Time-lapse capacitive resistivity imaging: A new technology concept for the monitoring of permafrost

Introduction
The British Geological Survey, in partnership with the Universities of Sussex and Bonn, is investigating and working to prove a new technology concept for the non-invasive volumetric investigation and monitor temperature of the thermal state of permafrost (Periglacial Concepts). A key incentive is to develop new methods for measuring permafrost temperatures. Quadrupole capacitance imaging (QCI) is based on the use of two galvanic sensors in order to emulate Electrical Resistivity Tomography (ERT) methodology, but without the need for galvanic contact on frost core or rock. Several new features have shown that temperature-calibrated ERT using galvanic sensors (Figure 1) is capable of measuring corrosion and of sections of rock permafrost in response to the ambient temperature regime. However, the use of galvanic sensors has been found to be subject to practical limitations. For example, measurements are subject to high levels of noise from unknown stray capacitance between sensors and noise sources to the detriment of the data quality. The capacitive technology developed here overcomes this problem and provides a more robust means of measuring high-quality resistivity with permanently installed sensors over time. Reducing the uncertainty associated with the transition from galvanic sensors increases the order of magnitude for CRI sensors in the context of monitoring permafrost.

Feasibility of 4D CRI
4D CRI is a new method of limited size to map the use of dense capacitive sensor networks installed across the accessible surface of a sample. Besides the technical challenges of designing and constructing a practical system electronics that can utilize multi-sensor geometry for spatially detailed capacitance resistivity measurements, there were initial issues about the feasibility of measuring accurate measurements with such dense arrays of capacitive sensors. Potential pitfalls are:

- Potential CRI theory is based upon a pair of point approximation, so that conventional ERT methodology is not applicable to CRI measurements. Although sensor arrays and calibration technologies might affect individual measurements of the complex transfer function.
- The use of finite-size plate sensors to image a wide range of limited extent might cause geometric error that could jeopardize the validity of the reconstruction and hence the effectiveness of the method.
- The expected sensor capacitance involved are very small but of the order of 0.1 pF, yet the methodology allows a range between 30 and 50 kHz. This poses particular challenges to the design of a capacitance current sources.

ERT synthetical modelling
We have simulated 3D ERT imaging of a sample with dense networks of electrodes, in order to test the sensitivity of such imaging techniques to the advance and recession of a strongly temperature gradient (permafrost table). The BERT software based on unstructured finite element analysis (Kuras et al., 2006) was used to carry out the synthetic modelling. An array geometry with a total of 128 sensors, distributed across the four vertical faces of the sample, was employed (cf. Figure 4). We expect to use this geometry for our future measurements as well as conventional DC measurements.

Concept
For quick to apply, 4D CRI (CD imaging with time) as well as conventional ERT to laboratory experiments stimulating/animating permafrost growth, permafrost and those in both in situ (Figure 6). The Periglacial Concepts Laboratory at the University of Sussex is being used, which is a unique facility for our experimental work carried out during 2011/2012. We expect our temperature-controlled geophysical imaging approach (Rücker & Günther, 2011) to provide new insights into the formation mechanisms of permafrost and the development and rate of permafrost in the bedrock.

Water saturated samples of limestone and chalk (400 mm high, 200 mm 200 mm wide) of varying porosity are being measured. The lower half of each sample is maintained at temperatures below 0ºC simulating permafrost and the upper half is cycled above and below 0ºC simulating seasonal thermal forcing and thawing of the surrounding epilithic layer. Samples are instrumented with both capacitance and conventional galvanic sensor arrays (Figure 2). In order to capture how changes occur in resistivity, the two imaging systems in the samples are incrementally decreased during 10 successive freezes to model active layer in order to test all functionalities of the periglacial instrumentation as well as to calibrate using synthetic resistivity measurements on the samples, for which P100 and TDR sensors are used.

Prototype instrumentation
Capacitive resistivity instrumentation has so far been used for measurements in the laboratory, which will allow us to validate capacitive data acquisition for the basic science experiments in the laboratory. This prototype instrumentation has so far been used to demonstrate the feasibility of measuring capacitance imaging (Kuras et al., 2006) on a range of limited extent. Here, a prototype array was attached to the samples (Figures 5 and 6), which were then fully hydrated. Capacitive measurements were repeated in air at any required conditions. The sample was then frozen and measurements were repeated. Results were found to be incompatible with corresponding ERT measurements on the same sample. Further measurements are planned on Montereau limestone samples described by Kraus et al. (2010).

Temperature calibration
Capacitive experiments were carried out after a quantitative assessment of the temperature distribution in the rock samples from the geophysical imaging data. The freezing lab at the University of Sussex was used for this purpose. Both mediums were used on velocity of Tuffeau Chalk samples were determined in function of temperature across a range between -0.5ºC and 20ºC (Figure 6). Resistance shows a strongly temperature dependent to a non-linear mechanism for the freezing lab. We expect to be able to use the geometry for our future measurements as well as conventional DC measurements. Enhanced and invasive measurements as repeated to a results to be found of the order of 0.1 pF (differential, per sample). After thermal measurement in the samples, the system is calibrated and the system is sufficiently accurate to assess the measurement of 3D CRI imaging concept.

Conclusions and outlook
Early results of our work have been encouraging and we are confident that the capacitive imaging techniques developed here will well complement the DC resistivity imaging of permafrost rock samples. We expect that the methodology will allow us to obtain calibrated images of the temperature distribution in the sample experiments stimulating permafrost growth, permafrost temperatures as well as a temperature sensor array that can be used to monitor the temperature changes and the evolution of permafrost area over time. At this point, the methodology should be able to the new generation of the methodological output of electrical effects.

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References
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