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# GELMON 2013

## 2nd International Workshop on Geoelectric Monitoring

Geological Survey of Austria

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# GELMON 2013

## 2nd International Workshop on Geoelectrical Monitoring

# Collection of Abstracts

International Workshop in the frame of the FWF project TEMPEL (TRP 175-N21)

December 4th – December 6th, 2013, Vienna

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Cover: Geoelectric monitoring of the protection embankment in Krems during the 100-year flood of the Danube River, June 2013. Photo © Robert Supper

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# Preface

In the frame of the FWF Translational Brainpower project **TEMPEL** (Geoelectric properties: temporal change as failure indicator - TRP 175-N21), the Austrian Geological Survey hosted the ***"Second International Workshop on Geoelectrical Monitoring - GELMON 2011"***. The workshop was held in the Presentation Hall of the Austrian Ministry of Science and Technology (BMWF) from December 4th to 6th 2013. 80 participants from 17 different countries attended the workshop.

After the big success of the "1st Workshop on Geoelectrical Monitoring", which was held in Vienna in 2011, many voices demanded a second scientific meeting. This proves that geoelectrical monitoring established as one of the most innovative emerging branches in the area of applied geophysics within recent years. It is now applied to solve problems in key areas of public and political interest, such as natural hazard mitigation, groundwater exploration and questions of energy budget and climatic change.

On December 3rd, a Special Course on Geoelectrical Monitoring (4D data inversion and monitoring instrumentation) was held at the Geological Survey of Austria in the frame of the GELMON Conference (17 participants). Within the consecutive three days of the conference, more than 50 speakers presented state-of-the-art results on geoelectrical monitoring. The scientific topics comprised applications at landslides and in agriculture, questions of $CO_2$-storage, applications in geothermal and permafrost monitoring, as well as new inversion algorithms and applications in hydro(geo)logy.

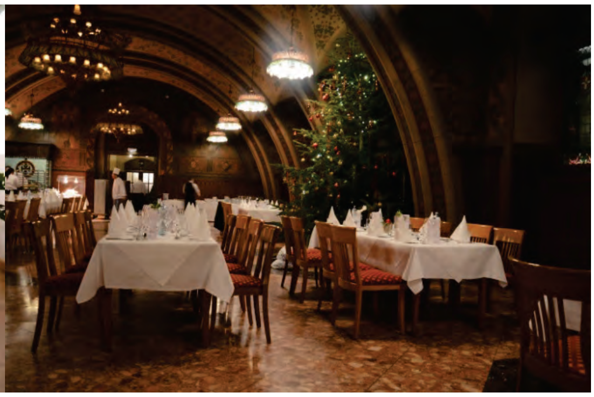
An important aspect was the discussion of the presentations, the exchange of ideas on special topics and the development of international scientific relations. Two discussion groups focused on the topics "Temperature correction of geoelectrical monitoring data" and "Quality assessment of monitoring data", respectively. Especially the topic "Quality assessment" raised a lively debate. A Panel Discussion on future perspectives of geoelectrical monitoring, and especially possible applications to hydrocarbon exploration, closed the workshop.

This time the meeting was held in the Presentation Hall of the Austrian Ministry of Science and Technology (BMWF). The central position in the 1st district of Vienna, as well as the Christmassy atmosphere in the Austrian capital imparted an amazing flair to the conference. Social highlight was the Conference Dinner in the "Wiener Rathauskeller", where delicious food and atmospheric music could be enjoyed in a magnificent ambience.

GELMON 2013 could tie in to the success of the first workshop and the quality of the meeting was even improved. This was proven by a questionnaire, which was anonymously answered by about

2/3 of the workshop participants. Approximately 95 % of the respondents rated the quality of the presentations as well as the benefit for their research as high or very high. All respondents voted for a continuation of the GELMON workshop in a 2-year cycle and therefore the next workshop will be held in Vienna in December 2015.

Impressions from the GELMON Conference



Conference Dinner at the "Wiener Rathauskeller"

As a product of the 1st GELMON workshop, a collection of contributions was published in a special issue on geoelectrical monitoring in the journal „Near Surface Geophysics"(*Near Surface Geophysics*, 2014, 12). A similar contribution is also planned as a result of the 2nd workshop, probably in the "Journal of Applied Geophysics".

This book contains the collection of abstracts summarizing the content of the talks and is intended to be a compendium of the GELMON 2013 workshop.

STEFANIE GRUBER and ROBERT SUPPER
GEOLOGICAL SURVEY OF AUSTRIA

# General Workshop Program Overview

**Wednesday, Dec. 4th**

| | |
|---|---|
| 10.00-10.30 | Workshop Opening |
| 10.30-12.30 | Application in $CO_2$ and Hydrocarbon Monitoring |
| 13.30-15.10 | Application in Contamination Monitoring |
| 15.30-16.30 | Applications in Permafrost Monitoring |
| 16.30-17.30 | *Discussion Group*: Data Quality Assessment |
| 17.30-18.30 | POSTER SESSION 1: $CO_2$, Contamination, Permafrost |
| 18.30-21.00 | Icebreaker |

**Thursday, Dec. 5th**

| | |
|---|---|
| 08.30-10.10 | Applications in Landslide Monitoring |
| 10.30-12.10 | Time Lapse Data Inversion and Modeling |
| 13.30-16.50 | Applications in Hydrology |
| 17.00-18.30 | POSTER SESSION 2: Hydrology, Landslides, Inversion |
| 19.00-24.00 | Conference Dinner at "Wiener Rathauskeller" |

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| 10.50-12.10 | Special Topics |
| 12.30-13.25 | *Panel Discussion*: Future Perspectives of Geoelectrical Monitoring: Possible Applications to HYDROCARBON EXPLORATION/MONITORING |
| 13.25-13.30 | Closing of Workshop |

# Conference Program GELMON 2013

## Wednesday, Dec. 4th

| | | | |
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| 10.50 -11.10 | DC/IP Monitoring of Injected $CO_2$ in a Shallow Aquifer | G. Fiandaca, J. Doetsch, E. Auken, A. Vest Christiansen | **02** |
| 11.10 -11.30 | Large-scale repeated DC geoelectric surveying for $CO_2$ monitoring at the Ketzin pilot site, Germany | A. Just, A. Schmidt, R. Voigt, C. Flechsig | **03** |
| 11.30 -11.50 | Investigation of time-saving monitoring techniques to detect possible brine migration into shallow aquifers as an impact of geological $CO_2$ storage | M. Möller, C. Schmidt-Hattenberger | **04** |
| 11.50 -12.10 | Estimating optimum electrode locations for high-resolution cross-hole resistivity monitoring | F. Wagner, T. Günther, C. Schmidt-Hattenberger, H. Maurer | **05** |
| 12.10 -12.30 | Geo-electrical Monitoring of Oil (and Gas) reservoirs | J.A.C. Meekes | **06** |

| | | | |
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# Wednesday, Dec. 4th

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| Electrical Resistivity Tomography (ERT) as a permanent monitoring tool to image the $CO_2$ migration at the Ketzin pilot site – Experiences from more than five years of operation | C. Schmidt-Hattenberger, P. Bergmann, T. Labitzke, F. Wagner | **P05** |
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| Long Electrode ERT: modeling and field experiment | M. Ronczka, T. Günther, C. Rücker | **P10** |
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## Friday, Dec. 6th

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| | |
|---|---|
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| 13.25 -13.30 | **Closing of Workshop** |

# Oral Presentations

## Applications in $CO_2$ and Hydrocarbon Monitoring

### 01

### Combination of constrained resistivity inversion and seismic reflection with an application to 4D imaging of the Ketzin $CO_2$ storage site, Germany

Bergmann Peter[1], Ivandic Monika[2], Norden Ben[3], Rücker Carsten[4], Kiessling Dana[5], Lueth Stefan[1], Schmidt-Hattenberger Cornelia[1], Juhlin Christopher[2]

[1]*GFZ German Research Centre for Geosciences, Centre for Geological Storage (bergmann@gfz-potsdam.de)*
[2]*Uppsala University, Department of Earth Sciences*
[3]*GFZ German Research Centre for Geosciences, Reservoir Technologies*
[4]*Technical University Berlin, Department of Applied Geophysics*
[5]*University of Leipzig, Institute of Geophysics and Geology*

A case study for the combination of geoelectric and seismic processing by means of a structurally constrained inversion approach is presented. Structural constraints are interpreted from the seismic data and integrated into the geoelectric inversion through a local regularization which allows inverted resistivities to behave discontinuously across defined boundaries. This arranges seismic processing and constrained resistivity inversion in a sequential workflow, making the generic assumption that the petrophysical parameters of relevant to each method change across common lithostructural boundaries.

The approach is evaluated using both a numerical example and a real data example from the Ketzin $CO_2$ pilot storage site, Germany. The latter demonstrates the efficiency of this approach for combining 4D seismic and surface-downhole geoelectric data. In consistence with the synthetic example, the constrained resistivity inversions of the real data produce clearer delineated images along the boundary between the caprock and the $CO_2$ storage reservoir. Near the $CO_2$ flooded reservoir, the seismic and geoelectric time lapse anomalies correlate well. At some distance to the downhole electrodes, however, the geoelectric images convey a notably lower resolution in comparison to the corresponding seismic images. Although a northerly direction for the $CO_2$ migration was initially expected, both methods confirm a rather northwesterly migration trend. The results confirm the relevance of the presented approach for the combination of both methods for geophysical $CO_2$ storage monitoring.

# 02

## DC/IP Monitoring of Injected $CO_2$ in a Shallow Aquifer

Fiandaca Gianluca[1], Doetsch Joseph[1], Auken Esben[1], Christiansen Anders Vest[1]
[1]*Aarhus University, Denmark*

Contamination of potable groundwater by leaking $CO_2$ is a potential risk of carbon sequestration. With the help of a field experiment, we investigate if DC resistivity and IP measurements can detect and image dissolved $CO_2$ in a shallow aquifer. For this purpose, we injected $CO_2$ at a depth of 5 and 10 m and monitored its migration using 320 electrodes on a 126 m × 20 m surface grid. In addition to the DC resistivity, we collected the full IP decay curves for all measurements.
We invert the DC resistivity data in 3D and image the geochemical changes induced by the dissolved $CO_2$ as a decrease in electrical resistivity for 120 days. The full IP decay curves for the main profile are inverted in 2D, in terms of Cole-Cole parameters, showing a signature of the $CO_2$ on the $m_0$ parameter.
Water electrical conductivity (EC) sampling using 68 sensors in 31 wells was carried out during the entire experiment. The sampling allows for very good verification of the ERT results. Water EC and DC/IP results generally agree very well, with the water sampling showing some fine scale variations that cannot be resolved by the ERT.

