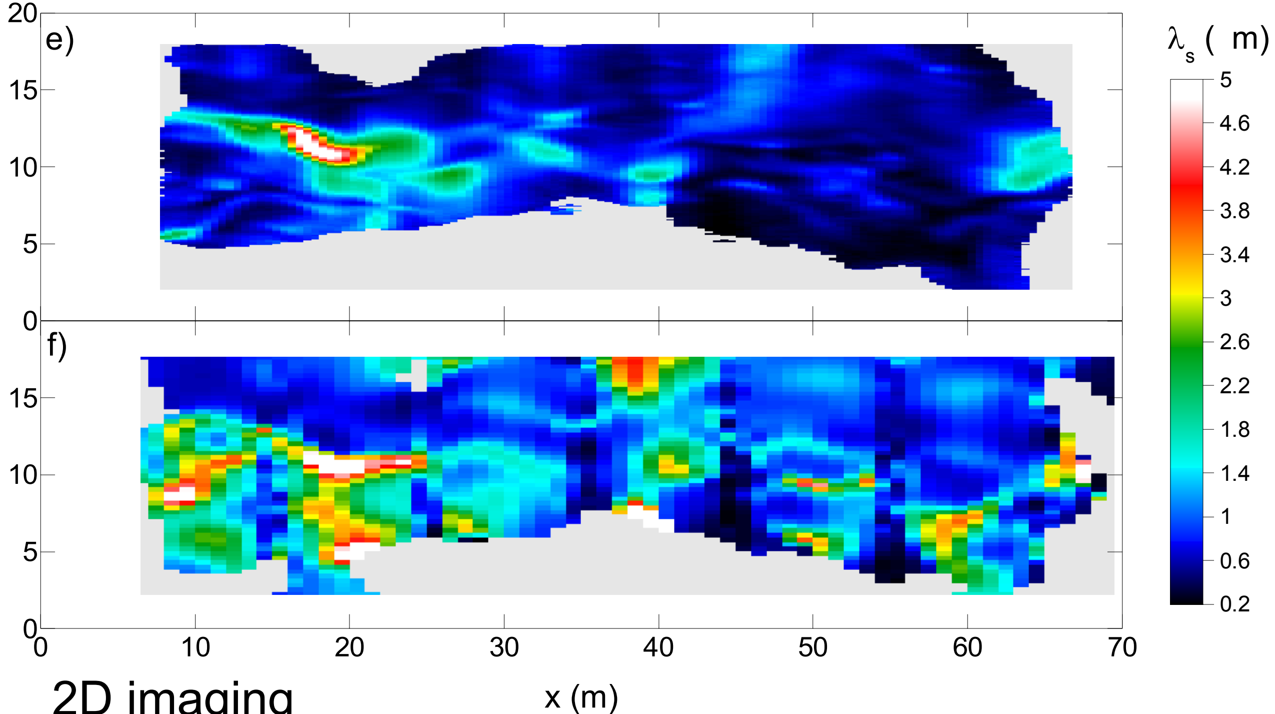
$\sigma^2_{v_s} = 0.10$ (m/d)²

Vanderborght et al., 2005, WRR

Synthetic Experiment

- Spatial variability of equivalent dispersivity

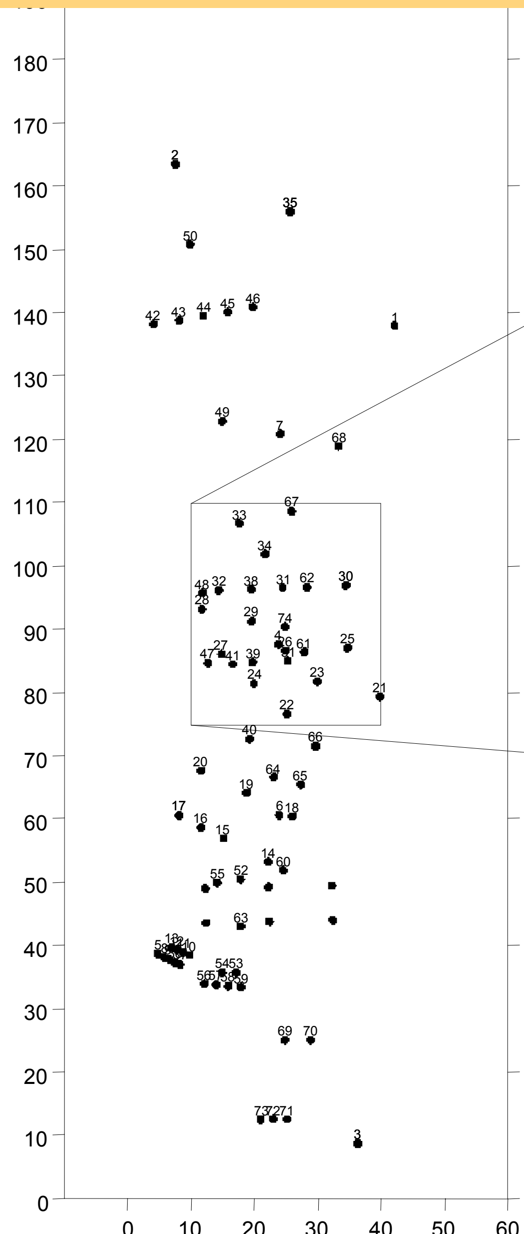
3D input model

