GPR in Hydrology

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Soil: Earth’s multi-scale skin

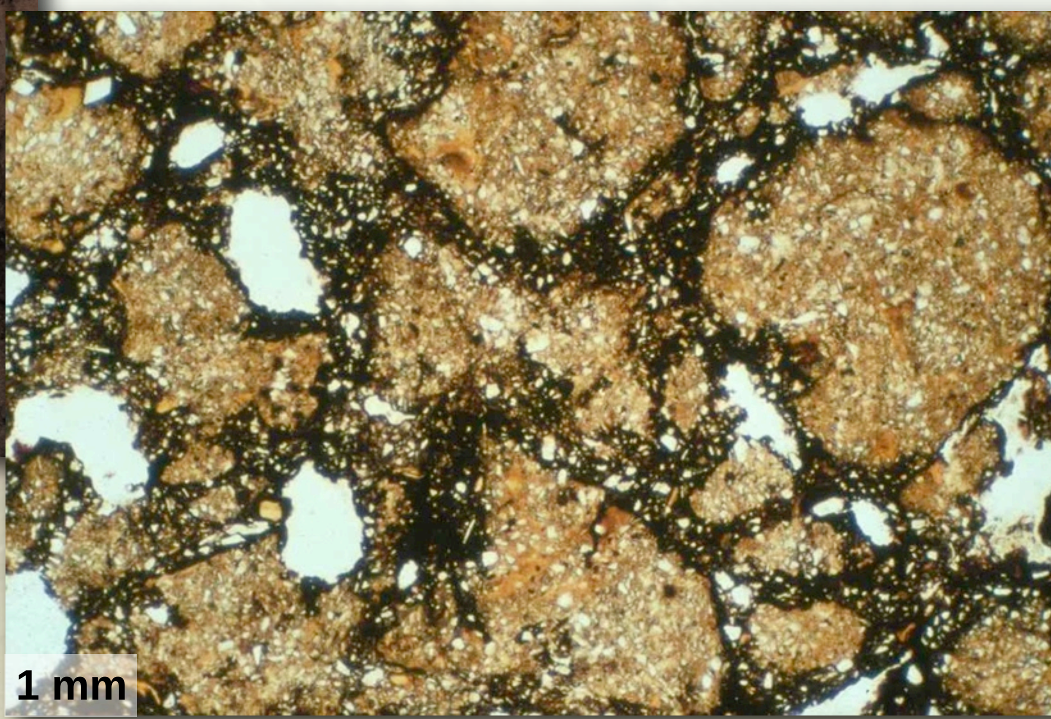
relevant structures
at all scales

different generators
at different scales

no simple transition
between scales

catchment
hydrology

soil
physics



chemistry &
microbiology

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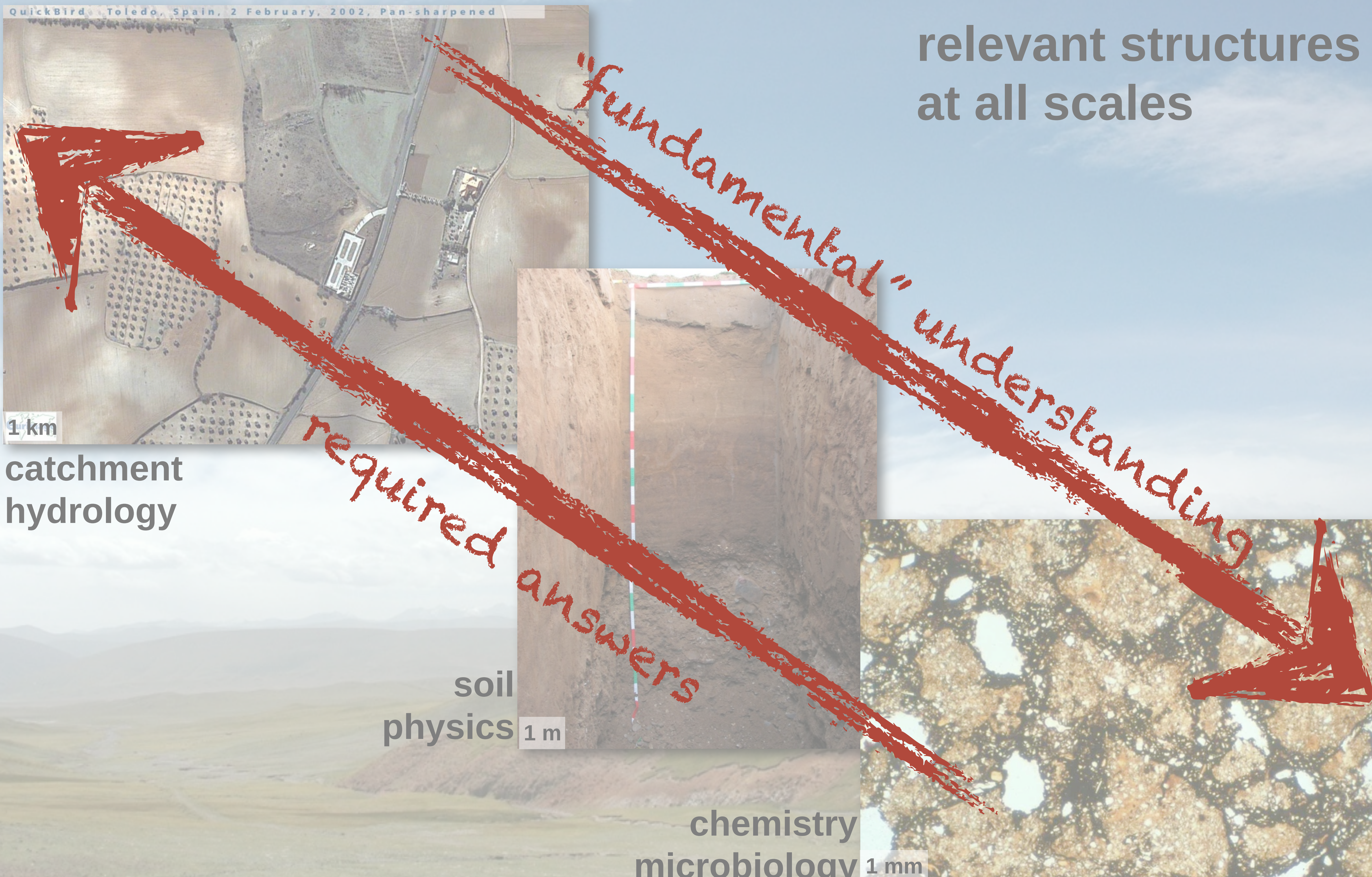
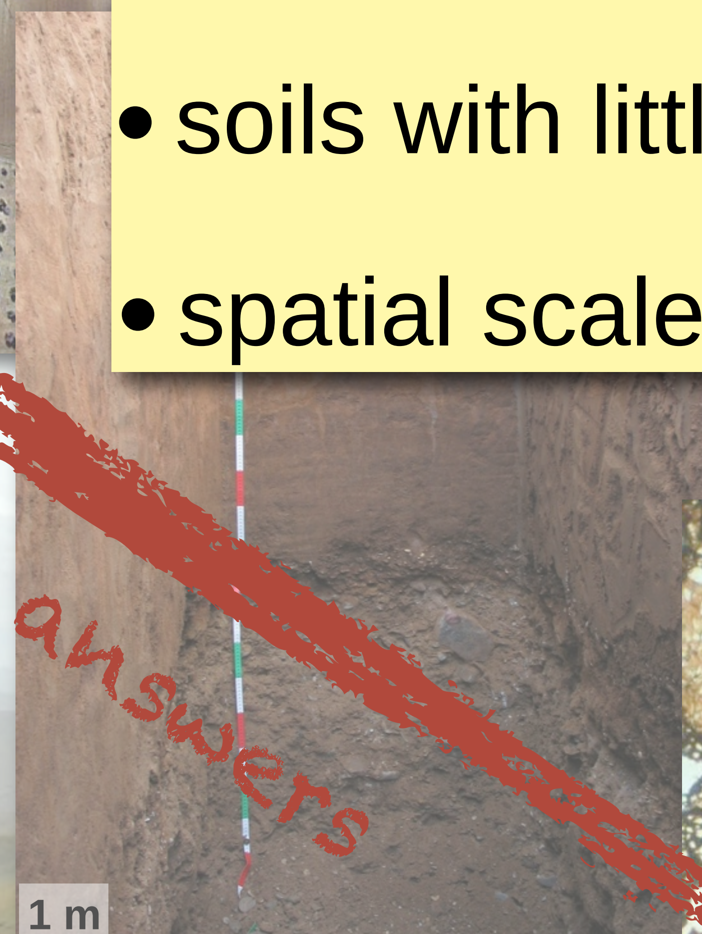
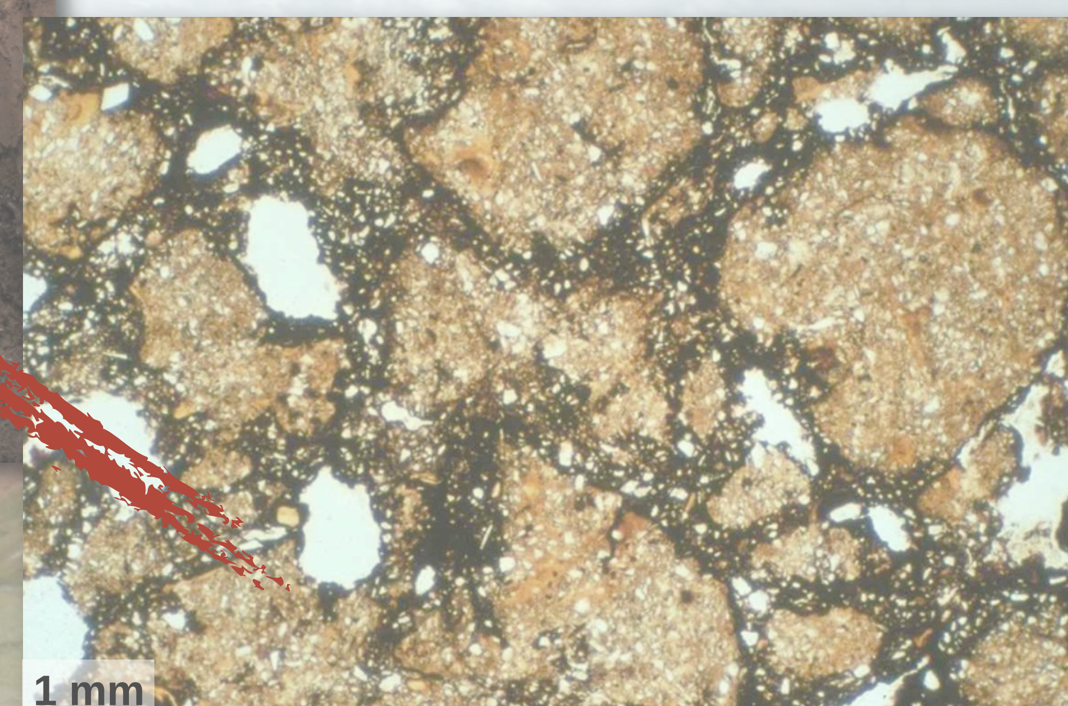
Soil: Earth’s multi-scale skin

relevant structures at all scales



Soil: Earth’s multi-scale skin





focus today

- physically-based understanding of water movement through soils
- soils with little vegetation
- spatial scale 1 m…1 km

Physically-based model

- **conservation of mass**
- **incompressible media**
- **Buckingham's conjecture**

$$\partial_t \theta + \nabla \cdot \mathbf{j} = 0$$

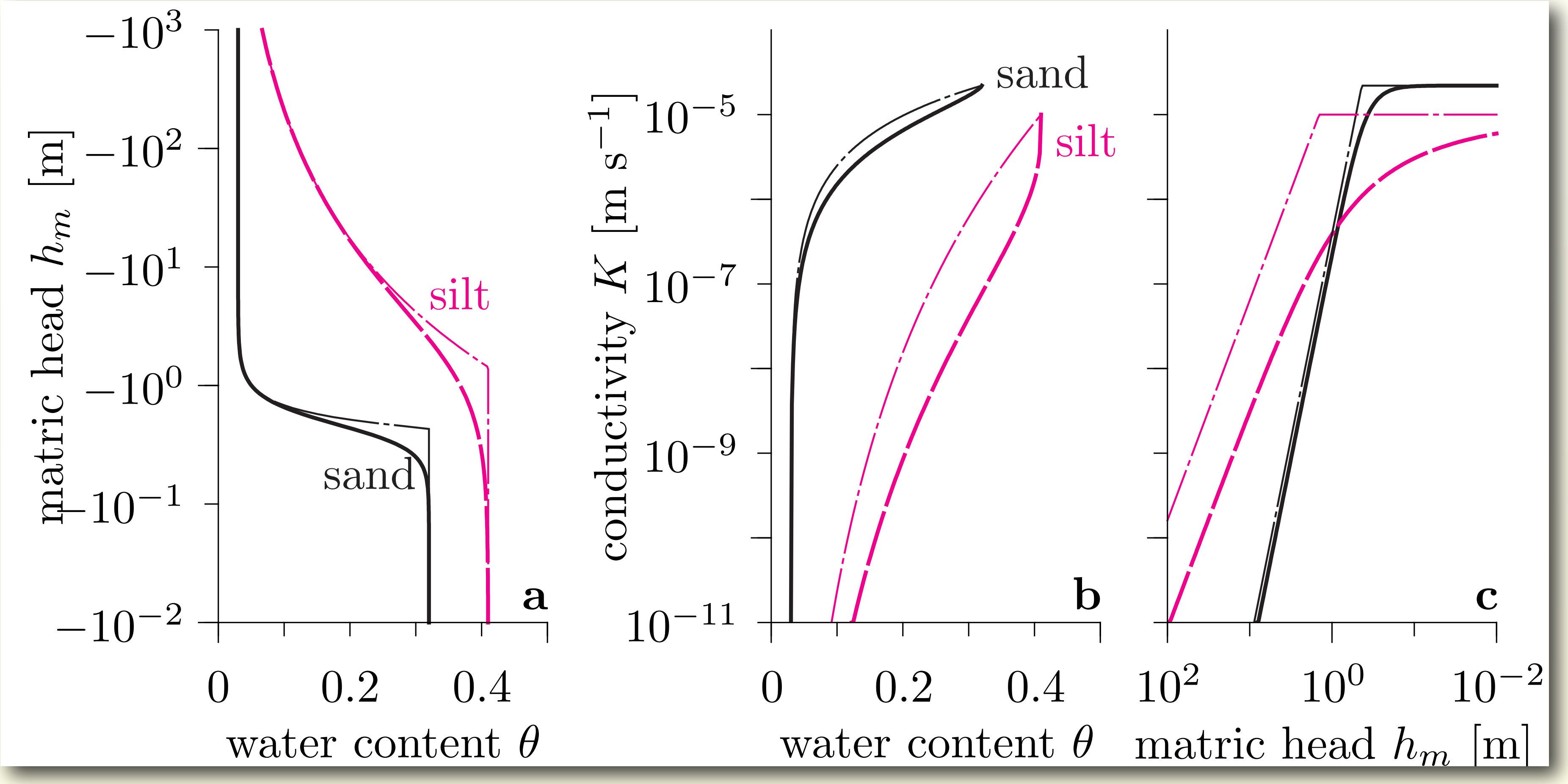
$$\mathbf{j} = -\mathsf{K}[\nabla \psi_m - \rho \mathbf{g}]$$

soil hydraulic properties

$$\theta(\psi_m),\ \mathsf{K}(\theta)$$

Richards equation

$$\partial_t \theta - \nabla \cdot \left[\mathsf{K}(\theta)[\nabla \psi_m - \rho_w \mathbf{g}]\right] = 0$$



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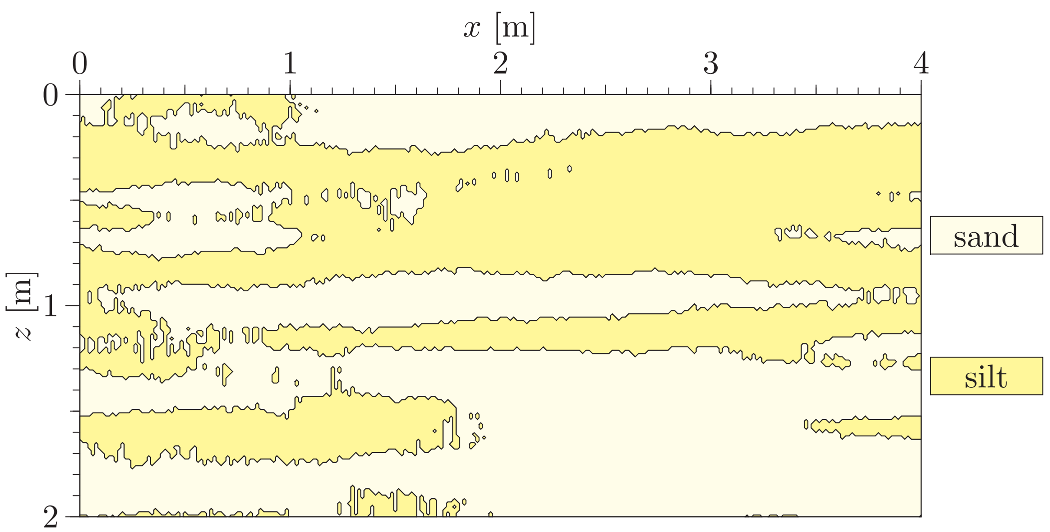
Physically-based model