# 03

## Large-scale repeated DC geoelectric surveying for $CO_2$ monitoring at the Ketzin pilot site, Germany

Just Anita[1], Schmidt Alina[1], Voigt Rene[1], Flechsig Christina[1]
[1]*Institute of Geophysics and Geology, University of Leipzig, Germany*

At the Ketzin pilot site, Germany, $CO_2$ has been injected into a deep saline aquifer since 2008. Before and during the $CO_2$ injection phase, a comprehensive geophysical monitoring programme has been conducted including seismic and geoelectric measurements. The main part of the geoelectric monitoring is a permanent electrode installation (VERA-vertical resistivity array) with 45 electrodes deployed in the three Ketzin wells to monitor subsurface resistivity changes associated with the migration of the $CO_2$ in cross-hole configuration by the GFZ German Research Centre for Geosciences (see presentation by C. Schmidt-Hattenberger et al.). Surface-downhole measurements using current injection at the surface on two rings centered around the injection well completed the monitoring concept on a periodic basis to yield additional information outside the volume of the crosshole investigations.

As a complementary part of the monitoring programme, large-scale 2D surveys on two profiles of 4.8 km length were performed aiming at the exploration of the geological structure surrounding the wells and their influence on the crosshole and 3D surface-downhole measurements. So far, these measurements have been carried out thrice (2009, 2011 and 2012) in periods that followed the start of the $CO_2$ injection. The survey method includes a special instrumentation and measurement concept with independent transmitter and receiving units as well as an adapted data processing including 2D and 3D tomographic inversion approaches. The results reveal a complex structure due to the Ketzin anticline including disturbed zones and a former gas storage zone above the $CO_2$ reservoir. Although large-scale ERT on long profiles is challenging in the noisy environment of the storage site and near industrial plants a good repeatability from the first to the following surveys is shown. In the later surveys a better spatial resolution is reached by an enhanced data acquisition scheme including adaptive current injection and potential registration using non-polarizable electrodes.

# 04

# Investigation of time-saving monitoring techniques to detect possible brine migration into shallow aquifers as an impact of geological $CO_2$ storage

Möller Marcus[1], Schmidt-Hattenberger Cornelia[1]

[1]*Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany*

Carbon capture and storage (CCS) is to be considered as a promising technique to realise climate change mitigation solutions. The preferential objective of this approach is to reduce the anthropogenic greenhouse gas emissions by a long-term storage in underground reservoirs. Induced by pressure propagation during the $CO_2$ injection, the reservoir saltwater could be displaced into shallow freshwater layers along leakage pathways. In order to ensure a safe storage operation, an adequate geophysical monitoring system is essential.

We will present the electrical resistivity tomography (ERT) as one module of an integrated geoelectrical/electromagnetical monitoring system. With its relatively high resolution on the scale of some tens of meters it is preferentially used in boreholes and near subsurface surveys. Based on modelled $CO_2$- and brine migration scenarios, different electrode configurations and analysis methods were investigated, in order to find an optimised monitoring workflow.

The modelling study simulates a saltwater intrusion into a freshwater aquifer complex as a worst-case scenario on a real potential storage site. In most cases, the number of the boreholes and consequently the number of the electrodes is limited due to costs and technical constraints. Therefore, one focus of the study concentrates on the irregular adaptive positioning of a few electrodes along the wellbore. Thus, both the large-scale background resistivity and the small-scale resistivity changes at critical points are covered. The second focus is directed on the assessment of fast and sufficient detection methods for the salinisation process.

## 05

## Estimating optimum electrode locations for high-resolution cross-hole resistivity monitoring

Wagner Florian[1,2], Günther Thomas[3], Schmidt-Hattenberger Cornelia[1], Maurer Hansruedi[2]
[1]*Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, Potsdam, Germany*
[2]*ETH Zurich, Institute of Geophysics, Sonneggstrasse 5, Zurich, Switzerland*
[3]*Leibniz Institute for Applied Geophysics, Hannover, Germany*

Cross-hole electrical resistivity tomography has recently been recognized as a method to monitor the migration of carbon dioxide injected into deep saline aquifers due its specific sensitivity to pore fluid changes. Given the potential environmental impacts and the substantial installation costs, the design of permanent electrode arrays becomes particularly important. In former studies, the model resolution has been identified as a computationally expensive but valuable image appraisal quantity, as it combines both sensitivity and linear interdependence of the measurements involved. By an iterative and parallelized evaluation of the model resolution on modern computing architectures, a methodology was realized to estimate optimum electrode locations along the borehole trajectories for given geologic scenarios with the objective to maximize the resolution within a prescribed target horizon. Based on synthetic experiments for a realistic $CO_2$ plume migration scenario, we present optimized layouts for different borehole spacings and reservoir thicknesses. Our results indicate that sparse setups with a refinement of the electrode spacing within the target horizon can yield comparable tomographic performances with respect to rather dense arrays.

## 06

## Geo-electrical Monitoring of Oil (and Gas) reservoirs

Meekes Sjef [1]
[1] *TNO Energy Utrecht*

Because of the large resistivity contrast between oil and brine, monitoring the oil-water contact during production is a potentially interesting technique. However, it is not used in practice today. We believe that this subject has possibilities and deserves more attention. Applying geo-electrical monitoring of oil reservoirs may e.g. possibly identify “bypassed areas”. The technique can be significantly cheaper than 4D seismic, especially on-land. At TNO we modeled (3D) different borehole-to-surface electrode configurations for monitoring the lateral position of the oil-water contact and inventoried e.g. their sensitivity versus depth of the reservoir. For this we looked at a rectangular reservoir, but also at a “realistic” reservoir with varying porosity and oil saturations derived from reservoir modeling. Results are looked at in terms of the difference between the potential fields (more than using apparent resistivities) at different time steps. In the modeling we see something we call “the dipole of monitoring”, a concept that can help to design effective electrode configurations for a specific hydrocarbon field. Results indicate that for a configuration applying an electrode above and below the reservoir in combination with surface electrodes, the sensitivity is not so depth dependent, whereas for a single-borehole to surface configuration the sensitivity decreases quickly with depth. Also results from some laboratory experiments that were conducted to test a specific configuration are shown. For this a pvc-tank of (75 cm * 55 cm) was filled with sand and electrodes (both buried and surface) were placed. The oil water contact was simulated using a very thin plastic plate whose position could be moved. The tank results encourage the further development of the geo-electrical monitoring technique.

# Applications in Contamination Monitoring

## 07

## Geoelectrical Monitoring for Mapping of Gas Migration in Landfills

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Short term resistivity and induced polarisation (IP) monitoring field experiments were conducted at the Filborna landfill in Helsingborg and the Albäck landfill in Trelleborg, Sweden. The objective was to detect variations in gas and fluid content due gas migration in the landfill. The monitoring resulted in a couple weeks of monitoring data with a 3D data set measured every 3 hours for each site, which may also be called 4D data sets. Methane is a powerful greenhouse gas and a growing concern regarding global climate changes. Landfill gas is regarded as one of the major sources for methane migration to the atmosphere. The migration of methane and carbon dioxide from a specific landfill depends on several aspects, such as the nature of the soil cover system, the gas collection system, and daily management.

We present results from short term monitoring performed in June-July and September 2011 respectively. The test sites measured 40 by 22 meter and were placed on old Municipal Solid Waste (MSW) landfills. Twelve parallel lines with 21 electrodes each were monitored with a remote controlled system during a couple of weeks. In addition to the resistivity-IP monitoring the weather was recorded locally.

The resistivity and IP measurements showed results that agree with existing documentation of the internal landfill structure, and are in line with results reported from previous investigations in waste. Variations in resistivity can partly be explained by the presence and migration of landfill gas. However, changes in soil moisture content and temperature may also have a considerable influence on the resistivity data showed in this study, and rainfall events followed by water infiltration into the landfill during the monitoring period are clearly imaged. Such events are often

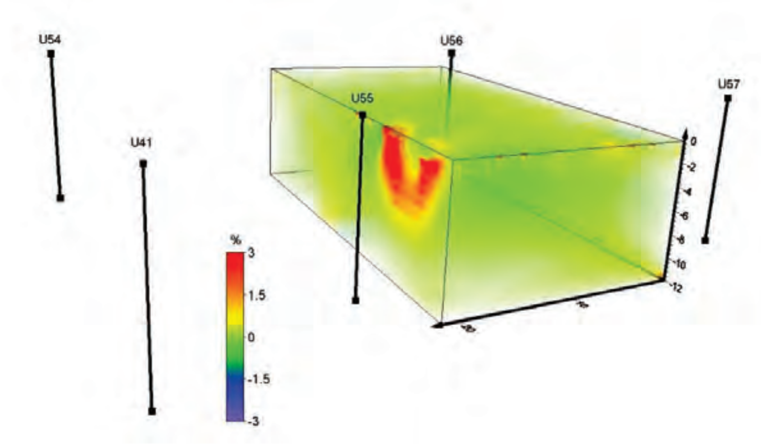


**Figure 1.** Percent change in resistivity 2011-09-15 16:00-19:00. Increase in resistivity is evident close to U55 which is the only open gas well.

followed by increase in resistivity that is interpreted as gas pressure build-up deeper below the water saturated upper part of the soil.

At the Albäck site the existing gas extraction system was used to study the impact on soil resistivity of gas wells being turned on and off (Figure 1). The measurements provided successful results showing an increase in resistivity in areas close to an active gas well, especially when all gas wells had been turned off for a longer period before. The results illustrated the importance of disturbed gas pressure balance on the gas dynamics in the soil.

# 08

# 3D ERT monitoring of the reactivation of waste biodegradation with fresh leachate injection

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The aim of this study is to monitor (bio) physical processes occurring in a landfill. The experiment consists in injecting leachate towards a drain in unsaturated and not yet digested waste to reactivate (or activate) waste biodegradation. The target is the first 15 meters of the studied landfill subsurface. The visualization of the wet front arrival (short term effect) is crucial because we want to ensure that waste is entirely humidified to allow the reactivation of waste digestion. The second process is a long term effect consisting in the increase of the internal temperature of the landfill which is synonymous of the reactivation of biodegradation processes.
We use 3D time-lapse ERT on a monthly basis to capture the decrease of electrical resistivity related to the increasing temperature. We also collect ground truth data, including distributed temperatures in a borehole to validate results. For short term effects, we monitored the wet front arrival with three 2D ERT profiles composing the 3D image, during an entire day. Preliminary results, corroborated by ground truth data, show that leachate flow in anisotropic (more rapid horizontally than vertically). So far, waste was completely humidified and slight changes of temperature occurred.

## 09

## 5D SIP monitoring of stimulated uranium bio-remediation

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Here, we demonstrate the use of spectral induced polarization (SIP) imaging for monitoring biogeochemical changes accompanying the stimulation of indigenous aquifer microorganisms with the purpose to immobilize uranium in tailings-contaminated groundwater at the Department of Energy's Rifle Integrated Field Research Challenge (IFRC) site near Rifle, Colorado (USA). Measurements have been collected with electrodes placed on the surface and in boreholes along diverse stimulation experiments. The aims of the SIP surveys were (1) to characterize the precipitation of metallic nano-minerals and changes in groundwater geochemistry due to microbial activity; (2) to investigate the distribution of the frequency dependence (e.g., spectral parameters) of the polarization response in an imaging framework, and (3) to evaluate the potential of these images to delineate changes in the hydraulic properties of the aquifer. Careful field procedures provided high quality SIP data from 0.060 to 256 Hz for different periods during the remediation experiment. Data quality was evaluated by means of analysis of the discrepancy between normal and reciprocal measurements. A Cole-Cole model was fitted to pixel values extracted from the inverted images in order to assess changes in the SIP response – particularly in time constant ($\tau$) and chargeability (m) - due to processes accompanying the stimulation of subsurface microbial activity. We observed an important decrease in m and no change in $\tau$ correlated with periods characterized by high rates of sulfate-reduction. A significant increase in both $\tau$ and m was observed after halting acetate injection, consistent with the accumulation of metallic nano-minerals (e.g., FeS) during biostimulation and the post-injection rebound in aqueous Fe(II).

