2001

A Comparison of Fresh and Weathered Marble from the Tweed Courthouse

Robert Lamb Ware
University of Pennsylvania

A Comparison of Fresh and Weathered Marble from the Tweed Courthouse

Disciplines
Historic Preservation and Conservation

Comments

Suggested Citation:

A COMPARISON OF FRESH AND WEATHERED MARBLE
FROM THE TWEED COURTHOUSE

Robert Lamb Ware

A THESIS

in
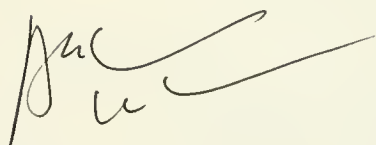
Historic Preservation

Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the
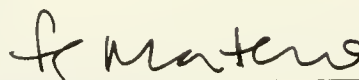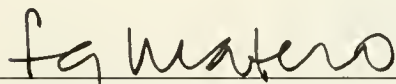Requirement for the Degree of

MASTER OF SCIENCE

2001

_____
Supervisor
A. Elena Charola
Lecturer in Historic Preservation

_____
Reader
Frank G. Matero
Associate Professor of Architecture
Chair, Graduate Group in Historic Preservation

_____
Graduate Group Chair
Frank G. Matero
Associate Professor of Architecture

CONTENTS

ILLUSTRATIONS

Frontispiece   Stereoscopic photograph taken circa 1872, Scrapbook
                     Collection, New York Public Library.

Chapter II

Figure

2.1   An October 7, 1871 illustration from *Harper's Weekly*
                     depicting the Tweed Ring's drain on the finances of New York
                     City. The photograph in Figure 1.4 shows how the courthouse
                     actually looked at this time.

2.2   A January 6, 1872 *Harper's Weekly* illustration depicting Tweed's
                     escape from the City Jail.

2.3   An 1863 daguerrotype of the construction site as seen from
                     Broadway. Numerous blocks of marble lie in the yard
                     directly behind the fence. A stonecarver's shanty appears to the
                     right behind a line of carved elements, and a hoist is seen to the
                     left of the image. Stonework has been completed on the first
                     floor/ rusticated basement. Courtesy of the Scrapbook
                     Collection, New York Public Library.

2.4   Image of the unfinished building taken from an 1873 stereoscopic
                     photograph. The columns on the North Portico are not
                     completed, and the pediment has yet to be installed. This view
                     became emblematic of the plagued construction process.
                     Courtesy of the Scrapbook Collection, New York Public
                     Library.

2.5   Circa 1900 photograph of the Tweed Courthouse as seen looking
                     southwest across Chambers St. Discoloration of the juxtaposed
                     Tuckahoe and Sheffield marble is evident even from this
                     distance. The granite staircase to Chambers St. was removed
                     in the 40's. Photograph provided courtesy of John G. Waite
                     and Associates.

Chapter IV

ACKNOWLEDGEMENTS

PREFACE

The current restoration of the Tweed Courthouse, initiated by the Economic Development Commission of the City of New York, provides a unique opportunity to analyze the comparative weathering of two types of marble. This analysis is especially worthwhile because of the nature of the exterior masonry repairs. The city governmenthas been careful to restore and maintain the distinctive architectural features of the courthouse as much as its current state will allow. It would not have been possible to gather the large number of samples used in this research if the building were not undergoing a major restoration. The author hopes that his research will inform an appropriate plan for maintenance of the building in the future.

In the past thirty years, the Tweed Courthouse has begun to receive recognition as an outstanding example of 19th century architecture. Long neglected because of its controversial origins, the courthouse was listed on the National Register of Historic Places only seventeen years ago. It stood for decades without any significant exterior maintenance and in the 1970's was considered for demolition. Steps to bring the building to a level of sustainability were initiated in the late 1980's; the full restoration of the building will be completed by the year 2002. The Museum of the City of New York, now located on Fifth Avenue and 96th St., is scheduled to occupy the courthouse at that time.

CHAPTER I
Introduction

Reasons for Analysis

Much has been written on the subject of marble decay, especially as it concerns the European varieties of marble. As far as the decay of North American marbles, and in particular those quarried in New York and Massachusetts, considerably less has been written. Westchester County, New York marble, commonly known as Tuckahoe marble, was used extensively as a building material from the early nineteenth to the early twentieth centuries throughout the northeastern United States. Marble from Sheffield, Massachusetts, on the other hand, was used only on a limited basis. A lesser-known cousin of Lee, Massachusetts marble, Sheffield marble was deemed by the builders of Tweed Courthouse to be a comparable material. Whether through aesthetic intent or due to external political forces, these two types of stones were used side by side on the same building. The result has been an interesting case study in comparative weathering.

Although Tuckahoe and Sheffield marbles are geologically related, the differential weathering observed on the Tweed Courthouse points out the problems of using superficial physical and geological characteristics to match stone for exterior uses. Mineralogical and microstructural differences in stone samples gathered from distant locations within a single geological formation can produce a bewildering diversity in observable physical properties. This diversity extends to the level of individual quarries

1

and to the level of individual rock strata within those quarries. A marble quarrying region such as Westchester County, New York will produce generally similar stone. Even so, one quarry may have a reputation for producing durable, architecturally well-suited stone while a neighboring quarry may have a reputation for producing stone that is fit only for the manufacture of lime. Because they were considered to be similar, Tuckahoe and Sheffield marble were used interchangeably during the construction of the courthouse.

Adding complication to any possible analysis, the building was cleaned to a general uniformity of color in 1981 and again in 1999 prior to commencement of the current restoration. It is therefore difficult to determine the identity of the stone based solely on visual observation of the building in its current state. The wide array of compositional and behavioral differences in the stone used on the exterior, partially masked by these recent efforts to make the building more presentable, leads one to question the feasibility of analysis of any kind. Repairs to the exterior of the building are being executed with a combination of stone from three sources: salvage stone from the building itself; quarried blocks left on the site of the now-defunct Sheffield quarry; and entirely new replacement stone from Georgia, known as Georgia Cherokee. It is hoped that characterization of the individual rock fabrics of Tuckahoe, Sheffield and Georgia marble through thin section analysis will provide a stronger basis for understanding their characteristic patterns of weathering.

This paper is not meant to perform the documentary work of a historic structure report. The history of the Tweed Courthouse has been researched and commented on thoroughly in a number of ways by professional historians, although much of this

research remains unavailable to a wide audience. Instead, this paper will focus on the microscopic texture of the three types of stone used in the current restoration while providing historical information that is contextually relevant to an assessment of the observations made.

For the purposes of this paper, marble from the Eastchester Marble Quarry Company used in the construction of the Tweed Courthouse will be referred to as Tuckahoe marble. Marble from the Briggs quarry in Sheffield, Massachusetts will be referred to as Sheffield marble. The white to gray replacement marble from Georgia will be referred to alternately as Georgia Cherokee marble and Cherokee marble.

Methodology

This investigation involves two major components: background research and the implementation of suitable analysis. The overall goal of the program is to contribute to the existing body of knowledge about the texture and fabric of Tuckahoe, Sheffield, and Georgia Cherokee marbles and to draw some conclusions about their weathering behavior.