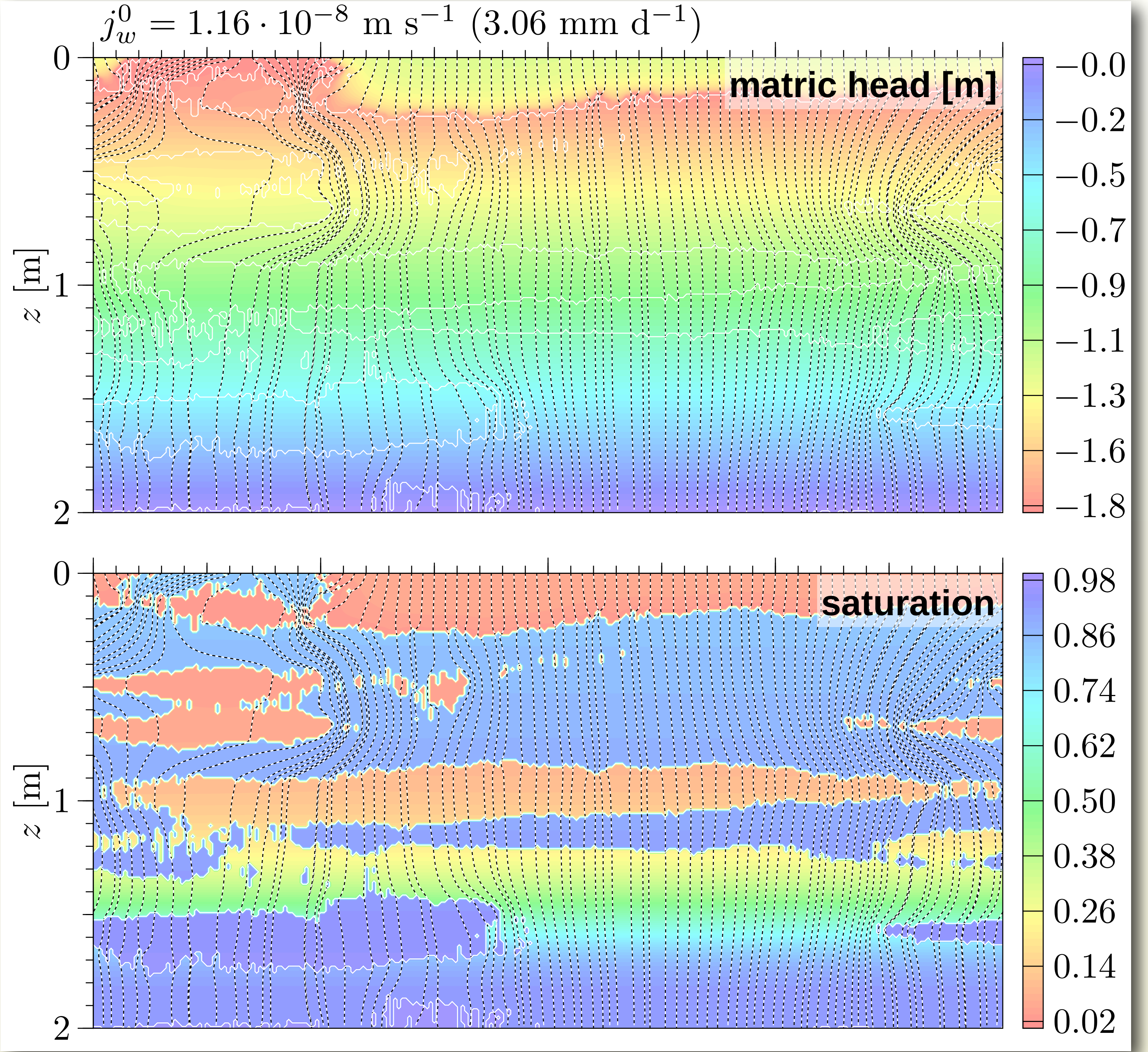
$$\partial_t \theta + \nabla \cdot \mathbf{j} = 0$$
$$\mathbf{j} = -\mathsf{K}[\nabla \psi_m - \rho \mathbf{g}]$$

$\theta(\psi_m),\ \mathsf{K}(\theta)$ →

$$\partial_t \theta - \nabla \cdot \left[\mathsf{K}(\theta)[\nabla \psi_m - \rho_w \mathbf{g}]\right] = 0$$

soil architecture





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Physically-based model

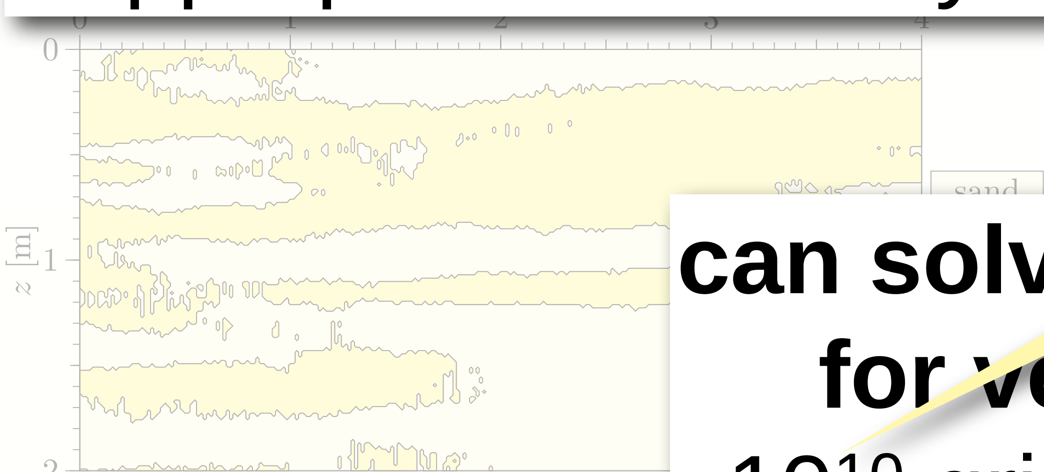
$\partial_t\theta + \nabla\cdot\mathbf{j} = 0$

$\theta(\psi_m),\ \mathsf{K}(\theta)$

$- \nabla\cdot[\mathsf{K}(\theta)[\nabla\psi_m - \rho_w\mathbf{g}]] = 0$

given

- spatially resolved material properties
- appropriate boundary conditions

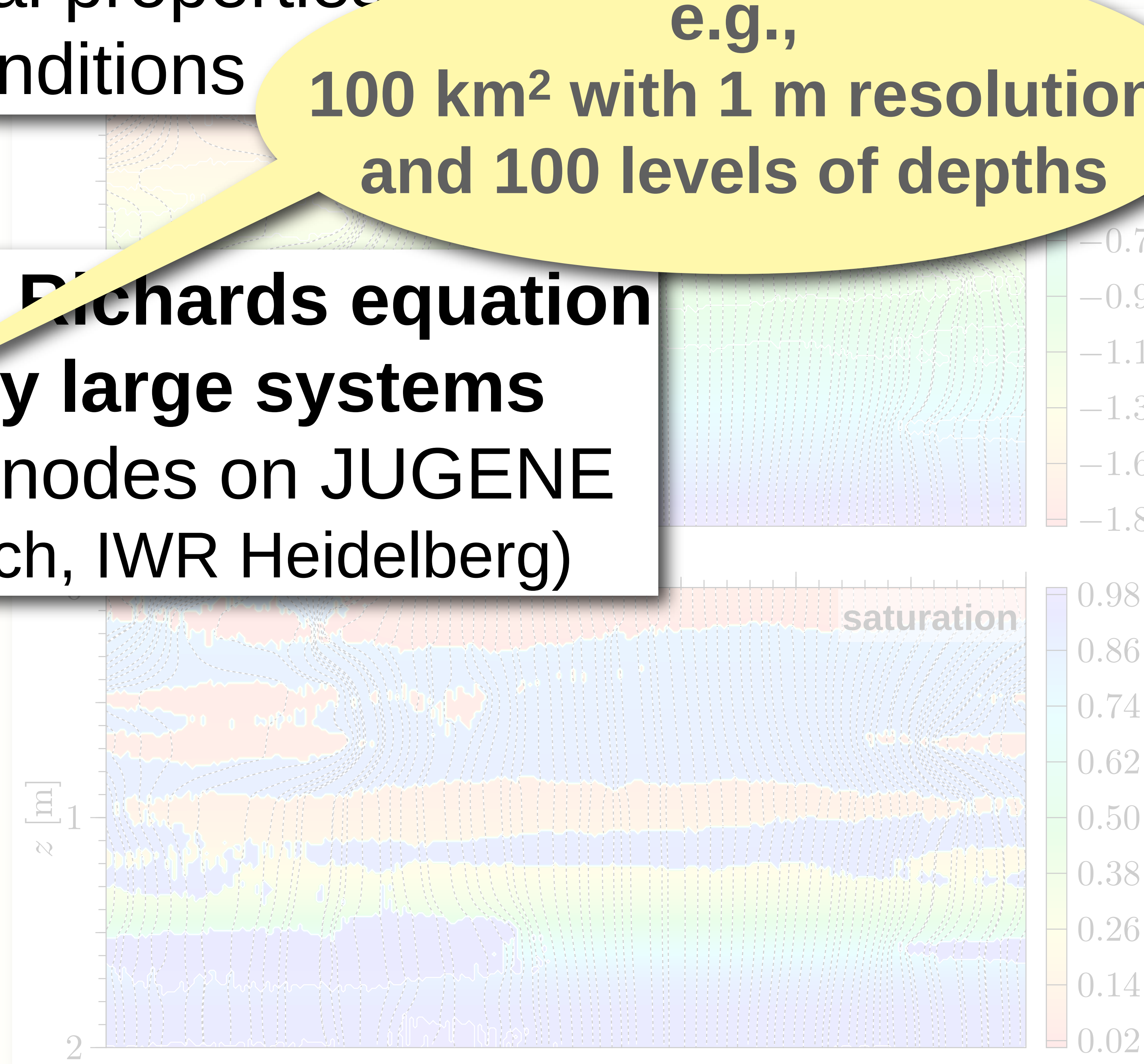


e.g., 100 km² with 1 m resolution and 100 levels of depths

can solve Richards equation for very large systems

10^{10} grid nodes on JUGENE

(O. Ippisch, IWR Heidelberg)



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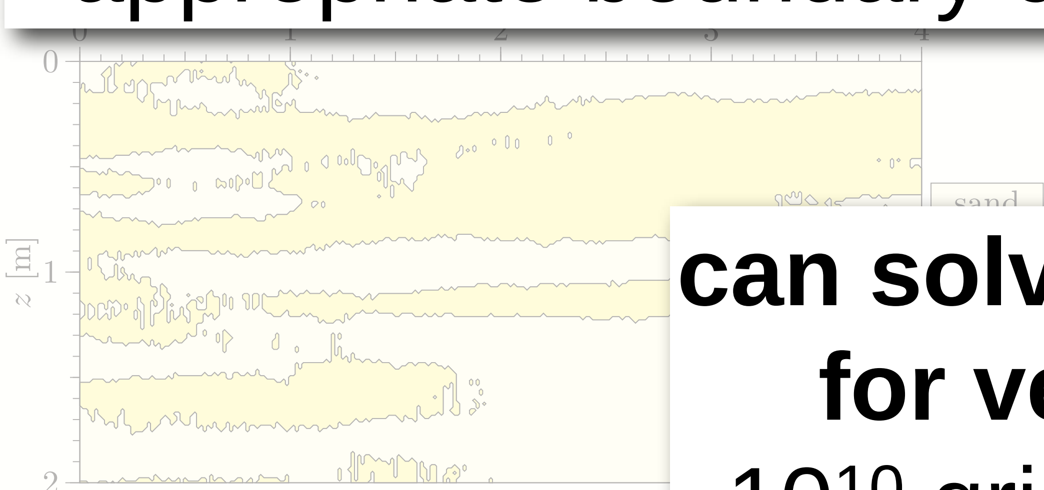
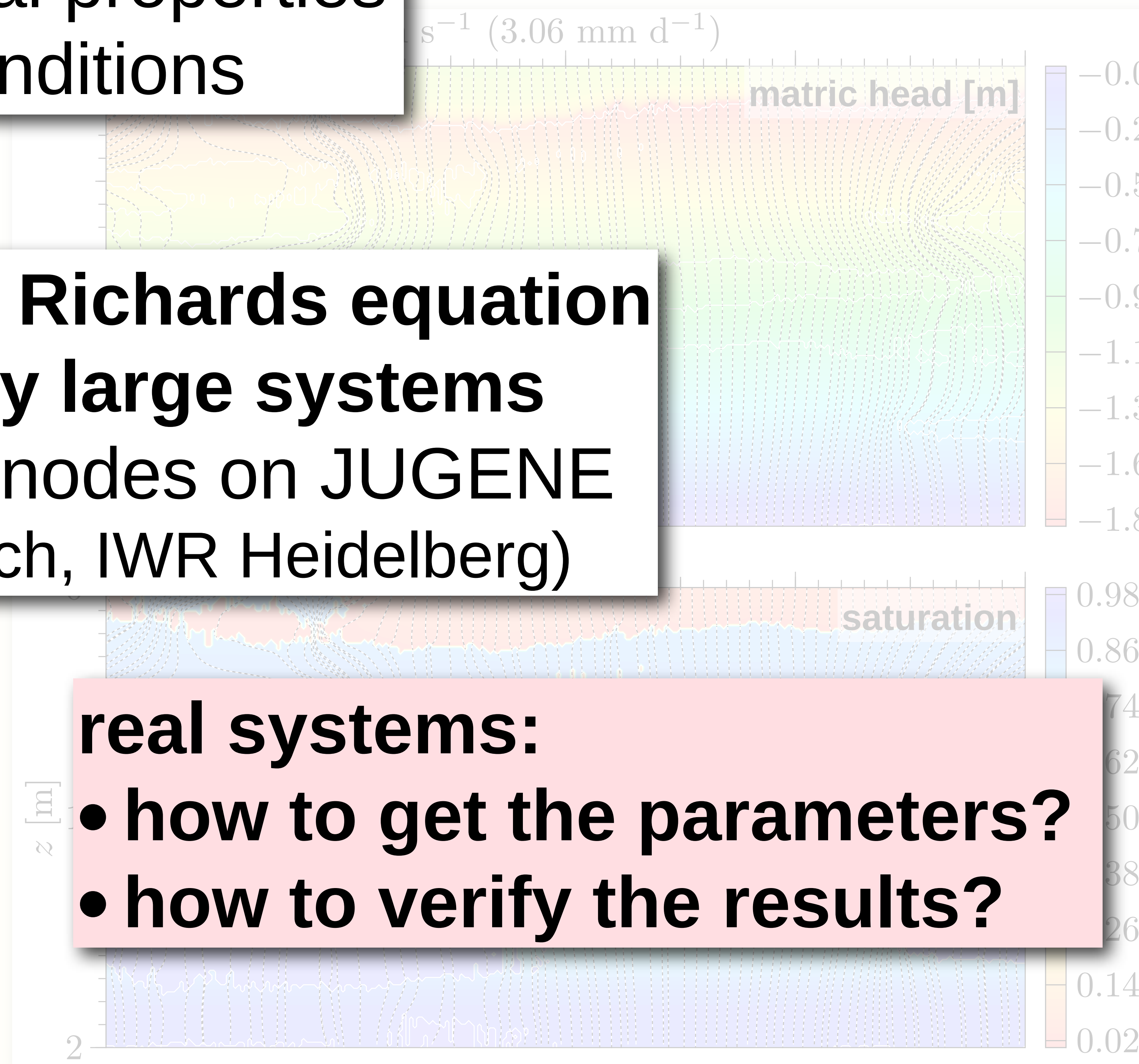
Physically-based model





given

- spatially resolved material properties
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can solve Richards equation for very large systems

10^{10} grid nodes on JUGENE

(O. Ippisch, IWR Heidelberg)

theory & scenarios ✓

real systems:

- **how to get the parameters?**
- **how to verify the results?**

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that’s gonna a be a long long road…

…but there are options

remote sensing
- passive radiometry
- active radar
- gravimetry,…

geophysical methods
- GPR, ERT, EMI
- NMR, SIP,…
- n-, Ra-emission,…

sensor networks
- individual, profile
- 2d spread, quasi 3d

assessment space
- quantity (measured vs wanted, applicability)
- accuracy (proxy relation)
- extent, coverage, resolution
  in space and in time
- installation & operation resources
- …

but,
nowhere near 10^{10} points!

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…but there are options

remote sensing
- passive radiometry
- active radar
- gravimetry,…

focus on GPR
specifically on GPR reflections
(neglecting air-groundwave)

- extent, coverage, resolution in space
- extent, coverage, resolution in time
- installation & operation ressources

geophysical methods
- **GPR**, ERT, EMI
- NMR, SIP,…
- n-, Ra-emission,…

sensor networks
- individual, profile
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but,
nowhere near 10^{10} points!

