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Salt Weathering on Buildings and Stone Sculptures

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Moisture dynamics in building sandstone: implications for transport and accumulation of salts

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ABSTRACT

Moisture is an important control on processes of stone decay. Future climate projections suggest an increasing seasonality in precipitation in parts of northwest United Kingdom, with 10-20 % increases in winter rainfall over the next half century. These changes will invariably be reflected in stone moisture dynamics. Results show an outer stone layer sensitive to environmental moisture cycling, that when subjected to prolonged periods of rainfall (with imbibition exceeding evaporative loss) allows moisture penetration to depths of 25 cm after six weeks of exposure. This migrating moisture has the ability to transport salt to depth; under periods of saturation this salt may re-distribute by processes of diffusion and has the potential to chemically alter the stone matrix. There is the need then to revise salt decay models premised on near-surface moisture cycling to include the penetration of 'deep' wetness, which could drive new patterns of salt distribution and thus new rates and patterns of decay.

Keywords: Moisture, Sandstone, Deep wetting, Climate change, Time-of-wetness

1 INTRODUCTION

Soluble salts have long been recognized as key agents of change in natural building stone. The interplay between salts and stone has become an arena of research that, especially over the last three decades and with input across disciplines, has amassed an extensive literature — largely based on field observations and laboratory simulations (Goudie and Viles 1997). Such studies have increased awareness of the propinquity between salt, environmental setting (and cycling), stone characteristics and the complex (historical) sequence of interactions that account for the varied nature and scale of stone response (Smith and McGreevey 1983; McCabe et al 2007).

Moisture is essential to the efficacy of salt weathering (Smith et al 2010a). It is in the presence of salts that cycles of wetting and drying are considered to be most effective in promoting stone deterioration (Snethlage and Wendler 1997). Salts are pervasive within natural stone; the arrival and entrance of moisture to building façades provides a potential external source. This includes moisture from the surface deposition of dew and fog (McGreevey et al 1983), rising groundwater (Goudie 1986), rainfall penetration (Srinivasan et al 2010; Smith et al 2011) and migration between contiguous stone blocks (Turkington and Smith 2000).

The persistent movement of moisture within building stones — in response to fluctuations in atmospheric environment and its need to equilibrate with the surrounding substrate — exercises a major control on the mobilization, concentration and accumulation of hydrating and crystallizing soluble salts (McKinley and McCabe 2010). The nature and severity of salt-related damage is often viewed as being, in part, dependent on the location of crystallization – which itself, is determined by the interaction of multiple substrate, environmental and brine/salt-related variables to control the rate of drying (see Doehne 2002). Traditional views of salt distribution have used these theories to link, for example, contour scaling to moisture cycles and the concentration of salt at a shallow typical wetting depth parallel to the surface (Snethlage and Wendler 1997; Smith et al 2010a). However, this model — based on the premise that the surface zone is characterized by rapid wetting and thorough drying — may belie the complexity of the weathering system and interactions between moisture dynamics of varying timescales. Turkington and Smith (2000) presented evidence to suggest that a shallow and fluctuating wetting front may not always hold in locations where prolonged rainfall and long periods of saturation are particularly common, for example, the NW UK.

Because of this, and rather than viewing short-term cycles in isolation, it may be more pertinent to consider the effects of near-surface wetting and drying, in relation to individual rainfall events, superimposed upon deeper penetrating cycles of seasonal moisture (Smith et al 2011). Such a proposal has relevance not only for current salt transport and stone deterioration but also how they may change under future climatic conditions. To examine such changes, this paper explores the need for robust models of likely sandstone response to projected future climatic shifts in the North West United Kingdom and presents preliminary field-based results from an ongoing stone moisture monitoring programme.