Various archival resources were consulted for the research phase. Primary areas of focus were the history of the building and its materials, the history of analysis and cleaning related to the building, and the literature pertaining to the study of marble in general. The most important source of background information turned out to be the project file of the architecture firm overseeing the restoration, John G. Waite & Associates of Albany, New York. John G. Waite & Associates has been involved with testing, cleaning, and restoration of the Tweed Courthouse for more than ten years.

Another important source of information was the project management staff of Bovis Lend-Lease, LMB Inc., who have gained an intimate knowledge of the building and the unique characteristics of its marble as a result of their involvement with the current restoration work. The archive of the Department of General Services of the City of New York also provided a great deal of useful information. Other resources include the libraries of the University of Pennsylvania, the New York Public Library, Avery Library at Columbia University, the National Institute for Standards and Technology, and the Federal Highway Administration. Notes, photographs, and interviews made on repeated visits to the courthouse also contributed to the research phase.

The format for the testing and analysis portion of the paper was suggested by the existing previous research.   Based on this research, it was decided to focus on thin section analysis of decayed and fresh samples of the stone. Microscopic thin section analysis is one method of petrographic examination that has not been used extensively for the study of Tuckahoe or Sheffield marble. By relating texture to weathering characteristics, it is hoped that a better understanding of these materials will be gained.

The first aspect of thin section analysis is visual characterization of microstructure, including dominant minerals and inclusions, grain size, grain boundary, and microcrack structure.   As a complement to thin section analysis, SEM, XRD, and EDS were performed on representative samples of marble.

Most samples for testing and thin section were gathered on site at the Tweed Courthouse from discarded original, salvage, and replacement stone. Additional samples come from the Briggs quarry in Sheffield, Massachusetts. Resources for analysis and testing at the University of Pennsylvania include the Geology Department, the

Architectural Conservation Laboratory, and the Laboratory for Research into the

Structure of Matter.

CHAPTER II

Historical Background

"The house that Tweed built was the Boss's legacy to New York, an Acropolis of graft, a shrine to boodle."

Alexander B. Callow, Jr.

Long before it was finished in 1881, the New York County Courthouse held a place in the imagination of the American public. The building that took twenty years and millions of dollars to complete was inextricably linked to the career of William Marcy "Boss" Tweed and the political machine that controlled New York City for over a decade. Astronomical cost overruns, pocket-lining, and brazen corruption marred the reputation of the courthouse long before a single case had been heard in its chambers. Helping to spread the building's notoriety was a burgeoning national press led by *Harper's Weekly*. Locally, the *New York Times* stood alone in chronicling the criminal activity of the Tweed Ring. In a series of articles published between 1868 and 1871, the *Times* single-handedly exposed the city government's illicit dealings. As the focal point of the Tweed Ring's biggest scandal, the courthouse became a national symbol of corruption and moral decay. This sense of decay was mirrored in the behavior of the exterior masonry, which began to blacken and weather at an alarming pace even before completion.

Beginnings (1858-1862)

Commercial expansion and population growth fed by European immigration during the middle of the 19th century propelled New York City to a level of national prominence that it continues to hold today. The growing pains felt by the port city that had previously played second fiddle to Boston and Philadelphia manifested themselves in a need for better municipal facilities that could accommodate a broader governing responsibilities. At the same time, these buildings needed to embody physically the city's newfound prominence. As the traditional seat of city government, the area of downtown now known as City Hall Park was the site of successive waves of demolition and new municipal construction. It was a natural choice for the New York County Courthouse, a facility that would symbolize the city's maturity as an economic and cultural center. Situated directly behind City Hall, the new courthouse's centrality to municipal and county control would be obvious. The triangle of land between Broadway and Center and Chambers Streets was the nexus not just of city rule but of a growing sphere of governmental influence.

On April 17, 1858, the Supervisors of the County of New York passed "An Act in Relation to the City Hall in the City of New York." [1] The act authorized a group of commissioners to supervise the erection of a building behind City Hall that would house chambers for a number of courts including the Supreme, Superior, Common Pleas, and Marine Courts. It would also house the office of the District Attorney and the County Sheriff. In 1859, $250,000 out of a projected budget of $1,000,000 was raised towards

---

[1] *Tweed Courthouse Historic Structure Report* (City of New York), 19.

the building's expenses.[2] As is still the practice, construction was financed by the issuance of public stock by the city government. Two years later, the Board of Supervisors passed the major piece of legislation leading to the creation of the new courthouse, an act enabling them to acquire land for the building. In the fall of that year, the land was appraised for $450,000.[3] The site encompassed a parcel of land where the Second Almshouse (later the New York Institution) once stood and where numerous colonial-era paupers' burials took place.

Construction for the New York County Courthouse began on September 16, 1861. During the twenty-year period of the courthouse's construction, the city was required to issue stock on numerous occasions to cover ballooning costs. The first of those additional issuances took place on April 9, 1862. The city amended the previous act with "An Act to Authorize the Board of Supervisors of the County of New York to Raise Money by Loan and to Create a Public Fund or Stock to Be Called 'The New York County Courthouse Stock,' and to Authorize the Commissioners of the Sinking Fund to Receive and Purchase Said Stock."[4] The amended act authorized another $1 million in funding. It would be amended again in 1864, 1869, 1870, and 1871 for a total $4.55 million.[5] These additional issuances of stock still would not take the project to completion.

---

[2] Ibid.

[3] Ibid., p. 21.

[4] Ibid.

[5] *Laws of the State of New York Passed at the 85th Session of the Legislature* (Albany: Munsell & Rowland, 1862), pp. 335-337.

Figure 2.1: An October 7, 1871 illustration from *Harper's Weekly* depicting the Tweed Ring's drain on the finances of New York City. The photograph in Figure 2.4 shows how the courthouse actually looked at this time.

William Marcy Tweed (1862-1872)

The years of William Marcy Tweed's involvement in the construction of the New York County Courthouse formed the definitive period in the building's history. If the decision to build the new courthouse was motivated by the desire to put a face on municipal progress and by the need to deal with growing demands on government, then Tweed's skillful manipulation of the mechanics of city finances and implementation of a pervasive network of patronage and graft demonstrated just how ill-equipped the city was to administer the law. As an architectural manifestation of the city, the courthouse showed both how far New York had come and how far it still had to go.

Tweed was an established figure in national, state, and local politics well before he took control of the city's courthouse project. He had already served as Assistant Alderman, Congressman, President of the County Board of Supervisors, and Chairman of the Democratic Central Committee of New York County.[6] By 1867, six years into the project, he was serving as State Senator, New York County Democratic Chairman, School Commissioner, Deputy Street Commissioner, and President of the Board of Supervisors.[7] In the words of *The Tweed Courthouse Historic Structure Report*, there was no man more powerful in New York State politics than "Boss" Tweed.

