

CHARACTERIZATION OF A SOLID WASTE LANDFILL THROUGH GEOPHYSICAL DATA FUSION

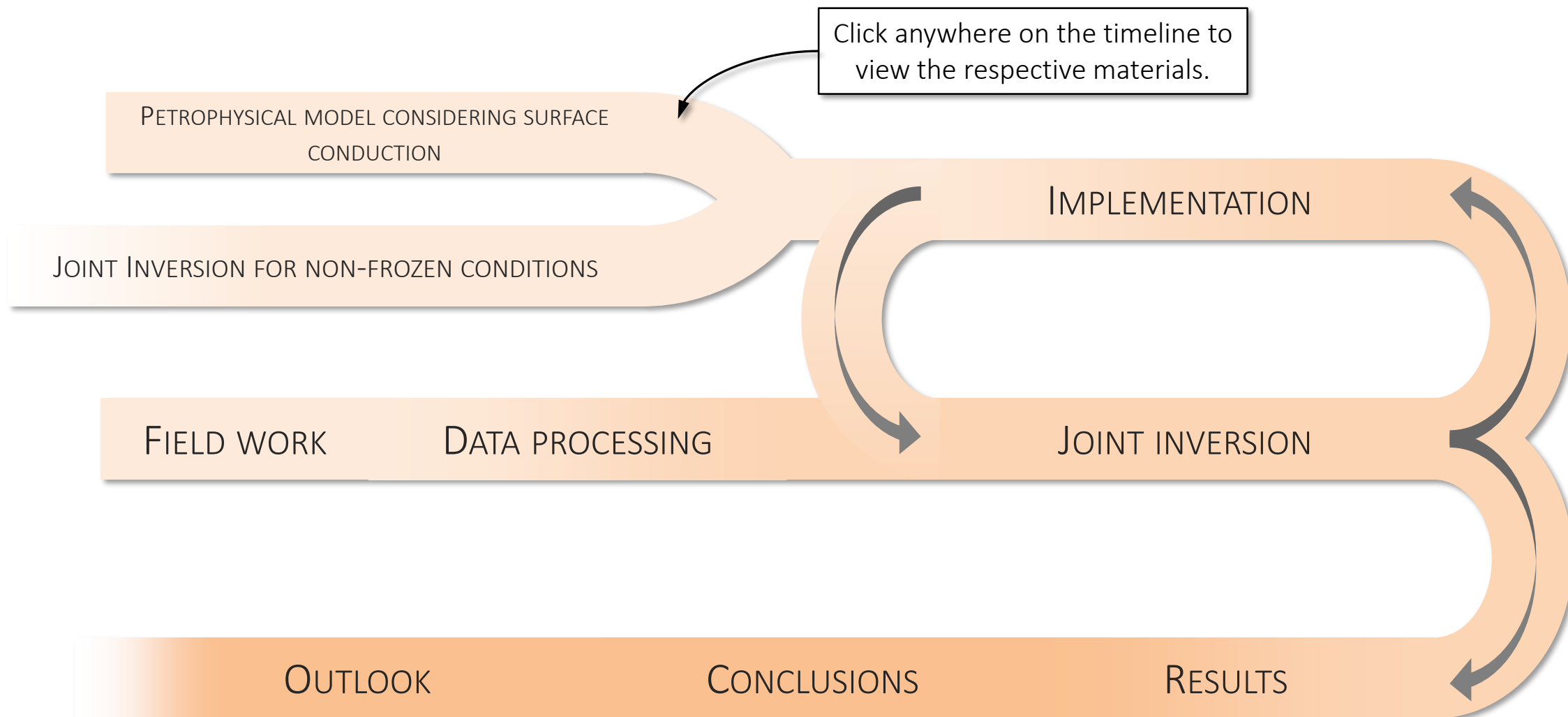
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This way if you want to check out the **References**.

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METHODS

- Based on the four-phase model (4PM) developed by Hauck et al. (2011)

- Assumes the soil to be composed by three phases (i.e., we removed ice related terms from the 4PM)

$$f_w + f_a + f_r = 1$$

- The seismic slowness of such system is described as

$$s = \frac{f_w}{v_w} + \frac{f_a}{v_a} + \frac{f_r}{v_r}$$

- The electrical conductivity is described based on Archie's second law

$$\sigma = \sigma_w (1 - f_r)^m \left(\frac{f_w}{1 - f_r} \right)^n$$



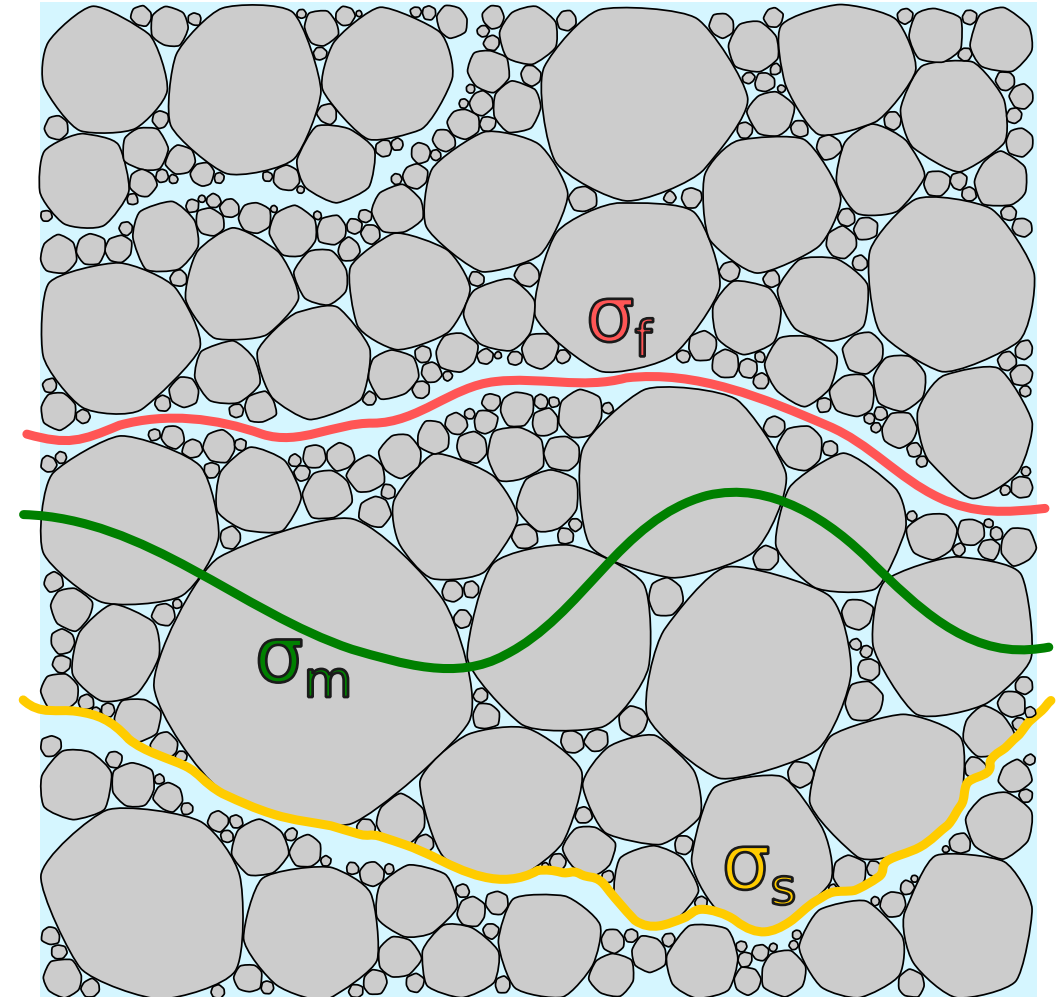
f_w	Volumetric water content	v_w	Seismic velocity for water
f_a	Volumetric air content	v_a	Seismic velocity for air
f_r	Volumetric rock content	v_r	Seismic velocity for rock
a	Tortuosity factor	n	Saturation exponent
m	Cementation exponent	σ_w	Pore water conductivity