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Outline

major findings

- **fundamentals**

  GPR yields information on
  - reflector topography $d(x_h;t)$
  - liquid water content $\Theta(x;t)$

- **single-channel GPR**

  traditional analysis useless for soils

- **multi-channel GPR**

  powerful extension for traditional analysis

- **constructive inversion**

  the way to go for complicated architectures

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GPR fundamentals

speed of light

$$c = \frac{c_0}{\sqrt{\mu_r \varepsilon_r}}$$

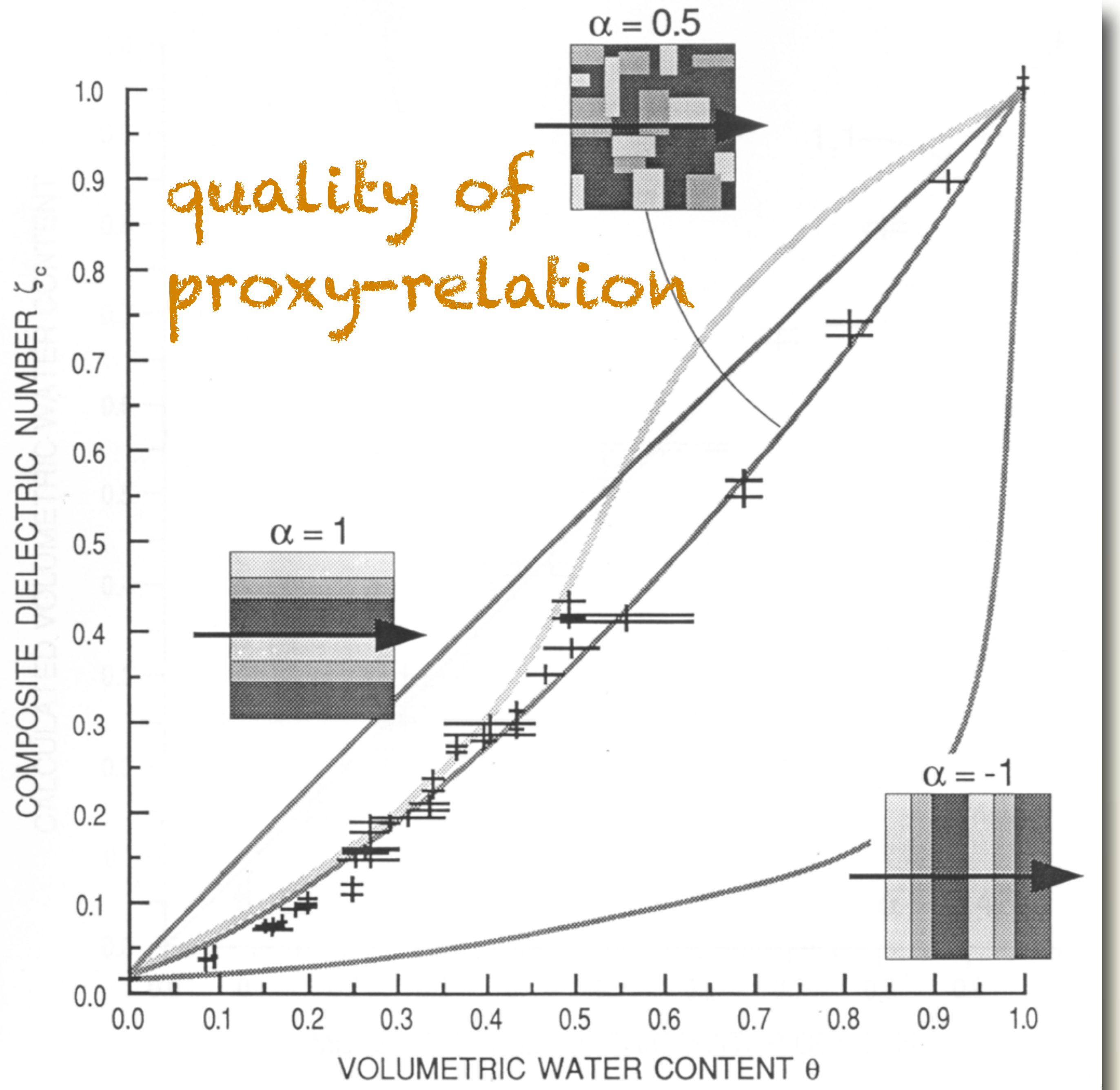
reflection coefficient $1 \rightarrow 2$ (μ_r=1)

$$\rho := \frac{A_{\text{in}}}{A_{\text{refl}}} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

composite dielectric number

$$\varepsilon_c^\alpha = \sum_i \theta_i \varepsilon_i^\alpha (T, \nu, \dots)$$

$\alpha = 1/2$: CRIM



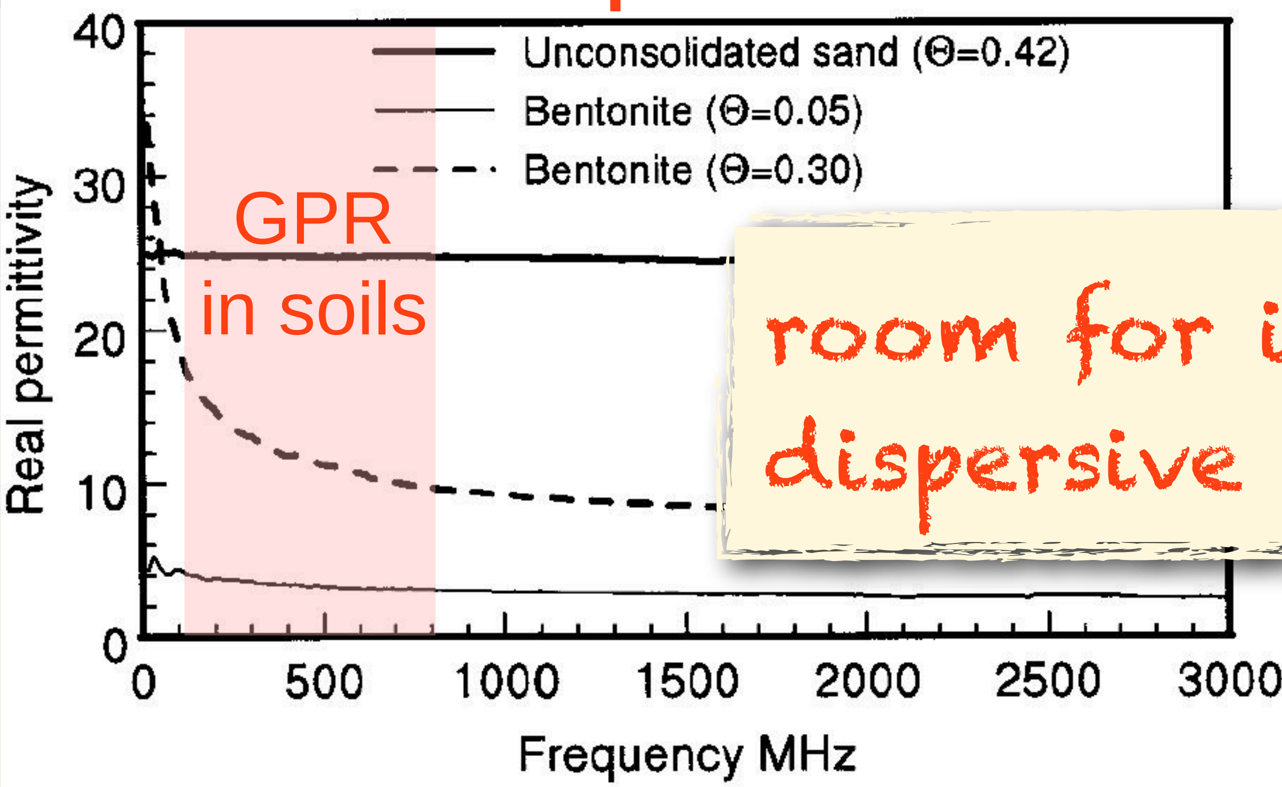
[Roth et al., 1990]

dielectric numbers of soil constituents

liquid water	80.4 (at 20°C and 1 GHz)
pure ice	3.2
quartz	4.3

GPR fundamentals

some minor complications

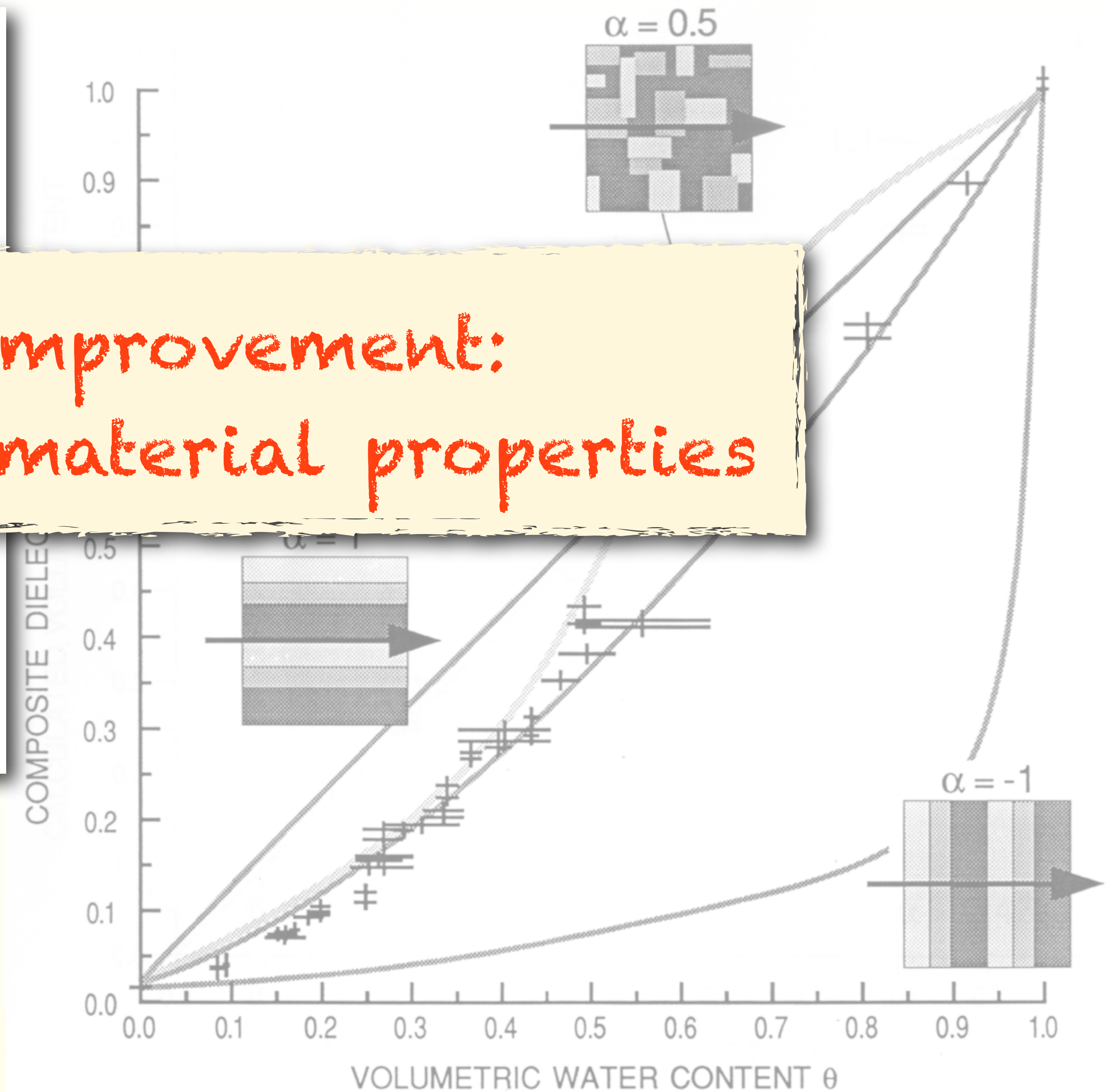


[Robinson et al., 2003]

room for improvement:
dispersive material properties

$$\varepsilon_c^\alpha = \sum_i \theta_i \varepsilon_i^\alpha(T, \nu, \dots)$$

$\alpha = 1/2$: CRIM



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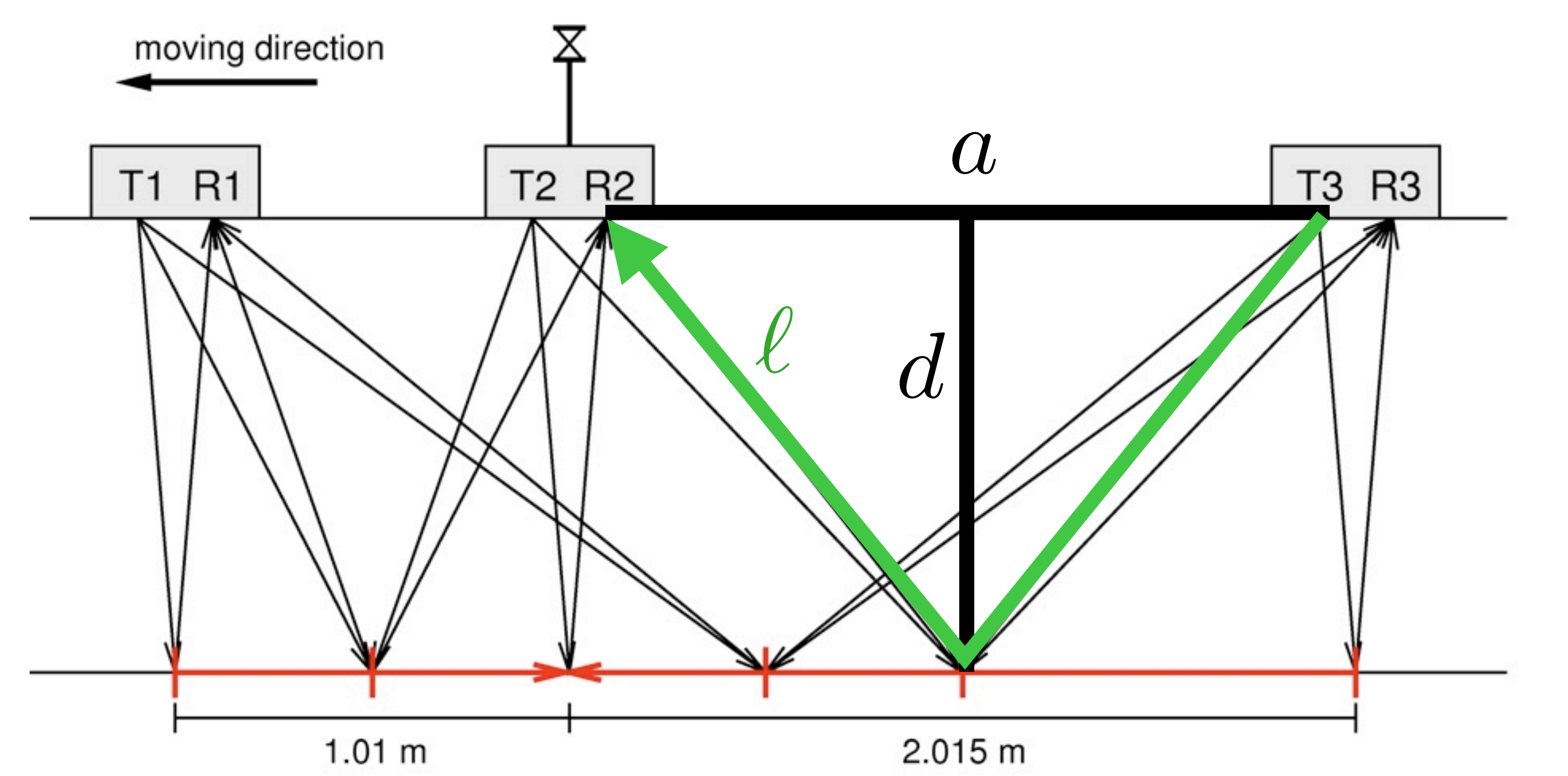
Single-channel GPR



[modified from Wollschläger et al., 2010]

single channel common-offset measurement

$$t = \frac{\ell}{v} = \frac{\sqrt{\varepsilon_c(\theta)}}{c_0}\sqrt{4d^2 + a^2}$$

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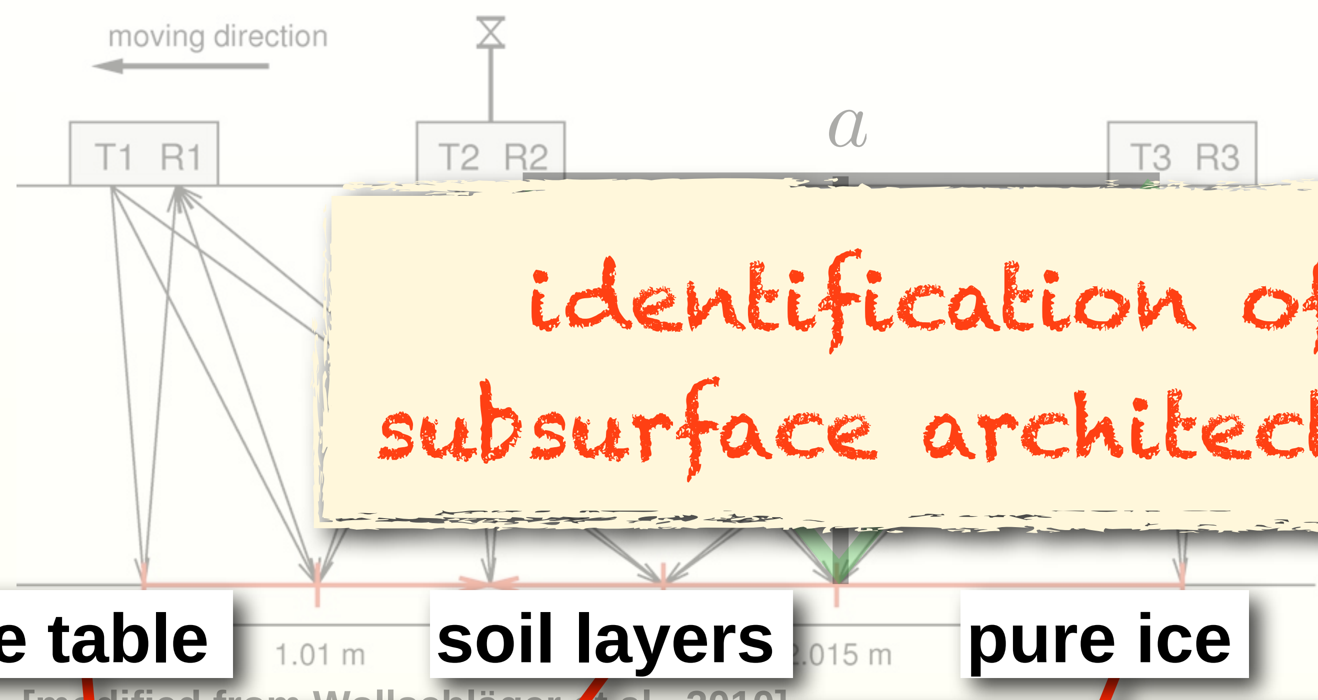
Single-channel GPR

