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Quantitative analysis of geoelectrical monitoring data

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
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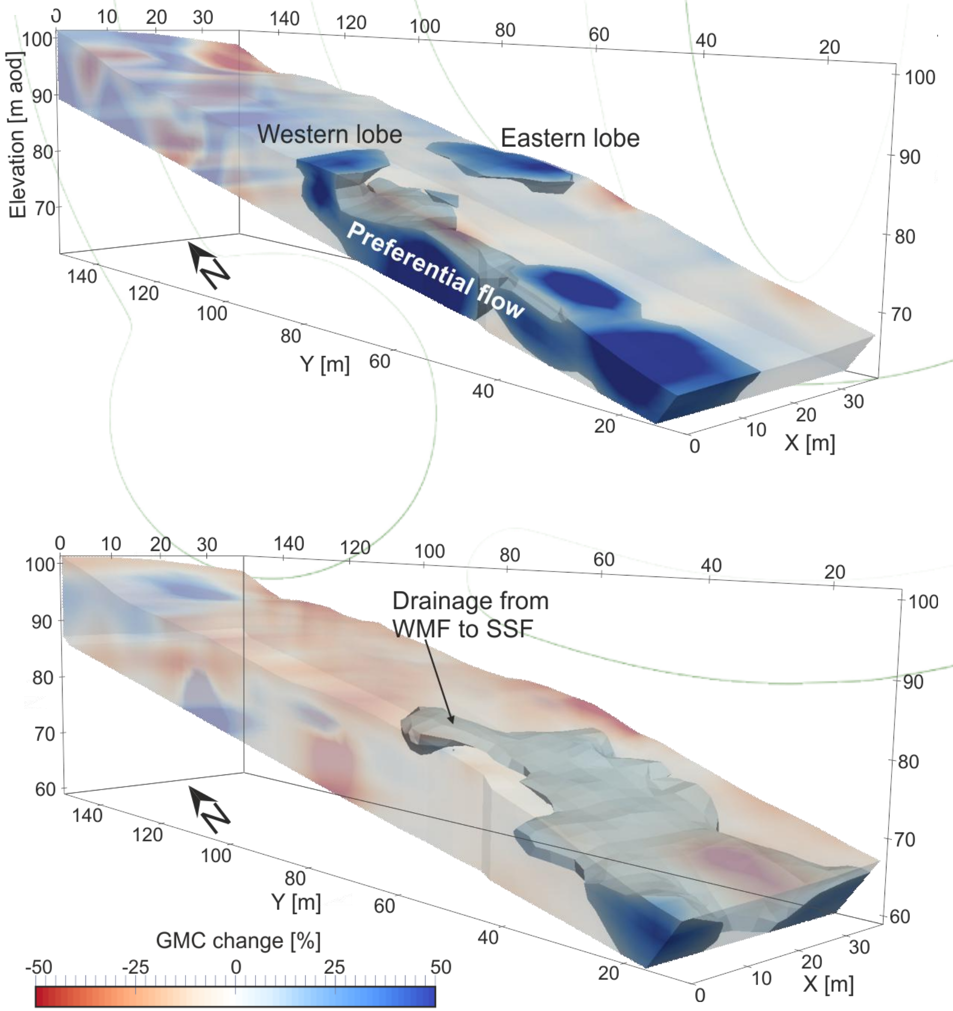
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani

Outline of the day

- **Fundamentals of electrical resistivity measurements**
  - Electrical properties of soils and rocks
- **Geoelectrical monitoring: measurement principles and properties**
  - Basic principles, inversion approaches
  - Practical considerations
  - Examples
- **Quantitative analysis of geoelectrical monitoring data**
  - Limitations & opportunities
  - Applications
- **Examples of integrated landslide monitoring**

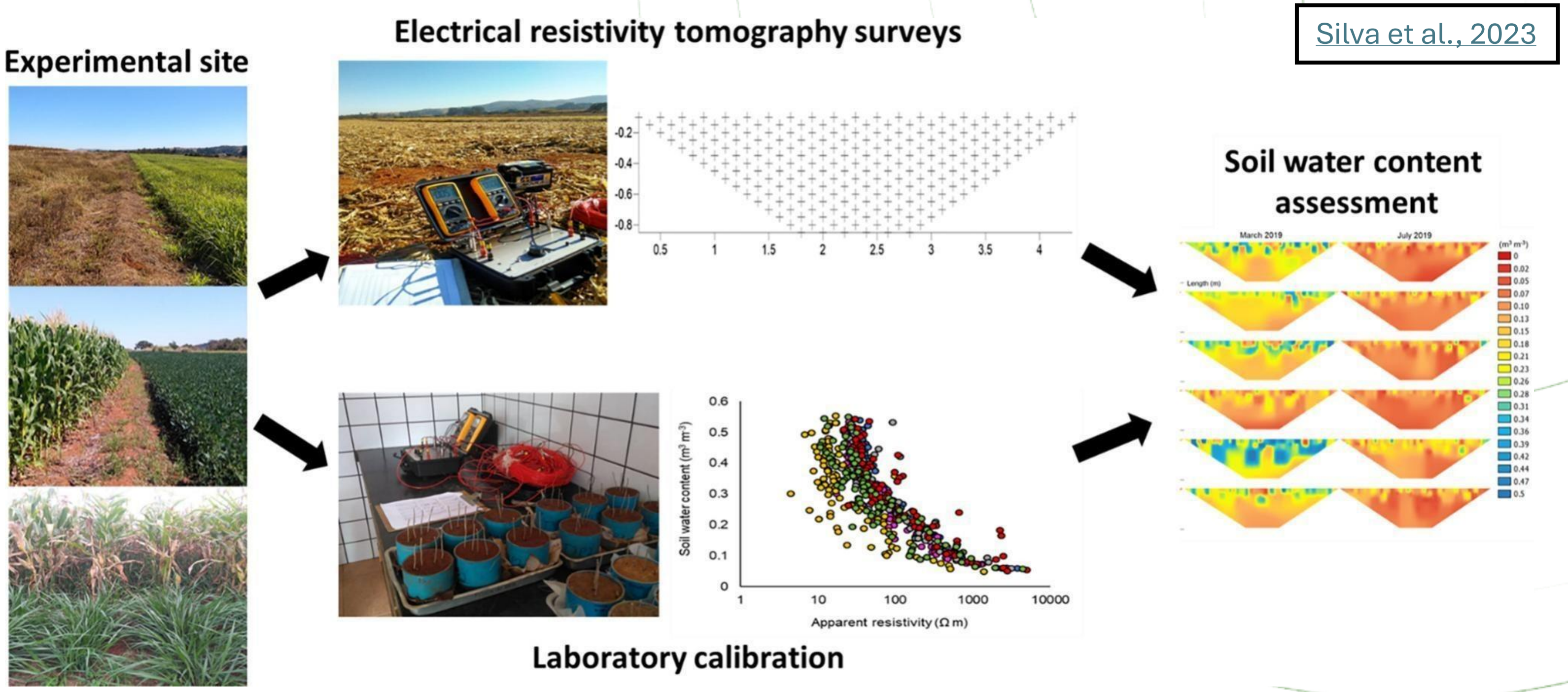


Why electrical and electromagnetic methods?

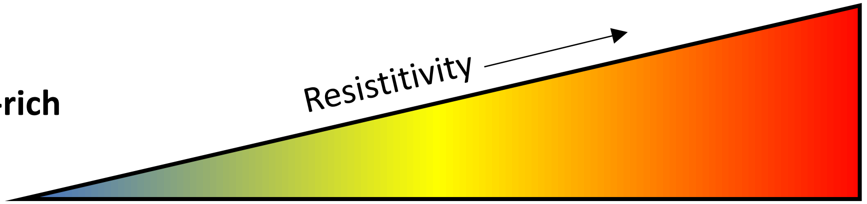
Silva et al., 2023

The electrical resistivity of Earth materials is highly sensitive to variations in the hydraulic properties of the subsurface:

- **Porosity**
- **Saturation**
- **Grain size distribution (hydraulic conductivity)**
- **Pore fluid conductivity**



Wet, warm, clay-rich, ion-rich (salty)



Dry, cold, no clay, ion-depleted

Why electrical and electromagnetic methods?

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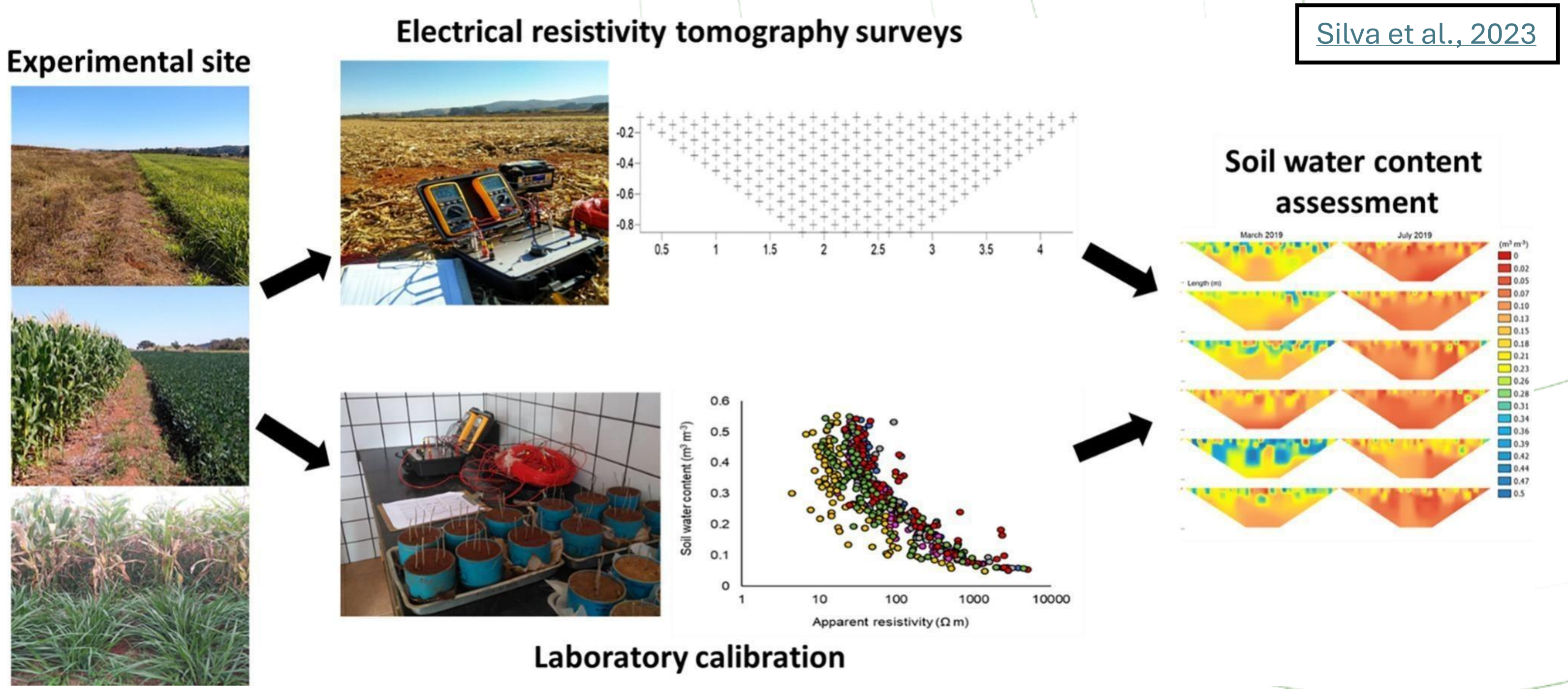
The electrical resistivity of Earth materials is highly sensitive to variations in the hydraulic properties of the subsurface:

- **Porosity**
- **Saturation**
- **Grain size distribution (hydraulic conductivity)**
- **Pore fluid conductivity**
- **Temperature**

Silva et al., 2023



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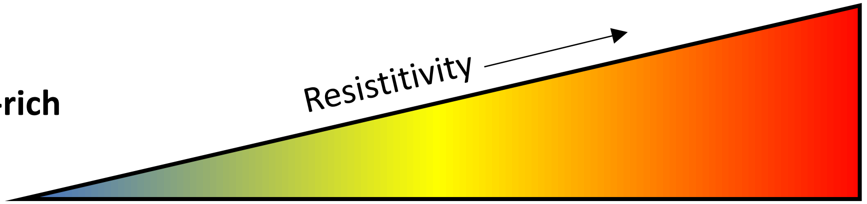
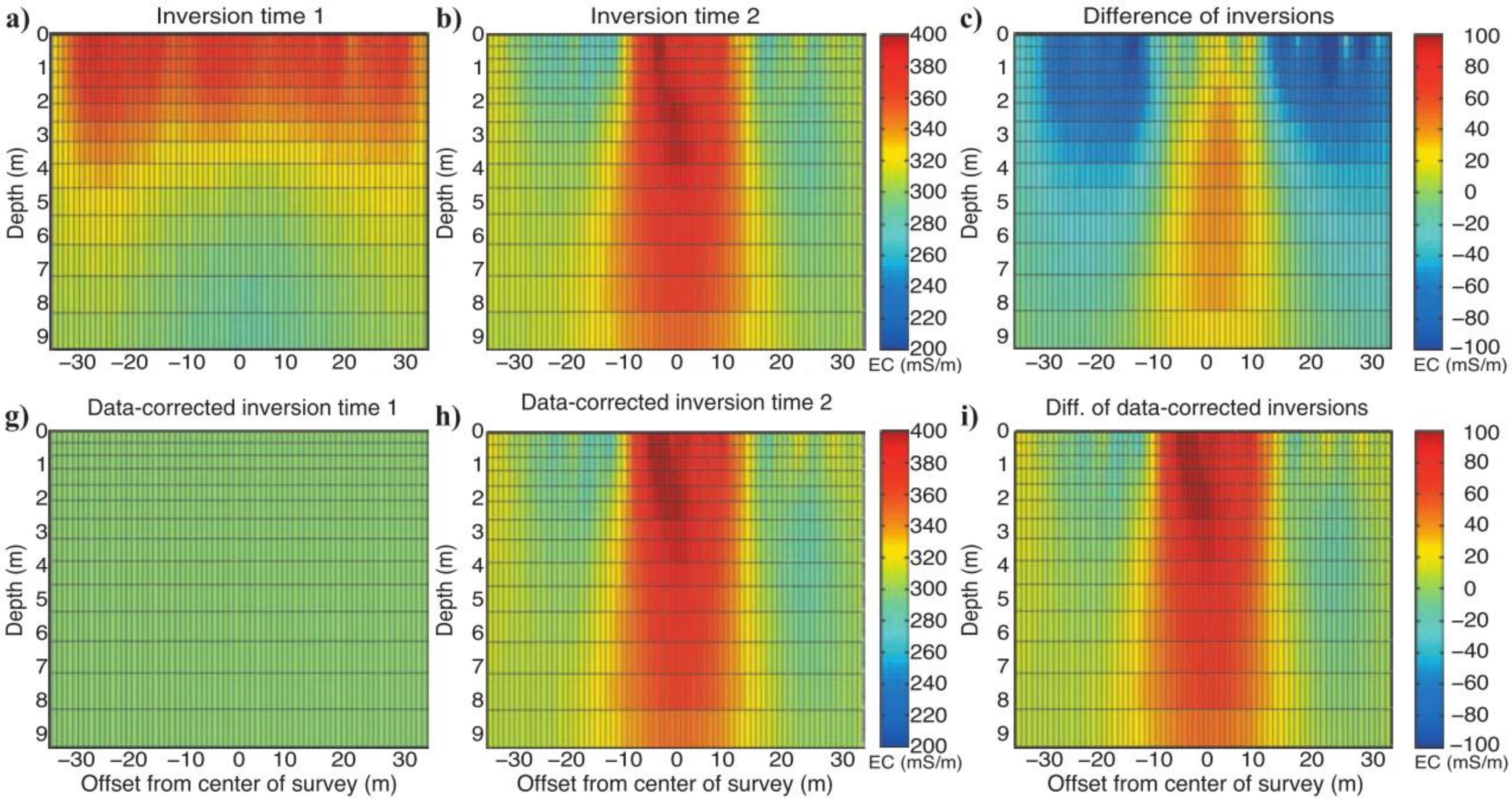


Dry, cold, no clay, ion-depleted

Temperature effects

Subsurface temperatures may change during monitoring



Hayley et al. (2010), Compensating for temperature variations in time-lapse electrical resistivity difference imaging, *GEOPHYSICS*, *75*(4), WA51-WA59

Modelling temperature effects

Simplified heat equation

- Temperature distribution in the subsurface can be modelled using a solution to the heat equation

Annual mean temperature

Temp. change amplitude

Depth

Julian day

Phase offset

$$T_{\mathrm{model}}(z,t) = T_{\mathrm{mean}} + \frac{\Delta T}{2}\exp\left(-\frac{z}{d}\right)\sin\left(\frac{2\pi}{365}t + \varphi - \frac{z}{d}\right)$$

Dispersion

Advection

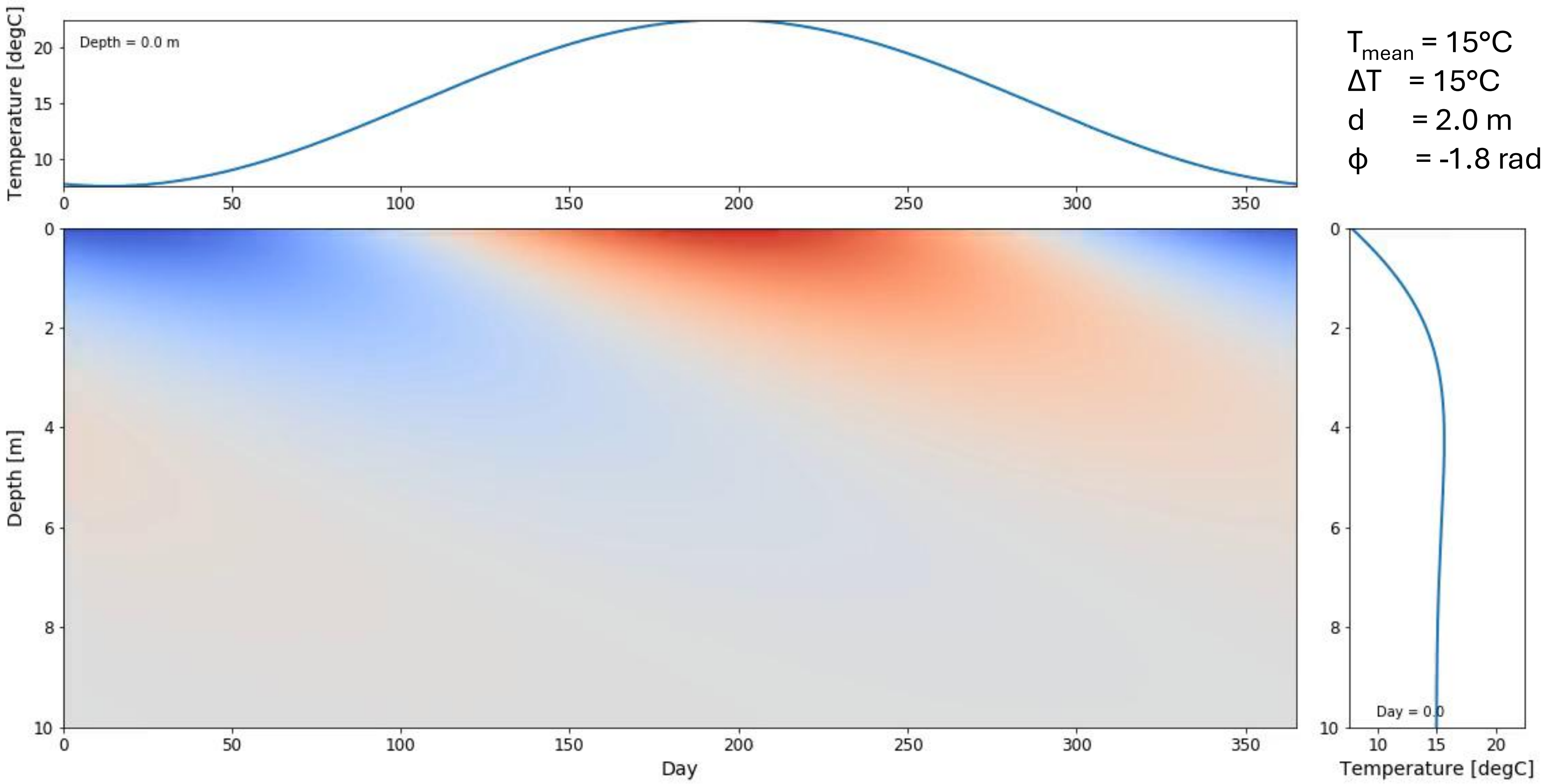
Characteristic depth

Uhlemann et al. (2017), Four-dimensional imaging of moisture dynamics during landslide reactivation, *JGR: Earth Surf.*, *122*(1)

Modelling temperature effects

Results for typical mid-latitude location

$$T_{\text{model}}(z,t) = T_{\text{mean}} + \frac{\Delta T}{2} \exp\left(-\frac{z}{d}\right) \sin\left(\frac{2\pi}{365} t + \varphi - \frac{z}{d}\right)$$



T_{mean} = 15°C
ΔT = 15°C
d = 2.0 m
ϕ = -1.8 rad

Temperature correction of resistivity data

Ratio model

If we know the temperature distribution in the subsurface in space and time, we can correct the resistivity data for seasonal temperature variation

Correction factor ~ -2.0°C^{-1}

Modelled temperature

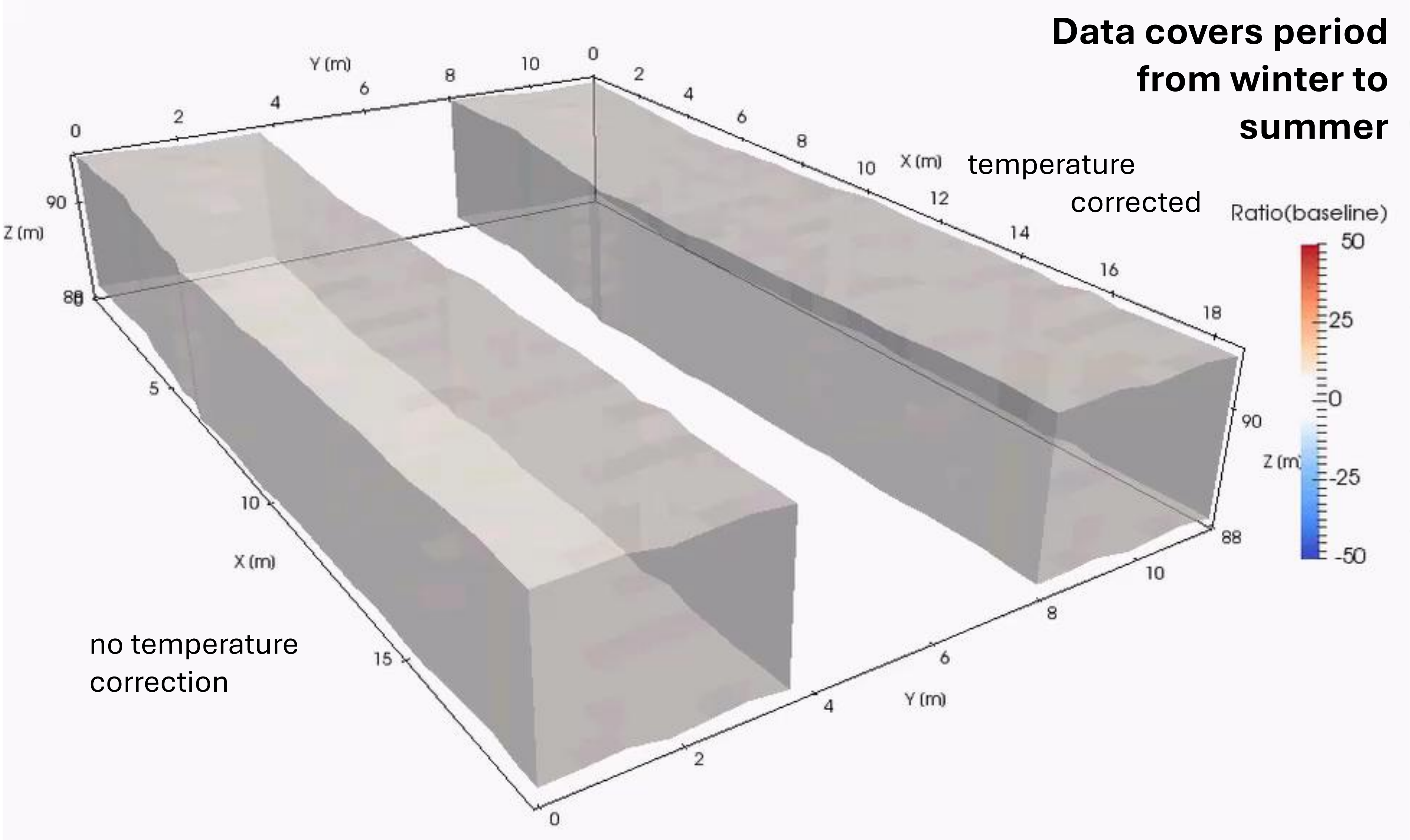
$$\rho_{cor} = \rho \left[1 + \frac{c}{100} \left(T_{target} - T_{model} \right) \right]$$

Measured resistivity

Standard temperature (e.g. Lab temperature)