Visit the next slide to see why Archie's second law is not valid for the ERT data collected at the Heferlbach landfill.

- Matrix conductivity σ_m
 - Electrical conduction through grains and minerals
 - Negligible in case of non-metallic minerals
- Electrolytic conductivity σ_f
 - Electrical conduction in the pore fluid
- Surface conductivity σ_s
 - Electrical conduction at the grain surface
 - Relevant for fine grained materials, e.g., clays, due to high surface area and charge (as found at the Heferlbach site)
- The bulk electrical conductivity can be written as

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



σ_s not considered by Archie's second law. The next slide shows how to resolve this problem.

- We consider the dynamic Stern layer model developed by Revil et al. (2017abc) as described by Tartrat et al. (2019)

$$\sigma^{\infty} = \sigma_f + \sigma_s(f_w, f_r, \rho_g, B, CEC)$$

$$\sigma^0 = \sigma_f + \sigma_s(f_w, f_r, \rho_g, B, CEC, \lambda_{DSL_M})$$



σ^{∞}	Instantaneous conductivity
σ^0	DC (direct current) conductivity
ρ_g (kg/m ³)	Grain density
CEC (C/kg)	Cation exchange capacity
B (m ⁻² s ⁻¹ V ⁻¹)	Apparent mobility of counterions for surface conduction
λ_{DSL_M} (m ⁻² s ⁻¹ V ⁻¹)	Apparent mobility of counterions for polarization

- Theoretically the DSL_M takes into account the surface conduction mechanism and thus, is applicable for data collected at the Heferlbach landfill
- Practically the surface conductivity is implicitly obtained from data collected at different frequencies ($\sigma^{\infty}, \sigma^0$)



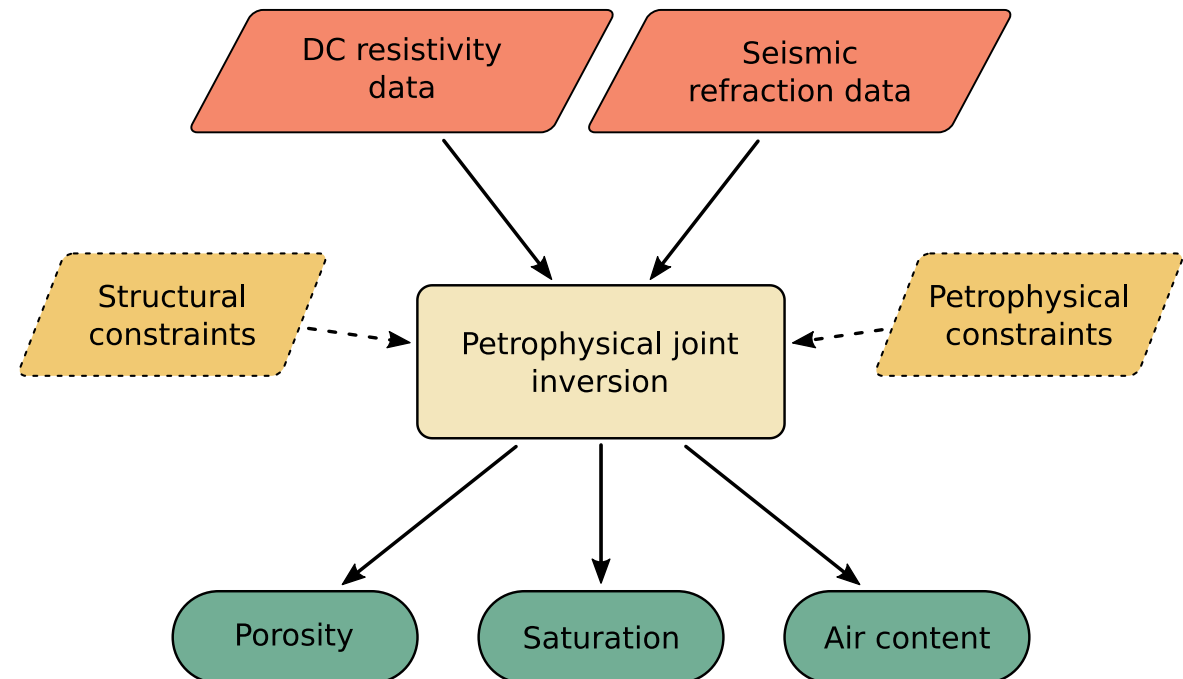
This makes the DSL_M an attractive model to be used in a petrophysical joint inversion framework. Check out the slides about the **Implementation** for more details.

