5th International Workshop on Induced Polarization

Rutgers University
Newark, NJ, USA
3-5 Oct 2018
The 5th International Workshop on Induced Polarization (IP) will take place from October 3-5, 2018 at Rutgers University-Newark, located just 10 miles outside of New York City, USA. An icebreaker is planned for the evening of October 2 to kick off the workshop.

The 5th workshop will critically evaluate the information content of induced polarization data based on the last decade of theoretical, laboratory and field-scale developments in the method.

The workshop will be built around 5 major themes each with a prestigious invited keynote speaker:

1. **Petrophysics:** Keynote speaker Matthias Halisch [Leibniz Institute of Applied Geophysics, Germany]
2. **Biogeophysical studies:** Keynote speaker Sarah Glaven [Naval Research Laboratory, USA]
3. **Modeling:** Keynote speaker Matthias Bücker [Universität Bonn, Germany]
4. **Field applications:** Keynote speaker Torleif Dahlin [Lund University, Sweden]
5. **Data processing and inversion:** Keynote speaker Douglas Oldenburg [University of British Columbia, Canada]

The workshop will be broken into invited keynote talks, poster sessions and roundtable discussions. Industry sponsors will showcase their most recent IP-related products.

The roundtable discussions will allow small groups to discuss in detail what the main challenges and opportunities are with respect to the five major themes described above. Attendees will be asked to sign up to participate in the discussion of 2 out of the 5 themes during registration on Day 1 of the meeting. In order to keep the discussion groups equally sized, there will be a limited number of spots in each discussion group. Group signups will be on a first come, first served basis. The closing session of the workshop will include reports from each of the five groups summarizing their discussions and identifying priorities and opportunities for future development of the IP method. Short (1-2 paragraph) charges for each group discussion will be posted to the website approximately one month prior to the workshop. Attendees are encouraged to read these charges prior to arrival in order to select their preference for discussion groups to join. Attendees are also strongly encouraged to bring questions/ideas to the table during each roundtable discussion.

Sponsors of the 5th IP Workshop include Ontash & Ermac, Mt. Sopris, Instruments, Iris Instruments, Advanced Geosciences Inc. (AGI), ABEM Maia and Aarhus Geosoftware (AGS). Visit the website for further details on abstract submission, registration, accommodation and social activities.

http://ncas.rutgers.edu/2018ipworkshop
Organizing Committee

Lee Slater  
Dimitrios Ntarlagiannis  
Judy Robinson  
Kristina Keating

Technical Committee

Andréa Ustra  
University of São Paulo  
Chair

Gianluca Fiandaca  
Aarhus University

Adrian Flores-Orozco  
TU Wien

Deqiang Mao  
Shandong University

Pauline Kessouri  
Technion - Israel Institute of Technology

Sabine Kruschwitz  
Bundesanstalt für Materialforschung und-prüfung (BAM)

Chi Zhang  
University of Kansas

Yuxin Wu  
Lawrence Berkeley National Laboratory

Edmundo Placencia  
Pacific Northwest National Laboratory

Sessions and Keynote Speakers

Petrophysics: Matthias Halisch  
[Leibniz Institute of Applied Geophysics, Germany]

Biogeophysical studies: Sarah Glaven  
[Naval Research Laboratory, USA]

Modeling: Matthias Bücke  
[Universität Bonn, Germany]

Field applications: Torleif Dahlin  
[Lund University, Sweden]

Data processing and inversion: Douglas Oldenburg  
[University of British Columbia, Canada]

Sponsors and Supporters
Ontash & Ermac, Inc.

Ontash & Ermac, Inc. (O&E) is a leading developer and supplier of spectral induced polarization (SIP) equipment for use in laboratory, surface, and borehole applications.

O&E’s SIP products:
Portable Field/Lab Spectral Induced Polarization (PSIP):
The PSIP is a high-performance multi-channel geophysical instrument optimized for laboratory and in situ near surface SIP, conventional resistivity, time-domain induced polarization and self-potential measurements.
Portable Spectral Induced Polarization (SIP) Full Switch Unit (PSFS):
The PSFS is a switching unit designed specifically as an accessory to the PSIP. The PSFS maintains the driven guards of the PSIP for optimal signal quality.
PSIP Stimulus Switch Unit:
PSIP accessory for time domain and self potential measurements.
PSIP Stimulus Amplifier:
PSIP accessory for measurements requiring more power.
SIP Sonde:
Complete electronics, firmware and acquisition and control software integrated with Mount Sopris sonde / borehole logging system. SIP stimulus and sensing performed entirely by SIP Sonde Electronics within the borehole. O&E SIP development is performed in collaboration with the Department of Earth and Environmental Sciences (DEES), Rutgers University-Newark, Mount Sopris, and ALT and aided by National Science Foundation Phase I, IB, II, and IIB funding awards.

We look forward to meeting with you and learning more about your research at the Rutgers IP Workshop.

Mount Sopris Instruments

Mount Sopris Instrument Company manufactures slimline borehole geophysical logging equipment and has been recognized as a leader in this field since our beginnings in 1953.

Borehole IP Tool
In the 1970’s and 80’s we manufactured a borehole IP tool for mining / exploration applications. This system produced a 3.75 Hz time-domain current waveform with a 50% duty cycle. Depending on the resistivity scale selected output current ranged from 380 mA – 0.76 mA. Synchronous rectifying of the received signal primary voltage was used to determine resistivity. Secondary voltage from the 40-cm normal electrode was gated into a 3rd synchronous rectifier to obtain borehole induced polarization.

Full Waveform Borehole IP Tool
Later in the 2000’s Mount Sopris and partner ALT – Luxembourg developed a full-waveform borehole IP tool. This IP measuring system features user-selectable standard injection-release times (100-250-500ms), along customizable injection-release times based on application. Simultaneous full-wave digitizing of electrode voltages and injected current enhance data processing and interpretation.

Borehole Spectral IP Tool
Today, Mount Sopris and partners Ontash & Ermac, and ALT are developing a new generation borehole spectral induced polarization tool (SIP). The new SIP tool applies sine wave currents at frequencies ranging from 1 mHz to 10 kHz. Impedance and phase are determined by correlating induced voltage and stimulus current. Recorded data helps us draw inference about formation permeability (hydraulic conductivity), effective porosity, grain/pore size distribution and surface area. Please visit with us at the Rutgers IP Workshop to discuss this new technology.

Aarhus GeoSoftware

AGS

Aarhus GeoSoftware is a leading provider of software for processing, inversion and visualization of electromagnetic- and electrical data. We have a common platform, Aarhus Workbench where data handling is integrated from raw data to processing, inversion, QC of inversion results and visualization of inversion models on GIS interface, sections, and 3D.

IP Software Capability
For IP data we do full waveform Cole-Cole, Constant Phase Angle and Maximum Phase Angle inversion.

Advanced Geosciences, Inc.

IP/SP Hardware and Software

Advanced Geosciences, established in 1989, designs, manufactures, sells and supports the SuperSting WiFi® resistivity/IP/SP systems with remote control and real-time data display on tablet. AGI also manufactures EarthImager inversion software, PowerSting transmitters, the PowerSting Node automated switching system, AGI FlexLite Passive Cables, Marine Guided Navigation software and numerous other systems at the facilities in Austin, Texas USA.

Guideline Geo

Guideline Geo provides solutions for non-destructive mapping of the subsurface. Through our brands ABEM and MALÅ, we are a world-leader in geophysical solutions necessary to map and visualize the subsurface. For more than 20 years ABEM has manufactured field equipment for Resistivity and IP surveys, and with each generation improvements have been made.

ABEM Terrameter LS2
The latest addition, the ABEM Terrameter LS 2, comes packed with features to be able to achieve excellent IP data quality. A built in powerful current transmitter delivers true constant current output. The 12 measure channels are galvanically isolated and uses a filter design which together with exponential background drift removal increases the useable spectral information content. For even further data processing full waveform data for lout, Vout and Vin can be stored with up to 9 kHz sampling rate for export to external processing software.

Iris Instruments

IRIS Instruments designs, manufactures and sells geophysical products (resistivity sounding and imaging, induced polarization, electro-magnetics, magnetic resonance) for mineral exploration, groundwater, geotechnical and environmental applications.

Full Waveform
These past years, we specially focused our efforts in new IP instrumentation measuring the Full Wave record for advanced processing.
Conference Venue Map and Details

1. Main Conference Location: Express Newark, Room 213, 54 Halsey Street
2. Lunch Day 1 & 2: University Club, Paul Robeson Campus Center, 2nd Floor
3. Lunch Day 3: Kilkenny’s Alehouse, 27 Central Ave.
4. Icebreaker: Clement’s Place, 15 Washington St.

Rutgers University, Newark

Rutgers University – Newark is an urban, public research university that is not merely in, but of its environment. A part of Rutgers, The State University of New Jersey, it is located in the city of Newark, the state’s largest city and cultural capital. Since 1997 RU-N has been rated as the most diverse national campus by U.S. News & World Report. The Department of Earth and Environmental Sciences, part of the School of Arts and Sciences Newark (SASN), has invested heavily in near surface geophysics. Three full-time faculty, along with postdoctoral scientists and graduate students, conduct basic and applied research in near surface geophysics, with a focus on electrical (specifically induced polarization) and nuclear magnetic resonance methods.
Social Program and Activities

The 5th IP workshop will have numerous social activities that will provide opportunities for networking with colleagues. These social activities are included in the registration fee, made possible by the generosity of our sponsors. Highlights include:

**Conference Dinner, Wednesday October 3:**

The conference dinner will be held at Iberia Restaurant, a popular Portuguese and Spanish restaurant located in Newark’s vibrant Ironbound neighborhood. The evening will include a full dinner with wine and sangria served “Iberia first introduced its Portuguese and Spanish cuisine to the area in 1926. A strong reputation was soon developed, and the Iberia name soon became synonymous with high-quality food (in large portions) for affordable prices and exceptional service. Soon, Iberia Tavern became known for classic, traditional dishes, such as: shrimp in garlic sauce; Paella a Valenciana (a seafood combination dish with rice); and chorico (Portuguese sausage). Today, the portions are as large as ever, the menu has grown with additional meat, fish, and seafood dishes, and the crowds are as loud as ever”.

**Conference Gala Evening, Thursday October 4:**

The gala evening event of the conference is a dinner cruise on the Hudson River on the Spirit of New Jersey. “Spirit of New York or New Jersey dinner cruise provides the ultimate destination to dine, dance and experience the iconic New York City skyline from a whole new perspective.” The dinner includes an open bar for wine and domestic beers. This is a great opportunity to experience the Manhattan skyline at night whilst enjoying a dinner with colleagues.

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**Sponsorship Levels**

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<th>Sponsor</th>
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<td>Ontash &amp; Emac</td>
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<td>Mount Sopris Instruments</td>
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<td>Aarhus Geosoftware</td>
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<td>AGI Instruments</td>
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<td>Guideline Geo</td>
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<td>Iris Instruments</td>
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## Conference Agenda and Schedule

**5th International Workshop on IP**

**Tue Oct 2 – Fri Oct 5, 2018 (Eastern Time - New York)**

<table>
<thead>
<tr>
<th>Time</th>
<th>Tue 10/2</th>
<th>Wed 10/3</th>
<th>Thu 10/4</th>
<th>Fri 10/5</th>
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<tr>
<td>8 am</td>
<td>REGISTRATION 8:00 - 8:45am</td>
<td>INTRODUCTORY REMARKS 8:45 - 9:00am</td>
<td>BIOGEOPHYSICS INVITED TALK: SARAH GLAVEN [Naval Research Laboratory, USA] 9am - 10am</td>
<td>FIELD APPLICATIONS INVITED TALK: TORLEIF DAHLIN [Lund University, Sweden] 9am - 10am</td>
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<td>9 am</td>
<td>PETROPHYSICS INVITED TALK: MATTHIAS HALISCH [Leibniz Institute of Applied Geophysics, Germany] 9am - 10am</td>
<td>COFFEE BREAK 10am - 10:30am</td>
<td>POSTER SESSIONS: [1] PETROPHYSICS; [2] DATAPROCESSING AND INVERSION 10:30am - 12:30pm</td>
<td>POSTER SESSION: FIELD APPLICATIONS 10:30am - 12:30pm</td>
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<td>11 am</td>
<td>LUNCH 12:30pm - 1:45pm</td>
<td>LUNCH 12:30pm - 1:45pm</td>
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<td>12 am</td>
<td>COFFEE BREAK 2:45pm - 3:15pm</td>
<td>WORKGROUP SESSION #1 3:15pm - 5:15pm</td>
<td>WORKGROUP SESSION #2 3:15pm - 5:15pm</td>
<td>CLOSING REMARKS AND WRAP UP 3:15 - 3:45 pm</td>
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<td>1 pm</td>
<td>DATAPROCESSING/INVERSION INVITED TALK: DOUGLAS OLDENBURG [University of British Columbia, Canada] 1:45pm - 2:45pm</td>
<td>MODELING INVITED TALK: MATTHIAS BUCKER [Universität Bonn, Germany] 1:45pm - 2:45pm</td>
<td>CLOSE OUT SESSION: [1] PRESENTATIONS FROM BREAK OUT DISCUSSIONS; [2] SPECIAL ISSUE DISCUSSION 1:45pm - 2:45pm</td>
<td>OPTIONAL: NEW YORK CITY WALKING TOUR 4:00pm - 9pm</td>
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<td>2 pm</td>
<td>MODELING INVITED TALK: MATTHIAS BUCKER [Universität Bonn, Germany] 1:45pm - 2:45pm</td>
<td>COFFEE BREAK 2:45pm - 3:15pm</td>
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<td>3 pm</td>
<td>COFFEE BREAK 2:45pm - 3:15pm</td>
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<td>4 pm</td>
<td>WORKGROUP SESSION #1 3:15pm - 5:15pm</td>
<td>WORKGROUP SESSION #2 3:15pm - 5:15pm</td>
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<td>5 pm</td>
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<td>6 pm</td>
<td>EXHIBITOR'S RECEPTION AND DEMOS 5:30pm - 7pm</td>
<td>RIVER CRUISE AND DINNER 6pm - 10pm</td>
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<td>7 pm</td>
<td>WORKSHOP ICEBREAKER 6pm - 7:30pm</td>
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<td>8 pm</td>
<td>DINNER: IRONBOUND RESTAURANT 7:30pm - 9:30pm</td>
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<td>9 pm</td>
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Invited Talks - KeyNotes

Petrophysics of / for SIP (Matthias Halisch¹)
Matthias Halisch¹, Andreas Weller², Sabine Kruschwitz³, Zeyu Zhang⁴, Raphael Dlugosch⁵
Leibniz Institute for Applied Geophysics (LIAG), Dept.5 – Petrophysics & Borehole Geophysics, (2) Clausthal University of Technology, Institute of Geophysics, (3) Bundesanstalt für Materialforschung und –prüfung (BAM), (4) Southwest Petroleum University, School of Geoscience and Technology, (5) Leibniz Institute for Applied Geophysics (LIAG), Dept.5 – Petrophysics & Borehole Geophysics

Strategies for 3D inversion of IP data (Douglas W. Oldenburg)
Douglas W. Oldenburg¹, Seogi Kang¹
(1) University of British Columbia, Earth, Ocean, and Atmospheric Sciences.

Electrical interactions between biofilms and surfaces (Sarah M. Glaven)
Lina J. Bird¹, Elizabeth Onderko¹, Daniel Phillips³, Brian J. Eddie³, Matthew Yates³, Anthony P. Malanoski³, Leonard M. Tender³ and Sarah M. Glaven³

IP Modelling (Matthias Bücker)
Matthias Bücker¹
(1) TU Braunschweig, Institute for Geophysics and extraterrestrial Physics.

Field Applications of Time-Domain Induced Polarisation (Torleif Dahlin)
Torleif Dahlin¹
(1) Lund University, Engineering Geology.

