British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

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The use of capacitive resistivity imaging (CRI) for monitoring laboratory experiments simulating permafrost growth, persistence and thaw in bedrock

Introduction

Understanding the impact on bedrock properties of permafrost degradation as a result of climate change (Figure 1) is of major interest in a number of areas, including the assessment of rising instability of high-altitude mountain rock walls. The remote sensing of rock walls with the primary aim of monitoring the spatial and temporal behaviour of rock temperature (and thus permafrost distribution) is an emerging field of research for geohazard mitigation where geophysical tomography has the potential to make a significant and lasting contribution. Recent work has shown that temperature-calibrated Electrical Resistivity Tomography (ERT) using galvanic sensors is capable of imaging recession and re-advance of rock permafrost in response to the ambient temperature regime, yet the use of galvanic sensors can impose practical limitations on field measurements (Figure 2). In this study, we evaluate the use of Capacitive Resistivity Imaging (CRI), a technique based upon low-frequency, capacitively-coupled measurements across permanently installed multi-sensor arrays (Kuras et al., 2006), in order to emulate well- established ERT methodology, but without the need for galvanic contact on frozen soils or rocks. The latter is associated with high levels of and large variations in contact resistances between sensors and the host material as it freezes and thaws (Figure 3).

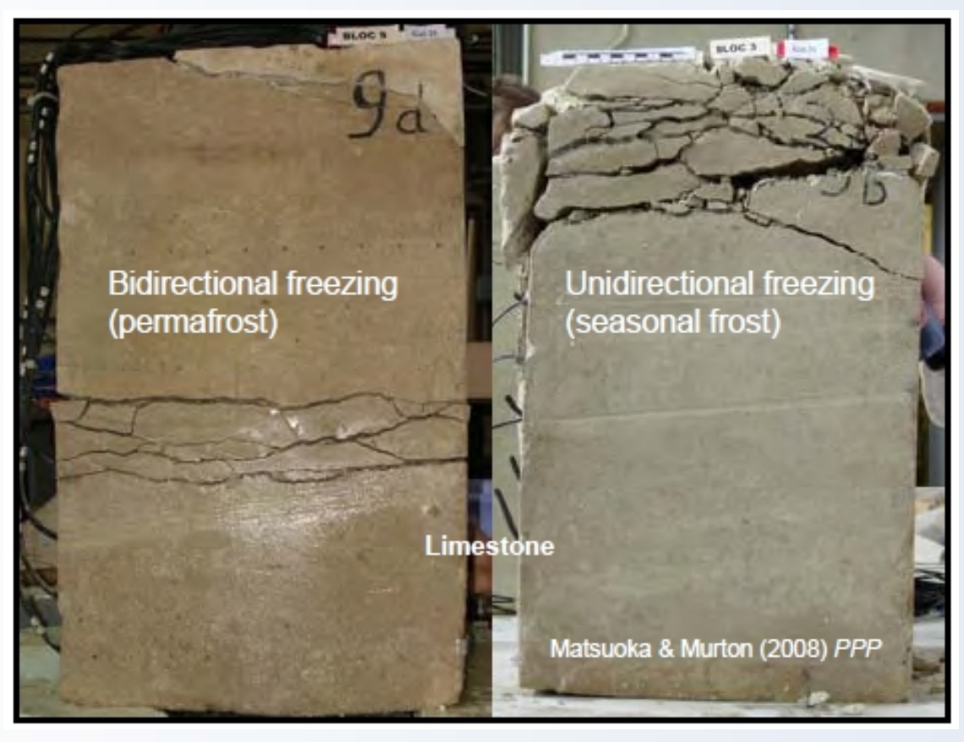
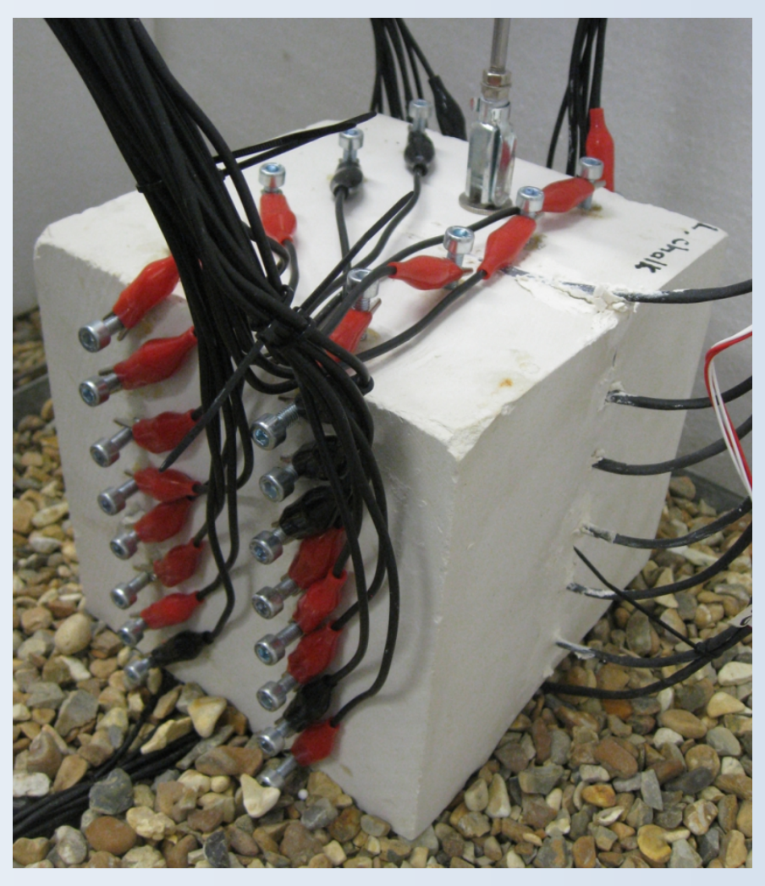