identification of subsurface architecture



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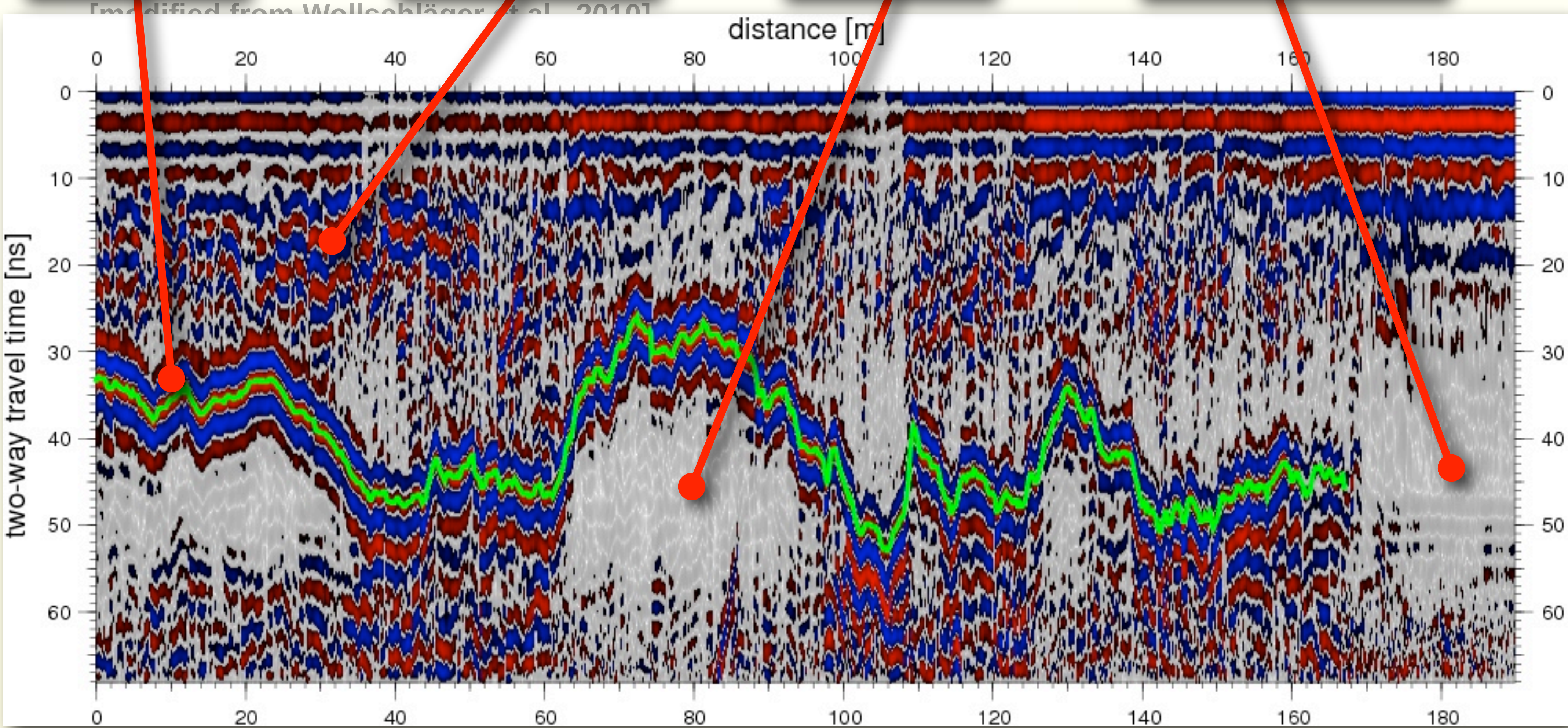

example from permafrost site, Xinjiang, China

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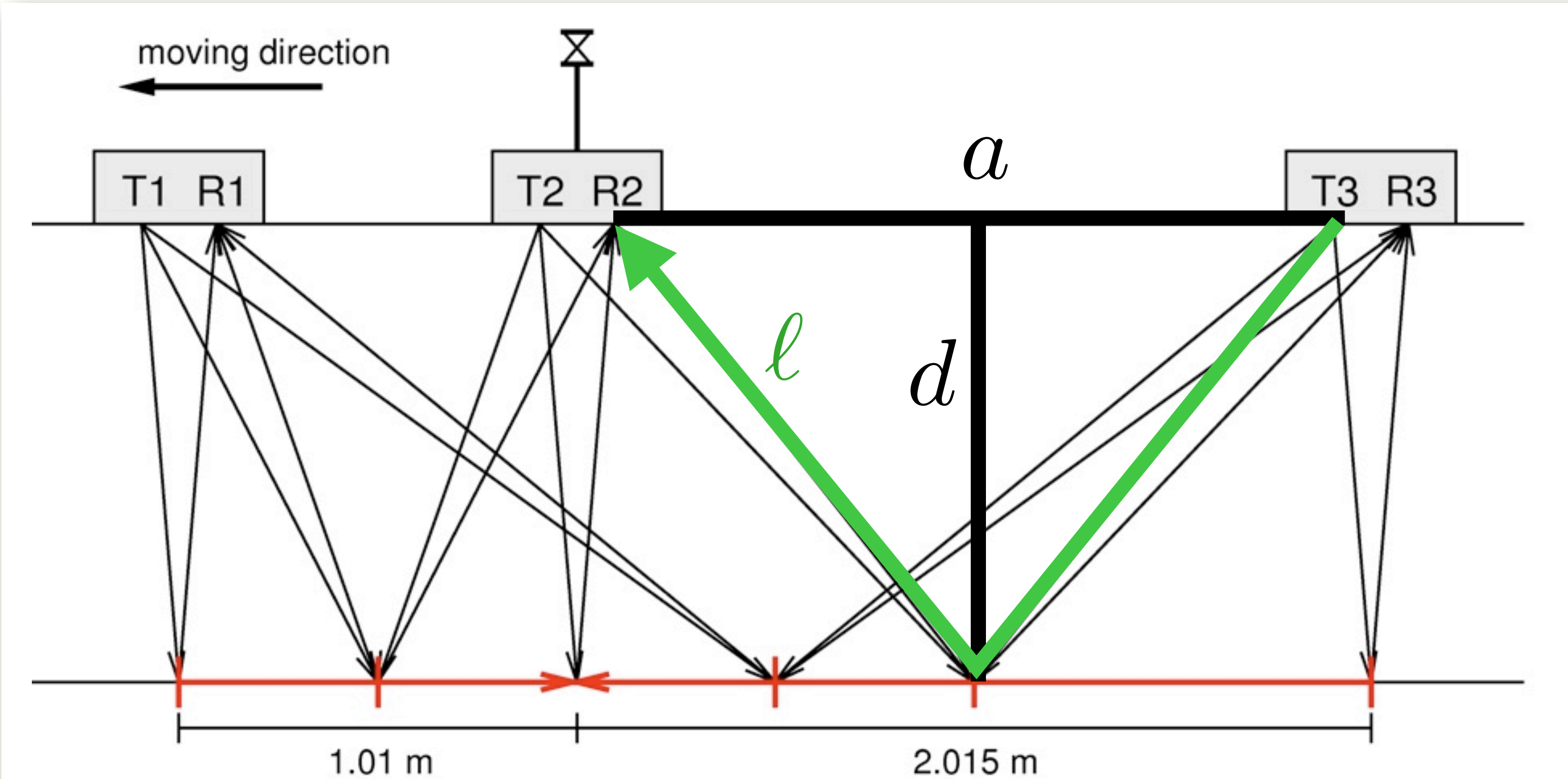
Single-channel GPR



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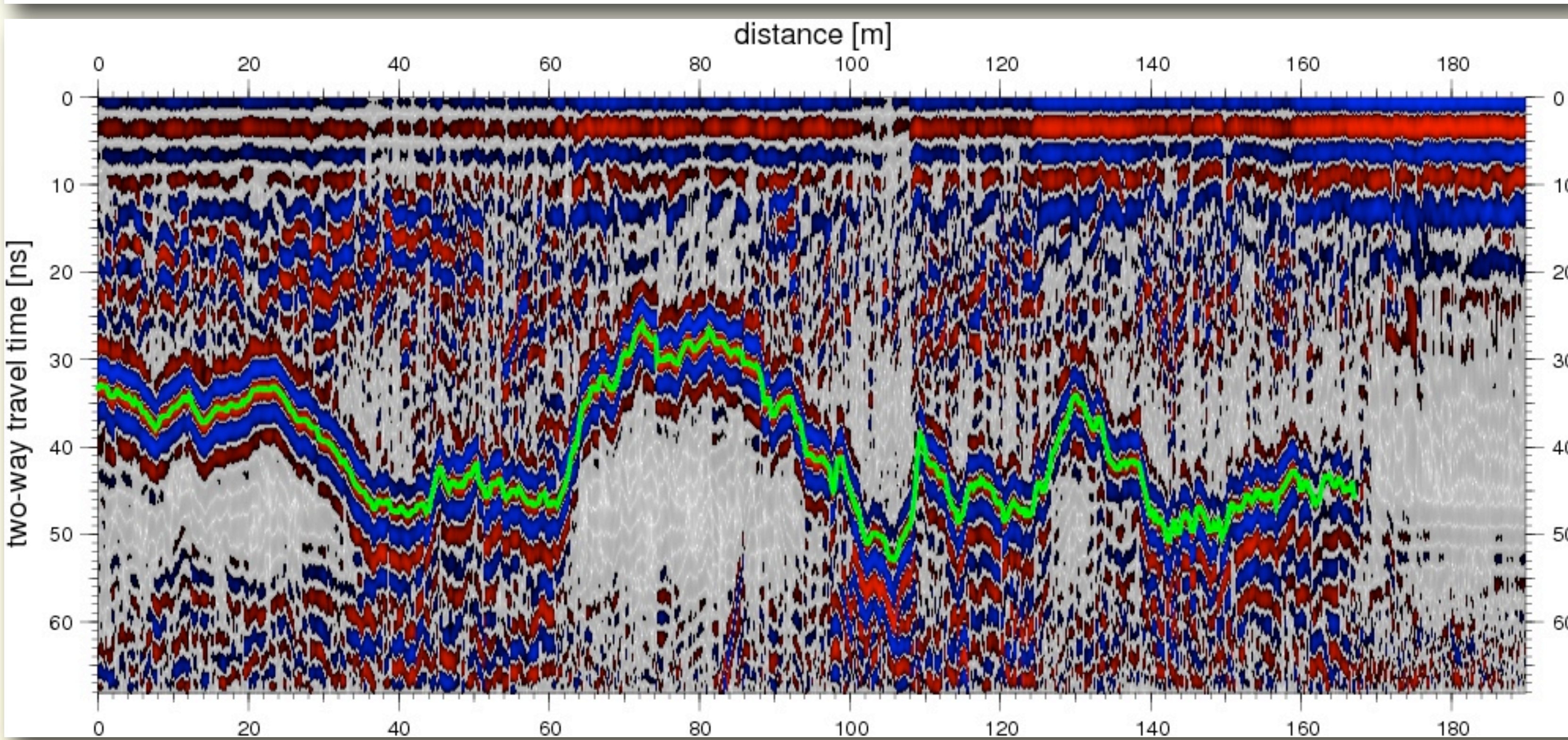

single channel common-offset measurement

$$t = \frac{\sqrt{\varepsilon_c(\theta)}}{c_0}\sqrt{4d^2 + a^2}$$

useless for soils

BUT:

one measurement

two unknowns!

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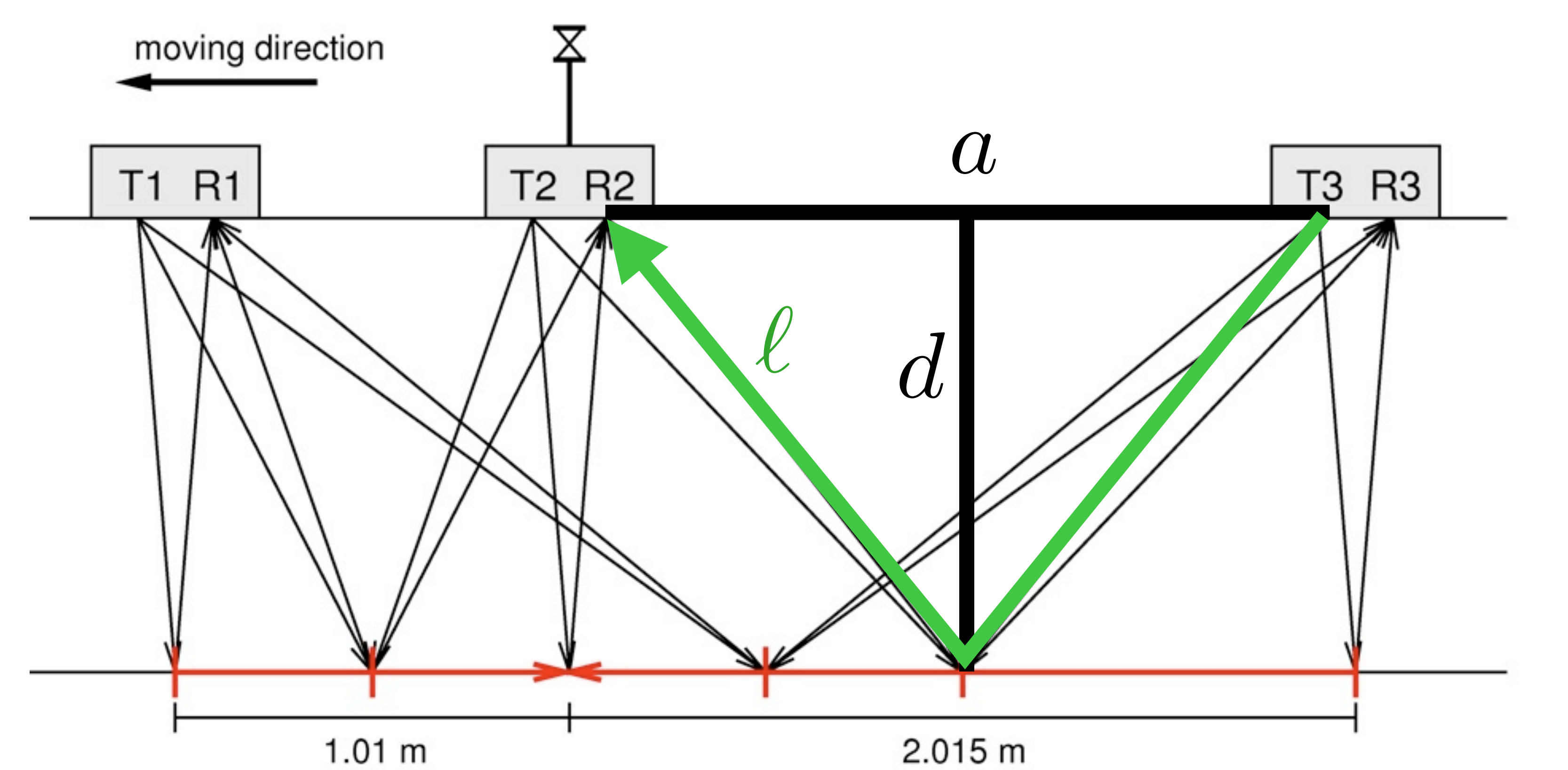
Multi-channel GPR

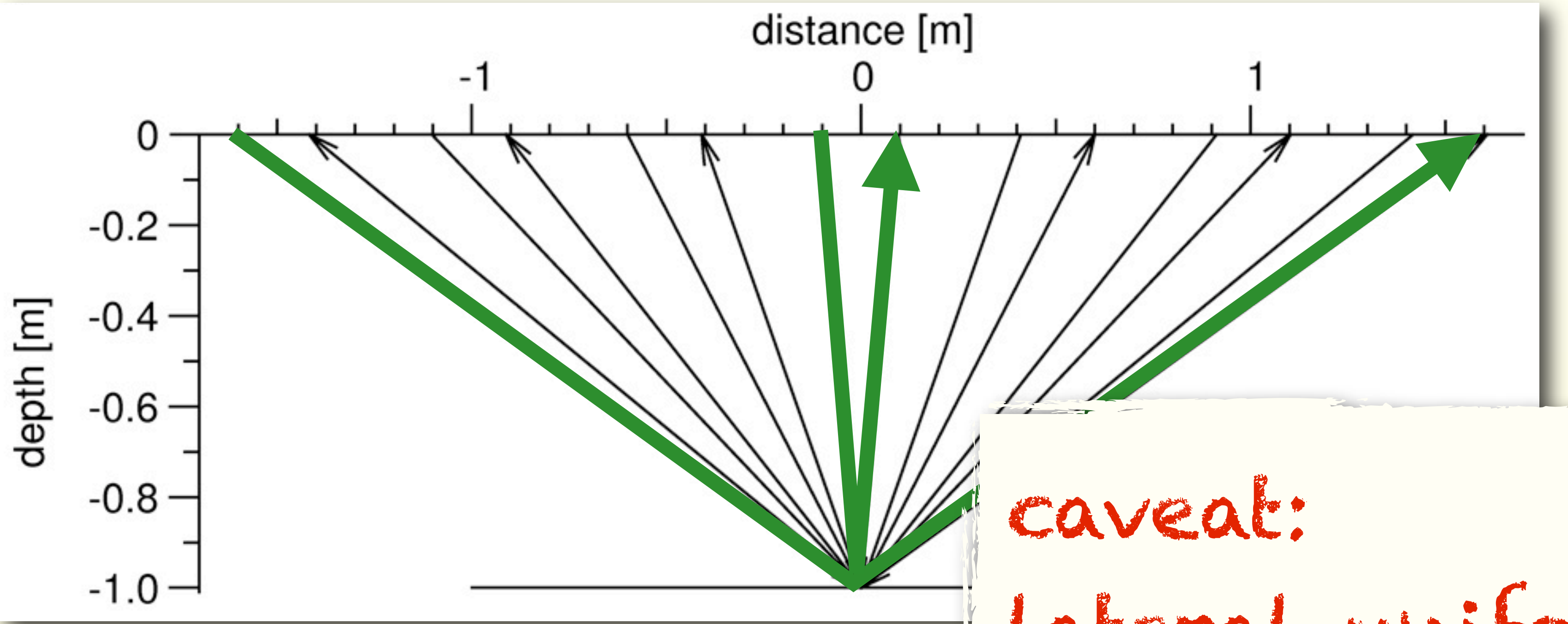


[modified from Wollschläger et al., 2010]

