Predictive Analysis of Stone Decay Mechanisms and Treatments on William Strickland's Second Bank of the United States

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Predictive Analysis of Stone Decay Mechanisms and Treatments on William Strickland's Second Bank of the United States

Abstract
This thesis examined the use of Geographic Information Systems (GIS) software for predicting areas at risk of future stone decay on the Second Bank. By analyzing correlations between stone conditions, characteristics, and locational situation it was possible to determine statistical relationships between these variables. By understanding these relationships through the lens of known mechanisms of stone decay it was then possible to predict which stones are at greatest risk of developing future decay. This process is valuable because it can highlight enabling factors for stone decay and relationships between the complex variables on a building's surface that may not be visible upon casual observation. The end result provided a way to determine which stones are potentially in danger and allowed for targeted preventative treatments to be employed.

Disciplines
Historic Preservation and Conservation

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PREDICTIVE ANALYSIS OF STONE DECAY MECHANISMS AND TREATMENTS ON WILLIAM STRICKLAND’S SECOND BANK OF THE UNITED STATES

Henry Martin Bernberg

A THESIS

In

HISTORIC PRESERVATION

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____________________________
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This thesis is dedicated to my family,
for all their support and encouragement
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# Table of Contents

Acknowledgements ................................................................................................................................. iii
Table of Contents ................................................................................................................................. iv
List of Figures ........................................................................................................................................ vii
List of Tables ......................................................................................................................................... xii

1. Introduction and History ................................................................................................................. 1
   1.1 Introduction ................................................................................................................................ 1
   1.2 Geographic Information Systems (GIS) ......................................................................................... 2
   1.3 Architectural Description .............................................................................................................. 3
   1.4 History ......................................................................................................................................... 5
   1.5 Treatment History ....................................................................................................................... 5
   1.6 Site Situation and Microclimate .................................................................................................. 7

2. Review of Literature ......................................................................................................................... 10
   2.1 Perception and Conditions Surveys ............................................................................................. 10
   2.2 GIS in Conservation ...................................................................................................................... 17
   2.3 Spatial Analyst and Predictive Modeling ....................................................................................... 20
   2.5 Marble Decay ............................................................................................................................... 26

3. Methodology .................................................................................................................................. 34
   3.1 Conditions Surveys ..................................................................................................................... 34
   3.2 Data Processing ............................................................................................................................ 34
   3.2 Data Types ................................................................................................................................ 36
      * Boolean Attributes ...................................................................................................................... 36
      * Non-Boolean Attributes ............................................................................................................. 37
   3.3 Bivariate Correlations ................................................................................................................. 37
   3.4 Visual Correlations ...................................................................................................................... 41
   3.5 Multivariate Correlations ............................................................................................................ 42
   3.6 Examination Criteria .................................................................................................................... 43
      * Conditions Correlations: ......................................................................................................... 43
      * Stone Characteristics: .............................................................................................................. 43
4. Mineralogical Analysis

4.1 Geological Description ..................................................................................................................45
4.2 Samples .........................................................................................................................................45
4.3 X-Ray Diffraction (XRD) ................................................................................................................46
4.4 Polarized Light Microscopy (PLM) ...............................................................................................46
4.5 Discussion of Mineral Composition ............................................................................................50
4.6 Stone Types ..................................................................................................................................52

5. Observations ....................................................................................................................................54
5.1 Conditions Correlations ..................................................................................................................54
5.2 Individual Stone Observations ......................................................................................................59
5.3 Normalized Characteristic Comparisons .......................................................................................63
5.4 Interpretations ................................................................................................................................67

6. Predictions .......................................................................................................................................68
6.1 Definition and Process .....................................................................................................................68
6.2 Results ..........................................................................................................................................70
   Contour Scaling .................................................................................................................................70
   Deformation ......................................................................................................................................70
   Differential Erosion ............................................................................................................................71
   Dimensional Loss ..............................................................................................................................71
   Efflorescence .....................................................................................................................................72
   Encrustation ......................................................................................................................................72
   Friability/Flaking .................................................................................................................................73
   Intrinsic Metallic Staining ..................................................................................................................73
   Insipient Spalling ...............................................................................................................................73
   Microflora ..........................................................................................................................................74
   Non-Intrinsic Metallic Staining ...........................................................................................................75
   Network Cracking ..............................................................................................................................75
6.3 Interpretation ...................................................................................................................................76

7. Conclusions ......................................................................................................................................77
7.1 Conclusions ....................................................................................................................................77
7.2 Recommendation for Further Research ................................................................. 78

Bibliography .................................................................................................................. 79

Appendix A – Architectural and Site Photos ................................................................. 83

Appendix B - Conditions Glossary and Surveys .......................................................... 89

  Chemical Bird Repellent Treatments: ................................................................. 89
  Composite Repairs: ....................................................................................... 89
  Contour Scaling/Exfoliation: ....................................................................... 89
  Deformation/Displacement: ........................................................................ 89
  Differential Erosion: ....................................................................................... 89
  Dimensional Loss: ........................................................................................... 89
  Efflorescence: ................................................................................................. 89
  Encrustation: .................................................................................................... 90
  Friability/Flaking: ............................................................................................. 90
  Insipient Spalling: ............................................................................................. 90
  Metallic Staining: .............................................................................................. 90
  Microflora: ........................................................................................................... 90
  Mineral Inclusions: ............................................................................................. 90
  Network Cracking: ............................................................................................. 90
  Orientation of Foliation Planes: ..................................................................... 91
  Previous Coatings: ........................................................................................... 91
  Sealant Repair: .................................................................................................. 91
  Stone Redressing: ............................................................................................. 91
  Stone Replacement: .......................................................................................... 91
  Tooling Marks: .................................................................................................. 91

Appendix C – Analytical Tables ................................................................................. 108

Appendix D – Mineralogical Analysis ....................................................................... 111

Appendix E – Bivariate Correlations ....................................................................... 133

Appendix F – Predictive Maps .................................................................................. 153

Index .......................................................................................................................... 166
List of Figures

Figure A1: The north elevation of the Second Bank of the United States as viewed from across Chestnut St looking south. (Bernberg 2011) .........................................................84
Figure A2: The north elevation of the Second Bank looking west down Chestnut St. (Bernberg 2011) ..................................................................................................................84
Figure A3: The south elevation of the Second Bank. (Bernberg 2011) ........................................85
Figure A4: The south elevation of the Second Bank looking north from Walnut St. (Bernberg 2011) ..................................................................................................................85
Figure A5: The west elevation of the Second Bank viewed from the southwest corner. (Bernberg 2011) ..................................................................................................................86
Figure A6: The west elevation of the Second Bank looking east from across 5th St. (Bernberg 2011) ..................................................................................................................86
Figure A7: The east elevation of the Second Bank viewed from the southeast corner. (Bernberg 2011) ..................................................................................................................87
Figure A8: The east elevation of the Second Bank looking west from across 4th St. (Bernberg 2011) ..................................................................................................................87
Figure A9: A detail showing damaged gutters and first floor level ledge. (Bernberg 2011).88
Figure B1: The conditions glossary from 2003 survey. (ACL 2003)........................................92
Figure B2: The conditions glossary from 2003 survey. (ACL 2003)........................................93
Figure B3: The conditions survey of north elevation. (ACL 1999)........................................94
Figure B4: the conditions survey of north columns. (ACL 1999)........................................95
Figure B5: The conditions survey of west elevation. (ACL 1999)........................................96
Figure B6: The conditions survey of west elevation. (ACL 1999)........................................97
Figure B7: The conditions survey of north pediment and soffit. (ACL 1999)......................98
Figure B8: the conditions survey of north stairs. (ACL 1999)..........................................99
Figure B9: The conditions survey of east elevation. (ACL 2003)..............................100
Figure B10: The conditions survey of east elevation. (ACL 2003)..............................101
Figure B11: the conditions survey of south pediment. (ACL 2003)..............................102
Figure B12: The conditions survey of south elevation. (ACL 2003)..............................103
Figure B13: The conditions survey of south columns. (ACL 2003)..............................104
Figure B14: The conditions survey of south columns. (ACL 2003)..............................105
Figure B15: The conditions survey of south stairs. (ACL 2003) ................................................. 106
Figure B16: The conditions survey of south soffit. (ACL 2003) ................................................. 107
Figure D1: Sample SEB-01, white stone spalled from unknown column. (Bernberg 2011) 113
Figure D2: Sample SEB-02, gray stone from an unknown location on building. (Bernberg 2011) ................................................................................................................................. 113
Figure D3: Sample SEB-03, white stone from the west cornice (accession # INDE 15703).
(Bernberg 2011) .......................................................................................................................... 114
Figure D4: Sample SEB-04, white stone from the west cornice (accession # INDE 15703).
(Bernberg 2011) .......................................................................................................................... 114
Figure D5: Sample SEB-05, white stone from the west cornice, exterior view (accession # INDE 15703). (Bernberg 2011) .......................................................................................... 115
Figure D6: Sample SEB-05, white stone from the west cornice, interior view showing mineral inclusion layer (accession # INDE 15703). (Bernberg 2011) ................................. 115
Figure D7: Sample SEB-06, white stone from the west cornice (accession # INDE 15703).
(Bernberg 2011) .......................................................................................................................... 116
Figure D8: Sample SEB-07, white stone from the west cornice (accession # INDE 15703).
(Bernberg 2011) .......................................................................................................................... 116
Figure D9: Sample SEB-08, mineral inclusion layer from an unknown white stone (accession # INDE 15703). (Bernberg 2011) .................................................................................. 117
Figure D10: Sample SEB-09, mineral inclusion layer from an unknown white stone (accession # INDE 15703). (Bernberg 2011) .................................................................................. 117
Figure D11: Sample SEB-10, encrusted fragment from an unknown white stone (accession # INDE 15703). (Bernberg 2011) .................................................................................. 118
Figure D12: Sample SEB-11, mineral inclusion layer from an unknown white stone (accession # INDE 15703). (Bernberg 2011) .................................................................................. 118
Figure D13: The X-Ray Diffraction (XRD) results for sample SEB-01.i ........................................ 119
Figure D14: The XRD results for sample SEB-01.ii ....................................................................... 119
Figure D15: The XRD results for sample SEB-01.iii ................................................................. 120
Figure D16: The XRD results for sample SEB-01.iv ................................................................. 120
Figure D17: The XRD results for sample SEB-02.i .................................................................... 121
Figure D18: The XRD results for sample SEB-03.i .................................................................... 121
Figure D19: The XRD results for sample SEB-03.ii ................................................................... 122
Figure D20: The XRD results for sample SEB-10.i.................................................................122
Figure D21: The XRD results for sample SEB-11.i.................................................................123
Figure D22: Calcite grains from a white stone under plain polarized light (PPL) at 5x magnification. (Sample SEB-01) (Bernberg 2011).................................................................124
Figure D23: Calcite grains from a white stone under cross polarized light (XPL) at 5x magnification. (Sample SEB-01) (Bernberg 2011).................................................................124
Figure D24: A metallic mineral inclusion under PPL at 5x magnification. (Sample SEB-01) (Bernberg 2011).................................................................125
Figure D25: A metallic mineral inclusion under XPL at 5x magnification. (Sample SEB-01) (Bernberg 2011).................................................................125
Figure D26: Mineral inclusions under PPL at 5x magnification. (Sample SEB-01) (Bernberg 2011).................................................................126
Figure D27: Mineral inclusions under XPL at 5x magnification. (Sample SEB-01) (Bernberg 2011).................................................................126
Figure D28: Calcite grains showing disaggregation under PPL at 5x magnification. (Sample SEB-02) (Bernberg 2011).................................................................127
Figure D29: Calcite grains showing disaggregation under XPL at 5x magnification. (Sample SEB-02) (Bernberg 2011).................................................................127
Figure D30: Gypsum crust and surface deterioration seen under PPL at 5x magnification. (Sample SEB-03) (Bernberg 2011).................................................................128
Figure D31: Gypsum crust and surface deterioration seen under XPL at 5x magnification. (Sample SEB-03) (Bernberg 2011).................................................................128
Figure D32: A small area of micaceous mineral inclusion within calcite matrix under PPL at 5x magnification. (Sample SEB-04) (Bernberg 2011).................................................................129
Figure D33: A small area of micaceous mineral inclusion within calcite matrix under XPL at 5x magnification. (Sample SEB-04) (Bernberg 2011).................................................................129
Figure D34: A single grain mineral inclusion under PPL at 5x magnification. (Sample SEB-05) (Bernberg 2011).................................................................130
Figure D35: A single grain mineral inclusion under XPL at 5x magnification. (Sample SEB-05) (Bernberg 2011).................................................................130
Figure D36: Large metallic mineral and other inclusions under PPL at 5x magnification. (Sample SEB-05) (Bernberg 2011).................................................................131
Figure D37: Large metallic mineral and other inclusions under XPL at 5x magnification.
(Sample SEB-05) (Bernberg 2011) ........................................................................................................ 131

Figure D38: A micaceous mineral inclusion layer under PPL at 5x magnification. (Sample
SEB-07) (Bernberg 2011) .................................................................................................................... 132

Figure D39: A micaceous mineral inclusion layer under XPL at 5x magnification. (Sample
SEB-07) (Bernberg 2011) .................................................................................................................... 132

Figure E1: The spatial distribution of stones displaying dimensional loss & contour scaling.
(Bernberg 2011) .................................................................................................................................. 138

Figure E2: The spatial distribution of stones displaying contour scaling & friability/flaking.
(Bernberg 2011) .................................................................................................................................. 139

Figure E3: The spatial distribution of stones displaying encrustation & differential erosion.
(Bernberg 2011) .................................................................................................................................. 140

Figure E4: The spatial distribution of stones displaying insipient spalling & contour scaling.
(Bernberg 2011) .................................................................................................................................. 141

Figure E5: The spatial distribution of stones displaying chemical bird repellents &
differential erosion. (Bernberg 2011) .................................................................................................. 142

Figure E6: The spatial distribution of stones displaying efflorescence & stone redressing.
(Bernberg 2011) .................................................................................................................................. 143

Figure E7: The spatial distribution of stones displaying microflora & friability/flaking.
(Bernberg 2011) .................................................................................................................................. 144

Figure E8: The spatial distribution of stones displaying intrinsic metallic staining & mineral
inclusions. (Bernberg 2011) ................................................................................................................ 145

Figure E9: The spatial distribution of stones displaying network cracking & intrinsic
metallic staining. (Bernberg 2011) ...................................................................................................... 146

Figure E10: The spatial distribution of stones displaying network cracking &
friability/flaking. (Bernberg 2011) ................................................................................................... 147

Figure E11: The spatial distribution of stones displaying intrinsic metallic staining & sealant
repairs. (Bernberg 2011) ................................................................................................................... 148