# 10

# Geoelectrical monitoring to support the decommissioning of legacy silos at the Sellafield Site, UK

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A strategic priority for the UK's Nuclear Decommissioning Authority (NDA) is the reduction of risk and hazard across its estate of nuclear facilities. Legacy ponds and silos at the Sellafield Site in Cumbria, UK, pose the most significant technical challenges in this context. The safe emptying and decommissioning of the Magnox Swarf Storage Silos (MSSS) is one of the flagship projects that Sellafield Ltd (SL) are currently undertaking on behalf of the NDA.

There is an increased risk that leakage from the facility to ground may occur during planned waste retrievals. Part of the strategy to demonstrate control of silo liquor under normal and abnormal conditions is to employ electrical resistivity tomography (ERT) for the in-ground detection and volumetric monitoring of potential leakage plumes.

We report the results of a full-scale field trial, which used 4D ERT to monitor a controlled injection experiment at the MSSS site. The trial involved an initial period of baseline measurements, followed by multiple controlled injections of benign conductive simulants (saline tracer solution) into the vadose zone via shallow boreholes. The simulants were developed to replicate the likely properties of the silo liquors. Repeated ERT cross-borehole measurements before, during and after the injections were made in order to assess the information content of the ERT data with respect to the occurrence of the simulated leak and the fate of the resulting plume.

Absolute images of resistivity resolved the complex geological setting at the MSSS site, which comprises superficial deposits composed of an accumulation of Quaternary glacial material and post-glacial sands and gravel; these lie unconformably over Triassic sandstone bedrock. The complexity of the geology, combined with the presence of clay-rich sediments and the small contrasts in electrical properties expected at the site had cast initial doubts over the likelihood of a successful application of ERT at MSSS, particularly when compared with previous applications of ERT to nuclear waste management reported in the literature. Moreover, leak detection based on ERT is challenging in any circumstance as competing (but unrelated) processes are known to affect resistivity, including soil temperature variations, groundwater recharge, and electrical noise from plant operation and natural sources. However, our approach proved sufficiently sensitive and images of resistivity change relative to a baseline date have revealed likely pathways of simulant flow in the vadose zone and upper groundwater system; these were found to be compatible with historic contamination detected in sediment cores retrieved from the trial boreholes.

Future plans envisage the deployment of a permanent ERT monitoring system at MSSS in order to support the scheduled decommissioning work over the coming decades.

## 11

## Time-lapse ERT monitoring of DNAPL Source Zone Remediation

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Successful remediation of sites contaminated with dense non-aqueous phase liquids (DNAPLs) represents a major geoenvironmental challenge. Electrical resistivity tomography (ERT) exhibits significant potential to provide rapid and non-intrusive spatio-temporal information for monitoring the evolution of DNAPL mass during remedial efforts at contaminated sites. However, this potential has not been realized due to challenges in interpreting the results at real sites where the initial condition (DNAPL mass and distribution, subsurface heterogeneity) is generally unknown. The objective of this study is to evaluate the effectiveness of time-lapse ERT to monitor the remediation of DNAPL source zones in near subsurface environments. A recently developed coupled DNAPL-ERT model was employed to generate realistic DNAPL release and remediation scenarios and calculate the corresponding resistivity response. Varying DNAPL types, ranging from high density to low density DNAPLs, were released within different heterogeneous clayey sand environments, with the resulting three-dimensional DNAPL source zone distributions exhibiting a wide range of complexity. Complete DNAPL mass removal by natural dissolution was then simulated, with simultaneous mapping via periodic ERT surveys. A newly developed four-dimensional ERT inversion algorithm was used to generate time-lapse imaging of the evolving DNAPL source zones and subsequently predict the DNAPL volume remediated over time. Results demonstrate that time-lapse ERT may provide valuable spatio-temporal information to inform and assess DNAPL remedial strategies. Delineation of the DNAPL volume remediated, in terms of the outline and center of mass, is promising with time-lapse ERT exhibiting the ability to map the treatment zone to within a few meters in each direction. Although ERT generally underestimates the temporal reduction of DNAPL volume, particularly for deeper source zones, it is evident that these measured DNAPL volume estimates can still provide valuable information for quantitatively monitoring the remediation of DNAPL source zones. In general, this study demonstrates that time-lapse ERT may be a valuable non-invasive site tool during DNAPL site clean-up.

# Applications in Permafrost Monitoring

## 12

## Automatic ERT monitoring in permafrost areas: logistical challenges and high-resolution process analysis

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Permafrost is a widespread phenomenon in arctic and high mountain regions and describes the permanently frozen state of the subsurface in lithospheric material. In the context of climate change, monitoring techniques are of great importance, which are able to quantify thaw (and freeze) processes in the subsurface. Geoelectrical monitoring approaches are especially well suited as they can detect even small changes in the unfrozen water content in permafrost areas. In addition, the depth of the seasonal thaw layer (active layer) can be monitored on a seasonal as well as a multi-annual time scale, which can be used as an indicator of long-term permafrost degradation.
We present results from automatic ERT monitoring data at the Schilthorn permafrost site (Swiss Alps) since 2009. The data set is not continuous due to several technical problems related to its high altitude location and the related harsh conditions. We will focus on (1) high resolution process analysis of the snow-melt and active layer thaw period in early summer as well as the freezing period in autumn and (2) a discussion of the influence of measurement errors and inversion choices on the interpretation of the results. Ground truth data exist in form of subsurface temperature data from two boreholes and soil moisture data from two sites along the profile line.

# 13

# Monitoring of active layer refreezing in Greenlandic permafrost

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The state of the high-latitude permafrost for the Earth's climate system has been widely acknowledged, but permafrost dynamics in a changing climate are poorly understood. Especially the annually freezing and thawing *active layer* is critical for climate dynamics, but it is difficult to monitor without disturbing the studied system.
We use minimally invasive surface geoelectrical monitoring to image active layer refreezing and its lateral variation at high temporal resolution. Our monitoring setup on Disko island, Greenland, allows acquisition of up to 12 data sets per day, using 54 electrodes on two parallel lines. Data is automatically acquired, backed up locally and uploaded to an online database.
We test different time-lapse inversion strategies on the large amount of data and correlate our inversion results with local temperature point measurements. The comparison of the time-lapse inversion results and the temperature and moisture content measurements aims at developing a petrophysical model for partially and fully frozen soils.

## 14

## Comparison of alternative electrode types for improvement of electrode-ground coupling in highly-resistive environment. Experience from the time lapse geoelectrical station for high-latitude permafrost monitoring, Ilulissat, West Greenland

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The contribution is concerning the experiments carried out in the spring 2013, having as purpose the improvement of grounding of the electrodes placed in fine-grained permafrost after we discovered that standard electrode types are surprisingly performing not well enough during the winter time (comparing to other, geologically less favorable sites in Greenland), when the ground resistance is extremely high.

The field experience revealed unexpected facts (unexpected based on previous experience) about problems with reliable ERT measurements that can be encountered in highly resistive environments (such as permafrost sites). We carried out a series of field test (and we still have ongoing laboratory test) in order to design the best electrode type for the challenging, highly resistive environments when reliable operation is required due to the remoteness of the sites.

# Applications in Landslide Monitoring

## 15

## Long term monitoring of landslide processes by automated time-Lapse Electrical Resistivity Tomography

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The stability of natural slopes is transient in nature and is often strongly dependent on the moisture content (water saturation) of the geological materials underlying the slope. In recent years, geoelectrical monitoring techniques have been increasingly applied to landslide monitoring studies due to their sensitivity to the internal moisture dynamics of slopes. Here, one such long term geoelectrical monitoring campaign at an active landslide system, located in the North Yorkshire, UK, is described. Three-dimensional Automated time-Lapse Electrical Resistivity Tomography (4D-ALERT) results are presented alongside conventional investigative techniques, thus enabling soil moisture accumulation to be observed in prior to landslide activation.

Several of the challenges associated with long term monitoring of a transient natural system, such as an active landslide, are outlined and methodological solutions are described and applied. Several types of geoelectrical monitoring results are presented, including: temperature-corrected transfer resistances; time-lapse 3D volumetric resistivity images; time-lapse volumetric images of gravimetric moisture content (determined using laboratory derived relationships between resistivity and soil moisture content).

Results from the BGS Observatory, Hollin Hill, display the spatial and temporal (4D) distribution of moisture related changes within the slope prior to, during and after landslide activation. In particular, they reveal that the ERT monitoring array is sensitive to soil moisture accumulation in response to intense and prolonged rainfall events, and also that landslide activation is typically preceded by a period of decreasing electrical resistance and electrical resistivity, and increasing soil moisture content.

# 16

# Geoelectrical Investigations and Monitoring in the Context of Disaster Response at the landslide in Pechraben, Austria

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Intense precipitation in late spring 2013 triggered a landslide in Pechgraben (Upper Austria). The landslide was activated in the night of June 6th and one family house had to be evacuated immediately. The mass movement covered an area of approximately 0.4 km² in total and endangered several family houses of the nearby village. To support the remediation measures a geoelectrical monitoring system was installed immediately (June 7th) on the active landslide, encountering displacement rates up to more than one meter per day, within the first week. In order to monitor the movement and to address the problem of data errors caused by substantial changes in profile geometry, several GPS bench marks and two automatic inclinometers (DMS) were installed. High precision GPS measurements were repeated every day to monitor geometry, displacement and velocity of the mass movement within the first weeks after activation of the landslide. Furthermore, a webcam, soil-humidity sensors and a rain-sensor were installed.

Soon after initiation of the landslide, an airborne geophysical survey (EM, magnetic, gamma-ray) was carried out over the whole landslide area. To support interpretation, some further geoelectrical profiles were measured.

The geoelectrical monitoring profile had to be relocated for two times and reached its final position on August 28th. The Implementation of the geometric information and the application of an innovative 4D inversion algorithm (Kim et al. 2012) led to enhanced interpretation results of subsurface electrical resistivity changes, which supported the remediation measures significantly.