Figure 1: Rock samples subjected to experiments simulating permafrost growth, persistence and thaw in bedrock

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



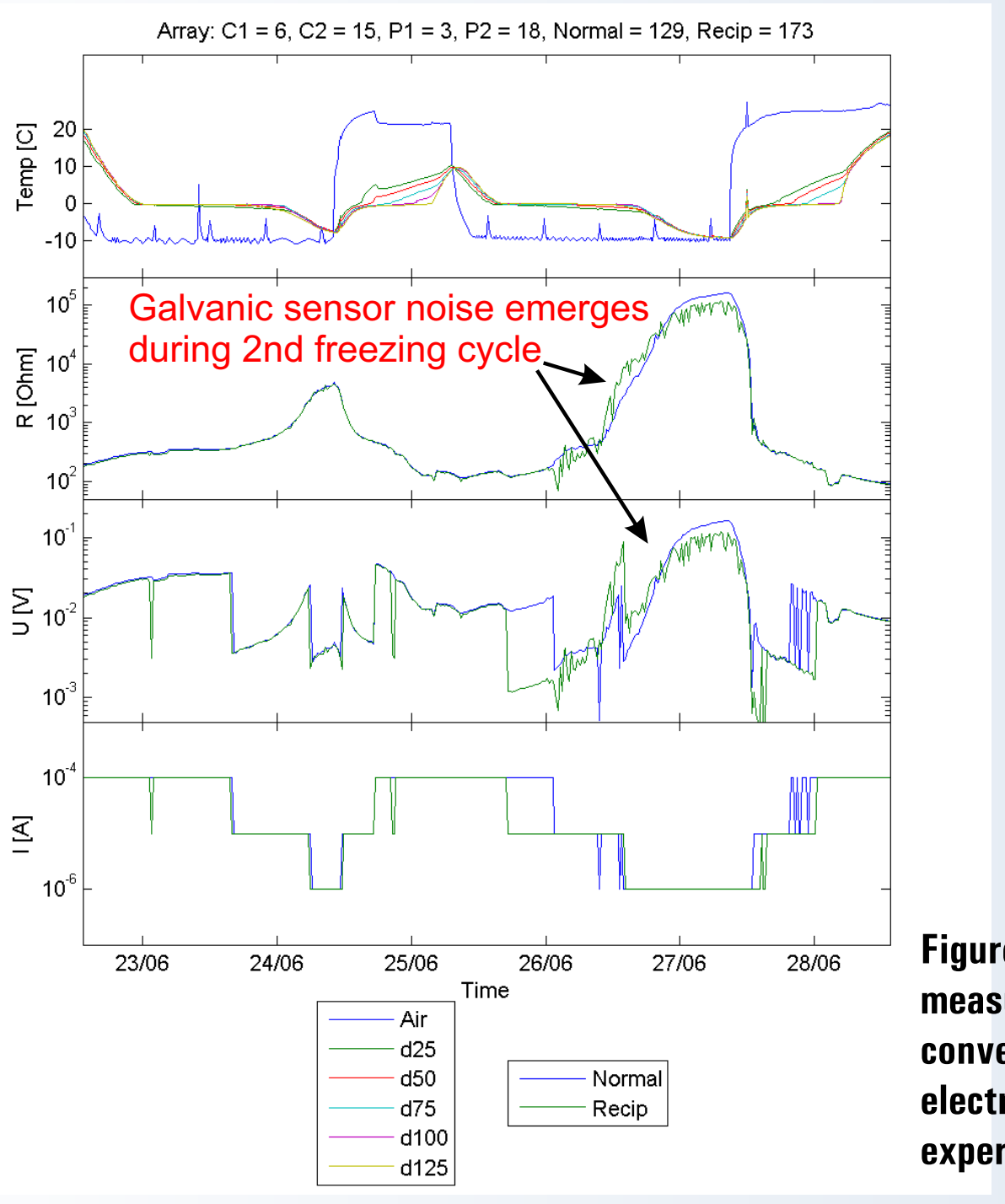


Figure 3: Resistance measurements over time with conventional galvanic electrodes during freeze-thaw experiment on a rocksample

