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DEVELOPING A 'NON-DESTRUCTIVE SCIENTIFIC TOOLKIT' TO MONITOR MONUMENTS AND SITES

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Introduction

Increasing awareness of climate change and its possible effects on our environment are now widely known. World heritage sites will, in the future, be subject to significant, complex transformations in direct response to changing climatic regimes. It is predicted that the changes we will see over the next 100 years include variations in temperature, rainfall, extreme weather events, groundwater and sea level. This concern often concentrates on the impact that climate change will have on natural environments, e.g. loss of habitats to sea level rise, and often neglects possible impacts on the material environment especially the historic built environment. Historic buildings and structures were designed for their specific local climate and changes to this local climate will accelerate some processes of decay whereas others may be delayed. The problem of decay and conservation of stone-built heritage is inevitably therefore a complex one, requiring input across many disciplines to identify appropriate remedial steps and management strategies. Over the past few decades, Earth scientists have brought a unique perspective to this challenging area, drawing on traditions and knowledge obtained from research into landscape development and the natural environment.

Weathering scientists have, for example, began to develop a clearer perspective on the likely impacts of climate and other environmental changes – most notably changes in pollution regime that have seen traditionally polluted areas improving air quality, at the same time as many cities in developing economies are experiencing a significant deterioration and whilst the nature of the pollutant mix is constantly evolving. Most of this work has previously focused on the operation of specific decay processes and even individual mechanisms of decay. Although over a completely different scale, much effort has been recently expended via the EU funded Noah's Ark Project to scope the possible impacts of global climate change on built heritage and cultural landscapes (http://noahsark.isac.cnr.it/). However, for such projections to be meaningful for material conservation at the building scale it will be necessary for detailed process studies (often conducted at the millimeter and often sub-millimeter scale over a very short duration) to be up-scaled and integrated to encompass process combinations. This must be accomplished first at the level of individual blocks of stone and ultimately to investigate how these blocks integrate across complex facades. Conversely, region-wide prognoses must eventually be downscaled to accommodate the micro-environmental variations that ultimately control the operation of alteration and decay processes.

Central to achieving both of these scale-jumps has to be an integrated methodology for characterizing those properties of the material under investigation that influence its initial susceptibility to decay. These properties are themselves changed during the process of decay and in turn control patterns of decay through a variety of feedback mechanisms. A classic example of these feedbacks is provided by the changes that occur in the surface morphology of stonework. Once stone begins to weather and erode, differential surface loss invariably results in pits and hollows, which in turn create local micro-environments that can favour further decay. In particular, the interiors of hollows favour salt accumulation and its penetration under more humid, sheltered conditions. Hence the ubiquity of features such as honeycomb weathering in salt rich maritime and polluted environments which without intervention can grow into much larger cavernous hollows (Figure 1). An understanding of these patterns of decay can, however, only be achieved if surface loss is linked in turn to the measurement of key physical properties and their change over time. Central to this strategy has to be not only the base-lining of individual characteristics, but once this is achieved mechanisms must also be established that allow their integration and the identification of causal relationships. After which, there is the need for precise re-survey that permits changes in these relationships to be established, understood and explained so that ultimately they can be used to inform conservation strategies.

In addition to the direct physical impact from changing environments, alleviation and adaptation measures will affect financial governance, and increase sustainability pressures on sites and monuments. Effects will occur over a wide range of scales that will demand changes in monitoring and conservation strategies. Because of this there is an urgent need to understand the material resilience of our Cultural Heritage and to identify means of improving the effectiveness of decision-making with respect to its management.

In order to meet these challenges, it will therefore be necessary to develop effective and adaptable monitoring strategies that utilize and integrate the latest scientific and technological developments. The aim of this research is therefore to produce an integrated scientific approach to monitoring sites by combining a range of technologies into a 'Non-destructive scientific toolkit' that can be readily adapted for use over different temporal, spatial and financial scales, and to develop protocols for building survey and re-survey that will promote a move away from 'rescue conservation' towards regular survey and pre-emptive intervention.

