British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

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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 seeking to prove a new technology concept for the non-invasive volumetric imaging and routine temporal monitoring of the thermal state of permafrost (Figure 1), a key indicator of global climate change. Capacitive Resistivity Imaging (CRI), a technique based upon a low-frequency, capacitively-coupled measurement approach (Kuras et al., 2006) is applied in order to emulate Electrical Resistivity Tomography (ERT) methodology, but without the need for galvanic contact on frozen soils or rocks. Recent work has shown that temperature-calibrated ERT using galvanic sensors (Figure 2) is capable of imaging recession and re-advance of rock permafrost in response to the ambient temperature regime. However, the use of galvanic sensors can lead to significant practical limitations on field measurements due to high levels of and large variations in contact resistances between sensors and the host material as it freezes and thaws Figure 3). The capacitive technology developed here overcomes this problem and provides a more robust means of making high-quality resistance measurements with permanently installed sensors over time. Reducing the uncertainty associated with uncontrolled noise from galvanic sensors increases the value of time-lapse ERT datasets in the context of monitoring permafrost.

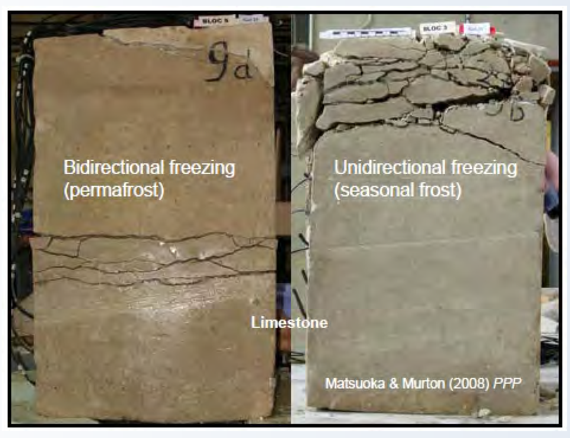

Figure 1: Rock samples subjected to experiments simulating permafrost growth, persistence and thaw in bedrock

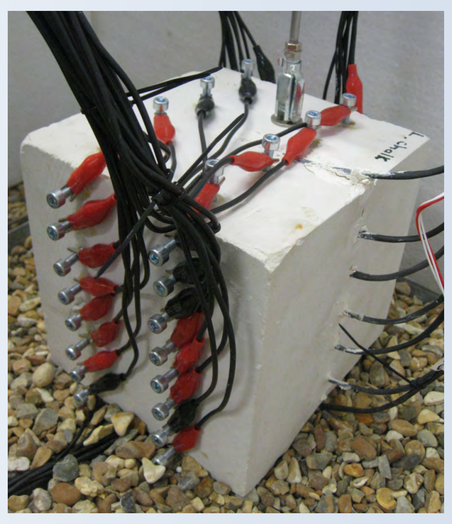

Figure 2: Rock sample instrumented with conventional ERT electrodes (galvanic coupling)

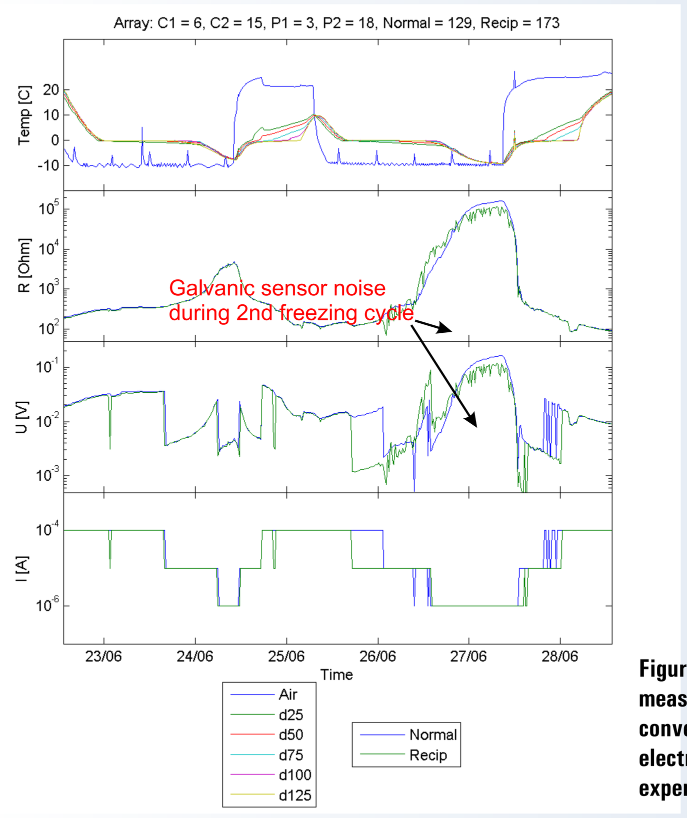

Figure 3: Resistance measurements over time with conventional galvanic electrodes during freeze-thaw experiment on a rocksample