Experimental concept

We apply 4D CRI (3D tomography with time) as well as conventional ERT to controlled long-term laboratory experiments simulating permafrost growth, persistence and thaw in bedrock (Figure 1). We use the Permafrost Laboratory at the University of Sussex, which is a unique facility designed to carry out large-scale rock freezing experiments under permafrost conditions. 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. We expect temperature-calibrated geophysical imaging (Krautblatter & Hauck, 2007; Krautblatter et al., 2010) to provide enhanced quantitative understanding of permafrost processes 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 (Figures 4,5) and conventional galvanic sensor arrays (Figure 2) in order to compare results between both resistivity methods. Time-lapse imaging of the samples during successive freeze-thaw cycles of the active layer is carried out to prove the functionality of prototype multi-sensor CRI instrumentation developed for this purpose (Figure 4). Experimental control and calibration of the resistivity images is being provided by simultaneous temperature (Pt100) and moisture content (TDR) measurements on the samples.

The experimental setup (Figure 5) comprises one tank with three samples where two-sided freezing is simulated; a second tank with three further samples simulates one-sided freezing. Our aim is to investigate:

- influence of freezing direction
- influence of rock type
- proof of concept: CRI can image samples in 3D
- investigate equivalence between DC and CRI

Figure 4: Prototype multisensor CRI instrumentation developed at BGS.

