

Geophysical monitoring of temperature variation and water movement in a frost weathering cave

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Context

Conduction
mechanisms

Objectives &
hypothesis

Study site

Induced
Polarization

Filtering
procedure

Inversion
approaches

Results

Temperature
correction

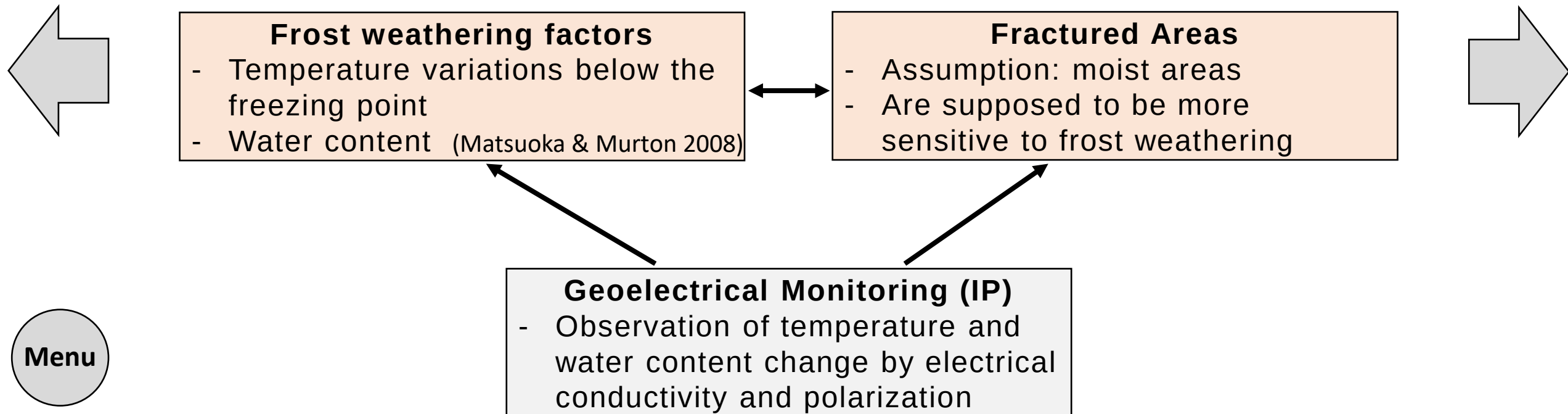
Temperature-
corrected results

Conclusion

References

Context

~1/3 of caves in north-eastern part of Eastern Alps are assumed to be created by frost weathering (Oberender & Plan 2015)



Conduction mechanisms

- Matrix conductivity σ_m :
 - Electrical conduction through grains
- Electrolytic conductivity σ_f :
 - Electrical conduction in pore fluid
- Surface conductivity σ_s :
 - Electrical conduction at grain surface (related to EDL – [click here](#))
- Bulk electrical conductivity σ :

$$\sigma = \sigma_m + \sigma_f + \sigma_s$$

→ σ_m negligible, if no metals

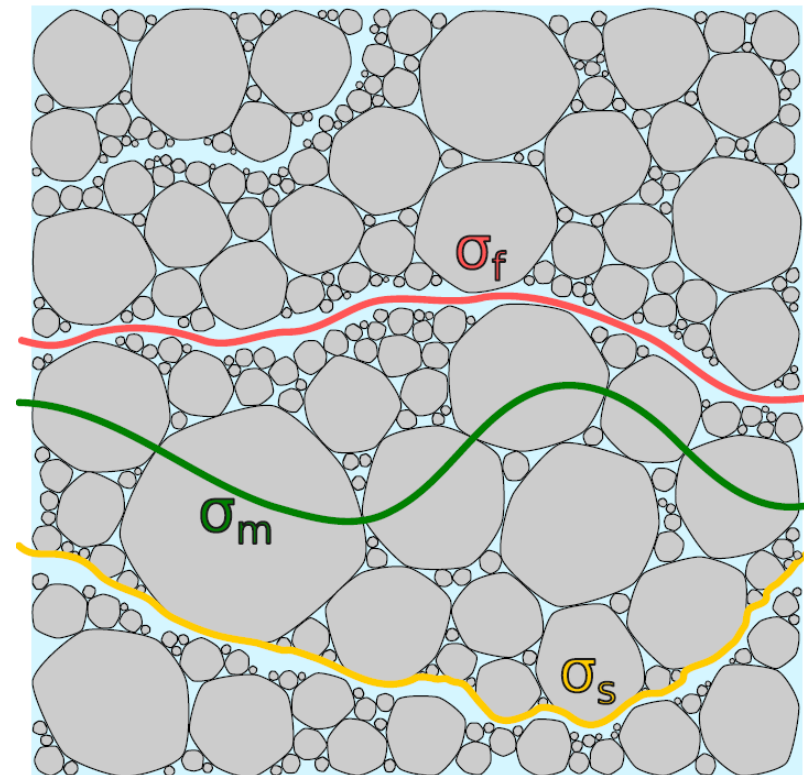


Fig.: Matthias Steiner

Complex Conductivity (CC)

- Conduction mechanisms (no metals):

$$\sigma = \sigma_f + \sigma_s$$

- Surface conductivity is related to the EDL ([click here](#)) and is complex (σ_s^*):

- Real part σ_s' : electromigration
- Imaginary part σ_s'' : reversible charge storage

→ Complex Conductivity:

$$\sigma^* = \sigma_f + \sigma_s^* = \sigma_f + \sigma_s' + i\sigma_s''$$

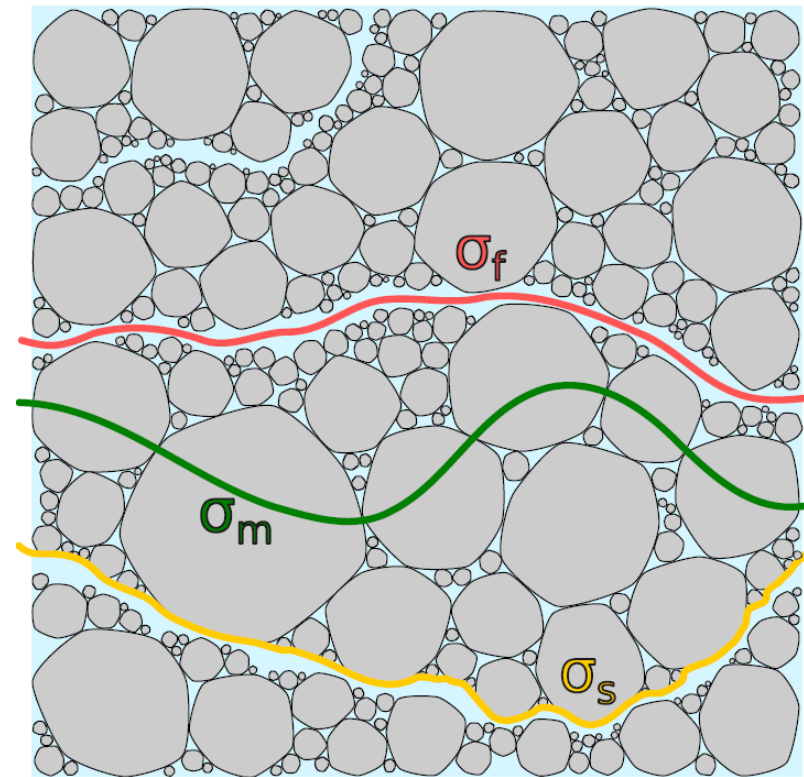
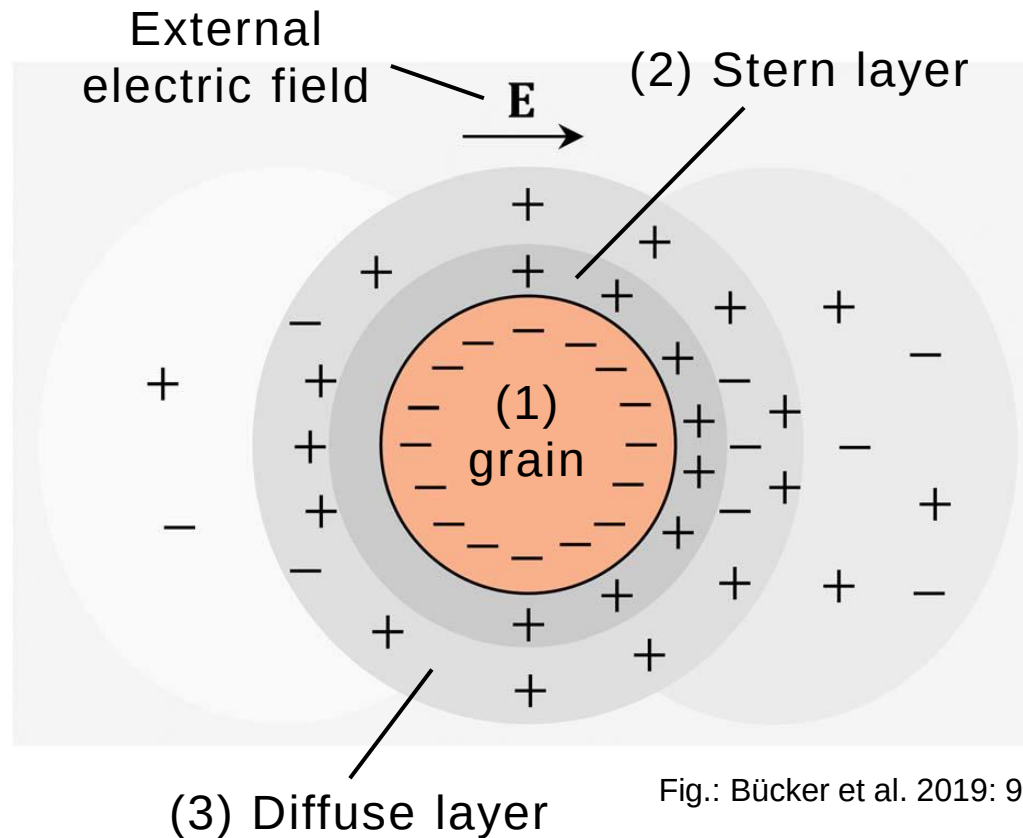


Fig.: Matthias Steiner

Menu

$\varphi = \arctan(\sigma''/\sigma')$	$\sigma' = \sigma^* \cos(\varphi)$	$\varphi \dots \text{phase (rad)}$	$\sigma' \dots \text{real part of CC (S/m)}$
$ \sigma^* = \sqrt{\sigma'^2 + \sigma''^2}$	$\sigma'' = \sigma^* \sin(\varphi)$	$ \sigma^* \dots \text{magnitude (S/m)}$	$\sigma'' \dots \text{imaginary part of CC (S/m)}$

Polarization of EDL



Electric double layer (EDL) without external electric field

- (1) Grain: negative surface charge
- (2) Stern layer: absorption of counterions, cannot leave the stern layer
- (3) Diffuse layer: balancing concentration gradient by diffusion

Electric double layer under application of an external electric field

- (1) Grain: non conductive
- (2) Stern layer: charges cannot leave but move in direction of external electric field
- (3) Diffuse layer (in direction of electric field):