The primary technique in this 'toolkit' is laser scanning – capturing surfaces ranging from small individual building blocks to complete buildings or even landscapes, coastlines and whole cities with millimetre accuracy in three dimensions. Laser-based scanners also called ground-based LiDAR (Light Detection and Ranging) used to survey at the larger scale, centimetres to kilometres, can now capture 1,000,000 coordinates on a surface in one second, others can scan from a distance of 300m away while still maintaining an accuracy of 2mm (Figure 2A). Being able to capture a surface on a structure at these distances has positive implications for health and safety, enabling monitoring of previously inaccessible or structurally unstable areas. As well as recording individual x,y,z coordinates, some laser scanners also record the return strength of the reflected laser form the surface for each point. This is known as a 'reflectance value' and can be valuable additional information in monitoring – often highlighting areas of rapid decay through the exposure of fresh, and usually more reflective surfaces (Figure 3A, B & C). Object scanners operate at the other end of this scale (sub-millimetre to centimetre resolution) and can capture over 300,000 points with a single scan on small objects, building stones or architectural detail with accuracies of 0.05mm in seconds (Figure 2B). The vast amounts of data collected by these systems are known as 'point clouds' and can be analysed using their own generic software or easily exported into more traditional formats e.g. CAD, GIS, VRML etc for further analysis, web based visualisation and dissemination. It is now possible to capture a whole building in 3D with millimetre accuracy in less than a day. This is digital reality, not virtual reality.

The Limestone Project

Previous research undertaken by the authors as part of a major study into the catastrophic decay of building limestone - The Limestone Project (www.limestonedecay.org) has acted as a catalyst for this project. This investigated the catastrophic decay of limestone, primarily in the built environment in Oxford, England. Traditionally, quantification of surface change on *in-situ* building blocks and laboratory based weathering experiments relied upon mechanical techniques. These were often time-consuming, risked damaging the surface being measured, and required a statistical interpolation between a limited number of points. To overcome these difficulties requires a rapid, non-contact mechanism for monitoring surface change using a dense network of measurement points. It is in search of improvement in the speed and precision of surface analysis that this study trialed the use of a laser object scanner and ground based LiDAR as a means of accurately and non-destructively monitoring the progressive decay of building stone in the field. Results from this trial proved that repeat scanning at regular intervals, using large and small scale laser scanning technologies can provide accurate measures of surface change over time on stonework.

Data from this *in-situ* monitoring allowed the production of extremely accurate Digital Elevation Models, DEMs (Figure 4), for the calculation of the volume and rate of material loss, analysis of the changes in surface morphology and surface swelling (Figure 5A, B & C). Geostatistical analysis of this data using Geographic Information System (GIS) software is helping to shed new light on the scale, rate, range and spatial patterns of the processes involved in the decay of limestone. Preliminary observations have shown that digital surface capture across a range of scales is a valuable tool in quantifying subtle trends and changes in surface characteristics that determine subsequent decay patterns in space and time as weathering proceeds.

By adopting this surface monitoring approach it is possible to replace often anecdotal evidence of change with time bound measures that can be expressed quantitatively, translated readily into traditional survey packages and presented in a range of visual formats that can be easily understood by non-scientists. This type of monitoring helps stakeholders make better informed decisions, as well as giving scientists valuable information to increase understanding of the decay processes involved and improve the accuracy of predictive models. Capturing and preserving sites of cultural importance in digital form also provides heritage professionals with tools and information they can use to help physically preserve their sites. As well as showing buildings as they are, computer modelling of historic structures based on scanning data can show us how they used to look in the past – virtual reconstruction. It is also possible to import these 3D baseline models into Computational Fluid Dynamics software (CFD) and bombard a virtual site with virtual wind, rain, sunlight, variations in temperature etc. and study how the structure or site may react to these various climate change scenarios. At the present this is quite difficult to achieve, it requires a clear understanding of all the processes involved, expensive software, relatively large computing power and a high degree of skill to carry out the analysis.

This practice can also provide data for a web-based, universally accessible repository of three dimensional cultural heritage information eg www.cyark.org, giving virtual access to sites around the world and therefore improving awareness of the problems our cultural heritage faces. These virtual tours also have the added benefit of giving access to those who have difficulty, either physically or financially in visiting a location as well as potentially reducing the average carbon footprint of site visitors. This information can also become a catalyst for numerous educational initiatives and ensures that future generations have access to a record of human history that may have otherwise been lost forever.