## 17

## Estimation of electrode positions from sparsely distributed reference points for long term geoelectric monitoring of an active landslide

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Recent improvements in the capabilities of electrical resistivity tomography (ERT) in ground imaging have resulted in an increased application of this technique to the characterisation of landslides. Time-lapse ERT offers the possibility to image changes in the resistivity distribution over time, which may indicate hydrological processes triggering landslide movement. However, these measurements depend on knowing the exact locations of the electrodes, which, especially on landslides, are changing over time.
We present and compare three different methods to estimate electrode positions from known locations of sparsely distributed reference points (RP). These methods include techniques estimating the electrode positions by the directional movement of the RP, by the deformation of a local plane that is described by 3 RP, and a more geostatistical approach, kriging.
To validate these techniques we present a synthetic example, in which the true electrode positions can be recovered within the numerical accuracy. Moreover, we present a real data example of a natural, slow moving landslide to which we applied the different techniques. By estimating the electrode positions with the introduced techniques we were able to recover the electrode positions to about 10% of the initial electrode spacing. Additionally, we justify the need for the estimation of electrode positions by showing artefacts in the inverted resistivity models which are caused by incorrect electrode positions and how they disappear if the estimated electrode positions are used.

# 18

# One year time-lapse electrical data to monitor natural hydrological processes acting on a clayey landslide

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Movements of water in the topsoil influence changes in slope stability which is the main controlling factor of landslide triggering. Among the petrophysical parameters that can provide time-lapse sections of the topsoil, we consider the electrical conductivity for its sensitivity to soil water contents.

Based on recent works which showed the possibility of monitoring the hydrological response of a clay-shale slope to a controlled rainfall experiment (Travelletti et al., 2012), we installed a permanent electrical monitoring experiment at the Super-Sauze landslide for long-term monitoring of natural meteorological events. We used the GEOMON4D resistivity meter, developed by the Austrian Geological Survey (Vienna, Austria) for experiments needing high rate of data acquisition, records of full signal samples for noise detection, remote controlled management and automatic data transfer (Supper et al., 2002, 2003 & 2004).

Several hydrological sensors were installed along the profile to measure soil temperature, water temperature and conductivity, ground water level and soil humidity in the vadose zone.

The main challenge is the processing of ca. 4.2 million of electrical resistivity data. In this difficult context, the potential factors influencing electrical resistivity with time without modification of soil saturation are the relative changes in the dipole geometry (linked to the displacement of the electrodes), changes in soil and water temperature, changes in material porosity due to compaction/dilatation caused by the landslide movement. Therefore, before any inversion of data, we verify the presence of possible 3D effects, and assess the measurement accuracy and uncertainty. An apparent resistivity variation threshold, from which a modification of the saturation can be attributed, is determined.

From those first results, we first investigate changes in the apparent resistivity. Responses to different hydrological processes (such as soil freezing/thawing, snow melting, high intensity rainfall, debris flow events) occurring during the monitoring period are detectable on the inversed resistivities over short periods.

The results of the study highlight the difficulty to monitor hydrological changes on a clay-shale landslide, and will permit to improve such future device. Although a quantitative interpretation of the apparent resistivity is impossible, typical responses are clearly detectable and allow a first qualitative interpretation of hydrological changes in the landslide.

# 19

# Time-lapse resistivity measurements in landslide monitoring on example of complex slope deformation Čeřeniště (České středohoří Mts, Czech Republic)

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Studies of complex landslides bring us knowledge on structure and behaviour of individual parts of such slope deformation which can differ in several aspects. In case of Čeřeniště complex slope deformation we can distinguish upper part close to the headwall which is affected by deep-seated gravitational processes such as spreading and block subsidence of basalt blocks and tuffites. Central part is formed by flat block (platform) which is followed by active landslide built by pyroclastics and tuffites.

This study is aimed to the distal, recently active part of the slope deformation. After the ERT survey along the whole deformation (2012), in 2013 resistivity monitoring of active colluvial lobe was implemented in form of a transversal profile. The profile is 189 m long, of which first and last 40 m reach surrounding slopes. Electrode stepping was 3 m, altogether 64 electrodes were used in Wenner-Schlumberger array. Also, Wenner Alpha and Dipole-dipole arrays were tested.

Repeated resistivity measurements with one month period together with the monitoring of precipitation, air and soil temperature and with soil moisture gauges are aimed to bring valuable and detailed information on conditions in the moving earthflow.

Furthermore, using the monitoring of movement velocity based on repeated geodetic measurements and laser scanning we shall be able to determine the causal connection between precipitation, soil saturation and (re)activation of mass movements. The time-lapse resistivity survey would serve as an effective tool which can yield information on subsurface water saturation and its changes and, also, it could help to reveal relations within the system „precipitation – subsurface saturation – mass movement activation“.

The permanent profile was also used as the testing site for other resistivity techniques, such as vertical electrical soundings (VES) and resistivity profiling (RP).

# Time Lapse Data Inversion and Modelling

## 20

## Simultaneous optimization of resistivity structure and electrode locations in ERT

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Electric Resistivity Tomography (ERT) is to visualize subsurface structure in terms of electric conductivity, and is categorized as a geometric sounding using the variations of measured potentials associated with the changes of the locations of current and potential electrodes. Accordingly, accurate coordinates of electrodes are essential in ERT, and electrode mislocation or inaccurate information on electrode positions inescapably results in crucial distortions of the subsurface images. These problems caused by the discrepancy between known coordinates and the true ones of electrodes are much more probable in an ERT monitoring especially performed in an area where ground deformations are expected, such as in landslide monitoring. Without careful considerations of possible movements of electrodes over time, in this case, interpretations may fail to evaluate the ground condition changes. To address these problems, we develop an inversion algorithm that resistivity distribution and electrode coordinates are simultaneously optimized. Using the developed algorithm, we performed numerical experiments based on several scenarios. Firstly, we tested a special case that the subsurface resistivity distribution was known, and almost exact electrode coordinates were calculated. When electrode positions and a resistivity structure are completely unknown and simultaneously inverted, the calculated electrode coordinates are much more erroneous compared to the case when the resistivity distribution is known, but they are reasonably close to the true positions. Furthermore, the reconstructed resistivity image well resembles the ground truth even though the inverted electrode coordinates are still erroneous to some extents. All the numerical experiments show that even with erroneous information on electrode locations, we are able to reconstruct a subsurface image that is close to the ground truth. The developed algorithm will be further combined with a 4-dimensional inversion scheme to precisely evaluate ground condition changes over time particularly when ground deformations cannot be ignored.

## 21

## Time lapse ERT Inversion Incorporating Structural Information

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The interpretation of time-lapse ERT data is complicated by both the presence of noise in the data and the influence of low sensitivity in parts of the model. A uniform space and time constrain is not able to address this problem. In this work, we propose a new approach to distinguish noise-related artefacts to true changes in resistivity, while at the same time addressing the problem of the lack of sensitivity of electrical resistivity tomography with depth. We propose transforming the space and time constrains to be active. We mean that the regularization parameters are distributed rather than being uniform for the entire model. This way, both time-related noise (assumed to be random) in the data and the lack of sensitivity are addressed and we can incorporate prior information in a natural way into the inversion scheme. Moreover, we propose the use of image guided inversion in a time-lapse scheme, where the structural information is used directly from high resolution geophysical methods (e.g. ground penetrating radar or seismic reflexion) or from geological cross-sections. This information then is introduced into the inverse problem through a weighted smoothens matrix, where it correlates and favours formations that belong to a structural feature and not just uniformly to the whole model. Using this strategy, the inversion scheme is able to favour areas where the expected changes are likely to occur while filtering out areas where no changes should occur. The favoured areas can be either selected from a preliminary analysis of the data, or by incorporating other type of prior information into the system based on the process that is monitored.

## 22

## Minimum gradient support and geostatistics regularization approaches for inverting time-lapse data

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Inversion of time-lapse resistivity data allows obtaining 'snapshots' of changes occurring in monitored systems for applications such as aquifer storage, site remediation or tracer tests. Based on these snapshots, one can infer qualitative information on the location and morphology of changes occurring in the subsurface but also quantitative estimates on the degree of changes in certain property such as temperature or total dissolved solid content. Analysis of these changes can provide direct insight into flow and transport processes and controlling parameters. However, the reliability of the analysis is dependent on survey geometry, measurement schemes, data error, or regularization. Except regularization, survey design parameters may be optimized prior to the monitoring survey. Regularization, on the other hand, may be chosen depending on available information collected during the monitoring. Common approaches consider smoothing model changes both in space and/or time. We here propose to use two alternative regularization approaches which may be better suited to invert time-lapse data. The first approach is the minimum gradient support (MGS) regularization, which focus the changes in tomograms snapshots. MGS will limit the occurrences of changes in electrical resistivity but will also restrict the variations of these changes inside the different zones. The second approach is based on geostatistics and requires first to derive variogram parameters for the model changes. In this contribution, we demonstrate the benefits and limitations of these regularization approaches to time-lapse data on numerical benchmarks and three case studies.

# 23

## Time-lapse optimised survey design for geoelectrical resistivity monitoring

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Optimised measurement arrays for resistivity surveys have been shown to provide superior image resolution with no increase in survey time or power when compared to standard array configurations. When applied to monitoring studies, sequential optimisation methods have the potential to increase the resolution further by using previous data and results to guide the design of subsequent surveys. This study describes the application of a sequential design technique to produce optimised time-lapse geoelectrical surveys, which focus a greater degree of the image resolution on regions of the subsurface that are actively changing, compared to conventional optimisation techniques which provide static optimised surveys only.

The sequential design method is applied to a synthetic 2.5D monitoring experiment comprising a well-defined cylindrical target moving along a trajectory that changes its depth and lateral position. The data are simulated to be as realistic as possible, incorporating survey design constraints for a real resistivity monitoring system and realistic levels and distributions of random noise, in order to match a forthcoming experimental test of the method. The results of the simulations indicate that sequentially optimised time-lapse surveys produce an increase in image quality compared to the results of a static (time-independent) optimised survey.

## 24

## Constraining time-lapse ERT inversions by hydrological point measurements

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Static and time-lapse ERT inversions suffer from resolution limitations and the non-uniqueness of the inverse problem. Especially for time-lapse data, the measurement error, its sources and its development over time are difficult to assess. Conservative assumptions about the error and strong regularization lead to underestimation of the time-lapse changes. For static ERT data, structural constraints and discontinuous regularization has been shown to improve inversion results.

Here, we test if hydrological point measurements of fluid conductivity can improve time-lapse ERT inversions. We use data from a $CO_2$ injection experiment in a shallow aquifer that was monitored using surface ERT. Water conductivity measurements are available at 30 locations on the main ERT profile.

We test different types of constraints for the resistivity models to the water conductivity and analyse its effect on the ERT inversions (e.g., data fit, convergence speed) and the images of the $CO_2$ plume (magnitude of change, size and shape of the plume).