Inner part: negative charges
Outer part: positive charges

Relation between conductivity, temperature and water content

Temperature (positive) vs. conductivity

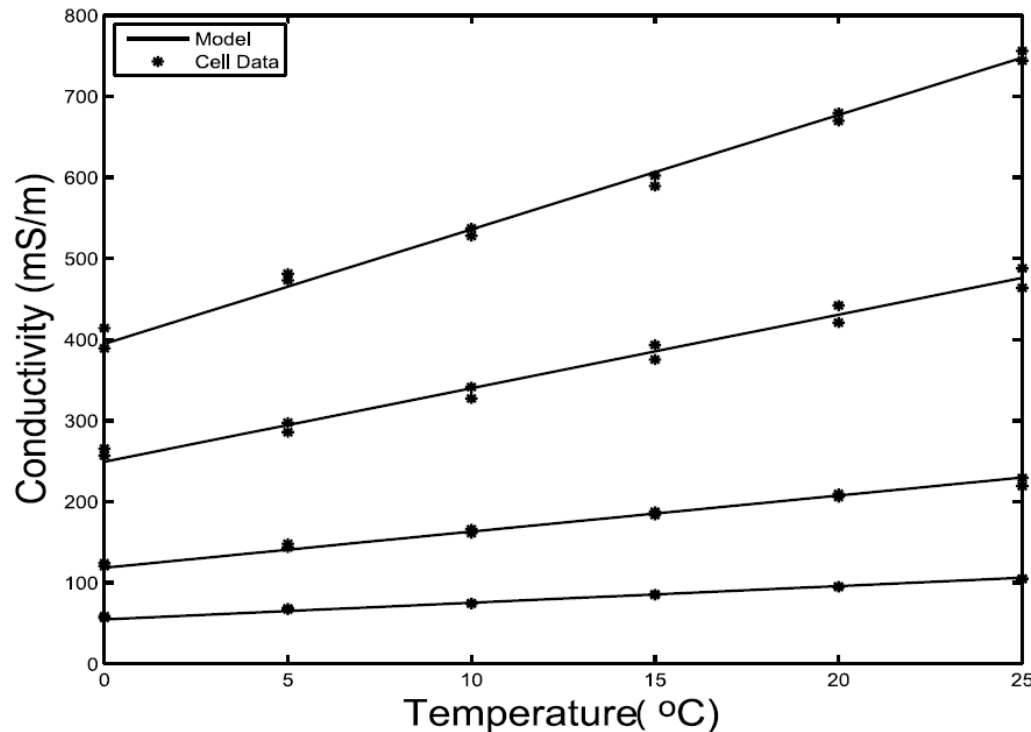


Fig.: Hayley et al. 2007: 2

Water saturation vs. conductivity

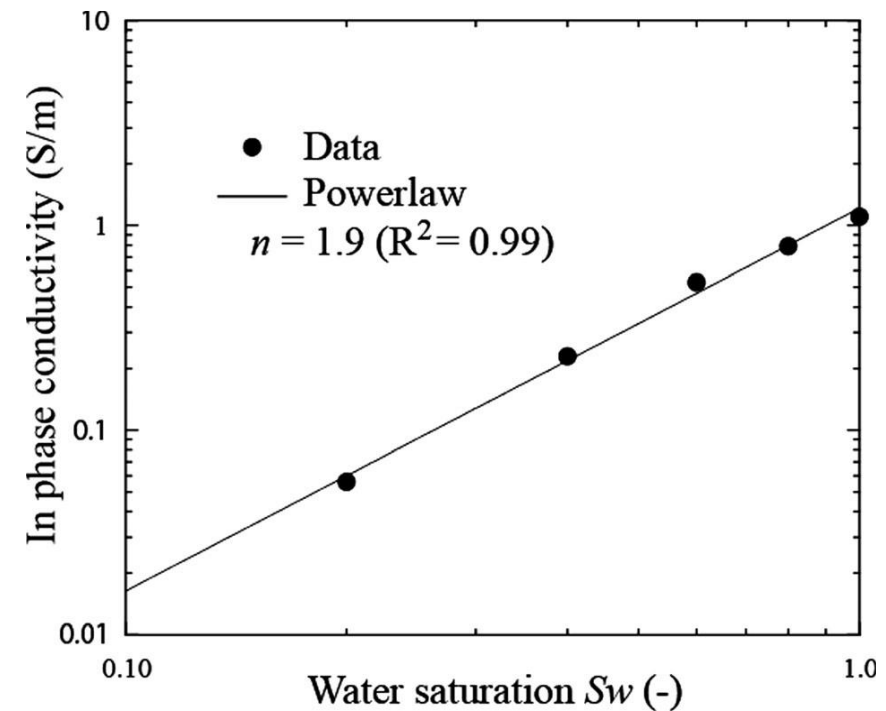


Fig.: Revil et al. 2017: 7145

Objectives & Hypothesis

Time-lapse inversion procedure

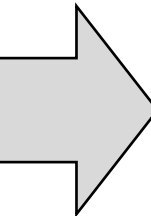
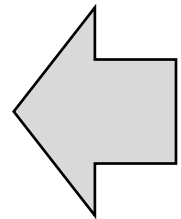
- Search for a time-lapse inversion procedure minimizing time-dependent artefacts
- Use of different time regularisations

Rock temperature & conductivity

- Observation how variations of air temperature influence the rock temperature in different depths and relation to conductivity
- Development of a convenient temperature correction model for conductivity

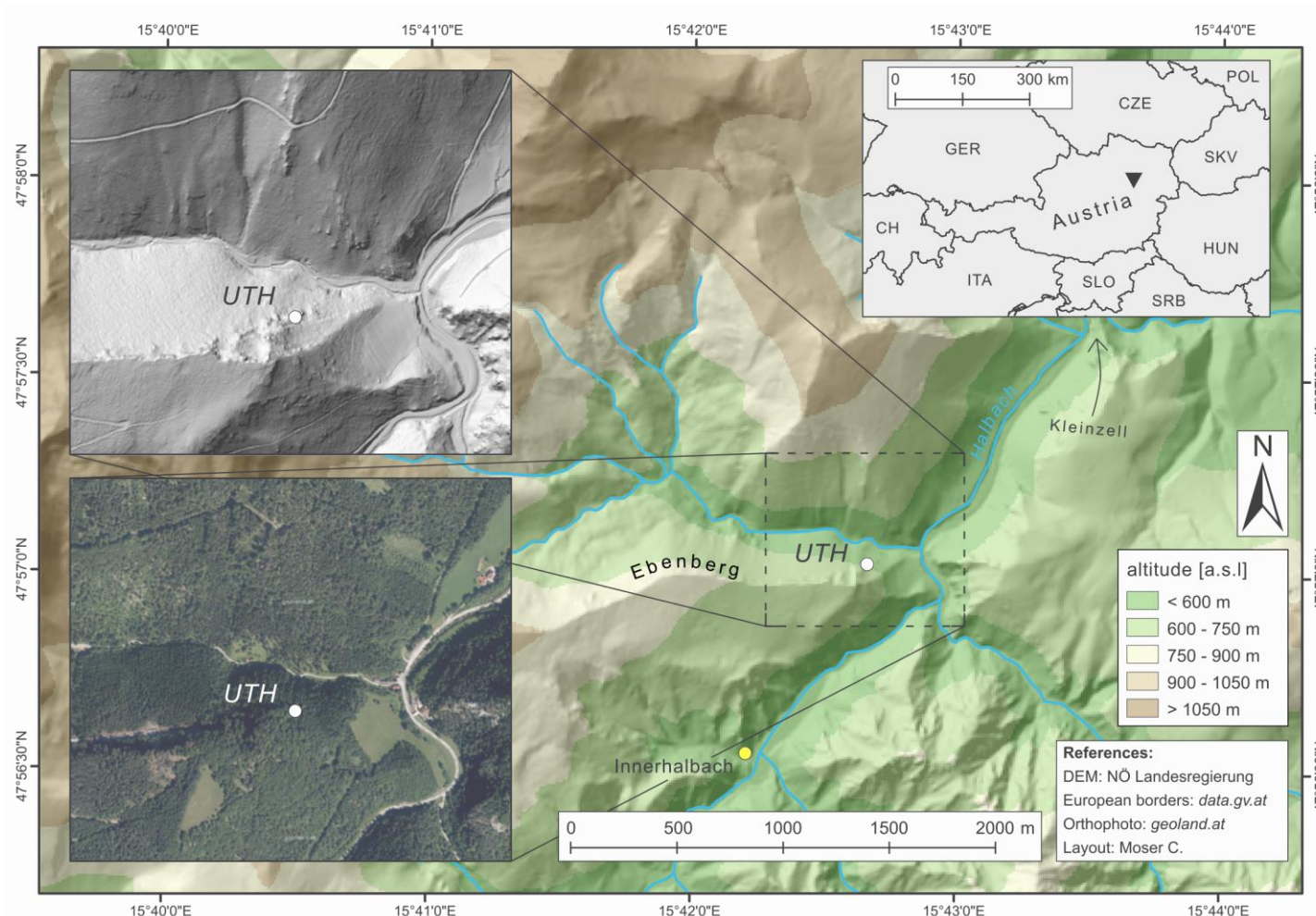
Water content & delineation of fractures

- Observation: drip water mainly from fractured areas (→ fractures as water paths)
- Hypothesis: fractured areas with high water content → delineation by higher conductivities



Menu

Study Site: Untere Traisenbacherhöhle (cave)



Frost weathering cave

- Calcareous Alps
- 12 m x 6 m x 2.5 m
- Drip water along fractures
- Ice stalagmites & stalactites during cold periods



Click on the image
to see more about the cave

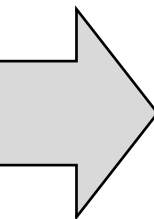
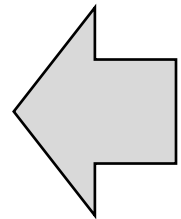
Study Site: Untere Traisenbacherhöhle (cave)



From the outside

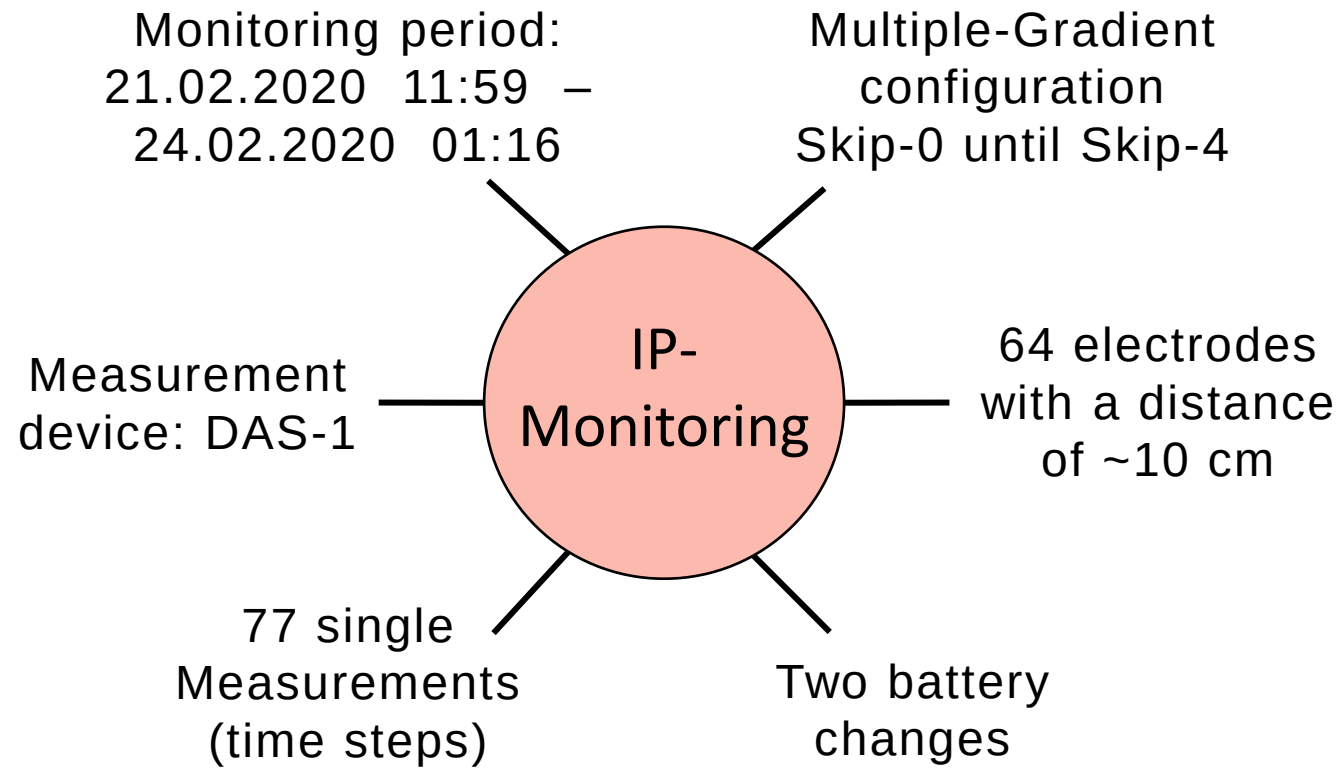


From the inside



Menu

Induced Polarization



+ Temperature loggers in a depth of 0 cm, 3 cm, 10 cm, 40 cm

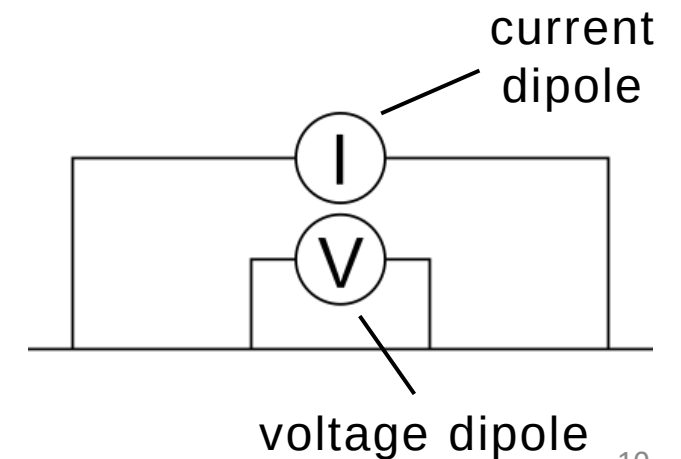
$$Z = \frac{V}{I} = |Z| * e^{i\varphi}$$

