Reigate Stone at the Tower of London: Improving resilience in vulnerable historic masonry

Thesis submitted for the degree of

Doctor of Philosophy in

Science and Engineering in Arts, Heritage and Archaeology

April 2020

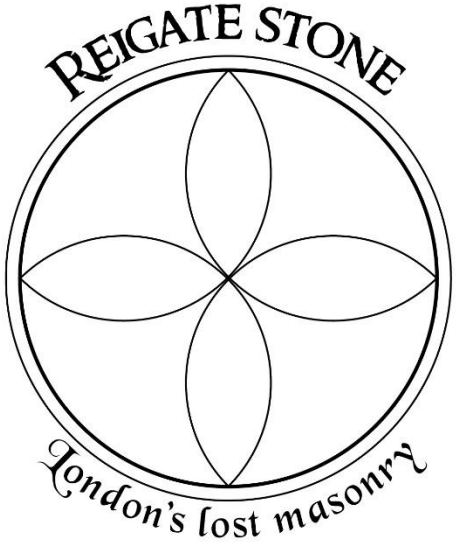
Martin A. K. Michette

St. Cross College

School of Geography and the Environment,

University of Oxford




REIGATE STONE
London's lost masonry

"The highest reward for a person's toil is not what

they get for it, but what they become by it."

Attributed to John Ruskin



The Tower of London's moat during WWII, when it was used as an allotment as part of the 'digging for victory' campaign. (HRP archives)

"Then backward rolled the ebb of Time

While I with eager steps pursue,

And though the hour had lost its prime,

Still as the dim beach wider grew,

I passed along the utmost verge

Of the inconstant fleeting surge.

Back and more back the waters rolled

And, faster yet the waves receding,

Made now, alas! my hopes grow cold,

As I, the vacant prospect heeding,

Gaze on the bleak and desert strand,

As sad I pace the barren sand."

Mary Shelley, *La Vida es sueno* 1833 (in: Shelley 2017)

Abstract

This thesis constructs a scientific framework for examining resilience in vulnerable historic masonry, focusing on Reigate Stone at the Tower of London. Reigate Stone was medieval London's principal freestone; it was used in high profile projects across South East England during a key economic growth period and represents an important chapter of architectural heritage. The UNESCO world heritage Tower of London is one of the UK's most recognisable and culturally valuable sites. This combination affords opportunity for evaluating the deterioration of the historic built environment and aligning scientific methodologies with emerging paradigms in the interpretation and management of cultural heritage.

An integrated methodology was developed, linking non-destructive field surveys at several scales of investigation with archival research and experiments conducted in controlled environments. This enabled scientific investigation of the complex system dynamics affecting decay. Rather than system balance along a static material/ environment interface, decay is controlled by three axes of variability. **(a)** An unusual geological context coupled with vast exploitation of limited resources resulted in a wide physical variation in building stone. Mineralogical variability can be expressed according to the relative content of three different cementing components: opal-CT forms a weakly cemented porous matrix; clay minerals include hygroscopic swelling clays; calcite improves strength. **(b)** The multifaceted character of the historic built environment results in a high degree of present-day environmental variability and associated decay mechanisms. This can be expressed in degrees of shelter at a micro-contextual scale, with complex topographies providing distinct microclimates within single masonry units. Variation is also expressed at larger scales, e.g. Reigate Stone in urban or rural environments. **(c)** Variability in the past treatment and exposure of masonry has formed a high level of contingency, with the memory effect of past decay pathways contributing to ongoing decay. This axis is also manifest in changing attitudes to deterioration across time, which establish a complex reciprocity between decay process and remediation.

The implication of these findings on practical stone conservation is that no single strategy can be successful for all Reigate Stone masonry. Calcareous stones respond well to *Hydroxylating Conversion Treatment*. However, this consolidation technique is at best benign when used on more vulnerable argillaceous stones; water uptake during application can accelerate decay. Limewashing is safer, although in damp, salty environments coats have detached quickly. Salts are a common source of decay. A variety of mechanisms contribute to different decay patterns. The precise relationship between salt, microclimate and decay pattern is highly intricate; observable decay patterns are not a clear indicator of underlying mechanisms. The identification of any appropriate environmental controls must occur on a case-by-case basis. Constructing detailed case histories of vulnerable masonry will facilitate a more holistic approach to treatment. This can move from active conservation of individual stones to a more preventive approach based on revealing underlying system dynamics. In highly exposed Reigate Stone for example, improving water run-off must not only mitigate moisture ingress in the stone, but also protect the correct functioning of pointing mortar to minimise conservation cycles. This systems approach can improve overall resilience by aligning the appreciation of historic built environment with cultural landscape. This paradigm recognises the importance of symbiosis and diversity to system sustainability and prioritises the safe-guarding of intrinsic value over the preservation of materiality.

Acknowledgements

This research has benefitted from a diverse, well balanced supervisory team. Heather Viles provided a breadth of perspective which comes only from profound understanding of scientific endeavour. Generous with her time, patient, willing to let me explore, then unerringly aware of what needed to be done; she has been an inspiration. Constantina Vlachou opened literal and metaphorical doors, enabling me to turn my hobby into my work and study some very special old buildings. Mindful, measured, yet warm, her guidance steadied this project between the choppy waters of practice and the bottomless depths of academia. Ian Angus shared a wealth of experience on caring for historic masonry. His advice, always delivered with a precise, rich language and gentle manner, was vital to making this work meaningful. Thank you all, it has been a great pleasure working with you.

Thank you also to the project advisory board, who variously shared their time at many lengthy meetings: Giulia Bertolotti, Jonathan Bridal, Kate Frame, Keith Garner, Ian Gibb, Kathryn Hallett, Patricia Les, Marta Melchiorre, David Odgers, William Page, Lucia Pereira-Pardo, Victoria Richards, Zoe Roberts, Agnieszka Sadraei, Kenta Sayama, Jane Sidell, Jane Spooner, Clara Willett, and Norman Weiss. Your input proved invaluable to the design of this research.

I crossed paths with several individuals and groups to whom I am indebted. Peter Burgess and members of the Wealden Cave & Mine Society took me on an excellent tour of the ancient Surrey mines (and provided useful insight on the return leg at the Tower of London). Johannes Weber, from the University of Applied Arts Vienna, offered generous help with the analysis of historic mortars. Katherine Clayton, from the Dept. of Earth Sciences, University of Oxford, went beyond the call of duty in helping interpret results of the XRD. Historic England, the Fraunhofer Institute for Building Physics, and Tim de Kock, from the University of Ghent, all provided generous help with laboratory or field tests.

My thanks to the administrative teams at the School of Geography and the Environment, University of Oxford (SOGE) and the Bartlett, UCL for helping me keep my disorganised gears running more or less smoothly. In particular: Jan Burke, Julie Eklund and Robyn Parker.

The following organisations provided the financial support that made this work possible: the UK Engineering and Physical Sciences Research Council, through the Centre for Doctoral Training in Science and Engineering in Arts, Heritage and Archaeology (SEAHA); Historic Royal Palaces (HRP); St. Cross College; and SOGE.

More friends and colleagues past and present from the Oxford Resilient Buildings and Landscapes Lab (OxRBL), SEAHA and HRP contributed with helping hands, important ideas or kind words than I can mention here. I was grateful for all the support and advice I received, even if I forgot to say so at the time. Special thanks to Mona Edwards, Karoline Messenzehl, Katrin Wilhelm and Hong Zhang (OxRBL), Josep Grau-Bove (SEAHA), and Jo Thwaites (HRP).

Everlasting thanks to my family. Dad, for setting me on this path when we last passed; Mum, for always being there for me and believing in me (and most especially for being *here* for me); Meine liebe Grossmutter, für Deine Barmherzigkeit; Louisa, who put things back into perspective and made them complete; and finally to my daughter Evangeline, who gave me the best reason to finish I could have imagined: to you I dedicate this, and all my future work.

Table of Contents

Abstract iv

Acknowledgements v

Table of Contents vi

List of Figures xiv

List of Tables xx

I. Introduction 1

I) 1. Context 2

I) 1.1. Vulnerable Historic Masonry 2

I) 1.2. Reigate Stone 4

I) 1.3. The Tower of London 5

I) 2. Outline 8

I) 2.1. Aims and objectives 8

I) 2.2. Thesis Structure 8

I) 2.3. Research framework 10

II. Literature Review: Complexity and contradiction in stone conservation 11

II) 1. Theoretical Framework 12

II) 1.1. Overview 12

II) 1.2. Purpose 13

II) 1.3. Terminology 17

II) 1.4. Complexity.....21

II) 1.4.1. Scale.....21

II) 1.4.2. Process.....24

II) 1.4.3. Contingency.....28

II) 1.5. Synthesis.....31

II) 2. Methodological Framework.....35

II) 2.1. Overview 35

II) 2.2. Archival.....37

II) 2.3. Field 39

II) 2.4. Laboratory 42

II) 2.5. Synthesis.....46

III. Reigate Stone: A history of use and conservation 49

III) 1. The many faces of Reigate Stone: an assessment of variability in historic masonry based on Medieval London's principal freestone 50

Abstract 50

Graphical Abstract.....51

III) 1.1. Introduction.....51

III) 1.2. Historical analysis.....57

III) 1.2.1. Geological context.....57

III) 1.2.2. Reigate Stone building economics 60

III) 1.2.2.1. Roman use 60

III) 1.2.2.2. Medieval London's expansion 61

III) 1.2.2.3. Repair, recycling and replacement 63

III) 1.3. Experimental analysis 67

III) 1.3.1. Objective 67

III) 1.3.2. Materials and Methods 68

III) 1.3.2.1. X-ray diffraction (XRD) 71

III) 1.3.2.2. Bulk density/ Open porosity 71

III) 1.3.2.3. Ultrasonic wave propagation 71

III) 1.3.2.4. Capillary absorption 72

III) 1.3.2.5. Sorptivity 72

III) 1.3.2.6. Optical microscopy 72

III) 1.3.3. Findings 73

III) 1.3.3.1. Petrographic variability 73

III) 1.3.3.2. Selective quarrying 79

III) 1.3.3.3. Variable resilience 81

III) 1.3.3.4. Building stone decay pathways 85

III) 1.4. Synthesis 88

III) 1.4.1. Discussion 88

III) 1.4.2. Synopsis 92

III) 1.5. Conclusion 94

III) 2. Assessing the long-term success of Reigate Stone conservation at Hampton Court Palace and the Tower of London. 96

Abstract 96

III) 2.1. Introduction.....97

III) 2.2. Reigate stone conservation.....98

III) 2.3. Experimental 103

III) 2.4. Results and Discussion 106

III) 2.5. Conclusion 109

IV. Contemporary conservation: Repointing vulnerable masonry 111

IV) 1. The role of pointing mortar in preventive conservation strategies for vulnerable historic masonry. A non-destructive field survey of Reigate Stone at the Tower of London. 112

Abstract 112

IV) 1.1. Introduction 113

IV) 1.2. Site and methods 117

IV) 1.2.1. Wardrobe Tower 117

IV) 1.2.1.1. Construction and conservation 117

IV) 1.2.1.2. Present condition 119

IV) 1.2.2. Non-destructive Testing (NDT)..... 122

IV) 1.2.2.1. Field survey methodology 122

IV) 1.2.2.2. Calibration of NDT 125

IV) 1.2.2.3. Survey conditions 128

IV) 1.3. Results and Discussion 130

IV) 1.3.1. Overview 130

IV) 1.3.2. Capacitance meter measurements 131

IV) 1.3.2.1. Local distribution 131

IV) 1.3.2.2. General distribution 134

IV) 1.3.3. Surface hardness measurements 135

IV) 1.3.3.1. General distribution 135

IV) 1.3.3.2. Local distribution 141

IV) 1.3.4. Material context 143

IV) 1.3.5. Synthesis 146

IV) 1.4. Conclusions 148

IV) 2. Modelling the effect of repointing and galleting on moisture dynamics in historic masonry at the Wardrobe Tower, Tower of London 150

Abstract 150

IV) 2.1. Introduction 151

IV) 2.2. Methodology 154

IV) 2.3. Results 157

IV) 2.4. Discussion 160

IV) 2.5. Conclusions 162

V. Environmental controls: Salt driven decay 163

V) 1. Bellweathered: Reigate Stone decay mechanisms at the Bell Tower, Tower of London.....164

Abstract 164

V) 1.1. Introduction 165

V) 1.2. Methodology 167

V) 1.3. Results and discussion 168

V) 1.3.1. Decay patterns 168

V) 1.3.2. Microenvironments 174

V) 1.3.2.1. Lower Chamber 175

V) 1.3.2.2. Stairwell 176

V) 1.3.3. Outlook 177

V) 1.4. Conclusions 179

V) 2. Do environmental conditions determine whether salt driven decay leads to powdering or flaking in historic Reigate Stone masonry at the Tower of London? 181

Abstract 181

V) 2.1. Introduction 182

V) 2.1.1. Salt decay in historic masonry 182

V) 2.1.2. Salt decay in Reigate Stone 186

V) 2.1.3. Salt decay at the Bell Tower, Tower of London 188

V) 2.1.4. Aim and objectives 191

V) 2.2. Methodology and Results 192

V) 2.2.1. Overview 192

V) 2.2.2. Ion Chromatography 193

V) 2.2.2.1. Method 193

V) 2.2.2.2. Results 194

V) 2.2.3. Thermodynamic modelling 196

V) 2.2.3.1. Method and Results 196

V) 2.2.4. Accelerated Ageing 199

V) 2.2.4.1. Method 199

V) 2.2.4.2. Results 202

V) 2.3. Discussion 208

V) 2.4. Conclusion 214

VI. Re-framing resilience: Towards a new Landscape 217

VI) 1. Summary 218

VI) 2. Antithesis: A history of Reigate Stone at the Bell Tower 226

VI) 2.1. Introduction 226

VI) 2.2. Construction 226

VI) 2.3. Medieval and early modern changes 228

VI) 2.4. Late 19th and 20th century changes 232

VI) 2.5. Summary 240

VI) 3. Conclusions 242

VI) 3.1. Synthesis 242

VI) 3.2. Outlook 246

VI) 3.2.1. Methodological advances 246

VI) 3.2.2. Practical advances 250

VI) 3.2.3. Theoretical advances 252

List of References 255

Appendices 280

Appendix A: Glossary 280

Frequently used acronyms 280

Terminology 281

Appendix B: Map of Tower of London and Statements of Significance 282

Tower of London 282

Wardrobe Tower Statement of Significance 283

Queens House and Bell Tower Statement of Significance 295

Appendix C: Author Agreements 311

List of Figures

Figure II.1: Conceptual ternary plot of three axes of variability affecting stone decay. 32
Figure II.2: Conceptual diagram of cycle of conservation within present scientific framework of building stone deterioration. 33
Figure II.3: Conceptual diagram of methodological framework linking theory of stone conservation science to guidance for practical stone conservation. Describes four methodical steps and links to methods and scales of investigation. 36
Figure II.4: Diagrammatic overview of how methodological framework has been applied to link separate projects of thesis into unified structure. 46
Figure III.1: Timeline of Reigate Stone quarrying and construction, showing different phases of use, key events and buildings, and corresponding, very broadly classified stone types 51
Figure III.2: Reigate Stone masonry at the Bell Tower, Tower of London, showing high level of variability. Majority of masonry is in Reigate Stone, with range of block colours and sizes, and decay patterns and rates. Second and third course are replaced with other lithologies (except central stones); approximately 15 stones on right of picture also replacement lithologies. 53
Figure III.3: **(A)** 12th century Wardrobe Tower, Tower of London, showing decayed, south facing Reigate Stone ashlar in upper part of buttress and to left of buttress. **(B)** 11th century White Tower, Tower of London with east facing Reigate Stone ashlar visible in two courses directly above batter, and predominantly Portland Stone replacements. **(C)** Reigate Stone tracery from 11th century Merton Priory on display in Museum of London. **(D)** Reigate Stone tracery in 16th century north cloister of Hampton Court Palace. **(E)** Large blocks of stone left in quarry near Chaldon (scale card is 8 cm across). **(F)** Quarry face near Merstham from which samples were extracted in 1998. 56
Figure III.4: Map of area around Reigate and London, showing **(1)** sampling locations in Tower of London, **(2)** sampled quarries and location of Upper Greensand in North Surrey, and **(main map)** other sampling locations. 58
Figure III.5: Selection of Reigate Stone specimens showing variation in colour and texture across different samples used in this study and explaining different sample dimensions. 69
Figure III.6: (A) Selection of results from XRD analysis showing mineralogical variation across and within separate quarries (Gatton and Quarry Field, Merstham), and across and within individual buildings and sites (White Tower and Wardrobe Tower, Tower of London, and Hampton Court Palace). **(B)** Chart showing differing correlation between opal CT and quartz within freshly quarried stone (R = -0.67) and stone used in buildings (R = -0.15), lower quartz content in building stone, and higher opal CT content in phase 1 building stone. 74
Figure III.7: Photomicrographs of selected thin sections, showing variability of mineralogy, texture and grain size within and across different quarries and buildings, different decay patterns within building stones, and highlighting some common mineral components. 77
Figure III.8: Box and whisker plots, showing **(A)** higher and more uniform bulk density in building stone, **(B)** slightly higher open porosity in building stone, and **(C)** more uniform

response to pulse velocity measurement in building stone. Central line of box depicts mean value; lower and upper edges of box correspond to 25th and 75th percentile (IQR); whiskers extend to the largest/ smallest value within 1.5 * IQR. 80
Figure III.9: Biplot of Principal Component Analysis showing variation of samples according to measured characteristics across two principal components and contribution of characteristics to the components. 81
Figure III.10: Ternary plot showing relationship between proportion of opal CT, calcite and clay (cementing components of stone), sorption hysteresis at RH80, and pulse velocity. Hygro-physical properties selected to represent performance of stone. One sample from each quarry deemed most suitable for building stone selected. Limited number of high calcite stones shown to perform well. 13th to 15th century stones are relatively higher in clay content and perform poorly. Other stones with variable performance.. 84
Figure III.11: Cardinal Wolsey Plaque at HCP showing acceleration of decay rate on wax-treated Reigate stone surface. 101
Figure III.12: (Left) limewashed Reigate stone at Cradle Tower, ToL, shortly after treatment in 1990 and **(right)** in 2018 showing good state of preservation. 101
Figure III.13: Reigate Stone at the Bell Tower, ToL treated with HCT during the 2001 trials (top left) and 2015 conservation work (bottom two rows). Greater decay visible in untreated control (top row), than in stone treated during trial (second row); However, ongoing, rapid decay visible in powdering, darker stones (third row) compared to flaking, lighter stones (bottom row) treated in 2015. 102
Figure III.14: HCT trial wall at ToL. **(Top):** shortly after treatemnt in 2001 (dark surfaces due to residual moisture following treatment). **(Middle):** individual stones in 2018. **(Bottom):** micrograph taking with Dinolight USB microscope showing consolidation of treated surfac 104
Figure III.15: DRM profiles of selected stones. 107
Figure IV.1: (A.) Extent of late- and post-medieval auxiliary construction surrounding White Tower (main building) and Wardrobe Tower (foreground). Photo from south-east c.1870 (HRP archives). **(B.)** Present-day condition of Wardrobe Tower, following 2017 conservation work, viewed from south. Photo November 2018 (Authors own). 118
Figure IV.2: Schematic views of Wardrobe Tower showing distribution of Reigate Stone and areas of NDT measurements in field surveys. Inset shows methodology of NDT measurements (used on dark blue blocks), with dotted squares describing regions in which joint, block edge and block centre measurements were taken. Between 1 and 8 measurements were taken for each circle, depending on survey date and device used. 121
Figure IV.3: Results of laboratory calibration of capacitance moisture meters on two large blocks of Reigate Stone from different sources (approx. 200x150x100 mm). Moisture meter readings decrease in steps as blocks dry out. Near maximum readings approximately correspond to above 90% saturation, during which time surface colour progressively lightens. As surface colour stabilises, moisture meter readings decrease more noticeably. 126
Figure IV.4: Correlation between T660 and Equotip readings on different materials across two separate surveys. Whilst there is no clear correlation, the distribution of

measurements on Reigate Stone suggests the Equotip may provide a better indication of moisture content at higher saturation. 127
Figure IV.5: Distribution of moisture meter readings at individual stone scale across three separate surveys, showing low, high and maximum readings for individual Reigate block edges and centres (three measurements per point). The measurements can provide some indication of differential drying following the recent wetting of the masonry prior to each survey. There is some indication that block edges adjacent to putty mortar are drying more rapidly, but no clear pattern according to mortar type or mortar width. Ambient climate and exposure (both aspect and micro-contextual shelter) provide better indicators. 133
Figure IV.6: Distribution of moisture meter readings at monument scale across three separate surveys, showing low, high and maximum readings for individual Reigate blocks (one measurement per point). The variation across different seasons highlights the role of macro-scale dynamics, which are likely to outweigh the influence of pointing mortar at individual joints. In particular, the effect of good drying conditions along the edge of the monument (August 2018), and recent rainfall along the top of the monument (October 209) can be seen. 135
Figure IV.7: Boxplot of surface hardness measurements across three separate surveys, organised by mortar type and adjacent Reigate block edge (or centre). Central line represents mean value, upper and lower extents of box represent interquartile range (IQR: all measurements within 25th and 75th percentile). Whiskers represent maximum range of measurements less than 1.5*IQR, outliers are single measurements more than 1.5*IQR. Only includes data used in ANOVA tests (i.e. measurements taken from same locations across all three surveys). 139
Figure IV.8: Distribution of surface hardness measurements at individual stone scale across two separate surveys, showing HLD for individual Reigate block edges and centres (5-8 measurements per point). Local variation across individual blocks irrespective of adjacent mortar type, and lack of clear patterns according to mortar type, demonstrate the caution is necessary when interpreting the generalised findings made in the ANOVA test. 143
Figure IV.9: Parts of north facing masonry included in Wardrobe Tower photographed shortly before 2017 conservation **(below)** and in October 2019 **(above)**. Water run-off channels have reformed, their location corresponds to past decay features. 143
Figure IV.10: Selection of individual Reigate Stone blocks photographed in November 2017 and October 2019. Some signs of ongoing decay can be associated with inadequate pointing (e.g. WRD16 and WRD14), some can be associated with exposure and macro-context (e.g. WRD03, WRD40, WRD54). There are few examples of ongoing decay which can be more closely associated with type of pointing mortar (WRD24, WRD30). 144
Figure IV.11: USB micrographs showing: **(A.)** well bonded putty mortar (WRD12); **(B.)** poorly bonded putty mortar (WRD27); **(C.)** well bonded NHL mortar (WRD29); **(D.)** poorly bonded NHL mortar with algal growth (WRD30); **(E.)** well bonded old mortar (WRD53); **(F.)** and poorly bonded old mortar (WRD39). (scale bar 1mm) 146
Figure IV.12: (Top) Decayed, south facing Reigate Stone masonry at the Wardrobe Tower, Tower of London and **(Bottom)** close up of north facing masonry, displaying a range of

pointing mortar scenarios, including a joint galleted with a tile and proud standing mortar..... 152
Figure IV.13: Schematic of WUFI model explaining different pointing scenarios and measurement areas..... 155
Figure IV.14: Results of WUFI simulations, counter clockwise from top: **(A.)** Water content in stone edges and bedding mortar of different pointing mortar scenarios across second year of simulation. **(B.)** Closer view of fluctuations in bedding mortar across two-week period of heavy rainfall, **(C.)** gradual drying of stone edges across subsequent 8-week period, and **(D.)** rapid wetting of stone edges across time period investigated in Figure 15..... 157
Figure IV.15: Dynamic moisture distribution in stones pointed with **(top)** narrow putty, **(centre)** wide putty and **(bottom)** galleted putty following driving rain spells beginning on 1st June..... 159
Figure IV.16: (A.) 48 hour moving average of relative humidity at stone surface during second year of simulation. **(B.)** Lowest recorded values, showing increased RH range in edges adjacent to proud standing mortar..... 159
Figure V.1: The 12th century Bell Tower from South East..... 166
Figure V.2: Axonometric of Bell Tower from South showing locations in this study (modified from a drawing by Terry Bell)..... 169
Figure V.3: Reigate masonry in lower chamber. Top left: NW alcove; Top right: W alcove; Bottom left: typical powdering decay; Bottom right: severe efflorescence..... 169
Figure V.4: Reigate masonry in stairwell. Top left: flaking decay on west flank (Jan 2018); Top right: west flank following detachment episode (Aug 2018); Bottom left: east flank; Bottom right: typical detached material and fresh subsurface..... 170
Figure V.5: Micrographs of detached flake (left) and powdering surface (right) showing salt contamination (scale bars 1 mm)..... 170
Figure V.6: Cumulative mass of material collected in trays at base of decaying masonry... 171
Figure V.7: Boxplots of readings taken with moisture meters, showing mean (x), median (middle line), interquartile range (box), range (whiskers) and outliers (i.e. datapoints over 1.5 times above or below IQR). **(Left)** Results for T660 near surface readings and **(right)** results for T610 sub-surface readings..... 172
Figure V.8: Karsten tubes attached to flaking surface in stairwell **(left)** and powdering surface in lower chamber **(right)** with water level after 3.5 minutes marked by dashed line..... 173
Figure V.9: Scatterplots showing seasonal distribution of temperature and RH at surveyed locations for period from March 2018 - February 2019..... 174
Figure V.10: 4-week period in Winter 2018/19 showing microclimatic temperature (dashed) and RH (solid) variations in lower chamber..... 175
Figure V.11: 5-week period showing correlation between surface-wetness sensor sealed against Reigate Stone in NW alcove and rainfall..... 176
Figure V.12: 6-week period in Spring 2018, showing correlation of solar radiation and rainfall with RH and Reigate surface temperature in stairwell..... 177
Figure V.13: Lower chamber in 1945 (top) and 1958 (bottom). North-west alcove on far right of image; west alcove immediately to left. (HRP archives)..... 179

Figure V.14: Powdering and flaking Reigate Stone at the Bell Tower, Tower of London. A. Flaking stone in south-east facing external masonry; likely to represent 19th century repair material. B. Powdering stone in south-west facing masonry with alveolars; likely to represent primary medieval material. C. Flaking stone in stairwell, with delamination occurring parallel to front and side faces. D. Powdering stone in north-west alcove of lower chamber. 186
Figure V.15: Axonometric cut-away of the Bell Tower, Tower of London, highlighting areas of investigation in this study and showing approximate location of stones depicted in Figure V.14.a-d. (original image by T. Bell)..... 189
Figure V.16: Diagrammatic description of hypothetical mechanics underlying powdering and flaking decay patterns. 190
Figure V.17: (A.) The concentration of soluble ions varies during different sampling periods and in different areas of the Bell Tower, Tower of London. **(B.)** The correlation between calcium and sulphate ions suggests that sulphate is mainly bound in gypsum and non- gypsum bound calcium content is consistent across samples..... 195
Figure V.18**: (A.)** Runsalt models based on ionic concentrations measured in the lower chamber alcove (Jan-Feb sample) and the stairwell (May sample). Relative humidity (RH) ranges established in Chapter V.1 are superimposed. Temperature set to 10° C for lower chamber and 25° C for the stairwell. **(B.)** Final iteration of Runsalt model developed to represent crystallisation scenarios in both lower chamber and stairwell environments using simplified, unified salt mixture of 250 g NaCl and 150 g $NaNO_3$ per litre of water. Temperature in model set to 15° C. RH range for proposed accelerated ageing regimes superimposed..... 197
Figure V.19: Diagrammatic overview of accelerated ageing regimes showing sample preparation steps and separate climate chamber programmes for two sets of replicates. NaCl and NaNO3 crystallisation/ deliquescence relative humidity marked by pink dotted line. Sequential photo numbering system used in main text and Figures V.20-21 shown in dark grey boxes. 199
Figure V.20: Grain size distribution (i.) and total loss, including salt, (ii.) at different stages of accelerated ageing regimes for environments A and B. 204
Figure V.21: Three stages of decay in selection of samples exposed to environments A and B. Referencing system in Figure V.19 explains timing of photos. Rate and pattern of decay in both environments is strongly dependent on quarry provenance and individual stone characteristics. Loss of larger pieces of material usually related to pre-existing structural flaws (e.g. GO2_A and GA2_B), but some phenomena reminiscent of flaking seen in response to environment A (e.g. GA2_A and intermediate stages of QF1_A & RS1_A). Rate and homogeneity of surface decay in response to phase 2 of environment B strongly dependent on formation of salt crust during phase 1. 206
Figure VI.1: The relative weighting of, and links between individual studies in this thesis overlaid on the conceptual axes of variability introduced in Chapter III. The integrated methodological approach achieves a broad, robust spread of investigation. 225
Figure VI.2: Bell Tower elevations A and B **(top left)**, elevations B, C and D **(bottom left)**, and elevations E and F **(right)** photographed in 2016. (Author) 227
Figure VI.3: Close-up of 1682 survey showing south west corner of Tower of London. Bell Tower (N) surrounded by later additions forming gatehouse (R). (HRP archives)..... 229

Figure VI.4: Close-up of elevation B in 2018 showing areas of successive replacement to right of image. (Author) 233
Figure VI.5: 1903 unrealised plan for restoration of Bell Tower, lower chamber. (HRP archives) 233
Figure VI.6: Photo of lower chamber from the 1940s, showing higher floor level and blocked in alcoves. (HRP archives) 234
Figure VI.7: Elevations B and C, early 20th century. Some extant replacement stones can be seen behind a thick layer of sulphation. (Historic England, with permission) 234
Figure VI.8: Photo of elevations D and F (c.1870) showing partial replacement of Reigate Stone with Magnesian Limestone. Four Reigate Stone blocks later incorporated into HCT trials are fully intact on right of picture. (Historic England, with permission) 237
Figure VI.9: Photo looking west dating to the 1910s showing the pebbeldash render beginning to detach along the Reigate quoins. Differential levels of soiling can also be seen to either side of the Virginia Creeper. (Historic England, with permission) 237
Figure VI.10: Photo looking south dating to 1940s showing persistent sulphation of elevations A and B. A small stone structure can be made out adjoining the base of elevation A. (HRP archives) 238
Figure VI.11: Photo of elevation E (1947), showing recent replacement being covered by growth of Virginia Creeper. Erosion of future HCT trial area can be seen (compare Fig. 7). (Historic England, with permission) 238
Figure VI.12: 19th century photo of upper chamber, showing thick limewash, which was removed in 1930s. (Historic England, with permission) 239
Figure VI.13: Diagrammatic description of interrelated environments (affecting decay process) and social contexts (affecting appreciation of value, or deterioration processes) 246
Figure VI.14: Integrated methodology, showing relationship between historic built environment, scientific framework and external forces. 248

List of Tables

Table III.1: List of quarries and buildings that provided samples for this study, with approximate date of construction/ quarrying, coding system, and information on shape, size and location of samples. Quarry dates from Burgess (2008). 70

Table III.2: Results of mineralogical and hygro-physical analysis. Mineral components determined using XRD. Bulk density and open porosity determined according to BS EN 772-4:1998. Pulse velocity determined in accordance with BS EN 14579:2004. Anisotropy coefficient determined according to Birch (1961). Capillary absorption determined according to BS EN 1925:1999. Sorptivity defined as mass-percentage gained following adsorption; hysteresis as difference between mass-percentage following adsorption and desorption. 76

Table III.3: Correlation matrix using Pearson's method on results shown in Table III.2. Mineralogical correlations made using all 33 samples. Mineralogical-physical and physical correlations made using 26 samples for which this data was available. R greater than 0.4 (or less than -0.4) marked in bold. R greater than 0.6 (or less than -0.6) marked in bold-italic. 76

Table III.4: Results of PCA, showing contribution of PC1-4 to overall variability, and contribution of individual variables to each PC. 84

Table III.5: Past Reigate stone conservation techniques. Works for which no reference is given are recorded in the archives of Historic Royal Palaces. 98

Table III.6: Results of NDT (*due to deterioration of drill bit, values measured on separate stones are not calibrated). 106

Table IV.1: Summary of field surveys, showing date, wetting and drying scenario, areas surveyed, techniques used, types of analysis performed on data, and number of measurements made. Also includes distribution of measurements according to spatial and material variables. 124

Table IV.2: Results of factorial ANOVA tests on surface hardness data, evaluating effect of individual variables and interactions of variables on distribution of surface hardness measurements. Main effects ($p<0.001$) in bold, less significant effects ($p<0.01$) in italics. *Combined dataset and January2019 dataset did not pass Levene's test ($p>0.05$) with block data. **November 2017 dataset scored $p=0.02$ on Levene's test. Block data was retained to enable better comparison of overall results. 138

Table IV.3: Methods and results of experimental programme to determine WUFI input data for Reigate Stone. When possible, experiments were also conducted on a single sample from the Wardrobe Tower and inputs were weighted slightly. *Wardrobe Tower sample measured at 20 C 90% RH **Pulse velocity used to approximate thermal conductivity. 154

Table V.1: Salt uptake, total loss, and type and size of largest lost piece from each replicate of every specimen in response to different accelerated ageing regimes. *Material characteristics taken from Chapter III.1. ** Additional salt uptake in environment B occurred during continuous and repeat partial immersion. ***no loss recorded in control samples. 203

I. Introduction

"An army without flexibility never wins a battle.

A tree that is unbending is easily broken.

The hard and strong will fall.

The soft and weak will overcome."

Lao Tsu, *Tao Te Ching* 4th century BC (in: Feng and English 1973, p.76)

I) 1. Context

I) 1.1. Vulnerable Historic Masonry

The historic built environment represents a major part of global cultural heritage (ICOMOS 1964). Successful management can contribute positively to cultural identity, sustainability and economic growth (Cassar 2009; English Heritage 2014). Stone-built architecture occupies a central role in this environment, forming famous monuments, providing places of worship, and giving character to human settlements across many parts of the world. Its relative longevity imbues it with immeasurable historical and pre-historical information. In historic masonry, everything from the type of stone used in buildings, to the form of construction, style of masonry and approach to repair is of great value to understanding historic architecture and the societies that have used it. Yet despite any appearance of permanence, masonry architecture requires care and maintenance; architectural conservation cut its teeth on monuments of stone, and continues to focus much attention on this diverse, natural building material (Jokhiletho 2007; Doehne and Price 2010). As we confront the Anthropocene, an increasingly intimate relationship between the built and natural environments is shaping new attitudes to the historic built environment and amplifying demands on its conservation (Gomez-Heras and McCabe 2015; Douglas-Jones et al. 2016).

Some stones used in historic masonry are prone to rapid decay (Odgers and Henry 2012). This is generally due to a mixture of aggressive environments, poorly suited material properties and complex histories of environmental change and material repair. Despite occupying a disproportionate amount of stone conservators' time, these stones are often poorly scientifically understood (Doehne and Price 2010, p.25).

They may defy typical classification, and decay mechanisms and processes may be obscure. This can make the selection of appropriate conservation strategies difficult. Until recently these stones were commonly referred to as *problem stones*. In many cases they represent important chapters of regional built heritage, during which only limited typologies of building stone were available and prior to significant environmental and societal changes (Hyslop et al. 2010); they often have great cultural value. Given their increased risk of deterioration, safeguarding the information stored in these stones for future generations is therefore both particularly important and particularly challenging.

This thesis builds on the emerging argument that problem stone is an unsuitable term[1] for scenarios which may be as much dependent on aggressive environments or aggressive past repair strategies as on inherently poor material properties. This complements several trends in stone conservation science. The theoretical framework of masonry conservation is shifting towards improving resilience to change, rather than resistance to decay (Viles 2013). This echoes aspects of a general trend in conservation over the past two decades, which has seen environmental control aimed at mitigating decay mechanisms (preventive conservation) emerge alongside invasive treatment aimed at improving material properties (active conservation) (Ashley-Smith 2018). It is related to nascent conservation strategies within several built heritage institutions that are based on the concept of 'curated decay' (Desilvey 2017). Masonry decay is also increasingly being understood in terms of complex system dynamics, in which the interactions between primary building

[1] Today, Historic England prefers the term 'hard to treat' (Clara Willett, personal communication).

stone, replacement stones, mortar, and invasive agents of anthropogenic or environmental origin are as important as the nature of the building stones themselves in controlling non-linear response to environmental mechanisms (Viles 2005; Yu and Oguchi 2009; Hyslop et al 2010; Smith et al 2011a). In a further trend, studies are revealing nuance within the value systems that underpin cultural heritage, which may be influencing attitudes to the aesthetics of decay (Brimblecombe and Grossi 2005; Douglas-Jones et al 2016). Whilst these developments point towards promising improvements on past approaches, integrating this diverse set of variables significantly increases the complexity of scientifically robust stone conservation. The focus of this thesis is on improving the resilience of vulnerable masonry by exploring the complex dynamics of deterioration.

I) 1.2. Reigate Stone

Reigate Stone is a good example of what the field until recently referred to as a problem stone. Used extensively in Medieval London and South-East England, it was arguably the region's principal freestone between the 11th and 16th centuries (Tatton-Brown 2001). In some scenarios the stone decayed rapidly, which led to declining use and wide-scale replacement between the 16th and 20th centuries. However, some stones have survived well. Past conservation strategies have often been ineffective and in some cases may have accelerated decay (Sanderson and Garner 2001). Given the extent to which the stone was exploited, several known mineralogical variations, the environmental stresses of industrialising London, and the dynamics of past construction and repair, it has been difficult to ascertain the relative influence of environmental mechanisms and material properties in decay processes.

Reigate Stone is a vulnerable building stone with a complex history of use, high cultural value and poorly understood decay processes. Detailed investigation can provide transferable knowledge and skills for research into other types of vulnerable masonry. The topic is also well placed for further development of the emerging field of built heritage science. There are several areas of current research in the discipline of stone conservation science to which the thesis contributes. These include the role of mortars in masonry systems (Fusade et al. 2019a), the dynamics of salt driven decay (Flatt et al 2017; Lubelli et al 2018) and the impact of climate change (Smith et al 2011a; Orr et al. 2018). There are also several knowledge gaps in the wider, emergent field of heritage science which this thesis addresses through research on Reigate Stone. These include common language and terminology in defining and describing phenomena (Vergès-Belmin 2008; Doehne and Price 2010 p.2-3) and defining robust methodological frameworks, for example integrating non-destructive field protocols and laboratory experiments (Erkal and D'Ayala 2015; Wilhelm et al. 2016a).

I) 1.3. The Tower of London

The Tower of London and Hampton Court Palace, managed by Historic Royal Palaces (HRP), contain a large amount of Reigate Stone. These represent numerous different build periods, can be found in diverse environments ranging from highly exposed to completely sheltered, and have been subject to several, documented treatment and repair programmes (e.g. Bowley 1975; Sanderson and Garner 2001). As such, these important historic sites can provide a range of different case studies for investigating Reigate Stone decay and will benefit directly from any developments made towards improving current conservation strategies. As a UNESCO world heritage site, the

Tower of London is also well placed to incorporate a broader appraisal of the relationship between conservation science and policy into the research framework (Lyon 2007). The choice of these sites has maximised opportunities both for the meaningful scientific research, and the impact on practice and policy feasible within the scope of a DPhil project.

The Tower of London provides a suitable location for case study due to a relatively large stock of primary Reigate Stone. Construction of the Tower of London started with the Norman conquest of 1066 and continued through three major phases of expansion into the 14th century (Parnell 1993). This marks the period in which Reigate Stone use became wide-spread (Tatton-Brown 2001). First use of Reigate Stone was as ashlar in the lower part of the White Tower (1066-78) (Impey and Ashbee 2008, p.54–56) and it can be found throughout the site. Later medieval or early Victorian repairs are also likely. Until very recently there were supplies of unused Reigate at the Tower for use in replacement works. Mineralogical variations are highly probable due to changes in quarry provenance across these centuries. Treatment history and past changes in local environment will be relatively well documented given the importance of the site. A diverse present-day setting, which includes masonry facing all aspects, sheltered and indoor examples in rooms of varying use, adds variation to the type of environmental mechanisms that can be expected to drive deterioration. Individual locations at Hampton Court Palace are selected to augment the variation present at the Tower of London.

There have been several studies on the causes of stone decay at the Tower of London. Sabbioni et al. (2004) found two distinct pollutant deposition typologies on Kentish

Rag masonry at the Tower; black crusts composed of gypsum and calcite, and grey-brownish crusts composed mainly of calcite but with a higher concentration of organic carbon. The crust variation reflects changes in air pollution in London, which found a rapid decline in sulphur-dioxide levels in the early 20th century followed by a sharp increase in pollutants relating to automobile emissions (Brimblecombe and Grossi 2009). The effect of organic carbon is further investigated at the Tower (Bonazza et al. 2007); bio-colonisation and associated deterioration may be stimulated. Although positive about the impact environmental legislation can have, the studies note the lasting damage that historical pollution can cause. However, Brimblecombe and Grossi (2005) highlighted the subjectivity associated with the aesthetics of decay in a study of the White Tower, with some user groups attributing age value to the effects of pollution. Advances in stone conservation science have also been made in research at the Tower of London. Clarke and Ashurst (1972) pioneered the long-term, field-based evaluation of different stone consolidants in trials at the Balium Wall. In a series of papers, Price (1993; 2000; 2007) used an analysis of Reigate Stone masonry at the Wakefield Tower to test the ECOS model that has become the standard for predicting salt crystallisation. There have also been important studies on general conservation theory and practice at the Tower of London. Inglesby (2017) found that the stylistic restoration programme associated with the mid-19th century, and responsible for largescale change in the historic built environment, continued in to the 20th century in ongoing attempts to control historical narrative.

I) 2. Outline

I) 2.1. Aims and objectives

The overall aim of this thesis is to facilitate the development of sustainable conservation strategies for improving the resilience of Reigate Stone masonry. This necessitates scientific understanding of the mechanisms driving decay and appreciation of the interplay between decay and deterioration, in order to balance material preservation with the complex set of values underpinning the world heritage site. The main research objectives are:

I. To understand the composition of Reigate Stone masonry, including lithological variations, historical developments, common contaminations and decay patterns, and the effect these have on deterioration,

II. To assess past and present conservation strategies,

III. To characterise decay and link processes to measurable environmental mechanisms.

Improving knowledge within these three areas will enable a holistic, scientific understanding of Reigate Stone masonry which will then facilitate the development of tailored conservation strategies in ongoing, more practically focused work.

I) 2.2. Thesis Structure

This thesis follows the paper route and is divided in to five chapters. Chapter II reviews literature on stone conservation science. This first contextualises the subject within the broader discipline and describe the theoretical framework which guided research. It then describes the methodological framework, with further reference to relevant

literature. Chapters III-V represent the main body of research. Each contains one paper submitted for publication to a scientific journal and a shorter article submitted to conference proceedings. The narrative arc of these chapters guides the reader through progressively increasing scales of influence in Reigate Stone decay.

- **Chapter III** focuses on the stone itself and considers the impact of *mineralogical variations* and *past conservation*.
- **Chapter IV** moves beyond the fabric of the stone, whilst remaining within the masonry system. It shadows *contemporary conservation* work, focusing on the *role of pointing mortar* in regulating moisture dynamics and mitigating environmental decay mechanisms.
- **Chapter V** moves beyond the masonry system and examines environmental interactions with Reigate Stone. It investigates *micro-environmental controls* for the *ongoing conservation* of salt contaminated masonry.

Book-ending this narrative are considerations of the role societal change plays in contextualising the decay of historic masonry. Chapter III begins with an analysis of how past economies have impacted ongoing decay; Chapter VI includes a discussion on the relationship between heritage values and changes to the historic built environment. This is intended to tie the body of research to a transdisciplinary framework and make it meaningful to heritage studies, architectural engineering and conservation practice. Chapter VI also synthesises the findings and provides a brief outlook on the implications for Reigate Stone conservation.

I) 2.3. Research framework

The present research has taken place within the framework of the Centre for Doctoral Training in Science and Engineering in Arts, Heritage and Archaeology (SEAHA). HRP and the conservation architects Carden and Godfrey Architects have co-supervised the project alongside the School of Geography and the Environment. Besides providing logistical and operational guidance to fieldwork, their involvement is improving research impact by facilitating close cooperation with stakeholders and informing practical conservation at the Tower. Reciprocally, the research has benefitted from shadowing active conservation and maintenance schedules.

II. Literature Review: Complexity and contradiction in stone conservation

"I am for richness of meaning,
not clarity of meaning"

Robert Venturi, *Complexity and Contradiction in Architecture* 1966 (in: Venturi 1966)

This chapter is split into two sections, which critically review literature on the theory and methodology of stone conservation science. Robert Venturi wrote *Complexity and Contradiction in Architecture* (1966) as a counterweight to Le Corbusier's Modernist manifesto *Vers une Architecture* (1923). Venturi argues that architecture cannot be guided by simplicity and internationalism, instead it must embrace plurality and context.

II) 1. Theoretical Framework

II) 1.1. Overview

This section describes the prevailing theoretical framework of stone conservation science. It will start by reviewing literature that explores underlying complexities in defining the purpose and scope of stone conservation. It will examine the emergence and convergence of conceptual approaches to demystifying this complexity. It will then summarise the framework that has been adopted in this thesis.

Stone conservation science is complex for a variety of reasons. These range from problems in selecting appropriate terminologies for concepts and phenomena, to difficulties in identifying and monitoring the causes and effects of change, to challenges in balancing frequently conflicting values when using scientific data to guide management strategies. Schaffer (2004) was perhaps the first to attempt an overarching treatise of the scientific field in *The Weathering of Natural Building Stones* (first published 1932). More recently, Doehne and Price (2010) produced a thorough overview of current research. Odgers and Henry (2012) provide an encyclopaedic volume linking practical guidance to scientific research, part of a 10-book series which supersedes Ashurst and Ashurst (1988). Whilst several relatively recent papers have provided more concise reviews of specific aspects of stone conservation science (e.g. Smith et al. 2008; Viles 2013; Gomez-Heras and McCabe 2015) the field lacks a review focussed on the ontological and phenomenological discourse underpinning scientific research.

II) 1.2. Purpose

The emergence of architectural conservation theory in the 19th and the first half of 20th century critically engaged with value systems inherent to the historic built environment (Jokilehto 2007, p.255-308). These systems were largely implicit previously, but the rapid changes of the industrial and inter-war periods provoked a focussed reaction which culminated in stylistic notions and codes of practice. In vernacular culture, care for the historic built environment happened in accordance with local material, environmental and economic demands. The relationship between built, natural and intangible heritage was a manifestation of place (Heidegger 1971). This culminated in a cultural diversity that ranges from the annual re-plastering of adobe mosques in Mali (Brunet-Jailly and Scherrer 2018; Bourgeois 1987), to the generational reconstruction of timber shrines in Japan (Nute 2004, p.62-70; Adams 1998). In globalising culture, various forces have coalesced to replace such traditions with dogma. In Europe, factors such as an increasing interest and study of ancient Roman civilisation, the emergence of scientific method, and the devastation of the French revolutionary wars converged at the end of the 18th century. These contributed to the establishment of legislation and national commissions committed to the survey and repair of historic buildings (Jokilehto 2007, p.144-189). This resulted in the restoration of monuments across Europe throughout the first half of the 19th century. Emerging restoration principles began to favour a stylistic re-appraisal of the historic fabric, perhaps most famously embodied in the works and writing of E.E. Viollet-le-Duc (Price 1996, p.307-323). The conservation movement, spearheaded by J. Ruskin, grew out of opposition to the notion that historic architecture could be restored to a former or idealised state (ibid.). The movement, which gained traction

following the foundation of the Society for the Protection of Ancient Buildings (SPAB) in 1877, instead emphasised the need for maintenance and care, and argued that much work that was being done in the name of restoration amounted to destruction of historical evidence.

The dichotomy of these differing theoretical approaches should be considered within the cultural context from which they emerged. In England, the dissolution of the monasteries had centuries earlier bequeathed the landscape a set of ruined architecture, which embedded a romantic notion of the ruin (Jokilehto 2007, p.127-140). France was reacting to the recent trauma of more than a decade of revolution and war. Ruined buildings marking the landscape could be associated with events that remained in living memory. Restoration to an idealised state was a form of social healing. The role of the Italian school, led by C. Boito, in taking large steps towards the unification of principles by advocating authenticity and documentation (ibid, p.243), can similarly be viewed within the context of Italy's own set of circumstances, principally the omnipresence of Roman archaeology. A. Riegl took further steps towards codification in his discourse on value, which was seminal in defining and differentiating the varying premise and purpose of historic architecture (Price 1996, p.69-83). The philosophical discourse and social upheaval of Modernity isolated inherent value from the process of building and dwelling. The value systems associated with the historic built environment were laid bare; protecting them is now no longer simply a case of maintaining tradition, it requires deliberation and decision-making.

The present-day practical framework of care for the historic built environment is sometimes referred to as *conservation-restoration* (e.g. Vergès-Belmin 2008). On the one hand, this reflects the dichotomous attitudes of the 19th century, and the political nature of synthesis and eventual codification of practice in Athens and Venice (ICOMOS 1931; 1964). On the other hand, it is a tacit acknowledgement of the highly individual nature of each historic site, building, or wall. Any universal framework must provide a plausible approach for every specific case. The term conservation as it is generally accepted today when applied to architecture, and as it is used in this thesis, is taken to include a wide range of remedial action, including targeted restoration, repair, consolidation and environmental control (ICOMOS 1999). As aggregating heritage lists and increasing environmental pressures begin to result in a 'crisis of accumulation' (Harrison 2013), the option of 'curated decay' is also emerging within this broad definition of conservation (DeSilvey 2017). Typically, however, material or structural preservation is the practical objective of architectural conservation, with the overall aim being the safeguarding of historic, aesthetic and some degree of functional value; evaluation occurs on a case-by-case basis.

The complexity of this practical framework has demanded an increasingly interdisciplinary effort (Smith and Turkington 2004). Besides ontological and phenomenological discourse, general architectural conservation practice must incorporate specialist knowledge from various scientific fields (Torraca 1982). In stone conservation, early scientific endeavour borrowed heavily from existing disciplines. Geological techniques were used to characterise building stones and the physical and chemical processes we recognise today were broadly identified (e.g. Shore 1957; Schaffer 2004). Whilst pioneers such as R.J. Schaffer were remarkably accurate in

many areas, and laid the foundation for contemporary stone conservation science, there were gaps in the joined-up thinking. These contributed to the proliferation of unsuitable repair materials (Odgers and Henry 2012, p.80-81), inadequate testing standards (Inkpen et al. 2004), and ongoing challenges surrounding authenticity and urban context, particularly in response to war (Jokilehto 2017, p.399-420). Advances in conservation science, archaeological science and Earth systems science contributed to a partial desilofication, which brought stone conservation theory, practice and science closer together. These manifested themselves in more nuanced approaches to remedial activity, including a rediscovery of more traditional techniques (Ashurst and Dimes 1990), an exploration of preventive conservation strategies (Demas 2002), and a systems perspective to cause and effect (Prikryl 2007). Recent advances have increasingly integrated humanities and ecological paradigms. This has developed more synergistic approaches, which incorporate inherent subjectivities into the scientific framework (e.g. Brimblecombe and Grossi 2005; Douglas-Jones et al. 2016; Fatoric and Seekamp 2018) and nature-based solutions into the practical framework (e.g. Sternberg et al. 2010; Hanssen and Viles 2014; Gadd 2017). Balancing this interdisciplinarity exposes tensions in the management of cultural heritage (Lyon 2007; Ashley-Smith 2018). However, it also endows the historic built environment with a depth of meaning that goes beyond tradition and place-making, occupying a central role in the science of the Anthropocene and efforts to build cyclic economies (Gomez-Heras and McCabe 2015; Watson 2019). This perspective begins to tie the historic built environment closer to the concept of *cultural landscapes*, a term used to describe ‘the combined works of nature and man’ (UNESCO 2012).

II) 1.3. Terminology

A common challenge in studies on stone deterioration is encountered in terminological confusion. This arises from the interdisciplinary nature of stone conservation and is compounded by the international nature of scientific research. Bracken and Oughton (2006) argue that interdisciplinary research projects need to allocate time to the development of shared vocabularies. They highlight three aspects of language which are important when communicating across traditional disciplinary boundaries. *Dialects* represent the difference between every-day and expert use of a word. *Metaphors* are interpretative communication tools which require a contextual 'speech community' (Klamer and Leonard 1994). *Articulation* is the process of deconstructing disciplinary knowledge in the context of interdisciplinarity in order to realign conceptual boundaries (Ramadier 2004). These issues are particularly significant for a field in which scientific research is closely linked to practice and requires the integration of vernacular usage. Specific examples of persistent confusion between stone conservation practice and science include the use of the word lime (Elert et al. 2002) and differences in the meaning of similar sounding actions across different languages, such as *restoration* in English and *restauro* in Italian[2]. Bracken and Oughton (2006) suggest a process of 'active listening', meaning a mindfulness of developing common understanding, is crucial.

Medical analogy has provided architectural survey and conservation with a useful set of metaphors (ICOMOS 2003; Van Balen and Verstrynge 2016). A medical case history,

[2] The Italian word *restauro* is an umbrella term, which can entail maintenance, repair and renovation, as well as what would more commonly be understood by restoration, which in Italian might best be described as *restauro storico*.

or *anamnesis*, can be constructed in order to identify causes of decay. Assessment of these informs *diagnosis*, which in turn informs an appropriate remedial *therapy*. Tailoring this approach to stone conservation equates stone decay to illness, with pathological symptoms, and masonry to a patient, with a unique case history (Smith and Prikryl 2007). This approach provides the discipline with ready-made nomenclature that enables the framing of complex issues within a common reference system (Fitzner 2004). Whilst this represents a clear methodological framework in itself, some studies have extended the medical analogy beyond a mnemonic to incorporate formal assessment tools based on staging systems (Warke et al. 2003; Giesen et al. 2011). As ecological sensibilities and economic necessities increasingly demand alternatives to interventive conservation, DeSilvey (2017, p.155-175) argues that *palliative care* provides a valuable simile to processing the inevitable loss of built heritage. It can provide "another mode of attention that involves care without the attempt to control" (ibid, p.169). The medical metaphor provides a rich set of terminologies that have given character to the historic built environment whilst strengthening the conceptual framework of conservation science.

Hall et al. (2012) discuss the time-lag between the conceptual development of a growing discipline and the establishment of suitable scientific terminology. They question ongoing use of the term *weathering* in geomorphology, by arguing that intrinsic rock properties, rather than climatic weathering processes, dominate the emergence of landscape. The study proposes the term *rock decay* as being a more appropriate umbrella term to frame the energy transfers that take place. Whilst some have adopted this change (e.g. Dorn et al. 2013), use of the term weathering is persistent in geomorphology (e.g. Warke et al. 2019). This further highlights the

importance of 'active listening', in order to continuously interpret the use of entrenched terminology within prevailing conceptual frameworks. Hall et al. (2012) direct their argument mainly at the spatiotemporal scale of landform evolution; at the building stone scale, climatic variability can be a significant factor in the rate and pattern of decay and related conservation activity (Brimblecombe and Grossi 2009; Steiger et al. 2011; McAllister et al. 2017). Nevertheless, the study highlights the general importance of semantic nuance in scientific progress and the specific issue of scale in relation to defining phenomena within Earth system dynamics.

More specifically to the field of stone conservations science, use of the term *durability* has come under scrutiny (e.g. Prikryl 2013). Turkington (1996) argues that, rather than the fixed properties the word connotes, its use is vague and ambiguous across different disciplinary dialects. Duffy and O'Brien (1996) introduce a sociocultural factor by arguing that aesthetic thresholds can change over time, making durability transient. Both studies suggest that a systems approach is necessary to define durability within a framework of interrelated processes. Inkpen et al. (2004) expand on this argument by highlighting the role of operator variability in standardised tests to assess durability. Their study also comments on the prevailing use of Portland Stone as the basis for comparison amongst other building stones. They argue that this reductionism enables only broad categorisation and may not be able to supply useful information for how a stone will respond in the context of built environment. This reflects long-running discourse on standardised tests not replicating real-world behaviour (Lewry and Crewdson 1994; Schaffer 2004, p.101; Lubelli et al. 2018). Viles (2013) proposes a more dynamic view of durability, which sees it in terms of *resilience*,

rather than resistance. This is defined as the ability to 'tolerate disturbances' and can provide a more realistic picture of interrelationship and episodic change.

The ambiguity of key terminology such as weathering and durability is also reflected in the definition of phenomena to affect building stones, with terms such as *deterioration*, *decay* and *degradation* being largely interchangeable. Viles et al. (1997) use deterioration as an umbrella term for classifying the breakdown of material at three different scales: degradation for microscale change (cm or less), distress for mesoscale change (cm to m), and decay for macroscale change (whole facades or buildings). Their study focuses on defining the underlying mechanics of physical change and does not directly address issues relating to the value or conservation of historic building stones. This raises the issue of articulation discussed by Bracken and Oughton (2006), relating to how terminologies can function usefully across the disciplinary boundaries. B. Fitzner and colleagues have developed perhaps the most extensive scientific taxonomy of decay related phenomena (e.g. Fitzner et al. 1995; Fitzner and Heinrichs 2001); however, this system has received criticism for being impractical to conservation activity (Rodrigues 2015). ICOMOS provide a generalised glossary on stone deterioration patterns aimed at informing both scientific and practical usage, which associates photographs of common phenomena with descriptive terms (Verges-Belmin 2008). The glossary is based on a review of seven pre-existing glossaries, standards and proto-standards produced by national and international working groups and is available in 11 languages. The definition of general terms introduces the notion of value and distinguishes concepts such as decay and deterioration; however, change is generally associated with a loss of value. As non-intervention and loss are increasingly incorporated into practical frameworks

(Lowenthal 1989; DeSilvey 2007, p.81; Ashley-Smith 2018), language will need to reflect more precisely the relationship between value and change.

These past studies anticipate ongoing terminological confusion. Bracken and Oughton (2006) conclude that the development of a common language for interdisciplinary research would be counter-productive, as it would remove much of the richness of disciplinary expertise; instead, through 'active listening' they argue for the development of a common understanding and an awareness of language differences. Stone conservation science is well placed in this respect as there is an acute awareness of the challenge. Discussion of terminological nuance and idiosyncrasy is a common theme at workshops and conferences (e.g. Viles et al. 1997). It is important for ongoing research to be respectful of the discourse that has taken place in the past and appreciate the richness of its vocabulary, whilst nevertheless being unafraid of re-evaluating existing paradigms and articulating new concepts.

II) 1.4. Complexity

II) 1.4.1. Scale

Increasing involvement in stone conservation science by Earth scientists has led to the adoption of systems thinking (Smith et al. 2008; Prikryl 2007). Stone deterioration is understood to take place within a dynamic, interconnected system of interdependent processes (Viles 2013). Early studies introduced a long-term perspective (e.g. Trudgill et al. 1991) and new approaches to complexity (e.g. Smith 1996). Later work began to consider the effect of interrelated processes (e.g. Viles and Turkington 2005; Warke et al. 2006) and how systems thinking could influence formal management (e.g. Wright 2002; Vazquez et al. 2013). Recent studies have called for heritage science

more generally to adopt an Earth systems perspective (Richards et al. 2019) and argued that the historic built environment is intimately linked to climatology in the Anthropocene (Gomez-Heras and McCabe 2015). This emergent paradigm has been useful for constructing a scientific framework around the historic built environment, which captures and combines processes examined by independent disciplines such as archaeological science, environmental science, material science, and chemistry, and can inform data-led policy in architectural conservation (Doehne and Price 2010; Wells 2019).

Defining processes within an Earth science framework is, however, itself highly relational. Schumm and Lichty (1965) argue that a geomorphic system is described according to the dependencies on the spatiotemporal scale in which it is considered; factors change from independent to interdependent as scale changes. Viles (2001) characterises distribution scales according to the metric system and associates phenomena with each of these. This leads to the spatial classification of decay features such as crusts (μm) and blisters (mm) and enables the selection of appropriate analytical techniques. The study proposes a qualitative, diagrammatic approach to understanding processes and forms. The example given in the study is the use of system dynamics (box-and-arrow plots), however the concept can also be considered as the principle behind the mapping techniques used to characterise building stone decay (e.g. Fitzner et al. 1995; Rodrigues 2015). Inkpen (2011) explores these ideas further, distinguishing between the fixed framework of absolute views of space and time and the open framework of relational views. They argue that in relational views, measured points (entities) are defined by their behaviour. Rather than change occurring within space and time, it is the relationship between processes

and entities which produces observable spatiotemporal scales; scale is derivative, whilst process is fundamental. However, process can only be defined through the entities it forms. Moreover, the role of the observer or operator is implicit in the description of the system: “The forms and processes identified cannot be separated from the measurement systems used to identify and monitor them” (Inkpen 2004).

Both these concepts are important. Viles’ perspective enables a categorisation of complex phenomena in order to construct queries and find appropriate methodologies. Whilst any data will necessarily represent a partial simplification of the complex entirety, the resolution of spatial distribution can be increased in line with technological improvements (Viles 2016). By linking cause and effect at measurable scales, it is arguably more useful for defining specific issues and designing targeted conservation strategies. Inkpen’s perspective reveals the inherent subjectivity of any reasonably user-friendly metric. This enables a vantage point which can expose knowledge gaps and help define new research. Adopting both perspectives can enable a systematic assessment of phenomena, whilst simultaneously taking advantage of apparent chaotic behaviour within the defined system.

Trofimov and Phillips (1992) suggest that apparent instability in geomorphic systems can be a source of order in higher spatiotemporal scales. Exploiting this property can inform forecasting; however, suitable experimental design presents a challenge. The limitations of short-term studies in the field of stone decay were identified at an early stage (Schaffer 2004, p.101). Smith (1996) illustrates the dangers of extrapolating decay rates measured over short periods to explain behaviour within masonry

systems, describing fundamental differences of scale between the system and any experimental set-up. Experiments must also consider multiple spatial scales in order to associate the emergence of decay patterns with underlying structural and mineralogical features (e.g. Dewanckele et al. 2013; Martinez-Martinez et al. 2013; Bruthans et al. 2018). Hall et al. (2012) argue that there is an increasing need to 'scale-up' geomorphic research. Crossdisciplinarity and specialisation has resulted in reductionist studies and a huge increase in data, which can no longer adequately explain real-world phenomena (i.e. landform evolution). Translating this call to stone conservation science requires a multimethodology approach to experimental design, which joins up interrelated processes and adequately describes the multiscale complexity of stone decay.

II) 1.4.2. Process

Decay occurs as environmental mechanisms impart force on the fabric of stone and cause physical change (Steiger et al. 2011). This force can be either direct, such as mechanical strain caused by settlement, or indirectly affect more responsive agents within the fabric, such as soluble salts. Resultant decay can be sudden or cumulative. A framework for describing decay in building stones must consider both low frequency, high magnitude events, such as fire and flood, and high frequency, low magnitude events, such as diurnal or seasonal temperature and humidity fluctuations (Goudie and Viles 1999). Water plays a central role in many processes, acting both as an agent of decay in its own right and as an engine for chemical and biological agents (Hall and Hoff 2011; Smith et al. 2011a). Salts are a major cause of decay in building stone (Charola 2000; Doehne 2002). Salt contamination has many environmental and anthropogenic sources, ranging from the soil and sea, to past storage (e.g.

gunpowder) or regular maintenance (e.g. de-icing) (Goudie and Viles 1997). Whilst local past or present environment can therefore provide evidence as to the nature of individual contaminates, masonry often contains a complex mixture of salts (Lubelli et al. 2018). These can also form within the fabric of the stone. Alkaline earth metals present in native rock or mortar are a common source of cations such as magnesium or calcium (e.g. Lopez-Arce et al. 2008); atmospheric pollution is a common source of anions such as sulphates and nitrates (Goudie and Viles 1997). Besides salt contamination, atmospheric pollution can also drive other chemical decay processes such as dissolution and crust formation (e.g. Sabbioni et al. 2004; Smith et al. 2010). Whilst biological growth can contribute with independent decay processes or augment chemical processes, several recent studies have also began identifying potential direct benefits and broader synergies related to bio-colonisation (e.g. Sternberg et al. 2010; Hanssen and Viles 2014; Gadd 2017). These begin to highlight the overall complexity of building stone decay, with multiple processes overlapping and intersecting across spatial and temporal scales. As a result, decay pathways in historic masonry are frequently non-linear.

Several studies investigate non-linear decay processes in building stones. Smith (1996) conceptually identifies various dynamic or metastable equilibrium conditions within stone decay systems. These include critical thresholds which can result in episodic, catastrophic change when breached in response to system stresses. Viles (2005) adapts a conceptual approach based on sources of non-linearity in geomorphic systems (Phillips 2003) to discuss a total of 10 potential sources of non-linearity in stone decay systems. These include thresholds, storage effects, self-reinforcing and limiting processes, competitive interactions, and synergisms of processes. The study

identifies these sources as the cause of seemingly chaotic phenomena, such as the spatial distribution of weathering patterns and complex behaviour in simple experiments. Non-linear decay processes have also been reproduced in laboratory experiments (e.g. Beck and Al-Mukhtar 2014; Bruthans et al. 2018). Martinez-Martinez et al. (2013) recorded the rapid onset of catastrophic decay in limestone subjected to freeze-thaw cycles once a critical threshold was passed. The threshold was shown to be the point at which individual micro-cracks began to coalesce. These studies provide further evidence that experimental frameworks must be carefully constructed to deliver meaningful results. They begin to highlight the importance of what is known as *memory effect*.

Current patterns and rates of stone decay can be a consequence of former environmental conditions (Warke 1996). By comparing measurements taken at St. Pauls Cathedral over a 30 year period (Inkpen et al. 2012a; Trudgill et al. 1991) with dose-response functions derived from atmospheric data, Inkpen et al. (2012b) show that whilst lower sulphur dioxide (SO_2) levels can clearly be associated with lower erosion rates, there is a noticeable discrepancy which may be attributable to a temporally lagged relationship. Temporal lag has also been recorded in biodegradation processes (e.g. Moroni and Pitzurra 2008). Other studies have demonstrated the dynamic disequilibrium, which results from the continuous interaction between atmospheric temperature and humidity, and material surface (Franzen and Mirwald 2004; Smith et al. 2011b; McAllister et al. 2017). This can be a source of hysteresis and interference at much shorter time-scales; each of these studies notes the differential effect such disequilibria have on near-surface and deeper regions of building stone. This reveals the complexity of overlaying and

overlapping processes affecting the response of masonry systems to dynamic environments.

The St. Pauls study raises the issue of process change in a rapidly changing climate. Brimblecombe and Grossi (2009) combine damage functions for stone with historical climate data in order to approximate changing stone decay rates between the 12th and 22nd centuries. Results suggest surface recession intensified in the 18th century following increased atmospheric SO_2 and peaked in the late 19th century. The authors note that with declining atmospheric pollution levels, historic building management will need to shift its emphasis towards the impact of extreme weather events. Bonazza et al. (2007) identify two types of crust at the Tower of London and link these to changes in atmospheric pollution, with a noticeable shift from gypsum crusts to organic matter. Other studies report an increasing importance of nitrogen oxides and particulate matter in ongoing stone decay (Massey 1999; Auras et al 2013). Smith et al (2010) explore these synergies further and suggest that gypsum crusts can be a constraint on accelerated decay in building limestone. They argue that a reduction of pollution levels could therefore lead to increased erosion. They note that whilst such crusts can be associated with sub-surface weakening and act as sources of salts, this simply adds a further level of complexity to their removal as it is likely to result in episodic, catastrophic decay. Several recent studies have also investigated the impact changing rainfall patterns will have on historic masonry (e.g. Smith et al 2011a; Orr et al. 2018). The implication of these findings is that future patterns and rates of decay may shift dramatically in response to changing environmental conditions.

II) 1.4.3. Contingency

A holistic framework for conceptualising stone conservation science must also consider the long-term effects of past remedial activity and the context within which these were performed. This must account for factors such as the subjectivity of aesthetic thresholds of intervention (Duffy and Obrien 1996; Brimblecombe and Grossi 2005), changes in management policies and societal attitudes towards heritage (Lyon 2007; Douglas-Jones et al.2016), and changes in the scientific understanding of decay processes (Rodriguez-Navarro et al. 2000; Price 2007). Inkpen and Turner (2012) use topographical metaphors to describe "a complex landscape of contingency and necessity" formed by historical events and processes. Their study builds on earlier work by Ben-Menahem (1997), which argues that a process exhibits historical necessity when similar outcomes would result from a wide variety of starting conditions, and historical contingency when small changes to an initial condition result in greater differences to the end condition. The notion is useful for understanding human agency in history; when historical processes are contingent, human actions can have a significant consequence on their result. Inkpen and Turner (2012) supplement this with the notion of external disturbance. They use the example of a ball rolling down the side of bowl, which will inevitably result in it coming to rest at the bottom of the bowl unless, for example, a child picks it up. This disturbance would originate from outside the system as it had initially been described (unless it had taken account of the child in the first place). They also discuss changing degrees of contingency and necessity as events unfold, using the metaphor of a catchment to describe how scale, external forces and internal deformation can affect the position of an observed point within the network of water channels: "It might not be enough

to ask how much contingency or necessity there is in historical processes. We might also want to investigate how the topography of historical contingency/necessity has changed over time" (Inkpen and Turner 2012, p.14). This perspective is useful for evaluating human agency within the system of stone deterioration and conservation. Even if processes such as repeated, varied, interventive conservation are unpredictable and must sit outside the boundary of a described stone-environment system, they can be ascribed a general pattern and aligned with the overall framework of dynamic interrelationships.

Returning to the medical analogies discussed earlier, determining the case-history of a masonry system is an important step in understanding present condition (Smith and Prikryl 2007). This will frequently highlight the use of unsuitable repair material (e.g. Urquhart et al. 1996; McCabe et al. 2010). This can in turn help explain the presence of building defects or specific pathologies such as salt contamination. Lopez-Arce et al (2008) conclude that a primary source of magnesium sulphates in masonry lies in chemical reactions between magnesium-rich construction material and gypsum mortars. Changes to the understanding of how best to mitigate complex processes such as salt driven decay present a further challenge. Past studies have found that the use of certain consolidants can increase the risk of decay in salt-laden limestone (Ruffolo et al. 2017) and that previously recommended safe environmental conditions would increase the likelihood of crystallisation cycles (Price 2007). Whilst recent studies are improving the models and standards used to assess the complex issues surrounding salt contamination (e.g. Flatt et al. 2017; Lubelli et al. 2018), forecasts suggest climate change may fundamentally alter the common process of salt decay (McCabe et al. 2013). Viles (2013) recognises the dynamic setting for contemporary

stone deterioration and conservation and considers the current and future impact of aspects such as climate change, globalisation and sustainability on both historic fabric itself and efforts to manage it. The study recognises synergies between shifts in economic and environmental context and corresponding attitudes to conservation. A move towards traditional, reversible treatment is cited as an example of increased awareness of sustainability issues. Framing case-histories within a wider socio-environmental context can enable more holistic models of stone deterioration to incorporate human agency; this relies on detailed understanding of past events.

Stone conservation practice is often severely hampered by both poor understanding of the long-term effects of many conservation strategies and incomplete documentation of past activity. Uncertainty over the type and scope of past interventions is a common theme in case-studies of historic masonry (e.g. Colston et al. 2001; Sanderson and Garner 2001). Often past activities prove to be detrimental in the long run. Hansen et al. (2003) review a wide range of stone consolidants and identify improved understanding of their long-term consequences as a key area for ongoing research. However, protocols for incorporating this understanding into a scientific framework are limited by the different timescales of research and practice. Some studies have been able to carry out long-term assessments of varied conservation treatments (e.g. Clarke and Ashurst 1972; Odgers 2013). These tend to highlight the overriding influence of case specifics, such as individual stone types or micro-environmental factors, and limited findings of general significance. There is increasing recognition within stone conservation practice of the importance of robust documentation, in order to provide future generations with a map of the 'complex landscape' of contingency.

II) 1.5. Synthesis

Constructing an effective theoretical framework for stone conservation science is highly challenging. It is important to define both the precise role and the limits of scientific method within the wider framework of practical stone conservation. Doehne and Price (2010, p.80) argue that "knowledge of stone [is] outstripping the practical application of that knowledge to stone conservation problems". Earth systems thinking has provided a suitable paradigm for reframing the complexity of stone conservation science. The conceptualisation of scale, process and contingency which this has enabled must be aligned with the purpose of stone conservation, without itself oversteering that purpose by prescribing solutions to a problem which cannot be defined in clear scientific terms. Douglas-Jones et al. (2016) recognise the difficulty of using science-based approaches in practical stone conservation, in which decision making needs to reflect on a wide range of contextual factors. The study argues that the over-arching purpose of stone conservation is not to *arrest* material transformation. Whilst any generalisation is contradictory to the highly individual nature of a case-by-case practice, a more suitable scientific goal would be to *understand* material transformation in its cultural context. Douglas-Jones et al. (2016) suggest this requires a greater integration of humanities within an inter-disciplinary framework. Rather than defining clear boundaries to the systematic description of stone conservation science, an effective theoretical framework must therefore be relational and adaptable, whilst still capable of characterising and quantifying condition and change.