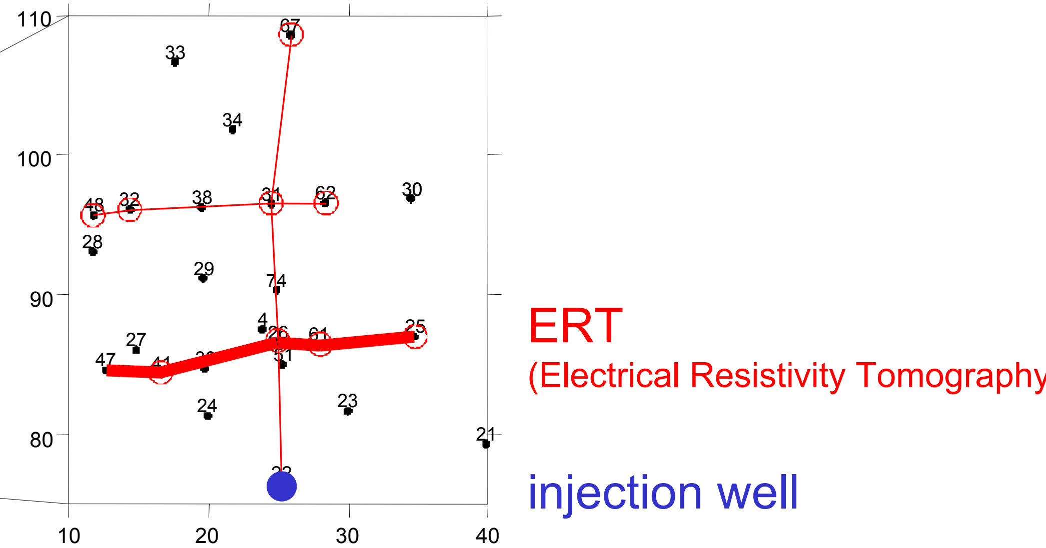


2D imaging

Vanderborght et al., 2005, WRR

Recent Tracer Experiments at Krauthausen

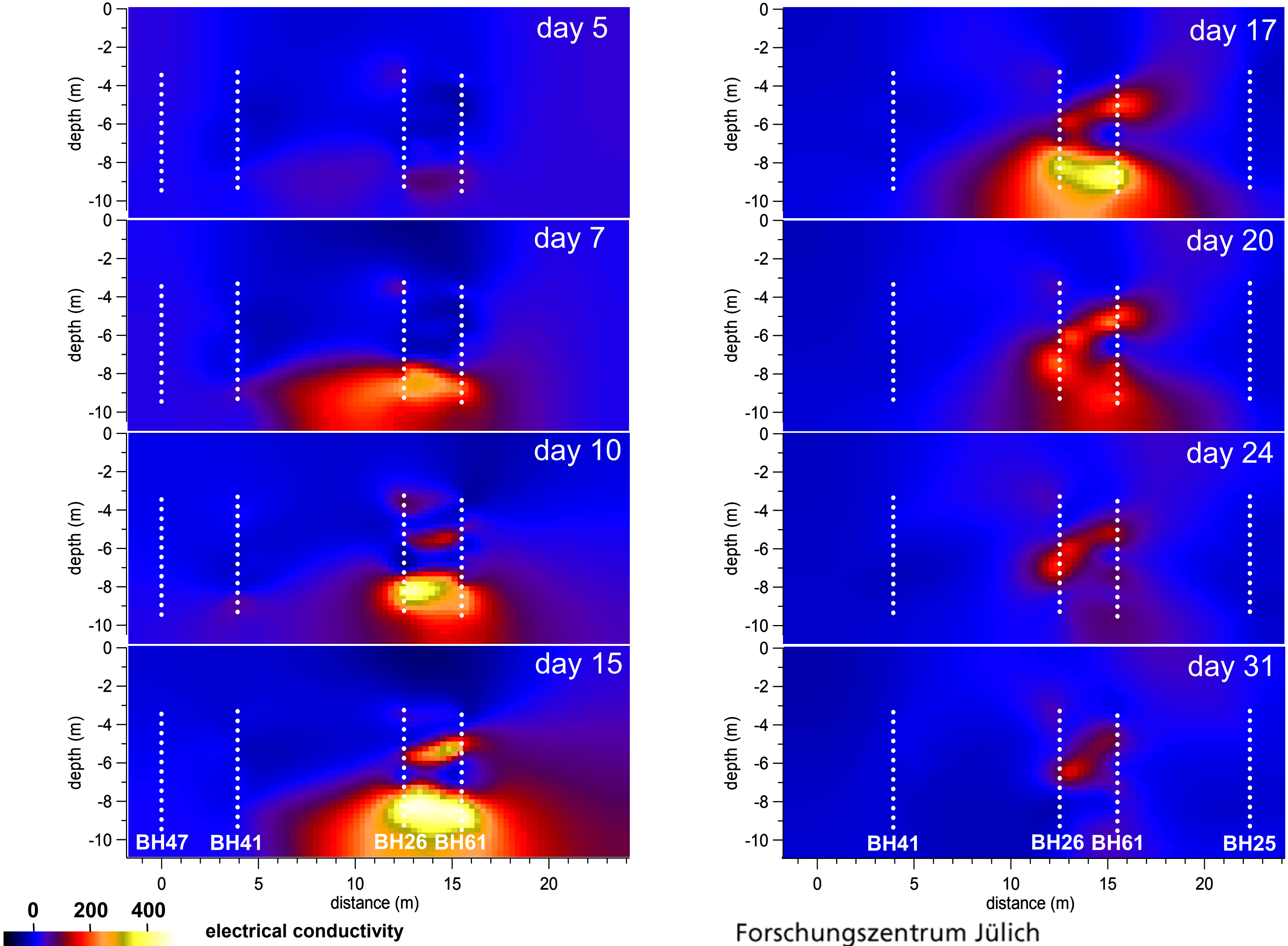




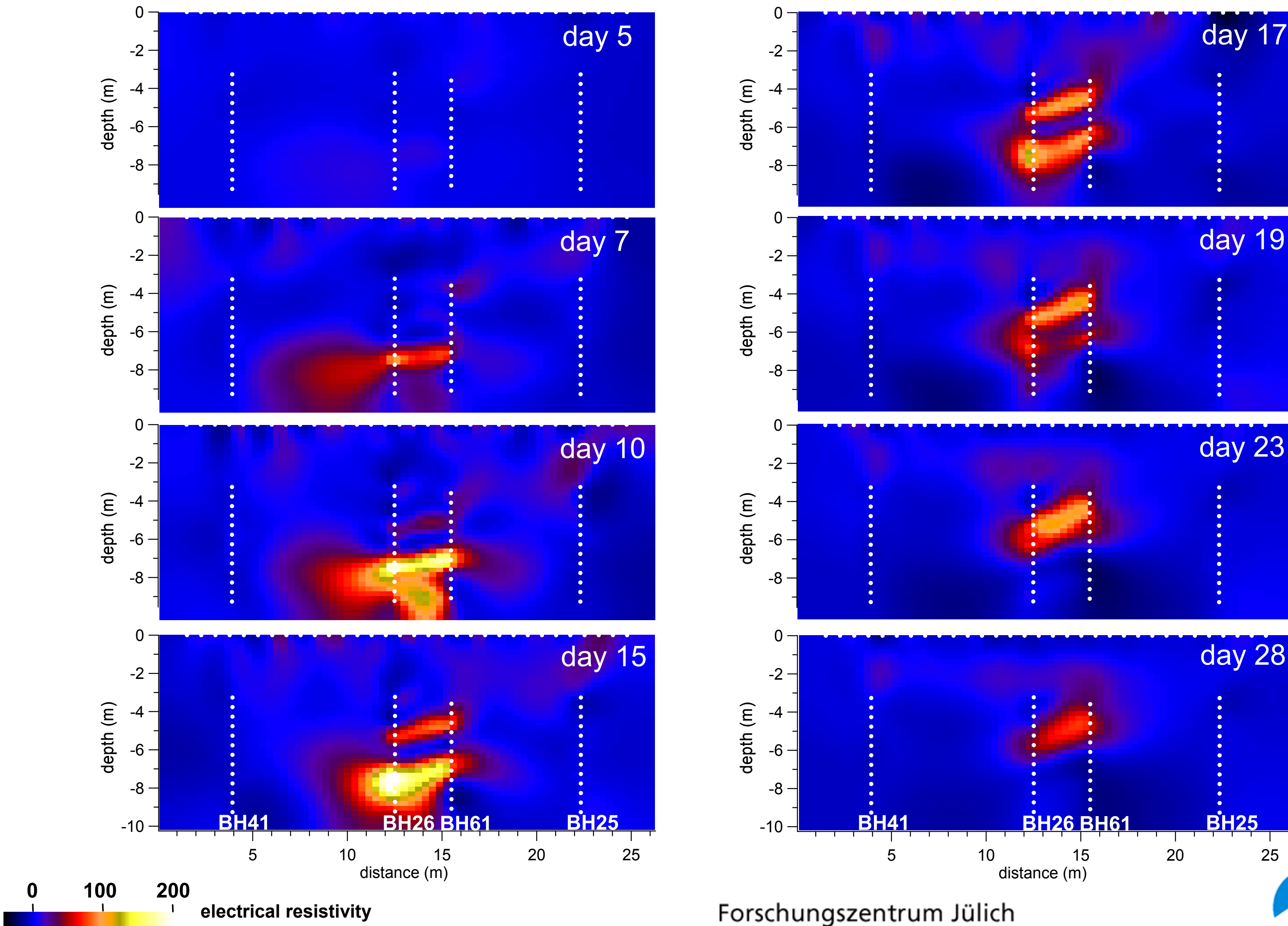
Sep - Nov 2002
400 kg $CaCl_2$ / 140 000 l
injected over 7 d
between -3 and -10 m
(~ 2.86 g/l @ 835 l/h)
electrical contrast ~7:1

Sep - Nov 2003
repeated with
“negative tracer”
electrical contrast ~4:1

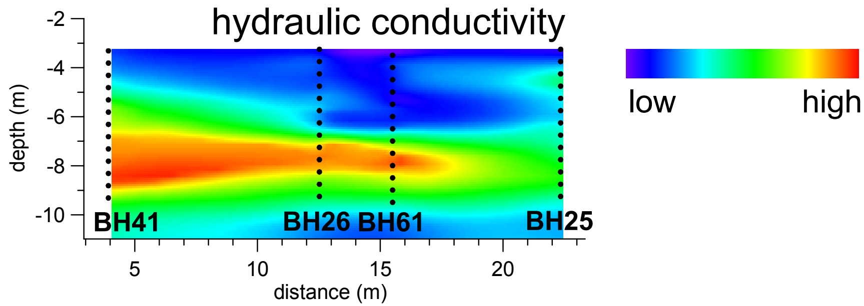
ERT Results from Conductive Tracer Experiment