Z ... impedance (Ω)

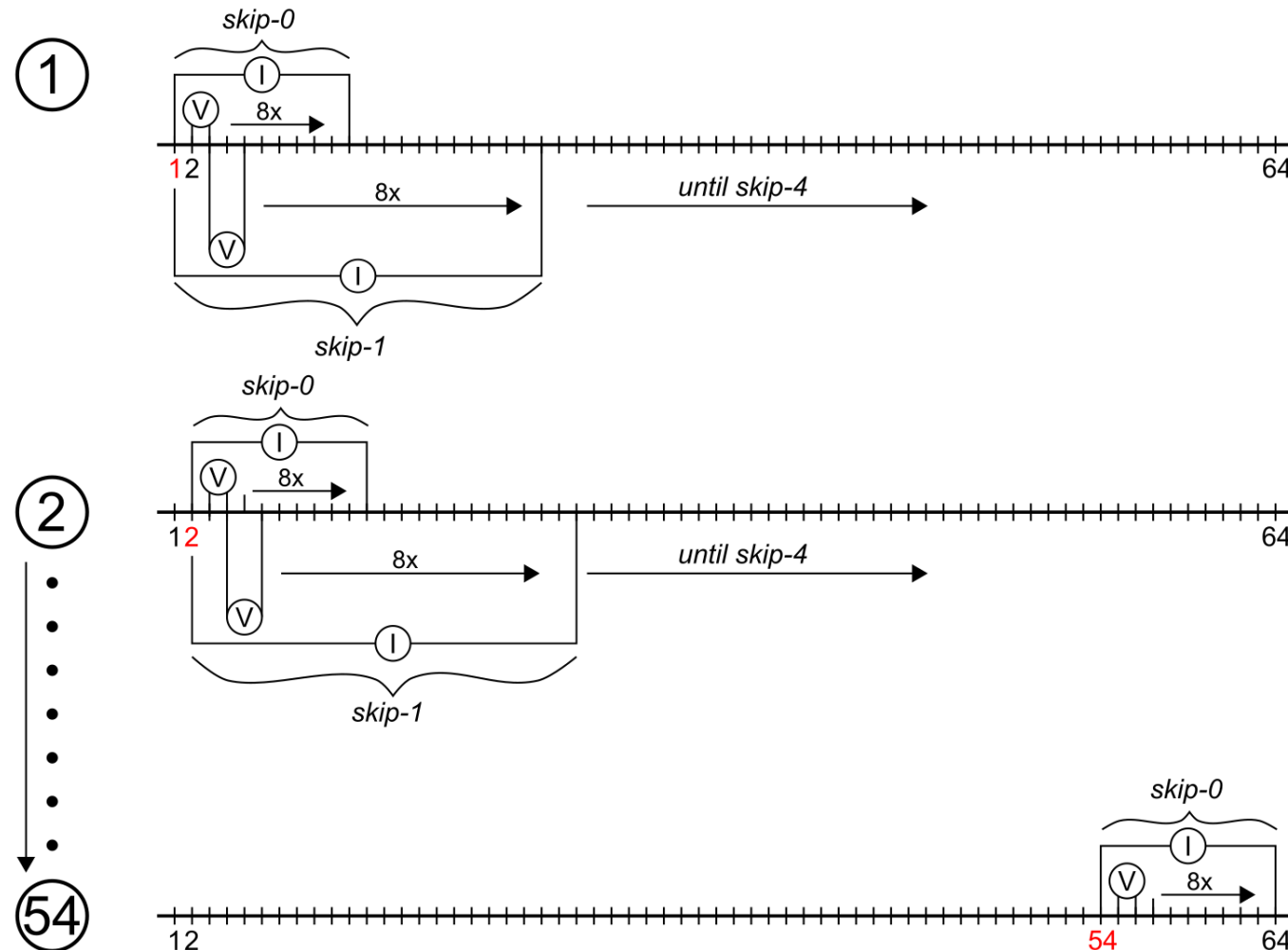
U ... voltage (V)

I ... current (A)

φ ... phase shift (mrad)

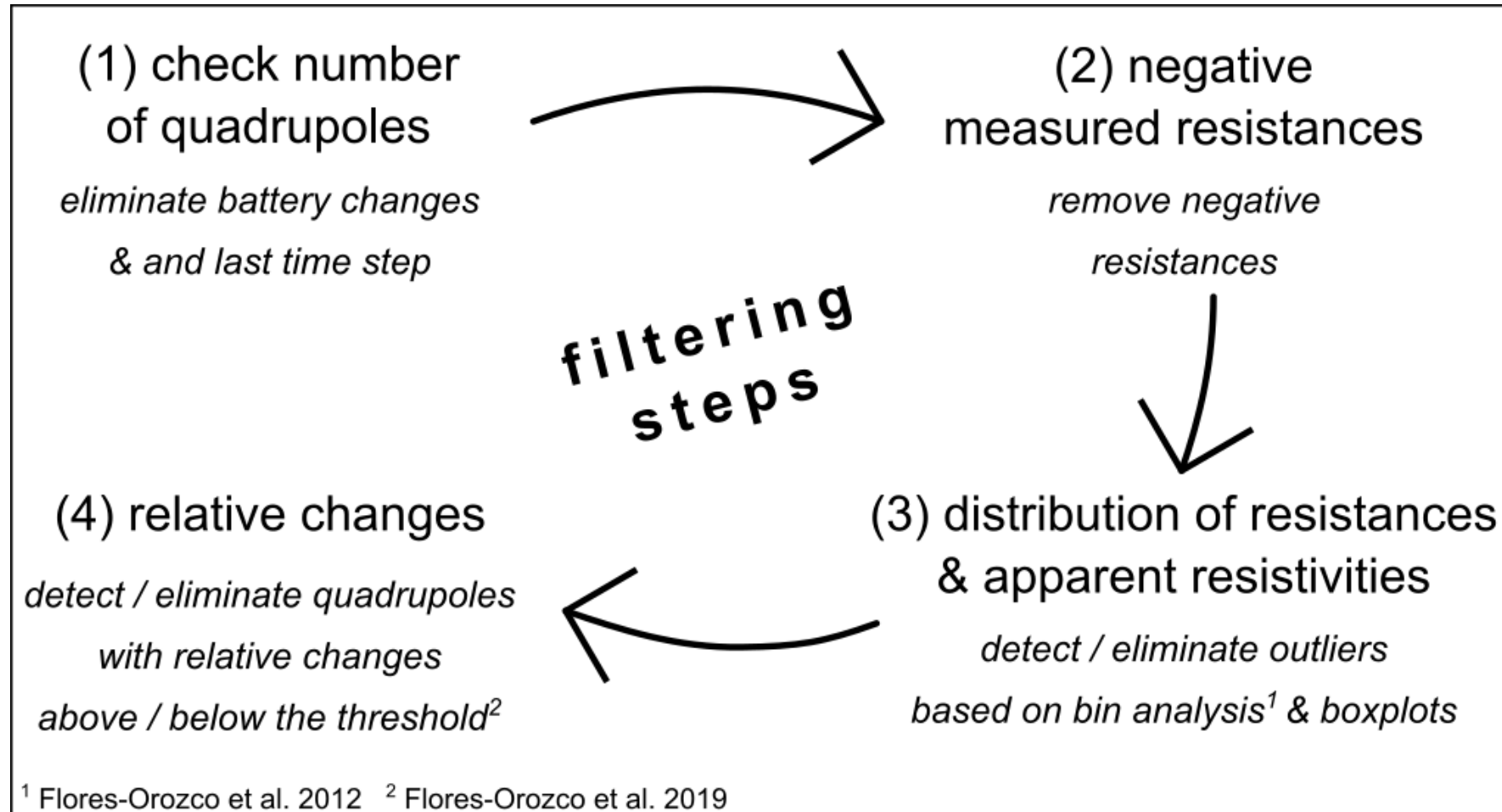


Induced Polarization (MG-Configuration)



