**Introduction**

Transport processes can be monitored using geophysical methods when the tracer changes the geophysical properties of the aquifer (e.g. electrical conductivity, permittivity) and when these changes can be resolved in space and time. Time-lapse single-hole ground penetration radar (GPR) imaging of saline tracer in fractured rock demonstrated the potential to monitor transport processes (e.g. Shakas et al., 2017). Crosshole GPR measurements processed by the full-waveform inversion (FWI) method show models with significantly higher resolution and improved localization of fine-scale heterogeneity compared to their ray-based counterparts (Klotzsche et al., 2010). In the current research, a time-lapse crosshole GPR imaging of a saline tracer test is planned in an alluvial aquifer in Krauthausen test site (Kemna et al., 2002), to test the potential of GPR-FWI to detect transport processes. Hereby we present synthetic time-lapse GPR-FWI imaging of a saline tracer test.

**Synthetic Tracer Test - Workflow**

1. **Realization of heterogeneous aquifer with three facies ($k_i, k_j$)**
2. **3D spatio-temporal concentration dataset $C(t, x)$**
3. **Tracer transport simulation**
4. **Spatio-temporal correlation $r(x, y)$**
5. **Phytophysical relations**
6. **Simulation of 3D GPR**
7. **2D cross-hole full waveform inversion**
8. **Phytophysical relations**
9. **Inverted concentration $C(x, t)$ in image plane**

**GPR acquisition setup:** Synthetic crosshole GPR forward model simulations (Ricker wavelet, $f_0 = 120$ MHz) were performed in a multi-offset gather semi-echoic acquisition setup, with spatial sampling of 0.1 m and 0.2 m for the receivers and transmitters, respectively. The crosshole plane distance was 3.4 m, located 20 m downstream from the injection borehole, perpendicular to the mean flow direction (Fig 2d). Time-lapse GPR were simulated for the background (ambient conditions, 1,0), and at selected tracer arrival time (t=20 days), when salinity and electrical conductivity were 30% higher than the counterpart ambient groundwater.

**Full-waveform inversion setup:** The real models (RM) of the background and tracer were taken from GPR-FWI field measurements ($\sigma$ of both cases - Fig. 3a; $\sigma$ background - Fig. 3b; Gueting et al., 2015) and from transport simulation (c tracer - Fig. 2g). The starting models (SM) for $\sigma$ for background and tracer were generated by smoothing the RM (Fig. 3c), where the SM for both conductivity cases were both a uniform mean of $\sigma$ background RM (Fig 3d).

**Time-lapse crosshole GPR-FWI:** The background and tracer were taken from GPR-FWI field simulations similar to the real models (Fig. 3b). For the tracer case, whilst the $\sigma$ FWI model (Fig. 4c) was similar to the RM, the $\sigma$ model (Fig. 4d) generated an image which reconstructs successfully the tracer location (at 4.5 m depth) but smooths the heterogeneity in $\sigma$ at the cell scale (0.5m), to a region of intermediate $\sigma$. Residuals from time-lapse $\sigma$ FWI models of tracer and background cases (Fig. 4f) resulted in a smoothed reconstruction of the plume (compare with Fig. 2a). The mean inverted salinity of the plume from FWI ($0.16$ g/kg) is similar to that of the transport simulation ($0.12$ g/kg). Residuals from the $\sigma$ FWI models is very low, as expected.

**PETROPHYSICAL RELATIONS**

- Bulk electrical conductivity ($\sigma$) is influenced by introducing electrolysis in the groundwater, whereas permeability ($k$) is not affected by $\sigma$. Residuals of the tracer concentration ($C$) was converted to bulk electrical conductivity by the following relations:
  - The total groundwater salinity ($S_{GW}$) was calculated as sum of the ambient salinity (0.398 g/kg) and the tracer salinity:
    $$\frac{\text{tracer concentration}}{\text{tracer concentration} + \text{ambient salinity}} = \frac{S_{GW}}{S_{GW} + S_{ambient}}$$
  - The bulk conductivity was calculated from Archie’s empirical law (Archie, 1942), using the formation factor ($F$), an intrinsic measure of material microgeometry:
    $$\sigma_k = \frac{\mu \cdot F \cdot S_{water}}{\phi}$$

**Tracer Transport Simulation**

A 3D tracer model was simulated through hydrogeological model (Fig. 1) of an alluvial aquifer in Krauthausen test site, composed of three facies (Table 1). Distribution of the tracer (Fig. 2) manifests a leading plume in the top gravel part of the aquifer, and a slower plume in the more sandy part at the bottom of the aquifer. Tracer concentration in crosshole plane was converted to electrical conductivity (Fig. 2a-g) using petrophysical relations (eq. 1-3).

**CONCLUSIONS AND OUTLOOK**

- **GPR-FWI detected infiltration of saline tracer at the decimeter scale, however it smoothed finer scale heterogeneities (Fig. 2a-f).**
- **Based on the prediction from transport simulation and the ability to detect the tracer in various concentrations, a field tracer is planned in Krauthausen test site.**
- **For future work we plan:**
  - Test the full-waveform inversion for larger electrical conductivity contrasts, which were found to be a more challenging case for conversion to the real model.
  - To use zero-offset (ZOP) crosshole acquisition to analyze whether using with quick method a tracer infiltration can be detected and on which conductivity contrasts.

**References**

Archie, 1942. Transactions of the AIME, 146(1), 54-62.

**Testing the Potential of GPR-FWI to Detect Tracer Plumes in Time-Lapse Monitoring**

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