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# Comparative investigation of the spatial distribution of past weathering impacts on sandstone masonry

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ABSTRACT

Inspection of the deterioration of both natural outcrops and historical built stone facades reveals that patterns of disruption are not uniform, indicating the influence of material and environmental properties. Sandstones have a spatial variability in weathering response. For this reason, geostatistical techniques have been applied to studies of sandstone properties, mineralogical and structural, that influence susceptibility to decay. For this study, a comparative analysis of permeability data acquired from a 'quarry fresh' stone and a weathered sample is undertaken.
The depositional processes that resulted in the formation of sandstone also create structures of spatial variation such as laminations or larger bedding planes within the material. Using geostatistical techniques, the permeability variance observed within 'quarry fresh' blocks of sandstone indicates the subsampling of larger geological structures when cut from the quarry face. Once blocks have been emplaced within a building they will be subjected to the increased stress of the urban environment. These conditions result in exacerbated weathering through processes such as salt and chemical weathering. Weathering can alter material properties such as permeability with the creation of a secondary permeability produced by the opening pores and alteration of pore connectivity. Through the application of geostatistics in the analysis of permeability data observed from the weathered block, variography reveals the presence of smaller scale structures. This suggests that alteration of the sandstone's permeability has led to the creation of new weathering structures within the stone, overwriting the initial sedimentary structures.
These weathering-related structures will affect both the magnitude and spatial distribution of permeability within the weathered block. The interconnected pathways of permeability, created by past weathering, facilitate the migration of moisture and salts in solution through the substrate. This work has demonstrated that through a geostatistical approach with the application of co-kriging, these potential moisture pathways can be identified and visualised.

## 1. Introduction and background

Sandstone has historically been the material of choice in the construction of culturally significant buildings, with its selection for each structure based upon its versatility and aesthetics (Fitzner and Heinrichs, 2002; Turkington and Paradise, 2005). These appealing qualities of the stone are the result of the intrinsic structure and the mineralogy of the material (Muir, 2006; Smith et al., 2008). The same characteristics and their spatial variability may influence the initial deterioration of the material. Evidence of spatial variability can also be observed in the colouration and texture of sandstones, such as the large-scale bedding features or finer laminations across quarry faces (McKinley et al., 2012). However, even visually homogenous stone can be heterogenous when considering the structure or cementing of the material. The inheritance of such characteristics created during formation and the susceptibility of the material's properties to change under environmental stresses that, in part, determine the stone's longevity within the built environment (Turkington, 1996; Inkpen et al., 2004; Di Benedetto et al., 2015; Goudie, 2016).

However, change is an inherent characteristic for stone (McCabe et al., 2015). Past alteration of the material properties through weathering can have an influence upon the contemporary deterioration processes and their spatial distribution across the block surface (Turkington and Smith, 2004; André et al., 2011). One property commonly used as part of studies observing material alteration associated with decay is permeability, the capacity of fluid movement within the stone (McKinley and Warke, 2007). Permeability can be changed through past weathering processes altering pore shapes and size, creating a secondary porosity (Angeli et al., 2008). A comprehension of the nature of the spatial distribution of alteration will aid in the development of an understanding of weathering patterns across the block, and ultimately the wall, scale. Parallels could also be drawn between patterns of building stone deterioration and the spatial distribution of weathering features across natural rock outcrops, aiding in the comprehension of weathering processes in both settings.

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The aim of this project is twofold: firstly, to investigate how past weathering affects the contemporary spatial distribution of permeability in a historical sandstone block; and secondly, to observe the spatial distribution of potential moisture pathways within the block.

### 1.1. Urban weathering and weathering legacies

Within the natural environment, weathering refers to an exogenetic group of mechanical and chemical processes that breakdown rock into smaller constituent components (Yatsu, 1988; Summerfield, 2013). Under the influence of the anthropogenic conditions found within the urban environment, weathering processes have developed at an accelerated rate (Pope and Rubenstein, 1999; Gomez-Heras and McCabe, 2015). However, it needs to be noted that alteration is not only surficial, it extends to the maximum depth of moisture ingress within the stone work.

Sandstone masonry within the urban setting is particularly vulnerable to the impact of salt weathering, widely considered to be a dominant weathering process (Benavente et al., 2001; Smith et al., 2005). Salt weathering is not a simplistic process but rather represents a range of physio-chemical reactions occurring within and subsequently altering the pore spaces of the block (Fitzner, 1990; Goudie and Viles, 1997; Doehne, 2002). As a result, understanding the developing pathways facilitating the passage of moisture and salts is essential to attempts to understanding the deterioration of masonry blocks.