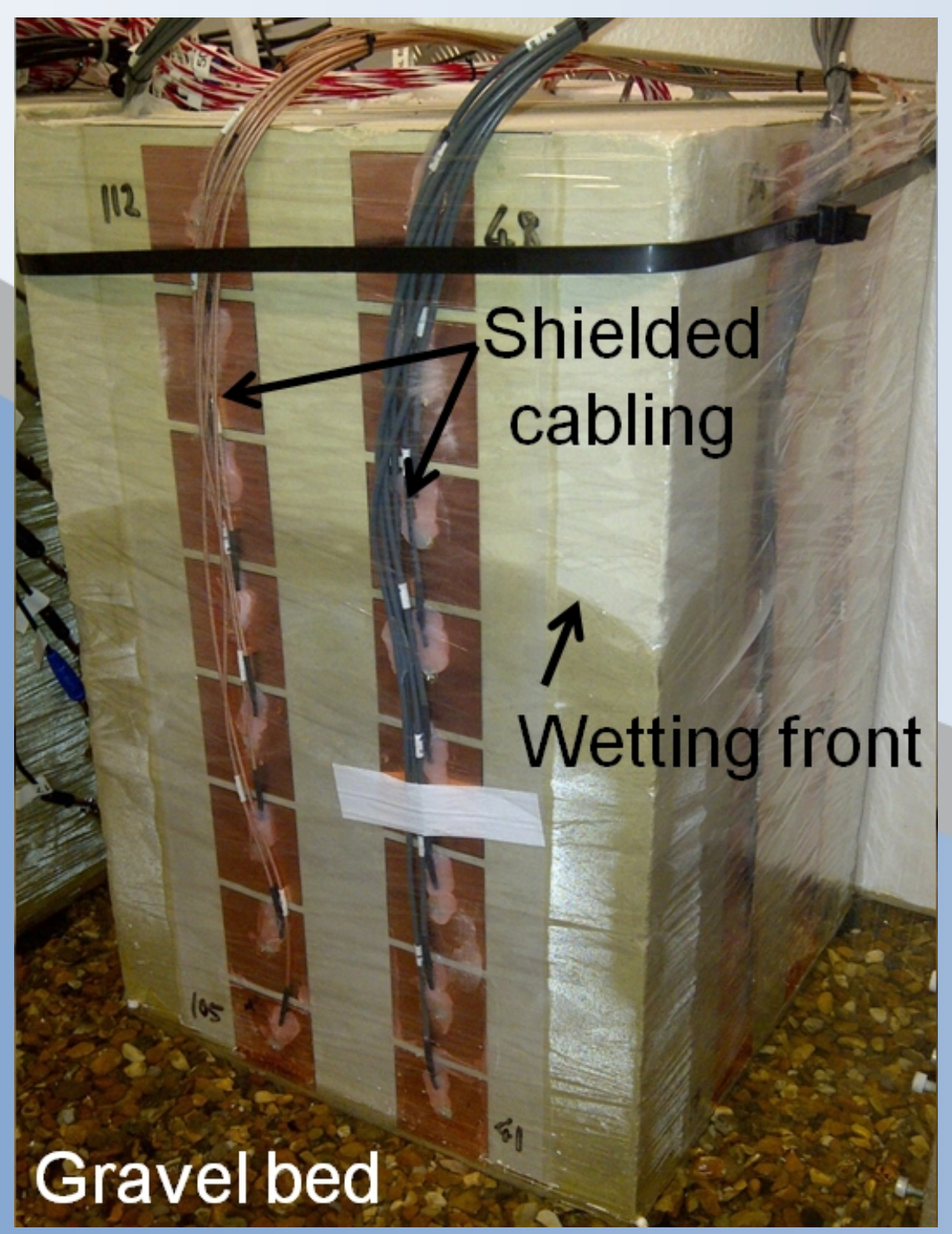


Figure 5: Rock sample (Tuffeau Chalk) during hydration, instrumented with a permanent capacitive sensor array allowing time-lapse imaging.

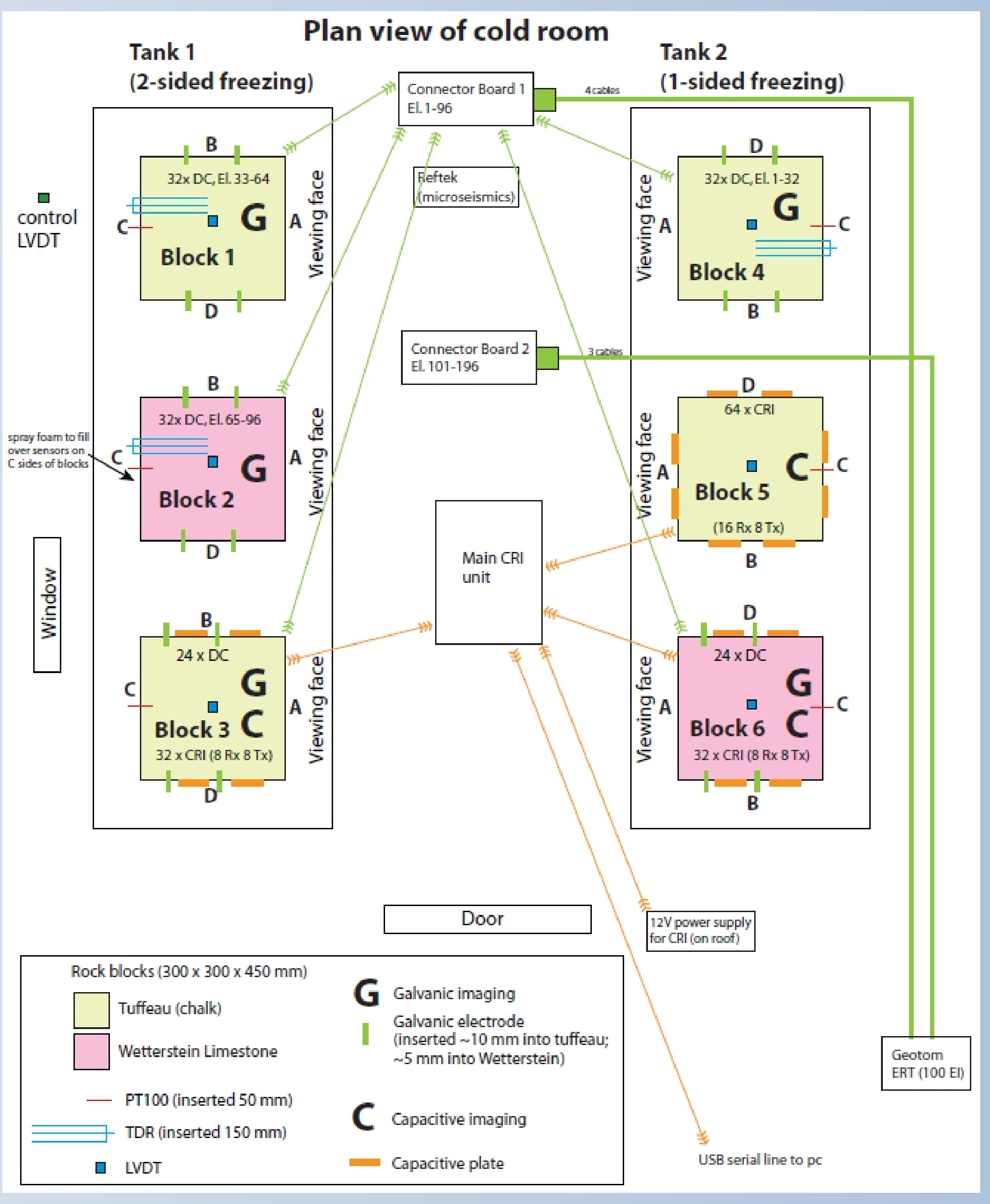


Figure 6: Experimental setup in the Permafrost Laboratory at the University of Sussex.