2 CONTEXT

Stone-built heritage is not likely to be immune to changing future environmental conditions. The impact of climate change on stone decay processes was brought to the fore by Viles (2002), who suggested that important (and direct) controls of change will be alterations in temperature and precipitation regimes and the occurrence of extreme events. To date, most studies have focused on the effect of temperature-related change on specific processes (see, for example, Grossi et al 2007). However, in the context of the NW UK, and sandstone in particular, it could be that variations in internal moisture regimes are most likely to drive future change.

Climate projections for the NW UK typically project an increased uncertainty in daily conditions and an underlying trend toward wetter winters (Smith et al 2010b). Downscaled future scenarios for a site in the west of Northern Ireland (Lough Navar, ~5km north of Derrygonnelly – see below) show that the seasonal balance of precipitation receipt is likely to change, with projections for the 2050s (2041-2070) indicating drier summers and wetter winters (Fig. 1a). This has complex implications for changes to internal moisture dynamics and resultant weathering mechanisms. In response to these seasonal shifts, stone moisture contents and time of wetness, at depth, are likely to show increasingly divergent behaviour between winter and summer months (Smith et al 2010b). In winter, with the successive penetration of frequent wetting events, the interior is likely to remain wetter for longer; whereas in summer internal moisture is likely to be reduced. However, superimposed upon these deep-penetrating seasonal cycles is the effect of repeated surface moisture cycling (across all seasons) in response to stochastic wetting events and/or diurnal cycles of capillary condensation-evaporation (Smith et al 2010b). The conceptual diagram presented (Fig.1b), highlights this likely interaction between moisture dynamics of varying timescales showing that the impact of short-term moisture cycling decreases with increasing distance from the surface. Therefore there may be a need to distinguish between the surface and block interior when considering definitions of time of wetness; at depth, it is continuous wetness that may better reflect the controlling factor of seasonal moisture, whereas at the surface, it is the total time of wetness (irrespective of wet-dry cycles) that will permit quantification of whether, over a year, the surface or interior is wetter.

With climate projections indicating increased winter wetness, it seems increasingly possible that prolonged and more deeply-penetrating wetness is likely to lead to internal block saturation (McCabe et al 2010). In this case, internal salts are not able to move by processes of advection; instead movement occurs along gradients of ionic activity. A recent paper (McCabe et al this volume) considering the rate at which ions diffuse through a saturated block, has shown that this method of transport may also have the ability, to liberate and mobilize silica from within the stone. Therefore in winter, asynchronous moisture dynamics between surface and depth, may allow internal chemical damage and near-surface crystallization to occur simultaneously (Smith et al 2010b).