- The basis for the implementation is the petrophysical joint inversion (PJI) framework developed by Wagner et al. (2019)
- The PJI framework itself uses the forward modeling capabilities of pyGIMLi (Rücker et al., 2017)
- Although not used in this study (at this point) the PJI framework accepts petrophysical and structural constraints (e.g., Steiner et al., 2021)



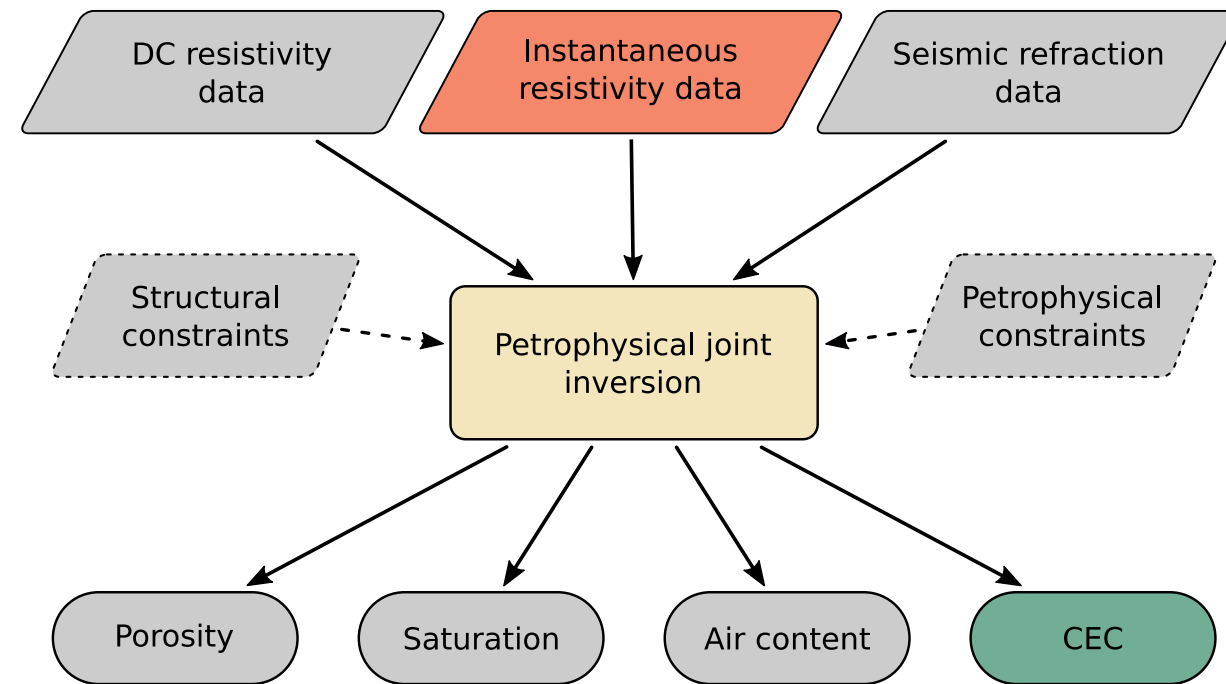
The next slide shows how we implemented the DSLM in the PJI framework.

- We modified the PJI framework to accommodate the equations of the 3PM
- Biggest difference to the 4PM-PJI is that no model for the ice content is estimated



- The basis for the implementation is the petrophysical joint inversion (PJI) framework developed by Wagner et al. (2019)
- Obviously, the site-specific CEC is the only parameter of the DSLM that cannot be described by a general range of values
- Consequently, our implementation of the DSLM in the PJI framework recomputes the CEC model at each iteration step

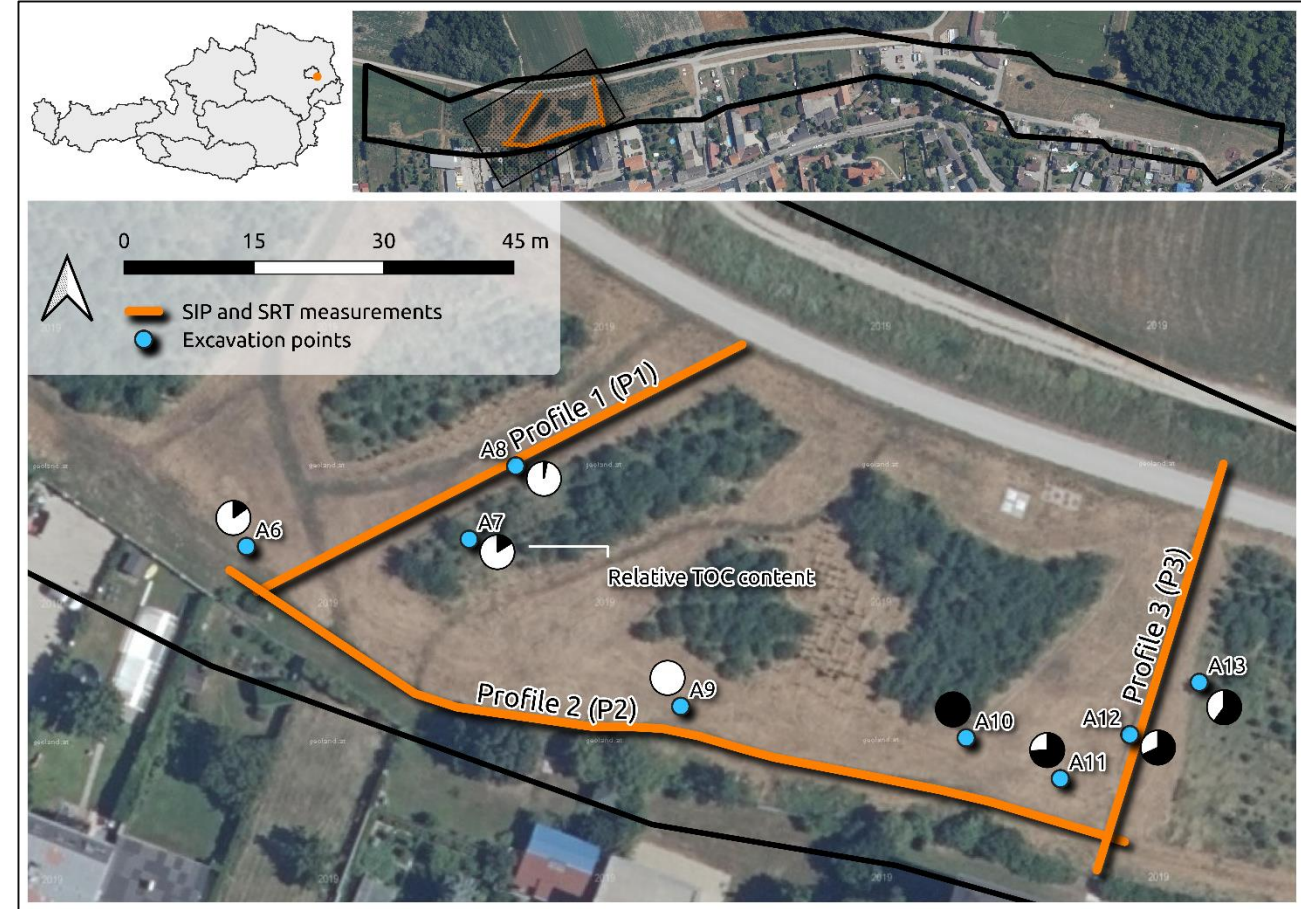
- By including instantaneous electrical resistivity data the DSLM-PJI
 - implicitly takes into account surface conductivity, and
 - resolves a model for the subsurface CEC