In 1861, Tweed was appointed a member of the New York County Board of Supervisors' Special Committee on the New Court House.[8] This position enabled him to delve directly into the activities of the new courthouse. On September 23, 1861, three days after the Board took possession of the land for the new courthouse, Tweed, acting

---

[6] Alexander B. Callow, Jr. *The House That Tweed Built* (New York, 1871), pp. 17-32.
[7] Historic Structure Report, p. 8.
[8] Ibid., p. 7.

on behalf of the Board of Supervisors, paid John R. Briggs $1,250 for Briggs' Marble

Quarry, a surface quarrying operation in Sheffield, Massachusetts.[9] Briggs was a New

York associate of Tweed and an original member of the Tweed "Ring" which voted as a

block on the Board of Supervisors and bribed Board members to stay away from

important meetings.[10] Subsequently, the city awarded a contract to the quarry for the

provision of raw quarried marble for use in the construction of the new courthouse.[11]

This marble was used in addition to another marble from the Eastchester quarries to the

north of New York City owned and operated by John Masterdon.

Transactions for the Sheffield marble never appeared in Tweed's name, and he is

never identified as the owner of the quarry in any of the records, but there is little doubt

that he ultimately benefited from the city contract. Under an elaborate leasing

arrangement with Briggs, the existing quarry supervisor, and a man acting for Briggs by

the name of Henry MacMurray, the City Board would purchase marble from the quarry

until 1871, at which time ownership of the site and any remaining marble would revert to

the original purchaser.[12] In a December 25, 1866 article, however, the *New York Times*

reported on a questionable arrangement between the board and the quarry to provide

stone for the basement.[13] In response, the city appointed a commission to oversee

construction. The contract was re-advertised for bidding, and two entirely new

---

[9] *New York Times*, December 25, 1866, p. 4.

[10] *Restoration and Rehabilitation of 52 Chambers St (Tweed Courthouse) Prepreliminary Report Masonry Cleaning* (Albany: Mesick, Cohen, Waite Architects), p. 14.

[11] In what became his preferred modus operandi, Tweed would buy a controlling interest in a business and secure exclusive government contracts with it. A prominent example of this tactic was the New York Printing Company. Railroads, ferries, and insurance companies with city or county contracts were required to use the services of the Tweed-controlled New York Printing Company or risked losing their contracts altogether. See *The Dictionary of American Biography* (Charles Scribner's Sons), pp. 79-82.

[12] Mesick, Cohen, Waite, 12. The architects report refers to the Southern Berkshire Register of Deeds, v. 125, p. 536. to document the city's original purchase.

[13] Ibid. The article is referred to in a discussion of the Sheffield quarry in the report byMesick, Cohen, Waite.

subcontractors provided the lowest figures[14]. Nevertheless, before the actual work could take place, the county supervisors were back in control of the project and one of two contracts finally awarded was given to the Sheffield quarry.

The new contract with Briggs provided that the marble could be billed on a per foot basis rather than at a fixed price for the entire scope of work. In terms of cost, this was to the Board's advantage since Briggs could remove any percentage markup on the stone and presumably the shadow owners would still receive a profit.[15] Acting on behalf of Briggs, Henry MacMurray ran the quarry and signed all deeds and receipts.[16] Although it is unclear just how long the quarry provided marble to the city, records show that MacMurray sold the quarry in 1866.[17] Strangely, it was granted back to John Briggs in 1870. One can assume that Sheffield marble was no longer being shipped to New York City after about 1866, an important detail to note in the construction history of the building.

From 1862 to 1870 Boss Tweed consolidated his control over New York City government. In 1868, The Board of Supervisors passed the "Adjusted Claims" Act, which enabled the city comptroller to adjust any claims against the city and to obtain payment by means of the issuance of bonds.[18] The act allowed the city to continue selling bonds to cover expenses for the courthouse, effectively extending the source of funding indefinitely. Two years later, a new city charter was adopted that abolished the County Board of Supervisors and replaced it with the Board of Special Audit which

---

[14] Ibid., p. 13.
[15] Ibid. Mesick, Cohen, Waite refer to a *Report of the Special Committee of the Board of Alderman Appointed to Investigate the Tweed Frauds*, January 4, 1878, Document 8, (New York: Martin B. Brown), p. 47.
[16] Ibid.
[17] Mesick, Cohen, Waite, p. 13.
[18] Historic Structure Report, p. 10.

consisted solely of the Mayor, the Comptroller, the Commissioner of Public Works, and the President of the Parks Department.[19] Not surprisingly, all of these positions were held by Tweed associates. The new charter was dubbed the "Tweed Charter," because of the boss's unmistakable influence.

The area of greatest focus for the Tweed Ring during this period remained the new courthouse project. It became a required practice for contractors involved with the courthouse to bill an additional 20% on top of their expenses that would go directly to the city officials administering the project.[20] This was only a suggested amount, and the payments generated by the practice were frequently much higher. Andrew J. Garvey, the contractor hired to do the interior plasterwork, also happened to be Grand Marshal of Tammany Hall. His excessive bills earned him minor legend status in New York City and the nickname the "Prince of Plasterers."[21] James H. Ingersoll, another Tweed associate and a furniture maker by trade, received more than $5.6 million, about half the final estimated cost for the entire building, to fabricate chairs and tables for the courtrooms.[22] Nonexistent contractors received payment as well, and the proceeds went directly to the Board of Supervisors. By one estimate, $9 million in graft was expended on the construction of the New York County Courthouse.[23] Many years after the fact, the Board of Estimate and Apportionment reported that the entire project probably cost between $11 and $12 million.[24]

---

[19] Ibid.
[20] Historic Structure Report, 11.
[21] Callow, p. 212.
[22] Historic Structure Report, 11..
[23] Callow, p. 197.
[24] Historic Structure Report, 21. The HSR refers to the 1914 *Minutes of the Board of Estimate and Apportionment of the City of New York*, II, pp 893-97.

This activity did not go without notice. *The New York Times* and *Harper's Weekly* covered the story locally and nationally. *Harper's Weekly* utilized the artistic abilities of Thomas Nast in covering the story. Political cartoons by Nast and C.G. Parker proved to be a true irritant to Tweed, who remarked, "…my constituents don't know how to read, but they can't help seeing them damned pictures."[25] An October 7, 1871 cartoon by C.G. Parker, seen in Figure 1.1, captures the popular sentiment. Despite the Tweed Ring's effective efforts to bribe much of the city press, the *Times* continued to cover the story.[26] From early on the *Times* had criticized the cost overruns and lack of substantial progress at the courthouse. An 1867 article in the New York Times calculated that for what it cost to construct the New York County Courthouse, 14 structures identical to Brooklyn's Borough Hall could have been built, furnished and kept in repairs for 6 years.[27]

But in 1871, what previously had been speculation became impossible to dispute. In July of that year, Matthew O'Rourke, a replacement for Ring bookkeeper and ex-convict James Watson, went to the *Times* with a copy of the Comptroller's ledger that he had secretly transcribed.[28] Once the contents of the ledger were published in the *Times*, detailing phony payments and illicit transactions, the Ring began to disband. After two years of legal wrangling, Tweed was convicted of 204 counts of corruption in the Oyer & Terminer court of the still incomplete New York County Courthouse. Despite escaping briefly to Cuba and Spain, Tweed spent his final days in the Ludlow Street jail, his name and career ruined. Nevertheless, the Tweed name carried on in the New York County Courthouse, which was so closely associated with the man and his colorful career. New

---

[25] Ibid., p. 214.
[26] Callow, p. 214.
[27] *New York Times*, May 6, 1867, p. 8.
[28] Callow, pp. 259-260.