Concept

Our goal is to apply 4D CRI (3D tomography with time) as well as conventional ERT to laboratory experiments simulating permafrost growth, persistence and thaw in bedrock (Figure 1). The Permafrost Laboratory at the University of Sussex is being used, which is a unique facility designed specifically to carry out large-scale rock freezing experiments. A methodology investigating the process of bedrock fracture by ice segregation was pioneered there (Murton et al., 2000; 2001; 2006), which forms the basis for our experimental work carried out during 2011/2012. We expect our temperature-calibrated geophysical imaging approach (Krautblatter & Hauck, 2007; Krautblatter et al., 2010) to provide new volumetric insight into and quantitative control over the fate of permafrost in bedrock.

Water-saturated samples of limestone and chalk (450 mm high, 300 mm x 300 m wide) of varying porosity are being monitored. The lower half of each sample is maintained at temperatures below 0°C (simulating permafrost) and the upper half is cycled above and below 0°C (simulating seasonal thawing and freezing of the overlying active layer). Samples are instrumented with both capacitive (Figure 4) and conventional galvanic sensor arrays (Figure 2) in order to compare results between both resistivity methods. Time-lapse imaging of the samples is undertaken during ~ 10 successive freeze-thaw cycles of the model active layer in order to test all functionality of the prototype instrumentation.

Experimental control and calibration of resistivity images is provided by simultaneous temperature and moisture content measurements on the samples, for which Pt100 and TDR sensors are used.

Figure 4: Rock sample instrumented with a capacitive sensor network allowing 4D capacitive resistivity imaging. A wetting front is clearly visible.

Feasibility of 4D CRI

4D CRI on a rock sample of limited size requires the use of dense capacitive sensor networks installed across the accessible surface areas of the sample. Besides the technical challenges of designing and constructing a practical system architecture that can utilise multi-sensor geometries for spatially distributed capacitive resistivity measurements, there were initial concerns about the feasibility of making accurate measurements with such dense arrays of capacitive sensors. Potential pitfalls are:

- Preferred CRI theory is based upon a point pole approximation, so that conventional ERT methodology (DC interpretation schemes) becomes applicable to CRI measurements. Mutual inter-sensor coupling and stray capacitances might affect individual measurements of the complex transfer impedance.
- The use of finite-size plate sensors to image a 3D volume of limited extent might cause geometric errors that could jeopardise the validity of the reconstruction and hence the effectiveness of the methodology.
- The expected sensor capacitances involved are very small (of the order of 20 pF), yet the useful frequencies of operation lie in a range between 10 and 50 kHz. This poses particular challenges to the design of a capacitive current source.

ERT synthetic modelling

We have simulated 3D ERT imaging of rock samples with dense networks of electrodes, in order to test the sensitivity of such imaging geometries to the advance and recession of a strong temperature gradient (permafrost table). The BERT software based on unstructured finite element meshes (Rücker et al., 2006; Günther 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 be able to use this geometry for capacitive as well as conventional DC measurements.

Forward and inverse calculations were carried out for a range of vertical positions of the permafrost table, which was assumed to advance vertically as a flat plane throughout the sample. A scheme of bipole-bipole measurements was made across the sensor network, and resulting resistances were presented to the inversion algorithm to try and recover the position of the permafrost table in the forward model. Examples of inverse resistivity models for permafrost tables located at different depths from the top of the sample are shown in Figure 5.

At first glance, the capacitive sensor array envisaged here (Figure 4) clearly violates the point source assumption of DC resistivity algorithms, and it is not immediately obvious that this approach of using DC forward and inverse modelling algorithms is permissible. The approach can be critically appraised by incorporating the finite size electrodes into the forward and inverse calculations. This is the object of the "Complete Electrode Model (CEM)" method incorporated into the BERT algorithm and described by Rücker and Günther (2011).

Differences in the results associated with the use of plate electrodes as opposed to point electrodes were found to be of the order of 2 to 5% (Günther, pers. comm.). We are therefore encouraged that simulations based on point electrodes will be sufficiently accurate for the assessment of 3D CRI imaging scenarios.