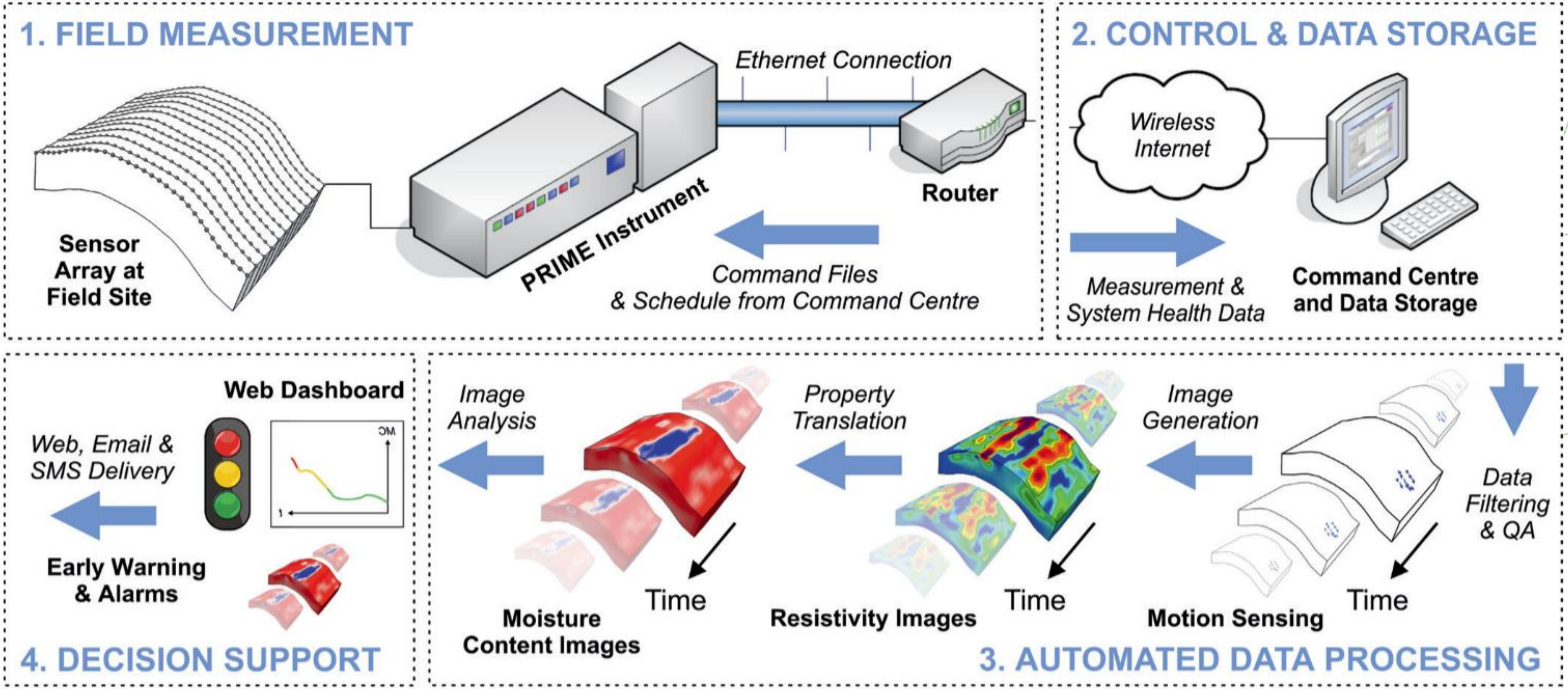
Temperature correction of resistivity data

Example of seasonal drying processes



Monitoring examples

Automated monitoring workflows



The Hollin Hill Landslide Observatory

A long-standing research site for understanding landslide processes

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Field Research Site

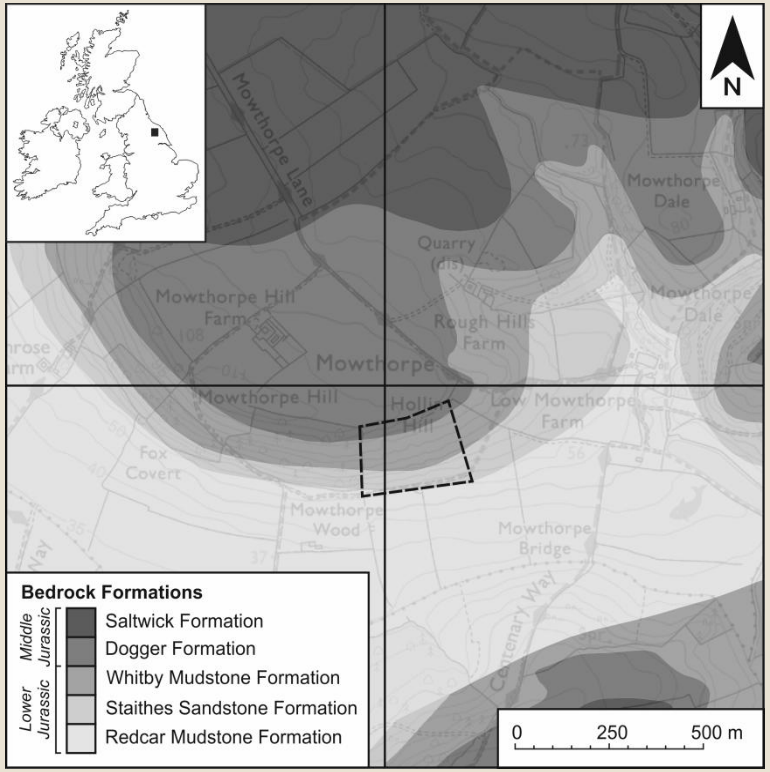
- Hollin Hill Research Site
- North Yorkshire, North England

- South-facing hill slope
- Lias group of Lower Jurassic
- Instability prone
- Complex site history

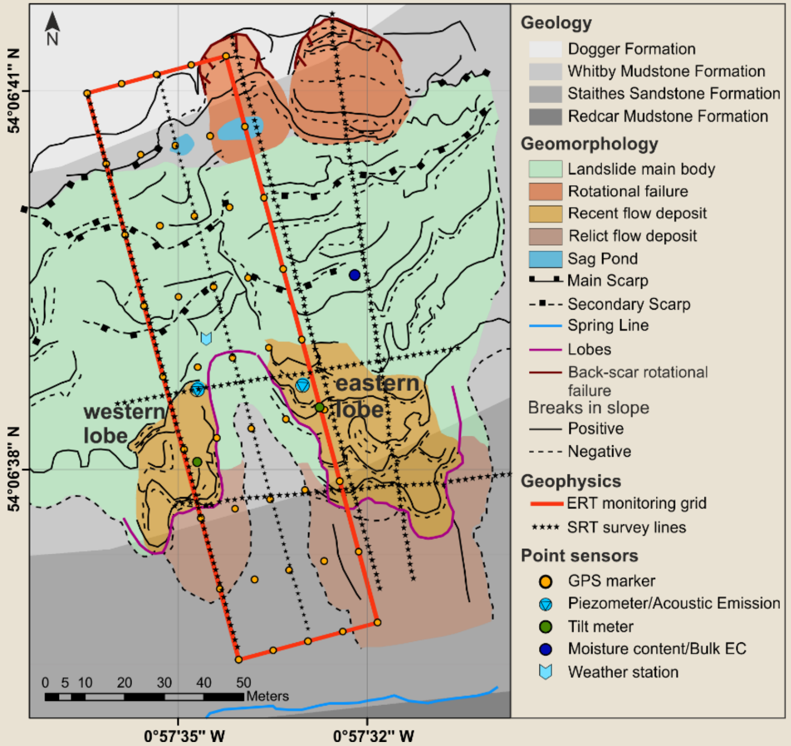
"Very slow to slow composite multiple earth slide-earth flow" (Chambers et al., 2011)

Landslide Dimensions:

- Back scarp – toe: ~140 m
- Slope gradient: 12°
- Lateral extent: >450 m



Geological Map



Monitoring Instrumentation

Chambers, J. E., Wilkinson, P. B., Kuras, O., et al. (2011). Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK. *Geomorphology*, *125*(4), 472–484.

Uhlemann, S., Smith, A., Chambers, J. E., et al.(2016), Assessment of ground-based monitoring techniques applied to landslide investigations, *Geomorphology*, *253*, 438–451.

Geophysical Characterization of the Hollin Hill Landslide Observatory

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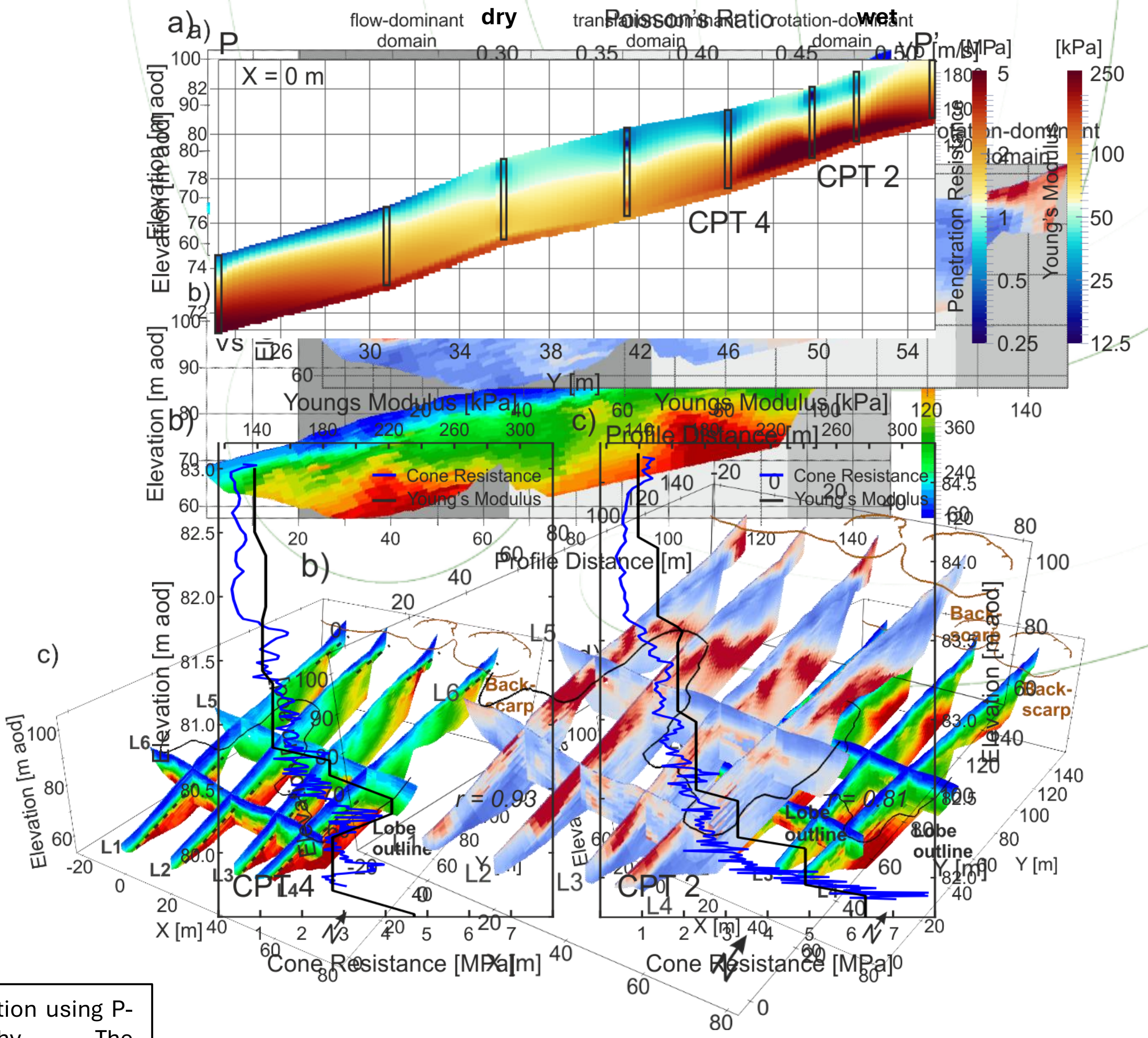
Importance of elastic parameters

- **Seismic characterisation** of the landslide material
- **Novel application** of P- and S-wave seismic refraction tomography
    - > 3000 shots
    - ~ 500 geophone locations
- Seismic results were indicative of "water saturation" of the material



Uhlemann et al. (2016), Landslide characterization using P- and S-wave seismic refraction tomography — The importance of elastic moduli, *J. Appl. Geophys.*, *134*

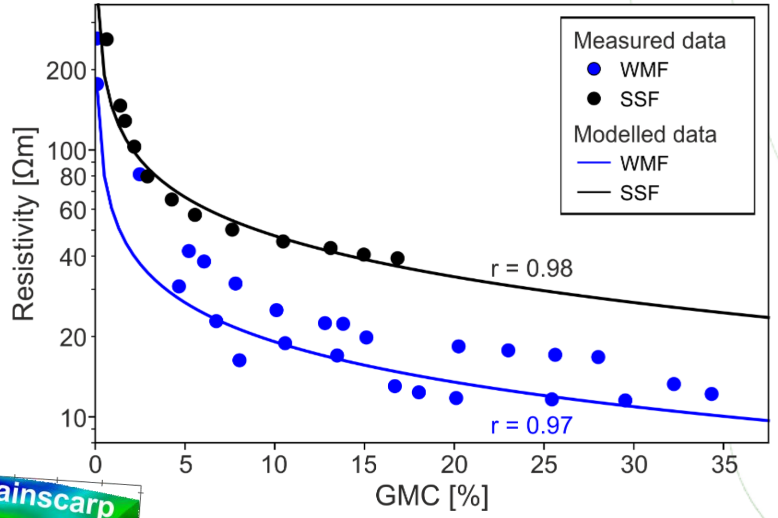
Long-term geoelectrical monitoring of Hollin Hill

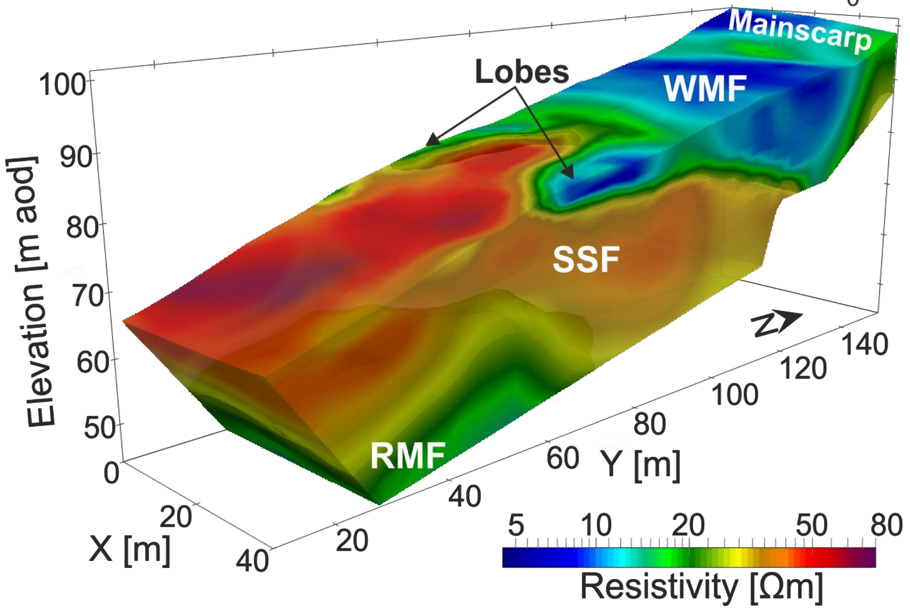
Translating models of electrical resistivity into moisture content

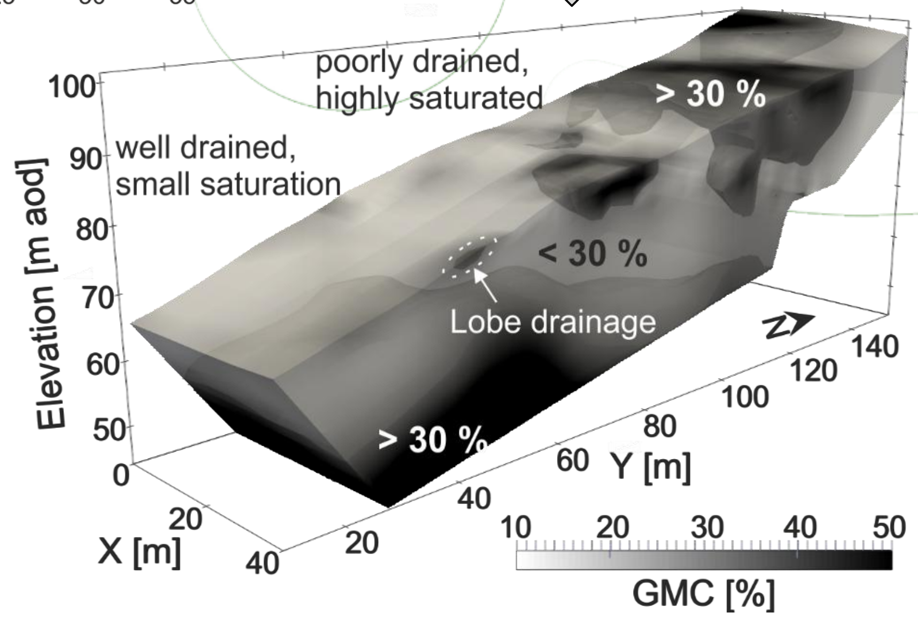
- Monitoring frequency: 2 days
- 3D data acquisition (5x32 = 160 electrodes)
- Operational since 2009

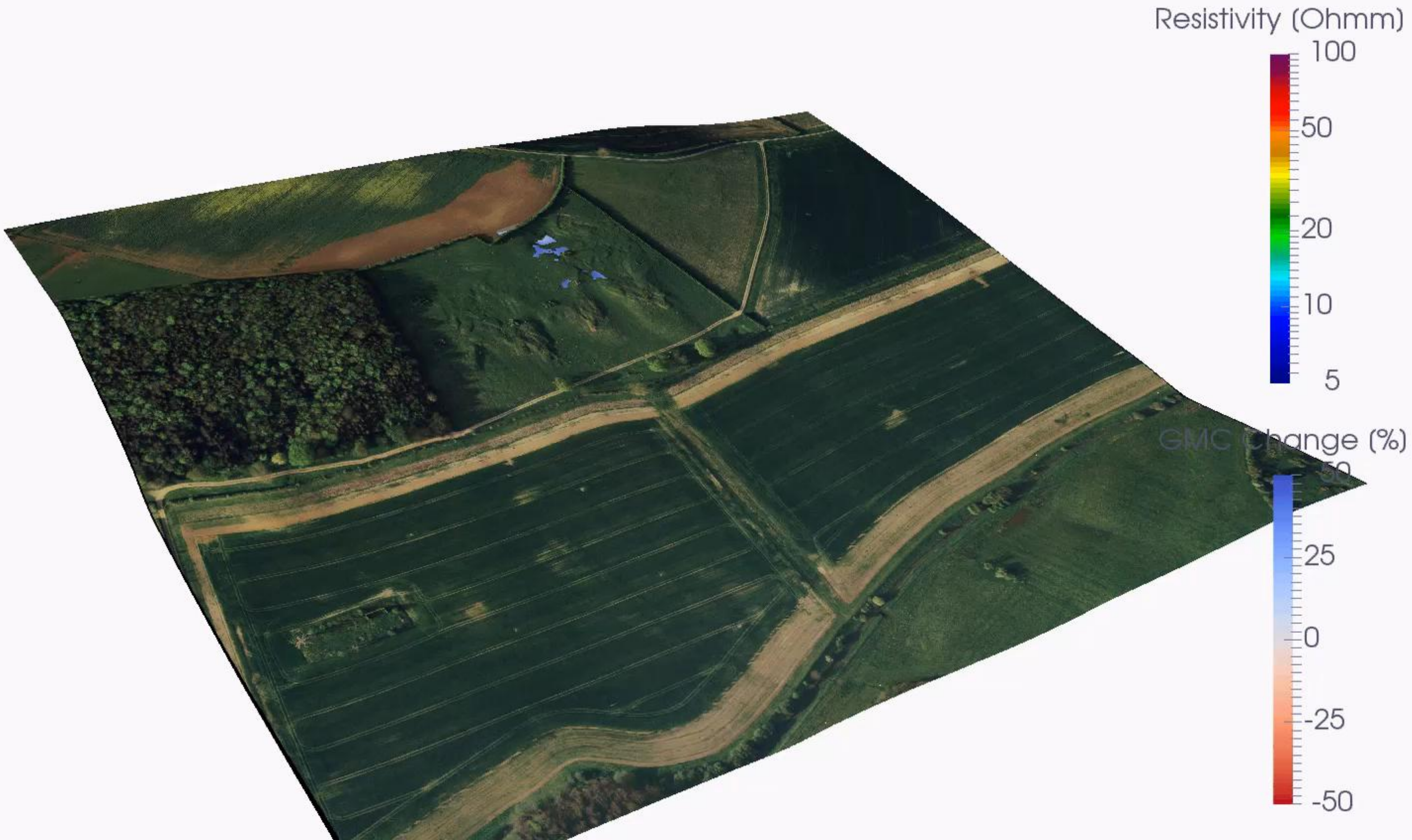
Uhlemann et al. (2017), Four-dimensional imaging of moisture dynamics during landslide reactivation, *JGR: Earth Surf.*, *122*(1)

Temp. cor







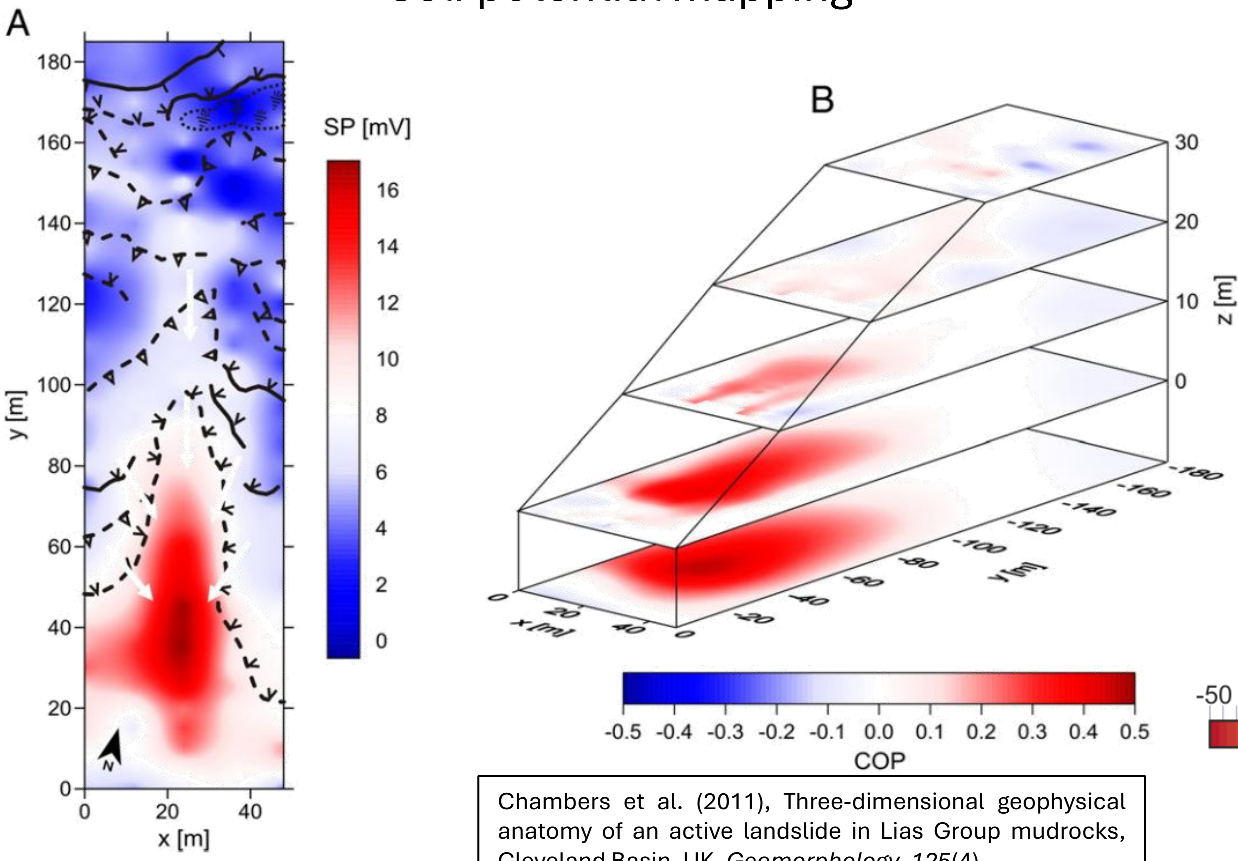


Resistivity (Ohmm)
100
50
20
10
5
GMC Change (%)
25
0
-25
-50

Long-term geoelectrical monitoring of Hollin Hill

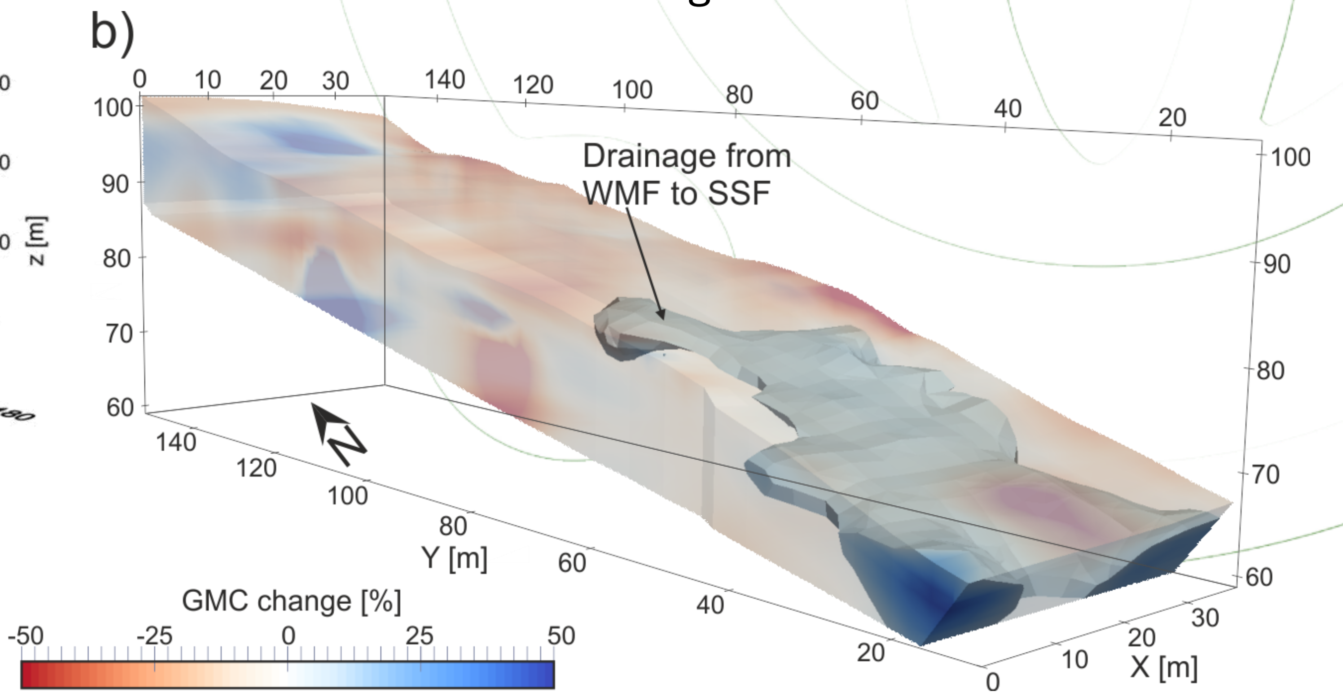
Imaging hydrological processes that control landslide behavior