Yorkers could not separate Boss Tweed from the building that had been his domain for

ten full years, and the New York County Courthouse became known simply as the Tweed

Courthouse.

The fallout of the Tweed Ring's financial arrangements eventually extended to

the provider of the
Tuckahoe marble used in
the courthouse. John
Masterton, second
generation proprietor of the
Eastchester Marble Quarry
Company, was indicted on
four counts of first-degree
larceny in 1884.[29]
Masterton had entered a
banking business with the
Tweed Ring between 1870
and 1871. The business,

"STONE WALLS DO NOT A PRISON MAKE."—*Old Song.*
"No Prison is big enough to hold the Boss." In on one side, and out at the other.

Figure 2.1: A January 6, 1872 *Harper's Weekly* illustration depicting Tweed's escape from the City Jail.

although successful, inexplicably went bankrupt a decade after its chartering. Despite

this, Masterton continued to receive deposits from investors. As part of the judgment

against him, he was required to convey the quarry, its buildings and machinery to one of

his creditors.[30]

---

[29] Torres, p. 59.
[30] Ibid.

Architecture

Architecturally, the most interesting aspect of the Tweed Courthouse derives from the inordinate amount of time it took to complete the building. Spanning the period from 1858 to 1881, from the first drawings to total completion of the building, the courthouse itself can be said to span two distinct stylistic movements in American architecture. Originally conceived by the obscure New York architect Thomas Little in the late 1850's, the plan was implemented by John Kellum, a popular commercial architect. When Kellum passed away in 1873, renowned Victorian architect Leopold Eidlitz refurbished and completed the building in a manner more suited to his time. The building displays the attitudes of all three of these men. Often described as Anglo-Italianate, the courthouse blends a dominant picturesque revivalism with contemporary technological breakthroughs in cast-iron and a late 19th century preference for the "organic" architecture of the Victorian Romanesque.

The most significant influence on the design of the New York County Courthouse was the United States Capitol building in Washington, D.C. designed by William Thornton, Thomas Ustick Walter, and others. To attain the desired level of gravitas, government buildings of the mid-nineteenth century often mimicked the Capitol's monumentality. The similarities between the two are remarkable. Like the Capitol, the courthouse incorporated a central, pedimented portico supported by Corinthian columns. A grand staircase leads up to the front entrance of the building, and on either side were flanking pavilions. A rusticated basement, pedimented window surrounds, a modillioned cornice topped by a balustrade, and a large iron dome are other features of the building that it shares with the Capitol. The dome, as it was depicted in Joseph Shannon's 1868

Manual of the Corporation of the City of New York, was never executed. [31] Shannon's drawing is the first known published view of the courthouse, and it is fairly close to the completed building.

Reflecting a shift in taste away from the darker colors of New York's brownstone era, the building was designed with a brighter, more timeless material in mind: marble. A factor working in marble's favor at this time was the continuing appeal of classical revivalism. It is difficult to separate classical revivalism as an architectural movement from its use of "noble" building materials like marble. The dominant white aesthetic of the Greek Revival, which began to flourish in the 1830's, still had an influence on architectural tastes in the 1850's. In 1827, not long after marble deposits were uncovered in Westchester County and buildings began to incorporate the local stone, a New York weekly noted:

> It is not a little gratifying to an observer to witness the many recent evidences of improvement in the style shown in the erection both of public and private edifices. Since the discovery of the vast quantities of white marble in Westchester County...the effect is everywhere manifest...We anticipate the period when entire blocks—nay, whole streets—will show that the provident kindness and liberality of nature are moulded to the noblest and most useful purposes. [32]

In the opinion of critics in the 1850's, granite, the dominant building stone of the 30's and 40's, created a gloomy appearance. White marble's renewed popularity in the 50's soon caused it to eclipse granite in new construction. [33] One contemporary source remarked, "We rejoice to see these new materials employed in building; the aspect of the

---

[31] Joseph Shannon, *Manual of the Corporation of the City of New York*, (New York, 1868), p. 639.
[32] *New-York Mirror and Ladies' Literary Gazette* 5 (December 9, 1827), p. 174. Quoted in Louis Torres, *Tuckahoe Marble: The Rise and Fall of an Industry, 1822-1930* (Harbor Hill Books, 1976), p. 13.
[33] Torres, p. 44.

city is greatly enhanced by their judicious adoption..." [34] The Westchester marbles also had a reputation for durability that compared favorably with other building materials. [35]

It is generally agreed that the first person to design the building was Thomas Little, an architect whose other surviving buildings include the Italianate New England Congregational Church in Brooklyn (1852.) A member of the Board of Supervisors, Little came to the project through city politics at a time when the new Capitol was gathering praise for its design. He provided an Anglo-Italianate design based on the Capitol and on George Dance, Sr.'s Mansion House (1735.) The Italianate palazzo mode was widely imitated in London during the decades prior to Little's work on the courthouse. Several details confirm Little's presence on the project prior to John Kellum. One of these is an article in the *New York Times* referring to the "original architect" at a time when Kellum was in charge of design. In the same article, the large iron dome is mentioned as a "recent addition," suggesting that it was among Kellum's contributions to the courthouse. [36] In an 1866 inquiry into misappropriation of funds for construction, Thomas Little & Son are named directly by Supervisor Smith Ely, Jr. as the provider of the original plans. [37]

John Kellum assumed responsibility for the execution of Thomas Little's plans in 1861. It is possible that Kellum's association with multi-millionaire Alexander T. Stewart, whose dry goods department store (1846) still stands across Chambers Street from the courthouse, led to his involvement in the city project. Stewart's impressive

---

[34] *Putnam's Monthly Magazine of American Literature, Science, and Art* 1, No. 2, (February 1853), p. 128. Quoted in Torres, p. 44.

[35] Contemporary accounts of the durability of Westchester marble are discussed in more detail later in this chapter.

[36] *New York Times*, March 27, 1866, p. 8. The article also mentions a budget not to exceed $800,000, identical to the budget for the Brooklyn City Hall (Borough Hall).

[37] New York City Board of Supervisors, *Report of the Special Committee on the Investigation of the Contracts for Building the New Courthouse*, Doc. No. 9, June 26, 1866, p. 14. Quoted in *HSR*, p. 43.

store, which was built largely of Tuckahoe marble, became known as "The Marble Palace."[38] By 1859, Stewart's business had outgrown the Marble Palace, and he hired John Kellum to design a new store in cast-iron at Broadway and 10th Street. This commission enabled Kellum to break from Gamaliel King, his partner in King & Kellum, and start his own practice in 1860. With this and other large-scale commercial projects under his belt, Kellum must have seemed more suited for the New York County Courthouse project than Thomas Little.[39]

Although in charge of design by 1861, Kellum did not alter much about the building's exterior. Joseph Shannon's depiction in the *Manual of the Corporation of New York City* is largely as Thomas Little first drew the building. Little is said to have remarked that the only difference between his plan and the completed building was the addition of the basement.[40] Kellum's main contributions seem to have been the elevation of the building on a rusticated basement similar to the Capitol, the iron dome, which was never executed in his lifetime, and the extensive Italianate cast-iron interior. John Kellum's use of cast-iron provides an interesting technological juxtaposition to traditional Classical Revival design. Cast-iron, while structurally an ideal material for the time, was an innovation unknown to the earliest practitioners of the Classical Revival. Its extensive incorporation into the plans is one of the most striking aspects of the courthouse. The interior is one of the best examples of cast-iron work in the country and a major reason for the building's nomination as a National Historic Landmark in 1980.