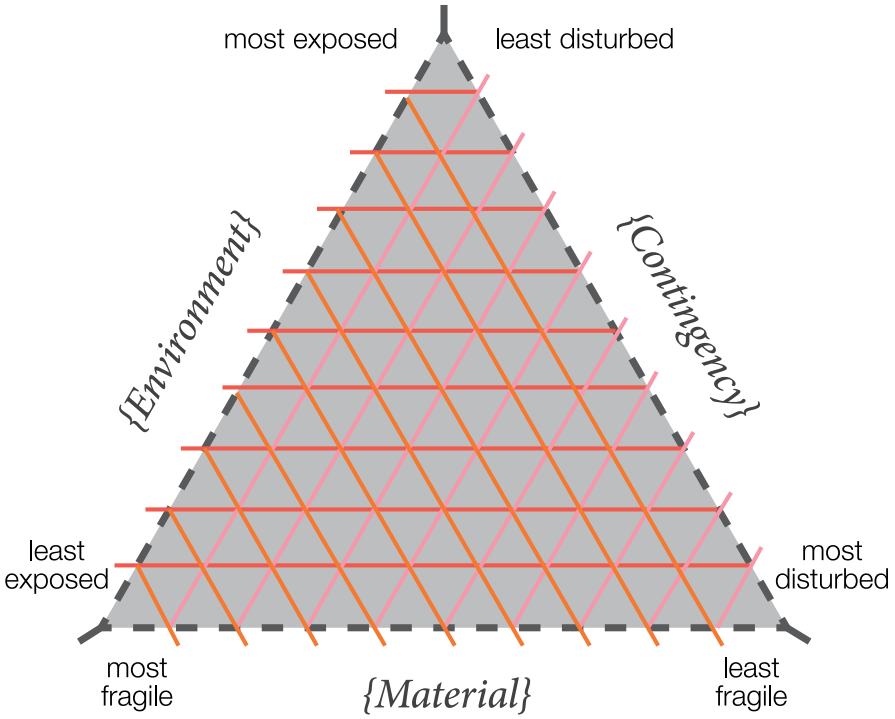


Figure II.1: *Conceptual ternary plot of three axes of variability affecting stone decay.*

Figure II.1 explores how this framework can describe the condition of building stone according to three axes of variability. It uses a ternary plot to show that the present-day condition of a stone is a combination of materiality, environmental exposure and contingency. The plot is a simplification of a complex set of interrelated variables, which themselves do not occupy clear two-dimensional spectra. Materiality can be defined by mineralogical composition, porosity, homogeneity etc. Environmental shelter from driving rain will not necessarily provide shelter from localised pollution. As discussed by Inkpen and Turner (2012), even the landscape of contingency is subject to inherent variation. Each of these axes therefore conceal a further system dynamics, which would require detailed analysis in order to determine specific characteristics that define condition. Although this framework can be used to explore these dynamics in detail, by underpinning the gradual construction of a relational model that interlinks variability across separate scales, interpreting complexity

according to this schema is not its primary objective. Rather than providing a fixed framework for plotting individual conditions, this diagram describes the conceptual approach taken to scientific investigation in this thesis; that an understanding of the dynamics of a masonry system must balance not only a static interface between material and environment, but also consider the fluctuations of this interface across time.

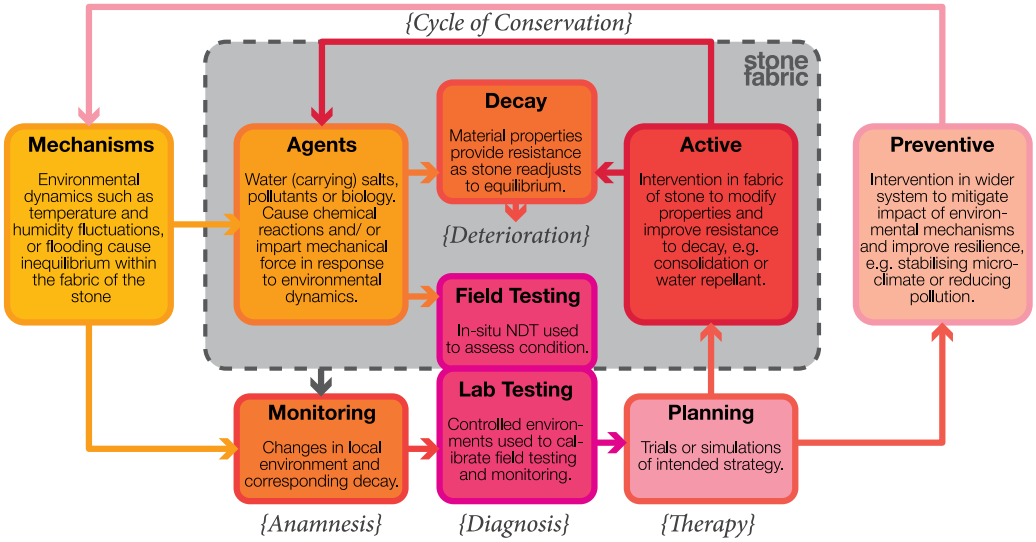


Figure II.2: *Conceptual diagram of cycle of conservation within present scientific framework of building stone deterioration.*

Figure II.2 proposes a systematic description of the current approach to stone conservation. This aligns concepts described within an Earth systems framework and a conservation science framework in order to characterise processes, entities and dependencies within a 'cycle of conservation'. Rather than fully defining the theoretical framework itself, this functions as a blueprint for the direction of scientific method within the adopted framework. This can be used to characterise and quantify change within a system dynamics of historic building stone with appropriate terminologies and focussed methodologies.

Precise use of terminology is considered vital for the adopted framework. Important general terms are listed in Appendix A. There are minor variations to usage in the ICOMOS glossary and other key reference texts (Verges-Belmin 2008). A more nuanced differentiation between *decay* and *deterioration* is proposed. The important distinction is that deterioration is considered to entail a loss of quality or cultural value, whilst decay is a less anthropocentric process which equates to physical change in response to environmental mechanisms. Decay can result in deterioration, through loss of strength or undesirable aesthetic changes. Decay can, however, also be considered to add value to heritage, typically be emphasising age or relationship to the environment (Lowenthal 1994). Conversely, deterioration can express itself in a framework of societal rather than material change, for example during urban renewal or cultural upheaval (Inglesby 2017). This interpretation of decay remains distinct to alteration, which can include the immediate consequences of direct anthropic action, such as a surface treatment. Decay can be an indirect consequence of anthropic action, such as material loss due to unsuitable surface treatment or atmospheric pollution. Furthermore, there is a distinction between *decay pathway*, meaning the mechanisms and agents controlling decay (e.g. salt crystallisation cycles), *decay phenomena*, meaning the physical response to a specific pathway (e.g. subflorescence), and *decay pattern*, meaning the emergence of observable features in response to phenomena (e.g. flaking). Whilst Historic England now encourage the term *hard to treat* stone in place of problem stone, this thesis proposes a further adjustment to *vulnerable masonry* as more inclusive of the interrelated processes affecting decay. This thesis also advocates the use of *resilience* as a general term for

describing the property of masonry (or other elements of the historic built environment) to withstand deterioration.

II) 2. Methodological Framework

II) 2.1. Overview

Whilst theoretical frameworks are used for conceptualising and constructing paradigms, methodological frameworks are necessary for measuring these constructs and testing hypotheses. They provide tools for validating the abstract concepts identified within the theoretical framework. They rely on scientific method to classify general patterns and establish specific rules. The findings made using these methodologies can inform practice and policy.

This section will begin by describing the overall scientific aims of a methodological framework within the adopted theoretical framework. It will then review methodologies used throughout this thesis. The first part will review approaches to historical research and documentation. The second part will review approaches to gathering data in-situ, focussing on environmental monitoring and non-destructive testing (NDT). The third part will review approaches to controlled experiments, focussing on ageing tests, and modelling techniques. The section will end by outlining the overall approach that has been adopted in this thesis.

An appreciation of matters that are beyond scientific method in the broader field of stone conservation must be central to an effective methodological framework. For example, whilst empirical research can explain processes of decay in building stone, it is less well suited to explain deterioration. This does not preclude discourse on these matters from scientific study, but it is important to distinguish between research

objectives that can be achieved with evidence from those that are more subjective. This can inform decision-making processes that take place within a practical framework, whilst respecting their contextual nuance.

Within the adopted theoretical framework, a robust methodological framework for stone conservation science would aim to follow the steps described in Figure II.3. This diagram also explains the general methodological approach to each step, and the issues of scale which need to be resolved. Methodological approaches within this framework can be grouped into three categories. Archival research, field work and controlled experiments. Whilst there is a significant overlap, these can be broadly aligned to the axes of variability identified in the theoretical framework (Figure II.4).

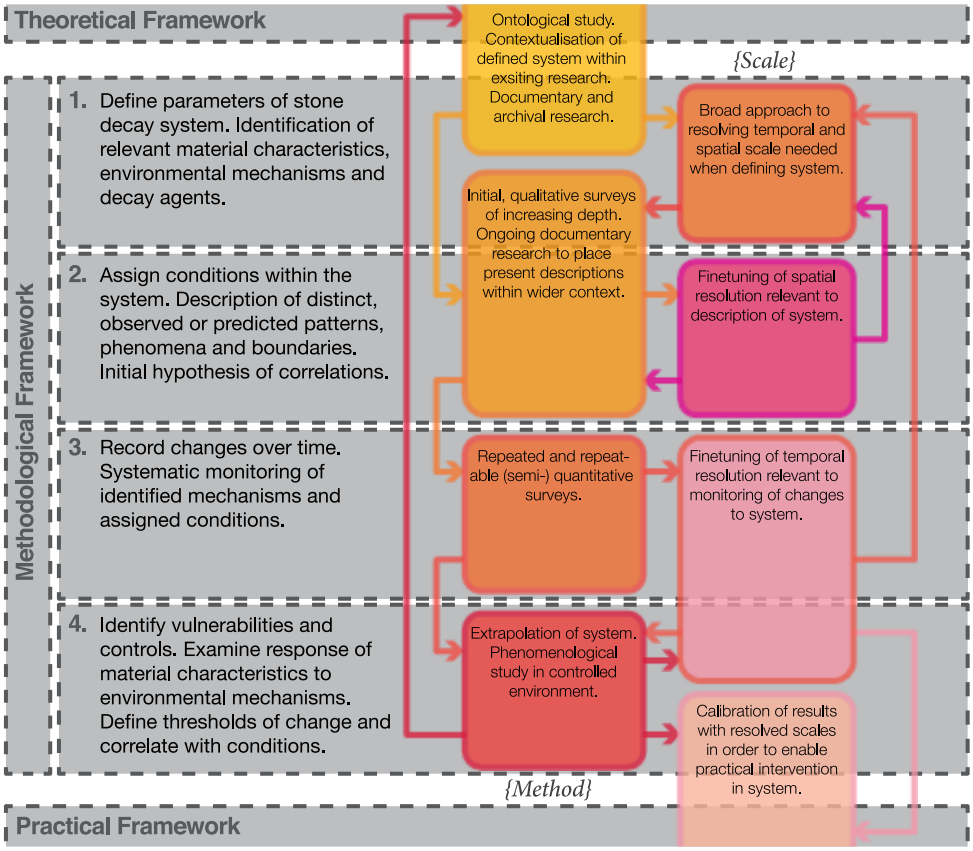


Figure II.3: *Conceptual diagram of methodological framework linking theory of stone conservation science to guidance for practical stone conservation. Describes four methodical steps and links to methods and scales of investigation.*

II) 2.2. Archival

Background research is an important stage of the assessment of a masonry system, which is too often overlooked (Odgers and Henry 2012, p.89-90). Thorough archival research can provide technical and historical information from a wide range of sources; often this information is vital to understanding present-day condition. Case-studies of stone decay at historic sites generally include at least a brief overview of historical developments (e.g. Urquhart et al. 1996; Erkal et al. 2013). Bonazza et al. (2007) incorporate available information on past remedial activity in order to make sense of changes in crust formation on a limited number of samples from the Tower of London. Studies on salt decay typically include relevant historical information to help identify potential sources of salt contamination (e.g. Colston et al. 2001; Sawdy and Price 2005a; Lopez-Arce et al. 2008). Other studies which focus more on specific conservation approaches or building materials will often include historical information in order to provide context (e.g. Elert et al. 2002; Odgers 2013). Very few studies are able to build precise case-histories; frequently, incomplete past documentation is cited as a mitigating factor for more conclusive findings.

Mapping classified conditions on to drawings or photographs of buildings has emerged as a common approach to recording and monitoring decay. Fitzner and colleagues (e.g. Fitzner et al. 1995; Fitzner and Heinrichs 2001) developed a comprehensive system in the 1990s. Classification is based on visual inspection of individual stones and areas and includes 19 weathering forms and numerous sub-categories. Whilst it provides a rigorous framework for anamnesis and can be a useful tool for diagnosing pathologies, this makes the technique time consuming. It has also

been criticised for being too reliant on specialist knowledge (e.g. Dorn et al. 2008) and for not providing a working tool for prioritising conservation action (e.g. Rodrigues 2015). Rodrigues (2015) proposes a system which moves from mapping individual decay patterns towards defining areas requiring similar conservation needs. The system relies on the critical faculties of an experienced conservation scientist to produce a true assessment, which can then be translated into a working plan. Many case-studies develop their own mapping systems or indices. Whilst some are largely based on Fitzner's method (e.g. Grifa et al. 2016), others are highly specialised to local requirements (e.g. Thornbush 2012). Inkpen et al. (2008) use a geographical information system (GIS) as a spatial reference tool for monitoring weathering form evolution on sections of two stone building facades in Oxford since the 1920s. The authors highlight potential issues with the quantity and quality of available historic images as a limiting factor in the wider application of this technique. Their study also highlights the issues surrounding technological progress. More recently, building information modelling (BIM) and structure-from-motion photography have outpaced GIS in the field of stone conservation and emerged as standard tools for mapping and documentation (e.g. Stefani et al. 2014; Scherer and Katranuschkov 2018) . However, viewing these technologies as strict methodological frameworks is dangerous, as further technological progress may render them equally incompatible. Sustainable mapping and documentation may require a more flexible approach, which relies less on a strict format and more on the general accessibility of data. This can be achieved with metadata management, such as spatial referencing of photos, terminological clarity and hierarchical folder layouts.

II) 2.3. Field

Given the cultural context of stone conservation and prevailing heritage values, a crucial factor of any methodological framework is to minimise intervention in the historic fabric (Drury and McPherson 2008). Extracting material samples from historic sites is generally limited and monitoring systems need to be inobtrusive. Given the high variability of the historic built environment, this poses challenges to effective field work (Pender et al. 2014; Camuffo 2019). Erkal and colleagues (Erkal et al. 2013; Erkal and D'Ayala 2015) link on-site monitoring and laboratory testing to build a hygrothermal profile of historic masonry at a site in SW England. The research includes an assessment of techniques for testing non-standard samples of historic building materials, which reflect the sampling opportunities at listed buildings. The study found that with a rigorous approach that examines a variety of properties with a range of techniques, results obtained from non-standard samples can be considered satisfactory. D'Ayala and Aktas (2016) use a rigorous environmental monitoring set-up at two historic buildings in south-west England to compare wind-driven rain measurements with semi-empirical calculations. Calculations are made using both local and regional data, with local data providing a close correlation to empirical measurements. Orr and Viles (2018) expand this concept to estimate wind-driven rain exposure at different locations in the UK using a semi-empirical approach. The study suggests standard models for predicting exposure cannot describe moisture dynamics at scales relevant to masonry decay. These studies demonstrate the need for macro- and micro-climatic data in order to construct both plausible models and assess specific risks of environmental interaction with building fabric.

Non-destructive testing (NDT) and minimally-destructive testing (MDT) provide a vital opportunity for the in-situ examination of historic masonry. The terms refer to a wide range of portable techniques that can be used to examine certain material properties without the need for destructive sampling. These include high-tech approaches, such as imaging and radar methods that have migrated from civil engineering and archaeology (e.g. McCann and Forde 2001; Moropoulou et al. 2013), and the use of spectrometric instruments previously confined to laboratories (e.g. Madariaga et al. 2014; Arrizabalaga et al. 2015). In many cases such techniques will prove to be unaffordable or impractical (Drdácký and Slížková 2013; Frankovic et al. 2015). A range of low-cost techniques such as surface peeling and water uptake methods also exist (e.g. Hendrickx 2012; Scrivano and Gaggero 2017). These can be more applicable to general practice whilst still delivering meaningful data; however, establishing user-friendly protocols for enabling comparison of these methods across different studies is proving challenging (e.g. Scrivano et al. 2017). Somewhere in between sit a variety of hand-held devices which have found increasing success in measuring or approximating certain material properties. These include instruments for measuring surface hardness (Viles et al. 2011; Wilhelm et al. 2016c), moisture content (MC) (Camuffo and Bertolin 2012; Eklund et al. 2013), ultrasound (Fort et al. 2013; Moropoulou et al. 2013) and drilling resistance (Odgers 2013; Modestou et al. 2015).

Recent studies have used these NDT individually or in combination to monitor decay rates and assess conservation strategies. Surface hardness has been related to a variety of material properties, such as strength (Aoki and Matsukura 2007; Yilmaz 2013) and porosity (Fort et al. 2013), and measurements can be used to indicate decay (Viles et al. 2011; Wilhelm et al. 2016b). Wilhelm et al. (2016c) investigated the

statistical confidence of using a low impact hardness tester. Their findings suggest large datasets (45+ readings) are necessary to enable a robust analysis, which should also consider statistical outliers. Fort et al. (2013) combine surface hardness measurements with ultrasound propagation, a good indicator of porosity which has been used to monitor subsurface decay (e.g. Weiss et al. 2000; Martinez-Martinez et al 2013). Results indicate these methods are corroborative. Whilst drilling resistance measurements leave small holes and must be classified as MDT, they have proven useful in comparing the long-term effect of past consolidations (Odgers 2013) and can deliver precise data on surface and near-surface alterations (Modestou et al. 2015). Hand-held moisture meters function according to a variety of different electro-magnetic principles (Camuffo and Bertolin 2012; Orr et al. 2019). Whilst some of these have found use in general practice, gathering and interpreting data requires care (Eklund et al. 2013). Conductivity/resistivity measurements can be taken at different depths and used to construct moisture profiles but are highly susceptible to salinity (e.g. Sass and Viles 2010). Capacitance devices are less susceptible but can be affected by moisture gradients and decrease in accuracy at high MC (Camuffo and Bertolin 2012). Comparing measurements taken with conductivity/resistivity devices and other devices could be used to provide information on salt content (Mauricio et al. 2005; Wilhelm et al. 2016a; Michette et al. 2018). Most NDT, and hand-held moisture meters in particular, use abstract or proxy units. In some cases, these cannot be compared across different material surfaces; NDT requires careful calibration in order to interpret results of general significance.

Care must also be taken to define the scale of investigation. Distinguishing between rapid and in-depth NDT protocols is vital to producing meaningful datasets. NDT can

be used to support broad conceptual arguments (e.g. Viles 2013) or investigate the need for further surveys (e.g. Michette et al 2018). In these cases, small datasets based on individual point readings can suffice and calibrating measurements in controlled environments is not always necessary; the NDT is used to highlight spatial or temporal patterns. In other cases, NDT can be used to gather empirical data and linked to specific material properties. This demands more rigorous and robust protocols (e.g. Sass and Viles 2010; Wilhelm et al 2016c). An in-depth approach may benefit from combining two or more NDTs in order to triangulate results (e.g. Fort et al. 2013; Drdacky and Slizkova 2013), and calibration with laboratory tests (e.g. De Boever et al. 2016). Provided data is collected accordingly, NDT can be useful for both rapid field surveys and in-depth, data rich analysis.

II) 2.4. Laboratory

Findings made in the archive and the field can be used to design experiments in controlled environments, which can deliver quantitative data on building stone decay. These have played a central role in stone conservation science since the early 20th century (Schaffer 2004). Test walls have also long provided an opportunity for research to be carried out under semi-controlled environments, which may closer resemble the reality of historic sites (e.g. Fusade et al. 2019a). More recently, computational modelling has emerged as a tool for simulating environments (e.g. Stück et al. 2013). As discussed in Chapter II.1, careful consideration is needed to make the scale of these experiments relevant to reality.

Accelerated ageing tests consist of laboratory experiments designed to investigate the long-term response of building materials to specific mechanisms and agents by

provoking rapid decay. They typically expose specimens to repeated cycles of controlled environmental change and/ or chemical contamination, which are calculated to cross thresholds of change. They provide a framework for analysing decay pathways and patterns within realistic project timeframes. Combined with other laboratory experiments they can also be used to determine the controlling material parameters in specific decay processes. Past experiments on building stone have investigated the effects of temperature induced stress (e.g. Smith et al. 2011b; Germinario et al. 2015), freeze-thaw action (e.g. Martinez-Martinez et al. 2013; Deprez et al. 2020), chemical dissolution (e.g. Van den Eynde et al. 2013; Beck and Al-Mukhtar 2014) and salt driven decay (e.g. Menendez and Petranova 2016; Sun and Zhang 2019). Some studies have combined two or more decay mechanisms (e.g. Warke and Smith 2007; Dewanckele et al. 2013). Accelerated ageing tests have been used to compare different stone types (e.g. Benavente et al. 2007a; Vazquez et al. 2013) and assess conservation treatments (e.g. Di Benedetto et al. 2015; Ruffolo et al. 2017). Several standards and recommendations exist (e.g. EN 12370; EN 12371), however due to limitations in these methods and the specific goals of individual research projects, most scientific studies use bespoke tests (Lubelli et al. 2018).

Standardised tests typically simplify decay processes to a set number of threshold cycles focused on a single decay mechanism. This enables the comparison of different building stones and can form the basis of quality control protocols and readily correlate durability to measured properties such as porosity. A frequent criticism is that standards do not reflect real world conditions and fail to replicate natural decay pathways. Studies which have deviated from standards have found that the prescribed number of threshold cycles can prove largely insufficient in causing decay

(Martinez-Martinez et al. 2013) and prescribed specimen shapes can distort decay patterns (Janvier-Badosa et al. 2015). The European standard salt crystallisation test has been criticised for prescribing highly aggressive conditions (Lubelli et al. 2018). Moreover, it focuses on a single salt solution (sodium sulphate). Different salts have been shown to produce markedly different decay patterns in replicate samples (Yu and Oguchi 2009). Mixed salt solutions are likely to reflect real-world conditions (Sawdy and Price 2005b; Price 2007) and result in more complex decay phenomena than single salt solutions (Menendez and Petranova 2016). Warke and Smith (2007) ranked the durability of different stones both according to the standard salt crystallisation test and a test combining freeze-thaw action and salt crystallisation. The two experiments produced different decay pathways and resulted in different rankings, particularly in the vulnerable, lower order stone types. The level of complexity present in stone decay systems is not adequately reproduced in existing standards (Flatt et al. 2017); accelerated ageing tests which aim to replicate specific decay pathways and patterns require appropriately specific environmental and chemical inputs.

Test walls have emerged as a useful approach to balancing control and scale when assessing masonry decay systematics. Fusade et al. (2019a) used test walls to assess the impact upon moisture regulation of repointing using different mortar recipes. Hannsen and Viles (2014) used test walls to investigate different approaches to capping masonry. Their study found measurable benefits to implementing soft, plant capping as opposed to widely used hard, cementitious caps. Other test wall setups have been used to assess the response of different material to flooding (Valek et al. 2010) or consolidants (Doehne and Price 2010, p.52). Test walls can be used to assess

decay processes, treatments and material-environment interactions over longer time periods and provide a link between field and laboratory studies.

Computational models can be useful for simulating the response of masonry to complex environmental mechanisms at spatial and temporal scales that aren't replicable in traditional laboratory set-ups. They necessarily require a further simplification of real-world processes; defining the limits of this simplification is a key aspect to effective simulation (Krus and Holm 1999; Grementieri et al. 2017). Hall et al. (2011) model masonry structures as a uniform slab standing in a free-water reservoir, and rising moisture as a sharp-front flux, in order to simulate the capillary rise and evaporation zone of masonry walls in different ambient environments. This enables a calculation based on only a few measurable parameters, which is broadly compatible with more complex models and real-world observations. Stück et al. (2013) numerically model moisture transport through an idealised sandstone monolith over a three-year period under real climatic conditions. The authors investigate the effect hydrophobic treatments upon the surface of the monolith. They find that fluctuations can increase at the interface between areas of different porosity. Whilst useful in identifying general trends, these study highlight some of the limitations in using models. The reliance on simplified geometries and parameters and the absence of micro-climatic variability mean it is not possible to draw any conclusion for specific cases of stone decay. Instead, models function as a valuable method for investigating controls within the system, for example as a first step towards designing preventive conservation strategies.

II) 2.5. Synthesis

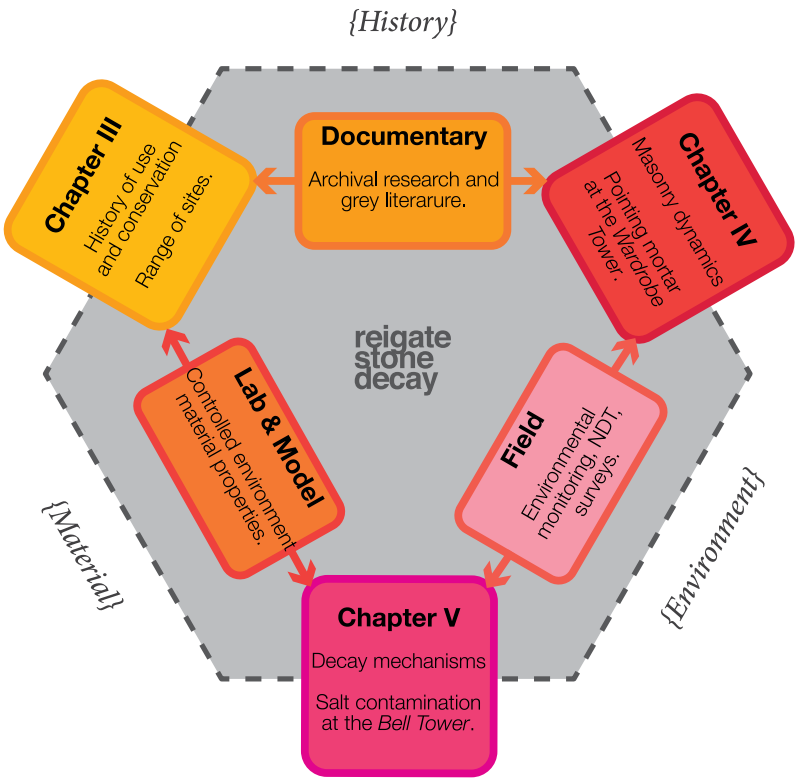


Figure II.4: *Diagrammatic overview of how methodological framework has been applied to link separate projects of thesis into unified structure.*

In order to enable a suitably holistic assessment of the dynamics of Reigate Stone deterioration, a transdisciplinary, multi-method approach has been adopted for this thesis. Field surveys occupy the central part of this approach; however, the research methodology also combines archival and documentary analysis, laboratory experimentation, and numerical simulation (Figure II.4). Laboratory experimentation has focused on determining the response of Reigate Stone to controlled environmental mechanisms and calibrating measurements made during the extensive field surveys. Field investigations have implemented a wide range of portable NDT used in combination with monitoring techniques to define and establish the pattern and variety of Reigate Stone conditions. Documentary analysis has scrutinised

extensive grey literature, within HRP archives and elsewhere, to uncover evidence of construction, treatment and other changes to Reigate Stone masonry deterioration dynamics. As shown in Figure II.4, aspects of each of these dominate specific projects within the overall thesis; however, research has been conducted holistically from the outset and gradually adapted to individual project methodologies. As specific research questions and gaps in data became clearer, tailored approaches and specialised techniques were developed.

The methodological framework for field work is based on the Problem Stone Progressive Survey Technique (ProSt-ProST), which was designed during the MRes SEAHA preceding this DPhil research (Michette 2016). This proposed increasingly detailed survey methods to gradually focus a large area of investigation into representative scenarios. Initial surveys map general spatial patterns and define notable conditions; rapid NDT are used to assign qualities and basic characteristics to these observations; ongoing surveys utilise progressively more time-intensive methods to link the characteristics and measurable properties deemed significant to particular research questions. This method forms the fulcrum for controlled experiments, which are designed to address issues uncovered during the field surveys.

The selection of buildings and areas for investigation within the Tower and Hampton Court Palace was made following extensive background research and initial surveys. The Bell Tower and the Wardrobe Tower (see Appendix B) were selected for most extensive analysis as they provided a good combination of varied materiality and environment, past documentation and recent or ongoing conservation activity. Several other locations across both sites were selected for ancillary investigation. Any

destructive testing or sampling was performed after several stages of this surveying methodology have identified locations of high scientific but low cultural impact. Samples for laboratory analysis have been obtained either at the culmination of the ProSt-ProST process, or from collection of detached material at locations of ongoing decay. Additional samples were inherited from a previous phase of research (Sanderson and Garner 2001) and represent both freshly quarried Reigate Stone and samples taken from buildings. A test wall constructed in 2001 to assess the long-term impact of a novel consolidant on Reigate Stone was also inherited for this project.

The HRP archives include treatment reports, condition surveys and historical photos of the Tower and Hampton Court Palace, as well as a vast library of anecdotal observations in notes and communications stretching back to the mid-1990s. This material has formed a key resource in understanding recent developments and selecting suitable sites for investigation. Material prior to this period is sparse due to changes in management; the National Archives provide a further repository going back centuries. This has been used in a targeted manner once key sites were selected, and research questions were more precisely defined. HRP employ clear metadata standards for the naming of files and description of photos. These are being observed as data is archived for posterity.

III. Reigate Stone: A history of use and conservation

"To know is to care, to care is to use,
to use is to transform the past. Continually refashioned,
the remade past continuously remoulds us"

David Lowenthal, *The Past is a Foreign Country - Revisited* (2015, p.1)

The first section of this chapter is an unaltered version of a paper resubmitted in June 2020 to the journal *Heritage Science* after initial submission in March 2020 and response to subsequent review. The second section is an unaltered version of a paper accepted in December 2019, after review, to a special issue of *Studies in Conservation*, as part of the proceedings of the *International Institute for Conservation Congress* in Edinburgh, November 2020. Both papers co-authored with H. Viles, C. Vlachou and I. Angus.

III) 1. The many faces of Reigate Stone: an assessment of variability in historic masonry based on Medieval London's principal freestone[3]

Abstract

Reigate Stone was used in high profile projects across London during a key growth period and represents an important chapter of architectural heritage. Historic Reigate masonry is subject to inherent variability. It is prone to rapid decay; however, highly decayed and well-preserved stones are frequently adjacent. This inherent variability in masonry can present a challenge to the design of conservation strategies by obscuring or complicating the identification of decay processes. This paper presents a model for assessing the combined impact of construction economies and mineralogical variability (Graphical abstract), by synthesising archival research on the history of Reigate Stone with experimental analysis of its properties. The limitations of the local geography coupled with the demands of the medieval building industry are shown to have introduced inherent variability into the built fabric at an early stage. Later socio-economic factors are shown to have compounded these by contributing to selective recycling, replacement and contamination of Reigate Stone. These historic factors augmented pre-existing mineralogical variability. This variability makes classification according to commonly used stone types difficult. Experimental analysis correlates variable cementing components with hygro-physical properties related to resilience. Calcite content influences strength properties and capillarity; clay content influences moisture adsorption and retention; opal-CT forms a weakly cemented, porous matrix. These presented different decay pathways to a range of environmental mechanisms and agents of decay. The findings suggest that inherent mineralogical variability, environmental changes, and historic contingency must all be considered in the design of ongoing Reigate Stone conservation strategies.

[3] As submitted in March 2020 to the journal *Heritage Science*, with only minor editing of style and format.

Graphical Abstract

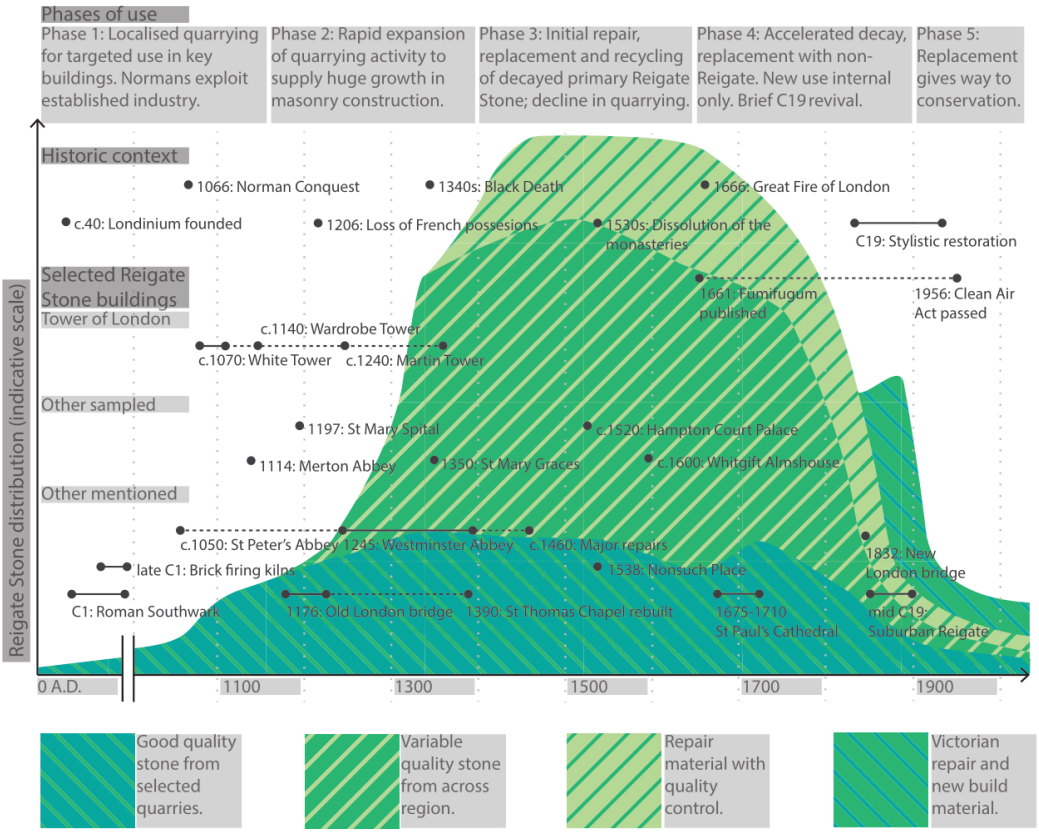


Figure III.1: *Timeline of Reigate Stone quarrying and construction, showing different phases of use, key events and buildings, and corresponding, very broadly classified stone types*

III) 1.1. Introduction

Reigate Stone was used as a freestone across south-east England from the 11th until the 16th century, contributing significantly to the re-emergence of masonry architecture in Britain during this period (Tatton-Brown 2001). Freestones are stones used for ashlar and ornamental masonry. Suitable lithologies can be cut freely in any direction and worked easily with a chisel; they tend to be fine-grained, soft and homogeneous. Whilst this makes them easy to sculpt, it can also make them prone to rapid decay. Many architecturally important regions have inherited a legacy of vulnerable historic masonry due to the nature of their principal freestone; such as

Tuffeau in central France, Lede Stone in Belgium and Opuka in Prague (Beck and Al-Mukhtar 2010; Dewanckele et al. 2013; Přikryl et al. 2017). Other examples exist in England, such as Clunch and Headington Stone (Odgers 2013; Gomez-Heras et al. 2010). Given the historical information stored in regional building stones and the aesthetic contribution of ornamental masonry, the decay of these valuable freestones impacts significantly on the deterioration of architectural heritage.

Reigate Stone masonry displays a wide range of conditions, varying in pattern, rate and state of decay. These are frequently visible within single masonry units (Figure III.2). Historically, it was widely replaced due to rapid decay, initially with fresh Reigate Stone and later with alternative lithologies (Lockwood 1994). However, there are examples of primary Reigate masonry which has survived in relatively exposed locations, such as the base of the White Tower, for almost 1000 years. Since replacement gave way to conservation in the mid-20th century, there has been persistent uncertainty regarding the relative role of stone petrology and environmental mechanisms in decay processes (Sanderson and Garner 2001). Whilst there have been attempts to associate exposure with patterns and rates of decay, these have failed to account for the full variability evident in historic masonry. There has been little consideration of the role historic contingency can play in long-term decay processes; the cumulative effect of past context, be it factors pertaining to the initial construction, environmental exposure, or remedial treatment of masonry. Several attempts at conservation have accelerated decay. In order to more fully understand the deterioration of Reigate Stone, and design appropriate conservation strategies, it is necessary to understand the variable decay found within historic masonry.

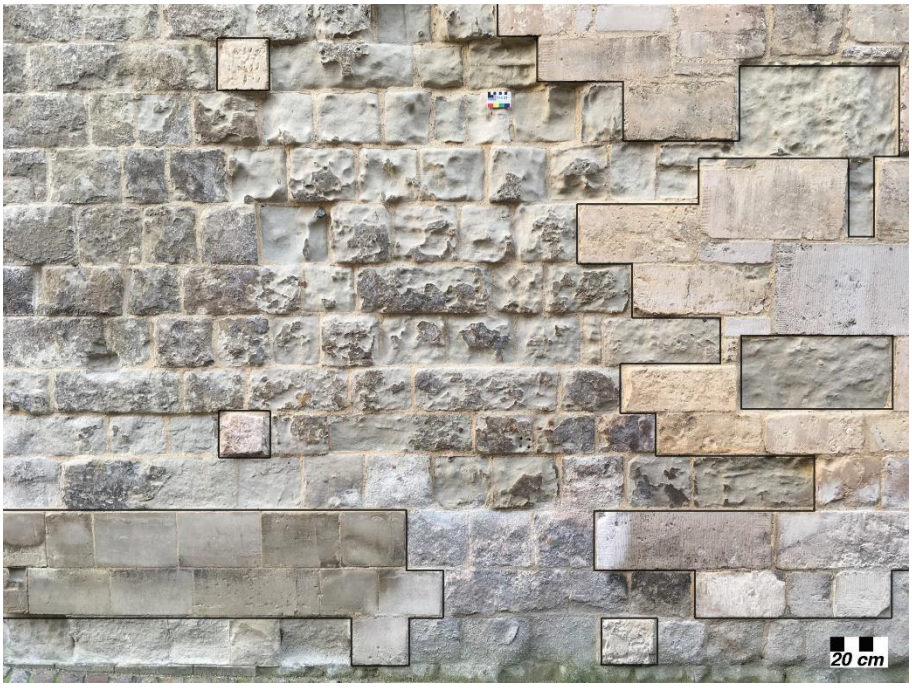


Figure III.2: *Reigate Stone masonry at the Bell Tower, Tower of London, showing high level of variability. Majority of masonry is in Reigate Stone, with range of block colours and sizes, and decay patterns and rates. Second and third course are replaced with other lithologies (except central stones); approximately 15 stones on right of picture also replacement lithologies.*

Several factors are likely to contribute to differential decay in masonry construction.

- Differences in petrology result in different resistance to decay. These arise from mineralogical variability and physical characteristics such as porosity. Petrographic variability is not restricted to different lithologies; there can be considerable variation across the facies of a single geological formation (Tucker 2003).
- Differences in workmanship, seasoning or laying can amplify petrographic variation.
    - Seasoning is an important process in calcareous freestones (Schaffer 2004, p.15-17). It involves the case hardening of the stone following its extraction, as moisture from within the pore matrix migrates to the surface, a process which could take several years. Whilst its importance

has long been noted in stone conservation practice, it has received little scientific attention. Case hardening has been noted in Reigate Stone (Howe 2016; Jukes-Brown 1900, p. 420); stone was sometimes stored within the mines for seasoning (Figure III.3) (Burgess 2008).

- The orientation of stones laid within masonry can greatly impact their resistance to decay due to anisotropy (Odgers and Henry 2012, p.52-53). Anisotropy is an expression of heterogeneity in a stone. It is present in many sedimentary rocks due to bedding. The compressive strength tends to be highest in the direction of bedding (Fort et al. 2011). It also affects capillarity. Incorrect bedding is not uncommon, particularly in stones where bedding planes are difficult to determine.

- Once within the building, material variations can be compounded by micro-climatic variations at the stone-environment interface, and once decay patterns emerge within a masonry system, non-linear dynamics can amplify any initial differences (Viles 2005). Frequent changes to the micro- or macro-environment are likely over the long life-span of a building, for example due to the removal of nearby shelter or a reduction in atmospheric pollution. Past environments can have ongoing effect on stone decay (McCabe et al. 2010).
- Finally, repair of the masonry, including selective replacement or treatment of deteriorated stones and mortar, will alter existing properties and introduce new variability, whilst frequently obscuring evidence of past variability.

The cumulative effect of these factors upon historic masonry can be complex compositions of individual stones bearing unique mineralogical, chemical and environmental signatures.

Studies of Reigate Stone have focussed either on its conservation (Lockwood 1994; Sanderson and Garner 2001) or an assessment of its quarrying and use in architecture (Sowan 1975; Tatton-Brown 2001; Hatton 2001; Burgess 2008). These valuable contributions have highlighted mineralogical features and decay processes, or provided detailed historical analysis, which can explain specific differences in Reigate Stone, but have not formed a combined approach which can adequately describe the cumulative effect of processes contributing to variability in historic masonry. As part of a wider project on understanding Reigate Stone decay at the Tower of London, this paper aims to build a hypothetical, general model of these processes.

Building a model of the processes which have contributed to variability in historic masonry can improve the understanding of stone decay in general and identify controls for ongoing conservation strategies. The purpose of this paper is to investigate the role of Reigate Stone variability in predetermining the emergence of differential decay. The investigation will synthesise historical analysis of Reigate Stone economics with experimental analysis of its material properties. This combined approach is vital for establishing a complete picture of historic building materials. Synthesising detailed historical analysis can also help to overcome some common problems in the field of historic building material analysis, such as limited access to samples. The objectives are to establish a timeline of Reigate Stone exploitation which can identify patterns of use and factors pertaining to inherent variability within masonry systems, define variability in mineralogical terms, and link mineralogical composition to physical characteristics known to influence decay. This will facilitate ongoing identification of the specific mechanisms which drive the decay of vulnerable masonry. It is also intended to contribute to persistent debate on the correct

lithological definition for Reigate Stone (Sanderson and Garner 2001). The overall aim is to inform a methodological framework for evaluating architectural heritage under severe threat.

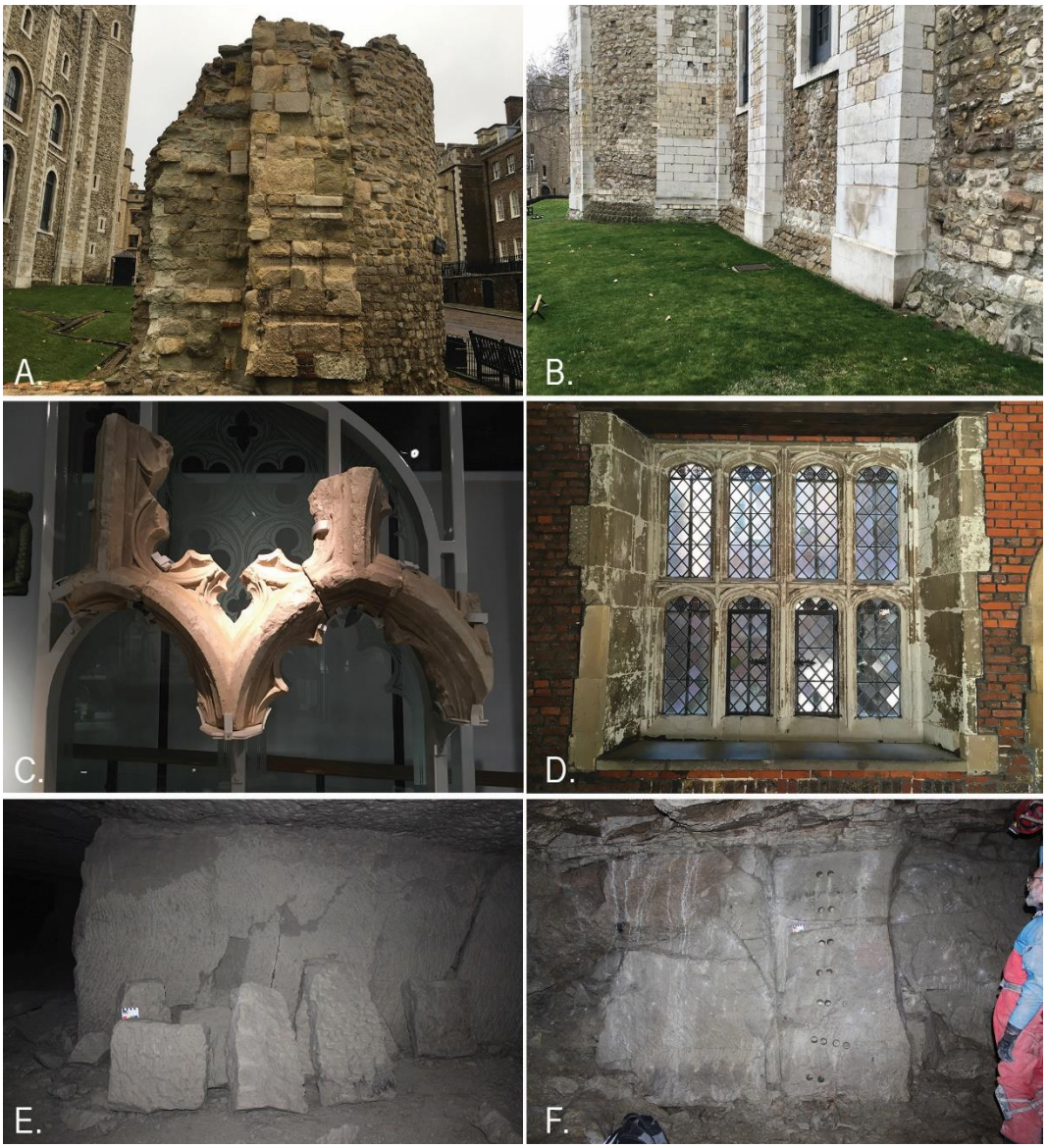


***Figure III.3**: **(A)** 12th century Wardrobe Tower, Tower of London, showing decayed, south facing Reigate Stone ashlar in upper part of buttress and to left of buttress. **(B)** 11th century White Tower, Tower of London with east facing Reigate Stone ashlar visible in two courses directly above batter, and predominantly Portland Stone replacements. **(C)** Reigate Stone tracery from 11th century Merton Priory on display in Museum of London. **(D)** Reigate Stone tracery in 16th century north cloister of Hampton Court Palace. **(E)** Large blocks of stone left in quarry near Chaldon (scale card is 8 cm across). **(F)** Quarry face near Merstham from which samples were extracted in 1998.*

III) 1.2. Historical analysis

III) 1.2.1. Geological context

Reigate Stone was quarried from a thin band of Upper Greensand in northern Surrey. The Upper Greensand is a Cretaceous deposit of lenticular masses formed in shallow sea conditions, which extends across southern England (Jukes Brown 1900). Upper Greensand lithologies are characterised by fine-grained silicate minerals and green, clay mineral bearing glauconite; however, an unstable paleogeography with changes in sea level, climate and faunal deposition has resulted in a complex geology with inherent variability at macro- and micro-scales (Owen 1975; Dean 1994). The facies exploited for Reigate Stone consist of intercalated lenses of varying hardness and homogeneity (Dines and Edmunds 1933, p.84-91). Early characterisations of the building stone noted roughly equal proportions of silica and calcium carbonate (Watson 1911; Shore 1957, p. 9). Whilst it has been referred to as both a siliceous limestone and more commonly a calcareous sandstone, Sanderson and Garner (2001) state it cannot truly be classified as either. Its dominant mineral phase is opal-CT, precipitated crystalline silica which forms both a highly micro-porous matrix and functions as the main cement of very fine-grained quartz and bioclastic components.



Figure III.4: *Map of area around Reigate and London, showing* ***(1)*** *sampling locations in Tower of London,* ***(2)*** *sampled quarries and location of Upper Greensand in North Surrey, and* ***(main map)*** *other sampling locations.*

The Reigate Stone industry saw the development of a vast network of mines, running approximately 15 km from Godstone in the East to Brockham in the West (Figure III.4) and exploited for several purposes (Sowan 1975). This has led to terminological and lithological ambiguities. In medieval times Reigate Stone and spelling variations thereof were already being used as superordinate terms for stones from nearby areas, such as Merstham. Despite this, specific references to Merstham Stone and Chaldon Stone are not uncommon. Whilst these may refer to individual quarries or workings, there is no indication that they implied a difference in quality or function. References to Greensand or green Sandstone may indicate Reigate Stone usage; however, a range of Upper and Lower Greensand lithologies were used as building stones (Lott and Cameron 2005). The terms Firestone and Hearthstone relate to 18th and 19th century industrial uses; Firestone was used for lining ovens, Hearthstone for cleaning (i.e. whitening) doorsteps and other stone surfaces. There is some ongoing confusion as to whether they are distinct lithological varieties and if so, what their defining characteristics are. Jukes-Brown (1900, p.97) distinguishes Firestone and Hearthstone

beds within the geological stratum, however their order is reversed within some mines (Hatton 2001). Several sources identify Firestone as being more calcareous, comparable to stone used in buildings, and Hearthstone as being far softer and more friable (Dines and Edmunds 1933; Sanderson and Garner 2001). Other sources claim that Firestone is more siliceous, and Hearthstone contained more calcite, lending it its whitening properties (Jukes-Brown 1900, p.93; Lott and Cameron 2005). Records of Greensand and Firestone in archaeological or architectural texts relating to London are in most cases likely to indicate Reigate Stone, particularly when prefixed by Surrey (e.g. Potter 2013). Reigate Stone should be considered as a descriptive term rather than a fixed material classification; whilst other names persist in contemporary literature and references thereto are included in this study, Reigate Stone is by far the most common name for building stone from the North Surrey Upper Greensand.

Past studies of Reigate Stone used within buildings have noted high lithological variability, even within single buildings or sites. During excavations at the 14th century abbey St Mary Graces, built beside the Tower of London in East Smithfield, three different types of Reigate Stone were identified (Grainger and Phillpotts 2011, p. 87). These include a dense variety associated with the earliest phase of construction in the 1350s and a softer variety used in the main phase of construction. Excavations at St. Mary Spital, built in the late 12th and early 13th century, found two distinct typologies of Reigate Stone (Thomas et al. 1997, p.186-195). Variations in mineralogy, including glauconite colour and morphology and the nature of microfossils were identified (De Domingo 1994). The study concluded that several sources must have been used during construction. Attempts to determine precise provenance or link to building phases proved inconclusive. Sanderson and Garner (2001) analysed Reigate Stone

from several different quarries and buildings ranging from the Medieval to the Victorian periods and found significant mineralogical variation across samples. They suggested that calcite content was a determining factor in building stone quality.

III) 1.2.2. Reigate Stone building economics

III) 1.2.2.1. Roman use

There is clear evidence that Reigate Stone was used in Roman times. Archaeological excavations in Southwark have yielded the earliest confirmed use of the stone in building, with potential 1st century use documented at two sites (Burnham et al. 1995; Drummand-Murray et al. 2002). 2nd or 3rd century use at a funerary site in Southwark has been linked to a temple (Mackinder 2000, p.9-10). There are indications that Reigate Stone was used in bastions and barracks along the city wall, with some references to 'green sandstone' made during excavation of the Roman fabric (e.g. Howe and Lakin 2004, p.31; Royal commission 1930, vol.3 p.103). Several Roman sites near Reigate are documented as having walls built of 'local Greensand' (Williams 1971), including a villa in Titsey 'partly built of sandstone (…) probably quarried on Limpsfield Common', 15 km to the east of Reigate (Gower 1869) (Figure III.4). Several sculptures found in Southwark and Ashtead and dating back to the late-1st century have been identified as Reigate Stone (Coombe et al 2015). A tile kiln possibly dating to the late-1st century and discovered near Reigate represents the earliest known use of the stone in large, squared blocks (Jones 2004). The tilery produced ceramics found at multiple sites across London and Kent (e.g. Mackinder, 2000 p.60; Brigham and Woodger 2001, p.107). Even if Reigate Stone was not widely used in pre-medieval masonry architecture, there is enough evidence of quarrying, artistic and industrial

use to indicate it played an important role in the Romano-British economy of South-East England.

III) 1.2.2.2. Medieval London's expansion

Ongoing, large-scale use of the stone coincides with the re-emergence of masonry architecture in the 11th century. There is some evidence of earlier Anglo-Saxon quarrying and usage. 'Local firestone' was used in parish churches at Stoke D'Abernon and Fetcham (Johnston 1907, p. 14-15), with the large, walled-in lintel at St Mary's in Stoke D'Abernon suggestive of local quarrying in the late-7th or early-8th century (Jope 1964). Reigate Stone was used in large quantities in the mid-11th century construction of churches in Westminster and Waltham (Tanner and Clapham 1933; Huggins et al. 1992). Following the conquest, Norman masons came to regard Reigate as a local alternative to Caen Stone, although the latter was still favoured for some time. Primary Reigate ashlar can be found in the lowest courses of the White Tower (Figure III.3), indicating use during the first building phase (1066-78) (Impey and Ashbee 2008, p.54-56). This suggests existing stockpiles or supply-chains were exploited immediately after the conquest. The Domesday Book (1086) refers to two stone quarries in Surrey, which are likely to have included the Limpsfield Common site that may have been used in Roman times, but do not mention locations closer to Reigate itself (Fagg 1914; Burgess 2008, p.11). Robbing of existing building stock should also be considered, especially in the form of the Roman city wall adjacent to the White Tower. Reigate Stone was used in detailed work for the interior of the White Tower, where its location corresponds with the building break in the 1080s. Whilst precise reasons for the break remain unclear, it is notable that courses of Reigate interspace the use of Caen Stone (Impey and Ashbee 2008, p.104-105). This may reflect

complications in supply chains to northern France. Use in this period, with masonry construction limited to a few key buildings, suggests that knowledge of the stone had persisted and some degree of industry in the Reigate area was able to respond to fluctuating demand.

From the mid-12th century onwards the use of Reigate Stone became more prevalent (Royal Commission 1930, vol.4 p.xxiv). It was chosen for detailed masonry in the construction of the priories and abbeys emerging across the city, but use is also documented in secular buildings (Schofield et al. 1990, p.220; Thomas 2002; Thomas et al 2006, p.58-59). Starting in the 1170s, it was used in the construction of two bridges crossing the Thames, at Kingston and further downstream at the first stone-built London Bridge (Shore 1957, p.67; Potter 1988; Schofield 2003, p.135). The loss of the French possessions in 1206 is likely to have limited the ongoing use of Caen Stone. The first half of the 13th century sees the establishment of several new quarries around Reigate and stockpiling sites along the Thames (Tatton-Brown 2001; Burgess 2008, p.17). This expanding market is reflected in accounts for building works, with four different sources providing Reigate Stone for the construction of Westminster Abbey in the 1250s (Royal Commission 1930). Reigate Stone from various sources continues to arrive at Westminster for over 300 years; it appears that no single quarry consistently provided stone for more than 4-5 years and accounts suggest material was frequently sourced from stockpiles rather than directly from quarries (Rackham 1909). In other cases, individual quarries can be more closely associated with specific sites or buildings. A 1218 quarrying grant for land near Reigate to the canons of Waltham Abbey, the site of the 11th century church, suggests long standing relationships between the mining parishes and their clients (Tatton-Brown 2001). It

also reveals an ongoing need for fresh stone at large sites, possibly in relation to early repair work. Another quarry was opened in 1241 solely to provide stone for the Tower of London (Public Record Office 1902, vol.4 p.271). This coincides with a major expansion of the site's defensive capabilities, including the construction of several towers along the inner wall (Royal Commission 1930, vol.5 p.75). During this period of intense building, demand may have outstripped the supply of well-sourced, well-seasoned Reigate Stone.

There are signs that the industry had largely centralised by the 14th century. Templates for mouldings at Westminster Palace were being sent to the Reigate quarries so that the stone could be roughly worked on the spot (Salzman 1952, p.21-22). Individual families took ownership of several quarries; the Prophete family managed quarries supplying Royal Works for over 100 years (ibd, p.130). Increased output from Merstham and Chaldon quarries in this period has been linked to an exhaustion of beds closer to Reigate (Burgess 2008, p.44).

III) 1.2.2.3. Repair, recycling and replacement

There is evidence that by the 15th century certain limitations to Reigate Stone were well understood and large-scale repair programmes were underway. Royal accounts for the late 14th century make specific reference to Reigate Stone intended for repair work (Colvin 1982, vol.2 p.1008). In some 14th and 15th century buildings, architectural details evolve to protect exposed Reigate masonry (Robinson and Worssam 1989; Thomas 2002, p.138); in others, the exposure of Reigate Stone to damp is avoided entirely (Knoop and Jones 1938, p.20; Salzman 1952, p.527; Jackson 1971, p.19). Significant restoration activity on Reigate masonry at Westminster Abbey took place

in the 14th and 15th centuries (Ashurst and Dimes 1990, p.219-227). This included extensive repairs to the lower south transept in 1457-61, 200 years after its construction in Reigate Stone (Rackham 1909, p.27). In the 16th century, use of Reigate Stone is predominantly restricted to sheltered areas; demand is likely to have drastically fallen. In an indication of declining quarrying activity, the earliest working faces in the re-opened mines around Reigate can be dated to the 16th century (Burgess 2008, p.).

A decline in external use and any apparent decline in quarrying activity should be considered within the socio-economic context of late Medieval and Tudor London. The Black Death changed the dynamic of London's urban expansion in the mid-14th century (Lilley 2015) and impacted labour markets for two centuries. Economic recovery coincided with the dissolution of the monasteries in the 1530s, which provided salvageable material to fuel a renaissance in masonry architecture. Whilst it had long been used as flooring material in the form of large slabs, Tudor floors also used crushed Reigate, which may represent demolition material (Thomas et al 2006, p.80;118;136). The majority of Reigate Stone for Nonsuch Place (1538) came from the demolition of Merton Priory; 3643 loads of stone were sourced from Merton and only 96 loads directly from Reigate quarries (Colvin 1982, vol.3 p.184). The re-use of building material was a common medieval practice; materials used in royal works were frequently recycled elsewhere within the royal estate. After the royal residence at Sheen (now Richmond) was demolished in the 1390s, accounts show the reuse of materials at other buildings, including the Tower of London and a new manor built in Sutton, Surrey. Large quantities of Reigate used at Sutton then found their way back to Sheen when the former was demolished after only 20 years and the latter was

rebuilt (ibd., vol.2 p.998-1004). Widespread recycling of building stone is likely to have occurred following economic downturn and recovery, resulting in a significant increase in the inherent variability of individual masonry units.

Later centuries saw a further refinement of the use of Reigate Stone and replacement with other stones. A major building phase in London began in the late-17th century in response to the Great Fire and saw the introduction of new freestone, most notably Portland Stone, and further developments in brick manufacturing (Knoop and Jones 1938). The medieval Reigate quarrying infrastructure would have been insufficient for the scale of rebuilding and expansion London underwent. Quarries in places such as Portland and Oxfordshire could be exploited on a much larger scale and stone could be transported via water along the coast or newly built canals (Gomez-Heras et al. 2010). Ongoing replacement of decaying Reigate masonry was now possible using these more robust lithologies. Freshly quarried Reigate Stone was still used internally, and recycled stone was used as rubble infill. Despite reservations, Christopher Wren used large quantities of Reigate Stone in his rebuilding of the city's churches (Hatton 2001; Campbell 2013). At St. Pauls, where Wren made deliberate, targeted use of several different types of stone, it was used as infill and for ashlar and mouldings (Schofield 2016, p.69-70). Wren was particularly attentive to the sourcing, transport and sheltering of Reigate Stone; having identified a susceptibility to frost, he had sheds built to protect the stone during the winter (Hatton 2001). As with the large medieval construction projects, supply came from multiple sources over the years (Campbell 2013), so despite this quality control, inherent variability is likely to have been built into the masonry.

Significant mining activity did recommenced in the mid-19th century (Sowan 1975). This fed a growing demand for stone used in industrial processes, but also provided building stone for the rapid development of suburban Reigate and Redhill. Several mines were newly opened or vastly expanded in this period (Burgess 2008). The mines at Merstham were extensively developed to provide stone used as infill in the construction of London and Waterloo bridges. There is evidence that some material used in buildings in this period was of poor quality, with the decay of several Victorian churches near Reigate progressing particularly rapidly (Lockwood 1996). Increasing pollution levels and the use of cementitious repair materials accelerated masonry decay (Brimbelcombe and Grossi 2009; McCabe et al. 2010). It is likely that the impact was particularly severe on Reigate Stone. Simultaneously, Victorian stylistic restoration programmes drove widescale replacement of deteriorated fabric at historic sites across the city, including the Tower of London (Inglesby 2017). Whilst the decline in overall stock will have drastically sharpened, it should be considered that fresh Reigate Stone may have entered the historic fabric as repair material in this period.

Replacement of decaying Reigate Stone continued until the mid-20th century, when conservation policy shifted to preservation. Whilst initially little attention was paid to replacement typologies, later work recognised not only the importance of aesthetic compatibility, but also geochemical compatibility with remaining Reigate masonry. Chilmark and Ketton limestone were widely used, however neither is entirely compatible. A wide range of different consolidants were trialled or extensively used on Reigate Stone in the late-20th century, often with sparse documentation and mixed success (Sanderson and Garner 2001). There are records of isolated replacement

programmes using small quantities of available, fresh Reigate Stone in recent years. Since the closure of the last Hearthstone mines in the 1960s ongoing replacement with fresh Reigate Stone has become practically impossible; however, fresh stone was procured for a new stairwell at Westminster Abbey completed in 2018.

III) 1.3. Experimental analysis

III) 1.3.1. Objective

The documentary analysis has shown that building stone economies are likely to have resulted in complex masonry systems, with selective extension, replacement, recycling and treatment of Reigate Stone masonry occurring across a period of several centuries. This will have compounded the effects of environmentally induced changes. Any inherent differences in individual stones would further augment the resulting variability; these will be investigated in the following section.

Experiments were conducted on Reigate Stone samples collected from different quarries and buildings in order to enable petrographic characterisation and investigate physical and hygric properties. Samples were selected to be representative of a broad geographical and historical range. Non-destructive techniques were favoured to allow a reuse of samples and enable calibration with field tests in ongoing work. Measured variables were subject to statistical analysis in order to determine correlations (Pearsons method) and identify patterns between freshly quarried stone and stones used in medieval buildings. The objective was to establish inherent variability in Reigate Stone and link this to mechanisms likely to drive decay processes.

III) 1.3.2. Materials and Methods

Three samples each from five quarries were selected. These make up part of a larger archive of samples gathered to facilitate research by Sanderson and Garner (2001). Quarries in Gatton, Merstham, Chaldon and Godstone were sampled (Figure III.4). The quarries make up networks of mines that have been gradually re-explored by local interest groups over the last 50 years (Burgess 2008). Samples were extracted from a single gallery face near an entrance to each mine as 45 mm diameter cylinders using a diamond tipped core drill (Figures III.3 and III.5). No water was used during the drilling. 50 mm pieces were cut from these cylinders for most characterisation tests, with some tests performed on smaller pieces taken from the same cylinder.

Samples from 10 different buildings were investigated (Figure III.3 and III.4). Samples from seven buildings were collected for Sanderson and Garner (2001). Two samples were taken by Historic Royal Palaces from the Tower of London. A sample from Merton Priory was supplied by the Museum of London archives. The other samples were supplied by curators or archaeologists working at the individual sites. Detailed records on sampling locations were not available. Samples from three further buildings were made available by Historic Royal Palaces during this study. Four seperate building phases at the Tower of London are represented. Five further sites were selected to approximate one building per century in Medieval South East England, although samples may be representative of repair material or later work. Hampton Court Palace samples 1-6 were taken from material which had been buried and was rediscovered during landscaping work in 2016. Samples were cut into prisms of 50 x 50 x 50 mm from suitably large parent material for most characterisation tests, with some tests performed on smaller pieces taken from the same parent; for

Wardrobe Tower and Hampton Court Palace samples, additional material was taken from related pieces for petrographic characterisation tests (Figure III.5). Sampling sites are listed in Table III.1 along with approximate build dates and information on the samples.

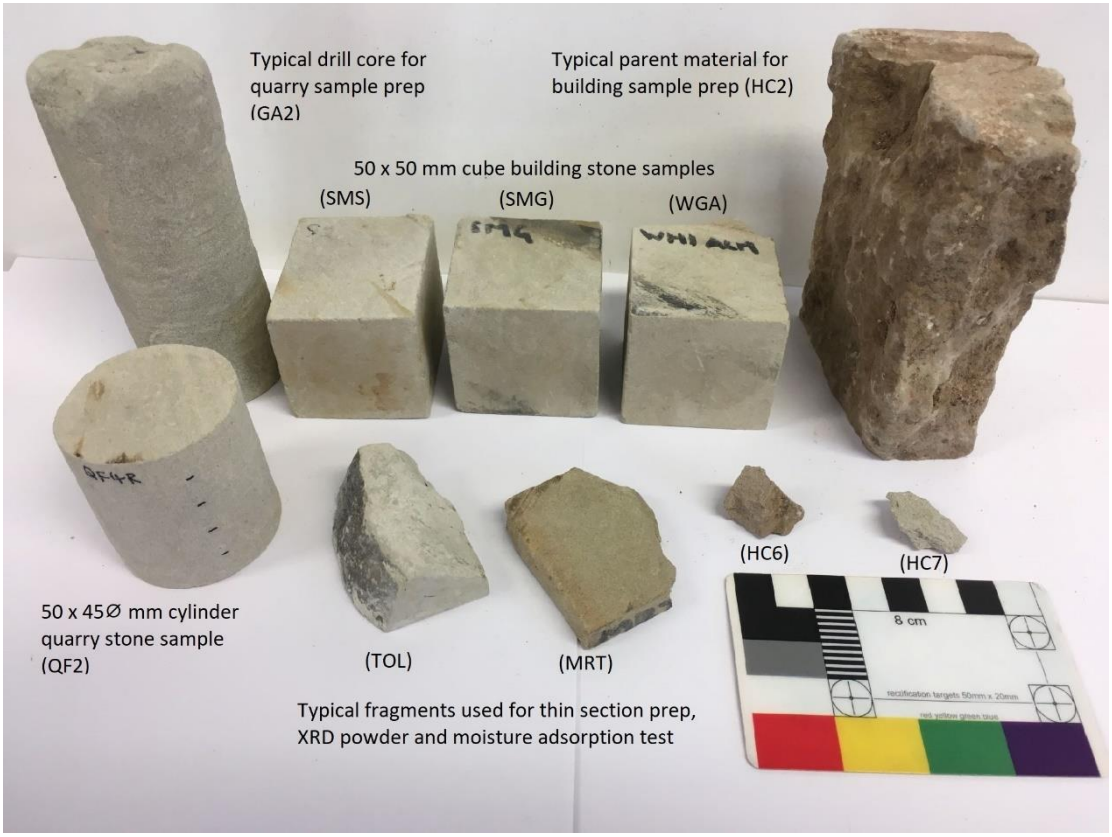


Figure III.5: *Selection of Reigate Stone specimens showing variation in colour and texture across different samples used in this study and explaining different sample dimensions.*

Building/ Quarry	*Date*	*Sample code*	*Sample size*	*Sample location info*
Rockshaw Lodge Quarry, Chaldon	Medieval to 19th century	RS1	Cylinders 45 mm ø 50 mm h	All quarry samples extracted from gallery faces near quarry entrances in 1998 (e.g. Fig 2a). Approx. 14 samples extracted per quarry at different heights. Numbered here from quarry ceiling (i.e. 3 closest to floor). Precise locations known.
		RS2		
		RS3		
Quarry Dean, Merstham	Medieval to 19th century	QD1	Cylinders 45 mm ø 50 mm h	
		QD2		
		QD3		
Gatton Quarry	Medieval? to 19th century	GA1	Cylinders 45 mm ø 50 mm h	
		GA2		
		GA3		
Godstone Quarry	17th to 20th century	GO1	Cylinders 45 mm ø 50 mm h	
		GO2		
		GO3		
Quarry Field, Merstham	19th century	QF1	Cylinders 45 mm ø 50 mm h	
		QF2		
		QF3		
White Tower, Tower of London	1070	TOL	Cube 50 mm	Sample removed in 2000. Location unknown.
Wardrobe Tower, ToL	1190	WT1	Cube 50 mm	Detached from south facing buttress during conservation work (04.2017).
		WT2	Fragment	
		WT3	Fragment	
Balium Wall, ToL	12th century	BAL	Cube 50 mm	Date unknown. Location unknown.
Martin Tower, ToL	Mid-13th century	MRT	Cube 50 mm	Detached from internal door reveal (2015).
Merton Priory	Early 12th century	MER	Cube 50 mm	Location unknown. Obtained from Museum of London archive in c.2000.
St Mary Spital	Early 13th century	SMS	Cube 50 mm	Location unknown.
St Mary Graces	Mid-14th century	SMG	Cube 50 mm	Location unknown.
Throwley Church	15th century	THR	Cube 50 mm	Location unknown. Marked as 15th century material.
Hampton Court Palace	Early 16th century	HC1	Cube 50 mm	Excavated from garden in 2016. Likely to have come from window jambs and been buried following 18th or 19th century replacements with other stone types.
		HC2	Cube 50 mm	
		HC3	Fragment	
		HC4	Fragment	
		HC5	Fragment	
		HC6	Fragment	
		HC7	Fragment	Detached from external east facing window jamb (2017).
Whitgift Almshouse	Late 16th century	WGA	Cube 50 mm	Location unknown.

Table III.1: *List of quarries and buildings that provided samples for this study, with approximate date of construction/ quarrying, coding system, and information on shape, size and location of samples. Quarry dates from Burgess (2008).*

III) 1.3.2.1. X-ray diffraction (XRD)

XRD was performed to identify minerals present in powdered samples. Powder samples were mixed with acetone and deposited on a zero-background single crystal silicon substrate. Analysis was performed using a Panalytical Emyrean Series 2 diffractometer operating at 40 kV and 40 mA with a Co Kα source. Measurements were taken in the 5° to 85° 2theta range using a step size of 0.026° in reflection-transmission mode. The HighScore Plus software suite was used to reduce data, and mineral identifications were based on the correspondence of d-spacings, intensities and profiles to the International Centre for Diffraction Data Powder Diffraction File 4+ database and quantified through the reference intensity ratio method (Snyder and Bish 1989). In addition to bulk mineral phase analysis, clay mineral phase analysis was performed on a selection of powder samples following decarbonation.

III) 1.3.2.2. Bulk density/ Open porosity

Bulk density ρ_b (g/cm^3) and open porosity P_O were calculated in accordance with the standard methodology (BS EN 772-4:1998).

III) 1.3.2.3. Ultrasonic wave propagation

A PUNDIT Lab (Proteq) was used to measure ultrasonic wave propagation through the samples. The pulse velocity *Vp* (m/s) is related to strength characteristics (Benavente et al. 2006). The standard methodology (BS EN 14579:2004) was adapted, with velocity measured along each axis of a sample, in order to enable the determination of the anisotropy coefficient k according to the formula

$$k = \left(\frac{Vp_{max} - Vp_{min}}{Vp_{mean}}\right) x\ 100$$

Whereby Vp_{max} is the mean maximum velocity obtained along any one axis, Vp_{min} is the mean minimum velocity and Vp_{mean} is the average of all measurements (Birch 1961; Fort et al. 2011).

III) 1.3.2.4. Capillary absorption

The capillary absorption coefficient *wk* ($g/m^2s^{0.5}$) was calculated using the standard methodology (BS EN 1925:1999). Results of the ultrasonic wave propagation tests were observed in order to ensure capillary absorption was measured along comparable planes of anisotropy.

III) 1.3.2.5. Sorptivity

To measure moisture adsorption due to atmospheric pressure, small pieces of each sample were taken from the parent material (between 2 and 10 g per sample depending on availability). These were oven dried, weighed and placed in a climate chamber at a constant temperature of 20 C. Relative humidity (RH) was increased in steps until mass equilibrium (±5 mg). Sorptivity is expressed as the amount of moisture adsorbed at 95% RH as a percentage of total mass of the sample. The hysteresis between adsorption and desorption at 80% RH was calculated to provide a measure of moisture retention.

III) 1.3.2.6. Optical microscopy

Thin sections of selected samples impregnated in blue resin were analysed using an Olympus BX43. Thin sections of WT, HC and MRT were prepared during this study, all other thin sections were prepared for Sanderson and Garner (2001). Optical microscopy was performed qualitatively in order to support and corroborate findings made using other techniques.

III) 1.3.3. Findings

III) 1.3.3.1. Petrographic variability

XRD reveals quartz, opal-CT, calcite and clay minerals present in all samples (Table III.2). There is notable variation in the relative proportion of these minerals (Figure III.6). Feldspar was identified in most samples. Gypsum was identified in several building stone samples. Clay analysis of decarbonated samples yielded fairly amorphous and low profile peaks which suggest the presence of discrete smectite (trioctahedral smectite, glauconite and/or montmorillonite) represented by peaks in the region of 1.513-1.519 Å, and 1.507 Å respectively, in addition to illite/muscovite (1.50-1.502 Å). The presence of muscovite can account for flakes of mica seen both macroscopically and in thin section (Figure III.7). Within the discrete smectite regions, some samples yielded peaks at or near 1.511 Å which could indicate the presence of glauconite. Glauconite can refer both to a morphological form and a mineral, typically glauconitic smectite, with considerable variation from one mineral to the next (Thompson and Hower 1975; Odin and Matter 1981). Glauconite pellets generally form in semi-confinement to replace carboniferous parent material with expandable smectite minerals. The diversity of clay minerals identified therefore reflects different stages of glauconization. This is visible in different shades of green, when comparing thin sections (e.g. comparing GA1 and WT2 in Figure III.7). The distribution of clay minerals is likely to be inhomogeneous, with mica flakes and glauconite pellets representing concentrations, but dispersed pore-filling cement also possible.

Optical microscopy and physical characterisation tests indicate a physical diversity beyond the fundamental mineralogical variability. Thin sections also highlight the

presence of amorphous bioclastic components such as foraminifera and sponge spicules which will not have been identified by XRD (Figure III.7). Physical differences include the definition of bedding planes, and degree to which diagenesis and bioturbation have affected this; the homogeneity of fabric; the size and sorting of grains; and the distribution and shape of porosity. The overall open porosity varies widely across samples (Figure III.8). The abundance and density of the matrix-filling, microcrystalline opal-CT appears to affect the shape and distribution of porosity, with a microporous network extending throughout all but the densest areas of this matrix and expanding in sparser areas to larger, highly connected pores in the 10^2 µm region.