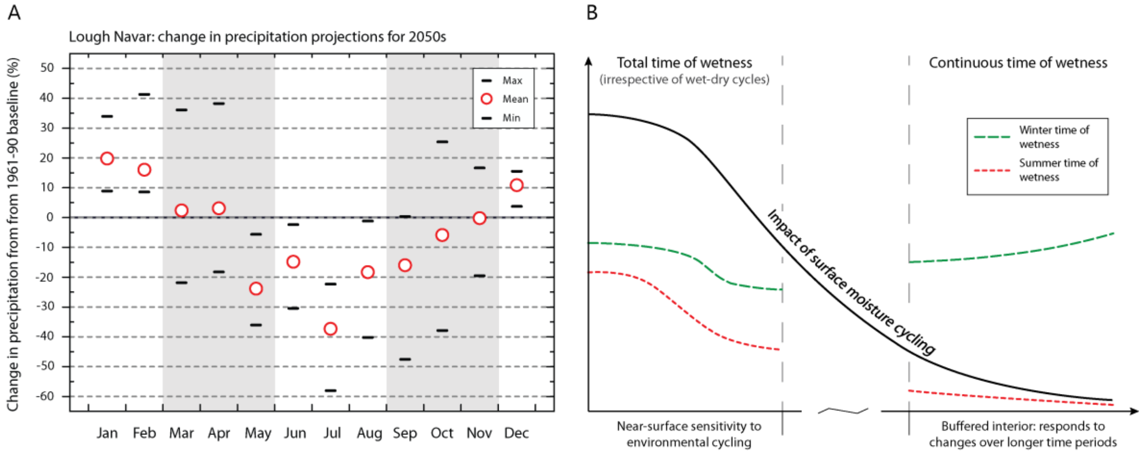

Figure 1. a) Statistically downscaled climate projections (from a 120 member ensemble – 3 climate models and two emission scenarios) showing future change in rainfall relative to 1961-90 baseline, b) Conceptual diagram differentiating between wetness at depth - time of continuous wetness –and a near-surface zone sensitive to environmental cycling – total time of wetness (adapted from Smith et al 2010b and Turkington et al 2003).

Of course, the future remains uncertain and the complexity of the stone system makes it difficult to know fully how amplifiers and/or filters will interact to mediate stone response. Therefore, before linking climate change to its impact on decay, it is first essential to understand how the environment drives present moisture regimes. From this, suggestions can then be made as to how moisture dynamics may change in the future and what this could potentially mean for patterns of stone response. To begin to answer such questions this paper presents initial results from sandstone test-walls (northeast and southwest aspect) to consider the moisture flux deep within building sandstone (over a two month period, October to November 2010 – at the beginning of the climatically wet late autumn-early winter months) in relation to successive wetting events.

3 MATERIALS & METHODS

3.1 Test-wall description

To test the interaction between deep seasonal moisture waves and shallower wetting and drying cycles, a series of test walls, were constructed. This ‘field’ laboratory is situated in Derrygonnelly (see Fig 2a), a lowland village in the west of Northern Ireland where, on average (1963-90), more than 200 ‘wet’ days (daily rainfall >1 mm) contribute to the annual total of 1496mm. These walls (400-475 mm thick) have been designed to consider aspect- and geometry-related influences on moisture dynamics, whilst (at the same time) discounting for the effects of capillary rise from soil/ground moisture stores (see Fig 2b). The present paper is concerned with changing patterns of moisture in Peakmoor sandstone. This medium-grained Carboniferous siliceous sandstone (~16 % porosity), quarried in Central England, is commonly used for construction and restorative programmes in the UK and beyond. To begin linking moisture patterns to prevailing conditions, the test walls have been linked to an automatic weather station. A Delta-T raingauge (tipping bucket; 0.2 mm threshold), was connected to a Delta-T DL2e logger, and was programmed to count the number of tips every 10 minutes. An anemometer and windvane were also connected to monitor changing conditions at 10 minute intervals.

3.2 Measures of 'deep' wetness

Moisture is a difficult variable to monitor, with existing methods emphasizing either spatial or temporal variability at the expense of the other. An ongoing monitoring programme captures in tempo change in sandstone moisture profiles, at varying depths, using a commercial capacitance based moisture-detection system. The capacitor is formed by placing a hygroscopic dielectric material between a pair of electrodes and water absorption is registered by the sensor as an increase in sensor capacitance and recorded as a change in relative humidity. The capacitance system is connected to a data logger recording moisture condition, at hourly intervals, since the beginning of October – when the walls were first exposed; prior to exposure blocks were kept under plastic sheeting to prevent moisture ingress. Probes are embedded at depths of 5, 15 and 25 cm behind the exposed ashlar surface. This set-up therefore gives a detailed picture of moisture change over time at three internal depths.