Self potential mapping



Chambers et al. (2011), Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK, *Geomorphology*, *125*(4)

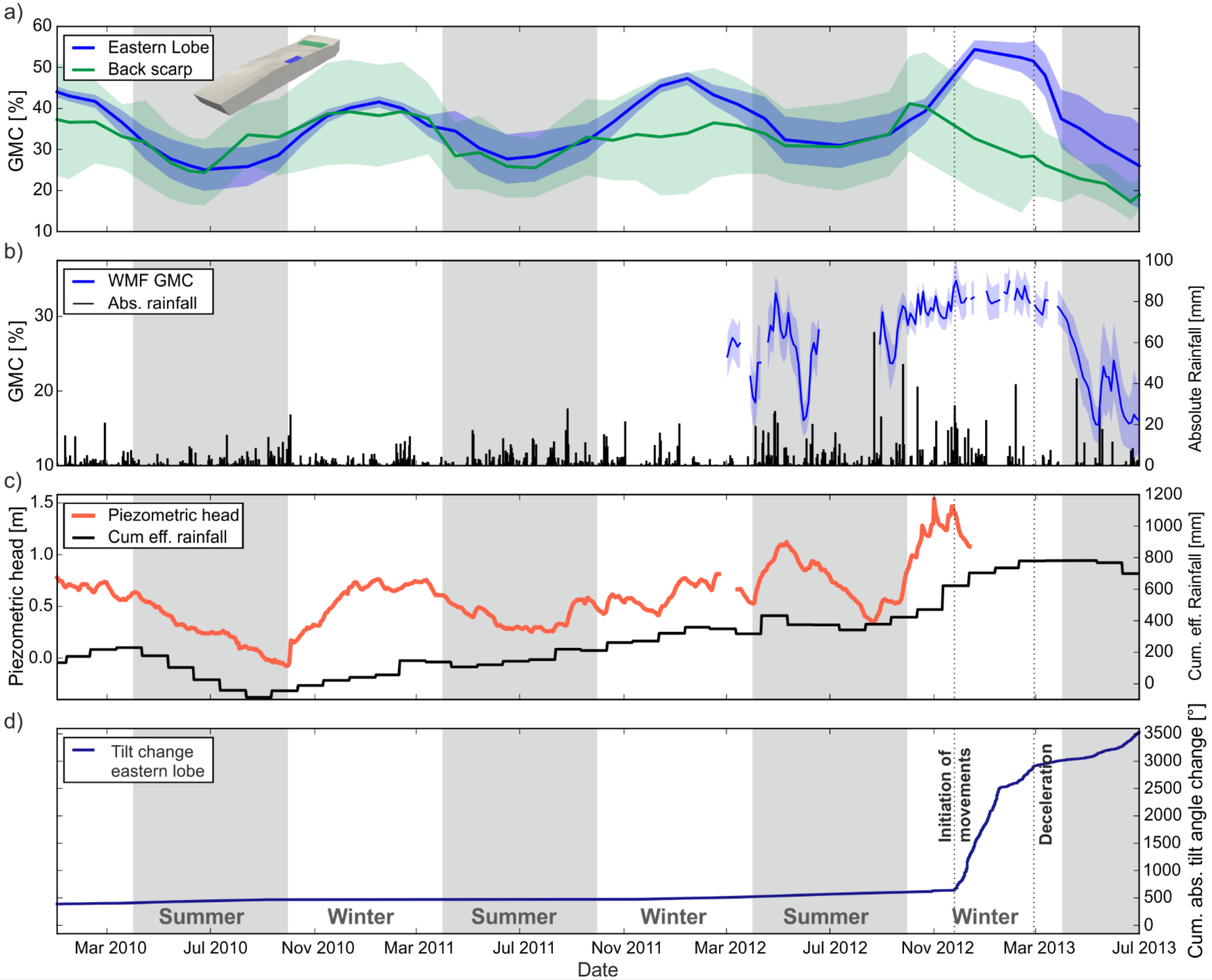
Drainage



Geoelectrical imaging can reveal processes that control landslide movements

Long-term geoelectrical monitoring of Hollin Hill

Imaging hydrological processes that control landslide behavior

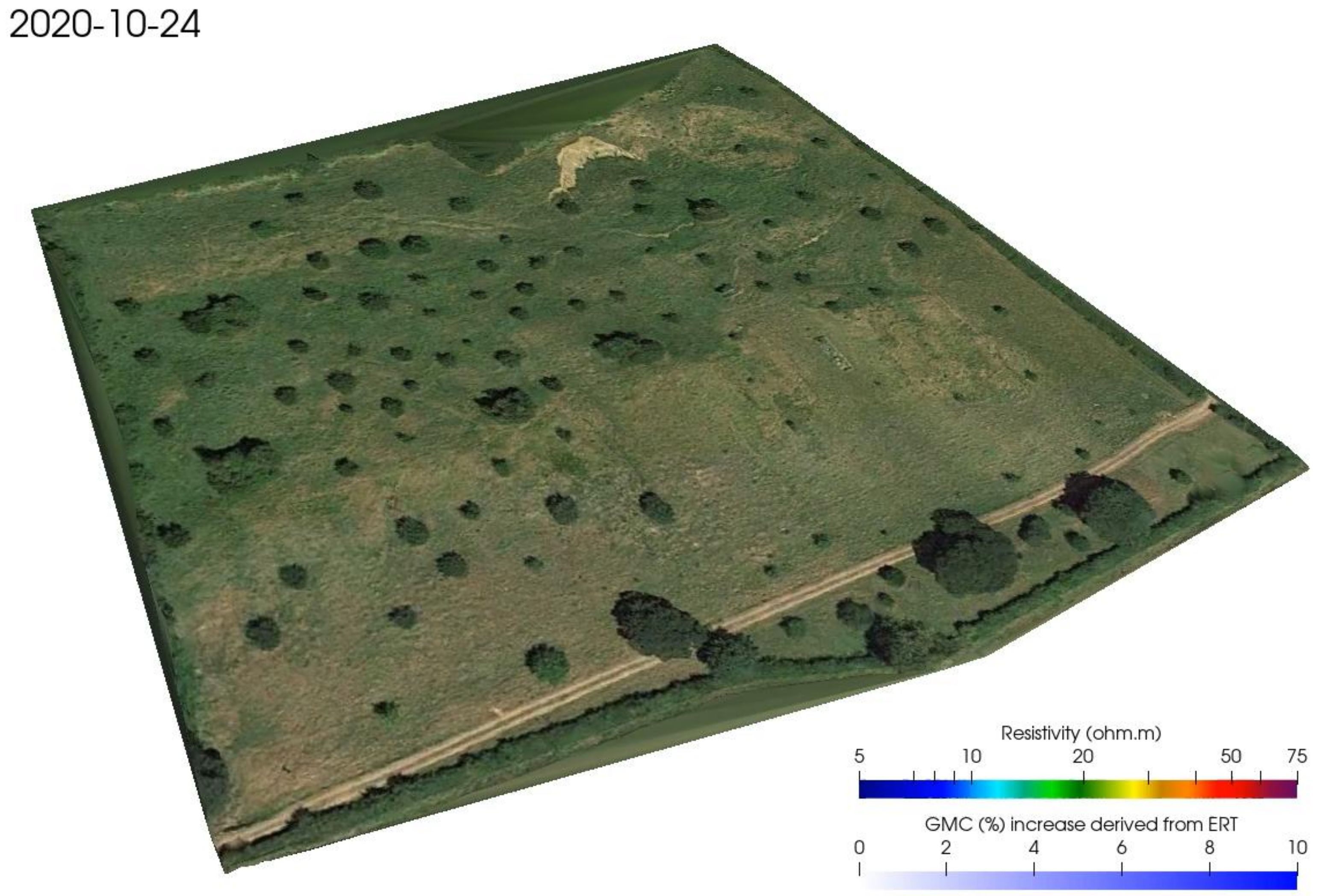


- **Geophysical results agree with direct data sources:**
  - Point moisture probes
  - Piezometer
  - Deformation measurements
- This data allows to **set thresholds for early warning**
  - i.e. for **moisture contents >48% movements** have to expected
  - This threshold **proved valid** in the last years

Uhlemann et al. (2017), Four-dimensional imaging of moisture dynamics during landslide reactivation, *JGR: Earth Surf.*, *122*(1)

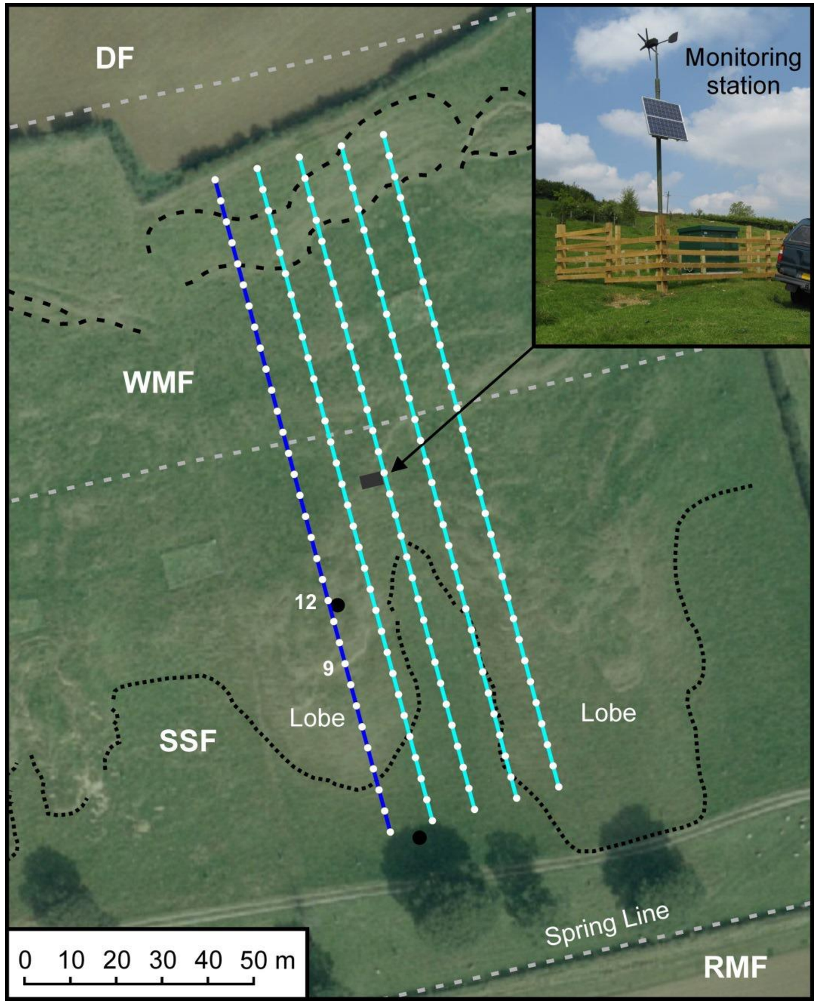
Long-term geoelectrical monitoring of Hollin Hill

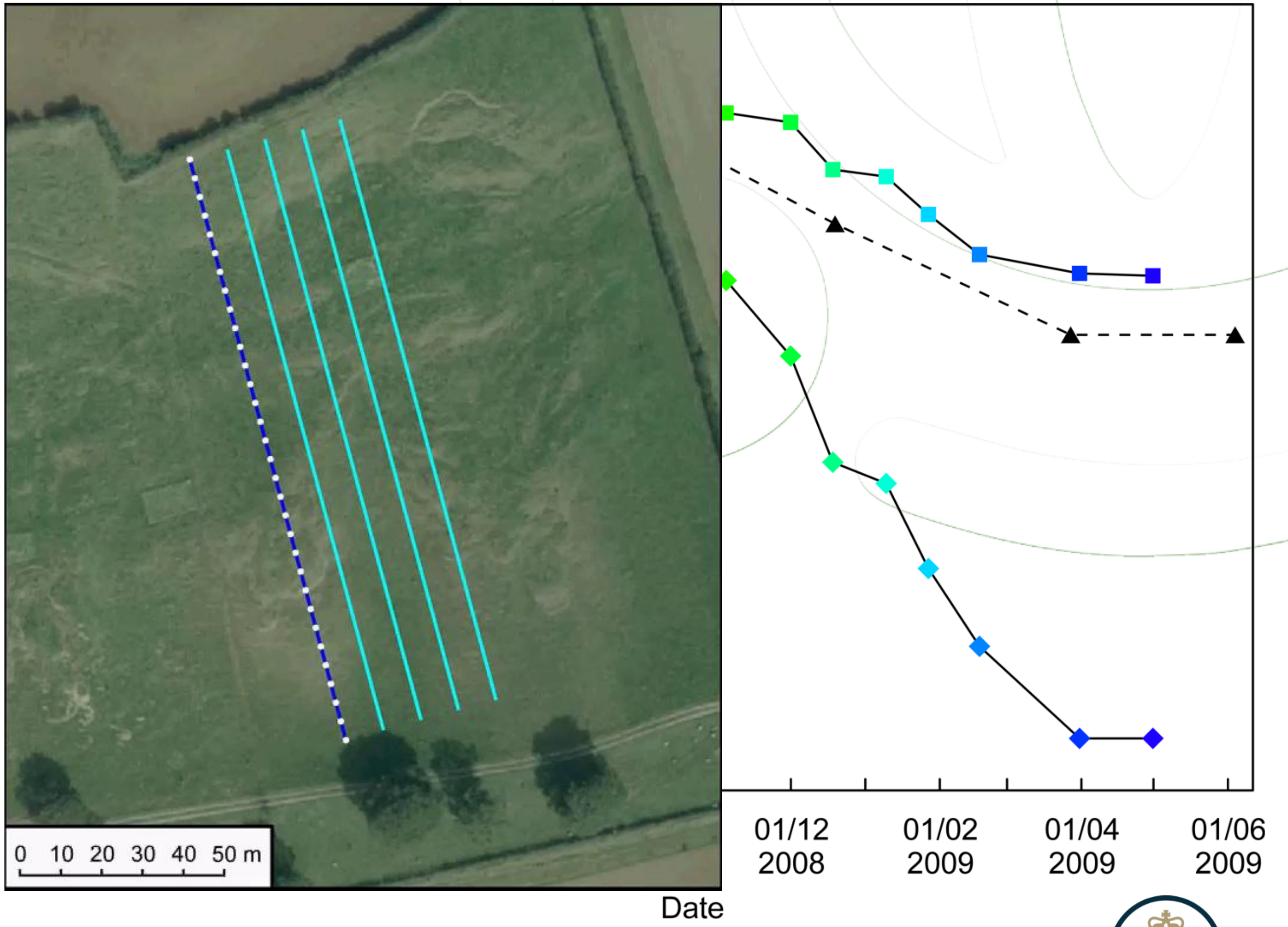
Imaging hydrological processes that control landslide behavior



Long-term geoelectrical monitoring of Hollin Hill

Using resistivity measurements to obtain landslide displacements





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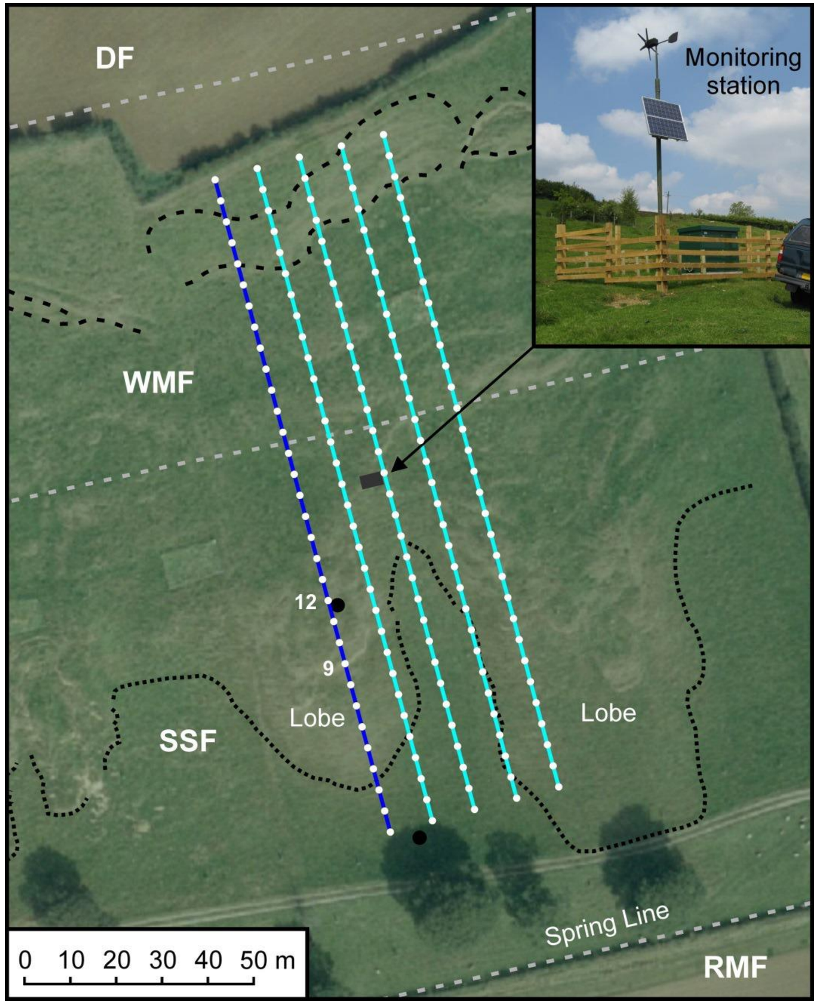

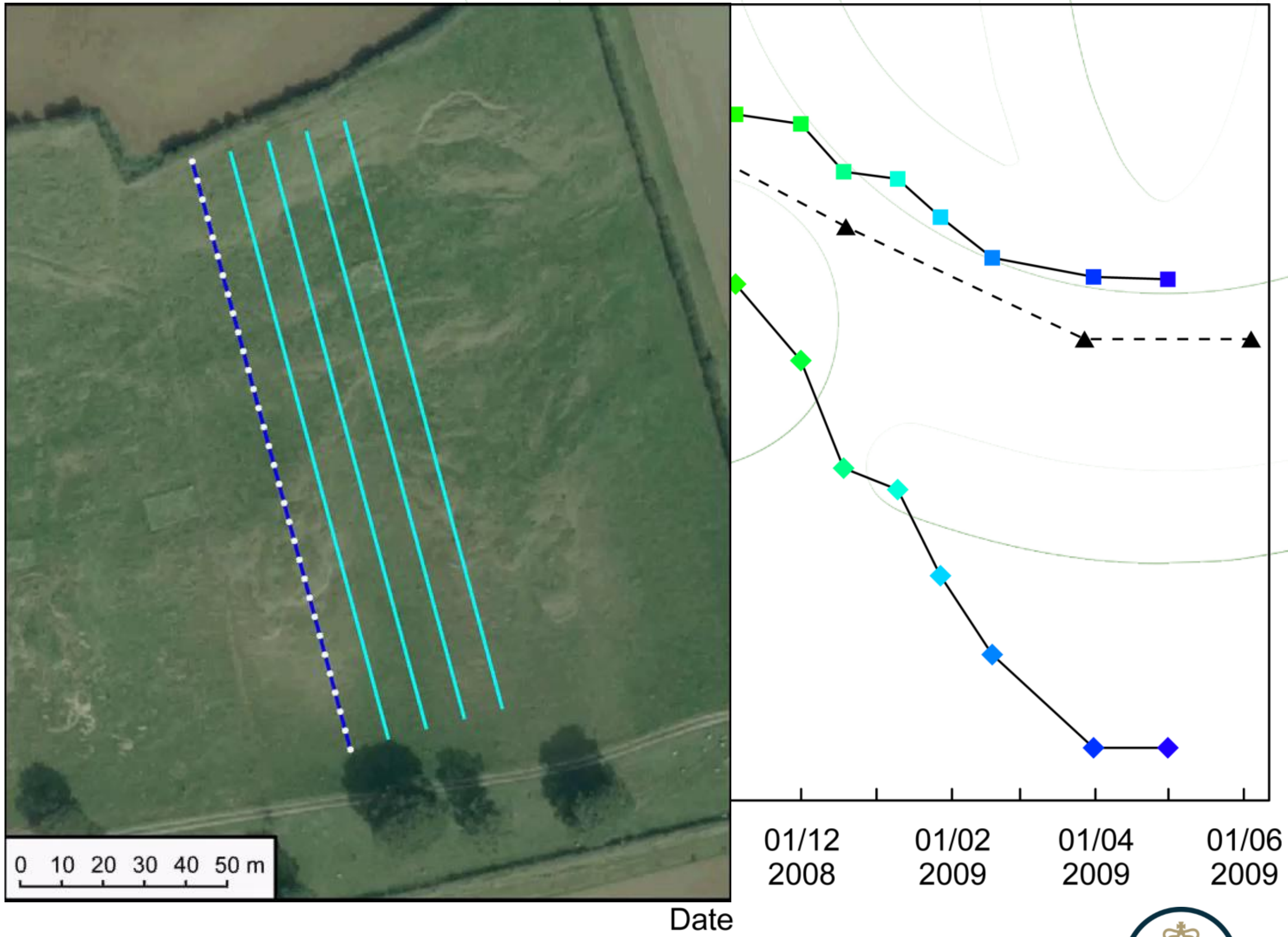

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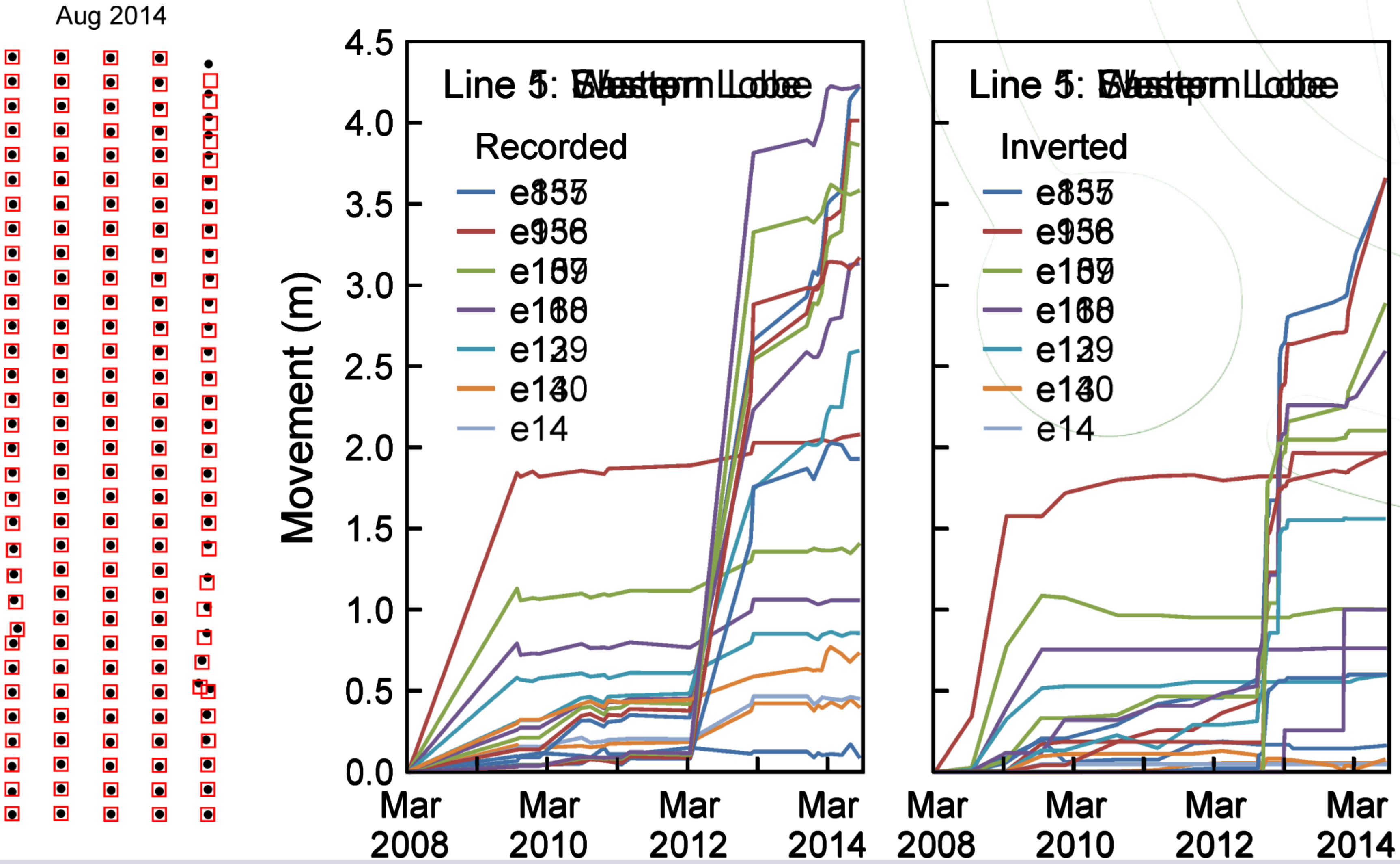