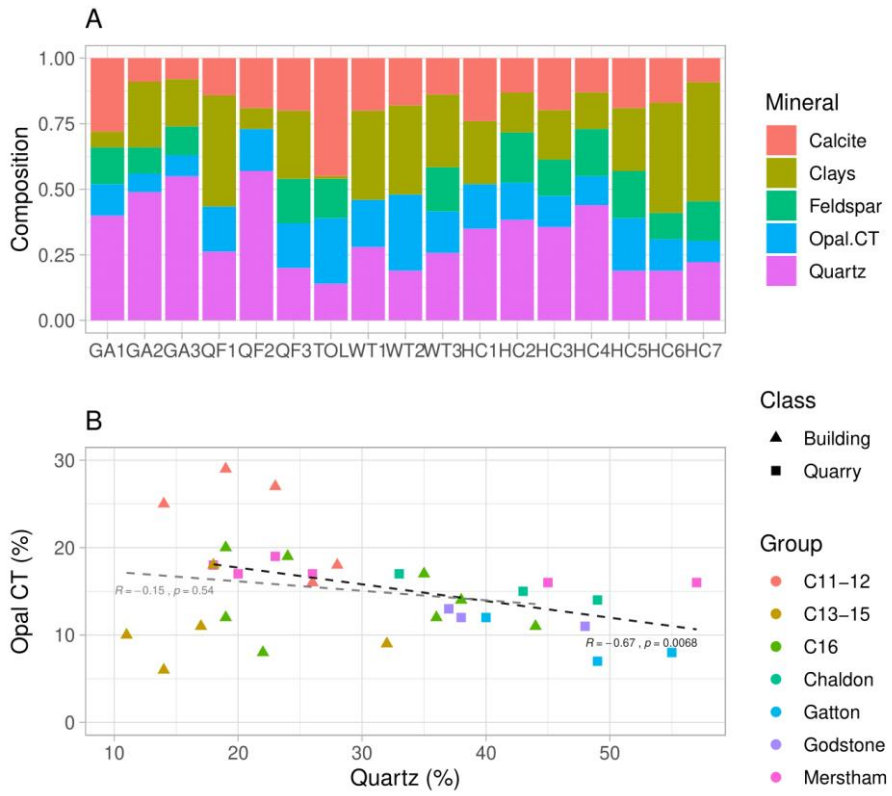


Figure III.6: (A) *Selection of results from XRD analysis showing mineralogical variation across and within separate quarries (Gatton and Quarry Field, Merstham), and across and within individual buildings and sites (White Tower and Wardrobe Tower, Tower of London, and Hampton Court Palace).* ***(B)*** *Chart showing differing correlation between opal CT and quartz within freshly quarried stone (R = -0.67) and stone used in buildings (R = -0.15), lower quartz content in building stone, and higher opal CT content in phase 1 building stone.*

Sample	Quartz (M%)	Opal CT (M%)	Calcite (M%)	Feldspar (M%)	Clays (M%)	Bulk density (g/cm^3)	Open porosity (V%)	Pulse velocity (m/s)	Anisotropy coefficient (-)	Capillary absorption ($g/m^2s^{0.5}$)	Sorptivity RH_{95} (M%)	Hysteresis RH_{80} (M%)
GA1	40	12	28	14	6	1.72	27.6	2573	9.5	53.9	7.3	0.8
GA2	49	7	9	10	25	1.52	35.0	1175	22.4	174.9	5.7	0.7
GA3	55	8	8	11	18	1.49	35.7	1591	6.8	131.7	7.3	1.0
RS1	43	15	12	20	10	1.46	33.9	1818	6.5	200.8	7.3	1.7
RS2	49	14	18	14	6	1.51	33.9	2064	2.6	95.6	8.6	1.7
RS3	33	17	16	11	22	1.41	35.2	2034	9.0	125.3	8.7	1.9
QD1	45	16	21	0	17	1.34	35.1	1977	1.2	106.9	9.4	1.7
QD2	23	19	17	0	41	1.38	35.6	2067	6.9	141.5	9.7	1.8
QD3	18	18	17	22	26	1.56	33.7	2203	4.4	105.2	10.0	1.9
GO1	38	12	15	18	17	1.44	36.1	1673	2.3	192.3	8.4	1.1
GO2	48	11	17	10	14	1.45	35.4	1924	6.0	125.8	9.4	1.3
GO3	37	13	16	15	18	1.40	38.6	1687	4.1	139.1	9.3	1.4
QF1	26	17	14	0	42	1.38	33.7	2120	3.1	137.9	8.3	1.4
QF2	57	16	19	0	8	1.38	34.5	2228	9.6	81.7	9.3	2.0
QF3	20	17	20	17	26	1.56	30.6	2465	3.6	60.5	9.2	2.0
TOL	14	25	45	15	1	1.85	26.8	2968	6.5	26.8	7.5	0.8
WT1	28	18	20	0	34	1.68	37.7	1911	1.7	112.2	8.3	1.7
WT2	19	29	18	0	34	-	-	-	-	-	-	-
WT3	26	16	14	17	28	-	-	-	-	-	-	-
BAL	18	18	16	18	30	1.57	36.0	2080	4.4	87.2	9.6	2.0
MRT	11	10	16	17	46	1.57	33.0	2084	5.7	101.2	9.7	1.2
MER	23	27	23	0	28	1.51	35.7	1946	8.1	136.1	8.6	1.6
SMS	17	11	12	22	38	1.49	36.5	2005	7.4	123.7	9.7	1.7
SMG	32	9	10	18	31	1.55	33.2	2062	10.3	85.2	7.7	1.3
THR	14	6	12	31	37	1.57	35.7	2151	3.6	92.9	10.2	1.8

Sample	Quartz (M%)	Opal CT (M%)	Calcite (M%)	Feldspar (M%)	Clays (M%)	Bulk density (g/cm^3)	Open porosity (V%)	Pulse velocity (m/s)	Anisotropy coefficient (-)	Capillary absorption ($g/m^2s^{0.5}$)	Sorptivity RH_{95} (M%)	Hysteresis RH_{80} (M%)
HC1	35	17	24	0	24	1.61	34.8	2184	5.7	69.9	9.4	1.3
HC2	38	14	13	19	15	1.57	37.0	2073	2.2	102.6	6.9	1.6
HC3	36	12	20	14	19	-	-	-	-	-	-	-
HC4	44	11	13	18	14	-	-	-	-	-	-	-
HC5	19	20	19	18	24	-	-	-	-	-	-	-
HC6	19	12	17	10	42	-	-	-	-	-	-	-
HC7	22	8	9	15	45	-	-	-	-	-	-	-
WGA	24	19	17	0	40	1.58	35.0	2200	12.2	60.7	9.8	1.9

Table III.2: *Results of mineralogical and hygro-physical analysis. Mineral components determined using XRD. Bulk density and open porosity determined according to BS EN 772-4:1998. Pulse velocity determined in accordance with BS EN 14579:2004. Anisotropy coefficient determined according to Birch (1961). Capillary absorption determined according to BS EN 1925:1999. Sorptivity defined as mass-percentage gained following adsorption; hysteresis as difference between mass-percentage following adsorption and desorption.*

	Quartz	Opal CT	Feldspar	Calcite	Clays	Bulk density	Open porosity	Pulse velocity	Capillary absorption	Sorptivity	Hysteresis
Quartz	1										
Opal CT	-0.34	1									
Feldspar	-0.21	**-0.49**	1								
Calcite	-0.21	**0.58**	-0.23	1							
Clays	***-0.65***	-0.06	-0.12	**-0.42**	1						
Bulk density	**-0.40**	0.18	0.24	**0.59**	-0.14	1					
Open porosity	0.17	-0.19	-0.12	***-0.65***	0.35	**-0.57**	1				
Pulse velocity	**-0.46**	**0.48**	0.05	***0.75***	-0.16	**0.55**	***-0.72***	1			
Capillary absorption	0.31	-0.26	0.03	***-0.60***	0.09	***-0.62***	**0.55**	***-0.82***	1		
Sorptivity	**-0.45**	0.17	-0.02	0.02	**0.43**	-0.24	0.24	0.26	-0.24	1	
Hysteresis	-0.23	0.31	-0.04	-0.21	0.28	-0.35	0.37	0.14	-0.08	***0.64***	1

Table III.3: *Correlation matrix using Pearson's method on results shown in Table III.2. Mineralogical correlations made using all 33 samples. Mineralogical-physical and physical correlations made using 26 samples for which this data was available. R greater than 0.4 (or less than -0.4) marked in bold. R greater than 0.6 (or less than -0.6) marked in bold-italic.*

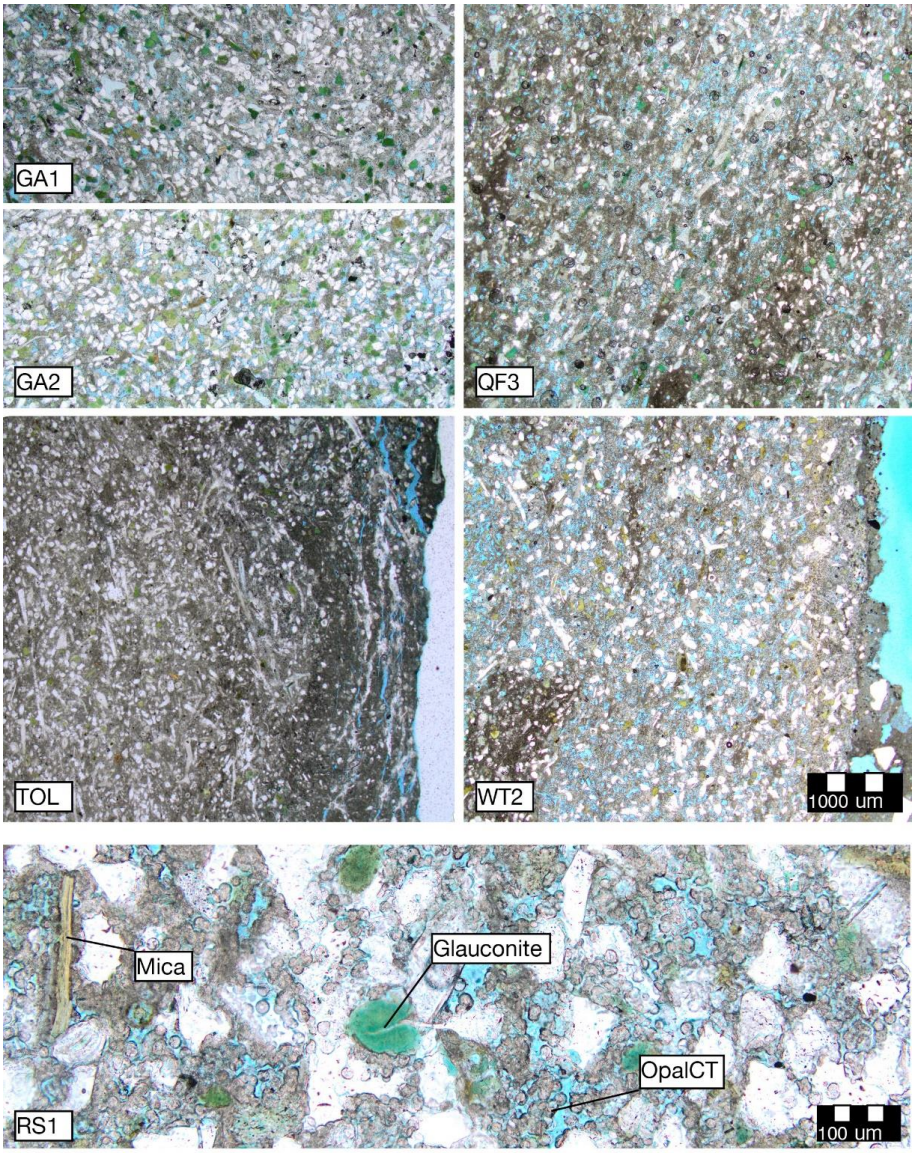


Figure III.7: *Photomicrographs of selected thin sections, showing variability of mineralogy, texture and grain size within and across different quarries and buildings, different decay patterns within building stones, and highlighting some common mineral components.*

Petrographic variability is likely to relate to the chemistry of sedimentary deposition, the frequency and amplitude of changes inducing diagenesis and the overall maturity of the facies. Quartz grain size and content, and glauconite abundance and saturation are all likely to increase as a result of diagenesis from native siliceous and calcareous bioclasts respectively, with opal-CT representing a transition stage of the siliceous component (Tresise 1960; Flörke et al. 1976). Demonstrative of two extremes are TOL and GA2 (Table III.2; Figure III.7):

- TOL is high in opal-CT and calcite and low in quartz and clay. It has an abundance of bioclastic components, sparse, olive-green glauconite pellets and very fine quartz grains in a very dense, matrix supported fabric that shows faint signs of discontinuous bedding. The relatively low open porosity is not visible in thin section other than in some near surface fissures and is likely to be almost entirely in the microporous region.
- GA2 is dominated by slightly larger quartz grains with a high clay content reflected in abundant glauconite pellets, ranging from light- to dark-green, in a grain supported fabric with sparse opal-CT and highly disturbed bedding. Calcite content is low. The open porosity is higher, and large pores are visible between individual grains.

GA2 represents a mature sample which has undergone much diagenesis, with the majority of siliceous microfauna having transformed fully to quartz via opal-CT, whilst TOL is likely to have undergone less change, with most of the silica present in opal-CT form and traces of initial faunal deposition still present. Significant variations are also present in samples extracted from the same facies, probably as a result of initial sedimentation. GA1 displays a denser, more matrix supported fabric, and is also more calcareous and less clay-bearing than GA2 (Table III.2; Figure III.7). Whilst its open porosity is comparable to TOL, the structure is heterogeneous and includes pore sizes similar to those in GA2. These findings serve to illustrate the relative variability in Upper Greensand beds ranges across several mineral and physical properties, and the challenges in extracting building stone of uniform composition.

III) 1.3.3.2. Selective quarrying

Several correlations in mineralogical composition indicate selective quarrying of building stone. In quarry samples there is a good correlation between decreasing opal-CT content and increasing quartz content (R= -0.67) (Figure III.6). This reflects the diagenetic transition from the former to the latter. This correlation is not present in building stones (R = -0.15), where quartz content is generally lower and opal-CT content is more variable than in quarry samples. There is a good correlation between decreasing quartz content and increasing clay content in all samples (R = -0.65) (Table III.2). The average proportion of clay minerals in building samples (29.4%) tends to be higher than in quarry samples (19.7%). Viewed together with the lack of correlation between quartz and opal-CT, this may reflect a process of selecting suitable building stones which tends towards reduced quartz content. This could have favoured finer grained, homogeneous, matrix-supported stone which proved easier to finely carve.

Further analysis suggests these selection criteria may have resulted in shifts in mineralogical composition across different periods of quarrying and use. Calcite content varies but the mean value is comparable in quarry samples (16.5%) and building samples (17.7%). Pre-13th century building stones contain relatively higher proportions (mean = 24%, or 18.8% without TOL), particularly when considering the formation of gypsum in WT1-3 has removed soluble calcium. 13th to 15th century samples contain lower proportions (mean = 13.2%). There is a correlation between increasing calcite content and increasing opal-CT content (R = 0.58) (Table III.3), with calcium perhaps able to precipitate and carbonise more readily in stone with a more abundant micro-porous matrix. 13th to 15th century samples contain a high proportion of clay minerals (mean = 36.4%), at the expense of opal-CT/ calcite (Figure III.6). Clay

content in 16th century samples is lower (mean = 27.9%), but variability is high. This may reflect further shifts in selection and use. HC2-4 have a lower than average clay content (Table III.2), which could indicate refined quality control in response to the decay of earlier building stone. However, the consequent trend in this sample set is higher quartz content; calcite content is variable. Others, such as WGA, have notably high clay content and may represent a reuse of earlier material. These shifts in selection criteria can be related to the fluctuating supply and demand discussed in the previous section.

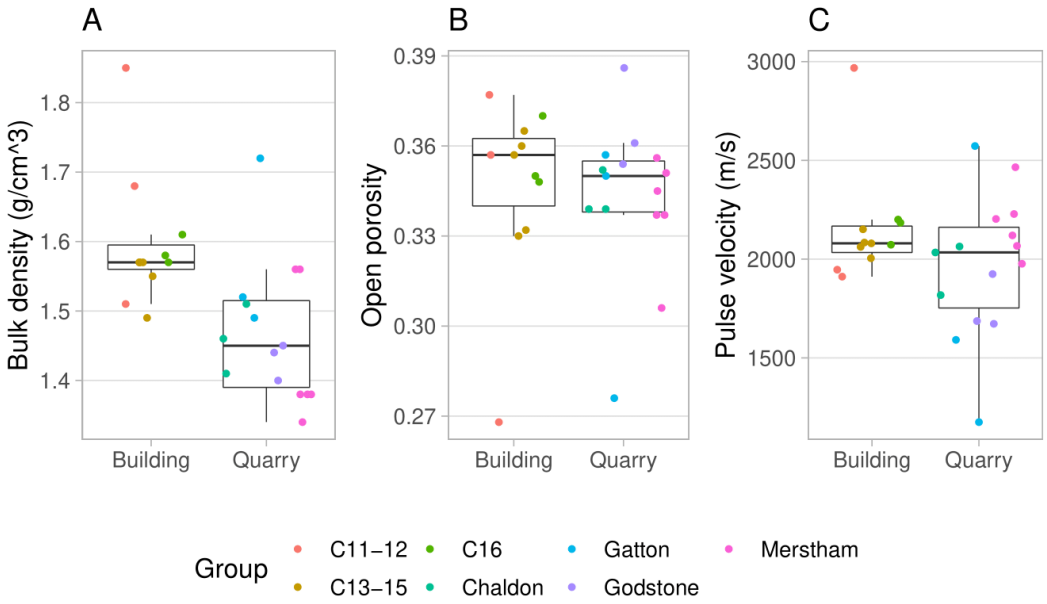


Figure III.8: *Box and whisker plots, showing* ***(A)*** *higher and more uniform bulk density in building stone,* ***(B)*** *slightly higher open porosity in building stone, and* ***(C)*** *more uniform response to pulse velocity measurement in building stone. Central line of box depicts mean value; lower and upper edges of box correspond to 25th and 75th percentile (IQR); whiskers extend to the largest/ smallest value within 1.5 * IQR.*

These findings should be treated with caution given the small sample set of building stones; however, they do support claims made elsewhere that building stones were selectively quarried (e.g. Sanderson and Garner 2001). This is reflected in a more uniform bulk density in building stone samples (Figure III.8). The mean value for p-wave propagation is also higher in building stones (2151 m/s) than in quarry samples

(1973 m/s). Extant building stones are characteristically denser and stronger. However, rather than a selection based on or even reflected in calcite content, observations here suggest that ease of working may have been the principal criterion. This is likely to have favoured textural homogeneity, present in stones with a more abundant matrix and/ or softer, finer grains. As demand outstripped the supply of calcareous, matrix-supported stones, an increase in the proportion of clay minerals is therefore likely to have become an unintended consequence of stones supplied to buildings.

III) 1.3.3.3. Variable resilience

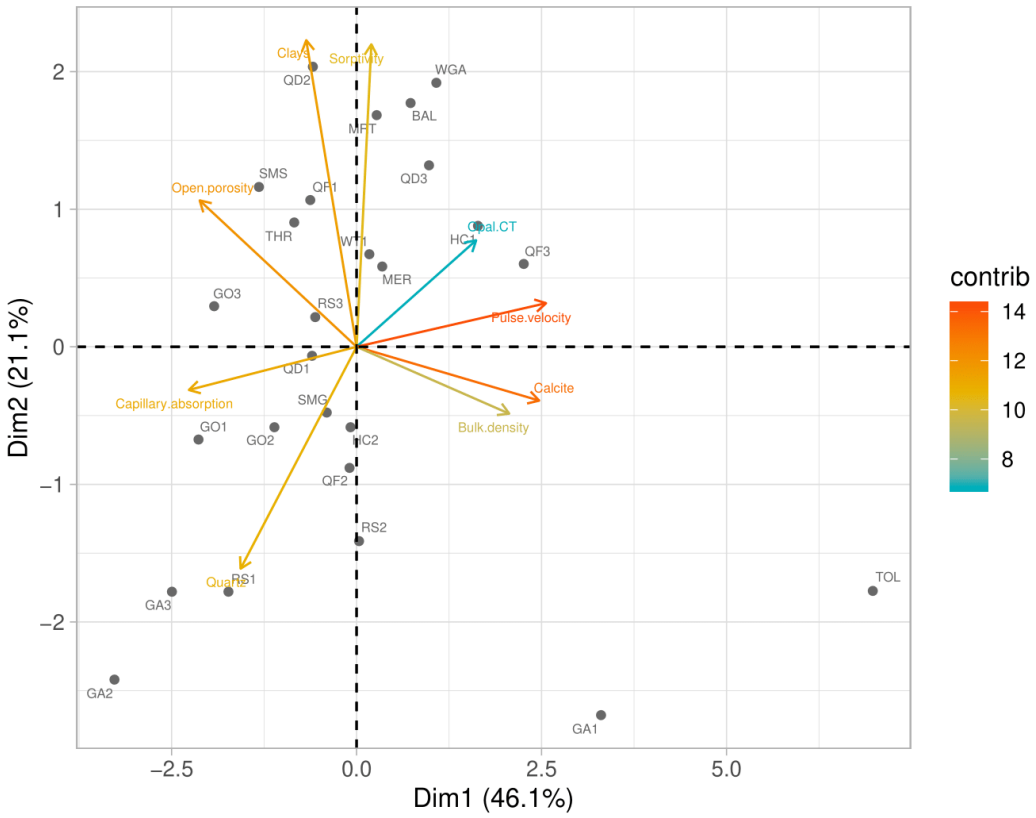


Figure III.9: *Biplot of Principal Component Analysis showing variation of samples according to measured characteristics across two principal components and contribution of characteristics to the components.*

In order to investigate the potential impact of variable mineralogical composition on hygro-physical characteristics, Principal Component Analysis (PCA) was performed (using the facto-extra package in RStudio). PCA is a statistical procedure to convert separate variables into linear, 'best fit' composites (called principal components (PC)), which account for the largest possible variance within a dataset (Jolliffe 2016). The first PC accounts for as much variability in the data as possible; each succeeding PC has the highest variance possible whilst remaining orthogonal (uncorrelated) to its precedent. This procedure can be used to plot individual variables and samples as vectors and points in a low-dimensional data space, in order to visualise their contribution to correlated groups. It therefore provides a useful method for identifying correlations and clusters in a dataset. The facto-extra package was used in RStudio; this automatically scales and normalises data from separate variables. The analysis was performed on all samples which were tested both for mineral and hygro-physical properties, in order to explore correlations between key mineral components, strength characteristics, and hygric mechanisms. After initial runs, feldspar content, anisotropy and hysteresis were not included in order to simplify the final analysis.

Two dimensions account for almost 70% of variation (Figure III.9). These associate two mineral components with distinct hygro-physical mechanisms. PC1 groups ultrasonic wave propagation, surface hardness, water uptake and calcite content. Bulk density and effective porosity also contribute. PC1 therefore links calcite content with strength characteristics such as compressive strength, elasticity and fabric density. This indicates calcite functions as a pore clogging cement in harder, denser samples. This results in a decrease in capillarity. PC2 groups clay mineral content with moisture

adsorption and retention. The specific importance of these components to individual stones should be treated with caution. Especially PC1 is dominated by the contribution of a small number of samples. Whilst this does not invalidate the identified groupings of variables, it indicates that variability across samples is complex. The lack of any significant correlation between hygro-physical properties and opal-CT content is also noteworthy, given the apparent importance of opal-CT in determining the shape of the porous matrix. However, PC3 and PC4, which each account for approximately 10% of variance, do group opal-CT content with bulk density, moisture adsorption and water uptake (Table III.4). This suggests more complex interrelations, with the distribution of components throughout the matrix likely to be crucial to individual properties. These results should be treated with caution given the small number of samples and high variation within the dataset. PC1 is dominated by TOL, which accounts for 45% of the contribution. However, removing TOL from the dataset and running the PCA again results in a similar dimensionality, with PC1 and 2 accounting for over 60% of variability and respectively linking increased calcite content with strength and slow water uptake, and increased clay content with higher sorptivity (as well as reduced open porosity and quartz content). The correlations identified here should be viewed as patterns, which can explain Reigate Stone characteristics in terms of the relative abundance of different cementing components, and account for different rates and patterns of decay in relation to hygric mechanisms.

Variable	PC1 (46%)	PC2 (21%)	PC3 (11%)	PC4 (10%)
Quartz	9.9%	23.4%	4.7%	3.1%
Opal CT	5.8%	1%	33.6%	28.1%
Calcite	14.5%	6.5%	14.1%	4.9%
Clays	2.2%	33%	7.2%	1.7%
Bulk density	7.1%	2.7%	25.6%	23%
Open porosity	7.2%	16%	5.8%	0.9%
Pulse velocity	24.5%	1.4%	0%	5.6%
Capillary absorption	19.4%	2.4%	2.3%	7.3%
Sorptivity	9.4%	13.7%	6.7%	25.1%

Table III.4: *Results of PCA, showing contribution of PC1-4 to overall variability, and contribution of individual variables to each PC.*

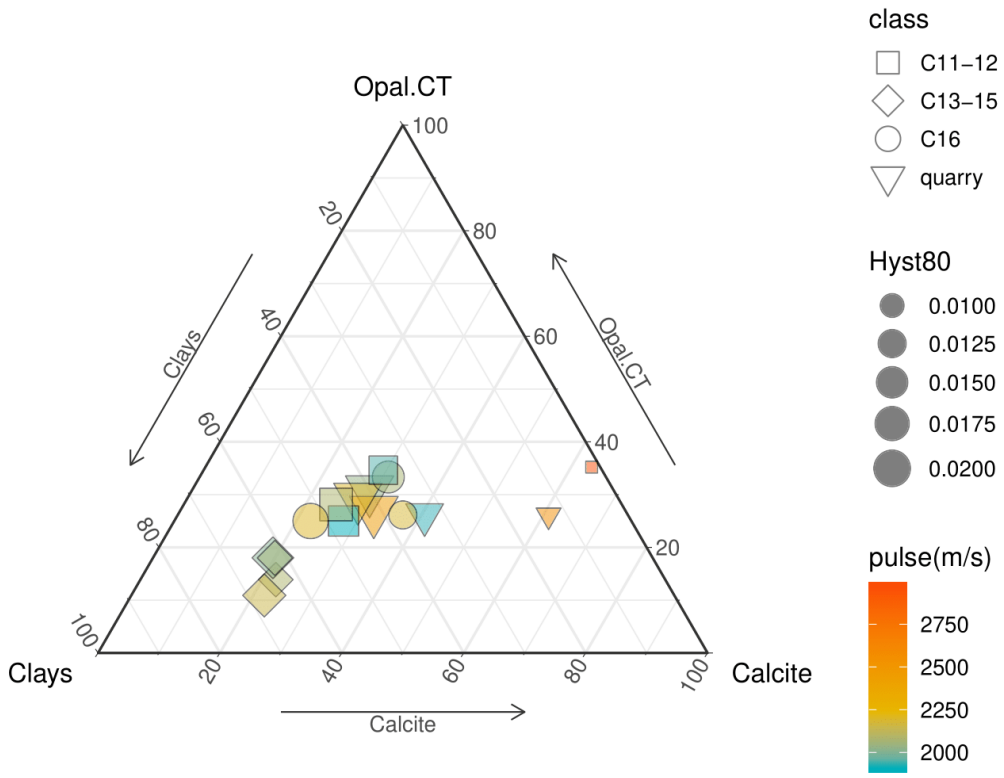


Figure III.10: *Ternary plot showing relationship between proportion of opal CT, calcite and clay (cementing components of stone), sorption hysteresis at RH80, and pulse velocity. Hygro-physical properties selected to represent performance of stone. One sample from each quarry deemed most suitable for building stone selected. Limited number of high calcite stones shown to perform well. 13th to 15th century stones are relatively higher in clay content and perform poorly. Other stones with variable performance.*

Reigate Stone has several characteristics which are linked to poor resilience in building stone. The mean open porosity of 34.5% is high for stones used in building (Stück et al. 2013). Clay minerals have a low weathering resistance and can induce swelling (ibd.). Moisture retention of between 1% and 2% at an RH of 80% indicates residual moisture will be present at high atmospheric humidity and dynamic equilibrium will increase the risk of salt crystallisation cycles (Franzen and Mirwald 2004). Whilst it is uncommon in building stones, opal-CT forms a weak, highly soluble cement (Přikryl et al. 2017). However, the picture painted by the relative proportion of cementing components in relation to hygro-physical properties likely to control decay, such as strength and moisture retention, is not as clear as the PCA might suggest (Figure III.10). Beyond baseline mineralogy, lower values for p-wave propagation in older buildings indicate more advanced decay in some samples, whilst others such as TOL appear to remain resilient.

III) 1.3.3.4. Building stone decay pathways

Different decay patterns visible in the building stone thin sections shown in Figure III.7 can be indicatively linked to the dominance of cementing components. In calcareous TOL, near surface fissures run parallel to faintly visible bedding orientation and through a pronounced crust, resulting in a progressive delamination of the dense fabric. In clay-bearing WT2, dissolution of fabric at a greater depth has resulted in more heterogeneity, with areas of very high porosity reflected in the high measured open porosity and low p-wave propagation of its partner sample WT1 (Table III.2). These samples come from buildings dating to a similar era, and whilst it is unclear precisely what part of the White Tower was sampled, TOL and WT1-3 all come from currently external masonry. However, whilst large areas of the White Tower base

were enclosed by later structures for long periods, WT samples were highly exposed in the south facing Wardrobe Tower for several centuries and there is evidence of repair using inappropriate materials. The aspect and contingency of exposure, and past repair programmes can be a further factor in the varying emergence and rate of decay.

Several results provide further evidence that variation is amplified in-situ as a result historic contingency, micro-environmental and/ or baseline mineralogical variation. Gypsum was identified in WT1-3, MRT and HC7. It is likely to have formed from soluble calcite reacting with atmospheric sulphur dioxide. Gypsum is absent in samples HC1-6, which are likely to have been buried before industrial scale coal burning. The different levels present in WT1-3 indicate that variable contamination is possible in highly proximate stones, possibly due to slight petrographic or microclimatic differences. Initial hygric characterisation tests on MRT indicate the effect contamination can have on physical properties: capillary absorption was very low (28.2 $g/m^2s^{0.5}$), presumably as a result of the pore clogging effect of near surface gypsum; sorptivity was very high (46.2%), possibly due to the hygroscopicity of other trace salts. After the sample was thoroughly rinsed and retested, results were closer to those of uncontaminated samples (Table III.2). The mineralogical variability present in samples from the same building implies that in some cases stone came from a variety of sources. Variability in HC1-7 is higher than any of the measured variability within individual quarries (Table III.2). Macroscopic inspection of the samples suggests that they are representative of at least two distinct typologies, evident in different colour. Provenance from multiple quarries and/ or material recycled from several buildings appears likely.

Other results indicate that some degree of homogenisation can result from decay. Whilst there is no significant difference in the average or range of open porosity between quarry samples and building stone samples, it is notable that building stones have a slightly higher open porosity (Figure III.8). This does not reflect the overall correlation between higher bulk density and lower open porosity (R = -0.57) (Table III.3). This could partly be due to the dissolution of matrix opening previously closed areas of porous network. The pore-size distribution, which has not been measured here, may be a crucial factor in determining variable durability. Although the primary, opal-CT matrix will form a regular porosity in the 10^2 µm region, the clay mineral fraction may result in highly bimodal distributions. This will increase the risk of salt decay mechanisms (Benavente 2007b). The role of calcite as a pore filling cement will play an important role in pore size distribution and open porosity. Weathering of calcite could increase connected, open porosity in near surface areas, especially in case hardened stones.

There is no clear pattern to anisotropy (Table III.2). The highest value is in GA2, an example of mature Reigate Stone, with more advanced diagenesis and bio-perturbed bedding; its anisotropy is therefore unlikely to be a consequence of bedding structure. With variation within and across individual quarries high, neither maturity nor paleoenvironment are good indicators of anisotropy. Samples in which bedding direction is visible in thin section, such as QF3 and TOL (Figure III.7), have low anisotropy. The low anisotropy in WT1 is notable given the advanced state of decay of its partner WT2 (Figure III.7). Rather than compounding pre-existing bedding structure, this suggests that decay has had a levelling effect on the internal fabric. The implication of these findings is that Reigate Stone is at most weakly anisotropic. Post-

sedimentary processes prior to quarrying and decay processes following construction can override bedding structure.

III) 1.4. Synthesis

III) 1.4.1. Discussion

The largely 19th century differentiation between Firestone and Hearthstone, used to distinguish stones for different purposes as much as of different properties, has led to contemporary discourse describing two distinct typologies of Reigate Stone (Sowan 1975; Sanderson and Garner 2001). This typically associates Firestone with calcite and Hearthstone with clay. The reality is that there are likely to be as many different mineralogical compositions as there are intercalated beds in the geological stratum. When defining the macro-geology of the Upper Greensand, Jukes-Brown (1900, p.38 onwards) described zones of deposition defined by space, time and life (i.e. organic sediment). Particularly due to the characteristic species of a thus defined zone, there can be considerable overlap in resulting mineralogy. This is reflected in the findings presented here; compositional variability is present in stones sampled at relative proximity within single quarry faces. Furthermore, the stones used in medieval construction do not conform to a clear typology or necessarily contain increased calcite. Whilst Firestone and Hearthstone may be representative of two selectively exploited sub-types, when discussing the full history of Reigate Stone used in buildings, it may be more useful to consider a broad mineralogical range. This will not alleviate persistent difficulties in classifying Reigate Stone according to common lithologies such as sandstone or limestone. Instead it demands that each use in masonry is assessed individually and conservation strategies are tailored accordingly.

There are nevertheless patterns evident in Reigate Stone selection and use over time. Identifying these has benefited from synthesising documentary research with material analysis, which was only possible on a small sample set due to the restrictions of the historic built environment. The samples investigated here do not reflect the full variability of quarry samples. Whilst they vary in mineralogical composition, density and strength characteristics are more uniform. The earliest building stone investigated here (TOL), sampled from the 11th century White Tower, supports anecdotal evidence that early use Reigate Stone conformed to a particularly durable variety, which became exhausted during London's rapid growth. A single quarry sample (GA1) matches the hygro-physical properties of this building stone. As with many of the quarry samples investigated here, its coarse, less homogeneous texture suggests it may not have been a suitable freestone. No quarry face reliably provides stone that is comparable to those sampled from buildings. Large quantities of waste material found in later medieval quarries suggest quarrymen became adept at purposefully selecting stone (Sowan 1975). It is possible that this was a process of trial and error, and that particularly the Reigate Stone industry boom of the 13th century saw lesser quality material extracted and used in buildings. This is supported by findings presented here, which associate a second phase of Reigate Stone exploitation with increased clay content. This could be a reason for some of the early failings of the stone, which had tarnished its reputation by the 15th century. This does not contradict findings made elsewhere, which suggest extant Reigate Stone is more calcareous (Sanderson and Garner 2001). Any attempted characterisation of building stone according to extant masonry is however to ignore potentially vast amounts of stone which were being replaced by the 13th century. Following centuries of limited,

targeted use, which developed a quarrying industry around reliable sources, selection criteria for easily workable stone during the rapid expansion of quarrying activity in the 12th century are likely to have introduced inferior quality.

Beyond the selection of suitable stone, there is further evidence that workmanship may have influenced the performance of stone in-situ. The presence of calcite and its correlation with harder, denser stone suggest that seasoning of freshly cut stone will have been important. Roughly cutting stone to shape before this case hardening will also have greatly improved resilience. Knowledge and mastery of these processes are likely to have refined over time, with templates being sent to quarries and adequate shelter for seasoning being provided perhaps only after initial difficulties became apparent. When Cristopher Wren did make use of the stone in later centuries, he demanded great care be taken during storage (Hatton 2001). Anisotropy does not appear to affect Reigate Stone, however there is some evidence of flaking occurring along bedding planes in samples where these are visible (e.g. TOL). This suggests in some environments incorrect laying of the stone may have accelerated decay. Especially given the poor visibility of bedding planes, errors during construction following lengthy transport and stockpiling are likely to have occurred. In the case of TOL, the stone appears to have been face bedded rather than surface bedded. These factors will have contributed to divergent decay pathways.

This study identifies correlations between different cementing components and hygric mechanisms affecting resilience. These underline complex decay processes in relation to the environment, which will be affected by spatial, micro-climatic variations and temporal, macro-climatic changes. Increased calcite content impacts

positively on strength characteristics; its pore-clogging properties are shown to reduce capillarity, but water uptake is still rapid in most stones. Coupled with high moisture absorption and retention, particularly in stones with abundant clay minerals, Reigate Stone will be prone to moisture related decay processes and is likely to be highly sensitive to alterations caused by salt contamination. Associated decay phenomena such as gypsum crust formation and spalling have been well documented in other vulnerable historic freestones (Beck and Al-Mukhtar 2010; Dewanckele et al. 2013). Varying calcite and clay contents are likely to preclude standard stone conservation treatments being suitable for all types of Reigate Stone, with targeted selection necessary depending on mineralogical composition.

The cumulative effect of decay and changing approaches to conservation will have increased variability over time. The dynamics of building stone decay are known to be complex and non-linear (Viles 2005). Minor physical differences may diverge thresholds at which decay becomes evident. Besides the impact of environmental change upon rates and patterns of decay, the impact of cultural change upon the perception of deterioration has been a significant factor in shaping variation in the historic built environment. Within an overall pattern that has shifted from replacement and renewal to preservation and consolidation over the past two centuries, there has been nuance and disparity in response to socio-economic context. Overlaying these two complex trajectories, non-linear physical decay and idiosyncratic perception of deterioration, imparts a lack of contingency on conservation strategy; one area of Reigate masonry may cross a decay threshold and be replaced one decade, only for the rest to cross the same threshold yet be treated with a consolidant the following decade. Introducing the new materials of

replacement or consolidation, and the memory effect of past environmental stresses, into this already intricate system dynamic serves only to augment the variability of initially minor, physical differences.

III) 1.4.2. Synopsis

The objectives of this investigation were to establish patterns of use in Reigate Stone exploitation pertaining to variability, define variability in mineralogical terms, and link mineralogical composition to physical characteristics known to influence decay. This was intended to contribute to the overall aim of building a model of the processes which have contributed to variability in historic masonry. This model can be visualised as a timeline, tracking Reigate Stone use in building through several phases (Figure III.1).

1. Early use, prior to and in the first century following the Norman conquest, was limited and targeted. The focus was on detailing and supplementation of other more widely used lithologies such as Kentish Ragstone and Caen Stone. Quarrying was restricted to a small number of locations and it was possible to supply durable stone of uniform quality.
2. The second phase of use, from the 12th to the 15th centuries, witnessed huge growth in masonry building and accordingly a significant expansion of quarrying activity. Whether due to inherent variability found in new quarrying locations, or due to the stresses of increased demand leading to a decline in workmanship and quality control, this phase saw the introduction of less resistant stones into the built fabric. Growing logistical complexity may have resulted in masonry with stones of variable provenance or maturity, as stockpiling locations became a

necessary juncture between quarry and building site and centralisation streamlined supply.

3. The third phase of use sees a first wave of replacement, repair and refinement in response to the decay of less durable stones, beginning in the 15th century following several centuries of weathering activity. Understanding of the limitations is likely to have improved and ongoing use may have been subject to more stringent quality control. However, it is possible that supplies of the best quality Reigate Stone had been exhausted. Compounded by socio-economic factors, which led to reduced demand for freestone, quarrying activity gradually declined. Good quality Reigate Stone was still a valued resource; robbing of disused buildings and reuse in new buildings is likely to have occurred in many cases. This will have further increased the inherent variability found within individual masonry units.
4. The fourth phase brings gradual changes to London's environment, beginning in the 17th century and climaxing in the intense pollution of the late-19th century, which accelerated the decay of even good quality Reigate Stone. The value of the stone decreases and as the construction industry grows anew, replacement with newly available alternatives becomes more common. Whilst a brief Victorian revival introduced a small amount of fresh Reigate Stone into the historic fabric, the overall stock drastically falls.
5. A final phase beginning in the 20th century focussed on attempts at conserving and consolidating remaining Reigate masonry. Selective treatment is likely to have further amplified inherent variability.

III) 1.5. Conclusion

This paper has investigated the causes of inherent variability in historic Reigate Stone masonry. The methodological approach has been to synthesise historical analysis of its use with scientific examination of its properties. This approach has revealed patterns which can be used to build a hypothetical model of processes resulting in variability. Reigate Stone was Medieval London's principal freestone. It was used in vast quantities during a key growth period in London's history. Huge demand may have outstripped the supply of good quality building stone as quarrying adapted from localised supply for specific projects prior to the 12th century, to industrial exploitation in step with rapid, regional economic growth in the following centuries. This introduced mineralogical variability into the built fabric.

Different mineralogical components are shown here to influence key material properties known to control the onset of decay in building stones. Calcite content influences strength and capillarity. The abundance of clay mineral phases affects adsorption. As the main matrix forming cement, the highly soluble opal-CT content will play an additional role in long-term moisture transport and durability. Whilst the precise interplay of these cementing components and their net effect on the resilience of individual building stones is likely to be complex, small initial differences can result in variable response to environmental processes and the divergence of decay pathways.

In historic buildings, any resulting variation in the onset of decay would have been further augmented in response to changing economic and environmental context. Successive material interventions and recycling of built fabric occurred as a reflection

of changing attitudes to architectural heritage and introduced further complexity. Understanding the material and environmental, but also the historical contingency underlying inherent variability in Reigate Stone masonry is key to the design of ongoing conservation strategies. In terms of practical guidelines, this demands a thorough documentary analysis of past changes to a masonry system, and careful documentation and archiving of any new changes for the benefit of future work.

III) 2. Assessing the long-term success of Reigate Stone conservation at Hampton Court Palace and the Tower of London.[4]

Abstract

Reigate Stone was extensively used in medieval London and is prone to rapid decay. A variety of different conservation treatments have been applied in the past; in many cases these have not mitigated ongoing decay. This paper presents an overview of wax, limewash, silane and ammonium tartrate treatment at the Tower of London and Hampton Court Palace. Documentary analysis and visual inspection indicate that whilst these methods have provided protection to some stones, no single method has resulted in protection of all stones. Non-destructive and minimally-destructive testing is used to more closely assess the effects of ammonium tartrate treatment. The results imply that inherent stone mineralogy, past decay pathways and/ or present environmental factors are a greater control on ongoing decay than treatment histories.

[4] As accepted to a special issue of *Studies in Conservation* in December 2019, after review, with only minor changes to style and format.

III) 2.1. Introduction

A wide range of treatments have been used to conserve vulnerable building stones (Doehne and Price 2010). These are frequently tailored to suit particular lithologies: the lime-method is a common technique for treating limestone, silanes are more suitable for sandstones. It can be difficult to select appropriate treatment for lithologies which do not fall into standard categories. Frequently such stones represent unique chapters of architectural history. Furthermore, there has long been awareness of limitations and challenges associated with stone conservation (Schaffer 2004). The purpose of active stone conservation is usually to improve water repellence (surface coating) and/ or restore fabric strength (consolidation); however, past assessment of field-based experiments has concluded that many attempts are ineffective in the long-term (e.g. Clarke and Ashurst 1972; Odgers 2013). Factors such as the penetration depth of consolidants and moisture entrapment due to impermeable surface coats are of ongoing concern. The effects of climate change, such as increased intense rainfall are predicted to put historic masonry under increasing risk of rapid decay (Smith et al. 2011a). Furthermore, active conservation protocols are being re-evaluated in response to advances in conservation science and shifts in cultural perceptions of deterioration (Douglas Jones et al. 2016). As a result of this, assessment of past treatment methods is increasingly necessary.

III) 2.2. Reigate stone conservation

Date	**Technique**	**Sites**	**Outcome**
Early C19 (1820?)	Roman cement	Bloody Tower gateway ceiling, ToL.	Survey in 2002 identified ongoing decay of stone beneath plaster.
1840s	Aluminium Hydroxide	"experiment made upon a cistern of Reigate stone" (Anon 1844)	Unknown.
1882?	Wax coating	Widespread at HCP	Survey in 2008 linked rapid decay of Reigate Stone plaque to impermeable wax coating. Similar decay patterns can be observed elsewhere, however there are also examples of well-preserved coatings.
Early C20	Barium Hydroxide	Chapter House at Westminster Abbey (North 1930, p.381)	Protective crusts soon delaminated.
1963	Calcium Hydroxide (limewater) and various organic polymers	Internal Salt Tower, ToL (Experiment including control areas)	Treatment had no significant effect (Clarke and Ashurst 1972, p.43).
1984	*Brethane* (Alkoxysilane)	Upper Wakefield Tower.	Surveys in 1999 and 2003 found that the treated pier, which had since been found to be heavily salt contaminated, was decaying more rapidly than nearby untreated masonry (Price 1993, Church 2003).
1988-91	Lime-method	ToL: Bell (1988), Wakefield (1990), Salt (1991), Cradle Tower (1991) and Wardrobe Tower (1991)	Ongoing decay in many treated areas. Limewash coats detached rapidly in some areas, mainly attributed to high moisture content of masonry. Other coats still visible now. Casein, pigment and linseed oil variously mixed into limewash and lime mortar.
2001	*HCT* (solvent based)	Trials at HCP, ToL and Winchester Palace	Some treated areas have resisted decay. Mineralogy and micro-climate likely to be key factors.
2013	*CalolSil* (Nanolime)	Trials at Westminster Abbey	Assessment of trials ongoing.
2015	*HCT* (water based) and lime-mortar	External Bell Tower	Ongoing surface loss noticeable in exposed areas.

Table III.5*: Past Reigate stone conservation techniques. Works for which no reference is given are recorded in the archives of Historic Royal Palaces.*

Reigate Stone has a variable calcite and clay mineral content, an unusual silicate grain structure and is prone to rapid decay (Sanderson and Garner 2001). It was widely used for detailed masonry in South East England from the 11th to 16th century and was the principal freestone at sites such as the Tower of London (ToL) and Hampton Court Palace (HCP) (Tatton-Brown 2001). Attempts at conserving Reigate Stone are likely to have commenced as soon as techniques became available, however scant documentation makes reliable identification and dating difficult. Table III.5 provides an overview of past conservation for which documentation or robust evidence is available, focussing on ToL and HCP. Few techniques have successfully mitigated decay; some have accelerated decay. Given its notoriety, stone consolidants may frequently have been trialled on Reigate Stone; there is evidence to suggest Roman Cement, Aluminium Hydroxide and Barium Hydroxide were all used on decaying Reigate masonry shortly after their development; none successfully. Newly developed techniques continue to be tested against Reigate Stone. Ongoing trials using nanolime at Westminster Abbey await full evaluation. A brief documentary and visual assessment of three widely used treatments methods applied to Reigate Stone follows.

Waxes were widely used surface treatments in late-19th and early-20th century England. Much Reigate Stone at HCP displays evidence of past treatment. Reference to restoration of stonework in 1882 provides a possible date for such work at HCP (Colvin 1976, p.158). Intended as a water repellent, waxes are prone to adsorb pollution and trap moisture (Odgers and Henry 2012, p.136). This can result in accelerated decay patterns, which have been documented at HCP on the Cardinal Wolsey plaque (Figure III.11). Coatings do not show uniform signs of decay. In some

sheltered areas coats have partially detached, spalled or eroded to reveal sound stone. In other sheltered areas coats have blistered and flaked to reveal flaking stone and gypsum crust. In many exposed areas remnants of coat are isolated, and the stone surface is friable and soiled. Most coats appear discoloured by pollution. Microclimatic stability appears to control the performance of wax treatment.

The lime-method emerged in the 1980s as a holistic technique for treating limestone. It consists of consolidation with calcium hydroxide (limewater), plastic repairs with lime-mortar and protective coatings of lime diluted in water (limewash) (Doehne and Price 2010, p.36-37). Various additives are added to the limewash in attempts to improve resilience. The technique was widely used on Reigate masonry at ToL in the early 1990s. Initial use of limewater in the upper Bell Tower in 1988 caused concern over the high level of water uptake. There are conflicting accounts of where it was applied after this; contemporary documentation suggests masonry at the Cradle and Wardrobe Towers was also treated with the full lime-method (Table III.5). Most coats have since detached from Reigate Stone at the highly exposed Wardrobe Tower, however some remain intact. Coats have also largely detached from the lower Bell Tower and the Bell Tower parapet. Rapid decay has been recorded in all three areas, with distinct environmental mechanisms likely to be responsible in each case, ranging from deep wetting of the masonry to rapidly fluctuating conditions (see chapter V.1). The more benign environment of the upper Bell Tower has produced longer lasting coats, however recent prolonged moisture ingress in the southern alcove due to defective guttering has rapidly accelerated localised decay. Intact coats are not exclusive to internal masonry; coats applied to the external Cradle Tower have also survived (Figure III.12). These observations imply microclimate and stone mineralogy

affect the success of limewashing. Despite producing some long-lasting coats limewashing has not been repeated, although lime mortar repairs make up a part of the current conservation strategy at HCP and ToL.



Figure III.11: *Cardinal Wolsey Plaque at HCP showing acceleration of decay rate on wax-treated Reigate stone surface.*



Figure III.12: (Left) *limewashed Reigate stone at Cradle Tower, ToL, shortly after treatment in 1990 and* ***(right)*** *in 2018 showing good state of preservation.*

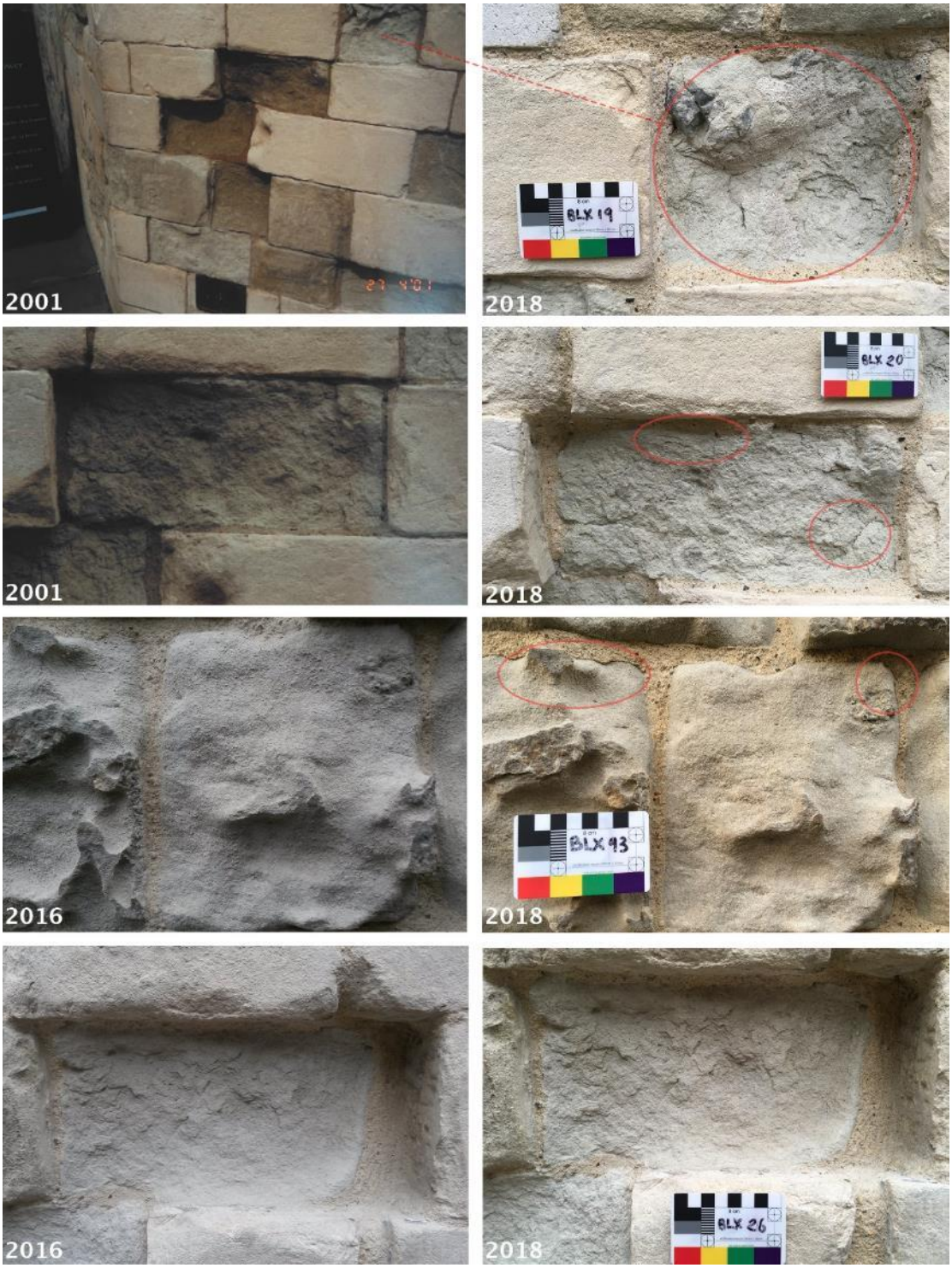


Figure III.13: *Reigate Stone at the Bell Tower, ToL treated with HCT during the 2001 trials (top left) and 2015 conservation work (bottom two rows). Greater decay visible in untreated control (top row), than in stone treated during trial (second row); However, ongoing, rapid decay visible in powdering, darker stones (third row) compared to flaking, lighter stones (bottom row) treated in 2015.*

Hydroxylating Conversion Treatment (HCT) forms a crystalline deposit of ammonium tartrate on calcite within the pore structure of a stone. It was developed to enhance the adhesion of silanes to calcareous matrices (Weiss et al. 2000). Laboratory testing has shown that use on Reigate stone may be effective even without subsequent application of silanes; treated stone performed positively in freeze-thaw and abrasion tests. Trials were carried out at ToL and HCP in 2001 using HCT and a silane (*Conservare OH*). Visual assessment of trial areas at the Bell Tower indicates treated stones have become more resistant to decay than an adjacent untreated control (Figure III.13). Large areas of Bell Tower masonry were treated with HCT in 2015, however erosion of some treated surfaces has continued. Whilst the trials were carried out with an organic solvent, recent treatment used water as a solvent. Different appearance and decay patterns of stones also suggests various mineralogical compositions. Microclimatic and contextual factors may present a further reason for the varying decay rates within and across the separate treatment phases. Further assessment of the HCT trials on Reigate Stone will attempt to establish factors which can determine the success of ongoing conservation strategies.

III) 2.3. Experimental

An HCT test wall was built at ToL in 2001 (Figure III.14). Eight stones were cut in half and separated by an impermeable membrane. The right half of each stone was treated with HCT, the left acted as an untreated control. Photos taken shortly after construction of the wall show that the stones displayed a range of different textures, colours and pre-existing decay features. This suggests various sources. HCT.1, HCT.2 and HCT.4 had a yellow-brown discolouration of varying density but covering most of

the surface area, probably related to a previous surface treatment, possibly linseed oil or wax (Odgers and Henry 2012, p.136). HCT.3 and HCT.5 had rough surfaces. HCT.6, HCT.7 and HCT.8 had smooth, pale grey surfaces with localised damage.

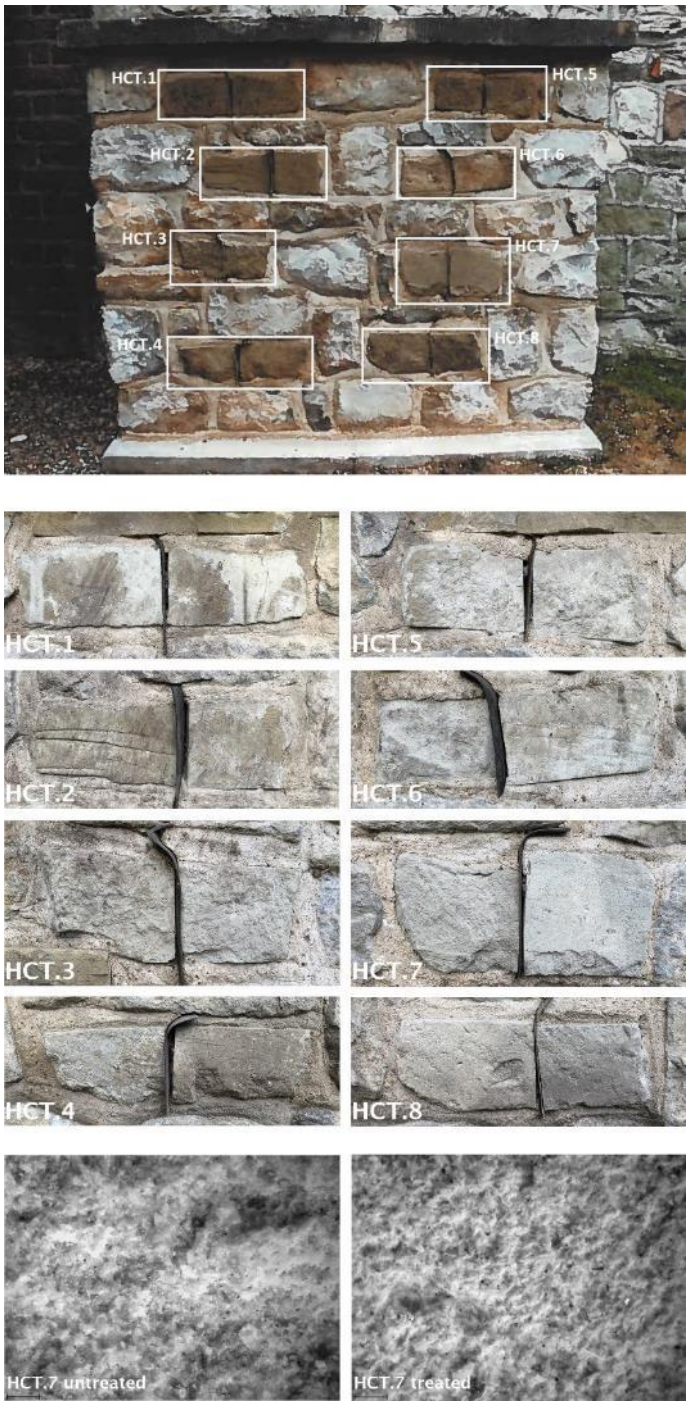


Figure III.14: *HCT trial wall at ToL.* ***(Top):*** *shortly after treatemnt in 2001 (dark surfaces due to residual moisture following treatment).* ***(Middle):*** *individual stones in 2018.* ***(Bottom):*** *micrograph taking with Dinolight USB microscope showing consolidation of treated surfac*

Individual stones were investigated in 2018 using non- and minimally-destructive techniques (NDT). Measurements were taken on treated and untreated surfaces of each HCT stone; for comparison, measurements were taken on a single stone treated with wax or limewash.

Surface hardness (SH) was measured using an *Equotip* rebound hammer (*Proteq*). 20 scattered measurements were taken on each surface. Leeb hardness (HLD) is given as an average of these readings.

Water uptake was determined using *Karsten* tubes sealed against each surface with putty and filled with distilled water. The amount of water absorbed by the stone was recorded at intervals of 5, 10, 20, 40 and 80 seconds. The absorption coefficient *wp* ($g/m^2s^{0.5}$) was calculated using the formula

$$wp = \frac{\frac{[m(1) + m(2) + \cdots m(5)]}{A}}{\left[\sqrt{t(1)} + \sqrt{t(2)} + \cdots \sqrt{t(5)}\right]}$$

Where *m(n)* is equal to the mass of absorbed water in g weighed at the interval *t(n)* in s. *A* is equal to $5x10^{-4}$, the area of the surface in m^2 that is in contact with water.

Drilling-resistance measurements (DRM) (*SINT Technology* attached to *Makita* with 3 mm drill bit) were made to investigate depth of consolidation and crust formation. Two measurements were taken on each surface, with the drilling velocity set to 1 cm/min and the penetration depth set to 25 mm. Resistance (N) is given as an average of these measurements for outer (1 - 4.9 mm depth) and inner (5 - 25 mm) parts of the stone. Before and after the measurements a reference block was used to calibrate the instrument. DRM has been used in previous assessments of stone consolidants

(e.g. Odgers 2013) and is being used to assess the nanolime trials at Westminster Abbey, making it a useful technique for this study.

III) 2.4. Results and Discussion

Visual inspection of the test wall reveals that HCT.6 and HCT.7 have become noticeably more resistant to decay following treatment (Figure III.14). In both cases, granular disintegration has affected large parts of the untreated area, but only small parts of the treated area. Decay has progressed most rapidly around pre-existing decay features, which were more evenly spread across the surface of the untreated areas. Whilst decay was visible in other stones, there was no apparent difference between the decay rate of treated and untreated areas.

	Surface hardness (HLD)				Absorption coefficient ($g/m^2s^{0.5}$)		Drilling resistance (N)*			
	Untreated		Treated		Untreated	Treated	Untreated		Treated	
	M	SD	M	SD			1 -4.9 mm	5 -25 mm	1 -4.9 mm	5 -25 mm
HCT.1	477	26	451	48	921	-	18.6	20.3	18.1	19.4
HCT.2	465	30	446	55	1021	620	7.4	9.4	7.4	7.2
HCT.3	451	51	426	62	1499	663	10.2	17.1	15.6	17.7
HCT.4	516	111	447	73	43	773	49.6	28.6	36.3	28.7
HCT.5	440	20	411	39	1496	1130	16	16.9	14.5	15.1
HCT.6	442	63	528	39	156	223	7	9	9.6	8.8
HCT.7	362	71	520	46	482	904	43.1	42.8	36.7	43.9
HCT.8	464	35	419	25	673	2179	23.3	26.9	19.8	17.3
Wax	345	47	422	57	526	91	-	-	12.7	7.4
Lime	-	-	314	83	-	1170	22.5	25.3	3.3	25.2

Table III.6: *Results of NDT (*due to deterioration of drill bit, values measured on separate stones are not calibrated).*

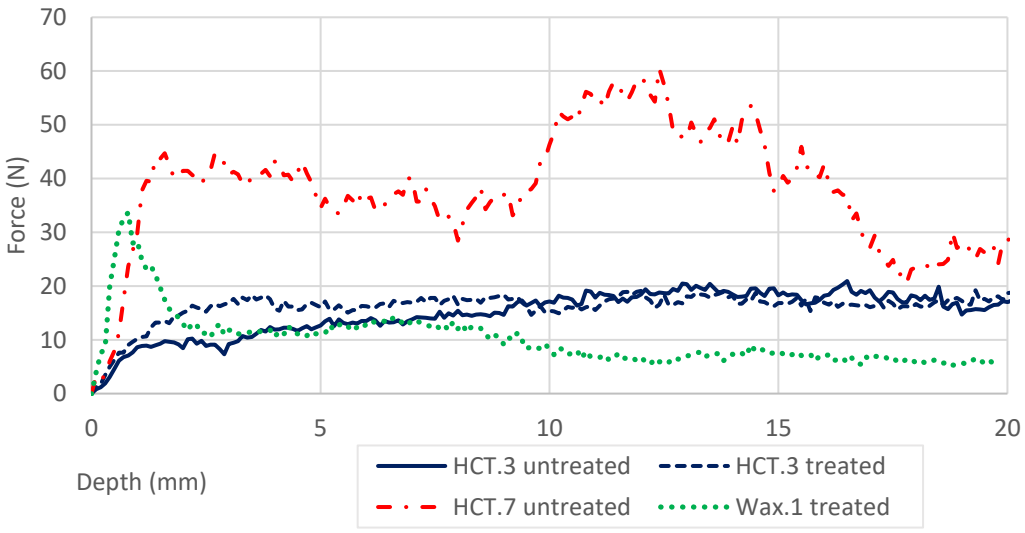


Figure III.15: *DRM profiles of selected stones.*

Results of the NDT support the visual observations (Table III.6). HCT.6 and HCT.7 are the only stones to show an increase in SH following treatment. There is no clear correlation between water uptake and treatment, suggesting that HCT does not have a water repellent effect. Absorption was lower in treated areas on fewer than half the stones. Instead factors such as individual stone composition or position appear to control water uptake. Environmental and mineralogical factors also appear to influence DRM more than treatment. Only HCT.3 and HCT.6 required a slight increase in force to penetrate the initial subsurface of the treated area. Where DRM does indicate a consolidating effect, profiles suggest a penetration depth of at least 5 mm (Figure III.15). Comparison of resistance across stones should be treated with caution due to rapid deterioration of the drill bit: HCT.2 and HCT.6 were measured on a different day to the other stones using a new drill bit and appear accordingly less resistant. Nevertheless, HCT.7 was significantly more resistant and more heterogenous than any other stone (Figure III.15). This could reflect a higher calcite content, which would explain effective treatment. HCT.4 displayed crust formation or

case hardening of the outer 3-4 mm of both treated and untreated areas. HCT.4 sits on the lowest course of the test wall and showed signs of salt contamination. Regardless of any effect treatment may have had, inherent mineralogy and environmental stresses appear to exert a greater control on ongoing decay.

Similar measurements taken on wax coated and limewash samples highlight characteristics of both treatments. DRM and SH suggest that limewash produces a softer outer layer, whilst high absorption coefficient indicates the coating is moisture permeable. The wax coating is noticeably harder and less permeable than the underlying stone. DRM indicates that the coat forms an outer case of several mm thickness with significantly different properties to the underlying stone. This can explain the decay patterns seen at HCP, with moisture entrapment behind the coating eventually leading to blistering and spalling to reveal decayed surface. Limewash offers a more benign protective coat, which is also prone to decay but unlikely to damage underlying stone.

These findings support documentary and anecdotal evidence that indicate specific treatment methods are only suitable in certain circumstances. This supports previous assessments of stone consolidants, which have failed to identify an overwhelming impact of individual techniques term (e.g. Clarke and Ashurst 1972; Odgers 2013). In highly exposed or fluctuating environments no treatment appears able to provide long lasting protection. The evidence presented here indicates that wax treatment can accelerate decay in unsuitable environments. Although HCT and lime-method treatment appear more benign, mineralogical factors should be considered. Whilst calcite content is likely to improve compatibility, harder, calcareous stones are likely

to be less at risk of rapid decay. Lime-watering and water-borne HCT may present a risk to more vulnerable, clay bearing stones. This could explain the different response of stones treated in 2001 and 2015; treatment has only improved resistance in paler, probably calcareous stones. In-situ identification of Reigate Stone typologies can facilitate more effective treatment. Ongoing use of limewash would benefit greatly from controlled field experiments.

III) 2.5. Conclusion

The objective of this study was to assess historic Reigate Stone conservation, with the purpose of informing ongoing conservation strategies. Stones believed to have been treated with wax in the 1880s, known to have been treated with the lime-method in the 1980s and 90s and treated with HCT in a controlled field-experiment in 2001 were investigated. No technique provides long-term protection of every treated stone; however, whilst impermeable wax coatings can trap moisture and cause a sudden acceleration in decay rate, limewash is benign and detaches quickly. HCT was only effective on certain stones. This is likely to be related to variable calcite content. The findings imply that inherent stone mineralogy, past decay pathways and/ or present environmental factors are a greater control on ongoing decay than past treatment. These findings support previous research, which suggests long-term consolidation is frequently ineffective without regular maintenance. Ongoing conservation must be tailored to specific circumstances; different mineral typologies are likely to necessitate precise techniques; certain environments or histories may preclude any effective conservation.

IV. Contemporary conservation: Repointing vulnerable masonry

"The greatest glory of a building is in its age,
and in that deep sense of voicefulness,
which we feel in walls that have been washed
by the passing waves of humanity"

John Ruskin, *The Seven Lamps of Architecture* (1849, s.10)

The first section of this chapter is an unaltered version of a paper submitted in April 2020 to the journal *Construction and Building Materials*. The second section is an unaltered version of a paper accepted in February 2020, after review, to the published proceedings of the *Stone2020 Congress* in Goettingen, September 2020. Both papers co-authored with H. Viles, C. Vlachou and I. Angus.

IV) 1. The role of pointing mortar in preventive conservation strategies for vulnerable historic masonry. A non-destructive field survey of Reigate Stone at the Tower of London.[5]

Abstract

The correct choice of pointing mortar is considered crucial to the conservation of historic masonry. A proliferation of cement and eminently hydraulic lime mortars since the late 19th century has accelerated the deterioration of built cultural heritage in many parts of the world. Whilst the use of softer, lime-based mortars in stone conservation is now common practice, their role in the overall conservation strategy of highly vulnerable building stones such as Reigate Stone requires assessment. In this paper non-destructive testing (NDT) is used across a two-year period to investigate the impact of different pointing mortar types on moisture regulation of Reigate Stone masonry at the Wardrobe Tower, Tower of London, following repointing carried out in 2017. Joints repointed using a hydraulic lime mortar (NHL3.5) are shown to regulate moisture in adjacent Reigate Stone blocks less well than those repointed using a lime putty mortar. However, despite an initially inappropriate recipe, older hydraulic lime mortars are in some instances shown to perform similarly to the lime putty mortar, suggesting that NHL can weather sympathetically. The results also indicate that, whilst pointing mortar type does play a role in the moisture regulation of individual stones, its effect is outweighed by both properties of the stone itself, such as strength and past decay, and wider micro-contextual factors, such as exposure or adjacent topography. Findings made at the Wardrobe Tower indicate that pointing mortar only plays a part in overall moisture regulation; to enable its effective functioning and minimise the need for repeated interventions, it may be necessary to take additional protective measures to mitigate moisture ingress, such as water run-off and channelling following heavy rainfall. The overall implication is that in vulnerable historic masonry such as Reigate Stone, sustainable conservation strategies must incorporate a broad appraisal of and tailored response to specific decay mechanisms.

[5] Submitted April 2020 to *Construction and Building Materials*, with minor changes to style and format.

IV) 1.1. Introduction

Pointing mortar plays an important role in regulating moisture in masonry structures. During driving rain, exposed stone can absorb large amounts of water (Erkal et al. 2012; Orr et al. 2018). Ideally this moisture should be drawn back out through the mortar, rather than evaporating through the face of the stone (Fusade et al. 2019a). This minimises moisture fluctuations at the exposed stone surface, which can drive salt crystallisation cycles and the swelling of clay minerals (Charola 2000; Wangler and Scherer 2008). When it is drawn out through the mortar, the moisture instead evaporates through the joints between two stones. The correct functioning of this process depends on various properties of the mortar in relation to the surrounding stone, such as its porosity and plasticity (Wiggins 2017). In the pre-industrial era, locally sourced lime-based mortars were used in many parts of the world and functioned well if they were correctly worked and maintained. Maintenance included regular replacement of decayed pointing mortar which was no longer functional. The pointing mortar can be more easily replaced than the stones themselves and is generally considered sacrificial to this effect. Whilst mortar may have implicit cultural value itself, repointing is therefore an important part of the conservation of historic masonry (Henry and Stewart 2011).

Pointing mortar should neither trap moisture, nor leave masonry unprotected from moisture penetration (Wiggins 2017; Maurenbrecher 2012). This requires a well-sealed joint without any cracks or fissures, with an unbroken surface contact area between the pointing mortar, the surrounding stone, and the bedding mortar within the joint. The pointing mortar needs to be worked to a consistency and applied in a

manner which ensures such surface contact and cover, whilst also being able to deform plastically to maintain contact. Furthermore, the mortar must act as a poultice to the stone, drawing moisture from the pores of the stone into its own porous matrix. This requires a pore-size distribution with a high proportion of interconnected capillaries. Traditional, non-hydraulic lime-based mortars generally fit these requirements, however they proved difficult to work and maintain in damp environments. Hydraulic limes and natural cements began to replace ordinary lime mortars in the mid-18th century (Weber et al. 2008). Whilst these could set in damp conditions, the chemistry necessary to enable this hydraulic set frequently resulted in increased brittleness and a denser microstructure more prone to trap moisture. The proliferation of cement-based material in the 19th century introduced new types of hard, dense mortar into the historic built fabric, which proved inadequate for the effective moisture regulation of historic masonry (e.g. Urquhart et al. 1996; McCabe et al. 2010).

Repointing occupies an ambiguous space within the practical framework of architectural conservation. Whilst it involves an intervention in the masonry system, the primary functional role is of a sacrificial nature. By regulating moisture exchange with the environment, pointing mortar functions as a mediator between the more permanent elements of a masonry system and the surrounding environment. In this respect, the maintenance of functioning pointing mortar could be considered a preventive conservation strategy. On the other hand, mortar may have significant cultural value itself. It provides documentary evidence and aesthetic complexity (Henry and Stewart 2011). Furthermore, beyond the simple removal of decayed mortar, repointing works can constitute a significant interruption of a masonry

system's equilibrium, even when using suitable, lime-based materials. Correct protocol of lime mortar repointing involves a prolonged wetting of the stonework, which can damage vulnerable building stones, and frequently a defrassing (removal of loose material) and surface cleaning, which can expose fresh layers of fabric to new cycles of decay (Odgers and Henry 2012). Removal of hard pointing mortar can damage the ariss (edge) of a stone and widen the joint, increasing the risk of moisture penetration. It is important to weigh up the immediate intervention with any long-term benefit mortar repair can provide. For vulnerable, valuable masonry and in a new era of changing climate, this may require a reappraisal of the complex, dynamic relationship between conservation values and the physics of decay.

Since the 1970s there has been a revival in the use of lime mortars for conservation. However, there are knowledge gaps and persistent misunderstandings as to their correct application, particularly on vulnerable masonry. Whilst the potential damage caused by excessively strong, hydraulic lime mortars is well documented, imprecise specification or product description often results in the use of material which may be unsuitable (Torney et al. 2014; Fusade and Viles 2019). Furthermore, the properties of a non-hydraulic lime mortar are determined by a wide range of parameters during the production process (Elert et al. 2002). Recent studies advocate a return to traditional recipes and methods, such as hot lime mixes and wood ash additives (e.g. Forster 2004; Fusade et al. 2019b). As in other areas of architectural conservation, improvement of mortar design and application depends on a reciprocity between practice and research. Scientific study has focused on controlled laboratory experiments. These have included assessments of standards and their applicability to conservation practice, sampling strategies for the analysis of historic fabric and test-

wall simulations (e.g. Erkal and D'Ayala 2015; Fusade and Viles 2019; Fusade et al. 2019b). Inevitably, the emphasis of these studies is on one aspect of the complex set of interrelated challenges found at any historic site. Conducting science at world heritage sites such as the Tower of London provides an opportunity to investigate how the implementation of research-based protocol affects the management of vulnerable, valuable masonry. Recent best conservation practice on Reigate Stone masonry at the Tower of London has involved repointing with lime putty but has not in every case halted rapid decay.