# Applications in Hydrology

## 25

## Measurements in a freshwater/saltwater transition zone with an automated electrical resistivity tomography system

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At the North Sea island Borkum the required drinking water is provided by a freshwater lens. In 2009 two vertical electrode systems were installed in the water catchment areas Waterdelle and Ostland to monitor possible changes in the freshwater/saltwater transition zone below the pumps (part of the Interreg project CLIWAT). Each of the two vertical electrode chains is about 20 m long and includes 78 stainless steel ring electrodes (spacing 0.25 m). These systems were installed between about 45 m and 65 m depth. The ongoing measurements are carried out using a modification of the commercial resistivity meter 4point light 10W (Lippmann). The power is supplied by batteries recharged by solar panels. Since end of December 2009 the data are regularly transmitted to Hannover by telemetry.
For the measurements a Wenner-alpha array is used. The data show a clear transition from apparent resistivities of about 80 Ohmm in the upper part of the measuring section around 45 m depth (freshwater) to about 2 Ohmm (saltwater) in the lower part around 65 m depth (spacing a = 0.25 m). Large changes occurred only within the first year of the measurements, i.e. between September 2009 and September 2010; these are due to the readjustment of the local conditions (disturbed by drilling) to the undisturbed situation. Between September 2010 and April 2013 only small changes occurred in all depths, although the resistivity variations in time are different in different depths. Within the last years a very stable situation of the transition zone between freshwater and saltwater has been observed at both locations.

# 26

## Cross-hole ERT monitoring to investigate mixing processes of freshwater injection in a hyper-saline aquifer

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A freshwater injection experiment was carried out in the hyper-saline aquifer underlying the Molentargius-Saline Regional Park located near Cagliari (Sardinia, Italy). The experiment was monitored using time-lapse Electrical Resistivity Tomography (ERT) through five boreholes, which are positioned in a square with an 8 m long side and one borehole in the centre and with a depth of 20 m. All boreholes are equipped with twenty-four stainless steel cylindrical electrodes, separated by 0.8 m. The aquifer sediments are mostly composed of sands with thin layers of silty sand, clayey sand and silty clay. The water table is stable around 5.2 m depth. Electric fluid logs recorded in the boreholes allowed to discriminate two zones, with a transitional layer in between: (a) from the water table to 7.5 m the water electrical conductivity is about 2 S/m; (b) below 12 m depth the water electrical conductivity reaches 18.5 S/m. We injected 19.4 m³ of freshwater using a double packer system positioned in the central borehole, with an injection chamber located between 13 and 14 m depth. The injection rate was only controlled by the natural pressure gradient. ERT monitoring was achieved by measuring along two 2D ERT planes corresponding to the two square diagonals, thus involving three boreholes at a time with a total of 72 electrodes. A mixture of dipole-dipole and bipole-bipole configurations was used in each acquisition. To investigate mixing processes, numerical flow and transport modeling was carried out using a 3D density-driven mixed-FEM/FV aquifer simulator. The injection borehole was simulated as a preferential flow path and the injection was modeled by imposing higher pressure within the injection chamber nodes. Results at different times show a vertical upward migration of the freshwater body as observed in the ERT field experiment. The salt concentration values of the simulations were converted into electrical conductivity using Archie's law and a 3D geoelectrical forward modeling was performed. The inverted synthetic images are compared with the observed ERT images.

# 27

# Monitoring hillslope infiltration on mountainous catchments using ERT and tensiometers

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The knowledge of system-internal water-flow pathways within catchments is of great importance for predicting runoff generation as well as water quality and quantity. To improve the knowledge of subcutaneous flow pathways on hillslopes, hydrometrical measurements are carried out on a small spring catchment in the eastern Erzgebirge since November 2007.
In addition, surface ERT measurements on several profiles were applied to enhance resolution of punctual hydrometric data. From May to December 2008, geoelectrical monitoring in nearly weekly intervals, was implemented to trace seasonal moisture dynamics on the hillslope scale. To getting the link between water content and resistivity, the parameters of Archie's law were determined using different core samples. To optimize inversion parameters and methods, the derived spatial and temporal water content distribution was compared to tensiometer data and showed remarkable coincidence.
As anticipated, the measured resistivity shows a close correlation with precipitation. Depending on the amount and intensity of rain, different depths were affected by seepage water. Three different cases (small, medium, heavy), could be differentiated. A small rain event causes a short interruption of the drying pattern at the surface in summer, while a medium rain event causes a distinctive reaction at shallow depth (< 0.9m) and a heavy rain event results in a response down to 2 m.

## 28

# Electrical Resistivity Tomography Monitoring of a Water Infiltration Test on Johannishus Esker, Sweden

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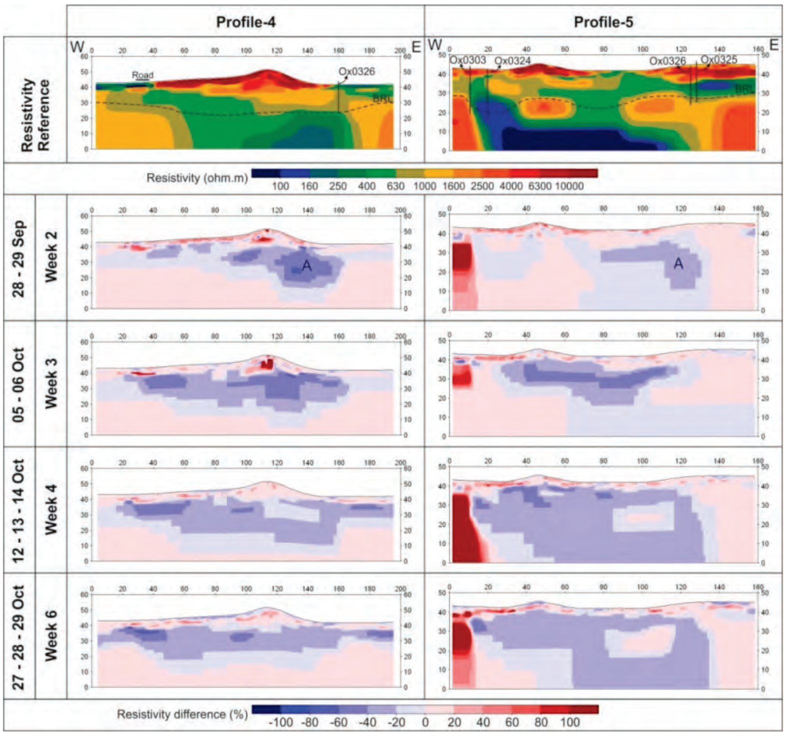
An artificial groundwater recharge (AGR) site constructed on the Johannishus esker (Karlskrona) was monitored with conductivity measurements and electrical resistivity tomography (ERT) during a nine week tracer infiltration test. The aim of the monitoring was to provide a quantitative basis to increase the efficiency of the AGR site. ERT provided useful results to understand the nature of the Johannishus esker and the pathways of the infiltrated water was mapped by time-lapse monitoring. The Johannishus esker follows a tectonically controlled paleo-valley which is evidenced by magnetic data and ERT. During the test, the infiltrated water was detected in the area close to the infiltration ponds, whereas far situated observation wells were less affected by the infiltrated water. ERT monitoring combined with the conductivity tests indicated that the location of the recharge wells and timing of the recharge are important factors for an efficient recharge. Natural groundwater flow direction was a determinant in the infiltration process as expected. The test showed that ERT can be efficiently used to monitor the functionality of the AGR sites. It is both useful for the sustainability of the sites and a good way to increase the knowledge on the AGR's geological, hydrogeological and structural characteristics.



# 29

# SaMoLEG – development of a geoelectrical large scale monitoring system using long electrodes

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Salt water intrusion trough tectonic weakness zones or eroded clay layers threatens the fresh water supply in some regions of northern Europe. The aim of this project is to develop an ERT monitoring system that covers a typical catchment area of water plants using metal cased boreholes as long electrodes (Daily et al. 2004) in conjunction with surface-electrodes.
A first measurement for a static case was made in late 2012 on a 500 x 500 m test site in Müllrose (Brandenburg). The setting consists of 12 boreholes and 7 additional surface-electrodes. A permanent cabling is installed and ready for further time lapse measurements on a field scale. For testing a time lapse approach for Long Electrode Electrical Resistivity Tomography (LEERT) a laboratory experiment was designed. An 88 x 76 x 48 cm aquarium filled with filter gravel was saturated with tap water. Twelve electrodes inserted up to a depth of 20 cm were distributed on a regular 3 x 4 grid with 20 cm spacing. An optimal set of electrode combinations with the highest data importance was calculated. An inflow of a common salt solution mixed with uraninetracer was made on the left side of the tank over the whole front. The saturation with salt water and the following desaturation was monitored by ERT measurements. Inversion results coincide with photographs of the aquarium and prove the effectiveness of the method in a small scale.
3D static inversion results of the test site Müllrose show good agreement with 2D ERT profiles and water samples allowing for first monitoring tests. The time lapse results of the laboratory measurement using the first time step as a base line model show reasonable resistivity distributions comparable to the optical observation.

# 30

# Geoelectrical Monitoring of infiltration processes at two embankment dams during the 100-year flood in Austria

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In June 2013, a “hundred-year-flood” threatened large parts of Austria and caused enormous loss of properties. After the last “hundred-year-flood” in 2002, several communities, especially along the Danube river, had built mobile flood walls or embankment dams, which had to stand the test for the first time. In Lower Austria, the flood started on 1st of June and had its maximum on the 5th with discharge rates of 11000 m³/s instead of usually around 2000 m³/s at Kienstock (Wachau, Lower Austria).

On 5th of June, two geoelectrical monitoring profiles were installed at the embankment dam in Krems (Lower Austria). One profile with 45 electrodes at a spacing of 0.6 m was installed perpendicular to the dam; a second profile with 45 electrodes at a spacing of 1 m was installed parallel to the dam at approximately 30 cm lateral distance to the water level at its maximum. 6 measurements per day were measured until June 11th, when the water level reached almost its normal level. As the measurement of the first geoelectrical section didn’t show any significant indication of infiltration of river water into the dam body, the main focus of the embankment dam monitoring in Krems was on the 3D effect caused by decreasing water level. The 3-D effect leads to an increase of apparent resistivity at a certain depth which corresponds to the area of influence where the water level change took place. Comparison of the results with the 4D-Inversion of theoretical data of a 3D-Model of the dam showed that the magnitude of the 3D-effect is much higher than the expected changes of subsurface resistivity due to infiltration or drying.

Another monitoring site was found at an embankment near Korneuburg (Lower Austria) on June 6th, where a weakness zone had to be investigated. At this time, water level had already started to decrease. 61 electrodes were positioned at a spacing of 0.5 m, whereas the detected weakness zone was located in the middle of the profile. Due to the lack of equipment, only one further measurement (after the flood) could be performed on June 11th. A 4D inversion of the two datasets showed a resistivity decrease at the surface due to infiltration of rain water. At the assumed weakness zone, a strong resistivity increase due to drying of the embankment could be observed.