Figure E12: The spatial distribution of stones displaying intrinsic metallic staining & stone
replacement. (Bernberg 2011) ........................................................................................................... 149

Figure E13: The spatial distribution of stones displaying dimensional loss & less than 50%
of original tooling marks remaining. (Bernberg 2011) ................................................................. 150
Figure E14: The spatial distribution of stones displaying friability/flaking & less than 50% of original tooling marks remaining. (Bernberg 2011) .......................................................151

Figure E15: The spatial distribution of stones displaying network cracking & less than 50% of original tooling marks remaining. (Bernberg 2011) .......................................................152

Figure F1: A map showing the predicted distribution of contour scaling. (Bernberg 2011) ......................................................................................................................................................154

Figure F2: A map showing the predicted distribution of deformation. (Bernberg 2011)....155

Figure F3: A map showing the predicted distribution of differential erosion. (Bernberg 2011).....................................................................................................................................................156

Figure F4: A map showing the predicted distribution of dimensional loss. (Bernberg 2011)
........................................................................................................................................................................................................157

Figure F5: A map showing the predicted distribution of efflorescence. (Bernberg 2011). 158

Figure F6: A map showing the predicted distribution of encrustation. (Bernberg 2011) ... 159

Figure F7: A map showing the predicted distribution of friability/flaking. (Bernberg 2011)
........................................................................................................................................................................................................160

Figure F8: A map showing the predicted distribution of intrinsic metallic staining. (Bernberg 2011).....................................................................................................................................................161

Figure F9: A map showing the predicted distribution of insipient spalling. (Bernberg 2011)
........................................................................................................................................................................................................162

Figure F10: A map showing the predicted distribution of microflora. (Bernberg 2011) .... 163

Figure F11: A map showing the predicted distribution of non-intrinsic metallic staining. (Bernberg 2011).....................................................................................................................................................164

Figure F12: A map showing the predicted distribution of network cracking. (Bernberg 2011)................................................................................................................................................................165
List of Tables

Table C.i: The table showing bivariate conditions intersection percentages.......................... 109
Table C.ii: the normalized values for proportional appearance of condition on stone
characteristics........................................................................................................................................ 110
Table D.i: List of detected minerals and their chemical compositions. ..................................... 111
Table D.ii: List and description of stone hand samples............................................................... 112
Chart E.i: Dimensional Loss and Contour Scaling as percentages of the entire building..... 134
Chart E.ii: Contour Scaling and Friability/Flaking......................................................................... 134
Chart E.iii: Encrustation and Differential Erosion......................................................................... 134
Chart E.iv: Insipient Spalling and Contour Scaling................................................................. 134
Chart E.v: Chemical Bird Repellents and Differential Erosion................................................ 135
Chart E.vi: Efflorescence and Stone Redressing.......................................................................... 135
Chart E.vii: Microflora and Friability/Flaking.............................................................................. 135
Chart E.viii: Intrinsic Metallic Staining and Mineral Inclusions............................................... 135
Chart E.ix: Network Cracking and Intrinsic Metallic Staining.................................................... 136
Chart E.x: Network Cracking and Friability/Flaking................................................................. 136
Chart E.xi: Intrinsic Metallic Staining and Sealant Repairs....................................................... 136
Chart E.xii: Intrinsic Metallic Staining and Replaced Stone...................................................... 136
Chart E.xiii: Dimensional Loss and Less than 50% of Tooling Mark Remaining...................... 137
Chart E.xiv: Friability/Flaking and Less than 50% of Tooling Mark Remaining.......................... 137
Chart E.xv: Network Cracking and Less than 50% of Tooling Mark Remaining....................... 137
1. Introduction and History

1.1 Introduction

The Second Bank of the United States was chartered by the US government in 1816 and constructed between 1818 and 1824. The Second Bank was designed by William Strickland as part of a competition. The building is located at 420 Chestnut St, Philadelphia, PA. It is at the midpoint of the block on the south side of the street; built between Chestnut and Sansom Streets.

Stone deterioration began soon after the building was completed and multiple treatment campaigns have attempted to address the issues. In 1999 and again in 2003 conditions surveys were conducted by the University of Pennsylvania Architectural Conservation Laboratory (ACL) in concert with the National Park Service (NPS) at Independence National Historical Park (INHP) as part of the Pennsylvania Blue Project and have led to further investigations including this thesis.2

This thesis examined the use of Geographic Information Systems (GIS) software for predicting areas at risk of future stone decay on the Second Bank. By analyzing correlations between stone conditions, characteristics, and locational situation it was possible to determine statistical relationships between these

variables. By understanding these relationships through the lens of known mechanisms of stone decay it was then possible to predict which stones are at greatest risk of developing future decay. This process is valuable because it can highlight enabling factors for stone decay and relationships between the complex variables on a building's surface that may not be visible upon casual observation. The end result provided a way to determine which stones are potentially in danger and allowed for targeted preventative treatments to be employed.

1.2 Geographic Information Systems (GIS)

An understanding of the core concepts of GIS is necessary to understand this thesis. The concept of using GIS to make predictions based on spatial relationships goes back to the concept that a map can be tied to a database of one type or another. A GIS does not necessarily denote the use of software, though most modern applications do. A GIS is simply a database that has been given locational reference (coordinates in space). This is called georeferencing or geolocating, when an object is assigned a specific location in two or three dimensional space. GIS software, commonly ESRI’s ArcGIS suite, Quantum GIS, GRASS GIS, and others, combine computerized drawings and related databases to store information about each element on the map. ArcGIS was utilized for this thesis because of availability, familiarity, and known compatibilities with other software such as Microsoft’s Excel and Access.

GIS operates in either of two modes, vector or raster. Vector is the most commonly used mode in GIS; it relies on mathematical equations to define points,
polylines, and polygons. This format allows for very precise placement of objects within a map because the user can zoom in infinitely without sacrificing an accurate view of an object since objects scale. Vector format excels when displaying discrete objects.

Raster GIS is based around the use of pixels, each of which are given a regular size and have their position defined as an XY coordinate. Each pixel is assigned a numerical value, which can be analyzed in relation to its neighboring pixels. Raster data is processed at a resolution set at the beginning of work, and working beyond this resolution sacrifices accuracy. Raster data is best used to represent continuous surfaces or object that operate in similar ways. Data must also be representable as a meaningful numeric value.

Vector format was chosen for this thesis for multiple reasons. While the surface of a building may appear uniform and continuous at a casual glance, variations in stone type, bedding direction, and location act to make each stone operate as a discrete unit that is independent from its neighbors. Vector format embraces this separation of elements. The infinite scalability of vector also ensures that even the smallest overlaps between conditions will be recorded, even if it would have been beyond the resolution of a raster dataset to detect.

1.3 Architectural Description

The Second Bank of the United States is a Greek revival style building on the south side of the 400 block of Chestnut Street in Philadelphia, Pennsylvania. The building consists of two sets of paired, nearly identical, elevations: north-south and
east-west. The exterior dimensions are approximately 86’ wide on the north and south elevations and approximately 139’ on the east and west elevations. The exterior is clad in marble ranging in color from white through a deep bluish grey. The Second Bank is an early example of true classical styling found in the United States.

The north and south entrance elevations are raised Greek style octastyle Doric porticos that are a single column deep (figs. A1 & A3). The columns are fluted for their entire length. The back wall of each portico has three massive door openings, one centered and the other two flanking, all of which are aligned with the intercolumnar spaces. The two flanking door opening are filled in with single slabs of marble that appear to be original. The south façade also has two windows, one set between each door opening. The pediments themselves are undecorated as is the entablature. Triglyphs separate blank metopes above an empty frieze. The stone used for use on the north and south elevations is predominately white and light gray.

The east and west secondary elevations are symmetrical and can be divided into three sections (figs. A5 & A7). The flanking sections are mirror images of each other, with three sets of windows, each four lights wide and five tall with a corresponding four by four light windows set above at the height of the portico columns. The central section is set forward slightly to accentuate the main room on the interior of the building and contains three windows, a large central arched window and two flanking windows of the same design as the rest on the building.
Copper gutters descend along the edges of the central portion of each elevation. These are in disrepair and leak seriously (fig. A9). There is a slight edge that runs along the east and west elevations at the height of the portico floor. The stones on the east and west elevations are primarily shades of gray.

1.4 History

The building functioned as a bank between 1824 and 1841, when the institution was bankrupted. The building has changed uses and hands since then, first acting as the U.S. Customs House into the 20th century before being included in Independent National Historic Park (INHP) under the administration of the National Park Service (NPS). The Second Bank now serves as a portrait gallery for INHP. A Historic American Buildings Survey (HABS) survey was conducted on the building in 1939 and it was added to the national register in 1987.

1.5 Treatment History

The Second Bank has a long history of cleaning and treatments including modern studies run through the ACL. The first cleanings were recommended as early as 1844, only 20 years after completion. Another cleaning was conducted in 1873 using unknown materials. In the early 1920s stone loss had become a major issue, both to public safety and to the building’s aesthetic. Waterproofing may have occurred at this time, though records are unclear. Historic visual evidence suggests

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3 Catterall (1902).
the application of a hot wax coating, which led to future soiling. Regular cleanings appear to have occurred again in the 1940s and 60s, using methodologies reflective of the times and including waterproofing treatments. The 1940s restoration was conducted as part of the Works Progress Administration.\(^5\) Spalling continued even after waterproofing treatments and repair work was conducted in the 1970s and later. Repairs have been conducted using concrete patching, epoxy repairs, and limestone Dutchmen. Cleaning has been continued as needed.\(^6\) In 1996 Jocelyn Kimmel conducted tests on the effects of various consolidant treatments on marble samples from the Second Bank as part of a proposed conservation plan, this thesis also included mineralogical characterization of stone sample from the building.\(^7\) Complete architecture documentation and conditions surveys of the exterior were conducted by the ACL in 1999 and 2003 as part of the Pennsylvania Blue Project.\(^8\) In 2004 John Glavan conducted testing on the application of mechanical pinning using stainless steel bone screws for the reattachment of spalling stone on the columns on the south portico.\(^9\) This was then implemented in 2005 by Milner + Carr

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Conservation on the columns of both porticos. Most recently, in 2009, Tejaswini Aphale undertook a quantitative analysis of stone conditions on the Second Bank.

1.6 Site Situation and Microclimate

Chestnut St, on the north side of the building, is a major thoroughfare in Philadelphia and has heavy traffic constantly (fig. A2). The 400 block of Sansom St, to the south of the building, is permanently closed and is only used for service vehicles and those used by the National Park Service. The American Philosophical Society stands immediately west of the bank but separated by a wide footpath and row of large trees (fig. A6). There is a corresponding footpath and row of trees on the east side, but the neighboring lot is a garden without structures (fig. A8). The north elevation is set back slightly from Chestnut St but is otherwise unshielded from the busy road, which can affect the building through pollution and vibration form traffic. The south elevation faces a large open park that runs the full width of the block and reaches from Sansom to Walnut Streets (fig. A2).

The Second Bank experiences the same climate as the rest of Philadelphia but given its size, the four elevations experience different environmental conditions that can influence the stone decay processes that are affecting it. These variations in

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exposure create microclimates for each elevation. Each elevation experiences different exposure to pollution, wind and wind driven rain, and sunlight, which can create temperature variations. Microclimates can cause difference in stone decay that is related more to the stones location than its inherent characteristics.

The south elevation is the most exposed of the four. It is fully exposed to sunlight, rain, and wind. The entrance face is more protected than the rest of the elevation because it is partially shielded by the pediment and columns. The columns have shown different degrees of weathering dependent on their positions and the how much of the columns is exposed, columns at the corners show the most decay, while those closest to the center show the least.

The east and west elevations are very similar in regards to situation. Key differences occur due to the wind patterns in Philadelphia. The prevailing winds in the city come from the west-northwest. Greater exposure to wind can lead to greater water penetration due to driving rain as well as quicker drying due to lower air pressure at the stone’s surface. Wind can also create more stress due to mechanical loads being placed on the west elevation. The west elevation does receive some protection from the wind and sunlight due to the presence of the building near the southwest corner. Otherwise, elemental exposure of the two elevations is relatively comparable.

The north elevation is the most protected from the environment of the four. It receives no direct sunlight and is partially shielded from driving rain by the buildings across Chestnut St. The lack of sunlight slows drying, though the prevailing winds come from the west-northwest means that there is more exposure on the north elevation, which could aid in drying. As is seen with the south elevation, the entrance face is protected by the pediment and columns. As is also seen on the south elevation, the columns are suffering from different extents of decay due to differences in exposure.\textsuperscript{15} The environmental protection is contrasted by exposure to traffic and the associated pollution and mechanical vibrations.

\textsuperscript{15} ACL, (2004).
2. Review of Literature

This thesis attempts to synthesize a number of fields to create a complete understanding of the conditions present at the Second Bank and their relationships to each other and to the inherent characteristics of the stone. Therefore the background literature reviewed for this work comprises research found in a number of interrelated fields.

2.1 Perception and Conditions Surveys

The perception of a condition on the surface of the building being studied is the first step in documentation. It is also subjective to the person documenting the condition. A number of factors can affect this and proper understand of these can allow for some level of control to be employed. The original conditions surveys of the Second Bank were done completely independently from this analysis. It can be difficult to gauge the extent of subjectivity during documentation, but removal from the original analysis can allow for some level of objectivity in the observer. Independent analysis allows for the revelation of variations in data that can be due to faults or inconsistencies in survey methodology. This can include the scale of recording and the relative size of the area being recorded.

Perception is governed by psychophysics, the way in which the brain interprets physical stimuli. This theory can be applied to any sensory input that has a continuous range of magnitude (sight, hearing, etc). The perception of a condition is directly related to the scale of the area being examined and the size of the affected
area. This is expressed through Weber’s theory of Just Noticeable Differences (jnd),
developed through the work of E.H. Weber and Gustav Fechner. This theory states
that the difference between two stimuli is noticeable in relationship to the
proportion of their intensity or size. The magnitude of the difference that is required
to be noticeable is directly related to the magnitude of the original stimuli. A
difference that would be noticeable between any two small objects would not be
noticeable between two larger objects given their relative magnitudes. This is
expressed as the Weber Fraction:

$$\Delta S/S = K$$

where $\Delta S$ is the change in magnitude of the stimuli, $S$ is the magnitude of the original
stimuli, and $K$ is a constant for the given type of stimuli.\(^{16}\) Through this it can be
inferred that the area of a condition would have to be larger to be noticeable to a
surveyor working within a larger area.