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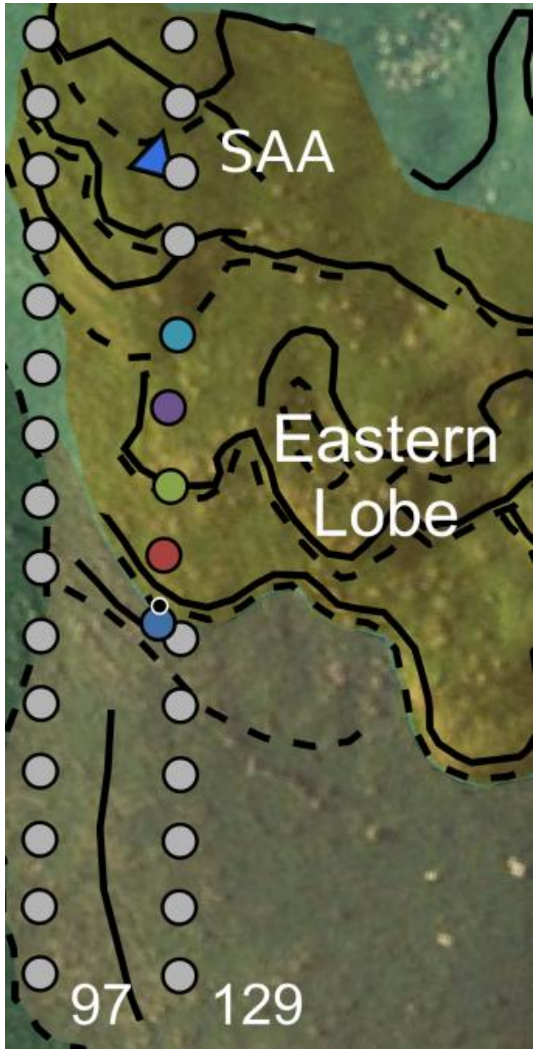
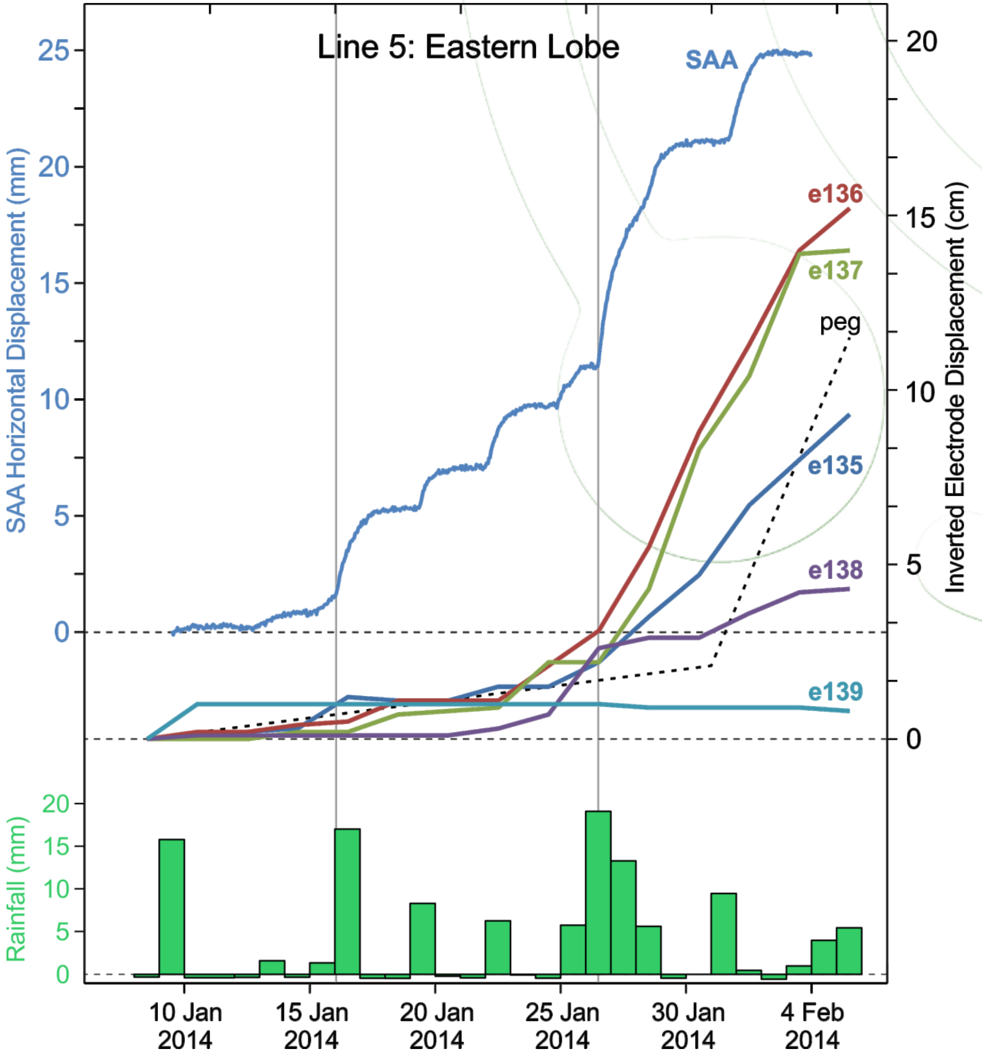
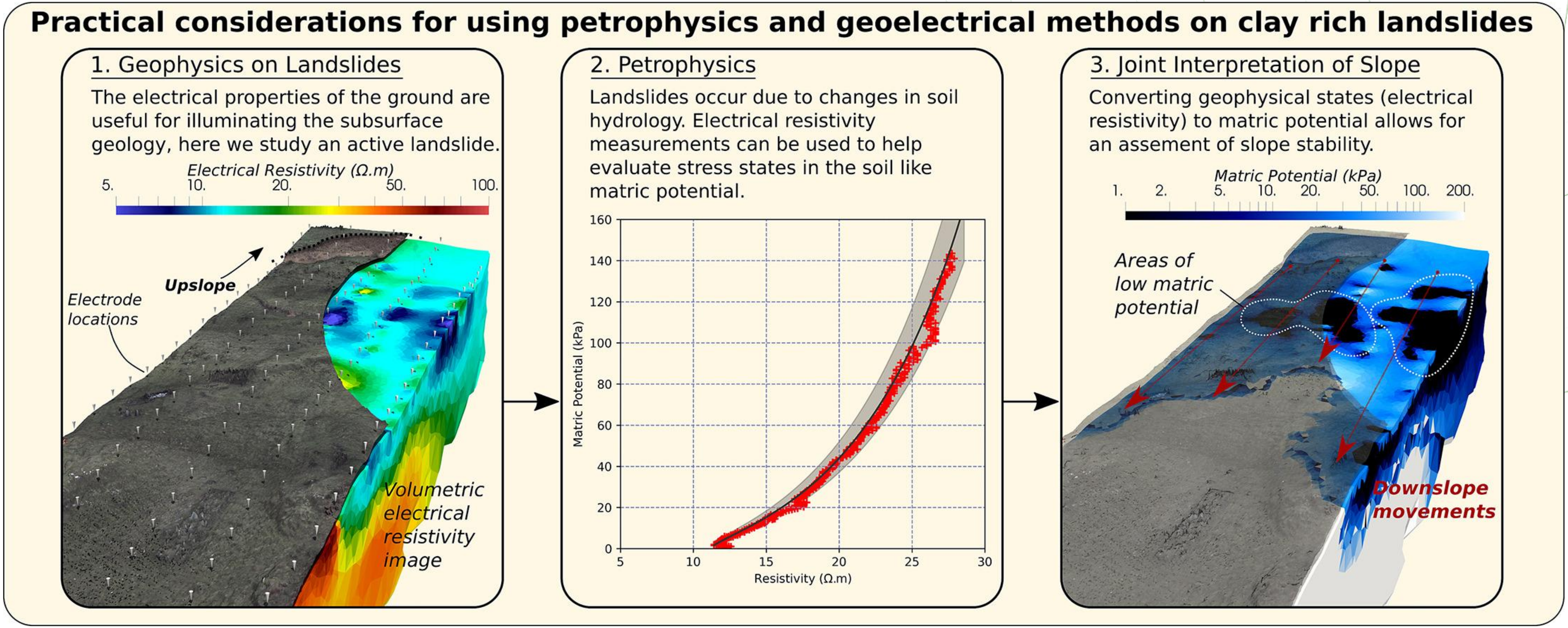




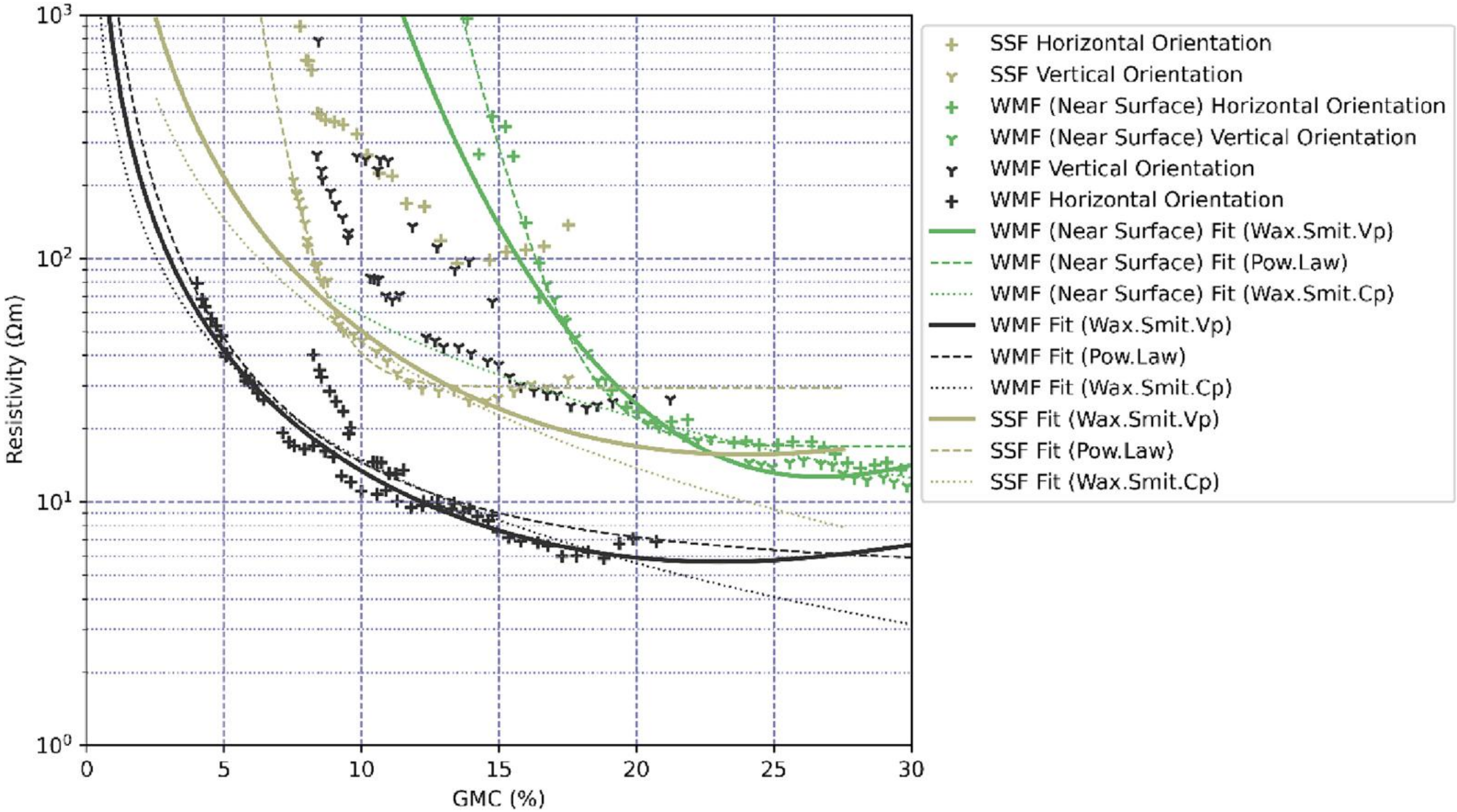
Assessing variations in geomechanical parameters

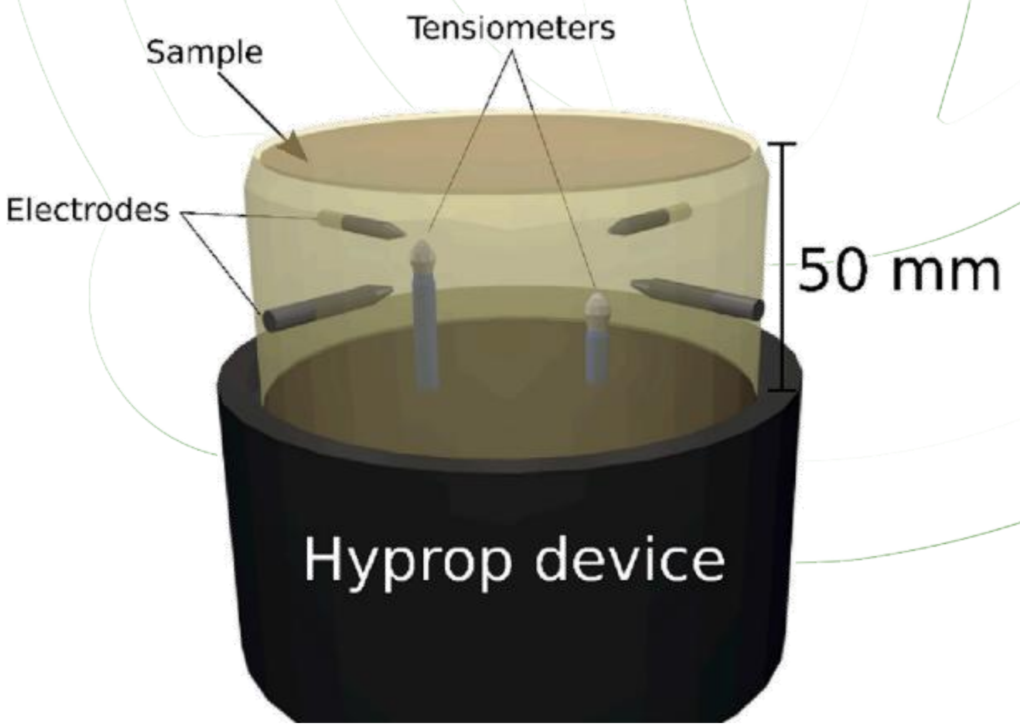
Translating electrical measurements to matric potentials



Boyd et al., 2024

Assessing variations in geomechanical parameters
Translating electrical measurements to matric potentials





Boyd et al., 2024

Assessing variations in geomechanical parameters

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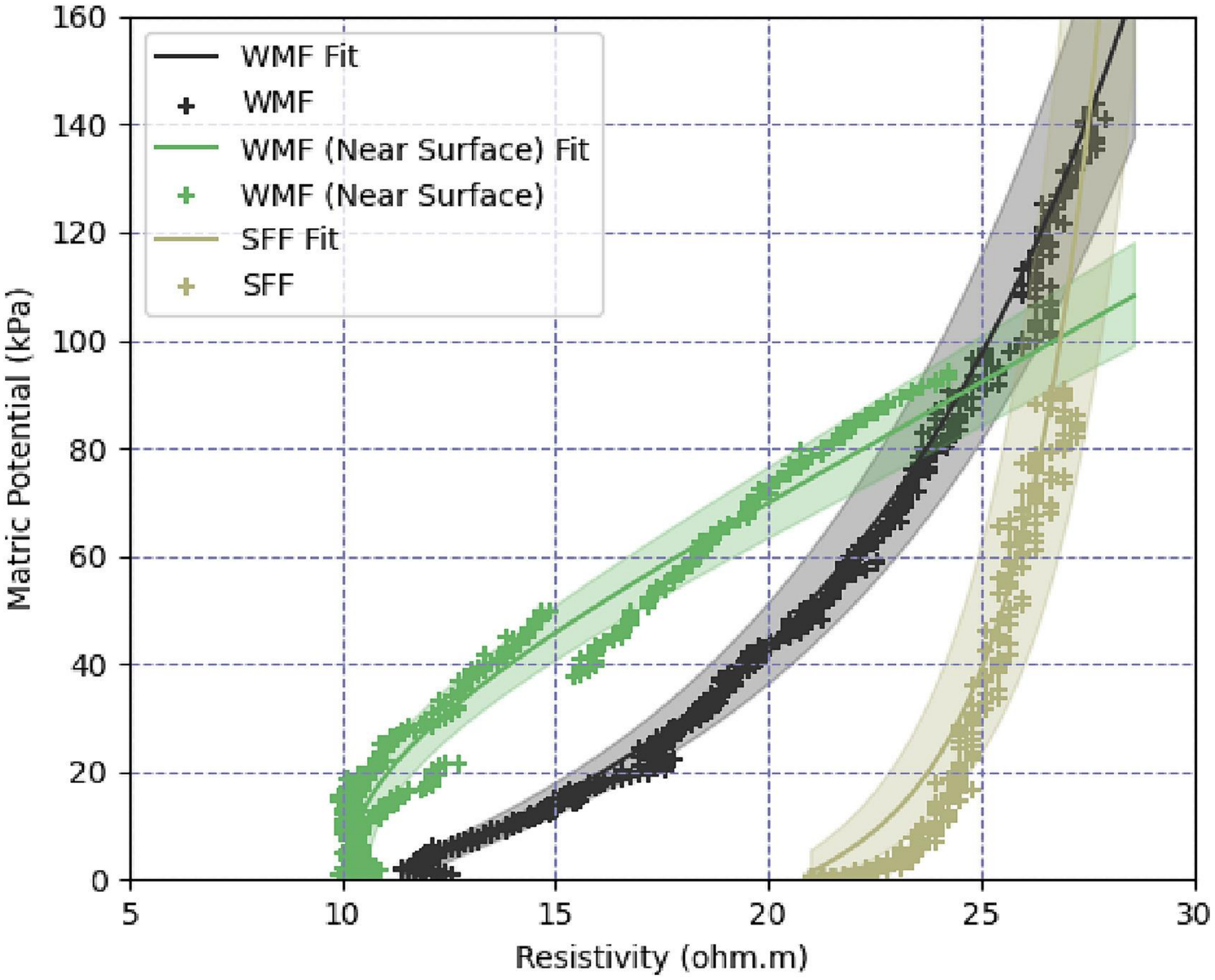


Boyd et al., 2024

The saturation conditions within a clay-rich material can be described as one of three states: **saturated, partially saturated and residual.**

We can treat electrical conductivity (EC) the same as saturation, and can define a relative conductivity EC_{norm}

$$EC_{norm} = \frac{EC_{meas} - EC_{res}}{EC_{sat} - EC_{res}}$$

EC can be related to matric potential *h* like the **Van Genuchten** equation

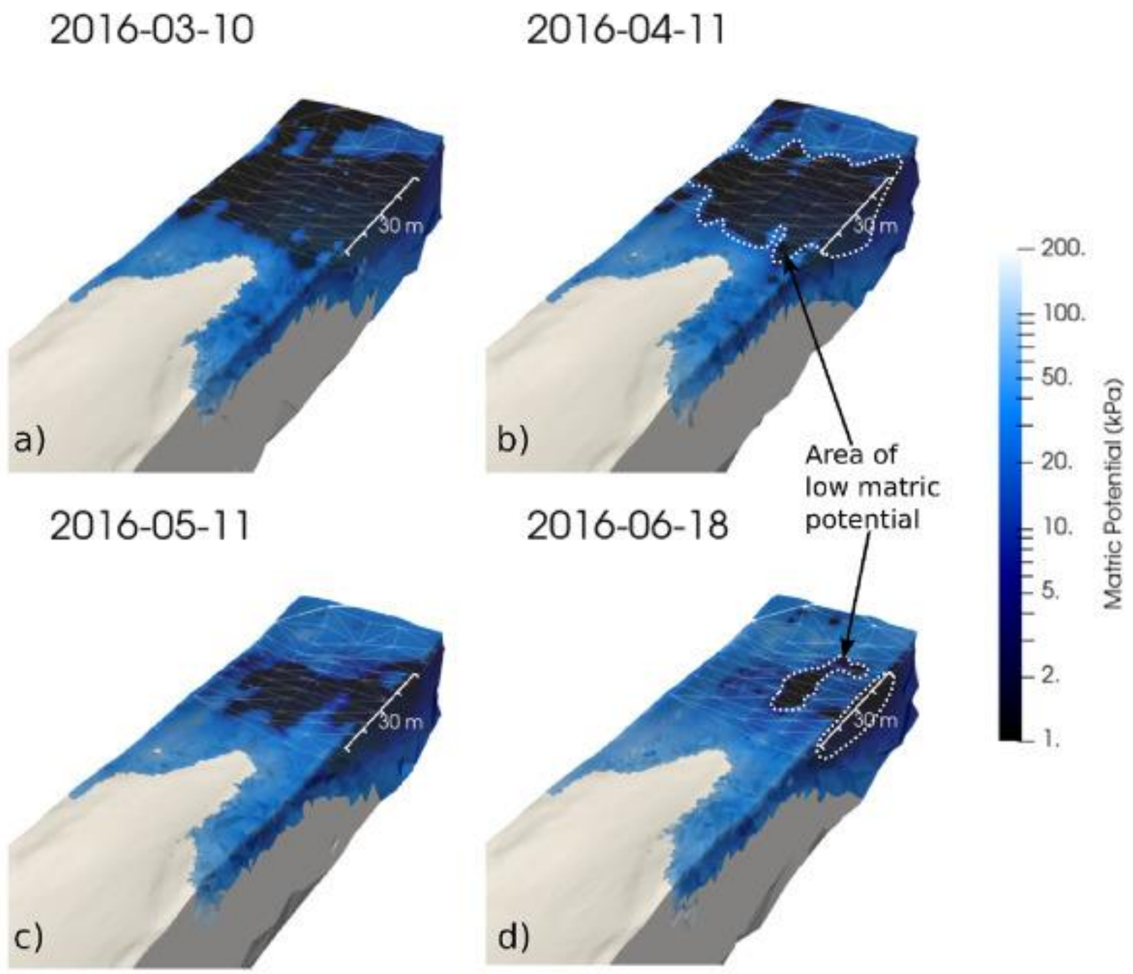
$$EC_{norm} = (1 + [\alpha h]^n)^{-m}$$

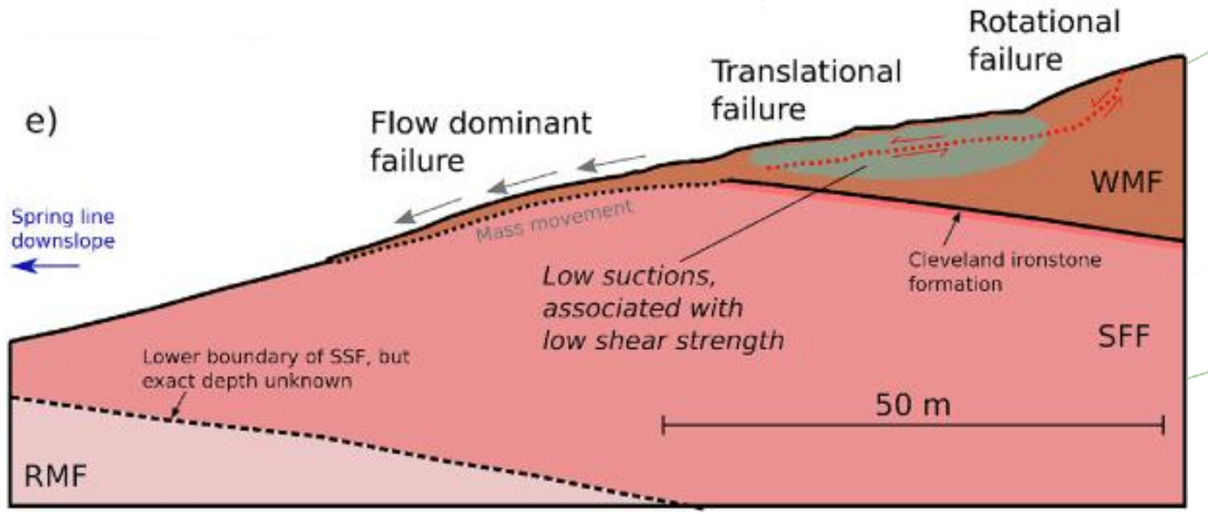
Note: α and n do NOT have the same physical meaning as in the Van Genuchten equation!