## 31

## Long-term geoelectrical monitoring for estimation of changes in water content of the slope of an embankment

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For prevention of disastrous slope failures, it is important to be able to monitor changes in water content within a slope in both time and space, because permeating water reduces the strength of the foundation of the slope and increases the likelihood of landslides and base rock collapses. We have conducted repeated monthly geoelectrical surveys since February, 2011, on the slope of an experimental embankment in the large-scale rainfall simulator of the National Research Institute for Earth Science and Disaster Prevention (NIED). The results clearly show seasonal changes in the resistivity structure of the embankment, with resistivity becoming low in the summer wet season and high in the winter dry season. It is obvious that the long-term change in resistivity is greatly affected by the change in temperature although shorter-term changes in resistivity correspond to changes in water content caused by heavy rain. This means that the temperature correction to resistivity is required in order to estimate the water content change from the geoelectrical monitoring data. Therefore we measured the temperature dependency of the resistivity of the soil samples extracted from the embankment. As a result, the empirical formula of the linear relation between resistivity and temperature was acquired. We confirmed that the resistivity corrected by the formula and the water content have a nearly linear relation. This indicates that changes in water content in the slope can be estimated by geoelectrical monitoring in conjunction with temperature correction.

# 32

# Imaging of hydrological processes in a lowland wetland of the Lambourn river, Berkshire, UK

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The River Lambourn and the associated wetlands comprise some of the least impacted chalk river systems in Britain. The associated lowland wetlands, due to their hydrological characteristics, may form a key conduit for, or barrier to, aqueous fluxes between land, rivers and groundwater. At Boxford, Berkshire, UK, a research site has been monitored for a number of years to establish the degree of groundwater and surface water interaction. Recently, two geoelectric monitoring lines have been added and measurements have been repeated every month.
The imaging of shallow processes in a regime where moisture content is hardly changing generates an environment for time-lapse electrical resistivity (ERT) monitoring in which accurately modelling temperature effects and their correction is necessary to define changes caused by hydrological processes. We present the methodology of temperature correction, as well as the corrected resistivity models, which are compared to geotechnical data (i.e. moisture content, water level, soil temperature, bulk conductivity). By applying edge-detection on the inverted, temperature-corrected resistivity models we obtain the thickness of a peat layer throughout the monitoring period. By comparing these thicknesses with dGPS measurements we evaluate the capability of ERT for imaging shrinking and swelling processes of this peat layer.

# Applications in Geothermal Monitoring

## 33

## Reliability of resistivity-derived temperature: insights from laboratory measurements

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This contribution consists in studying the reliability of resistivity-derived temperature, for example from time-lapse electrical resistivity tomography (ERT) surveys. The idea of using temperature as a quantitative tracer is growing in the hydrogeophysical community, especially to simulate geo/hydrothermal systems. However, plenty of physico-chemical processes are influenced by temperature and most of them impact directly resistivity measurements. Therefore, one needs to take them into account to retrieve quantitative temperature estimates from resistivity measurements but, up to now, it is seldom the case. The experiment we conducted consisted in simulating an ERT monitoring of heat storage in a sandy aquifer. We show that using experimental relationships between fluid electrical conductivity and temperature alone does not allow reliable temperature estimates, simply because rock-water interactions are neglected. Worst, from a certain temperature (45°C here), the bulk resistivity starts to increase with temperature although this is not expected from the experimental law. Chemical analyses made on water samples collected during the experiment highlight the importance of accounting chemical reactions (e.g. calcite precipitation with increasing temperature) occurring when temperature changes as well as their kinetics. Finally, other parameters as surface conductivity cannot always be neglected when estimating temperature from resistivity measurements. This means that retrieving reliable temperatures from bulk resistivity measurements (e.g. time-lapse ERT) requires the knowledge of water mineralization as well as the rock / soil mineralogy in order to fully integrate physico-chemical reactions between groundwater and the host rock, for example with a joint inversion scheme.

# 34

# Monitoring temperature changes during heat tracing experiments using electrical resistivity tomography

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Thermal tracing experiments are becoming common in hydrogeology to estimate parameters governing heat transport processes and to study geothermal reservoirs. Electrical resistivity tomography (ERT) has proven its ability to monitor salt tracer tests, but few studies have investigated its performances, both qualitatively and quantitatively, in thermal tracing experiments. In this study, we monitored a heat injection and pumping experiment in an alluvial aquifer using both surface and crosshole ERT. The data sets of the surface profile, located along the main direction of flow, are distorted during injection by an electrical short-circuit through the external pumping-heating-injection experimental set-up. Current is flowing outside the subsurface leading to bad data for electrode dipoles located near the pumping and injection wells. The crosshole ERT panel is perpendicular to the main direction of flow. Difference inversion time-lapse images clearly show a preferential flow path in the bottom of the aquifer related to the presence of a coarse and clean gravel layer. Direct temperature measurements are available in control piezometers during the experiment to validate the ERT-derived temperatures and confirm the spatial pattern of temperature observed with ERT. Breakthrough curves are correctly retrieved in time and difference of 10 to 20% are observed for temperature estimation. The latter requires site-specific petrophysical laws and chemical stability assumptions that must be carefully verified. Our study proves that ERT, especially crosshole ERT, is a reliable tool to follow thermal tracing experiments but also to characterize heat transfer in the subsurface and to monitor geothermal resource exploitations. We also show that surface ERT may be impacted by the survey layout in unsuspected ways.

## 35

## Geoelectric measurements as an efficient monitoring strategy for shallow geothermic reservoirs

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In the context of the national energy transformation the utilization of the near surface underground as thermal reservoir gains increasing importance, particularly with regard to the periodic availability of renewable energies, e.g. of wind and solar. With the growing number of shallow geothermal systems being used in the last two decades, discussions arise about potential negative consequences for groundwater and subsurface environment. Up to now, no consistent economic, political or environmental legislation for utilization of geothermal reservoirs exists (Hähnlein et al. 2012). It is generally stipulated that running geothermal plants may not influence the groundwater regime of neighbouring plots. Conversely, there is still no protocol agreement for a reliable large scale monitoring of geothermal systems. Currently, local temperature measurements carried out in the thermal exchangers themselves are the only monitoring data routinely acquired. Such single point measurements do not allow for a realistic assessment of the effect of geothermal reservoir utilization on groundwater and subsurface environment.

Geoelectric measurements could provide spatially continuous information about geothermal reservoir. Temperature-dependence of electrical resistivity may enable the utilization of geoelectric measurements for time and cost efficient geothermal monitoring. The main challenge would be to find the most simple and adequate electrode configurations and arrangements. In order to validate geoelectric measurements as efficient monitoring method, we conduct different experiments. First, the correlation between the temperature and the electrical resistivity shall be analysed on laboratory scale, taking additional influencing parameters e.g., porosity and water content, into account. Knowing the mutual dependencies between these parameters, we can consequently describe the real correlation between the temperature and the electrical resistivity. When monitoring shallow geothermal plants in the field, additional hydrological features of the underground need to be known. Here, we use data predicted by numerical simulations based on the open source software OpenGeoSys for each field site. These parameters can be used in a forward modelling to find the best fitting electrode arrangement and configuration for each field situation.

# Special Topics of Geoelectrical Monitoring

## 36

## Development of a Geophysical and Geotechnical remote observatory platform

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Creating a remote geophysical-geotechnical observatory platform presents its own unique challenges, which includes the development of robust field instrumentation as well as associated software systems to facilitate the automated storage and processing of very large time series datasets.

Here we describe the development of the BGS ALERT (automated electrical resistivity tomography) system, and associated geotechnical monitoring capability, for end-to-end data capture, storage, data processing, modelling and information delivery. We discuss the instrument architecture and measurement system design, including the practical considerations of power supply and wireless communications at remote field sites. System control (scheduling and data acquisition), data archiving and data processing are also considered in the context of the ALERT database management scheme (DBMS), which has been implemented to automate many of the data processing tasks required for monitoring activities.

We provide examples of the practical deployment of the ALERT monitoring platform for applications including slope stability assessment and groundwater management.

# 37

# Long term ERT monitoring of sinkholes using 3D surface arrays: a laboratory experiment

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Accurate methodologies are required to manage risks linked to land-use planning in covered karst terrains, especially in densely urbanized areas. The main risk lies in the occurrence of sinkholes at the base of buildings or infrastructure. We conducted a laboratory experiment to evaluate the contribution of ERT monitoring in the long term management of such karst risks. After presenting the design of the laboratory experiment, we detail the selected scenarios. The methodology proposed to process the data and manage the inversion results relies on two steps: (1) we estimate the resistivity variations due to measurement and inversion errors based on Monte-Carlo simulations and (2) we define a resistivity changes index for every cell of the 3D model. The methodology is tested on a 3D surface survey including classical array configurations (inline dipole-dipole, equatorial dipole, Wenner-Schlumberger) and optimized survey protocols. Several plastic balls (7, 14 and 21 cm in diameter) are used to model sinkholes of 2.5, 5 and 7.5 m in diameter at depths ranging from the surface to 56 cm, corresponding to a maximum depth of 20 m at the field scale. The PVC tank used for the laboratory experiment was filled with deionized and demineralized water in which NaCl salt was added to reach a 550 ohm.m background resistivity. Variations in water resistivity and temperature during the experiment were monitored using conductivity and temperature probes. Based on the proposed methodology, we draw maps of the deepest detection depths depending on the target size, the array configuration selected and the lateral position of the target (from the centre to the border of the 3D survey).

# 38

# Integrated Geophysical Monitoring for a Reclaimed Land with Geotechnical Investigation

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Geoelectrical monitoring for three months at a reclaimed land by drainage with additive geophysical exploration including MASW, micro tremor and some geotechnical investigation such as CPT (Cone Penetrating Test) and lab tests from drilled core was performed to understand the variation of the physical property of target material. The main purpose of the test is to find any relation between the result of geoelectrical monitoring and geotechnical characteristics, and geostatistical method was applied to integrate different kinds of information. The result showed that the boundaries of layers are distinguished only from the monitoring result and showed very good correlation with the CPT result, but single exploration by MASW did not show any distinct information to recognize the geotechnical boundaries.

## 39

## Adopting 4D resistivity survey to Geocentrifuge for efficient monitoring the inside of the physical model

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In the field of geotechnical engineering, reduced-scale physical modeling is often conducted within a large centrifuge in order to provide correct scaling of the self-weight stresses. The application area of centrifuge modeling has expanded from traditional geotechnical engineering problems to more complex geotechnical systems. Long term electrical resistivity monitoring technique has also been developed for solving various geotechnical and geoenvironmental problems. Because it is easier to make a model than to conduct full-scale tests while the centrifuge also provides more accurate and realistic stress conditions in the model system than a 1-g experiment and resistivity survey can provide additional information for monitoring the inside condition of the model which conventional measurement equipment such as camera and point based sensors cannot easily show, adopting resistivity survey system to the geocentrifuge can be a powerful tool for efficient monitoring study. Additionally, using geocentrifuge can be a good alternative to verify the applicability of 4D resistivity survey as it is difficult to find adequate full-scale verification site. Acrylic plates where many nails are planted by equal interval are used for electrode system. Electrodes are connected to the AGI Supersting 8P installed at the center of centrifuge. Remote interface box is employed to control Supersting 8P from the outside. As the basic step of the study, we performed two cases of geocentrifuge physical modeling combining time lapse resistivity survey. One is for underground saline water intrusion from the ground surface and another is for water intrusion into a levee body during filling with water. Results show the feasibility of the resistivity survey in detecting the change of model condition during geocentrifuge physical modeling.