There is a need to develop an understanding of the influence that alteration, resulting from exposure to past environmental conditions, can have upon future deterioration of masonry. The Building Effects Review Group (BERG) (1989) coined the term, ‘memory effect’, referring primarily to accumulated salts from past environmental conditions that have the potential to exacerbate future weathering (Inkpen, 1991; Smith et al., 1994; Viles, 2005). Other authors have since used the term ‘weathering legacies’, referring to the accumulated material alterations that have occurred post-emplacement (McCabe et al., 2007, 2015; Gomez-Heras et al., 2009). Properties of the rock fabric resulting from the depositional environment and diagenetic processes can be referred to as inheritance effects (Warke, 1996). The amassing of these past influences will affect the strength of the material and the accumulated stresses acting upon the blocks (McCabe et al., 2007).

### 1.2. Geostatistics and permeability

As the migration of moisture and associated salts is linked to the spatial variations of the stone's material properties, it is essential that an understanding of characteristic variability is developed (Corbett and Jensen, 1993; Beggan et al., 1996). Gas/air permeametry provide a rapid and non-destructive technique for measuring permeability across rock outcrops (Goggin, 1993). However, due to the size of the probe permeameter's aperture and time requirement of sampling a sufficiently dense dataset, it is not feasible to measure at the required density to represent the spatial variability of properties present in natural stone (Carey and Curran, 2000; McKinley et al., 2006). It is therefore necessary to apply a geostatistical approach to the estimation and simulation of values to ‘fill the spaces’ between known sample points. Through such techniques, geostatistics can be used to assess the heterogeneity and anisotropy of porous masonry (Grover et al., 2016).

Unlike other interpolation techniques such as inverse distance weighting, through the application of geostatistics it is possible to minimise the effect of smoothing out important features of the material through the retention of hard ‘known’ data (Zhao et al., 2014). This increases the usefulness of the technique for modelling patterns of spatial variability in geological structures. Sedimentary stone permeability variation has been observed through the use of the experimental variogram in geostatistics (Jensen et al., 1994). Jensen et al. (1996) demonstrated that structures existing at a range of scales will affect the variogram in various ways dependent upon the sampling approach and instrumentation. This work also highlighted the experimental variogram's value as a tool for data analysis. At a larger scale, McKinley et al. (2004) observed the influence of the wider depositional environment upon the variance in permeability values recorded from a series of outcrops.

More recent studies have shown the effectiveness of this approach, both to the assessment of the spatial variability of fresh building materials (McKinley et al., 2006) and in the determination of the spatial variability of structures created through simulated weathering processes (McKinley and McCabe, 2010, Buj et al., 2011). McKinley and McCabe (2010) used cross-variograms to demonstrate the presence of spatial correlation between a point on a block surface and corresponding points at increasing depths through a masonry block.

## 2. Methodology

### 2.1. Material description

Scrabo sandstone or Scrabo stone is a member of the Triassic Sherwood Sandstone Group (SSG), lain down in a fluvial environment with periodic aeolian influences (Smith, 1991; Buckman et al., 1997). The result of this depositional heritage is that the substrate is spatially variable in terms of the size of grains and subsequent pore sizes (Table 1). Two blocks of Scrabo sandstone were chosen for this study (Fig. 1). Scrabo sandstone's versatility for construction, aesthetic properties and local availability made it an appealing building stone in the Belfast area during the city's rapid urban expansion in the 19th Century (Curran et al., 2010). One such building was the Crescent Arts Centre (CAC), the source of the recovered historical block discussed in this paper, located in the south of the city (Fig. 2). Belfast's expansion at that time was rapid, driven by industrialisation relating to the city's position as a prominent harbour and shipyard. This meant that the stones within these buildings were exposed to high levels of pollutants and marine salts since their emplacement. In recent years, the concentration of pollutants within the Belfast urban area has remained higher than in other cities in the UK (Cooke and Gibbs, 1995).

Scrabo sandstone exhibits characteristic well-defined laminations and bedding, resulting from variations in mineralogy, structure and texture (Warke and Smith, 2000). Whilst these properties are partly due to depositional processes and burial diagenesis, past contact diagenetic processes, resulting from the intrusion of igneous sills, have played a part in the material's development (McKinley et al., 2001). The magnitude of this process was dependent upon the proximity of the dykes and sills, meaning that there is a strong spatial component to the variation in properties across the quarry. The south face of the quarry was the location used for the recovery of the block of ‘fresh’ sandstone and is the likely original source of the recovered historical block at the time of the construction.

### 2.2. Sample preparation

The first of the blocks acquired for this study is a historical block from the Crescent Arts Centre, recovered during restoration work in 2009. This block had been exposed for approximately 114 years. The

**Table 1**
Properties of Scrabo sandstone.

| | Scrabo sandstone |
|---|---|
| Grain size[a] | Medium (range 0.1–0.5 mm) |
| Cementing[a] | Clay minerals (smectites), actinolite and Talc (approx. 10% wt) |
| Porosity (% vol)[b] | 20–25 |
| Permeability (mD)[a] | 5–1500 (mean 500) |
| Saturation coefficient[a] | 0.7 |

[a] Adapted from Smith et al. (2002).
[b] Acquired through mercury intrusion porosity testing.