The Toolkit

The real power of adopting this initial 3D laser scan approach to monitoring sites lies in the ability to spatially map data collected from other techniques and sources using a Geographical Information System (GIS) onto the baseline data collected by laser scanning. Other 'tools' that could be included this toolkit and some of their possible uses are listed below;

- Digital Photography – High quality digital cameras have now become very inexpensive and accessible. Images can be draped onto the 3D baseline data; this is excellent for visualization of a site.
- Colourimetery – measuring colour. This technology has now become relatively cheap, rapid and very portable. Uses include the study of the 'greening' of buildings, development of black crusts and fading of painted surfaces.
- Permeability – Measuring the permeability of stone used to be a solely lab-based process and required the destructive analysis of a large sample. Small, light and relatively quick field portable systems are now available (Figure 6).
- Ground Penetrating Radar (GPR) – this is a geophysical method that uses radio pulses to image the subsurface. This technique can be used over a range of scales from landscapes, imaging meters below the surface to vertical surfaces on a building imaging centimetres into the stone. Data collected using GPR can give clues to subsurface processes such as water movement and the location of subsurface cracking and metal objects, Figure 7.
- Thermography – measuring temperature. This data can be collected and spatially mapped onto the baseline data using a variety of techniques, from temperature data loggers left on site at specific locations, infrared handheld temperature guns that can measure temperature on a surface rapidly and accurately from a distance to digital infrared photography.
- X-Ray Fluorescence (XRF) – analyzing surface chemistry. As with permeability this analytical technique used to involve large, expensive lab based machines. With the development of small, portable, gun-style equipment, surface chemistry can now be easily measured and could be used to monitor pollution accumulation on building stone.
- Stone condition Survey – Very detailed 'Stone by Stone' 2D drawings produced from laser scan data allow specialist surveyors to accurately map the condition of a structure in the field.
- Sea Level Rise – ground based LiDAR surveying allows the production of millimetre accurate 3D models of coastlines and associated structures. By digitally raising sea level within these models, site mangers can forecast areas at risk under a range of climate change models.

Monitoring Frequency

The frequency at which monitoring should be repeated is controlled by many variables. Financial and logistical constraints obviously play their part, but the controlling factor should be the rate of change at the site under investigation. This is a difficult question to answer, in that the rate of change can only be known after implementing a monitoring program and obviously depends on the linearity of decay. Recession rates are, of course highly influenced by the stone in question. For example marble usually has a linear surface recession while sandstones and limestones can have distinctly non-linear rates of recession, with long periods of apparent stability being overtaken by instantaneous loss as complete sections of stone fall away. We would therefore suggest that at the very least initial 3D monitoring is carried out annually, but if possible; seasonal measurements should be taken for the first year. This nested approach could then be used to determine an optimal long-term survey programme. Irrespective of this, it should be possible to use some of the additional tools on a more frequent basis – possibly daily, and with the addition of data loggers on temperature probes for example, sampling intervals can be in the region of minutes.

This three dimensional multi-layer approach can give scientists and site managers a unique insight into the surface/subsurface processes occurring at a site, if and how they interact and the role of geographical controls such as aspect. This 'toolkit' can be easily expanded to encompass other portable non-destructive technologies or adapted depending on budget and access to equipment. Preliminary trials of this approach have been well received by local government agencies and conservation architects.

Funding for the research described in this paper is through the UK Knowledge Transfer Partnerships (KTP) programme (www.ktponline.org.uk). This is part funded by UK Government organisations led by the Technology Strategy Board and involves the formation of partnerships between commercial companies and an academic institution and is targeted specifically at small and medium enterprises which cannot support their own research units. Typically this supports a two-year project that employs a graduate associate and is thus a mechanism that not only aims to translate research into action, but is also designed to bring a new generation of trained professionals into the workplace. KTP's help businesses and organisations to improve their competitiveness and/or productivity through the use of the knowledge, technology and skills that reside within academic institutions. The partnership in this programme is between the School of Geography, Archaeology and Palaeoecology at Queens University, Belfast and Consarc Design Group, Irelands leading conservation architects.

Conservation research only has value if it is made available in a format that is easily understood by non-scientists and ultimately translated into action. If academics fail to set process studies in the context of their wider, practical significance then they run the risk of pursuing the irrelevant. Similarly, a failure to accurately diagnose the causes of decay can often lead to conservators treating symptoms instead of causes. In effect, this partnership between theory and application is vital to this research if meaningful progress and conclusions are to be made.

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Figure 1. Honeycomb weathering of a limestone in Malta resulting from salt weathering that typically creates hollows, allowing salts to concentrate.

Figure 2. **A**. Small scale laser scanner – Konica Minolta Vi9i, Donaghmore Cross, Northern Ireland

Figure 2. B. Large scale laser scanner - Leica HDS 3000, Giants Causeway, Northern Ireland.