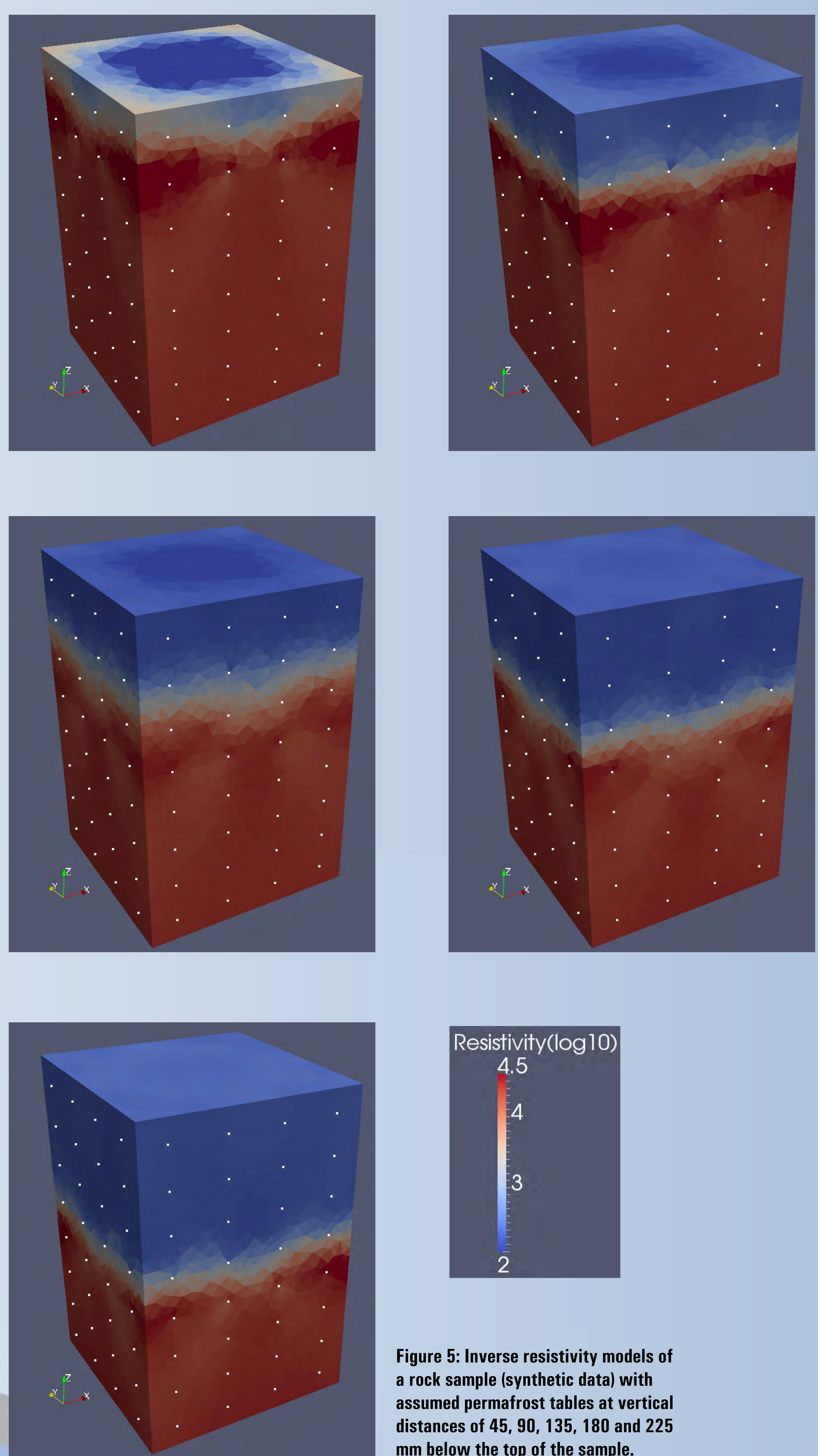

Figure 5: Inverse resistivity models of a rock sample (synthetic data) with assumed permafrost tables at vertical distances of 45, 90, 135, 180 and 225 mm below the top of the sample.

Prototype instrumentation

Capacitive resistivity instrumentation at the field scale has been in existence for some time. This project has developed prototype multi-sensor instrumentation for measurements at the sample scale, which will allow us to undertake capacitive data acquisition for the freeze-thaw experiments in the laboratory. This prototype instrumentation has so far been used to demonstrate the feasibility of making capacitive measurements on samples of Newhaven Chalk (source: Test Valley, Hampshire, UK) and Tuffeau Chalk (source: Caen, France). A four-plate sensor array was attached to the samples (Figure 6), which were then fully hydrated. Capacitive measurements were made in dry and saturated conditions. The samples were then frozen and measurements were repeated. Resulting resistivities were found to be compatible with corresponding DC resistivity measurements on the same samples. Further measurements are planned on Wetterstein limestone samples described by Krautblatter et al. (2010).