---

[38] Torres, p. 34.

[39] Kellum helped design the Cary Building at 105-107 Chambers St., one of the oldest cast-iron buildings in the city. Interestingly, Gamaliel King was the architect of Brooklyn City Hall, now known as Borough Hall, one of the precedents for the New York County Courthouse. *HSR*, p. 27.

[40] *HSR*, p. 43.

Construction dragged on for ten years during Kellum's tenure as chief architect. His death in 1871, long before completion, coincided with the dissolution of the Tweed Ring. In the culture at large, Kellum's death also coincided with a changing tide in American architectural styles. The dominance of picturesque modes ebbed during the Victorian era. Less literal, more idiosyncratic quotations of the past started to dominate. This was evident in the continuing evolution of the New York County Courthouse.

Leopold Eidlitz was chosen to take over for John Kellum. Eidlitz, a native of Prague, Czechoslovakia, worked in the office of Gothic Revival architect Richard Upjohn before starting his own practice. Eidlitz's mature style was decidedly unique, mixing influences from the Gothic Revival and Romanesque Revival modes with a belief in the honest "organic" structural expression of these traditions. While his ideas are strikingly similar to those of his contemporaries John Ruskin and Viollet-le-Duc, Eidlitz developed them independently of their influence.[41] His aesthetic was "...the fullest statement of the functional-organic view of architecture, based on a medieval-inspired approach to structure and composition, produced by any nineteenth-century American."[42] Eidlitz applied this aesthetic in the New York State Capitol Building in Albany (1875) together with Henry Hobson Richardson and Frederick Law Olmstead. His main contribution to the Capitol was the Assembly Chamber, which is very similar to the wing he would design for the Tweed Courthouse.

It took several years after the Tweed trials for the New York City government to regain any enthusiasm for the unfinished county courthouse. By 1876, funding that had been appropriated in 1870 was finally allocated to a modified plan for completion. This

---

[41] HSR, p. 40.
[42] William Jordy and Ralph Coe, *American Architecture and Other Writings by Montgomery Schuyler* (New York: 1964), p. 17. Quoted in HSR, p. 40.

plan called for an office wing to be built on the south of the building rather than an open

portico like the one on the north elevation. It also called for completion of the dome. As

one of New York's most prominent architects, Eidlitz was a natural choice for the

project.

The "Eidlitz Wing," as it is now known, was strongly Victorian. Eidlitz's fantasy

Romanesque incorporated rounded window arches, ornate floral friezes, and retractable

awnings on the exterior in an addition that fit four new floors against the three floors of

the existing building. Eidlitz paid respect to the earlier structure by designing the new

wing in Tuckahoe marble. Inside, the offices and judges' chambers were sandstone

groin-vaulted spaces with polychrome brick on the lower floors, and more polychrome

brick with less sandstone on the higher floors. Encaustic tiled floors were installed

throughout. Eidlitz also reconceived the courthouse dome. While still made of cast-iron,

the dome was smaller, took an octagonal, prismatic shape, and rested on squat pillars.

Beneath the dome hung a pendant stained-glass window.

Eidlitz's influence was not limited to these areas of the building, however.

Beyond the work on the new wing, he retrofitted parts of the Kellum Wing to look more

appropriate to the era. Whole sections of the interior cast iron were torn out and replaced

with more Victorian materials. The second, third, and attic floors of the rotunda space

were rebuilt with massive polychrome sandstone pillars and polychrome brick arches.

The ground floor was redesigned in the same vein as well.

The criticism aroused by the completed product demonstrates how much

architectural styles had changed since the days of Thomas Little. The *New York Times*

scathingly compared the building to a Yorkville brewery.[43] *American Architect and Building News* wrote:

> Of course no attention was paid to the design of the existing building and within and without a rank Romanesque runs cheek by jowl with the old Italian, one bald, the other florid; cream-colored brick and buff sandstone come in juxtaposition to white marble.[44]

Unfavorable remarks like this combined with a lingering cloud of scandal to keep the Tweed Courthouse in disfavor with city politicians. In 1881, after twenty long years, the building was finally completed. By 1903, it was being targeted for demolition because the courts had outgrown the space. Despite its dubious heritage, or perhaps because of it, the Tweed Courthouse was able to avoid any major alterations, and it has survived with a high degree of integrity. The building's strange agglomeration of styles has aged well, and it creates a more harmonious appearance now than it must have 120 years ago. Elevations of the courthouse as it appears today are included in Appendix 1.

Structural Description

The Italianate historicism of the Tweed Courthouse belies the 19th century engineering that supports the design. Masonry and iron construction forms the backbone of the building. The high performance of the original structural elements accounts for the limited need for any retrofitting during the current restoration. This is partly due to the limitations of engineering in the 19th century. By modern standards, the courthouse is considerably "over-engineered." Calculations performed in 1981 by Ammann & Whitney Consulting Engineers indicate that stresses in the bearing walls are less than 100

---

[43] *New York Times*, April 29, 1877, p. 7. Quoted in *HSR*, p. 67.
[44] *American Architect and Building News*, III (March 16, 1878), p. 94. Quoted in *HSR*, p. 67.

pounds per square inch. Even with a mixture of cement and lime mortars in various states of repair in the wall interiors, the walls have considerable reserve capacity.[45] The massiveness of the primary structure should continue to serve the building well into the future.

The Basement: Beneath the first floor is a basement level which accommodates the mechanical plant for the building. The original recirculating hot-air system is located here. In the areas of the basement where the ventilation system was installed the floor was left uncovered. The large fans for the hot-air system sit on the bare earth of the basement, a fact that may have been responsible for early employee complaints about air quality in the building.[46] The basic interior structure of the building is visible at this level. A system of massive stone walls, brick walls and arches supports the load of iron and masonry on the upper floors.

The Foundation and First Floor: Exterior access to the building from Chambers Street was via the staircase at the North Portico to the second floor, which means that in practical usage the first floor was much like a basement. This level is also offset architecturally on the exterior by the rustication of the ashlar marble and is aesthetically distinct from the higher levels of the building. According to an 1861 *New York Times* article, the exterior foundation contained 6,300 linear feet of Kipp's Bay granite, the interior stone walls contained 38,000 cubic feet of mortar and undressed stone, and the brick walls contained 650,000 units of brick.[47]

The Wall and Floor System: The structure of the building is based on traditional masonry construction but incorporates untraditional materials for the time, chiefly iron.

---

[45] Ammann & Whitney Consulting Engineers, *A Report on the Reconstruction and Improvement to the New York County Courthouse (Tweed Courthouse), Technical Report 'B'-Exterior Survey*, 1981, p.1
[46] *HSR*, p. 69.
[47] *New York Times*, December 27, 1861, p. 4. Quoted in HSR, p. 48.