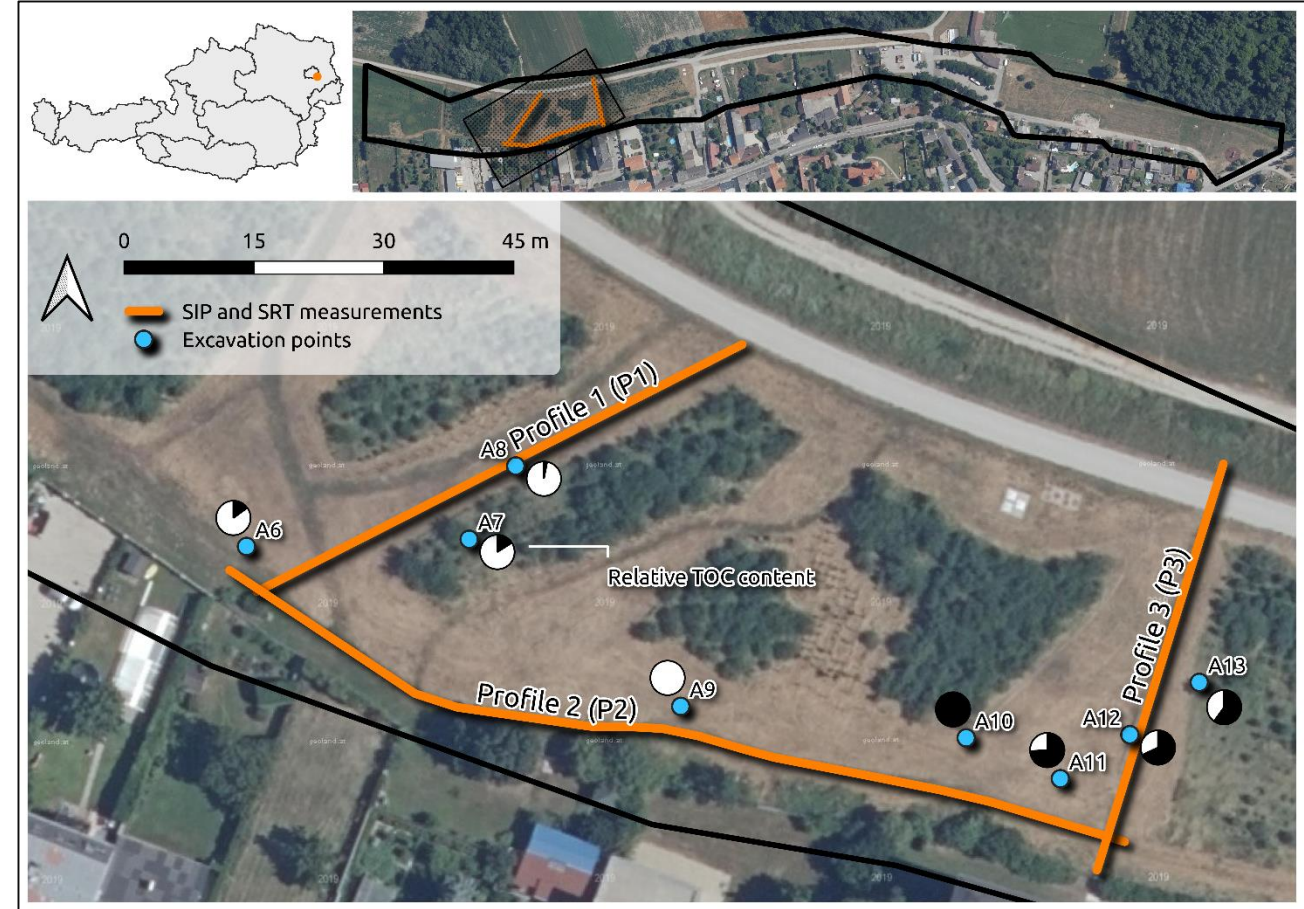
DATA ACQUISITION

- Heferlbach landfill close to Vienna (Austria)

- Length ~ 950 m, width between 50 and 150 m, depth between 3 and 4.5 m
- Groundwater table found approximately 10 m below the bottom of the landfill
- No membrane, leachate is not collected
- Equipped with an aeration system to accelerate biodegradation of organic matter and thus, the production of methane
- Further details regarding the landfill can be found, e.g., in Fellner et al. (2015) and Brandstätter et al. (2020), and previous geophysical investigations in Flores Orozco et al. (2020) and Barone et al. (2021)



- Key motivation for this study is the quantification of the water content as this is a critical parameter to avoid methane production
- We collected electrical and seismic datasets along three profiles
 - Here we will focus on the results obtained for profile P3
 - P3 provides a full cross-section of the landfill and also crosses the dam built along the northern boundary of the landfill



The next slide provides details regarding the SIP data collection.

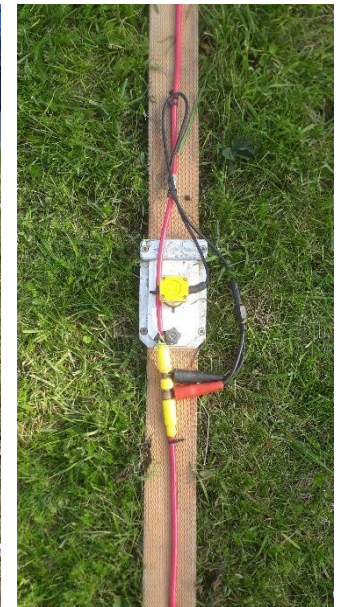
- Campaign on 20th October 2020
- Equipment
 - Multi-Phase Technologies DAS-1
 - Unshielded multi-core cables
 - 64 stainless steel electrodes deployed with 1 m spacing
- Measurements
 - Frequencies 0.5 to 225 Hz
 - Pulse length 0.125 s
 - 50% duty cycle
 - Combination of multiple gradient and dipole-dipole configurations (skip 0-3, e.g., described by Flores Orozco et al., 2018)



Visit the next slide to find information regarding the SRT data collection.