Posters Sessions

Poster Session - Wed 10/3 10:30 am – 12:30 pm
[1] Petrophysics
[2] Data processing and inversion

Poster Session - Thu 10/4 10:30 am – 12:30 pm
[1] Biogeophysics

Poster Session - Fri 10/5 10:30 am – 12:30 pm
[1] Field applications
# Posters Sessions – Poster Titles

<table>
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<tr>
<th><strong>PETROPHYSICS: Wed 10/3</strong></th>
<th><strong>10:30 am-12:30 pm</strong></th>
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<tr>
<td><strong>IMPACT OF PORE FLUID CHEMISTRY ON COMPLEX CONDUCTIVITY OF GRAPHITE</strong></td>
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<td>Yuxin Wu¹, Luca Peruzzo¹</td>
<td>(1) Lawrence Berkeley National Lab.</td>
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<tr>
<td><strong>Permeability estimation directly from logging-while-drilling Induced Polarization data</strong></td>
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<td>Gianluca Fiandaca¹, Pradip Kumar Maurya¹, Nicola Balbarini², Andreas Hördt³, Anders Vest Christiansen¹, Nicolaj Foged¹, Poul L. Bjerg² and Esben Auken¹</td>
<td>(1) HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus, Denmark, (2) Technical University of Denmark, Department of Environmental Engineering, Lyngby, Denmark, (3) Institute for Geophysik und extraterrestrische Physik, Braunschweig, Germany.</td>
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<td><strong>The Geo-Electrical Signature of Heavy Metals</strong></td>
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<td>Tamar Shalem¹, Johan Alexander (Sander) Huisman², Egon Zimmerman³, Wu Yuyuan⁴, Renduo Zheng⁵ and Alex Furman¹</td>
<td>(1) Civil and Environmental Engineering, Technion, Israel, (2) Institute of Bio- and Geosciences, Forschungszentrum Jülich, Germany, (3) Central Institute of Engineering, Electronics and Analytics, Forschungszentrum Jülich, Germany, (4) School of Environmental Science and Engineering, Sun Yat-sen University, Guangzhou, China.</td>
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<tr>
<td><strong>Evidence of sorption processes observed with IP in dual domain porosity rock cores during injection/flush solute tracer experiments</strong></td>
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<td><strong>Spectral induced polarization response of calcite precipitation</strong></td>
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<td>Satoshi Izumoto¹, Johan Alexander Huisman¹, Egon Zimmermann², Odilia Esser¹, Franz –Hubert Haegel¹, Harry Vereecken¹</td>
<td>(1) Institute of Bio- and Geosciences, Agrosphere, Forschungszentrum Jülich, (2) Central Institute for Engineering, Electronics and Analysis, Electronic System, Forschungszentrum Jülich.</td>
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<tr>
<td><strong>Tracking secondary mineralization in hydrothermal systems with complex electrical measurements: laboratory observations on natural core samples from the Krafla volcano (Iceland)</strong></td>
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<td>Léa Lévy¹³, Benoit Gibert², Freysteinn Sigmundsson³, Damien Deldicque¹, Fleurice Parat², Gylfi Páll Hersir⁴, Olafur G. Flóvenz⁴, Pierre Briole¹</td>
<td>(1) Ecole Normale Supérieure, Department of Geosciences, (2) University of Montpellier, Géosciences Montpellier, (3) University of Iceland, Nordic Volcanological Center, Institute of Earth Sciences, (4) ÍSOR-Iceland Geosurvey.</td>
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<tr>
<td><strong>COMPLEX RESISTIVITY MEASUREMENTS OF ARTIFICIAL SAMPLES CONTAINING VARIOUS MINERALS</strong></td>
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</table>
PETROPHYSICS: Wed 10/3

**Spectral induced polarization of nanoporous media**

Philippe Leroy¹, Andreas Hördt², Matthias Bücker², Egon Zimmermann³, Johan Alexander Huisman⁴

(1) French Geological Survey, Water Department, Orléans, France, (2) Braunschweig Technical University, Institute for Geophysics, Braunschweig, Germany, (3) Wien Technical University, Geoinformation Department, Vienna, Austria, (4) Forschungszentrum, Electronic Systems ZEA 2, Jülich, Germany, (5) Forschungszentrum, Agrosphere institute IBG 3, Jülich, Germany.

**Monitoring and assessing effects of carbonate rock dissolution on spectral induced polarization data**

Matthias Halisch¹, Sarah Hupfer¹, Andreas Weller¹, Raphael Drulgosch¹, Hans-Peter Plumhoff²

(1) Leibniz Institute for Applied Geophysics (LIAG), Dept. 5 – Petrophysics & Borehole Geophysics, (5) Westphal Präzisionstechnik GmbH & Co. KG, Celle, Germany.

**Can we effectively characterize pore geometric properties from spectral induced polarization (SIP) measurements on low porosity mudstones?**

Judy Robinson¹, Lee Slater², Andreas Weller³, Tonian Robinson², Manika Prasaad⁴, Kristina Keating²

(1) Pacific Northwest National Laboratory, Subsurface Science and Technology Group, Richland, Washington, (2) Rutgers University Newark, Department of Earth and Environmental Sciences, Newark, (3) Institut für Geophysik, Technische Universität Clausthal, Clausthal-Zellerfeld, (4) Colorado School of Mines, Department of Petroleum Engineering, Golden, Colorado.

**Evaluation of IP parameters for permeability prediction of sandstones**

Andreas Weller¹, Lee Slater²

(1) Technische Universität Clausthal, Institut für Geophysik, (2) Rutgers University - Newark, Department of Earth and Environmental Sciences.

**Enhanced characterization of pore systems by simultaneous use of SIP, µ- CT and NMR**

Sabine Kruschwitz¹, Matthias Halisch², Raphael Drulgosch², Carsten Prinz³

(1) Bundesanstalt für Materialforschung und –prüfung (BAM), 8.0 Non-destructive testing, (2) Leibniz Institute for Applied Geophysics, Petrophysics & Borehole Geophysics, (3) Bundesanstalt für Materialforschung und –prüfung (BAM), Structure Analysis.

**SIP signals of artificial rocks**

Zhuang Xu¹², Chi Zhang¹, Wanzhong Shi²

(1) Department of Geology, The University of Kansas, (2) School of Resources, China University of Geosciences (Wuhan), Wuhan, China.

DATA PROCESSING AND INVERSION: WED 10/3

**3D modelling of time-domain full-decay induced polarization**

Line Meldgaard Madsen¹, Gianluca Fiandaca¹, Hong Zhu Cai¹, Kim Engebretsen¹, Esben Auken¹

(1) Aarhus University, Department for Geoscience, HydroGeophysics Group.

**Extending accurate four-electrode spectral induced polarization measurements into the kHz range by quantifying the phase errors resulting from leakage currents**

Chen Wang¹, Dimitrios Ntarlagiannis¹ and Lee Slater¹

(1) Rutgers University-Newark, Department of Earth and Environmental Science.

**Three dimensional forward modelling of induced polarization in inhomogeneous media in time-domain electromagnetic soundings**

Marco A. Oliva Gutiérrez¹, Luis A. Gallardo¹ and Carlos Flores¹

(1) Dept. of Applied Geophysics, Ensenada Center for Scientific Research and Higher Education, Ensenada, Mexico.

**Field-scale comparison of frequency- and time-domain spectral induced polarization**

Pradip Kumar Maurya¹, Gianluca Fiandaca¹, Anders Vest Christiansen¹, Esben Auken¹

(1) HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus C, Denmark.
<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
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<tbody>
<tr>
<td>Comparison of TDIP and SIP measurements in the field scale</td>
<td>Tina Martin¹, Adrian Flores-Orozco², Thomas Guenther³, Torleif Dahlin¹</td>
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<tr>
<td>(1) Lund University, Engineering Geology,</td>
<td>(2) TU Wien, Department of Geodesy and Geoinformation,</td>
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<tr>
<td>(3) Leibniz Institute for Applied Geophysics, Geolectric and Electromagnetics.</td>
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<td>2D inversion of time domain induced polarization data: Investigation of the LIAS Epsilon black shales near Bramsche/Germany</td>
<td>J. Hauser¹, P. Yogeshwar¹, B. Tezkan¹</td>
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<tr>
<td>(1) Institute of Geophysics and Meteorology, University of Cologne, Germany.</td>
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<tr>
<td>Induction-free acquisition range in spectral time- and frequency-domain induced polarization at field scale</td>
<td>Gianluca Fiandaca</td>
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<td>Aarhus University, Department for Geoscience, HydroGeophysics Group.</td>
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<td>Examining the relaxation time distribution determined from time-domain induced polarization method</td>
<td>Deqiang Mao¹, André Revili², Bin Liu¹</td>
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<td>(1) School of Civil Engineering, Shandong University, Jinan, China, (2) Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France, (3) Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan, China.</td>
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<td>First application of the newly developed 3D Cole Cole inversion algorithm on the time domain IP data from Krauthausen/Germany</td>
<td>Hannah Langenbach¹ and Bülent Tezkan¹</td>
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<td>(1) Institute of Geophysics and Meteorology, University of Cologne, Germany.</td>
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<td>Automated Detection of IP Effects in AEM Data Using Deep Neural Networks</td>
<td>Dave Marchant¹, Justin Granek¹, Mike McMillan¹, Eldad Haber²</td>
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<td>(1) Computational Geoscience Inc, (2) University of British Columbia, Department of Earth, Ocean and Atmospheric Sciences.</td>
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<td>Inclusion of time-domain induced polarization data resolves wellknown resistivity-thickness equivalences</td>
<td>Line Meldgaard Madsen¹, Gianluca Fiandaca¹, Anders Vest Christiansen³, Esben Auken¹</td>
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<td>SIP simultaneous inversion method giving geological connection among multi-frequency data</td>
<td>Bitnarae Kim¹, Myung Jin Nam¹, Jeong-Sul Son³</td>
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<td>Assessing the potential of spectral induced polarization to detect in situ changes in iron reduction</td>
<td>C. Rosier¹, Gamal Abdel Aal², A. Price³, S. Sharma³, E. Atekwana¹,²,³,⁴</td>
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<td>Towards an effective characterization of root electrical properties: a spectroscopic approach</td>
<td>Solomon Ehosioke¹,², Sarah Garré³, Thomas Kremer¹, Sathyanarayan Rao³, Andreas Kemna⁴, Johan Alexander Huisman⁵, Eggon Zimmermann⁶, Mathieu Javaux⁵,⁶, and Frédéric Nguyen¹</td>
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<td>The effect of interactions between dissolved organic matter and organic contaminant on the electrical properties of soil</td>
<td>Gal Zakai¹, Nimrod Schwartz¹</td>
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<td>Pauline Kessouri¹, Omer Katzir¹, Matteo Camporese², Giorgio Cassiani³, Anna Botto², Mario Putti⁴, Alex Furman¹</td>
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<td>Gianfranco Morelli¹, Vusal Jalilov Eldar², Douglas LaBrecque³, Mikayil Naghiyev⁴, Fuad Huseynov⁴</td>
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<td>Thue Bording¹, Gianluca Fiandaca¹, Esben Auken¹, Anders Vest Christiansen¹</td>
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<td>Monitoring of in-situ remediation of chlorinated solvents contamination with the use of the Direct Current resistivity and time-domain Induced Polarization method</td>
<td>Aristeidis Nivorlis¹, Torleif Dahlin¹, Matteo Rossi¹</td>
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## FIELD APPLICATIONS: FRI 10/5  
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<td>(1) Geophysics Research Group, Department of Geodesy and Geoinformation, Technische Universität Wien, (2) Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, (3) Geological Survey of Austria, Department of Geophysics, (4) Geomorphological Systems and Risk Research, Department of Geography and Regional Research, University of Vienna.</td>
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<td>Waterborne spectral induced polarization imaging to investigate stream- aquifer exchange</td>
<td>Philipp Hoehn¹, Adrián Flores Orozco², Thilo Hofmann¹</td>
<td>(1) University of Vienna, Department of Environmental Geosciences Vienna, (2) TU-Wien, Department of Geodesy and Geoinformation.</td>
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<td>(1) TU-Wien, Geophysics Division, Department of Geodesy and Geoinformation, (2) TU-Braunschweig, Institute for Geophysics and extraterrestrial Physics.</td>
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Roundtable Breakout Sessions - Questions

Questions for roundtable “Petrophysics”

What are new tools or methods to better characterize pore spaces? Which new evolving techniques should we involve in our portfolios (for solids and/or unconsolidated materials) and why? (Maybe digital rock physics and machine learning?) How can we make sure the measurements procedures are consistent, given that different researchers using different experimental apparatus? Can we build a benchmark test to verify the data repeatability? What petrophysical relationships are universal? If none, how can we wisely choose the appropriate relationship for different applications? During the round-table discussion, we hope to generate a list of the petrophysical relationships that have been established and another list of these relationships that need more intensive research.

What are the challenges for the joint interpretation of multiple datasets (geophysical, chemicals, geological, microbial, etc) in the perspective of petrophysical relations? What measured petrophysical parameters can we provide for join inversion of multiple geophysical data and how certain are they? How can we promote and strengthen the cooperation between experimental and inversion related working groups within and beyond our IP community?

Questions for roundtable “Data processing and inversion”

1) How to get unbiased, quantitative inversion results from time-domain IP data, easily comparable with laboratory and modelling results? For example taking into account the current waveform, but also in terms of model parameterization.

2) Spectral inversion of time-domain and frequency-domain data or integral chargeability/single frequency? What are the available spectral inversion approaches? What are the most efficient approaches in 3D?

3) EM induction and capacitive coupling in time-domain and frequency-domain IP data: how to identify them and how to deal with them? Examples of approaches: data rejection, data calibration or full EM modeling.

4) What are the challenges for the joint interpretation of multiple datasets (geophysical, chemical, geological, microbial, etc) in the perspective of data inversion?

Questions for roundtable “Biogeophysics”

We will address 3 main scientific questions for some of the major hot topics in Biogeophysics, such as: (i) Soil biogeochemical transformations and organic pollutants; (ii) Biofilms detection, with emphasis on the role of EET (Extracellular Electron Transfer); (iii) Organic matter and peatlands; (iv) Root detection; (v) Microbial-induced calcite precipitation (MICP)

1) What is missing to link the biogeochemical property to the IP signal and what are the steps needed to solve it?

2) What are the modeling challenges left to build a physical based model explaining the polarization mechanisms? What (if any) established markers of microbial activity can be linked with IP? Does the IP response from biogeophysical mechanisms fit into existing polarization theory?

3) Are lab measurements useful to establish petrophysical relations at the field scale? Are we observing the same biogeochemical mechanisms?

4) What are the challenges for the joint interpretation of multiple datasets (geophysical, chemicals, geological, microbial, etc) in the perspective of biogeophysical studies?

Questions for roundtable “IP Modeling”

1) Empirical vs mechanistic models: How can empirical models provide parameters to assist mechanistic models?

2) How can numerical modeling approaches be used to better understand the relative contributions of different IP mechanisms?

3) Development of a general modeling framework: How to incorporate field scale heterogeneity into models and the contributions of different mechanisms and their interactions?

4) What are the challenges for the joint interpretation of multiple datasets (geophysical, chemicals, geological, microbial, etc) in the perspective of modeling? How can mechanistic models jointly incorporate parameters from these multiple datasets?

Questions for roundtable “Field Applications”

1) Is the IP (time- or frequency-domain) a suitable method for industrial applications? Which applications at the field scale offer a clear advantage of the IP method over the common ERT? What are the limitations for quantitative interpretation of IP imaging results?

2) Is it possible to provide clear guidelines on the application of IP measurements (time and frequency-domain) for new users? In this regard, can such guidelines provide conclusive information about measuring protocols, cables lay-outs, and acquisition parameters for both time-domain and frequency-domain? What are the advantages and drawbacks of time- and frequency-domain measurements? Are there clear needs regarding instrumentation?

3) How to deal with EM coupling in IP data (inductive and capacitive coupling and cross-talking between the cables)?

4) What are the challenges of joint interpretation of multiple datasets (geophysical, chemicals, geological, microbial, etc) for field studies?
Organizing Committee

Lee Slater

Lee Slater is the Henry Rutgers Professor of Geophysics at Rutgers University Newark. He was on the organizing committee of the first International Workshop of Induced Polarization held in Bonn, Germany, in 2009. He is delighted to see the 5th workshop being hosted at Rutgers University.

Judy Robinson

Judy Robinson is a computational scientist at Pacific Northwest National Laboratory. Her research focuses primarily on using electrical resistivity for field-based applications of contaminant migration and remediation monitoring. Her recent focus has been on coupling flow and transport modeling with geophysical modeling to determine the feasibility and risk associated with conducting large field-scale studies. Her work also focuses on laboratory scale SIP measurements on low permeability mudstones to better understand pore scale and hydrogeologic properties.

Gianluca Fiandaca

Gianluca Fiandaca is associate professor in hydrogeophysics - electric and electromagnetic methods at Aarhus University (Denmark). He obtained a PhD in applied geophysics from University of Palermo (Italy). His main research interests are data acquisition, processing and inversion in electric and electromagnetic methods, with emphasis on Induced Polarization.

Deqiang Mao

Deqiang Mao is Professor in the School of Civil Engineering at Shandong University, China. He has a PhD degree in Hydrogeology from the University of Arizona and post-doc research experiences in Geophysics in Colorado School of Mines. His major interest is developing state-of-art inversion algorithms to interpret hydrogeophysical data, and applying hydraulic tomography test, electrical resistivity survey, induced polarization measurement and self-potential survey to solve problems in subsurface hydrology.