The relative shape of the environment around a condition will also affect its
perceived size. As is seen in the Muller-Lyer and Ponzo figures, two objects that are
the same size can be easily mistaken as different depending on their surrounding
environment. This is explained through the theory of Size Constancy, where the

Newman, Edwin B. “The Validity of the Just Noticeable Difference as a Unit of Psychological
brain tries to compensate for the illusion of perspective through the misrepresentation of the size of an object.\textsuperscript{17}

An understanding of the mechanisms for interpreting sight helps to understand possible biases that may inadvertently be introduced to a conditions survey. It is possible that condition recording could inadvertently be done at a higher resolution on smaller stones due to a normalization effect where the surveyor records smaller conditions on smaller stones, which would not have been deemed significant on larger stones. Accordingly, conditions may not be recorded at all if they exist below a given threshold set for recording.

Condition mapping can be done at many scales reflected in either the overall resolution that the building is recorded with or in the resolution used to record the conditions themselves. The issue of resolution is addressed based on the level of detail required to diagnose a condition and the level of detail that can be applied during treatment. The recording resolution is determined by the distance from which the survey is done and the relative detail with which conditions are recorded. Studies where high levels of detail are required will need high-resolution recording. For this thesis, a balance must be determined between high enough resolution to accurately display the building and conditions without overwhelming the end results.

Bernd Fitzner demonstrates that conditions can be classified at varying scales of detail based on schemes ranging from broad to very specific depending on the intended application.\textsuperscript{18} This gradation is reflecting in the ICOMOS Illustrated Glossary on Stone Deterioration Patterns.\textsuperscript{19} These systems allow for generalization of the condition types, the comparison of related conditions and the identification of specific conditions for diagnostic purposes if need be. This classification system was applied to the Second Bank in Tejaswini Aphale’s thesis work on the (see below). For example, contour scaling, differential erosion, and dimensional loss are all different conditions, but are all classified as “Subtractive”. Conversely, encrustation and staining are both amongst the “Additive” conditions.\textsuperscript{20}

The conditions surveys that this thesis is based off of employed two different methodologies and difference survey teams for recording. The 1999 survey of the Second Bank was done by individuals recording all conditions within a given area of the building, while the 2003 condition survey utilized individuals assigned to groups of conditions, recording them for the entire study area of the building.\textsuperscript{21} This distinction is important because of the subjective nature of conditions surveys. When one individual records the same condition across the entirety of a building the survey will remain internally consistent because there is less variation in the

\textsuperscript{20} Aphale (2009). p. 30-36.
perception of an individual surveyor as opposed to that of multiple surveyors. The multiple phases of conditions surveys done on the Second Bank illustrate this problem well. In addition to the discrepancies in the overall amount and type of data being collected by the survey teams, some data was not recorded for all stones during the first survey. There were also changes in the conditions definitions used for the survey between 1999 and 2003.\(^22\) The differences between the surveys are important to consider during analysis because it can manifest itself as variations in the recorded occurrences of conditions.

Konrad Zehnder stresses that conditions surveys, as well as all documentation, should be goal oriented. Though it may be constrained by time or budgetary considerations, documentation should “acquire, release, and store specific information,” in the case of the Second Bank, the spatial distribution of stone conditions and characteristics.\(^23\) A documentation program should be designed with an end goal in mind so that the proper information can be collected at the required resolution. Documentation should be independent from analysis. Field analysis should be avoided until all the data is collected and can be considered as a whole to avoid misrepresentation of facts due to an incomplete picture of the object being documented.\(^24\) This approach was not entirely followed for the conditions surveys of the Second Bank due to budgetary and planning restrictions. Because of the

evolving nature of the project methodologies set forth at the beginning are no longer the most appropriate. This has resulted in the necessity to interpolate some data regarding stone characteristics to standardize between the two campaigns of conditions surveys undertaken and to fill in gaps in data that was not recorded during the original survey. The majority of stones do not have a recorded color and almost \( \frac{1}{3} \) do not have a recorded foliation direction. For the 2003 survey the face oriented foliation was added. This makes it difficult to determine if stones with no foliation data from the 1999 survey were face bedded or indeterminate.

Francesca Piqué, in “A Protocol for Graphic Documentation,” stressed the importance of standardization of documentation, both within and between projects to avoid confusion in interpretation of data. Documentation is important for the assessment of conditions as well as proper recording of treatments, samples, and monitoring. Long term monitoring can be greatly aided through the use of standardized graphic documentation. Piqué suggests that a variable resolution be applied as the situation requires, allowing for higher resolution recording of specific areas that need it, while the general recording should be done at a resolution high enough to display information without becoming crowded. This is simply resolved by using vector rather than raster methodology, do to the flexible scaling. She also suggests that conditions glossaries be reviewed and revised during the project to

incorporate any necessary changes.\textsuperscript{26} This occurred between the two survey campaigns on the Second Bank and led to the revision of conditions terminology. The methodology suggested has the advantage of creating a standard that can be applied to multiple projects while being flexible enough to fit the idiosyncrasies of each one.

As Matero highlights, using Mesa Verde as a case study, proper documentation of a building and its conditions is the first step toward a proper understanding of the pathologies affecting the building. The standardization of the survey and recording methodologies is essential to ensuring that the produced documents are representative of the structure being recorded and are consistent within themselves.\textsuperscript{27} Without meeting these preconditions, a conditions survey cannot be used for comparison and analysis because there is no solid basis for comparison.

Fitzner’s case for documentation comes from the relationship between documentation, analysis, diagnosis, and treatment. A fault in one of these steps creates a chain reaction that can affect the conservation of the building. As such, the conservation goals must be set forth from the beginning of a project so that the proper decisions can be made with regards to the level of documentation being


applied. This can be expanded to say that proper documentation is necessary for the ability to monitor changes in condition over time and therefore diagnose conditions or predict future changes. If this had been done at the Second Bank from the beginning more attention would have likely been paid to the classification of each stone in regards to color and foliation direction. With his work at Luxor, Fitzner shows how documentation relates to analysis by applying advanced scientific techniques to provide a scientific explanation of observed conditions. This analysis would not have been useful without the accompanying documentation showing the locations and relationships amongst conditions because accurate relationships could not have been established.

2.2 GIS in Conservation

Geographic Information Systems (GIS) is a tool that has been widely used in the field of historic preservation. It is applied as a tool for planning on varying scales, the documentation of historic structures and districts, comparison of historical datasets and their modern equivalents, and for the spatial analysis of sites and materials for conservation purposes. The most common form of GIS seen is software applications such as ArcGIS, Quantum GIS, and GRASS GIS.

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GIS has the advantage of combining visual spatial data with non-visual descriptive data, allowing for more in depth analysis than data represented as drawings or tables. This is manifest as the database aspect of GIS, which allows for querying of both data and spatial relationships. GIS software works in concert with computer aided drafting (CAD) software, data can be interchanged between the two, taking advantage of the strengths of both software types. New data can be created based on the data that has already been collected and stored in the GIS. A thought out plan must be established at the beginning of any project to ensure accurate and consistent data collection. This is the basic approach that was followed for the Second Bank. Data was collected in the field and digitized using AutoCAD before being transferred to ArcGIS for analysis.

The use of GIS software for conditions surveys allows for a high level of accuracy for the recording of data on a surface. It allows for a conservator to mark a very specific point, line, or area due to the capabilities of vector GIS, as well as provide a near endless amount of information for that annotation. The application of GIS in the field aids in the standardization of recording between multiple conservators and allow for quick, on-the-fly changes to recording. Applications to

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mural painting conservation have also shown that annotations can be entered directly into the related database in the field.\(^{32}\)

Kyle Joly, Tony Donald, and Douglas Comer show how GIS can be applied to an entire building by constructing drawings of the Jefferson and Lincoln memorials based off of digital CAD drawings and importing them into a GIS. The GIS is not georeferenced but rather exists within a coordinate system local to the buildings, relying on the software's capabilities to run calculations and maintain a database that contains unreferenced spatial data. The lack of geolocation in these instances does not matter because the building survey exists within a local coordinate system, and spatial calculations can still be made as long as the units are known. This has become a standard practice for condition data in a GIS. These databases can be externally queried for stone conditions or used for spatial calculations.\(^{33}\) This approach is representative of what was originally done with the data from the Second Bank.

The data from the Second Bank was refined and analyzed by Tejaswini J. Aphale for her Master's thesis. The original data from the conditions surveys was combined, standardized, and analyzed for internal consistency. Aphale took the conditions glossaries from the 1999 and 2003 surveys and consolidated the data to compensate for any changes in definitions by merging related conditions.


Conditions were also classified according to broader categories, such as additive and subtractive conditions, for the purpose of making generalized conclusions about the building. Most importantly, the distribution of conditions was analyzed to check the two campaigns of conditions surveys against each other. Using statistical comparisons of the paired elevations (north-south and east-west) Aphale was able to conclude that the data collected in the multiple surveys were compatible. This was done by comparing the distribution of conditions over the entire surface of each elevation against the distribution that would be expected assuming that the individual faces of the east-west pairing were more similar than the north-south pairing.\textsuperscript{34} The results showed significant variations between the north and south elevations and some, but less, between the east and west elevations. Aphale's work was purely quantitative and did not reveal any possible explanations for the patterns that were revealed. This is the main weakness of the thesis, because without providing qualitative analysis to support the quantitative analysis there is no critical component to the study. Without critical consideration it is impossible to tell if a perceived pattern is relevant or if it is simple random noise.

2.3 Spatial Analyst and Predictive Modeling

An alternative application of GIS uses the analytical tools found in ESRI’s ArcGIS program suite. This expands the capabilities of the software beyond simply storing and displaying information and allows the user to analyze the data to look

\textsuperscript{34} Aphale (2009).
for patterns. Spatial Analyst includes a wide variety of features based around the creation and calculation of raster datasets, which can create value-based models of spatial data. The use of Spatial Analyst for purely predictive applications is often found in environmental and natural resource studies but has also been applied to the field of conservation.

Frank G. Matero, John Hinchman, Dana Tomlin, and Kyu-Bong Song took the conditions survey of the plaster ceiling of the Great Hall at Drayton Hall and used the raster GIS capabilities in ArcGIS to create a statistical model for the understanding of the interaction of conditions and structure on the ceiling. Spatial Analyst was used to create a series of maps based on the density of conditions and proximity to structural members at $\frac{1}{2}$ inch resolution. This was especially effective because the ceiling was one continuous unit that had fractured and could be analyzed as a single piece. The Drayton Hall study took the additional step of running statistical regression analysis on the resulting datasets in order to provide a solid basis for relational conclusions that were drawn from the mapping process. These conclusions showed a direct link between the structure of the above floor and the pattern and density of cracking and detachment of the plaster ceiling. This was used to influence the management of the building so as to help mitigate further damage to the ceiling.\textsuperscript{35} This situation differs from the Second Bank, where the map

is made up of many discrete units that are capable of acting independently of their neighbors.

An expansion of the theoretical aspects of the Drayton Hall study was done by Marlene Lauren Goeke in 2008. A conditions survey was conducted on the plaster ceiling at the Wagner Free Institute of Science in Philadelphia, PA. Seven different conditions were recorded using gradations to determine their severity. Of these, only the variables that were linked to known causes of damage were analyzed. These were chosen based on historic documentation of building problems and references on plaster damage. Goeke used this data to create quantitative and qualitative analyses of the plaster damage. Quantitative analysis consisted of providing raw statistics about the conditions, including attributes such as area or length and distributions. Qualitative analysis was done by creating raster maps showing the spatial distribution of conditions through density and distance calculations that were supported by knowledge of plaster decay mechanisms. Raster images were created at a 3-inch resolution, low compared to what was used at Drayton Hall, but appropriate given the larger area being analyzed. The analytical process was achieved though hypothesizing causal relationships between conditions based on the reviewed conservation literature and creating raster calculations to test them.36 This example is very similar to the Second Bank with the exception that, like the Drayton Hall ceiling, the Wagner Free Institute ceiling

contains large areas of continuous surface in contrast to the Second Bank’s smaller
discrete units. The focus on specific conditions of interest is important to note
because without narrowing the evaluation the amount of data could have displayed
relationships that were statistically significant but scientifically meaningless.

A more traditional application is seen with Montserrat Fuentes and Adrian E.
Raftery’s study of air pollution. The researchers used GIS’s raster functionality and
the ability to run spatial statistics calculations to predict the distribution of dry \( \text{SO}_2 \)
deposition with regards to the locations of power plants by including information
about location, production levels, and wind patterns. The result was a map showing
predicted levels of pollution across the eastern half of the United States.\(^{37}\) This was
successful because air is a fluid medium that behaves in a similar fashion to the
continuous plaster surfaces seen at Drayton Hall and the Wagner Free Institute of
Science.

The dangers of reliance on data of unknown or questionable origin for
predictive modeling applications are pointed out by Kimberly P. Van Niel and Mike
P. Austin. Digital Elevation Maps (DEM)s created using different methodologies
were tested against each other. Errors and uncertainty in the original dataset were
found to compound errors in the calculations made based off of them. The
differences in these original data formulation types can directly affect the output of
the modeling calculations. This source of error is important to consider when

\(^{37}\) Fuentes, Montserrat, and Adrian E. Raftery. “Model Evaluation and Spatial Interpolation
by Bayesian Combination of Observations with Outputs from Numerical Models.”
working with any raster base layer for data processing. This is also directly related to the different methods for raster calculations used within Spatial Analyst. Different mathematical operations used in raster calculation can affect the data differently depending on the source. It is important to choose the right calculation type and resolution to ensure that the data is representative of the original building. A Euclidean calculation is appropriate for most buildings because it maintains the simple two-dimensional grid allowing each pixel to represent the data for its precise location.

One study of the habitat of China Cedar trees for the purposes of creating protected areas illustrates the predictive power of raster GIS systems. Datasets for elevation, microclimate, and soil type were used to create a model of the region of interest. Some of this data was used to interpolate new datasets, such as elevation data being used to calculate terrain slope. These datasets were then statistically compared to the data for regions known to house China Cedar. By establishing the required environmental criteria, it was possible to calculate which areas in the study region would be most amenable to the survival of the species in comparison to areas that do not suit their needs as well. The use of raster data allowed the investigators to score areas based on their compatibility with the requirements for China Cedar. This approach is reliant on the original datasets showing continuous data types, which can be assigned a value for analysis purposes. This is particularly

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important for datasets such as elevations, which cannot be easily broken down into discrete areas. The statistical analysis was done using IBM’s Statistical Package for Social Sciences (SPSS) for regression modeling due to the software’s versatility in handling diverse datasets, and ability to perform multiple types of statistical calculations. These examples work by assigning values to specific attributes and calculating which areas show the highest value related to the objective of the study. This approach calculates values on a per-pixel basis. The Second Bank is represented as individual stones, which could operate in a similar fashion to pixels if appropriate values can be attributed to each condition and characteristic present on the building.