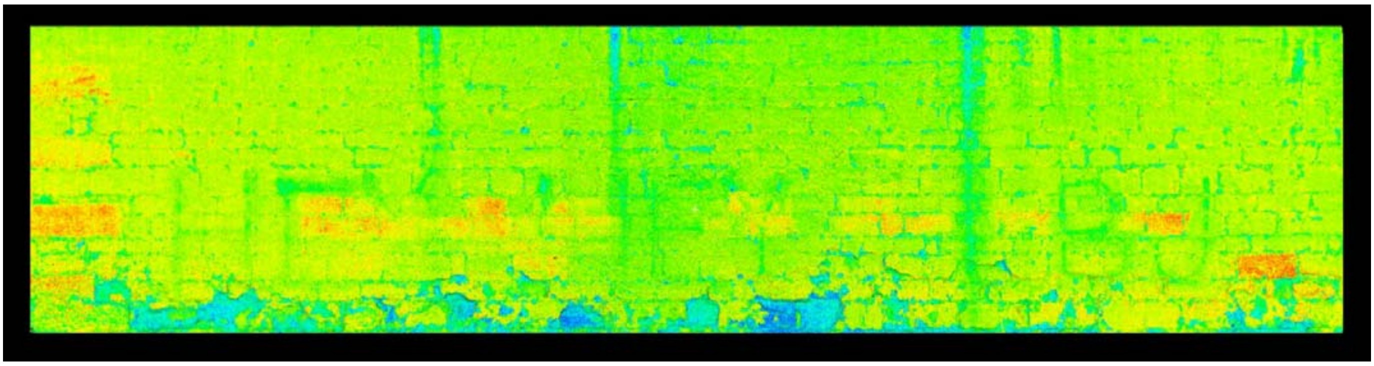

Figure 3 A. LiDAR scan of a 13.6m x 3.2m section of limestone wall, New College, Oxford. This image is made up of 100,000s of individual points artificially coloured based on their reflectance value. Blue – High Reflectance, Red – Low reflectance.

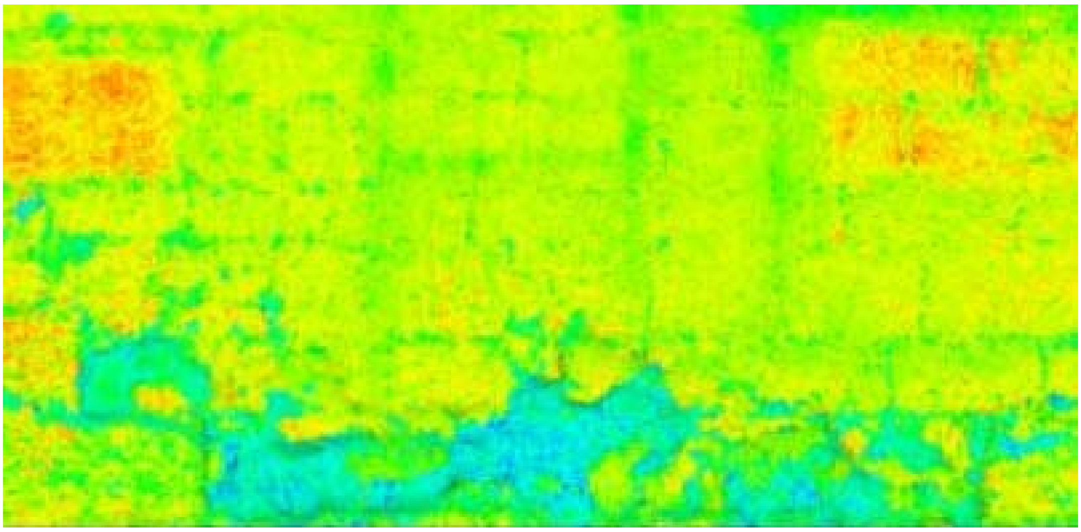

Figure 3 B&C. Photograph of a section and associated LiDAR reflectance data, bottom left of figure 3A.