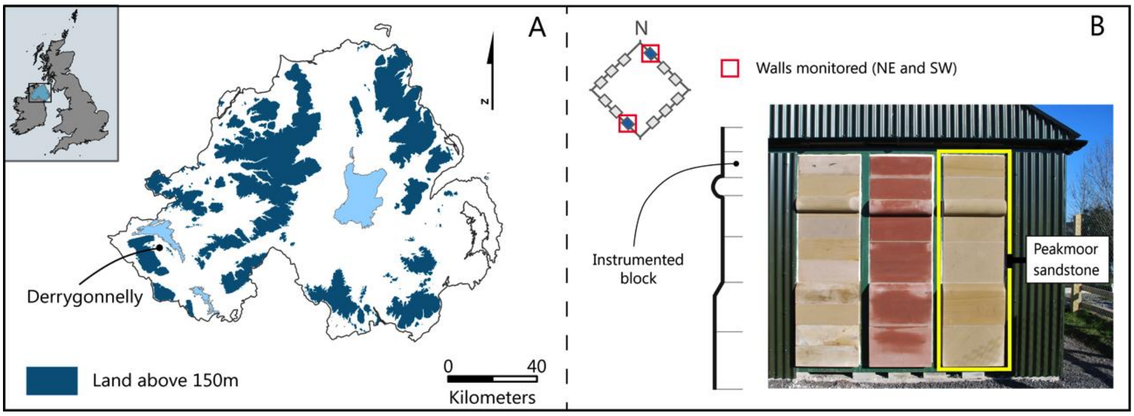

Figure 2.a) Location of test walls, and b) Test walls: identification of instrumented monitoring walls.

4 RESULTS

4.1 Prevailing meteorological conditions

Observed data indicate that rainfall in October (240.6mm) and November (229.6 mm) 2010 was 161 % and 146.1 % of the 1961-90 monthly average, respectively. The cumulative total was 470.2 mm (see Fig 3a). Each day over the two month period qualified as a 'wet' day, 15 of which record totals in excess of 10 mm – with the greatest daily total of 26 mm recorded on the 4th November. During this period southwesterly to northerly winds were the most common and accounted for the greatest speeds (see Fig 3b).

4.2 Tracking the wetting front: internal moisture change over time

Results for changing internal moisture contents over time for the northeast and southwest facades are shown in Figure 4 (a-b). Initially moisture was distributed unevenly with depth; in general, the data indicate greatest moisture content at 15 cm depth, and less in the near-surface zone (5 cm depth). The capacitance probes record, in all cases, considerably high humidity levels (above 86 %); this appears to reflect the experimentally derived conclusion of Srinivasan et al (2010) that this bias towards a high initial humidity is attributable to sensor design.

The probes pick up sub-daily 'spikes' in the time-series — these are amplified in the southwest wall and are attenuated with increasing depth in both aspects. These appear to relate to changing internal temperatures, which (especially during periods of high insolation) increase the capacitance (and hence humidity) recorded; thus, these apparent sub-daily moisture fluctuations can partly be explained as artefacts of the sensing system.

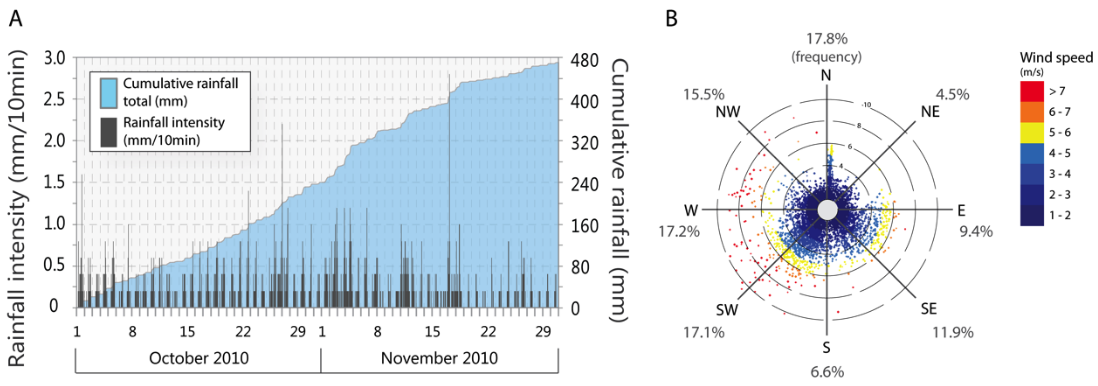

Figure 3. a) Observed rainfall (cumulative total and 10 minute intensity) for October and November, and b) Wind directional plot showing wind speeds and frequency statistics (October-November data).