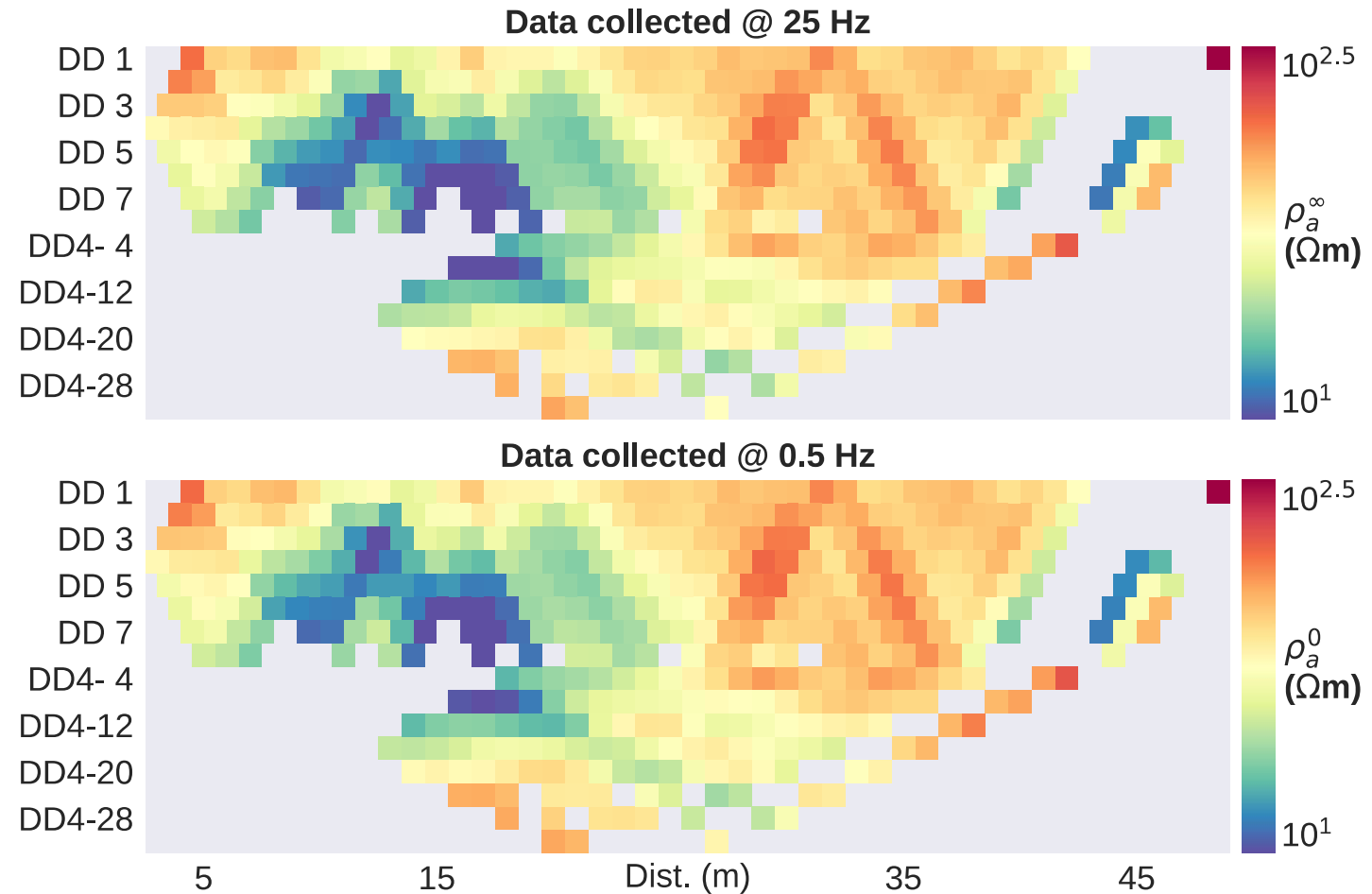
- Campaign on 20th October 2020
- Equipment
 - DMT Summit data acquisition system
 - Land streamer with 24 geophones (4.5 Hz) mounted with 2 m spacing
 - 7.5 kg sledgehammer
- Measurements
 - Shot points located between geophones + offset shots 2 m before and after the land streamer
 - Four hammer blows stacked to improve the signal-to-noise ratio
 - On P1 and P2 roll-along measurements by sequentially redeploying the land streamer with 50 % overlap

- Factors affecting data quality
 - Strong wind (gusts) throughout the day
 - Motorway and airport nearby