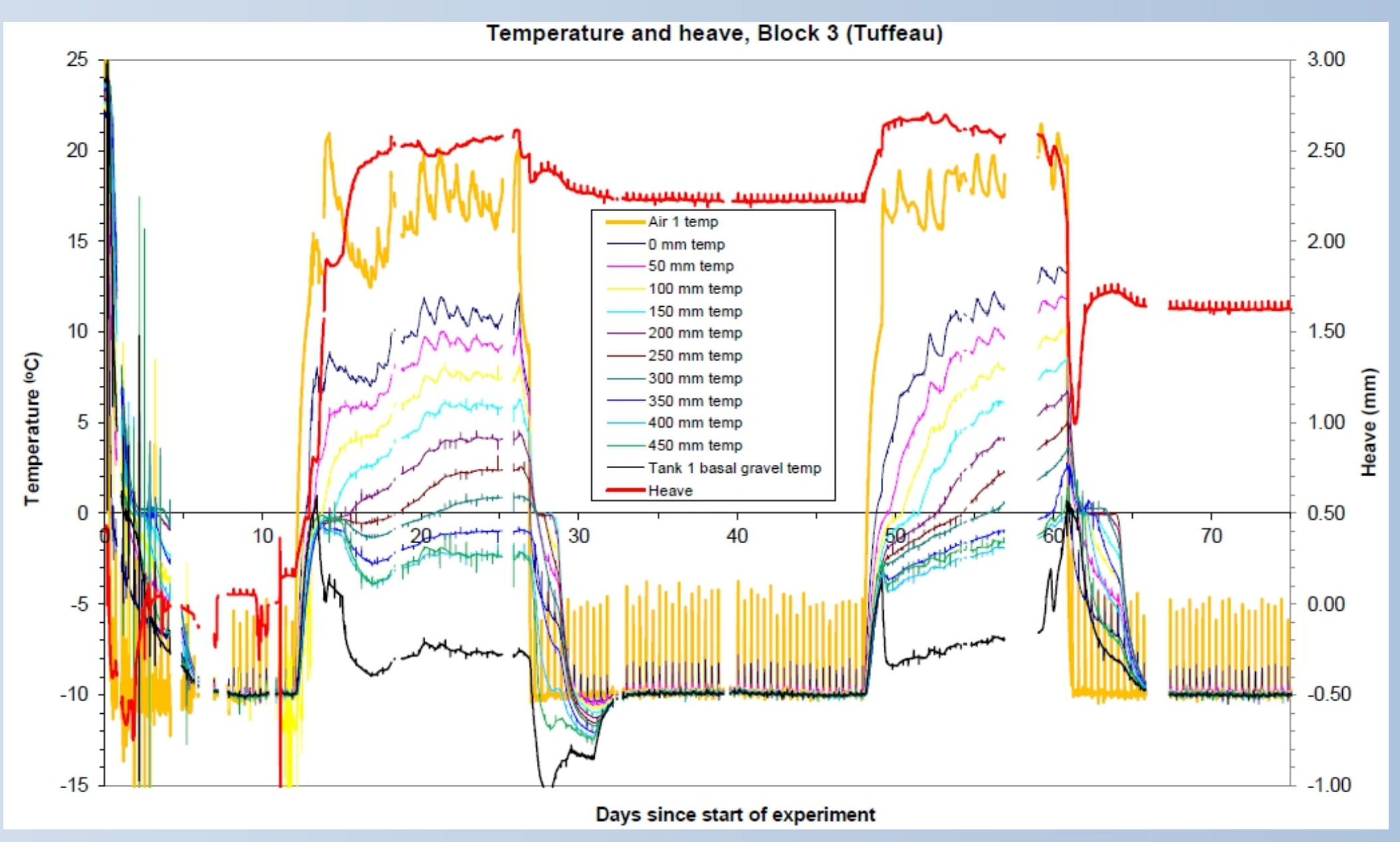


Figure 7: Time series of air temperature, rock temperature, basal gravel temperature and rock heave during two simulated annual freeze-thaw cycles.

ERT synthetic modelling

We have simulated 3D ERT imaging of rock samples with permanent electrode arrays, in order to establish the validity of our approach and 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 for this purpose. An array geometry with a total of 128 sensors, distributed across the four vertical faces of the sample, was employed (cf. Figure 4).

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 inverted 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.

As the capacitive sensor arrays investigated here (Figure 4) violate the point source assumption of DC resistivity, it is not immediately obvious that the use of a DC modelling algorithm is permissible for CRI. We have critically appraised our approach by incorporating the finite size capacitive sensors into the forward and inverse calculations. This is achieved with the "Complete Electrode Model (CEM)" method incorporated into BERT (Rücker and Günther, 2011).