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^{1-1/n}}$$

Assessing variations in geomechanical parameters

Translating electrical measurements to matric potentials



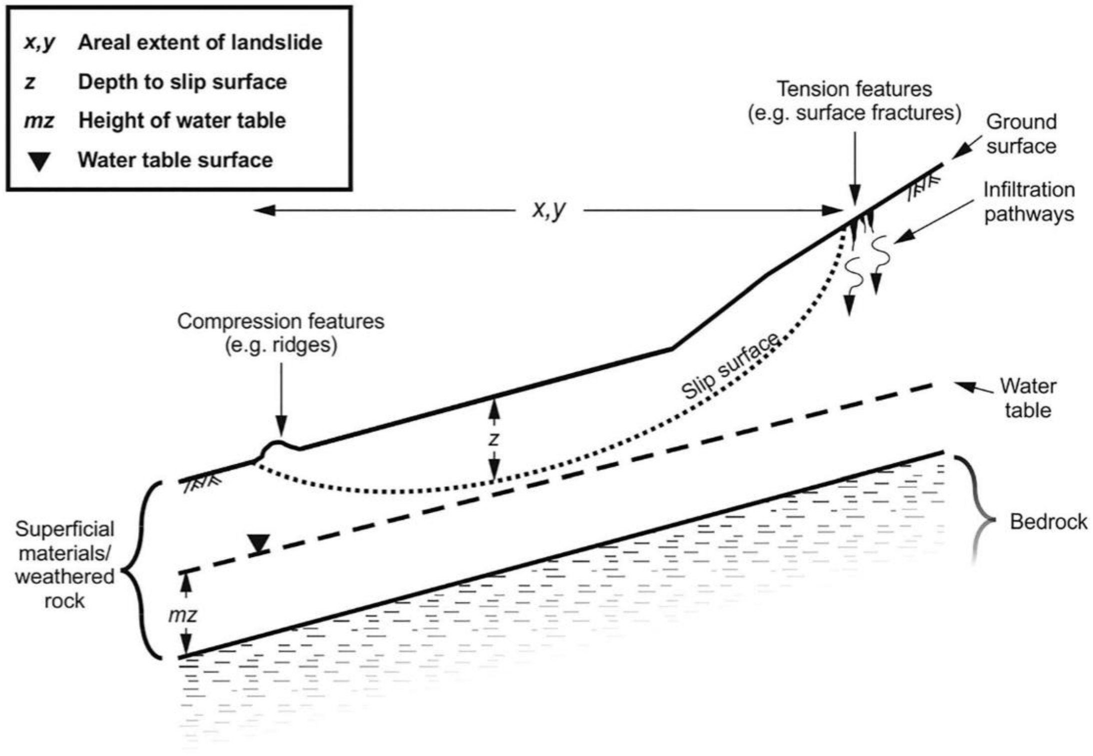


Boyd et al., 2024

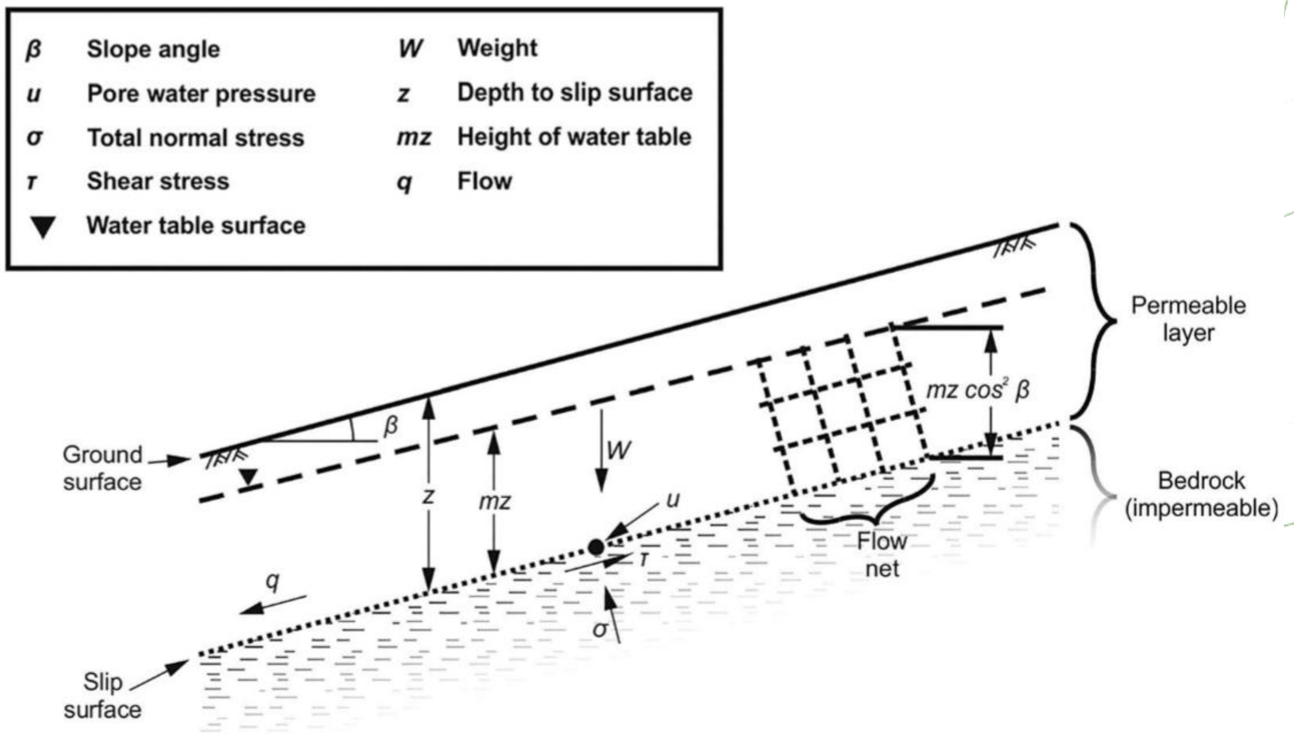
Quantitative analysis of geoelectrical monitoring data

Opportunities and limitations

Landslide features



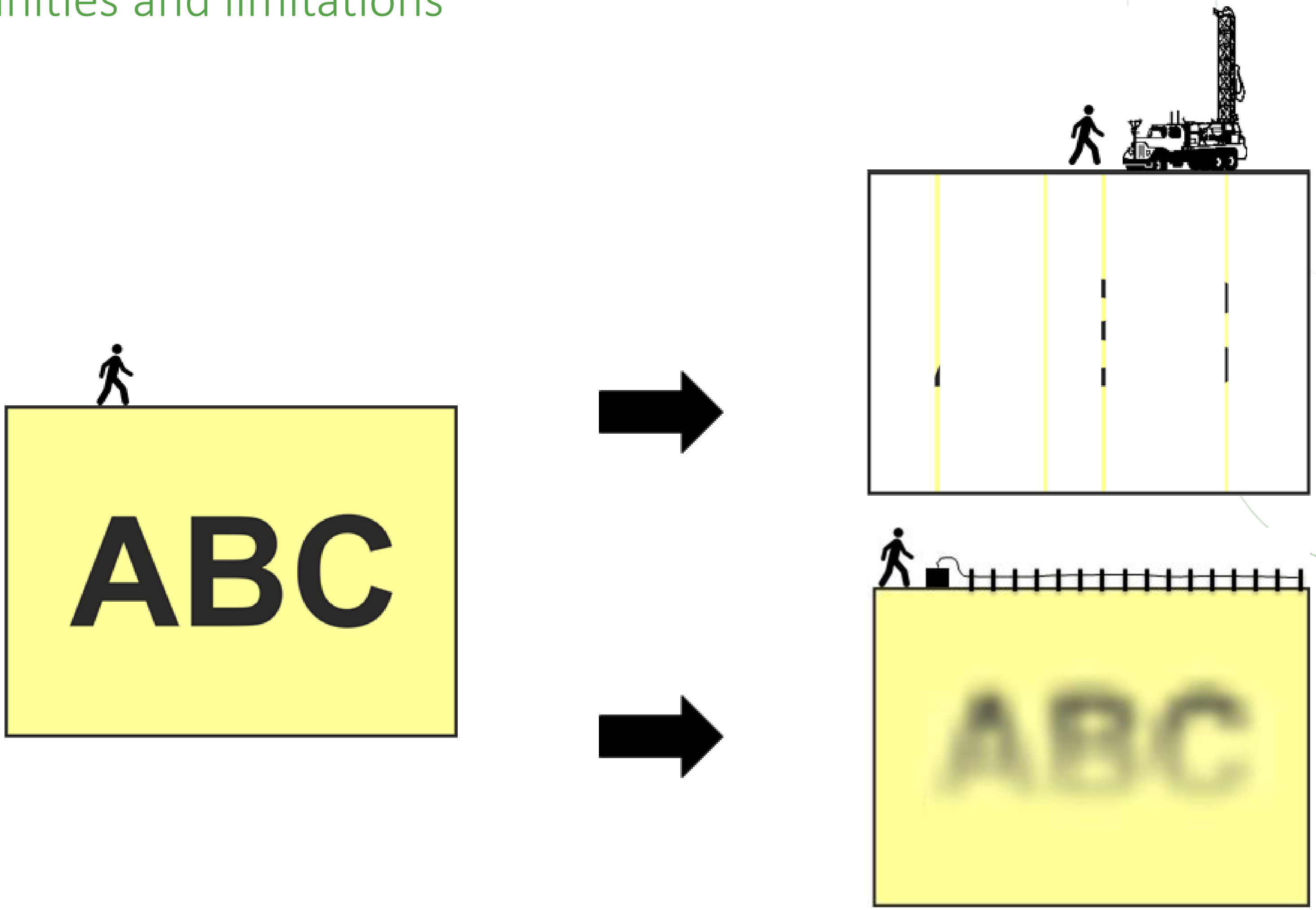
Landslide properties



Geophysics can provide continuous subsurface data at high spatial (and temporal) resolution

Quantitative analysis of geoelectrical monitoring data

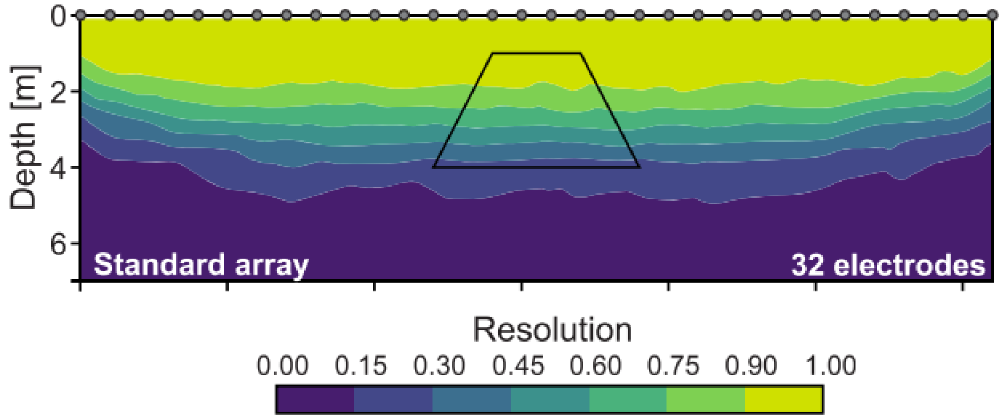
Opportunities and limitations

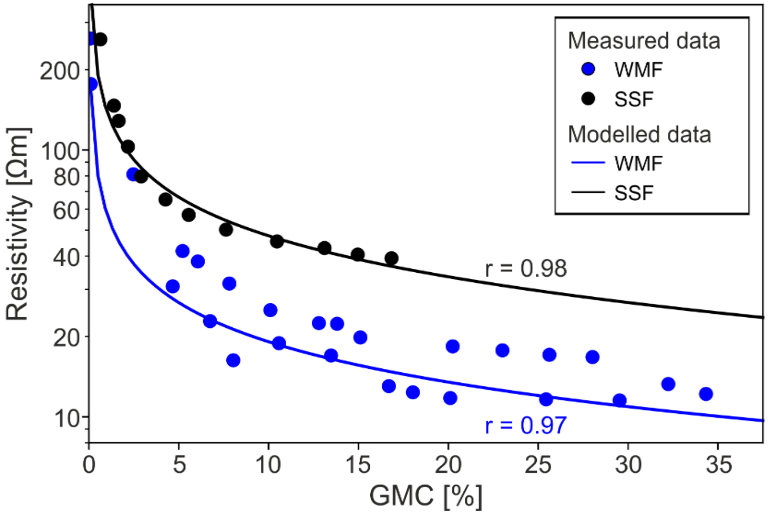


Borehole
Discrete, high resolution data

Surface geophysics
Spatially distributed, blurry information

Quantitative analysis of geoelectrical monitoring data
Opportunities and limitations





<u>Resistivity imaging has limited resolution</u>

Decreases with increasing distance to electrodes

1. Imaged resistivity may not be the true resistivity
2. Lab-scale calibration and field-scale measurements may not relate to the same processes

→ Applying petrophysical relationships may result in the wrong values

→ Treat results carefully

<u>Possible „solutions“:</u>

Petrophysical joint inversion

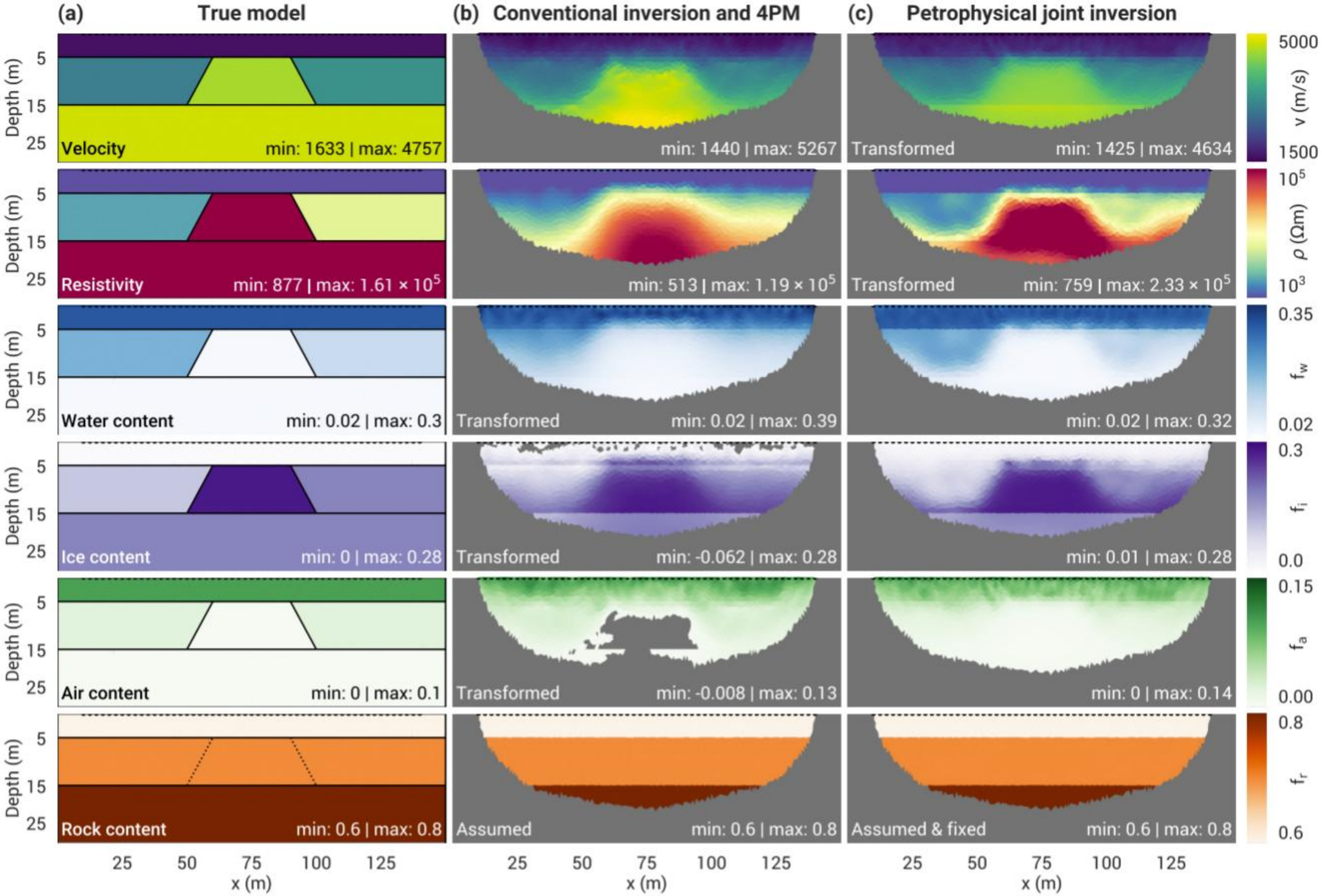
→ Invert for petrophysical properties directly

→ Smoothness constraints will limit the benefit

Geostatistical approaches

Day-Lewis et al., 2005

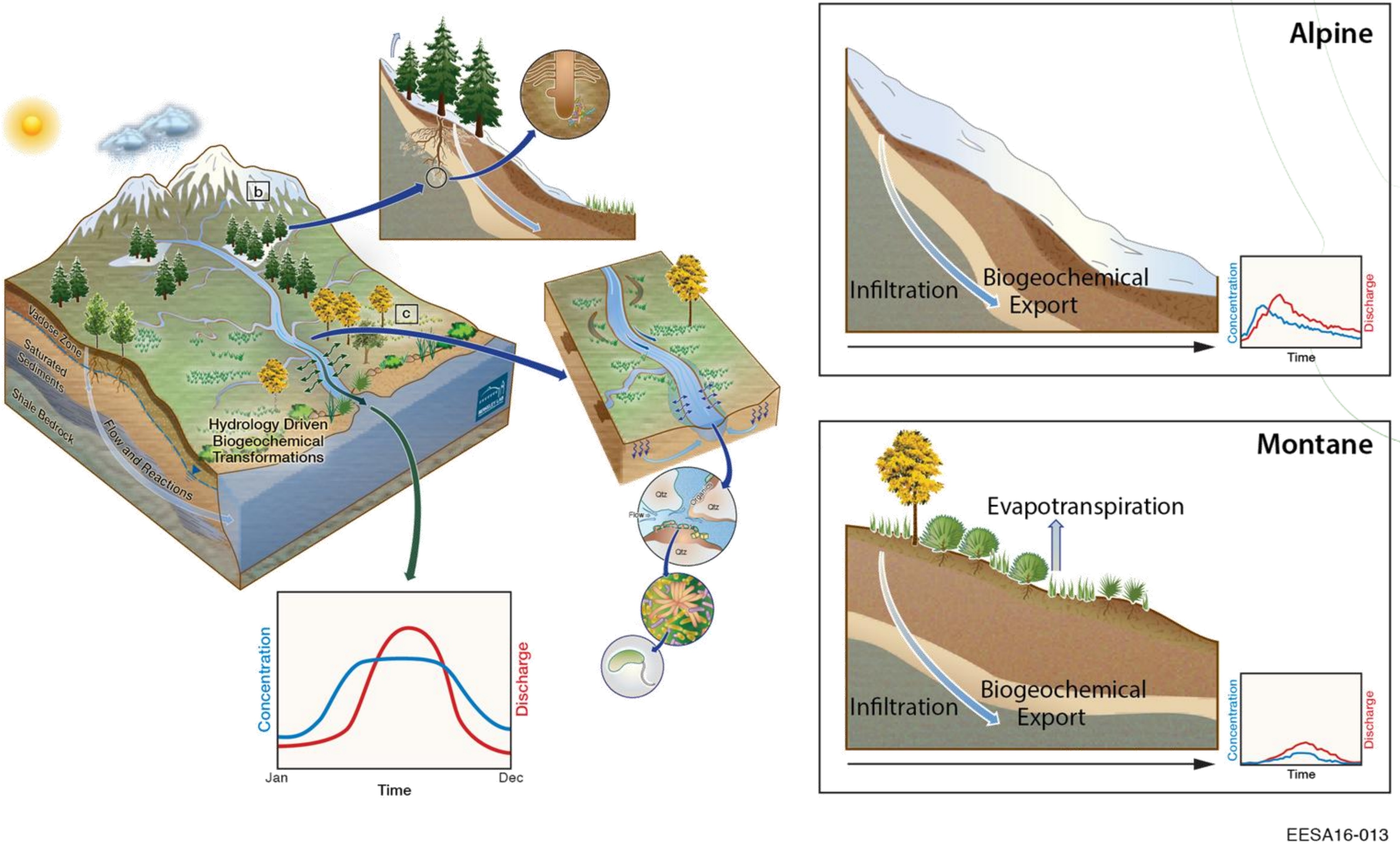
Quantitative analysis of geoelectrical monitoring data
Opportunities and limitations



Wagner et al., 2019

Hillslope Hydrology

An integral part to understanding the functioning of mountainous watersheds



How do mountainous watersheds retain and release water, nutrients, carbon and metals over episodic to decadal timeframes?

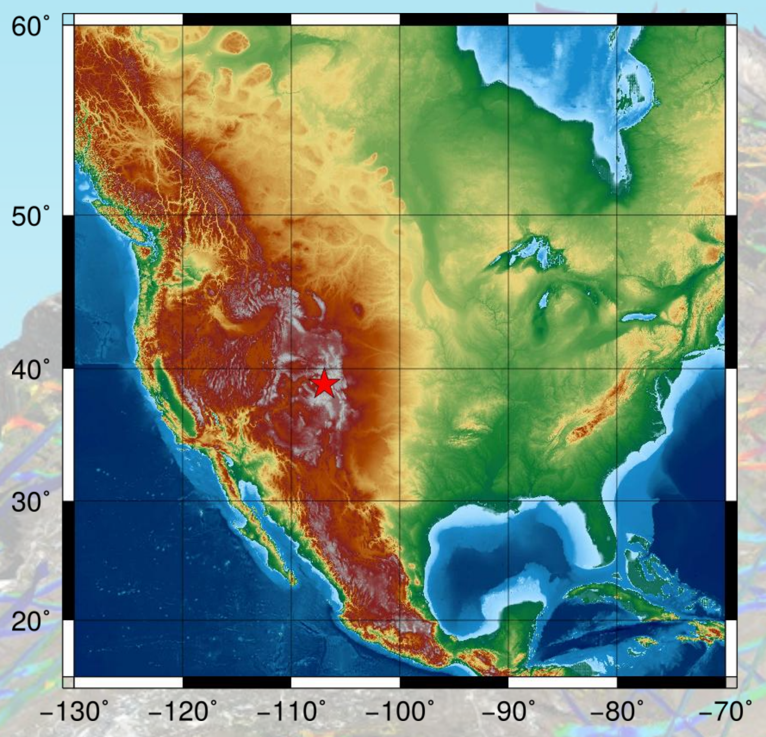
Understanding **bedrock characteristics and flow** is critical to answering this question.

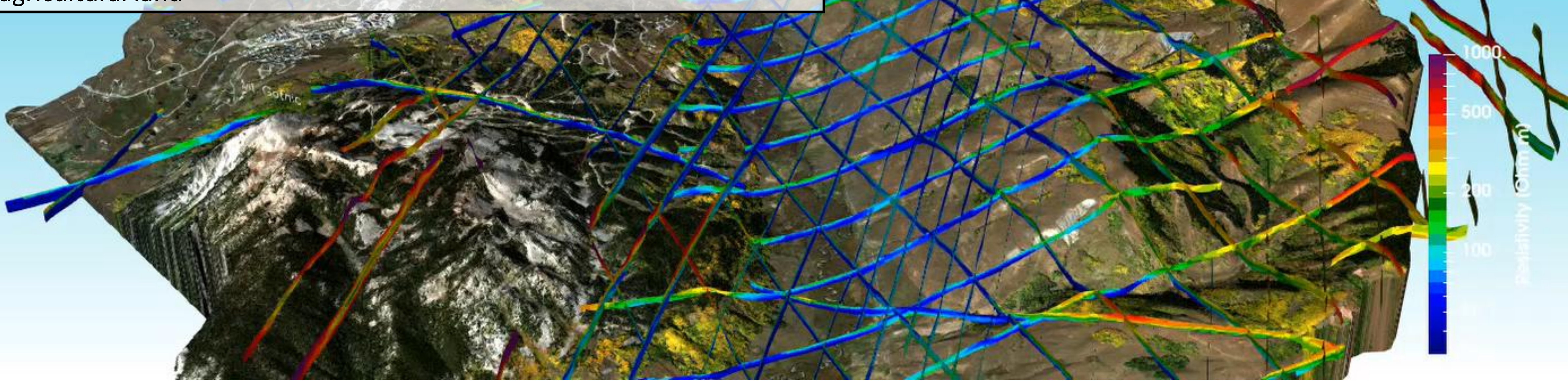
The East River Watershed

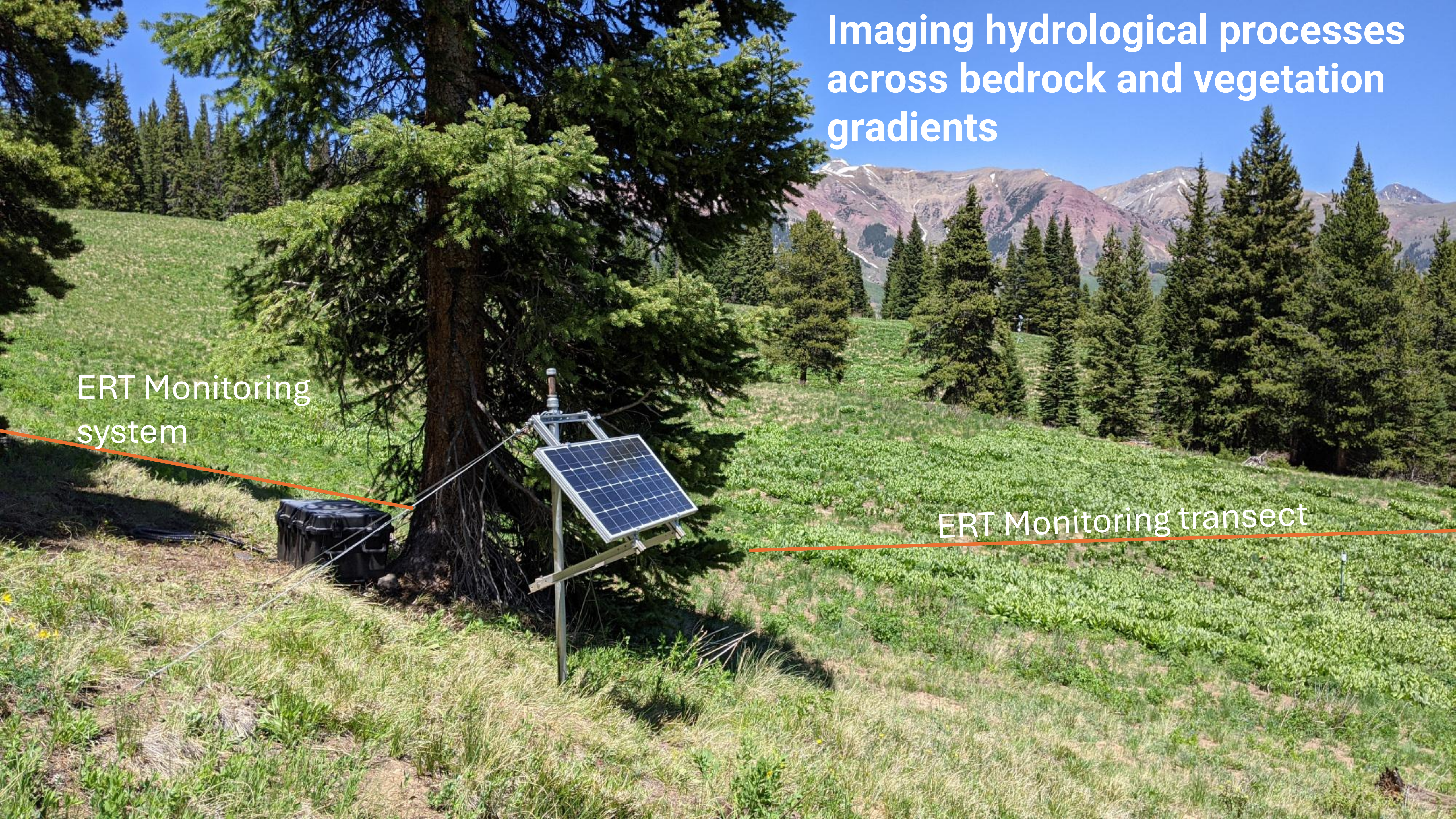
- **Area:** ~ 300 km^2
- **Average Elevation:** 3266 m
- **Topographic relief:** 1420 m