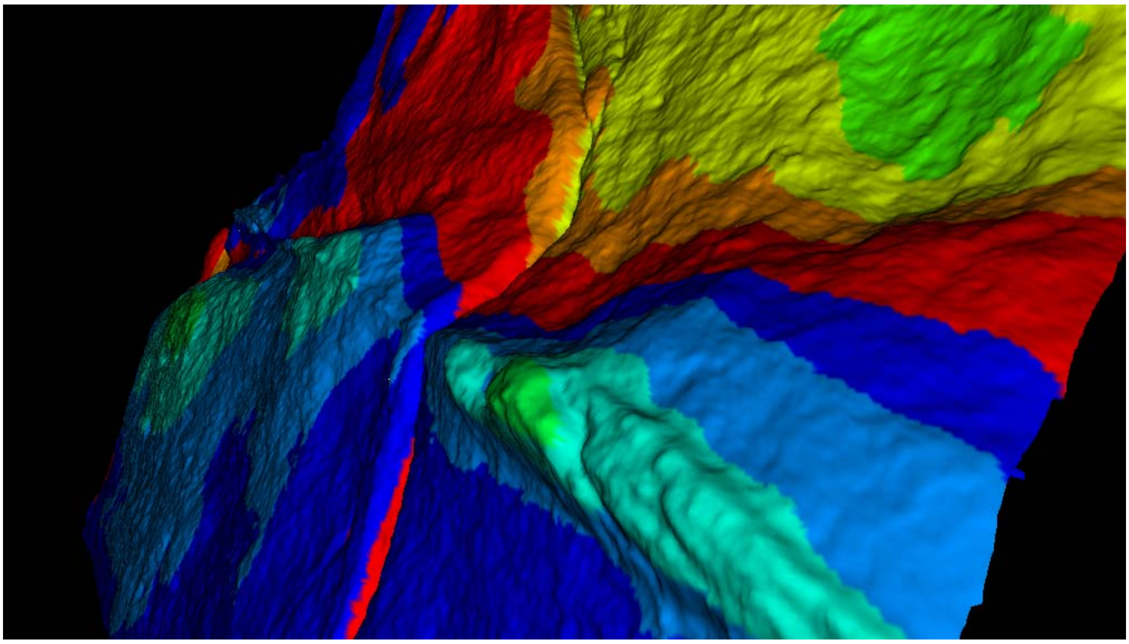

Figure 4. A Digital Elevation Model, DEM of a small area containing a pronounced vein and a hollow - crack on Donaghmore Cross, Northern Ireland. (See Figure 2A).