More details:
Dahlin & Zhou 2006

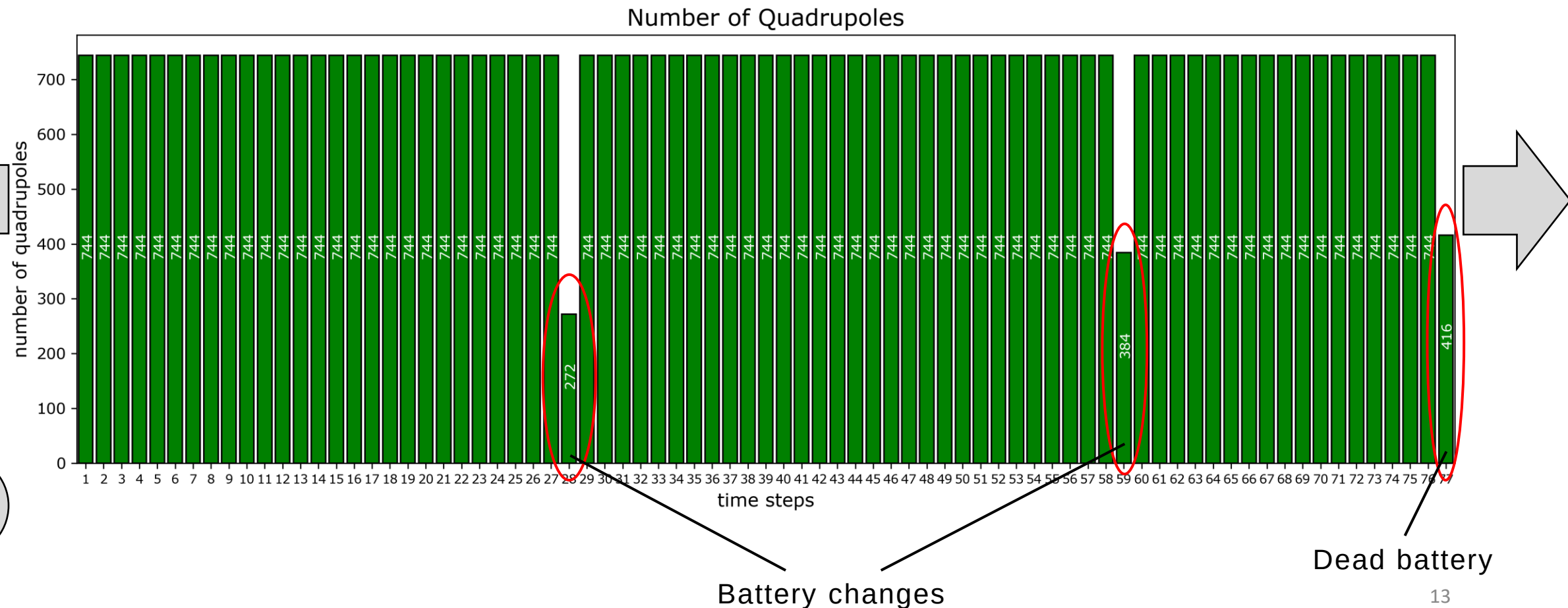
Filtering Procedure



Menu

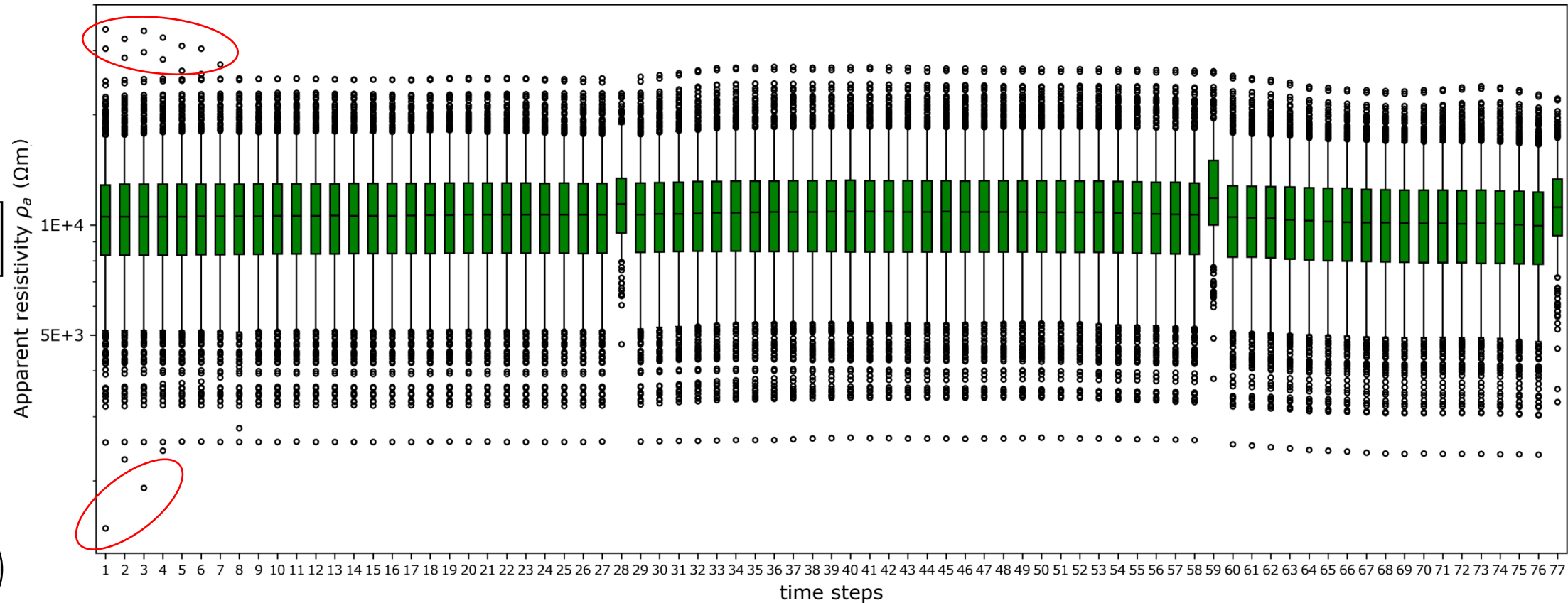
Click on a filtering step to see more details

Filtering Step 1 – no. of quadrupoles



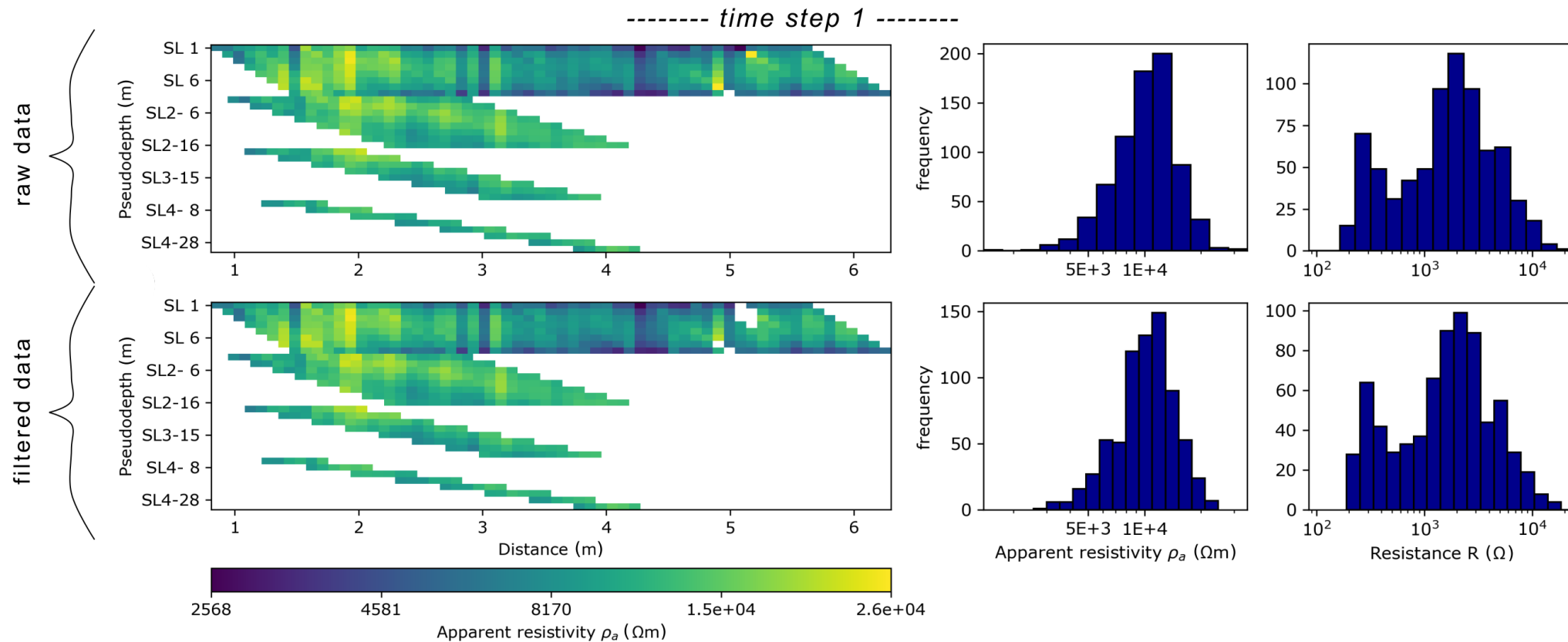
Filtering Step 3 – distribution of ρ_a & R

all time steps - raw data



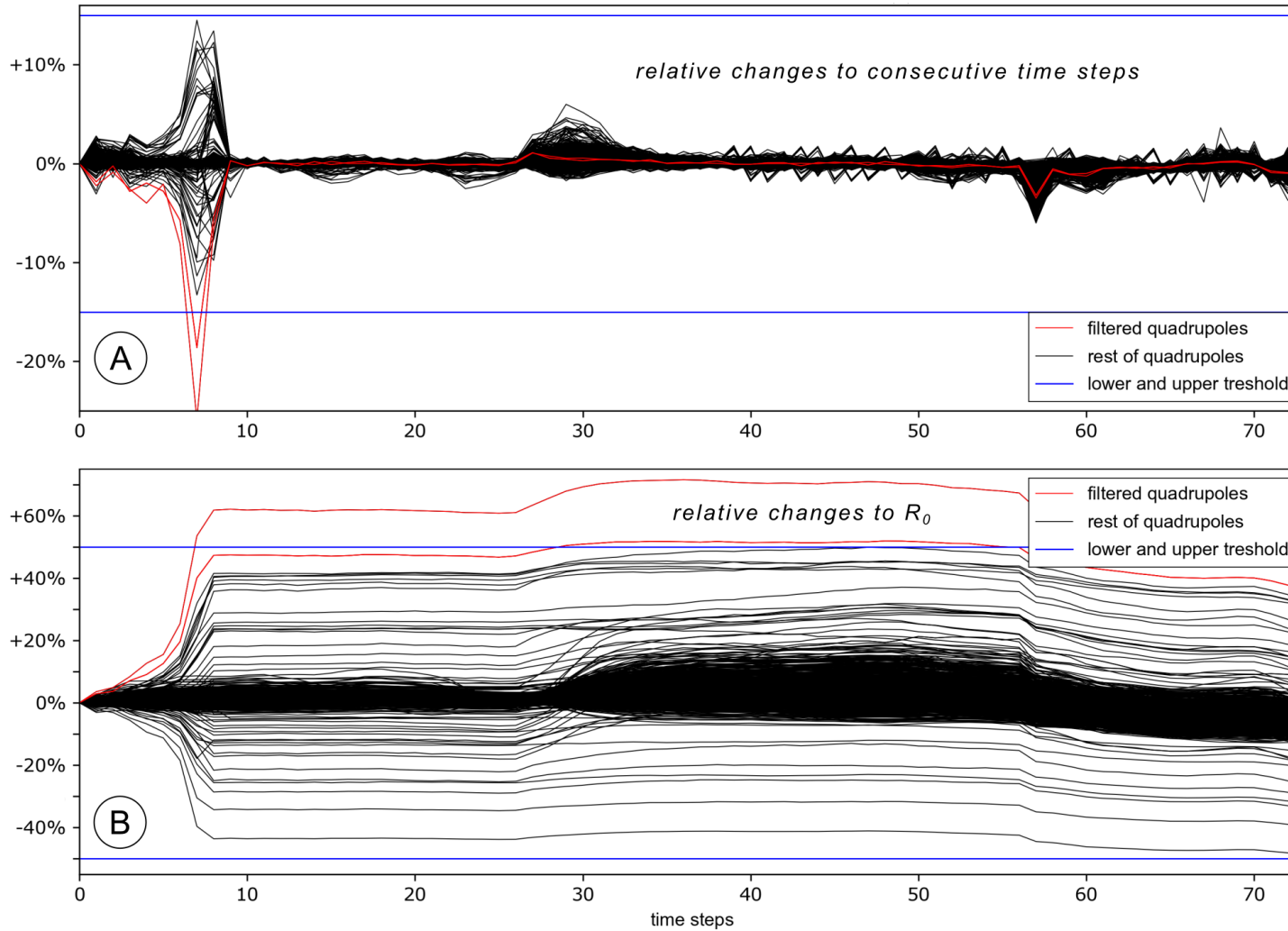
ρ_a ... Apparent resistivity (Ωm)
 R ... Resistance (Ω)