Dimitrios Ntarlagiannis

Dimitrios Ntarlagiannis is an associate research professor at Rutgers University Newark. His interests focus on the use of electrical methods, particularly spectral induced polarization, for understanding chemical and biological processes in the Earth. He has also been actively involved in the development of laboratory and borehole induced polarization instrumentation.

Kristina Keating

Kristina Keating is an associate professor in the Department of Earth and Environmental Sciences at Rutgers University Newark in near-surface geophysics. Her research in near-surface geophysics primarily focuses on using laboratory and field based nuclear magnetic resonance (NMR) measurements to understand processes occurring in the top 100 m's of Earth's surface. Recently, she has become interested in coupling NMR measurements with SIP measurements to reduce uncertainty associated with a single measurement and improve our ability to map subsurface properties, e.g. permeability.

Adrián Flores-Orozco

Adrián Flores Orozco is currently the head of the Geophysics Research Division at the TU-Vienna (Austria). He obtained his PhD in Geophysics from the University of Bonn (Germany). His main area of research is the understanding of biogeochemical processes in the subsurface and their associated geophysical signatures.

Pauline Kessouri

Dr. Pauline Kessouri is a research associate at the Department of Civil and Environmental Engineering at the Technion (Haifa, Israel). Her research links applied geophysics, petrophysics and biogeochemistry to understand the physical, chemical and biological evolution of soils and rocks through their electromagnetic (EM) signatures. She currently works on the IP signature of hydrocarbon contaminated soils.

Technical Committee

Gianluca Fiandaca

Gianluca Fiandaca is associate professor in hydrogeophysics - electric and electromagnetic methods at Aarhus University (Denmark). He obtained a PhD in applied geophysics from University of Palermo (Italy). His main research interests are data acquisition, processing and inversion in electric and electromagnetic methods, with emphasis on Induced Polarization.

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Technical Committee

Sabine Kruschwitz
Sabine Kruschwitz is Professor at the Civil Engineering Institute of the Technical University Berlin since 04/2016. She obtained her PhD in Geophysics from Technical University Berlin in 2007. Her main interests are SIP for characterizing pore structures of consolidated (building) materials, petrophysics, material characterization with non-destructive methods, multi-methodical approaches, NMR.

Andréa Ustra
Andréa Ustra is a postdoctoral associate, member of Paleomagnetism Laboratory (USPmag) at University of São Paulo. She has a PhD degree in Geophysics from University of São Paulo. Her main interest is the development of interpretation methodologies for Biogeophysics and Environmental Magnetism studies.

Edmundo Placencia
Edmundo Placencia is a postdoctoral research associate at PNNL. He obtained his doctoral degree at Aalto University (Finland) in applied geophysics. His main current research is focused on the induced polarization signatures of Hanford sediments for environmental purposes at laboratory scale.

Yuxin Wu
Dr. Yuxin Wu is a Scientist at the Lawrence Berkeley National Laboratory. His research focuses on the application of geophysical methods to energy and environment topics. His current research topics include (1) hydro- and bio-geophysical monitoring of subsurface hydro-biogeochemical processes (2) geophysical monitoring of fracture and flow related to energy production and waste storage; (3) enhanced fracture imaging using geophysical contrasting agents; and (4) the development of novel imaging approaches for plant root and root-soil interactions.

Chi Zhang
Chi Zhang is an Assistant Professor in the Department of Geology at The University of Kansas (KU) since 2015. Prior to KU, Chi was a postdoctoral scholar at Idaho National Laboratory, Colorado School of Mines, and Rutgers University from 2011 – 2014. Dr. Zhang received her Ph.D. from Rutgers University. At KU, Chi’s research group investigates the tightly coupled physical, chemical, and biological processes that govern the behavior of geologic media and their constituent fluids using electrical geophysical methods and nuclear magnetic resonance.
Invited talk 1:

Petrophysics of / for SIP

Matthias Halisch, Leibniz Institute for Applied Geophysics (LIAG), Dept. 5 – Petrophysics & Borehole Geophysics

Dr. Matthias Halisch got his diploma degree in Geophysics from the Clausthal University of Technology (Clausthal, Germany) in 2006. In 2007 he started as a well logging scientist at the Leibniz Institute for Applied Geophysics (LIAG, Dept. 4 - Geothermics and Geohydraulics, Hannover, Germany) and was in charge for all deep scientific well logging operations for geothermal energy exploration. In 2009, LIAG has been re-organized and he moved to the new Dept. 5 – Petrophysics and Borehole Geophysics, working as a Petrophysicist. In 2012 he finished his PhD thesis at the Technische Universität Berlin (Berlin, Germany) entitled “Application and Assessment of the Lattice Boltzmann Method for µ-CT based Fluid Flow Modeling in Porous Rocks”. Since 2013, he is working as a Senior Scientist and is in charge for the Petrophysics and Imaging Laboratory of LIAG’s Dept. 5. His special research interest covers µ-CT imaging, digital rock physics and digital image analysis, spectral induced polarization and capillary pressure measurements.

Invited talk 2:

Strategies for 3D inversion of IP data

Douglas W. Oldenburg, University of British Columbia, Earth, Ocean, and Atmospheric Sciences

Dr. Douglas W. Oldenburg is a professor of Geophysics and director of the Geophysical Inversion Facility (GIF). His research career has focused upon the development of inversion methodologies and their application to solving applied problem in a variety of fields. Motivated to make geophysics more accessible and engaging, he has contributed to co-lead efforts for developing open source resources for students, researches and practitioners, that increase the use and usefulness of geophysics.

Invited talk 3:

Electrical interactions between biofilms and surfaces

Sarah M. Glaven, Naval Research Laboratory, Washington, DC

Dr. Sarah Glaven is a Research Biologist at the Naval Research Laboratory in Washington, DC, where she leads research programs on understanding microbial extracellular electron transfer and microbial communities that carry out this metabolic strategy. She currently serves as the President of the International Society for Microbial Electrochemistry and Technology (ISMET).

Invited talk 4:

IP Modelling

Matthias Bücker, TU Braunschweig, Institute for Geophysics and extraterrestrial Physics

Matthias Bücker received a B.Sc. (2008) and a M.Sc. (2011) in physics both from TU Braunschweig (TUBS), Germany, and a Ph.D. (2018) in geophysics from the University of Bonn, Germany. He has worked as research assistant at the UB and the TU-Wien, Austria, as geophysical engineer at the CFE in Mexico, and is currently working as research assistant at the TUBS. His research interest includes geoelectrical and electromagnetic methods, and in particular pore-scale modelling of the induced-polarization phenomenon.

Invited talk 5:

Field Applications of Time-Domain Induced Polarisation

Torleif Dahlin, Lund University, Engineering Geology

Torleif Dahlin completed a M.Sc. in Civil Engineering at Lund University in 1984, specialising in water and geo-resources engineering, and continued with a doctorate degree in 1993 at Engineering Geology in Lund where he is now professor. His primary research interest is geoelectrical imaging and monitoring for engineering and environmental applications, including DC resistivity and time-domain induced polarisation (DCIP). A prototype data acquisition system developed during the doctorate studies was later commercialised as the ABEM Lund Imaging System. He has pioneered and lead development of methodology and instruments for DCIP tomography. He has been teaching engineering geology, hydrogeology, field investigation methodology and applied geophysics for universities and industry, and supervised master and doctorate level students. Research activities include industry and international cooperation, including field work with focus on electrical and EM methods in Scandinavia, Cape Verde Islands, eastern and southern Africa, Central America, South America and the Arctic.
PETROPHYSICS INVITED TALK: MATTHIAS HALISCH
[Leibniz Institute of Applied Geophysics, Germany]

Petrophysics of / for SIP

Matthias Halisch¹, Andreas Weller², Sabine Kruschwitz³, Zeyu Zhang⁴, Raphael Dlugosch⁵
1 Leibniz Institute for Applied Geophysics (LIAG), Dept.5 – Petrophysics & Borehole Geophysics, matthias.halisch@leibniz-liag.de
2 Clausthal University of Technology, Institute of Geophysics, andreas.weller@tu-clausthal.de
3 Bundesanstalt für Materialforschung und –prüfung (BAM), sabine.kruschwitz@bam.de
4 Southwest Petroleum University, School of Geoscience and Technology, zeyuzhangchina@163.com
5 Leibniz Institute for Applied Geophysics (LIAG), Dept.5 – Petrophysics & Borehole Geophysics, raphael.dlugosch@leibniz-liag.de

Spectral Induced Polarization (SIP) measurements are used in many different ways to characterize natural rocks and soils. Main foci of interest are the enhanced characterization of the causes of polarization effects in sedimentary rocks, the interactions between the matrix-fluid-system and within the electrical double layer as well as the correlation with classical petrophysical parameters (e.g. porosity, permeability, etc.). Consequently, a large variety of polarization models, either grain based or pore based, have been developed over the past years. All in common, specific pore scale geometrical features are addressed such as specific surface area, pore and pore throat distributions, pore lengths, and tortuosity, to name few. Nevertheless, for all of these investigations, knowledge of the sample material is essential in order to create reliable and validated models as well as to interpret and to assess the data most completely. Unfortunately, many of the methods used to get access to the inner structure of rocks are destructive (e.g. mercury injection porosimetry, thin sectioning, etc.) and the valuable sample is lost. In addition, data is either of volume integrated nature or only available for the two-dimensional case and the usage of equal, so called sister cores does not necessarily lead to reliable results. In this manuscript, the authors would like to showcase the possibilities and limitations of classical petrophysical methods and state of the art imaging and image analysis for the combination with induced polarization measurements.

DATAPROCESSING/ INVERSION INVITED TALK: DOUGLAS OLDENBURG
[University of British Columbia, Canada]

Strategies for 3D inversion of IP data

Douglas W. Oldenburg¹, Seogi Kang²
1 University of British Columbia, Earth, Ocean, and Atmospheric Sciences, doug@eos.ubc.ca
2 University of British Columbia, Earth, Ocean, and Atmospheric Sciences, skang@eos.ubc.ca

Enhancements in instrumentation (e.g. higher sampling rate and distributed arrays) and signal processing provide us with large amounts of high quality IP data. Our goal is to invert those data to recover 3D information about the complex conductivity, \( \sigma(x, y, z; \omega) \). The inverse problem is non-unique and computationally challenging. Numerous factors need to be considered when designing a final algorithm: (a) type of source (grounded or inductive); (b) waveform (harmonic or tailored time domain signal); (c) choice of parameterization of the complex conductivity (e.g. Cole-Cole, stretched exponential, constant phase angle etc). Also do we want to find parameters all at once, or find them sequentially (conductivity first then other IP parameters)? We provide an overview of possible routes, but focus on the sequential inversion option and time-domain IP data. We investigate traditional grounded IP surveys as well inductive source IP obtained with modern airborne EM systems.

We formulate a multi-stage process where early-time data are used to extract information about the background conductivity and we use this conductivity to remove the contaminating EM induction effects from late time data. This enhances the time range over which IP signals are available and thereby makes them more useful in detection and discrimination problems. The decontaminated multiple-time channel IP data can be simultaneously inverted to find the IP parameters. Both grounded and inductive sources can be treated this way but details differ. We apply the technique to an airborne time-domain EM survey over a kimberlite deposit in Canada.
**BIOGEOPHYSICS INVITED TALK:**

**SARAH GLAVEN**

[Naval Research Laboratory, USA]

**Electrical interactions between biofilms and surfaces**

Lina J. Bird¹, Elizabeth Onderko¹, Daniel Phillips², Brian J. Eddie¹, Matthew Yates³, Anthony P. Malanoski³, Leonard M. Tender³ and Sarah M. Glaven³

1 National Research Council 500 5th St. NW, Washington, DC 20001
2 American Society for Engineering Education, 1818 N St. NW, Washington, DC 20036
3 Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375, sarah.glaven@nrl.navy.mil

The iron-reducing bacteria Geobacter and Shewanella, as well as acetogenic, methanogenic, and iron-oxidizing bacteria have all been shown to perform extracellular electron transfer (EET) when grown as biofilms on the surface of electrodes. However, our understanding of the microbial electrical wiring that enables this non-natural connection is remarkably limited. Moreover, some bioelectrochemical systems (BES) perform optimally when a mixed microbial community is present, further complicating our ability to track the flow of electrons and associated electron carriers. Understanding electrode EET processes could result in leap-ahead technological advancements in applications including microbial electrosynthesis, bioremediation, and microbial bioelectronics. In this talk I will describe how our group has used metagenomics, metaproteomics, and metatranscriptomics to study an electroautotrophic microbial community (Biocathode-MCL) presumed to “eat” electricity and use the energy gained to fix CO₂. This work led to the discovery of a previously uncharacterized electroautotroph, which we have proposed as the candidate genus and species “Candidatus Tenderia electrophaga”. By using a BES as a cultivation platform, we have been able to study the electron transfer properties and redox mediators of Biocathode MCL using electrochemistry, microscopy, and microbiology. Measurements of “Ca. Tenderia electrophaga” at open circuit potential indicate that capacitive charge from the electrode can sustain cell viability and possibly support cell growth. In addition to bioelectrochemical technologies, these results have implications for biogeochemical cycling and corrosion.

**MODELING INVITED TALK:**

**MATTHIAS BUCKER**

[Universität Bonn, Germany]

**IP modelling**

Matthias Bücker¹

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IP modelling aims at understanding experimentally observed relations between electrochemical and microscopic geometrical properties and the macroscopic electrical response of heterogeneous media. The underlying processes are known to be related to the transport of charge carriers through the porous medium and their accumulation and relaxation at internal boundaries. Depending on the particular properties of the medium, the measured electrical response is the result of an interplay of five main polarization mechanisms: (1) Maxwell-Wagner polarization, electrode polarization, (3) polarization of the Stern layer and (4) polarization of the diffuse layer of the electrical double layer of charged surfaces, and (5) membrane polarization. Mechanistic models, i.e., models based on first principles, describe all five mechanisms based on the Poisson-Nernst-Planck (PNP) equations for charge transport and the characteristic responses are the result of particular geometries and boundary conditions. Ideally, solving these mathematical problems does not only provide a model suited to explain measured data but provides insight into the underlying physical and electrochemical processes. In this contribution, I review long-known classical solutions and recent developments by integrating them into a general physical picture of polarization, which is needed to describe all relevant polarization mechanisms and predict their relative importance. I will round this overview up by some own recent findings, which are mostly based on numerical solutions of the PNP system, and identify some key questions, which urge to be resolved in order to provide the basis for the interpretation of the fast-growing number and variety of new lab- and field-scale experimental findings.
Data acquisition equipment for direct current electrical resistivity tomography (ERT) today commonly supports time-domain induced polarisation (TDIP) since a couple of decades (DCIP tomography). Since the last decade equipment is available that can deliver TDIP data of good quality at sites with favourable field conditions, where as skilled operators and special field procedures are re quired at other sites. Data are typically inverted as integral chargeability in time intervals from tens of milliseconds to few seconds. The inverted models have proved to be very useful in a number of applications, including mineral prospection, delineation of waste deposits, characterisation of contaminated sites, engineering geological characterisation, etc.. In some cases the ERT part alone provides relatively unambiguous results, whereas for e.g. waste deposits and disseminated ores the resistivity parameter provides inconclusive results the addition of chargeability is essential for an interpretation of the site characteristics. Inverted chargeability based on integral chargeability de pends on the instrument type, transmitted pulse and in tegration interval. The results are thus generally not comp arable between surveys unless identical instruments are used and minute attention is given to the instrument setup. Recent developments, including optimised input filter design and current transmission waveform, and signal processing has opened possibilities for extracting quantitative spectral IP (SIP) information from DCIP data acquired in a time efficient way. This opens potential for developing approaches for routine application of SIP in e.g. groundwater resources and vulnerability mapping, in a more quantitative way than has been possible to date. Graphite is an abundant Earth mineral with unique electrical, thermal, and mechanical properties, and has found many uses in a variety of industries, including energy geoscience. The electrical property of graphite is a key parameter of interest. A few studies on the complex electrical properties of graphite mixed with geological material exist, yet the results have been limited and sometimes controversial. We present here a set of laboratory experiments with the intent to better understand the impact of pore fluid chem istry on the complex conductivity (or resistivity) of graph ite particles. Micrometer scale graphite power samples of different sizes and concentrations were used in the ex periments and the main fluid chemical parameters tested were focused on fluid conductivity and pH. While the sig nificant polarization response of graphite observed during the experiment was consistent with previous studies, we found that fluid chemistry appears to have an effect on both the polarization magnitude and the relaxation time constant in a way different from what has been present ed latterly in the literature. The effect of fluid conductivity on the electrical signal of graphite was found to be much stronger than pH. Different from previous tests with fairly large graphite grains, our experiments using micrometer scale particles showed strong alignment effects when concentrations were increased during the tests. These resulted in the changes of the shapes of the IP spectrum as well as the overall magnitude of the signals. Debye decomposition modeling was used to better understand the signal characteristics under changing pore fluid geochemistry.
Permeability estimation directly from logging-while-drilling Induced Polarization data

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In this study we present the prediction of permeability from time-domain spectral induced polarization (IP) data, measured in boreholes on undisturbed formations using the El-log drilling technique, in which resistivity and chargeability decays values are recorded while drilling. We collected El-log data and hydraulic properties on unconsolidated Quaternary and Miocene deposits in boreholes at three locations at a field site in Denmark, characterized by different electrical water conductivity and chemistry. The high vertical resolution of the El-log technique matches the lithological variability at the site, minimizing ambiguity in the interpretation originating from resolution issues. Full IP voltage decay data were inverted in 1D using re-parametrized version of Cole-Cole model. The permeability values were computed directly from IP model parameters, using a laboratory-derived empirical relationship presented in a recent study for saturated unconsolidated sediments, without any further calibration. A very good correlation, within one order of magnitude, was found between the IP-derived permeability estimates and those derived using grain size analyses and slug-tests, with similar depth-trends and permeability contrasts. Furthermore, the effect of water conductivity on the IP-derived permeability estimations was found negligible in comparison to the permeability uncertainties estimated from the inversion and the laboratory-derived empirical relationship.