2.4 Multivariate and Spatial Statistics

Multivariate statistics is the field in which more than two individual variables are compared and tested against each other. This is best applied to variables that are discrete or can be rounded to a predetermined level of accuracy through the use of significant digits. While datasets used in multivariate statistics may represent a measurement that is in reality continuous, the data is transformed into discrete datasets during measurement. This is best applied to vector data, which also deals in discrete units such as area.

Spatial statistics work with continuous datasets that are located within R^n space, where R^n represents that number of dimensions present. This is usually two

or three dimensions when working with simple datasets, but more dimensions can be included depending on the complexity of the data.\(^{40}\) \(R^2\) space represents a flat, two-dimensional surface, as can be seen in a simple building elevation or conditions survey the dimensions represent only the coordinates of the data in question. Third dimensions can be added to represent elevation or a non-Euclidean property such as value. Beyond a third dimension, data is representative of non-Euclidean properties. In GIS, data are usually found as representative of formats such as density or distance. Data is presented as a value that is assigned a coordinate, in the case of two or three dimensional space this is a Euclidean coordinate \((x,y,z)\). In the form of raster datasets each coordinate as represented by an individual pixel can only have a single numerical value. The values of these pixels can be measured in relation to each other to determine statistical patterns.

### 2.5 Marble Decay

An understanding of the methods through which stone decay occurs is necessary to properly interpret data about the resulting conditions. Erhard M. Winkler has compiled what is often considered the ultimate treatise on architectural stone, describing the variations in stone types and the processes through which they decay. Marble is a metamorphic stone derived from exposing limestone to high temperatures and pressures. The chemical composition of the stone remains the same, while the crystalline and pore structures are changed. Metamorphosis can

occur non-homogeneously, resulting in a range of possible stone properties. Marbles display mineral grains that interlock due to the reformation of crystals during metamorphosis.\textsuperscript{41} The arrangement of pore spaces within the stone determined the way that water can travel through the stone, and therefore what kind of affect it will have on the physical and chemical decay of the stone. Pore space and water sorption are determined through the use of standardized tests performed in the lab.\textsuperscript{42} Standards have been established for other stone characteristics such as hardness, strength, conductivity, and others as well. These tests are important because they highlight potential differences in stones that can appear otherwise the same under macroscopic observation, but will have significantly different characteristics under testing. A relevant example of this is the difference in thermal expansion between limestone and dolomite. While they appear similar to the naked eye, dolomite will expand significantly more under lower temperatures than limestone.\textsuperscript{43} This knowledge of stone behavior is applicable to stone classification for statistical analysis because it indicates whether or not the occurrence of particular patterns in the data are due to random distribution or are signs of a larger relationship.

Amongst his descriptions of the properties of various stones, Winkler also described the ways in which the environment works to decay the stones. Water and atmospheric exposure are the two largest contributors to the weathering of stone.\textsuperscript{44}

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\begin{itemize}
\item Winkler (1975). p. 27-30.
\item Winkler (1975). p. 44.
\item Winkler (1975). p. 89.
\end{itemize}
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Water is the biggest contributor to stone decay because it provides the mechanism for both mechanical and chemical damage. Water acts as a vector for acids, which can dissolve calcite or salts, as an oxidizing agent for metallic mineral inclusions, and as a device for mechanical damage through freeze thaw cycling. Salts and ice crystals both cause mechanical damage through crystallization within the pore spaces of the stones, creating internal pressure, which can create larger pores and fractures. This effect can build up until surface spalling occurs. Dry deposition of sulfates through atmospheric pollution is key in urban environments as sulfates can convert calcareous stones into more readily soluble minerals. Exposure to sulfur converts calcite to gypsum, which is readily soluble in water and results in the loss of surface material. The factors all contribute to the stone decay seen on the Second Bank, but in a non-uniform fashion due to the different microclimates experienced by each elevation.

W.D. Keller points out that stones are by nature a stable material, and decay occurs only when they are placed in an environment different from that of their origin. Changes in the equilibrium state of the stone allow for variations in climate to cause chemical and physical changes to occur to the stone. These variations exist on multiple scales, from the macroclimate of a region to the differences in

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45 Winkler (1975). p. 96-100, 111-112.
microclimate experiences by different parts of a building. The lack of equilibrium and differential exposure is important to consider when examining the Second Bank's distribution of conditions. If the differential microclimate around the building is having a large influence on the irregularity of stone conditions, it should be easily detectible in the distribution of the conditions.

Stone decay is influenced by four main factors: the material properties, their form and placement, the way that weathering processes interact with the stones and each other, and the environmental context of the stone. The important point that traditional geological uniformitarianism does not apply in the architectural context is raised. Due to a changing environment and the different forms and exposures of different architectural elements, it cannot be assumed that the observed decay has been consistent for the life of the building or that it is consistent across the entire surface. The interactions between multiple decay mechanisms and the environment create a very complex series of relationships and make it very difficult to predict the future trends that a particular stone will follow. Fortunately, the Second Bank is relatively consistent in architectural detailing, the main exception being the columns. Most stone is of consistent thickness and size; decoration is mostly isolated to the cornice level. This allows for some control to be emplaced so that variations in the stone's characteristics and placement can be the main

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variables examined. This should help mitigate the difficulties in the predictions of stone decay referenced by controlling for the variable of size that could confound other relationships.

Patricia Warke further expands on the hypothesis that stone decay must be examined as a series of complex interactions rather than a few simple variables. Some of these, such as irregular environmental stresses, can cause damage that is not part of a larger pattern of deterioration experienced by the building. Variations in climate can alter the types and rates of decay, while past decay can make a stone more susceptible to future decay. These factors are important to consider during any predictions made on the Second Bank, but since predictions will focus more on risk of decay than on rate, many of the complexities involved in prediction can be mitigated. The extent of damage was not measured during the conditions surveys, only the presence or absence of the conditions; therefore calculations of rate of decay are not possible. The surveys conducted for the Pennsylvania Blue Project were the first of their kind for the Second Bank and there is no historical baseline for comparison to calculate rate of loss.

McAlister suggests a number of ways that the properties of a stone can be qualified through the use of chemical analysis. There are a wide variety of methods that are available depending on what it is that the investigator is trying to determine about the stone. Each technique excels at determining specific qualities about the

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material. This highlights the importance of having an understanding of a stone and the specific questions for examination before testing begins. Qualification of stone cannot exist in a vacuum and the investigator needs to know how the mineralogical description will manifest itself in stone behavior. In the case of the Second Bank, mineralogical examination has been used to qualify the differences between stone types to explain any differences in the occurrence of conditions or the lack thereof.

Johannes J. Feddema conducted a study of stone decay in Philadelphia, specifically focused on marble tombstones and atmospheric pollution. Feddema suggests multiple causes of surface decay on marble including freeze/thaw action, differential thermal stresses, salt decay, and sulfate deposition. While the focus of their study was on tombstones, the decay mechanisms operate in the same ways on building stone. There are key differences between the two contexts though. Tombstones tend to be significantly smaller and thinner than the stone blocks seen in the Second Bank, they are exposed on all sides as opposed to only one or two, and are placed directly into soil which may contain nitrate salts. Taking these factors into account, the physical mechanisms for stone decay remain the same, though they may differ in severity. Feddema stressed the importance of climate, both macro and micro, in the decay of marble. Wind speeds and exposure to rainfall are key to this and can be affected by directional exposure of the stone. This is particularly

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important when considering a building, since each elevation experiences its own microclimate. This can be considered in observations and statistical analysis of stone conditions seen on the Second Bank. Multiple studies have shown that atmospheric pollution in Philadelphia spikes during the summer and the winter, and more recent studies have shown a decrease in the amount of pollution between 1966 and 1986.\textsuperscript{54} While the general reduction in pollution levels can affect the deposition on the building, seasonal variations are less likely to, given its proximity to a bust street. Feddema’s methodology was to sample tombstones at cemeteries within and around Philadelphia, controlling for material (all Pennsylvania marble), shape, and relative age. Observations and measurements were done on each stone to calculate the amount of decay. Means and standard deviations were calculated for each cemetery sampled and used to chart decay trends in the regions.\textsuperscript{55} The amount of stone loss was finally plotted against the age of the stone to calculate trends in decay. The results were verified through lab testing for the presence of sulfates and nitrates in the sample stone.\textsuperscript{56} The approach used in this model can be adapted to the Second Bank model by calculating the relative areas of conditions compared to the area of the stone while controlling for conditions occurring. Likewise, the use of mineralogical analysis can inform the analysis of stone differences in the same way that chemical tests validate the proposed decay mechanisms in the tombstones.

\textsuperscript{54} Feddema (1986). p. 28-29.
\textsuperscript{55} Feddema (1986). p. 31-38.
\textsuperscript{56} Feddema (1986). p. 43-45.
A similar study was conducted in Montana by Sheila M. Roberts as well as a number of others across the United States. A rate of stone loss was calculated by comparing the thickness of the tombstone at the base and the top and dividing the amount lost by the age of the stone. The sampling methodology varies between Roberts, Feddema, and other similar studies. This study covers a much broader geographic range, and thus a broader range of environment, than the one conducted by Feddema. Roberts compensates for variables such as manufacturing quality, but does not appear to compensate for things like microclimate to the same extent as Feddema. The establishment of a simple rate curve is achieved through regression modeling showing the relationship between time and stone loss.57 This statistical analysis can be applied to the Second Bank in a similar fashion as described above, through the use of relative area rather than age to compare stones of similar characteristics and the amount and type of loss they have experienced.

3. Methodology

3.1 Conditions Surveys

As discussed above, the data used for this thesis was collected over the course of two survey campaigns, the first in 1999 and the second in 2003 (figs. B3-B16). Conditions definitions were standardized between the two surveys and the 2003 conditions glossary is the one that has been used for subsequent projects (figs. B1 & B2).\textsuperscript{58}

3.2 Data Processing

A GIS is a spatial database. The database that is linked to vector or raster data within a coordinate system.\textsuperscript{59} The database can behave as a normal database and be queried or have calculations run without the spatial data, or the spatial data can be used to run further calculations.\textsuperscript{60}

The original data provided was in vector format, covering a discrete area or path defined by a specific mathematical equation. Vector formats for the original data either represent areas (stones and their related attributes or conditions that fill discrete areas) as polygons, or follow linear paths (cracking, mortar joints, etc) as

\textsuperscript{58} ACL (2004).
\textsuperscript{60} Mitchell (1999). p. 18-19.
polylines.\textsuperscript{61} Calculations and predictions done in this thesis focused on area rather than proximity; therefore only polygon conditions were used and linear conditions were disregarded. Analysis of linear conditions through raster GIS analysis was not performed.

The original stone by stone drawing of the Second Bank was used as a base for all calculations because it contained the unique identifying number for each stone. Individual drawings showing the areas of each condition across the whole building were also used as primary data sources.

Two new databases were created for analysis purposes: a stone by stone Boolean conditions database and an intersected conditions database. The Boolean conditions database showed each stone and simply recorded the presence or absence of the conditions on its surface. This was done using the Spatial Join analysis tool found in ArcGIS 10's toolbox. The Spatial Join tool simply appends the contents of one or more database(s) to that of another based on their spatial relationship to each other.\textsuperscript{62} This allowed for simplified queries to be run on the building. This database did not indicate the area of each condition on the stone or whether or not conditions overlapped each other. It was primarily used for simplified stone by stone representations of conditions distributions because the detail shown in a conditions area overlap map would not be visible on a whole building scale.

A more precise database was created using the Intersect analysis tool in ArcGIS 10’s toolbox. This tool works by taking two or more objects and finding their overlapping area while combining their attributes for that area. Layers with multiple overlapping features will produce an output layer with many smaller features.\(^{63}\) Boolean representations of each condition were intersected in sequence followed by an intersection with the individual stone layer. The result was a database showing every combination of conditions and stone characteristics present on the Second Bank. This was primarily used to calculate areas of overlapping conditions and characteristics.

### 3.2 Data Types

For the purposes of properly representing the data types, conditions and characteristics were broken down into Boolean and non-Boolean attributes.

**Boolean Attributes**

Boolean attributes are used to represent the presence or absence of the condition in question and are only effective for conditions that can be described in such terms. Boolean attributes are ideal because they display the information in the simplest form possible, either on or off, and provide the ability to easily list the occurrence of multiple conditions on a per stone level.

Non-Boolean Attributes

Some characteristics have more possible values than simply present or absent. These are represented as non-Boolean attributes. This approach is more manageable than attempting to distribute each possible value for the characteristic as a different Boolean attribute. This attribute type is important because the stone characteristics that it is used to represent do not have inherent values that could be quantified. A value would not be suitable to assign to an attribute such as stone color or foliation direction because each possible option is not necessarily better or worse than another, rather they are simply different.\textsuperscript{64}

3.3 Bivariate Correlations

The first tests run using the spatial data from the Second Bank were simple bivariate correlations between the recorded conditions and stone characteristics. This was done in two ways: a direct correlation and a normalized percentage. Direct correlations showed the amount of one condition in relation to its overlap with a second condition (table C.i). Normalized percentages showed the amount of a condition in relationship to a stone characteristic, adjusting for the characteristic's representation on the building (table C.ii). These correlations were done in order to look for direct relationships that could guide further inquiry. Spatial intersections were done in ESRI’s ArcGIS and calculations were done using Microsoft Excel.

\textsuperscript{64} Mitchell (1999). p, 45.
Direct correlation was executed by calculating the overlapping area of two or more variables and dividing this calculated area by the area of the condition of interest. This was represented as:

\[(A \cap B) \div A\]

where ‘A’ and ‘B’ each represent different conditions and the equation ‘A ∩ B’ represents the area where they intersect. By dividing this intersected area ‘A ∩ B’ by ‘A’ the percentage of the area of ‘A’ that also contains ‘B’ is calculated. In contrast, ‘(A ∩ B) ÷ B’ represents the percentage of the area of ‘B’ that also contains ‘A’.

These relationships were calculated using the Intersect tool in ArcGIS to create a representation (Table C.i) of the overlapping area between each combination of conditions (Charts E.i-E.xv). The total area was then calculated using the XToolsPro extension for ArcMap. All areas were calculated in square inches. The choice of units was based on the fact that the original drawings were done in AutoCAD with a default unit of inches but could have been done in any unit of area. Units were later calculated in feet for ease of communication. An intermediate table was created in Microsoft Excel showing the total area of each condition along the X- and Y-axes and the area of the intersection of the two conditions at the corresponding cell. This was used to calculate a second table (table C.i) from the first, showing the percentage of the area of condition ‘A’ that contained condition ‘B’.