The objective of this research is to establish and test a field protocol for assessing pointing mortar in highly vulnerable, historic masonry. The use of portable, accessible, non-destructive techniques (NDT) is explored in order to facilitate general practice. Recent re-pointing of the Wardrobe Tower, Tower of London provides an appropriate case study for this purpose. The specific research questions are:

- How can NDT best be used to determine the effect of pointing mortar on surrounding masonry?
- Is there a discernible difference between the performance of different pointing mortar recipes used in Reigate Stone conservation?
- Does pointing mortar constitute a measurable control on the decay of the Wardrobe Tower?

The wider aim is to investigate the complex relationship between pointing mortar and valuable masonry, inform debate on the extent to which repointing can be incorporated into sustainable conservation strategies and provide baselines for the potential improvement of recipes used on highly vulnerable building stones.

IV) 1.2. Site and methods

IV) 1.2.1. Wardrobe Tower

IV) 1.2.1.1. Construction and conservation

The Wardrobe Tower was selected for this study because it was recently repointed in accordance with accepted Reigate Stone conservation protocol, and because of a rich and relatively well documented history of past use and repair. It was built in 1190 as an annexe to the White Tower, directly on the remains of a Roman mural tower, with Reigate and Caen stone ashlar and a rubble core (Tatton-Brown 1991). Throughout the medieval and early modern period, a dense cluster of buildings grew around the White Tower (Figure IV.1a). Between 1879 and 1885 the south eastern annexe was removed in line with the stylistic notion of the era to restore the Tower to 'its original condition' (Compton 1881, p.283). Much of the Wardrobe Tower was destroyed until remnants of medieval and Roman masonry were uncovered and preserved. Its present-day condition is ruinous, with only a small area of the south facing elevation surviving. The Wardrobe Tower is especially important for its historical and evidential value, with strong links to both the Tower and the city present in its material record and its illustration of architectural function (Appendix B).

There is evidence of historic repair and conservation work in the material fabric and documentary history of the Wardrobe Tower (Figure IV.1b). Several stones exhibit decay features which clearly predate their current location, indicating recycling of material during the original construction or early repair of the tower. Historic records show work was carried out to the Wardrobe Tower in 1532 and 1673-42 (Parnell 1993). Repairs in 18th century red brick are also evident. Since its partial demolition in

the 1880s, remnants of a coarse render and a patchwork of pointing mortars suggest conservation work was carried out on several occasions. Records indicate 'lime-method' repairs were carried out in 1995 by St Cuthbert Conservation, London. In total at least four different historic pointing mortars are evident. These include sparse remnants of a lime putty mortar of likely medieval origin, a late 19th century Portland cement mortar that appears to have been used to consolidate and cap the masonry after its partial demolition, a cement-gauged lime mortar and a moderately hydraulic lime mortar both likely to date to the second half of the 20th century.

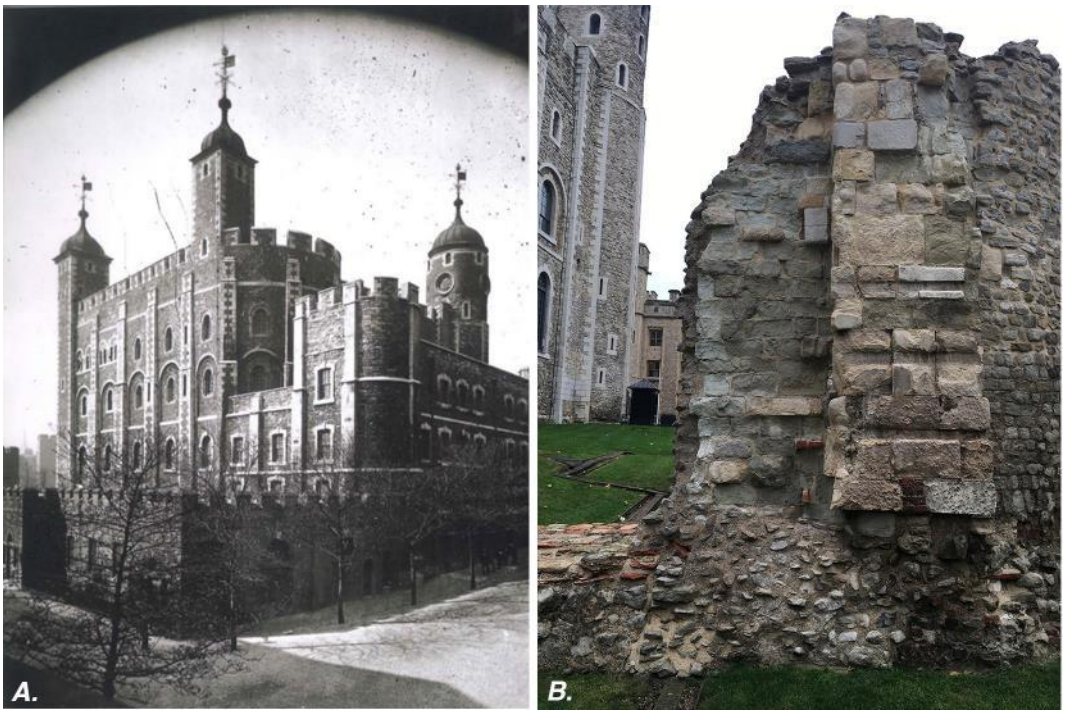


Figure IV.1: (A.) *Extent of late- and post-medieval auxiliary construction surrounding White Tower (main building) and Wardrobe Tower (foreground). Photo from south-east c.1870 (HRP archives).* ***(B.)*** *Present-day condition of Wardrobe Tower, following 2017 conservation work, viewed from south. Photo November 2018 (Authors own).*

In April/ May 2017 conservation work was commissioned by Historic Royal Palaces (HRP) and carried out by Carden & Godfrey Architects in line with the protocol adopted at HRP sites and elsewhere, focusing on cleaning of the masonry, removal of damaging materials, mechanical consolidation and sensitive lime mortar repair.

Ashlar masonry was subjected to careful soft brushing to remove any exfoliated fragments or flaking surface crusts. Most of the remaining coarse render was removed at this stage. This was followed by variable pressure steam cleaning of all surfaces. Selective depointing was performed to 50-75% of ashlar masonry, focussing on the removal of proud mortar around eroded stone and hard cement mortar. Loosened masonry was re-bedded where possible; tile supports and stainless-steel pins were added if structurally necessary. Repointing was performed with a lime putty mortar mixed from 1 part mature fat lime putty (Singleton Birch), 2.5 parts sand and 0.5 parts grit (up to 4 mm). For the purposes of this study, two areas of approx. 1 m^2 paired across a section of the wall were repointed with a moderately hydraulic natural hydraulic lime mortar (NHL 3.5) (Singleton Birch) using the same mixing proportions.

IV) 1.2.1.2. Present condition

An initial assessment of the Wardrobe Tower was conducted between March and May 2017. The objective was to identify Reigate Stone locations and define and determine relative condition, identify pointing mortar types and locations, and assess the immediate impact of conservation work. Whilst there are isolated Reigate Stone blocks spread across the monument, large areas of Reigate masonry are restricted to the following locations (Figure IV.2):

- The entire western flank of south facing ashlar masonry. The upper part of this area was more extensively repointed in 2017; the historic pointing mortar appears to be mainly the moderately hydraulic lime mortar, believed to date to the 1995 work.

- An area of ashlar interspaced with brick courses at the upper eastern flank of north facing masonry. This area was almost entirely repointed in 2017, and it includes the area repointed with NHL.
- A large area of ashlar and rubble interspaced with brick courses and other stone types, covering the upper half of the central and western parts of north facing masonry. This area was only partially repointed in 2017 and contains a patchwork of historic pointing mortars.

Different patterns of Reigate Stone decay are evident, including cracking, flaking, powdering and discolouration, alongside different rates of material loss. There is evidence of widespread salt contamination. All Reigate masonry shows signs of decay, however there is no immediately clear correlation between rates or patterns of decay and exposure, aspect, height or material context. The 2017 work removed large areas of proud mortar. In some cases, larger fragments of stone were removed along edges, leading to a widening of mortar joints. Despite removal of friable material, the surface of many stones still displayed signs of flaking or powdering; efflorescence was visible across many stones, particularly on freshly exposed surfaces. Isolated proud or poorly bonded mortar joints remain. Whilst the hardest, cementitious pointing mortars are now limited to just a few areas of Reigate masonry, they continue to dominate other parts of the structure, including the cap, the exposed rubble core at the outer flanks and the rubble batter at the base of the masonry. The findings of this survey were used to define areas of interest for the ongoing surveys and establish baselines for assessing ongoing decay.

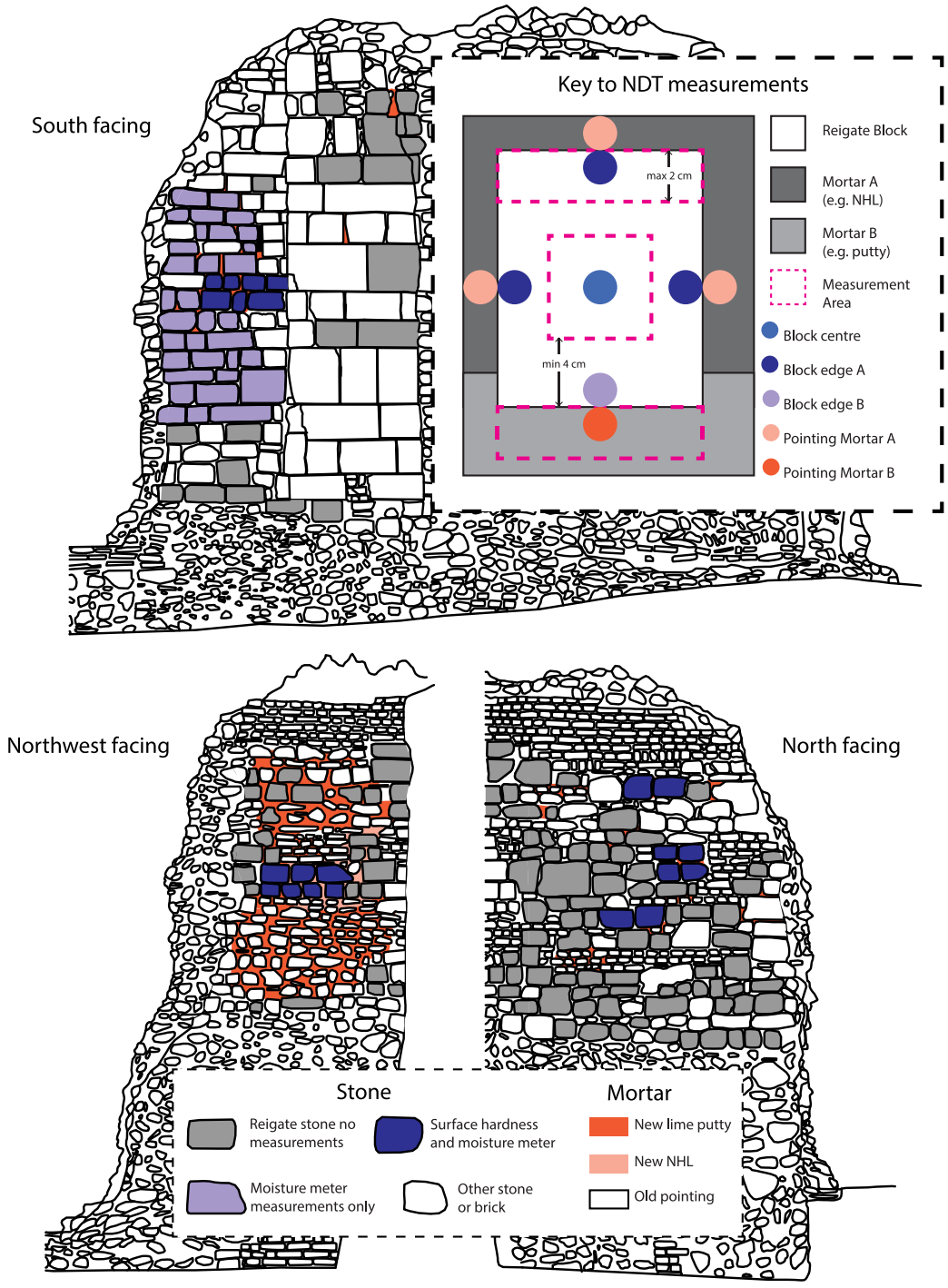


Figure IV.2: *Schematic views of Wardrobe Tower showing distribution of Reigate Stone and areas of NDT measurements in field surveys. Inset shows methodology of NDT measurements (used on dark blue blocks), with dotted squares describing regions in which joint, block edge and block centre measurements were taken. Between 1 and 8 measurements were taken for each circle, depending on survey date and device used.*

IV) 1.2.2. Non-destructive Testing (NDT)

IV) 1.2.2.1. Field survey methodology

Five detailed surveys using on-site NDT were conducted over a two-year period at the Wardrobe Tower, Tower of London. The surveys were conducted in November 2017, May 2018, August 2018, January 2019 and September/ October 2019. Survey dates were planned to acquire data during different environmental conditions. The aim was to assess the role of pointing mortar in the decay of Reigate Stone masonry, by correlating moisture dynamics with different mortar types. 29 Reigate Stone blocks spread across the main Reigate masonry areas were selected for surveying, to reflect the following variables (Figure IV.2):

- Type and condition of pointing mortar. Condition was initially determined based on bond, width and profile. Type was defined as one of three categories:
    - New lime putty mortar used in April 2017 conservation.
    - New NHL applied to test area in April 2017.
    - Old pointing mortar. In order to avoid misidentification, no further subdivision was applied to this type. Old pointing mortars included in the survey areas were independently analysed and determined to represent moderately to eminently hydraulic lime mortars.
- Contextual factors, including aspect, height and adjacent masonry.

A meteorological station (Vaisala, Finland) positioned on site recorded ambient temperature and relative humidity (RH), as well as rainfall, solar radiation, wind direction and speed over the two-year period. These data were used to construct wetting and drying profiles for the time period prior to each survey (Table IV.1).

Non-destructive techniques (NDT) were used to investigate surface hardness (SH) and moisture content (MC), in order to monitor seasonal change in response to environmental variations across repeat surveys and total change across the two-year period. Point measurements were taken at the centres and edges of individual blocks and along adjacent mortar joints (Figure IV.2 inset). Table IV.1 provides a full break-down of survey techniques and areas across the separate surveys.

Two hand-held capacitance moisture meters (T610, Trotec, Germany and CEM, Shenzhen Everbest Machinery, China) were used to investigate drying rates under different conditions[6]. Capacitance moisture meters provide a reference value for MC based on the dielectric constant of a material (Camuffo and Bertolin 2012). This can make comparisons between different materials, or even different areas of inhomogeneous material, difficult. Capacitance meters are also affected by salts, but not as strongly as conductivity meters (Wilhelm et al. 2016a). Whilst an imprecise method of measuring absolute MC, they have been shown to be effective at determining relative, spatial and temporal moisture distribution on the same material. Whilst microwave based non-invasive measurement methods may be more reliable, capacitance devices were chosen because they are cheaper and more widely available and offer a more immediate benefit to the development of practical frameworks. Field surveys were conducted 24-48 h after rainfall in order to investigate drying rates under different environmental conditions.

[6] It was necessary to use different devices due to instrument availability within the timeframes in which surveys were possible at the Tower of London.

Dates	Summary of environ. conditions	Moisture meter							Equotip										
		Areas	*Used for*	*Total n (blocks)*	*Stone n*	*Mortar n*			*Areas*	*Used for*	*Total n (blocks)*	*Stone n*					*Mortar n*		
												By type				*By aspect*				
						NHL	*Putty*	*Old*				*Centre*	*NHL*	*Putty*	*Old*	*N*	*S*	*NHL*	*Putty*	*Old*
14. - 16.11. 2017	Prolonged wetting and poor drying	S.1; N.1; NW.1	Calibration	122 (18)	90	10	8	14	S.1; N.1; NW.1	Calibration; ANOVA	710 (18)	90	70	135	155	280	170	50	85	125
3. - 4.05. 2018	Prolonged wetting and good drying	S.1; N.1; N.2; N.3; NW.1	Calibration; Spatial distribution (micro)	396 (15)	221	21	74	80	N.1; N.2; N.3	Calibration	494 (10)	110	n.a.	224	160	494	n.a.	n.a.		
12. - 13.08. 2018	Rapid, heavy wetting and good drying	S.1; S.2; N.1; NW.1	Calibration; Spatial distribution (micro and macro)	606 (34)	397	51	87	71	S.1; N.1; NW.1	Calibration; ANOVA; Spatial distribution	1410 (21)	174	162	264	270	570	300	126	228	186
20. - 22.01 2019	Mild wetting and poor drying	S.1; S.2; N.1; N.2; N.3; NW.1	Calibration; Spatial distribution (micro and macro)	555 (35)	372	36	57	90	S.1; N.1; N.2; N.3; NW.1	Calibration; ANOVA; Spatial distribution	1009 (22)	129	123	173	221	436	210	72	112	179
30.09-2.10 2019	Recent, mild wetting	S.2	Spatial distribution (macro)	52 (17)	52	n.a.			Not used		n.a.									

Table IV.1: *Summary of field surveys, showing date, wetting and drying scenario, areas surveyed, techniques used, types of analysis performed on data, and number of measurements made. Also includes distribution of measurements according to spatial and material variables.*

SH was measured across three different surveys using an Equotip rebound hammer (Equotip 550 and Equotip Piccolo, Proceq, Switzerland). The single impact method was used to determine mean values for each point with at least six scattered readings per point, which translated to 30 readings per block. SH has been shown to provide a useful proxy for a range of different rock properties (Wilhelm et al. 2016b; Desarnaud et al. 2019). These include porosity, strength, MC and surface change. Laboratory tests on Reigate Stone found that SH was sensitive to MC, however physical characteristics of the stone such as porosity and mineralogy were a greater determiner. A range of interdependent factors are likely to influence Equotip measurements in-situ; they can provide a useful measure of condition. With careful interpretation, it is possible to infer relative change to Reigate Stone MC in field surveys.

Individual blocks and Reigate masonry areas were photographically documented across separate surveys in order to assess visual indicators of decay. A USB microscope (Dino-Lite Edge AM7915MZT, AnMo Electronics, Taiwan) was used to further investigate areas of interest.

IV) 1.2.2.2. Calibration of NDT

Laboratory tests were performed using the two capacitance moisture meters on two large blocks of Reigate Stone from different sources in order to calibrate measurements and enable a better interpretation of results of the field surveys. The blocks were oven dried, weighed, fully saturated and re-weighed in order to determine saturated MC gravimetrically. The blocks were stored in stable environmental conditions and reweighed at daily intervals to determine a saturation coefficient. Six readings were taken with each capacitance meter and a

spectrophotometer (CM-700d, Konica Minolta, Japan), with readings taken from the same area after each weighing.

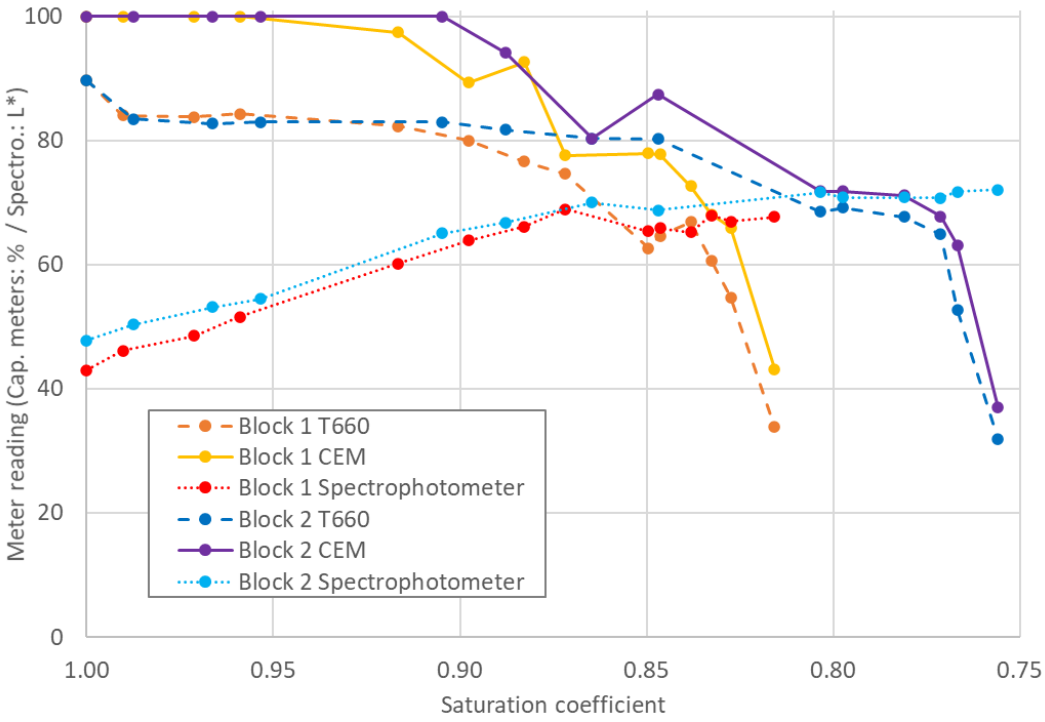


Figure IV.3: *Results of laboratory calibration of capacitance moisture meters on two large blocks of Reigate Stone from different sources (approx. 200x150x100 mm). Moisture meter readings decrease in steps as blocks dry out. Near maximum readings approximately correspond to above 90% saturation, during which time surface colour progressively lightens. As surface colour stabilises, moisture meter readings decrease more noticeably.*

Figure IV.3 shows the result of the moisture meter calibrations. The response of both devices to different levels of saturation is broadly comparable, with high or maximum readings corresponding to a saturation coefficient of above 0.9 and readings then decreasing in two steps, with notable differences between the two blocks. The range of saturation levels in which moisture meter values remain high and stable corresponds well with a progressive lightening of surface colour; the range in which moisture meter values decrease corresponds to more stable surface colour. The stabilisation in surface colour is likely to indicate a transition from the first drying phase to the second drying phase (Scheffler and Plagge 2005). These results suggest

that the moisture meters are both broadly comparable, and capable of identifying relative changes during the drying of non-saturated Reigate Stone. However, discrete values are not comparable across the devices or necessarily across different Reigate Stone blocks, and the meters are less capable of differentiating MC above approximately 85% saturation. Based on these results, moisture meter measurements made during the field surveys were sorted into three groups, representing maximum values (saturated or close to saturation), high values (wetter) and low values (drier).

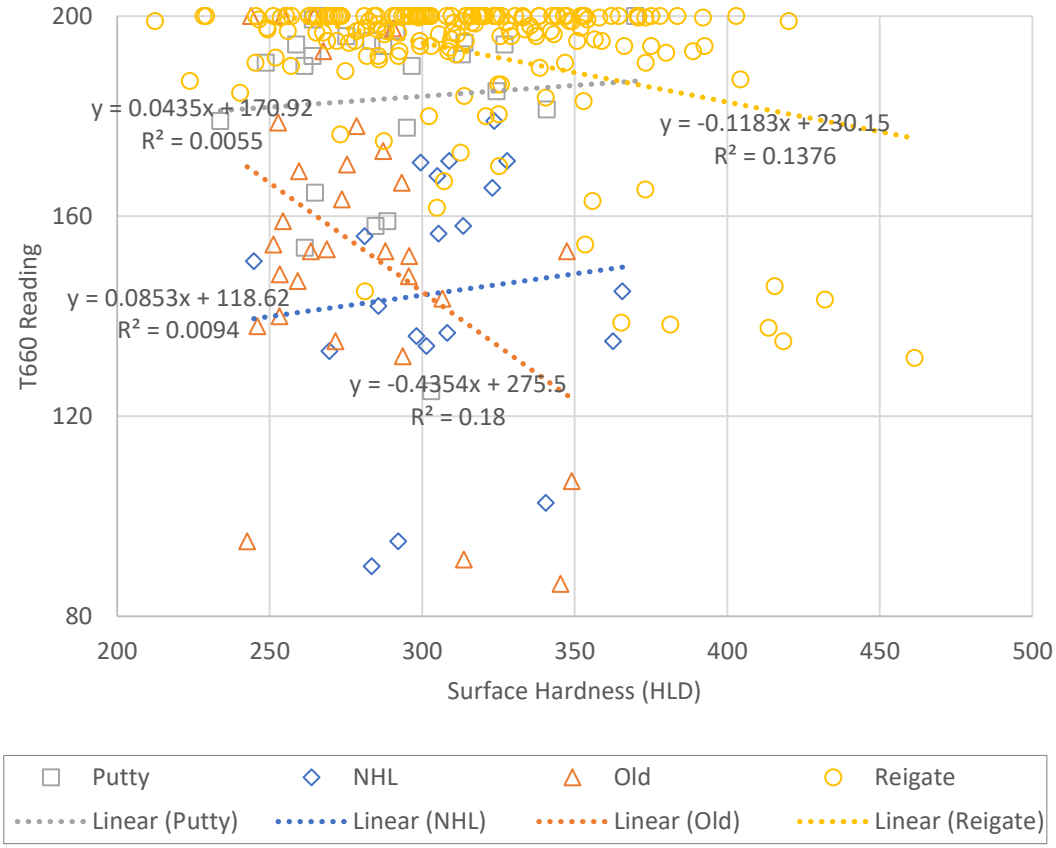


Figure IV.4: *Correlation between T660 and Equotip readings on different materials across two separate surveys. Whilst there is no clear correlation, the distribution of measurements on Reigate Stone suggests the Equotip may provide a better indication of moisture content at higher saturation.*

Equotip measurements have been shown to be affected by MC, with higher MC resulting in lower SH on tested sandstone (Desarnaud et al. 2019). The correlation

between SH and capacitance measurements taken at the Wardrobe Tower was investigated in order to aid the ongoing interpretation of results. Figure IV.4 plots mean SH against T660 moisture meter readings taken at individual points on different materials across two separate field surveys (November 2017 and January 2018). There is no good correlation between SH and moisture meter readings in any single material measured in this study. Whilst this implies that differences in SH reflect factors other than MC, it may also in part indicate that the capacitance readings are themselves not an accurate measure of absolute MC. This is apparent in the distribution of Reigate Stone measurements, with maximum T660 readings registered in many blocks and corresponding to a range of SH values. The laboratory test suggests that maximum capacitance meter readings do not necessarily equate to full saturation. Changes in SH are likely to reflect several parameters including inherent physical variations and uneven salt distribution, as well as MC. However, as MC approaches saturation and all else being equal, SH may in fact provide a more precise measure of relative change than the capacitance meters.

Equotip measurements taken on Reigate Stone are also prone to a disproportionally high number of error readings. In the field, this was particularly found to be the case on the frequently powdering and flaking surfaces; up to four out of five readings returned errors on some surfaces. Measurements below 200 HLD were omitted from the results as likely to have been made on unstable surface.

IV) 1.2.2.3. Survey conditions

Table IV.1 summarises the environmental conditions that characterised the field surveys. The individual surveys present a range of wetting and drying scenarios with

which to assess relative change in the properties of the masonry, as measured using the NDT methods. They also serve to highlight the variety of decay mechanisms affecting the Wardrobe Tower, including heavy driving rain, prolonged deep wetting and fluctuating surface conditions.

The weeks leading up to the November 2017 survey were characterised by temperatures around 10° C and repeated rainfall with light wind, including a series of heavy spells on the 10th and 11th, in which a total of 18 mm fell (peaking at 8 mm in one hour). During the survey from 14th to 16th November average solar radiation was 100-150 W/m^2.

The weeks leading up to the May 2018 survey were characterised by prolonged rainfall, relative humidity (RH) above 70% and temperatures around 10° C. The last rain event before the survey was a heavy, wind driven spell in which 5 mm fell in 5 hours on 2nd May, with wind direction varying from S to NWW at speeds of up to 5 m/s. Immediately prior to and during the survey on 3rd and 4th May, RH fell below 70%, daytime temperature rose to 20° C, with average solar radiation of 500-600 W/m^2.

In the weeks leading up to the August 2018 survey RH was mostly under 80%, daytime temperatures were between 20° and 30° C and there was no rainfall. There was heavy, wind-driven rain on 9th and 10th August, with 25 mm falling in a series of spells with SSW wind direction (peaking at 8.5 mm in 20 minutes with wind speeds of 6.5 m/s). Immediately prior to and during on 12th and 13th August the survey daytime temperature remained at 18° C with average solar radiation of 250-300 W/m^2.

RH was mostly above 70% and temperatures below 10 C in the weeks leading up to and during the January 2019 survey. There was little rainfall, with 2 mm falling on 16th

and 17th January in a series of light spells. During the survey from 20th to 22nd January, average solar radiation was 150-250 W/m^2.

The weeks leading up to the October 2019 survey were characterised by temperatures between 15 and 20 C, variable RH and occasional light showers. There were several light rainspells on the first two day of the survey from 30th September to 2nd October 2019, with varying wind direction and speed up to 5 m/s.

IV) 1.3. Results and Discussion

IV) 1.3.1. Overview

The following section presents and interprets the results of the field surveys and assesses the role of pointing mortar in moisture regulation at the Wardrobe Tower. It begins by analysing the capacitance meter measurements at two scales. The local distribution of measurements at the stone scale across three separate surveys is analysed. This evaluates variation within individual stones which may be attributable to micro-contextual features, such as the width or type of mortar joint. The general distribution of measurements across three separate surveys is then analysed at the monument scale, in order to identify patterns relating to macro-contextual influence, such as the height of the masonry. Following on from this, the Equotip measurements are also investigated at two scales. The general distribution of all measurements across three surveys is statistically analysed using a series of factorial ANOVA (Analysis of variance) tests. This evaluates the significance of varying weather, aspect and mortar type in the overall distribution of surface hardness measurements. The local distribution of surface hardness at the stone scale across two separate surveys is then investigated, in order to more closely assess the role of micro-contextual factors.

Finally, the photographic documentation is used to examine visual indicators of the micro- and macro-contextual determiners identified using the NDT.

IV) 1.3.2. Capacitance meter measurements

IV) 1.3.2.1. Local distribution

Figure IV.5 maps the distribution of moisture meter readings across different survey dates and areas, along with type and size of mortar joint and adjacent masonry. Three readings at each centre and edge of individual Reigate blocks are averaged and resulting values are sorted into groups. The May 2018, August 2018 and January 2019 surveys were selected as being reflective of three different wetting and drying scenarios. Edge readings are interpreted as being more likely to be affected by adjacent pointing mortar, due to differences in localised moisture ingress or subsequent poulticing effects. This produces few patterns which directly relate moisture distribution or drying rates across Reigate Stone surfaces to pointing mortar type. However, the overall effect of the different wetting and drying scenarios can be observed, and the influence of exposure and material context is apparent.

The good drying conditions in May 2018 and August 2018 are reflected in relatively drier points across several stones in all areas. During the May 2018 survey, some south and north-west facing points appear saturated by the recent wind-driven rain spell; north facing stones, which were sheltered from wind, appear relatively drier. The heavy wind-driven rain spells prior to the August 2018 survey appear to have fully saturated much of the masonry; run-off or deep penetration may be responsible for the wetting of areas not directly exposed to the wind. There is some apparent effect of pointing mortar on drying rates across these surveys. There is some indication that

the lime putty mortar is a more effective poultice than the NHL or historic mortars. Approximately half of dry edges are adjacent to lime putty mortars (16 out of 33). There are indications that mortar width also plays a role; in several cases, stones surrounded by both narrow and wide joints have relatively drier edges towards the narrow joints. However, there are also cases in which the opposite is true and cases in which relatively drier edges are adjacent to historic mortar joints. Rather than directly recording an effect of pointing mortar, these results may be reflecting physical differences within individual stones, such as variations in porosity or level of salt contamination. Material context also appears to play a role. Most stone edges directly below overhanging, denser stone or brick are saturated (8 out of 11).

The high ambient relative humidity during the January 2019 survey is reflected in relatively higher, more homogeneous readings across all areas. The recent, light, southerly wind-driven rain spell can explain higher moisture content (MC) across south facing stones. There is little differentiation of MC in relation to type, width or position of mortar joint. The overall distribution of moisture across all surveys is best explained by exposure to seasonal or diurnal weather patterns; however, individual observations do suggest that pointing mortar can play a subordinate role in regulating the drying of Reigate Stone.

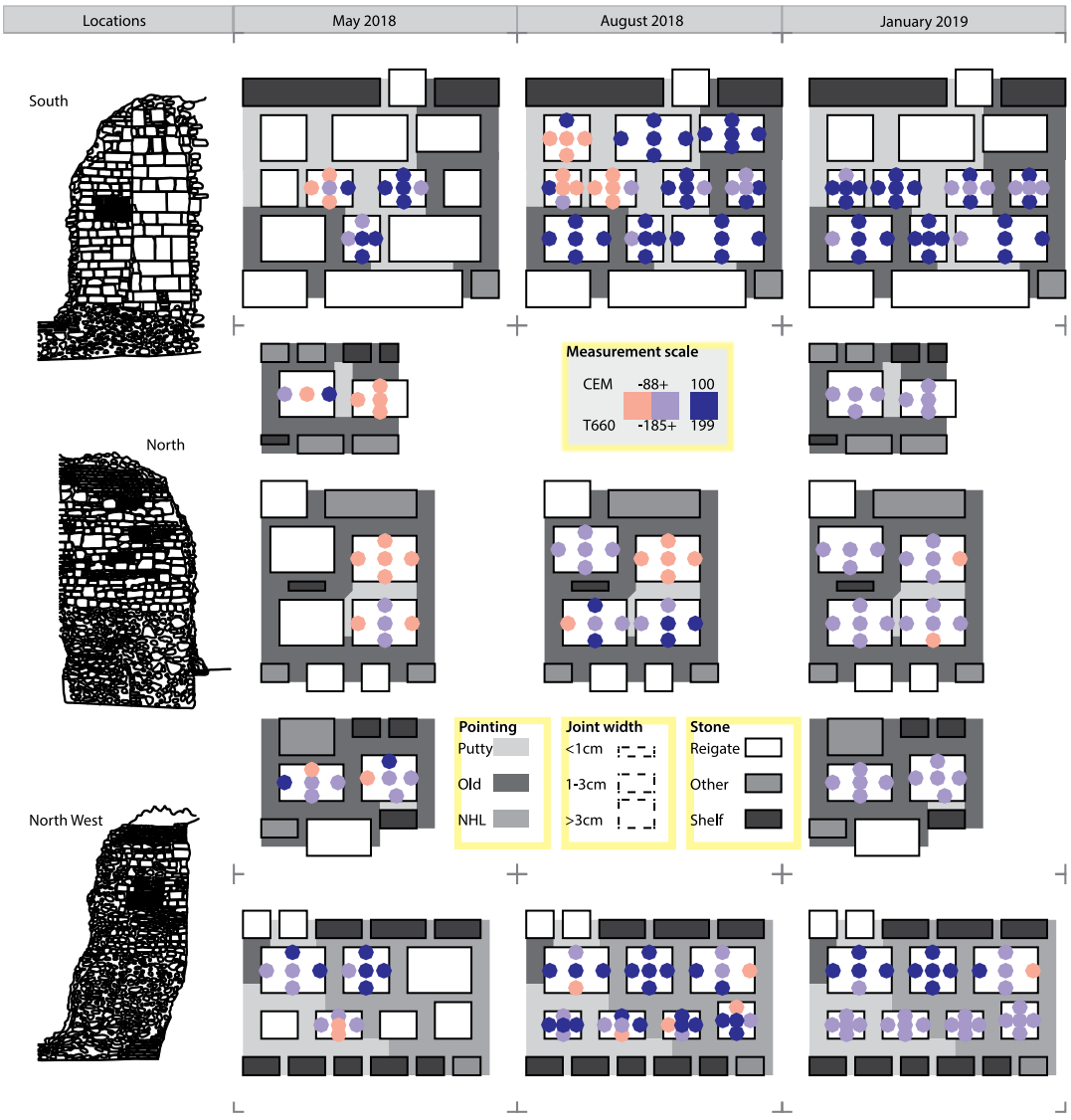


Figure IV.5: *Distribution of moisture meter readings at individual stone scale across three separate surveys, showing low, high and maximum readings for individual Reigate block edges and centres (three measurements per point). The measurements can provide some indication of differential drying following the recent wetting of the masonry prior to each survey. There is some indication that block edges adjacent to putty mortar are drying more rapidly, but no clear pattern according to mortar type or mortar width. Ambient climate and exposure (both aspect and micro-contextual shelter) provide better indicators.*

IV) 1.3.2.2. General distribution

In Figure IV.6, moisture meter measurements from the August 2018, January 2019 and October 2019 surveys are mapped across a larger area of the south facing Reigate Stone ashlar masonry. Results are again grouped into maximum, high and low values. This provides more insight into the effect of seasonal and diurnal weather patterns at the monument scale. During the August 2018 survey, the central core of the masonry is saturated, whilst the outer and upper areas are drier. Run-off from the recent heavy rainfall is likely to have caused a band of increased wetness in high-lying masonry. During the January 2019 survey, lower evaporation rates have resulted in an expansion of the saturated core. In October 2019, the core has receded once again, and recent rainfall is again evident in the upper band. This persistently saturated core is clearly visible as an area of darker stone besides the buttress framed by a band of lighter stone along the outer edge (Figure IV.1b). It can be explained by the greater volume of masonry in this central part retaining moisture, which as well as due to rain penetration may be the result of rising damp and the high hygroscopicity of Reigate Stone, particularly if contaminated with salts. Observing moisture distribution at the monument scale serves to further highlight some of the factors which can outweigh the role of pointing mortar or individual mortar joints.

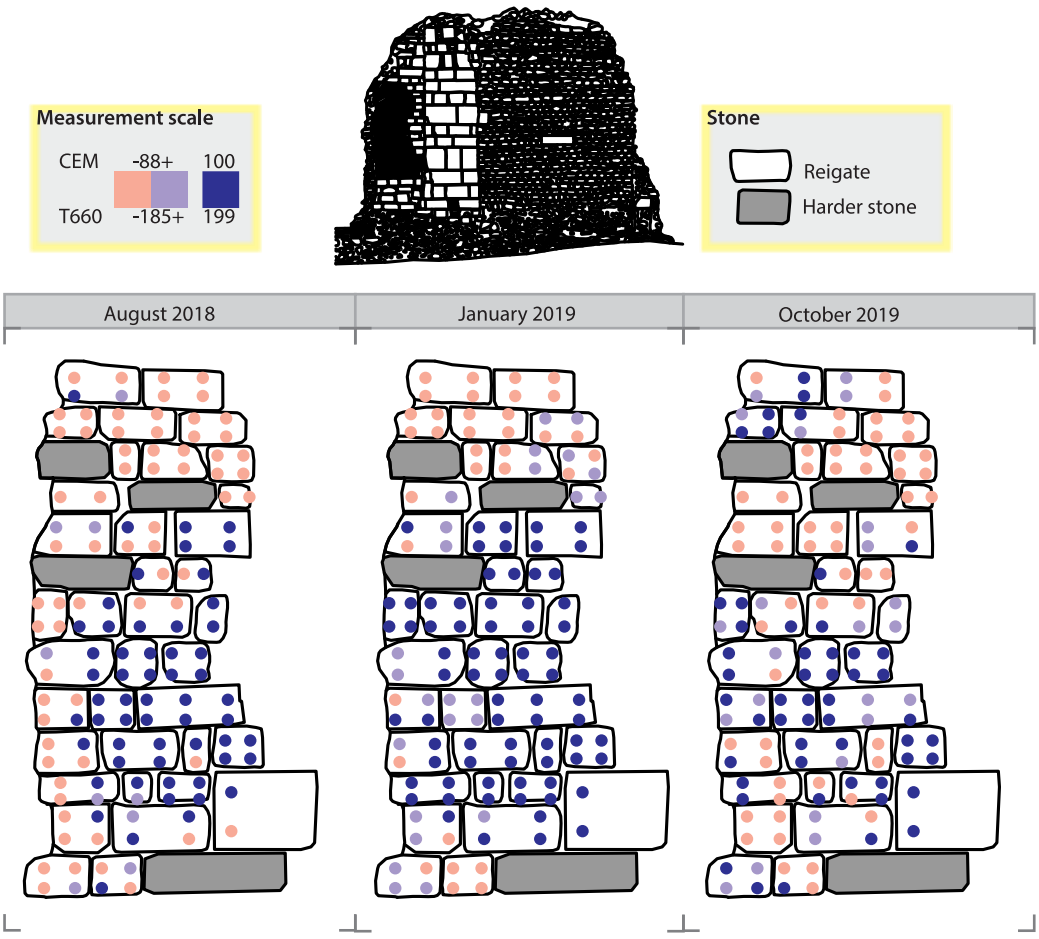


Figure IV.6: *Distribution of moisture meter readings at monument scale across three separate surveys, showing low, high and maximum readings for individual Reigate blocks (one measurement per point). The variation across different seasons highlights the role of macro-scale dynamics, which are likely to outweigh the influence of pointing mortar at individual joints. In particular, the effect of good drying conditions along the edge of the monument (August 2018), and recent rainfall along the top of the monument (October 209) can be seen.*

IV) 1.3.3. Surface hardness measurements

IV) 1.3.3.1. General distribution

A series of factorial ANOVA tests were performed (using the aov. function in R) on Reigate Stone surface hardness (SH) data to establish the effect of specific variables on the overall distribution of SH. The objective was to investigate the significance of pointing mortar in determining the SH of adjacent block edges. ANOVA is a statistical model used to analyse group means within a sample. Factorial ANOVA compares means across two or more independent groups, known as factors. As well as

identifying variations in the means of individual factors, factorial ANOVA can be used to identify interactions between factors. The test can therefore evaluate which factor variables or interaction of factor variables significantly affects a response variable (in this case SH); a significant variable or interaction is described as a main effect. The factor variables were defined as:

- Date of survey. SH data from the November 2017, August 2018 and January 2019 surveys was included to be representative of different wetting and drying scenarios.
- Aspect. The data was grouped into north and south, to evaluate the role of exposure across the different wetting and drying scenarios.
- Mortar. The data was grouped into all measurements taken along edges adjoining specific mortar types (i.e. putty, NHL or old mortar) or at the centres of all blocks.
- Block. The data was grouped into all measurements taken on a single block.

To enable a meaningful comparison, only measurements taken at the same locations (i.e. on the same block) across all three surveys were included in the dataset. This resulted in over 1500 observations, with approximately 500 individual measurements per survey date across 18 separate blocks, and at least 5 measurements per point (i.e. individual block edge or centre) during each survey.

Results of the ANOVA tests are summarised in Table IV.2. An initial test performed on the full dataset (i.e. accounting for each factor and every interaction of multiple factors) did not pass the Levene's test for homogeneity of variance ($p<0.05$). This indicates that the variance of the different factors is significantly different, and the

group means should not be compared using ANOVA. This could be due to the small number of observations per group at factor interactions involving individual points (e.g. comparing 5 measurements at an individual block edge during one survey with 5 measurements of a different block edge at another survey). A second factorial ANOVA was performed without block being defined as a factor. This passed the Levene's Test ($p=0.26$) and the normality assumption. It returned main effects for all the remaining factors (aspect, mortar and date) but no interactions between factors. The Tukey test was performed to find significantly different means within the individual factors. It identified significant differences between NHL edges and block centres ($p=0.003$), old edges and NHL edges ($p=0.03$) and putty edges and NHL edges ($p=0.001$), and also between the January 2019 survey and the other surveys ($p=0$ for both) (but not between November and August). The dataset was reorganised into subsets taken during each individual survey (November 2017, August 2018 and January 2019) and three further factorial ANOVAs were performed (one per set), with block initially reintroduced as a factor. The August 2018 dataset passed the Levene's test ($p=0.12$) and the normality assumption. The January 2019 dataset failed the Levene's test ($p=0.005$); block was removed, and it passed ($p=0.3$). The November 2017 dataset was considered borderline on the Levene's test ($p=0.02$); block was retained as a factor to enable a more detailed evaluation of its varying effect. Aspect was a main effect across all surveys, but less significant in January 2019. In November 2017 and August 2018 block was also a main effects and there was a significant interaction between mortar and block. Only in August 2018 was mortar type by itself a significant determiner of variation in SH. For this subset, the Tukey test identified differences

between NHL edges and block centres, NHL edges and putty edges (both p=0.001),and NHL edges and old edges (p=0.003).

	All dates			November 2017			August 2018			January 2019		
	Df	F value	Pr (>F)	Df	F value	Pr (>F)	Df	F value	Pr (>F)	Df	F value	Pr (>F)
Date	2	46.32	**< 2 x10^{-16}**	-	-	-	-	-	-	-	-	-
Aspect	1	40.43	**2.67 x10^{-10}**	1	14	**0.0002**	1	30.34	**5.50 x10^{-08}**	1	9.18	*0.0026*
Mortar	3	6.28	**0.0003**	3	0.8	0.5	3	6.72	**0.0002**	3	1.13	0.34
Block*	-	-	-	16	4.65	**1.38 x10^{-08}****	16	6.1	**1.50 x10^{-12}**	-	-	-
Date: Aspect	2	1.08	0.34	-	-	-	-	-	-	-	-	-
Date: Mortar	6	0.87	0.52	-	-	-	-	-	-	-	-	-
Aspect: Mortar	2	1.07	0.34	2	0.71	0.49	2	0.5	0.61	2	0.66	0.52
Mortar: Block*	-	-	-	24	2.26	**0.0007****	24	2.7	**2.92 x10^{-05}**	-	-	-
Date: Aspect: Mortar	4	1.2	0.31	-	-	-	-	-	-	-	-	-
Residuals	1560			377			572			531		

Table IV.2: *Results of factorial ANOVA tests on surface hardness data, evaluating effect of individual variables and interactions of variables on distribution of surface hardness measurements. Main effects (p<0.001) in bold, less significant effects (p<0.01) in italics. *Combined dataset and January2019 dataset did not pass Levene's test (p>0.05) with block data. **November 2017 dataset scored p=0.02 on Levene's test. Block data was retained to enable better comparison of overall results.*

The results of the factorial ANOVAs suggest SH is most affected by weather (date of survey) and exposure (aspect); however, adjacent pointing mortar can play a role. The significance of mortar type is linked to seasonal changes, possibly due to different moisture regimes. During the most extreme wetting and drying scenario (August 2018), adjacent mortar type alone was significant in determining SH. Whilst mortar type was not a significant determiner overall following recent wetting and poor drying in November 2017, it was a good indicator of variation within individual blocks. There was no variation according to mortar type in January 2019, reflecting the lack of recent wetting and more even moisture distribution. When mortar type was significant, NHL edges were responsible for the variation; in particular, there were

differences between putty edges and NHL edges. The model has been able to identify some regulatory function in different types of pointing mortar, and their role in controlling changes in SH at different blocks across different moisture regimes. However, caution is required because of underlying differences in the SH of individual blocks and other factors which were not considered, such as size of block or salt content.

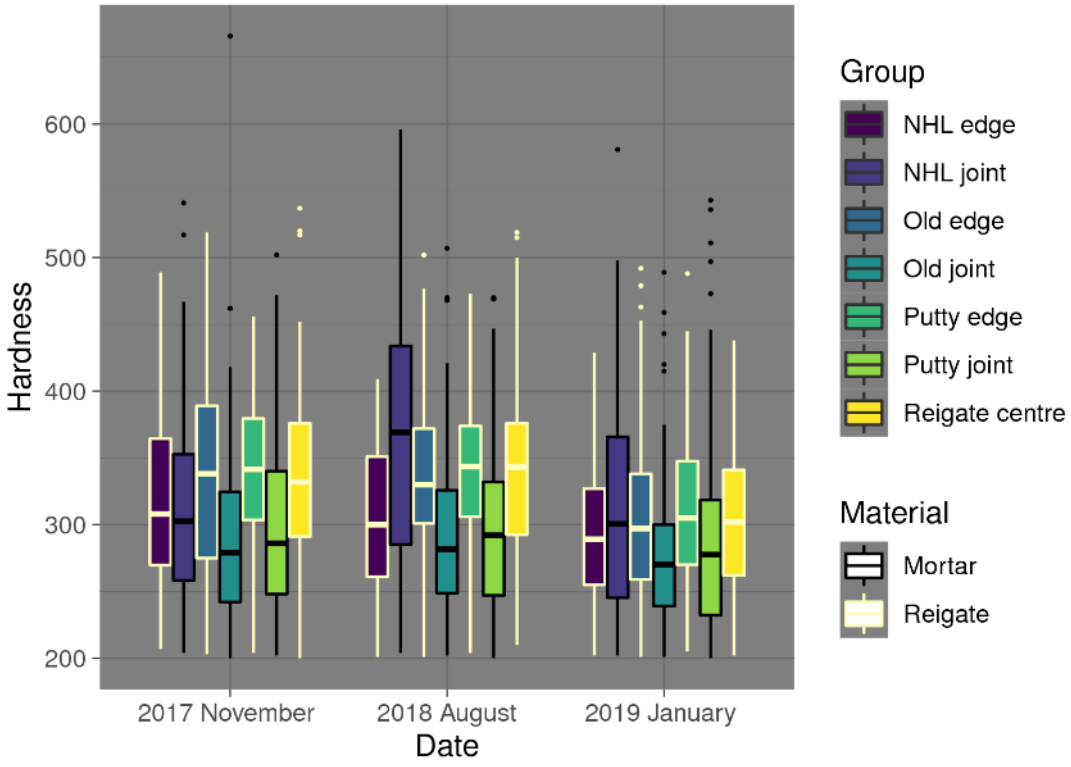


Figure IV.7: *Boxplot of surface hardness measurements across three separate surveys, organised by mortar type and adjacent Reigate block edge (or centre). Central line represents mean value, upper and lower extents of box represent interquartile range (IQR: all measurements within 25th and 75th percentile). Whiskers represent maximum range of measurements less than 1.5*IQR, outliers are single measurements more than 1.5*IQR. Only includes data used in ANOVA tests (i.e. measurements taken from same locations across all three surveys).*

Having established that pointing mortar can in some circumstances be significant in determining the SH of adjacent block edges, the results were more closely examined. This aimed to identify patterns in changing SH across the separate surveys which

explain the variation between NHL edges and other Reigate material groups. In Figure IV.7, the distribution of individual SH measurements made on different material groups (block centres and edges, and different mortar joints) is plotted across separate surveys. In putty and old mortar joints, the Nov 2017 and Aug 2018 surveys return a similar distribution, whilst values are lower in Jan 2019. This pattern is reflected along putty and old mortar block edges, and at the centre of Reigate blocks. These results imply block centres and block edges adjacent to putty or old mortar joints are responding similarly to parameters affecting SH, and a similar response is taking place within the mortar joints themselves. Along NHL joints, SH is higher in Aug 2018 than in Nov 2017 or Jan 2019; along corresponding block edges SH decreases across all three surveys. The response pattern of this mortar type is different to that of its adjacent block edges. If these changes can be partially attributed to moisture, this could imply that putty and historic mortar joints are performing a suitable role in moisture regulation, by maintaining the block edges in a comparable state to the block centre. The general distribution of SH values at Reigate centres, putty edges and old edges, and their adjacent mortar joints reflects ambient conditions, with lower values recorded during the wetter, winter survey. The increase in NHL SH from Nov 2017 to Aug 2018 could reflect ongoing setting of the hydraulic binder (Fusade and Viles 2019). The corresponding lower SH along NHL block edges may indicate a higher MC, resulting from the denser NHL performing a less effective poulticing.

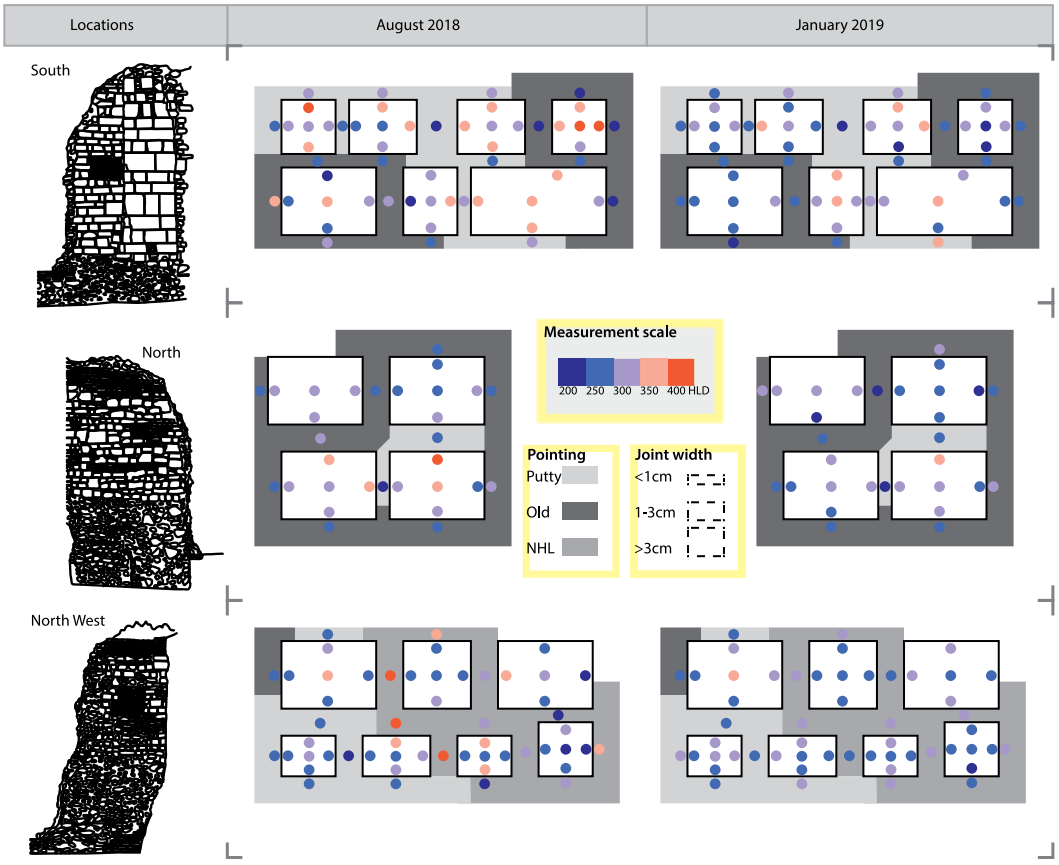


Figure IV.8: *Distribution of surface hardness measurements at individual stone scale across two separate surveys, showing HLD for individual Reigate block edges and centres (5-8 measurements per point). Local variation across individual blocks irrespective of adjacent mortar type, and lack of clear patterns according to mortar type, demonstrate the caution is necessary when interpreting the generalised findings made in the ANOVA test.*

IV) 1.3.3.2. Local distribution

As indicated by the significance of exposure and individual block properties in the ANOVA, any findings according to generalised material group should be treated with caution and cross examined for the effect of local factors. In Figure IV.8, SH readings are mapped to locate changes across repeat surveys and localise patterns of change according to mortar type or material context. The August 2018 surveys and January 2019 surveys were chosen to provide the most variable set of results. Inhomogeneities in the distribution of NHL SH during the August 2018 survey reflect the overall increase in SH variance and suggest the rate of hardening or subsequent

weathering is susceptible to micro contextual variations such as the width and exposure of the joint. The relatively greater homogeneity of lime putty is visible both across separate surveys and separate areas during the same survey. The results provide further evidence that the lime putty mortar forms reliably soft, elastic joints, but only very few of the measured joints appear to be dangerously hard; these are almost exclusively new NHL joints, with even old, cementitious mortars appearing to have softened. Only in a small number of blocks is SH stable across the entire surface of the stone and both surveys. In most blocks, variation is recorded between separate edges and separate surveys. The distribution of SH values across individual blocks and different aspects suggests that generalised conclusions on the role of pointing mortar type lose some significance when considering local factors.

IV) 1.3.4. Material context

The effect of over 2 years of rainfall and water run-off is clearly visible when comparing photos of the upper masonry taken after the Spring 2017 conservation with those taken in October 2019 (Figure IV.9). Water run-off channels are visible as areas of algal growth, often following recessed masonry and wide mortar joints. In some cases, these channels also define areas of more advanced decay, which affect stones that lie several meters below the masonry cap. Comparing these with photos taken before 2017 conservation work suggests that the channels have re-formed and continue to concentrate water run-off along the same routes as previously.



Figure IV.9: *Parts of north facing masonry included in Wardrobe Tower photographed shortly before 2017 conservation* ***(below)*** *and in October 2019* ***(above)****. Water run-off channels have reformed, their location corresponds to past decay features.*



Figure IV.10: *Selection of individual Reigate Stone blocks photographed in November 2017 and October 2019. Some signs of ongoing decay can be associated with inadequate pointing (e.g. WRD16 and WRD14), some can be associated with exposure and macro-context (e.g. WRD03, WRD40, WRD54). There are few examples of ongoing decay which can be more closely associated with type of pointing mortar (WRD24, WRD30).*

Topographical features can also be seen to limit the effect of good pointing and augment the effects of inadequate pointing. The wide joint to the left of WRD3 defines a gully which functions as a bottleneck for one of the main run-off channels along the north-west facing masonry (Figures IV.9 and IV.10). It is likely to be saturated following any heavy rainfall and unable to effectively poultice moisture from the adjacent stone, resulting in increased decay along this edge. WRD14 lies on one of the main run-off channels along north facing masonry. There is evidence of ongoing decay across the entire surface; however, the poorly bonded old mortar joints along the top and left edges have not functioned as a poultice, resulting in a build-up of moisture and algal growth. The joints at the right and bottom edge, whilst in the same cementitious mortar, have remained in bond and appear to perform a more effective poultice. WRD40 also sits along a run-off channel. Besides algal growth on the centre

of the stone surface, there appears to have been greater ongoing decay at the intersection between the upper edge and the more permanently saturated portion of the joint, which may not have been able to regulate moisture properly, despite being in repointed lime putty. Observing these changes since the most recent cycle of conservation indicates that water run-off is key to the emergence of decay pathways in highly exposed masonry. Measures to help reduce run-off include replacing hard, cementitious masonry caps with soft, vegetation caps (Hanssen and Viles 2014).

There are few visual indications conclusively linking pointing mortar with ongoing decay. Generally, these can be attributed more to contextual or morphological features than mortar type. WRD16 for example, which was in a highly decayed condition in November 2017, has continued to decay rapidly despite repointing with lime putty (Figure IV.10). This is likely to be due to the wide joint below the stone forming a shelf, which may result in moisture pooling and inhibit the poulticing function of the mortar. Decay to the exposed right edge of WRD54 could be explained by the lack of adjacent mortar and poulticing effect, with moisture fluctuations and salt crystallisation taking place at the surface of the arris. In cases where decay appears to progress more rapidly along NHL or old, cementitious joints, such as WRD24 (left edge) and WRD30 (top left), pre-existing decay features appear to have played a role. USB microscopy identified emergent biological growth on several poorly bonded joints, new NHL joints (Figure IV.11). However, there were both well and poorly bonded joints along putty, NHL and historic pointing, indicating that soft or hard mortar types are not a guarantee for good or poor long-term bonds respectively. The timescale of the project and lack of uniformity between initial conditions along block edges makes it hard to assess the impact of pointing mortar on specific stones.

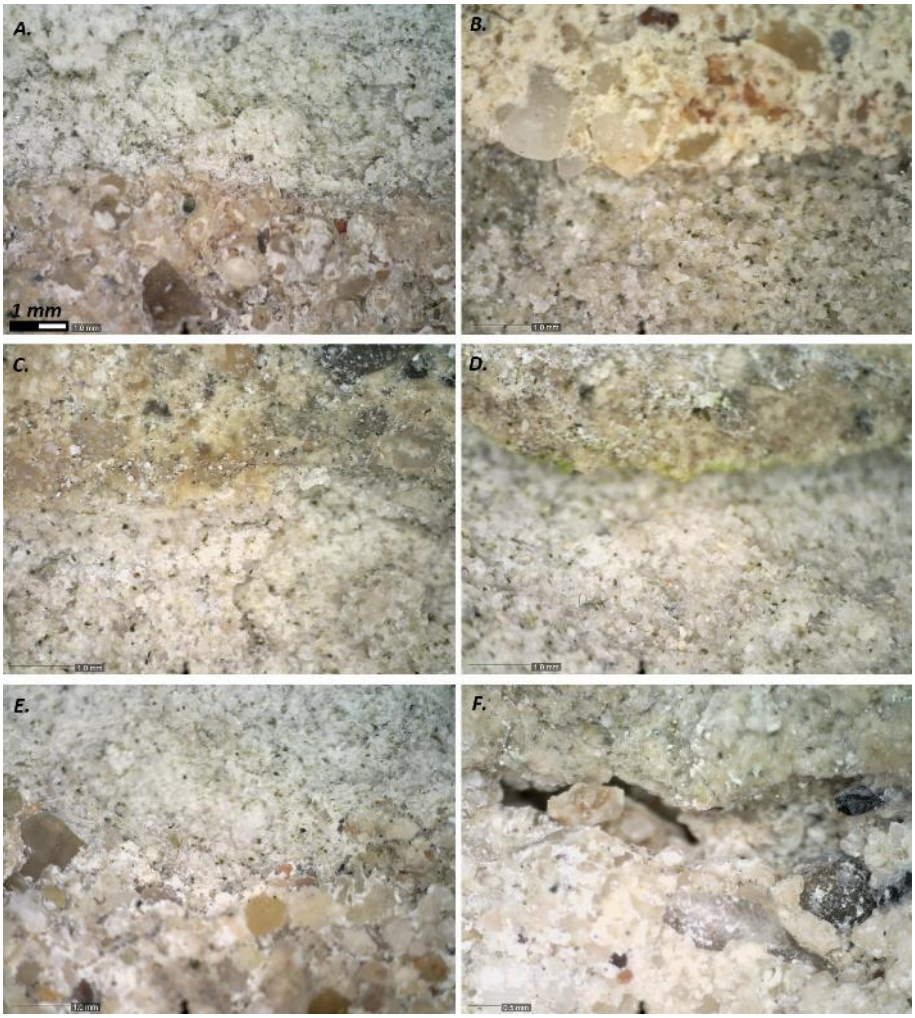


Figure IV.11: *USB micrographs showing:* ***(A.)*** *well bonded putty mortar (WRD12);* ***(B.)*** *poorly bonded putty mortar (WRD27);* ***(C.)*** *well bonded NHL mortar (WRD29);* ***(D.)*** *poorly bonded NHL mortar with algal growth (WRD30);* ***(E.)*** *well bonded old mortar (WRD53);* ***(F.)*** *and poorly bonded old mortar (WRD39). (scale bar 1mm)*

IV) 1.3.5. Synthesis

This research set out to establish how best NDT can be used to determine the effect of pointing mortar on surrounding masonry. It aimed to establish whether pointing mortar constituted a measurable control on the decay of the Wardrobe Tower; specifically, whether there was a discernible difference between the NHL and lime putty recipes used in 2017 conservation work. The results provide some evidence that pointing mortar does have a measurable effect on adjacent block edges. In particular, ANOVA tests of surface hardness distribution according to different material

categories across different surveys suggest that when viewing the overall distribution of measurements, harder, new NHL joints trap moisture, whilst softer putty joints enable a response that is similar to the centre of Reigate Stone blocks. Old NHL pointing mortar performed similarly to new putty. Viewed locally, there are some indications of better moisture regulation along putty joints; however, these are outweighed by a range of other contextual factors, such as the location of an individual block in relation to the monument, local topography forming shelves or shelters, and the width of the joint.

The approach used here involved the long-term data collection across multiple surveys using several NDT. Constraints of working in the field at a large heritage site were a complicating factor on gathering comparable data across multiple surveys; however, whilst the NDT did not establish clear patterns according to pointing mortar type when the data were viewed spatially, this approach enabled a multi-scale evaluation of the data. Combining local observations made with relatively small datasets with the statistical analysis of larger datasets, whilst incorporating more traditional surveying techniques such as photographic documentation, identified controlling effects on the decay of the Wardrobe Tower. These included moisture regulation at the monument scale, most notably water run-off during heavy rainfall, which compounds efforts to adequately re-point the masonry and contributes to ongoing cycles of decay. The use of portable, relatively accessible devices demonstrated here provides a model for incorporating such techniques into regular maintenance schedules. Alongside existing approaches, such as test-walls and laboratory experiments, this can monitor the role of pointing mortar within the wider system dynamics of masonry decay.

IV) 1.4. Conclusions

Non-destructively assessing the impact of pointing mortar on historic masonry in-situ is highly complex, due to factors such as site logistics, inherent variability in the masonry system and the limitations of NDT. However, whilst controlled 'test-wall' experiments may be more suited to identifying specific issues pertaining to the mortar itself, these sorts of tests can identify additional parameters that must be considered during the design of holistic conservation strategies. This study has highlighted the importance of micro-contextual features, such as overhangs or gullies. These could be incorporated in future 'test-wall' experiments.

Whilst the correct functioning of pointing mortar can mitigate stone decay, repointing can only be one aspect of a holistic preventive conservation strategy. Additional measures are necessary not only to protect vulnerable building stones, but also to enable correct functioning of the pointing mortar. In unsuitable conditions, even suitable mortar recipes can contribute to, rather than arrest stone decay. This can include the channelling or pooling of moisture along joints during rainfall, or the rapid decay of the mortar, which can result in inadequate bonding with the stone or chemical leaching.

Regular mortar maintenance and repointing schedules are necessary long-term stone conservation strategies, however the immediate impact on vulnerable building stones of depointing hard mortars needs to be considered alongside the mid-term benefits of repointing according to current best practice. In some cases, initially inappropriate mortar recipes may have weathered sympathetically. In other cases, repointing a damaged area of masonry without mitigating against ongoing decay mechanisms such

as driving rain, may drive a cycle of decline by which weakened stone arrises are removed, mortar joints widen, and moisture penetration increases. Decisions on the specific repointing of a mortar joint must be taken on a case-by-case basis.

Sustainable repointing requires tailored strategies, with several different approaches adopted for the individual joints of a single building. The results of this project suggest that, whilst ongoing work is needed to better define a specific protocol, accessible NDT used across repeat surveys can provide a meaningful assessment of the relationship between stone blocks and adjacent mortar joints. Localised findings using handheld devices will be most effective in conjunction with more traditional surveying methods, such as photographic documentation and holistic, structural appraisal. Taken together, the techniques presented here can provide detailed long-term monitoring of moisture regulation in masonry structures, which could be used to validate computational modelling and support targeted decision making in repointing and general conservation strategies.

In situations where repointing is appropriate and once measures have been taken to protect the correct functioning of the pointing mortar, the evidence presented here suggests that the choice of mortar recipe is important in Reigate Stone conservation. Whilst conclusions are difficult in the 2-year timeframe of the project, there are early indications that the lime putty mortar is weathering more sympathetically and drawing moisture more effectively than the NHL. However, ongoing rapid decay following repointing with lime putty, noted at the Wardrobe Tower and elsewhere, suggests that further improvements in recipe and technique could be of benefit.

IV) 2. Modelling the effect of repointing and galleting on moisture dynamics in historic masonry at the Wardrobe Tower, Tower of London[7]

Abstract

The moisture regulation of different pointing mortar scenarios in highly porous masonry systems is simulated based on a study of the Wardrobe Tower, Tower of London. This is part of a wider research project on the conservation of Reigate Stone, a vulnerable historic building stone. The effects of hydraulic lime and lime putty pointing on narrow and wide mortar joints are compared in a simplified WUFI model of Reigate Stone masonry. The effects of proud mortar and galleting are also investigated. The results indicate that the type of pointing mortar is subordinate to the width of the joint in the wetting and drying of masonry. Moisture storage in non-hydraulic lime may initially increase the risk of prolonged wetting in wider joints. However, proud mortar, which is more likely to form in harder lime with a hydraulic set, further increases the risk of moisture ingress. Galleting reduces moisture ingress. The effects are greatly amplified by exposure. This supports findings made during field surveys of the Wardrobe Tower, which indicated that contextual factors outweigh the impact of repointing with different types of mortar. The implication of these findings is that alongside repointing with suitable mortar, additional measures may be necessary for the conservation of vulnerable building stones.

[7] As accepted in February 2020, after review, to the published proceedings of the *Stone2020 Congress* in Goettingen, September 2020, with only minor changes to style and format.

IV) 2.1. Introduction

There is ongoing concern about repointing protocol in vulnerable historic masonry, such as Reigate Stone. Whilst there is clear evidence of the damage caused by cementitious pointing mortars, the most suitable recipes and approaches for treating this highly porous, clay-bearing stone remain less clear. Reigate Stone was used widely in Medieval London, but much has been replaced or is an advanced state of decay (Sanderson and Garner 2001). Causes of decay are poorly understood and past conservation strategies have had mixed success (see Chapter III.2).

A recent study of the Wardrobe Tower highlighted several of the challenges facing the ongoing role of repointing in the conservation of Reigate Stone (see Chapter IV.1). The ruined Wardrobe Tower is one of the oldest parts of the Tower of London, with Reigate Stone masonry dating to the 12th century, most of it in an advanced state of decay (Figure IV.12). At least four different historic pointing mortars were identified, ranging from a medieval lime mortar to a pure Portland Cement mortar, with 20th century hydraulic lime mortars of varying strength in between. There are isolated examples of galleted joints. Galleting is a technique in which small pieces of material, such as flint or tiles, are inserted in to mortar joints (Henry and Stewart 2011). It was widely used in South East England and is generally regarded as a method for reducing shrinkage, however its impact on moisture regulation has had little attention. Galleting was frequently performed with flint; however, there are examples of tile galleting, such as here at the Wardrobe Tower.



Figure IV.12: (Top) *Decayed, south facing Reigate Stone masonry at the Wardrobe Tower, Tower of London and* ***(Bottom)*** *close up of north facing masonry, displaying a range of pointing mortar scenarios, including a joint galleted with a tile and proud standing mortar.*

The most recent conservation of the Wardrobe Tower was commissioned by Historic Royal Palaces and carried out by Carden & Godfrey Architects in spring 2017. It included the depointing of hard, proud standing mortar joints in areas of Reigate

Stone masonry. Repointing was done using a soft lime putty mortar. As part of the extended research project, one small area of Reigate masonry was repointed with a natural hydraulic lime (Singleton Birch NHL3.5), to enable a comparison of the effects of different mortars over the course of several years. In-situ tests were carried out using a range of non-destructive techniques across different drying regimes. The tests found some evidence that mortar type can play a role in the drying rates of adjacent stone edges. However, the effect of mortar type was outweighed by several other factors, most noticeably exposure to driving rain and solar radiation and proximity to material features which affected water run-off. There was also some evidence to suggest that joint width played a role in drying rates. Furthermore, there was some suggestion that initially inappropriate hydraulic lime mortars may have weathered over time to perform as well as the putty mortar considered current best practice.

Given the risk of a further widening of joints during the depointing of vulnerable building stones, the study recommended that further analysis of the interplay between, mortar type, joint width and Reigate Stone moisture dynamics was necessary to inform ongoing conservation strategy.

The aim of this paper is to build on Chapter IV.1, and investigate more closely the effect of different mortar types, joint widths and wetting/drying regimes on Reigate Stone moisture regulation by performing a hygro-thermal simulation of specific scenarios found at the Wardrobe Tower. The effect of galleting will also be investigated, as a potential technique to be incorporated in future repointing works.

IV) 2.2. Methodology

Different pointing mortar scenarios found at the Wardrobe Tower were modelled using the hygrothermal simulation tool WUFI 2D. WUFI 2D enables the calculation of transient, coupled, two-dimensional heat and moisture transport in multi-layer building components. A model was constructed in order to investigate the effect of mortar type and joint width on the wetting and drying of adjacent Reigate Stone edges and associated relative humidity (RH) fluctuations at the stone surface.

Parameter	Method	Number of specimens	Mean	Std Dev	Wardrobe Tower	Input
Bulk density (kg/m^3)	BS EN 772-4:1998	11	1600	93	1680	1650
Open Porosity (-)	BS EN 772-4:1998	11	0.347	0.028	0.377	0.365
Vapour Resistance (μ)	EN ISO 12572	3	9.6	0.3	n.a.	9.5
Reference Water Content (kg/m^3)	Sorption at 23 C 80% RH*	7	73.5	6.29	105	80
Absorption Coefficient ($kg/m^2\sqrt{s}$)	BS EN 1925:1999	11	0.09	0.03	0.11	0.1
Ultrasound pulse velocity (m/s)	BS EN 14579:2004	11	2083	263	1891	n.a.**

Table IV.3: *Methods and results of experimental programme to determine WUFI input data for Reigate Stone. When possible, experiments were also conducted on a single sample from the Wardrobe Tower and inputs were weighted slightly. *Wardrobe Tower sample measured at 20 C 90% RH **Pulse velocity used to approximate thermal conductivity.*

A simplified Reigate Stone dataset was built from the results of an experimental programme (Table IV.3). Experiments were conducted on samples of Reigate Stone from a variety of sources, including one gathered during 2017 conservation work at the Wardrobe Tower. The dataset made use of several approximation methods and reference values (Krus and Holm 1999). The measured open porosity was increased by 5% to approximate the total porosity. The difference between total porosity and

open porosity is likely to be small in Reigate Stone, due to the shape of the porous matrix (Sanderson and Garner 2001). The thermal conductivity was approximated from ultrasound pulse velocity measurements using charts in El Sayed and El Sayed (2019). The specific heat capacity and thermal conductivity supplements were estimated based on values for other highly porous stones in the WUFI database. In experiments which were possible with the Wardrobe Tower sample, input values were slightly weighted accordingly.