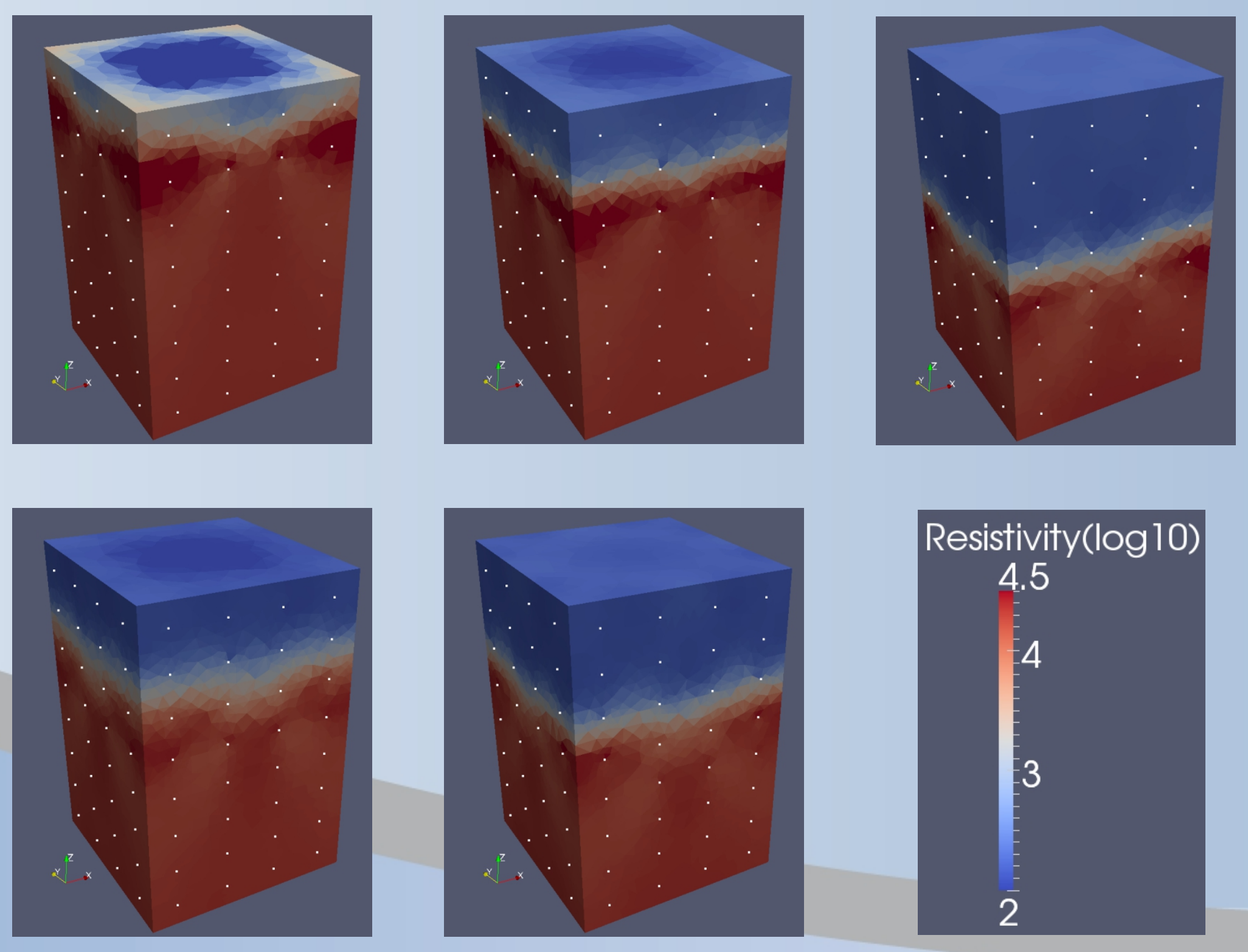


Figure 5: Inverse resistivity models of a rock sample (synthetic data) with assumed permafrost tables at vertical distances of 45, 90, 135, 180 and 225 mm below the top of the sample.

Interim results

We commenced our full-scale freeze-thaw experiments in April 2012 and have so far completed three simulated annual freeze-thaw cycles. Significant alteration of the samples (fracturing) is not expected until several such simulated cycles have passed, hence our experiments will continue for several months. The results presented here are therefore preliminary.

Time series of air and rock temperature on Block 3 (Tuffeau Chalk) during two full cycles are shown in Figure 7. The rock temperature is resolved vertically at 10 discrete elevations, showing very clearly the temperature gradient introduced by the simulated permafrost layer during the thaw cycle. Rock-surface heave is plotted alongside the temperature data, showing a noticeable response to the onset of each thawing cycle. Sustained periods of rock-surface heave during thawing cycles are expected with sustained periods of ice segregation (Murton et al., 2006).

