Induced polarization for the spatial characterization of biogeochemical hot spots

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Introduction

- Biogeochemical hot spots are spatially limited areas where processes such as sulfate or iron reduction take place in high reaction rates compared to the surrounding area.
- Biogeochemical hot spots are of major interest due to the possible emission of greenhouse gases (carbon dioxide).

Objective

- Biogeochemical hot spots are sensitive environments. Classical geochemical sampling methods (e.g., piezometers or suction cups) bring oxygen into anoxic areas.
- Delineate field scale biogeochemical hot spots and their geometry without disturbing the system.
- Resolve the granite bedrock and the overlying peat.
  - If the granite is resolved, we can focus on the changes in the peat.
- Noninvasive geophysical method – induced polarization.
- Hypothesis:
  - Granite has lower polarization response than peat.
  - Biogeochemical active areas have higher polarization response than peat.
Induced polarization

- Induced polarization (IP)
  - Imaging 4-electrode array
    - Two electrodes used for current injections, two electrodes used for voltage measurements
    - Interchange electrode pairs → normal and reciprocal measurements
  - Impedance is measured → complex conductivity/resistivity
  - Developed for detecting metallic minerals

\[ Z = \frac{U}{I} = |Z| \cdot e^{i\varphi} \]

\[ \rho^* = \frac{1}{\sigma^*} = \sigma' + i\sigma'' = |\sigma|e^{i\phi} \]

- \( Z \) – impedance, \( U \) – voltage, \( I \) – current, \( \varphi \) – phase shift, \( \rho \) – resistivity, \( \sigma \) – conductivity, \( i = \sqrt{-1} \)
Induced polarization

- In the presence of an external electrical field the electrons in a metallic conductor relocate along the conductor’s surface.
- In the electrolyte the charged conductor attracts ions.
- Migration currents charge the electrolyte around the poles of the conductor.
- The charging continues until it reaches the equilibrium.

Fig: Bücker et al., 2018

$J_{\text{mig}}$ - migration current
$J_{\text{diff}}$ - diffusion current
$E_{\text{ext}}$ - external electric field

Bücker et al., 2018
Study site

- Lehstenbach catchment in Bavaria (Germany).
  - Granite bedrock
  - Riparian wetland: peat soil, with the vegetation peat moss (Sphagnum) and purple moor-grass (Molinia caerulea)
Experimental setup

- Thickness of the peat was measured by sticking a metal rod of 0.5 cm diameter into the soft ground until it reached a solid surface.

- IP measurements at 1 Hz
  - 64 profiles (black lines)
    - 3 profiles presented here: By 25, By 46 and By 68
  - 64 electrodes per line
  - 20 cm separation between electrodes and lines
  - coaxial cables
  - stainless steel electrodes
  - DAS1 unit Multi-Phase Technologies

- Geochemical analysis
  - Fluid samples
    - 3 locations: S1, S2 and S3
  - Freeze core
    - 2 locations: S1 and S2
Experimental setup

By 25
4.4 m

By 68
3 m

By 46
8.2 m
Pictures of the site

Electrode

Sphagnum

Thick grass and moss, electrode spacing: 20 cm

Measurement setup and DAS1 instrument
Data quality

- Normal – reciprocal measurements
- The pseudosection of By 25 in terms of apparent resistivity ($\rho_a$) and apparent phase ($\phi_a$).
- Data collected with coaxial cable show high data quality
Normal-reciprocal analysis

- Analysis of the normal and reciprocal misfit helps to identify outliers and to define error model parameters (Flores Orozco et al., 2012).
- The histograms of the misfit show normal distribution with low standard deviation (\( \sigma_R=0.027 \), \( \sigma_\phi=1.1 \)).
Results

- Phase values help to resolve the granite and the peat
  - $\varphi < 13$ mrad - granite
  - $\varphi > 13$ mrad - peat
- Varying values in the peat, top 10-20 cm – low resistivity and high phase: hot spot
  - $\rho < 200 \Omega m$ (however, only in the top 10-20 cm below surface)
  - $\varphi > 22$ mrad (spatial changes in the phase values)
Results

- Granite is below the sensitivity of the electrode configuration at By 46 → we cannot resolve the granite at By 46
Results

- By 68 is a perpendicular profile to the previous By 25 and By 46
- Validate the geometry of the phase distribution we measured at By 25 and By 46
IP results

- The IP in the peat is varying between 13 and 30 mrad \( \rightarrow \) varying biogeochemical activity
  - Peat, where the phase >22 mrad we interpret as hot spot
Geochemical analysis

- High dissolved organic carbon (DOC), iron ($\text{Fe}_{\text{tot}}$), potassium (K) and sodium (Na) concentrations at S1 and S3 in the top 10-20 cm → indicator for biogeochemical hot spots.
IP analysis

- The conductivity ($\sigma'$) and polarization ($\sigma''$) are high at the surface and steeply decrease with depth across the top 20 cm.
- The decrease of the phase ($\phi$) is less pronounced than $\sigma'$ or $\sigma''$.
- The conductivity, polarization and phase in the top 20 cm at S1 and S3 are remarkably higher than at S2.
- Corresponding to the geochemical analysis (DOC and iron), the top 20 cm at S1 and S3 are interpreted as biogeochemical hot spots.
- $\sigma'>5 \text{ mS/cm}$ and $\sigma''>80 \mu\text{S/cm} \rightarrow \text{Hot spot}$
Conclusion

- We characterized biogeochemical hot spots and resolved the peat-granite interface with induced polarization
- IP results could be verified by
  - the manually measured peat thickness
  - the geochemical analysis
    - Dissolved organic carbon (DOC), iron (Fe), potassium (K), sodium concentration (Na) correlates to the polarization ($\sigma''$)
    - Chloride (Cl) concentration correlates to the conductivity ($\sigma'$)
References

• Sumner, J. S. Principles of Induced Polarization for Geophysical Exploration. 1976.