The total number of bivariate conditions combinations was represented as:

\[N \cdot (N-1)\]
where ‘N’ is the total number of conditions that represent a spatial area. 22 conditions were compared for a total number of possible combinations of 462. Intersections between the same conditions were discounted because they would produce a 1:1 correlation that simply stated that the area of condition ‘A’ was explained entirely by the area of condition ‘A’. This is seen as greyed out cells in table C.i. Intersections with absolutely no overlap were also discounted; this was separated from intersections with a calculated overlap of 0% due to the fact that there was some, if miniscule, correlation that was below the threshold of significant digits used.

All calculations were rounded to one decimal place, or to 1/10th of a square inch. This was justifiable based on knowledge of the recording processes. Since original condition recording was done by hand and then transcribed to digital format there were multiple potential sources for error including: original recording, misrepresentation due to pen width or scanning distortions, or inexact tracing during digitization.

The resulting table (C.i) provided an initial correlation between conditions, which was used to inform further investigative queries by indicating combinations with strong relationships. Conditions were highlighted based on their percent of correlation, with stronger percentages highlighted in darker colors. The average correlation was 5% with a standard deviation of 10%.
This approach did not work for conditions that were represented as polylines, such as cracks, because these did not contain area and could not be correlated with conditions that do.

A further calculation was applied to the correlations between conditions and stone characteristics, where a normalized ratio was calculated for each condition based on the stone characteristics as an independent variable. The distribution of each condition was related to the proportional distribution, out of 100%, of the characteristic being compared to.\(^5\) Normalization created a value for each condition that was a ratio between the condition’s distribution in relation to the characteristic and the characteristic’s relative area on the building.\(^6\) This was expressed as a value in relationship to 1. The number calculated was the percent multiple of how likely the condition was to occur in relation to random chance. Values above 1 showed a multiple relationship while numbers below 1 showed a fractional relationship. A value of 2.5 indicated that the condition occurred 2.5 times more often that it should have given a random distribution of occurrences. A value of 0.5 indicated that the condition occurred 1/2 as often as it should have given a random distribution. This was calculated as such:

\[
\frac{(A \cap C) \cdot C}{\%C}
\]

---


where ‘A’ is the area of the condition, ‘C’ is the area of the stone characteristic and ‘A \cap C’ is the area of intersection between the two. Therefore the entire term ‘(A \cap C)/C’ represents the percentage of the area of ‘C’ that is covered by ‘A’. This was further divided by ‘%C’, the percentage of the entire building that ‘C’ represents, to create a normalized value. If ‘%C’ is 30% of the building’s surface area and ‘(A \cap C)/C’=30% then the normalized value is 1 and it is shown that the distribution of the condition is the same as a random distribution. If ‘(A \cap C)/C’=60% then the normalized value becomes 2, indicating that condition ‘A’ is twice as likely to occur on stones with characteristics ‘C’. A table was constructed showing the distribution of normalized values for conditions with relation to stone color, elevation, and foliation direction (table C.ii). Shades of red and blue were used to distinguish values below and above 1, with darker colors indicating a lower or higher value.

‘%C’ was determined based off of the separation of different attributes for stone characteristics. For example, ‘%C’ was calculated for each of the possible values for foliation orientation independently from the values for stone color. The percentages for each value within an attribute equaled 100%, representing the entire building.

3.4 Visual Correlations

A stone by stone visual analysis was conducted to look for larger scale patterns in the distribution of the bivariate conditions sets showing the highest correlations. Using the Spatial Join tool in ArcGIS, Boolean values for conditions were assigned to the individual stones. This allowed for a comparison of conditions
distributions that, while not entirely accurate, was still informative. This approach created a simplified model of the building. As the conditions were listed on a per-stone resolution rather than absolute position, there was the possibility that two conditions may appear on the same stone without actually overlapping. This model did not account for the total amount of each stone that was actually covered with the conditions in question. Bivariate combinations of conditions were compared through symbolizing the conditions to emphasize stones where both conditions were present and looking for apparent patterns (figs. E1-E15). Given the large number of combinations possible, only combinations that displayed 20% or higher correlation were compared. 20% was chosen because it fell at 1.5 standard deviations above average, which placed it in the 98th percentile for the distribution of bivariate conditions correlations. Observations from these comparisons were then compared to bivariate calculations for stone characteristics to validate them.

3.5 Multivariate Correlations

Multivariate correlations were calculated by querying the database showing all of the combinations of conditions and characteristics. The database was separated from the spatial data and queried using Microsoft Access software. The approach allowed for quick manipulation of variables without the need for the SQL coding used in ArcGIS. Combinations of conditions were tried based on correlations suggested by tables C.i and C.ii. These combinations were then mapped on a stone by stone basis to create predictive maps (figs. F1-F12).
3.6 Examination Criteria

Given the total possible number of combinations of conditions and stone characteristics it was necessary to limit the combinations being examined. Only combinations of conditions with 20% or higher correlation were considered for further examination.

Factors used to investigate stone conditions were classified into three categories, which can be weighted differently based on contextual examination.

Conditions Correlations:

Conditions correlations were the amount to which the condition in question related to other conditions. Stronger correlations or ones that could be explained through known mechanisms of stone decay were favored.

Stone Characteristics:

Stone characteristics were the inherent attributes of a stone that could affect its performance and relationship to the development of conditions. These primarily focused on the stone’s color and foliation direction.

Stone Situation:

Stone situation referred to the situational context with regards to the location and use of stones suffering from the condition in question. This could include factors such as the elevation the stone was located on, if its primary face was vertical, horizontal, or suspended, or which part of the building it as used on
(column, pediment, etc). These were factors that could influence the climatic exposure of the stone and potentially affect the development of conditions that way.
4. Mineralogical Analysis

Mineralogical classification of the stone types used on the Second Bank was important for providing a basis for differentiating the stones and explaining differences in behavior. Jocelyn Kimmel conducted a similar study on stone from the Second Bank as part of her Master’s thesis in 1996.\(^{67}\) Later examination was done during the 2003 conditions survey using samples from the north elevation.\(^{68}\) X-Ray Diffraction (XRD) and Polarized Light Microscopy (PLM) were used in this thesis to identify the mineralogical composition of the stones used in the Second Bank.

4.1 Geological Description

41,500\(^3\) ft of marble was used in the original construction of the Second Bank.\(^{69}\) The stone used for the building is commonly called Pennsylvania blue marble, though it is not a true geologic marble. The stone is only weakly metamorphosed, creating a crystalline limestone.\(^{70}\) Multiple quarries have been cited as the source of the Pennsylvania marble, helping to explain the differences in color and characteristics found in the stone. Both types were quarried to the northwest of the city in Montgomery County.\(^{71}\) The white marble has a well-graded grain size distribution and has many large mineral inclusions. The grey/blue marble

\(^{67}\) Kimmel (1996).
\(^{68}\) ACL (2004). p. 52-57.
\(^{70}\) ACL (2004).
\(^{71}\) Dickinson (1985).
has mostly uniform sized grains and is heavily foliated and contained veins of
darker mineral deposits.\textsuperscript{72}

### 4.2 Samples

11 hand samples of stone were acquired from the Second Bank for analysis
(figs. D1-12). All samples had spalled naturally and only general locations were
known. One sample of white stone from a column was provided by the ACL
collection. A single sample of gray stone from an unknown location was provided by
Charles Tonetti of Independence National Historical Park (INHP). Nine other
samples were loaned from the INHP Study Collection, accession # INDE 15703.
These samples were white stones from the cornice level and some showed
remaining architectural detailing.

### 4.3 X-Ray Diffraction (XRD)

X-Ray diffraction was performed with the assistance of Dr. Gomaa I. Omar of
the Department of Earth and Environmental Sciences at the University of
Pennsylvania.

X-Ray Diffraction (XRD) is a method for the chemical identification of non-
organic substances. It works by projecting an x-ray beam through a powdered
sample of the material while rotating it at a measured angle and rate. As the sample
rotates, the amount of energy diffracted through the sample is measured by a
detector. Spikes in the recorded amounts of energy at specific angles relate to

\textsuperscript{72} Kimmel (1996). p. 3.
specific crystalline compounds. Statistical comparison against known samples are then run through specialized software for identification. This method is dependent on the user having a basic understanding of what minerals are likely to be present in the sample.

Nine samples were prepared for testing, representing five different hand samples from the Second Bank (table D.ii). Multiple XRD samples were prepared from samples SEB-01 and SEB-03 in order to isolate specific minerals for identification.

Representative portions of hand samples were broken off and ground for ten minutes using a steel ball grinder. The ground samples were then scanned with a Philips XPert X-Ray Diffractometer using a copper anode set at a voltage of 45kV and a current of 40mA measuring between 3-75° for three hours per sample. Analysis was conducted using XPert HighScore Plus software. The results were as followed:

SEB-01.i (fig. D13): Taken from the interior of sample SEB 01, attempted to isolate the primary mineral in the sample. The sample was primarily composed of calcite (CaCO₃) with auxiliary minerals consisting of muscovite (KAl₂(AlSi₃O₁₀)(F,OH)₂) and gypsum (CaSO₄·2H₂O).

SEB-01.ii (fig. D14): A sample section of the entire stone taken to identify general mineral composition. Results showed calcite, muscovite, and gypsum, with trace
occurrences of covellite (CuS), magnetite (FeO·Fe₂O₃), cubanite (CuFe₂S₃), ilmenite (FeTiO₃), and chalcopyrite (CuFeS₂).

SEB-01.iii (fig. D15): An isolated selection of metallic mineral inclusions were removed from the hand sample for specific identification of trace minerals. The results showed calcite, muscovite, pyrite (FeS₂), quartz (SiO₂), and covellite.

SEB-01.iv (fig. D16): Material from the surface of the stone was removed with the intention of isolating minerals seen on the surface of the stone resulting in discoloration and soiling. The result showed only calcite and muscovite.

SEB-02.i (fig. D17): A sample of material from the interior of the hand sample. The testing detected only calcite.

SEB-03.i (fig. D18): This sample attempted to isolate an area of encrustation for chemical classification. Analysis found calcite, gypsum, pyrite, and monohydrocalcite (CaCO₃·H₂O).

SEB-03.ii (fig. D19): A sample of the interior of the stone including a portion of the mineral inclusion layer seen in the stone. Calcite and muscovite were detected.
SEB-10.i (fig. D20): A sample of a thicker encrustation layer looked for auxiliary minerals. Results showed calcite, gypsum, and muscovite.

SEB-11.i (fig. D21): This sample was an isolated mineral inclusion layer looking for trace minerals. The minerals calcite, gypsum, muscovite, sphalerite ((Zn,Fe)S), pigeonite ((Ca,Mg,Fe)(Mg,Fe)Si$_2$O$_6$), and quartz were identified.

4.4 Polarized Light Microscopy (PLM)

Mineralogical composition was confirmed using polarized light microscopy (PLM). PLM uses slides of materials cut to a thickness where light can be transmitted through (thin sections). Transmitted light is polarized before passing through the sample. This is called plane-polarized light (PPL). If the light is polarized again after passing through the sample it is called cross-polarized light (XPL). These two types of light create different effects as they pass through the sample and highlight differences in the mineralogy present. Interpretations of variations in color and extinction patterns can be used to precisely identify minerals through the their refractive index, how much light is slowed when it passes through the material. This technique is used to confirm results from XRD.

Six thin sections were prepared representing different stone traits and characteristics for examination under PPL and XPL. Thin sections were impregnated with blue epoxy to highlight pore space. One half of each section was stained with Alizarin Red to highlight calcite grains and differentiate them from dolomite. One
half was left unstained in order to allow observations of the stone to show accurate colors under PPL.

The majority of stone grains were determined through staining to be calcite rather than dolomite. Metallic minerals were located but could not be specifically identified using PLM. The presence of quartz, muscovite, and gypsum were also confirmed through PLM.

4.5 Discussion of Mineral Composition

The primary mineral observed in all samples was calcite (figs. D22-23 & D28-29). In contrast to the results shown by Kimmel, no dolomite was detected in XRD results. This was substantiated through the staining used for the thin sections. The variations between the results seen in the two sets of testing can possibly be explained through the fact that neither sample set may have been fully representative of the stones on the whole building. Calcite grains showed evidence of secondary genesis through metamorphic processes. Grains were well packed and show significant twinning, suggesting recrystallization during metamorphism.

A white mica was visible in the hand sample SEB-01. This has been confirmed to be muscovite, a mica commonly found in association with metamorphic rocks. Positive identification was made using the combination of XRD and PLM. Testing of the mineral inclusion layer found on the white stone from

the cornice level showed that muscovite is also the primary mica found there (figs. D32-33 & D38-39).

Gypsum was found both on the exterior of the stone, as encrustation, and in small quantities on the interior of some samples (figs D30-31). Exterior occurrences were due to the transformation of calcite to gypsum when exposed to atmospheric sulfates. Interior gypsum occurrences may be resultant of original deposition in the source limestone.\textsuperscript{76}

Quartz and pigeonite were two silicate accessory minerals observed in stone samples. Small amounts of quartz were seen in white stones. Due to its abundance of occurrence as a mineral this was not unexpected. Quartz is a highly stable mineral inclusion.\textsuperscript{77} Pigeonite is of igneous origins and is not common in metamorphic rocks. It was probably a remainder from the parent rock.\textsuperscript{78}

A series of copper and iron sulfides and oxides were found as metallic inclusions within the white stones, including within the muscovite inclusion layers. These metallic inclusions were responsible for the intrinsic metallic staining seen on some stones.

Chalcopyrite, sphalerite, cubanite, covellite, and pyrite were all sulfide accessory minerals found in the white stones from the Second Bank. These are some

\textsuperscript{77} Klein, et al. (2007). p. 536.
of the most common mineral forms of zinc, copper, and iron. These minerals are not entirely stable and can convert to other forms in the presence of water.\textsuperscript{79}

Ilmenite and magnetite were oxide minerals found as accessories to calcite. They are both accessory minerals associated with metamorphic rocks.\textsuperscript{80} This indicates that they were probably of secondary origin from minerals found in the parent rock.

4.6 Stone Types

As has already been mentioned, the stone seen on the Second Bank came from multiple quarries and had different characteristics. These characteristics have led to differences in performance depending on environmental exposure. Based on the data that was collected during the condition surveys it was only possible to accurately classify the stones by their primary colors.

White stones were seen mainly on the north and south elevations. They consisted primarily of fine grained angular to sub-angular calcite that was arranged in a well-packed formation. There was little pore space seen in these samples (figs. D22-23). Calcite grains also showed a high degree of twinning caused by recrystallization during metamorphosis. Layers of muscovite were distributed throughout the stone, either as thin sheets of white mica or combined with metallic minerals to create inclusion layers. Iron and copper sulfides and oxides were also

\textsuperscript{80} Klein, et al. (2007). p. 379, 385-386.
scattered throughout the calcite matrix. Gypsum was found both on the surface as a
crust and in small amounts within the stone matrix.