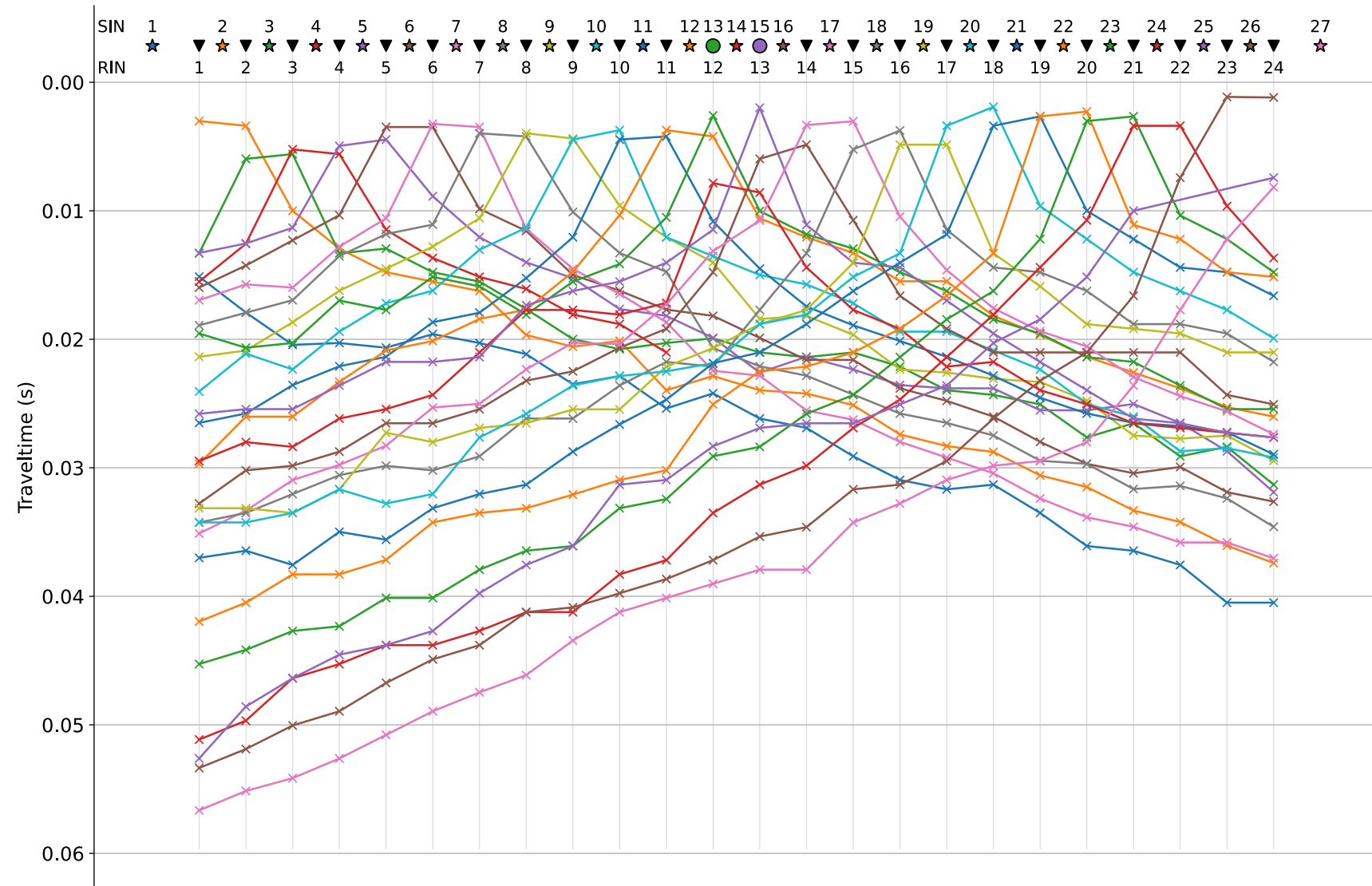
DATA PROCESSING

- We use electrical resistivity data collected at 0.5 and 25 Hz as ρ_a^0 and ρ_a^∞ , respectively.
- We remove erroneous readings associated to
 - negative apparent resistivities or zero current injection, and
 - Poor reciprocity (e.g., Flores Orozco et al., 2012; 2018)
- Moreover, we use only quadrupoles found in both data sets after filtering yielding 554 data points



The next slide illustrates the seismic data processing.

- First break picking based on shot, receiver and absolute offset gathers
- 80 Hz low-pass filter applied on the seismograms
- Traveltimes (tt) obtained for 631 of 648 shot-receiver combinations



- For both the 3PM and DSLM joint inversion we use the same regularization parameters and error models
- The Archie parameters are identical for both petrophysical models
- As shown before, the **DSLM** requires further parameters to be taken into account. Typical values (or ranges) of these parameters are provided in, e.g., Revil et al. (2020) or Tartrat et al. (2019) and the references therein.

INVERSION PARAMETERS				
REGULARIZATION		ERROR MODEL		
λ	<i>zWeight</i>	ρ^0	ρ^∞	<i>tt</i>
100	0.1	6 %	6 %	4 ms

PETROPHYSICAL PARAMETERS										
3PM & DSLM							DSLM ⁽ⁱ⁾			
<i>a</i>	<i>m</i>	<i>n</i>	v_w (m/s)	v_a (m/s)	v_r (m/s)	ρ_w (Ωm)	$R = \frac{B}{\lambda_{DSLM}}$	B ($m^{-2}s^{-1}V^{-1}$)	λ_{DSLM} ($m^{-2}s^{-1}V^{-1}$)	ρ_g (kg/m^3)
1	2	1.5	1500	330	2000	1	0.1	$3.1 \cdot 1e-9$	$3.0 \cdot 1e-10$	2650

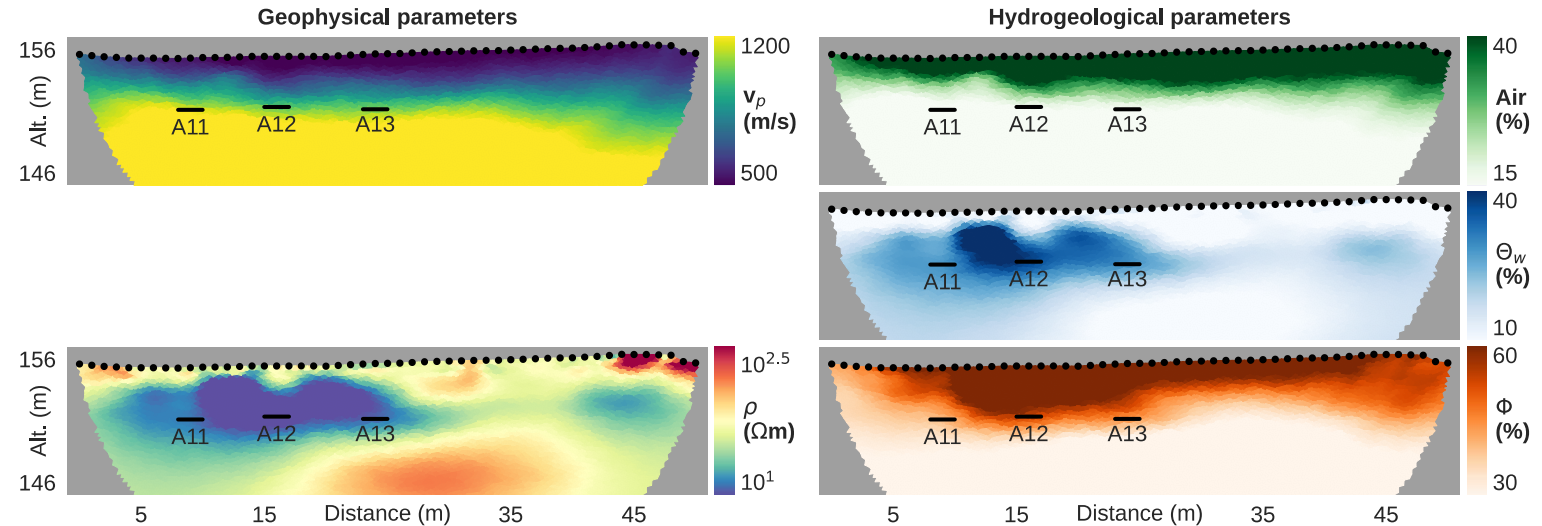
[Click here to view our Results.](#)

(i) Values based on Revil et al. (2020)

RESULTS & DISCUSSION

CONVERGENCE PARAMETERS		
χ^2	ERT χ^2	SRT χ^2
0.94	0.53	1.23

- To aid the evaluation of the resolved models we illustrate the depth of the landfill obtained from direct investigations at point A12 (see **Map**) as black solid line
- The landfill geometry can be delineated from the resolved porosity and the air content, although we know that the 3PM is not valid for data collected at the Heferlbach landfill