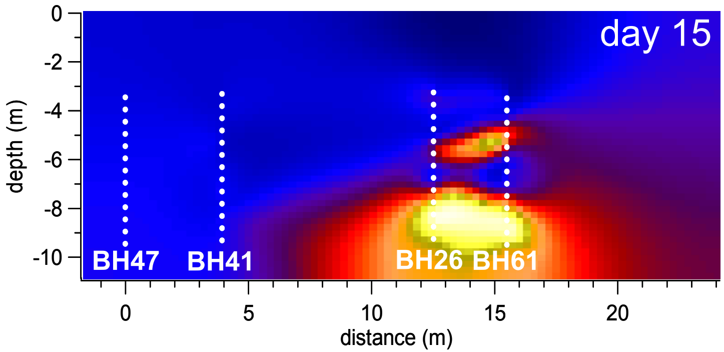


ERT Results from Resistive Tracer Experiment

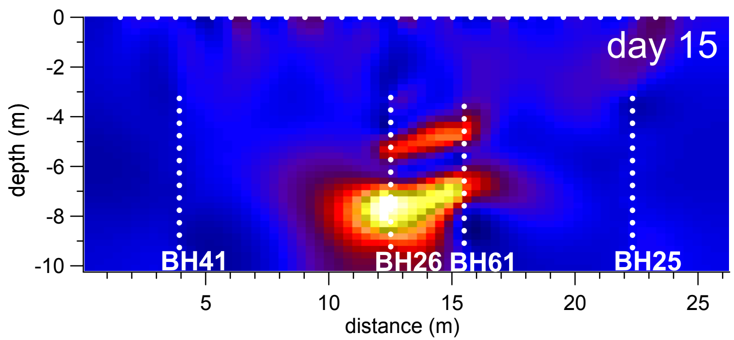


Structure vs. Process Characterisation





conductive tracer



resistive tracer

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Conclusions

- In combination with petrophysical and hydrological models, electrical imaging can provide quantitative information about structures (e.g. hydraulic conductivity) and processes (e.g. solute transport) in aquifers with relatively high spatial resolution.

However …

- Improved hydrologic-geophysical (e.g. hydraulic-electrical) parameter relationships are needed for the linkage of measured electrical properties with structural characteristics and/or state variables of hydrologic systems.
- Improved data fusion methodologies are needed to optimally integrate hydrological and geophysical information – either in terms of data, models or general concepts.

➢ improved understanding of structures and processes in hydrologic systems

➢ improved hydrological models for a more reliable scenario prediction

➢ improved (sustainable) management of water resources

Acknowledgements

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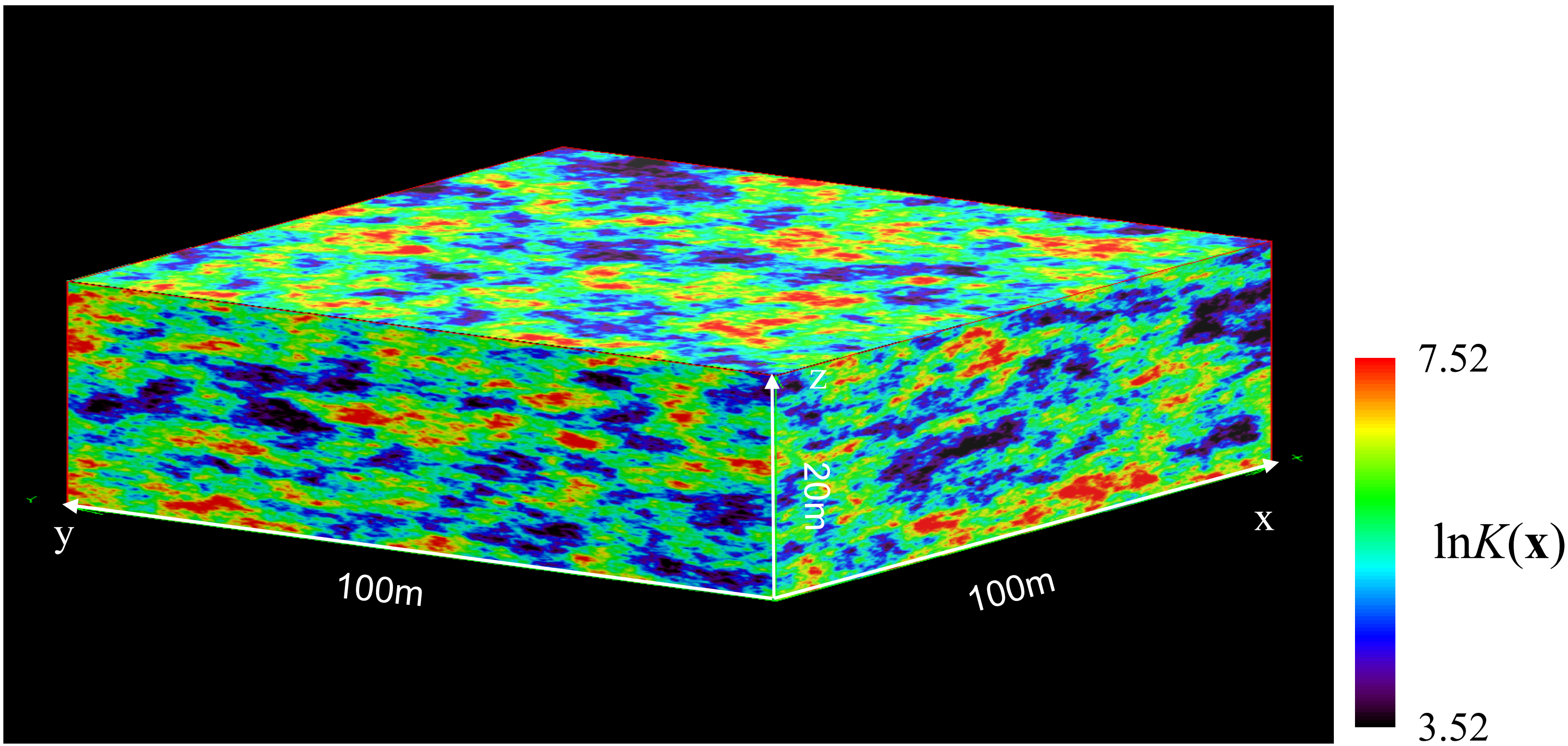
- Andreas Englert
- Kerstin Müller
- Martin Münch
- Jan Vanderborght