The Geo-Electrical Signature of Heavy Metals

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Soil pollution in general, and by heavy metals in particular, is a major threat to human health, and especially in rapidly developing regions, such as China. Fast, accurate and low-cost measurement of heavy metal contamination is of high desire. Since heavy metals in normal conditions have high affinity to be sorbed, Spectral induced polarization (SIP) may be an alternative to the tedious sampling techniques typically used. This is as SIP is sensitive to the chemical composition of both the absorbed ions on the soil minerals and the pore fluid and to the interface between the two.

The goal of this research is to examine the electrical signature of soil contaminated by heavy metals and of the pollution transport and remediation processes, in a non-tomographic fashion. Specifically, we are looking at the SIP response of various heavy metals in several settings: 1) at equilibrium state in batch experiments; 2) following the progress of a pollution front along a soil column through flow experiments and 3) monitoring the extraction of the contaminant by a chelating agent. Using the results, we develop and calibrate a multi-Cole-Cole model to separate the electrochemical and the interfacial components of the polarization. Last, we compare our results to the electrical signature of contaminated soil from southern China.
Evidence of sorption processes observed with IP in dual domain porosity rock cores during injection/flush solute tracer experiments

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Adsortion and desorption of solute to the mineral surface of porous geologic media is dependent on the pore volume normalized surface area (Spor) of a sample, likely dominated by less-mobile porosity domains and therefore coupled to mass transfer. Recent studies have developed an electrical model for dual-domain mass transfer (DDMT) that allows resistivity measurements to be used to characterize mass transfer between porosity domains. This model is based on analyzing the non-linear relationship of bulk (σb) and fluid (σf) conductivity during tracer experiments, measured with electrical geophysical methods and fluid conductivity (EC) probes respectively. The approach allows the porosity domain ratio (∝) and the mass-transfer rate coefficient (α) to be estimated. These experiments have thus far not utilized induced polarization (IP), which has been shown to be sensitive to sorption processes.

Using IP and EC measurements, collected during a tracer experiment on rock cores, we were able to simultaneously characterize changes in the surface conductivity (σsurf), the electrolytic conductivity (σel), and the fluid conductivity (σf). Experiment results indicate that sorption processes lag behind mass transfer between mobile and immobile domains during changes in fluid conductivity. Our results indicate (1) that IP measurements collected during mass transfer can provide information on coupled transport and sorption and (2) that sorption results in a hysteresis loop in the IP data that suggests variable rate transfer coefficients and available surface area.

Spectral induced polarization response of calcite precipitation

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Induced calcite precipitation is used in a range of geotechnical applications to improve the mechanical properties of porous media. It has been shown that spectral induced polarization (SIP) allows to monitor calcite precipitation, although results were partly inconsistent. Therefore, this study aims to investigate how the SIP response of calcite depends on solute composition, since this may explain the differences in previous studies. SIP measurements were made on a column filled with sand while calcite precipitation was created by injecting Na$_2$CO$_3$ and CaCl$_2$ solutions through two different ports. The experiment consisted of five phases. In phase I, calcite precipitation was generated for a period of 12 days. This resulted in a well-defined calcite precipitation front, which was associated with an increase in the imaginary conductivity. In phase II, the injected solutions were increasingly diluted. This resulted in a clear decrease in imaginary conductivity. In phase III, the injection of the two solutions was stopped. Nevertheless, calcite precipitation continued and solute concentrations in the mixing zone decreased. As in phase II, this led to a decrease in the imaginary conductivity. In phase IV, the injection rate of the Na$_2$CO$_3$ solution was reduced to shift the mixing zone, which also decreased the imaginary conductivity. Finally, the column was flushed with a solution in equilibrium with calcite in phase V, which led to a very small SIP signal. These results imply that calcite only generates a SIP response when it is in contact with solution which is strongly oversaturated with respect to calcite.
Tracking secondary mineralization in hydrothermal systems with complex electrical measurements: laboratory observations on natural core samples from the Krafla volcano (Iceland)

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We explore the added value of Induced Polarization measurements (IP) for detecting the presence of smectite and pyrite in altered volcanic rocks. Tracking these minerals is of interest for geothermal exploration, as they are witnesses of active hydrothermal circulations. The electrical impedance of 88 natural cores samples from four boreholes at the Krafla high-temperature geothermal field, containing various amount of smectite (0 to 30 vol. %), pyrite (0 to 7 vol. %) and iron-oxides (0 to 2 vol.%), is measured between 100 mHz and 1 MHz at fluid conductivities ranging from 0.02 to 11 S/m. In samples with little amount of pyrite and iron-oxides, we compare the quadrature and surface conductivity over the whole range of fluid conductivities. We do observe a proportionality relationship but not strong enough to allow a reliable estimate of the surface conductivity from the quadrature conductivity at any salinity. In samples with pyrite or iron-oxides, the impedance spectra are fitted with a Cole-Cole model. The asymptotic DC conductivity, mainly affected by the smectite content and the fluid conductivity, affects the relaxation time and chargeability. For a given DC conductivity, the relaxation time can be used as an indicator of metallic grain size. Since iron-oxides are systematically associated to resistive crystalline matrices, we suggest a new approach to distinguish pyrite and estimate its grain size in hydrothermal systems, based on the comparison of chargeability, relaxation time and DC conductivity.

Complex resistivity measurements of artificial samples containing various minerals

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The induced polarization (IP) method has been used in many cases of exploration for nonferrous metal ore deposits, such as volcanogenic massive sulfide, porphyry copper, and iron-oxide-hosted copper gold deposits. IP was used because sulfide minerals such as pyrite and chalcopyrite have the IP phenomenon. However, it was known that some oxide minerals, such as magnetite, and clay minerals, such as smectite and sericite, also had the IP phenomenon. The spectral IP (SIP) method, which measures complex resistivity at many frequencies, is one of the methods used to identify various minerals. Therefore, the complex resistivity of artificial samples containing ore mineral particles (pyrite, chalcopyrite, magnetite), metal concentrates (copper, zinc, lead), and clay powders (smectite, sericite) were measured. Then, analysis of the complex resistivity data was attempted using Cole-Cole models. The results showed that as the content of minerals increased, a larger SIP signal was observed. However, the SIP signatures of the artificial samples had different frequency characteristics depending on the various contained minerals. The sulfide minerals had quite large SIP signals compared with clay minerals, and the frequency characteristics of the SIP signature between pyrite and magnetite clearly differed, while the SIP signals for the metal concentrates were relatively small. The size of the minerals affected the frequency characteristics of the SIP signatures. These results indicate that the complex resistivity data obtained using the SIP method could be applied to discriminate between types of subsurface minerals.
Spectral induced polarization of nanoporous media

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Nanoporous materials such as clays and concretes are relevant for the storage of oil, geothermal energy, CO₂, and nuclear waste in deep geological formations because of their high specific surface area and resulting low permeability that confer them remarkable confining properties. Their mineralogical nature and petrophysical properties can be in-situ identified and quantified using non-invasive geoelectrical methods such as spectral induced polarization (SIP). Despite their observed high chargeability, the SIP response of these nanoporous materials should also be better understood. In this work, SIP laboratory measurements on montmorillonite suspensions and concrete, and their interpretation using grain or pore (membrane) polarization models, are presented. We show that it is possible to explain their SIP response using the electrochemical properties of the double layer at the mineral surface and the Poisson-Nernst-Planck equation, to get the surface electrical and petrophysical properties such as grain or pore size distribution. Nevertheless, more work should still be done to better describe the pore-scale SIP response and a more general and upscaling approach is necessary to use mechanistic models to better interpret field-scale SIP measurements.

Monitoring and assessing effects of carbonate rock dissolution on spectral induced polarization data

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Investigating complex electrical properties of natural rocks and soils by using spectral induced polarization (SIP) is of high research interest for all pore space and boundary surface specific processes and properties between the matrix and the pore fluid. The deduction of hydraulic and pore space related structural properties, as well as the correlation of SIP-data with core and special core analysis data is recently in the focus of research. In the first stage of this project, a case study has been conducted that investigates the complex electrical conductivity of carbonate samples using spectral induced polarization. Within the next phase, a specifically designed experimental setup for temperature controlled acidification of carbonate rock samples has been constructed. The setup features a special core holder for saturating the samples with a retarded (i.e. temperature activated) formic acid, which is connected to adjacent fluid reservoirs by high-precision piston pumps. Fluid type can be easily switched for flushing/cleaning of the material after acidification without removing the sample from the core holder. The core analysis program includes a multi-methodical and interdisciplinary approach, combining petrophysical, mineralogical and geochemical techniques. Before and after each core acidification step, porosity, specific surface area, nuclear magnetic resonance (NMR) T2 distributions as well as complex conductivity spectra as well as data from 2-D and 3-D imaging techniques have been obtained. The authors would like to present the experimental setup, the workflow as well as first results of the SIP and petrophysical investigations on selected carbonate samples.
Can we effectively characterize pore geometric properties from spectral induced polarization (SIP) measurements on low porosity mudstones?

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Spectral induced polarization (SIP) is extensively used in laboratory studies to characterize pore scale and hydrogeologic properties of sandstones. In these low permeability materials, geometric length scales such as the pore volume normalized surface area and the characteristic length from mercury porosimetry are related to SIP length scales defined from imaginary conductivity ($\sigma''$) and relaxation time. Less often have similar studies been undertaken in tighter formations with permeabilities in the micro-Darcy range. We conducted a laboratory study on cores obtained from an unweathered laminated and massive mudstone formation. Acquisition of physical properties (e.g. pore size distribution, permeability) and SIP data proved challenging for these low porosity samples. In several samples the specific surface area was unrealistically low, inconsistent with low porosity and permeability values; the character of intrusion curves using mercury porosimetry were atypical compared to sandstone samples. SIP phase spectra did not show a peak associated with a dominant relaxation frequency, preventing a characteristic time constant from being defined. Furthermore, $\sigma''$ measured at a single frequency did not reliably predict permeability from empirical relationships established for sandstones. No improvements were found when the mean relaxation time and normalized chargeability, obtained from Debye Decomposition, were used for permeability predictions. The small pore sizes in mudstones likely limits the ability of SIP to sense the length scales controlling fluid flow when the conventional frequency range is used. Recent correction procedures which extend the measurable frequency range to 20 kHz might permit smaller length scales to be distinguished in future studies.

Evaluation of IP parameters for permeability prediction of sandstones

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A variety of approaches to permeability ($k$) prediction from induced polarization (IP) parameters have been reported. Most of the methods enable a reliable $k$ estimation for limited sets of sandstone samples. We present an approach that is based on the capillary bundle model where an effective hydraulic radius ($r_{eff}$) is related to the resistivity formation factor ($F$) and $k$. The effective hydraulic radius ($r_{eff}$) is a length scale controlling permeability that we compared against IP-derived geophysical length scales. We utilized a comprehensive database consisting of complex conductivity measurements on 119 well characterized sandstones to determine different parameters describing the polarization process. Supporting data includes pore size distribution from mercury porosimetry, surface area from gas adsorption, porosity and $F$. The dominant pore radius determined from the maximum increment in mercury intrusion is well correlated with $r_{eff}$, resulting in good $k$ estimates using this length scale. Reasonable estimates are also obtained when using the pore volume normalized surface area ($S_{por}$) as the length scale. In contrast, geophysical length scales related to the polarization strength and relaxation time distribution are weakly correlated with $r_{eff}$, leading to poor $k$ estimates. We identify an alternative geophysical length scale $r F \sigma'' \propto 1/(F \sigma')$. The correlation of this geophysical length scale with $r_{eff}$ and the resulting $k$ estimation are both similar to that obtained when $2/S_{por}$ is used as the length scale. The resulting permeability equation predicts $k \propto F^{-3}$, consistent with recent empirical models determined for large databases that imply a strong dependence of $k$ on $F$ in sandstones.
**Enhanced characterization of pore systems by simultaneous use of SIP, µ-CT and NMR**

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Other than commonly assumed the relaxation times observed in the electrical low-frequency range (1 mHz – 40 kHz) of natural porous media like sandstones and tuff stones cannot be directly related to the dominant (modal) pore throat sizes, measured (e.g.) with mercury intrusion porosimetry (MIP). Working with a great variety of sandstones from very different origins and featuring great variations in textural and chemical compositions as well as in geometrical pore space properties, we observed that particularly samples with narrow pore throats were characterized by long (low-frequency) relaxations. These, however, can (following the current theories) be rather explained by long “characteristic length scales” in these media or low diffusion coefficients along the electrical double layer. However, there is no straightforward way (or single approved method) of getting reliable numbers for properties such as the lengths of pore throats, the diameter and length of the wide pores and their respective distributions. Consequently we follow a multi-methodical approach and combine the benefits of MIP, micro-computed tomography (µ-CT) and nuclear magnetic resonance (NMR) to achieve much deeper insight due to the different resolutions and sensitivities to either pore constrictions (throats) or wide pores. This helps us to understand, whether the observed electrical relaxation phenomena actually depend on geometric length scales or rather on other properties such as chemical composition, clay content, clay type or cation exchange capacity. Our poster showcases selected results of a systematic study on texturally and petrophysically very different sandstones.

**SIP signals of artificial rocks**

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Artificial rocks have been designed and synthesized to study the how lithification factors such as mineralogy, grain size and shape, and compacting pressure alter important rock properties such as porosity and permeability. The artificial rocks also allow benchmark tests to help us better understand or develop petrophysical relationships for different rock types. In this laboratory study, we aimed to investigate the dependance of SIP signals on sample lithology and porosity using artificial rocks. We tested 33 synthesized rocks which represent three main sandstone groups: quartz sandstone (quartz content is 96%, feldspar is 2%, and clay is 2%), feldspar sandstone (quartz content is 60%, feldspar is 32%, and clay is 8%), and high clay content sandstone (quartz content is 60%, feldspar is 8%, and clay is 32%). Each group has 11 samples with varied porosity from ~2% to ~33%. The porosity and permeability of all the synthesized samples were measured using helium gas adsorption. We coupled SIP with NMR measurements for all the samples. The imaginary conductivity spectra showed peak values associated with characteristic frequencies for all the quartz sandstone and some feldspar sandstones, but did not reveal peak values in the clay sandstones. The recent developed joint inversion of NMR T2 relaxation time and SIP imaginary conductivity data might allow the accurate description of pore size distribution in these samples in future studies. Our study provides the baseline for studying the impact of lithology on SIP responses.
Extending accurate four-electrode spectral induced polarization measurements into the kHz range by quantifying the phase errors resulting from leakage currents

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Spectral induced polarization (SIP) data collected at frequencies higher than 100 Hz are contaminated by errors that obscure the true sample electrical properties. In this study, we developed and tested a correction method for phase data up to 20 kHz collected with an SIP instrument that measures differential voltages on input channels. Measured phase ($\phi$m) was modeled as the sum of the true sample phase ($\phi$s) and an error term $-\omega CinZx$, where $\omega$ is the angular frequency, Cin is the instrument input capacitance and Zx is an impedance function determined by 1) the electrode impedance of the two potential electrodes, 2) the impedance between the negative potential electrode and negative current electrode, and 3) the resistance of the reference resistor used for current measurement. We tested the model using electric circuits, NaCl solutions and three NaCl saturated unconsolidated samples (sand, sand-clay and sand-pyrite mixtures). For each sample, $\phi$m was collected under five different Zx conditions. At each frequency, a strong linear relationship between $\phi$m ($\phi$m > 1 mrad) and Zx was observed (R$^2$>0.99 for all the samples). $\phi$s was solved as the intercept while Cin was obtained as 8.8±0.5 pF from the slope. In the case of Zx ranging from 12 to 150 kΩ across all measurements, phase error ($\omega CinZx$) ranges from 0.7 to 8 mrad at 1 kHz, from 6 to 83 mrad at 10 kHz and from 13 to 166 mrad at 20 kHz. This shows that most of the information contained within $\phi$m at these frequencies represents errors rather than the response from the sample. The corrected $\phi$s for the circuit and NaCl solution experiments shows excellent agreement with the calculated phase response (errors <0.1 mrad at 1 kHz, <1 mrad at 10 kHz and <2 mrad at 20 kHz). For unconsolidated samples, removal of errors results in phase spectra more consistent with expected polarization mechanisms, e.g. expected location of phase peaks from small pyrite and clay particles at high frequencies. These phase peaks could not be identified in the uncorrected data.