All of the major walls are predominantly brick up to the level of the roof. The interior bearing walls are solid brick with vertical channels for hot air circulation vents and gas pipes. According to Ammann & Whitney, the total thickness of the exterior walls ranges from about 3' at the roof to 4'-6" at the basement.[48] Since it would have been impractical and far more expensive to use marble as a dimension stone, the exterior walls are brick with marble ashlar laid on the granite foundation. The thickness of the ashlar ranges from 8" to 12."[49] With the exception of the Corinthian columns on the North Portico, the exterior marble does not act as dimension stone. The marble is attached to the brick bearing walls with mortar and has no additional pinning or reinforcing. The brick walls were constructed integrally with the marble ashlar, and there is no doubt that they are mutually reinforcing to some degree. The original steps leading up to the entrance at the North Portico were made of Kipp's Bay granite.

The floor-framing system iron I-beams and girders mimics wood-floor framing in a masonry building. Iron for the basement level was provided by the Trenton Iron Company of New Jersey. The remainder of the iron, including ornamental and structural iron, was provided by John B. and William W. Cornell, who had worked previously with John Kellum.[50] The floor I-beams weigh 40,000 lbs. apiece and stretch from bearing wall to bearing wall. They are in-filled with trabeated brickwork, and a marble floor is laid on top of this in the hallways and part of the rotunda. The rest of the rotunda floor is made of cast glass-block illuminating tiles set in an iron frame. In the courtrooms, the floors are pine board laid on top of concrete supported by trabeated brick and iron. In addition

---

[48] Ibid.
[49] Ammann & Whitney, p.1.
[50] *HSR*, p. 50.

to supporting the floor, the iron I-beams provide bracing for the walls. All of the interior stairs are iron as well.

In the Kellum wing of the building, metal lath, an extremely unusual material for the time, was attached to the brick walls and covered by a rough "browncoat" of plaster. At least one finish coat of plaster was applied to this. The ornate molding, window and door frames, and ceiling detailing are all made of cast-iron.

The Dome and Roof: The dome is an octagonally-shaped frame of cast iron in-filled with glass and raised on squat wooden piers, also in-filled with glass. The piers were later replaced with cast-iron replicas. Beneath the interior of the dome is a pendant stained-glass skylight. Like the majority of the ironwork in the courthouse, the dome was fabricated by John B. and William W. Cornell. The original roof was made of corrugated iron.

Construction Timeline

It is difficult to pinpoint dates for completion of the different portions of the Tweed Courthouse, but a great deal of information can be inferred from secondary sources and recorded observations. Only one photograph of the phase of construction prior to substantial completion, and there are only a handful of depictions and photographs of the courthouse from substantial completion to total completion. One photo in particular, a view of the building taken circa 1862, provides useful detail about the handling of stone and the progress of construction. Many of the dates are drawn from the *Tweed Courthouse Historic Structure Report*, pages 46-75.

1861   *September*   Ground is broken on the 16th.

	December	Mayor Fernando Wood lays the granite corner stone on the 17th. A block of Tuckahoe marble is placed above this.
	Year End	By the end of 1861, all brick, granite, and stone for the foundation has been laid. William Tweed purchases the Briggs Quarry in Sheffield, Massachusetts. The quarry wins a contract to provide marble jointly for the new courthouse, but the contract is thrown out and the job is re-bid after Tweed's connection to the quarry is exposed.
1862	*Spring*	Construction is stopped as one of the Commissioners for the New Court House retires. The Special Committee on the New Court House, under the direction of Supervisor William Tweed, assumes oversight of construction. Work does not resume until the following year.
1863	*September*	New project specifications, presumably different from previous specifications, indicate that "All stone be of white marble,and of the very best quality, from either Eastchester, New York State, or from Sheffield, Massachussetts Quarries."[51]
	November	John Masterdon signs a contract to provide marble from the Eastchester Quarry Company to the Courthouse. Henry MacMurray, representing the former Briggs Quarry of Sheffield, Massachusetts, also signs a contract to provide marble for the courthouse.[52]
	Year End	The exterior walls of the first floor and the floor of the second floor are complete. Fabrication of architectural marble elements from large blocks and finish dressing takes place in an area to the west of the building. In a daguerrotype taken that year, numerous marble blocks and completed elements are seen on the Broadway side of the site stored in the open air (Figure 2.3). A small shed apparently serves as a shop for the stonecarvers, and a hoist of some kind stands in the center of the yard. It is possible that the ashlar marble for the first floor is entirely from the Eastchester Quarry since Tuckahoe is the first type of stone mentioned as being on site in 1861.
1865	*July*	The shell of the building, comprising the bulk of the exterior marble, brick, and other stone work for the Kellum building, is complete up to the level of the roof. Iron girders for the floors are in place and the fireproof arches of the trabeated brick floor are complete. The upper floors can be reached only by a ladder. A New York Times reporter visiting the site on July 15 describes the "polished walls" of marble "high up in the air,

[51] *Proceedings of the Board of Supervisors of New York City,* 1861-1868, Doc. 9., pp. 327-338
[52] Ibid.

bright and clean as a mirror."[53] The North Portico, with its Corinthian columns, has not been built.

1867   *March*   Although the building is far from complete, The Court of Appeals occupies the southeast corner of the First Floor. The main cast-iron stairway is not complete beyond the Second Floor, and only a few of the chambers have been stuccoed. The large opening in the roof intended for the dome is left uncovered, permitting rain and snow to enter the rotunda.[54] According to a critical article in the New York Times, the courthouse is still without windows and only partially roofed over.[55]

1868   *April*   One year later, the *Times* reports that little progress has been made and the courthouse is no more than two-thirds complete. Large quantities of furniture have been delivered but none of the chambers are finished. Only a few workmen, mostly painters and glaziers, are still on site. More importantly, the *Times* reports that just 7 years after work began, the exterior marble is showing signs of weathering: *Already the marble of which the Court house is built has become terribly discolored, particularly in the east and south sides-quite as much in fact as the marble of City Hall, which has been exposed to the elements for the last fifty years. This certainly seems to show, not withstanding the immense cost of the building and the promise that every portion of it should be the very best material, that at least in the article of marble an inferior quality has been used.*[56]

            Year End   Marble flooring in the hallways and wood flooring in the chambers are installed at the end of the year.[57]

1871   *April*   On April 4, a *New York Times* reporter writes: *Up to the present time they have completed the front of the building on Chambers Street, with the exception of the marble columns, and derricks are now being built for these columns, which are very handsome and massive, in their places. The Broadway front is entirely completed, and the stoops for the back, facing City Hall, are being constructed.*[58] It appears that the marble

[53] *New York Times*, July 15, 1865, p. 5.
[54] *HSR*, p. 52
[55] *New York Times*, March 12, 1867, p. 4. Quoted in *HSR*, p. 52.
[56] All information from *New York Times*, April 22, 1868, p. 8. Quoted in *HSR*, p. 52-54. It is especially noteworthy that the reporter sees the greatest deterioration on the east and south elevations of the building. These are the sides of the building considered to be most in need of repair by the architect during the current restoration. Observations on differential weathering are discussed in Chapter 2.
[57] *HSR*, p. 54.
[58] *New York Times*, April 4, 1871, p. 2.