3D Hydraulic Conductivity Field

- $\ln K(\mathbf{x})$ represented as spatial stochastic process with mean value $K_0 = 250$ m/d, variance $\sigma_{\ln K} = 1$, and exponential covariance structure (5 m horizontal and 0.5 m vertical correlation lengths)

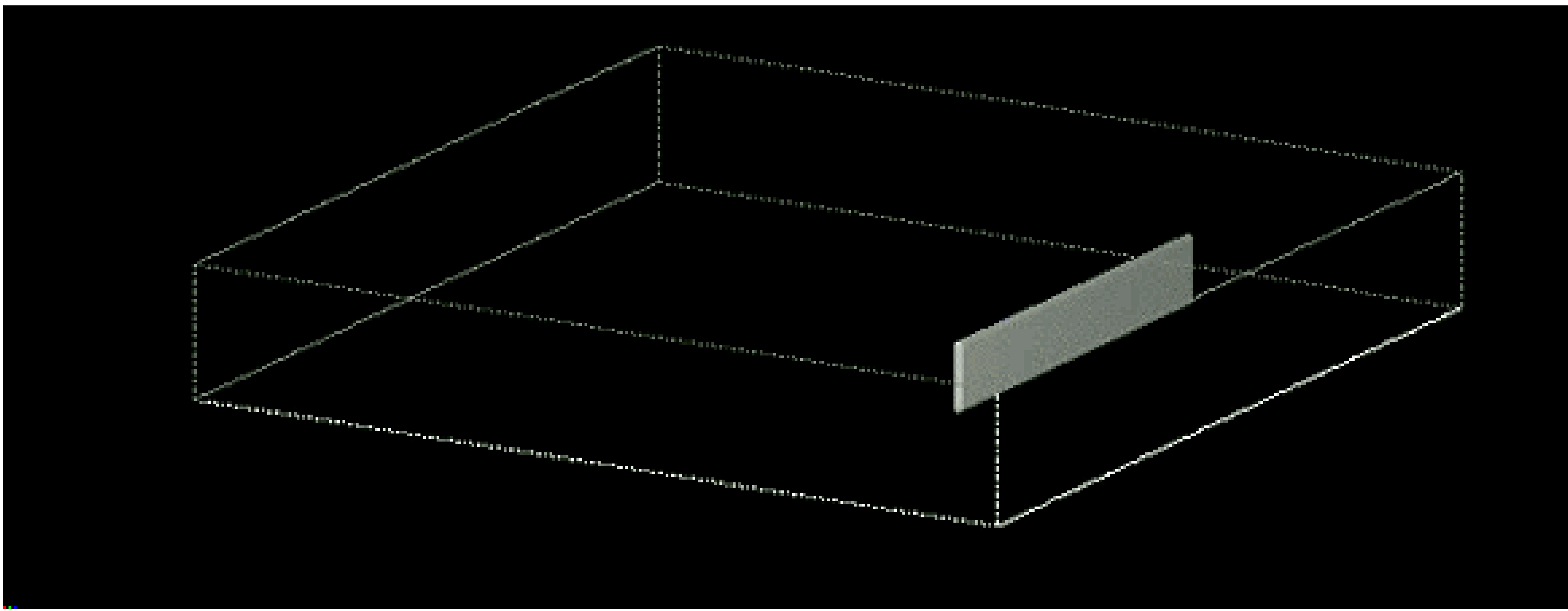


Vanderborght et al., 2005, WRR

Simulation of Solute Transport

- $$\frac{\partial C}{\partial t} = -\mathbf{v}(\mathbf{x})\nabla C + \nabla\left(\mathbf{D_d}\nabla C\right); D_{dL} = \left|\mathbf{v}(\mathbf{x})\right|\lambda_{dL}; D_{dT} = \left|\mathbf{v}(\mathbf{x})\right|\lambda_{dT}$$

  mean hydraulic gradient: $J_y = 0.001, J_x = J_z = 0$
  porosity: $\phi_0 = 0.25$
  mean pore water velocity: $v = 1$ m/d
  longitudinal and transverse dispersivities: $\lambda_{dL} = 0.1$ m, $\lambda_{dT} = 0.01$