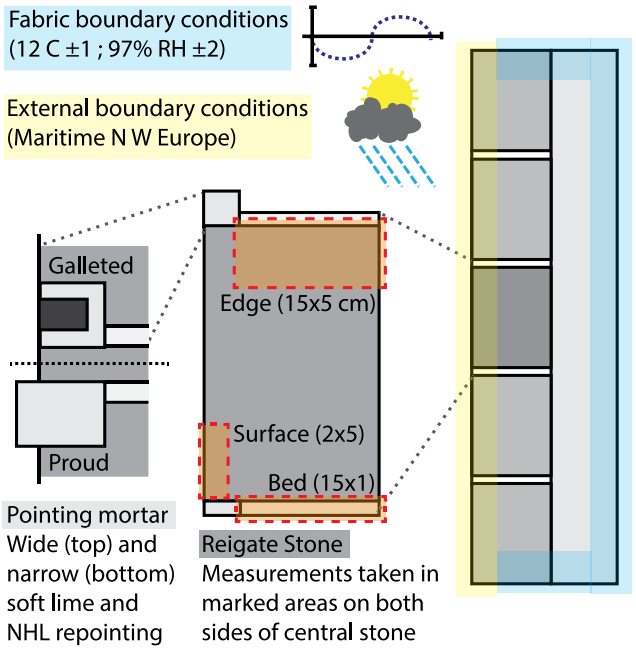


***Figure IV.13**: Schematic of WUFI model explaining different pointing scenarios and measurement areas.*

The Wardrobe Tower was modelled as a severely exposed, low wall subject to rain runoff. The climate was set to *Brussels*, which is the closest to London available in the WUFI database. The model was built to represent one section of a double leaf masonry construction with five 30 cm x 20 cm blocks of Reigate Stone separated by 1 cm of bedding mortar (Figure IV.13). Pointing was modelled as a plug of either 1 x 3 cm for narrow joints, or 4 x 4 cm for wide joints. Additional scenarios were modelled

for wide joints. Galleting was modelled as a 2 x 3 cm brick fragment in the centre of a wide joint. Proud mortar was modelled as a 1 cm protrusion beyond the face of the Reigate Stone face. The interior of the wall was modelled as a solid, 20 cm thick layer of *Cottaer Sandstone* (from *Fraunhofer IBP, Natural Stone* folder). This medium density sandstone was chosen to represent the mix of high-density rubble and inhomogeneous mortar likely to make up the core of the structure. Internal boundary conditions were modelled as low amplitude sine waves; however, output measurements were taken from the central stone in order to minimise their effect.

Mortars were chosen from those available in the WUFI material library to be representative of different types used at the Wardrobe Tower in 2017 and assessed during the field study. *Hydraulic Lime Mortar, coarse* and *Lime mortar, fine* (both from *University of Technology Vienna* folder) were selected to represent the NHL3.5 and lime putty pointing mortar respectively; *Lime mortar, fine* was also chosen to represent the bedding mortar.

A total of 8 runs were simulated: Narrow, wide and proud NHL joints facing south; narrow and wide putty joints facing south and north; and galleted putty joints facing south. The period of calculation was set to two years, with hourly time steps. Internal moisture contents of the materials in relation to external conditions had balanced by the end of the first year enabling comparison of moisture regulation patterns in different materials. Measurements were taken from the bedding mortar and adjacent stone edges, and at the stone surface (Figure IV.13).

IV) 2.3. Results

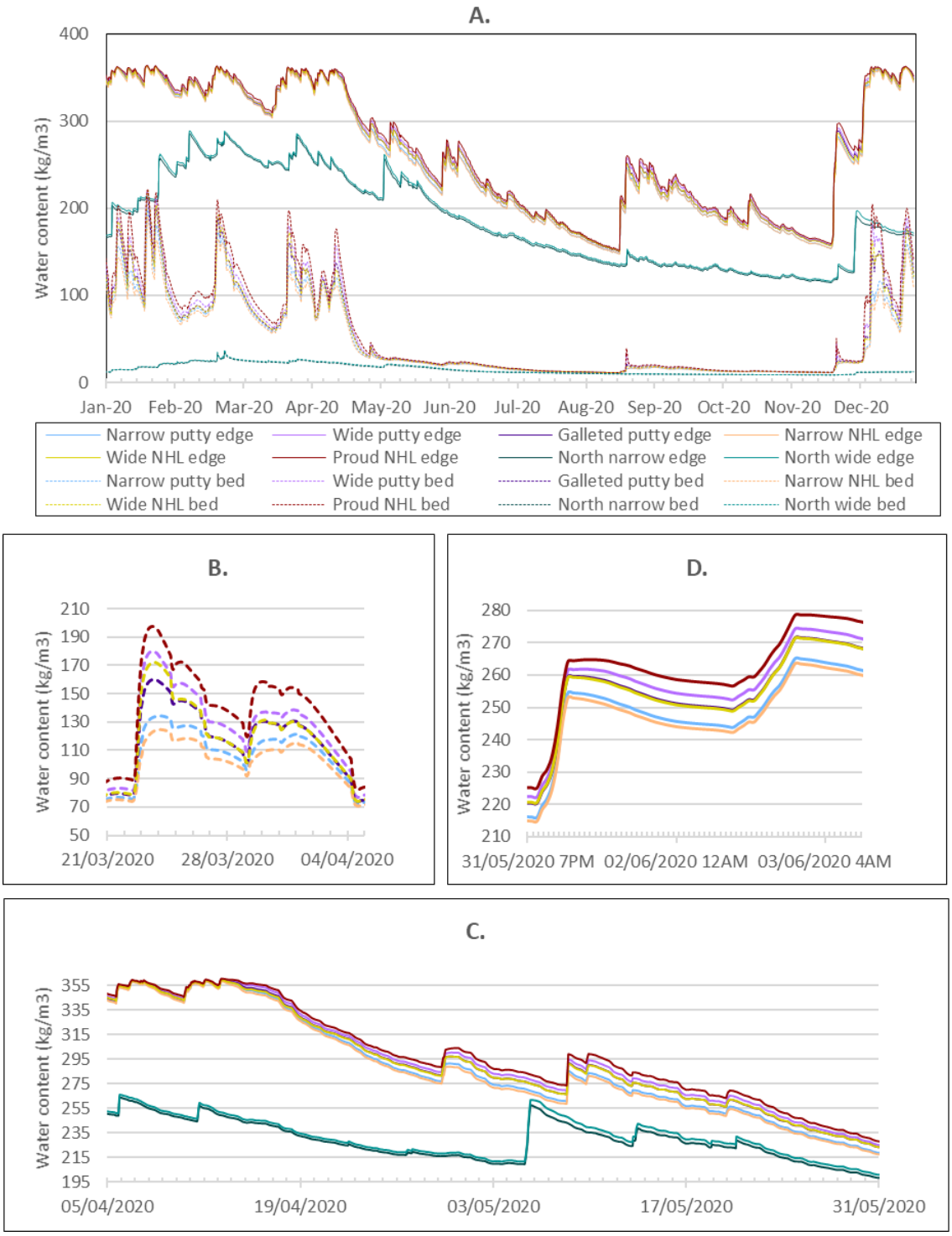


Figure IV.14: *Results of WUFI simulations, counter clockwise from top:* ***(A.)*** *Water content in stone edges and bedding mortar of different pointing mortar scenarios across second year of simulation.* ***(B.)*** *Closer view of fluctuations in bedding mortar across two-week period of heavy rainfall,* ***(C.)*** *gradual drying of stone edges across subsequent 8-week period, and* ***(D.)*** *rapid wetting of stone edges across time period investigated in Figure 15.*

Figure IV.14 plots water content in stone edges and mortar joints across a full year. In the bedding mortar, there is noticeable variation according to pointing mortar scenario. Besides clear variation according to aspect, it is also possible to distinguish patterns according to mortar width. Moisture ingress is higher in response to rainfall in wider joints. The different mortar types have slightly different wetting and drying patterns, which are more evident in the wider joints, however the effect of proud mortar or galleted joints on these patterns is greater than the effect of the material itself. In the stone's edges, there is very little variation according to mortar type or width. North facing edges remain noticeably drier throughout the year. Observing individual wetting and drying cycles in more detail indicates that variations according to mortar type reflect the moisture regulation patterns in the bedding mortar. During winter, fluctuations are much greater in the mortar, in summer, rapid wetting and slower drying becomes apparent in the stone.

Figure IV.15 compares the effects of intense rainfall on south facing stones with lime putty joints. Moisture ingress progresses most rapidly along mortar joints, particularly wider joints. Drying is slowest adjacent to mortar joints, with residual moisture collecting near wide joints. Galleting reduces these effects. Besides reducing joint width, the use of absorbent tile gallets provides a further moisture sink.

Figure IV.16 plots RH at stone surface across a full year (along a moving 48 h mean). There is little variation according to mortar type or width. Proud standing mortar decreases the lower boundary of RH by several %, increasing the risk of crystallisation for several common salts. In south facing stones, RH rarely drops beneath 80%; in north facing stones it fluctuates between 80% and 90% for much of the year.

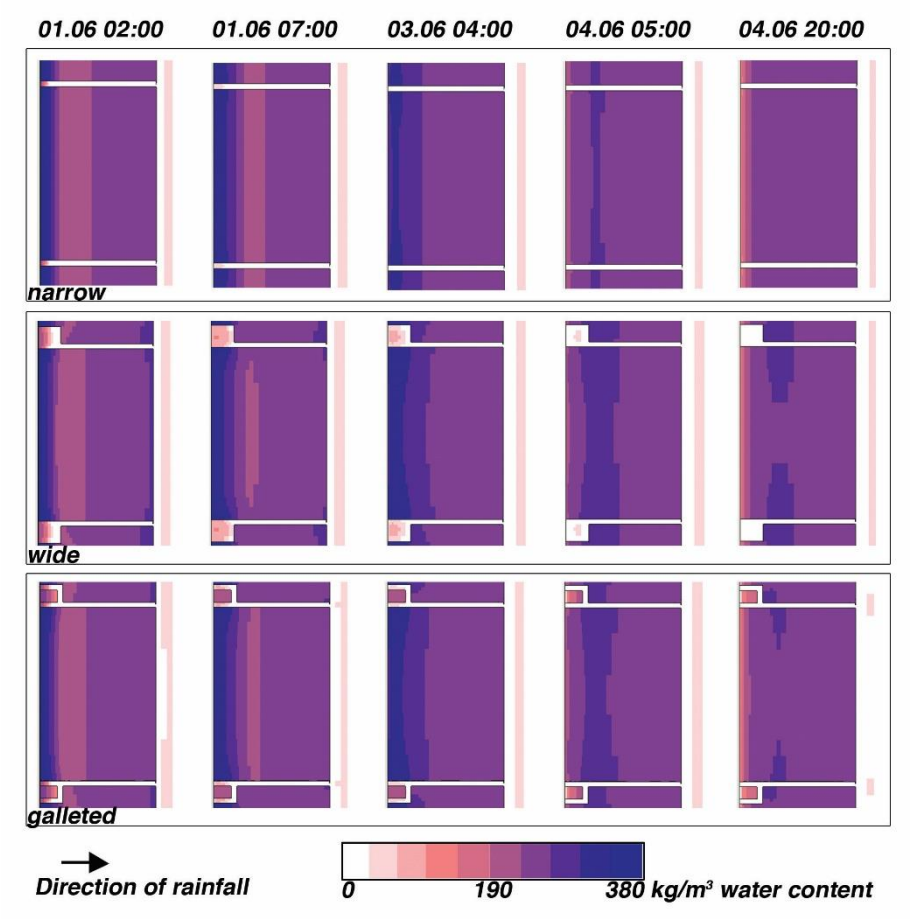


***Figure IV.15**: Dynamic moisture distribution in stones pointed with **(top)** narrow putty, **(centre)** wide putty and **(bottom)** galleted putty following driving rain spells beginning on 1st June.*

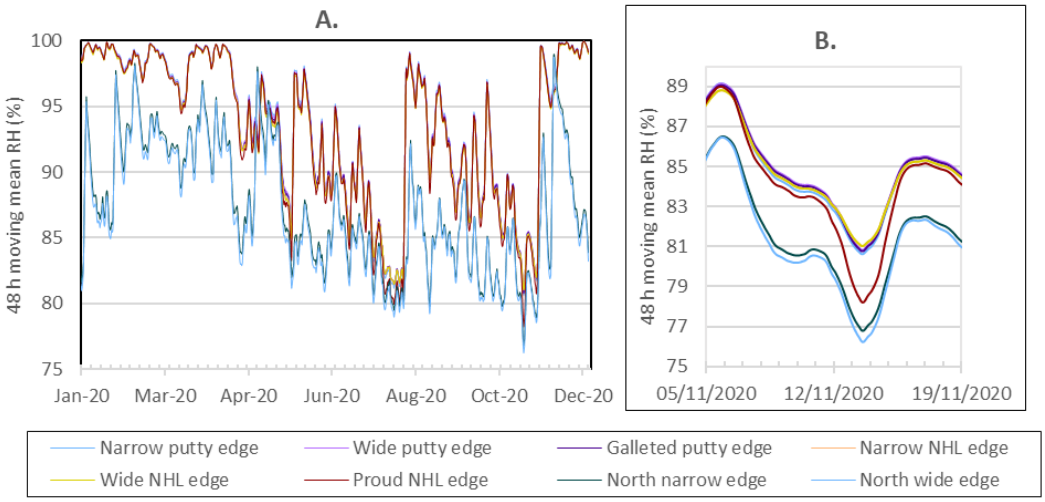


***Figure IV.16: (A.)** 48 hour moving average of relative humidity at stone surface during second year of simulation. **(B.)** Lowest recorded values, showing increased RH range in edges adjacent to proud standing mortar.*

IV) 2.4. Discussion

The results suggest that the impact on moisture regulation in a masonry system of the mortar recipe used in repointing can be subordinate to the exposure and width of the joint. This supports the findings made in Chapter IV.1, which indicated that contextual factors outweighed the importance of individual mortar joints. Furthermore, the hygrothermal simulations presented in this study imply that in certain scenarios softer, lime putty mortars can prolong deep wetting of the masonry. This is related to the moisture dependent liquid and gas transport properties of the materials used in this study, and their impact on wetting and drying cycles. The hydraulic pointing mortar is more resistant to water penetration and more effective at releasing moisture from the bedding mortar and the adjacent stone. In the context of the Wardrobe Tower, findings on mortar type should be treated with caution, as the materials used in this study were selected to compare typological opposites and are unlikely to be fully representative.

These findings should not be interpreted as a denial of the importance of repointing vulnerable historic masonry with suitably soft mortars. The damage caused by hard, cementitious mortars to soft building stones is well known (Wiggins 2017). The results presented here on the effect of proud mortar on moisture and RH regulation are an indication of the longer-term impact of harder mortar, which does not erode in step with adjacent stone. Instead, these findings should urge caution in ongoing conservation projects where repointing work is planned, particularly if mortar joints are wide or at risk of widening as a result of the work. The overall impact of different

pointing mortar options must be carefully weighed up against wider conservation needs.

When repointing of wide joints is necessary, galletting should be considered as an option for reducing moisture ingress. However, ongoing work is necessary to investigate more closely the full impact of this technique. Test walls could be built to investigate various pointing scenarios and contextual features and build on findings made on moisture regulation in less porous building stones (Fusade et al 2019).

Ongoing work can also develop a more detailed set of material parameters for future hygrothermal simulations. Most important would be a closer examination of the performance of Reigate Stone at high moisture content. The simulations imply the mortars used in the model are not effectively poulticing moisture from the stone. This reflects the approximation curves WUFI generates to calculate transport coefficients from limited input data (Krus and Holm 1999). Given their higher moisture storage capacity, precise data may be crucial to modelling the interactions between highly porous building stones and lime mortars. The high clay content of Reigate Stone is also likely to be significant for behaviour at higher moisture content (Stück et al. 2013).

Whilst the differences in moisture regulation identified in this model are small, they suggest that the cumulative effect of seasonal weather cycles can gradually result in divergence across historic masonry that displays a range of different mortar types and joint sizes. Prolonged, deep wetting of stone can be associated with a higher risk of decay due to factors such as binder leaching and clay mineral swelling. The choice of suitable pointing mortar alone may not be a sufficient conservation strategy for highly

porous, historic building stones. Exposed, vulnerable structures such as the Wardrobe Tower may require a range of different pointing mortar solutions.

IV) 2.5. Conclusions

The choice of mortar when repointing vulnerable historic masonry can only be one aspect of a holistic conservation strategy. In highly porous stones such as Reigate Stone, adequate moisture regulation in response to driving rain may not be possible using current recipes, unless additional protective measures are taken. In buildings with varied exposure and complex decay, such as the Wardrobe Tower, tailored recipes or techniques may be required in response to different scenarios. In some scenarios where mortar joints have widened, galleting may be an effective technique for mitigating prolonged, deep wetting. These findings, based on computational modelling, should be considered in the design of ongoing field and lab-based study of vulnerable building stones.

V. Environmental controls: Salt driven decay

"Only after dust settles on an object
do we begin to long for its lost splendour"

Celeste Olalquiaga, *Museum of dust* (2007)

The first section of this chapter is an unaltered version of a paper published, after review, in the conference proceedings of *Monuments in Monuments 2019* in Stirling, September 2019. The second section is an unaltered version of a paper submitted in April 2020 to the journal *Engineering Geology*. Both papers co-authored with H. Viles, C. Vlachou and I. Angus.

V) 1. Bellweathered: Reigate Stone decay mechanisms at the Bell Tower, Tower of London.[8]

Abstract

At the Bell Tower, Tower of London, Reigate Stone decay patterns can be associated with different internal locations. The decay phenomena are surveyed using non-destructive techniques, and the micro-climates of these locations are monitored over an 18-month period in order to associate specific environments with patterns of decay. Results are compatible with the hypothesis that distinct environmental mechanisms govern the emergence of powdering and flaking decay phenomena. Powdering is driven by deep wetting of the stone and a steady ambient climate; evaporation and salt crystallisation can take place at or near the stone surface. Flaking is driven by a dynamic moisture profile and ambient temperature cycles; salt crystallisation takes place beneath the stone surface. Identifying these controls with appropriate, low-impact methodologies is crucial to developing preventive conservation strategies.

[8] As published, after review, in the conference proceedings of *Monuments in Monuments 2019* in Stirling, September 2019, with minor changes to style and format.
https://www.engineshed.scot/publications/publication/?publicationId=400000d1-8cc4-46f9-8e4f-aabc00a954c1

V) 1.1. Introduction

Historic masonry is often at risk from severe deterioration. Centuries of weathering, pollution and inappropriate repair can result in lasting salt contamination and advanced stages of decay (Siegesmund and Snethlage 2011). Finely carved stone, usually in softer lithotypes, is both particularly vulnerable and culturally valuable. Reigate Stone was a principal freestone in medieval London (Tatton-Brown 2001). It is highly porous, weakly cemented and prone to rapid decay (Sanderson and Garner 2001). The precise mechanics of decay remain poorly understood. Different patterns and rates are evident in similar environments. Past treatments and pollutants complicate matters further. Understanding the relative importance of material, environmental and historical factors in ongoing decay is vital to improving the resilience of Reigate Stone masonry in the face of changing climate. The Bell Tower (Figure V.1), one of the oldest parts of the Tower of London, contains a large amount of primary masonry, including Reigate Stone exposed to a range of environments and treatments and displaying distinctive decay patterns. As such it can be a useful bellwether and case study for understanding decay in vulnerable historic masonry.

This paper presents results from an 18-month monitoring programme and non-destructive testing (NDT) protocol designed to characterise decay and investigate internal environmental conditions at different locations within the Bell Tower. The objective is to associate specific mechanisms with observable patterns of decay. Flaking and powdering have been identified as common Reigate Stone decay patterns (Sanderson and Garner 2001). There have been suggestions that these correspond to sheltered and exposed areas respectively, but many cases do not clearly fit this trend.



Figure V.1: *The 12th century Bell Tower from South East*

There has been no investigation into the mechanisms which drive the emergence and propagation of these distinct patterns; however, salts have been identified as a major cause of Reigate Stone decay in several studies at the Tower of London. Severe degradation in the Salt Tower is attributed to historical storage of saltpetre (KNO_3). The masonry was treated with a poultice in the 1970s (Bowley 1975). Decay is ongoing. Parts of the Wakefield Tower were found to be heavily salt contaminated in a study which proposed relative humidity (RH) regimes as a preventive conservation strategy (Price 1993). In a later study based on thermodynamic modelling, Price (2007) found that the proposed regimes would have been potentially damaging and suggests

alternative regimes[9]. This highlights the challenges of conserving salt contaminated masonry, demonstrating that even preventive strategies could prove detrimental if it has not been possible to model all potential decay mechanisms and their dynamic interactions; when salts are involved, this can be practically impossible (Menendez and Petranova 2016). An increased understanding of the mechanisms driving decay at the microclimatic scale could be a first step towards developing more effective preventive conservation strategies.

V) 1.2. Methodology

Repeat surveys were made of different locations within the Bell Tower in order to assess active decay. Flaking and powdering were assigned to individual stones and areas and recorded with photographs and micrographs (Vergès-Belmin 2008). Dust trays were placed at the base of selected masonry to provide a measure for ongoing decay rates. A T660 capacitance moisture meter and a T610 microwave moisture meter (Trotec) were used to perform a rapid assessment of relative moisture content (MC), with multiple point readings ($n \approx 20$) taken across different locations. The T660 measures to a depth of approximately 2-4 cm, whilst the T610 measures to approximately 20-30 cm (Trotec 2019). Water uptake tests were performed on a representative example of each decay pattern using Karsten tubes sealed against the stone surface with putty and filled with distilled water. The NDT was designed to provide a rapid assessment of material qualities associated with observable decay patterns, in order to inform a more in-depth characterisation in ongoing studies.

[9] Neither were implemented.

A network of sensors was installed in the Bell Tower to record a range of environmental parameters over an 18-month period. Hygrochrons (iButton) were used to record localised internal temperature and RH variations. Surface-wetness (Campbell Scientific) and surface-temperature (Gemini) sensors were attached to selected Reigate masonry, so that the sensor was pressed and sealed against the stone surface. Surface sensors were used in areas proximate to the monitored micro-environments and connected to dataloggers (Gemini). A weather station (Vaisala) placed on the roof of the Bell Tower recorded temperature, RH, precipitation, solar radiation and wind speed and direction. Recording intervals were set to between 10 and 180 minutes, depending on sensor location and expected rates of change determined in trials. Sensors were calibrated at the start of the monitoring period and on several further occasions as and when they were repositioned.

V) 1.3. Results and discussion

V) 1.3.1. Decay patterns

Decay patterns on internal masonry can be grouped into categories distinguished by location (Figure V.2):

- Powdering dominates the lower chamber, ranging from gentle to severe. Differential erosion is noticeable in the west alcove. Decay is severe in the northwest alcove. Some stones display efflorescence (Figure V.3).
- Flaking dominates the spiral stairwell leading to the Bell Tower roof. Severely flaking stones are concentrated in but not limited to the upper west flank, particularly near the treads. Many stones on the east flank are in a sound condition (Figure V.4).

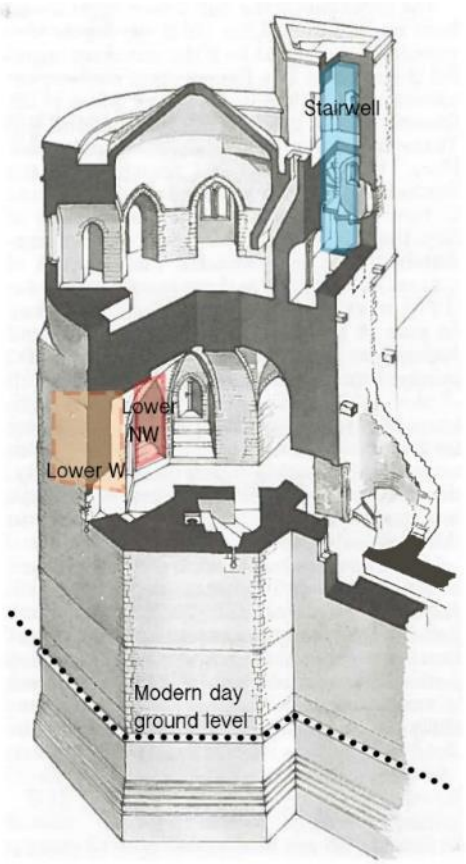


Figure V.2: *Axonometric of Bell Tower from South showing locations in this study (modified from a drawing by Terry Bell).*

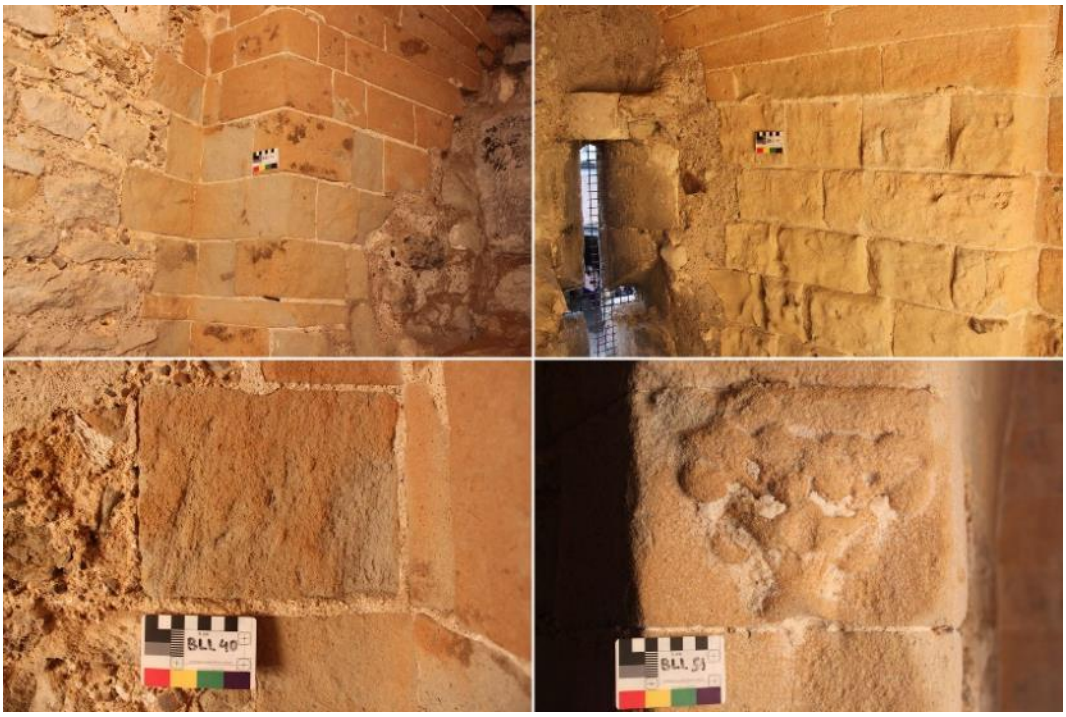


Figure V.3: *Reigate masonry in lower chamber. Top left: NW alcove; Top right: W alcove; Bottom left: typical powdering decay; Bottom right: severe efflorescence.*



Figure V.4: *Reigate masonry in stairwell. Top left: flaking decay on west flank (Jan 2018); Top right: west flank following detachment episode (Aug 2018); Bottom left: east flank; Bottom right: typical detached material and fresh subsurface.*

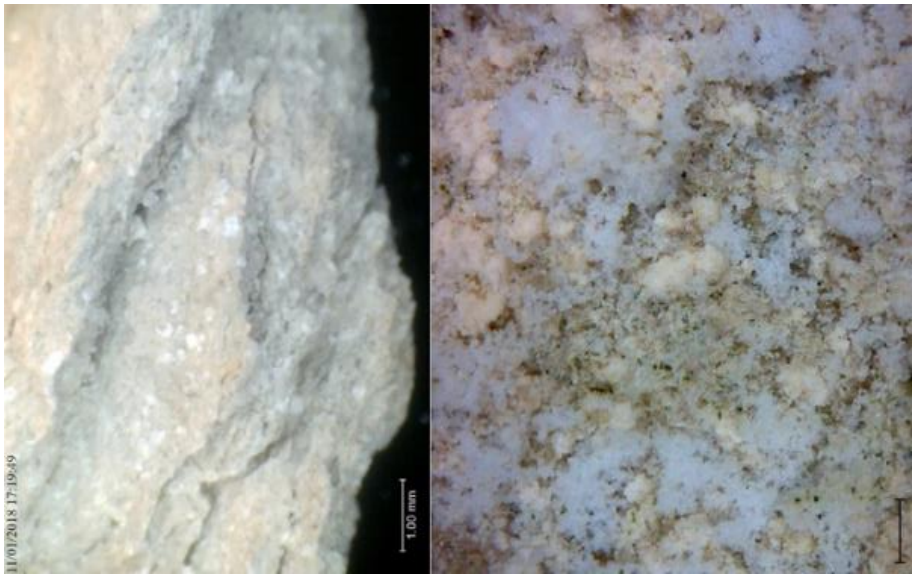


Figure V.5: *Micrographs of detached flake (left) and powdering surface (right) showing salt contamination (scale bars 1 mm).*

Micrographs of detached material found in the stairwell show a laminar propagation of flaking decay occurring irrespective of faintly visible bedding planes, with parallel fissures visible in the exposed sub-surface (Figure V.5). Salt crystals can be seen embedded in the stone, including some which lie directly along the grain of a fissure. Micrographs of powdering stones show signs of efflorescence and a grainy, unconsolidated surface. Visual observations strongly suggest that salt contamination is driving the decay of Reigate masonry.

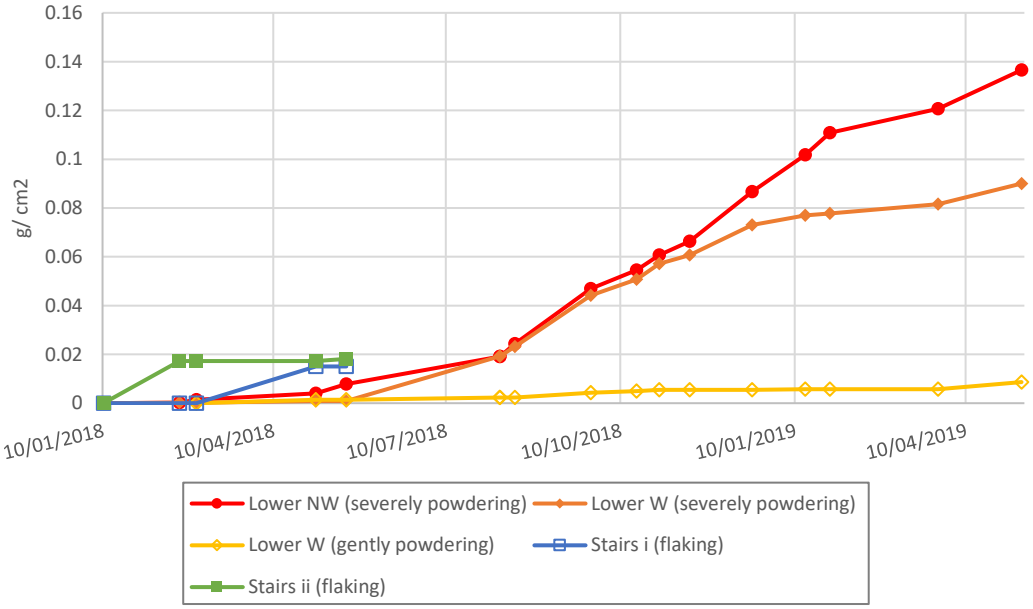


***Figure V.6**: Cumulative mass of material collected in trays at base of decaying masonry.*

Dust trays placed in the lower chamber recorded gradual granular disintegration of the surface across the entire monitoring period (Figure V.6). Whilst there was very little material loss in some areas, parts of the west and north-west alcoves were decaying rapidly. In areas of rapid decay, there were noticeable increases in the rate of material detachment in spring and summer months, and slight decreases in the rate of detachment in winter months. Detached material was very fine and damp. There was some evidence of gradual granular disintegration on the flaking stones of the

stairwell, however their decay was dominated by the episodic disaggregation of large amounts of surface material. This occurred as a series of laminar flakes became unstable and collapsed, rather than the detachment of single flakes. Newly exposed surfaces show signs of powdering. Stairwell dust trays were removed in June 2018. Further evidence of flaking was found throughout the year (e.g. Figure V.4).

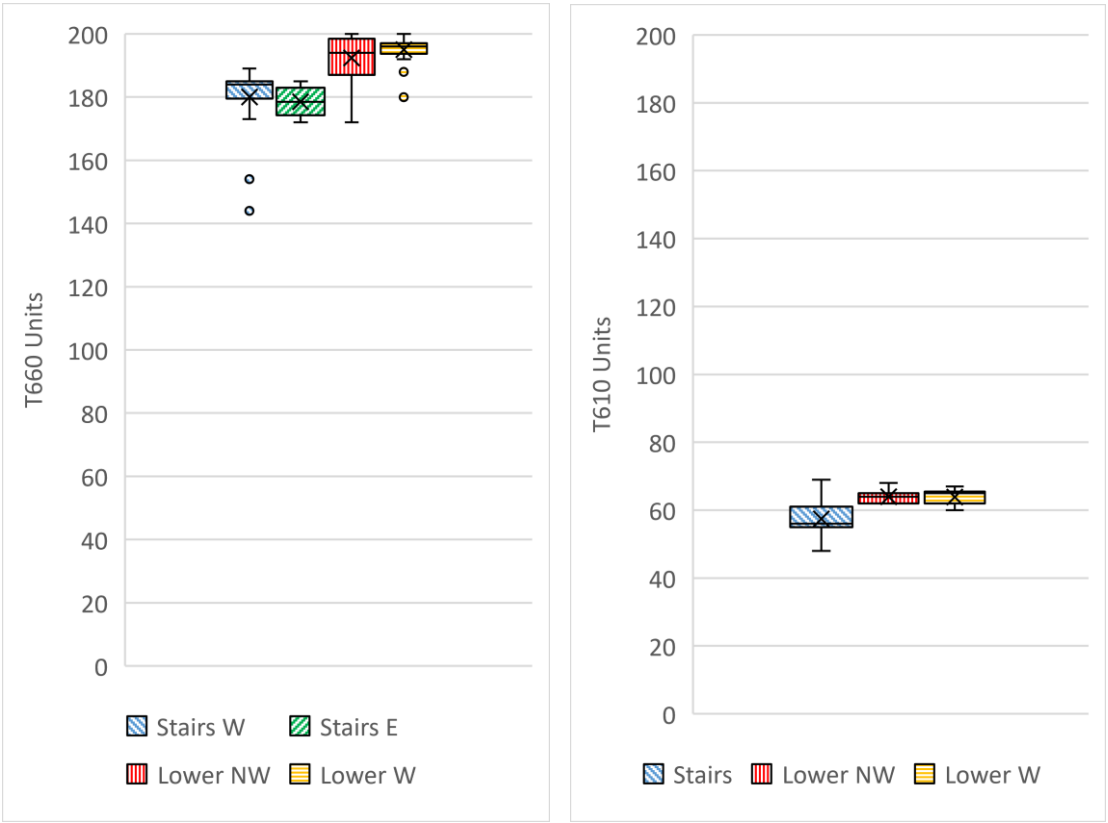


***Figure V.7**: Boxplots of readings taken with moisture meters, showing mean (x), median (middle line), interquartile range (box), range (whiskers) and outliers (i.e. datapoints over 1.5 times above or below IQR). **(Left)** Results for T660 near surface readings and **(right)** results for T610 sub-surface readings.*

MC as measured with both moisture meters was higher in the lower chamber than in the stairwell (Figure V.7). There was no significant difference between the average MC of different areas within the two locations. MC at depth was more variable in the stairwell. Visually apparent state of decay on individual stones was not necessarily reflected in higher MC, particularly on flaking stones. It is possible that cavities within

flaking stones interfere with the readings. It may also reflect that near-surface moisture fluctuation, not moisture content itself, is driving decay. The powdering stone absorbed significantly less water during the water uptake test than the flaking stone (Figure V.8). When the tests were ended after 3.5 minutes, moisture could be seen seeping from the surface of the flaking stone. This could indicate the powdering stone is close to saturation. It could also indicate a more fractured and open near-surface pore network on the flaking stone. Considered alongside the visual survey, the general indication is that differing proximity of an internal moisture profile to the stone surface may be resulting in salts crystallising at depth to drive flaking, and near the surface to drive powdering.



***Figure V.8**: Karsten tubes attached to flaking surface in stairwell **(left)** and powdering surface in lower chamber **(right)** with water level after 3.5 minutes marked by dashed line.*

V) 1.3.2. Microenvironments

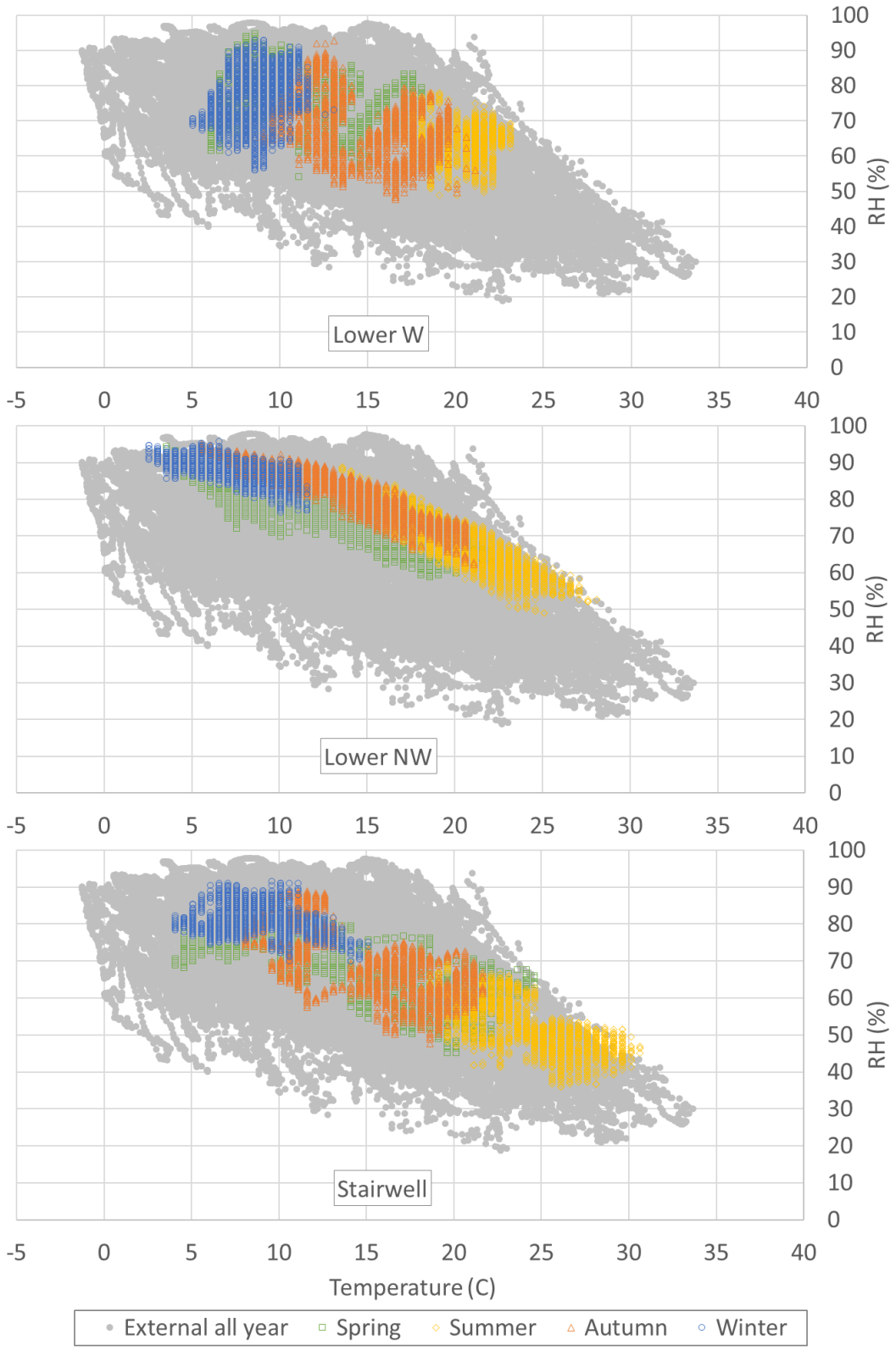


Figure V.9: *Scatterplots showing seasonal distribution of temperature and RH at surveyed locations for period from March 2018 - February 2019.*

V) 1.3.2.1. Lower Chamber

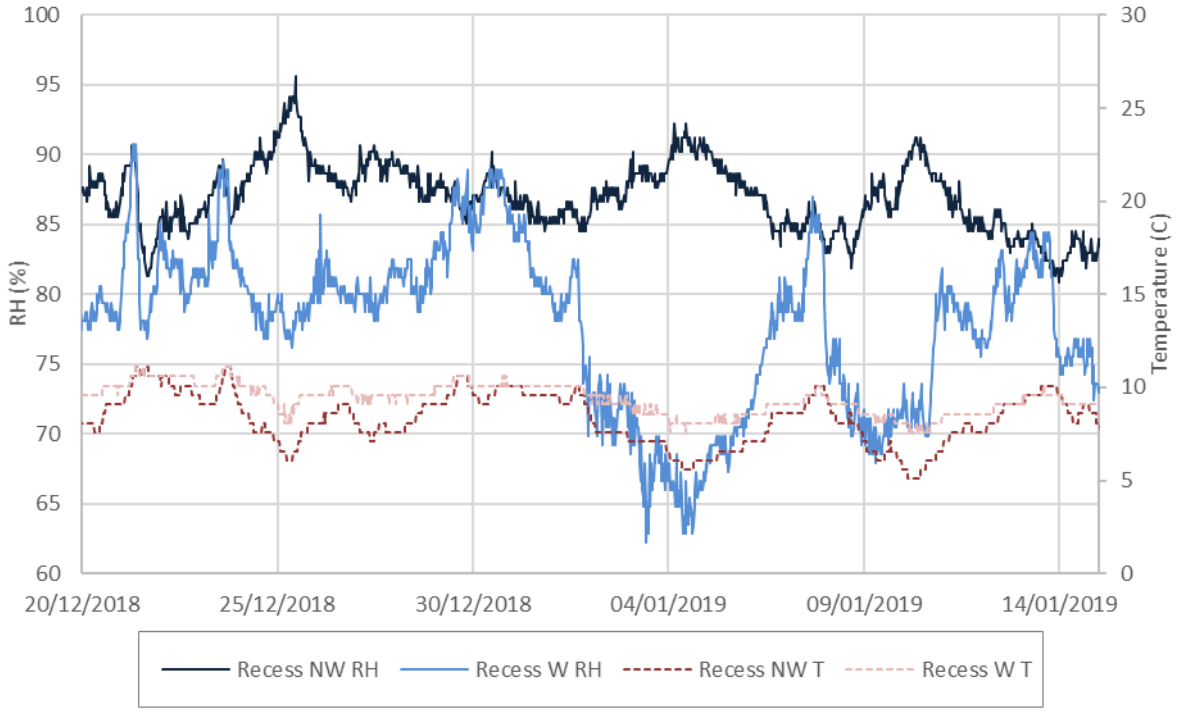


***Figure V.10**: 4-week period in Winter 2018/19 showing microclimatic temperature (dashed) and RH (solid) variations in lower chamber.*

Noticeably different micro-environmental conditions were recorded within the lower chamber (Figure V.9). RH is more consistently high in the north-west alcove. This can be explained by the open arrow-loop in the west alcove; conditions are affected by constant air exchange with the outside. The arrow loop of the north-west alcove is by contrast sealed. Sensors for monitoring the alcoves were placed within the recess of each arrow loop. This resulted in high daily temperature cycles in the north-west alcove during summer, as direct sunlight from the setting sun hit the external north-west elevation. During winter, increases in RH correspond with decreasing temperature around the dew point. As condensation does not generally form on Reigate Stone due to its high sorptivity, this could be a further indication of saturation (Figure V.10). A surface-wetness sensor attached to Reigate masonry in the north-west alcove responded to a period of heavy rainfall in June 2018 with a sharp increase

in activity (Figure V.11). These findings suggest moisture infiltration in response to a deep wetting of the masonry. The correlation between increased activity on the surface-wetness sensor and increased detaching material captured in the proximate dust tray in late Spring 2018 is notable. The indication is that increased wetting from external sources combines with increased drying at the internal stone surface to accelerate decay.

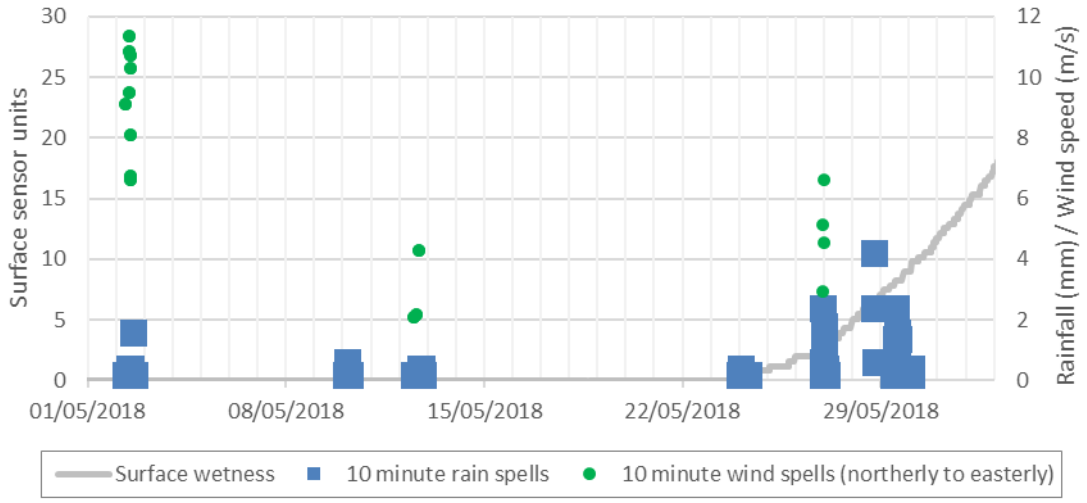


Figure V.11: *5-week period showing correlation between surface-wetness sensor sealed against Reigate Stone in NW alcove and rainfall.*

V) 1.3.2.2. Stairwell

Conditions at the top of the stairwell display a broader temperature and RH range and more distinct seasonal shifts than the lower chamber (Figure V.9). Winters in which RH rarely drops below 75% and hot, dry Summers are interspersed with highly changeable conditions in Spring and Autumn. Key to these differences is the exposed location of the upper stairwell at the roof of the Bell Tower. Diurnal and prolonged solar radiation correspond to incremental changes in internal surface temperature and ambient RH; prolonged or heavy rainfall corresponds with increases in RH (Figure V.12). In this environment the masonry is likely to be in dynamic equilibrium with

atmospheric humidity (Franzen and Mirwald 2004). Extended periods of high humidity will result in moisture adsorption, capillary condensation and deliquescence of salts. Interruptions will form an unevenly distributed solution. Intense dry spells will drive rapid evaporation and salt crystallisation within the porous network. During re-wetting the moisture front will retreat from fissures formed in the previous evaporation zone and the sequence repeats. Whilst the growth of flakes is likely to be controlled by environmental factors, a major cause of collapse during the monitoring period appeared to be abrasion caused by passing people. The area of advanced decay near the treads suggests vibrations may be an additional factor.

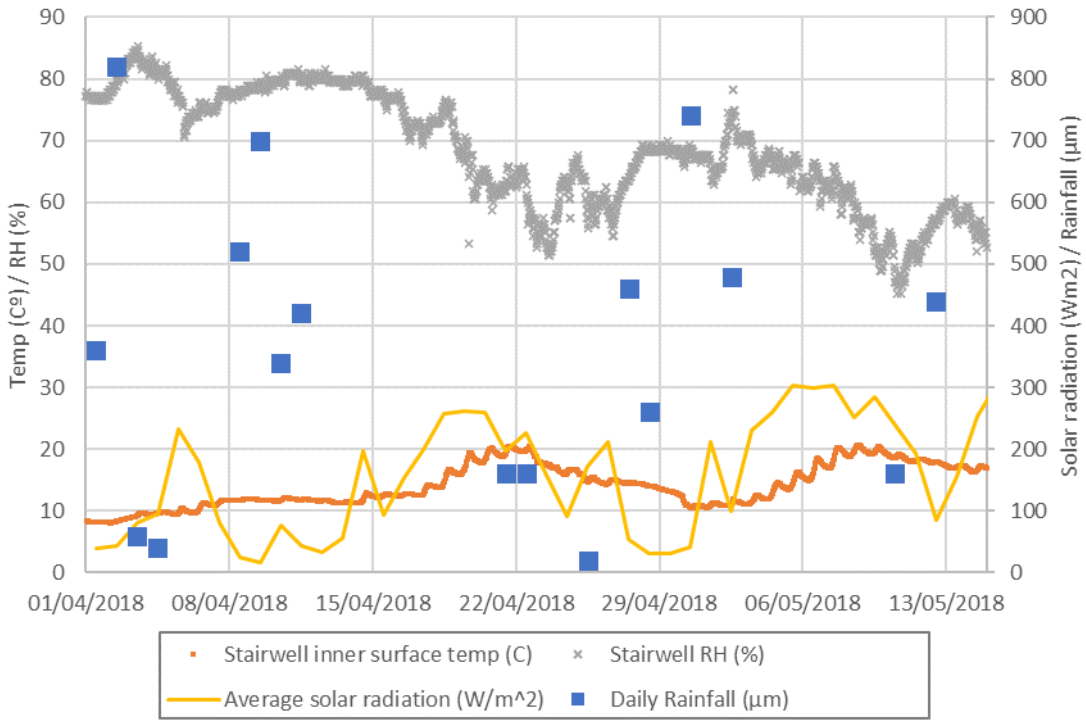


Figure V.12: *6-week period in Spring 2018, showing correlation of solar radiation and rainfall with RH and Reigate surface temperature in stairwell.*

V) 1.3.3. Outlook

Linking measurable environmental conditions to observable patterns of decay is a first step to developing preventive conservation strategies (Michette *et al.* 2018). These

can be designed to control specific mechanisms in order to mitigate ongoing decay. The mechanisms identified here will be further modelled and investigated in order to determine realistic strategies of control.

Besides the variations in active environmental mechanisms identified here, the nature of any salt contamination is certain to play an important part in Reigate Stone decay. Significant differences in the type and concentration of salts have been recorded in masonry within the same building elsewhere at the Tower of London (Price 1993). Sampling masonry in the surveyed areas of the Bell Tower will be vital to building accurate models of the overall processes of decay. Reigate Stone was sourced from numerous quarries along a varied band of rock (Sowan 1975). Different colourations of Reigate Stone were observed in the stairwell, indicative of several mineralogical variations used in construction. These inherent variations are also likely to play a part in the emergence of decay patterns. Ongoing work will consider the composition of native Reigate Stone in physio-chemical interaction with contaminates as part of a larger project in order to develop appropriate conservation strategies.

Photos of the lower chamber taken in 1945 and 1958 highlight the significance of contingency when considering the emergence of decay patterns (Figure V.13). Rubble can be seen blocking the western alcove, the line of which closely matches the differential erosion visible today. The photos also show changes to the dressed masonry; what appears to be a thick limewash or plaster coat applied to the main arch and the emergence of the present-day discolouration in the north-west alcove, thought to be the result of a fire. Exceptional or episodic interruptions, such as fire or building-works, introduce systemic shock which can outweigh or abruptly alter stable

long-term processes. Whilst constructing an accurate timeline for historic buildings often proves impossible, ongoing work will integrate documentary analysis.



Figure V.13: *Lower chamber in 1945 (top) and 1958 (bottom). North-west alcove on far right of image; west alcove immediately to left. (HRP archives)*

V) 1.4. Conclusions

The objective of this research was to investigate patterns and controls of internal Reigate Stone decay. The results of NDT in combination with a high-resolution environmental monitoring programme are compatible with the hypothesis that specific environmental mechanisms are responsible for driving observable patterns of salt driven decay. These can be associated with distinct microclimates found in the Bell Tower, Tower of London. Gradual granular disintegration was observed in the

lower chamber. This powdering phenomenon can be associated with highly saturated stones and a relatively steady ambient climate. Whilst temperature changes affect drying and subsequent decay rates, deep wetting and consistently high ambient RH maintain a fixed zone of evaporation. Salt crystallisation takes place at or near the stone surface. Episodic collapse of larger amounts of material was observed in the stairwell leading to the roof. This flaking phenomenon can be associated with a fluctuating ambient climate and dynamic moisture distribution within the stone. Extended periods of high RH followed by dry, hot spells result in a cyclic redistribution of solution and a shifting zone of evaporation. Salt crystallisation progressively results in the formation of sub-surface fissures. Once the build-up of fissures has reached a critical point, further disturbance results in the detachment of loosened material. Whilst the multiple analytical techniques presented here provide initial evidence that these factors are key controls in the ongoing development of distinct decay patterns, the nature of salt contamination, inherent stone properties and historic contingency must be considered in their emergence. Identifying these controlling mechanisms can inform preventive conservation strategies of vulnerable historic masonry.

V) 2. Do environmental conditions determine whether salt driven decay leads to powdering or flaking in historic Reigate Stone masonry at the Tower of London?[10]

Abstract

In order to evaluate the potential for using environmental controls as a preventive conservation strategy for Reigate Stone masonry, this paper tests the hypothesis that powdering and flaking decay patterns are a direct consequence of climatic variables. Samples of masonry affected by each decay pattern are analysed for soluble salt content using ion chromatography. The results are used to build thermodynamic models in ECOS Runsalt. These identify NaCl and $NaNO_3$ crystallisation in both environments, with NaCl dominating in powdering masonry and $NaNO_3$ dominating in flaking masonry. Freshly quarried samples of Reigate Stone with a range of physical characteristics are contaminated with a mixture of these salts. Replicates of each sample are subjected to two distinct accelerated ageing regimes. These regimes are based on environmental monitoring and designed to reproduce the observed decay pathways. One set is subject to partial immersion and relatively stable, high RH, to stimulate a zone of NaCl crystallisation near the surface. The replicate set is subject to occasional wetting and frequent drops in RH, to stimulate $NaNO_3$ crystallisation within the fabric of the stone. The results provide some indication that the intended decay mechanisms were achieved, supporting the hypothesis; however, physical variation in the stone was a far greater control on the rate of decay and the emergence of distinctive decay phenomena. This extended to both the mineralogical composition of the stone and to pre-existing decay features, such as crusts and cracks. The implication of these results is that the emergence of decay patterns in Reigate Stone cannot be explained solely by environmental mechanisms; baseline mineralogy and historical contingency can play a crucial role. Whilst environmental controls may provide a conservation strategy in some cases, it is likely that detailed assessment of the case specifics will be necessary.

[10] Submitted in April 2020 to the journal *Engineering Geology,* with minor changes to style and format

V) 2.1. Introduction

V) 2.1.1. Salt decay in historic masonry

Salts are a major cause of deterioration in historic masonry (Charola 2000). Predicting the dynamics of salt driven stone decay is a highly complex task, which requires carefully designed experimental frameworks (Flatt et al. 2017). Designing experimental procedures is complicated by the fact that rates and patterns of stone decay depend on interactions between petrophysical characteristics, type of salts and environmental conditions (Menendez and Petranova 2016; Yu and Oguchi 2009). Whilst computational tools such as ECOS Runsalt have been developed to assist with this complexity, appropriate sampling strategies are vital when linking experimental models to field data (Sawdy and Price 2005a). Seasonal variations in salt concentration can present a further challenge when collecting field data (Sawdy and Price 2005b). Building general theories from the discrete observations made in experimental data can overlook or exaggerate the effect of specific mechanisms or attributes (Sun and Zhang 2019; McCabe et al. 2013; Warke and Smith 2007). Theoretical predictions are frequently undone by practical observations, both in laboratory and field environments (Menendez and Petranova 2016; Price 2007). These factors combine to present significant challenges for the design of laboratory tests which reflect field behaviour (Lubelli et al. 2018); this in turn is an obstacle to identifying conservation strategies for salt contaminated masonry.

Salt driven decay is intrinsically linked to moisture transport. Advection and diffusion are responsible for the distribution of salts within a porous matrix (Flatt et al. 2017). During wetting, moisture from the environment can cause salt crystals to deliquesce;

capillary forces and/ or differences in vapour pressure will cause the subsequent solution to migrate through the porous network (Liefferink et al. 2018). During drying and given suitable thermodynamic conditions determined by equilibrium relative humidity (RH), salts will re-crystallise. If moisture is evaporating from the surface of the material, this can result in efflorescence (crystallisation at the outer surface). If environmental conditions can no longer maintain an evaporation front at the surface of a material, this can result in subflorescence (crystallisation beneath the surface) (Modestou et al. 2015). The resulting crystallisation pressures can result in damage to the building stone and drive surface loss.

Colston et al. (2001) highlight the influence of drying phases in an investigation of decaying limestone piers inside a church in Norfolk. An area of deterioration starting at a height of approximately 2.5 m corresponds with an area of historic sodium chloride (NaCl) contamination. The area is too high to be affected by capillary rise and the moisture content is shown to be in balance with atmospheric humidity. Under these conditions, adsorbed atmospheric moisture cannot re-supply evaporation at the stone surface during drying phases; suitable thermodynamic conditions will result in crystallisation cycles taking place below the surface of the material, leading to the observed decay pattern. The lower part of the piers is strongly affected by capillary rise. Due to the constant supply of moisture, evaporation occurs at the surface and the salt contamination has been emitted from the fabric without causing decay.

Petrophysical characteristics that play an important role in salt driven decay can be divided into two groups (Flatt et al. 2017). The first group covers properties affecting the accumulation of salts. These include the chemical composition of the stone,

principally the presence of alkali anions, which will determine whether salts can be formed in-situ in reaction to cationic contamination. They also include pore space open to capillary flow, which enables rapid moisture uptake (Yu and Oguchi 2009). The second group covers properties affecting the resistance to salt decay mechanisms. These include the strength and anisotropy of the rock (Benavente et al. 2007a); tensile strength is the key determiner, however a good correlation to compressive strength has been determined. They also include porosity susceptible to crystallisation pressures; generally, this covers the micro-porous region (Benavente et al. 2007b). Combining these factors indicates that weakly cemented, alkaline stones with a high, bimodal porosity are likely to be the most susceptible to salt damage.

The shape and size of pores can further influence salt driven decay. Accelerated ageing tests were used to determine that large pores and fissures act as a sink to consume high supersaturation (Benavente et al. 2007b). On the other hand, narrow fissures were found to be particularly susceptible to the crystallisation pressures generated by salt. Ongoing crystallisation cycles caused these to coalesce and form larger fissures. The study also found that a high porosity, low pore-radius, weak strength matrix could be linked to granular disintegration. Liefferink et al. (2018) found that during deliquescence of NaCl in porous media, the invasion of salt solution is controlled by capillary pressure within the porous network. In hydrophilic media, the liquid formed by deliquescence preferentially invades adjacent small pores and migrates towards higher vapour pressure. Repeat wetting and drying cycles can thereby cause a progressive expansion of porous matrix, which could generate near surface flaking. These findings begin to associate specific decay pathways with distinct pore network characteristics.

The nature of the salt contamination influences the onset and pattern of crystallisation and resultant decay pathways. Under equal conditions different salts will crystallise at different depths or heights as a function of their solubility (Arnold 1982). Different salts have been shown to produce different decay rates and patterns in stones (Yu and Oguchi 2009). However, whilst certain salts are shown to be highly aggressive across numerous studies, rates and patterns vary from stone to stone and it is not possible to construct clear categories based on the efficacy of salts (Lubelli et al. 2018). Mixed salt solutions complicate matters further and may be more, or less aggressive than single salts depending on their composition (Menendez and Petranova 2016; Lopez-Arce et al. 2008); recent studies have emphasised the importance of testing procedures using mixed salt solutions to better reflect scenarios encountered in historic masonry (Lubelli et al. 2018).

These complex synergies make generalised associations between agents and pathways of decay impossible (Charola 2000). However, in individual cases it has been possible to correlate decay patterns with specific types of salt contamination or environmental conditions. Using an accelerated ageing test to compare the effects of pure magnesium sulfate ($MgSO_4$) with a salt mixture, Lopez-Arce et al. (2008) were able to reproduce the characteristic flaking of a Magnesian limestone church in York. Pel et al. (2019) were able to describe decay functions for situations in which a sandstone has a continuous flux of NaCl solution from a moisture source (i.e. advection due to ground water) to a surface exposed to evaporation. Rodriguez-Navarro and Doehne (1999) were able to associate sodium sulfate ($NaSO_4$) and NaCl damage with the location of crystallisation, which itself was determined by evaporation rates. Associating decay patterns with the underlying dynamics can be an

effective diagnostic tool, and an important step in the design of preventive conservation strategies aimed at controlling specific environmental mechanisms.

V) 2.1.2. Salt decay in Reigate Stone

The most highly valued building stones are often the most vulnerable: soft stones used for detailed carving at heritage sites, which have subsequently been exposed to centuries of weathering and use. Reigate Stone, an important freestone used widely in medieval London, frequently displays signs of salt contamination and falls into the category of weakly cemented, alkaline, porous stones susceptible to salt damage (Sanderson and Garner 2001; Price 1993). Two distinctive decay patterns are frequently encountered in Reigate Stone (Figure V.14).

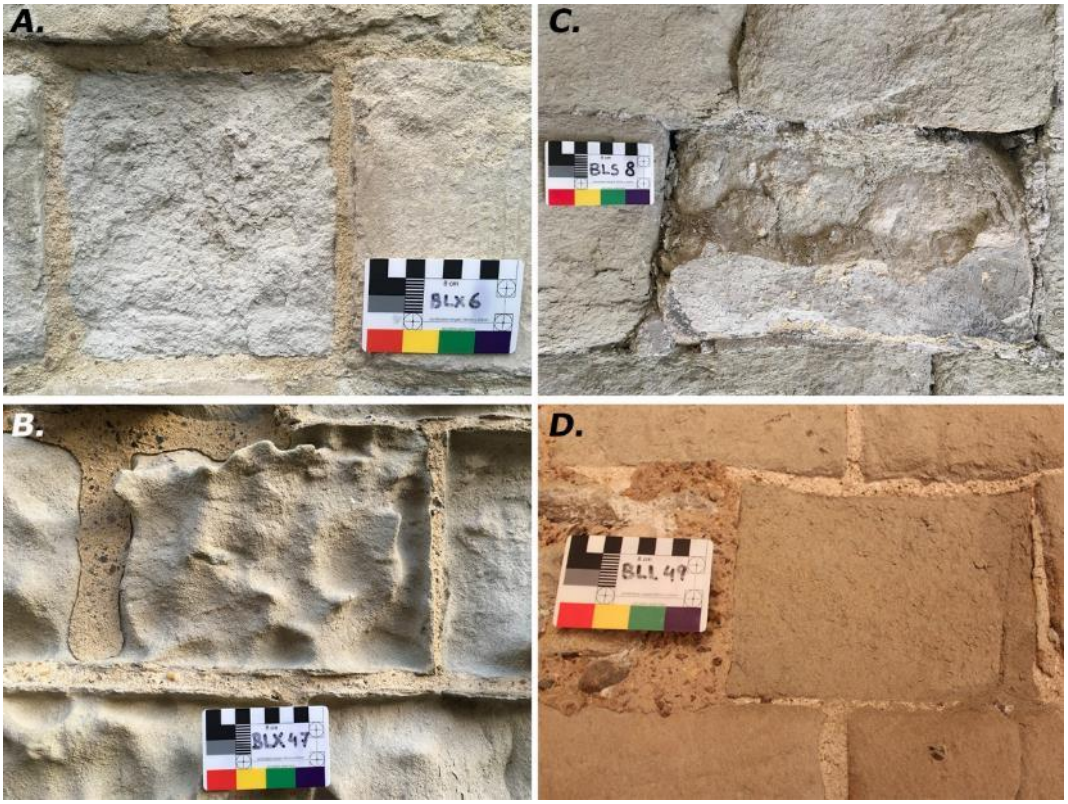


Figure V.14: *Powdering and flaking Reigate Stone at the Bell Tower, Tower of London. A. Flaking stone in south-east facing external masonry; likely to represent 19th century repair material. B. Powdering stone in south-west facing masonry with alveolars; likely to represent primary medieval material. C. Flaking stone in stairwell, with delamination occurring parallel to front and side faces. D. Powdering stone in north-west alcove of lower chamber.*

A gradual powdering of the stone surface characterised by the continuous loss of material ranging in size from individual, silt-sized grains to millimetric agglomerations. Agglomerations tend to take the form of very fine plate like flakes with a thickness of only a few grains. Erosion can progress evenly or lead to relief formation. Differential erosion is particularly evident on stones which have a harder crust or superficial layer. In these cases, surface loss appears to gain a foothold in pits or perforations in the outer crust and progress locally; this can lead to alveolar formation.

A more episodic flaking characterised by periodic detachment of centimetric agglomerations. Agglomerations take a range of sizes but differentiate from those above in their greater thickness. In all but the most severe cases, agglomerations form plate like structures which appear to progressively delaminate from the surface. In some cases, these form fish-scale patterns. In some severe cases the stone breaks up into fragments irrespective of orientation. A series of laminar flakes or scales may build up gradually before sub-surface detachment occurs and leads to significant material loss. In some cases, flaking appears to take place behind crusts or superficial layers. This eventually leads to the catastrophic loss of the entire outer surface.

Both patterns are evident in more and less severe forms. Combinations of both decay patterns do exist, generally in very severe cases of decay in which they appear to be developing concurrently. In some cases, different parts of the same stone exhibit different patterns. Often, recently detached flakes reveal a powdering sub-surface. The precise mechanics that generate these different patterns are unclear; past studies have linked them to level of exposure (Sanderson and Garner 2001; Lockwood 1994); however, this is not a definite indicator. Whilst bedding planes are faintly visible in

Reigate Stone, cleavage does not appear to propagate solely in one direction; stones will flake and delaminate on two non-parallel external faces and in some cases will show evidence of delamination occurring parallel to mortar bedding at their edges (Figure V.14c). Different typologies of Reigate Stone were used throughout the medieval period, and the wide range of different environments and histories that extant masonry have been exposed to is likely to have resulted in highly varied salt contaminations (see Chapter III.1 and V.1; also Price 1993). Determining to what extent the controlling factors in these distinctive decay patterns are governed by the intrinsic properties of the stone, the nature of the contaminate, or the localised environment will inform the design of conservation strategies.

V) 2.1.3. Salt decay at the Bell Tower, Tower of London

At the Bell Tower, a 12th century structure with a significant amount of surviving, primary Reigate masonry dating to the first major expansion of the Tower of London, varying forms of both decay patterns correspond to distinct spatial areas (Chapter V.1). Combinations of both patterns are also evident, as are areas of sound Reigate Stone which have suffered very little material loss. Decay patterns on internal masonry can be grouped by area (Figure V.15).

- Powdering dominates the lower chamber, ranging from gentle to severe. Differential erosion is noticeable in the west alcove, which has an open arrow slit. Erosion is severe yet regular in the north-west alcove, where the arrow slit has been covered.
- The upper chamber displays remarkably sound Reigate Stone with remnants of plaster and limewash. One noticeable exception is the southern alcove of

the upper chamber, which contains severely powdering stones and combinations of severe powdering with flaking. Superficial plaster coats have detached entirely or are extremely fragile.

- Flaking dominates the spiral stair leading to the Bell Tower roof. This area is faced in fine Reigate ashlar, some of which is in a sound condition. Some of these stones are severely flaking. These are concentrated in but not limited to the west.

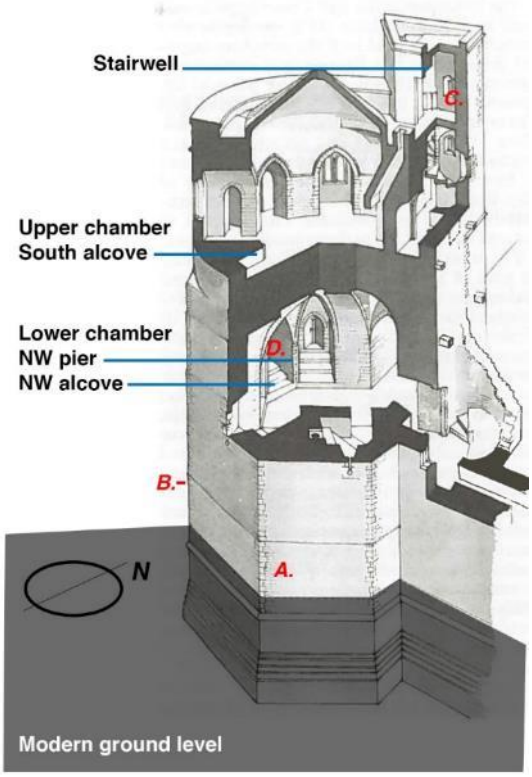


***Figure V.15**: Axonometric cut-away of the Bell Tower, Tower of London, highlighting areas of investigation in this study and showing approximate location of stones depicted in Figure V.14.a-d. (original image by T. Bell).*

As part of a wider project on Reigate Stone at the Tower of London, the environments of the Bell Tower were monitored over an 18-month period in order to detect whether specific climatic variables are associated with these observable patterns of decay (Chapter V.1). The results suggested that powdering is related to deep wetting of the

stone and a steady ambient climate; evaporation and salt crystallisation can take place at or near the stone surface. Flaking is related to a dynamic moisture profile and seasonal and diurnal temperature cycles; salt crystallisation takes place beneath the stone surface. These results are compatible with a hypothesis that distinct environmental mechanisms govern the emergence of powdering and flaking decay phenomena in Reigate Stone, due to underlying differences in the dynamics of wetting and drying (Figure V.16). Similar hypotheses have been proposed by Lewin (1982), Colston et al. (2001), Lubelli et al. (2006), Lopez-Arce et al. (2008) and Goncalves and Brito (2014).

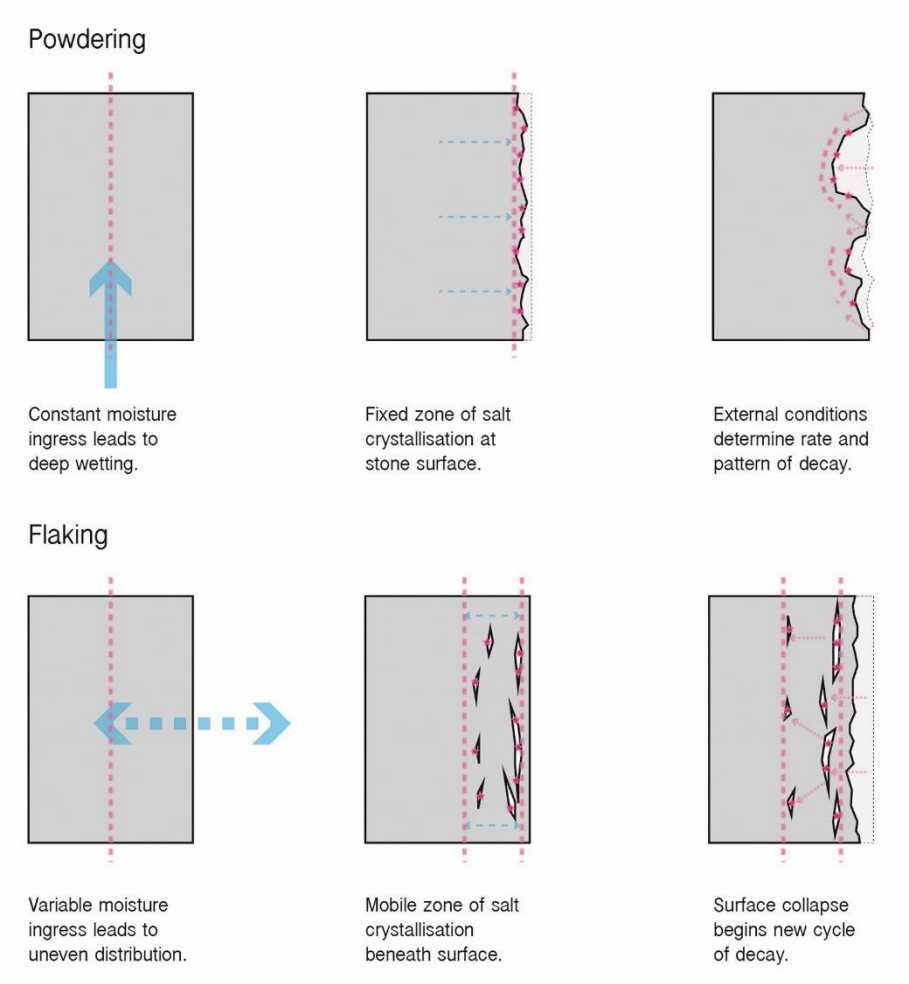


Figure V.16: *Diagrammatic description of hypothetical mechanics underlying powdering and flaking decay patterns.*

Decay patterns on the external masonry of the Bell Tower can also be clearly subdivided according to flaking and powdering. Powdering dominates the west, north-west and north elevations. Flaking dominates the south-east, south and south-west elevations. Close inspection of the Reigate masonry indicates that the powdering and flaking stones belong to two separate mineralogical types (see Chapter III.1). The paler colour of the flaking stones suggests a higher calcite content; the greenish, grey hue of the powdering stones suggests a higher clay content. It is likely that the south facing Reigate masonry represents 19th century repair work. Whilst a variety of environmental mechanisms may be contributing to decay in different orientations of external masonry, these observations imply that the emergence of decay patterns is governed by petrophysical characteristics.

The Bell Tower therefore present two contradictory explanations for the emergence of distinctive flaking or powdering decay patterns. Environmental monitoring provides evidence in support of a hypothesis on separate hygro-physical mechanisms leading to divergent decay pathways; however, observations of more widespread occurrence of the resulting decay patterns indicate that underlying petrophysical characteristics may also explain variation.

V) 2.1.4. Aim and objectives

The main aim of this paper is to determine the role of environmental conditions on salt driven decay in Reigate Stone. This will assist the design of ongoing conservation strategies aimed at mitigating the effects of salt driven decay. In particular, it will help determine whether interventive conservation procedures, aimed at improving petrophysical resistance, can be replaced by preventive measure, such as by

maintaining safe RH ranges for locations that display specific decay phenomena. In order to assess the relative role of environmental conditions, a secondary aim will be to determine the influence of petrophysical variability. The objective is to develop a methodology for laboratory experiments which reflect field behaviour that can be applied to Reigate Stone and other vulnerable historic building stones by:

- Determining typical compositions for salt solutions found in rapidly decaying Reigate masonry.
- Modelling a simplified mixture, designed to simulate salt dynamics found in-situ whilst eliminating salt variability as a factor.
- Simulating typical environments which appear to contribute to rapidly decaying Reigate masonry and subject a range of mineralogical typologies to accelerated ageing tests.

V) 2.2. Methodology and Results

V) 2.2.1. Overview

A three-step methodology is used to address the objectives and develop an experimental framework that reflects field behaviour. The aim is to stimulate flaking and powdering decay phenomena observed in Reigate Stone at various locations around the Bell Tower, Tower of London.