		for the columns has been carved and is waiting to be installed at this point.
	July	After the *New York Times* publishes transactions from the ledger of the courthouse project, legal proceedings against members of the Tweed Ring begin. The major remaining work on the exterior includes completion of the North Portico, installation of a Portico on the South, stoops for the south pavilion, and the dome. Even so, many courts and several city government offices have occupied the building. The rooms are largely stuccoed and painted.[59]
	Fall	Several views of the courthouse at this time indicate the degree of completion. In an undated stereoscopic photo, derricks above the North Portico are visible, as is scaffolding around the columns, which have been placed by this time. The pediment over the columns is not yet installed. (See Figure 2.4) The Ring's financial misdeeds become national news. A September drawing and an October political cartoon in *Harper's Weekly*, as well as a drawing from Alexander Callow's *The House that Tweed Built*, published in the same year, corroborate the lack of activity. The view of the courthouse from Chambers Street, with its inanimate derricks, empty scaffolding, and blackening marble, becomes emblematic of the troubled project.
1872		Construction stops completely.
1873		The Tweed Trial takes place in the Court of Oyer & Terminer. The Panic of 1873 increases the unlikelihood that construction will be completed in the near future.
1874		A photograph of City Hall taken from the roof of the Post Office Building includes a partial view of the courthouse. The derrick above the North Portico is still in place and the balustrade on the south façade is incomplete at the pediment. The unfinished south pediment awaits the south portico's eventual construction. Pilasters on this façade are complete, and the dome still is not installed.[60] A suggestion to the Board of Aldermen to resume construction is ignored as "unwise (and) opposed to the interests of the people…"[61]
1876	*July*	The Commission to Complete the County Courthouse reports

---

[59]*HSR*, p. 61.

[60] Panorama of New York City, North, East, South and West from the Roof of the Post Office Building, Park Row and Broadway, Taken 1874 by W.W. Wilson, Section VI. New York Historical Society.

[61] *New York Times*, May 15, 1874, p.5. Quoted in *HSR*, p. 63.

that completion of the north portico will be undertaken and that, in place of a south portico which would provide no usable space, a new wing will be built to accommodate office needs.

October   Contracts are awarded and construction begins. The four large entrances to the rotunda space on the first floor are in-filled with massive polychrome brick arches. Eidlitz removes large sections of the original ironwork to the consternation of city officials and architectural critics.

1877   *April*   The pediment over the Corinthian columns on the north portico is put in place.[62] It is unclear from city records who the provider of marble for the new south wing is. It is assumed that the marble is largely from the Eastchester Quarry Company.

1881   Completion of the Eidlitz improvements to the building takes more than twice as long as expected. In the summer of 1881, after nearly twenty years of construction, the courthouse is complete. Little notice is taken of this fact in the local media. A view of the courthouse circa 1900 is provided in Figures 2.4 and 2.5.

The timeline brings out several aspects of the construction period as they relate to the exterior marble These facts will help to identify the origin of samples gathered from the building:

1) By the time that the 1863 site photo was taken (Figure 2.3), both the Tuckahoe marble and the Sheffield marble were specified for construction. It can be assumed that both types are present on site at this time and are being used in some combination from this point until 1866, when the Briggs Quarry is sold.

2) It can also be inferred from the sale date of the Briggs Quarry that any marble subsequently used did not come from Sheffield, Massachusetts.[63] Sheffield marble is most likely to occur on the sections of the building designed by John Kellum and

---

[62] *New York Daily Tribune*, April 7, 1877, p.3. Quoted in *HSR*, p. 65.
[63] While it is possible that stone sat on site for several years and was used later, this is unlikely given the typical arrangement between quarry and client. Quarries usually included dressing in their unit price, therefore every slab delivered to the site had a predetermined use. Since the quarry provided both services, there is little likelihood that Sheffield slabs would have been left on site and dressed by Briggs employees after the quarry was sold.

executed prior to 1866. This would include the entire building minus the Eidlitz addition, the north portico columns and pediment.

3) This sequence is supported by the photographic record and primary sources, which indicate that the columns and pediment for the north portico were not installed until 1871-1879. These sections are likely to contain only the Tuckahoe marble.

4) The time from installation of the exterior marble to manifestation of clear signs of weathering was between 3 and 4 years. Substantial completion of the shell occurred in 1864-1865, and by 1868 obvious blackening and staining were noted. While pollution levels in New York City have changed since the 19th century, it would not be unreasonable to see similar discoloration occur within the next ten years.

Figure 2.2: An 1863 daguerrotype of the construction site as seen from Broadway. Numerous blocks of marble lie in the yard directly behind the fence. A stonecarver's shanty appears to the right behind a line of carved elements, and a hoist is seen to the left of the image. Stonework has been completed on the first floor/ rusticated basement. Courtesy of the Scrapbook Collection, New York Public Library.

Figure 2.3: Image of the unfinished building taken from an 1873 stereoscopic photograph. The columns on the North Portico are not completed, and the pediment has yet to be installed. This view became emblematic of the plagued construction process. Courtesy of the Scrapbook Collection, New York Public Library.

Figure 2.4: A circa 1900 photograph of the Tweed Courthouse as seen looking southwest across Chambers St. Discoloration of the juxtaposed Tuckahoe and Sheffield marble is evident even from this distance. The granite staircase to Chambers St. seen here was removed during the 40's. Photograph provided courtesy of John G. Waite and Associates.

Figure 2.5: Close-up view of the same photograph showing differential staining of exterior marble around the second floor windows. The darker blocks are probably Sheffield marble.

Tuckahoe and Sheffield Marble

When analyzing the two types of marble used in the construction of the Tweed Courthouse, it is helpful to remember their essential relatedness. Tuckahoe and Sheffield marbles were installed side by side on the same building largely because of their superficial similarity. Both are considered durable, medium to coarse-grained white marbles, and both are classified broadly as dolomitic marbles, although this classification is less accurate than generally assumed.[64] Both are found in quarries situated along the Grenville belt of marble, which was formed during the Cambrian period 500 million years ago.[65] Reaching from Quebec to Georgia, the Grenville belt accounts for most of the marble quarried in the eastern United States.[66] In the vicinity of New York, the belt is exposed at the earth's surface in a strip that runs from Inwood at the tip of Manhattan northward through portions of western New England and Vermont. Mutual location of the Sheffield and Eastchester quarries along this belt accounts for their shared mineralogical and behavioral characteristics.

From the earliest days of its use, marble from Westchester County was valued for its color, durability, and workability. Tuckahoe marble, so-called because of the proximity of a number of 19th century marble quarries to the village of Tuckahoe, New York, has played a large role in the architectural history of the northeastern United States and of New York City in particular. Of the Tuckahoe marble quarries, the Eastchester Marble Quarry Company is the most well-known. Tuckahoe marble gained a favorable

---

[64] A summary of previous mineralogical tests performed on samples from the courthouse is presented in Chapter 3.