Filtering Step 3 – distribution of ρ_a & R



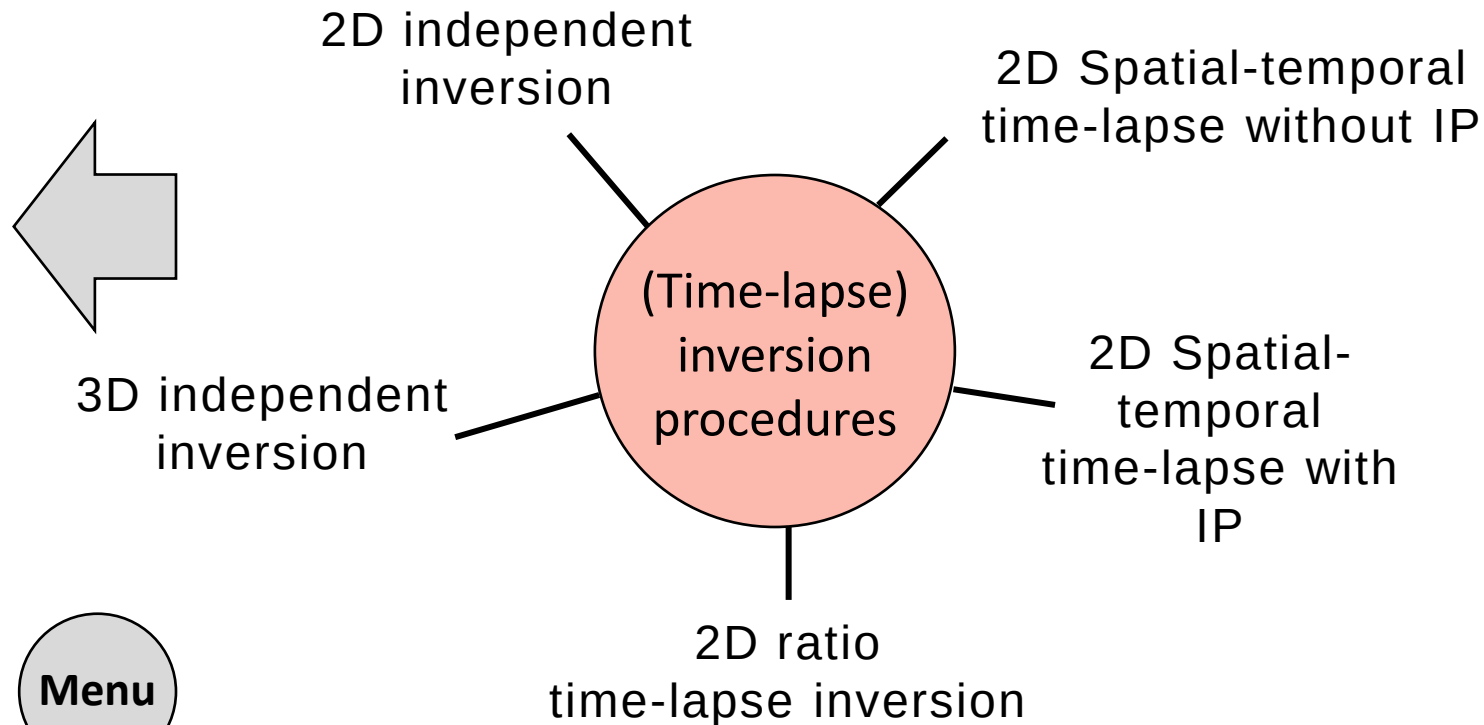
Menu

Filtering Step 4 – change of R



R ... Resistance (Ω)

Inversion approaches



Inversion of the data by using the open-source libraries **pyBERT** (Günther et al. 2006) and **pyGIMLi** (Rücker et al. 2017)

→ Based on Gauss-Newton approach

$$\|W_d(F(m) - d)\|_2^2 + \lambda \|W_m(m - m_0)\|_2^2 \rightarrow \text{Min}$$

W_d ... data weighting matrix

W_m ... model constraint matrix

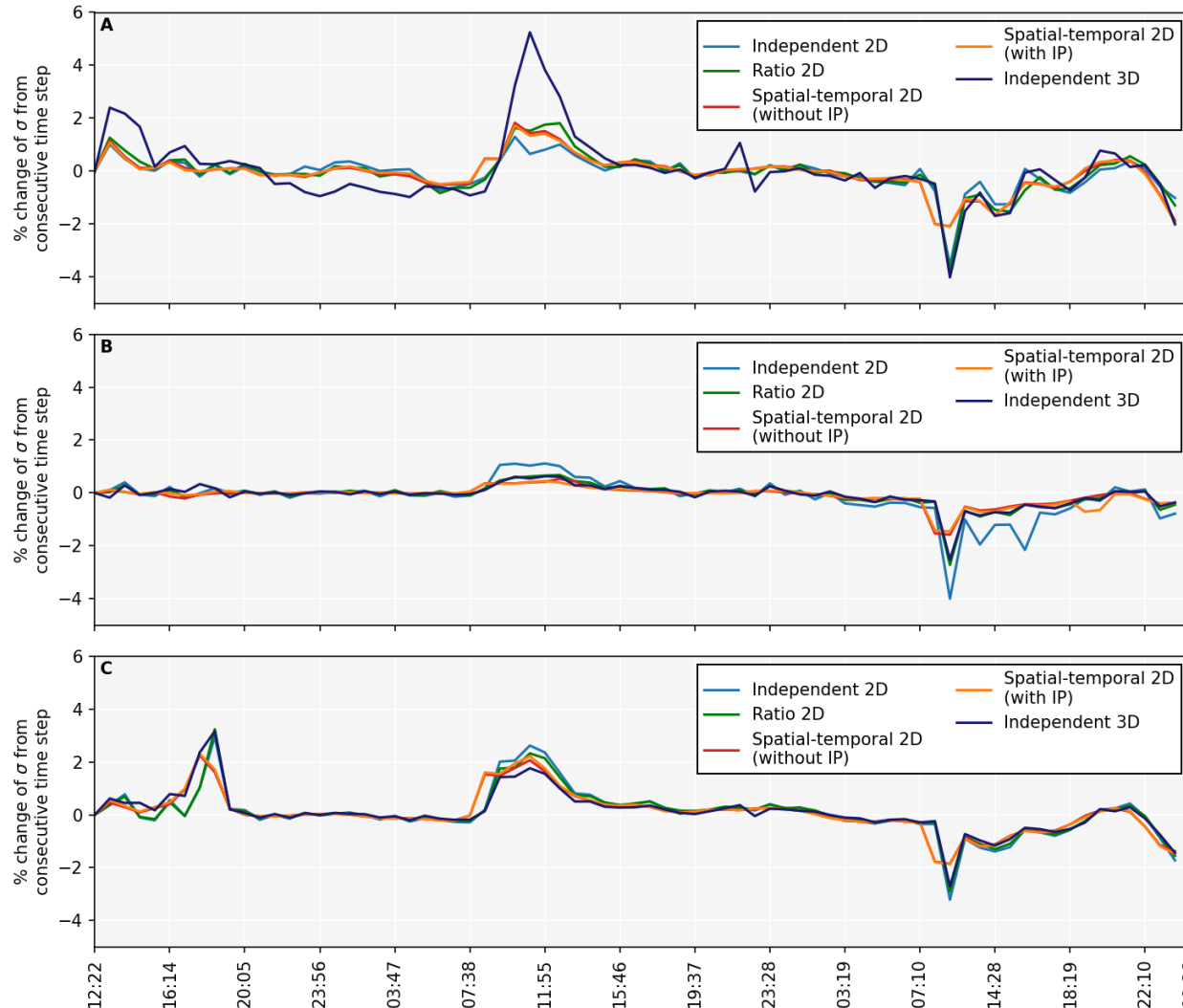
m ... model

d ... data

m_0 ... reference model

λ ... regularization term

Temporal change of different inversion approaches



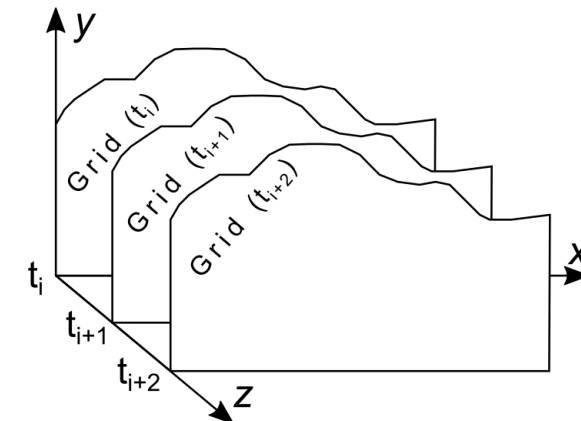
Inversion approaches:

- Independent 2D: independent inversion of each time step with 2D geometry
- Independent 3D: independent inversion of each time step with 3D geometry
- Ratio 2D: inversion of

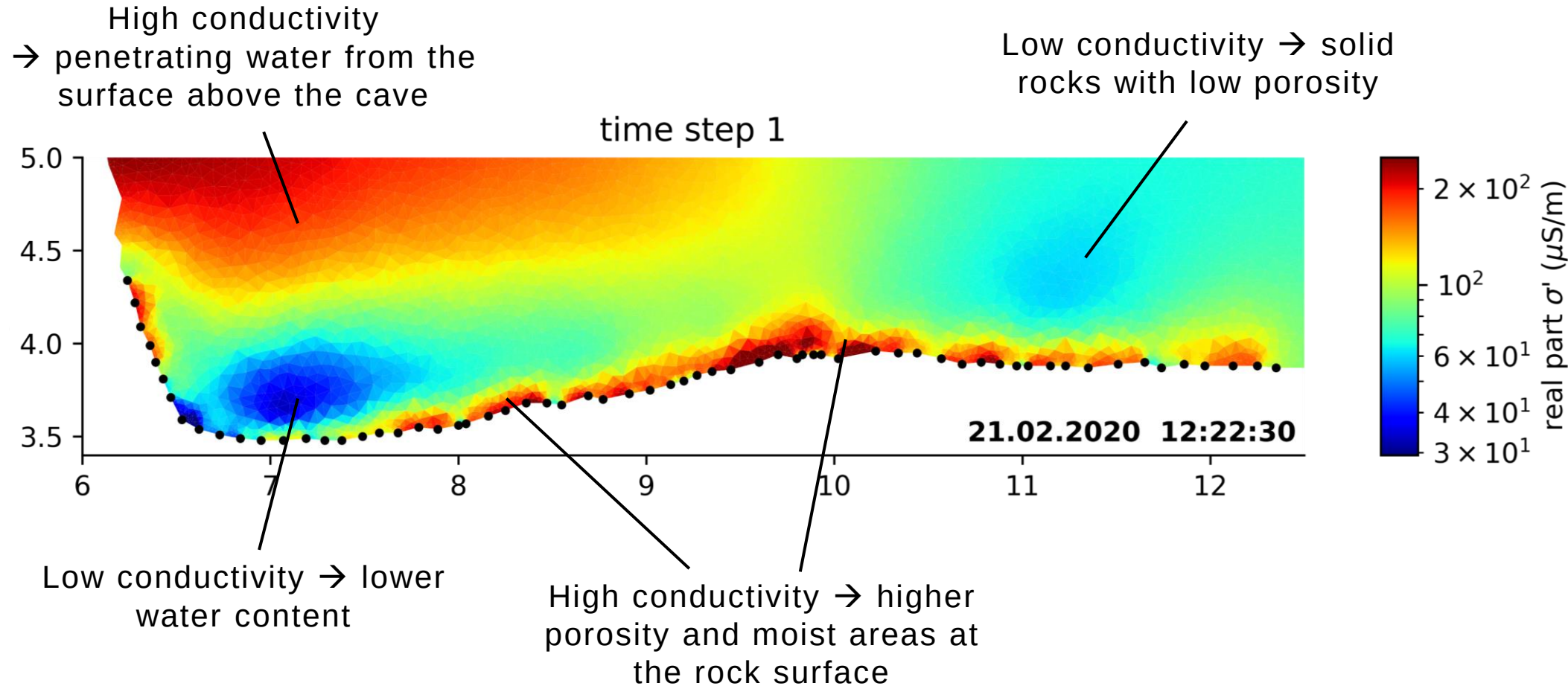
$$\frac{\rho_{ai}}{\rho_{a0}} \cdot response(t_0)$$

- Spatial-Temporal 2D: simultaneous inversion of 3 consecutive time steps by using z axis as time dimension

(ongoing work)
→ smoothest results
(yellow/red line)