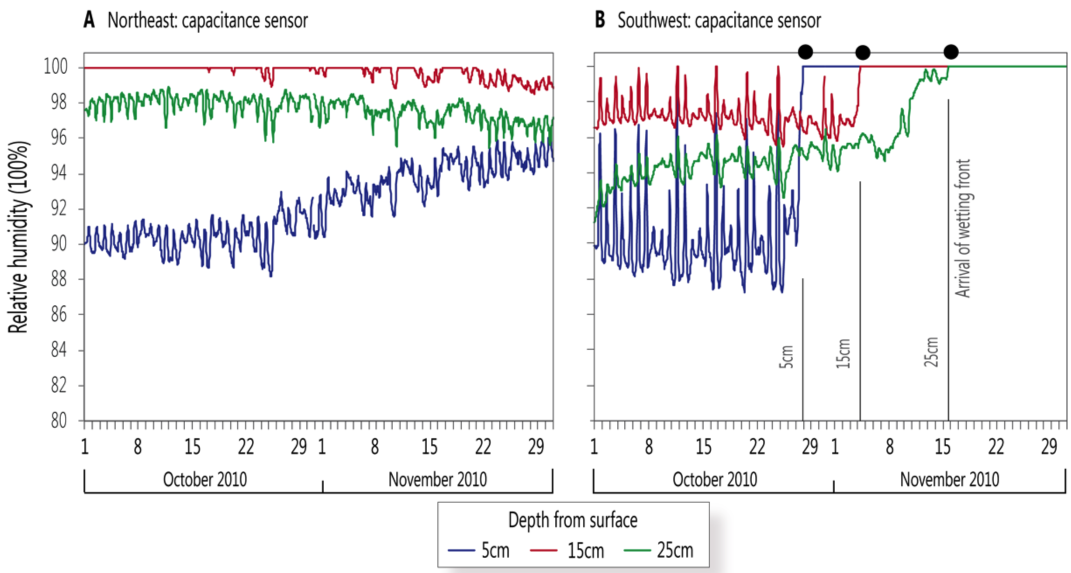

Figure 4. Internal stone moisture change for: a) Northeast wall; b) Southwest wall.

The sensing of the arrival of the wetting front does not appear to be affected by this methodological limitation. The capacitance probes record the wetting front arrival only in the southwest wall over the study period (Fig. 4b). For the northeast wall the capacitance probes show higher initial moisture contents and indicate a slow progressive increase in moisture at 5cm depth; although the humidity values shown are high (and remembering the bias) the wetting front is not discernible (Fig. 4a). The data indicate that the moisture front reaches 5 cm depth (southwest wall) after 4 weeks of exposure (Fig. 4b). This migrating moisture wave is detected at 15 cm depth six days later (and again later at 25 cm) indicating what seems to be more rapid transmission at depth. The arrival of the wetting front was confirmed by another embedded resistivity-based sensor system (data not shown), albeit with subtle differences over timing related to sensor positioning in different blocks at different heights.

5 DISCUSSION

Monitoring of moisture, at depth, within building sandstone has illustrated that in response to successive rainfall events moisture has the ability to penetrate to considerable depths. Data indicate uneven moisture content in the sandstone blocks prior to exposure. This internal wetness is the likely result of either the uptake of meteoric water prior to emplacement and/or a residual product from the construction period; this finding has wider resonance as this is a common building problem and shows that stone decay is historically contingent — this initial moisture can modify the stone making it more/less susceptible to future (post-emplacement) processes of decay (McCabe et al 2007).