Gray stones were seen mainly on the east and west elevations. Since only one
sample was available, classifications have been treated skeptically. The stone was
almost pure calcite, with any auxiliary minerals occurring at undetectable amounts.
Calcite grains were large and sub-angular (figs. D28-29). The stone was highly
friable and this was visible in the disaggregation of stone grains seen in thin section.
The calcite in the gray stones also showed a significant amount of twinning from
metamorphosis.
5. Observations

5.1 Conditions Correlations

Direct bivariate correlations were calculated as explained in the chapter on methodology. The majority of conditions showed some level of correlation with each other. (table C.i) Correlations ranged from 0% up to 89%, though most were too low to be linked to any observable pattern. The relatively high or low correlations associated with some conditions (14 out of 22 conditions had a correlation above 5% with tooling marks and four out of these 14 had a correlation above 20%) can be explained by the large or small areas that are covered by the condition rather than by a causative relationship. In order to look for more meaningful relationships between conditions, only the combinations that displayed a correlation of 20% or higher were considered for further evaluation along these lines. The following comparisons were based purely on the calculations displayed in table C.i. Distributions along the building are discussed below.

Contour scaling accounted for 21% of the area of dimensional loss (chart E.i). This can be explained by the fact that dimensional loss is a more sever manifestation of the material loss that occurs during contour scaling.

Contour scaling also accounted for 23% of the area of insipient spalling (chart E.iv). The overlapping areas show where future loss is developing over areas of past loss.
Differential erosion was seen on 26% of the encrusted surfaces (chart E.iii). Encrustation is associated with gypsum, which leads to the loss of surface material as the calcite is converted to more soluble material. Since differential erosion is defined by a specific measurement of depth of loss there is the possibility that more of the encrusted areas were suffering from loss that was not significant enough to be considered differential erosion, this is a hypothesis and cannot be confirmed with the current data. Conversely, only 8% of differential erosion was explained by encrustation. This can be explained either by alternative causes for differential erosion or the fact that as the surface was eroded the associated encrustation on the surface was also lost. 26% was a significant overlap, but does not necessarily indicate a causal relationship.

There was a large overlap of differential erosion with the areas treated with chemical bird repellents. 40% of the area showing evidence of repellent treatments was experiencing differential erosion (chart E.v). There was no clear causal relationship though, since repellent treatments were specifically applied to the selected areas of the building, less than 1% of the total surface area. The high level of overlap is most likely explained by the fact that differential erosion is a fairly common condition on the building, covering $1929^2$ ft, approximately 6% of the building, while chemical bird repellents only cover $2.8^2$ ft.

The overlap between contour scaling and friability/flaking warrants further investigation. 24% of contour scaling also showed friability/flaking (chart E.ii), implying that there may have been a common cause for the conditions, either
inherent in the stones affected or environmentally shared that could be investigated in multivariate analysis.

Friability/flaking accounted for 55% of the area experiencing microfloral growth (chart E.vii). This could either be a direct causal relationship or one related to a common cause. Microflora may have caused the stone to decay in such a way that it displayed these characteristics through either chemical or mechanical actions.

Friability/flaking was also seen on 34% of the area of network cracking (chart E.x). Network cracking involves damage to the surface of the stone that exposed more surface area to water, making the stone more susceptible to further damage. The occurrence of friability/flaking is one possible result of this.

Intrinsic metallic staining was seen on 20% of the area of stones containing visible mineral inclusions (chart E.viii). There were a variety of minerals inclusions present in the Pennsylvania marble used in the Second Bank, some of which were metallic. The disparity between the areas of mineral inclusions and of staining can be attributed either to non-metallic minerals or to differences in water exposure as seen on different parts of the building.

In a related correlation, 30% of the area of network cracking also experienced intrinsic metallic staining (chart E.ix). This correlation, combined with others, implies a direct relationship between exposure to water, the inherent characteristics of the stone, and the appearance of network cracking.
This is further backed by the fact that 89% of the stone area with mineral inclusions was suffering from network cracking. This was the strongest bivariate correlation observed. The converse relationship showed that 36% of network cracking was within areas of mineral inclusions. The disparity between these numbers raised the question of what other characteristics or environmental factors were affecting the stones to cause network cracking. As is noted in table C.ii, network cracking and mineral inclusions both showed strong relationships with the south elevation and stones that were vertically edge bedded.

Intrinsic metallic staining accounted for 25% of the area that showed efflorescence of soluble salts. Since both these conditions were related to the transportation of soluble minerals in water it was important to examine how these distributions relate to areas exposed to water and to inherent stone characteristics.

There was a high percentage of intrinsic metallic staining on stones that have been redressed, 24%. Redressing was done on stones that had previously suffered surface deterioration. The previous damage could be related to mineral inclusions and network cracking as seen independently. This can be verified by comparing the characteristics of the stones that have been redressed to those that have network cracking.

Stone redressing appeared on 23% of the areas experiencing efflorescence (chart E.vi), possibly suggesting that this condition had been occurring for a long enough period of time and that it had been addressed in some locations as part of restoration efforts. Stone redressing and intrinsic metallic staining have occurred on
a similar amount of area associated with efflorescence but there was a low converse
association between efflorescence and stone redressing, where efflorescence
accounts for less that 1% of the redressed area, indicating that the relationship was
incidental. This was explained by the fact that efflorescence was only recorded on
0.1% of the building while stone redressing was seen on 5%.

Some correlations exposed the intention of past treatment regimes. 36% of
the area showing indications of the use of sealants for repairs also showed intrinsic
metallic staining (chart E.xi). The staining may have been a resultant symptom from
the sealant repairs; because the repairs change the permeability of the stone, water
may have been trapped inside the stone and caused dissolution and oxidation of the
intrinsic metallic inclusions. The relationship can also be explained by the fact that
there was a very small area of sealant repairs (72 ft) in contrast to intrinsic metallic
staining (32312 ft).

Tooling marks were recorded only if they were visible on at least 50% of the
individual stone in question; the stones that they were recorded on now represent
approximately 20% of the surface area of the Second Bank. Tooling marks were
evidence of a lack of decay rather than decay itself, therefore observations focused
on areas that had the lowest amount of area covered by tooling marks: dimensional
loss, friability/flaking, and network cracking, 1%, 2%, and 0% respectively (charts
E.xiii-xv). These conditions were ones where the stone’s surface was actively lost,
and most likely explained the lack of tooling marks on their surfaces though a
general loss of surface.
5.2 Individual Stone Observations

The bivariate sets of conditions were graphed on a per-stone basis to look for visual patterns of distributions over the entire building. Due to the large number of combinations of conditions only the combinations that showed a correlation of 20% or higher were graphed. These bivariate sets represent the 98th percentile of the distribution of bivariate correlations. Some pairs showed a distinct pattern of physical distributions, while other appeared to be more random.

Dimensional Loss & Contour Scaling: This was observed on most surfaces of the Second Bank to varying degrees. Of particular note were the columns, of which most stones displayed both conditions (fig. E1). The relatively random distribution across the rest of the building surfaces suggested the need for further investigation of correlations between stone characteristics and this pair of conditions.

Contour scaling & friability/flaking: This was observed most dramatically on the columns and the east and west elevations. The combination was also heavily observed on the north pediment but was mostly absent on the south. Occurrences on the north and south entrance faces were minimal, with more appearing on the south (fig. E2). The strong appearance of this combination on the east and west elevations with less exposure on the north and south indicated that their appearance was probably influenced either by exposure to rainfall or by differences in the stone types used on the different paired elevations. This hypothesis can be verified by comparing the distribution of stone characteristics in these stones.
Encrustation and differential erosion were very strongly represented in the south and east elevations and almost entirely absent from the north and west elevations (fig. E3). This suggested a possible discrepancy in the recording methods between the 1999 and 2003 survey campaigns and that this combination may be invalid. The visible distribution showed a very strong occurrence on the south columns and stair runners with less on the pediment and entrance face. Distribution on the east elevation was located mostly around ledges and windows or areas where the depth of the elevation shifts. These distributions can be further refined by comparison of occurrences and undisplayed stone characteristics. Both conditions appeared to be similarly distributed by stone color, suggesting that the stone type was influencing both similarly.

Insipient spalling and contour scaling occurred together across most of the surface of the building, with very strong representation at the north and south columns, the north pediment, and the west elevation. The combination appeared randomly scattered over the rest of the building surfaces (fig. E4). The discrepancies between the distribution of the conditions on the columns and the rest of the building could be indication of damage being caused by different types of stresses such as compressive stresses seen on the columns but not the main elevation faces.

The overlap between chemical bird repellents and differential erosion was seen only on four cornice level stones and the north and east elevations (fig. E5). The location can be explained by the distribution of chemical bird repellents alone, since bird repellents were applied along areas where birds can perch or nest, as was
seen near the cornice level. As stated above, this was not a causal relationship or an indicator of alternative factors and is disregarded.

Stone redressing occurred over areas of efflorescence only on the south portico, on the S1 and S2 columns and the entablature (fig. E6). As stated above, this relationship appeared to be incidental due to the fact that stone redressing was 23% of the area of efflorescence while efflorescence was only 0.4% of the area of stone redressing.

Microflora and friability/flaking showed a fairly consistent trend on the east, west, and south elevations to appear on the lower portion of the building. Patterns appeared near the ground and floor level and below windows. The most noticeable exception was on the north pediment where the combination appeared above the edge of the bottom of the pediment (fig. E7). These patterns indicated that there was a relationship between surface wetting and the coincident of these conditions. Areas that retain water due to improper drainage, such as ledges and windowsills, were more likely to experience the conditions together.

The occurrence of intrinsic metallic staining and mineral inclusions were focused on the north and south elevations, with the strongest level of occurrence on the north side. Distributions on the other surfaces were minimal (fig. E8). The occurrence on the north and south elevations was an indication that these conditions were only occurring simultaneously on stones primarily of a particular color while the difference level of occurrence between north and south could be explained by microclimate.
Network cracking and intrinsic metallic staining occurred together almost entirely on the columns, and mostly on the north elevation (fig. E9). This was an indication that the columns were behaving differently than the rest of the building surface due to different mechanical stresses and that the different microclimates at the north and south elevations may have been causing different amounts of deterioration.

The combination of network cracking and friability/flaking was seen only on the columns, both north and south (fig. E10). This suggested a unique circumstance, either characteristic of the stones or situational to the columns, such as compressive stress not seen on façade stones.

The concurrence of intrinsic metallic staining and sealant repairs showed stones on the south columns and east elevation (fig. E11). This distribution could be disregarded as indicative due to the small size of the overlap of sealant repairs relative to intrinsic metallic staining.

Stones experiencing intrinsic metallic staining that have been redressed were seen mostly on the south columns and pediment with some also seen on the east elevation (fig. E12). The stones on the east elevation were concentrated around the location of one of the gutters, suggesting that the area is experiencing higher than average water exposure due to damaged joints in the gutter (fig. A9).

The distribution of dimensional loss and less than 50% tooling marks remaining was well distributed across the building, occurring on the columns, pediments, stairs, and east and west elevations. The north and south entrance faces
did not show any occurrences of the combination. The west elevation also showed a higher concentration than the east elevation (fig. E13). This combination of conditions appeared to be geographically concentrated rather than randomly distributed, suggesting that it was related to the context of the affected stone rather than its individual characteristics.

The concurrence of friability/flaking and a loss of tooling marks was concentrated on vertical surfaces, especially the columns, north pediment, and east and west elevations. Again, there was a higher concentration on the west elevation (fig. E14). This combination could also be best explained by individual stone’s situations on the building rather than their characteristics.

Network cracking and the loss of tooling marks occurred almost entirely on the columns (fig. E15). This was highly related to the concentration of network cracking on the columns and the lack of occurrence across the rest of the building due to compressive stresses.

5.3 Normalized Characteristic Comparisons

A table was compiled showing the occurrence of conditions in relation to the normalized surface area of various stone characteristics (table C.ii). This created a value for each condition showing how often it occurred in any given situation compared to a completely random distribution. A value of 1 indicated that the condition was occurring at a frequency equivalent to random chance on that stone characteristic, numbers above 1 showed an occurrence more often than random
chance, and numbers below 1 indicated a fractional relationship less likely than random chance.

Contour scaling occurred with slightly higher and random frequency respectively on gray stones and those with no color data recorded. This contrasted with a frequency approximately $\frac{1}{2}$ that of random distribution seen on white stones. This suggested that stones that white stones that experienced contour scaling were exposed to a particular stress that was causing the manifestation. Contour scaling was also seen with a significantly higher distribution on the west elevation (2.5x) while all other elevations were less than random distribution, with the south elevation being particularly low, at only 30% of random distribution. This suggested that microclimate was affecting the distribution of the conditions.

Deformation occurred at higher rates, almost three times, in association with gray stones and with correspondingly lower rates on white stones. The west elevation was also strongly represented on the condition, 2.42 times as likely. The condition also occurred $\frac{3}{4}$ as often as random on stones that were edge vertically bedded.

Differential erosion showed no strong patterns of occurrence but was slightly more common on gray stones and on the south elevation and slightly less common on the north and west elevations.

Dimensional loss was seen in particularly low quantities on gray stones and on the east and west elevations. These observations complimented each other, as
the primary stone color on the north and south elevations was white. Dimensional loss was also more common on stones that were bedded vertically.

Efflorescence was seen most often on white stones and had a strong correspondence with the south elevation while showing much less of a relationship with the other three elevations, suggesting that its occurrence was related to microclimate.

Extrinsic metallic staining was more common on white stones and the south elevation, particularly on edge vertically bedded stones (7.4x). These factors were all indicative of the columns, which share these characteristics.

The only strong relationships that encrustation showed was that it was more common on the south elevation and occurred with very little frequency on the north and west elevations. This indicated either the influence of microclimate or possible recording errors between the two phases of the conditions survey.

Friability/flaking was more common on the east and west elevations and less common on the north and south, suggesting situational variations affecting the occurrence of the condition.

Intrinsic metallic staining showed a higher rate of occurrence on white stones and a lower rate on gray stones. It was also more common on the north and south elevations and less so on the east and west. Both of these factors could be explained by the occurrence of mineral inclusions and their lower rate of occurrence on the east and west elevations.
Insect damage occurred with significantly (4.45x) higher rates on the west elevation, otherwise it was seen at a random distribution or less common.

Insipient spalling occurred at a much lower rate (1/5) on gray stones. It was also much less common on the east and west elevations, normally distributed on the north, and more common on the south. Correspondingly, it was also more common on edge vertical bedded stones.

Microflora was fairly evenly distributed over different stone characteristics, but was almost nonexistent on the south elevation and edge vertically bedded stones. The regular distribution suggested that factors not related to stone characteristics were affecting the occurrence on microflora.