The East River is a **major tributary** to the Gunnison River and in turn the **Colorado River**

- Supplies water to **40 Million** people and **20,000 km^2** of agricultural land






Imaging hydrological processes across bedrock and vegetation gradients
ERT Monitoring system
ERT Monitoring transect

Assessing the hydrological impact of vegetation and bedrock gradients

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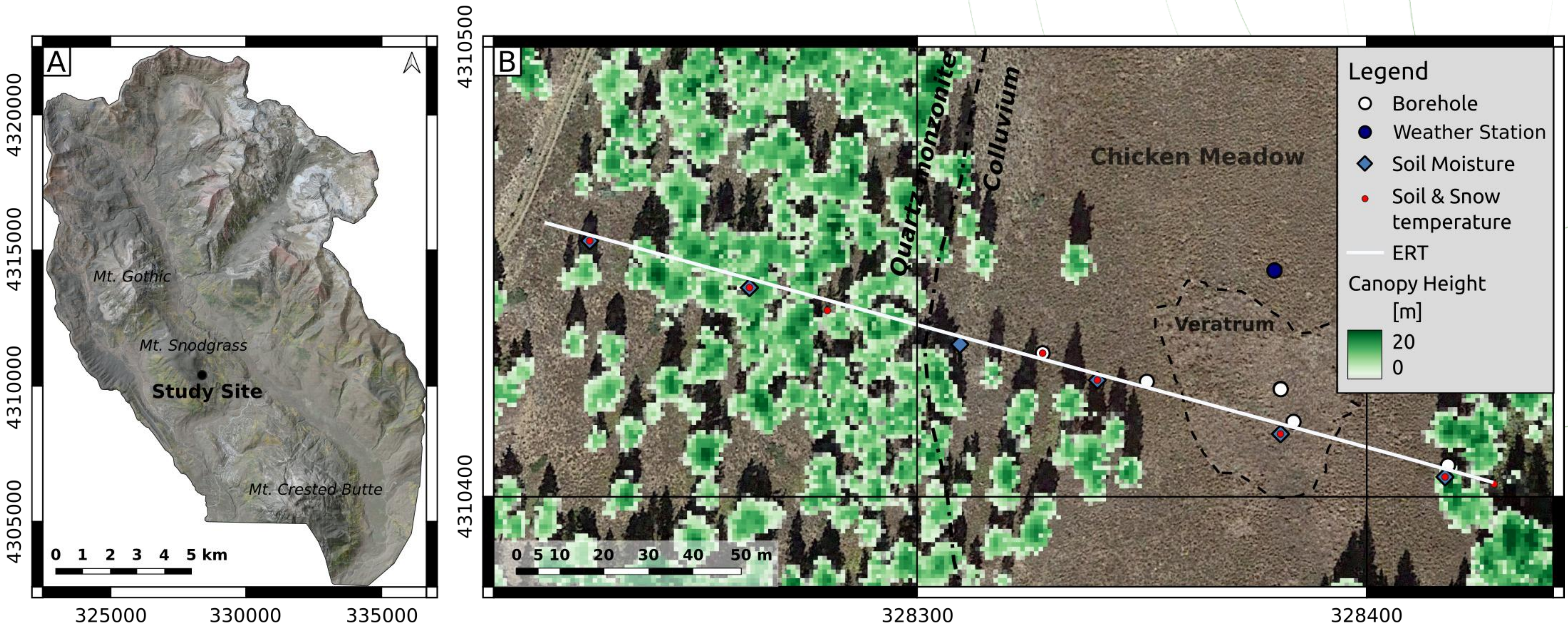
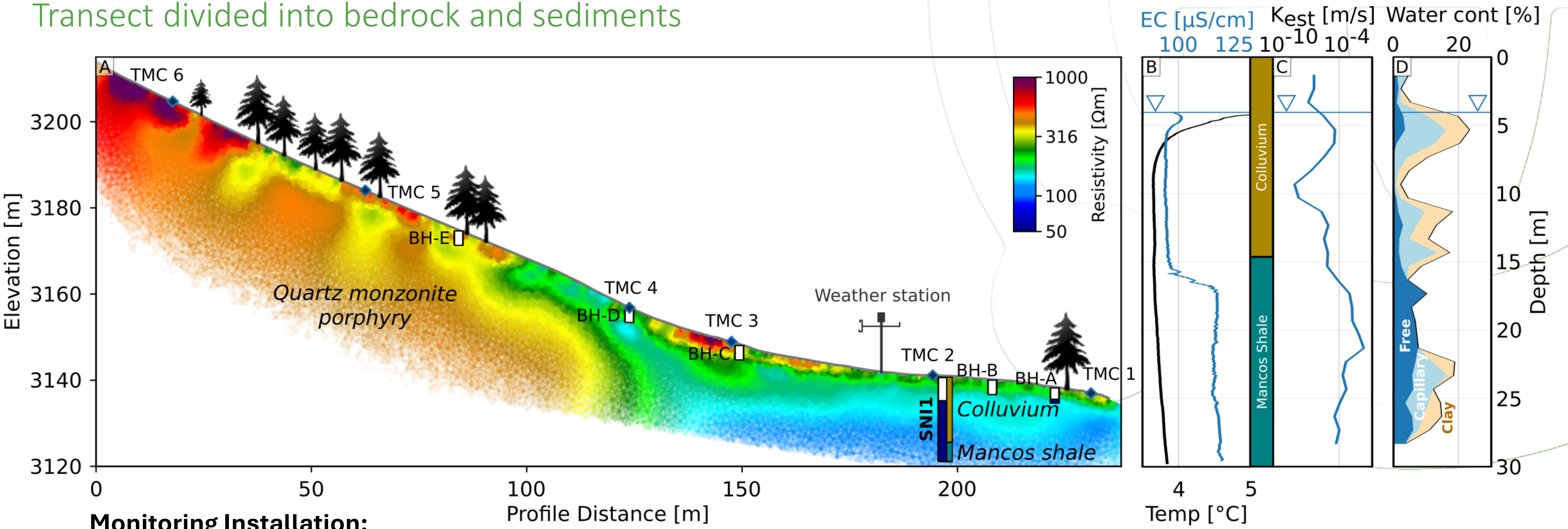
Going into the mid-elevations of Mt. Snodgrass



Uhlemann et al. (2024), *Bedrock and vegetation gradients modulate subsurface water flow dynamics of a mountainous hillslope*. Water Resources Research

Subsurface resistivities highlight strong gradient

Transect divided into bedrock and sediments



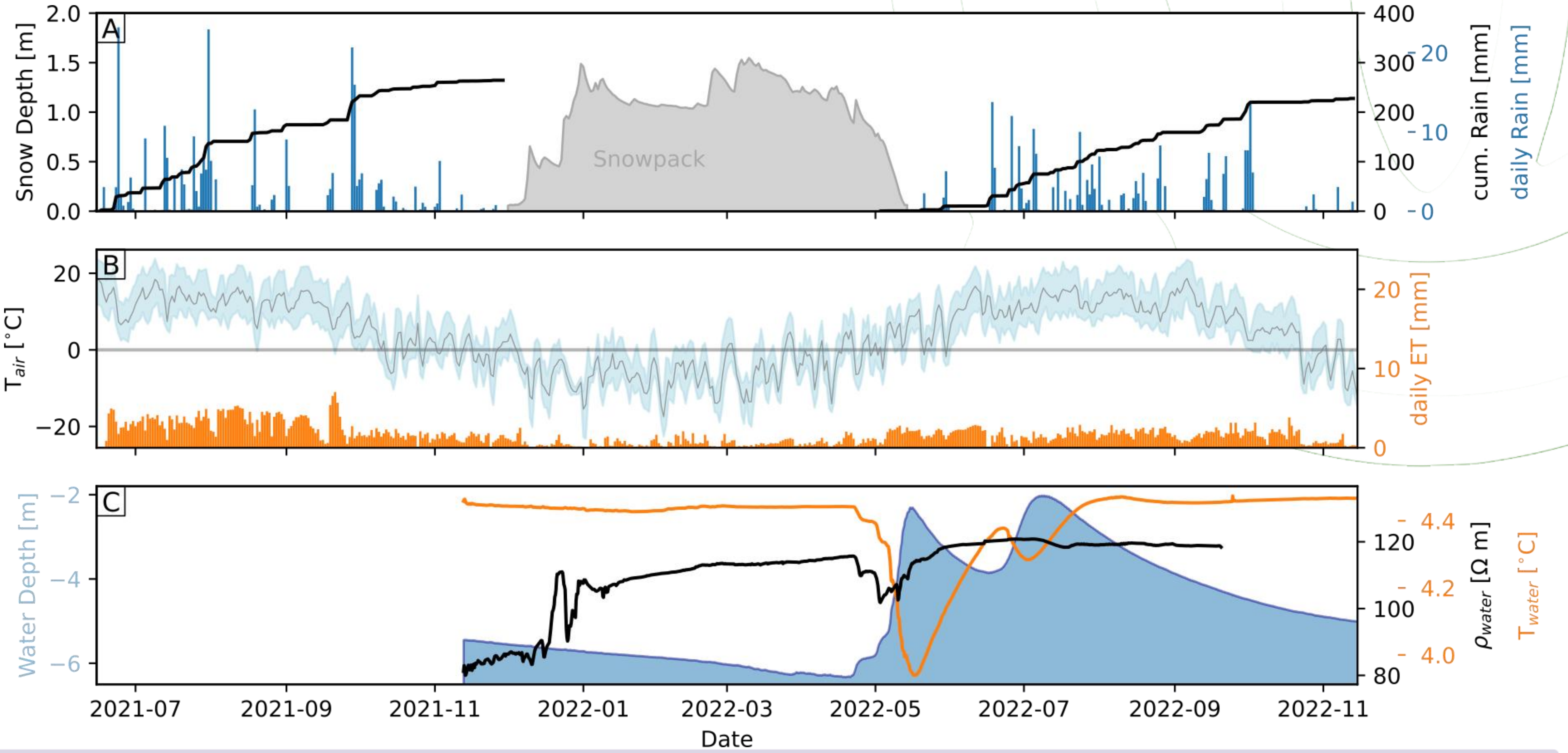
Monitoring Installation:

- ERT measurements (1 to 6 times per day)
- 1 deep + 5 shallow piezometers
- Soil moisture, temperature and snow temperature at 6 locations
- Weather station

- ERT, soil temperature, and deep piezometer data transmitted in **near real-time**
- **Electrical resistivity sensitive to changes in moisture content**

Environmental monitoring shows strong influence of snowmelt

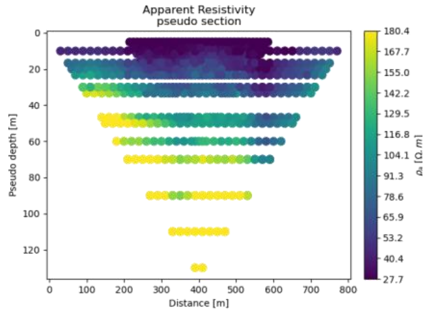
Summer rainfall only leads to water-limited conditions



Long-term ERT monitoring workflow

Data collection and processing

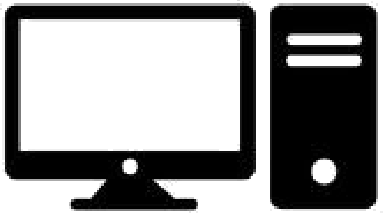
Monitoring data (up to 6/day)



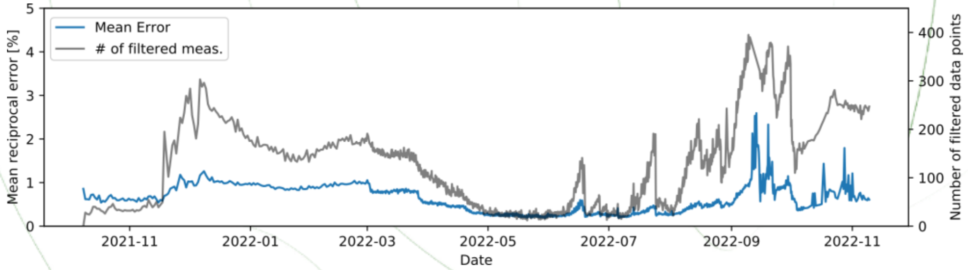
Solar powered, 10W system

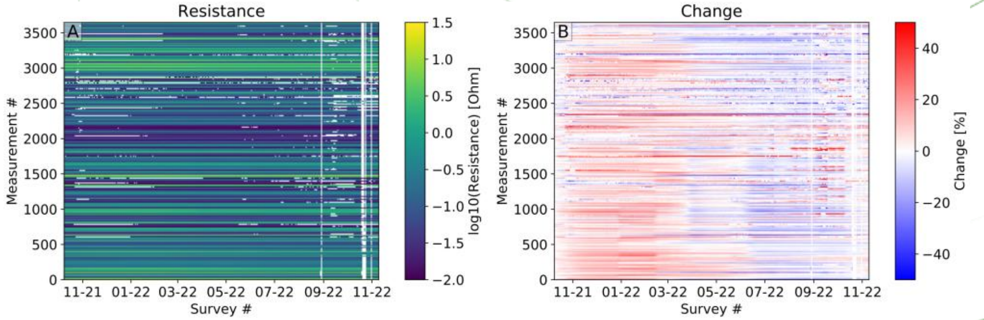
E-mail

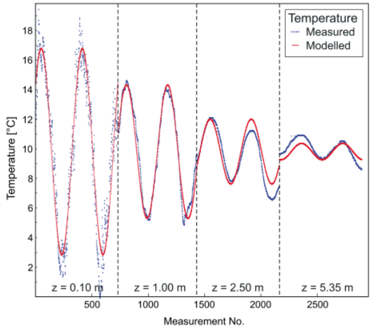
Data QA, storage



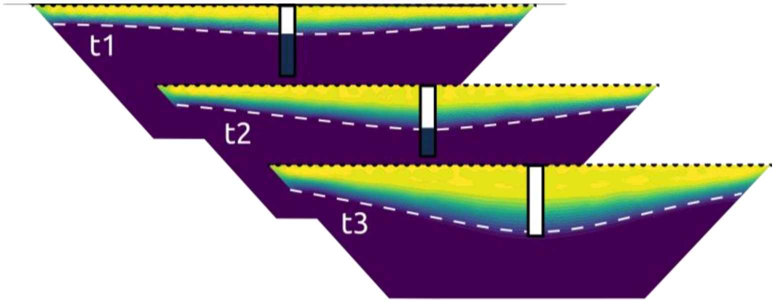
Time-lapse data processing
→ Creating a consistent data set







Temperature correction



Inversion

Windowed 4D

Sequential Time-lapse

PNNL

Approach:

1. Filtering of data with large (>20%) reciprocal error
2. Fitting of linear error model
3. Inverse-distance weighted interpolation → temporally consistent data set
4. Assignment of large error to interpolated data

Long-term ERT monitoring requires correction of temp. variation

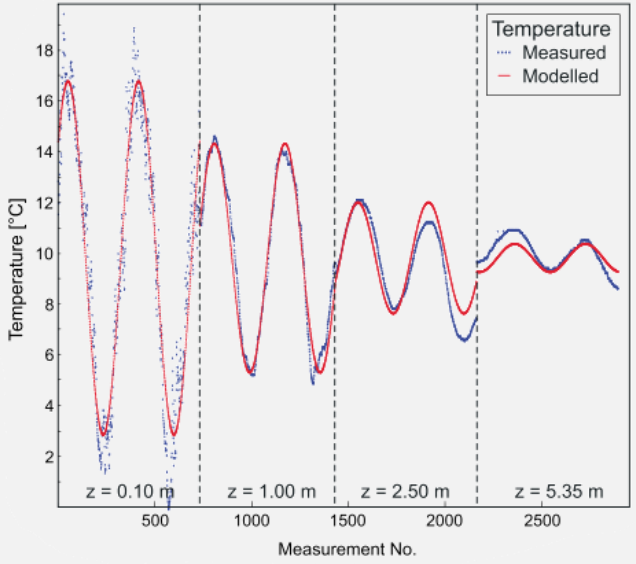
Workflow and limitations

Aim: Correction of **seasonal temperature variation**

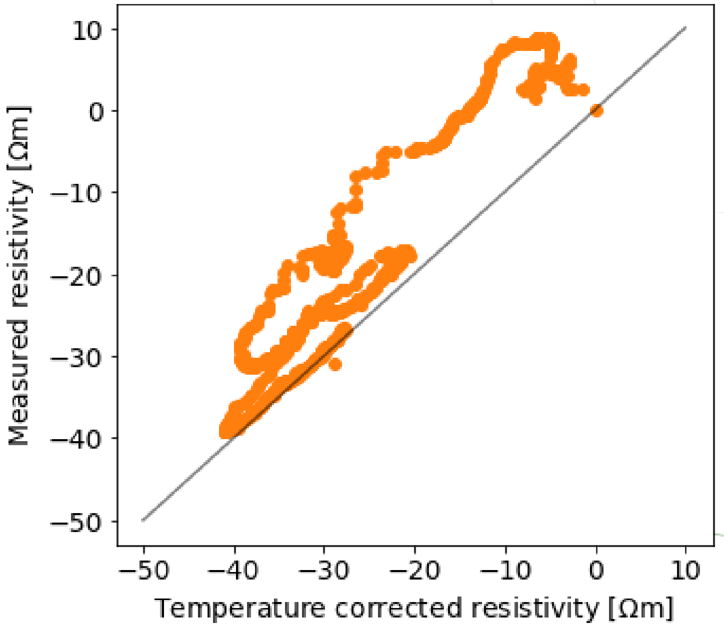
1. Fit heat equation to measured temperatures
2. Apply ratio model to correct resistivity

$$T_{\text{model}}(z,t) = T_{\text{mean}} + \frac{\Delta T}{2} \exp\left(-\frac{z}{d}\right) \sin\left(\frac{2\pi}{365}t + \phi - \frac{z}{d}\right)$$

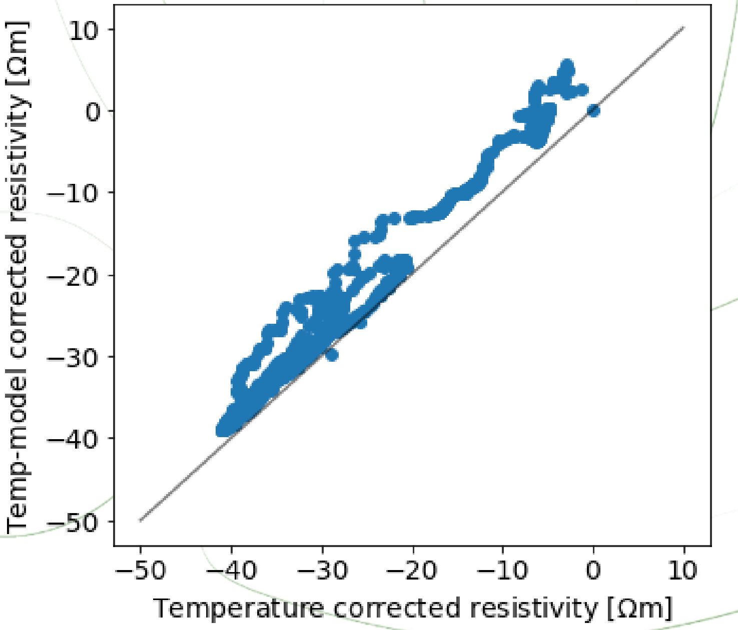
$$\rho_{\text{cor}} = \rho\left[1 + \frac{tc}{100}\left(T_{\text{standard}} - T_{\text{model}}\right)\right]$$



Corrected vs. uncorrected



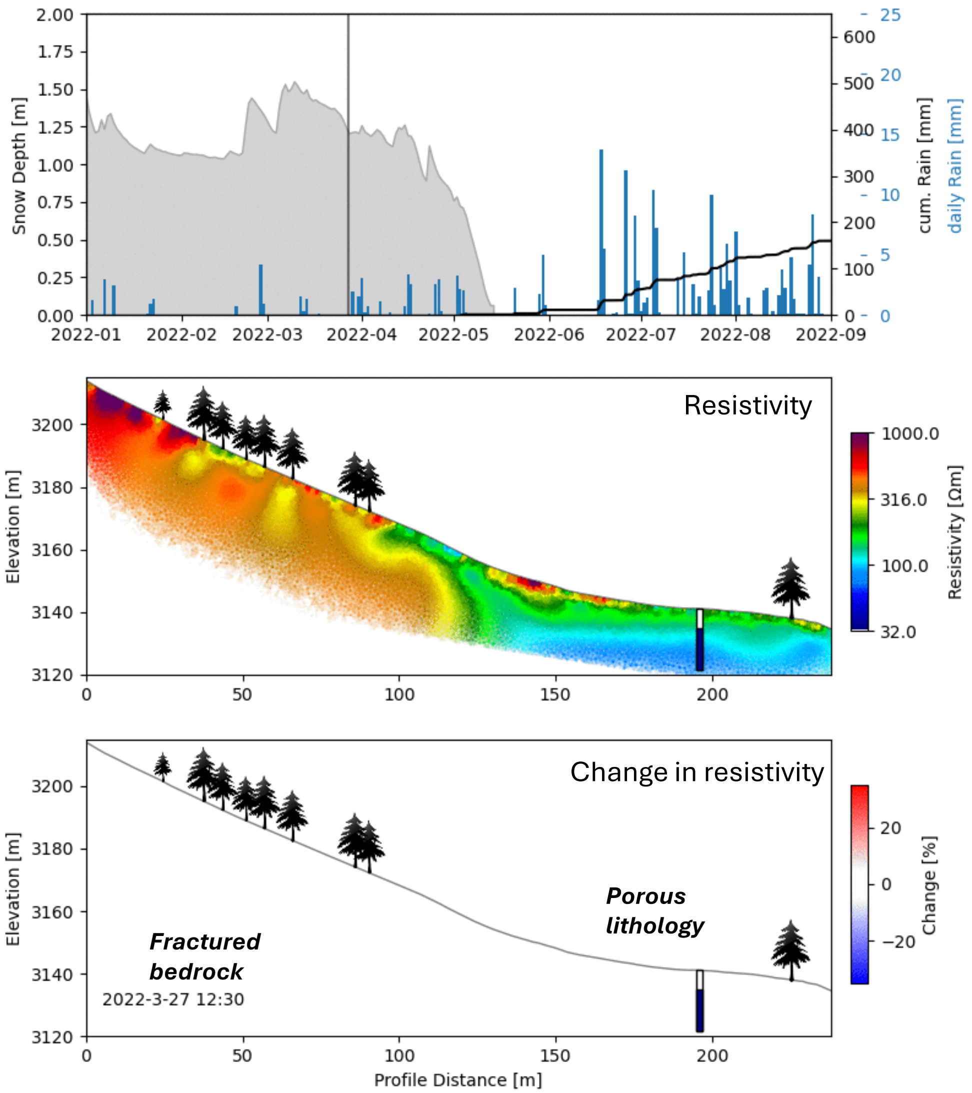
Measured vs. modelled Temp



- Diffusive heat equation assumes a sinusoidal annual temperature variation
- In snow-dominated environments that is not the case
- Error within 10% - modelled temperatures are sufficient to predict and correct resistivity data

Snowmelt provides large, heterogeneous water input to the system

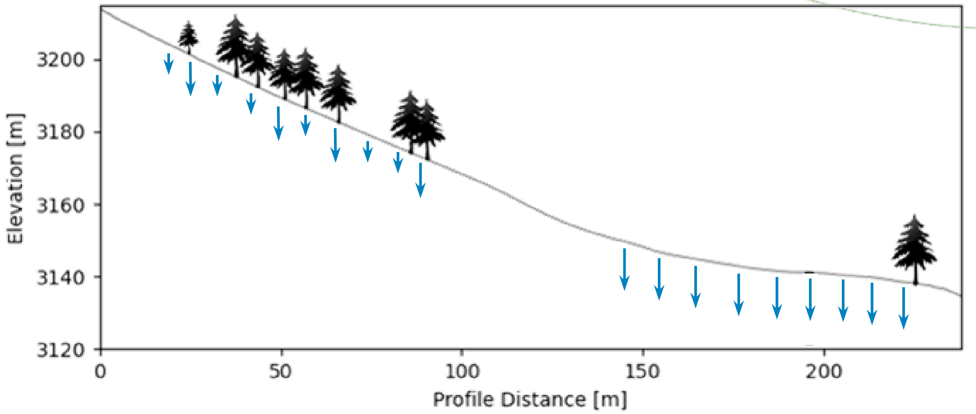
Small changes in upper, large changes in lower part



Monitoring of snowmelt of 2022 – measurements twice per day

Main Observations:

- No notable change during the first weeks
- Snowmelt leads to decrease in resistivity
  - First in lower, gentle part
  - Later in upper, steep part
- Horizontal feature coincides with large changes in groundwater level