Step 1. Masonry exposed to the micro-environments monitored in Chapter V.1 is sampled and analysed using ion chromatography. Distinct, complex, ionic mixtures are found in each area of the Bell Tower, with some seasonal variation also present.

Step 2. The ionic concentrations are modelled in ECOS Runsalt to determine which salts are at risk of crystallisation cycles under climatic conditions measured in Chapter V.1. A simplified salt mixture is modelled by isolating salts at risk of crystallisation in both the lower chamber and stairwell environments (Figure V.15).

Step 3. A wide range of mineralogical Reigate Stone types examined in Chapter III.1 is contaminated with a highly concentrated mixture of NaCl and sodium nitrate ($NaNO_3$). This includes stone from quarries believed to have supplied building material during the construction and repair phases of the Bell Tower (Burgess 2008). Replicates of each type are exposed to two distinct accelerated ageing regimes, designed to simulate the environmental mechanisms identified in Chapter V.1 and described in Figure V.16.

In the following section each step is described sequentially. As the results of one methodological step inform the design of the following step, these descriptions include both a detailed explanation of the experimental method and an outline of the results.

V) 2.2.2. Ion Chromatography

V) 2.2.2.1. Method

Samples of Reigate Stone were collected from three distinct micro-environments in the Bell Tower for determination of soluble salt content. As well as from the lower chamber and stairwell environments, characterised by powdering and flaking surfaces respectively and monitored in Chapter V.1, material was gathered from powdering surfaces in the upper chamber.

Powdering material was gathered in dust trays placed at the foot of rapidly decaying masonry. To enable an investigation of spatial distribution, dust trays were placed at two different locations in the lower chamber (Figure V.15). One dust tray was placed in the south alcove of the upper chamber. To enable an investigation of changes in seasonal distribution, material gathered in dust trays was collected at bi-monthly intervals for laboratory analysis. Following episodic detachment of surface flakes in the stairwell, small flakes were collected for laboratory analysis.

Collected material was analysed using liquid ion chromatography (Dionex). Samples were ground to a fine powder. 1 g of each sample was added to 50 ml of deionised water, agitated, sonicated and filtered to produce solution. The solution was appropriately diluted (x10 or x100) following conductivity testing to keep the results of Dionex analysis within standards range.

V) 2.2.2.2. Results

Figure V.17a shows the concentration of soluble anions and cations present in the samples in parts per million. Sodium, potassium, magnesium and calcium cations, and chloride, nitrate and sulphate anions are present to varying degrees in all samples. The overall concentration of ions is high in all samples, even when compared to previously measured salt content in Reigate Stone at the Tower of London (Church 2003). In material collected from the lower and upper chamber, this reflects that detached dust sampled from powdering surfaces is likely to contain a disproportionately high amount of salt. Whilst still high, the lower concentrations measured in flake samples collected form the stairwell are more comparable to previous results.

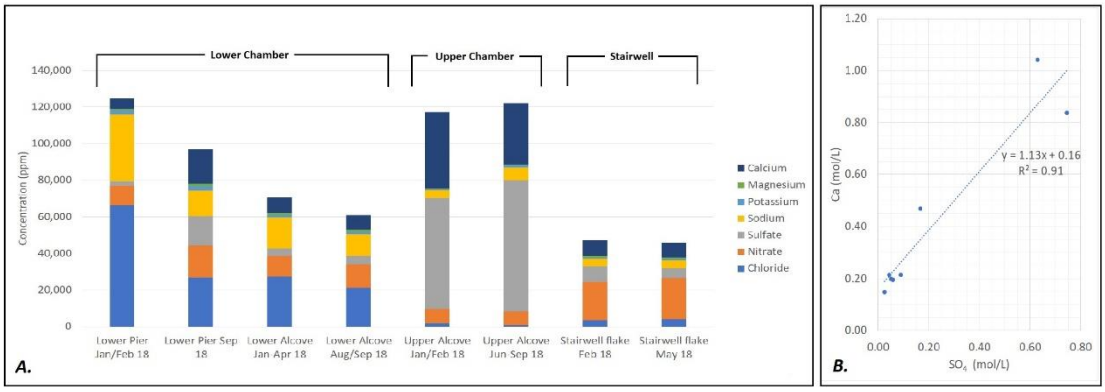


Figure V.17: (A.) *The concentration of soluble ions varies during different sampling periods and in different areas of the Bell Tower, Tower of London.* ***(B.)*** *The correlation between calcium and sulphate ions suggests that sulphate is mainly bound in gypsum and non- gypsum bound calcium content is consistent across samples.*

There is a correlation between the concentration of sulphate and calcium ions in all samples (Figure V.17b). The function describing this correlation suggests the majority of sulphate ions are bound in gypsum ($CaSO_4$); converting the ppm concentration to molarity indicates approximately 1 M of SO_4 per M of Ca, with an additional, relatively constant surfeit of Ca. The unbound calcium may be representative of soluble calcite in the native stone (see Chapter III.1). Material sampled from the alcove of the upper chamber is dominated by sulphate and calcium ions. Due to the likely dominance of insoluble gypsum, these samples were not considered in the ongoing thermodynamic modelling. The lower chamber samples are dominated by sodium and chloride ions, with notable variation in seasonal and spatial distribution. Stairwell samples have a high concentration of nitrate ions.

In the lower chamber, the overall concentration of salts decreases in summer months. This decrease correlates with an increase in detaching material, particularly in material collected from the pier (see Chapter V.1). The increase in detaching stone can also explain the increase in gypsum and calcite implied by the redistribution of ionic concentration. There is also a notable increase in the relative amount of nitrate

in material collected from the lower chamber during summer months. In the upper chamber, where the rate of detachment was steadier throughout the year, and in the stairwell, where detachment was episodic, there is less seasonal variation in concentration.

V) 2.2.3. Thermodynamic modelling

V) 2.2.3.1. Method and Results

For each sample from the lower chamber and stairwell environments, the measured ionic concentrations were entered in to Runsalt in order to model salt solutions and potential crystallisation/ deliquescence scenarios. Runsalt is a graphical interface to the ECOS (Environmental Control of Salts) thermodynamic model developed by Price (2000), which predicts the crystallisation and deliquescence points, as well as the volumetric expansion of salt crystals in complex mixed salts solutions under dynamic temperature or RH (Bionda 2005). An option to automatically remove gypsum from the simulation was selected; as gypsum solubility is very low, ions bound in gypsum are unlikely to contribute to dynamic crystallisation and deliquescence. Temperatures for each environment were set to means measured in chapter V.1, in order to assess the effect of changes in RH and identify which salts were at risk of crystallisation.

The autobalance option was used to correct minor discrepancies in the molecular balance of the analysed solutions. In case of larger discrepancies, the concentration was manually balanced by reducing calcium content to account for the presence of calcite in the samples. This is similar to the approach used by Price (2007). In most models autobalance and manual balance made no difference on calcium content; in some lower alcove models manual balance slightly increased the amount of $NaNO_3$.

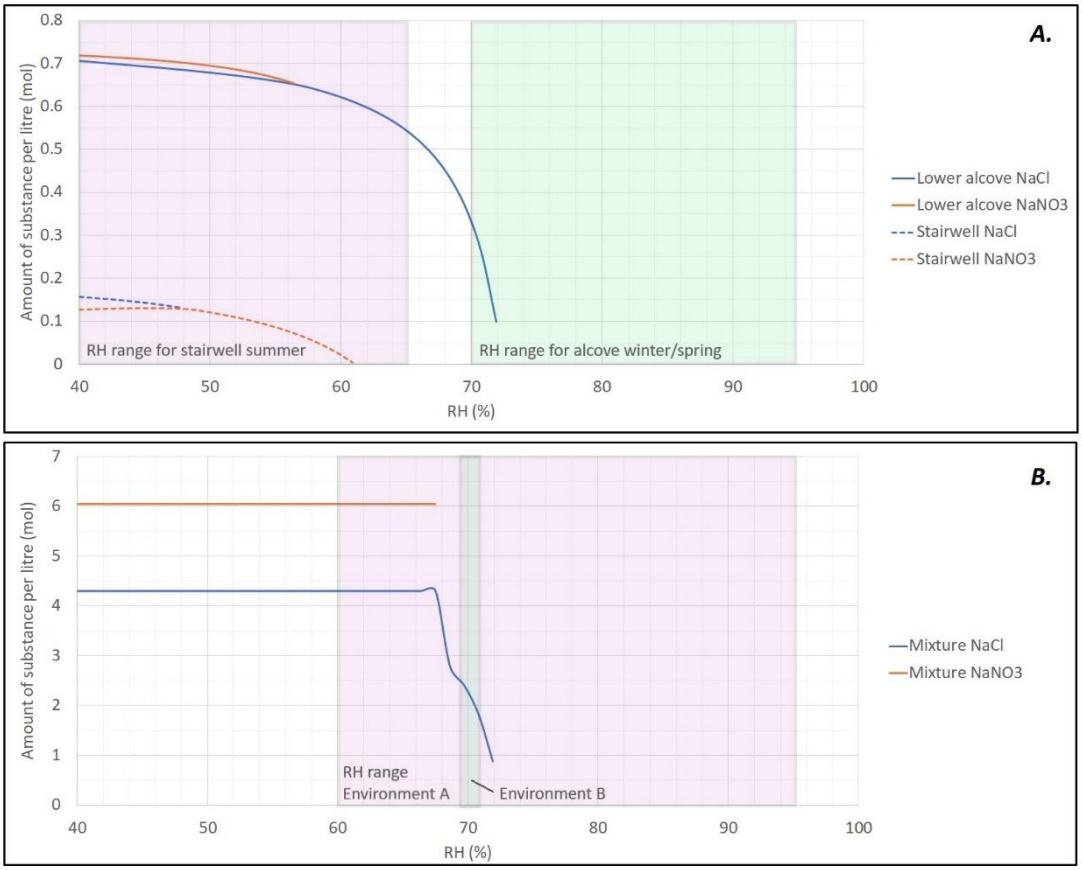


Figure V.18: ***(A.)*** *Runsalt models based on ionic concentrations measured in the lower chamber alcove (Jan-Feb sample) and the stairwell (May sample). Relative humidity (RH) ranges established in Chapter V.1 are superimposed. Temperature set to 10° C for lower chamber and 25° C for the stairwell.* ***(B.)*** *Final iteration of Runsalt model developed to represent crystallisation scenarios in both lower chamber and stairwell environments using simplified, unified salt mixture of 250 g NaCl and 150 g $NaNO_3$ per litre of water. Temperature in model set to 15° C. RH range for proposed accelerated ageing regimes superimposed.*

Figure V.18a shows a selection of the Runsalt models, plotting the amount of crystallising salt in response to changes in RH given the ionic compositions measured at various locations. In models of the lower chamber, a risk of NaCl crystallisation was identified in every location and throughout the year, although the risk is low in winter months. Of other potential compounds within the ionic compositions, only $NaNO_3$ is at risk of crystallisation under the conditions measured in Chapter V.1; this risk is restricted to the alcove locations, and, whilst the ionic composition is more favourable for $NaNO_3$ in winter months, conditions for crystallisation are more favourable in

summer months. The results suggest it is highly likely that near surface NaCl crystallisation is the main cause of powdering in these locations. A risk of NaCl crystallisation was also identified in models of the stairwell, particularly in summer months when RH falls below 50% for long periods of time. However, $NaNO_3$ crystallisation is more common here and likely to take place when RH falls below 60%, which happens in spring, summer and autumn months.

A unified model was built based on salts at risk of crystallisation in both environments (Figure V.18b). This was used to design a representative salt mixture for contaminating the samples of Reigate Stone to be subjected to accelerated ageing. The model was based on a mixture of NaCl and $NaNO_3$. Iterations identified a mixing proportion of 10 sodium ions to 7 chloride ions to 3 nitrate ions as providing a solution which would form NaCl crystallisation throughout the year under conditions monitored in the lower chamber, with some risk of $NaNO_3$ crystallisation in summer months. The more pronounced swings in RH monitored in spring, summer and autumn months in the stairwell would result in multiple $NaNO_3$ crystallisation cycles, although it should be noted that the order of crystallisation is reversed from that predicted in the stairwell models.

V) 2.2.4. Accelerated Ageing

V) 2.2.4.1. Method

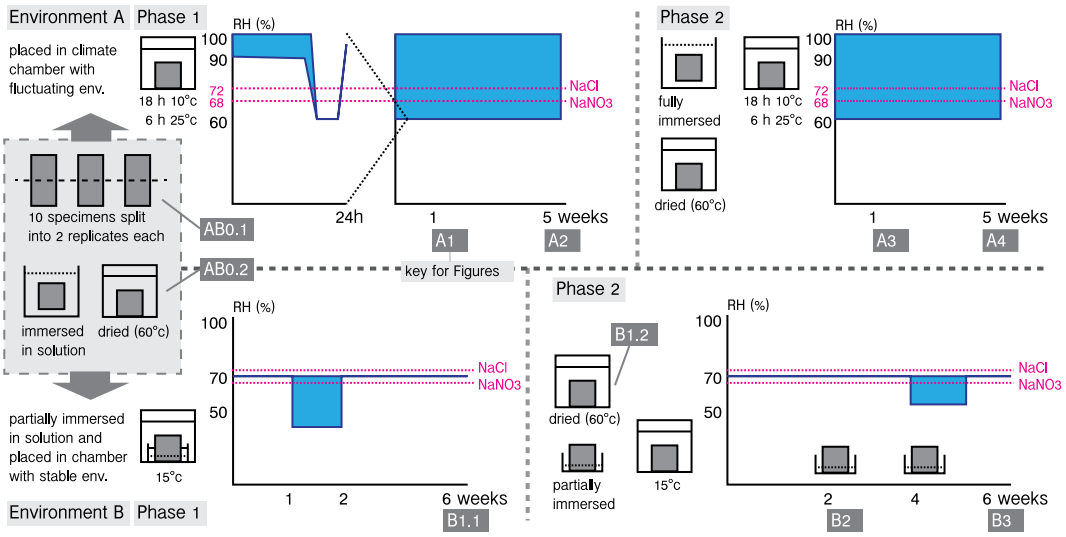


Figure V.19: *Diagrammatic overview of accelerated ageing regimes showing sample preparation steps and separate climate chamber programmes for two sets of replicates. NaCl and NaNO3 crystallisation/ deliquescence relative humidity marked by pink dotted line. Sequential photo numbering system used in main text and Figures V.20-21 shown in dark grey boxes.*

Figure V.19 provides a diagrammatic overview of the final methodological step, which aimed to reproduce the decay phenomena observed in Chapter V.1 under controlled environmental conditions. A set of Reigate Stone samples selected from material extracted from quarries in a project coordinated by Historic Royal Palaces in 1999 and analysed in Chapter III.1 was contaminated with a mixed salt solution and subjected to accelerated ageing regimes designed to simulate the environmental decay mechanisms identified in Chapter V.1. 10 Reigate Stone specimens were selected from four different, historic quarries (Sowan 1975). Petrophysical characteristics, such as mineralogical composition, porosity and strength, varied across and within the individual quarries (Table V.1). Quarry RS is known to have supplied medieval building works; quarry QF is known to have supplied 19th century building and repair works

(Burgess 2008). Samples from quarry GA show remarkable physical diversity within a single working face; samples from quarry GO are more homogeneous (see Chapter III.1). Each specimen was divided in to two 4.5 cm diameter x 4.5 cm high replicates. Replicates were prefixed according to quarry, numbered, and then suffixed according to the accelerated ageing environment they were exposed to.

A highly concentrated solution was made based on the results of the thermodynamic modelling, consisting of 250 g NaCl and 150 g $NaNO_3$ per litre of deionised water (Figure V.18b). These measurements were chosen to provide an easily reproduceable recipe and a mixture which was not fully saturated. Full saturation was avoided to minimise viscosity and likelihood of pore clogging (Lubelli et al. 2018). The samples were dried at 60^{o} C until mass equilibrium. Both replicates from 8 specimens and one replicate from GO1 and GO3 were submerged in the salt solution until mass equilibrium. The remaining replicates from GO1 and GO3 were submerged in deionised water. The samples were again dried at 60^{o} C until approaching mass equilibrium (<1% change over 12-hour period) in order to determine the amount of absorbed salt (Table V.1). One replicate from each specimen was then placed in one of two simulated environments (henceforth Environments A and B). Uncontaminated replicates of GO1 and GO3 were placed in the same environment as their contaminated replicates, one sample in each environment, to provide a control. The small number of control samples reflects the lack of working quarries and the limited availability of Reigate Stone; the control set was built from the more homogeneous GO samples.

Environment A was simulated in a Binder climate chamber. Conditions were programmed to cycle between an 18-hour period at 95% RH and 10° C, and a 6-hour period at 60% RH and 25° C for a total of 10 weeks, divided in to two phases of 5 weeks. After 1 week the samples were removed and loose material was brushed off using a stiff toothbrush. The samples were replaced. After 5 weeks the samples were again removed, and loose material was brushed off. The samples were then weighed, re-immersed in salt solution for 48 h, dried for 48 h, re-weighed and replaced under the same conditions for the second phase. The control sample was re-immersed in deionised water rather than solution. Loose material was again removed after 1 week and 5 weeks. This environment was chosen to stimulate rapid, sub-surface NaCl and $NaNO_3$ crystallisation, and simulate the Bell Tower stairwell, which was dominated by flaking.

Environment B was simulated in a Weiss climate chamber, with brief periods in a Sanyo and a Binder climate chamber due to technical issues. The samples were subjected to a first phase of continuous partial immersion, and a second phase of repeated partial immersion. In phase 1, the samples were placed in individual containers so that the bottom 1 cm was sealed, and the bottom 0.5 cm was in contact with approx. 0.5 ml of salt solution. The top 3-3.5 cm of the sample was exposed. The control sample was placed in deionised water rather than solution. Samples and containers were then placed in stable environment of 70% RH and 15° C for 6 weeks. After 6 weeks the samples were removed, loose material was collected and weighed, and the samples were dried for 48 h. For the second phase, partially immersed outside the cabinet in 0.5 ml of salt solution until the solution had been fully absorbed, and then replaced under the same conditions without individual containers. The control

sample was partially immersed in deionised water rather than salt solution. After 2 weeks the samples were removed, and loose material was brushed off using a stiff toothbrush. Partial immersion and replacement in the cabinet was repeated twice. During both phases, there were periodic, localised variations in RH and temperature due to technical issues, with RH dropping into the $NaNO_3$ crystallisation range for up to a week (Figure V.19). During phase one, these drops in RH were not evenly distributed around the climate chamber and affected some samples more strongly than others. This setup was designed to stimulate gradual NaCl crystallisation at the outer surface (although technical issues resulted in occasional drops into the $NaNO_3$ crystallisation range), and simulate the lower Bell Tower, which was dominated by powdering.

Loose material collected from the samples was dried, weighed, sorted by grain size and photographed to determine the nature of material (salt or stone) and the size of the largest detached fragment. Sorting was done using 1 mm and 0.25 mm sieves, with care taken not to break down detached grains further during sieving. The samples were also regularly photographed to document surface change.

V) 2.2.4.2. Results

Figure V.20 shows the weight loss and grain size distribution of individual samples following the successive cycles of the accelerated ageing programmes. Figure V.21 shows photographs taken of a representative selection of samples at various stages of the experiment. The same stages are not shown for each sample, instead a selection was made in order to best describe the various observed decay phenomena. Table V.1 shows total weight loss for each replicate of all samples, with additional data

on petrophysical characteristics taken from Chapter III.1. The samples responded differently to the two accelerated ageing regimes. Surface loss commenced in most samples subjected to the fluctuating RH of environment A after less than 1 week. Efflorescence formed on some samples during the continuous partial immersion phase of environment B, but only GA2 experienced surface loss. Besides efflorescence, some samples experienced surface loss during the repeat partial immersion phase of environment B. There was no loss or surface change recorded in the control samples, indicating that all measurable decay was in response to the salt contamination.

Specimen	Calcite content (%)*	Clay content (%)*	Porosity (%)*	Env. A salt uptake 1 (g)	Env. A salt uptake 2 (g)	Env. A total loss (g)	Env. A largest loss (mm)	Env. A largest loss type	Env. B salt uptake 1 (g) **	Env. B loss (g)	Env. B largest loss (mm)	Env. B largest loss type
GA1	28	6	27.6	12.4	0.6	2.03	15	Salt crust	11.8	0.3	3	Salt crystal
GA2	9	25	35	9.1	2.6	18.01	20	Stone flake	10.8	17.98	25	Stone flake
QF1	14	42	33.7	14.8	3.8	0.42	10	Salt crust	11.8	0.3	4	Salt crystal
QF2	19	8	34.5	14.6	2.3	0.69	18	Salt crust	14.5	0.37	4	Salt crystal
RS1	12	10	33.9	13	2.9	1.64	15	Salt crust	11.5	0.45	5	Salt crystal
RS2	18	6	33.9	13.9	3.1	0.34	12	Salt crust	12.1	0.33	5	Salt crystal
RS3	16	22	35.2	15.2	3.7	1.08	12	Salt crust	12.7	0.21	3	Salt crystal
GO1 ***	15	17	36.1	13.3	3.1	1.56	25	Salt crust	-	-	-	-
GO2	17	14	35.4	12.8	4.7	6.7	30	Stone flake	11.3	0.46	4	Salt crystal
GO3 ***	16	18	38.6	-	-	-	-	-	14.7	0.36	17	Stone flake

Table V.1: *Salt uptake, total loss, and type and size of largest lost piece from each replicate of every specimen in response to different accelerated ageing regimes. *Material characteristics taken from Chapter III.1. ** Additional salt uptake in environment B occurred during continuous and repeat partial immersion. ***no loss recorded in control samples.*

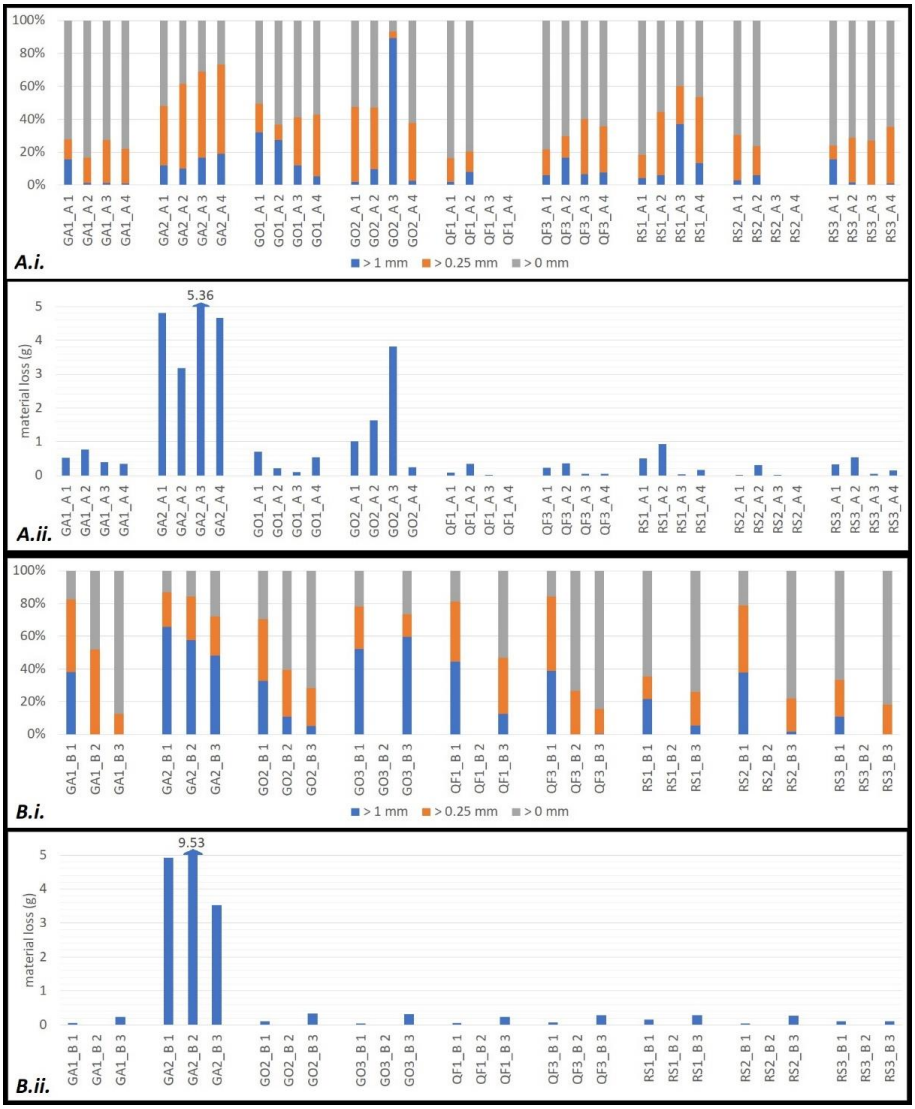


Figure V.20: *Grain size distribution (i.) and total loss, including salt, (ii.) at different stages of accelerated ageing regimes for environments A and B.*

The initial drying of samples prior to placement in accelerated ageing environments resulted in a thin crust formation. This rapidly detached in environment A, with the largest detaching piece in most samples consisting of films of salt crust lost during the first phase of RH fluctuations. In environment B, the crust did not detach during the continuous partial immersion phase and was still evident during the intermediate drying prior to the second phase of ageing. In GA2, cracks appeared in the crust during the intermediate drying. Following the subsequent round of wetting and placement in the cabinet at stable RH, this resulted in an explosive loss of surface material. The

initial and intermediate drying of samples was done in order to calibrate response to the distinct ageing environments; however, it is likely that their effect on the decay of the samples was as significant as the more long-term environmental simulations.

Environment A resulted in differential rates of material loss. These appear to be loosely governed by petrophysical characteristics, such as calcite and clay content and porosity, which can be linked to strength and hygric performance (see Chapter III.1). There are no immediately clear patterns, with the most argillaceous samples (QF1) losing only a small amount of material, and the most calcareous sample (GA1) losing a relatively large amount of material. Following the detachment of the outer salt crust formed during initial drying, the general pattern of decay in samples exposed to environment A more strongly resembles forms of severe powdering found on Reigate Stone in historic masonry. Only in GA2 did the general pattern of decay resemble the flaking encountered in historic masonry; however, this sample represents a highly clay, low calcite typology, which is unlikely to be representative of extant building stone (see Chapter III.1; also Sanderson and Garner 2001). During the second phase of humidity cycling, a large fragment of GO2 detached along a pre-existing structural fault. There are some indications that environment A was driving a decay mechanisms which broadly supports the hypothesis being tested, with frequent, high amplitude cycles in RH driving subflorescence, deliquescence and redistribution of salts; however, the pathways and rates of decay, and the emergence of distinct patterns, was more strongly linked to structural idiosyncrasies.



Figure V.21: *Three stages of decay in selection of samples exposed to environments A and B. Referencing system in Figure V.19 explains timing of photos. Rate and pattern of decay in both environments is strongly dependent on quarry provenance and individual stone characteristics. Loss of larger pieces of material usually related to pre-existing structural flaws (e.g. GO2_A and GA2_B), but some phenomena reminiscent of flaking seen in response to environment A (e.g. GA2_A and intermediate stages of QF1_A & RS1_A). Rate and homogeneity of surface decay in response to phase 2 of environment B strongly dependent on formation of salt crust during phase 1.*

In environment B, samples remained fully saturated throughout the continuous partial immersion phase. The amount of efflorescence was strongly dependant on the location of the samples in response to uncontrolled drops in RH; it was highest in GA1, which was closest to the source of the uncontrolled fall in RH. During this phase, a thick salt crust built up in some samples (e.g. GA2 and RS3). The presence of this crust strongly influenced ongoing decay during the second phase of environment B. During the repeat partial immersion phase, the samples were able to begin drying when replaced in the cabinet. This resulted in some surface loss. Surface loss on all but two samples placed in environment B was limited to small amounts of granular disintegration. In many samples, the majority of recorded loss during the second phase was in the form of salt crystals, with no significant loss of stone surface. The grain size distribution of material loss in environment B is strongly affected by the formation of these millimetric salt crystals. The pattern of ongoing efflorescence was strongly dependent on the formation of a crust during continuous partial immersion; samples in which a thicker crust formed (e.g. RS3) were prone to differential ongoing decay; samples in which there was little efflorescence or crust during continuous immersion (e.g. QF3) decayed more homogeneously during the second phase. Following the final repeat partial immersion and drying cycle, during which RH fell to 55% for 1 week, there was noticeably more material loss in most samples, including more granular disintegration. The salt crust also began to blister. One larger stone flake detached from the edge of G03 during this cycle. As with environment A, there were signs that a specific mechanism was being achieved, in this case surface evaporation and near surface crystallisation in response to ambient climate; however,

this did not result in the emergence of a specific decay pattern, with pathways strongly dependant on the particularities of the individual samples.

V) 2.3. Discussion

The results of this study indicate that incidents of powdering and flaking decay in the masonry of the Bell Tower cannot be fully reproduced on the basis of environmental controls alone. This echoes findings made in other studies which aimed to unpick the relevant weighting of stone type, salt type and environment in salt driven decay processes. Menendez and Petranova (2016) were unable to make clear correlations between the decay caused by mixed salt solutions on different lithotypes subjected to different environmental mechanisms. Yu and Oguchi (2009) suspected that individual stone-salt interactions could be a key control in diverging decay pathways. Whilst Lopez-Arce et al. (2008) were able to reproduce observed decay patterns in historic masonry using a methodological approach similar to the one presented in this study, their findings also highlighted the importance of reproducing accurate salt contamination and using comparable stone types in accelerated ageing tests. There was a strong reliance on relevant baseline data in the interpretation of results from these studies which is mirrored in this study. Given these specific factors, findings may be of limited use to a generalised model of stone driven decay. However, a step-by-step methodological approach which establishes laboratory conditions based on field data may be a useful framework for standardising future tests (Lubelli et al. 2018). Understanding limitations to methodologies such as the one presented here will help the ongoing development of such a framework.

The nature of salt crystallisation stimulated by the accelerated ageing regimes is likely to have been a key cause of deviation in the reproduced decay phenomena. The mixture used in this study was based on a simplified interpretation of measured ionic compositions from two environments. Differences in concentration and composition will have affected wetting and drying cycles and are likely to have influenced the emergence of decay patterns. The morphology of crystal formation can influence ongoing evaporation. Both theoretical and experimental evidence has shown that crust formation can reduce evaporation whereas patchy efflorescence can enhance evaporation (Veran-Tissoires and Prat 2014; Eloukabi et al. 2013). The high concentration of the mixture used in this study and complete saturation of the samples are likely to have resulted in a clogging of the pores during the gradual evaporation of samples in environment B (Espinosa-Marzal and Scherer 2013; Rossi-Manaresi and Tucci 1991). This 'crust formation' inhibited ongoing surface evaporation, both whilst the samples were in the climate chamber and during the intermediate drying. In the most extreme case of GA2_B, this resulted in a catastrophic flaking episode as subsurface decay caused the crust to collapse. In environment A, the order of crystallisation was reversed, with ECOS Runsalt predicting $NaNO_3$ crystallisation prior to NaCl crystallisation based on the sampling. The order in which salts precipitate out of a mixed solution should be taken into account (Charola 2000). The experimental methodology used in this study was designed to eliminate the potential variability of diverging decay pathways due to differences in salt contamination; the findings indicate that this approach cannot fully explain field behaviour. Different contaminating solutions can result in similar patterns, for example in the powdering upper and lower chambers of the Bell Tower, and single

salts can induce both flaking and powdering depending on environmental conditions (Amadori et al. 1990). However, unifying complex solutions in order to recreate dissimilar patterns may have excluded crucial components of the underlying chemistry.

The thermodynamic models produced here also expose some contradictions within the overall hypothesis of environmentally driven decay. The ionic concentrations measured in powdering samples from the lower chamber are representative of detached material, but not necessarily of the overall composition within the masonry. Composition is likely to be skewed towards salts which have crystallised near to the surface and detached along with powdering stone (Sawdy and Price 2005a). However, despite the noticeable seasonal change in measured ionic composition of material collected from the pier, ECOS Runsalt predicts only NaCl crystallisation in both winter months and summer months. This indicates either the introduction of new contaminates throughout the year, or a significant redistribution of salt concentration within the masonry across the year, or it suggests decay mechanisms which are not explained by the crystallisation scenarios predicted in Runsalt, such as additional crystallisation or phase change activity, hygric swelling of clay, or thermal activity. There are similar contradictions exposed by the flaking episodes during winter months monitored in Chapter V.1, at times when RH is unlikely to have dropped within the range predicted to result in crystallisation by Runsalt. The proximity to a wooden spiral staircase and the vibrations and abrasions this causes is likely to represent an additional cause of detaching material. Whilst the hypothesis tested here can explain the general direction of decay pathways, contradictions within the model imply that

there are additional environmental and contextual factors which contribute significantly to the phenomenology and pattern of decay.

Further constraints to the methodology exist within the limitations of accelerated ageing in climate chambers, and the upscaling of phenomena recorded in experiments to identify corresponding patterns in historic masonry (Hall et al. 2012). The use of cores reduces some of the edge phenomena often encountered with small, rectangular samples in accelerated ageing tests (Lubelli et al. 2018). However, the geometry of the samples is fundamentally different from the historic masonry in the Bell Tower; this will be reflected in the shape and scale of moisture transport dynamics. Dry weight loss does not always provide a good indication of decay taking place within a porous network. Wave-length velocity has been proposed as an alternative or complementary indicator (Benavente et al. 2007b). Limitations to this technique were encountered in this study relating to the comparison of measurements at different stages of the experiment, and the influence of any additional drying or wetting to make the samples more comparable. The grain size distribution approach adopted from Goudie (1986) provides a useful additional metric, but care must be taken to differentiate detached stone from salt. Ongoing work can include a destructive analysis of the samples and a comparison of pore structure with comparative samples that have not been aged.

Past studies have associated pore-size distribution and other physical characteristics with resistance to decay and the emergence of decay pathways (Dewanckele et al. 2013, Benavente et al. 2007b, Charola 2000). Differences in the pore-size distribution within single materials have been linked to specific decay patterns as a result of

resistance to crystallisation pressures, (Rossi-Manaresi and Tucci 1990). These can explain the detachment of a surface crust or the emergence of alveolar weathering in heterogeneous stone. Similarly, the presence and distribution of clays in compact stone can result in distinct patterns determined by their structural alignment (Aires-Barros et al. 1998). Pre-existing petrophysical factors can explain the different decay rates and slight divergence in decay patterns observed in the Reigate Stone samples used in this study. Past studies have suggested the relative presence of clays and calcite is likely to be a major control on resistance to decay (see Chapter III.1; also Sanderson and Garner 2001). Both function as pore filling cement, with calcite also improving strength characteristics and clay improving moisture retention. They are likely to impact differently on the overall shape and heterogeneity of the porous matrix; the rapid decay of GA2_A/B in this study could be linked not only to its weaker, clay bearing matrix, but also to a higher proportion of small pores and higher interconnectivity due to less clogging by calcite. This would place more clay bearing Reigate Stone within the most at-risk category identified by Benavente et al. (2007b). The results of this study clearly indicate that in addition to any hypothesis on environmental control, a hypothesis on material control must be incorporated into models of salt driven decay in Reigate Stone; this confirms observations made on the exterior masonry of the Bell Tower, where powdering and flaking decay patterns correlate to visibly different stone types.

The powdering of stones in the west and north facing elevations of the Bell Tower may be further linked to the formation of an outer crust or casing, which historic photos suggest occurred in response to sulphation in the 19th century. Previous studies have shown that gypsum crust formation depletes calcium ions from the

subsurface of calcareous stone (Charola 2000). When the relatively harder outer layer erodes or detaches, the weakened subsurface is prone to rapid granular disintegration. This decay pathway would explain the presence of alveolars (Bruthans et al. 2018; Mol and Viles 2012). The underlying mechanics, with capillary migration maintaining a relatively steady state at the exposed surface, could be covered by the hypothesis tested here (Lewin 1982); a similar process could explain the collapse of sample GA2_B in this study.

The complicating factors in interpreting the results of this study reveal deeper complexities within the current conceptual framework of salt driven masonry decay. Pasts studies queried the accepted mechanics of Na_2SO_4 driven decay, and the relative role of crystallisation and hydration pressures induced by phase change (Flatt 2002; Rodriguez-Navarro et al. 2000). This led to greater appreciation of the role supersaturation plays in accelerated ageing experiments. There is still acceptance within the field that salt driven decay is not fully understood (Flatt et al. 2017). Current thermodynamic modelling approaches may be insufficient at fully describing interrelating processes. Even within the framework of existing models, the minute differences and continuous fluctuations between moisture in porous networks and ambient RH can render the predictive capabilities of software such as ECOS imprecise at best (Franzen and Mirwald 2004).

These issues reflect similar challenges encountered during previous developments of the conceptual framework, some of which were made during a study of Reigate Stone masonry at the Tower of London (Price 1993; Price 2007). Parts of the Wakefield Tower were found to be heavily salt contaminated. In an initial study, based on semi-

quantitative analysis, Price (1993) tentatively proposed humidity regimes for stabilising the salts present in the masonry. In a later study based on the then newly developed ECOS thermodynamic model, Price (2007) found that the proposed regimes (which had not been implemented) would have been potentially damaging due to unforeseen crystallisation scenarios. In any case, implementing room-scale RH regimes at historic tourist sites has proven highly impractical. Church (2003) found ambient RH in the Wakefield Tower to lie within the range later predicted to be most damaging in the ECOS model. The most heavily contaminated and rapidly decaying masonry was treated with *Brethane* in 1984 (Sanderson and Garner 2001). Inadequate pointing is thought to have contributed to the increased contamination of this south-west lying masonry. The decay rate was shown to have probably increased since treatment. Silanes can increase salt crystallisation pressures in contaminated samples (Ruffolo et al. 2017). This example serves to highlight the complexity of predicting decay and conserving salt contaminated masonry. Even frameworks that account for the thermodynamics of complex salt solutions are of limited value unless they can integrate real world idiosyncrasies such as past treatment history and account for the practicalities of building use.

V) 2.4. Conclusion

The aim of this paper was to determine the role of environmental conditions on the emergence of decay patterns in Reigate Stone, by simulating typical salt-laden environments which appear to contribute to rapidly decaying Reigate masonry and subject a range of mineralogical typologies to accelerated ageing tests. The focus was on the Bell Tower, which contains Reigate masonry in a range of different

environments and of likely different mineralogical typologies, displaying powdering and flaking decay patterns.

Distinct types of complex, mixed salt contaminations are present in different areas of the Bell Tower; however, thermodynamic modelling suggests only two salts are likely to crystallise under ambient conditions. NaCl crystallisation is likely to be occurring in powdering masonry in the lower chamber. In the flaking masonry of the stairwell $NaNO_3$ crystallisation is likely, with NaCl crystallisation occurring during more pronounced drops. These findings were used to test a hypothesis that powdering is controlled by continuous surface evaporation of saturated masonry at relatively high, stable RH, whilst flaking is controlled by subflorescence in response to a variable moisture profile within the masonry and repeated cycles in RH.

Correlating these crystallisation scenarios with the distinctive patterns of decay observed in the Bell Tower is challenging. There are some indications that the mechanics of decay can be replicated in laboratory conditions. Simulated environment A was characterised by frequent, sharp drops to 60% RH to stimulate $NaNO_3$ crystallisation, followed by longer periods of 95% RH to stimulate deliquescence and redistribution of the solution. This caused rapid decay of weaker Reigate Stone samples, as well as the detachment of larger flakes in weaker samples or along structural imperfections. This bears some resemblance to the aggressive pattern of flaking decay found in parts of the stairwell. Simulated environment B, designed to mimic powdering in the lower chamber, caused efflorescence when samples were in continuous contact with moisture, and differential rates of loss in response to different RH during drying. This corresponds with phenomena observed

in the field. However, viewed in comparison the distinct environments cannot be said to have had a controlling effect on the emergence of decay patterns. Most samples decayed through loss of surface powder, suggestive of near surface crystallisation. Isolated incidents of flake detachment along pre-existing structural imperfections, suggestive of subflorescence, occurred in samples placed in both environments. Widespread subflorescence only occurred in the weakest, most porous sample. Whilst this resulted in immediate surface loss in the aggressive, fluctuating environment A, the response in the stable environment B implied gradual decay beneath a harder surface crust building up to a catastrophic collapse of material. The emergence of distinct decay patterns in response to wetting and drying was therefore governed by stone type and pre-existing structural characteristics, with the specific environmental conditions in this study only affecting the rate of decay.

The implication of these results is that the emergence of decay patterns in Reigate Stone cannot be explained solely by environmental mechanisms; baseline petrology and historical contingency can play a crucial role. Anamnesis of distinct decay patterns in Reigate Stone masonry can therefore not function as an independent method for diagnosing underlying decay mechanisms and designing conservation strategies based on environmental control. Whilst environmental controls may provide a conservation strategy in some cases, it is likely that detailed assessment of the specific dynamics of salt contamination, environmental parameters and material characteristics will be necessary in every case. With some further development, the methodology presented here should provide an effective contribution to such an assessment.

VI. Re-framing resilience: Towards a new Landscape

"The business of Architecture is to establish
emotional relationships by means of raw materials,
(…) passion can create drama out of inert stone"

Le Corbusier, *Towards a new Architecture* (1927, p.4)

This concluding chapter ties the narrative thread which began in the literature review back together. It references Le Corbusier's *Vers une Architecture* (1923), a manifesto on architecture at the dawn of a new technological era. Le Corbusier sought a fundamental change in how humans interacted with buildings.

VI) 1. Summary

This chapter brings together the separate strands of the thesis, synthesises a narrative, and discusses the implications of this research. It first summarises the main findings made in Chapters III-V, and briefly places these within the context of the frameworks constructed in Chapter II. It then recounts an architectural history of the Bell Tower in order to realign these findings to a broader narrative. This critically evaluates the role of scientific research in the historic built environment by reassessing the significance of the quantifiable system constructed in this thesis to the overall dynamics of decay and deterioration in a historic architecture. The subsequent section discusses how the findings made in this research project fit together and proposes a small but significant paradigm shift. This builds more overtly on the frameworks set out in Chapter II. It describes how an enhanced understanding of vulnerable masonry can improve the resilience of cultural landscapes. The chapter ends by framing this outlook in a set of methodological and practical recommendations for the ongoing research and conservation of Reigate Stone.

The overall aim of this thesis was to facilitate the development of sustainable conservation strategies for Reigate Stone. Reigate Stone was widely used in medieval London at sites such as the Tower of London and Westminster Abbey. Much of what remains is in a vulnerable condition. Developing sustainable conservation strategies requires a scientific understanding of the mechanisms driving decay, the impact of decay processes upon the stone, and the corresponding effects in the wider context of historic masonry and built heritage. This can be used to identify controls and ultimately improve the resilience of the historic built environment. The specific

research objectives were (a) to better understand the composition of Reigate Stone masonry, including lithological variations, historical developments, common contaminations, and decay patterns, (b) to assess past and present conservation strategies, and (c) to characterise decay and link processes to measurable environmental mechanisms.

The methodological framework combined laboratory experimentation, field work and archival research. This enabled an analysis of Reigate Stone within a conceptual framework which defined vulnerable historic masonry along three axes of variability: material, environmental and historical. Underpinning the methodology was a progressively detailed series of site surveys at the Tower of London and Hampton Court Palace, two of the major sites with significant amounts of extant Reigate Stone. These surveys facilitated the gradual identification and investigation of representative sites and samples. This centred on two buildings at the Tower of London. (1) The Wardrobe Tower, a highly exposed ruin with 12th century Reigate Stone ashlar in advanced stages of decay. Conservation work was carried out near the beginning of the DPhil project, using an approach common to contemporary Reigate Stone conservation. (2) The Bell Tower. Also containing 12th century masonry, but with a more varied environment and several mineralogical types of Reigate Stone showing different decay patterns. Additional field work was done at HCP and on a test-wall built at the Tower in 2001. This broad approach integrated a diverse documentary history into the research and enabled a better calibration with experiments conducted in controlled environments. The resultant studies were structured to fit a narrative arc, which began by focussing on the stone itself, and progressively broadened to eventually frame a comprehensive interconnected system.

Chapter III focused on Reigate Stone itself, examining its mineralogy, and history of use and conservation.

In **Chapter III.1** the causes of inherent variability in Reigate Stone masonry were investigated. Inherent variability can result in highly heterogeneous present-day condition within individual sites, buildings or even single walls. This can obscure causes and rates of decay, which complicates conservation. Historical analysis of Reigate Stone construction and repair was combined with material analysis of its physical characteristics in order to build a timeline of use which can explain diverging decay pathways.

- Reigate stone used in medieval construction displays high lithological variability. This variability is present at individual sites and in some cases even in individual buildings. It is a key contributor to the differential decay rates and decay patterns observed in historic masonry.
- Physical variability can be defined along mineralogical composition; calcite content can be associated with durability and clay content with vulnerability.
- Use of the most suitable building stone lithologies can be associated with an initial phase of quarrying and construction (pre C13). The supply of good quality stone could not match growing demand. This introduced lesser quality building stone, which decayed more rapidly. Consequently, confidence in the use of Reigate Stone diminished in C16.
- Decay rates increased in C18 and C19 following changes to London's atmosphere and the introduction of unsuitable replacement and repair materials, such as harder (non-Reigate) stone and cementitious mortars.

Chapter III.2 presented the more recent history of Reigate Stone conservation, and focused on evaluating three past techniques: wax, limewash and Hydroxylating Conversion Treatment (HCT). Minimally-destructive testing was performed at a test wall built to trial HCT in 2001, and a representative selection of other locations at the Tower of London and Hampton Court Palace.

- Past treatments have been largely unsuccessful. The most promising techniques improve the underlying durability of calcareous stones. It is not clear that any treatment is suitable for more vulnerable stones.
- Limewashing should be incorporated into future test walls to assess its suitability more fully.

Chapter IV moved beyond the stone itself to investigate interactions taking place within the masonry system and begin analysing the mechanics of decay.

In **Chapter IV.1** non-destructive techniques (NDT) were used to assess the moisture regulation of Reigate Stone masonry at the Wardrobe Tower over a two-year period following conservation work. The objective was to establish the role of pointing mortar type, by comparing soft lime putty mortar (current best practice) and natural hydraulic lime mortar (NHL) used in recent work with older NHL pointing. Effective pointing mortar aids moisture regulation by drawing moisture out of the edge of a block through the mortar joint.

- Combining an extensive use of different NDT with more traditional surveying techniques can enable a multi-scale evaluation of a masonry system. This can form the fulcrum of a science-based approach to understanding real-world masonry dynamics.

- There was evidence that lime putty performs better than new NHL mortar, which can trap moisture at block edges. Old NHL performed similarly to new putty, suggesting NHL may age sympathetically.
- Contextual factors, such as the aspect and topography of the masonry, outweigh the role of mortar type in local moisture regulation.
- In order to maximise long-term benefits and prevent frequent intervention, repointing must be part of a more holistic conservation strategy, which also protects repointed masonry from ongoing, rapid moisture ingress due to other contextual factors.

In **Chapter IV.2** a model of the Wardrobe Tower was built using the hygro-thermal simulation tool WUFI 2D, in order to investigate more closely the different pointing mortar scenarios identified in the field surveys.

- Joint width outweighed the role of mortar type in minimising moisture fluctuations at block edges, providing further evidence that interventions need to be weighed up carefully in order to balance long-term benefits with the potential for short-term damage of repointing works.
- There was evidence that galletting joints could mitigate prolonged, deep wetting in wider joints. This technique should be investigated further in ongoing research.

Chapter V increased the scale of investigation again by examining more closely the environmental dynamics that underly decay.

Chapter V.1 combined rapid NDT with long-term monitoring of micro-climatic variation at the Bell Tower, in order to associate specific micro-climates with observable patterns of decay.

- Distinct flaking and powdering decay patterns in Reigate Stone were associated with specific, moisture related, environmental mechanisms and salt contamination. Powdering was linked to deep wetting and a steady zone of near surface crystallisation. Flaking was linked to fluctuating humidity and a dynamic zone of sub-surface crystallisation.
- There were indications that material properties and historic contingency may contribute to these divergent decay pathways.

In **Chapter V.2** the environments investigated in the previous chapter were examined more closely, in order to determine the role of the environmental mechanisms monitored in the previous section in the emergence of the distinct decay patterns. A direct, positive correlation would enable the design of preventive conservation strategies, by providing a link between the identification of decay patterns and controlling mechanisms to disrupt decay pathways. A three-step, mixed methodology was used to analyse the salt content of the masonry, formulate a mixed salt solution representative of contamination in both environments, and then subject a range of Reigate Stone types to two different accelerated ageing tests designed to simulate each environment.

- Whilst different, complex salt solutions are present in both environments, only a small number of salts are likely to crystallise under the monitored conditions. Whilst, this enabled the design of a unified solution based on NaCl and $NaNO_3$,

removing variability in salt contamination may have oversimplified underlying dynamics.

- The accelerated ageing tests provided some indication that the decay mechanisms identified in the previous chapter were achieved; however,
- Material properties and pre-existing decay features were more important in the emergence of distinct decay phenomena; these are likely to correspond to differences in porosity and strength.
- Observable decay patterns are not a clear indicator of underlying decay processes. Each case is likely to require specific investigation in order to identify a suitable conservation approach.

The overall implication of these findings is that past treatment and decay, present environment, and underlying lithology each contribute to ongoing decay. This project has shown that, when used in conjunction with findings made in laboratory and archival contexts, non-destructive field survey techniques, such as handheld moisture and surface hardness devices, can form a robust methodology for understanding the relevance of each of these axes of variability. By linking together several studies at different scales, which focus on describing no more than two of these axes within a single study, this thesis was able to triangulate a complex interconnected system and investigate it in meaningful detail. The conceptual ternary plot introduced in Chapter II.1 can be refashioned to diagrammatically explain this approach (Figure VI.1). Each individual study in the thesis is plotted according to the weighting of variables being investigated; the overall spread covers what was described in Chapter II as the framework for scientific inquiry. This scientific understanding can be used to identify

controls within the system dynamics of masonry decay, which is the first step to developing sustainable conservation strategies.

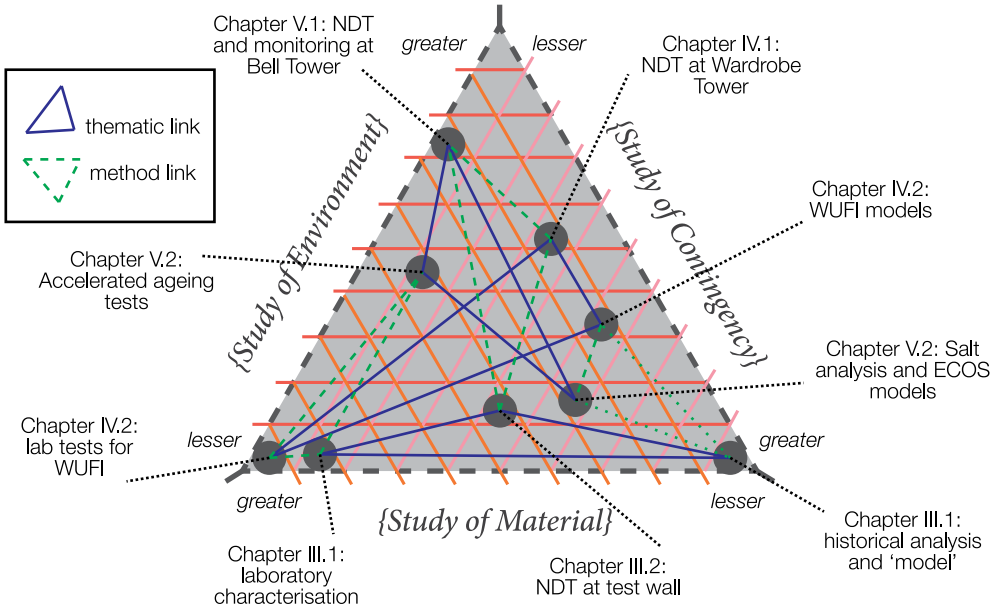


Figure VI.1: *The relative weighting of, and links between individual studies in this thesis overlaid on the conceptual axes of variability introduced in Chapter III. The integrated methodological approach achieves a broad, robust spread of investigation.*

Beyond the specific discoveries made within this scientific description, the thesis has framed the decay of building stones within a wider context. This has enabled an appreciation of changing values in the historic built environment. These can result in changing attitudes to conservation and repair, which themselves can be out of synch with the timeframe of decay processes. This demands greater understanding of the interplay between societal and environmental change and the way in which they are reflected in built environment. In order to draw this interplay into focus, the following section of this chapter will trace the architectural history of the Bell Tower, one of the oldest buildings at the Tower, and observe changes to the built fabric through the prism of this thesis.

VI) 2. Antithesis: A history of Reigate Stone at the Bell Tower

VI) 2.1. Introduction

The Bell Tower was built c.1190-1200 at the south-west corner of the inner curtain wall, during the first major expansion of the Tower of London (Parnell 1993). Approximately 20m in height, it contains an upper and a lower chamber. Both exhibit fine masonry in Reigate Stone, with the asymmetrical vaulted ceiling of the lower chamber amongst the earliest ribbed vaults in the country. Externally, much of the masonry is thought to date to primary construction, with a significant proportion of Reigate Stone remaining. These reasons, along with a colourful history, which may have included the imprisonment of Thomas More in the 16th century and certainly included the brief internment of Rudolf Hess in 1941, have afforded the Bell Tower Grade I listing and 'exceptional significance', the highest classification within the Tower of London Conservation Plan (Kennedy 2010; Appendix B). Much of the external, primary Reigate Stone of the Bell Tower has been replaced and the building has undergone significant alterations in its 800+ year history; viewing these through the lens of Reigate Stone provides a unique insight into societal and environmental change, and the interplay between decay and deterioration in historic architecture.

VI) 2.2. Construction

The Bell Tower occupies an octagonal footprint, which at the time of construction would have projected into the Thames (Parnell 1993). It may have been built on the base of an existing Roman mural tower. As with other early buildings at the Tower of London, the robbing out and re-use of material from the adjacent Roman wall and

ancillary buildings is a distinct possibility. A plinth of offset Sussex Marble courses offered some protection from high tides and suggests an early understanding of the limitations of Reigate Stone[11]. Above this, the tower was originally faced with squared ashlar of Reigate to a height of approximately 8m. Reigate quoins continue to a height of 14m, at which point the tower becomes cylindrical.



Figure VI.2: *Bell Tower elevations A and B* ***(top left)****, elevations B, C and D* ***(bottom left)****, and elevations E and F* ***(right)*** *photographed in 2016. (Author)*

Extant Reigate Stone can be divided in to two types, visibly different both in their colour and their pattern of decay. Elevations A-C (Figure VI.2) contain mainly grey-green stone, with varying amounts of a darker grey surface crust, probably resulting from sulphation. Where the crust has detached the stone is powdering and alveoli are forming. Elevations D-F (Figure VI.2) contain a lighter grey stone, which is decaying via

[11] This understanding was not demonstrated in the Wakefield Tower, built 30 years later and with its lowest courses of Reigate Stone exposed to the tides.

the detachment of larger flakes. Rather than exhibiting a distinct crust, original surfaces are partially soiled. The upper part of the octagonal section and the entire cylindrical section are faced predominantly in Kentish Ragstone rubble. Remaining medieval arrow-loops are carved from Caen Stone in elevations D and E and from Ragstone in elevation C. These changes in building shape and stone type suggest there may have been breaks in construction.

As discussed in Chapter III.1, the local quarrying industry was experiencing rapid growth in the late 12th and early 13th century. This was in response both to increasing demand from London's monumental building projects and possibly also to declining supply of Normandy's Caen Stone due to the loss of the French possessions. Shifting availability and favourability among different Reigate quarries, or even between Reigate Stone and Kentish Ragstone, would have been likely over the course of a lengthy construction project, especially following any building breaks. Different master masons would have responded to changes in budget and timing and called upon their own existing network of suppliers. It was not until the next major phase of expansion, in the mid-13th century, that a quarry was specifically opened for the Tower of London.

VI) 2.3. Medieval and early modern changes

Whilst there is no clear archaeological evidence, it is inferred that following the construction of the outer curtain wall in the late 13th century, cross walls were built between the Bell Tower and the outer walls to form a gateway around what then became the main landward entrance to the Tower site. These are believed to have run east to west from the south half of elevation B, and north to south from the west

half of elevation D. This period would also have seen the infilling of the lower 3-4m of the Bell Tower to construct a new embankment which, besides a 20th century excavation at the base of elevation F, remains the ground level to this day.

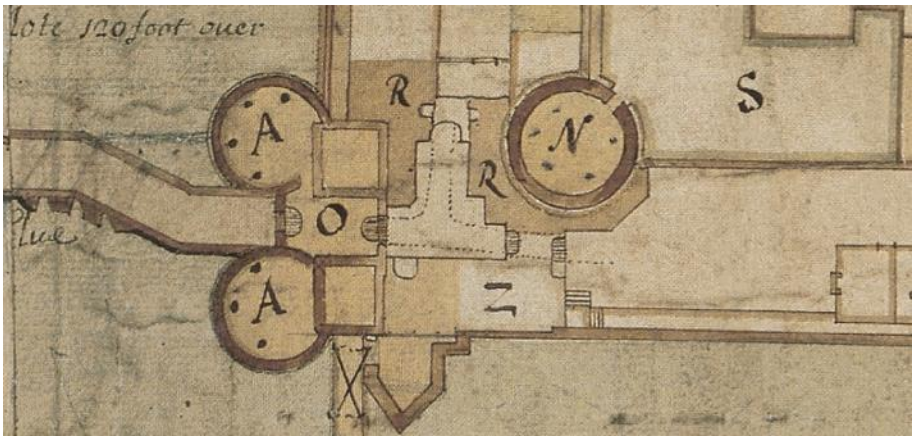


Figure VI.3: *Close-up of 1682 survey showing south west corner of Tower of London. Bell Tower (N) surrounded by later additions forming gatehouse (R). (HRP archives)*

The earliest survey drawings of the Tower of London indicate that the cross walls had been replaced or augmented with gabled structures by the late 16th century (Figure VI.3). Initially, these appear to have been porters' lodgings associated with the adjacent Royal Mint, but from the mid-17th century they housed two alehouses, *The Bunch of Grapes* to the south and *The Stone Kitchen* to the west. The first orthographic survey in 1682 clearly shows the location of these buildings in ground plan, along with another structure abutting elevation A. Read in conjunction with an isometric drawing dated to 1688, it appears that buildings completely enclosed the lower part of the Bell Tower up to different heights on each elevation. This situation persisted until 1796, when *The Bunch of Grapes* was demolished due to danger of collapse (TNA 14/4/4)[12]. This presumably re-exposed elevations D-F. *The Stone Kitchen* was documented in T.

[12] There are documents dating back to the 1780s which discuss the poor condition of *The Bunch of Grapes* and the southern gateway, but work appears to have been expediated when a falling stone struck a footman in November 1796!

H. Shephard's 1846 watercolours[13], and probably pulled down in 1851. Other than a small stone store built up against elevation A until the 1940s or 50s, this appears to have completely re-exposed the Bell Tower. For several centuries, these buildings would have sheltered much of the Reigate Stone masonry from the elements, whilst simultaneously exposing it to a variety of micro-climates at which we can only guess[14].

The patchwork masonry of elevation B offers some clues to early repair and restoration in response to these medieval changes to the fabric. Whilst the lower left side retains primary Reigate ashlar, with small amounts of Chilmark replacement in the bottom courses, the right side is almost completely made up from three or four successive phases of replacement blocks. This area probably corresponds to the historic junction between the demolished medieval fabric of the cross wall and *The Stone Kitchen*, and the Bell Tower.

The first phase of repair appears to have been made with large ashlar blocks of Reigate Stone, identical in colour to the green-grey Reigate used elsewhere in north and west facing elevations. This work could correspond to damage caused by the demolition of the cross wall to enable the construction of the gabled structure sometime in the 16th century. This would predate the availability of other freestone types in London. As discussed in Chapter III.1, external use of Reigate Stone had fallen out of favour by this time. Repairs might otherwise have been carried out in Kentish Rag or even brick had the wall not been immediately enclosed. The large ashlar blocks of Magnesian

[13] These provide a valuable record of the Tower of London before much of the remaining late medieval fabric was demolished in the mid-19th century, tantalisingly close to the advent of photography.
[14] The consequences for a stone wall of existing next to an alehouse are probably best left to the imagination. Suffice to say, chapter V uncovered high concentrations of nitrates in parts of the Bell Tower.

Limestone, which intersect the replacement Reigate ashlar, must correspond to repairs made after the demolition of *The Stone Kitchen*; Magnesian Limestone was used in London from the mid-19th century onwards.

The large ashlar blocks sit as high as, and to either side of the replacement arrow-loop (Figure VI.4). From the historic surveys and paintings, it seems the gable of *The Stone Kitchen* would have reached the height of the lowest string course, indicating it would have blocked off the opening. The arrow-loop is likely to have been restored shortly after demolition of *The Stone Kitchen*. A plan dated July 1903 appears to be for a more substantive and stylistic restoration of the lower chamber (Figure VI.5). It is possible that the present situation is the result of a pared down implementation of this plan; however, it seems more likely that the plan was for an uncompleted project and the Portland Stone blocks, which actually form a blind window, date to the mid-19th century.

Engravings and photos of the lower chamber indicate that various alcoves of the lower chamber were blocked in or blocked off at different times throughout much of at least the 19th and early 20th centuries (Figure VI.6). The floor-height of the chamber is also known to have changed by up to a metre at least twice. Photos indicate that these sudden changes resulted in damage to the masonry. Furthermore, they are likely to have significantly altered micro-climatic dynamics, such as airflow and humidity. Following its use as a prison, the lower chamber was for some time used as a kitchen, with ovens installed into the blocked-in alcoves. These, or indeed a subsequent use as a storage for large wooden objects, may have been the cause of a hypothetical fire, believed to have caused the red discolouration to large areas of Reigate masonry. The

historic evidence suggests that, as with the buildings surrounding the Bell Tower, the lower chamber underwent several changes in form and function throughout the medieval period, which can be linked to episodic, high impact changes to the fabric.

These changes resonate with findings made in Chapter V, which focused on salt contamination and micro-climatic variability in an assessment of decay processes at the Bell Tower. They indicate that linking high frequency, low magnitude processes to ongoing mechanisms cannot adequately explain the present state of the fabric. Viewed across longer timeframes, the overriding effect of high magnitude, low frequency processes become clear; however, in the historic built environment these processes tend to sit outside of the defined stone-environment system.

VI) 2.4. Late 19th and 20th century changes

Returning to elevation B, squared Kentish Ragstone rubble sits inside the area of Magnesian Limestone replacement, suggesting a subsequent repair phase. The stonework is faintly visible behind a thick layer of sulphation in a photo from the early 20th century (Figure VI.7). Whilst it is hard to make out, the Kentish Ragstone does not appear to be present in the photo. Examining other areas of the Bell Tower, and the changes that are recorded in photographic evidence, can help to further understand the processes of deterioration and repair which led to the building's present-day appearance.



Figure VI.4: *Close-up of elevation B in 2018 showing areas of successive replacement to right of image. (Author)*

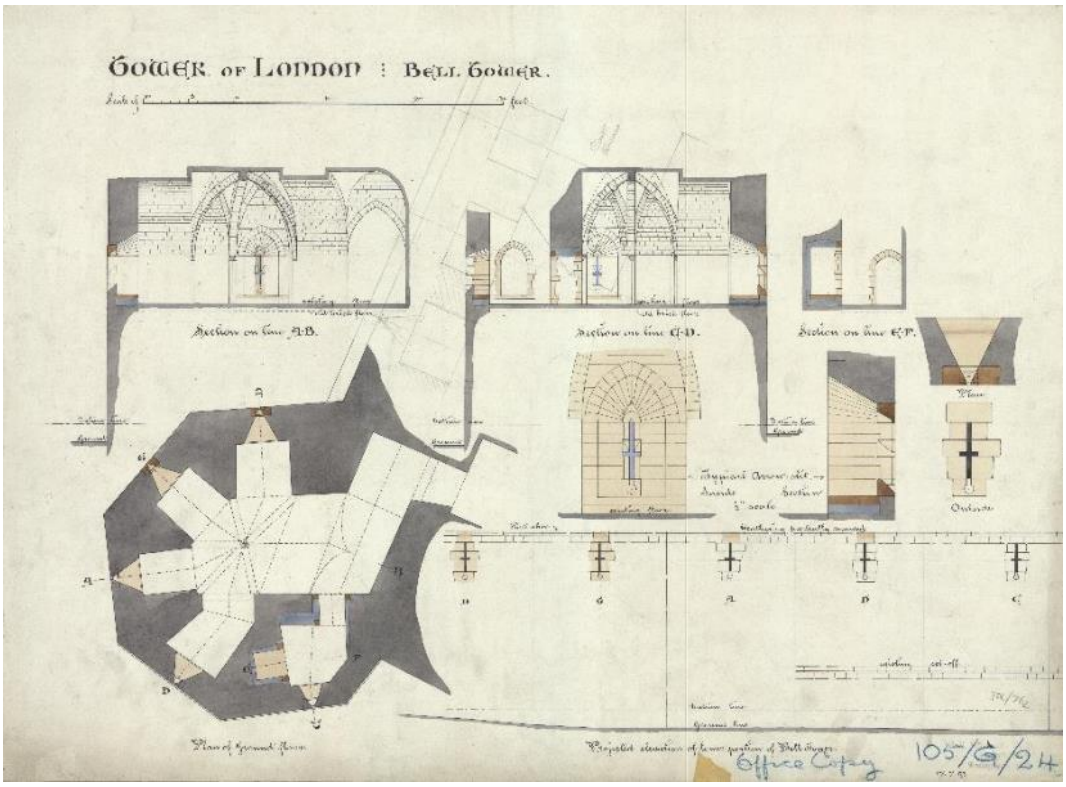


Figure VI.5: *1903 unrealised plan for restoration of Bell Tower, lower chamber. (HRP archives)*

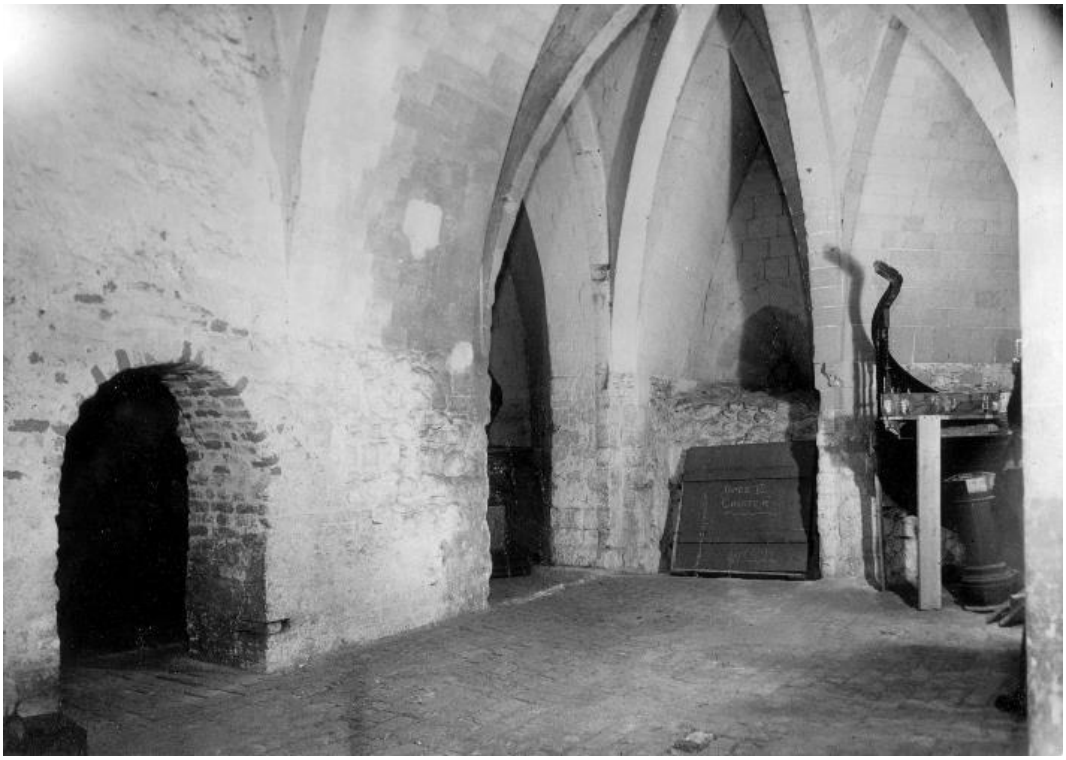


Figure VI.6: *Photo of lower chamber from the 1940s, showing higher floor level and blocked in alcoves. (HRP archives)*



Figure VI.7: *Elevations B and C, early 20th century. Some extant replacement stones can be seen behind a thick layer of sulphation. (Historic England, with permission)*

The earliest photos, which date to c.1870, show areas of mostly Magnesian Limestone replacement in the lower parts of elevation E in between partially extant Reigate Stone (Figure VI.8). The replacements imply that masonry had deteriorated following re-exposure since the demolition of *The Bunch of Grapes*. The extent of decay necessary to demand this replacement is unclear. Of the Reigate masonry visible in the historic photos, the bottom courses, which were later also replaced with Magnesian Limestone, are heavily decayed. Elsewhere Reigate blocks appear to be completely intact. Particularly noteworthy are the blocks to the lower left corner, which were selected for the HCT trials in 2000. In the earliest photos they appear fully intact, with surface erosion appearing progressively in later photos. The possibility that these remarkably sound Reigate blocks are in fact late 18th or early 19th century replacements themselves should be considered. They are visually similar to stone which is known to have been used in mid-19th century bridge building, extracted from the Merstham mines when these were vastly expanded thanks to technological advance enabling the lowering of the water table (examples from Quarry Field were analysed in Chapter III.1). Whatever the date and provenance of the extant Reigate blocks, it seems that Reigate masonry at the Bell Tower may have been resilient to change for over 600 years before undergoing rapid deterioration due to the consequences of changing environmental and societal pressures. Rapid decay may partly have been in response to the change in moisture dynamics caused by the newly surrounding harder stone.

Early photographic evidence also shows that the upper half of the Bell Tower was covered in a thick pebbledash plaster from at least the late 19th century until the 1910s (Figure VI.9). A contiguous layer appears to come down as far as the base of the arrow-

loops and was probably applied to give the building a unified appearance after the removal of the late medieval fabric. Remnants of a plaster with slightly smaller aggregate are also visible attached to decaying stonework in masonry below the height of the arrow-loops. In photos dating to the first decade of the 20th century, the plaster is detaching along the quoins, revealing decayed Reigate Stone. Falling plaster is mentioned in a survey carried out in 1910 (TNA 14/174). By the time of a series of photos dated to the mid-1920s, the plaster has been removed and the process of replacing the Reigate quoins with Chilmark is underway.

As with Magnesian Limestone, replacement with Chilmark occurred in at least two phases; decayed quoins, presumably Reigate Stone, are still present in photos dating to the 1940s (Figure VI.10). The later phase may correspond with Chilmark replacements in lower parts of the Bell Tower. One area of replacement marks the silhouette of the small stone store built against elevation A. Whilst the rest of the elevation is heavily sulphated in these photos, much of the Reigate Stone has survived today, bearing its distinctive greyish crust as a scar from that time (Figure VI.2 top left). Ironically, it was the area which was apparently sheltered from the worst of the 19th century pollution which was deemed most needing of repair. This suggests that these blocks may have decayed rapidly following re-exposure.



Figure VI.8: *Photo of elevations D and F (c.1870) showing partial replacement of Reigate Stone with Magnesian Limestone. Four Reigate Stone blocks later incorporated into HCT trials are fully intact on right of picture. (Historic England, with permission)*



Figure VI.9: *Photo looking west dating to the 1910s showing the pebbeldash render beginning to detach along the Reigate quoins. Differential levels of soiling can also be seen to either side of the Virginia Creeper. (Historic England, with permission)*



Figure VI.10: *Photo looking south dating to 1940s showing persistent sulphation of elevations A and B. A small stone structure can be made out adjoining the base of elevation A. (HRP archives)*

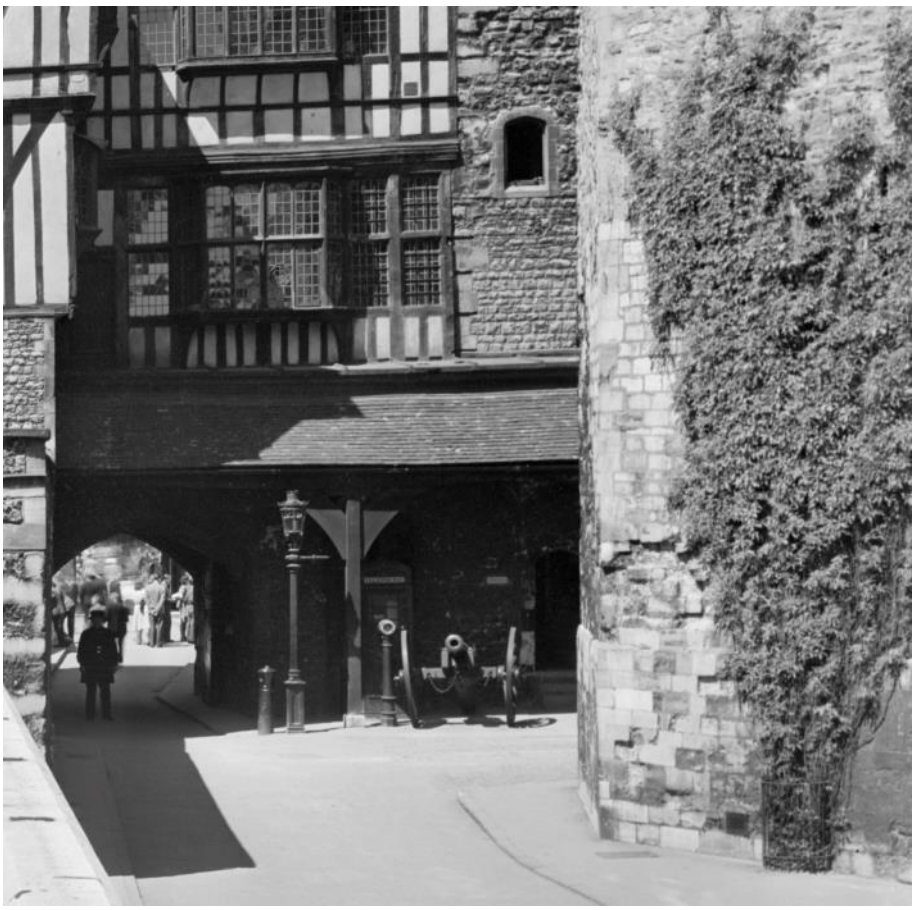


Figure VI.11: *Photo of elevation E (1947), showing recent replacement being covered by growth of Virginia Creeper. Erosion of future HCT trial area can be seen (compare Fig. 7). (Historic England, with permission)*

Replacement stone in elevation B is already heavily soiled in early photos, the lower left side less so than the right side (Figure VI.9). This contrast seems to increase in time, and the heavier soiling most likely corresponds with a rain shadow cast by a Virginia Creeper. This plant waxes and wanes across the decades, by turn sheltering and revealing areas of decayed masonry, protecting them from the elements and then exposing them to successive phases of restoration. In a photo dating to the mid-1930s, the plant has been cut back completely to reveal the extent of decay to the lower Bell Tower. This is in stark contrast to the upper parts of the Tower, which were covered by the thick plaster and appear in good condition. In a photo dated to 1947, the extant Ketton and Portland Stone replacement to the left of the arrow-loop in elevation E can be seen (Figure VI.11). By 1950, the remaining areas of decay had been replaced with squared Kentish Ragstone. Photographic evidence is lacking here, but this could provide a date for Ragstone replacements in elevation B, and by association also the cleaning of the persistent sulphation on north and west facing elevations.