PRESENTED ABSTRACTS
DATA PROCESSING/ INVERSION

3D modelling of time-domain full-decay induced polarization

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We present an algorithm for modelling of 3D resistivity and time-domain induced polarization (TDIP) data. The finite-element forward algorithm is based on unstructured tetrahedral meshes and therefore handles both topography and arbitrary shaped boundaries. The unstructured mesh allows for local refinement, and together with modelling of the secondary field for singularity removal around the sources (the secondary potential approach), this ensures high accuracy. Sources may be placed on the boundaries or arbitrarily in the subsurface thus allowing for both surface and cross-borehole applications. The forward response is computed in frequency-domain as the complex resistivity, $\rho$(ω), and parallelised over the frequencies (ω). The response is hereafter transformed into time-domain using the Hankel Transform, taking into account the current waveform and eventual system filters for a quantitative IP modelling of either full-decay IP responses or integral chargeability. The IP phenomenon can be parameterised using any IP parameterization, among which the Constant Phase Angle (CPA) model and the Cole-Cole model (classic resistivity and conductivity forms) may be used in either the classic form or in the newly introduced re-parameterizations which improve resolution, e.g. the Maximum Phase Angle and the Maximum Imaginary Conductivity Cole-Cole re-parameterizations.
Three dimensional forward modelling of induced polarization in inhomogeneous media in time-domain electromagnetic soundings

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We have been working on developing a new direct time-domain model to incorporate induced polarization phenomena in transient electromagnetics for a 3D model. Our methodology allows to estimating several values of electric permittivity of a time-lapse by introducing the dielectric function on Maxwell's equations to obtain a diffusive model. The vector diffusion equation has been modified to incorporate convolutions terms those contain the polarization parameters of the medium by a weighted sum of exponential functions.

In order to avoid the convolutions terms that arise to considering dispersive media in the solution of the proposed model, we have employed the concept of memory variables to transform convolution integral between polarization velocity and the tie derivative of a magnetic field in a set of first-order ordinary differential equations in tie whereupon the full-tie history is no longer needed.

Finally, we're working to test our formulation by implementing a computational finite difference scheme to analyze the behavior of magnetic field in the presence of induced polarization first, on a homogeneous and then in an inhomogeneous media.

Field-scale comparison of frequency- and time- domain spectral induced polarization

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In this study, we present a comparison of the time-domain (TD) and frequency-domain (FD) spectral induced polarization (IP) methods at field scale. We acquired spectral IP data (both TD and FD) on three surface profiles with identical electrode setups. In addition, TDIP data were collected in two boreholes using the El-Log drilling technique.

We adopted similar approach for processing and inverting TD and FD spectral IP data. The IP voltage decays and complex impedance spectra were inspected quadrupole by quadrupole for outliers. In the inversion, the apparent resistivity values and the full IP decays (in TD) or the full complex impedance spectra (in FD) for all quadrupoles were inverted simultaneously in 2D using a re-parametrized version of the Cole-Cole model. The comparisons reveal that TD and FD results are comparable not only qualitatively, but also quantitatively. In particular, comparable spectral IP parameters were retrieved for both sites with both measurement approaches, with relaxation times between 10⁻¹⁻ and 1 s, suggesting a spectral coverage at least up to 100 Hz for both TD and FD measurements.

However, for the employed data acquisition procedures and instrumentations, the TD measurements had an advantage in terms of acquisition speed and usable spectral acquisition range compared to the FD measurements. We conclude that the TD method, as the FD method, is a suitable tool to recover spectral IP information in the field, provided that the measurement procedures are planned accordingly and the subsurface IP response is in the spectral range covered by the measurements.
Comparison of TDIP and SIP measurements in the field scale

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The frequency-dependence of the induced polarization effect (IP), in the so-called spectral IP (SIP), has been demonstrated to be strongly correlated to important parameters in hydrogeological and environmental investigations. This has prompted the development of measuring instruments and modelling techniques towards the collection of laboratory and field data with enhanced accuracy and at a broader frequency bandwidth. Although SIP datasets were traditionally collected in the frequency-domain (FDIP), recent developments have demonstrated the capabilities to solve for the frequency-dependence of the complex conductivity through the inversion of measurements collected in the time-domain (TDIP).

In recent years comparison of both methods has been conducted in a few studies; however, mostly related to the imaging results and not the actual signal-strength and sources of error affecting TDIP and FDIP. In particular, the EM-coupling is a limiting factor for the application of petrophysical models (observed in laboratory) in field in both FDIP and TDIP. Hence, the aim of our investigations is comparison of the resulting frequency-dependence parameter at a broad frequency range resolved through FDIP and TDIP. Furthermore, a detailed discussion on the different sources of error effecting the IP data readings. To provide as fair comparison as practically possible for TDIP and FDIP measurements, we conducted measurements with different instruments. For FDIP we deployed measurements with the Radic-Research SIP 256C and MPT DAS-1; whereas ABEM Terrameter LS and IRIS Sy- scal Switch Pro were used for TDIP. We present our results regarding the analysis of data errors, performed through statistical analysis of the misfit between normal and reciprocals. Analyses of signal strength are evaluated through comparison of data collected at different electrode separation. Additionally, we present a comparison of the inversion results as obtained by different algorithms.

2D inversion of time domain induced polarization data: Investigation of the LIAS Epsilon black shales near Bramsche/Germany

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Induced polarization measurements in the time domain (TDIP) were carried out in the northern part of Rulle, near Bramsche/Osnabrück. The study area is well known for a lateral IP anomaly caused by a thermally metamorphosed layer of Jurassic clays which marks the Lias/ Dogger boundary. The IP measurements were realized with the ABEM Terrameter LS device using the full waveform data acquisition mode. In total, six parallel profiles with a length of 202.5 m and an electrode spacing of 2.5 m were investigated. A gradient array with a separate cable spread was chosen to eliminate electromagnetic disturbances by capacitive coupling of the potential and current electrodes. Additionally, measurements were carried out on a reference profile where DCR, RMT and SP data are available. The scalar measurement of the apparent chargeability as well as the full waveform data in the form of processed IP transients are analyzed. For the inversion of the apparent chargeability a recently developed 2D inversion algorithm of the University of Cologne is used. A distinct IP anomaly with a lateral extent of 100 m in a depth of 20 m could be derived as a result of the 2D inversion calculations. A good fitting between data and model response was obtained. The reconstructed anomaly has a chargeability of 200 mV/V and a resistivity of 1 Ωm. The anomaly is associated with the LIAS Dogger formation.
Induction-free acquisition range in spectral time- and frequency-domain induced polarization at field scale

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Spectral induced polarization imaging is a valuable method in near-surface hydrogeological and environmental investigations. Many field applications have been presented during the last 20 years, both in frequency and time domain. Despite the electromagnetic inductive effects always occurring in induced polarization measurements, they are usually disregarded in the spectral inversion of the data. Consequently, in order to invert only data with negligible inductive effects, the frequency and time ranges of both frequency-domain and time-domain data have often to be restricted, limiting the higher invertible frequency and the smaller invertible time.

Consequently, this study investigates the induction-free acquisition range of frequency-domain and time-domain acquisitions, computing the electromagnetic inductive effects of homogeneous media, with theoretical and field examples. It is found that it is much easier to get induction-free early times than induction-free high frequencies. For nested arrays it is difficult to measure a significant spectral range in the frequency domain, but also with the dipole-dipole array the inductive effects are not negligible with the typical settings used in field applications. Furthermore, it is shown that a wider acquisition range means an increased spectral content and parameter resolution, for both frequency-domain and time-domain data, and that the time-domain approach has an advantage in terms of resolution of the spectral parameters when the induction-free acquisition range is used. Moreover, the differences in spectral content between electromagnetic induction and dielectric-like polarization are discussed, showing that an induction of the same magnitude of the dielectric-like polarization in frequency domain is negligible for time-domain gradient array.

First application of the newly developed 3D Cole Cole inversion algorithm on the time domain IP data from Krauthausen/Germany

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A newly developed 3D inversion algorithm for time-domain Induced Polarisation (IP) data is presented. The efficiency of the algorithm is demonstrated using synthetic data and field data measured in Krauthausen near Jülich. The calculated 3D time-domain IP model is based on the time-dependence of the resistivity. The IP model considers chargeability, relaxation time and frequency exponent. The electrical field at each time point is inverted independently using a DC inversion code. In the applied algorithm, an approximate solution is utilized where the forward problem is solved directly in the time-domain. Thereby, every time point is calculated independently from and parallel to each other. First, the last time point of all transients is inverted resulting in a resistivity model. The resulting model of the previous time point is used as a starting model for the inversion of all time points using different type of regularizations. Afterwards, the estimated time-dependent resistivity for each cell is independently fitted using a homogeneous IP model. 9 parallel time-domain IP profiles were measured in Krauthausen using the Terrameter LS by ABEM. A gradient array with an electrode spacing of 2.5 m was used to measure transients of up to 6 s. These transients were processed and used as an input of the inversion algorithm. The inversion of the field data with the newly developed 3D algorithm results in a satisfying 3D IP model for the survey area. A two layer resistivity model is estimated, where the second layer is partly interrupted.
Automated Detection of IP Effects in AEM Data Using Deep Neural Networks

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The identification of induced polarization (IP) effects in airborne electromagnetic (AEM) data is important for many reasons. If the data is interpreted or inverted using techniques that neglect the influence of IP, the resulting conductivity model will be significantly distorted. In addition, the presence of IP itself may be of utmost importance to an exploration program and can help detect economic mineralization.

Typically, IP effects are identified manually. As the volume of data collected increases, this task becomes impossible. Manual identification depends on the knowledge and experience of the geophysicist. Strong sign reversals may be obvious to everyone, but smaller, subtle responses may be interpreted differently. Automated IP identification is currently available in the market, but the majority of these techniques rely on fitting the decays to a low dimensional model that includes chargeability. This approach has drawbacks and can erroneously label 3D conductivity effects as chargeable material. It can also fail to identify subtle IP effects.

Deep learning techniques are becoming commonplace in many applications, and are ideal for extracting information from structured data. We apply cutting edge deep learning algorithms to the identification of IP effects in AEM data. The viability of any machine learning model depends on the quality and volume of training data used to tune the model. We utilize three dimensional simulation techniques to produce a large volume of data simulated from random models. After training a deep net on this database, the viability of the technique is demonstrated on additional synthetic and field data.

Inclusion of time-domain induced polarization data resolves well-known resistivity-thickness equivalences

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The principle of equivalence is known to cause non-uniqueness in interpretations of direct current (DC) resistivity data. The low/high-resistivity equivalences arise when a thin geologic layer with a relative low/high resistivity is embedded in a relative high/low-resistivity background formation. Due to strong correlations between the resistivity and the thickness of the imbedded layer, the equivalences make it impossible to resolve the layer. We show that the equivalence problem is significantly reduced when the DC data is combined with full-decay time-domain induced polarization (TDIP) measurements. We applied a 1D Markov Chain Monte Carlo (MCMC) algorithm to invert synthetic DC data of models with low and high-resistivity equivalences. The MCMC method makes it possible to study the space of equivalent models, which all have an acceptable fit to the observed data, and furthermore to make a full uncertainty analysis of the model parameters. By including a contrast in chargeability into the models, modelled in terms of spectral Cole-Cole IP parameters, and inverting DC and IP data in combination, we find that the addition of IP data largely resolves the equivalences. We also present a field example of DC and IP data measured on a sand formation with an embedded clay layer known from borehole drillings. The inversion results show that the DC data alone do not resolve the clay layer due to equivalence, but by adding the IP data to the inversion, the layer is well resolved.
SIP simultaneous inversion method giving geological connection among multi-frequency data

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Spectral induced polarization (SIP) method measuring complex resistivity of medium with a range of alternative current source frequencies (especially relatively low frequencies, \(10^{-3}\)–4 kHz) has been primarily applied to mineral exploration and recently to environmental field. SIP data can be interpreted as amplitude and phase depending on current source frequencies or SIP parameters which have geological meaning. SIP data are conventionally interpreted using single-frequency inversion method although multi-frequency SIP data is measured as performing survey. Therefore, multi-frequency SIP inversion method has advantage to give relationship among frequency data set, whereas single-frequency SIP inversion method doesn’t. In this study, we developed simultaneous SIP inversion method with a frequency constraint, giving geological connection for multi-frequency SIP data. Frequency constraint assumes multi-frequency SIP data set are measured in the same medium and the background doesn’t change. Also, we gave weights to control degree of free at the same positioned inversion block. If the weight is low in an inversion block, the block is considered anomalous area with high possibility. Meanwhile, if the block is estimated free SIP anomalous area, the weight is close to 1. We will compare and analyze our new SIP inversion algorithm and a conventional inversion method with a three-dimensional synthetic model.

PRESENTED ABSTRACTS

BIOGEOPHYSICS

Assessing the potential of spectral induced polarization to detect in situ changes in iron reduction

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Spectral Induced Polarization (SIP), provides an effective measure of in situ biofilm growth. However, interactions of biotic processes affecting the magnitude of SIP response are not clearly understood. To address this knowledge gap, we assessed the influence of Shewanella oneidensis (MR1) cell density, biofilm production and iron reduction on SIP response. Ninety days of laboratory measurements were collected on columns packed with iron-coated or iron-free sands and amended with artificial ground water/acetate to stimulate biofilm and microbial iron reduction. In under 30 days of incubation of iron-coated columns, phase and imaginary conductivity increased 4-fold as concentrations of reduced iron increased from 0-50 mM. Late stage (>75 days) SIP measurements of incubated columns revealed that phase and imaginary conductivity decreased as the concentration of reduced iron descended below 2.0 mM. In contrast, we observed a moderate increase in phase and imaginary conductivity (~30%) within iron-free columns due to increases in S. oneidensis cells (CFU 1.5 x 10¹¹) and biofilm production (7.0 mg ml⁻¹). SEM analysis confirmed the presence of biofilm and cells within both iron-coated and iron-free columns. We hypothesize that microbial metabolic byproducts are a potential mechanism explaining large phase shifts observed in previous studies (~50 mrrads) rather than the conductivity of cells or biofilm. Our findings support that the ratio of cells to biofilm production moderately influences phase and imaginary conductivity and largest phase and imaginary conductivity resulted from microbial metabolism (i.e. iron reduction) and potentially biofilm trapping of conductive materials (i.e. cations).
Towards an effective characterization of root electrical properties: a spectroscopic approach

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The application of geophysical methods to root investigation has been increasing in recent years because of the limitations associated with the use of traditional methods (root excavation, monoliths, minirhizotron etc.). Geophysical methods address these limitations by offering high resolution and non-invasive approaches to root investigation due to their ability to infer properties and structures of the subsurface, at various spatial scales. Recent studies (Weigand and Kemna 2017; Mary et al. 2017) have reported a low frequency polarization of root systems and have shown that SIP/EIT (spectral induced polarization/electrical impedance tomography) holds a promising future for root system characterization. Despite these significant improvements, there is still a knowledge gap regarding the electrical response of fine roots at the segment scale which is essential to enable us to account for the effect of roots in the estimation of soil moisture content of rooted soils. In this study, we use SIP to characterize the electrical properties of single root segments of various plants. A sample holder was designed and tested on ideal resistors and root segments, and was found to be suitable for assessing the electrical properties of root segments of Maize and Brachypodium in the laboratory. The resistivity of maize and brachypodium roots at 8 days averaged between 9-14 Ωm, while their polarization averaged 430 mrad and 700 mrad, respectively at high frequency (10 KHz). The resistivity of these roots is much lower than that of saturated sand (110-225 Ωm), dry sand (400-1000 Ωm) and till (17-28 Ωm) as described by Ernst and Kirsch (2006), also they polarized more strongly than geological materials (0.2 - 20 mrad) (Binley et al. 2005; Boerner et al. 1996). These results suggest that fine roots can be differentiated from soils because they show lower resistivity and stronger polarization.