The migrating wetting front, in the southwest wall, is interesting with respect to the time of arrival at various depths. After four weeks of exposure (and 200 mm of rainfall – of which the total absorbed is unknown) the wetting front reaches 5 cm and then 25 cm after another two weeks. This result, for the southwest wall, appears to identify a near-surface zone subject to frequent moisture cycling. What is perhaps novel (although completely expected) is the ability to show that in certain environments with periods of consistent rainfall it appears that repeated wetting with insufficient drying between events eventually allows near-surface saturation to develop. This moisture progressively penetrates to depth in a manner that can accelerate when moisture moves beyond the effects of surface evaporation. In the case presented the initial triggering of the passage of this wetting front appears to be related to the 10.8 mm of nearly continuous rainfall within 12 hours on the 26th October – but could be expressed more generally as a prolonged period of rainfall. The discontinuities between the walls with different aspect, linked to the information on wind speed and direction, suggest that driven rain may be particularly effective in producing the steep wetting front and described saturation conditions in the southwest wall, whereas the gradual build-up of moisture (at 5c m) in the northeast wall is likely to be related to both less effective near-surface evaporation and less-effective wetting through driven rain. This suggests that a key control on saturation is the frequency of rainfall combined with the occurrence of conditions unfavorable for evaporative drying between wetting events. This means that there will be subtle aspect-related variations in the wetting patterns experienced by building stones and this is related to the controlling environmental factors. Given the timing of the observations it is not yet possible to examine when and how the stone will dry under summer conditions, or how it will respond to periodic wetting during summer months. Future work will involve monitoring moisture at depths 0.5 cm and more from the surface to understand more fully the balance between moisture transmission to depth and evaporative loss.

A previous study of stone decay in this part of Northern Ireland (~45 km from Atlantic coast) showed that salt weathering was relatively rapid in response to salts derived from marine aerosols (Smith et al 1991). Marine aerosols at the test-walls (30 km from Atlantic) are expected to be of, at least, a similar concentration. Therefore, there is the possibility of marine salts along with the re-mobilisation of in-situ salts being carried deep into the stone blocks with the migrating moisture front. Under periods of saturation these salts may move from areas of high to low activity by processes of diffusion; ion diffusion has been used by Turkington and Smith (2000) to explain inconsistent anion/cation ratios in a building stone. McCabe et al (this volume) have shown that under saturated conditions salts can diffuse through stones and that silica dissolution may be brought about by salt-related chemical activity. The dissolution, movement and re-precipitation of silica (and possibly other cementing agents) is likely to lead to spatially variable alterations in the stone matrix that can be exploited by future processes of decay. If winters are to become wetter it would seem that as a mechanism of salt distribution, ion diffusion warrants further attention. Consequently, there is the need to move beyond near-surface salt decay models to include the transport of deep salt with moisture flux, the inconsistent distribution under saturated winter conditions and the pockets of spatially weakened/strengthened stone. Such a quest requires an understanding of how moisture controls vary with distance from the stone surface, interactions of moisture dynamics over different timescales, location or mechanism specific views at times of wetness and implications for processes of decay.

6 CONCLUSIONS

It is in the presence of moisture that salts enter, are distributed throughout and cause damage to porous building stone. This paper has shown that, in response to successive wetting events under natural conditions of exposure, sandstone has the ability to transmit moisture to depths of (at least) 25 cm after as little as six weeks. This ‘deep’ penetration requires moisture flux to first overcome a near-surface zone affected by surface evaporation; the passing of this threshold is likely to be related to periods of prolonged rainfall. The data suggest that in certain environments with consistent periods of rainfall, there may be a need to rethink models of salt decay premised on shallow moisture cycling to include deeper wetting and the possibility of ion diffusion as a potential mechanism of salt distribution; the influence of summer drying remains to be seen. Climate change projections suggest that the conditions observed during the course of the study could become more common; therefore future climatic impacts on the response of natural building stone must acknowledge the complexity of changing moisture dynamics which are likely to drive new patterns of salt distribution and therefore rates and patterns of decay.

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