# Poster Presentations

## P01

### 3D time-lapse ERT monitoring on a small Municipal Solid Waste Landfill cell

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Leachate recirculation is a key process in the operation of Municipal Solid Waste Landfills (MSWL) managed as bioreactors. To observe distribution and diffusion of the water content and to evaluate the performance of leachate pipe injection, in situ methods are required. Electrical Resistivity Tomography (ERT) is usually proposed since the last ten years. However, MSWL are lined by geomembranes, which are perfect electrical insulators, to collect leachate and biogas. These boundaries constituting a high resistivity contrast with the waste body can impact ERT measurements in modifying electrical current circulation and produce resistivity artifacts. In most previous in situ studies, geomembranes were neglected in the inversion process and supposed located far enough from the electrode line. However, the geomembrane location can change the boundary conditions of the inversion models, which have classically infinite boundary conditions. This study is divided into two steps. First, we demonstrate on a small MSWL cell that a standard inversion considering infinite boundary conditions produces many artifacts into the interpreted resistivity models. To improve these results, we propose an advanced inversion solution which consists in introducing the complex geometry and geomembrane location into the inversion tools. Second, these advanced inversion solution are validated on a field data set gathered on a small MSWL cell during a 3D time-lapse ERT monitoring where boundaries have to be taken into account.

# P02

## ERT Monitoring of a Reclaimed Landfill in Thessaloniki (N. Greece)

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In this work we present an ERT monitoring case study which was part of a larger environmental monitoring project regarding the Derveni Landfill situated at the NW outskirts of the city of Thessaloniki (N. Greece). The landfill seized operation in 1989 and was subjected to reclamation in 2006. However, recently, leakage of water polluted with leachate was observed both at a location at the foothills of the landfill as well as at a nearby stream. In order to investigate the local conditions of this polluted water leakage and to find ways to mitigate it, a large scale geophysical and hydrogeological study was commissioned. A dense network of 2D ERT measurements was carried out at larger scales in order to investigate the general site conditions. Further, a dense 3D ERT smaller scale survey was carried out at the area where the leachate leakage was observed. On the basis of the ERT images, ways for mitigating the problem were proposed and as these solutions were implemented ERT measurements were repeated at fixed intervals in order to monitor the progress of the remediation. In this work the results of the time-lapse ERT measurements obtained over this area are presented. Despite the lack of permanent monitoring installation the repeated time-lapse ERT data illustrate that, even at relatively sparse time intervals, they can provide high value and low cost information which is important for evaluating the overall progress of the remediation process.

# P03

## 4D-High resolution ERT for monitoring the nutrient infiltration in biostimulation

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Contamination of the vadose zone by petroleum hydrocarbons (PHC) can be remediated by biostimulation. In biostimulation a nutrient solution containing nitrogen and phosphorus salts is added to the soil to stimulate PHC-degradation by present microorganisms. A homogenous infiltration of the nutrient solution is crucial to reach an optimal degradation of the contaminants. For this purpose one of the 6 existing plots that were established in the project BIOSAN at the "Petroleumhof" (Vienna) for investigation of biostimulation and bioventing was chosen. The test site consisted of an irrigation system 3x3m in size, located around a shallow borehole. Within 120 hours 5 irrigation cycles were conducted with 55mm precipitation depth each, summing up to 275mm in total (comparison: annual precipitation in Vienna 600-900mm). To obtain full depth penetration of the whole investigation site down to a depth of 6m (estimated groundwater level) the ERT survey grid was extended to 9x9m. Choosing a dense network of 1m electrode spacing 100 electrodes were deployed and measurement using the Pole-Pole method were carried out. For the duration of the experiment the ERT system was permanently installed in the field and several measurement cycles in 48h time steps were conducted. The changes and distribution of the resistivity values from time-lapse measurements clearly showed the migration of the infiltrating solution which could be traced with depth in time. In detail a horizon of significantly reduced resistivities (30-50 ohm.m, depending on the permeability of the underlying layer) was mapped which migrated approximately 1m in depth every 48 hours. The results showed that the infiltration front of the nutrient reached a depth of 4 m within the measurement period of 6 days.

# P04

## Application of geoelectrical monitoring techniques at a natural $CO_2$ release site to identify degassing areas and related transport processes

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The complexibility of fluid transport and dissolution processes of $CO_2$ in the subsurface represents challenges in evaluating monitoring methods for leakage detection at Carbon Capture and Storage (CCS) sites. Within the framework of the R&D project “MONACO” (MONACO=Monitoring approach for geological $CO_2$ storage sites using a hierarchical observation concept), surface-based $CO_2$ soil gas concentration measurements in combination with geophysical methods, such as DC geoelectrics, electromagnetic (EMI) and self-potential (SP) measurements, were applied for the mapping and monitoring of $CO_2$ spread in the subsurface and atmosphere within an hierarchical monitoring concept. The applied geophysical methods are used to characterize geological settings and provide insights into the structural features of the covering sediments. Especially, the repeated determination of spatial resistivity distribution in subsurface using Electrical Resistivity Tomography (ERT) is considered to be useful when investigating disturbances caused by variations in lithological parameters and fluid content. In addition, the presence of flow and concentration gradients, $CO_2$ dissolution effects in groundwater and fluid transport ($CO_2$ and $H_2O$) factors influence the measured self-potentials (SP). The investigations were carried out at a natural degassing site, which provides excellent opportunities for evaluating and validating methods used for the detection and monitoring of $CO_2$ migration in the shallow subsurface and leakage into the atmosphere. Since 2009 we have been undertaken geoelectrical monitoring at this test site to gain information about the influence of changing soil properties and meteorological conditions on the diffused degassing process. These measurements indicate that the correlation between environmental, geophysical and soil gas parameters needs to be considered when attempting to give an interpretation about potential migration paths and $CO_2$ leakages.

# P05

## Electrical Resistivity Tomography (ERT) as a permanent monitoring tool to image the $CO_2$ migration at the Ketzin pilot site – Experiences from more than five years of operation

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At the Ketzin pilot site, Germany, electrical resistivity tomography (ERT) is part of a multidisciplinary geophysical monitoring concept, which was established in order to image $CO_2$ injection into a saline aquifer. For more than five years a vertical electrical resistivity array (VERA) is operating as a permanent reservoir monitoring tool at the three Ketzin wells Ktzi200, Ktzi201, and Ktzi202. The VERA system covers the depth range of 590-735 m and was at its time of inception the first and deepest ERT application in a real $CO_2$ injection project globally.
Based on the experience gained so far at the Ketzin pilot site, this contribution reports the essential technical and methodical elements of such a behind-casing electrode installation for tracking the $CO_2$ migration in the subsurface. First, the time-lapse resistivity images allow for valuable interpretations when they are integrated with process data, inverse petrophysical relations, and well logging data. Secondly, the permanent installation can be used for continuous crosshole measurements and periodic surface-downhole surveys (e.g. large-scale DC geoelectrics and controlled-source EM). Thirdly, the ERT array proved to deliver significant information about the presence of $CO_2$ in the well annulus. Forth, a properly calibrated and integrated ERT monitoring system allows for mapping of quantitative $CO_2$ saturation estimates.
Finally, with regard to the required long-term application in $CO_2$ storage projects, the Ketzin ERT concept will be critically evaluated concerning reliability and longevity of the deployed downhole components.

# P06

## Geotechnical properties of $CO_2$ hydrate bearing sediments for $CO_2$ storage in shallow-sea sediments

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Carbon dioxide capture and storage (hereafter CCS) had received attention which may reduce $CO_2$ in the use of fossil fuels. CCS technology was anticipated to contribute 19% of $CO_2$ emission reduction. The cost of $CO_2$ reduction was increased 70% without applying CCS technology. Currently, CCS was required to be a low cost for less than of \$30/t$CO_2$ and to be stored in large quantities. Therefore, the innovative storage technology using $CO_2$ hydrate bearing sediments in the role of cap rock was introduced for solving the problem of high storage-cost and the limit of geological conditions (cap rock). In other words, a fluid-permeability was decreased more than 4~800 times as forming gas hydrate in sediments and these characteristic were used to $CO_2$ geological storage with $CO_2$ hydrate bearing sediments for replacing cap rock. This study presents geotechnical properties of $CO_2$ hydrate bearing sediments using elastic wave and electrical resistivity.

# P07

## Data error quantification for improved time-lapse ERT monitoring of Alpine permafrost

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The development of robust, efficient and remotely controlled measuring equipment has resulted in a renewed interest in the inversion of time-lapse electrical resistivity tomography (ERT) monitoring datasets. In recent years several approaches have been proposed for the inversion of time-lapse ERT datasets including different constraints. However, to date the assessment of ERT data quality and the quantification of data error in monitoring datasets have received only little attention. It is well known that the over-estimation of data error leads to the loss of resolution in the inverted images; whereas its under-estimation results in the creation of artifacts. Hence, the removal of outliers, the quantification of data error and its use in appropriate error models in the inversion (i.e., inverting the data to an adequate error level) is critical in quantitative imaging to optimally balance resolution and reliability of the images. This issue becomes more critical when comparing inversion results computed for different datasets (i.e., collected at different time-lapses) as required in monitoring applications.

The analysis of normal-reciprocal misfit is a well-established approach for the quantification of data error for single datasets. However, not all field conditions or applications permit the collection of reciprocal datasets. Moreover, the extension of the normal-reciprocal analysis for time-lapse measurements has not been thoroughly evaluated and to date there is no model that describes the data error for time-lapse datasets.

Here, we present different approaches to quantify the data error for time-lapse measurements as well as the corresponding inversion results. Measurements were collected at Schilthorn (Switzerland) aiming at the investigation of spatiotemporal processes associated with Alpine permafrost. Data were collected over six years monitoring period on regular intervals and the last year on daily basis. Hence, it is possible to evaluate the application of our methodology for different temporal conditions and time intervals. Our results reveal that the analysis of the ratio between a baseline (i.e., a static model) and the time-lapse data provide the most robust approach for the detection of outliers and for the quantification of the temporal data error. We also propose a linear model to characterize the temporal data error with respect to resistance. The proposed methodology provides inversion results consistent for different monitoring periods and for the two different arrays.

# P08

## Highlights from two years of geoelectrical monitoring of permafrost at the Magnetköpfl/Kitzsteinhorn

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Changes of climate parameters due to global warming generate increased permafrost warming and deglaciation in alpine regions. The area of interest is the Magnetköpfl, a peak below the Kitzsteinhorn (3203 m), where scientists observe increasing rock instability due to the probable degradation of permafrost as well as the decrease of glacier height followed by a lack of counter pressure at the flanks of the slope. Geoelectric measurements are an adequate method to measure permafrost, since the underground electric resistivity is highly dependent on temperature and the amount of unfrozen pore water. In October 2011 a geoelectrical monitoring profile with the GEOMON4D was installed on the north facing ridge of the Magnetköpfl. Measurements of soil temperature on the profile support the interpretation of geoelectric data.