Figure VI.12: *19th century photo of upper chamber, showing thick limewash, which was removed in 1930s. (Historic England, with permission)*

Early photographs of the upper chamber show a thick limewash covering most of the masonry (Figure VI.12). There are records of plans to strip this limewash from the masonry in the 1930s, which were clearly carried out (TNA WORK 14/979). Limewash was then re-applied here in the late 1980s (discussed in Chapter III.2), in work which represented an important step in the rediscovery of this technique for Reigate Stone. Remnants of several different coats can be found on the present-day masonry; these are likely to include both the historic and modern limewash coats. Comparing Reigate masonry in the early photos with more recent photos suggests that rapid decay may have occurred in response to the removal of the limewash, perhaps due some abrasive procedure.

The changing materiality of the Bell Tower traced out here is both an expression of the interface between society and the environment, and itself a controlling factor in ongoing decay. It represents a technological response to the macro-contextual dynamics of factors such as atmospheric pollution and the societal perception of heritage, but fundamentally alters the micro-contextual dynamics of moisture transport and geo-chemistry. This resonates with findings made in Chapter IV, which suggested that cycles of repair and conservation can be out of synch with changes in over-arching environmental process and may not address the underlying mechanisms of decay.

VI) 2.5. Summary

The Bell Tower has undergone almost continuous change since its construction began. These changes have occurred in a series of interwoven patterns in response to external economic, cultural and environmental forces. Successive construction phases

introduced waves of different primary building material and gave a composite shape to the tower. External and internal rearrangements reflected changes in function and echoed gradual societal shifts. More fundamental social upheaval was followed by increased environmental stress, this caused rapid decay which in turn drove a programme of stylistic restoration. These environmental and social forces combined to overlay a new materiality on the fabric of the tower; a fluctuating amalgamation of replacement ashlar, plaster, mortar and even vegetation, which was both a response to over-arching drivers of change and itself a significant, differential factor in ongoing rates of decay to different stones and different areas of the building.

These observations at the Bell Tower serve to reinforce and develop the conceptual framework set out at the start of this thesis. They show that the relationship between science and the historic built environment must be carefully managed. Given its status, it is unsurprising that the Tower of London has been and continues to be a field-lab for cutting edge architectural conservation. Many of the past changes made to the Bell Tower were no less rooted in the scientific understanding of the day than contemporary conservation strategies; engineering replacement stone and developing mortars and plasters required technological advance. Replacement stones at the Queens House, adjacent to the Bell Tower include an early use of Portland Stone in the 1630s (TNA E351/3267). Early 19th century engravings of the Bloody Tower, slightly further down Water Lane, suggest its Reigate Stone vaulted ceiling was an early (and, from today's perspective, ill-advised) object of restoration using Roman Cement. These early advances were no less scientific[15] than the recent work

[15] In the sense of being based on the measurable concepts of the current time.

developing new models for mixed salt dynamics at the Wakefield Tower (Price 2007), or the novel HCT consolidant at the Bell Tower (Weiss et al. 2000); only time will tell if these more recent advances are viewed positively by future generations.

VI) 3. Conclusions

VI) 3.1. Synthesis

The theoretical and methodological frameworks underpinning this thesis conceptualise the control of Reigate Stone decay according to three axes of variability.

1. Material variability within the stones used in construction. Stones can be harder or softer, more or less porous, more or less homogeneous, etc. As a result, their baseline resistance to decay processes will differ. Given equal environmental mechanisms, and equal histories of use and repair, they will decay at different rates and according to different patterns.
2. Environmental variability within the current and recent exposure of historic masonry. Stones can be completely sheltered, highly exposed and everything in between. The same stone, with the same history of use and repair, will follow different decay pathways in different locations.
3. Historical variability. Alterations to the material characteristics of the stone or its surrounding masonry, or to the environment it is exposed to will have resulted in diverse contingencies, or 'case histories'. Initially comparable stones found in similar present-day environments may display very different decay features.

Breaking down the cause and effect of physical decay into these abstract variables can only provide a simplified version of real-world behaviour. Attempting to construct

methods for investigating them individually or in pairs revealed a fundamental connectedness. A principal finding of each chapter was merely to expose the significance of the variable which had been excluded from a study in order to enable some degree of correlative analysis. In **Chapter III**, material typologies and historical contingency were investigated to construct a model of changing use, and to assess the long-term effect of past conservation techniques. By largely removing the role of environmental mechanics from these equations, it was possible to make generalised statements on the emergence of differential decay in historic masonry, but not possible to formulate causation that would fully explain the pathways to such divergence. In **Chapter IV**, environmental mechanisms were investigated alongside a form of varying contingency, in this case the use of different pointing mortars in Reigate Stone masonry. This delivered useful findings on some elements of an idealised system dynamics of historic masonry, specifically the balance of intervention and prevention when using pointing mortar to regulate moisture control. However, by reducing the role of Reigate Stone itself in this system, little could be said about the actual process of decay in the stone. In **Chapter V**, variation within the characteristics of the stone were re-introduced and investigated alongside different environmental mechanisms. Whilst this told us something about the physics of decay, simplifying the idiosyncrasies of the historic masonry that was being simulated was partly responsible for results which did not fully match observed, real-word behaviour. Reconstructing the findings of these discrete studies into a coherent thesis does support the underlying paradigm, but rather than making it clearer, the final verdict is still moderated by an overarching complexity; an ever-present footnote that the science of stone conservation has missed some vital element.

In order to rationalise this impediment to painting a complete picture, it is important to consider the second principle which underpinned this thesis. This was to claim that rather than being the same thing, decay and deterioration are interrelated processes. Whilst decay equates to physical change in response to external mechanisms, deterioration is a more nuanced concept which relates to a loss of value. Decay processes are subject to change over time, but so is the appreciation of value in the historic built environment; depending on social context, decay can even contribute value. This infers an inherent subjectivity to the purpose of stone conservation, which is to arrest deterioration rather than decay. Rather than directly informing the methodological framework of the research, this principle functioned more as a viewpoint from which to guide its perspective. Stone conservation science can bypass this broader perspective and deliver a functional description on the active processes of decay at a historic site; this can be used to inform practical conservation frameworks. However, when describing the more deeply interconnected system of vulnerable heritage, it can also contribute to a wider discussion on value and meaning, which in itself can help shape social context and re-frame our understanding of cultural landscapes.

Figure VI.13 describes how the relationship between decay and deterioration might play out in an idealised timeline of a masonry structure. A stone monument is constructed during benign environment 1, under social context A, which desires monumental architecture to have an unblemished appearance. As environment 1 is benign, the corresponding rate of decay means that this desire is met with minimal maintenance. At some point, environment 2 commences, which is highly aggressive. After a brief lag, this causes the monument to decay rapidly. Given the social context,

this results in the replacement with new stone. Shortly after this, social context B begins, which, perhaps as a result of the more polluted macro-environment, no longer expects pristine monumental architecture and tolerates a certain level of decay. Nevertheless, as the environment is much more aggressive, the stone must be replaced twice in a relatively short space of time. Social context C emerges, which, perhaps realising the expense of this, seeks alternatives to replacement, whilst tolerating heavier decay. The monument undergoes intensive maintenance at regular intervals, such as abrasive cleaning of the masonry. This removes signs of visible decay. However, it causes the monument to decay more quickly in following years, until it is so heavily decayed that the stone is once again replaced. Social context D emerges, which is now less tolerant of decay in its new stone (whilst desiring some sign of ageing to give the monument a character befitting its age). Cleaning continues, but social context D also takes drastic measures to decrease pollution, ushering in environment 3. The rate of decay slows, but not long after this social context E decides that the appropriate level of decay in a historic building is much higher. The monument is allowed to decay, with only minimal, regular maintenance to mitigate uncontrolled acceleration.

This model is particularly relevant to vulnerable masonry in times of climate change. It is suggestive of the connectivity between environmental change and social change, with both the response of society to environmental drivers of change, and the subsequent adjustment of environmental mechanisms, subject to a lag which can bring these changes out of synch. These overarching waves of process change within a system dynamics of the historic built environment are themselves related, but often poorly aligned, to various processes of higher frequency and lower magnitude. A

sustainable implementation of strategies must be aligned with processes. Systematic understanding can enable this, but contemporary work must be aware not only of changing climate but also of presently shifting paradigms. With various pressures coalescing to a crisis of accumulation in the built heritage sector, a re-framing of value in the historic built environment is underway which is affecting the dynamics of deterioration and decay.

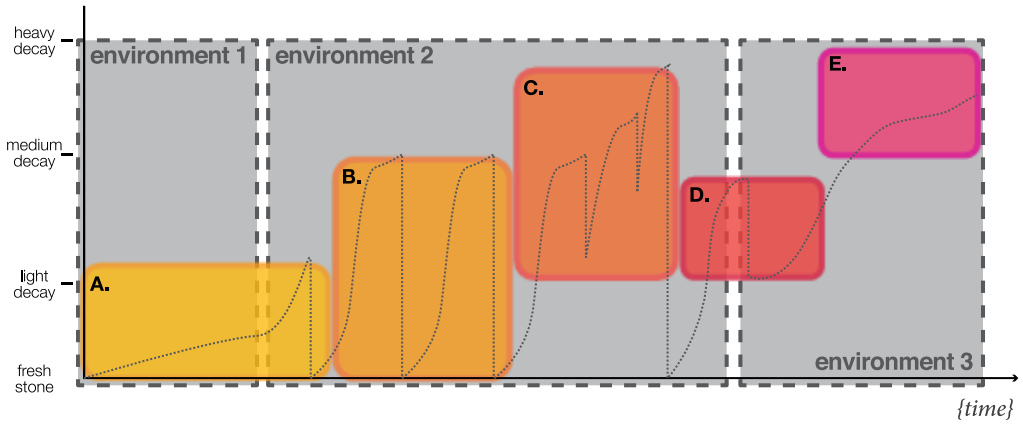


Figure VI.13: *Diagrammatic description of interrelated environments (affecting decay process) and social contexts (affecting appreciation of value, or deterioration processes)*

VI) 3.2. Outlook

VI) 3.2.1. Methodological advances

This thesis has demonstrated that applying scientific method to the study of the historic built environment requires an integrated approach in order to make sense of complex system dynamics. Field work can form the central piece in the jigsaw of a robust methodological framework, by fulfilling three criteria: (a.) be sensitive to cultural heritage, by relying mostly on non-destructive techniques (NDT), and integrating destructive testing only after rigorous investigation to identify locations of high scientific impact (i.e. representative, measurable) but low cultural value (i.e. tolerable intervention); (b) enable and inform the documentation needed for future

generations to understand the 'landscape of contingency'; (c) facilitate calibration with laboratory and computational simulations needed to build models of system behaviour. A successful field-work protocol can itself be broken down into a set of interlinked methodologies. These can take advantage of NDT designed to operate at different temporal and spatial scales. Whilst long term studies are important for monitoring response patterns under real world conditions, short term studies can be of use when examining particular behaviours. Similarly, targeting and interlinking studies at different spatial scales can reveal both broad patterns and specific behaviours. When integrated with archival research and controlled testing, this approach will enable a range of analytical methods; layering deductive, inductive and abductive reasoning is a recognised requirement of geomorphic science.

Chapter II.2 set out a case for differentiating between rapid and in-depth NDT protocols in order to tailor field surveys to performing initial investigations or producing rich datasets. A distinguishing factor of these approaches could be the extent to which they focus on resolving environmental or spatial (i.e. material) scale. Combining both approaches within a holistic integrated methodology can improve synergy and aid calibration with experiments in controlled environments. In this thesis, a long term, high-resolution non-destructive survey was performed to combine environmental and material testing (Chapter IV.1). Two further non-destructive protocols were designed to perform a high-resolution environmental monitoring and targeted material testing (Chapter V.1), and a high-resolution material analysis of a static, 15-year-old test wall (Chapter III.2). Using the same NDT across these surveys and in parallel laboratory tests increased confidence in the interpretation of results

and enabled synergism of datasets. This broadened the overall findings on the general theme of Reigate Stone decay, whilst still tackling three specific research questions.

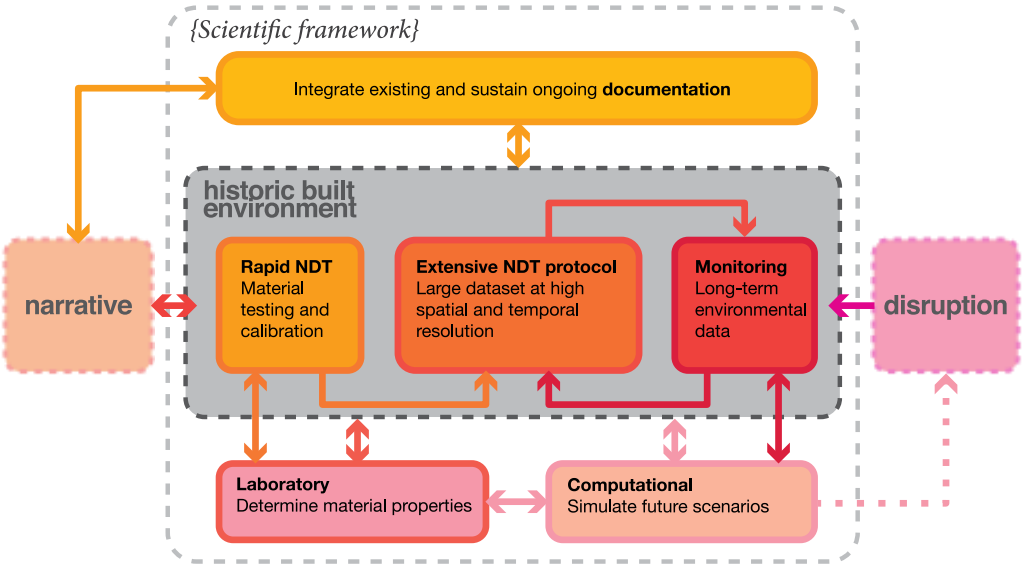


Figure VI.14: *Integrated methodology, showing relationship between historic built environment, scientific framework and external forces.*

Figure VI.14 is a diagrammatic representation of this integrated approach. It describes how NDT field surveys of the historic built environment can interconnect across several scales, and how this can in turn link to research in archival and controlled environments to construct a robust scientific framework. However, it also indicates the limits of this framework, with several external forces affecting the historic built environment which cannot be adequately described using scientific method. As discussed in Chapter II, one of these is the notion of disturbance, described by Inkpen and Turner (2012) as a force of external origin that cannot be predicted in the initial quantification of the overall system. Whilst such disturbances will continue to be common in attempts to describe with any precision the complexities of the historic built environment, advances in complexity science will increase the accuracy with which computer models are able to predict future events (Spinney 2019). More

fundamental is the notion of narrative. Changes in cultural appreciation of the historic built environment play a major role in defining processes which control its physical change and vice-versa. Cultural heritage is by its very nature ephemeral; its quality is to provide narrative that transcends language and memory (Lowenthal 2015). Like the best stories, this quality can only be fully expressed with a large dose of mystery. However, by understanding its own limitations, science can take advantage of this idiosyncrasy. Currie and Sterelny (2017) argue that by "forming scaffolds from which new evidence becomes relevant (…) narratives can track complex changes in a trajectory over time". In terms of informing scientific methodology, a direct consequence of this approach would be to rigorously document all forms of study of the historic built environment and build future research on the foundation of recent projects.

A new test wall would present a valuable resource for ongoing long-term study and calibration with future controlled experiments. The test wall built in 2001 during a previous phase of focussed research into Reigate Stone proved very useful to understanding the role mineralogical variation can play in consolidation using HCT. A new test wall could take advantage of the increased understanding of mineralogical variability and investigate a more varied suite of conservation techniques. This should include limewashing and different pointing mortar recipes. It could also incorporate micro-contextual features, such as shelves and alcoves, or different neighbouring stone types. This would provide a methodological approach to investigating several controls on decay which have been identified in this thesis but could not be fully assessed in the project timeframe.

VI) 3.2.2. Practical advances

This thesis adopted a comprehensive framework to investigating resilience in Reigate Stone masonry. This revealed an inherent complexity to understanding decay and deterioration, which prevents general practical guidance on conservation. Specific conservation strategies must be developed on a case-by-case basis. There are some findings relating to past and present conservation strategies which will be of direct benefit to ongoing protocol for Reigate Stone treatment: re-introducing limewashing should be considered as a low-risk, short-term protective measure; HCT treatment will be more effective on lighter stones; de-pointing should only be performed after thorough assessment of current condition; re-pointing with NHL should be avoided. Other more general findings serve to provide conservators with a list of three questions they must ask themselves when faced with Reigate Stone masonry:

1. What type of Reigate Stone is this?
2. Are there distinctive micro-contextual or micro-climatic features?
3. What amount of environmental change and past repair has this masonry experienced?

The more valuable yet less direct practical consequence of findings made in this project will be to support an approach which integrates targeted stone conservation with a holistic strategy to understanding and protecting the historic built environment. This demands rigorous and systematic documentation and interdisciplinary cooperation throughout a continuous process of management, maintenance and care.

The research has already demonstrated practical benefit to the project partners (Historic Royal Palaces and Carden & Godfrey Architects). Findings have been used to influence local policy decisions and ongoing conservation strategies at the Tower of London and Hampton Court Palace. Further funding has been granted by the EPSRC IAA (Impact Acceleration Account). This will be used to translate research findings into practical guidelines in collaboration with the existing project partners. This will directly benefit the conservation of Reigate Stone masonry on a regional scale. It will also be an opportunity to develop a next phase of research questions for ongoing scientific investigation into vulnerable historic masonry. More broadly, the findings will contribute to emerging paradigms in the management of the historic built environment. These will emphasise 'joined-up' thinking in the design of ongoing research projects and the development of global policy.

These methodological and practical advances will impact directly on the future of the Tower of London. A more robust, resilient approach to understanding the causes of decay and evaluating deterioration will become increasingly necessary in response to mounting pressures on the management of large historic sites. As rapid climate change begins to alter the processes of decay (Smith et al. 2011a), a granular, integrated methodology will be vital for interpreting the effects of new rainfall and pollution patterns. It will be necessary to identify controls and implement targeted conservation strategies within short timeframes in order to mitigate the scale of change seen in previous eras of rapid environmental change. The ongoing conservation of structures such as the Bell and Wardrobe Towers will benefit from a perspective which draws the focus away from materiality towards a more holistic appraisal that appreciates the dynamic nature of the historic built environment.

Beyond climatic factors, the Covid-19 pandemic has revealed the vulnerability of the complex economic systems underpinning the management of cultural heritage; HRP's revenue forecast for 2020 has been revised down by almost 90% due to a huge drop in visitor numbers (Jolly 2020). The charity is predicting unprecedented staff cuts. These shocks to fiscal and human resources risk a devastating impact to the conservation of the Tower of London, not least its vulnerable historic masonry. This demands methodological documentation and robust protocol in order to mitigate the long-term effects of a short- to mid-term adjustment in organisational infrastructure, which is likely to include the premature loss of knowledgeable, veteran personnel and the merger of departments.

VI) 3.2.3. Theoretical advances

In response to increasing environmental pressures and shifting cultural paradigms, conservation principles are beginning to explore strategies which reframe decay more positively. After a period in the mid-20th century, which regarded historic buildings as museum objects, valuing preservation of their appearance and emphasising their individuality, rather than contextualising them within a symbiotic human/ natural environment, the past decades have witnessed the emergence of a new social context, which aligns the historic built environment more closely to the concept of cultural landscapes. This is partly manifest in an appreciation of the ruin. This echoes the romanticism of the late 19th century, which was a precursor to the Ruskinian school of conservation; however, there is a distinctively 21st century flavour to this revival. Lowenthal (2015, p.287) states that "Today's ruin penchant imbues decaying buildings and artefacts with ecological angst." The present-day Zeitgeist views the environment as a fragile ecosystem and a finite resource. This is gradually being

reflected in our approach to managing the historic built environment, in which individual areas, buildings and even sites can only be understood as part of a greater, dynamic ensemble of tangible and intangible heritage, natural environment, and contemporary culture. Architectural conservation, and perhaps even the built environment more broadly, will increasingly benefit from a cultural landscapes approach to sustainability. This understands the value of an interconnected, diverse ecosystem to overall resilience.

This paradigm also brings positivity to the meaning of resource sustainability. DeSilvey (2017, p.185) argues that "Heritage can be continually renewed if the social relations and practices that give it meaning are sustained over time." In this sense, scientific research is in itself playing an increasingly important role in sustaining heritage. As the historic built environment is repurposed into a 'field laboratory for the Anthropocene' (Gomez-Heras and McCabe 2015), scientific understanding of the dynamics of decay, and interdisciplinary discourse on the interplay between decay and deterioration, give new meaning to heritage. Caring enough about Reigate Stone, or other vulnerable masonry, to study it in scientific detail is already providing a valuable contribution. Yet DeSilvey's dictum is also suggestive of something more fundamental. As one of very few freestones available to medieval London, Reigate Stone is intimately tied to placemaking. In the paradigm of cultural landscape, it is a keystone, a rare material connection between a global city and its hinterland. Perhaps the most sustainable conservation strategy for Reigate Stone would be to explore steps to renewing the quarrying industry which for centuries fed the growth of the region.

Reigate Stone saw its first use in new build in at least 100 years recently, as part of the Queen's Diamond Jubilee Galleries at Westminster Abbey (Wainwright 2018). The project depended on close collaboration between the architect P. Dean and the Wealden Cave and Mining Society (WCMS), the Surrey based local interest group who helped on several occasions during my own research. The WCMS were able to reach out to landowners, facilitate the digging of a new quarry, and even assist in the selection of appropriate building stone (Burgess personal communication). If we imagine the WCMS, who have spent decades meticulously exploring and mapping the Reigate mines (Sowan 1975), as the successors to the medieval quarrymen, this is probably as close as we can come in urbanised South East England to what Watson (2019, p.21) terms 'Lo-TEK'[16]; "A design movement to rebuild an understanding of indigenous philosophy and vernacular architecture that generates sustainable, climate resilient infrastructures." By engaging with heritage beyond what is embodied in historic buildings, and actively incorporating more distant, intangible offshoots into the interdisciplinary framework, architectural conservation does not only enrichen the narrative, it also steers us closer to resilient, circular economy. Conservation is not about saving the past; it is about safeguarding the future.

[16] A portmanteau of 'Lo-Tech' and 'Traditional Ecological Knowledge' (TEK), which in the case of our quarrymen would amount to the haptic feedback of their pick-axe when mining a seam of good quality building stone.

List of References

Adams, C. (1998) Japan's Ise Shrine and Its Thirteen-Hundred-Year-Old Reconstruction Tradition. *Journal of Architectural Education*, *52*(1), 49-60.

Aires-Barros, L., Basto, M. J., Graça, R. C., Dionísio, A., Rodrigues, J. D., Henriques, F. M. A., & Charola, A. E. (1998). Stone Deterioration on the Tower of Belem/Zerstörung des Natursteins am Turm vom Beiern. *Restoration of Buildings and Monuments*, *4*(6), 611-626.

Amadori, M. L., Lazzarini, L., & Massa, S. (1990). Il deterioramento da sodio cloruro di rocce compatte e porose a Venezia. In *The conservation of monuments in the Mediterranean Basin: the influence of coastal environment and salt spray on limestone and marble. Proceedings of the 1st International Symposium, Bari, 7-10 June 1989* (pp. 83-89).Anonymous (1844). Easy Method of Rendering Walls Impervious to Wet. *Provincial Medical Journal and Retrospect of the Medical Sciences*, 7(175), 361-362

Aoki, H., & Matsukura, Y. (2007). A new technique for non-destructive field measurement of rock-surface strength: an application of the Equotip hardness tester to weathering studies. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *32*(12), 1759-1769.

Arnold, A. (1982). Rising damp and saline minerals. In *Deterioration and preservation of Stone Objects, Fourth International Congress July 7-9, 1982, Proceedings* (pp. 11-28).

Arrizabalaga, I., Gómez-Laserna, O., Carrero, J. A., Bustamante, J., Rodríguez, A., Arana, G., & Madariaga, J. M. (2015). Diffuse reflectance FTIR database for the interpretation of the spectra obtained with a handheld device on built heritage materials. *Analytical Methods*, *7*(3), 1061-1070.

Ashley-Smith, J. (2018). The ethics of doing nothing. *Journal of the Institute of Conservation*, *41*(1), 6-15.

Ashurst, J., & Ashurst, N. (1988). *Practical Building Conservation: Stone masonry*. Gower Technical Press.

Ashurst, J., & Dimes, F. (1990). *Conservation of building and decorative stone* (Butterworth-Heinemann series in conservation and museology). London: Butterworth-Heinemann.

Auras, M., Beer, S., Bundschuh, P., Eichhorn, J., Mach, M., Scheuvens, D., Schorling, M., von Schumann, J., Snethlage, R., & Weinbruch, S. (2013). Traffic-related immissions and their

impact on historic buildings: implications from a pilot study at two German cities. *Environmental earth sciences*, *69*(4), 1135-1147.

Banfill, P. F., Szadurski, E. M., & Forster, A. M. (2016). Deterioration of natural hydraulic lime mortars, II: Effects of chemically accelerated leaching on physical and mechanical properties of carbonated materials. *Construction and Building Materials*, *111*, 182-190.

Beck, K., & Al-Mukhtar, M. (2014). Cyclic wetting–drying ageing test and patina formation on tuffeau limestone. *Environmental earth sciences*, *71*(5), 2361-2372.

Beck, K., & Al-Mukhtar, M. (2010). Weathering effects in an urban environment: a case study of tuffeau, a French porous limestone. *Geological Society, London, Special Publications*, *331*(1), 103-111.

Benavente, D., Cueto, N., Martínez-Martínez, J., García del Cura, M., & Cañaveras, A. (2007a). The influence of petrophysical properties on the salt weathering of porous building rocks. *Environmental Geology, 52*(2), 215-224.

Benavente, D., Martínez-Martínez, J., Cueto, N., & García-Del-Cura, M. (2007b). Salt weathering in dual-porosity building dolostones. *Engineering Geology, 94*(3), 215-226.

Benavente, D., Martínez-Martínez, J., Jáuregui, P., Rodríguez, M., & Del Cura, M. (2006). Assessment of the strength of building rocks using signal processing procedures. *Construction and Building Materials*, 20(8), 562-568.

Di Benedetto, C., Cappelletti, P., Favaro, M., Graziano, S. F., Langella, A., Calcaterra, D., & Colella, A. (2015). Porosity as key factor in the durability of two historical building stones: Neapolitan Yellow Tuff and Vicenza Stone. Engineering Geology, 193, 310-319.

Ben-Menahem, Y. (1997). Historical contingency. *Ratio*, *10*(2), 99-107.

Bionda, D., 2005. RUNSALT - A graphical user interface to the ECOS thermodynamic model for the prediction of the behaviour of salt mixtures under changing climate conditions. http://science.sdf-eu.org/runsalt/ (accessed April 2020)

Birch, F., 1961. The velocity of compressional waves in rocks to 10 kilobars: 2. *Journal of Geophysical Research*, *66*(7), pp.2199-2224.

Bonazza, A., Brimblecombe, P., Grossi, C.M. and Sabbioni, C., 2007. Carbon in black crusts from the Tower of London. *Environmental science & technology*, *41*(12), pp.4199-4204.

Bourgeois, J. (1987). The History of the Great Mosques of Djenné. *African Arts, 20*(3), 54-92. doi:10.2307/3336477

Bowley, M. J. (1975). Desalination of stone: a case study. *Building Research Establishment*

Bracken, L.J., & Oughton, E.A. (2006). 'What do you mean?' The importance of language in developing interdisciplinary research. *Transactions of the Institute of British Geographers*, *31*(3), 371-382.

Brigham, T., & Woodger, A. (2001). *Roman and medieval townhouses on the London waterfront: excavations at Governor's House, City of London* (Vol. 9). Museum of London Archaeology Svc.

Brimblecombe, P., & Grossi, C. M. (2005). Aesthetic thresholds and blackening of stone buildings. *Science of the Total Environment*, *349*(1-3), 175-189.

Brimblecombe, P., & Grossi, C. M. (2009). Millennium-long damage to building materials in London. *Science of the total environment*, *407*(4), 1354-1361.

Brunet-Jailly, J. and Scherrer, O. (2018). Protecting architectural heritage in Djenné: a civil society point of view. *Journal of African Cultural Heritage Studies*, *1*(1), 72-94.

Bruthans, J., Filippi, M., Slavík, M., & Svobodová, E. (2018). Origin of honeycombs: Testing the hydraulic and case hardening hypotheses. *Geomorphology*, *303*, 68-83.

BS EN 14579:2004 (2005). *Natural Stone Test Methods. Determination of Sound Speed Propagation*.

BS EN 1925:1999 (1999). *Natural Stone Test Methods. Determination of Water Absorption Coefficient by Capillarity.*

BS EN 772-4:1998 (1998). *Methods of Test for Masonry Units. Determination of Real and Bulk Density and of Total and Open Porosity for Natural Stone Masonry Units.*

Burgess, P. (2008). *Surrey's Ancient Stone Mines*. P. Burgess. ISBN: 9780955608117

Burnham, B., Keppie, L., Hassall, M., & Tomlin, R. (1995). Roman Britain in 1994. *Britannia, 26*, 325-390.

Campbell, J. W. (2013). The supply of stone for the rebuilding of St Paul's Cathedral 1675-1710. *Construction History*, 23-49.

Camuffo, D. (2019). *Microclimate for cultural heritage: Measurement, risk assessment, conservation, restoration, and maintenance of indoor and outdoor monuments* (3rd ed.). Amsterdam.

Camuffo, D., & Bertolin, C. (2012). Towards standardisation of moisture content measurement in cultural heritage materials. *E-Preserv. Sci*, *9*, 23-35.

Cassar, M. (2009). Sustainable Heritage: Challenges and Strategies for the Twenty-First Century, APT Bulletin. *Journal of Preservation Technology*, *40*(1), 3-11.

Charola, A. E. (2000). Salts in the deterioration of porous materials: an overview. *Journal of the American institute for conservation*, 39(3), 327-343.

Church, L. (2003). An investigation into the deterioration of Reigate Stone at the Wakefield Tower, HM Tower of London. *MA dissertation, Institute of Archaeology*. University College London.

Clarke, B. L., & Ashurst, J. (1972). *Stone preservation experiments*. HMSO Dept. of Environment.

Colston, B., Watt, D., & Munro, H. (2001). Environmentally-induced stone decay: The cumulative effects of crystallization–hydration cycles on a Lincolnshire oopelsparite limestone. *Journal of Cultural Heritage, 2*(4), 297-307.

Colvin, H. (1963-82). *The history of the King's works*. (6 Volumes). London: H.M.S.O.

Compton, C. H. (1881). Recent Discoveries at the Tower of London. *Journal of the British Archaeological Association: First Series*, *37*(3), 279-284.

Coombe, P., Henig, M., Grew, F., Hayward, K. M., & Blagg, T. F. C. (2015). *Roman sculpture from London and the South-East*. Oxford University Press.

Currie, A., & Sterelny, K. (2017). In defence of story-telling. *Studies in History and Philosophy of Science Part A*, *62*, 14-21.

De Boever, W., Bultreys, T., Derluyn, H., Van Hoorebeke, L., & Cnudde, V. (2016). Comparison between traditional laboratory tests, permeability measurements and CT-based fluid flow modelling for cultural heritage applications. *Science of The Total Environment*, *554*, 102-112.

Domingo, C. (1994). The provenance of some building stones in St Mary Spital by geological methods. *The London Archaeologist, 7*(9), 240.

Dean, W. (1994) The relationship between sea-level change, facies change and ammonite distributions in the Aptian-Albian of the Anglo-Paris Basin. *PQDT - Global. Web.*

Demas, M. (2002). Annotated bibliography on protective shelters for archaeological sites. *Conservation and Management of Archaeological Sites*, *5*(1-2), 91-105.

Deprez, M., De Kock, T., De Schutter, G., & Cnudde, V. (2020). A review on freeze-thaw action and weathering of rocks. *Earth-Science Reviews*, 103143.

Desarnaud, J., Kiriyama, K., Bicer Simsir, B., Wilhelm, K., & Viles, H. (2019). A laboratory study of Equotip surface hardness measurements on a range of sandstones: What influences the values and what do they mean?. *Earth Surface Processes and Landforms*, *44*(7), 1419-1429.

DeSilvey, C. (2017). *Curated decay: Heritage beyond saving*. U of Minnesota Press.

Dewanckele, J., Boone, M. A., De Kock, T., De Boever, W., Brabant, L., Boone, M. N., ... & Cnudde, V. (2013). Holistic approach of pre-existing flaws on the decay of two limestones. *Science of the Total Environment*, *447*, 403-414.

Diaz Gonçalves, T., & Brito, V. (2014). Alteration kinetics of natural stones due to sodium sulfate crystallization: Can reality match experimental simulations? *Environmental Earth Sciences, 72*(6), 1789-1799.

Dines, H. G., & Edmunds, F. H. (1933). *The geology of the country around Reigate and Dorking* (No. 286). HM Stationery Office.

Doehne, E., & Price, C. A. (2010). Stone conservation. *An Overview of Current Research: Second Edition.* Getty Conservation Institute, Los Angeles.

Doehne, E. (2002). Salt weathering: a selective review. *Geological society, London, special publications*, *205*(1), 51-64.

Dorn, R. I., Whitley, D. S., Villa Cerveny, N., Gordon, S. J., Allen, C. D., & Gutbrod, E. (2008). The Rock Art Stability Index: A new strategy for maximizing the sustainability of rock art. *Heritage Management*, *1*(1), 37-70.

Dorn, R. I., Gordon, S. J., Allen, C. D., Cerveny, N., Dixon, J. C., Groom, K. M., ... & Sumner, P. (2013). The role of fieldwork in rock decay research: Case studies from the fringe. *Geomorphology*, *200*, 59-74.

Douglas-Jones, R., Hughes, J. J., Jones, S., & Yarrow, T. (2016). Science, value and material decay in the conservation of historic environments. *Journal of Cultural Heritage*, *21*, 823-833.

Drdácký, M., & Slížková, Z. (2013). Enhanced affordable methods for assessing material characteristics and consolidation effects on stone and mortar. *Journal of Geophysics and Engineering*, *10*(6), 064005.

Drummond-Murray, J., Thompson, P., Cowan, C., & Burnell, S. (2002). *Settlement in Roman Southwark: Archaeological Excavations (1991-8) for the London Underground Limited Jubilee Line Extension Project* (Vol. 12). Museum of London Archaeology Svc.

Drury, P. & McPherson, A., (2008). Conservation principles: policies and guidance for the sustainable management of the historic environment. *English Heritage*

Duffy, A.P., & O'Brien, P.F., (1996). *A basis for evaluating the durability of new building stone* In: Smith, B.J., & Warke, P.A. *Processes of urban stone decay*, 253-260. Donhead Publishing: London, UK.

D'Ayala, D., & Aktas, Y. D. (2016). Moisture dynamics in the masonry fabric of historic buildings subjected to wind-driven rain and flooding. *Building and Environment*, *104*, 208-220.

Eklund, J. A., Zhang, H., Viles, H. A., & Curteis, T. (2013). Using handheld moisture meters on limestone: factors affecting performance and guidelines for best practice. *International journal of architectural heritage*, *7*(2), 207-224.

El Sayed, A.M.A. & El Sayed, N.A. (2019). Thermal conductivity calculation from P-wave velocity and porosity assessment for sandstone reservoir rocks. *Geothermics*, 82, 91-96.

Elert, K., Rodriguez-Navarro, C., Pardo, E. S., Hansen, E., & Cazalla, O. (2002). Lime mortars for the conservation of historic buildings. *Studies in Conservation*, *47*(1), 62-75.

Eloukabi, H., Sghaier, N., Nasrallah, S. B., & Prat, M. (2013). Experimental study of the effect of sodium chloride on drying of porous media: The crusty–patchy efflorescence transition. *International Journal of Heat and Mass Transfer*, *56*(1-2), 80-93.

EN ISO 12572 (2001). *Hygrothermal performance of building materials and products: Determination of water vapour transmission properties.*

EN 12370 (1999). *Natural Stone Test Methods. Determination of Resistance to Salt Crystallization*.

EN 12371 (2010). *Natural Stone Test Methods. Determination of Frost Resistance*.

English Heritage (2014). Heritage Counts 2014: The Value and Impact of Heritage. *London: English Heritage*. https://historicengland.org.uk/research/heritage-counts/2014-the-value-and-impact-of-heritage/

Erkal, A., & D'Ayala, D. (2015). Laboratory testing of non-standard original historic building materials and related implications for conservation. *Quarterly Journal of Engineering Geology and Hydrogeology*, *48*(1), 15-28.

Erkal, A., D'Ayala, D., & Sequeira, L. (2012). Assessment of wind-driven rain impact, related surface erosion and surface strength reduction of historic building materials. *Building and Environment*, 57, 336-348.

Erkal, A., D'Ayala, D., & Stephenson, V. (2013). Evaluation of environmental impact on historical stone masonry through on-site monitoring appraisal. *Quarterly Journal of Engineering Geology and Hydrogeology*, *46*(4), 449-458.

Espinosa-Marzal, R. M., & Scherer, G. W. (2013). Impact of in-pore salt crystallization on transport properties. *Environmental earth sciences*, *69*(8), 2657-2669.

Fagg, C. C. (1914) *The mineral and agricultural industries of the Regional Survey Area considered geographically.* Proc. Croydon Natural History and Scientific Soc. 7(5), 161 - 74 + pls iii - v [Surrey]

Fatorić, S. and Seekamp, E. (2018). A measurement framework to increase transparency in historic preservation decision-making under changing climate conditions. *Journal of Cultural Heritage*, *30*, 168-179.

Feng, G. F., & English, J. (1972). *Tao Te Ching*. Random House Inc.

Fitzner, B., & Heinrichs, K. (2001). Damage diagnosis at stone monuments-weathering forms, damage categories and damage indices. *Acta-Universitatis Carolinae Geologica*, *1*, 12-13.

Fitzner, B. (2004). Documentation and evaluation of stone damage on monuments. In *Proceedings of the 10th international congress on deterioration and conservation of stone* Vol. 27, 677-690. Elanders Gotab Stockholm.

Fitzner, B., Heinrichs, K., & Kownatzki, R. (1995). *Weathering Forms, Classification and Mapping: Verwitterungsformen-Klassifizierung und Kartierung*. Ernst and Sohn.

Flatt, R. J. (2002). Salt damage in porous materials: how high supersaturations are generated. *Journal of Crystal Growth*, *242*(3-4), 435-454.

Flatt, R. J., Aly Mohamed, N., Caruso, F., Derluyn, H., Desarnaud, J., Lubelli, B., ... & Shahidzadeh, N. (2017). Predicting salt damage in practice: a theoretical insight into laboratory tests. *RILEM Technical Letters*, *2*, 108-118.

Flörke, O. W., Hollmann, R., Von Rad, U., & Rösch, H. (1976). Intergrowth and twinning in opal-CT lepispheres. *Contributions to Mineralogy and Petrology*, *58*(3), 235-242.

Forster, A. (2004). Hot-lime mortars: a current perspective. *Journal of Architectural Conservation*, *10*(3), 7-27.

Fort, R., Varas, M., Alvarez de Buergo, M., & Martin-Freire, D. (2011). Determination of anisotropy to enhance the durability of natural stone. *Journal of Geophysics and Engineering*, 8(3), S132-S144.

Fort, R., de Buergo, M. A., & Perez-Monserrat, E. M. (2013). Non-destructive testing for the assessment of granite decay in heritage structures compared to quarry stone. *International Journal of Rock Mechanics and Mining Sciences*, *61*, 296-305.

Franković, M., Novaković, N., & Matović, V. (2015). Damage quantification of built stone on Dark Gate (Belgrade, Serbia): sample of damage index application for decay rate evaluation. *Environmental Earth Sciences*, *73*(10), 6181-6193.

Franzen, C., & Mirwald, P. W. (2004). Moisture content of natural stone: static and dynamic equilibrium with atmospheric humidity. *Environmental Geology*, *46*(3-4), 391-401.

Fusade, L., & Viles, H. A. (2019). A comparison of standard and realistic curing conditions of natural hydraulic lime repointing mortar for damp masonry: Impact on laboratory evaluation. *Journal of Cultural Heritage*, *37*, 82-93.

Fusade, L., Orr, S. A., Wood, C., O'Dowd, M., & Viles, H. (2019a). Drying response of lime-mortar joints in granite masonry after an intense rainfall and after repointing. *Heritage Science*, 7(1), 38.

Fusade, L., Viles, H., Wood, C., & Burns, C. (2019b). The effect of wood ash on the properties and durability of lime mortar for repointing damp historic buildings. *Construction and Building Materials*, *212*, 500-513.

Gadd, G.M. (2017). Geomicrobiology of the built environment. *Nature microbiology*, *2*(4), 1-9.

Germinario, L., Andriani, G. F., & Laviano, R. (2015). Decay of calcareous building stone under the combined action of thermoclastism and cryoclastism: A laboratory simulation. *Construction and Building Materials*, *75*, 385-394.

Giesen, M.J., Mazel, A.D., Graham, D.W., & Warke, P.A. (2011). Care and management of ancient stone monuments during environmental change. *Int. J. Heritage Sust. Dev*, *1*(1), 60-71.

Gomez-Heras, M., Smith, B. J., & Viles, H. A. (2010). Oxford stone revisited: causes and consequences of diversity in building limestone used in the historic centre of Oxford, England. *Geological Society, London, Special Publications*, *333*(1), 101-110.

Gomez-Heras, M., & McCabe, S. (2015). Weathering of stone-built heritage: A lens through which to read the Anthropocene. *Anthropocene*, *11*, 1-13.

Diaz Gonçalves, T., & Brito, V. (2014). Alteration kinetics of natural stones due to sodium sulfate crystallization: can reality match experimental simulations?. *Environmental earth sciences*, *72*(6).

Goudie, A., & Viles, H. A. (1997). *Salt weathering hazard*. Wiley.

Goudie, A. S., & Viles, H. A. (1999). The frequency and magnitude concept in relation to rock weathering. *Zeitschrift für Geomorphologie Supplement Volumes*, 175-189.

Goudie, A. S. (1986). Laboratory simulation of 'the wick effect' in salt weathering of rock. *Earth Surface Processes and Landforms*, *11*(3), 275-285.

Gower, G. (1869). On a Roman Villa discovered at Titsey. *Surrey Archaeological Collections, 4*, 214.

Grainger, I., & Phillpotts, C. (2011). *The Cistercian abbey of St Mary Graces, East Smithfield, London*. Museum of London Archaeology.

Grementieri, L., Molari, L., Derluyn, H., Desarnaud, J., Cnudde, V., Shahidzadeh, N., & De Miranda, S. (2017). Numerical simulation of salt transport and crystallization in drying Prague sandstone using an experimentally consistent multiphase model. *Building and Environment*, *123*, 289-298.

Grifa, C., Barba, S., Fiorillo, F., Germinario, C., Izzo, F., Mercurio, M., ... & Langella, A. (2016). The domus of Octavius Quartio in Pompeii: damage diagnosis of the masonries and frescoed surfaces. *International Journal of Conservation Science, 7(2)*, 885-900

Hall, K., Thorn, C., & Sumner, P. (2012). On the persistence of 'weathering'. *Geomorphology*, *149*, 1-10.

Hall, C., & Hoff, W. D. (2011). *Water transport in brick, stone and concrete*. CRC Press.

Hall, C., Hamilton, A., Hoff, W. D., Viles, H. A., & Eklund, J. A. (2011). Moisture dynamics in walls: response to micro-environment and climate change. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *467*(2125), 194-211.

Hansen, E., Doehne, E., Fidler, J., Larson, J., Martin, B., Matteini, M., Rodriguez-Navarro, C., Pardo, E.S., Price, C., de Tagle, A., & Teutonico, J.M. (2003). A review of selected inorganic consolidants and protective treatments for porous calcareous materials. *Studies in Conservation*, *48*(sup1), 13-25.

Hanssen, S. V., & Viles, H. A. (2014). Can plants keep ruins dry? A quantitative assessment of the effect of soft capping on rainwater flows over ruined walls. *Ecological engineering*, *71*, 173-179.

Harrison, R. (2013). Forgetting to remember, remembering to forget: late modern heritage practices, sustainability and the 'crisis' of accumulation of the past. *International Journal of Heritage Studies*, *19*(6), 579-595.

Hatton, M. (2001). The Exploitation, Distribution and Use in Buildings of Reigate Stone. MA Birkbeck College

Heidegger, M. (1971). Building dwelling thinking. *Poetry, language, thought*, *154*.

Hendrickx, R. (2012). Using the Karsten Tube to estimate water transport parameters of porous building materials, *Materials and Structures, 46(8)*, 1309-1320

Henry, A., & Stewart, J. (2011). *Mortars, Renders and Plasters (Practical Building Conservation). 1*. English Heritage, ASHGATE.

Howe, E., & Lakin, D. (2004). *Roman and Medieval Cripplegate, City of London: Archaeological Excavations, 1992-8* (Vol. 21). Museum of London Archaeology Svc.

Howe, J. (2016). *The geology of building stones*. London.

Huggins, P. J., Bascombe, K. N., & Huggins, R. M. (1992). Excavations at Waltham Abbey, Essex, 1985–1991: Three Pre-Conquest Churches and Norman Evidence. *Archaeological Journal*, *149*(1), 282-343.

Hyslop, E., McMillan, A., Cameron, D., Leslie, A., & Lott, G. (2010). Building stone databases in the UK: A practical resource for conservation. *Engineering Geology*, *115*(3-4), 143-148.

ICOMOS. (1931). The Athens charter for the restoration of historic monuments. *Athens, Greece*

ICOMOS (1964). The Venice Charter: International charter for the conservation and restoration of monuments and sites. *Venice, Italy*.

ICOMOS (1999). The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance. *Burra, Australia*

ICOMOS (2003). Principles for the analysis, conservation and structural restoration of architectural heritage. In *Proceedings of the ICOMOS 14th General Assembly and Scientific Symposium, Victoria Falls, Zimbabwe* (Vol. 2731).

Impey, E., & Ashbee, J. (2008). *The White Tower*. New Haven [Conn.] ; London : [London: Yale University Press ; in association with Historic Royal Palaces.

Inglesby, R. (2017). 'Let us Sin with Salvin': Architecture and Authority at the Tower of London, 1896–1905. *Architectural History*, *60*, 243-275.

Inkpen, R., Duane, B., Burdett, J., & Yates, T. (2008). Assessing stone degradation using an integrated database and geographical information system (GIS). *Environmental Geology*, *56*(3-4), 789-801.

Inkpen, R., & Turner, D. (2012). The topography of historical contingency. *Journal of the Philosophy of History*, *6*(1), 1-19.

Inkpen, R., Viles, H., Moses, C., & Baily, B. (2012b). Modelling the impact of changing atmospheric pollution levels on limestone erosion rates in central London, 1980–2010. *Atmospheric Environment*, *61*, 476-481.

Inkpen, R.J. (2004). Weathering scales, landscapes and change: some thoughts on links. In *Stone decay: its causes and controls,* 293-306. Donhead Shaftesbury.

Inkpen, R.J. (2011). Scale as a relational network in weathering studies. *Geomorphology*, *130*(1-2), 10-16.

Inkpen, R.J., Petley, D. and Murphy, W. (2004). *Durability and rock properties* in: Smith, B.J. and Turkington, A., 2004. *Stone Decay: Its Causes and Controls*, 33-52. Routledge.

Inkpen, R.J., Viles, H.A., Moses, C., Baily, B., Collier, P., Trudgill, S.T., & Cooke, R.U. (2012a). Thirty years of erosion and declining atmospheric pollution at St Paul's Cathedral, London. *Atmospheric environment*, *62*, 521-529.

Jackson, P. (1971). *London Bridge*. Cassell.

Janvier-Badosa, S., Beck, K., Brunetaud, X., Guirimand-Dufour, A., & Al-Mukhtar, M. (2015). Gypsum and spalling decay mechanism of tuffeau limestone. *Environmental earth sciences*, *74*(3), 2209-2221.

Johnston, P. (1907). Stoke D'Abernon Church. *Surrey Archaeological Collections, 20*, 1.

Jokilehto, J. (2007). *History of architectural conservation*. Routledge.

Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: a review and recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2065), 20150202.

Jolly, J. (2020, July). Beefeaters at Tower of London face job cuts amid coronavirus crisis. *The Guardian* https://www.theguardian.com/business/2020/jul/20/beefeaters-tower-of-london-job-cuts-coronavirus (accessed July 2020)

Jones, P. (2004). *A Roman Tile Kiln Discovered in Reigate*. SURREY ARCHAEOLOGICAL SOCIETY.

Jope, E. M. (1964). The Saxon building-stone industry in southern and midland England. *Medieval Archaeology*, *8*(1), 91-118.

Jukes-Browne, A. J. (1900). *The Cretaceous Rocks of Britain* (Vol. 1). Printed for His Majesty's Stationery Office by Wyman and Sons.

Kennedy, M. (2000, January). Historians scorn claims over Thomas More's cell. *The Guardian* https://www.theguardian.com/uk/2000/jan/10/maevkennedy (accessed April 2020)

Klamer, A., & Leonard, T.C. (1994). So what's an economic metaphor. *Natural images in economic thought: markets read in tooth and claw*, 20-51.

Knoop, D., & Jones, G. P. (1938). The English medieval quarry. *The Economic History Review*, *9*(1), 17-37.

Krus, M., & Holm, A. (1999). Simple methods to approximate the liquid transport coefficients describing the absorption and drying process. In *Proceedings of the 5th Symposium 'Building Physics in the Nordic Countries', Göteborg,* 241-248

Lewin, S. Z. (1982). The mechanism of masonry decay through crystallization. In *Conservation of historic stone buildings and monuments. Proceedings of the conference held in washington, dc, february 2-4, 1981* (pp. 120-144).

Lewry, A.J., & Crewdson, L.F.E. (1994). Approaches to testing the durability of materials used in the construction and maintenance of buildings. *Construction and Building Materials*, *8*(4), 211-222.

Liefferink, R. W., Naillon, A., Bonn, D., Prat, M., & Shahidzadeh, N. (2018). Single layer porous media with entrapped minerals for microscale studies of multiphase flow. *Lab on a Chip*, *18*(7), 1094-1104.

Lilley, K. D. (2015). Urban planning after the Black Death: townscape transformation in later medieval England (1350–1530). *Urban history*, *42*(1), 22-42.

Lockwood, S. (1994). Reigate stone: Geology, use and repair. *Structural Survey*, *12*(5), 18-22.

López-Arce, P., Doehne, E., Martin, W., & Pinchin, S. (2008). Magnesium sulfate salts and historic building materials: experimental simulation of limestone flaking by relative humidity cycling and crystallization of salts. *Materiales de Construcción*, *58*(289-290), 125-142.

Lott, G., & Cameron, D. (2005). The building stones of South East England: mineralogy and provenance. *10th Euroseminar on Microscopy Applied to Building Materials, Paisley, Scotland, 21-25 June, 2005.*

Lowenthal, D. (1989). Material preservation and its alternatives. *Perspecta*, 67-77.

Lowenthal, D. (1994). *The value of age and decay*. In: Krumbein, W.E., Brimblecombe, P., Cosgrove, D.E. and Staniforth, S., *Durability and Change: the science, responsibility, and cost of sustaining cultural heritage*. Chicester: John Wiley and Sons.

Lowenthal, D. (2015). *The past is a foreign country-revisited*. Cambridge University Press.

Lubelli, B., Cnudde, V., Diaz-Goncalves, T., Franzoni, E., van Hees, R. P., Ioannou, I., ... & Verges-Belmin, V. (2018). Towards a more effective and reliable salt crystallization test for porous building materials: state of the art. *Materials and Structures*, *51*(2), 55.

Lubelli, B., Van Hees, R., & Groot, C. (2006). The Effect of Environmental Conditions on Sodium Chloride Damage. *Studies in Conservation*, 51(1), 41-56.

Lyon, S. W. (2007). Balancing values of outstanding universality with conservation and management at three United Kingdom cultural world heritage sites. *Journal of Heritage Tourism*, *2*(1), 53-63.

Mackinder, A. (2000). *A Romano-British Cemetery on Watling Street: Excavations at 165 Great Dover Street, Southwark, London* (Vol. 4). Museum of London Archaeology Service.

Madariaga, J. M., Maguregui, M., De Vallejuelo, S. F. O., Knuutinen, U., Castro, K., Martinez-Arkarazo, I., ... & Pitarch, A. (2014). In situ analysis with portable Raman and ED-XRF spectrometers for the diagnosis of the formation of efflorescence on walls and wall paintings of the Insula IX 3 (Pompeii, Italy). *Journal of Raman Spectroscopy*, *45*(11-12), 1059-1067.

Massey, S. W. (1999). The effects of ozone and NOx on the deterioration of calcareous stone. *Science of the total environment*, *227*(2-3), 109-121.

Martínez-Martínez, J., Benavente, D., Gomez-Heras, M., Marco-Castaño, L., & García-del-Cura, M.Á. (2013). Non-linear decay of building stones during freeze–thaw weathering processes. *Construction and Building Materials*, *38*, 443-454.

Maurenbrecher, P. (2012). RILEM TC 203-RHM: Repair mortars for historic masonry: Requirements for repointing mortars for historic masonry. *Materials and Structures*, *45*, 1303-1309.

Maurício, A. M., Pacheco, A. M., Brito, P. S., Castro, B., Figueiredo, C., & Aires-Barros, L. (2005). An ionic conductivity-based methodology for monitoring salt systems in monument stones. *Journal of cultural heritage*, *6*(4), 287-293.

McAllister, D., Warke, P., & McCabe, S. (2017). Stone temperature and moisture variability under temperate environmental conditions: Implications for sandstone weathering. *Geomorphology*, *280*, 137-152.

McCabe, S., Smith, B. J., & Warke, P. A. (2010). A legacy of mistreatment: conceptualizing the decay of medieval sandstones in NE Ireland. *Geological Society, London, Special Publications*, *333*(1), 87-100.

McCabe, S., Smith, B. J., McAlister, J. J., Gomez-Heras, M., McAllister, D., Warke, P. A., ... & Basheer, P. A. M. (2013). Changing climate, changing process: implications for salt transportation and weathering within building sandstones in the UK. *Environmental earth sciences*, *69*(4), 1225-1235.

McCann, D. M., & Forde, M. C. (2001). Review of NDT methods in the assessment of concrete and masonry structures. *Ndt & E International*, *34*(2), 71-84.

Menéndez, B., & Petráňová, V. (2016). Effect of mixed vs single brine composition on salt weathering in porous carbonate building stones for different environmental conditions. *Engineering Geology, 210*, 124-139.

Michette, M. (2016). The Problem Stone Progressive Survey Technique. *MEng dissertation, The Bartlett School of the Built Environment*. University College London.

Michette, M., Viles, H., Vlachou, C., & Angus, I. (2019). Bellweathered: Reigate Stone decay mechanisms at the Bell Tower, Tower of London. In *Monuments in Monuments 2019 Conference Proceedings,* 43-52. https://pub-prod-sdk.azurewebsites.net/api/file/e99b4f10-3572-4459-a81f-aabc00ab0e4e (accessed April 2020)

Michette, M., Bichlmair, S., & Kilian, R. (2018). Diagnosing Decay Mechanisms at the Porta Nocera Necropolis, Pompeii: The First Step Towards Effective Preventive Conservation. *Studies in Conservation*, *63*(sup1), 195-202.

Modestou, S., Theodoridou, M., & Ioannou, I. (2015). Micro-destructive mapping of the salt crystallization front in limestone. *Engineering Geology*, *193*, 337-347.

Mol, L., & Viles, H. A. (2012). The role of rock surface hardness and internal moisture in tafoni development in sandstone. *Earth Surface Processes and Landforms*, *37*(3), 301-314.

Moroni, B., & Pitzurra, L. (2008). Biodegradation of atmospheric pollutants by fungi: a crucial point in the corrosion of carbonate building stone. *International Biodeterioration & Biodegradation*, *62*(4), 391-396.

Moropoulou, A., Labropoulos, K. C., Delegou, E. T., Karoglou, M., & Bakolas, A. (2013). Non-destructive techniques as a tool for the protection of built cultural heritage. *Construction and Building Materials*, *48*, 1222-1239.

North, F. J. (1930). *Limestones, their origins, distribution, and uses*. T. Murby & Company.

Nute, K. (2004). *Place, time, and being in Japanese architecture*. Psychology Press.

Odgers, D. (2013). Learning from the Past: A Review of Treatments carried out to Clunch in 1985. *Journal of Architectural Conservation, 19*(1), 3-17.

Odgers, D., & Henry, A. (2012). Practical Building Conservation: Stone. *English Heritage, Ashgate Publishing Limited, Farnham*.

Odin, G. S., & Matter, A. (1981). De glauconiarum origine. *Sedimentology*, *28*(5), 611-641.

Orr, S. A., Young, M., Stelfox, D., Curran, J., & Viles, H. (2018). Wind-driven rain and future risk to built heritage in the United Kingdom: Novel metrics for characterising rain spells. *Science of the Total Environment*, 640, 1098-1111.

Orr, S. A., Young, M., Stelfox, D., Leslie, A., Curran, J., & Viles, H. (2019). An 'isolated diffusion' gravimetric calibration procedure for radar and microwave moisture measurement in porous building stone. *Journal of Applied Geophysics*, *163*, 1-12.

Orr, S. A., & Viles, H. (2018). Characterisation of building exposure to wind-driven rain in the UK and evaluation of current standards. *Journal of Wind Engineering and Industrial Aerodynamics*, *180*, 88-97.

Owen, H. G. (1975). The stratigraphy of the Gault and Upper Greensand of the Weald. *Proceedings of the Geologists' Association*, *86*(4), 475-498.

Parnell, G. (1993). *Book of the Tower of London*. BT Batsford.

Pel, L., Pishkari, R., & Adan, O. (2019). Combined wicking and drying of a NaCl solution in porous building materials. In *MATEC Web of Conferences* (Vol. 282, p. 02095). EDP Sciences.

Pender, R., Ridout, B. & Curteis, T. (2014). Practical building conservation. Building environment. *English Heritage, Ashgate Publishing Limited, Farnham*.

Phillips, J. D. (2003). Sources of nonlinearity and complexity in geomorphic systems. *Progress in physical geography*, *27*(1), 1-23.

Potter, G. (1988) *The Medieval Bridge and Waterfront at Kingston-upon-Thames*. Waterfront Archaeology (CBA Research Report 74)

Potter, J. F. (2013). Field meeting report: the geology of some West London Churches, 22nd September 2012. *Proceedings of the Geologists' Association*, *124*(6), 1011-1019.

Price, C. A. (1993). Preventive conservation of salt-contaminated masonry in the Wakefield Tower, HM Tower of London. *Institute of Archaeology, Bulletin*, *30*, 121-33.

Price, C. A. (2000). *An expert chemical model for determining the environmental conditions needed to prevent salt damage in porous materials* (pp. 131-135). In: *European Commission Research Report 11, (Protection and Conservation of European Cultural Heritage).* Archetype Publications, London.

Price, C. A. (2007). Predicting environmental conditions to minimise salt damage at the Tower of London: a comparison of two approaches. *Environmental geology*, *52*(2), 369-374.

Price, N.C. (1996). *Historical and philosophical issues in the conservation of cultural heritage* (Vol. 1). Getty Publications.

Přikryl, R. (2007). Understanding the Earth scientist's role in the pre-restoration research of monuments: an overview. *Geological Society, London, Special Publications*, *271*(1), 9-21.

Přikryl, R. (2013). Durability assessment of natural stone. *Quarterly Journal of Engineering Geology and Hydrogeology*, *46*(4), 377-390.

Přikryl, R., Přikrylová, J., Racek, M., Weishauptová, Z., & Kreislová, K. (2017). Decay mechanism of indoor porous opuka stone: a case study from the main altar located in the St. Vitus Cathedral, Prague (Czech Republic). *Environmental Earth Sciences*, *76*(7), 290.

Public Record Office. (1902). *Close rolls of the reign of Henry III : Preserved in the Public Record Office*. (14 Volumes). London: HMSO.

Rackham, R. (1909). *The nave of Westminster. From the Proc., Brit. academy*. Lond.

Ramadier, T. (2004). Transdisciplinarity and its challenges: the case of urban studies. *Futures*, *36*(4), 423-439.

Richards, J., Orr, S. A., & Viles, H. (2019). Reconceptualising the relationships between heritage and environment within an Earth System Science framework. *Journal of Cultural Heritage Management and Sustainable Development*.

Robinson, E., & Worssam, B. (1989). The geology of some Middlesex churches. *Proceedings of the Geologists' Association*, *100*(4), 595-603.

Rodrigues, J.D. (2015). Defining, mapping and assessing deterioration patterns in stone conservation projects. *Journal of Cultural Heritage*, *16*(3), 267-275.

Rodriguez-Navarro, C., & Doehne, E. (1999). Salt weathering: influence of evaporation rate, supersaturation and crystallization pattern. *Earth Surface Processes and Landforms, 24*(3), 191-209.

Rodriguez-Navarro, C., Doehne, E., & Sebastian, E. (2000). How does sodium sulfate crystallize? Implications for the decay and testing of building materials. *Cement and concrete research*, *30*(10), 1527-1534.

Rossi-Manaresi, R., & Tucci, A. (1991). Pore structure and the disruptive or cementing effect of salt crystallization in various types of stone. *Studies in conservation*, *36*(1), 53-58.

Royal Commission on Historical Monuments. (1924-30). *An inventory of the historical monuments in London.* (5 volumes). London: His Majesty's Stationery Office.

Ruffolo, S.A., La Russa, M.F., Ricca, M., Belfiore, C.M., Macchia, A., Comite, V., Pezzino, A., & Crisci, G.M. (2017). New insights on the consolidation of salt weathered limestone: the case study of Modica stone. *Bulletin of Engineering Geology and the Environment*, *76*(1), 11-20.

Sabbioni, C., Bonazza, A., Zamagni, J., Ghedini, N., Grossi, C. M., & Brimblecombe, P. (2004). The Tower of London: A case study on stone damage in an urban area. *Air Pollution and Cultural Heritage. London: AA Balkema*, 57-62.

Salzman, L. (1952). *Building in England down to 1540 : A documentary history*. Oxford: Clarendon Press.

Sanderson, R., & Garner, K. (2001). Conservation of Reigate Stone at Hampton Court Palace and HM Tower of London. *Journal of Architectural Conservation*, *7*(3), 7-23.

Sass, O., & Viles, H. A. (2010). Wetting and drying of masonry walls: 2D-resistivity monitoring of driving rain experiments on historic stonework in Oxford, UK. *Journal of Applied Geophysics*, *70*(1), 72-83.

Sawdy, A., & Price, C. (2005a). Salt damage at Cleeve Abbey, England: Part I: a comparison of theoretical predictions and practical observations. *Journal of cultural heritage*, *6*(2), 125-135.

Sawdy, A., & Price, C. (2005b). Salt damage at Cleeve Abbey, England. Part II: Seasonal variability of salt distribution and implications for sampling strategies. *Journal of Cultural Heritage, 6*(3), 269-275.

Schaffer, R. J. (2004). *The weathering of natural building stones*. Routledge.

Scheffler, G., & Plagge, R. (2005). Defined drying behaviour measurement for building materials. In *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries, Reykjavik June*.

Scherer, R.J. and Katranuschkov, P. (2018). BIMification: How to create and use BIM for retrofitting. *Advanced Engineering Informatics*, *38*,54-66.

Schofield, J., & Vince, A. (2003). *Medieval towns : The archaeology of British towns in their European setting* (2nd ed., Archaeology of medieval Europe, 1100-1600). London: Continuum.

Schofield, J., Allen, P., & Taylor, C. (1990). Medieval buildings and property development in the area of Cheapside. *Transactions of the London and Middlesex Archaeological Society*, *41*, 39-238.

Schofield, J. (2016). *St Paul's Cathedral: archaeology and history*. Oxbow Books Limited.

Schumm, S.A. and Lichty, R.W. (1965). Time, space, and causality in geomorphology. *American journal of science*, *263*(2), 110-119.

Scrivano, S., & Gaggero, L. (2017). Non-invasive analytical technique to address water uptake on stone surfaces: The implemented Contact Sponge Method (i-CSM). *Journal of Cultural Heritage*, *28*, 9-15.

Scrivano, S., Gaggero, L., Gonzalez, A. Y., & Aguilar, J. G. (2017). Assessing surface weathering by revision and implementation of the peeling-test: In situ sampling and integrated analyses. *Journal of Cultural Heritage*, *27*, 88-96.

Shelley, M. (2017). The Complete Poems. *Delphi Classics*. ISBN: 978 1 78877 394 2

Shore, B.C.G. (1957). *Stones of Britain: A pictorial guide to those in charge of valuable buildings*. L. Hill.

Siegesmund, S. and Snethlage, R., 2011, Stone in Architecture, Springer, 9783642144745, 558pp

Smith, B. J., McCabe, S., McAllister, D., Adamson, C., Viles, H., & Curran, J. (2011a). A commentary on climate change, stone decay dynamics and the 'greening' of natural stone buildings: new perspectives on 'deep wetting'. *Environmental Earth Sciences*, *63*(7-8), 1691-1700.

Smith, B.J., & Přikryl, R., (2007). Diagnosing decay: the value of medical analogy in understanding the weathering of building stones. *Geological Society, London, Special Publications*, *271*(1), 1-8.

Smith, B.J. (1996). Scale problems in the interpretation of urban stone decay. In: Smith, B.J., & Warke, P.A. *Processes of urban stone decay*, 3-18. Donhead Publishing: London, UK.,

Smith, B.J., and Turkington A. (2004). *The need for interdisciplinary thinking in stone decay and conservation studies* in: Smith, B.J. and Turkington, A., 2004. *Stone Decay: Its Causes and Controls*, 1-11. Routledge.

Smith, B. J., Gomez-Heras, M., & McCabe, S. (2008). Understanding the decay of stone-built cultural heritage. *Progress in Physical Geography*, *32*(4), 439-461.

Smith, B.J., Gómez-Heras, M., & Viles, H.A. (2010). Underlying issues on the selection, use and conservation of building limestone. *Geological Society, London, Special Publications*, *331*(1), 1-11.

Smith, B.J., Srinivasan, S., Gomez-Heras, M., Basheer, P.A.M., & Viles, H.A. (2011b). Near-surface temperature cycling of stone and its implications for scales of surface deterioration. *Geomorphology*, *130*(1-2), 76-82.

Snyder, R.L., & Bish, D.L. (1989). Quantitative analysis, *Reviews in Mineralogy and Geochemistry*, Mineralogical Society of America, 20(1), 101-44.

Spinney, L. (2019, November). History as a giant data set: how analysing the past could help save the future. *The Guardian*. https://www.theguardian.com/technology/2019/nov/12/history-as-a-giant-data-set-how-analysing-the-past-could-help-save-the-future (Accessed April 2020)

Sowan, P. W. (1975). Firestone and hearthstone mines in the Upper Greensand of east Surrey. *Proceedings of the Geologists' Association*, *86*(4), 571-591.

Sowan, P. W. (1975). Firestone and hearthstone mines in the Upper Greensand of east Surrey. *Proceedings of the Geologists' Association*, *86*(4), 571-591.

Stefani, C., Brunetaud, X., Janvier-Badosa, S., Beck, K., De Luca, L., & Al-Mukhtar, M. (2014). Developing a toolkit for mapping and displaying stone alteration on a web-based documentation platform. *Journal of Cultural Heritage*, *15*(1), 1-9.

Steiger, M., Charola, A.E., & Sterflinger, K. (2011). Weathering and deterioration. In *Stone in architecture*, 227-316. Springer, Berlin, Heidelberg.

Sternberg, T., Viles, H., Cathersides, A. and Edwards, M. (2010). Dust particulate absorption by ivy (Hedera helix L) on historic walls in urban environments. *Science of the total environment*, *409*(1), 162-168.

Stück, H., Plagge, R., & Siegesmund, S. (2013). Numerical modeling of moisture transport in sandstone: the influence of pore space, fabric and clay content. *Environmental earth sciences*, *69*(4), 1161-1187.

Sun, Q., & Zhang, Y. (2019). Combined effects of salt, cyclic wetting and drying cycles on the physical and mechanical properties of sandstone. *Engineering geology*, *248*, 70-79.

Tanner, L., & Clapham, A. (1933). XI.—Recent Discoveries in the Nave of Westminster Abbey. *Archaeologia, 83*, 227-236.

Tatton-Brown, T. (1991). Medieval building stone at the Tower of London. *The London Archaeologist, 6*(13), 361.

Tatton-Brown, T. (2001). The quarrying and distribution of Reigate Stone in the Middle Ages. *Medieval Archaeology*, *45*(1), 189-201.

Thomas, C. (2002). *The archaeology of medieval London*. Stroud: Sutton.

Thomas, C., Cowie, R., & Sidell, E. J. (2006). *The royal palace, abbey and town of Westminster on Thorney Island. Archaeological excavations (1991-8) for the London Underground Limited Jubilee Line Extension Project* (pp. 1-224). Museum of London Archaeology Service Monograph Series.

Thomas, C., Sloane, B., & Phillpotts, C. (1997). *Excavations at the priory and hospital of St Mary Spital, London*. MoLAS Monograph 1, London: Museum of London Archaeology Service.

Thompson, G. R., & Hower, J. (1975). The mineralogy of glauconite. *Clays and Clay Minerals*, *23*(4), 289-300.

Thornbush, M. J. (2012). A site-specific index based on weathering forms visible in Central Oxford, UK. *Geosciences*, *2*(4), 277-297.

Torney, C., Forster, A. M., & Szadurski, E. M. (2014). Specialist 'restoration mortars' for stone elements: a comparison of the physical properties of two stone repair materials. *Heritage Science*, *2*(1), 1.

Torraca, G. (1982). The scientist's role in historic preservation (with particular reference to stone conservation). In: *Conservation of historic stone buildings and monuments. Proceedings of the conference held in washington, dc, february 2-4, 1981,* 13-21.

Tresise, G. R. (1960). Aspects of the lithology of the Wessex Upper Greensand. *Proceedings of the Geologists' Association*, *71*(3), 316-IN2.

Trofimov, A. M., & Phillips, J. D. (1992). Theoretical and methodological premises of geomorphological forecasting. *Geomorphology*, *5*(3-5), 203-211.

Trotec, 2019, Operating manual for material moisture measuring device T660 (uk.trotec.com/fileadmin/downloads/Messgeraete/Feuchte/T660/TRT-BA-T660-001-EN.pdf, accessed April 2019)

Trudgill, S.T., Viles, H.A., Cooke, R.U., Inkpen, R.J., Heathwaite, A.L. and Houston, J. (1991). Trends in stone weathering and atmospheric pollution at St Paul's Cathedral, London 1980–1990. *Atmospheric Environment. Part A. General Topics*, *25*(12), 2851-2853.

Tucker, M. E. (2003). *Sedimentary rocks in the field*. John Wiley & Sons.

Turkington, A. V. (1996). Stone durability. In: Smith, B.J., & Warke, P.A. *Processes of urban stone decay*, 19-31. Donhead Publishing: London, UK.,

UNESCO. (2012). *Operational guidelines for the implementation of the World Heritage Convention*. Paris: UNESCO.

Urquhart, D. C. M., Young, M. E., MacDonald, J., Jones, M. S., & Nicholson, K. A. (1996). In: Smith, B.J., & Warke, P.A. *Processes of urban stone decay*, 76. Donhead Publishing: London, UK.,

Válek, J., Kruschwitz, S., Wöstmann, J., Kind, T., Valach, J., Köpp, C., & Lesák, J. (2010). Nondestructive investigation of wet building material: multimethodical approach. *Journal of performance of constructed facilities*, *24*(5), 462-472.

Van Balen, K., & Verstrynge, E. (2016). *Structural Analysis of Historical Constructions: Anamnesis, Diagnosis, Therapy, Controls: Proceedings of the 10th International Conference on Structural Analysis of Historical Constructions (SAHC, Leuven, Belgium, 13-15 September 2016)*. CRC Press.

Van den Eynde, V. C., Mateos, F. J., & Paradelo, R. (2013). Degradability of building stone: Influence of the porous network on the rate of dissolution of carbonate and evaporitic rocks. *Journal of Cultural Heritage*, *14*(2), 89-96.

Vázquez, P., Alonso, F.J., Carrizo, L., Molina, E., Cultrone, G., Blanco, M., & Zamora, I. (2013). Evaluation of the petrophysical properties of sedimentary building stones in order to establish quality criteria. *Construction and Building Materials*, *41*, 868-878.