single channel common-offset measurement

$$t = \frac{\ell}{v}$$

$$= \frac{\sqrt{\varepsilon_c(\theta)}}{c_0}\sqrt{4d^2 + a^2}$$



multi-channel common-offset measurement

caveat:
lateral uniformity

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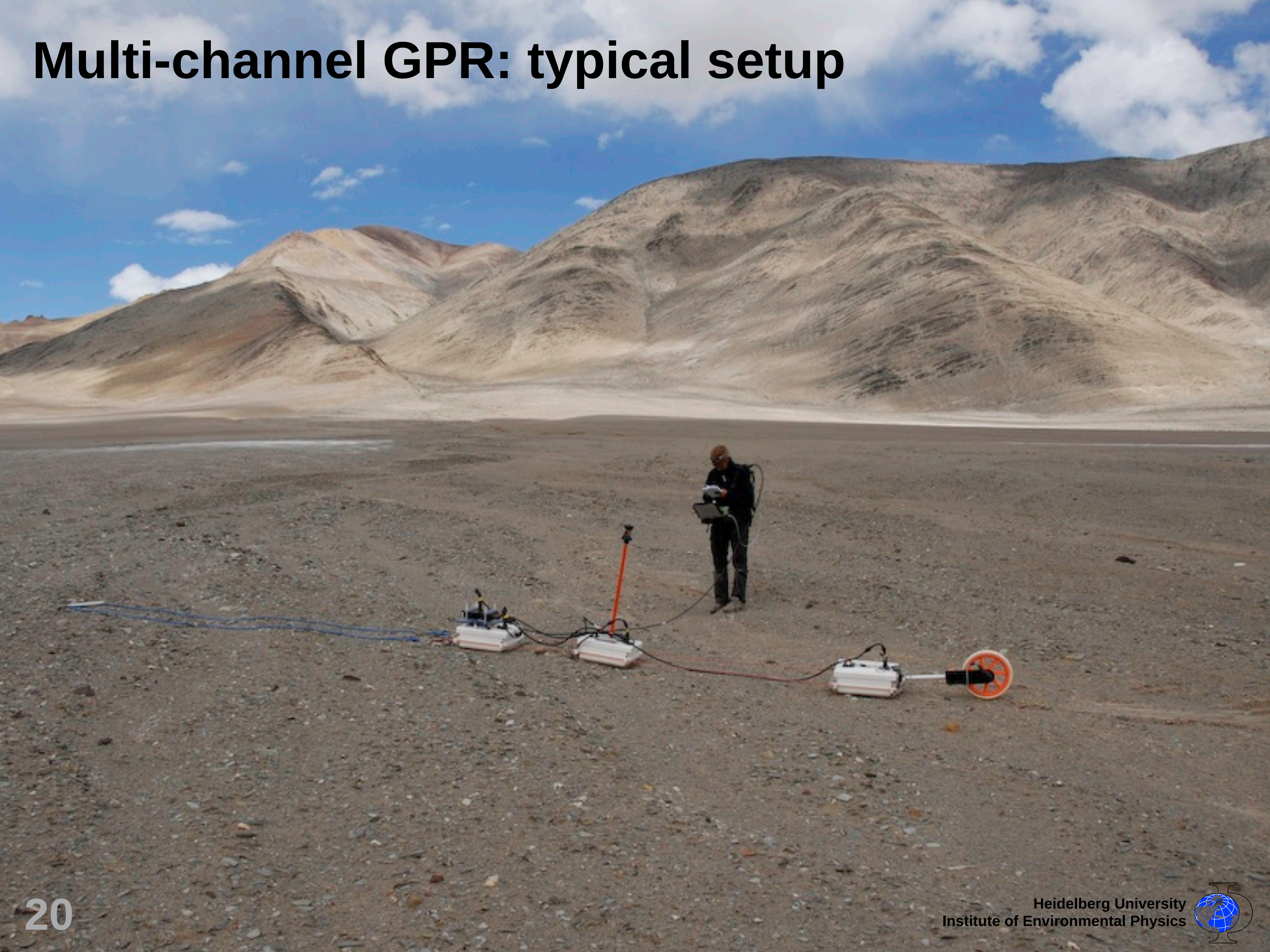
Multi-channel GPR: typical setup



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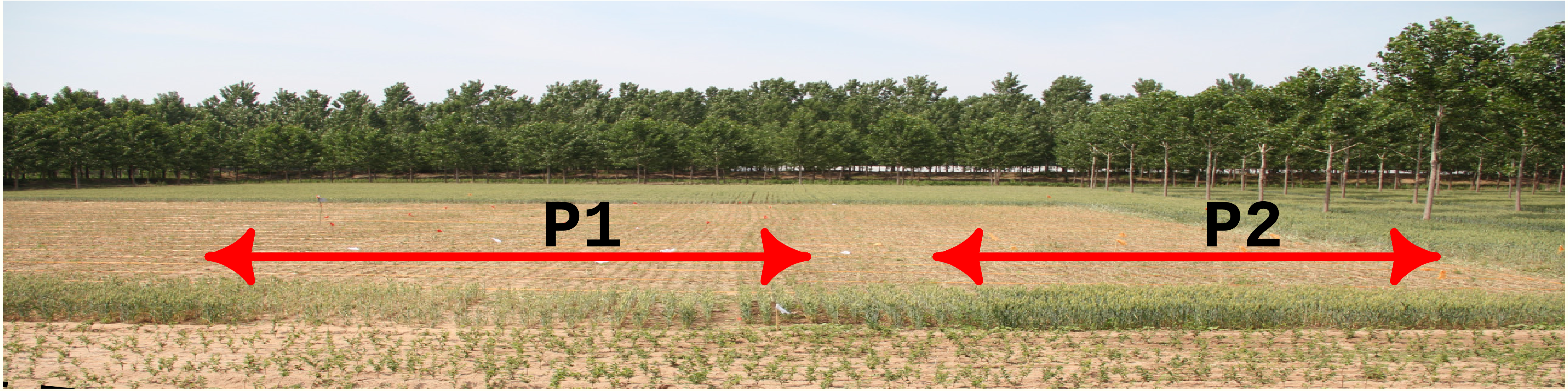
Application: Huang-Huai-Hai Plain, China
[exploratory study by Pan Xicai, 2011]



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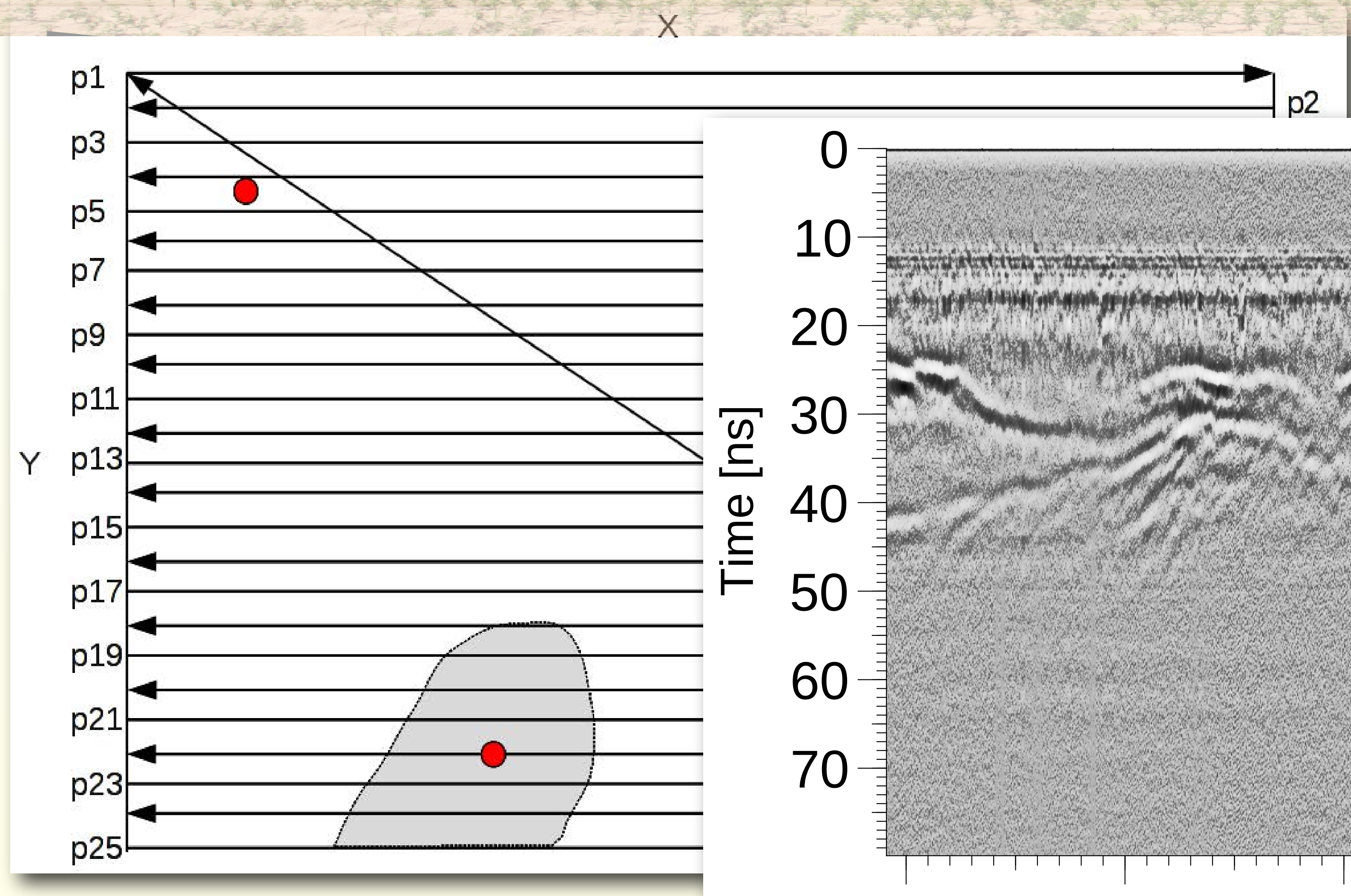
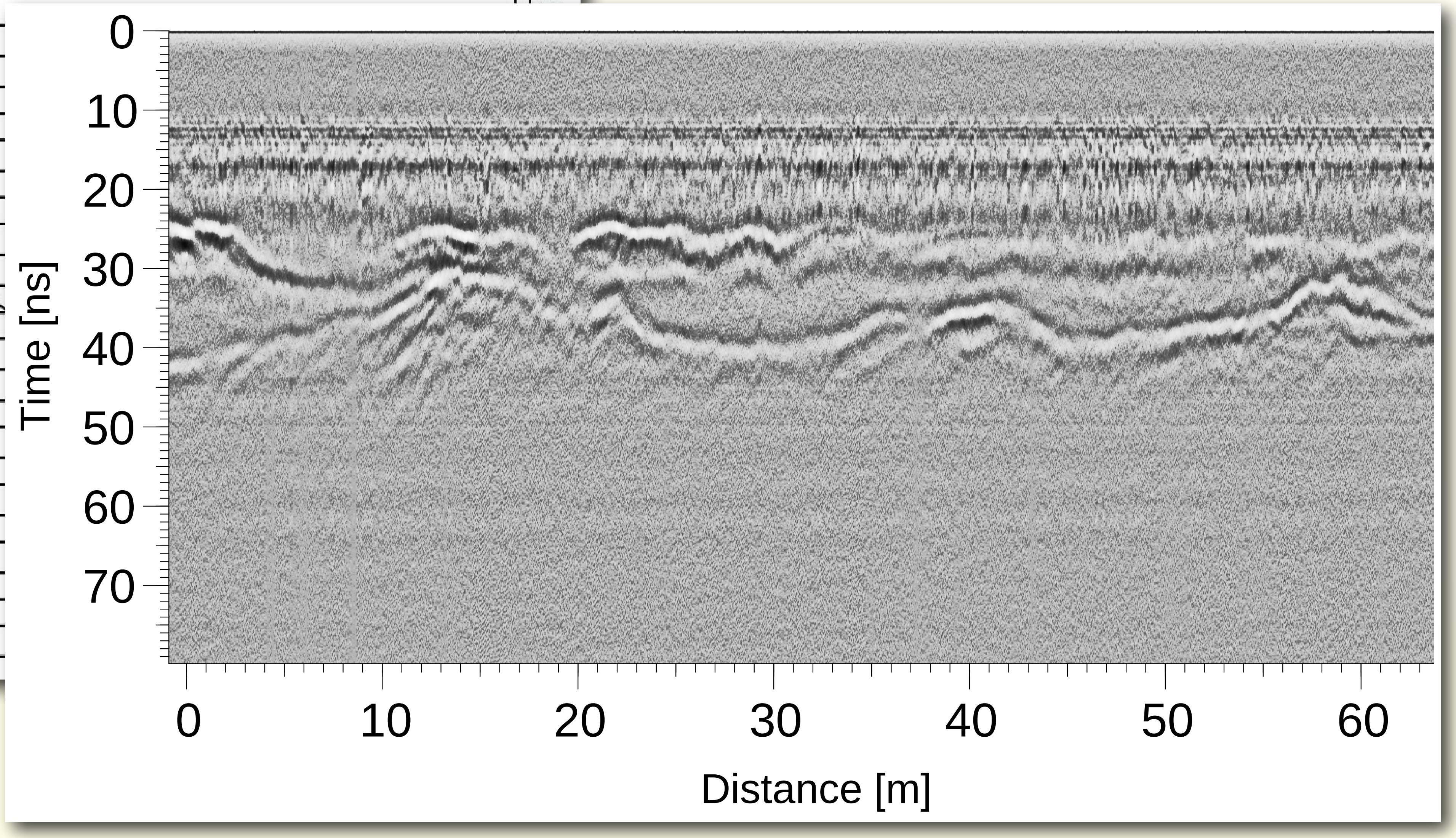
HHH Plain: subsurface architecture





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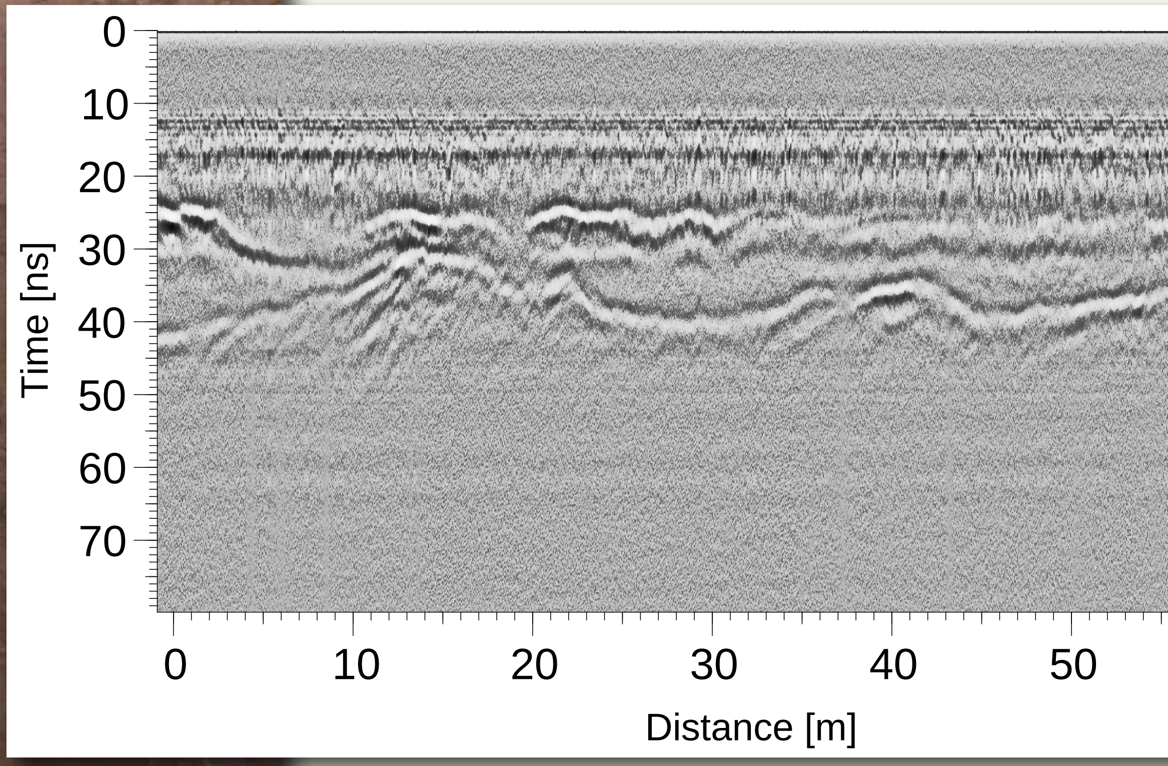
HHH Plain: subsurface architecture