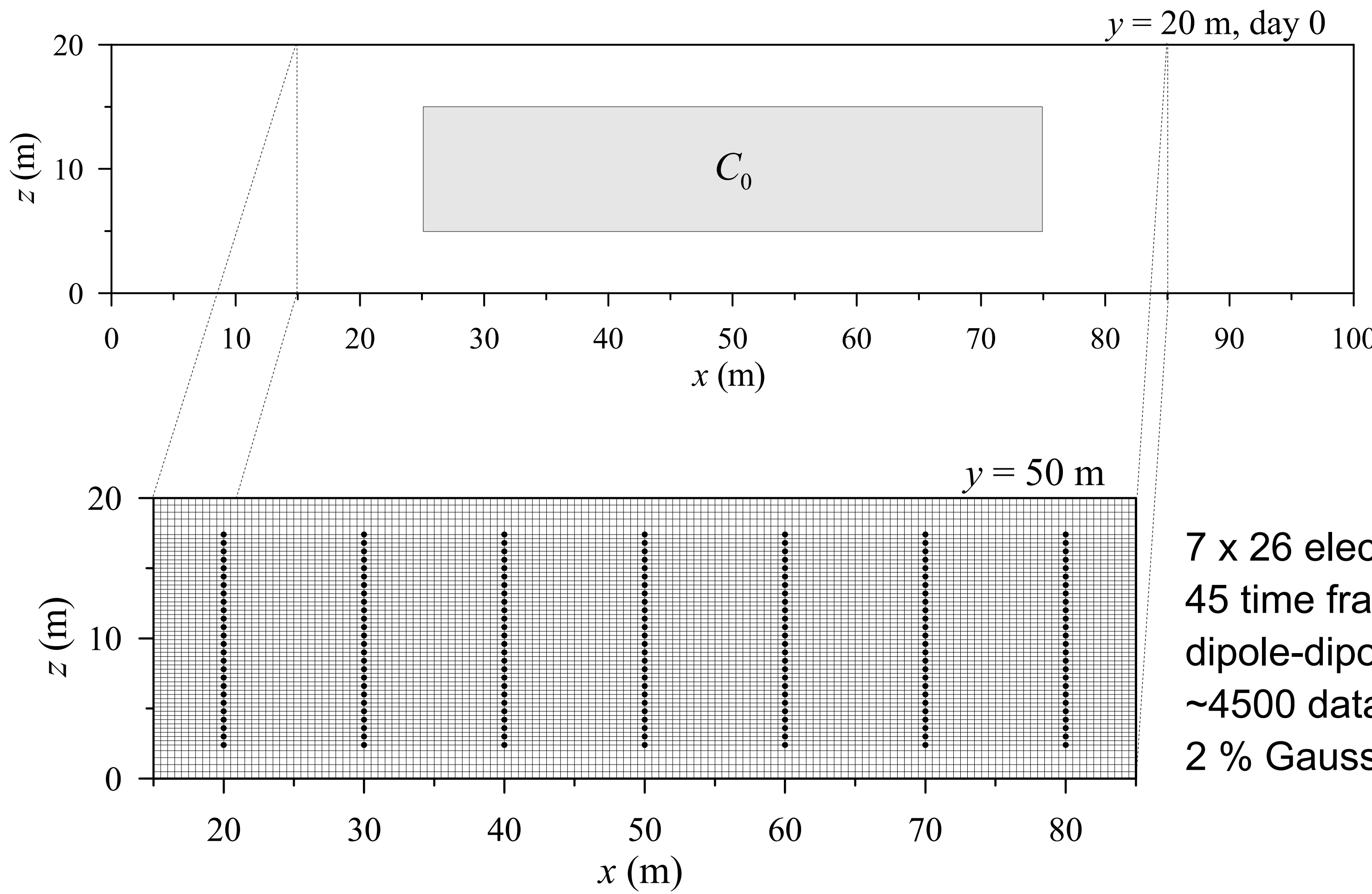


evolution of solute plume (day 0-100)

Vanderborght et al., 2005, WRR

Simulation of Time-lapse ERT Data Acquisition

- Assumption of linear calibration relation: $\sigma(\mathbf{x},t) = \sigma_{\text{in}} + \beta\, C(\mathbf{x},t)$



7 x 26 electrodes
45 time frames
dipole-dipole scheme
~4500 data per frame
2 % Gaussian noise

Vanderborght et al., 2005, WRR

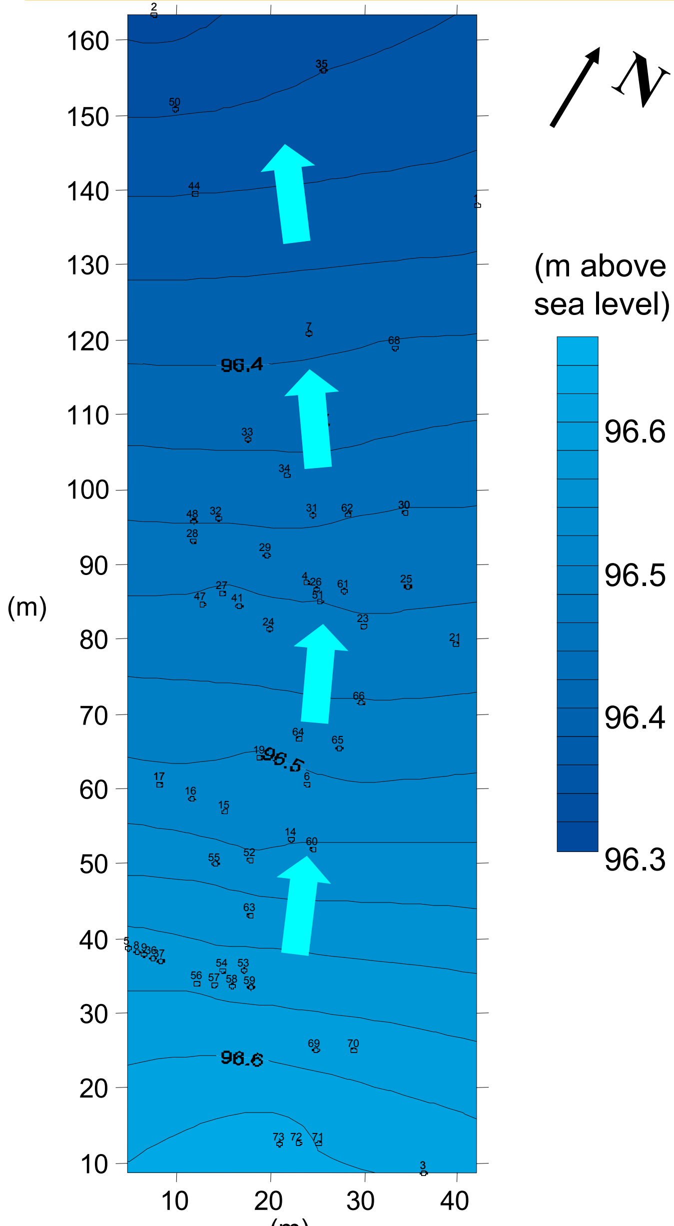
ERT 2D Imaging Approach

- 2.5D (finite-element) modeling
- Smoothness-constraint difference inversion *(LaBrecque & Yang, 2000)*:

$$\Psi_{\text{diff}}(\mathbf{m}_t) = \left\| \mathbf{W}[\mathbf{d}_t - \mathbf{d}_0 + \mathbf{f}(\mathbf{m}_0) - \mathbf{f}(\mathbf{m}_t)] \right\|^2 + \alpha \left\| \mathbf{R}(\mathbf{m}_t - \mathbf{m}_0) \right\|^2$$

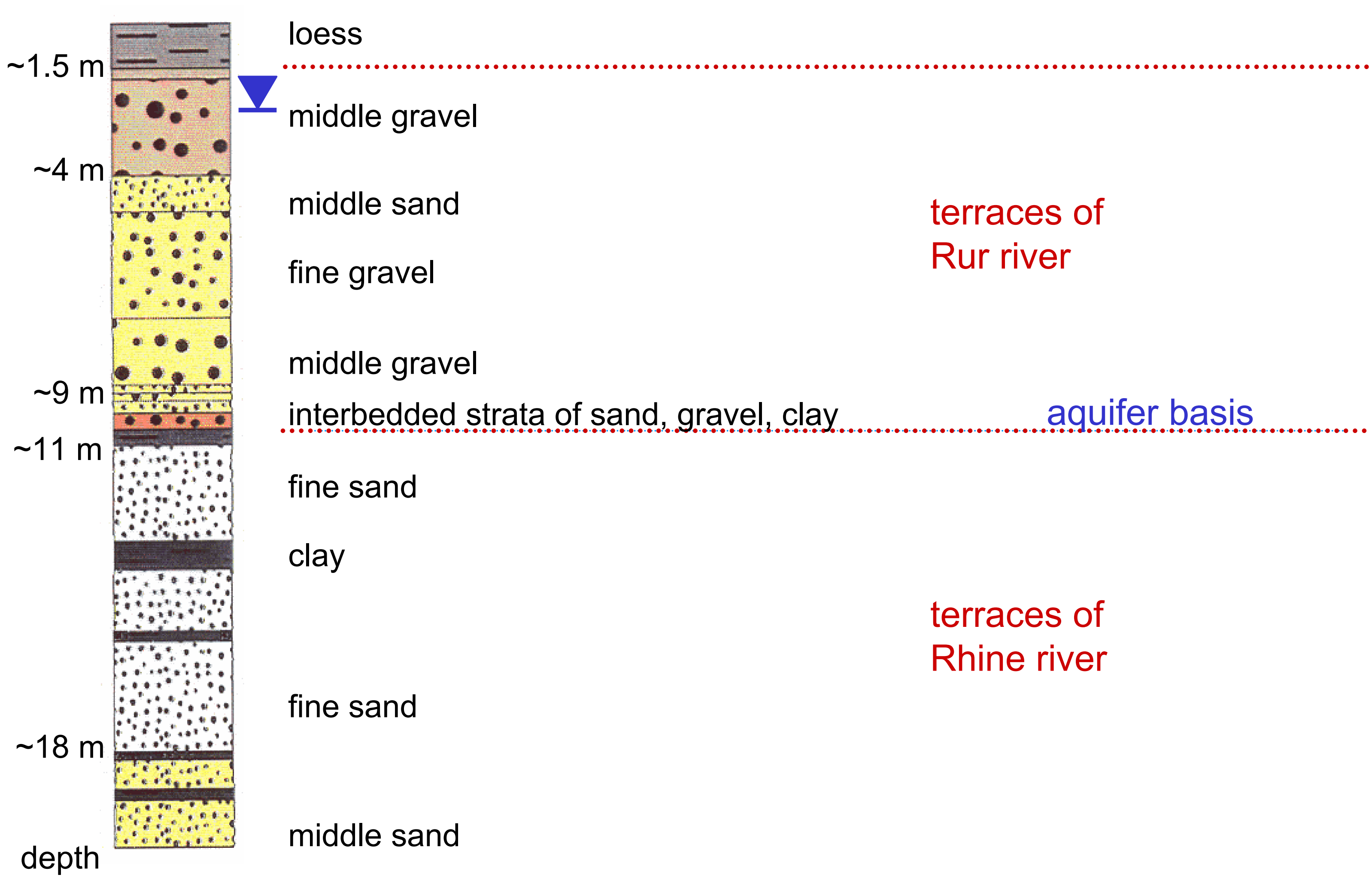
- “robust” iterative data reweighting *(LaBrecque & Ward, 1990)*

The Krauthausen Test Site: Hydrogeology



- heterogeneous aquifer
- mean porosity 26 %
- mean hydraulic conductivity $3.8 * 10^{-3}$ m/s
- hydraulic gradient 0.2 %
- mean flow velocity 0.65 m/d
- ground water table between 2.5 m (summer) and 1 m (winter)