Venturi, R. (1966). *Complexity and Contradiction in Architecture*. NEW YORK: THE MUSEUM OF MODERN ART

Veran-Tissoires, S., & Prat, M. (2014). Evaporation of a sodium chloride solution from a saturated porous medium with efflorescence formation. *Journal of fluid mechanics*, *749*, 701-749.

Vergès-Belmin, V. (2008). *Illustrated glossary on stone deterioration patterns*. ICOMOS.

Viles, H.A. (2001). Scale issues in weathering studies. *Geomorphology*, *41*(1), 63-72.

Viles, H. A. (2005). Can stone decay be chaotic?. *Special Papers of the Geological Society of America*, *390*, 11.

Viles, H. A. (2013). Durability and conservation of stone: coping with complexity. *Quarterly Journal of Engineering Geology and Hydrogeology*, *46*(4), 367-375.

Viles, H. (2016). Technology and geomorphology: Are improvements in data collection techniques transforming geomorphic science?. *Geomorphology*, *270*, 121-133.

Viles, H.A., Camuffo, D., Fitz, S., Fitzner, B., Lindqvist, O., Livingston, R.A., Maravelaki, P.N., Sabbioni, C., & Warscheid, T. (1997). Group report: What is the state of our knowledge of the mechanisms of deterioration and how good are our estimates of rates of deterioration?. *ENVIRONMENTAL SCIENCES RESEARCH REPORT ES*, *20*, pp.95-112.

Viles, H., Goudie, A., Grab, S., & Lalley, J. (2011). The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: a comparative analysis. *Earth Surface Processes and Landforms*, *36*(3), 320-333.

Wainwright, O. (2018, May) 'A gothic space rocket to a secret realm' – Westminster Abbey's new £23m tower. *The Guardian.* https://www.theguardian.com/artanddesign/2018/may/29/westminster-abbey-weston-tower-ptolemy-dean-gallery (accessed April 2020)

Wangler, T., & Scherer, G. W. (2008). Clay swelling mechanism in clay-bearing sandstones. *Environmental Geology*, *56*(3-4), 529-534.

Warke, P., & Smith, B. (2007). Complex weathering effects on durability characteristics of building stone. *Geological Society, London, Special Publications, 271*(1), 211-224.

Warke, P. A., Curran, J. M., Turkington, A. V., & Smith, B. J. (2003). Condition assessment for building stone conservation: a staging system approach. *Building and Environment*, *38*(9-10), 1113-1123.

Warke, P.A. (1996). Inheritance effects in building stone decay. In: Smith, B.J., & Warke, P.A. *Processes of urban stone decay*, 32-43. Donhead Publishing: London, UK.,

Warke, P.A., McCabe, S., McAllister, D., & McGreevy, J.P. (2019). Whither weathering? Challenges for rock weathering research in the 21st century. *Chikei/Transactions, Japanese Geomorphological Union 40(3),* 279-297.

Warke, P.A., McKinley, J. and Smith, B.J. (2006). Variable weathering response in sandstone: factors controlling decay sequences. *Earth Surface Processes and Landforms*, *31*(6), 715-735.

Watson, J. (1911). *British and foreign building stones: a descriptive catalogue of the specimens in the Sedgwick Museum, Cambridge*. University Press.

Watson, J. (2019). *Lo-TEK : Design by Radical Indigenism*. Cologne. Taschen

Weber, J., Gadermayr, N., Bayer, K., Hughes, D., Kozlowski, R., Stillhammerova, M., ... & Vyskocilova, R. (2008). Roman cement mortars in Europe's architectural heritage of the 19th century. In *Natural Cement*. ASTM International.

Weiss, N., Slavid, I., & Wheeler, G. (2000). Development and assessment of a conversion treatment for calcareous stone. *Proc. 9th Int. Cong. On Deterioration and Conservation of Stone, Venice*, 533-54.

Wells, J.C. (2019). Science for built heritage. *Science, 364*(6439), 413

Wiggins, D. (2017). Traditional lime mortars and masonry preservation. *The Journal of the Building Limes Forum*, 24, 28-37

Wilhelm, K., Viles, H., & Burke, Ó. (2016c). Low impact surface hardness testing (Equotip) on porous surfaces–advances in methodology with implications for rock weathering and stone deterioration research. *Earth Surface Processes and Landforms*, *41*(8), 1027-1038.

Wilhelm, K., Viles, H., & Burke, Ò. (2016a). The influence of salt on handheld electrical moisture meters: can they be used to detect salt problems in porous stone?. *International Journal of Architectural Heritage*, *10*(6), 735-748.

Wilhelm, K., Viles, H., Burke, O., & Mayaud, J. (2016b). Surface hardness as a proxy for weathering behaviour of limestone heritage: a case study on dated headstones on the Isle of Portland, UK. *Environmental Earth Sciences*, *75*(10), 931.

Williams, J. H. (1971). Roman building-materials in south-east England. *Britannia*, *2*, 166-195.

Wright, J.S. (2002). Geomorphology and stone conservation: sandstone decay in Stoke-on-Trent. *Structural Survey*.

Yılmaz, N. G. (2013). The influence of testing procedures on uniaxial compressive strength prediction of carbonate rocks from Equotip hardness tester (EHT) and proposal of a new testing methodology: Hybrid dynamic hardness (HDH). *Rock mechanics and rock engineering*, *46*(1), 95-106.

Yu, S., & Oguchi, C. T. (2009). Complex relationships between salt type and rock properties in a durability experiment of multiple salt–rock treatments. *Earth Surface Processes and Landforms*, *34*(15), 2096-2110.

Appendices

Appendix A: Glossary

Frequently used acronyms

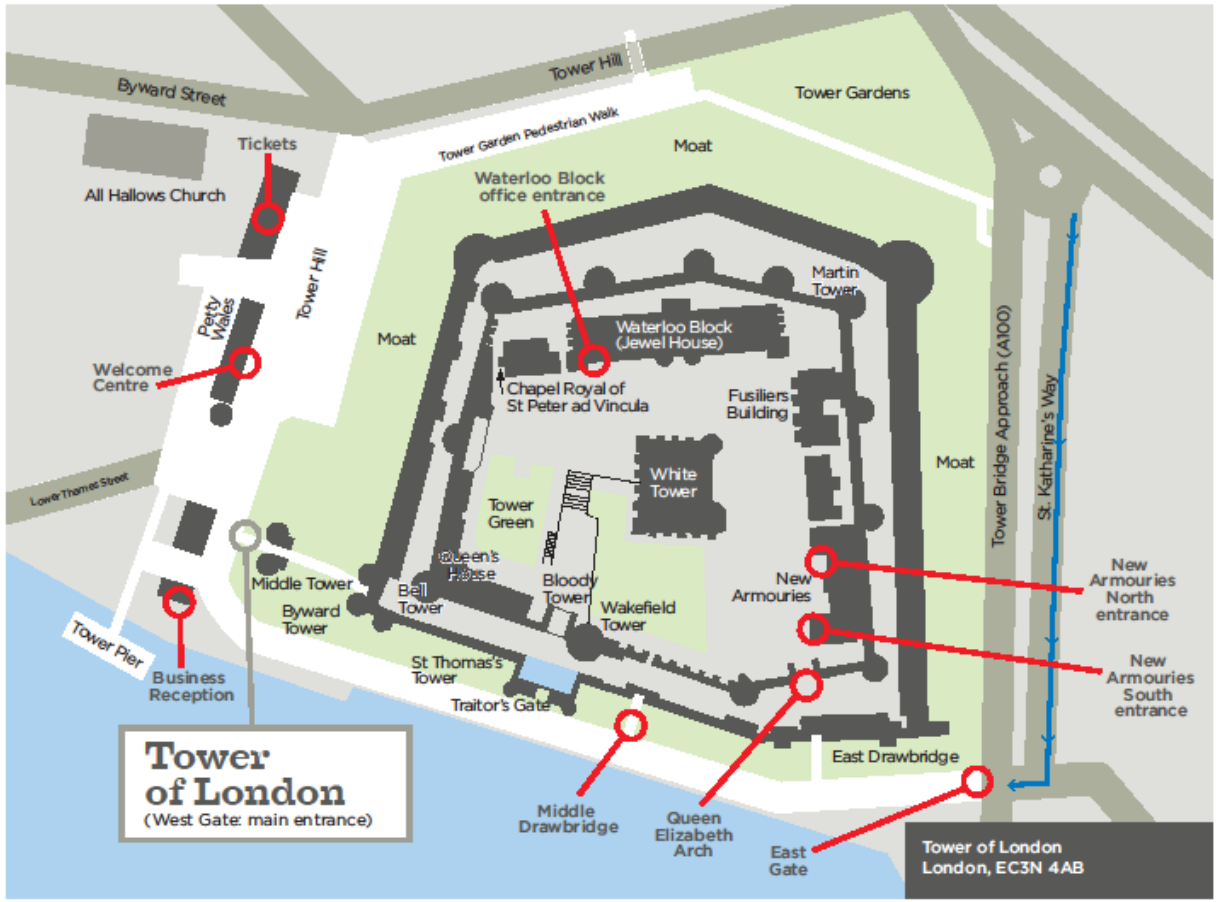
DRM	Drilling resistance measurement
ECOS	Environmental Control of Salts
EPSRC	Engineering and Physical Sciences Research Council
HCP	Hampton Court Palace
HCT	Hydroxylating conversion treatment
HRP	Historic Royal Palaces
ICOMOS	International Council on Monuments and Sites
MC	Moisture content
NDT	Non-destructive testing/ Non-destructive technique
NHL	Natural hydraulic lime
PCA	Principal Component Analysis
RH	Relative humidity
SEAHA	Science and Engineering in Arts Heritage and Archaeology
SH	Surface hardness
SPAB	Society for the Protection of Ancient Buildings
ToL	Tower of London
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USB	Universal Serial Bus
WUFI	Waerme- und Feuchtetransport integriert (Integrated heat and moisture transport)
XRD	X-Ray diffraction

Terminology

Problem Stone	Used until recently by Historic England to describe a group of building stones (including Reigate Stone) which were responsible for a disproportionate amount of conservation effort. Dropped in favour of **hard to treat stone**, due to concerns over negative associations. Proposal in this thesis to consider using **vulnerable masonry** as more inclusive of interrelated processes affecting decay.
Decay	Physical change in response to environmental mechanisms. Decay can result in deterioration, through loss of strength or undesirable aesthetic changes. Decay can, however, also be considered to add value to heritage, typically be emphasising age or relationship to the environment.
Deterioration	A loss of quality or cultural value. Occurs when decay crosses aesthetic or functional thresholds. Can manifest without physical change as thresholds fluctuate according to context.
Resilience	The property of masonry (or other elements of the historic built environment) to withstand deterioration.
Restoration	(Partial) reconstruction of historic fabric. Often used to describe stylistic re-appraisal of building (stylistic restoration).
Conservation/ Architectural conservation	Initially a mid-19th century movement opposed to stylistic restoration. Now frequently used as an umbrella-term for care of historic (built) environment, which is accepted to include a wide range of remedial action, including targeted restoration, repair, consolidation, and environmental control. Practical framework sometimes described as **Conservation-Restoration**.
Active conservation	Intervention into material fabric in attempt to improve resistance to decay processes.
Preventive conservation	Control of environmental mechanisms to mitigate decay processes.
Contingency	The absence of certainty in events. Used here to describe the propensity for an initial condition to have divergent possible end conditions when subject to a set of complex interrelated processes.

Appendix B: Map of Tower of London and Statements of Significance

Tower of London



Historic Royal Palaces

Statement of Significance:
Wardrobe Tower, Tower of London

Historic Royal Palaces is the charity that looks after:
Tower of London
Hampton Court Palace
Banqueting House
Kensington Palace
Kew Palace
Hillsborough Castle
We help everyone explore the story of how monarchs and people have shaped society, in some of the greatest palaces ever built.
We raise all our own funds and depend on the support of our visitors, members, donors, sponsors and volunteers.

Hirra Ateeq, Curatorial Intern &
George Roberts, Tower Future Projects Curator
12 January, 2017.



Historic Royal Palaces

Title:	*Statement of Significance: Wardrobe Tower, Tower of London*
Author(s):	Hirra Ateeq, Curatorial Intern George Roberts, Tower Future Projects Curator
Origination Date:	12 January, 2017
Version:	1



Historic Royal Palaces

Contents

1. Introduction 1
2. Scope 1
3. Location 1
4. Description of Site 2
5. Historical Summary 3
6. Statement of Significance 6
7. Recommendations 9
8. Bibliography 10
9. Appendices 12

Appendix 1: Site Chronology 12

Appendix 2: *Understanding Heritage Values* 15

Appendix 3: Images/Maps/Plans 20

1. Introduction

1.1. This Statement of Significance has been prepared by HRP's Curatorial Team.

1.2. A Statement of Significance identifies the important characteristic and significance of the existing site or building and looks to explain how the proposed works would affect them and justify why they are necessary or desirable.

1.3. It forms part of any application to gain consent for the proposed works from Historic England or other regulatory body and should be read and understood by all contractors involved in the project.

2. Scope

2.1. This statement concerns the remains of the Wardrobe Tower located due east of the White Tower at the Tower of London.

2.2. It focuses on the standing, above-ground archaeology and includes the remains of the tower itself, as well as the area of surviving Roman City Wall.

2.3. It has been prepared to support an SMC application for proposed conservation work to the Wardrobe Tower in early 2017.

3. Location

3.1. The ruins of the Wardrobe Tower are located in the north-east corner of the Inmost Ward of the Tower of London and shown on Figure 1.

3.2. This site is believed to have been constructed on the line of the Roman city wall and is situated to the east of the White Tower.

3.3. The Wardrobe Tower's National Grid Reference is 533648 180529.

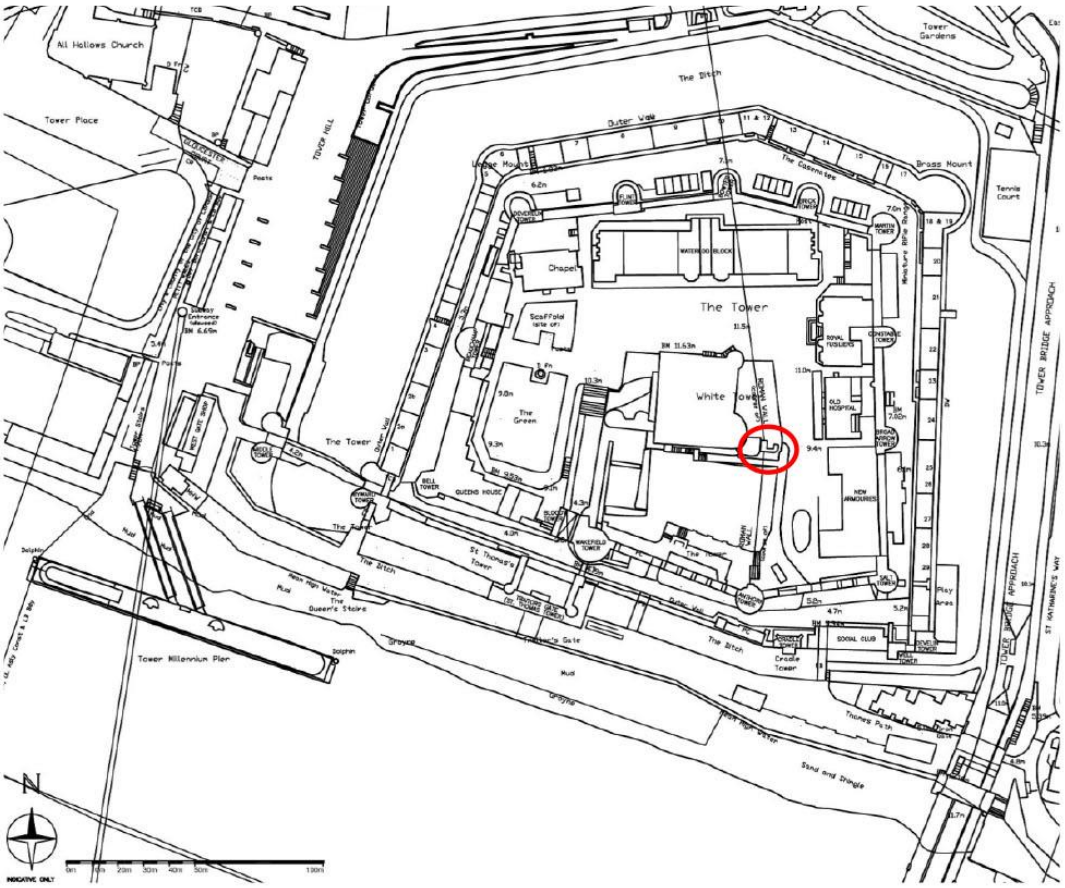


Figure 1 *Plan of the Tower of London with the Wardrobe Tower marked in red.*

4. Description of Site

4.1. The Tower of London is a Scheduled Ancient Monument and an UNESCO World Heritage Site (Reference 488).

4.2. The Wardrobe Tower forms part of the 'Tower of London' Scheduled Ancient Monument and agreement must be sought from Historic England in advance of any material changes to the fabric and archaeology.

4.3. The Wardrobe Tower is a surviving fragment of a former tower. In origin this is thought to date to the 1190s, being part of Longchamp's work during the reign of Richard I. The fragment is D-shaped in plan and is known to stand on the line of the Roman landward wall. It incorporates the base of a Roman bastion still visible as the foundation of Roman bricks and a section of the Roman city wall. The latter is nearly 2.4m wide with a projecting sandstone plinth. The external face of the wall is of neat rows of squared ragstone rubble with tile bonding courses set at regular intervals. The twelfth-century walling above is of

ragstone rubble with Caen and Reigate ashlar. Repairs in 18th-century red brick are also evident.

4.4. During its history the tower became the focus of the royal Wardrobe buildings. In Haiward and Gascoyne's plan of 1597 (Figure 2) it is shown as a cylindrical tower with the Wardrobe building running east from it to Broad Arrow Tower, and an east annex thought to be associated with the fourteenth-century wardrobe running northwards from it. In 1879 John Taylor demolished this east annex and destroyed the majority of the surviving twelfth-century tower as well. Work was stopped in time to salvage the fragment of the structure we see today. The twelfth-century pilaster-buttressed wall linking the tower to the south-east corner of the White Tower was later also demolished in 1883.

5. Historical Summary

5.1. Tatton-Brown has suggested that the Wardrobe Tower was constructed around the same time as Longchamp's Bell Tower, which is located south-west of the White Tower in circa 1190.[1]

5.2. The tower is believed to have been built on the surviving foundations of one of the Roman bastions of the city wall and was connected to the south-east corner of the White Tower with a contemporary pilaster buttressed wall[2]. This long-standing theory has been based on remnants of a roman bastion along with existing fabric that shows the medieval building was erected on top of its Roman forbear[3].

5.3. Wheeler designated the Wardrobe Tower as the location of Bastion 1 of the Roman city wall (Figure 3).[4] However, as Maloney noted, it is a rare example of an eastern bastion which is not solid above its foundations (Bastion 11 is the other exception).[5]

5.4. Renn's recent claim that the Wardrobe Tower may have been an Anglo-Saxon chapel[6] is unlikely due to the close proximity, and accepted pre-Norman origins of the chapel of St Peter ad Vincula.[7]

---

[1] Tim Tatton-Brown, 'Medieval Building Stone at the Tower of London', *London Archaeologist*, 6:13 (1991) pp.361-366; Alden Gregory, *The Queens' House and Bell Tower Statement of Significance* (Unpublished Report for HRP, 2014), 1-78.
[2] Geoffrey Parnell, *The Tower of London* (London, 1993), 23.
[3] Anna Keay, *The Elizabethan Tower of London* (London, 2001), 42.
[4] 'RCHM, *An Inventory of the Historical Monuments in Roman London*; *Volume 3 Roman London* (London, 1928), 83.
[5] John Maloney, 'The Discovery of Bastion 4A in the City of London and its implications', *Transactions of the London and Middlesex Archaeological Society*, 31 (1980) pp.68-76, 70.
[6] Derek Renn, 'Pause and Cause: The "Building Break" in the White Tower of London', *Transactions of the London and Middlesex Archaeological Society*, 65 (2015) pp.221-229, 228-229.

5.5. Similarly, the function of the Wardrobe Tower to a certain extent is unclear. Though evidence is limited on this issue, the generally accepted and most feasible theory is that the Wardrobe Tower was used by the Royal Wardrobe as a store to house wardrobe goods. The constant movement of monarchs from palace to palace around the country is an old custom that meant that when monarchs travelled their advisors and servants along with all their belongings travelled with them. This included: 'jewels, ornaments, coined money, books, accounts, arms and armour, furniture' and food.[8] These extravagant and precious belongings were known as the wardrobe. To allow for more ease, efficiency and safety officials responsible for the wardrobe began to store these goods in buildings. As a result this led to the construction of purpose-built buildings with the specific objective to house wardrobe goods.

5.6. The Great Wardrobe was responsible for the 'bulk storage of durable goods'.[9] In 1253 the Great Wardrobe became independent in its own right when it gained independence from its parent organisation. In the mid fourteenth century the Great Wardrobe started to relocate from the Tower of London to grounds near Baynard's Castle to create more room at the Tower for 'military stores and records'.[10] A further divide in the organisation resulted in the establishment of the privy wardrobe at the Tower of London in July 1323 which became known as the arsenal branch.[11]

5.7. In 1532-33 Henry VIII constructed a new timber-framed wardrobe building measuring 31 by 7m (101 by 24ft) that ran eastward from the Wardrobe Tower to the Broad Arrow Tower on the inner curtain wall.[12] Also known as the Wardrobe Gallery, it may have replaced an earlier wardrobe storehouse in the same location.[13]

5.8. The construction of the Wardrobe building seems to have helped name the tower, as prior to this date it seems that the Wardrobe Tower did not have a permanent name and was only identified in connection to other buildings in its immediate vicinity.[14] Its name as the 'Warderoap Tower' on Haiward and Gascoyne's plan of the Tower

---

[7] Jeremy Haslam, 'Parishes, Churches, Wards and Gates in Eastern London' in John Blair (ed.), *Minsters and Parish Churches; The Local Church in Transition 950-1200* (Oxford, 1988), pp.35-44.
[8] Parnell, *Tower of London*, 53.
[9] Ibid., 53.
[10] Jeremy Ashbee, 'The Structure and Function of the White Tower, 1150-1485' in Edward Impey (ed.), *The White Tower* (London, 2008), pp.141-160, 153.
[11] Ibid,. 153.
[12] Parnell, *Tower of London*, 56.
[13] George Clark, *Medieval Military Architecture* (London, 1884), 220.
[14] Keay, *Elizabethan Tower of London*, 42.

in 1597 seems to have been the earliest reference to its name (Figure 2).

5.9. In the late-nineteenth century there was an aggressive campaign across the Tower's site to demolish all the 'useless' contemporary annexes which 'obscured' the older buildings.[15] The work was overseen by the Board of Works architect, John Taylor who in 1878 recommended that the entire structures to the east of the White Tower must be removed to return it to 'its original condition' (Figure 4).[16] Partial demolition of the annexe to the White Tower took place in 1879, which included the buttressed wall, storehouse and much of the annexe itself.[17]. In the course of the demolition the remains of the Wardrobe Tower were exposed, along with traces of the Roman city wall onto which it had been built.

5.10. On inspection, the base of the Wardrobe Tower was identified as Roman. It was semi-circular in shape, and hollow, containing rubble masonry 5ft high made of stone and broken Roman brick along with brown and red mortar (Figure 5).[18] The remaining twelfth-century buttressed wall was eventually demolished in 1883.[19] In 1904 the Society of Antiquaries conducted further excavations to the south end of the remaining fragment of wall with the purpose of finding traces of the continuation of the wall toward the Thames, or where the angle of the wall was located but failed to find any further Roman remains.[20]

5.11. In the mid-1950s, three sites were excavated at the Tower of London to present evidence on the defences of Roman London. The 1954 excavation took place at the north east corner of the White Tower, where the foundation of the Roman wall was discovered 21ft 4 inches east of the White Tower (TOL 24). The 1955 excavations near the Lanthorn Tower revealed a length of 46ft of the wall, taking its line to a point 120ft south of the Wardrobe Tower (TOL 24). The 1956-7 excavation took place on the east side of the White Tower revealed north of the Wardrobe Tower foundations of the city wall and internal turret (TOL 25).[21]

---

[15] C. H. Compton, 'Recent discoveries at the Tower of London', *Journal of the British Archaeology Association*, 37 (1881) pp. 279-284, 279.
[16] Anna Keay and Roland B. Harris, 'The White Tower, 1855-2000' in Edward Impey (ed.), *The White Tower* (London, 2008), pp.209-224, 213.
[17] Ibid., 213.
[18] Loftus Brock, 'Roman remains in the Tower of London', *Journal of the British Archaeology Association*, 38 (1882) pp.127-135, 130.
[19] Anna Keay and Roland B. Harris, 'The White Tower, 1855-2000' in Edward Impey (ed.), *The White Tower* (London, 2008), pp.209-224, 214.
[20] Phillip Norman and Francis Reader, 'Recent Discoveries in connection with Roman London', *Archaeologia*, 60 (1907) pp.169-250, 239.
[21] These excavations are all summarised in S. A. Butcher, *Excavation of the Roman City Defences and a Building at the Tower of London, 1954-57* (Unpublished Report held by HRP, c.1957).

5.12. According to Parnell the Wardrobe Tower was examined again in 1962 when a double course of broken Roman tiles set in a hard pink coloured mortar was found, similar to that found in 1879.[22]

6. Statement of Significance

6.1. This section judges the significance of the asset using Historic England's four heritage values. These are explained in full, in Appendix 2 of this report.

6.2. *Evidential Value*

6.2.1. This value shows the potential of a place to yield evidence about past human activity.

6.2.2. The Wardrobe Tower has considerable evidential value providing evidence of past human activity dating back to the Roman period, through to the twenty-first century.

6.2.3. With so little written evidence for the age and development of the structure, its survival provides important information for us on its history.

6.2.4. This includes its relationship to other surviving portions of the Roman City Wall with the potential to understand the dates and techniques of their construction, including debates regarding the spacing between and the construction of, its bastions.

6.2.5. Its location also provides evidence for the extent of William I's original eastern defences at the Tower of London and it is now one of the few surviving examples of the site's original defences.[23] It shows the materials used for its construction, as well as the opportunity to observe additions and alterations to the fabric throughout its later history which have been poorly recorded by the written historical record.

6.2.6. Further loss of historic material on the Wardrobe Tower would further diminish the opportunity to understand the historic development of this structure. Therefore, with so little written information on the Wardrobe Tower, the remains are of very high evidential value. From the Roman period through to the modern day both for the Tower of London and for the City of London.

---

[22] Geoffrey Parnell, 'The Roman and medieval defences and the later development, of the Inmost Ward, Tower of London: Excavations 1955-77', *Transactions of the London and Middlesex Archaeological Society*, 36 (1985) pp.1-79, 33.

[23] The other main example is the stretch of excavated Roman river wall in the Inmost Ward to the west of the Lanthorn Tower.

6.2.7. By combining all these examples the Wardrobe Tower is considered to be of very high evidential value.

6.3. *Historical Value*

6.3.1. This value shows the ways in which past people; events and aspects of life can be connected through a place to the present.

6.3.2. Due to the fact that much of the Wardrobe Tower has been demolished, its historical value is predominantly based on its associative history as a place of defence and a place of storage.

6.3.3. As part of the city wall and the Tower, it has formed part of London's defences from the Roman period and into the Norman period, reflecting the desire to defend and control the capital. It helps to show the extent of these early defences, as well as providing some explanation for William I's decision to position his new castle in this location.

6.3.4. Furthermore, the remains of the Wardrobe Tower perfectly illustrate the importance of the Royal Wardrobe facility. Believed to have been constructed at an early period in the Tower of London's history, the Wardrobe would have held more than just the monarch's clothing. It also played an important part of monarchs' daily lives as it exemplified their practice of moving the court from place to place, requiring objects and possessions across the country.

6.3.5. Finally, the Wardrobe Tower's historic treatment reflects changing attitudes towards conservation at the Tower of London and more widely across Britain. As part of the White Tower's annexe it was scheduled for demolition as it was seen as a later addition to a Norman building. Unlike many other buildings at the Tower which were demolished during this period its demolition was halted, leaving some remains which can still be seen and understood today. It was decisions such as this that inspired the establishment of the Society for the Protection of Ancient Buildings (SPAB).

6.3.6. Due to this variety of different examples of associative history, the Wardrobe is considered to be of a very high rating for historical value.

6.4. *Aesthetic Value*

6.4.1. This value shows the ways in which people draw sensory and intellectual stimulation from a place.

6.4.2. Due to its ruinous state, the Wardrobe Tower would be considered of relatively low aesthetic value by many visitors,

especially due to its situation next to the White Tower However this is understandable as the structure has been almost entirely removed. However, many people find ruins romantic and on a site which has been maintained as well, and in use as long as the Tower there are relatively few such areas, some of which are not accessible to the public.

6.4.3. Due to its rather limited appearance and setting, the Wardrobe Tower is considered to be of low aesthetic value.

6.5. *Communal Value*

6.5.1. This value shows the meanings of a place for the people who relate to it, or for whom it figures in their collective experience or memory.

6.5.2. Much of the Wardrobe Tower's communal value has been accumulated through the passage of time, due to the Roman-origins of its foundations.

6.5.3. This means that the Wardrobe Tower has played a role within the history of London since around the year 200AD. The Roman Wall helped to mark the extent of the Roman-era City, and still defines the City of London today. Therefore it plays a role in the understanding of place and local history for London's modern residents and has high social value.

6.5.4. Furthermore, as part of the Tower of London Ancient Monument, it is part of the wider set of values and place which the site continues to be associated with. Perceived as a place of Royal power and control, as well as a place of imprisonment and torture it has played a major role within British and global history. This allows the Wardrobe Tower to have some amount of symbolic value to many people, although few would automatically link it to them.

6.5.5. Through this combination of social and symbolic value, the Wardrobe Tower is considered to have medium communal value.

6.6. The combinations of these values for the Wardrobe Tower suggest that it especially important for its evidential and historical values, with less importance attached to its aesthetic and communal values. It provides value which can be applied and used well beyond its local context, and can invite comparison with other Roman and Norman sites across the United Kingdom. Further research, may yet increase this importance, and allow it to be compared and considered internationally.

6.7. Therefore, due to its strong relationship both to the Tower and the City of London, the Wardrobe Tower is considered to be of national importance.

7. Recommendations

7.1. HRP is the custodian of the Tower of London and therefore conducts an on-going conservation programme and the Wardrobe Tower is scheduled to be conserved in the financial year 2016-2017.

7.2. Although the full extent of this proposed programme of conservation is still being established, it is clear that the site will benefit from sympathetic cleaning and repair. It should be overseen by experienced architects who have experience of working on similar heritage sites. Any conservation work should be carried out by experienced and well-qualified masons or other suitable professionals using historicall appropriate techniques and materials.

7.3. The work should be supported by a qualified and competent archaeologist to provide a well-informed watching brief as necessary, especially if work is required for stone replacement and repair.

7.4. The planned work also allows for archaeological recording of the fabric to take place, which may help to answer several fundamental questions concerning the Wardrobe Tower's construction and development that have not yet been answered clearly due to a lack of evidence and information. Examples of these questions include:

- What evidence, if any, is there for the surviving Roman bastion remains?
- Was Wheeler correct that the Wardrobe Tower was constructed on the site of a Roman bastion?
- How much, if any, of the original Roman city wall survives in the lower courses of the Wardrobe Tower?
- Is there any evidence for how the Wardrobe Tower was connected to the now lost buildings to which it used to adjoin- the eastern annexe of the White Tower, the Horse Armoury and the Tudor-era Wardrobe building?

7.5. With these conditions and opportunities met, we are happy to support the proposed conservation work to the Wardrobe Tower. It will help to preserve the structure for the foreseeable future as well as improving its appearance. The work also provides the opportunity to increase our knowledge about the structure and its development as well as its relationship to other now-lost structures.

The Queen's House and Bell Tower

Statement of Significance

Alden Gregory, Curator of Historic Buildings

v.2: October 2014

SUMMARY

This Statement of Significance is intended to summarise the current historical and archaeological knowledge regarding the both the Queen's House and the Bell Tower at HM Tower of London. It has been prepared in advance of proposed conservation project and should inform the scope of those works.

CONTENTS

Summary 1
Location and Statutory Designations 1
History of the Queen's House and Bell Tower 2
Outline Chronology 2
The Bell Tower 2
The Queen's House 5
Statement of Significance 15
Appendix I: Interim Curatorial Report: Queen's House: Council Chamber 17
Appendix II: 20th-Century Timber Repairs 27
Appendix III: Full Source Chronology 29
Appendix IV: Images (Compiled by Mary Gillespie) 59

LOCATION AND STATUTORY DESIGNATIONS

The Queen's House and Bell Tower is comprised, as the name suggests, of two separate but adjoining buildings forming the south-west corner of the inner ward of the Tower of London. The former is a 16th-century timber framed house arranged in L-shape with two wings on a north-south and an east-west alignment. The latter is a late 12th-century corner tower that originally formed part of the outer defences of the medieval castle.

The Tower of London is a Scheduled Monument (Greater London SM No 10) and a UNESCO World Heritage Site (No 488) and both the Queen's House and the Bell Tower lie within the boundaries of these designations. Designations of this level recognise that the Tower of London and its buildings are of international significance.

The *Tower of London Conservation Plan* (2010) lists both the Queen's House and the Bell Tower as of **exceptional significance**.

HISTORY OF THE QUEEN'S HOUSE AND BELL TOWER

Outline Chronology

c.1190-1200	Date of building for the Bell Tower.
1360	Probable date of first house on the site.
1535	Bishop John Fisher and Sir Thomas More imprisoned at the Tower, probably in the Bell Tower.
1540	Build date of the Queen's House south range.
1540-66	Build date of the Queen's House west range.
1605-06	Interrogation of Guy Fawkes and Gunpowder Plot conspirators in the great hall.
1607	Insertion of floor in to great hall to form Council Chamber.
1608	Erection of Gunpowder Plot memorial.
1662	Search for Barkstead's gold mounted by Samuel Pepys.
1663-4	Construction of single-storey building to front of the Queen's House.
1669-70	Balcony added to south wall of Queen's House accessed from the Dining Room and requiring remodelling of windows.
1679-70	Major refurbishment of house for new Lieutenant.
1687	Further major phase of refurbishment including insertion of sash windows and new staircase. Work seems to have been overseen by Christopher Wren.
1752	Roofs stripped for repairs.
1778	Request from Constable to demolish Queen's House because of its poor state of repair.
1914-15	Render stripped from exterior and sash windows replaced with Tudor-style casements. The main staircase inserted having been moved from a house in Stafford.
1940	Incendiary bomb damage.
1941	Rudolf Hess held in the Queen's House for four days.
1960	Removal of brick staircase tower.
1961	Remodelling of the Council Chamber.
1971	Replacement and repairs of sash windows in south wall of Queen's House.

The Bell Tower

By comparison with the Queen's House – a description of which follows – the history of the Bell Tower's development and use is sparsely recorded in the archival sources. This should not detract from its significance, however, and indeed the relatively few mentions of it in the historic accounts may simply reflect the fact that it has been little altered since its initial construction in the late 12th century. It has been attributed a build date on stylistic grounds of c.1190-1200, and

thus, almost certainly, formed part of the strengthened outer defences of the castle built by Justiciar William Longchamp, Bishop of Ely, for Richard I, the Lionheart.[1] Much of the surviving masonry, both external and internal, is thought to be from the primary build-phase and the fine vaulting and carved corbels and bosses of the rooms it contains demonstrate the high status of the building. As such it represents not only a remarkably complete example of the early mural defences and one of the oldest surviving components of the Tower but also a point of development in English castle architecture that combined defensive structures with elaborately decorated living space.[2]

The lower part of the structure is octagonal in plan with the upper part cylindrical. The structure has a solid base with two further storeys above this. Excavations around the base of the tower, still partially open on the south side, exposed its base, originally washed by the Thames and buried in the 13th-century when the Outer Ward was constructed. This base consists of a plinth of seven chamfered offsets set on a projecting rubble platform, above this the wall is ashlar faced – much of which is Reigate stone - up to a string course of Purbeck marble.

Internally the Bell Tower contains two large chambers, one above the other but no longer connected by a staircase, if they ever were. The ground floor chamber is reached via an irregular-shaped lobby leading to an inner lobby with garderobe, an original splayed embrasure to the south and a pointed barrel vault. This room leads to the main pentagonal chamber with an acutely pointed vault with foliate carved boss and square ribs springing from corbels with flattened stiff-leaf carving (three surviving). The room has four pointed embrasures, each slightly different and originally stepped up with high sills and plunging loops. That to the west is now blocked and that to the north fitted with a window, its sill hacked away. The rough earth floor was formerly paved with bricks – in 1663-4 a bricklayer was paid for mending the brick paving[3] – and surviving beam holes in the upper levels of the wall demonstrate the degrees to which the space has been subdivided, though the exact arrangement and dates of this work are unclear.

On the floor above the Bell Tower is entered through a modern porch created from the southern end of the wall walk to the north. This now provides access to an entrance lobby with two blocked doorways; that on the west originally led to the main chamber, while that to the east is thought to have connected with an earlier constable's house at first-floor level. A stone-flagged passage through the thickness of the wall leads to the main chamber with access to a barrel vaulted garderobe, the passage of which is laid with clay tiles. The main first-floor chamber is circular in plan with moulded rere-arches to windows, the mouldings of which form a continuous string course around the room. The masonry of the walls is extremely fragile and in places equally fragile fragments of historic render survive. The windows, set in deep embrasures, are thought to have formerly been of a two-light type, but the extant openings appear to be of 18th-century construction and contain 19th-century timber casement windows. Between the two westernmost embrasures is a blocked door to a wall passage which must have given access to a further window or loop on this exposed south-west angle of the late 12th-century castle. In the north wall is an inserted 14th-century square headed cupboard with a chase for a shelf and in the east wall the remains of a 14th-century fireplace with lost hood replaced by a brick head. Behind the fireplace the brick-lined flue is probably the chimney recorded as being cut into the wall by the bricklayer William Browne in 1609-10.[4] The floor is of stone flags supported by the vault below. The room has been heightened with a domed roof

[1] Impey (ed.), *The White Tower* (Yale: 2008), pp. 142-3
[2] Ibid.
[3] TNA WORK 5/4
[4] TNA E 351/3244

thought to be of 17th-century date, although the otherwise detailed 17th-century accounts make no mention of such substantial re-roofing. The ring beam of the original roof is visible beneath this. A 19th-century timber vice provides access up to the roof. This is the only staircase within the tower and the timber structure replaces an earlier stone newel stair presumed to be of 12th-century date.

The roof above is leaded, as it has been since at least the 16th-century, and rises to a conical over the domed ceiling below.[5] To the south-west there is a 17th-century timber bellcote with a concave lead roof topped by an orb containing the Tower's curfew bell. The bell bears the inscription 'W.B. 1651' and was probably cast in that year for the Tower of London. Though the construction of the bellcote is not recorded in the extant building accounts it must pre-date December 1662, when a carpenter was employed to mend the boarding on one side of the 'bell house', and may, therefore, be contemporary with 1651 casting date of the bell itself.[6] A further payment was made in 1669-70 to a carpenter for replacing the bell wheel.[7]

The upper part of the staircase turret appears to have been added or rebuilt in 1899 and the small lobby providing access from the wall walk to the north was subsequently rebuilt in 1904 to replace a timber structure seemingly built at the same time as the stair turret.[8] In 1934 admid discussions about opening the upper Bell Tower to visitors, proposals were drawn up to alter the space. The brick partitions and infills, including the fireplace hood, were to be removed and the limewash was to be scraped off of the walls to reveal the stonework.[9] Although the removal of the brickwork never happened because the plans to open the space fell through, it is clear that limewash has been stripped from the surfaces and this may have happened at about this date. The scheme of work also proposed removing the modern toilet from the garderobe in the upper chamber; a proposal that puts pay to the idea that it had been installed in preparation for Hitler's imprisonment in the event of his capture.

The Bell Tower gains added significance from its use as a prison and the prisoners associated with it. Although there is only one inscription in this tower, on the wall by the vice in the upper storey, dated to the late 16th century and thought to be by Thomas Meagh, the tower is well known as a prison.[10] Indeed the lower chamber has a sturdy 16th- or 17th-century prison door and was described as a 'prison' as late as 1687 when a mason was employed to mend the stonework there.[11] However, it is the association with Sir Thomas More and Bishop John Fisher, who were imprisoned at the Tower of London in 1535, which gives it its particular significance in this regard. Both men were canonised in 1935 and thus the places of their imprisonment and martyrdom have great resonance for the Catholic faith. Fisher, it seems certain, was kept in the upper chamber of the Bell Tower, though the place of More's imprisonment has never been proven. There is good reason, however, to believe that his cell was indeed the lower chamber of the Bell Tower; his close association with Fisher makes confinement in the same building likely and his son-in-law described More watching prisoners being led out of the Tower to their execution on Tower Hill from a window in his cell, something arguably uniquely possible from the Bell Tower with its direct views to the Tower gates and to Tower Hill. Despite the uncertainty the enduring tradition of More's

[5] Repairs to the roof leads are the most frequently occurring payment in the extant building accounts. The earliest surviving reference to such work is found in the accounts for the year 1585-86 (TNA E 351/3220)
[6] TNA WORK 5/3
[7] TNA WORK 5/13
[8] HRP Plans Archive, TOL-EH-766 & 772
[9] TNA WORK 14/976
[10] Spooner and Gillespie, *The Queen's House Inventory of Fixtures and Fittings,* unpublished report (2011)
[11] TNA WORK 5/41

association with this space must be considered significant in its own right and thus respected.

The Queen's House

By contrast with the Bell Tower the development of the Queen's House is, on the whole, well documented thanks to its continued role as the residence of the Lieutenant of the Tower and latterly of the Governor and the Constable. Though the majority of the accounts record relatively minor repairs and alterations they nonetheless provide a rich picture of the regular maintenance of a prominent timber framed building and on occasion witness more substantial changes.

There are however gaps in the record and notably the earliest history of the extant building and of its predecessor remain opaque. Though the extant building was constructed predominantly during the early 16th century it replaced an earlier structure. This was perhaps the house built in the 1360s for the Constable of the Tower at great expense and containing large stained glass windows showing the royal arms and fleur-de-lys.[12] Certainly the present house contains earlier material in the lower parts of the structure, notably in the half basement so-called *Coeur de Lion* room. Archaeological excavations undertaken in the Queen's House's cellars during the early 1960s found further evidence for the earlier structure beneath the cellars of the south range though provided scant evidence with which to reconstruct the medieval house in anything but the most basic form. A summary excavation report written in c.1962 concisely describes the conclusions of this investigation:

> *The fore-runner of the Queens House probably consisted of a main E.W. range slightly narrower but the same length as the Queen's House. Its ground floor which was lower than the floor level now obtaining was devided in two or more probably three rooms by stone cross walls abutting the curtain. Two, and probably the third rooms were interconnecting, and the third (western) room was probably connected with the Bell Tower, by an additional doorway – now blocked in the E. wall of the Tower's lower chamber. A further ground floor chamber may have existed abutting the W. curtain and N. side of the Bell Tower.*
>
> *The presence of the large buttress on the N.E. angle of the main south range and an intermediate buttress to the internal cross wall suggests that there was a substantial upper storey (or storeys) which then as now probably contained the living apartments. Indications in the East gable wall suggest that this superstructure may have been at least partially timber framed.*[13]

The earlier building stood, no doubt with alterations but largely undocumented, until the early 16th century. By that date it had become the residence of the Lieutenant of the Tower and was referred to as such in the documentary record.

By 1534 the Lieutenant's Lodgings were reported as being in poor condition. In July of that year James Nedeham, then Clerk of the Works, reported to Thomas Cromwell that the house was in need of repair.[14] Later in the same year a small

[12] HKW, II, 728; TNA E 101/472/10 m.2, E 101/472/12, E 101/472/17 m.1
[13] From a report in the files of English Heritage viewed at Waterhouse Square
[14] TNA SP1/85

payment was made for works to the roofs – *Rypping and Poyntyng ov^r m^r leuetennts hall and dyv^rs other places of hys house*[15] – but the scale of works was evidently insufficient to prevent further decay. In 1539 Cromwell's Remembrances record several reminders of the poor state of the building and the need to address it.[16] Of particular interest in Cromwell's papers is a note suggesting that stone and 'other things' from the recently dissolved friary of the Crutched (or Crossed) Friars should be re-used for the Lieutenant's House.[17] It is unclear, however, whether the salvage from the friary was actually used in subsequent building works. Certainly the most recent and most complete study of the London friaries found no evidence that the material was moved to the Tower, but this does not preclude the possibility that the Queen's House does contain salvaged fragments from the Crutched Friars.[18]

The work to rebuild the Lieutenant's House was underway by June 1540, the letters guaranteeing funds to the Lieutenant, Sir Edmund Walsingham, seemingly having been signed by Cromwell only weeks, if not days, before his own arrest and imprisonment at the Tower.[19] The extent of the rebuilding is unclear. It would seem, on the basis of the extant building, that the works of 1540 involved a wholesale demolition of the earlier house and that an entirely new building was constructed in its place. The archival evidence alone, however, is insufficient to prove this assumption, and the true early development of the building may only be possible to discern through archaeological methods.

What is clear, however, is that the extant building was constructed in at least two broad phases. The earliest, presumably that dating to 1540, is the range to the south containing the kitchen and Council Chamber as well as space for domestic chambers. The Council Chamber formed the hub of the house and in its original configuration was a double-height first floor great hall, the division of which was effected by the insertion of a floor at second-storey level in 1607 (the supporting structure of which is presumed to be of that date though the floorboards are much later replacements).[20] Above it retains its original open roof structure, though in a much altered form. Similarly the kitchen also appears to have been a double-height room, and like the Council Chamber retains its original roof structure. Both roofs have been identified as of broadly early 16th century date on the basis of their appearance and construction but both contain sufficient primary material for further archaeological analysis and dating and thus have significant potential to provide important evidence for the early development of the house.

The second build phase saw the addition of the west range which abuts awkwardly with the earlier south range and appears to have been built against it rather than as part of a single planned build. It is difficult to give an exact date to the construction of this addition since there is no record amongst the surviving accounts but it must have been added shortly after the completion of the south range and was certainly standing by 1566 when the servants of the Duchess of Lennox inscribed their names and the date on the stone lintel of a fireplace in a second floor room of the west range. The fireplace itself is of a type typical of the early- to mid-16th century.

Changes to the building made during the latter part of the 16th century are poorly documented so drawing solid conclusions is difficult. Accounts begin in 1570 and

---

[15] Oxford, Bodleian MS. Rawlinson D.777 f.119v
[16] L&P XIV.ii, 287, 427 & 495; TNA SP 1/153 f.171; BL Cotton Titus MS B/I f.446v
[17] TNA SP 1/153 f.171
[18] N Holder, 'The Medieval Friaries of London: A Topographic and Archaeological History, before and after the Dissolution', unpublished PhD thesis (Royal Holloway, University of London: 2011), p. 196
[19] BL Arundel MS 97 f.140; Cromwell was arrested on 10th June 1540 and was beheaded a little over one month later on 28th July. His connection to the Queen's House must not, therefore, be overstated.
[20] BL Add. MS 14044 f.9r

record, with little detail, repairs to both lead and tiled roofs at a frequency of about 4 to 6 years.[21] The accounts for 1590-91 refer to mending stone window jambs, and though equally lacking in detail, presumably refer to windows on the south elevation that predated the extant sashes and casements.[22] That there were stone windows on this elevation is confirmed by the account of 1602-03 that records repairs to the cill, mullions and jambs of the 'greate stonne windowe in mr Lewetenauntes hall'.[23] Since this cannot have been the window in the timber-framed north end of the hall it must have been that to the south and was probably the large, apparently double-height window shown on the Haiward and Gascoyne plan of 1597 (Fig. 01). A view of the Tower from the south drawn by Wenceslas Hollar in 1637-41 suggests a large traceried gothic type window in this location, and it is possible that this large window survived until 1669 when it was replaced by a balcony and two smaller windows which are discussed further below.[24]

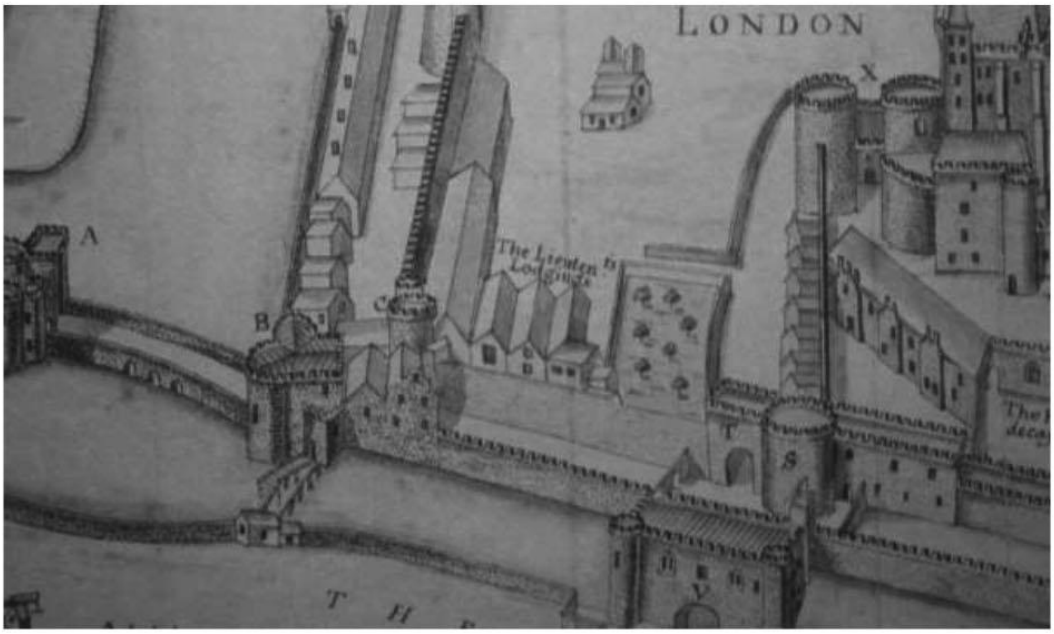


Figure 1: Copy of Haiward and Gascoyne's survey of 1597 made for the Society of Antiquaries in 1741 (The Society of Antiquaries of London)

The first few years of the 17th century saw further small repairs and alterations, but nothing in the way of substantial building phases. In 1600-01 the parapet wall of the wall-walk to the west was taken down and built up again in brick, and in 1604-05 the back wall of the kitchen chimney was broken down, 'to save the house the kitching beinge on fyer'.[25] In the following year, 1605-06, alongside various payments for works in the Lieutenant's kitchen there is a payment for re-laying the roof on the stairs going up to the Gentleman Porters' lodgings by the Bell Tower.[26] Although the document is not specific about the location of the Porters' lodging and subsequent histories of the Tower have not identified where it stood,

[21] TNA E351/3204, /3205, /3206, /3209, /3214, /3219, /3220, /3223, /3224
[22] TNA E351/3225
[23] TNA E351/3238
[24] British Museum 1859-8-6-389; TNA WORK 5/13 f.20v
[25] TNA E351/3240
[26] TNA E351/3241

accounts made later in the century suggest that there was direct access between the Lieutenant's and the Porters' houses, and the apparent proximity to the Bell Tower indicated by the 1605-06 account allows some speculation about the nature of the connection.[27] It is possible that the Gentleman Porter's lodging is the gabled building shown to the east of the Byward Tower on Haiward and Gascoyne's plan. Certainly Anna Keay's research has established that the Gentleman Porter lived in or near-to the Byward Tower, and as such the buildings identified to the east seem good candidates.[28] The building in question seems to have been demolished at some point in the 18th century though the exact date is yet to be determined. The location of the Porter's House is significant to both the Bell Tower and the Queen's House for two reasons. First it probably abutted the Bell Tower and thus may have impacted the external masonry of the building. Secondly it may account for the passage-like structure that Haiward and Gascoyne shows against the western-most gable of the Queen's House. This feature has not been considered or remarked upon before and suggests that buildings to the south of the Queen's House could formerly be accessed from a door in its south wall close to the junction with the Bell Tower. It is possible that some evidence for this structure can be found in the extant fabric of either the Bell Tower or the Queen's House.

The year 1605-06 holds a more significant place in the history of the Queen's House for the building served as a place of interrogation of Guy Fawkes and his fellow Gunpowder Plot conspirators. That event is commemorated in the Council Chamber by a unique memorial plaque erected in 1608 by William Waad, the Lieutenant of the Tower who oversaw the imprisonment and interrogation of the conspirators. The location of the memorial is, however, misleading since in 1605-06 the great hall, as it then was, had not yet been subdivided and in effect the interrogation took place on the floor below. Nonetheless, Waad chose to identify the upper part of the space with the event since the memorial is almost certainly *in situ* and indeed it was he who inserted the floor in 1607.[29] The building accounts for that year record a payment of £119 18s 10d for 'making of a rome for the Lordes Comissioners to sitt in for the examynyng of prisoners'.[30] It is unclear whether this refers to the formation of the Council Chamber within the former great hall, or whether to another building altogether, but the possibility that it does relate to the Council chamber suggests that the marble plaque represented both a commemoration and a warning to other prisoners. Alongside the plaque is a bust of James I. Its origins are unknown and it has been dismissed as late 18th century, but it was referred to by Strype in 1720, so is earlier than often thought, and may in fact be contemporary with the monument.[31]

Accounts of this early 17th century date mention of a gallery and suggest that the house had a long gallery, a feature that is to be expected in a building of this age and status. That the gallery does not survive is clear, but it is difficult to be certain whether it was located within the extant footprint and has disappeared through subdivision of spaces, or whether it formed a now lost adjoining building. The evidence, however, points to the latter. In 1606-07 carpenters were employed to make a timber pillar to bear up the corner of the Lieutenant's 'crooked gallerie'.[32] The apparent 'crooked' condition of the building might suggest that it was a survivor of the earlier lodging there, but more tellingly the work describes suggests that it was to some extent a distinct building, and this unlikely to be part of the extant ranges. A later reference in the Work's accounts for the year 1666-7

[27] For example, TNA WORK 5/10 f.9r
[28] Anna Keay, *The Elizabethan Tower of London* (London: 2001), p. 29
[29] BL Add. MS 14044 f.9r
[30] TNA E351/3243
[31] Strype, *Survey*, I, i, 75
[32] TNA E351/3242

suggests that the gallery was next to the Bloody Tower and thus it is possible that it stood on the site now occupied by numbers 7 and 8 Tower Green. A drawing of the Queen's House made in 1720 shows a long building in this location that could have held a long gallery on its upper floor (Fig. 02)



Figure 2: The Lieutenant's House from the north, 1720

Much of the work recorded in the early decades of the 17th century may be classed as minor repairs. They included masonry repairs to the curtain walls and re-tiling and re-leading over both the Queen's House and the Bell Tower, though the accounts are generally unspecific about the scope of these works. In 1633-34 masons were paid to lay new Purbeck paving on the wall walk between the Bell Tower and the Beauchamp Tower. At the same time they cut back the lower 16in of the brick wall of the Queen's House there along a length of 143ft and laid in Purbeck blocks on edge to provide a waterproof barrier between the wall-walk and the building, 'to keepe the raine from porring in'.[33] The same phase of work saw repairs to the south Thames-facing wall where decayed ragstone was cut out and replaced with new rag and the provision of 'a base of Portland stone wrought and sett under the Collumne at the Lewetenantes Hall dore'; a reference that is difficult to interpret in light of many subsequent changes to this part of the building.[34]

In 1662 carpenters and roofers were at work on the Queen's House, lathing and re-tiling over the 'hall' – presumably the Council Chamber – and repointing the rest of the tiling there.[35] In the same year the house featured in a series of entries in Samuel Pepys' diary for in October of that year Pepys had been informed that

[33] TNA E351/3267
[34] Ibid.
[35] TNA WORK 5/3 f.3r

£7,000 (a sum he later inflated to £50,000) had been hidden at the Tower by Colonel John Barkstead, the Lieutenant of the Tower under Oliver Cromwell. Pepys was granted permission to search for the gold, and mounted four unsuccessful attempts to find the money. His diary describes digging up the floor of an arched cellar in the Queen's House, which may be identified either as the Lower Bell Tower or, more likely, as the Coeur de Lyon chamber.[36] The works accounts for the following year record repairs to the floor of the Lieutenant's beer cellar where it, 'was digged up to finde money'. It describes the area as being 30ft long by 21ft wide, which are similar dimensions to the Coeur de Lyon.[37]

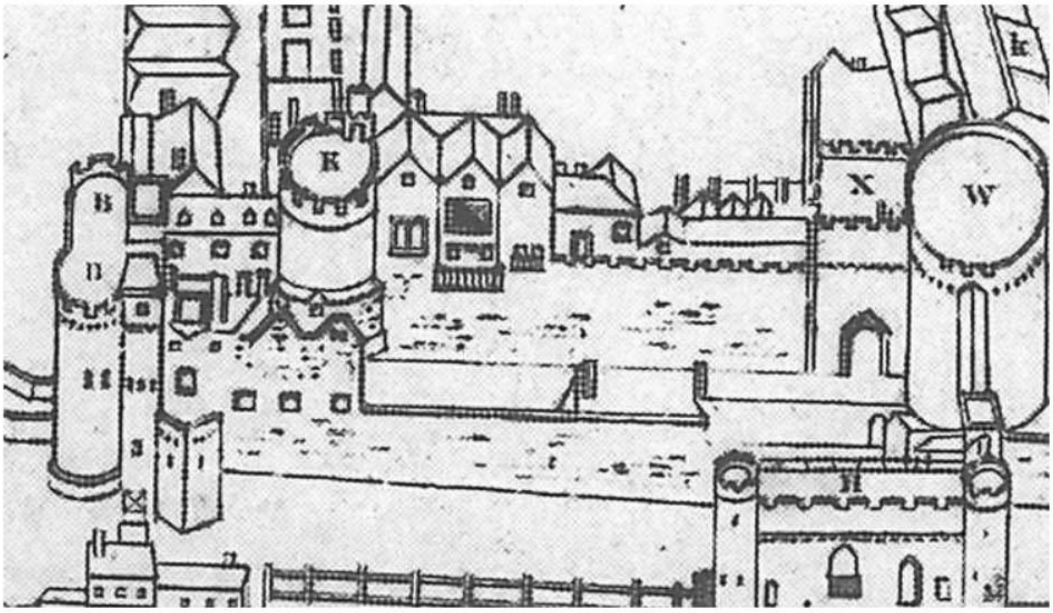


Figure 3: Detail from Holcroft Blood bird's-eye view of the Tower, 1688. Note the Queen's House's balcony.

In the same year, 1663-4, more substantial alterations began to be made to the house. Two new rooms were added to the building, one measuring 21ft by 19ft for the Lieutenant's use, the other 15ft by 9ft for his secretary.[38] Given their dimensions and a subsequent description of them in the same accounts as having a lead flat or platform with a timber balustrade over them it is almost certain that the rooms in question are the extant Entrance Hall and museum room to the north of the main building. However, it is also clear that these buildings have been substantially altered since, in the 1663-4 accounts, they are described as being built by carpenters, suggesting that they were timber framed structures, not the brick buildings that now stand in their place.[39]

In 1669 work began to add a balcony to the south elevation seemingly accessed from the present dining room on the first floor. The scaffold from which to build the balcony was constructed in March 1670 and the work was completed within

[36] S Pepys, *The Diary of Samuel Pepys: A New and Complete Transcription*, Vol III, ed. R Latham and W Matthews (London: G Bell and Son Ltd), pp. 240-286
[37] TNA WORK 5/4 f.9v
[38] TNA WORK 5/4 ff.13r-13v
[39] TNA WORK 5/4 ff.17r & 23r

the year.[40] This structure was 20ft long by 5ft wide and required the addition of substantial cantilevered beams to provide it support. Furthermore it required the remodelling of the associated windows which, until this date may still have been the large gothic traceried window shown in Hollar's 1638-41 view (Fig. 02).[41] In its place was a new window for the Council Chamber and a set of 'folding doors' leading out on to the lead balcony from the dining room below. An idea of the form and scale of the balcony can be gathered from Holcroft Blood's bird's-eye view of the Tower made in 1688 (Fig. 03)

The late 1670s and 1680s saw more substantial changes to the building, initiated by the appointment of a new Lieutenant, Captain Thomas Cheeke, in 1679. Two phases of work, those of 1679-80 and 1687-88 are particularly well recorded in the Office of Works accounts and provide useful and interesting information about the development and use of the building during this period.[42] Much of the work, however, was focused on remodelling and redecorating the interior of the house – including notably a very early reference to the installation of a servant bell system and a detailed description of a flushing toilet – but while the level of detail adds significance to the building it is not relevant here. Perhaps most useful is what the documents say about the development of the windows during the short period. In 1679-80 payments were made to the smith, William Beach for seven casement windows (presumably of a similar type to those that characterise the timber-framed elevation of the Queen's House today, though those are 20th century in origin).[43] However, in 1687 at least one sash window was installed – described as being for the bedroom and replacing a timber window – which suggests that the Queen's House was one of the earliest buildings in the country to receive this new type of window.[44] It is perhaps notable that Sir Christopher Wren, the architect often credited with ensuring the popularity of the sash window, was Surveyor of the Works in 1687 and indeed provided an initial estimate of prices for the works that probably included the installation of the windows. His signed estimate dated 14th July 1687 is unspecific but records that several windows should be 'reformed' and combining it with works to the floors and wainscoting of five rooms estimates a cost of £80.[45]

Wren also quoted for building a new 'great stair' and 'backstair' – at £45 – and it is clear from the Works accounts of the same year that this work was put in hand. It is unclear where the great stair was, although it may have been in the position of the lower flight of stairs leading from the Entrance Hall to the first floor. The extant upper part of this staircase was added in 1915, as described below (Fig. 06), but does not appear to have been preceded by another staircase and the principal access from the first floor upwards seems to have been a staircase built into the return between the south and west ranges above the lead platform.[46] The lower section is, however, shown on plans predating 1915 though may itself have been replaced by a staircase from a house on Clapham Common at that date.[47] Thus it is impossible to identify Wren's 'great stair'. However, the backstair appears to have been the external brick staircase tower that, until 1960, stood proud of the north-facing elevation of the Queen's House since the Works account describe that it provided access to the kitchen (it also provided access to the Lieutenant's bedchamber, presumably located on the floor above).It is clear,

[40] TNA WORK 5/16 f.1r
[41] TNA WORK 5/13 ff.15r & 20r
[42] TNA WORK 5/32; WORK 5/41
[43] TNA WORK 5/32 f.5r
[44] TNA WORK 5/41 f.17r; The earliest sash windows known in England are thought to have been installed at Somerset House in the early 1660s. HJ Louw, 'The Origin of the Sash-Window', *Architectural History*, 26 (1983), p. 61
[45] From a photocopied original in the EH record files. Archival reference unknown.
[46] HRP Plans Archive, TOL-EH-737
[47] HRP Plans Archive, TOL-EH-744

however, that the backstair was not a new addition, but a rebuilding of an existing staircase, and though the stair tower that was lost in 1960 was presumably that hat was built in 1687, it was an earlier feature of the house.[48] Like the original great staircase little is known about the backstair and no drawings or photographs were made of it prior to its demolition in 1960.



Figure 4: Photographic view of the Queen's House, c.1870-90, showing the brick staircase tower to the left.

The accounts for the following centuries are less detailed than those of the late 17th century and thus it is difficult to describe its subsequent development. Indeed, following the exceptionally complete accounts of the 1680s the next surviving reference to any works does not appear until 1752. This cannot be taken to suggest that no works occurred during this period, but rather that the accounts have been lost.

[48] TNA WORK 5/41

In July 1752 the accounts record that the Office of Ordnance had begun stripping the roofs from the Lieutenant's House. However, the work caused a dispute between the Ordnance and the Office of Works, whose responsibility the house had always been, and it was recorded that much of the area stripped by the Ordnance had been repaired by the Office of Works only six years previously.[49]

By 1778 the Queen's House was reported as being in a decayed state and the then Constable of the Tower, Lord Cornwallis, suggested to the Commissioners of the Office of Works that the building should be demolished and replaced with two new houses form the Deputy Lieutenant and the Major.[50] However, the Commissioners' response rejected the proposal and furthermore recorded that £400 worth of repairs had been carried out in the previous year.[51] Additional repair works were carried out in 1786 but while the phase of works appears to have included some roof works and repairs to the sash windows, the majority of the work was to the interiors.[52]

In 1812 repairs were once again being proposed, on this occasion amounting to £855.13.6, although despite the large sum of money the accounts give no detail as to the scope of the works. More detail is given of the works undertaken in 1816, and most notably the proposal included constructing a wall at the north end of the house to separate it from the Gentleman Gaoler's lodgings.[53] Further works were suggested in 1839 but here again the focus appears to have been on redecorating and cleaning the interiors.



Figure 5: Queen's House south range, c.1898

[49] TNA WO 94/10 p.51
[50] TNA WORK 6/19 p.176
[51] TNA WORK 6/19 p.178
[52] TNA WORK 5/75
[53] TNA WORK 1/7 p.215

More substantial and lasting changes to the building were made by works carried out in 1914 and 1915. Until that date the north and east facing elevations of the building had been rendered and white-washed (Fig. 05), but the works now proposed to strip the render and expose the 16th-century timber frame that was known to survive beneath it. Much of the historic timber survived having the render removed from it, but some repairs were required and replacement timbers were patched in to fill the gaps where decay had been found (Appendix II). The works were intended to improve the appearance of the building by stripping away what were considered to be unattractive and uninteresting later accretions and thereby return the building to its Tudor form. As well as stripping the render the windows in the timber-framed facades were all replaced with what were considered more appropriate gothic-style metal casements. By doing so, however, the sash windows, some of which may have dated to the late 1680s were removed and destroyed. The work programme also saw the removal of a staircase located in the return between the north and south ranges and providing access between the first and second floors, and a chimney stack that stood proud of the building on the east-facing elevation at its junction with the flat lead roof of the fore-building. In addition to these external works in 1915 the principal staircase was replaced with the extant early 18th–century timber staircase. This staircase had been removed from Chetwynd House, Stafford, during works in 1912 to convert that building into a Post Office. Given the quality of the staircase the Office of Works were reluctant to dispose of it and instead gave it a new home at the Tower.[54]



Figure 6: Main staircase of Chetwynd House, Stafford in situ, c.1912. This staircase was subsequently dismantled and installed in the Queen's House in 1915.

[54] TNA WORK 14/233

Minor repairs must have been carried out during the 1940s following bomb damage to the Queen's House, though it started a small fire, details of the damage and subsequent repairs were not recorded.

The final major phases of work were undertaken in the early 1960s. In 1960 the brick staircase tower that had been built in 1687 was removed from the north elevation of the building. The decision was again an aesthetic one intended to complete the work to make the house look more Tudor that had been begun by the stripping of the render in 1914. No record was made of the staircase before it was removed. The substantial loss of fabric required the façade behind the staircase to be repaired and sections of new timber frame to be inserted (Appendix II). To replace the staircase a small backstair was constructed to provide access from the ground floor to the east side of the kitchen.[55]

In the following year substantial works were undertaken to the Council Chamber and the historic interior and ceiling was stripped back to reveal the roof structure and the walls. This work has been considered in a previous report and details can be found in Appendix I of this document.

During subsequent decades more minor works have been undertaken. In 1971 the sash windows on the south side of the building were replaced. Those in the Council Chamber and the Drawing Room required new sashes only while those in the Dining Room also needed new frames. At the same time repairs were made to the floor of the Council Chamber.[56]

In 1985 the coping around the lead flat at the front of the Queen's House was remodelled and five years later in 1990 a tiled new roof was added to the small lobby entrance to the upper Bell Tower from the wall walk, replacing an earlier lead roof. Further works included, in 1995 the fire compartmentation work in the roof-spaces and in the same year reclaimed oak floor boards were laid in the Entrance Hall; and in 1996, 2003 and 2006 works to eliminate and repair dry rot in the Entrance Hall and museum room.

STATEMENT OF SIGNIFICANCE

Both the Queen's House and the Bell Tower are considered of **exceptional significance** and as such are amongst the most important buildings at the Tower of London.

The Queen's House is of exceptional significance:

- as the most important surviving Tudor building at the Tower, incorporating medieval features and fabric.
- for retaining a significant amount of original fabric, not least in its roof structures.
- as a rare survival of a high status timber-framed domestic building in London (the vast majority were burned down in the Great Fire of London).
- as the current building on a site of continued historic use as the residence of the Tower's senior officer. The current building is known to replace a 14th-century Constable's residence, itself a possible replacement of an

[55] HRP Plans Archive, TOL-EH-800
[56] TNA WORK 14/2823

earlier structure. It has been suggested that the site may have been the Constable's residence since the 12th-century.

- for its historical associations, including being the place of interrogation of the Gunpowder Plot conspirators in 1605-06 and the brief imprisonment of Rudolf Hess, Hitler's Deputy, in May 1941.
- for the unique surviving memorial commemorating the interrogation of the Gunpowder Plot conspirators and for the possibly associated bust of James I.
- for the relative completeness of the historical record detailing the development of the house.

The Bell Tower is of **exceptional significance**:

- as one of the earliest surviving mural towers it being part of Richard I's partial reconstruction of the Tower's defences.
- for the quality of the medieval masonry internally (especially in the lower chamber) and as an example of a building of its period that displays both defensive and domestic characteristics thereby representing a transition in castle architecture.
- for its strong historical associations most notably with Bishop John Fisher and Sir Thomas More.

Appendix C: Author Agreements

Prof. Heather Viles

As a co-author on the following publications (published or in preparation), I confirm that the first author **Martin Michette** has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). The many faces of Reigate Stone: an assessment of variability in historic masonry based on Medieval London's principal freestone. In Review

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Assessing the long-term success of Reigate Stone conservation at Hampton Court Palace and the Tower of London. *Studies in Conservation.* In Press

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). The role of pointing mortar in preventive conservation strategies for vulnerable historic masonry. A case-study on Reigate Stone at the Tower of London. In Review

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Modelling the effect of repointing and galleting on moisture dynamics in historic masonry at the Wardrobe Tower, Tower of London. In: B. Middendorf & S. Siegesmund. *Proceedings of Stone2020.* Goettingen September 2020. In Press

Michette, M., Viles, H., Vlachou, C., & Angus, I. (2019). *Bellweathered: Reigate Stone decay mechanisms at the Bell Tower, Tower of London*. In: Monuments in Monuments 2019 Conference Proceedings (pp.43-52). https://pub-prod-sdk.azurewebsites.net/api/file/e99b4f10-3572-4459-a81f-aabc00ab0e4e

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Do environmental conditions determine whether salt driven decay leads to powdering or flaking in historic Reigate Stone masonry at the Tower of London? In Review

Heather Viles, Professor of Biogeomorphology and Heritage Conservation, University of Oxford

_____(name and position)



8th April 2020. (signature and date)

Dr. Constantina Vlachou

As a co-author on the following publications (published or in preparation), I confirm that the first author **Martin Michette** has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). The many faces of Reigate Stone: an assessment of variability in historic masonry based on Medieval London's principal freestone. In Review

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Assessing the long-term success of Reigate Stone conservation at Hampton Court Palace and the Tower of London. *Studies in Conservation.* In Press

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). The role of pointing mortar in preventive conservation strategies for vulnerable historic masonry. A case-study on Reigate Stone at the Tower of London. In Review

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Modelling the effect of repointing and galleting on moisture dynamics in historic masonry at the Wardrobe Tower, Tower of London. In: B. Middendorf & S. Siegesmund. *Proceedings of Stone2020.* Goettingen September 2020. In Press

Michette, M., Viles, H., Vlachou, C., & Angus, I. (2019). *Bellweathered: Reigate Stone decay mechanisms at the Bell Tower, Tower of London*. In: Monuments in Monuments 2019 Conference Proceedings (pp.43-52). https://pub-prod-sdk.azurewebsites.net/api/file/e99b4f10-3572-4459-a81f-aabc00ab0e4e

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Do environmental conditions determine whether salt driven decay leads to powdering or flaking in historic Reigate Stone masonry at the Tower of London? In Review

_Constantina Vlachou, Conservation Science Manager, Historic Royal Palaces



_____8 April 2020_____

Mr. Ian Angus

As a co-author on the following publications (published or in preparation), I confirm that the first author **Martin Michette** has made a substantive contribution to the conceptualisation, planning, data collection, analysis, writing and revision of the manuscripts.

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). The many faces of Reigate Stone: an assessment of variability in historic masonry based on Medieval London's principal freestone. In Review

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Assessing the long term success of Reigate Stone conservation at Hampton Court Palace and the Tower of London. *Studies in Conservation*. In Press

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). The role of pointing mortar in preventive conservation strategies for vulnerable historic masonry. A case-study on Reigate Stone at the Tower of London. In Review

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Modelling the effect of repointing and galleting on moisture dynamics in historic masonry at the Wardrobe Tower, Tower of London. In: B. Middendorf & S. Siegesmund. *Proceedings of Stone2020*. Goettingen September 2020. In Press

Michette, M., Viles, H., Vlachou, C., & Angus, I. (2019). *Bellweathered: Reigate Stone decay mechanisms at the Bell Tower, Tower of London*. In: Monuments in Monuments 2019 Conference Proceedings (pp.43-52). https://pub-prod-sdk.azurewebsites.net/api/file/e99b4f10-3572-4459-a81f-asb:00ab0e4c

Michette, M., Viles, H., Vlachou, C. & Angus, I. (2020). Do environmental conditions determine whether salt driven decay leads to powdering or flaking in historic Reigate Stone masonry at the Tower of London? In Review

IAN ANGUS (name and position)
Architect & Director, Carden & Godfrey Architects Ltd.

(signature and date)
9th april 2020

"When we build, let us think that we build forever."

John Ruskin, *Seven Lamps of Architecture* (1849)



Illustration from Rudolf von Elm's 13th century Chronicle of the World, showing medieval masons at work. (Creative Commons)