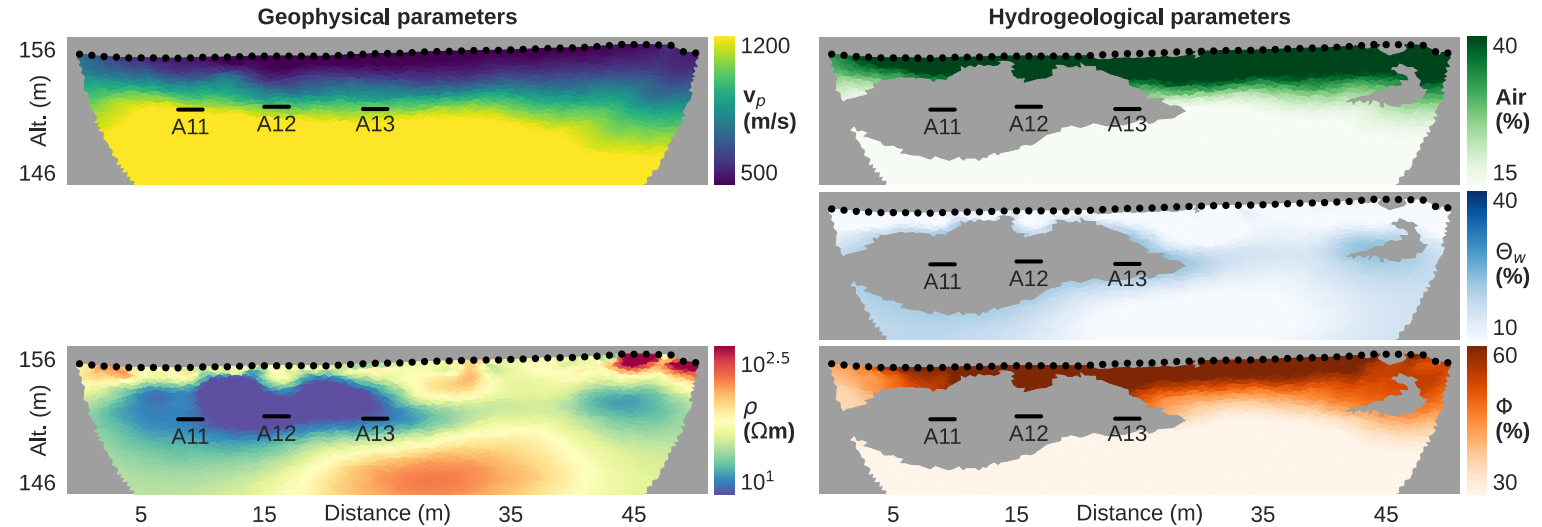


- Note, that the PJI cannot resolve dam located at the right-hand side of the profile (possibly due to a lack of resolution in the seismic data)



The next slide illustrates why we still should not trust in these models, though.

- Since the 3PM does not take into account the surface conductivity, we obtain physically implausible estimates for the hydrogeophysical parameters (blanked areas in the plots)



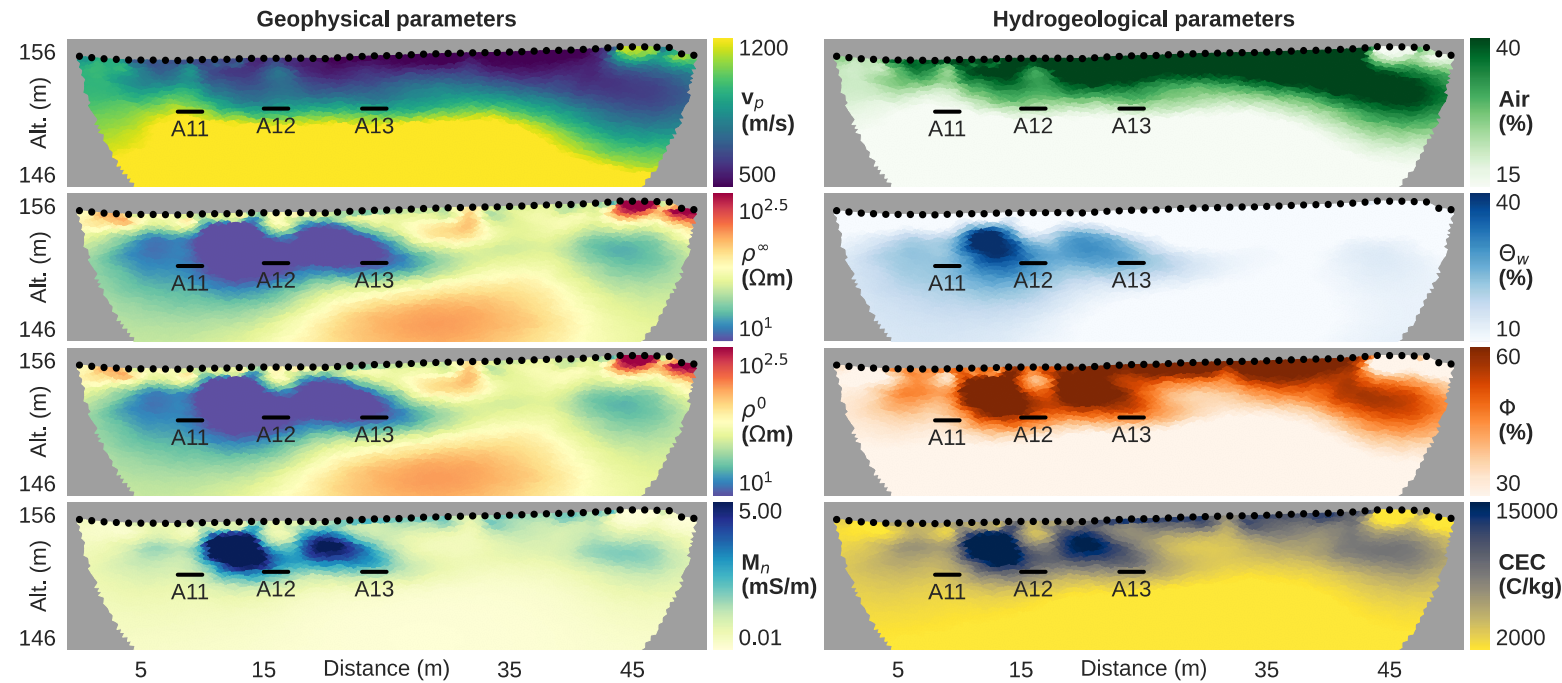
- Hence, any interpretation deduced from these models is biased or even invalid
- Note, that this is not clearly reflected by the χ^2 data fit

- Physically implausible could refer to, e.g.,
 - negative values in one or more models
 - the volume conservations constraint (see **here**) is not met for a specific model cell, i.e., the sum of the (hydrogeophysical) parameter values is greater than 1

→ On the next slide we present the physically plausible models resolved through joint inversion based on the DSLM.