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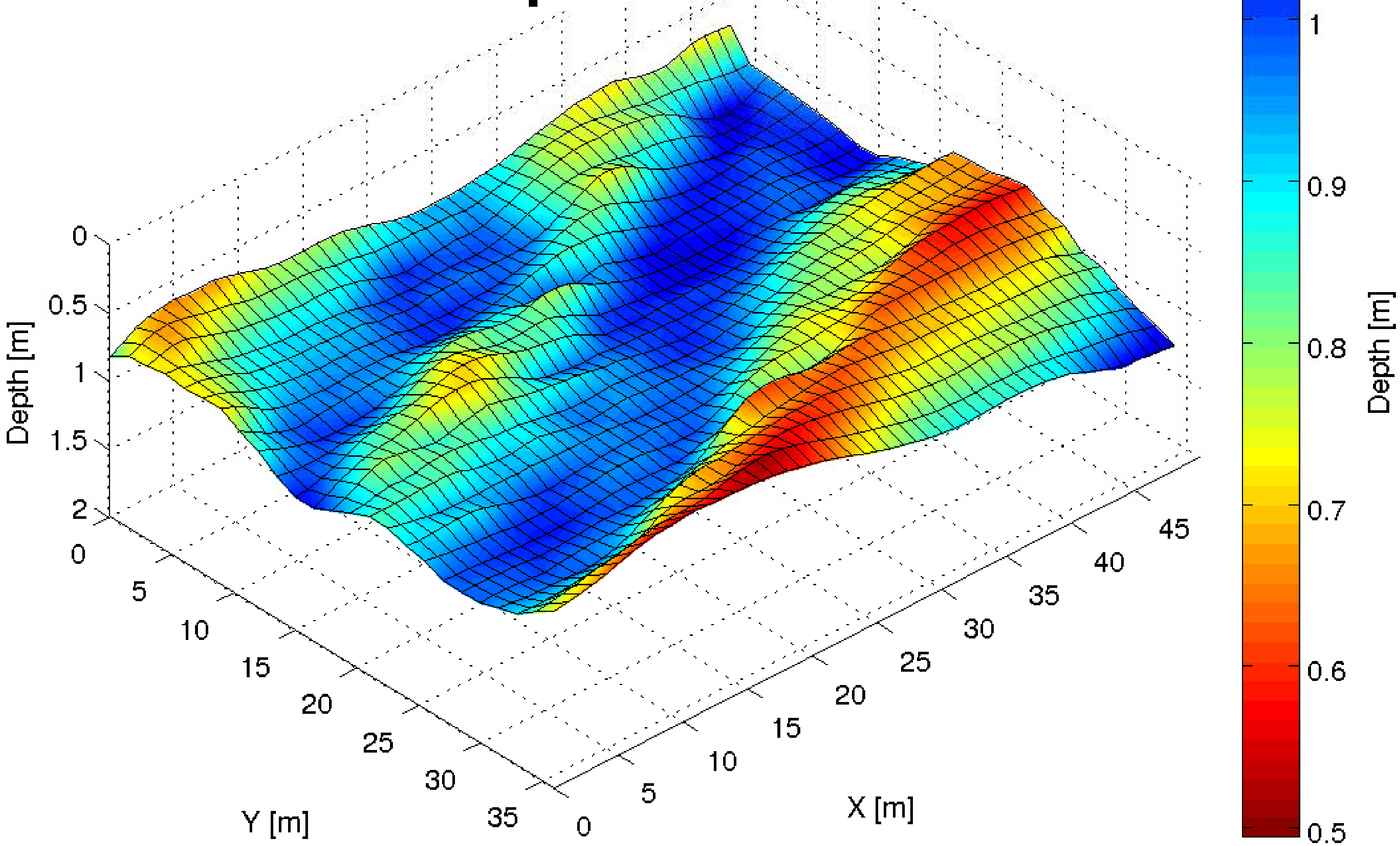
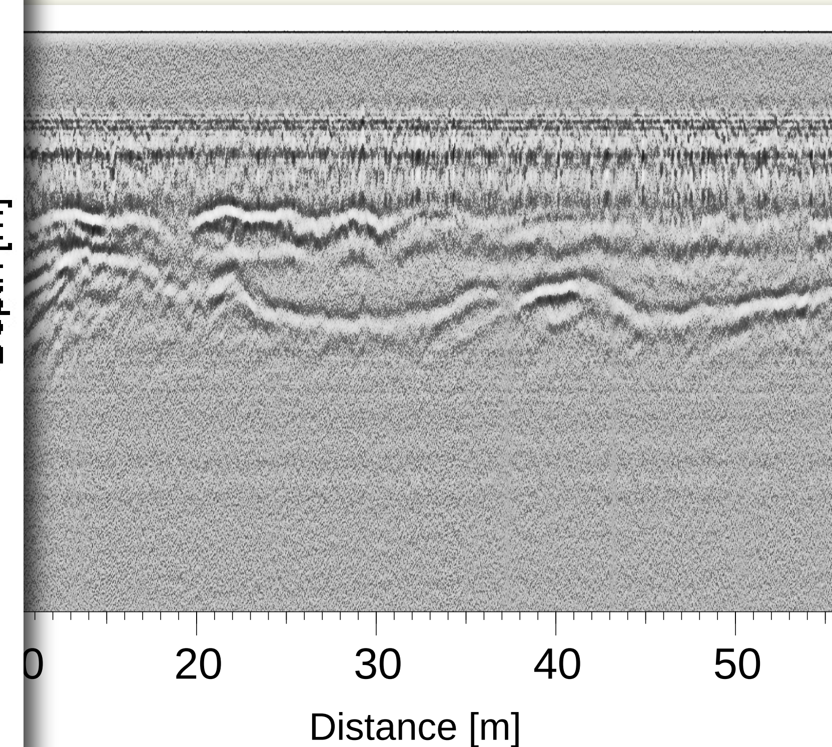
HHH Plain: subsurface architecture

main reflector:
old dune landscape





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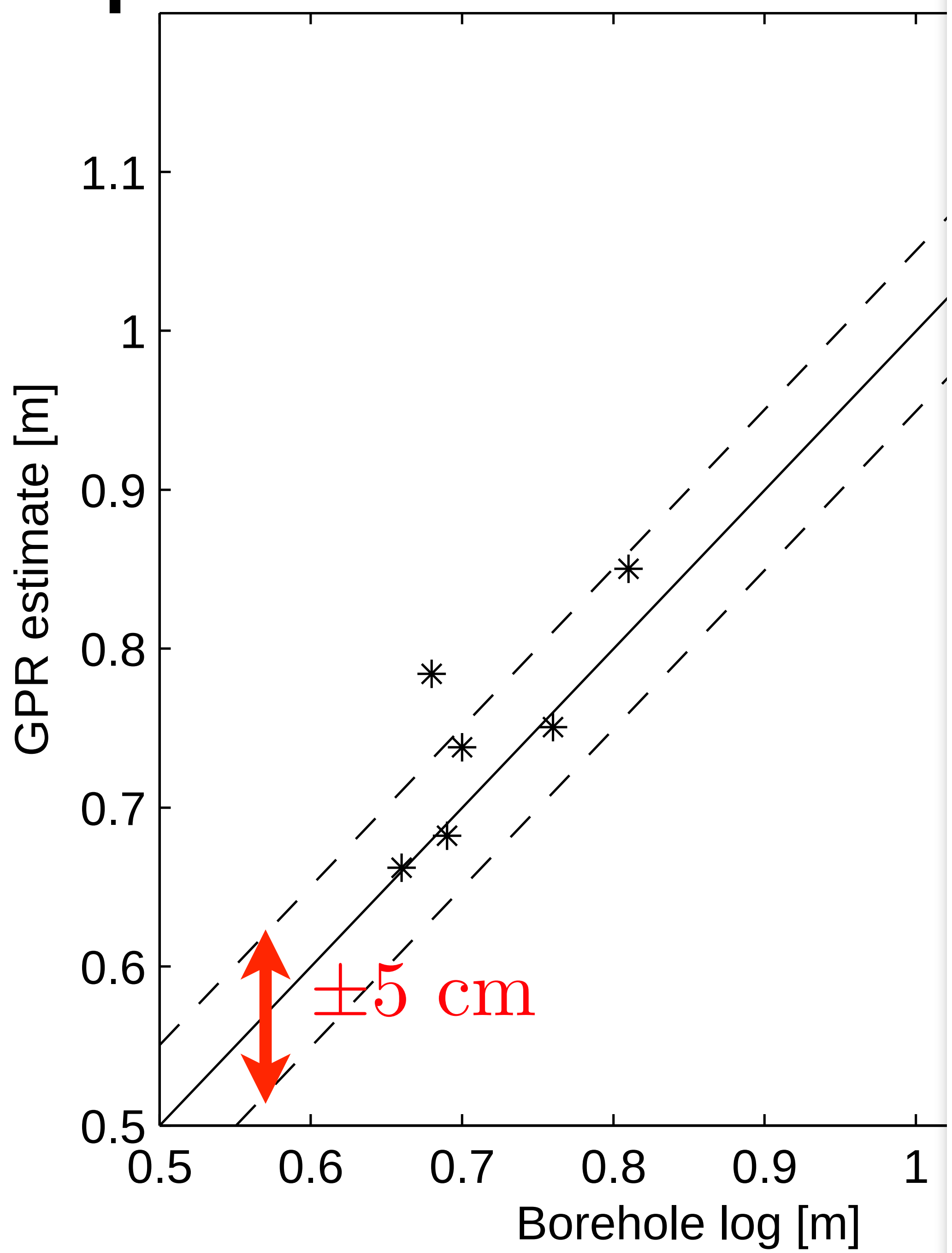
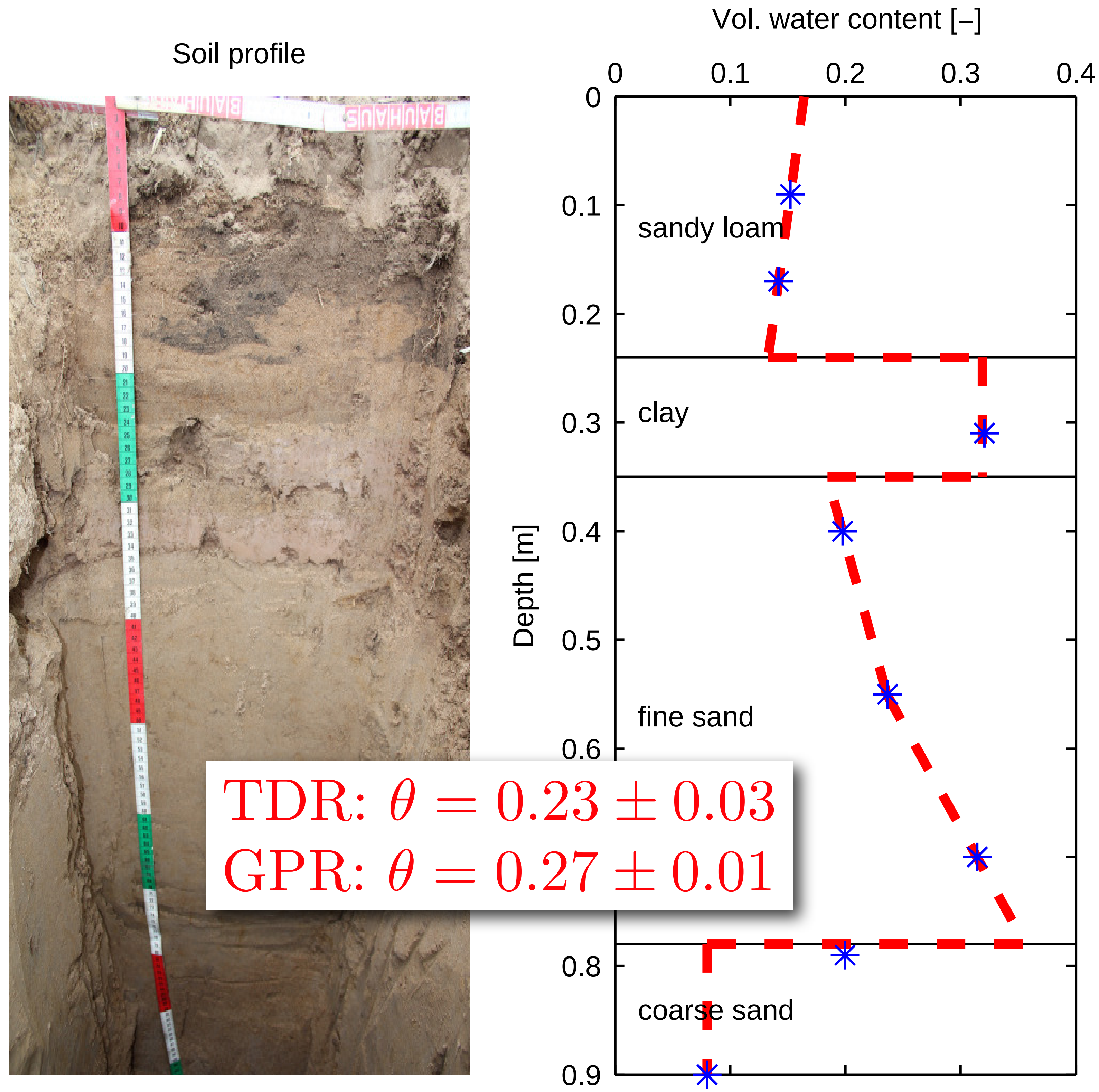
HHH Plain: assessment of accuracy

depth of main reflector



volumetric water content



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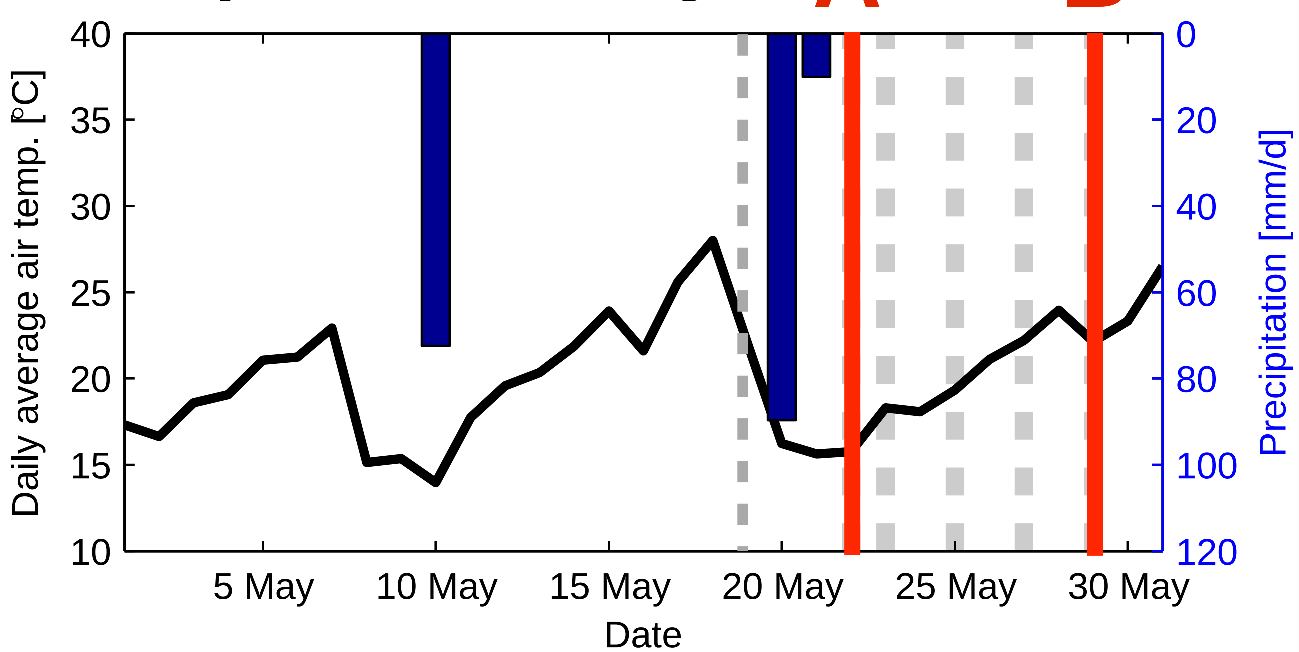
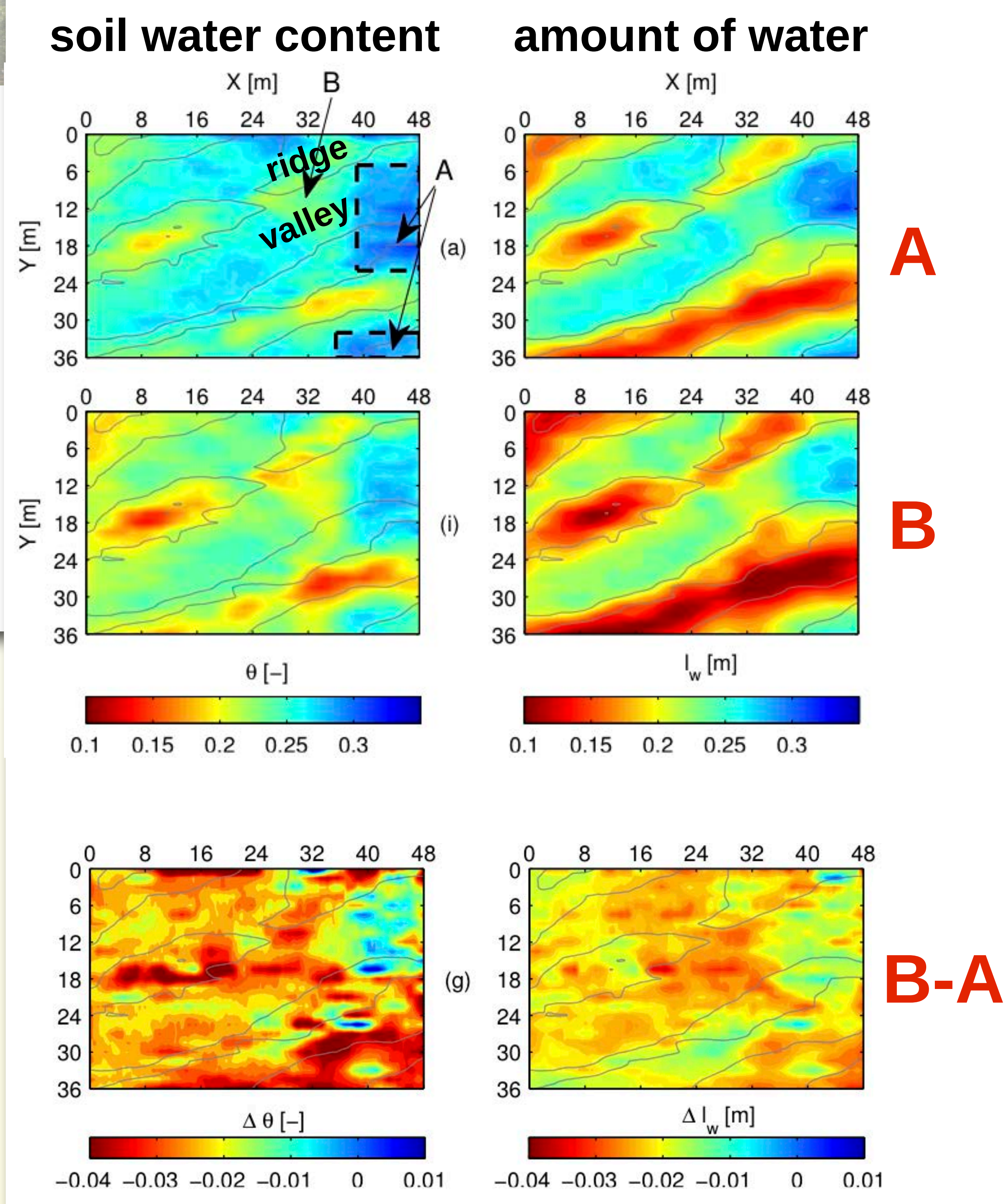
HHH Plain: soil hydrology