The effect of interactions between dissolved organic matter and organic contaminant on the electrical properties of soil

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Mapping the contaminants distribution in soil systems is essential for an efficient remediation. Geoelectrical methods are well established, noninvasive and cost-efficient approach to map the soil subsurface. Numerous studies examined the electrical signature of organic contaminants (OC) in soil. Recently the electrical signature of dissolved organic matter (DOM) was detected and reported. Due to the strong interactions between OC and soil DOM, it is expected that soil DOM will influence the electrical properties of OC soil. Yet the combined effect of DOM and OC on the electrical properties of soil was not assessed.

In this work, we attempt to quantify the relationship between clean soil, DOM and OC using the spectral induced polarization (SIP) method.

Natural DOM from red sandy loam was removed by combustion and samples were prepared as follows: (1) soil (control), (2) soil with commercial humus-derived DOM, (3) soil with OC and (4) soil with OC and DOM. The electrical conductivity and ions composition were normalized for all samples. The soils were packed to columns, saturated and SIP recorded 24 h after packing.

Preliminary results show a decrease in polarization by the presence of DOM. Further decrease was observed after CO treatment. DOM with CO demonstrated a moderate polarization decrease. Overall, our results demonstrate the ability of the SIP method to monitor OC and DOM in soils. In future examination we will use a variety of DOM and OC types and amounts that will provide a better understanding of their effect on soil electrical properties.
Electrical signature of roots in hydroponic solution and in soil

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Root systems influence vast number of processes in the biosphere and hence it is important to monitor them. Such monitoring is complicated by the absence of a direct access to the root. Application of the SIP method to this purpose is based on the polarizability of the root’s cell membrane. The objective of this study is to establish relations between root properties (e.g. biomass) and SIP signature.

We measured the SIP signature of a month-old plant in a column filled with hydroponic solution. During the experiment we cut part of its root, thereby we obtained the relation between the root biomass and the SIP signature. In a second experiment, we planted the wheat in a column with a sandy loam soil and measured the SIP for 13 days after planting.

In the hydroponic solution, the polarization positively correlated with the root biomass. The relaxation frequency increased from ~2.7 Hz to ~10 Hz in accordance to the increase in the average root diameter. In contrast, in all soil measurements, the low-frequency polarization, was lower when the root was present. This is a non-intuitive finding, as the root contributes to the polarization. One possible explanation is that organic carbon secreted by the roots changes the physicochemical properties of the mineral surface and decreases the soil polarization.

These preliminary results demonstrate the sensitivity of the SIP method to the presence of roots. Ultimately, this study will lead to the development of a non-invasive method to monitor roots in the subsurface.

Subsurface imaging of water electrical conductivity, hydraulic permeability and lithology at contaminated sites by induced polarization

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At contaminated sites, knowledge about geology and hydraulic properties of the subsurface and extent of the contamination is needed for assessing the risk and for designing potential site remediation. For this purpose, we have developed a new approach for characterizing contaminated sites through time-domain spectral induced polarization. The new approach is based on: 1) spectral inversion of the IP data, which disentangles the electrolytic bulk conductivity from the surface conductivity for delineating the contamination plume; 2) estimation of hydraulic permeability directly from the inversion parameters; 3) use of the geophysical results for supporting the geological modeling and planning of drilling campaigns.

The new approach was tested on a contaminated site located at Grindsted stream (Denmark). The geophysical results were compared against an extensive set of hydrologic and geological information. We found that, on average, the IP- derived and measured permeability values agreed within one order of magnitude, except for those close to boundaries between lithological layers (e.g. between sand and clay), where mismatches occurred due to the lack of vertical resolution in the geophysical imaging. The geophysical models were actively used for supporting the geological modeling and the imaging of hydraulic permeability and water conductivity allowed for a better discrimination of the clay/lignite lithology from the pore water conductivity. Furthermore, high water electrical conductivity values were imaged in a deep confined aquifer present at the site, and validated with post-survey drillings. The contamination in the deep aquifer was not expected.
IP lab measurements on E. coli-sand-mixtures

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Aim of the MIRACHL project is the characterisation and monitoring of in-situ remediation of chlorinated hydrocarbon contamination using an interdisciplinary approach. Therefore, geophysical methods, as e.g. DCIP are used to investigate the remediation process.

To interpret these geophysical field IP data, lab investigations with different kinds of bacteria are necessary to assess the sensitivity of the methods for these specific applications. A first experiment was conducted with E. coli bacteria. After some preliminary investigation with only a suspension of live cells, the bacteria were merged together with a rich source of nutrients (Luria-Bertani broth - LB) and mixed in different flasks with a certain amount of sterilised Ottawa sand. These bacteria-sand-mixtures were continuously shaken under specific conditions (30°C, 80 RPM). At definite times (days) the mixtures were harvested and packed in a 4-point sample holder to measure SIP, TDIP and SP under laboratory conditions. The same procedure was repeated with only the media-sand-mixture to exclude any influences from just the nutrient.

The first measurements show a slightly increase in phase and a decrease in resistivity after a couple of days but also a dying of the bacteria after more than a week and therefore a decrease in phase again. The resistivity in general is very low (between 3-10 Ωm) due to the high conductive LB-media (NaCl). So far, the self-potential measurements show no clear tendency and the TDIP data needs to be further processed.

Laboratory SIP signature associated with iron and manganese oxide dissolution caused by anaerobic degradation

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Degradation of organic chemicals in natural soils under different saturation conditions is a process highly relevant to the protection of groundwater resources. Available iron and manganese oxides are used as electron acceptors for anaerobic degradation and are reduced to the dissolved form of metallic cations in pore water. A few studies have shown an impact of iron reduction on spectral induced polarisation signature, often associated with bacterial growth. Our objective is to study the impact of iron and manganese oxide dissolution, caused by degradation of an organic compound, on spectral induced polarisation signatures. Twenty-six vertical columns (30cm high, inner diameter 4.6cm) were filled with a sand rich in oxides with a static water table in the middle. In half of the columns, a 2cm high contaminated layer was installed just above the water table. Every three days over a period of one month, spectral induced polarisation (twenty-two frequencies between 5mHz and 45kHz) data were collected on six columns: three contaminated replicas and three control replicas. Chemical analysis was done on twenty columns assigned for destructive water sampling, ten contaminated columns and ten control. Preliminary analysis of the results showed an increase of the real conductivity associated with the metallic ions release, independent of frequency. We also observed an evolution of the phase angle associated with manganese release at frequencies below 1Hz. Although the water samples showed iron oxide dissolution, this could not be directly correlated to the SIP data.
IP responses of jet fuel contaminated soils – a laboratory investigation

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At the NATO base of Decimomannu in Sardinia (Italy), three jet-fuel leaks have been identified since 2007. The estimated total amount of jet-fuel spilled in the ground is 50 000 L. A series of 62 wells have been drilled around the contaminated area to get hydrological and geological information on the spread and the degradation of the contamination. A preliminary field geophysical study, including EM, ERT and TDIP data, has also been lead to understand better the extent and the degradation state of the hydrocarbons. In order to properly interpret the results, we decided to lead a laboratory study. The goal is to quantify the IP signature of (i) the natural uncontaminated materials, (ii) the non-aqueous free phase of the LNAPLs, (iii) the soluble fraction of some of the contamination ingredients and (iv) the bio-degradation by-products. Regarding the soluble fraction, a particular attention has been drawn to understand the role of the micro-emulsified contaminants, resulting from the bacterial activity, as we suspect they have a significant role in aquifer water contamination. These IP signatures are studied through a series of batch experimentations, where the amount of jet-fuel is increased by controlled steps and the degradation of the hydrocarbon over time is monitored. A column experiment is also used to study in detail the IP signature in the smear zone through oscillations of the water level and complementary measures including visual track of the LNAPLs, monitoring of the water content (TDR probes) and of the water and oil capillary pressure (tensiometers).

Spectral induced polarization of biochar in variably saturated soil

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Biochar is considered as a promising soil amendment, but an effective method to detect and characterize the spatial distribution and temporal dynamics of biochar in soil is still missing. The aim of this study is to investigate the ability of the SIP method for the non-invasive detection of biochar in unsaturated sandy media. The measurements were conducted using a joint MSO-SIP system that allows making SIP measurements during pressure drainage of a porous media. In particular, a pure sand and two sand-biochar mixtures with 1% and 2% mass percent of biochar were investigated. The measured SIP spectra as a function of saturation were interpreted by fitting a Cole-Cole model to the low-frequency part of the SIP measurements. In particular, a pure sand and two sand-biochar mixtures with 1% and 2% mass percent of biochar were investigated. The measured SIP spectra as a function of saturation were interpreted by fitting a Cole-Cole model to the low-frequency part of the SIP measurements. The porous nature of the biochar particles strongly affected the SIP response of the partially saturated sand-biochar mixtures. Due to the high residual water content of the biochar in a dry background, the relationship between $\sigma_0$ and water saturation was nonlinear in a log-log representation. This non-linear behaviour could adequately be explained with a dielectric mixing model that considered the drainage of the biochar particles. Both the measured phase and chargeability of the sand-biochar mixtures showed a complex dependence on water saturation. This was attributed to the decrease in polarization strength of the biochar particles with desaturation and the simultaneous increase in phase of the sand background. Overall, field SIP measurement are considered to be a promising tool for the characterisation and monitoring of biochar amendments to agricultural soils.
Integration of geophysical and geochemical approaches to improve the understanding of peatland degradation

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In degraded peatlands under oxic conditions, phenol oxidase can freely degrade phenolic compounds to produce conjugated quinones within the solid phase. These compounds are electrophilic and polar, and can alter the geophysical characteristics of the peat. Normalization of chargeability with resistivity is an approach that can be used to map out degraded peat/quinones to understanding the mechanisms associated with the ‘Enzymatic Latch’ hypothesis, which is thought to be significant in the decomposition of organic matter. Research is limited on this, especially on peatland sites under different types of degradation (drainage/overgrazing). We have found that degradation of peat results in the creation of polarizable material in the subsurface which can be measured by normalizing resistivity with time-domain induced polarization. As the phenolic compounds breakdown, quinones, which are characterized by a C=O double bond, are produced. The occurrence of these quinones, as well as the presence of phenolic compounds, can be assessed using FTIR. We propose that the polarizable material results from the production of these quinones, which are electrophilic and polar, and may provide an insight into the occurrence of the ‘Enzyme Latch’ hypothesis and a measure of degradation as a result of water table decline and oxygen influx. By comparing normalized chargeability with the organic composition, this relationship can be used to better understand peatland degradation and restoration.

Inferring microbial abundance and metabolic state from spectral induced polarization (SIP) signals

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Spectral induced polarization (SIP) has been successfully applied to measure microbial abundance in porous media, relying on the charged properties of microbial cell membranes. However, despite its proven potential, SIP’s integration as a geo-microbiological tool necessitates robust relationships between microbial abundance and imaginary conductivity responses. Furthermore, a detailed understanding of the transient nature of bacterial cell membrane surface charge (dependent on microbial metabolic state), which controls polarization time-scales needs to be further explored. We present combined results from two separate studies on monitoring growth of Shewanella oneidensis using SIP in fully saturated iron-coated and quartz sand under no-flow and periodic flow conditions, along with complementary biogeochemical measurements, fitted to a reactive transport model. Our results provide further support to the direct dependence between imaginary conductivity and cell density. A Cole-Cole relaxation analysis of SIP spectra highlights the direct control of microbial cells themselves on polarization dynamics. Using Cole-Cole derived relaxation time (τ), we showed the direct dependence of the surface charging properties of the cells to metabolic state. We coupled τ to concurrent estimates of cell size, to estimate an apparent Stern-layer diffusion coefficient for S. oneidensis, which validates existing modelled values for a variety of cell strains. Our coupled geophysical-biogeochemical analysis provides encouraging evidence of the possibility of extracting meaningful biogeochemical information from SIP responses, specifically microbial dynamics.
Spectral induced polarization as a monitoring tool for in-situ microbial induced calcite precipitation processes

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Rapid growth of population led to the need of urban expansion into lands with problematic soils. Microbial induced calcite precipitation (MICP) is a promising soil stabilization technique that can enhance the soil quality in an economically sustainable and environmentally friendly fashion. Although MICP has shown to be an effective soil stabilization method, it needs to be examined thoroughly.

The spectral induced polarization (SIP) is one promising method in monitoring MICP processes due to its sensitivity on microbial activities as well as calcite precipitation. Additionally, SIP is a cost effective and environmentally non-disruptive method that can offer autonomous and long-term monitoring abilities.

Previous laboratory tests showed the sensitivity of the SIP method on soil strengthening as a result of abiotic calcite precipitation. Furthermore, time-domain induced polarization (TDIP) was successfully able to delineate subsurface MICP changes in field. In this study, we performed daily SIP measurements at a field site undergoing MICP for 15 days. The MICP treatment was monitored with 2 parallel (1 m separation) surface SIP lines (23 m long, electrode spacing 1 m). Early results show SIP is sensitive in tracking MICP changes at different frequencies, temporally and spatially. SIP results are supported by other geophysical (TDIP and shear-wave velocity), geo-chemical and microbiological monitoring techniques. X-ray diffraction analysis on samples (artificial substrate cores) incubated inside treatment zone, also showed the production of calcite at subsurface.

SIP contribution to plant/soil interaction study: first results

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Climate change and land-use changes are significantly reshaping interactions among the vegetation and compartments of ecosystems. Understanding soil-vegetation interactions requires new monitoring approaches that can provide a high spatial and temporal resolution, and that can ideally be performed in a minimally invasive manner. Here, we focus on advancing SIP as a tool to measure in-situ soil properties at the field scale, supported by lab measurements performed to quantify relations between SIP and physico-chemical properties. We tested the method in a Bordeaux vineyard during the June 2018 growing season. We acquired one set of six SIP profiles with DAS-1 (MPT, LLC) in the frequency range of 0.1 mHz to 225 Hz, namely: five perpendicular profiles and 1 parallel to the grapevine rows, each with 25 cm electrode spacing. We also collected soil samples along the lines to perform laboratory experiments to measure the main physico-chemistry parameters. The vegetation health was described/estimated by observation. We determined that plant roots were more resistive than the surrounding soil. We also documented some relationships between soil-vegetation properties and SIP response, including soil grain size distribution, the shape of the root zones, and plant size/health. The study suggests that SIP holds potential for providing insights about soil-plant interactions.
Spectral induced polarization signatures of sediments in reducing environments

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Field-scale prediction of long-term redox reactivity in engineered reducing subsurface environments requires characterization of the spatial distribution and temporal evolution of the redox potential, which is challenging at field scale. In this work, we have investigated the relationships between the concentrations of reduced iron phases (absorbed FeII ions and iron sulfide) and the spectral induced polarization response during reduction and oxidation of aquifer sediments in column experiments. Measurements of the induced polarization response were collected as aquifer sediments treated with differing amounts of ferrous iron, iron sulfide, and Na-dithionite reduction. Contrasts up to one order of magnitude in both the in-phase and quadrature conductivity were observed during treatments relative to the untreated sediment, primarily in the case of Na-dithionite. The quadrature conductivity appears to follow a power law relationship with both reduced phases the adsorbed ads-FeII and iron sulfide precipitates. Either the shape or magnitude of spectral induced polarization spectra were controlled by the textural features and mineralogical composition (clay content) of sediments, causing significant differences in the measured responses among different sediments. This result suggests the potential of the induced polarization method for diagnosing temporal changes of redox processes during contamination treatments. However, limitations may exist in cases where the bulk conductivity is largely raised by the high ion concentration in each treatment.

Monitoring the transformation of iron oxide into iron sulphide with the method of spectral induced polarization

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Biogeochemical processes in wetlands are related to the availability of oxygen in the subsurface, leading to a separation into an oxic and an anoxic zone. Spatial variations between regimes of high and low oxygen content result in the transformation of iron compounds that are present naturally in the soil. The SIP method has demonstrated to be a suitable method to delineate in-situ biogeochemical processes, such as changes in the redox-status of soils or the accumulation of biominerals. However, the parameters underlying the IP response are still not fully understood. Hence, in this study, we investigate the changes in the SIP response during the transition from iron oxides into iron sulphides. A column filled with goethite grains was flushed with a sulphide solution (pH 10 – 11) for one month. Daily SIP measurements at frequencies between 5 mHz and 10 kHz yield detailed information about the temporal changes in the complex electrical conductivity caused by the reaction with goethite to form sulphides.