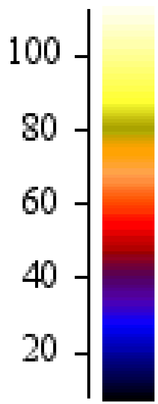
The Krauthausen Test Site: Lithology



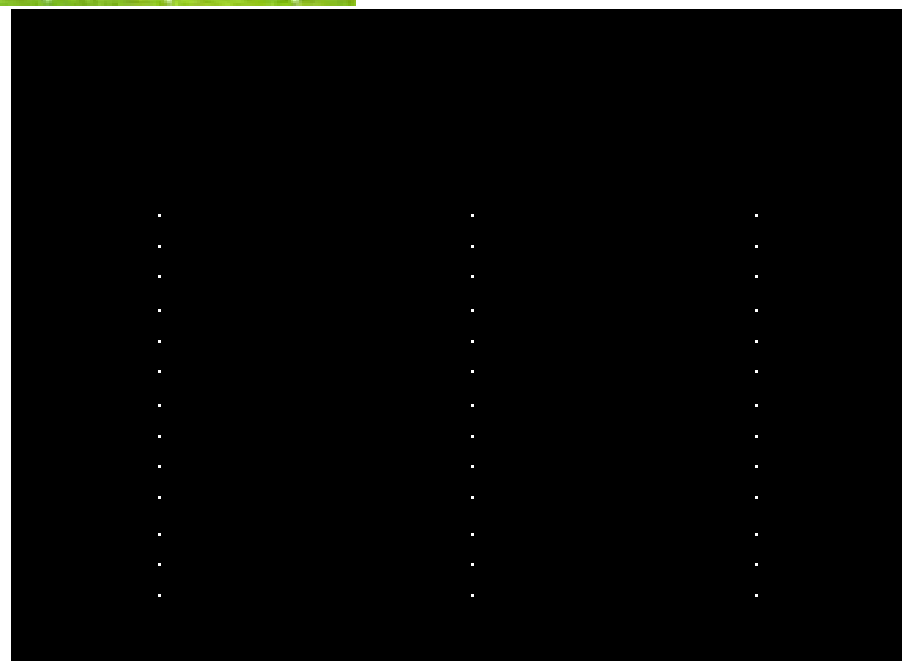
Time-lapse Electrical Imaging (Monitoring)

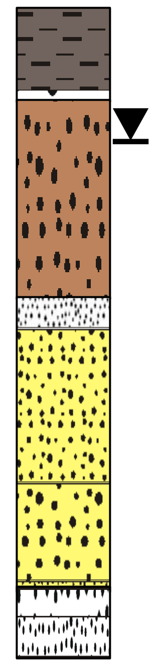
- Solute tracer experiment in heterogeneous aquifer (Krauthausen)

day 1



electrical conductivity changes (%)
due to injected NaBr solution



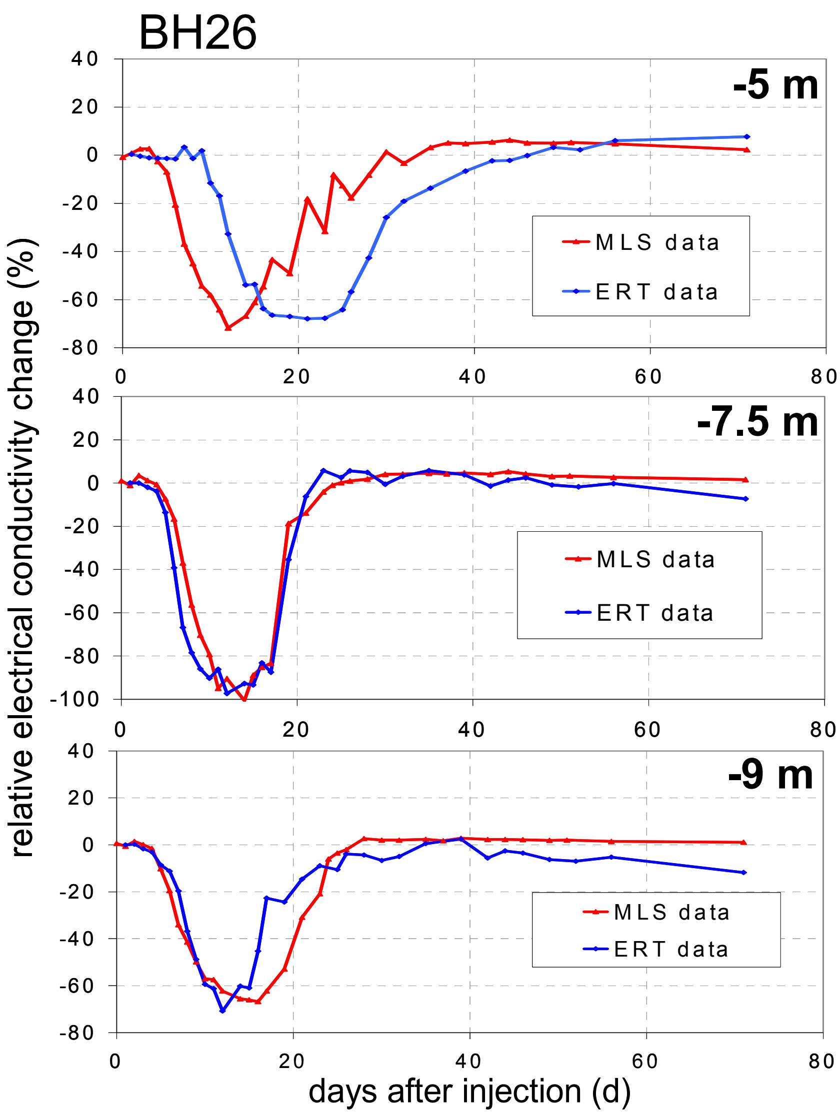


lithology

Kemna et al., 2002, J. Hydrol.

ERT vs. Multi-Level Sampling (MLS)

- Resistive tracer experiment



EIT Results at Krauthausen

- Background images in 2003