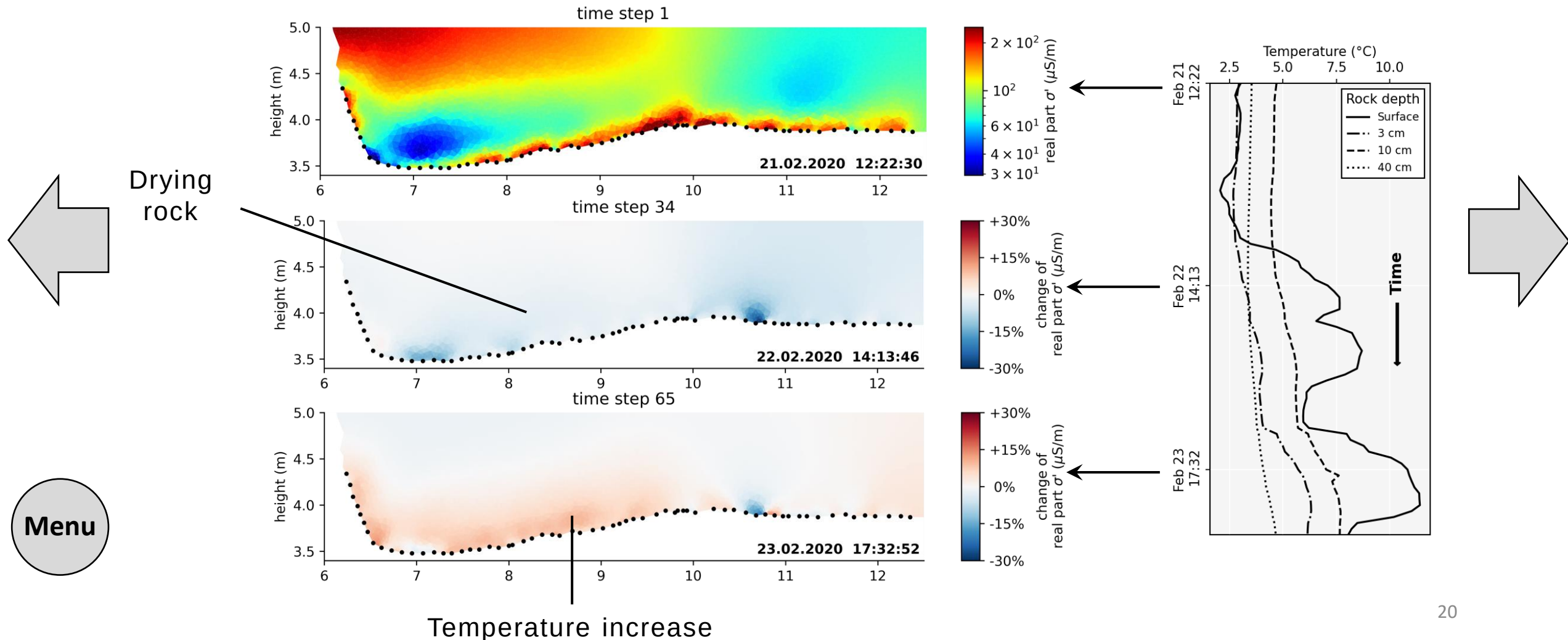


Conductivity (real part of Complex Conductivity)

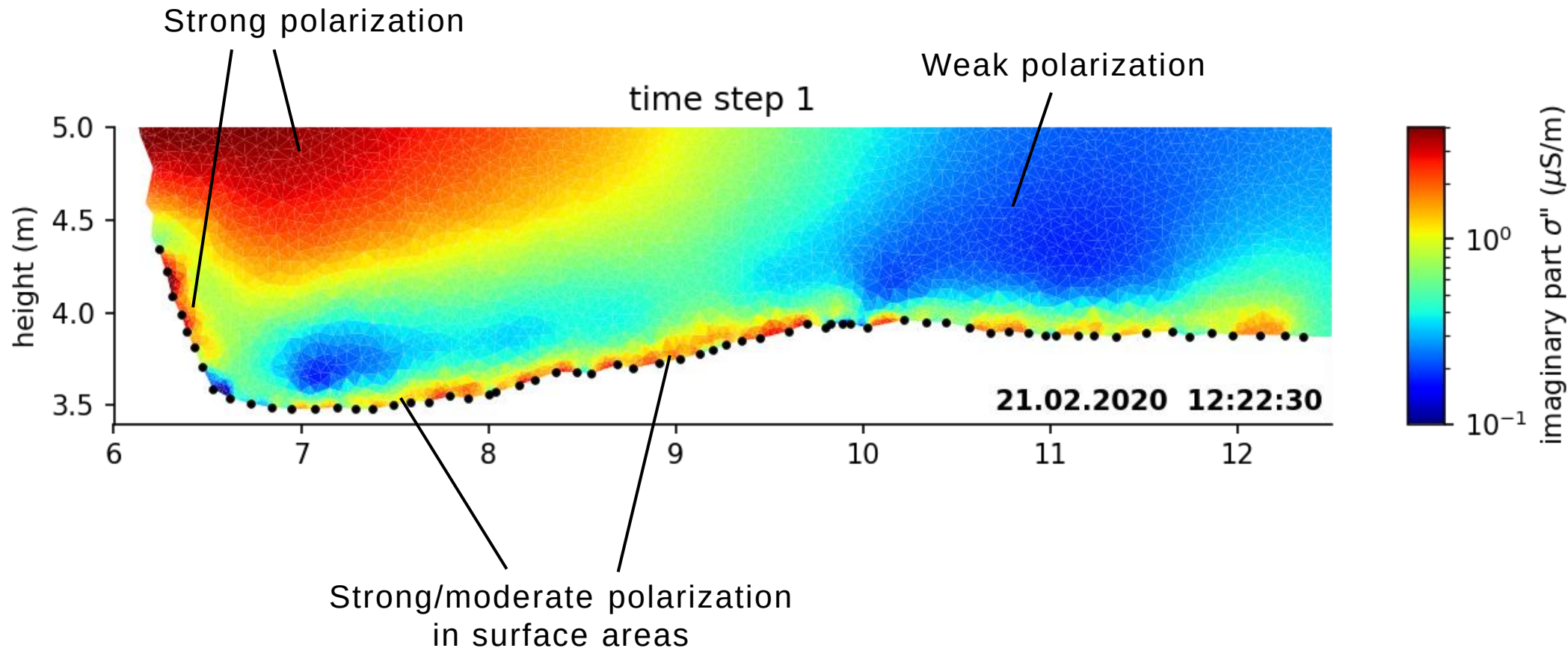


Menu

Conductivity (real part of Complex Conductivity) change

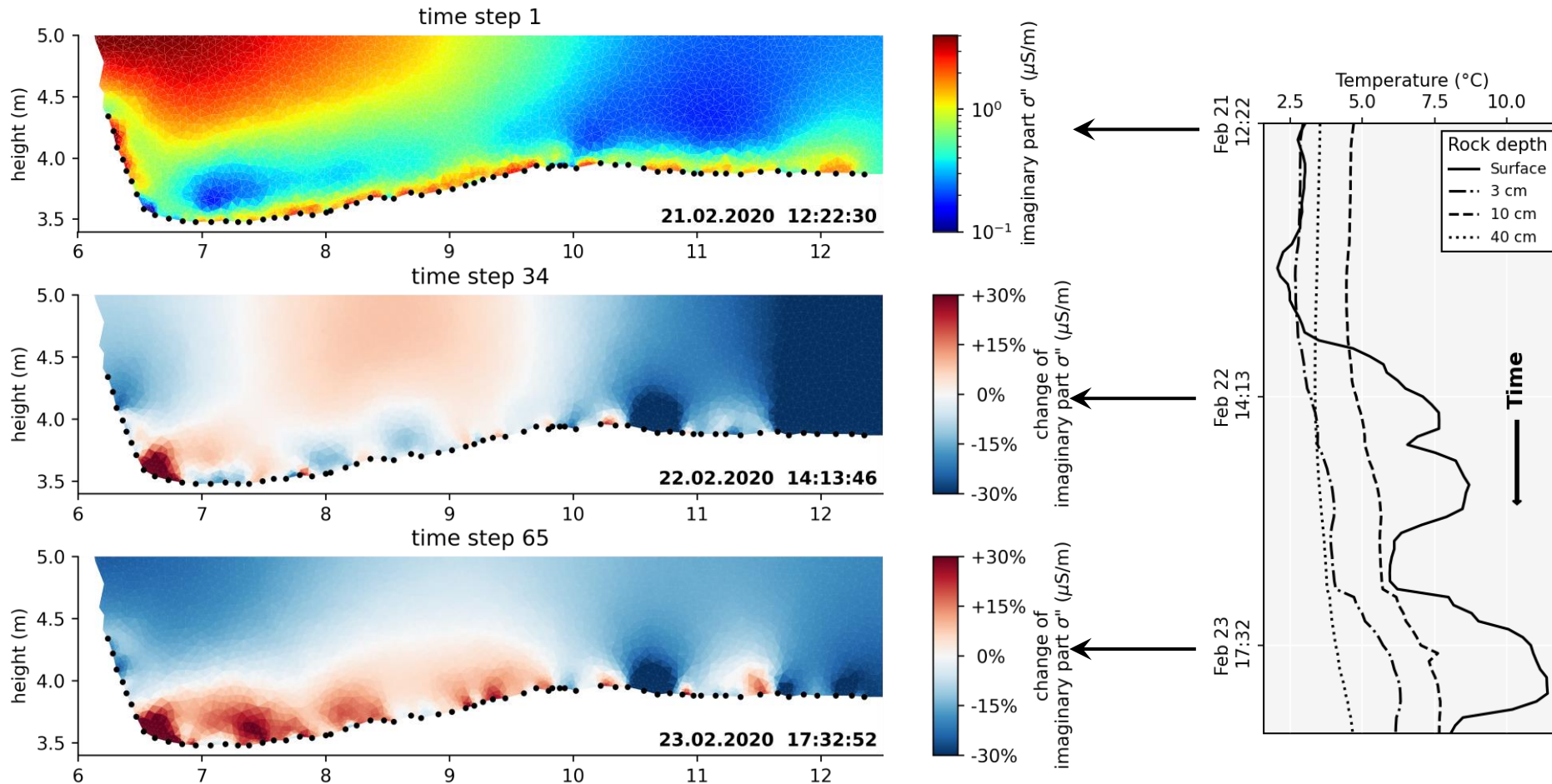


Polarization (imaginary part of Complex Conductivity)