We evaluate the complex conductivity spectra with a Debye decomposition. Two parameters resulting from this approach are identified to exhibit a strong correlation with the amount of sulphide retained by the sample: the normalized chargeability mn, which can be considered as a measure for the magnitude of the polarization effect, and the mean relaxation time τmean. Both observations can be attributed to a progressing transformation of goethite into iron sulphide and thus to an increasing volume of polarizable material in the sample holder.
Bioelectrical impedance spectroscopy and ERT plant root-soil system characterization

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Roots play a key role in regulating interactions between soil and plants, an important biosphere process critical for soil development and health, global food security, carbon sequestration, and the cycling of critical elements. Their underground location has hindered studies of plant roots and the role they play in regulating plant-soil interactions. Technological limitations for root studies and the lack of an integrated approach capable of linking root development and adaptation with subsequent impact on plant health and productivity are major challenges. We explore the use of the electrical methods, e.g. SIP and ERT, for the investigation of plant-soil interaction, with a particular focus on signals of root and how this data can be used for root characterization. To better correlate geophysical signals with plant growth dynamics and above and below ground co-variability, we also include the use of hyperspectral measurements and traditional plant analysis techniques. We combine novel experimental methods at both lab and field scales with numerical simulations, and conduct controlled studies to explore the fundamental processes that control the dynamic growth of crop roots. Specifically, our efforts are focused on (1) developing novel geophysical approaches for non-invasive plant root and rhizosphere characterization; (2) correlating root developments with key canopy traits indicative of plant health and productivity; (3) developing numerical algorithms for novel geophysical root signal processing; (4) using multichannel SIP measurements to better characterize the contributions from plant stem, roots, and soil; (5) exploring how root development modifies rhizosphere physical, hydrological, and geochemical environments for adaptation and survival. Our preliminary results highlight the potential of using SIP and ERT methods to quantifying key rhizosphere traits and processes.

The Effect of Microbial Growth on the Spectral Induced Polarization Response in Hanford Vadose Zone Sediment in the presence of Autunite Mineral

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Uranium contamination of the subsurface remains a significant problem at the Department of Energy Hanford site. A series of column experiments were conducted on Hanford sediment saturated with simulated groundwater to study the effects of aqueous bicarbonate and microbial growth on the mobility of Uranium. Spectral induced polarization (SIP) measurements in the columns were conducted concurrently with pore water sampling in order to monitor changes occurring inside the sediment after the initiation of microbial growth induced by glucose injection. The microbial growth caused significant increases in the real component of the conductivity is the result of ion release into the pore fluid. In addition, an increase in the imaginary conductivity was observed at low frequencies (<10 Hz) which may be due to biotic processes. Due to the use of natural sediment, the SIP response is complex and difficult to understand. However, results across all columns with microbial growth are consistent. Pore water testing showed that microbial growth leads to sudden increases in uranium concentrations; however, microbes also eventually create reducing conditions in the sediment which transforms soluble U\textsuperscript{6+} to insoluble U\textsuperscript{4+}. Bicarbonate leads to significant increases in uranium concentrations likely due to the formation of mobile uranyl carbonate complexes. For the purposes of field scale remediation, microbial growth in an oxic environment should be avoided. However, within reducing conditions in the deep vadose zone and phreatic zone microbial growth seems unlikely to significantly increase uranium mobility.
PRESENTED ABSTRACTS

MODELING

The implication of a new SIP model on pore attributes characterization

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To better understand electrical polarization mechanisms in porous media, simulation of the complex conductivity has been long conducted and compared with experimental results to examine viable SIP models. The complexity of a highly heterogeneous pore system like carbonate may preclude the formulation of a precise SIP model with only electrochemical polarization. Previous research revealed the imaginary conductivity misfits between simulated and experimental data at intermediate frequencies occurs in fine sand, Berea sandstone, and carbonate samples while only electrical double layer (EDL) polarization and dielectric polarization were applied. Here we propose a new SIP model, which is composed of the EDL polarization, membrane polarization, and dielectric polarization. We consider the ion diffusivity change among the sequence of narrow pore throats and wide pore nodes which leads to membrane polarization as suggested in Marshall and Madden (1959). The membrane polarization model is based on the modified form proposed by Bücker and Hördt (2013) in terms of the length (L₁, L₂) and radii (r₁, r₂) for pore node and pore throat. We applied our new SIP model on carbonate samples. The ion mobility contrasts and the resulting imaginary conductivity peaks at intermediate frequencies were observed in all modelled samples and fit the experimental data. The modelling results also implied the importance of length ratio control by narrow and wide pores where high(L₂/L₁) leads to more significant membrane polarization in carbonate. This study demonstrates possible mixed polarization mechanism exists in carbonate rocks and it can aid better extraction of pore geometry information from SIP responses.

What’s wrong with Wong?
Evaluation of the strengths and weaknesses of the Wong model – an electrochemical model for the IP signature of metallic particles

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Metallic particles are some of the most abundant minerals on Earth and are detected in multiple environments such as mine tailings, oil reservoirs and hydrocarbon polluted soils. For all these applications, it would be very useful to quantify the presence of disseminated metallic grains in terms of location, concentration, size and mineral type. Wong (1979) developed a physics-based electrochemical model that is still used today. The IP response of conductive particles disseminated in an electrolyte is modelled from the geometrical and electrochemical properties of the media. In recent years, multiple authors have explored the model and discussed its interpretation in terms of polarization mechanisms and its limitations with respect to estimating properties of the metallic particles. We further investigate the Wong model using a new database to explore the role of the background porous medium itself in determining the IP signature of disseminated metallic particles. We find that the relaxation time is proportional to the square of the grain diameter for all the grain sizes investigated (between 0.125 to 2 mm). We prove that the diffusion coefficient used in the Wong model is dependent on the background porous medium, showing that the polarization is not only related to an internal metallic grain mechanism as suggested by certain recent papers. We also discuss the influence of the low frequency effect of the pyrite grains on the effective conductivity of the medium and the degree to which the properties of the metallic particles that can be reliably estimated using the Wong model.
Examining the relaxation time distribution determined from time-domain induced polarization method

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Time-domain induced polarization (TDIP) measures the secondary voltage decay after the shut-off of external electrical field and recently receives a considerable attention in hydrogeophysics and ore exploration. Relaxation time distribution (RTD) determined from TDIP carries valuable information about the pore size distribution. Cole-Cole model was adopted in the numerical analysis. With the measured apparent chargeability data, the proposed inversion algorithm works for non-metallic porous materials with small chargeability as well as materials with metallic particles characterized by relative large chargeability. For the first time, a sensitivity analysis was developed to analyze the information content of different charging durations employed in TDIP tests, i.e. early measurements of the decay curve from short charging durations are more informative about estimating small relaxation times and late measurements of long charging durations are more useful for estimating large relaxation times. Therefore, it is more robust to apply sequential TDIP tests (performed with different charging durations) to explore RTD. During inversion, a correct decay model should be at least less non-linear than the true model for recovering the true RTD, characterized with a larger Cole-Cole exponent than the true one. A wrong decay model could mislocate the peak relaxation time. Our analysis further shows that the charging duration in TDIP tests could be shorter than the true relaxation time to successfully locate the relaxation time peak only if the true decay model is chosen. Otherwise, charging durations require to be at least four times of the true relaxation time to find the relaxation time peak.

Estimation of bacteria concentration from Debye decomposition of SIP response from bacterial growth in porous media

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Spectral induced polarization (SIP) measurements have been used to monitor changes in bacterial biomass and growth stage in recent biogeophysical studies. Mechanistic models of SIP response from bacterial growth in porous media have demonstrated the sensitivity of quadrature conductivity to the evolution of bacterial concentration during different growth stages. Specifically, normalized chargeability \( m \), derived from these models by using low and high frequency limits of in-phase conductivity, is found to be directly proportional to bacteria concentration. In this work we evaluate the ability of normalized chargeability calculated from the Debye decomposition of SIP data to be used as a direct estimation of bacteria concentration. The applied Debye formulation determines a relaxation time distribution (RTD) and two frequency-independent parameters that modulate the complex conductivity spectra. These two parameters represent (1) the direct current contribution and (2) the conductivity range spanned by the low- and high- frequency limits, which expresses the normalized chargeability. We tested the procedure with dataset from two different experiments with bacterial grow in suspension or porous media. The first experiment used suspensions of Zymomonasmobilis, at four different concentrations (including the background) of cell suspensions alone and cell suspensions mixed with sand. The second experiment involved the growth of Desulfovibrio vulgaris in suspension and the data from three concentrations of biomass were tested using the proposed DD procedure. The DD procedure was able to fit the SIP data and the estimated chargeability is linearly correlated with bacteria concentration.
Different types of induced polarization: considerations about their mathematical modelling

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From the General Physics we know that there are several types of Induced Polarization (IP) effects, which affect electrical and electromagnetic data. Among them, the electro-osmosis, the membrane polarization and the Maxwell-Wagner effects. All effects are based on different physical phenomena. Traditional use of the Cole-Cole formula cannot satisfy the requirements of exploration geophysics especially for membrane IP effect.

Electro-osmosis (EO) effect occurs in all kinds of rocks/sediments. The amount of double electric layer plays the major role. This phenomenon is linear and described by Helmholtz-Smoluchowski equation. Decay constant $\tau$ of electro-osmosis process normally assumes values in the range $10^{-6}$-$10^{-2}$ s and is mostly observed on time domain electromagnetic data.

Membrane Polarization (MP) effect is based on constrictivity of pores. When electrical current flows through rocks/sediments containing channels and pores with different size, an excess/loss of ions accumulates at the boundaries: membrane IP effect is based on different concentrations in the solution at ends of pore. Salinity distribution agrees with the diffusion process: this problem had been solved using an homogeneous diffusion equation with specified initial and boundary conditions. MP process is non-linear: electrical resistivity, decay constant and chargeability depend on applied current.

Maxwell-Wagner (MW) effect consists on isolated pores filled by fluid or ore grains. For MW effect the same one-dimensional diffusion equation can be used but boundary conditions will be different. The MW effect is linear. Decay constant is in the range of $10^{-6}$-$10^{-2}$ s especially if the polarization process occurs in conductive ore grains. However short time for charging and relaxation processes limits application of numerical methods for calculation, so for analyzing MW effect the isolated pore can be considered as a classical capacitor. Some examples from field and laboratory data are presented and discussed.

PRESENTED ABSTRACTS

FIELD APPLICATIONS

New perspectives brought by distributed systems for IP development

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Induced Polarization measurements for environmental purposes has developed a lot these past years with the aim of providing more information on the subsoil. For example, different research works have shown the dependence of IP to pore/grain size, surface area, chemistry, saturation, temperature, multiple fluid phases and permeability. While well measured in the laboratory, these tiny signals are difficultly measured on the field.

The recent development of distributed systems dedicated to Time Domain IP measurements could accelerate this development thanks to:
- The recording of the voltage and current full waveform allowing advanced re-processing by researcher and potentially the easier use of Cole-Cole type models to describe IP response.
- The separation between transmitter and receivers reducing EM coupling probability
- The possibility to perform IP acquisitions in inaccessible or hardly accessible areas thanks to heavy cable less systems.

These perspectives will be illustrated through different field cases study.
Two completely different questions are the motivation to carry out impedance measurements at high frequencies on field scale:

1. Lab SIP measurements show that the characteristics of pore space also control the resistivity above 1 kHz.
2. Impedance measurements on high-resistivity permafrost grounds: The frequency-dependent permittivity can be used, for example, to determine the soil temperature distribution.

With our new measuring instrument CHAMELEON II it is now possible to carry out impedance measurements up to 230 kHz also on field scale. Galvanic as well as capacitive electrodes can be used. Two transmitters (100 watt each) allow current dipole widths of up to 50 m. Impedance measurements of >10 Hz are more or less systematically distorted by inductive and capacitive couplings between the cables, as well as between these cables and the soil. Inductive coupling can, in principle, be taken into account with suitable inversion programs, while capacitive couplings must be reduced by a suitable measuring instrument design. To measure voltage, impedance converters are placed at each electrode. By doing this, coupling which typically appears with unshielded potential cables can be greatly reduced. In order to also reduce capacitive coupling of the current cable with the soil, a transmitter is placed at each of the two current electrodes. In addition, the current is measured at both of the electrodes. This set-up for the first time allows the potential of the current cable to be brought close to the potential of the soil. In doing so, disturbing capacitive leakage currents can be heavily reduced.
Application of resistivity and induced polarization methods during the study of sand-gravel deposits in Kaluga Region, Russia

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Sand-gravel mixtures are widely used as multipurpose minerals. Different modifications of resistivity methods are traditionally applied for locating and mapping sand-gravel mix (SGM) deposits. This method allows us to determine sand-gravel bodies against the background of more conductive enclosed rocks. The challenge faced by geophysicists today is not only to determine the boundaries of SGM deposits, but also, to locate the zones with high gravel contents within SGM deposits. Studies conducted in Kaluga region, Russia, have showed that additional measurement of induced polarization makes it possible not only to detect boundaries of deposits, but it also allows us to identify areas with high content of gravel fraction. The measurements were made at both known SGM deposits that are now being developed and at new prospecting areas where drilling has been done after geophysical surveys. The study results show that all SGM deposits are characterized by high values of induced polarization. Authors suggest that the anomalies of the induced polarization are probably associated with electronically-conducting minerals, such as magnetite and pyrite, contained in grains of gravel. The geophysical results were confirmed by drilling data and laboratory measurements of induced polarization on samples.

The grain size measurements were also made and thereafter compared with results of laboratory measurements. The high content of gravel material in the samples correlates well with high polarization values.

Field spectral induced polarization with square waveforms

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Many spectral induced polarization (SIP) equipment developed for laboratory applications relies on harmonic or sinusoidal waveforms. With these apparatus, either potential or current regulated, both modulus and phase (or real and imaginary resistivity or conductivity) are straightforwardly estimated by comparing a measured potential with an injected current using a four electrodes array. When used at the field scale with increased distances between various electrodes and cable length, electromagnetic coupling may also be estimated thanks for instance, to Sunde (1968) equations for the selected frequency.

However, SIP options available with some field equipment used classical square (ON+ ON-) waveforms generally designed for measuring apparent resistivity in time domain, defined either with the ON time duration or a repetition frequency. Moreover, the sampling rate used to sample current and potential signals may not high enough to correctly sample following harmonic components involved in Fourier analysis. As these devices are designed to be rugged enough to stand usual field conditions and harshness, they could be an alternative to time-domain-induced-polarization (TDIP) measuring devices. However, their reliability shall be evaluated and frequency resolution established. We therefore investigate their measuring capability from sample to field scale, along with a direct comparison with harmonic equipment, and fully understand computations of the modulus or the phase of complex resistivity or conductivity.
Induced polarization for monitoring solidification of cut-off walls: a first approach

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It is ecologically friendly and economically interesting to implement cut-off walls using in situ soils mixed with hydraulic binders. Yet, there is currently no non destructive tool to assess the quality of the mix and its solidification state. The pore size distribution and the water content change during the solidification of the mix. Therefore IP methods could monitor these changes.

We implemented a soil-cement mix into a trench located on an experimental levee, and we monitored the consolidation of the mix over 30 days using time-domain IP. The levee is composed of natural loam, compacted at 96% of its maximal dry density (standard Proctor optimum) and the mix is made from the extracted loam and 11% (t.w) CEMIII cement.

We used an equatorial dipole dipole configuration. The injection electrodes (stainless steel pikes) are located on a distinct parallel line of the potential electrodes (Petiau electrodes).

The results show a clear increase of the electrical resistivity of the mixture over time. Two distinct resistivity evolutions over time are observed, which could be related to different reaction kinetics in the mix. The measured decay curves show significant variations (inflexion and amplitude), which can be explained by cement hydration mechanisms. The data obtained on the undisturbed compacted loam show a very low variability over the 30 days.

We could obtain a good quality of measurements despite rough weather conditions. IP could be used in a near future for in situ monitoring of soil-cement mix.