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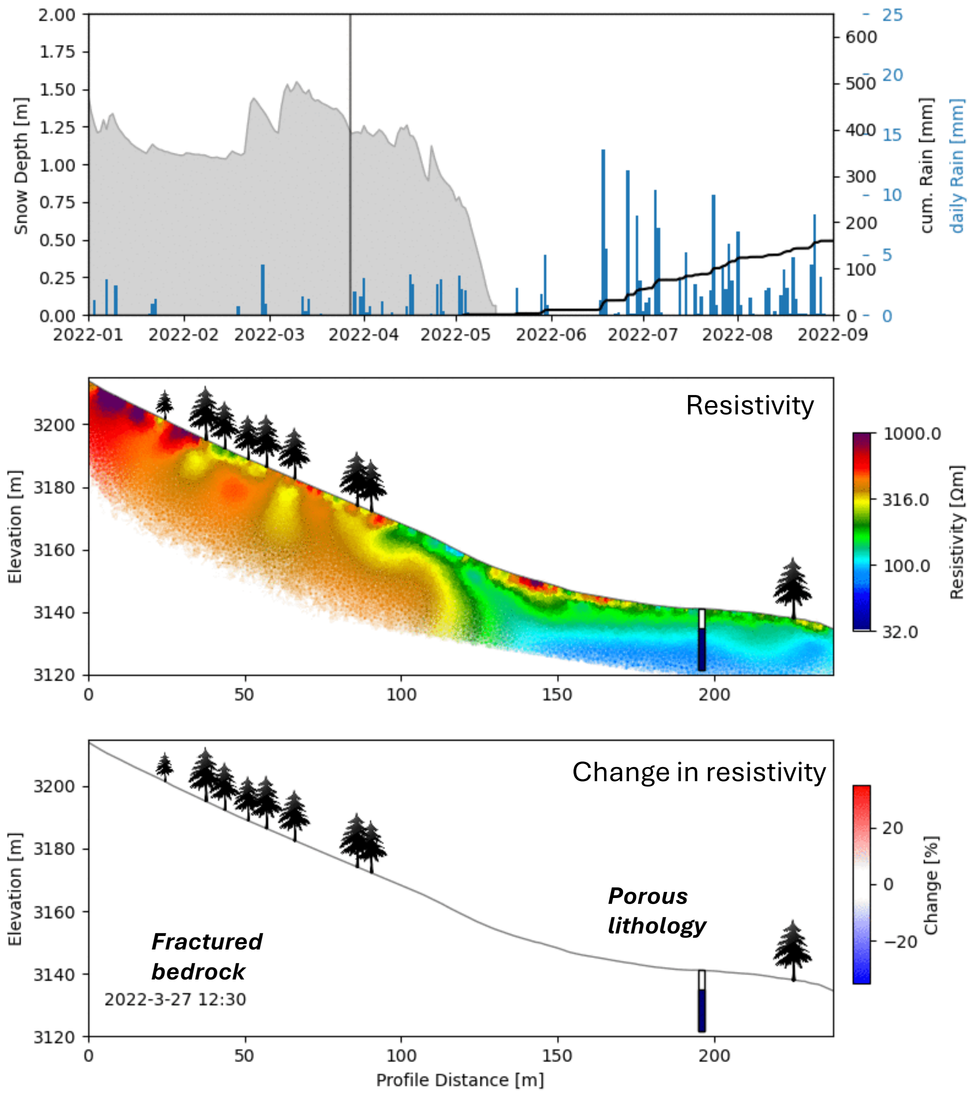

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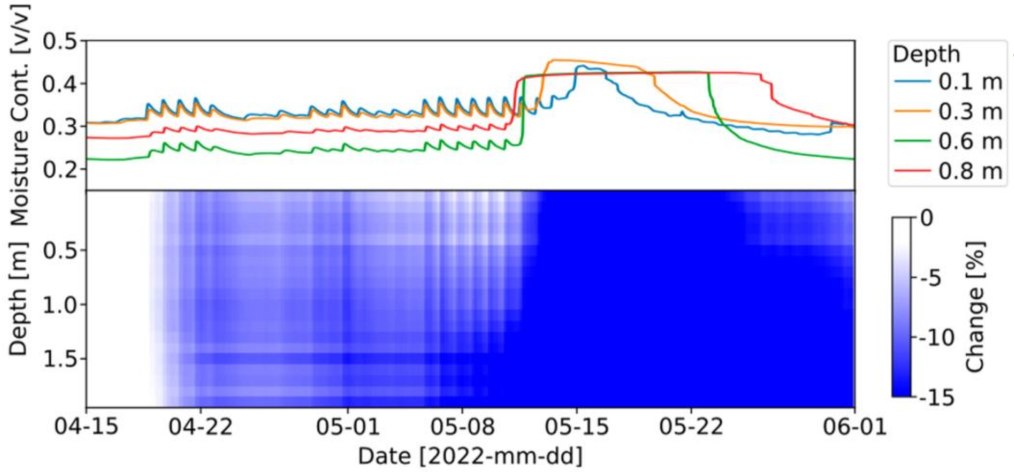
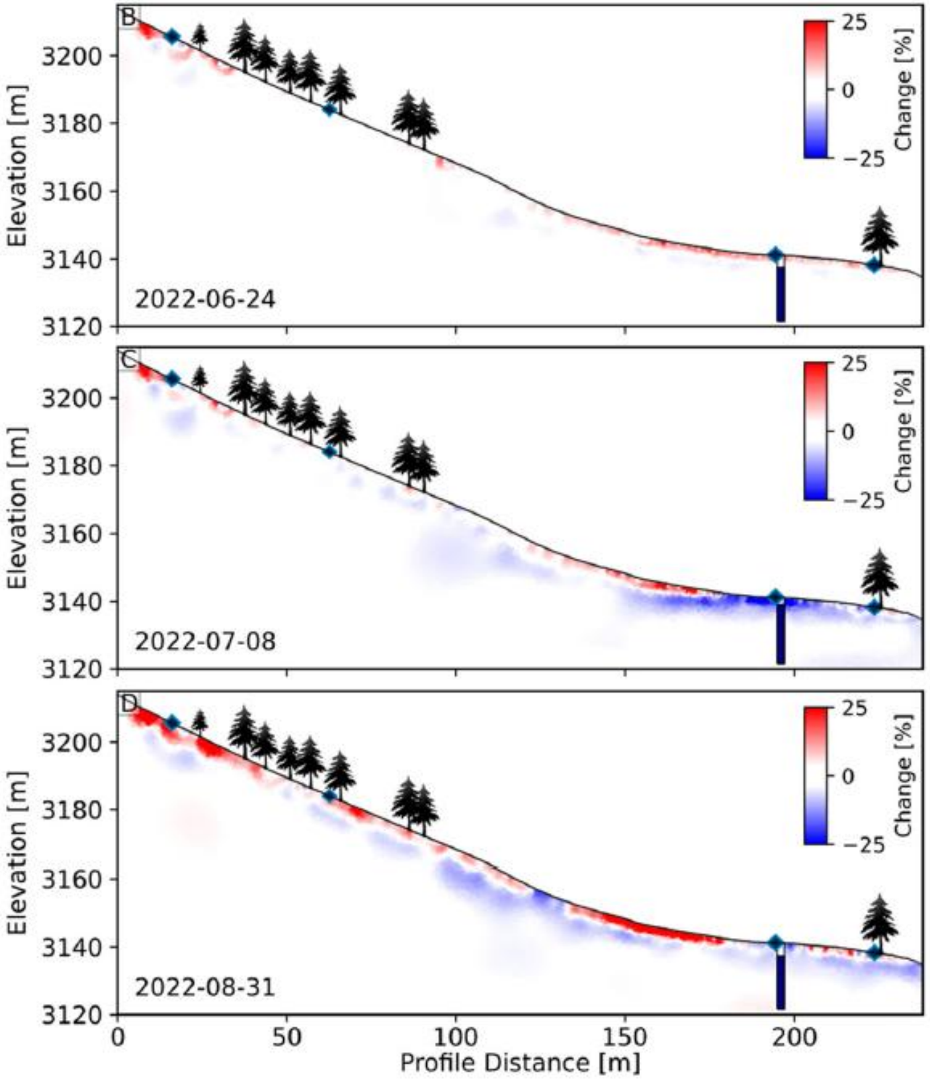
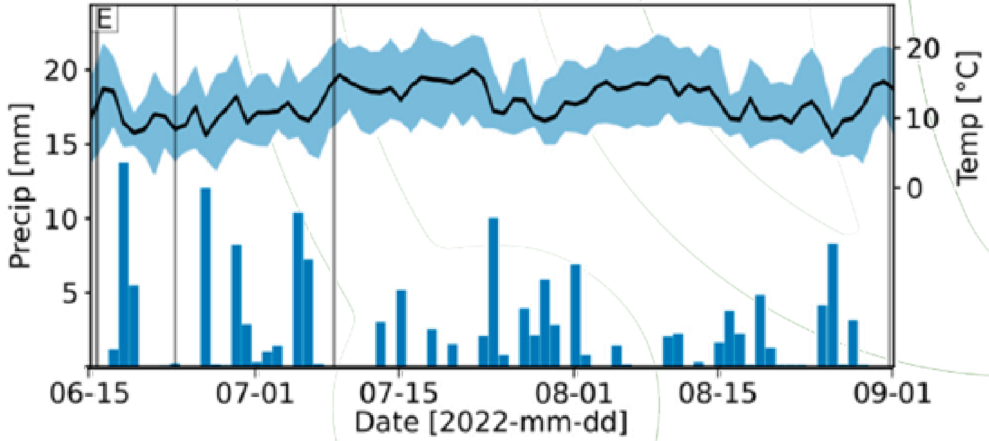


Summer monsoon is not providing significant water input

Evapotranspiration larger than recharge leading to drying of surficial soil layer





Despite frequent rain events (>10 mm/day) surface layers are becoming more resistive

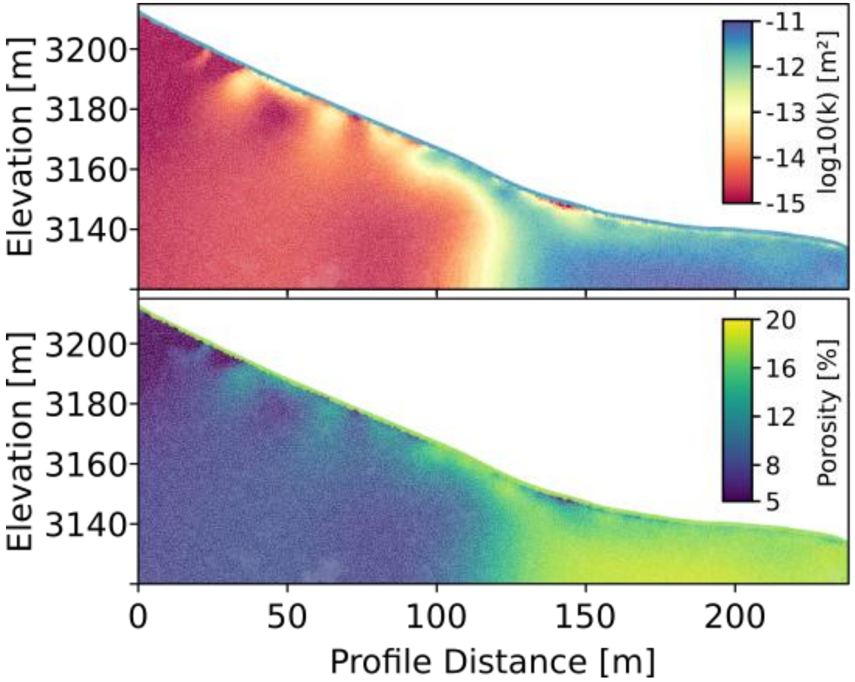
Main Observations:

- Mostly increasing resistivity in shallow soil layers
  - First in lower part, later in upper part
  - Delay suggests that litter and canopy reduce evaporation
- Decreasing resistivity in lower part related to second groundwater peak = upwelling
- Location of upwelling = location of veratrum

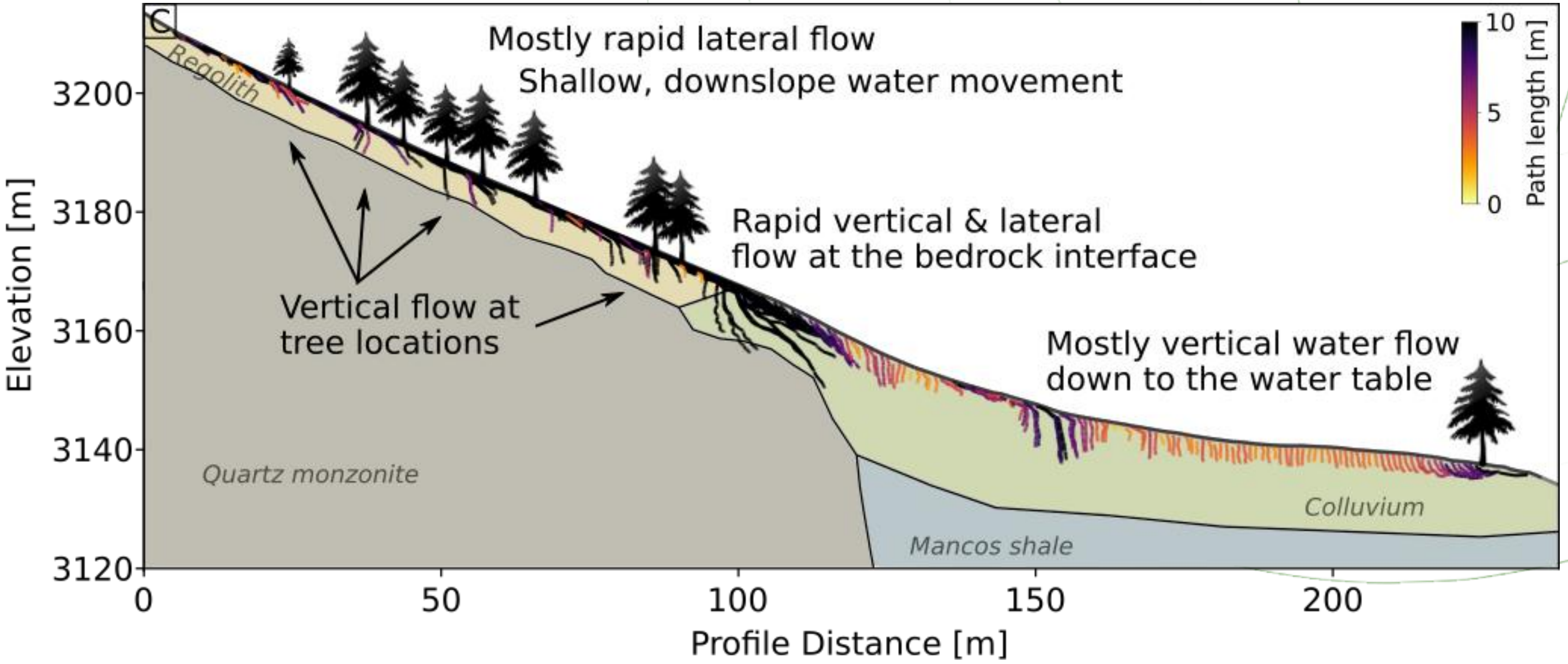
Modelling subsurface flow pattern

Model confirms the observations and provides details into recharge pattern

Model Parameterization



Simplified Ground Model & Modelling result

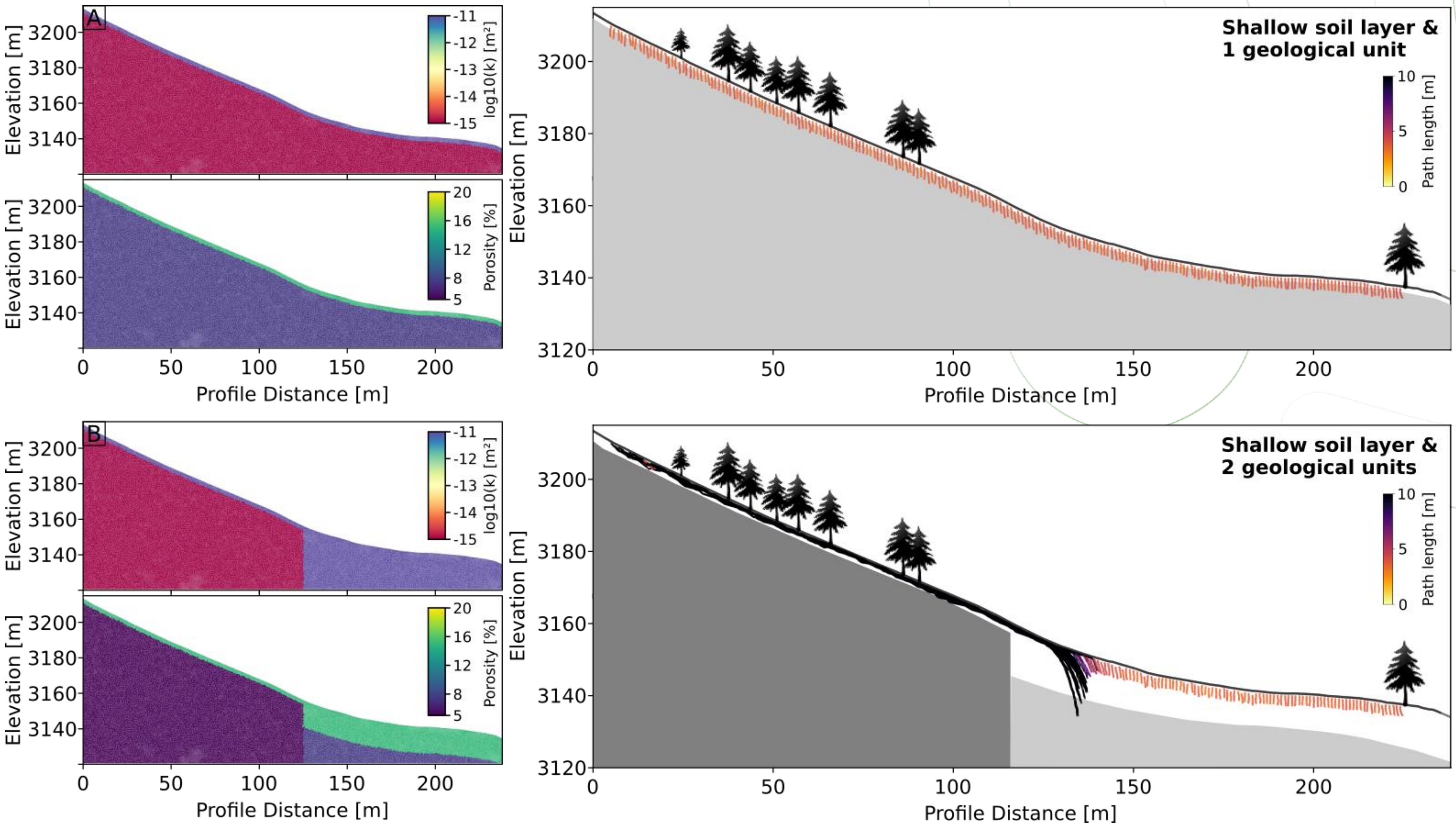


Main observations:

- Shallow lateral flow characterizes steep, shallow bedrock
- Deeper flow at tree locations
- Vertical up and downward flow prevails at gentle slope underlain by colluvium

Modelling subsurface flow pattern

Simplified models show topographic control of some observations



Modelling subsurface flow pattern

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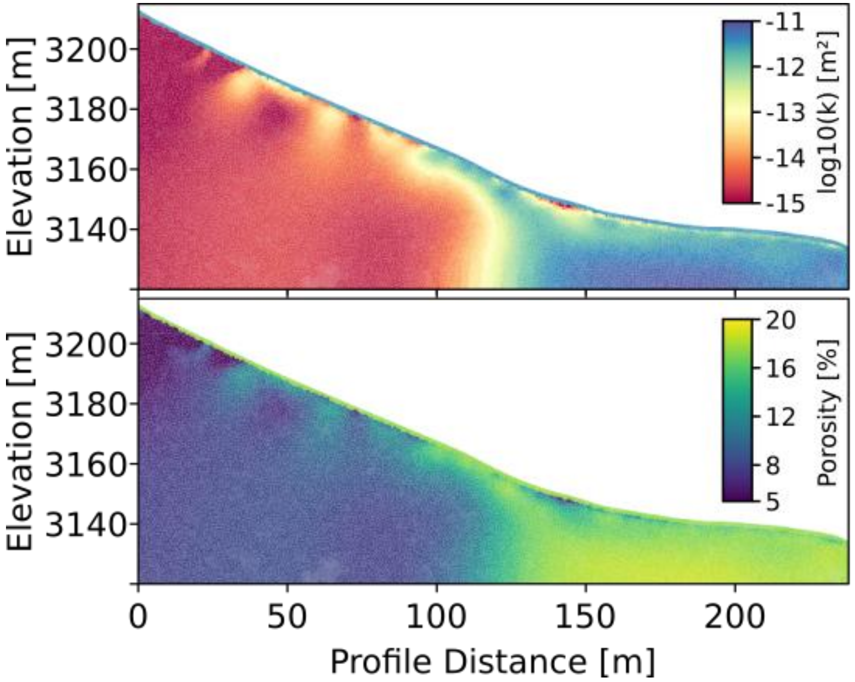
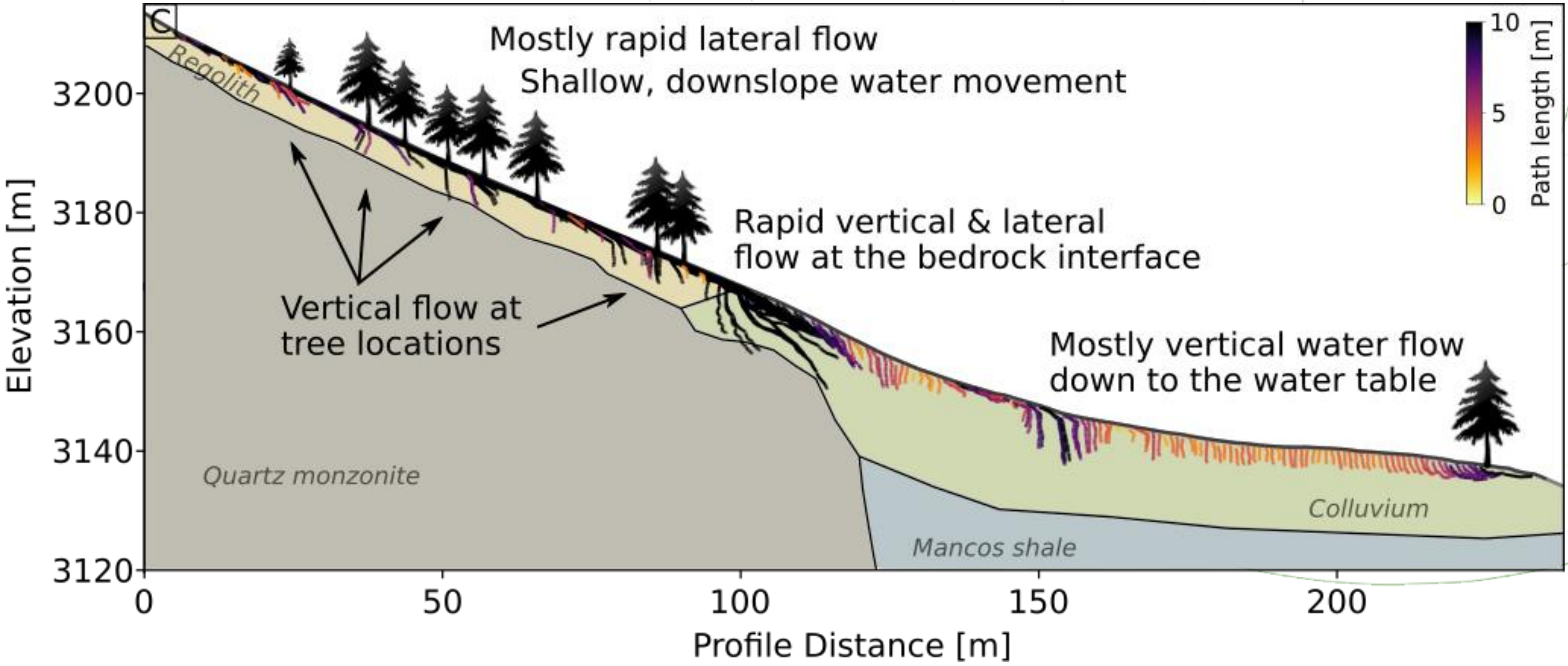


Simplified Ground Model & Modelling result



Conclusions

- Snowmelt provides critical input into hydrological cycle at this site
- Vegetation, bedrock and topographic characteristics define hydrological dynamics
- Shallow lateral flow characterizes steep, shallow bedrock, interrupted by more vertical flow at tree locations
- Vertical up and downward flow prevails at gentle slope underlain by colluvium
- High resolution, integrated ERT monitoring shows detailed hydrological dynamics

Methodological Developments

- Novel processing scheme for long-term, high-resolution ERT data
- Spatially variable temperature correction

Quantifying groundwater recharge through 4D geoelectrical monitoring

BERKELEY LAB
Bringing Science Solutions to the World

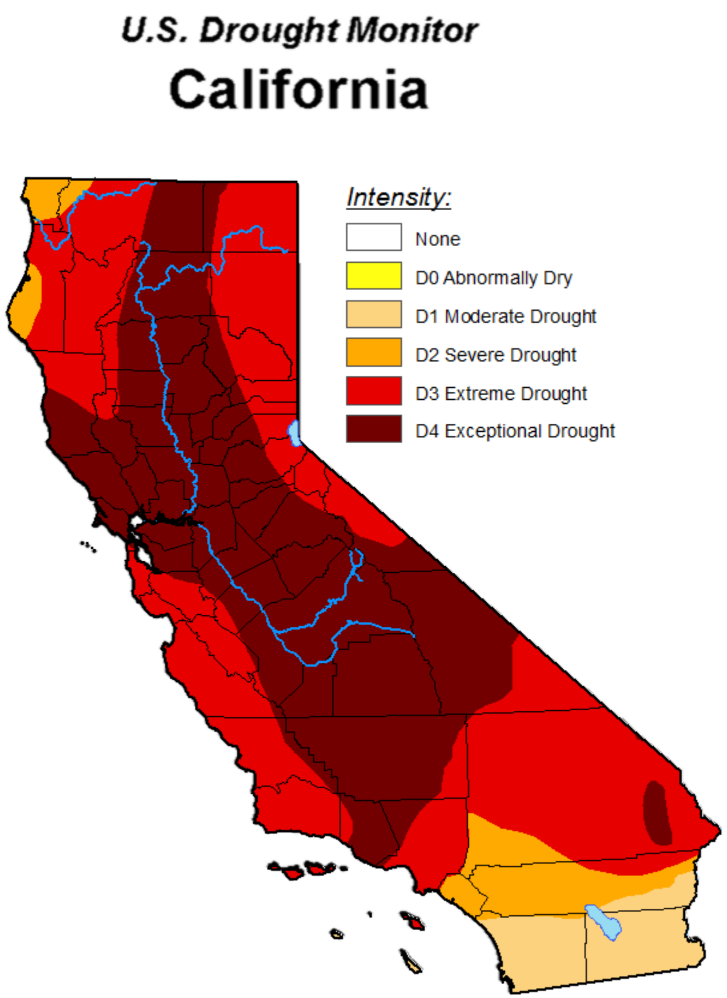
Geosyntec consultants

BUREAU OF RECLAMATION

Public Works
LOS ANGELES COUNTY

Assessing Performance of Sustainable Urban Drainage Systems

Groundwater recharge to ease urban groundwater stress



California is prone to droughts

“Solution”: **Managed aquifer recharge**

1. Provide more **stable water supplies** during drought
2. **Supplement the quantity** of groundwater available
3. **Conserve** and dispose of **runoff and floodwaters**