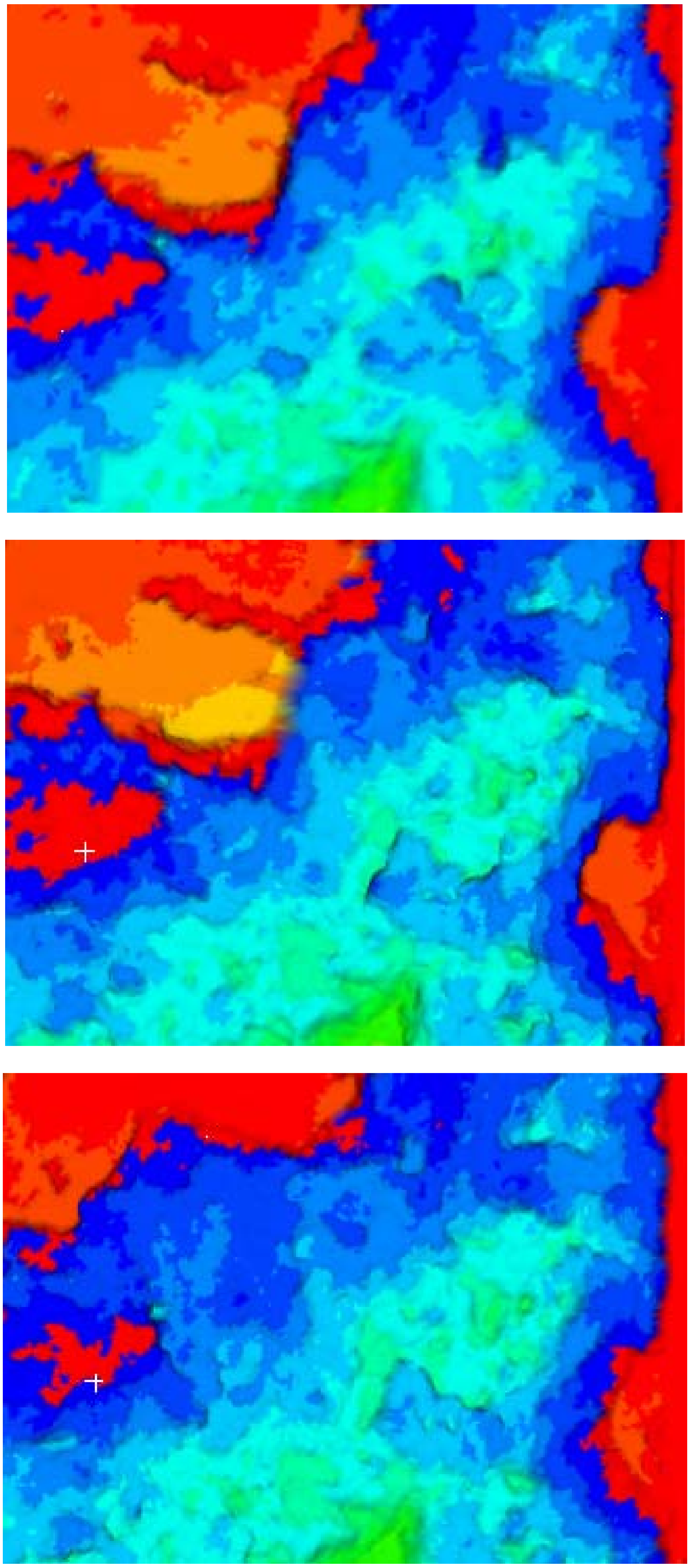

Figure 5. Successive DEMs, **A. 2006 B. 2007 C. 2008** of a small 10cm x 8cm area of Worcester College facade, Oxford, showing surface swelling, yellow (B) and material loss (C). (Yellow high, green low).

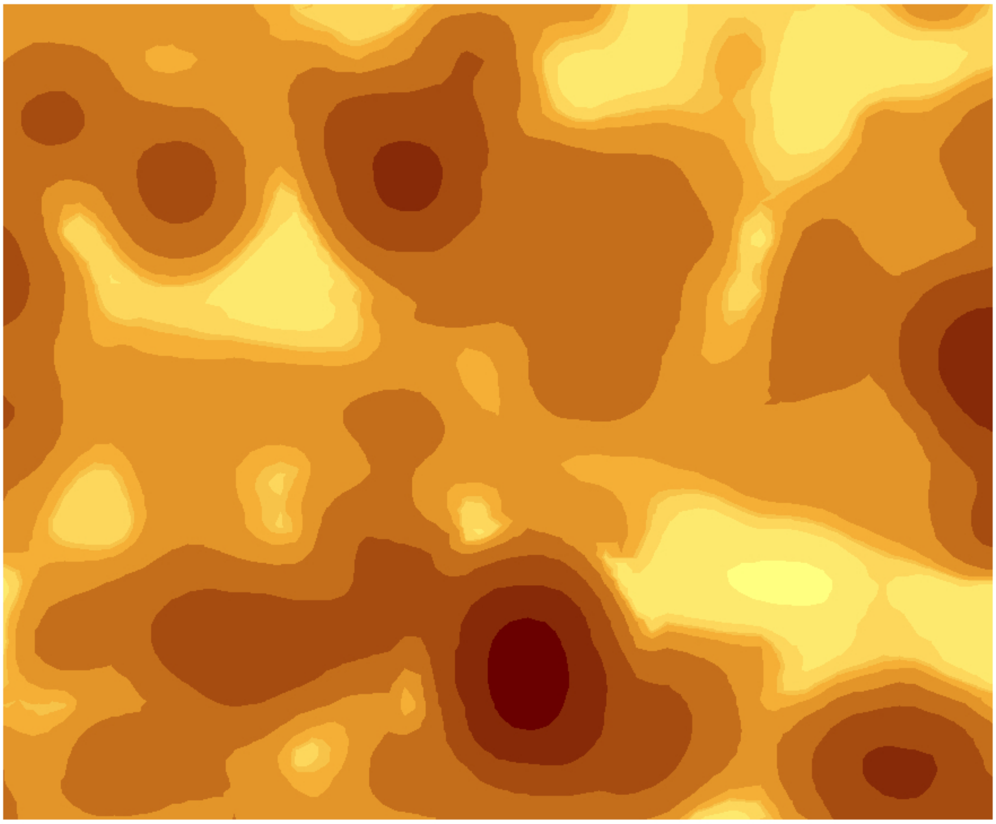

Figure 6. Permeability map created using GIS software, of a limestone ashlar block (40cm x 35cm). Dark - high permeability, Light – low permeability

Figure 7. Photograph of High Resolution Ground Penetrating Radar being used on site, Donaghmore Cross, N.Ireland.