Mineral inclusions showed much lower occurrences on gray stones and on the east and west elevations while showing a higher than random distribution on the west. They occurred almost seven times more often than random on edge vertical bedded stones, which corresponded to occurrences on the columns.

Network cracking did not occur at all of gray stones or on the east and west elevations and was extremely common on edge vertically bedded stones, suggesting a strong association with the columns, especially on the south elevation.

Tooling marks occurred less often on white stones and were especially uncommon on edge vertically bedded stones. It was otherwise fairly evenly distributed across the different stone characteristics. This was because various types of loss could affect the appearance of tooling marks on the stone’s surface.
5.4 Interpretations

The comparison of the bivariate correlation maps showed distinct patterns of distributions of conditions. Some were distributed randomly across the building’s surface, suggesting that characteristics inherent to the stones were related to the occurrence of the conditions. Others were grouped together spatially, suggesting localized phenomena affecting all the stones in that area regardless of characteristics. The fact that the columns tended to be affected regardless of the distribution of conditions across the rest of the building suggests that they were being affected by different factors and stresses and should be analyzed separately from the rest of the building.
6. Predictions

6.1 Definition and Process

Predictions were based on the identification of variables common to the condition of interest and determining their relationship to that condition. These variables could be other conditions associated with the one of interest, stone characteristics that the condition often occurred with, the location on the building, or any combination of the above. Areas of potential risk could be inferred by identifying the most common associations with the condition of interest and searching for stones that matched that criteria but were not already experiencing the condition.

Predictions could only be made for conditions that were manifestations of non-anthropogenic changes on the surface of the stone. Some recorded conditions, such as mineral inclusions, were also more related to inherent stone characteristics than stone decay. Of the recorded conditions, predictive maps were made for the following:

- Contour Scaling
- Deformation
- Differential Erosion
- Dimensional Loss
- Efflorescence
- Encrustation
- Friability/Flaking
- Intrinsic Metallic Staining
- Insipient Spalling
- Microflora
- Non-Intrinsic Metallic Staining
• Network Cracking

Three types of factors were considered when making predictions: inherent stone characteristics, situational context of the stone, and relationships with other conditions. Inherent stone characteristics included variables such as stone color, stone bedding orientation, and the presence of mineral inclusion. Situational context included the stone's location on the building, both elevationwise and in which architectural detail the stone was included (column, pediment, stairs, etc), and whether the exposed stone faces were oriented vertically, horizontally, or suspended from a ceiling or cornice. It was important to note that stones without specified color or bedding orientation were not included in the analysis because they could not be reliably classified. This made some predictions less reliable and has been noted where appropriate. The weight of any one variable could be influenced by the visual examination of the current patterns of stone decay seen in chapter 5. Severity of risk was designated as one of four categories:

• Minimal risk: Stones that did not share any characteristics strongly associated with the condition in question. Some risk was still implied because absolute certainty was not possible.

• Condition possible (moderate risk): The stone shared a characteristic, relationship, or situational context that had at least a 20% correlation with the condition in question.

• Condition probable (high risk): The stone shared at least two characteristics, relationships, or situational contexts that were associated with the condition
in question. At least one of these variables had a 40% or higher correlation with the condition in question.

- Currently affected stones: Stones that already displayed the condition in question.

6.2 Results

Contour Scaling

Contour scaling appeared on stones on all sections of the building. It had particularly strong relationships with friability/flaking (25%), a combination that was concentrated on the east and west elevations, and the columns. Contour scaling was also associated with stones that were edge diagonal bedded. Stones that shared these two characteristics showed a potential to develop contour scaling, while stones that had one or the other were considered possible candidates for the development of the condition (fig. F1).

Deformation

Deformation had a strong relationship with gray stones. It was three times more likely to occur on gray stones than given random chance, while it appeared on white stone 7/10ths as often as random chance. Gray stones accounted for 40% of deformation’s area. Stones with horizontal bedding also showed a 22% correlation with deformation. Areas where these overlapped were ranked as highest risk, and areas with horizontal bedding only were considered possible risks (fig. F2). Gray stones alone were not considered at risk because while they made up 40% of the
area of deformation, they were also much more widespread and occurred in many areas where deformation was witnessed.

*Differential Erosion*

Differential erosion had a very strong correlation with face bedded stones, which made up 61% of its area. 25% of the area of differential erosion overlapped with gray stones. There was a strong correlation of area with the south elevation (57%), but a distribution map showed that the condition was spread across the entire building; therefore the south elevation was not used as an indicator for predictions. Probable occurrences were predicted on areas with gray stones and face bedding, while possible occurrences were predicted only on stones with face bedding. The distribution of possible occurrences was particularly strong on the south elevation, suggesting that a factor particular to that elevation had prevented those stones from experiencing prior loss (fig. F3).

*Dimensional Loss*

Dimensional loss showed an association with contour scaling, which covered 21% of dimensional loss's surface area. The strongest association was with a lack of tooling marks, which appeared on 99% of the area. Dimensional loss also appeared 3.34 times more often than by random chance on stones that were set with vertical edge bedding orientation, and 1.48 times more often on stones that were face bedded. Vertical edge bedding accounts for 15% of dimensional loss area and face bedding accounts for 63% of the area. This discrepancy could be accounted for by
the fact that vertical edge bedding only accounted for 4% of total stone area on the building while face bedding accounted for 42% of surface area. The areas of highest risk for dimensional loss were stones that are face bedded, were lacking tooling marks, and displayed contour scaling (fig. F4).

**Efflorescence**

Efflorescence was strongly related to white stones (92%) and stones that were face bedded (80%). It also occurred almost entirely on the south elevation, which comprised 99% of the total area of the condition. Due to these strong correlations, probable risk was assigned to the stones that shared all three factors. Stones that shared the color and bedding were assigned as possible risks (fig. F5).

**Encrustation**

Encrustation was seen in relation to face bedded stones, primarily on the south elevation. Stones tended to be either gray or white and sometimes displayed differential erosion. Face bedding accounted for 77% of encrustation. 82% of the total area fell on the south elevation and 24% on gray and 34% on white stones. Differential erosion only had a 26% correlation with encrustation. Stones that displayed all of these characteristics, with the exception of either of the colors, were rated as probably risks. Stones displaying only gray or white coloration and face bedding were considered moderate risks (fig. F6).
**Friability/Flaking**

Friability/flaking showed associations with a lack of tooling marks, covering 89% of the area. There were also moderate correlations with the east and west elevations, 39% and 34% respectively. Because the condition appeared on other elevations besides east and west, these variables were excluded from the predictions and only a possible risk was assigned to stones with less that 50% of original tooling marks remaining (fig. F7).

**Intrinsic Metallic Staining**

Intrinsic metallic staining had an association with white stones (58%), and was therefore also associated with the north and south elevations (95% combined). Additionally, 34% of intrinsic metallic staining occurred on areas of stones laid with edge diagonal bedding. Stones that displayed all of the characteristics were assigned probable risk; edge vertical bedding was excluded for assignment of possible risk. While the condition did appear on the east and west elevations, it was in such low amounts that these were not considered areas of probable risk (fig. F8).

**Insipient Spalling**

Insipient spalling showed it’s strongest relationship with a lack of tooling marks, which comprised 98% of its area. It also had looser relationships with the north elevation, intrinsic metallic staining and edge vertical bedding, 58%, 18% and 15% respectively. Stones that combined these factors were ranked as high risk for development of insipient spalling. Edge vertical bedding was excluded from
moderate risk appraisals because it covered only 15% of the total area. The north elevation was also excluded from moderate risk because the condition was distributed across all elevations, though not to the same extent that it was seen on the north. Therefore all elevations should be considered at risk (fig. F9).

*Microflora*

Microflora showed strong correlations with multiple factors. The most important thing to note was that its presence was almost entirely explained by the north, east, and west elevations, with almost no presence on the south. Therefore predictions were only made on those three elevations. 55% of the area of microflora was also experiencing friability/flaking. There was also a 39% correlation with white stones and 34% with stones that were laid edge diagonally. Where all of these characteristics coincided, a high level of risk was assigned. Stones that were only experiencing friability/flaking on the north, east, and west elevations were considered moderate risks (fig. F10). Most risk appeared on the north pediment, which did correspond to the location of some current occurrences, but there was very little potential risk displayed on the east or west elevations. The patterning on these elevations showed grouping near the bottom of the walls rather than a random distribution, suggesting that there was a spatial characteristic influencing occurrence rather than just stone characteristics.
Non-Intrinsic Metallic Staining

Non-intrinsic metallic staining occurred almost entirely on the east and south elevations and was strongly associated with stones that were face bedded (85%). It also had a 32% correlation with white stones. Stones that were both face bedded and white in color were assigned high risk; stones that were only face bedded were assigned moderate risk. As with the recorded distribution of the conditions, these were primarily seen on the east and south elevations, with only a handful on the north and west elevations (fig. F11).

Network Cracking

Network cracking was associated with a number of conditions to varying degrees. The entire area of the condition was lacking tooling marks and nearly 100% was seen on the columns. 89% of the area displayed mineral inclusions, 34% occurred alongside friability/flaking, 30% with intrinsic metallic staining, and 45% on stones laid edge vertically. It was also of note that 69% of the area occurred on the south elevation. This was disregarded for the predictions based on the clear occurrence of network cracking on the north elevation as well. Because of the strong correlations seen with mineral inclusion, the columns, and loss of tooling marks and their relationship to the map of current occurrences, these were the factors considered for probable risk. No other stones met these criteria when further refined to include friability/flaking, intrinsic metallic staining, or edge vertical bedding after probable risk was assigned therefore only high risk was assigned (fig. F12).
6.3 Interpretation

Predictions were made based on a contextual examination of influential factors observed in relation to the condition in question. These factors had to include visual observations of distribution patterns, relevant correlations with other conditions that could be supplemented by an understanding of the mechanisms of stone decay, and relevant correlations with stone characteristics and situational variables. If the variables were applied too loosely every stone would be considered at risk, creating false positives. If the variables were applied too stringently, none would show danger creating false negatives. When applied using critical thinking these factors combined to create predictive models of the condition in question. These predictions can be further verified by comparing the predicted outcome to that already observed and with future conditions surveys of the building.
7. Conclusions

7.1 Conclusions

The adaptation of predictive modeling strategies to the Second Bank proved difficult due to two factors: the discontinuity of the buildings surfaces given the potential for stones to act independently of their neighbors due to differing characteristic and an inability to quantifiably assign values to stone characteristics that would be meaningful for calculations of potential risk.

An understanding of different mechanisms of stone decay is coupled with observed patterns in order to determine potential for future risk. Not all conditions recorded during the surveys were viable for predictions because of factors such as anthropogenic sources or extremely small surface area. Without a proper understanding of stone decay mechanisms and their relationships with each other, stone properties, and environmental factors informed conclusions could not be drawn from statistical data alone. Patterns may appear in statistical analysis that are meaningless in the context of architectural stone decay. Conversely, a lack of apparent pattern where one would be expected is also of note. A trained conservator is necessary to glean the most from datasets of this type.

The predictions made in this thesis can be tested by observing the development of future stone decay on the Second Bank. Because it is difficult to determine rate of decay it is also difficult to predict how long it will take for new conditions to present themselves.
7.2 Recommendation for Further Research

This thesis only examined condition and stone characteristics that could be assigned discrete areas. It did not include factors displayed as continuous datasets relative to proximity or density such as distance from a crack or visible surface wetting. Future investigations can incorporate these datasets to create a more complete picture of the building and all it's conditions. The analysis also included the entire building surface. It has been demonstrated that the columns show different patterns of conditions than the rest of the building. Future investigations should question how the statistical relationships are affected when excluding the columns and should also examine patterns on the columns alone.

Follow-up conditions surveys would allow for monitoring of the development of the conditions on the Second Bank while simultaneously validating or invalidating the predictions made in this thesis. Follow-up surveys could also be used to fill in gaps from the 1999 and 2003 surveys, such as stone color and foliation directions. With these recorded for the entire building it would be possible to revise the predictions made here to more accurately reflect the building. In order to be useful for comparison with previous conditions surveys, the visual conditions glossary developed for the Pennsylvania Blue Project should be used for future studies. Follow-up data can be used to monitor the rate of changes of conditions and further refine predictive modeling.
Bibliography


Appendix A – Architectural and Site Photos
Figure A1: The north elevation of the Second Bank of the United States as viewed from across Chestnut St looking south. (Bernberg 2011)

Figure A2: The north elevation of the Second Bank looking west down Chestnut St. (Bernberg 2011)
Figure A3: The south elevation of the Second Bank. (Bernberg 2011)

Figure A4: The south elevation of the Second Bank looking north from Walnut St. (Bernberg 2011)
Figure A5: The west elevation of the Second Bank viewed from the southwest corner. (Bernberg 2011)

Figure A6: The west elevation of the Second Bank looking east from across 5th St. (Bernberg 2011)
Figure A7: The east elevation of the Second Bank viewed from the southeast corner. (Bernberg 2011)

Figure A8: The east elevation of the Second Bank looking west from across 4th St. (Bernberg 2011)
Figure A9: A detail showing damaged gutters and first floor level ledge. (Bernberg 2011)
Appendix B - Conditions Glossary and Surveys

**Chemical Bird Repellent Treatments:**

Residue of chemical gels and coatings used on horizontal surfaces to deter birds from landing and nesting on the building.

**Composite Repairs:**

A mortar based system, used as a surface repair for losses greater than ¾ inch in width but not for cracks.

**Contour Scaling/Exfoliation:**

Distinctive localized or overall patterns of stepped irregular surface loss associated with cracks and foliation planes, and the loss is greater than ⅛ inch in depth.

**Deformation/Displacement:**

Movement and cracking or separation of the stone or stones resulting in the shifting of stone surfaces more than ½ inch out of plane.

**Differential Erosion:**

Surface weathering defined by large areas of coarse texture, localized loss greater than ¼ inch in depth (e.g. along foliation planes), or reduction of surface details (e.g. weathered arrises or edges).

**Dimensional Loss:**

Localized stone loss greater than 2 square inches in area and at least ½ inch in depth as measured in plane with the surrounding stone surface.

**Efflorescence:**

White crystalline, water-soluble deposits on the surface or within the pores of the stones indicating the presence of damaging salts.
**Encrustation:**

Formation of gray to black particulate deposits in protected areas that are noticeably more concentrated than the prevailing soiling patterns.

**Friability/Flaking:**

Surfaces with active disaggregation of individual grains and/or shallow flakes that dislodge under finger pressure.

**Insipient Spalling:**

Surface planar discontinuities that have become partially separated from the parent stone. The detached areas can be detected visually and audibly by sounding. The angle of separation will be approximately 0-60° from the surface plane of the surrounding stone and usually in association with foliation.

**Metallic Staining:**

Localized discoloration resulting from the weathering of either intrinsic (mineralogical) or extrinsic (copper or iron accessories) sources, usually black/brown (iron) or blue/green (copper) in color.