Tracking secondary mineralization in hydrothermal systems with complex electrical soundings: 2D inversions of ERT and time-domain IP data at the Krafjla volcano (Iceland) and comparison with laboratory data

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Smectite and pyrite are two witnesses of active hydrothermal circulations and therefore interesting for geothermal exploration. We explore the efficiency of time-domain Induced Polarization (IP), added to Electrical Resistivity Tomography (ERT), in mapping the distribution of smectite and pyrite in the active Krafjla hydrothermal system. The DC resistivity and the voltage decay are measured along two sets of four 1.6 km-long profiles. Each set of profile is centered around a borehole, where resistivity logs and laboratory measurements of complex conductivity on core samples exist. Metallic casings do not exceed 6 m depth in these boreholes. Two different cables are used for current injection and voltage measurement, with 40 meters between electrodes. Two different softwares are used for the inversion: Res2DInv with a smoothing constraint and AarhusInv with a 1D-layered constraint. The inversion results are compared to laboratory measurements of DC resistivity and chargeability, as well as to borehole log resistivity. A good agreement is observed between inversions, logs and laboratory resistivity around the borehole with low and constant temperature (10°C down to 300 m), whereas large deviations are observed between field and laboratory resistivity around the borehole with a strong temperature gradient (180°C at 200 m depth). The chargeability obtained by inversion at the vertical of the high-temperature borehole and the chargeability measured on cores also differ by one order of magnitude. The influence of in-situ temperature variations is considered to explain these discrepancies.
Electrical Responses of Proppants: Field Tests in Shallow Hydraulic Fractures

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Hydraulic fracturing is an important tool for water resources, and environmental remediation as well as for oil and gas production. We have been developing techniques for monitoring hydraulic fractures by injecting proppants that have anomalous electrical conductivity, intrinsic IP values, or high magnetic permeability values that can be used to image the proppants using electromagnetic geophysical methods.

Based on coupled laboratory and numerical modeling studies, three types of proppants were selected for field evaluation:

1) Pure carbon granules which should by strongly conductive;
2) A mixture of 30% carbon and 70% sand which should have a strong IP response; and
3) Recycled steel shot which should have strong permeability, IP, and conductivity responses.

A site near Powdersville, South Carolina was divided into six cells, allowing for two injections of each type of proppant. The proppants were injected at a depth of 1.5 m creating shallow sub-horizontal fractures extending several meters from the injection point. Each cell had a dense array of electrodes and magnetic sensors on the surface and four shallow vertical electrode arrays. Three-dimensional IP data sets were obtained before and after each hydraulic injection.

Cores from 130 boreholes were used to characterize the general geometries, and two of the fractures were excavated. Data from cores and trenching show that the hydraulic fractures were saucer-shaped with a preferred propagation direction. Geophysical data inversions generated images that were remarkably similar in form, size, and location to the ground truth from direct observation.

Multi-frequency EIT monitoring at the field scale - Challenges and experiences from the first year

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Multi-frequency electrical impedance tomography (EIT) is increasingly used to capture spatial variations in the spectral IP properties of the subsurface, thereby providing important additional information for an improved subsurface characterization. Compared to electrical resistivity tomography (ERT), a much more refined and controlled measurement setup is required to minimize measurement errors, especially for frequencies above 100 Hz. These requirements make long-term monitoring applications with high-temporal and spatial resolution challenging. In our work, we report on early findings in setting up and operating a multi-year EIT monitoring system on an agricultural test plot. Preliminary analysis suggests that reliable measurements up to 1 kHz are possible with this setup. Measurements using 40 electrodes with 25 cm spacing were performed up to 12 times per day (2 hour cycle) with measurement frequencies between 0.1 Hz and 45 kHz. A high temporal spacing potentially enables us to differentiate between various processes taking place in the subsurface (water flow, root-soil interactions, etc.). However, at the same time the amount of generated data requires automation of all processing steps and the need to establish new data management schemes. This was addressed using a distributed analysis system centered around a relational database. Preliminary analysis of the data focussed on recording and processing of telemetry data, which allowed us to detect anomalous states of the measurement system with only a few hours time delay. We further report on implications associated with long-term installation of electrodes and electromagnetic coupling issues that need to be addressed for accurate EIT measurements.
Using the Multi-Source Induced Polarization System for Gold Exploration in Azerbaijan

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The multi-source system built offers a unique approach for resistivity and IP surveys for targets as deep as several hundred meters. The system consists of small, battery powered transceivers each connected to three electrodes. Each transceiver has an internal 375 watt transmitter with a maximum current flow of 2.5 ampere. By having multiple units transmit simultaneously, the system can produce signal levels at depth that are comparable to those from a single large transmitter. For example, eight units transmitting 1.5 amps simultaneously will produce signal levels comparable to a single 12 amp source. In addition, distributing the source over a broader area can be shown to reduce the impact of near surface anomalies on the overall response.

In 2017, 20 units were deployed at Goydagh project, located in the Julfa district of Nakhchivan Autonomous Republic (Azerbaijan). The area is covered by volcanogenic-sedimentary rocks of Upper Eocene, andesites of early Oligocene, dacite and quartz-syenite intrusions with diorites of Oligocene-Lower Miocene. Gold mineralization of the area consists of by quartz-sulphide veins, ore-bearing alteration zones and large metasomatites.

Despite the rugged terrain of the region, high quality resistivity and TDIP data were collected at the site and inverted to provide 3D images to depths of more than 300 m.

Optimization of backwashing in rapid sand filters by time-domain IP monitoring

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In Denmark and several other countries drinking water originates from groundwater treated in open sand filters. Due to iron oxidation, the upper 30 cm of the filter clogs over time, so for optimal performance, the open sand filters must be backwashed periodically. However, often the waterworks has insufficient knowledge about the clogging process and the backwash is not performed efficiently. In this project, we try to optimize the backwash process by monitoring the clogging process, by time-domain induced polarization (TDIP) measurements. The setup consisted of 14 electrodes installed at various depth along a 2D profile within the filter, and full-waveform IP data, sampled at 3750 Hz, was recorded on a daily basis. The environment inside the water-filter proved to be very noisy, so special care in the signal processing was necessary. In particular, harmonic de-noising was essential to retrieve reliable IP data. We present the preliminary results from this study.
Monitoring seasonal variations of leaching from a landfill through time-domain induced polarization

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We present the results from a more than a year long time-domain induced polarization (TDIP) monitoring setup from the Pillemark landfill in the Danish island of Samsø. The setup consisted of a 100 m profile installed permanently in a 30 cm deep trench, placed orthogonal to the regional groundwater flow direction, and positioned between a landfill and a nearby waterwork, which is the sole waterwork on the island. Full-waveform IP data, sampled at 3750 Hz, were collected daily, and temperatures were measured in a borehole nearby at 7 different depths. Measurements, signal processing and data handling was done by a computer installed in the field, without human interaction required. In general the IP signal quality was really high, with almost four decades in time usable for spectral inversion. However, the IP signal quality decreased in extended periods without rainfall, also clearly visible in the increased contact resistances measured. Full-decay IP data were inverted in time-lapse for selected dates, in terms of a re-parameterization of the Cole-Cole model which includes temperature effects. The time-lapse inversions show changes in soil water content in the upper 5-8 m, but also a possible deeper plume having seasonal variations.

Monitoring of in-situ remediation of chlorinated solvents contamination with the use of the Direct Current resistivity and time-domain Induced Polarization method

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A significant number of sites contaminated with chlorinated solvents has been identified in Sweden. For remediation the soil is mostly excavated and moved to a secondary location, where it is treated. This technique migrates the problem, adds an extra cost in the treatment procedure and introduces a risk for secondary exposure, however it is used because it is well known and easier to control in comparison with in-situ remediation. For that reason, we are aiming to improve the control of the effectiveness of in-situ remediation by using the Direct Current resistivity and time-domain Induced Polarization (DCIP) method.

In Alingsås (Central Sweden), a dry-cleaning facility was operated for many years, and large amounts of the solvent PCE were spilled in the ground which contributed to an increasing concentration of PCE beneath the building. A pilot in-situ remediation program was launched in November 2018. For that reason, a fully autonomous and automatic monitoring system was installed to perform frequent automated DCIP measurements, supplemented by TDR, temperature, water levels, etc., to provide information about the changes in the subsurface. One of the challenges in this project is the processing of such data to successfully identify changes in the subsurface due to the remediation. The potential changes will be verified by the results from direct methods such as the Compound Specific Isotope Analysis (CSIA) and the Physical and BioGeochemical Characterisation (PBGC). Preliminary results will be presented at the workshop.
On Possible Induced Polarization responses from time-domain measurements

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Today, negative induced polarization (IP) time-domain responses and responses with non-standard shapes are generally considered as measurement errors and removed in data processing before inversion. However, synthetic and field measurements show that these responses are in fact physically possible and a simple theoretical explanation of the basic mechanism for their origin exist by means of the superposition of contributions from regions with different sensitivities. Furthermore, a mathematical classification of standard and non-standard IP responses into six different types is suggested based on the temporal development of the sign of their amplitude and derivative. The basic mechanism for IP responses with non-standard shapes is investigated by considering the subsurface Cole-Cole parameter sensitivities and time varying IP potential for 2D synthetic models. Time-domain IP responses will differ from the traditionally expected decaying-like response when the electrode geometry has IP potential sensitivities with different sign for areas with different IP parameters. With the increased understanding, previously disregarded IP responses which can contain valuable information of the subsurface can be kept for the inversion process and thus contribute to the final parameter distribution. Finally, an increased understanding of theoretically possible IP responses can also make way for more accurate processing of data in the future (manual or automatic), reducing the time and resources needed for spectral inversion of time-domain IP data.

Re-parametrizations of Cole-Cole models for improved modelling of spectral induced polarization

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The induced polarization phenomenon, both in time domain and frequency domain, is often parameterized using the empirical Cole–Cole model. To improve the resolution of model parameters and to decrease the parameter correlations in the inversion process of induced polarization data, we suggest here three re-parametrizations of the Cole–Cole model, namely the maximum phase angle (MPA) Cole–Cole model, the maximum imaginary conductivity (MIC) Cole–Cole model, and the minimum imaginary resistivity (MIR) Cole–Cole model.

The effects of the three re-parameterisations have been tested on synthetic time-domain and frequency-domain galvanic data as well as airborne electromagnetic data, using a Markov chain Monte Carlo inversion method, which allows for easy quantification of parameter uncertainty, and on field data using 2D gradient-based inversion. We show that the MPA, MIC and MIR models, compared to the classic Cole-Cole model, decrease the parameter correlations in the inversion and consequently gives a better resolution. This increase in model resolution is particularly significant for models that are poorly resolved using the classic Cole-Cole parameterization, for instance for low values of the frequency exponent or for low signal-to-noise ratio.
Induced-polarization imaging for the delineation of subsurface variability in clay-rich landslides

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Landslides still represent a major threat to human settlements and infrastructure. Particularly, those developing in clay-rich formations are hardly predictable landslides, often associated with high sediment volumes, and their triggering mechanisms are not fully understood, yet, are strongly related to precipitation and groundwater flow. Hence, detailed information about the internal structure of unstable slopes, as well as the estimation of textural and hydraulic subsurface properties, is a prerequisite for an improved understanding of their triggering mechanisms. In this context, electrical resistivity tomography (ERT) has been frequently used to delineate hydrogeological interfaces in landslides and changes in water content. However, the interpretation of the ERT images might not be fully conclusive, particularly for clay-rich landslides, where the electrical signatures are controlled rather by surface conduction mechanisms than due to variations in water saturation. In this study, we discuss the investigation of a landslide with single-frequency induced polarization (IP) and spectral IP (SIP) imaging. We present IP imaging results collected along 15 profiles at a shallow clay-rich landslide in Lower Austria (Austria), and an interpretation based on extensive hydrogeological and geotechnical data. Our results revealed a correlation between the electrical properties (electrical conductivity and induced polarization) and geotechnical parameters (textural parameters and estimations of soil strength obtained from dynamic probing). Interpretation of IP imaging results based on such correlation permitted to delineate subsurface areas associated to different weathering conditions. Moreover, SIP data collected along one profile shows sensitivity to changes in textural composition, closely related to soil strength. Our findings demonstrate the value of using the IP method for the imaging and thus understanding of clay-rich landslides.

Waterborne spectral induced polarization imaging to investigate stream-aquifer exchange

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Geometrical and hydraulic streambed properties define infiltration and are therefore important to manage bank filtration sites. Currently available methods tend to lack spatial resolution to capture these. Provision of spatially distributed estimates of hydraulic conductivity and thickness of colmated substream sediment as well as stream stage is considered to determine dataset worth for numerical groundwater flow models. We investigated the applicability of spectral induced polarization (SIP) imaging results to improve the prediction of stream-aquifer exchange. SIP imaging measurements were collected in a selected losing-disconnected subalpine stream reach in a broad frequency bandwidth (0.5-225 Hz) using a fully submerged array of 32 electrodes (0.5 m spacing). They were complemented with over 300 depth-discrete transient infiltration tests to determine horizontal hydraulic conductivity of the streambed along the arrays. SIP imaging results have provided two main observations: (i) the real component (σ') shows only consistency to the main lithological units, permitting to delineate stream stage and the general substream architecture; whereas (ii) the imaginary component (σ'') reveals a large spatial variability, which we compare with the variability observed in hydraulic conductivity measurements. Patterns of the first derivatives of σ'' with depth suggest variable thickness of an immediate sub-stream layer, associated to the strongest polarization effect, as expected of a streambed colmation layer. Our results illustrate that SIP images can constrain value ranges for parameters commonly required in groundwater flow models and can be used to reduce uncertainty in model predictions.
Laboratory and field IP investigations at the groundwater-surface water interface

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The groundwater-surface water (GW-SW) interface plays an active role in nutrient and contaminant cycling in rivers and streams. Interactions in this zone are influenced by hydrogeological (e.g., residence times and flow paths) and biogeochemical properties (e.g., cation exchange capacity) and conditions (e.g., redox state). However, assessing these parameters, and their spatial and temporal heterogeneity, can be challenging as they often require samples for laboratory work. Numerous studies demonstrate sensitivity of spectral induced polarisation to surface area and cation exchange capacity, yet there has been less work conducted under field conditions. The aim of this work is to link properties that influence the biogeochemical characteristics of river bed sediments with induced polarisation obtained in both the laboratory and field. Field work was conducted at the River Leith (Cumbria, UK) where the river bed consists of alluvial gravels and underlying sands. Whereas the surface areas, cation exchange capacities and grain size distributions of the sand samples are homogenous, the gravel samples are more variable. The frequency behaviour of the gravel and sand have distinctive characteristics, but have similar phase responses at 1 Hz, a frequency commonly used in the field. This has important implications in that in that potentially useful information is currently not practically obtainable in the field. In addition we consider some of the issues associated with modelling in-stream induced polarisation, such as the influence of the water column and the non-2D nature of rivers.

Induced Polarization imaging of nano- and micro-scale particle injections for in-situ groundwater remediation

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The injection of nano- and micro-scale particles has emerged as a promising in-situ remediation technology for the treatment of contaminated groundwater, particularly for areas difficult to access by other remediation techniques. The performance of nanoparticle injections, as a foremost step within this technology, is usually assessed through the geochemical analysis of soil and groundwater samples. This approach is not well suited for a real-time monitoring, and often suffers from a poor spatio-temporal resolution. To overcome these limitations we propose here the application of Induced Polarization (IP) imaging as a diagnostic tool to evaluate the fate and transport of the injected particles. Our results demonstrate that the analysis of spatial and temporal changes in the electrical images allows tracking the propagation of the injected suspension and detection of the induced geochemical changes in the subsurface in real time. IP monitoring results presented here refer to two different experiments conducted at the field-scale: (i) during the injection of nanoGoethite particles (NGP) used for the degradation of a BTEX plume (i.e., benzene, toluene, ethylbenzene, and xylene); and (ii) during the injection of microscale zero-valent iron (mZVI) to enhance chemical transformation of chlorinated aliphatic hydrocarbons (CAHs). Pre-injection imaging results revealed high electrical conductivities for data collected in both investigations. Such responses can be explained by the release of metabolic by-products accompanying the stimulation of microbial activity due to the presence of hydrocarbons in the subsurface. Moreover, background images of the induced polarization (IP) reveal contrasting signatures for the different pollutants. Such footprints can be explained by variations in the pore-space geometry imposed by the distinctive properties of the pollutants. Post-injection images revealed a significant change (>50%) in the electrical conductivity and induced polarisation response. Temporal changes in the electrical images are consistent with variations in particles concentration observed in groundwater and soil samples, as well as geochemical parameters such as pH and oxidation-reduction potential. Moreover, large variations in the electrical parameters, close to the surface, reveal the formation of preferential flowpaths and the deviation of the particles from the target area. Our results demonstrate the applicability of IP imaging for the real time monitoring of nano- and micro-scale particle injection.
5th International Workshop on Induced Polarization

http://ncas.rutgers.edu/2018ipworkshop