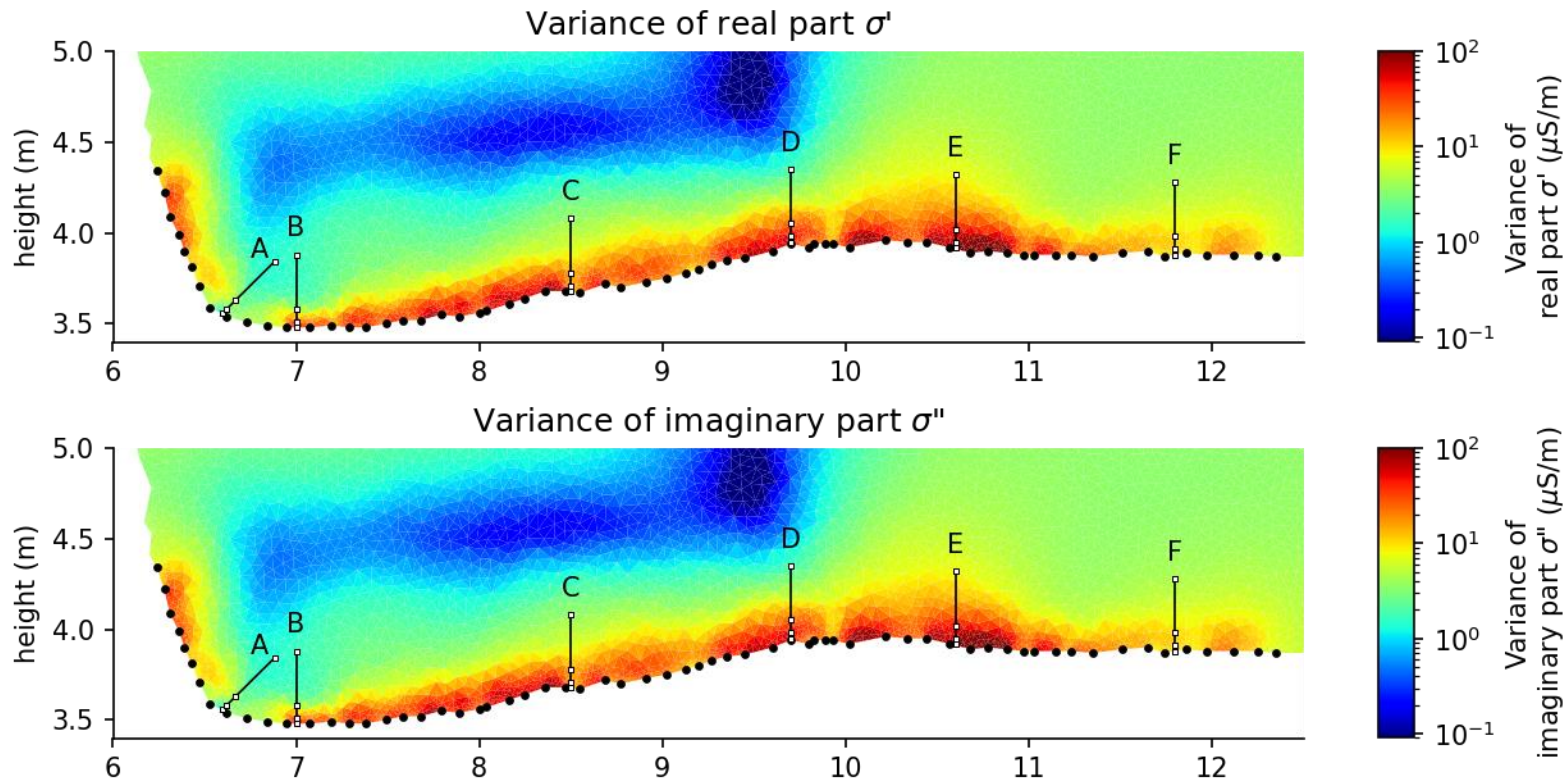


Menu

Polarization (imaginary part of Complex Conductivity) change



Pixel extraction based on variance of σ' and σ''



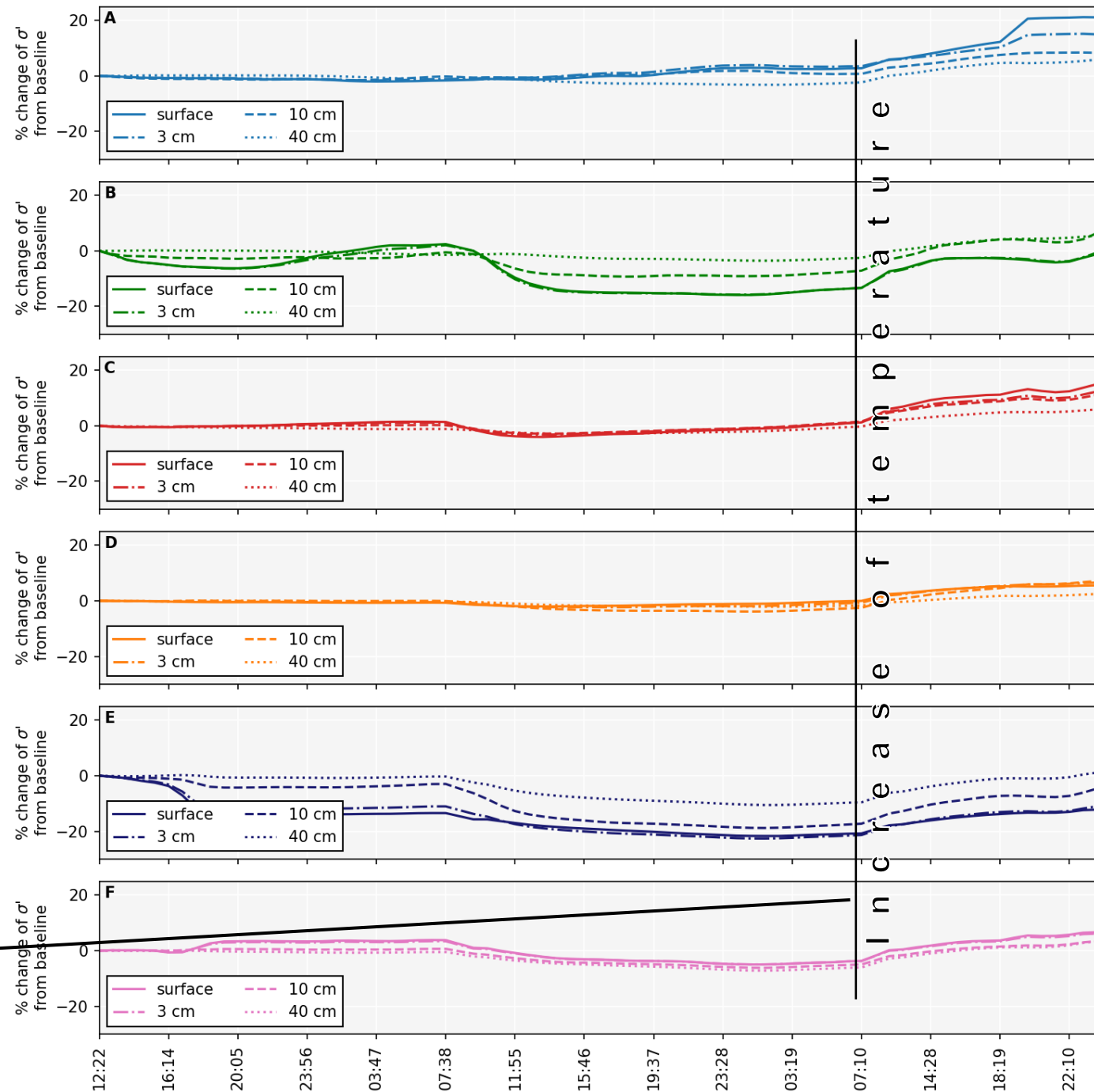
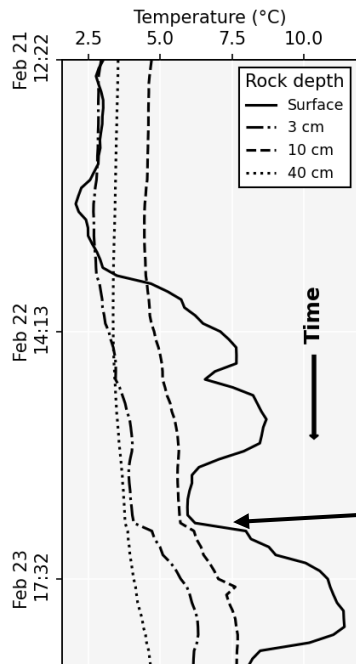
Menu

6 sites of interest (A,B,C,D,E,F):

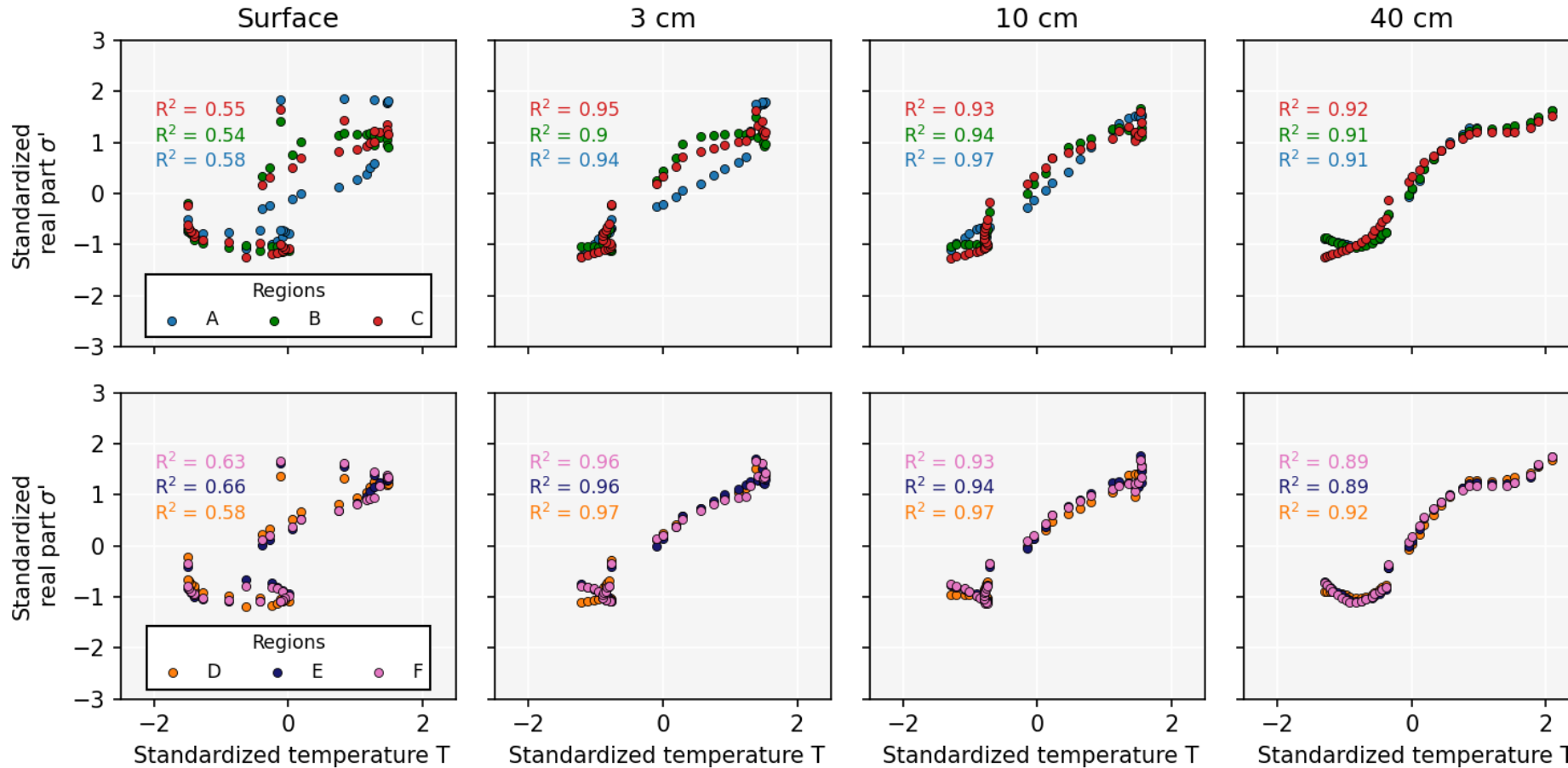
→ Extraction of conductivity at four pixels per site in different rock depths (surface, 3 cm, 10 cm, 40 cm)

Observation (1/3): Conductivity vs. Time:

- The deeper into the rock the lower are the variations of conductivity
- Increase of temperature → increase of conductivity in all investigated areas



Conductivity (real part of CC) vs. temperature



Standardization:

$$x_{i,st} = \frac{x_i - \bar{x}}{\sigma_x}$$

Menu

Temperature Correction

- Laboratory results reveal that above a temperature of 0°C conductivity increases linearly with temperature (Revil et al. 1998, Hayley et al. 2007, Revil et al. 2017)
- Linear model (Revil et al. 1998):

$$\sigma(T) = \sigma(T_0)[1 + \alpha_T(T - T_0)]$$

T ... temperature (°C)