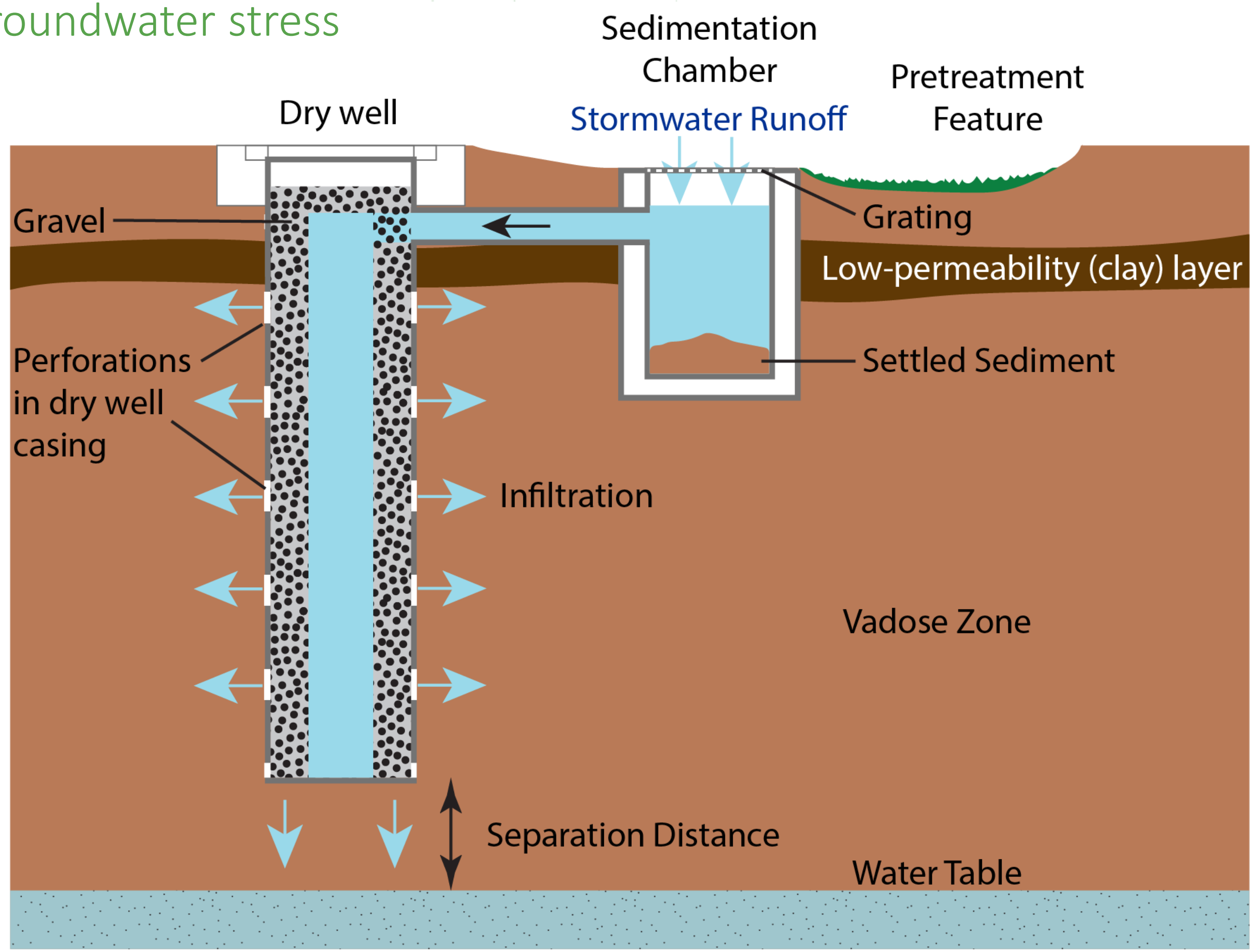
How do you quantify and control these effects?

Assessing Performance of Sustainable Urban Drainage Systems

Groundwater recharge to ease urban groundwater stress

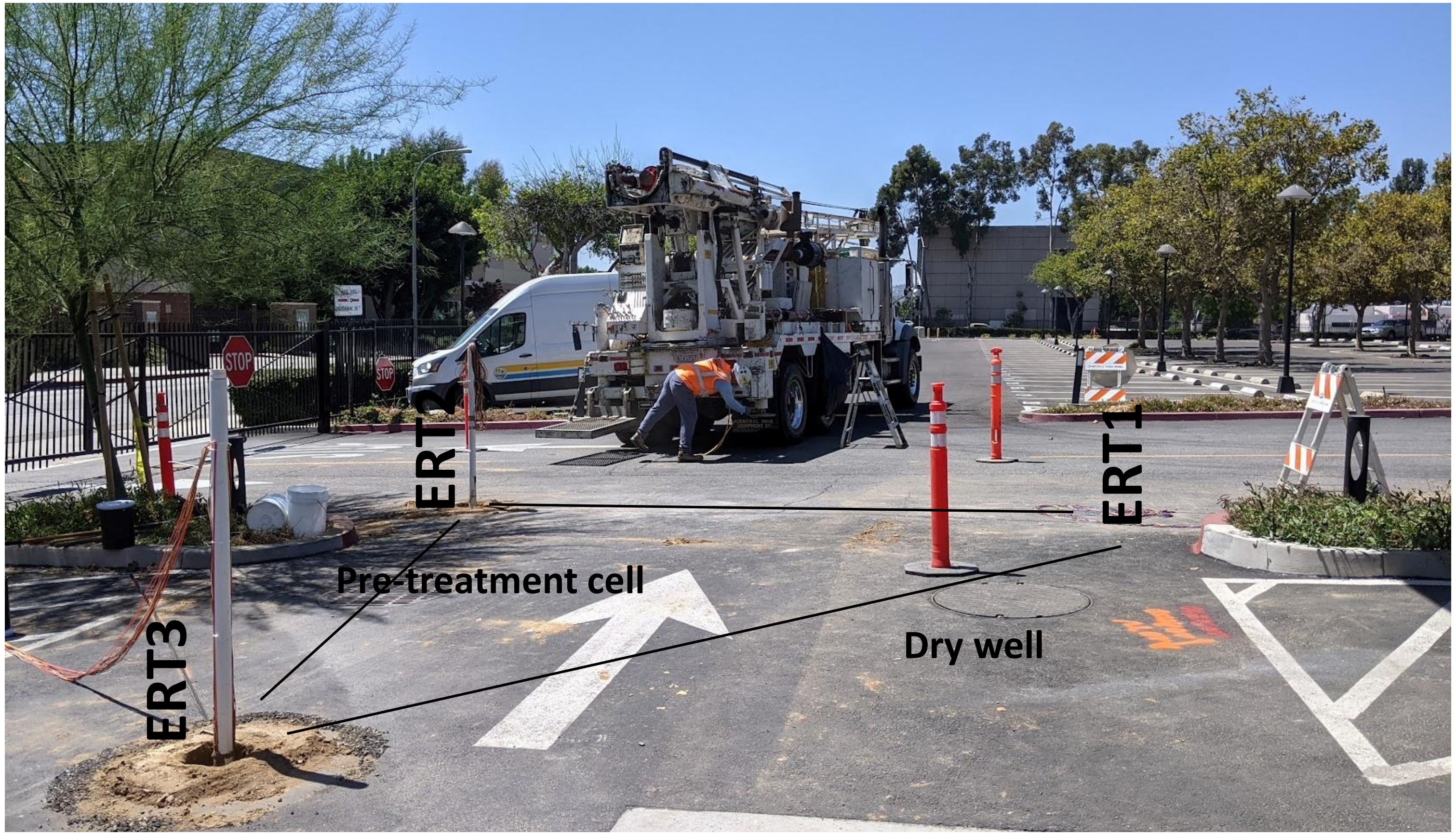
- **SUDS are designed for storm water control**
  - LA annual rainfall: 508 mm @ 35 days
  - Precipitation mostly linked to storm events
- SUDS come in many different types

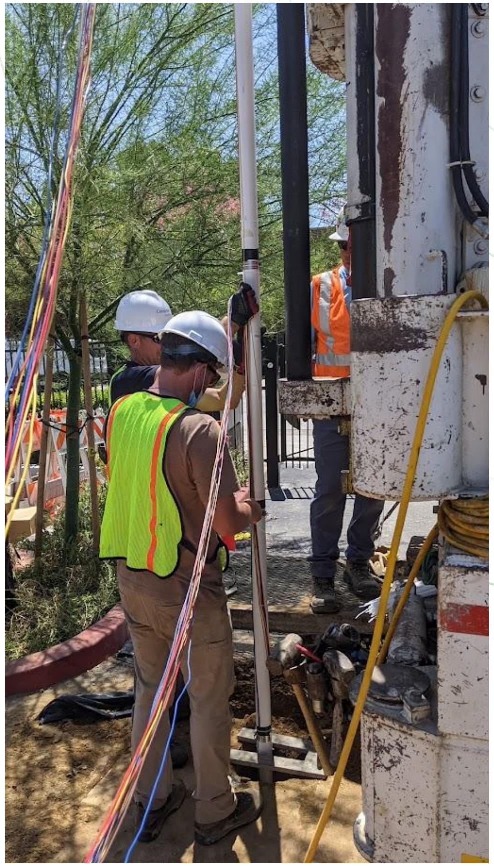
- **Actual infiltration patterns are poorly understood**
- **What is the contribution of SUDS to urban groundwater recharge?**



Assessing Performance of Sustainable Urban Drainage Systems

Installation of ERT monitoring system at LA County Public Works dry well

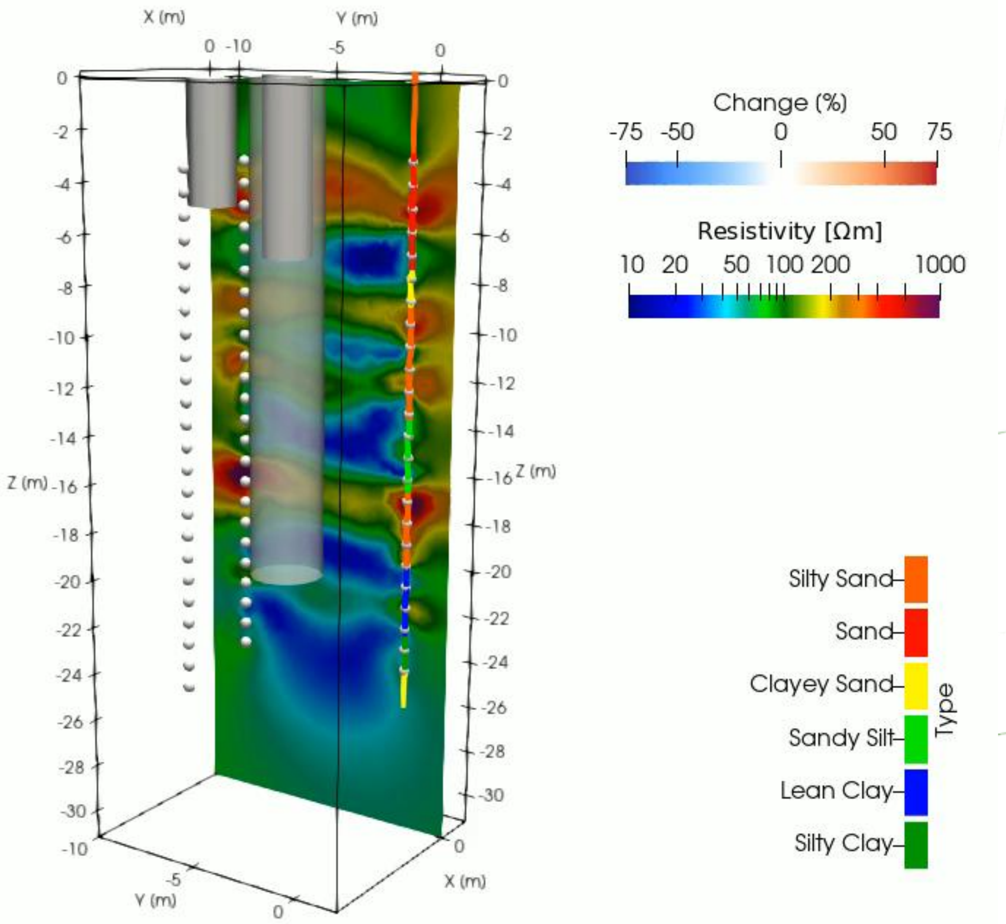


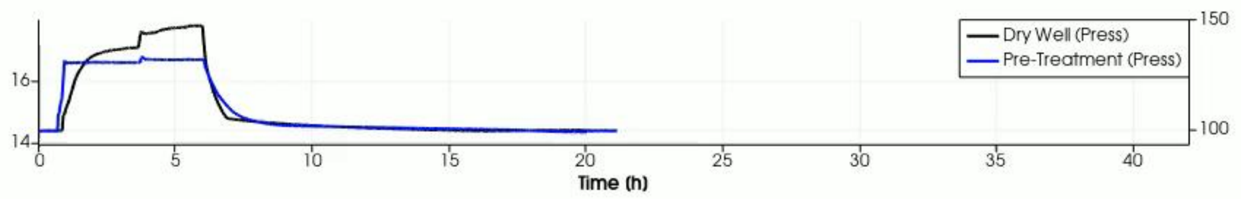


Assessing Performance of Sustainable Urban Drainage Systems

Results of controlled recharge experiment

- **Soil sampling and background resistivity show alternating clayey and sandy layers**
- **Simulated rainfall event**
  - 98 m^3 in 5.5 h
  - Simulating a typical rainfall event for Southern California
- Water moves mostly laterally, occupying more resistive layers
- **Rapid drawdown in the wells → system not saturated**

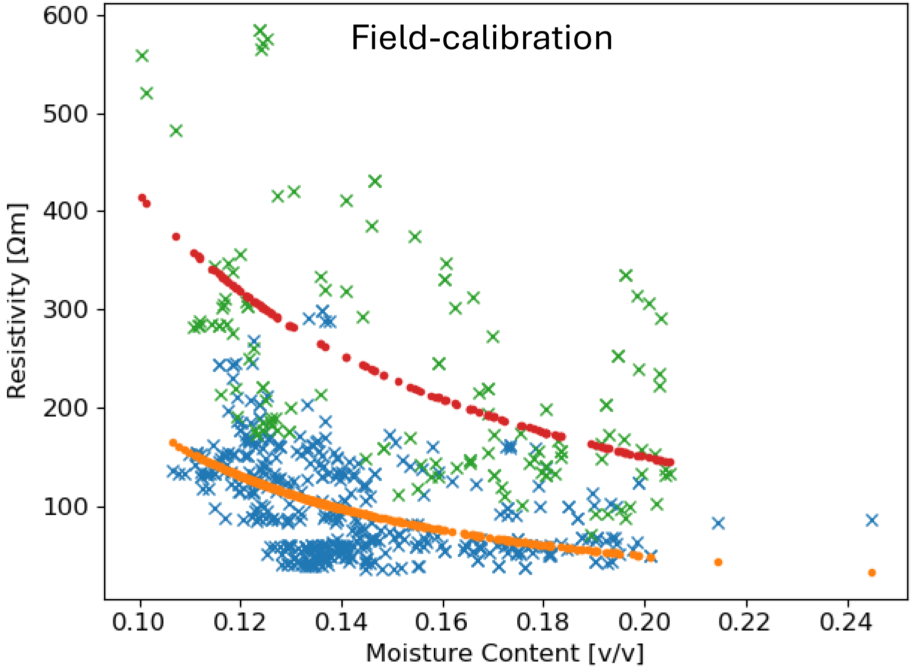




Assessing Performance of Sustainable Urban Drainage Systems

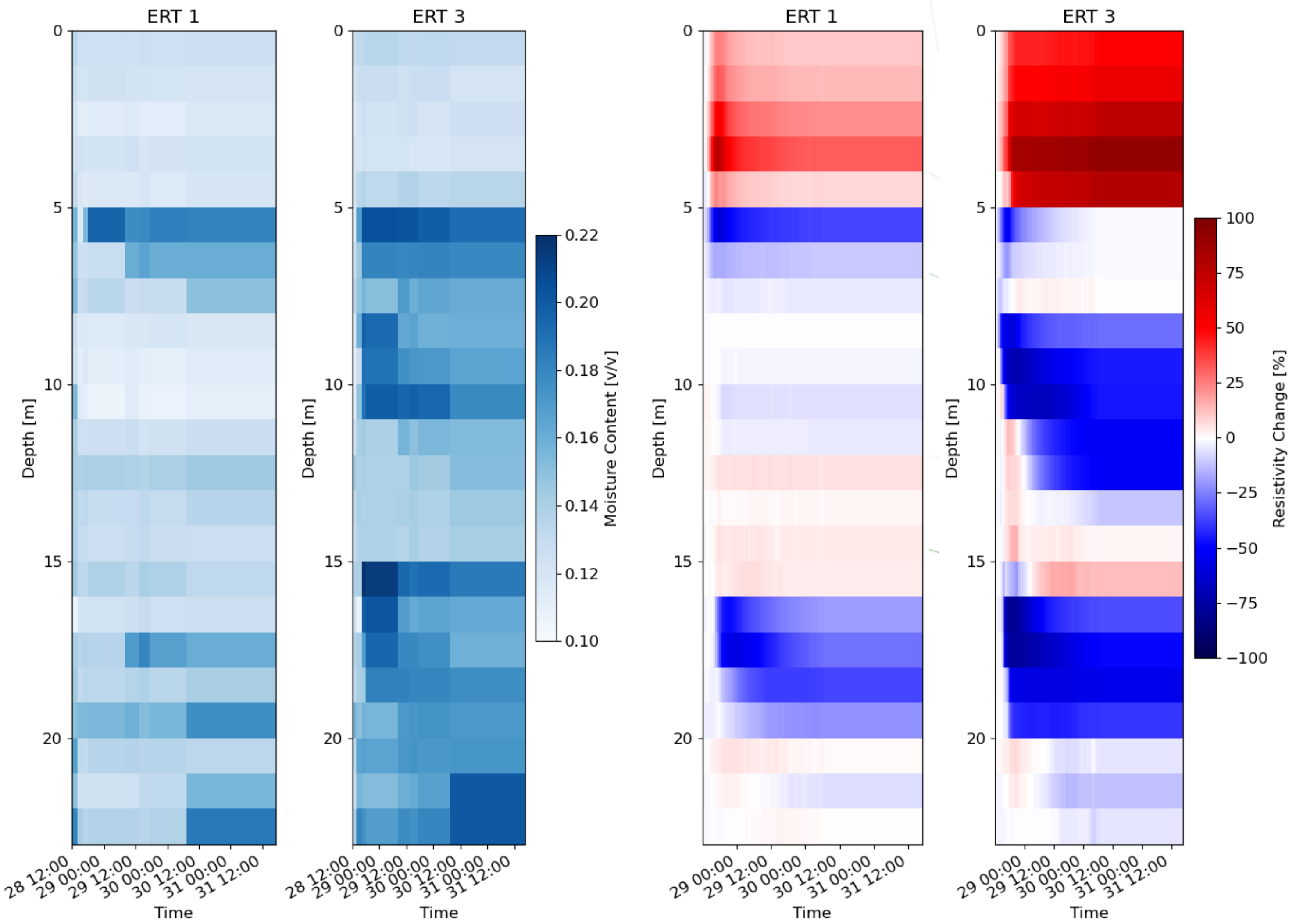
Enabling quantitative assessment

- **Changes in resistivity correlate with soil moisture data**
- In-field calibration of resistivity monitoring data to obtain models of moisture content



Direct measurements of moisture content

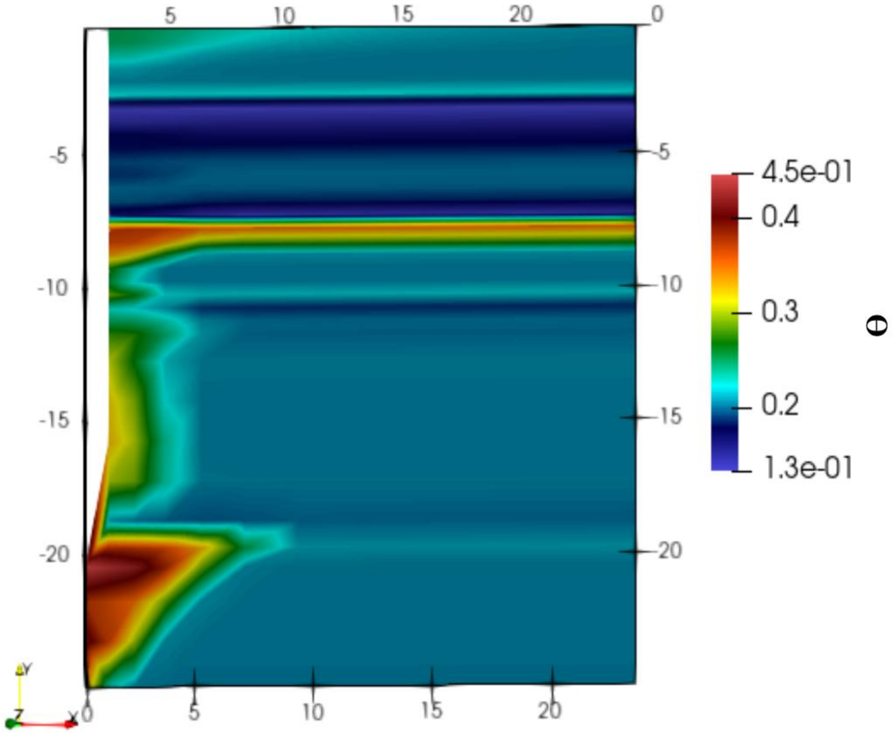
Electrical resistivity time series

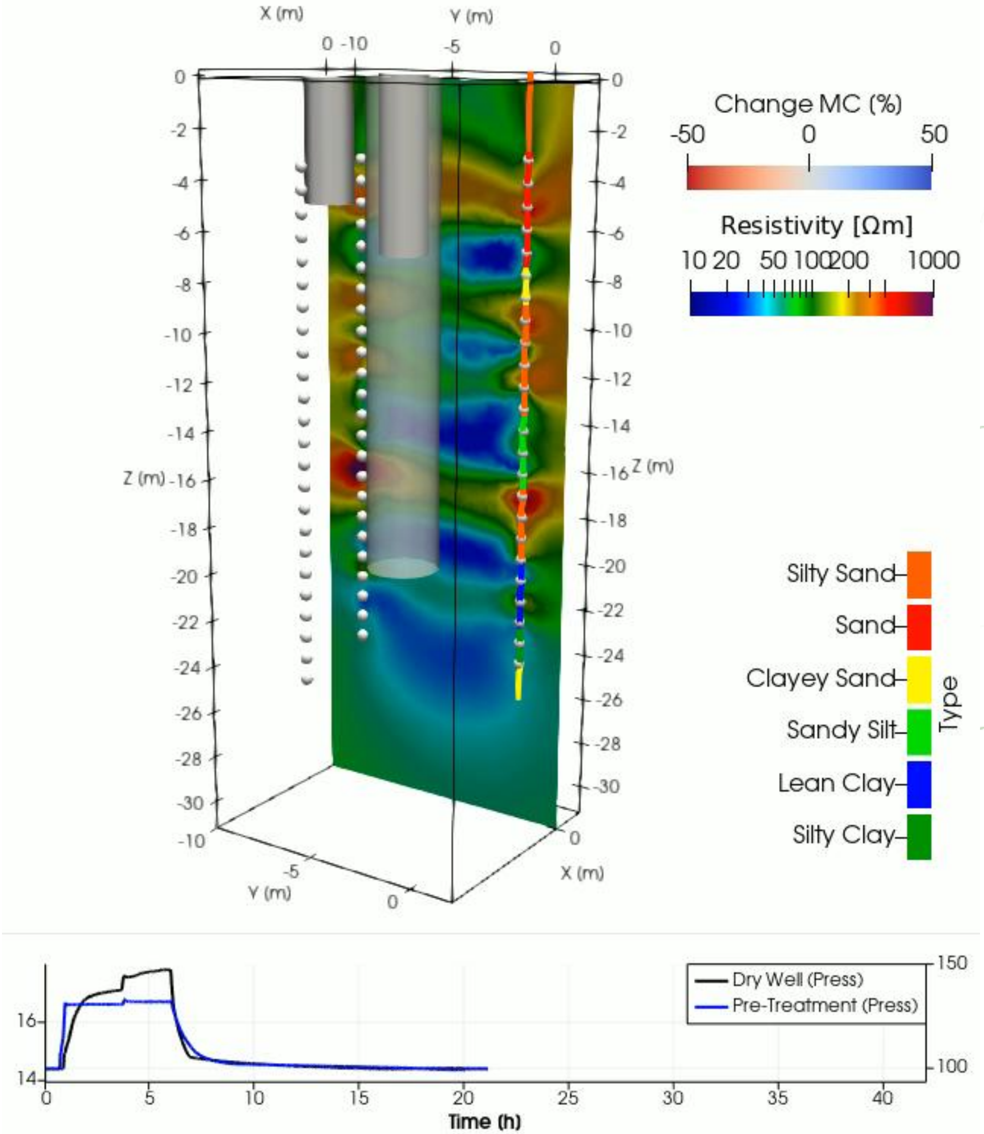


Assessing Performance of Sustainable Urban Drainage Systems

Enabling quantitative assessment

- Petrophysical transfer function translates resistivity into water content
- Water occupies drywell and feeds into the aquifer
- Input for 3D hydrological model calibration





ERT monitoring sheds light on urban infrastructure

- Changes in electrical resistivity linked to changes in soil moisture content
- Resistivity monitoring can be used to assess groundwater recharge processes
  - Drywell setup provides direct input to local aquifer
  - Other SUDS types not as effective

Outlook

- Linking observations with hydrological models to quantify the contribution of SUDS to groundwater recharge
- Extension of monitoring network to assess different SUDS designs

ITINERIS

THANKS!

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