atmospheric forcing





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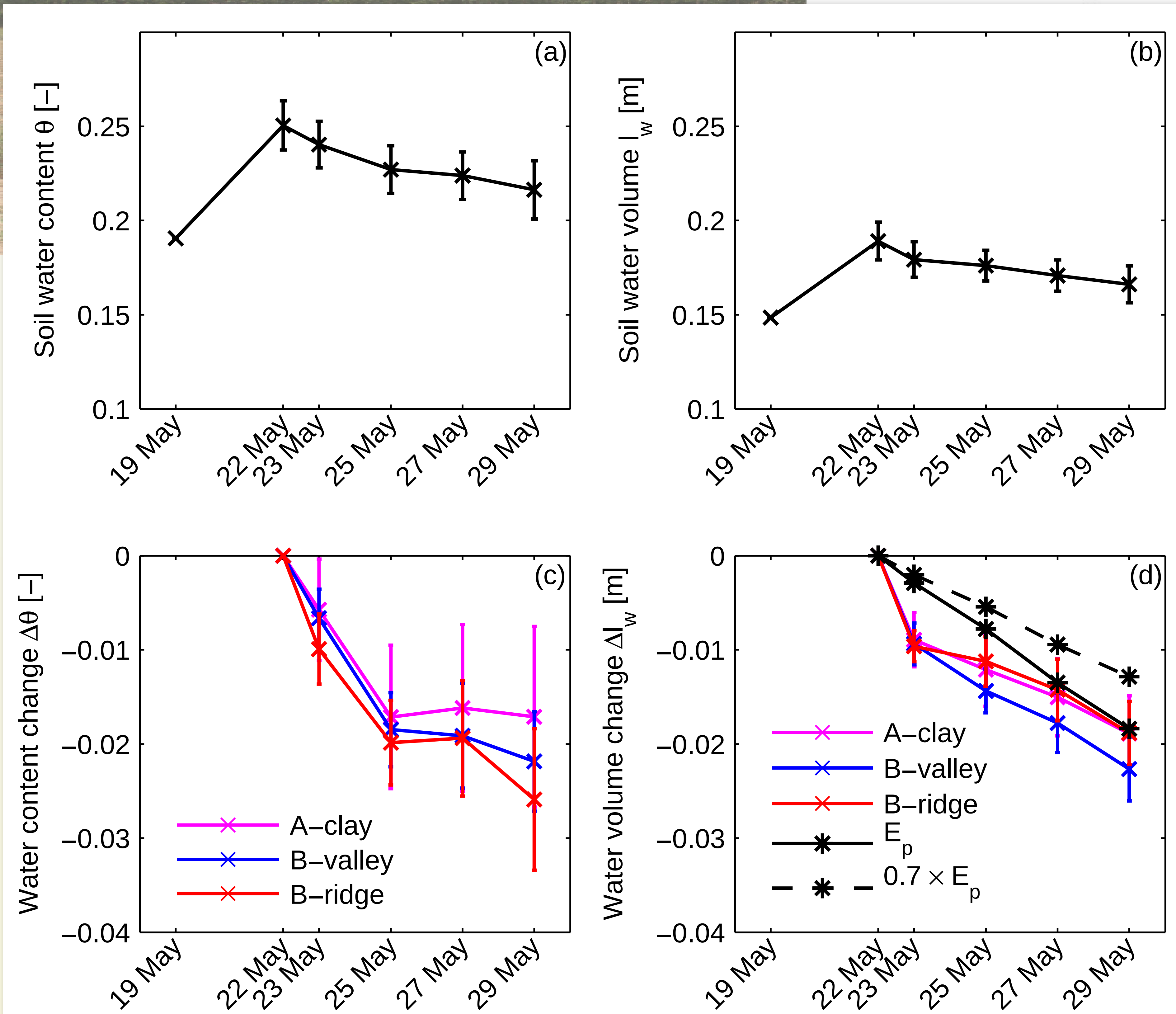
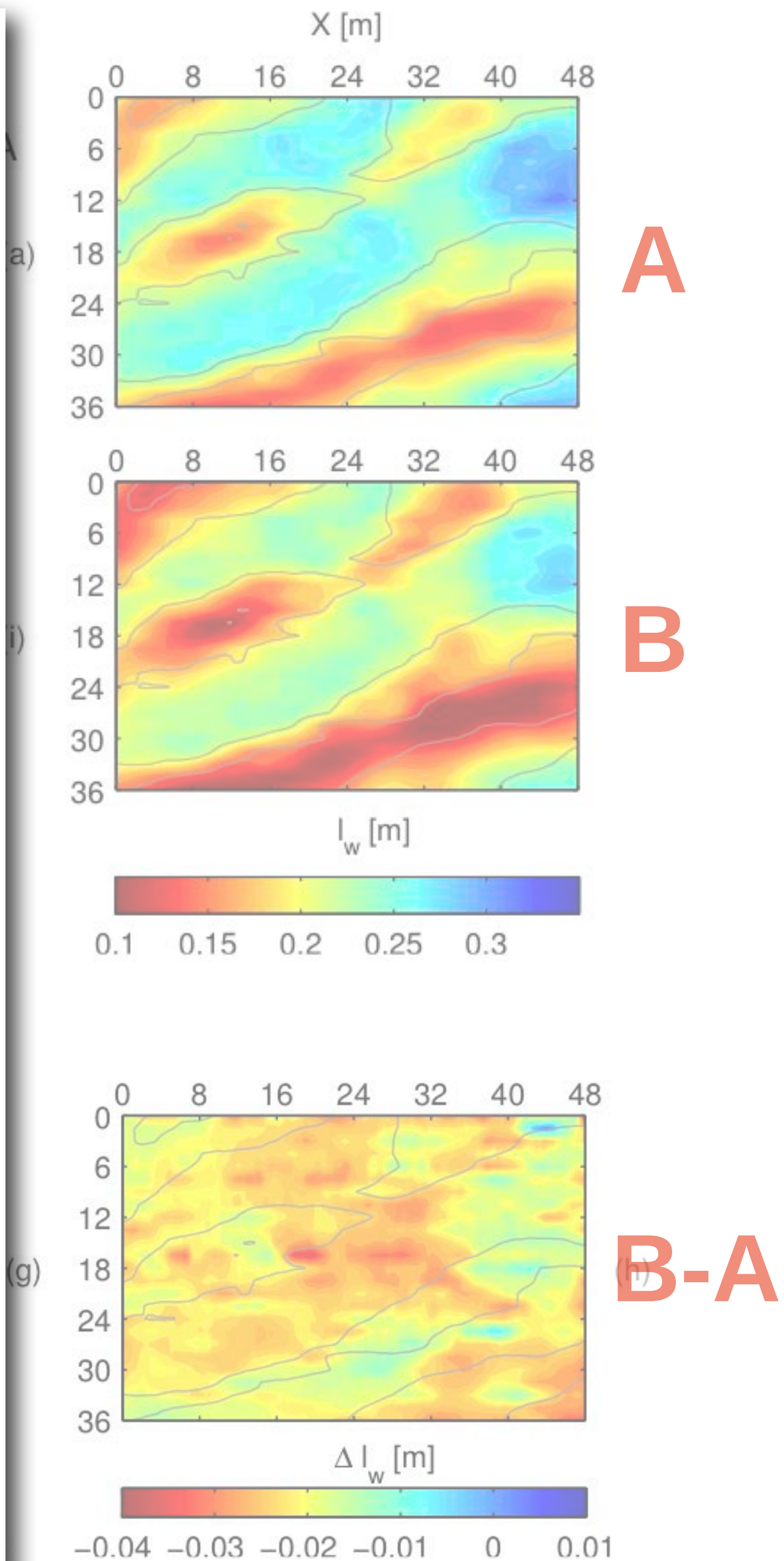
HHH Plain: soil hydrology

soil water content   amount of water





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HHH Plain: soil hydrology

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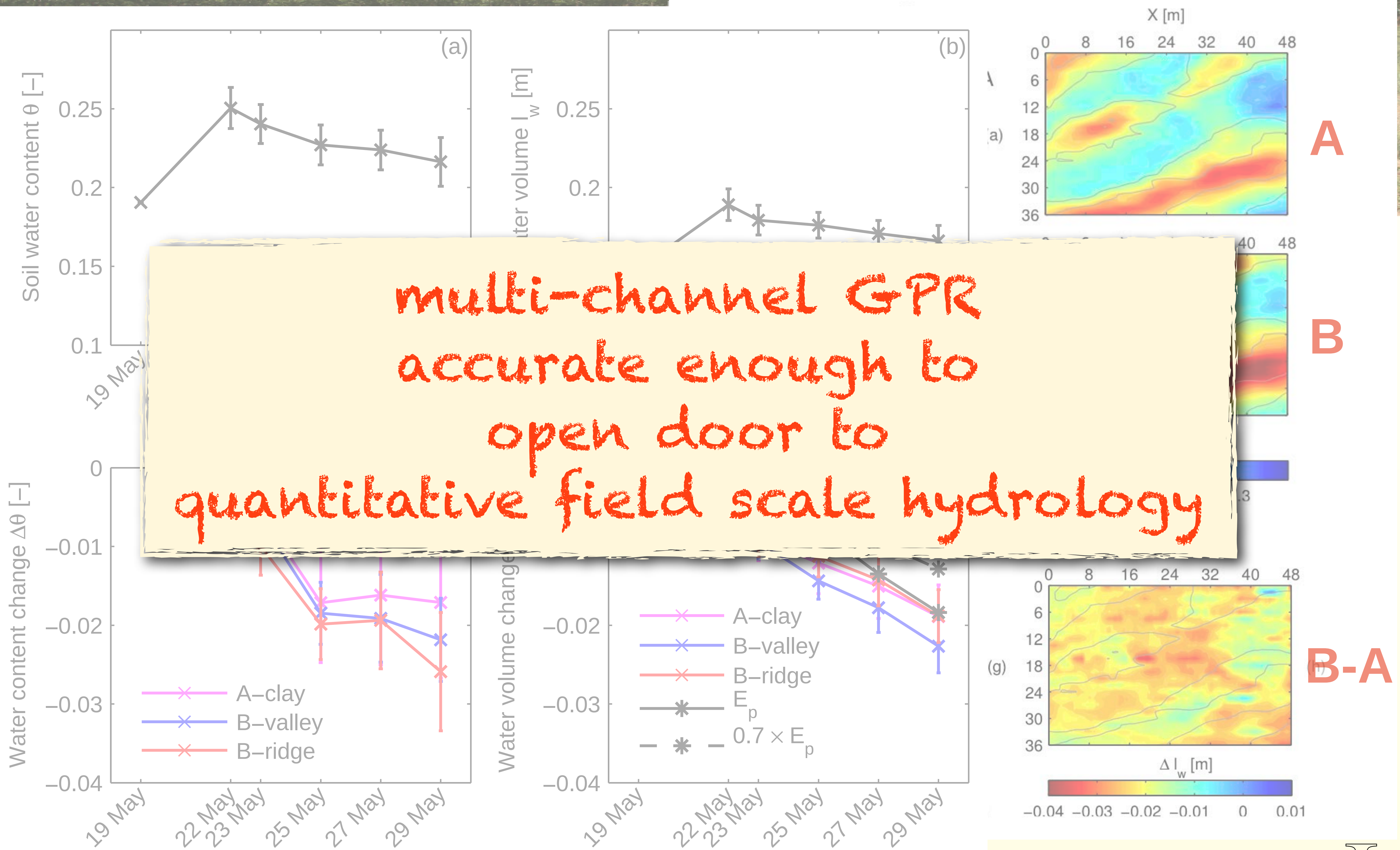

multi-channel GPR
accurate enough to
open door to
quantitative field scale hydrology

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Constructive inversion: rough concept

[PhD project of Jens Buchner, 2012]

- construct parametric representation of subsurface architecture from traditional single-/multi-channel scan
- simulate GPR measurement numerically
- identify prominent features in measured & simulated radargrams
- adjust architecture parameters for optimal agreement

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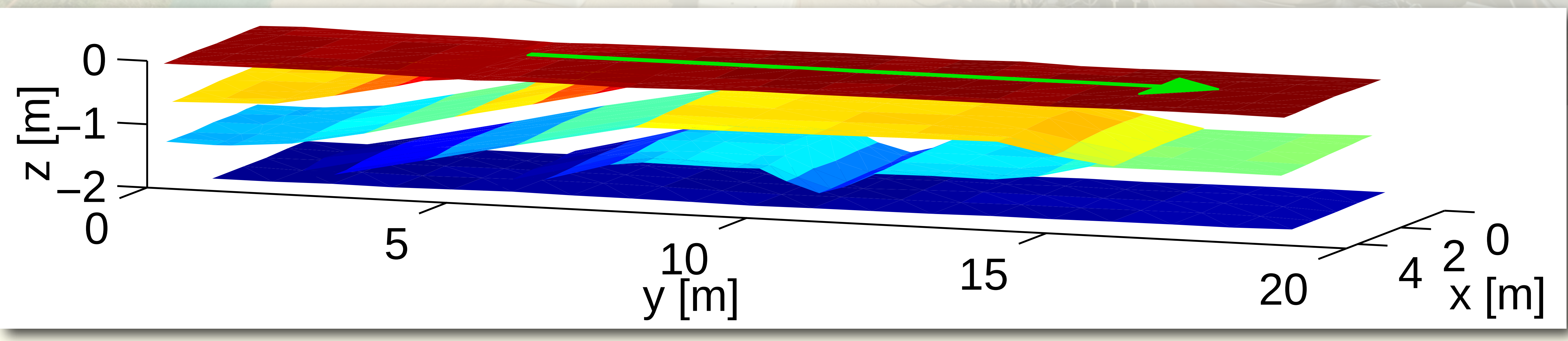
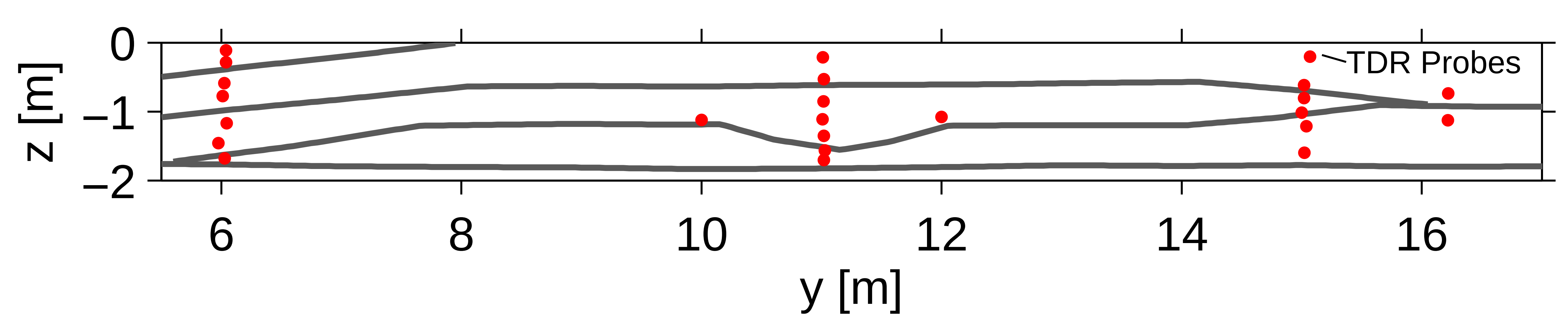
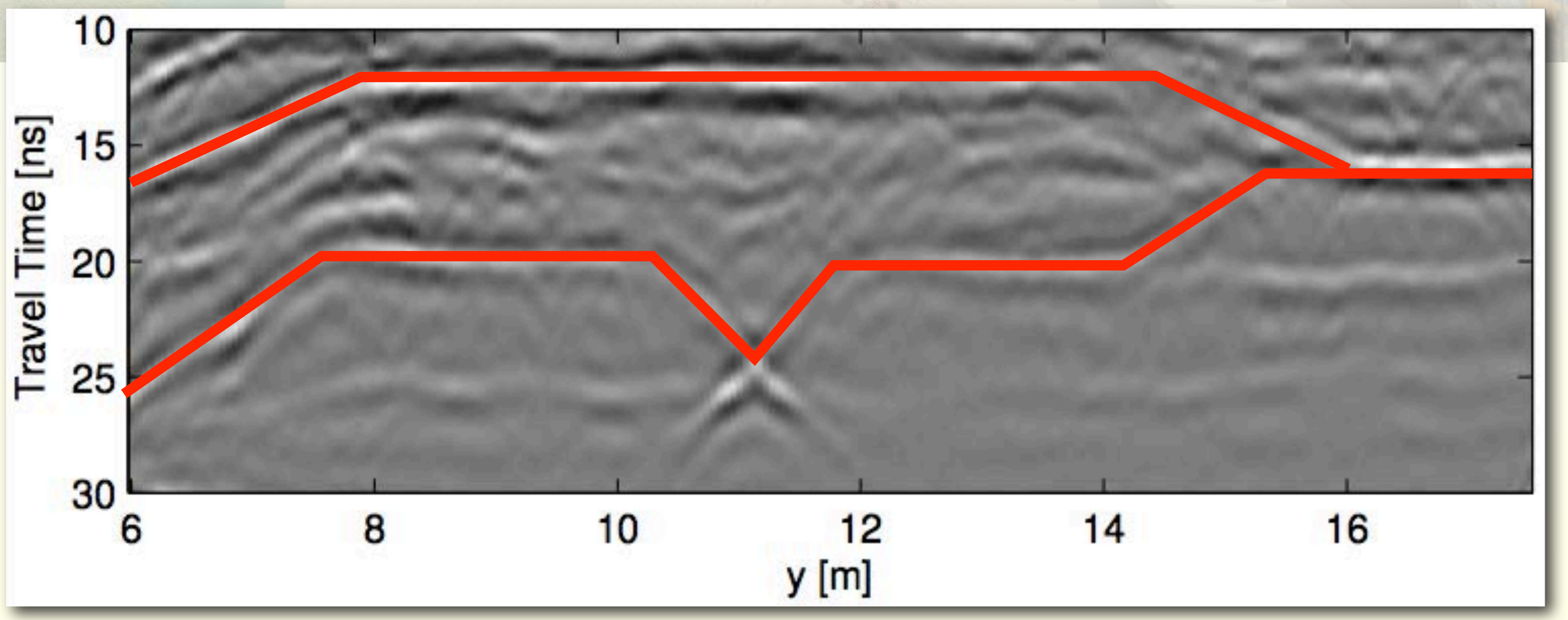
ASSESS-GPR site