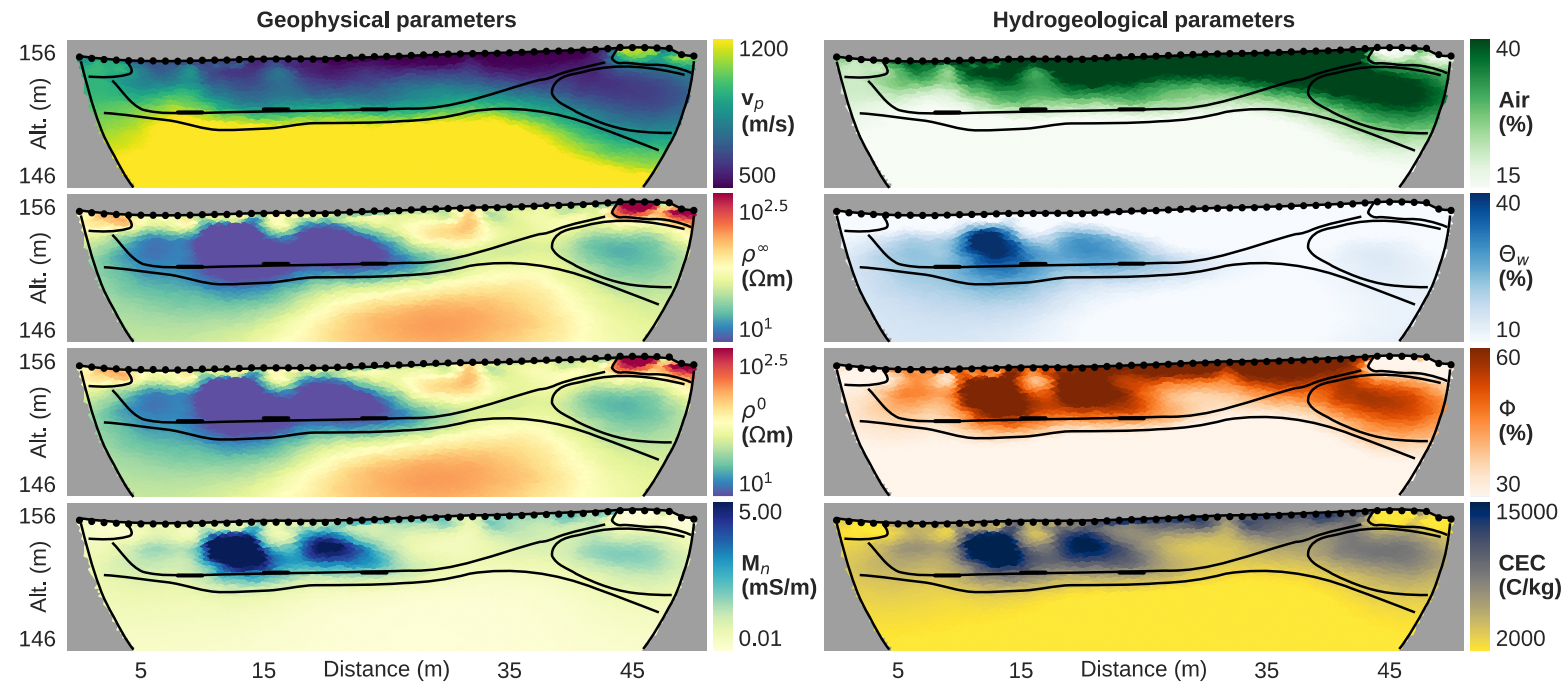
CONVERGENCE PARAMETERS			
χ^2	ERT (ρ^0) χ^2	ERT (ρ^∞) χ^2	SRT χ^2
1.49	1.39	1.31	1.46

- Based on the DSLMM the resolved models do not contain physically implausible values
- The resolved hydrogeological parameters yield a strong contrast between the landfill and the soil beneath
- High CEC values are found for areas with a high TOC content reported by direct investigations, i.e., high contents of organic matter cause a high polarization



- As expected due to the aeration system, the overall water content is below 20%, which is in agreement with available direct information

- The characterization of the landfill is mainly based on the hydrogeological parameters and supported by groundtruth data
- From the air content and porosity models we can delineate the dam that was not resolved by the 3PM-PJI
- Lateral variations in air content and porosity are likely related to waste composition and compaction



- Note, that the normalized chargeability
 - provides a more accurate delineation of the landfill geometry than the models of the seismic velocity and the electrical resistivity
 - coincides well with the polarization images presented by Flores Orozco et al. (2020)



Check out our illustrated **Interpretation** based on the resolved models on the next slide.

- Landfill body
- Transition zone
- Compacted materials
- Artificially compacted materials
- Strong polarization
- Area beneath the dam

Foundation of
adjoining
residential complex

Flood dam
with cycle path

Areas with high rates of biogeochemical
activity (methane production)
associated to high water content
and available carbon (TOC)
(cf. Flores Orozco et al., 2020)

High saturation and low water content
suggest that there is no leakage
through the materials beneath the dam.
Further investigations?

CONCLUSIONS

■ Our study demonstrates

- the reusability of the PJI framework developed by Wagner et al. (2019) for non-permafrost applications
- the applicability of the DSLM (e.g., Revil et al., 2020) as petrophysical model in a PJI framework
- The potential to implement even more complex petrophysical model based on the PJI framework of Wagner et al. (2019)
- that through the DSLM the surface conductivity can be taken into account implicitly based on electrical resistivity data collected at different frequencies
- that models of hydrogeophysical parameters allow for a more detailed and quantitative characterization of the subsurface (compared to the qualitative interpretation of geophysical parameters)
- That the obtained results are in agreement with those presented in a previous study (Flores Orozco et al., 2020)
- That the DSLM-PJI is able to assess the capacitive properties of the subsurface



But we are not done yet. The next slide shows what our next steps are going to be.

■ Short-term

- Investigate the porosity variations within the landfill and find possible correlation with the waste composition and compaction
- Manuscript is in preparation and upon completion to be submitted to Waste Management

■ Mid-term

- Collect additional data sets to close the gaps between profiles presented in this study
- Collect data sets with high spatial resolution in specific areas, e.g., those characterized by a high polarization or close to the dam

■ Mid- to long-term

- Run a 3D PJI of the data
- Extend the petrophysical model solve for the subsurface content of metallic materials
- Include the IP method in the PJI framework or the petrophysical model, respectively
- Initiate a geophysical monitoring along a relevant profile
- Apply the DSLM-PJI to data collected at other landfills