The permafrost at Magnetköpfl starts at a depth of approximately 3m below surface and seasonal temperature variations below 0°C can be observed down to 8-10 m below surface. The two year period of data collection allows us to analyse time series of average apparent resistivities compared with the climatic seasons. It can be seen that different temperature periods have a direct correlation to average apparent resistivity. Inversion results of geoelectrical monitoring data are derived from an innovative 4D resistivity inversion approach (Kim et al, 2013). In three selected events (thawing and freezing in spring, thawing in summer, freezing in fall) difference images of the 4D inversion show the depth range of the temperature influence. Since the temperature sensors at the profile only reach 0.8m bgl., the geoelectrical monitoring data can deliver far more information than single point temperature measurements since the underground electric resistivity is highly dependent on temperature.

The geoelectrical monitoring is supported by the project “TEMPEL”, funded by the Federal Ministry for Transport, Innovation & Technology (BMVIT) and the Austrian Science Fund (FWF): TRP 175-N21 and internal funds of the Geological Survey of Austria. The recording of the soil temperature is conducted in the framework of the MOREXPERT project by the University of Salzburg and AlpS.

## P09

## Assessing the influence of cover crop management on the spatio-temporal dynamic of soil water content under a maize crop by electrical resistivity tomography

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Amongst other functions, cover crops are known to increase the stability of the soil structure. Commonly, their suppression is realized by using conventional tillage, but that it has been demonstrated to damage the soil structure, which directly impacts the soil water content. The proposed alternatives vary in terms of date, depth and type of tillage. As the soil water content is a major factor in agriculture, it is essential to better understand the influence of the cover crop management on its spatio-temporal distribution. Recent studies demonstrated the relevancy of the electrical resistivity tomography (ERT) to estimate the three-dimensional soil water content distribution. However, only a few of them were performed under field conditions. This study aims at (i) validating the use of the ERT method to estimate the soil water content distribution under field conditions (ii) quantifying the influence of cover crop management on the dynamic of soil water content along the growing season of a maize crop and on Belgian soil types. Three types of cover crop management content will be daily monitored: strip tillage, spring tillage and winter tillage. In order to assess the impact of plants on the soil water distribution, an additional plot will be burned after winter tillage. ERT will be used on a surface of 2 m² for each cover crop management. The validation of the average soil water content will be attended by using Time Domain Reflectrometers (TDR) and suction cups. The water stock obtained by ERT will be validated by using data from a weather station for the estimation of the evapotranspiration and rainfall and minirhizotrons for the assessment of the root water uptake.

## P10

## Long Electrode ERT: modeling and field experiment

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The upward surge of saltwater due to a high extraction rate of water plants, tectonic weakness zones or eroded clay layers threatens the fresh water supply in some regions of northern Europe. For monitoring the movement of salt water the usage of borehole measurements is insufficient as only point information can be retrieved. Our aim is to develop a monitoring system that uses boreholes as electrodes (Long Electrode ERT - LEERT) in conjunction with surface-electrodes. As a first step we conducted synthetic analysis using Finite Element Method and the Complete Electrode Model in order to obtain a better insight on the influence of long electrodes ERT measurements. At this stage we investigated sensitivity distributions, the effect of changing contact impedances and simple resistivity distributions on a four point array and multi electrode settings. These analyses showed that surface electrodes have to be incorporated while conduction long electrode ERT measurements to enhance the vertical resolution. The synthetic study showed that an effect of changing contact impedances only takes place for large differences of about three to four orders.

# P11

## Time-lapse ERT monitoring of changes in groundwater content and flows in an epikarst system: implementation and challenges

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Present knowledge of karst systems has evidenced the importance of the unsaturated zone on the water dynamics. Karst Aquifer ReseArch by Geophysics (KARAG) project aims at leveraging our previous experience in karst, hydrogeology, gravimetry and geophysics to understand the water dynamics and storage in the unsaturated and epikarst zones of a karst system, which are the lesser known part in the karst water balance and dynamics. For a better understanding of the infiltration processes within the epikarst, a continuous monitoring of spatial and temporal changes in the water content within the epikarst is necessary. An ERT monitoring system is needed to image, at least on a daily basis, the spatial variability of resistivities due to the complex geometry of the epikarst. We present here a state of progress of the project focusing on the implementation of such a monitoring system at the Rochefort Cave Laboratory (Belgium). Onsite ERT response was tested on different locations by achieving different 2D profiles and 3D layouts. Some additional monitoring tools are required as well. A network of buried temperature sensors is needed to correct for thermal effects on resistivities. Flow recorders inside the cave are useful to monitor discharge, temperature and conductivity of the water that percolate throughout the epikarst. The ground moisture will also be monitored locally through a network of time domain reflectometry (TDR) and water conductivity probes. Finally, gravimetric measurements will also provide valuable insights on changes in the soil water content.

# P12

## Imaging and characterization of crop root systems using electrical impedance tomography at the rhizotron scale

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A better understanding of root-soil interactions and associated processes is essential to achieve progress in crop breeding and management, prompting the need for high-resolution and non-destructive characterization methods. To date such methods are lacking, in particular for characterizing root growth and function in the field. A promising technique in this respect is electrical impedance tomography (EIT), which utilizes low-frequency electrical conduction and polarization properties of the subsurface in an imaging framework. We investigated the capability of EIT to image crop root systems in a series of laboratory rhizotron experiments. Multi-frequency (450 mHz – 45 kHz) EIT data were collected with the tomographic acquisition system EIT40 over a span of 3 days with a high temporal resolution, and the corresponding EIT images were computed using the complex resistivity inversion code CRTomo. The electrical imaging results, including derived parameters describing the spectral response, exhibit a good agreement with the plant structure observed via photographs. Also, the polarization effects show a steady decline which corresponds to physiological processes within the root system due to a deficit of nutrients in the rhizotron (also evident in the photographs). The results demonstrate the non-invasive capability of EIT to image root systems at the rhizotron scale and suggest that EIT can be developed as a tool for imaging, characterizing and monitoring of crop roots at the field scale. The presented work is part of the subproject ImpTom funded by the DFG within the research unit FOR 1320 "Crop Sequence and Nutrient Acquisition from the Subsoil".

# P13

## Time-lapse inversion of daily ERT data from eight weeks Super Sauze landslide monitoring

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The Electrical Resistivity Tomography (ERT) can be used to monitor the variation of the water content and water flow in landslides. Understanding the spatial and temporal changes of the water content and the preferential flow paths is of great interest, because hydrology is an important triggering factor for landslide dynamic processes.

The research presented here is part of a larger field experiment conducted at the Super-Sauze landslide, which objective is the characterization of the existing relationship between small fracture processes and slope movement, fissure development and pore pressure build-up.

In this study, ERT measurements arranged in a Wenner configuration were carried out at the clay-rich Super-Sauze landslide (South French Alps) over a period of eight weeks in order to identify temporal and spatial variations in water content. The investigated area exhibits the highest landslide dynamics at the site, with average displacements greater than 0.01 m/day. One of the studied profiles is 100 m in length and has electrode spacings of 1m, whereas the other two are both 12.5 m in length and have electrode separations of 0.25m.

To analyse the collected electrical resistivity data, a time-lapse inversion was implemented. Heavy rainfall events occurred in the monitored period can be clearly observed in the presented results.

## P14

## Methodology to point out significant changes in resistivity en IP responses for time-lapse experiments assessed on a synthetic model

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Risks management of contaminated sites may require accurate mid and long term monitoring methods. Electrical Resistivity Tomography in time-lapse mode is frequently used for the monitoring of time-varying processes. Nevertheless, it is tricky to identify significant changes in resistivity and chargeability when the processes vary slowly in time. A new methodology is proposed to estimate the background and to point out significant changes in resistivity and chargeability. This method consists in the estimation the resistivity and chargeability confidence intervals of each model block based on Monte-Carlo simulations. To evaluate this methodology, synthetic models which simulate the evolution of geoelectrical properties at different time were created. This validation is based on two steps. In the first step, background model uncertainties have to be estimated for every block of the model to generate confidence intervals of each model block based on Monte-Carlo simulations. The time-lapse sections stimulated will be compared to this background model. We postulate that each resistivity is affected by an error which follows a normal distribution. The resistivity variations are obtained through random draws of the error that is assigned. The second step is to determine to what extent the observed changes are significant or not and to quantify significant variations.

# P15

## More crop per drop? Exploring root uptake under high frequency irrigation using electrical resistivity tomography

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In water-scarce countries, irrigation of agricultural crops is imperative. In many countries, precision irrigation has been adopted, since it provides water exactly in the root zone of the plant. However, the frequency of irrigation is not always well adapted to the dynamic water needs of the plant over the day and over the growing season. This is because it is difficult to assess the soil moisture status with both high spatial and temporal resolution. In this study, we investigated how high frequency irrigation of bell peppers (*Capsicum annuum L.*) changes the soil moisture dynamics and more specifically, the root water uptake dynamics in space and time. We did this by combining a non-invasive imaging technique with classical sensors and plant parameters. The results of this study can give direct guidelines for precision farming, but can also be used to gain a better understanding in the mechanisms of root water uptake under high evapotranspiration demand and irrigation.

The results are ongoing research. However, they show already that (i) there are important differences in soil moisture depletion between the low- and high-frequency irrigation and (ii) 3-D ERT gives interesting, additional information on the spatial distribution of water infiltration and root water uptake. Further data analysis will allow us to check the water balance, compare the results of the different methods and show in more detail how different irrigation practices affect water use efficiency.

## P16

## 3D ERT interpretation of a segment of Sudetic Marginal Fault: towards recognition of fault kinematics using resistivity survey and trenching

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Sudetic Marginal Fault is one of the most prominent tectonic structures, limiting Bohemian Massif on the NE. This fault can be traced both in the morphology and in geological structures and spans more than 140 km from Hrubý Jeseník Mts. towards NW.

Recently, an extensive systematic research has been launched, aiming particularly to understanding the faulting history with possible implications to the potential future hazard. The fault and its vicinity was studied directly by trenching, however, it was impossible to cover area large enough to track the position of different geological units, forming the surroundings of the fault.

The ERT was used to extrapolate the knowledge on lithology distribution around the trenching site, covering approximately area 600 x 300 m. Altogether, 25 ERT profiles using Wenner-Schlumberger array were measured in an irregular network, with the highest density around the trenching site. The measured profiles were inverted using Res2DInv64 software by Geotomo.

The 3D compilation of more than 30 000 measured resistivity points, forming one of the largest ERT datasets in such a small area, was processed in Voxler 2, using a 3D interpolation algorithm. As a result, an interactive blockdiagram of resistivity distribution was created and visualised, showing the 3D distribution of lithological units around the fault. The two main units, weathered crystalline rocks and Miocene clays have suitably very different resistivity (200-800 Ωm vs. 10-80 Ωm). Another unit important for interpretation consisted of rather high-resistivity (>1500 Ωm) alluvial deposits, covering the bedrock under thin layer of soil.

Due to that significant resistivity response difference, it was possible to trace the fault within the modelled block. Furthermore, the fault-cut and displaced alluvial deposits allowed, together with absolute dating and the results of the trenching, to reconstruct the offset amount and slip rate of the late Pleistocene/Holocene faulting.

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