Parametric architecture model

- construct parametric representation of subsurface architecture from traditional single-/multi-channel scan



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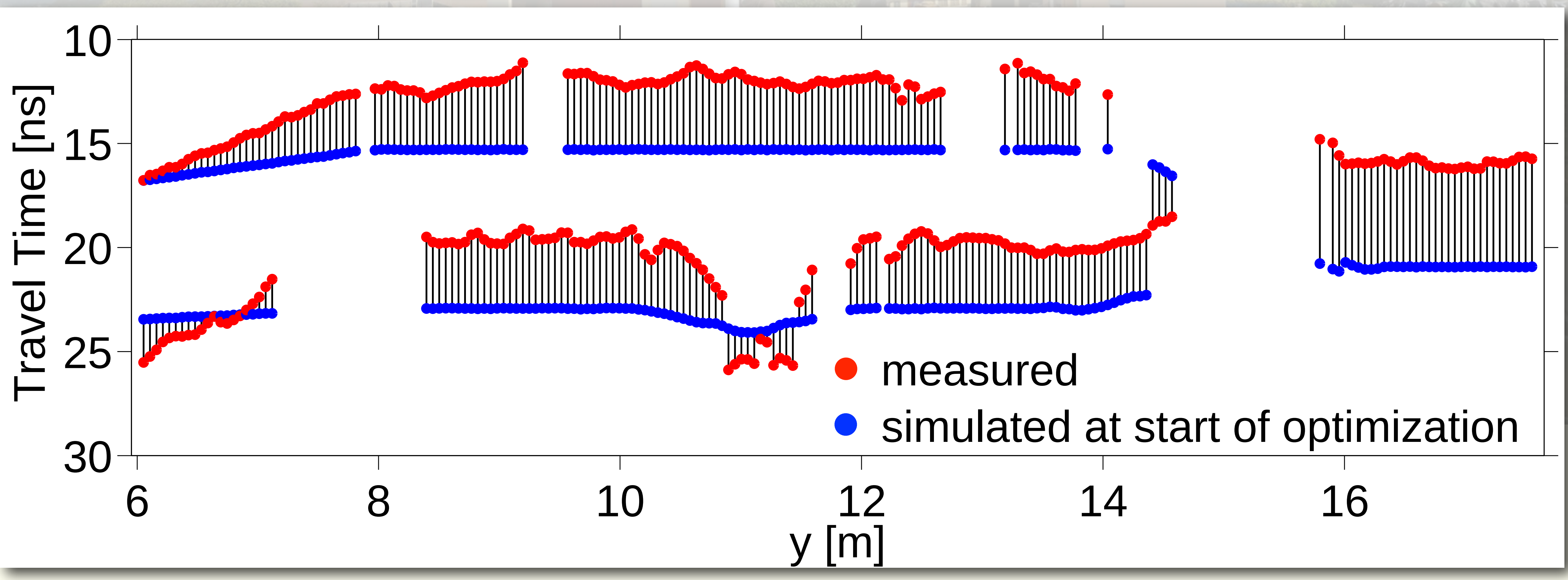
Identification of features and pairing



- adjust architecture parameters for optimal agreement

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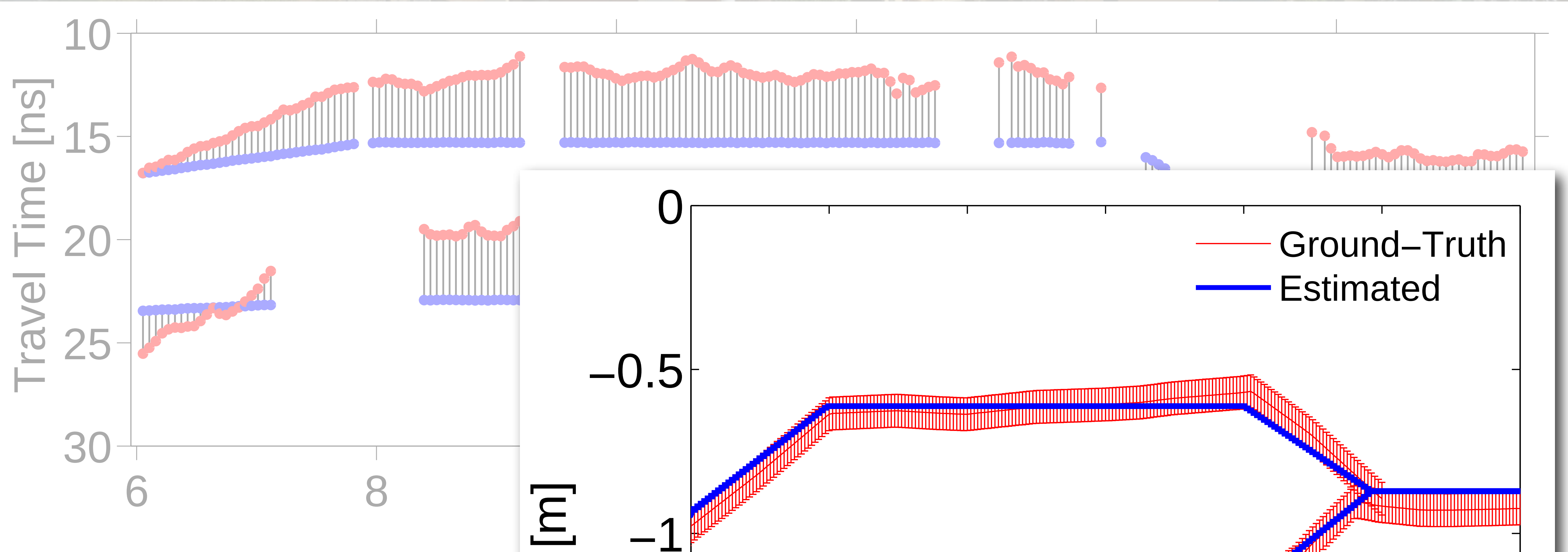
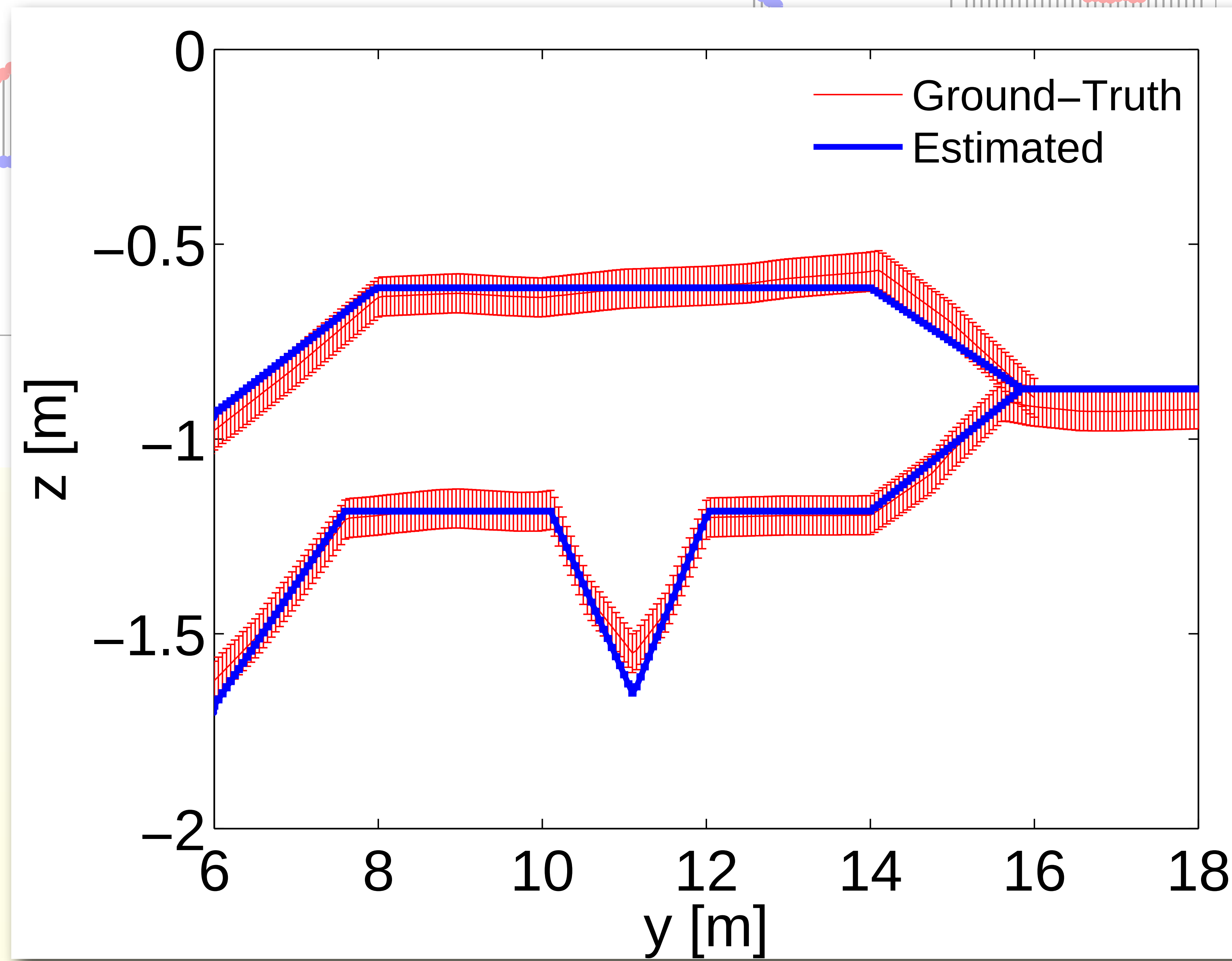
Assessment of accuracy





depth of reflector

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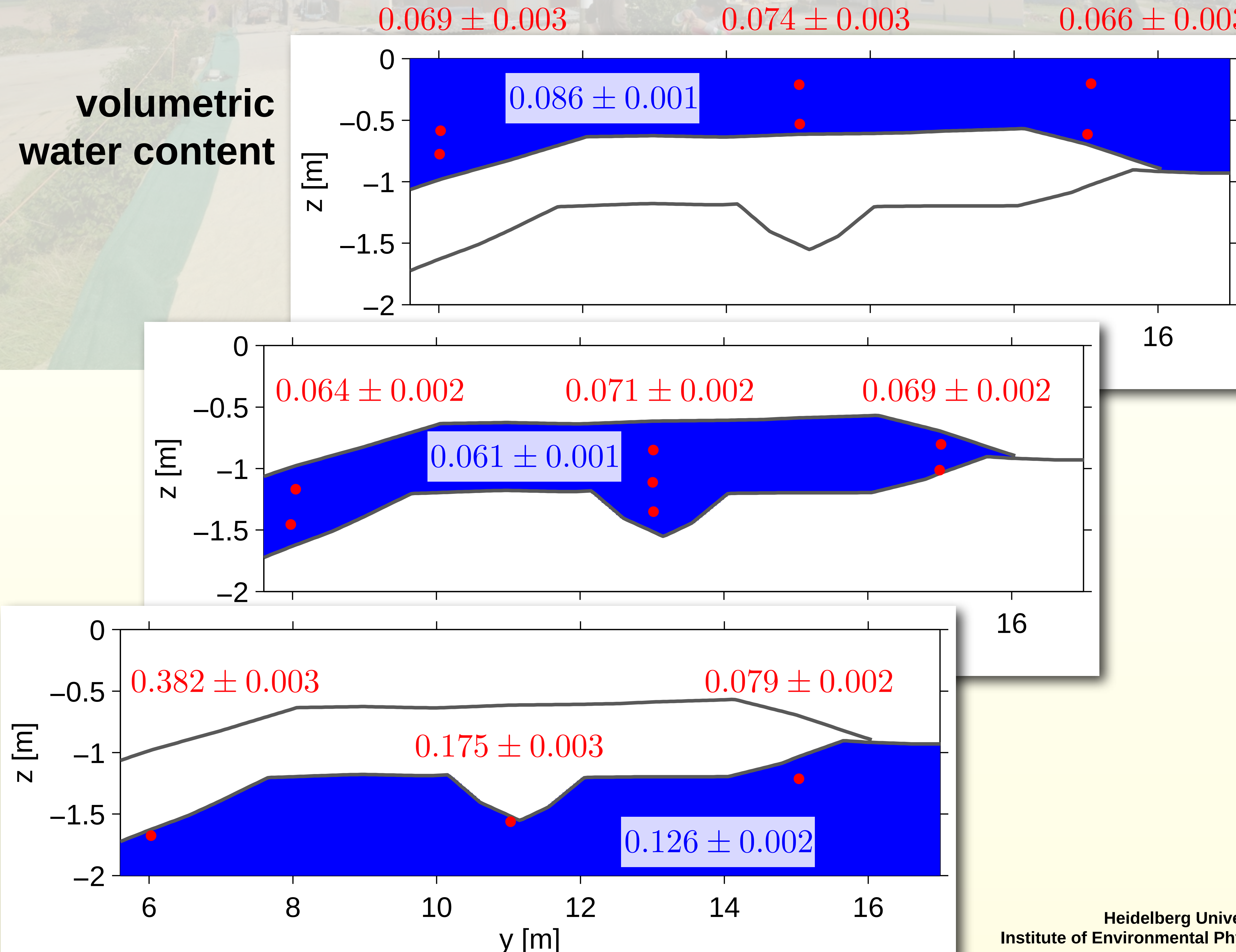
Assessment of accuracy

volumetric water content



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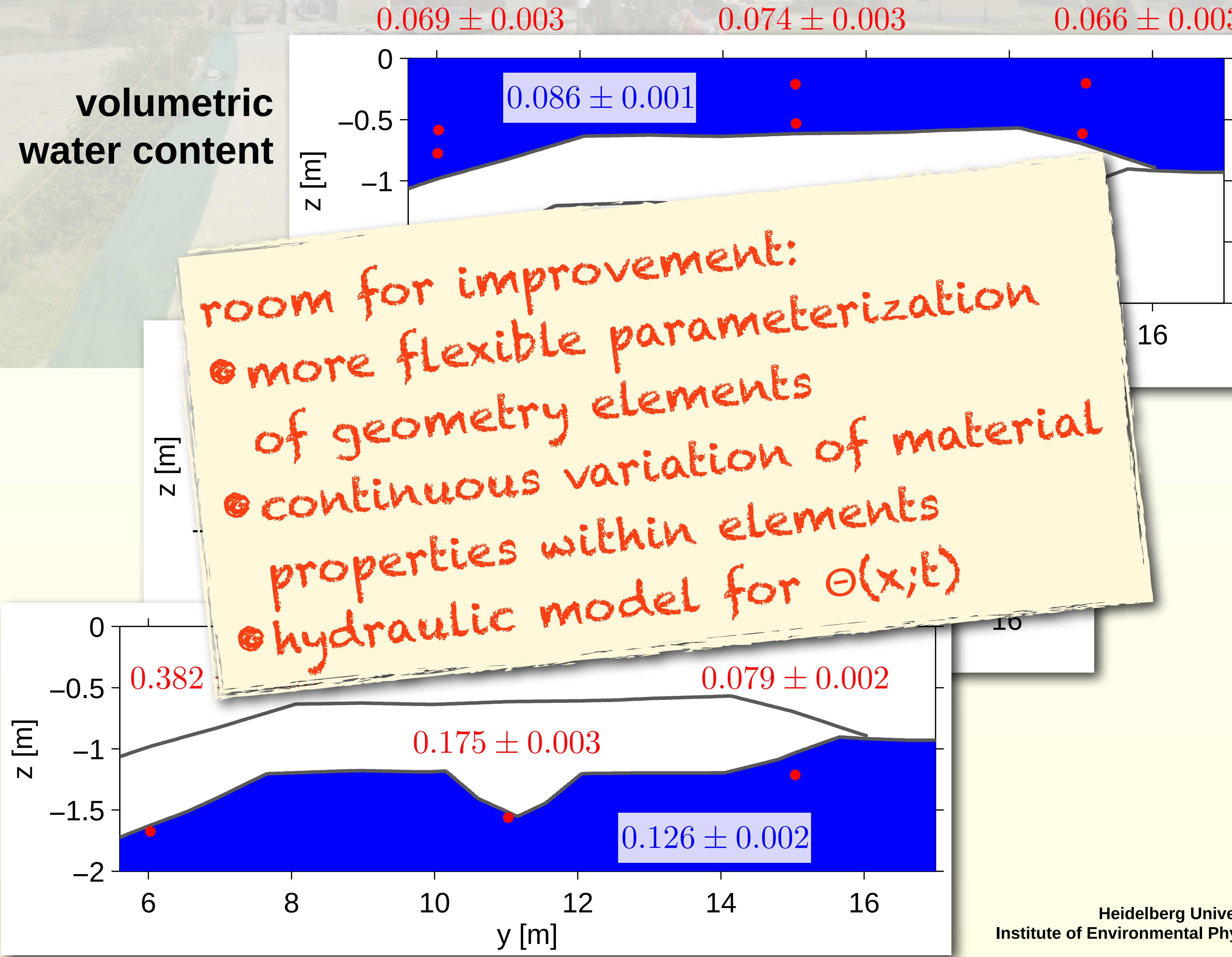
Assessment of accuracy

volumetric
water content



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- need to simulate with very high resolution in order to represent all relevant phenomena

- probably (hopefully) need not
  - explicitly parameterize
  - observe

  with that resolution


there’s light!
thank you
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