The response of the electrical data to the freeze-thaw regime is substantial. Figure 8 shows a time series of CRI resistances measured on Block 3, alongside the temperature and moisture content data. The change in resistance from a partially frozen sample (thawed active layer, simulated summer) to a fully frozen sample (simulated winter) spans more than one order of magnitude. This sensitivity of the electrical measurements to the seasonal variations in temperature, moisture content and ultimately the resulting fracturing of the rock matrix allow us to resolve these processes through resistivity imaging.

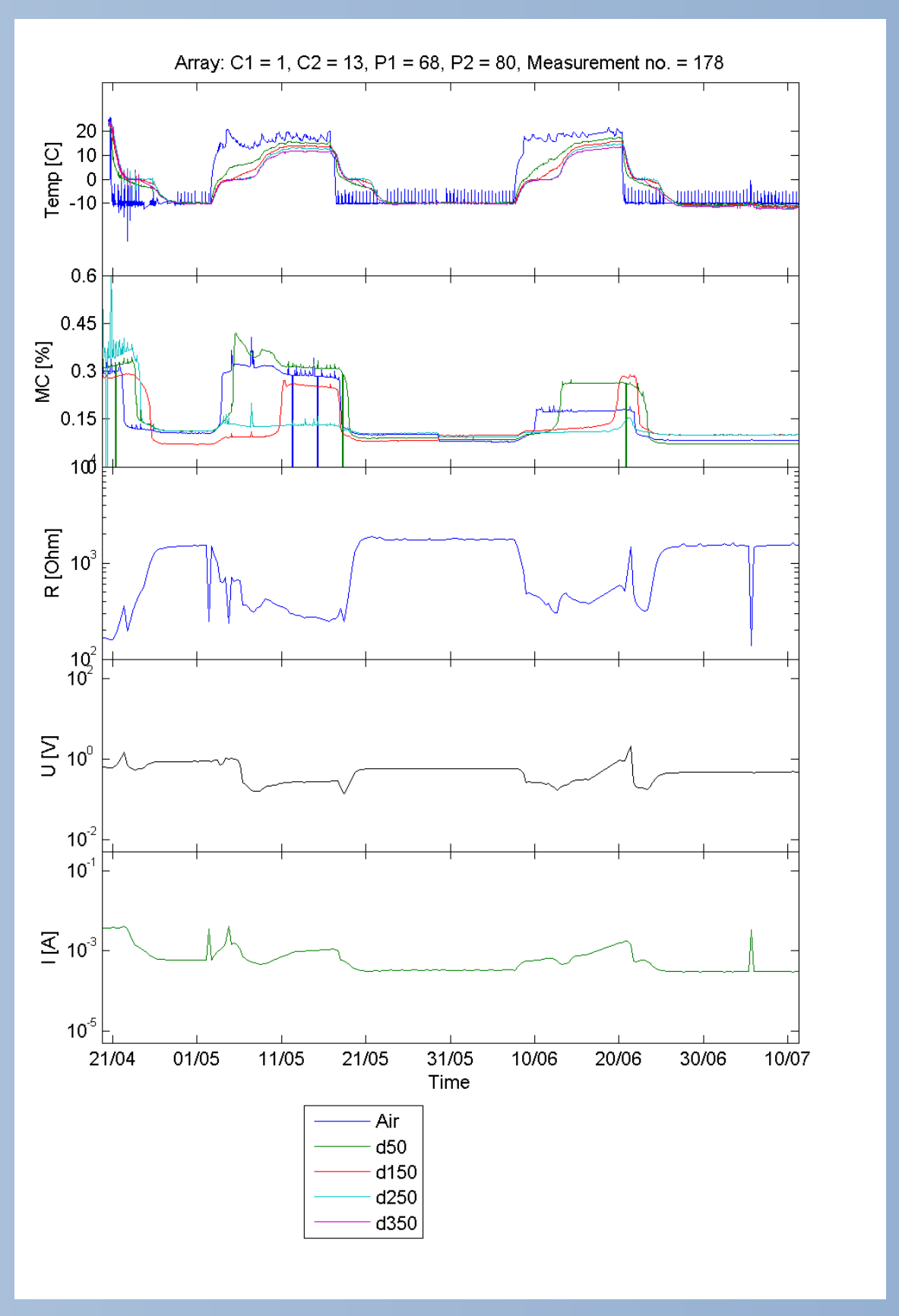


Figure 8: Example of time series of resistance measured with CRI on Block 3 (Tuffeau Chalk) during two freeze-thaw cycles. Panels from top to bottom: Air/rock temperatures, volumetric water content, CRI resistance, CRI potential, CRI current. The resistance is measured on one four-electrode array.