Figure 6: Prototype CRI instrumentation attached to sample of Newhaven Chalk, which has been instrumented with a four-plate capacitive sensor arrangement to determine resistivity.

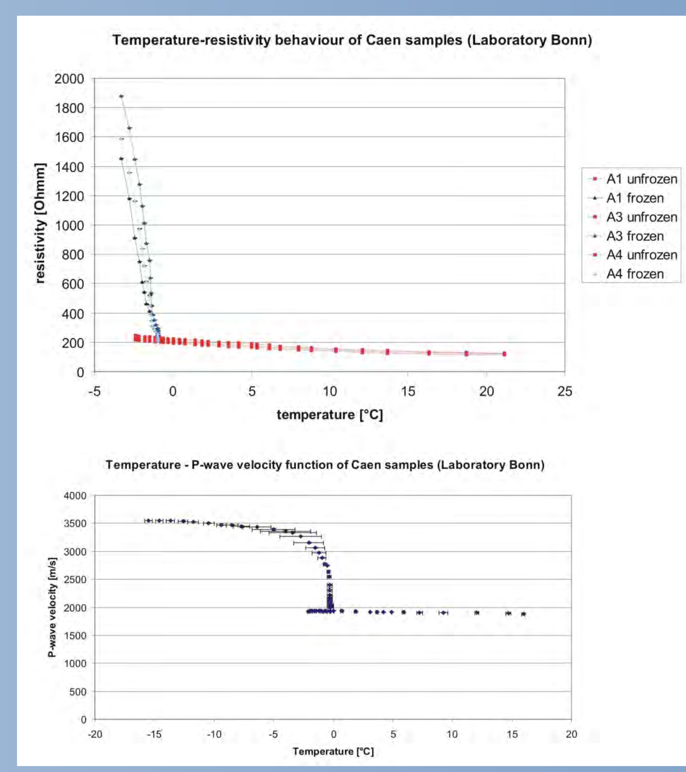

Figure 7: Resistivity and p-wave velocity as functions of temperature for a sample of Tuffeau Chalk derived from calibration measurements.

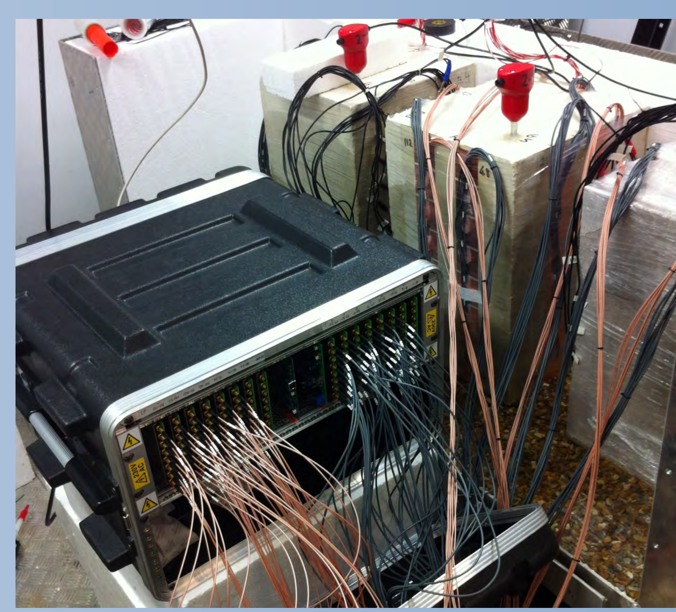

Figure 8: Prototype CRI instrumentation deployed in the permafrost lab at the University of Sussex.

Temperature calibration

Calibration experiments were undertaken to allow a quantitative assessment of the temperature distribution within the rock samples from the geophysical imaging data. The freezing lab at the University of Bonn was used for this purpose. Both resistivity and p-wave velocity of Tuffeau Chalk samples were determined as functions of temperature across a range between -15°C and 20°C (Figure 7). Resistivity shows a strongly bilinear behaviour divided by an equilibrium freezing point at approximately -0.5°C. The results indicate that below -0.5°C, temperature will dominate changes in resistivity while geological parameters become less important. As a consequence, ERT can be expected to show recession and readvance of frozen conditions in rock in correspondence with temperature data.

Conclusions and outlook

Early results of our work have been encouraging and we are confident that the capacitive imaging technology developed here will usefully 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 during experiments simulating permafrost growth, persistance and thaw. The capacitive measurement principle should help reduce the uncertainty in ERT monitoring data due to variations in contact resistance, thus adding value to the geophysical monitoring of permafrost-affected rocks.

Acknowledgements

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