T₀ ... reference temperature

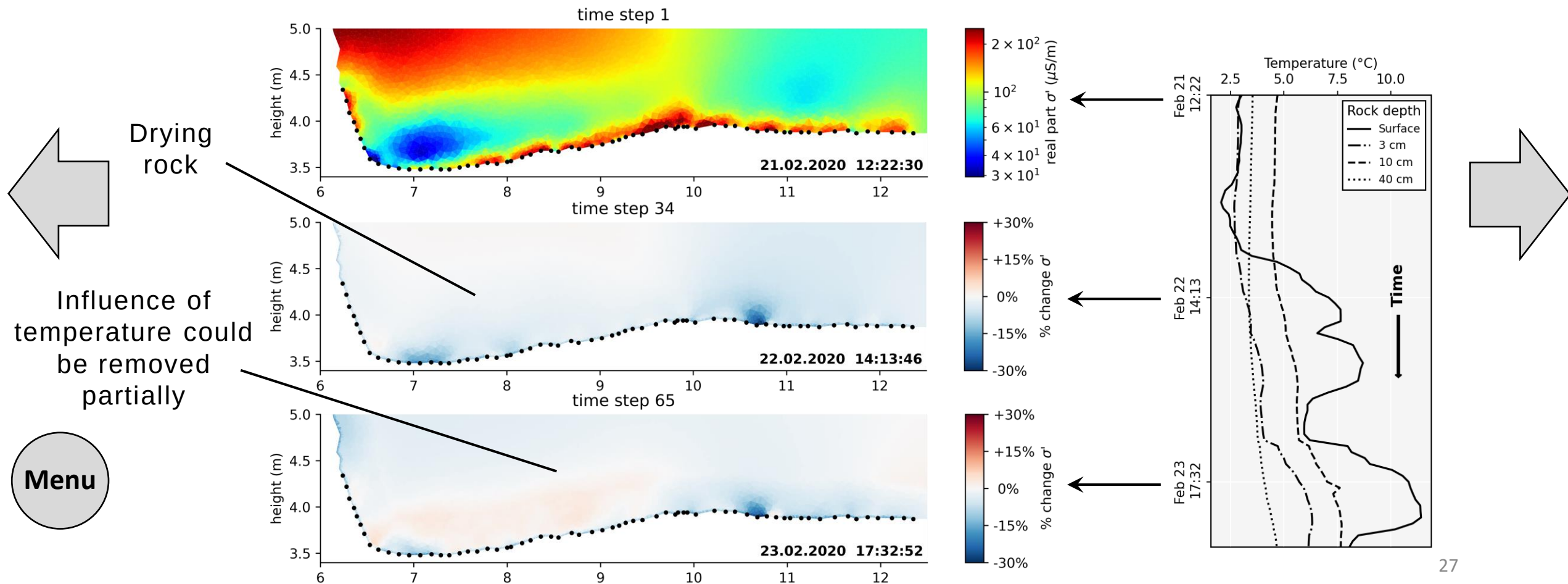
σ(T) ... conductivity at temperature T

σ(T₀) ... conductivity at reference temperature T₀

α_T ... sensitivity (0.020 – 0.025/°C)

- Temperature Correction (linear model (see above) was used):
 - Temperature: measured in four rock depths (linear interpolation between):
 - surface
 - 3 cm
 - 10 cm
 - 40 cm
 - Sensitivity coefficient used: 0.025/°C

Temperature-corrected conductivity (real part of CC) change



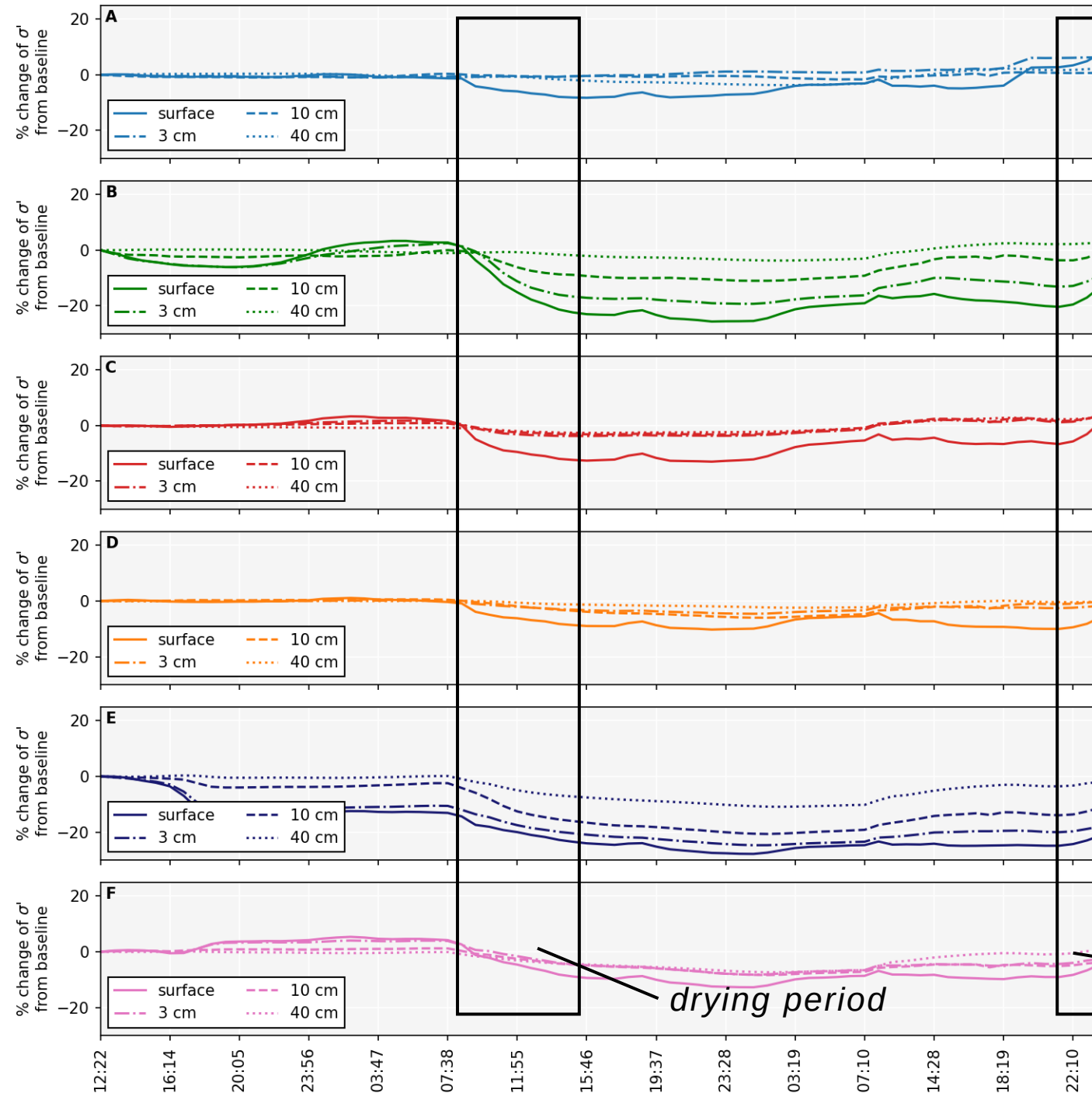
Observation (2/3): Temperature-corrected conductivity vs. Time:

- Temperature correction: enables interpretation of other processes like water content variations
- Drying period: increasing temperatures →

decreasing water content →
decreasing conductivity

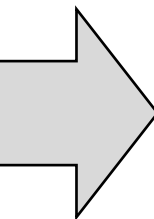
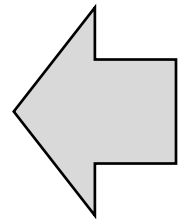
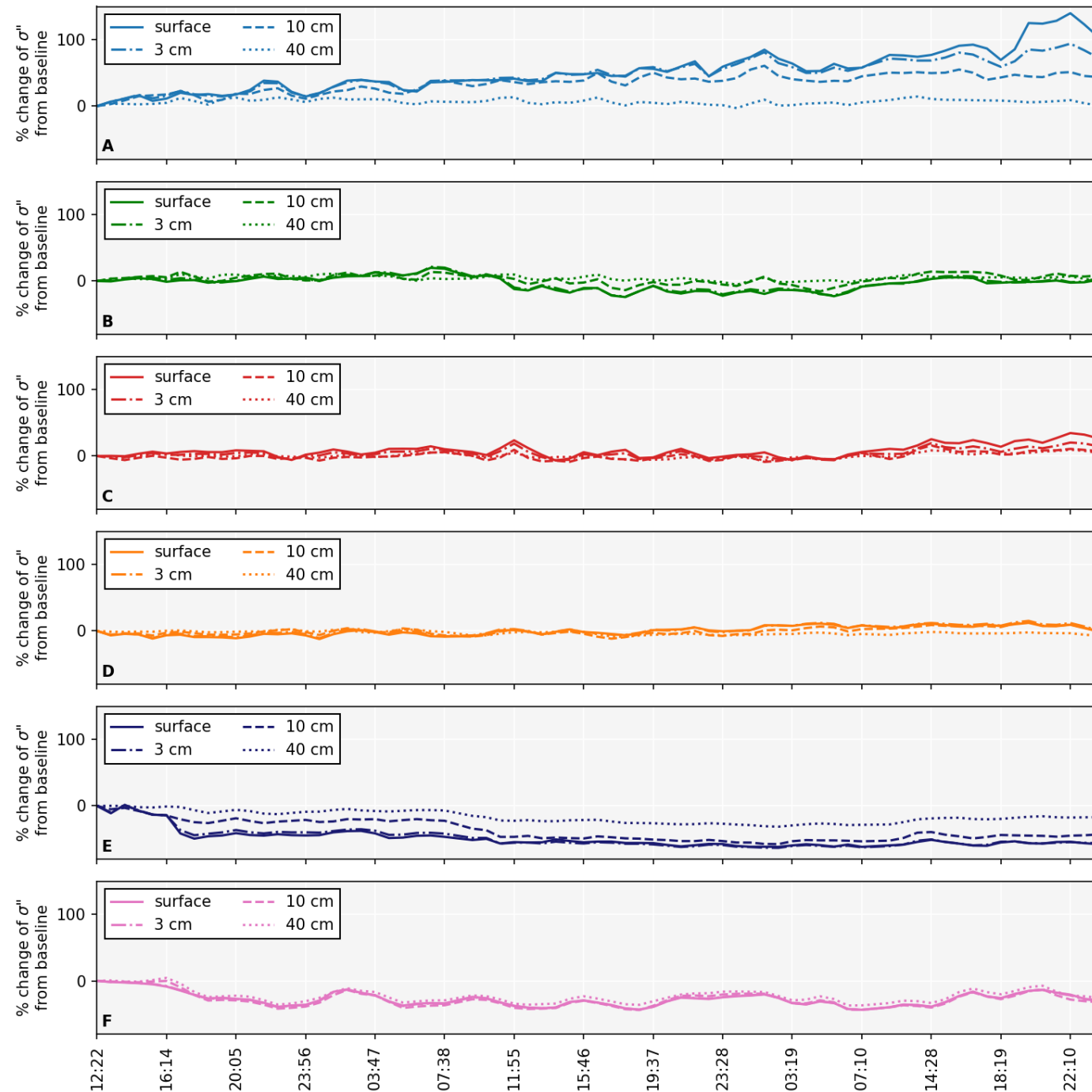
- Precipitation event: infiltrating rain water → increasing conductivity

Menu



Observation (3/3): Polarization vs. Time:

- The deeper into the rock the lower are the variations of polarization
- No temperature relation



Menu

Conclusion

Inversion procedures

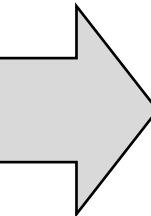
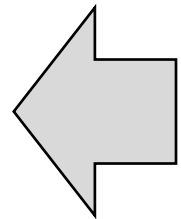
- Similar results of different 2D inversion procedures
- Spatial-temporal time-lapse inversion delivers smoothest results with time
- 3D inversion delivers strongest deviations with time (possibly due to coarser grid)

Rock temperature & conductivity

- Strong relation between temperature and conductivity → temperature data of different depths necessary for comparison
- Linear temperature correction to remove temperature impact

Water content & fractures

- Observation of:
 - Drying process (decrease of conductivity)
 - Precipitation event (increase of conductivity)
- in surface areas high conductivity (σ') & polarization (σ'') and high variation of σ' and σ''



Menu

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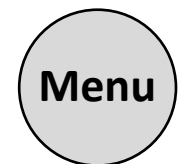
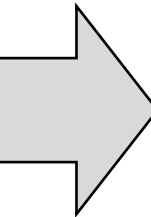
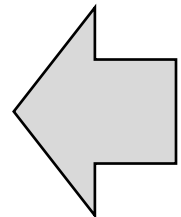
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