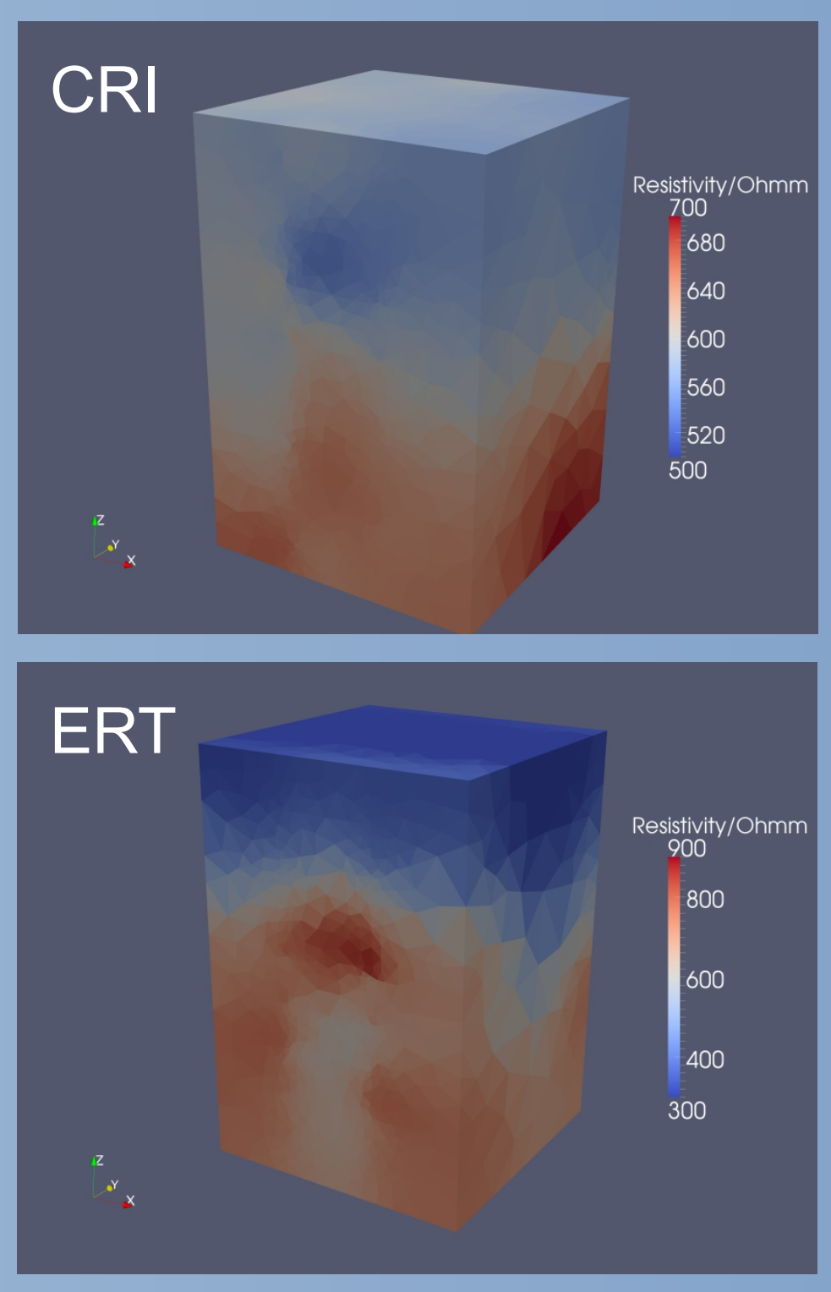


Figure 9: 3D inverse resistivity models of Block 3 (Tuffeau Chalk) obtained from CRI data (top) and ERT data (bottom).

3D resistivity inversions of the CRI and ERT data have been achieved with the BERT software. Figure 9 shows inverse resistivity models of Block 3 during a simulated summer season. The models clearly show the permafrost layer in the lower part of the sample, together with the unfrozen active layer at the top of the sample. The range of resistivities is very similar between the two methods, as is the spatial distribution. Some discrepancies are clearly observed; they are likely due to differences in acquisition geometry (CRI and ERT electrodes are physically separate, and CRI electrodes have a finite size) and acquisition timing (CRI and ERT datasets are acquired at a different time of day).

Over the coming months, we are planning to generate time series of inverted resistivity models (time-lapse inversions) for both methods, and ultimately to calibrate these models to show rock temperature. The latter can be achieved by recording the temperature-resistivity dependence as a function of rock type and moisture content in separate calibration experiments.

Conclusions and outlook

Interim results of our long-term experiments demonstrate that the capacitive resistivity imaging methodology developed here is capable of laboratory-scale imaging in the same way as conventional DC resistivity. CRI usefully complements the imaging of permafrost rock samples with ERT, particularly where galvanic coupling is problematic. The methodology allows us to obtain spatially resolved property distributions (i.e. tomographic images) of bedrock samples during controlled experiments simulating permafrost growth, persistence and thaw.

Our long-term freeze-thaw experiments will continue for several months, monitored with CRI and DC resistivity. In the future, field installations of the CRI technology are envisaged at sensitive sites where mountain permafrost is under threat of degradation.

Acknowledgements

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