**Microflora:**

Zones of biological grown including algae, fungi, and lichens visible as a black, greenish, or brown discoloration. Many of these areas are on the lower sections of the building, under windowsills, and along the cornice area at the tree line.

**Mineral Inclusions:**

Stones may display large mineral inclusions as veins of phenocrysts. These inclusions are at least ½ inch in diameter and noticeably larger than prevailing foliation patterns. They are typically raised in relief or weathered out and distinctive in color and texture from the surrounding stone matrix.

**Network Cracking:**

A patterned network of fine intersecting cracks occurring on the surface of the stone, often in association with mineral inclusion-rich areas.
Orientation of Foliation Planes:

Stones display a pattern of orientation based on their foliation planes. For edge-oriented stones, the position of these planes can be horizontal, vertical, or diagonal to the ground. For face-oriented stones, foliation planes are parallel to the face of the stone.

Previous Coatings:

The presence of a coating on the stone surface, generally off-white or pale yellow in color.

Sealant Repair:

Presence of elastomeric sealants used as a masonry repair or pointing material.

Stone Redressing:

Tooling marks that indicate the selective redressing of stone to address advanced surface deterioration.

Stone Replacement:

Physical and/or archival evidence that complete stones or section of the building, terraces, or perimeter walls have been replaced.

Tooling Marks:

Stones that are relatively protected still display their original surface tooling marks. The tooling marks are a relative indication of the degree of surface weathering of the stone. The condition was recorded only where the tooling is evident on at least 50% of the stone’s surface.
Appendix C – Analytical Tables
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### Appendix D – Mineralogical Analysis

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Table D.1: List of detected minerals and their chemical compositions.
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<td>White</td>
<td>Long, thin section of stone from spall. Exterior is weathered, with a tan color, as opposed to interior which is white. Exterior shows erosion and deposition. Mineral inclusions are common on interior and exterior, focusing on metallic flakes varying in size from ~1 mm-1 cm. Spall appears to have occurred along a thin plane of mineral inclusions.</td>
<td>Colman</td>
<td>ACL</td>
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<td>2</td>
<td>9.1</td>
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<td>852.20</td>
<td>Grey</td>
<td>Uniform color and grain size, highly friable. Surface has small areas covered in surface coating (possibly mortar) some of which appears to have deposition staining.</td>
<td>Unsure</td>
<td>Charles Tonetti</td>
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<td>White</td>
<td>Whitish grey tapered section. Black deposition on remaining dressed surface. Irregular erosion across sample. Varied grain size. Friability on exposed areas that show early deposition decolorization. Block originally had decorative carving. Backside shows planes of mineral inclusions in foliation. Appears to have been face bedded.</td>
<td>West, comice level</td>
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<td>Similar to Sample 2. Tapered across the width axis with wide end showing curvature and narrow end showing heavy deposition. Few mineral inclusions and some discoloration on exterior. Highly friable and brittle. Some inclusion planes visible on side. Appears to have been originally face bedded.</td>
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<td>Detachment occurred along thick plane of mineral inclusions. Heavy amount of small metallic mineral inclusion apparent throughout stone. Two perpendicular surfaces show deposition. Other surfaces are clean and appear to have been fractured, possibly caused by detachment. Little foliation visible. Friable.</td>
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<td>Highly visible metallic mineral inclusions on face of stone with lower occurrence on edges. Small area of black surface deposition. Detachment occurred along distinct mineral inclusion plane.</td>
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<td>Thin plane containing only mineral inclusion, composed of two distinct deposition planes. Darker grey than other samples. Small section of distinct mineral inclusion plane.</td>
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<tr>
<td>10</td>
<td>4.8</td>
<td>2.9</td>
<td>1.1</td>
<td>15.12</td>
<td>White</td>
<td>Small portion broken from weathered exterior. Sample contains significant mineral inclusion layer.</td>
<td>West, comice level</td>
<td>INHP</td>
<td>1996</td>
<td>INDE 15703</td>
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<tr>
<td>11</td>
<td>11.8</td>
<td>6.0</td>
<td>0.4</td>
<td>402.4</td>
<td>White</td>
<td>Single Layer of mineral inclusions. Friable.</td>
<td>West, comice level</td>
<td>INHP</td>
<td>1996</td>
<td>INDE 15703</td>
</tr>
</tbody>
</table>
Figure D1: Sample SEB-01, white stone spalled from unknown column. (Bernberg 2011)

Figure D2: Sample SEB-02, gray stone from an unknown location on building. (Bernberg 2011)
Figure D3: Sample SEB-03, white stone from the west cornice (accession # INDE 15703). (Bernberg 2011)

Figure D4: Sample SEB-04, white stone from the west cornice (accession # INDE 15703). (Bernberg 2011)
Figure D5: Sample SEB-05, white stone from the west cornice, exterior view (accession # INDE 15703). (Bernberg 2011)

Figure D6: Sample SEB-05, white stone from the west cornice, interior view showing mineral inclusion layer (accession # INDE 15703). (Bernberg 2011)
Figure D7: Sample SEB-06, white stone from the west cornice (accession # INDE 15703). (Bernberg 2011)

Figure D8: Sample SEB-07, white stone from the west cornice (accession # INDE 15703). (Bernberg 2011)
Figure D9: Sample SEB-08, mineral inclusion layer from an unknown white stone (accession # INDE 15703). (Bernberg 2011)

Figure D10: Sample SEB-09, mineral inclusion layer from an unknown white stone (accession # INDE 15703). (Bernberg 2011)
Figure D11: Sample SEB-10, encrusted fragment from an unknown white stone (accession # INDE 15703). (Bernberg 2011)

Figure D12: Sample SEB-11, mineral inclusion layer from an unknown white stone (accession # INDE 15703). (Bernberg 2011)
Figure D13: The X-Ray Diffraction (XRD) results for sample SEB-01.i.

Figure D14: The XRD results for sample SEB-01.ii.
Figure D15: The XRD results for sample SEB-01.iii.

Figure D16: The XRD results for sample SEB-01.iv.
Figure D17: The XRD results for sample SEB-02.i.

Figure D18: The XRD results for sample SEB-03.i.
Figure D19: The XRD results for sample SEB-03.ii.

Figure D20: The XRD results for sample SEB-10.i.
Figure D21: The XRD results for sample SEB-11.i.
Figure D22: Calcite grains from a white stone under plain polarized light (PPL) at 5x magnification. (Sample SEB-01) (Bernberg 2011)

Figure D23: Calcite grains from a white stone under cross polarized light (XPL) at 5x magnification. (Sample SEB-01) (Bernberg 2011)
Figure D24: A metallic mineral inclusion under PPL at 5x magnification. (Sample SEB-01) (Bernberg 2011)

Figure D25: A metallic mineral inclusion under XPL at 5x magnification. (Sample SEB-01) (Bernberg 2011)
Figure D26: Mineral inclusions under PPL at 5x magnification. (Sample SEB-01) (Bernberg 2011)

Figure D27: Mineral inclusions under XPL at 5x magnification. (Sample SEB-01) (Bernberg 2011)
Figure D28: Calcite grains showing disaggregation under PPL at 5x magnification. (Sample SEB-02) (Bernberg 2011)

Figure D29: Calcite grains showing disaggregation under XPL at 5x magnification. (Sample SEB-02) (Bernberg 2011)
Figure D30: Gypsum crust and surface deterioration seen under PPL at 5x magnification. (Sample SEB-03) (Bernberg 2011)

Figure D31: Gypsum crust and surface deterioration seen under XPL at 5x magnification. (Sample SEB-03) (Bernberg 2011)
Figure D32: A small area of micaceous mineral inclusion within calcite matrix under PPL at 5x magnification. (Sample SEB-04) (Bernberg 2011)

Figure D33: A small area of micaceous mineral inclusion within calcite matrix under XPL at 5x magnification. (Sample SEB-04) (Bernberg 2011)
Figure D34: A single grain mineral inclusion under PPL at 5x magnification. (Sample SEB-05) (Bernberg 2011)

Figure D35: A single grain mineral inclusion under XPL at 5x magnification. (Sample SEB-05) (Bernberg 2011)
Figure D36: Large metallic mineral and other inclusions under PPL at 5x magnification. (Sample SEB-05) (Bernberg 2011)

Figure D37: Large metallic mineral and other inclusions under XPL at 5x magnification. (Sample SEB-05) (Bernberg 2011)
Figure D38: A micaceous mineral inclusion layer under PPL at 5x magnification. (Sample SEB-07) (Bernberg 2011)

Figure D39: A micaceous mineral inclusion layer under XPL at 5x magnification. (Sample SEB-07) (Bernberg 2011)
Appendix E – Bivariate Correlations
Chart E.i: Dimensional Loss and Contour Scaling as percentages of the entire building.
Chart E.ii: Contour Scaling and Friability/Flaking.
Chart E.iii: Encrustation and Differential Erosion.
Chart E.iv: Insipient Spalling and Contour Scaling.
Chart E.v: Chemical Bird Repellents and Differential Erosion.
Chart E.vi: Efflorescence and Stone Redressing.
Chart E.vii: Microflora and Friability/Flaking.
Chart E.viii: Intrinsic Metallic Staining and Mineral Inclusions.
Chart E.ix: Network Cracking and Intrinsic Metallic Staining.
Chart E.x: Network Cracking and Friability/Flaking.
Chart E.i: Intrinsic Metallic Staining and Sealant Repairs.
Chart E.xii: Intrinsic Metallic Staining and Replaced Stone.
Chart E.xiii: Dimensional Loss and Less than 50% of Tooling Mark Remaining.
Chart E.xiv: Friability/Flaking and Less than 50% of Tooling Mark Remaining.
Chart E.xv: Network Cracking and Less than 50% of Tooling Mark Remaining.
Bivariate Conditions Interactions

North Soffit

South Soffit

North Pediment & Entablature

South Pediment & Entablature

North Columns

South Columns

West

East

Distribution of stones displaying contour scaling & friability/balking (Bernberg 2011)
Bivariate Conditions Intersections

Distribution of stones displaying encrustation & differential erosion. (Bernberg 2011)
Distribution of stones displaying chemical bird repellents & differential erosion. (Bernberg 2011)
Bivariate Conditions Interactions

North Soffit

South Soffit

North Pediment & Entablature

South Pediment & Entablature

North Columns

South Columns

East

West
Bivariate Conditions Intersections

North Columns
North Pediment & Entablature
North Soffit

South Columns
South Pediment & Entablature
South Soffit

East
West

0 25 50 100 Feet
Network Cracking & Intrinsic Metallic Staining. (Bernberg 2011)
Bivariate Conditions Intersections

North Pediment & Entablature
North Columns
North Soffit

South Pediment & Entablature
South Columns
South Soffit

East

West

Intrinsic Metallic Staining & Sealant Repairs. (Bernberg 2011)
Bivariate Conditions Intersections

North

North Columns

North Pediment & Entablature

North Soffit

South

South Columns

South Pediment & Entablature

South Soffit

East

West

Intrinsic Metallic Staining & Stone Replacement. (Bernberg 2011)
Bivariate Conditions Interactions

North

North Columns

North Pediment & Entablature

North Soffit

South

South Columns

South Pediment & Entablature

South Soffit

East

West

Friability/Flaking & >50% distribution of stones displaying friability/flaking & less than 50% of original tooling marks remaining. (Bernberg 2011)
Appendix F – Predictive Maps
Condition Predictions

North Columns

North Pediment & Entablature

North Soffit

South Columns

South Pediment & Entablature

South Soffit

East

West

0 25 50 100 Feet

Current

Condition

Condition
Condition Predictions

North Column

North Pediment & Entablature

North Soffit

South Column

South Pediment & Entablature

South Soffit

East

West

0 25 50 100 Feet

Showing the predicted distribution of microflora. (Bernberg 2011)
Condition Predictions

North

North Pediment & Entablature

North Soffit

South

South Pediment & Entablature

South Soffit

East

Current

West

0 25 50 100 Feet

showing the predicted distribution of non-intrinsic metallic staining. (Bernberg 2011)
# Index

## A

ACL ........ iii, 1, 5, 6, 8, 9, 13, 14, 15, 34, 45, 46, 79, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107
ArcGIS........ 2, 17, 18, 20, 21, 35, 36, 37, 38, 40, 41, 42, 81
Architectural Conservation Laboratory 1, 6, 79
AutoCAD................................................. 18, 38

## B

Bivariate............................................. 37, 42, 109, 133
Boolean................................................. 35, 36, 37, 41

## C

CAD............................................................. 18, 19, 81
Calcite............................... 48, 50, 52, 53, 111, 124, 127
Condition.......................... 6, 12, 16, 69, 79, 80
Contour scaling......................... 54, 59, 64, 70

## D

Deformation......................... 64, 68, 70, 89
Differential erosion....................... 55, 64, 71, 72
Dimensional loss.............................. 64, 71
Documentation 1, 14, 15, 16, 17, 18, 19, 79, 80, 81, 82

## E

Efflorescence................................. 65, 68, 72, 89, 135
Encrustation............................... 55, 60, 68, 72, 90, 134

## F

Foliation............................................. 91
Friability/flaking............................. 56, 65, 73

## G

GIS........ 1, 2, 3, 7, 17, 18, 19, 20, 21, 23, 24, 26, 34, 35, 40, 79, 80, 81
Gypsum................................. 51, 53, 111, 128

## I

Independence National Historical Park .... 1, 46
INHP.................................................... 1, 5, 46
Insipient spalling.............................. 60, 66, 73
Intrinsic metallic staining............... 56, 57, 65, 73

## M

Marble.............................................. 1, 6, 26, 33, 79, 80, 81
Microclimate....................................... 7
Microflora...................... 56, 61, 66, 68, 74, 90, 135
Mineral inclusions............................. 66, 126
Muscovite............................................. 111
<table>
<thead>
<tr>
<th>$N$</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network cracking</td>
<td>6, 7, 68, 73, 81, 90, 134</td>
</tr>
<tr>
<td>Non-intrinsic metallic staining</td>
<td>29</td>
</tr>
<tr>
<td>$P$</td>
<td>Stone decay</td>
</tr>
<tr>
<td>Perception</td>
<td>Stone redressing</td>
</tr>
<tr>
<td>polarized light microscopy</td>
<td>57, 61</td>
</tr>
<tr>
<td>PPL49, 124, 125, 126, 127, 128, 129, 130, 131, 132</td>
<td>Strickland</td>
</tr>
<tr>
<td>$R$</td>
<td>Tooling marks</td>
</tr>
<tr>
<td>Raster</td>
<td>Treatment</td>
</tr>
<tr>
<td></td>
<td>2, 3, 34</td>
</tr>
</tbody>
</table>

167