[65] Urquhart, Gordon Ross. *The Architectural History of the Westchester Marble Industry.* Unpublished Master's Thesis, School of Architecture, Columbia University, 1986, p. 5.

[66] Ibid.

reputation as a building material during the 19th century and was specified for use in buildings as far away as Charleston, South Carolina and New Orleans, Louisiana.[67]

In 1824, soon after the discovery of marble in the area of current day Westchester County, S.L Mitchell remarked on some of the characteristics of the stone. He described it as,

> ...granular, the result of incipient or compressed crystallization. It is wholly free from shells, crusts and all sorts of organic remains. A fresh fracture exhibits many shing surfaces, glistening in the sunshine. It is remarkably free from impregnation by iron; and even a small speck or lump of permanent and indecomposable pyrites, is a rarity. The color is white; and the stripes of other hues that sometimes occur, are inconsiderable, and easily avoided in quarrying. The material is exceedingly compact; and as the proof of its durability, the edges of the strata which have been exposed to the atmosphere for ages, seem to be unaltered by the elements, and to be as coherent and solid as ever. [68]

Agreement on a proper geological description of Tuckahoe marble has never been clear. Marbles are broadly made up of metamorphic carbonate rocks formed by the recrystallization of calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) through some combination of heat and pressure. They must be capable of taking a polish, although limestones and dolomites capable of taking a polish are often classified as marbles by the building trades. The American Society for Testing and Materials defines calcitic marble as containing 5 percent or less magnesium carbonate; marble with between 5 and 40 percent magnesium carbonate is considered magnesium or dolomitic marble, and those with more than 40 percent are dolomite marbles.[69]

---

[67] Torres, pp 30, 33, and 52. The Custom House in Charleston (1870) was constructed with marble from Hastings and Eastchester, NY. The front façade and portico of New Orleans City Hall (1845), now known as Gallier Hall, is made of Tuckahoe marble from the Eastchester Marble Quarry Company. Tuckahoe marble was also used for the Andrew Jackson Memorial (1855) and the interior of the New Orleans Custom House (1854).

[68] S.L. Mitchill, *The Quarries Situated Between East-Chester and the River Bronx, New York, August 19, 1824*. Eastchester Historical Society, Eastchester, New York. Quoted in Torres, p. 13.

[69] Ammann & Whitney, p. 3.

Variously described as crystalline limestone, dolomitic limestone, limestone, marble, and dolomitic marble, Tuckahoe marble is most accurately described as a dolomitic marble. The surface graininess and friability commonly observed in some weathered specimens of Westchester marble have led to a desire to characterize them separately from more common marbles. Nevertheless, the stone fits accepted criteria for classification as a dolomitic marble, and some of the earliest observers of Tuckahoe marble were correct in their descriptions of it as such. Geologist John Strong Newberry noted of the location of the Westchester marble quarries along the Achaean belt of dolomite. In 1841, state geologist Lewis C. Beck characterized the stone's mineralogical classification and considered it without doubt to be marble:

> ...all the varieties belong to what are called the primitive class, and most, if not all of them, contain a portion of magnesia, and are thus properly named dolomites. ... Blocks can be obtained of almost any shape and these are susceptible of a sufficient polish for building purposes.[70]

The Tenth Census also describes the stone as dolomitic containing small amounts of iron and mica.[71] Because the Eastchester Marble Quarry Company comprised at least four separate quarries in the vicinity of the villages of Eastchester and Tuckahoe, the likelihood of variation in mineralogy and texture is high. This fact, exacerbated by the length of construction, may account for the diversity of stone types used in the construction of the Tweed Courthouse.[72]

---

[70] Beck, Lewis C. *Report of the State Geologist & Paleontologist.* Albany: New York State Museum, 1841, p.13.

[71] *A Report on the Coke and Building Stone Industries in the United States, Tenth Census of the United States*, v.10. Washington: Government Printing Office, 1884, p. 135.

[72] Ammann & Whitney, *Technical Report B-Exterior Survey, A Report on the Reconstruction & Improvements for the New York County Courthouse*, 1981, p. 2.

The stone's properties as a building material were widely praised, although, as early as 1841, the shortcomings of Westchester marble were evident. Beck observed in his report to the State Assembly that year,

> ...the Eastchester Quarries are said at present to furnish the best material-The marble from these has a more compact structure, and it is stronger and more durable than that from other quarries...The objection to some of the other marbles from the county is, that in consequence of their friable character, they absorb water largely and hence, during the winter, they crumble and are defaced.[73]

Tuckahoe marble was considered by many to be superior to Vermont marble, Italian marble, and even granite.[74] An 1851competition for stone to be used in the new wings of the United States Capitol placed Tuckahoe marble ahead of all others in compressive strength.[75] Thomas Ustick Walter, the architect of the Capitol expansion, was impressed with John Masterton's quarry and the seemingly inexhaustible supply of Tuckahoe marble, but the stone was eventually turned down due to its high cost. Some 25 years later, the U.S. Army Corps of Engineers also rated the coarsely crystalline but compact and durable stone ahead of New Hampshire granite and Vermont marble for compressive strength.[76]

Another boost for the Tuckahoe reputation occurred with the Boston fire of 1872. Tuckahoe marble structures withstood the intense heat of the blaze better than their iron and granite counterparts. A laboratory analysis of the Tuckahoe stone in 1887 concluded that it was relatively free of sulfur, iron or other constituents that might negatively influence its performance.[77] John C. Smock praised the marble from Masterton's quarry

---

[73] Beck, p.13.
[74] Torres, p. 14.
[75] Ibid.
[76] Ibid.
[77] ibid.

above all others, describing it as "…coarse crystalline and pure white…buildings erected 60 years ago show the excellent quality of this marble."[78]

By the mid-1880's, however, Tuckahoe marble had been in use long enough that the impact of weathering could not be ignored. For the Tenth Census of the United States, Alexis Julien catalogued the stone's decay patterns in New York City where so many buildings had incorporated it. The surface of the U.S. Hotel, built in 1823, showed one of the most characteristic signs of Tuckahoe weathering. The snowy whiteness so valued by early admirers had taken on a cement gray tone, and areas of the surface had converted into a brittle gypsum crust under which the stone continued to change to a powdery, grainy consistency.[79] Another characteristic of Tuckahoe weathering, surface pitting due to the ejection of tremolite inclusions, was evident on the U.S. Hotel as well. Pitting was also visible at the United States Treasury, previously the old Customs House. The presence of iron in the stone gave a rusty tint to many Tuckahoe buildings. More generally, surface crystals had simply fallen off on broad areas of building façades, producing a rough texture.[80] The classical purity of mid-century New York had shifted to a decaying gray and orange thanks to the weathering of Tuckahoe marble.

George Merrill, the Smithsonian geologist, agreed with Julien's assessment of Tuckahoe weathering. He noticed that,

> By exposure to the impure atmosphere of the city, its color changes to a light gray. This is apparently due to its coarseness of texture, which gives a roughness to the surface, and causes the smoke and dust to adhere to it more closely than they would to a finer stone.[81]

---

[78] Smock, John Conover. *Building stone in the state of New York.* New York: C. Van Benthuysen & Sons, 1888, p. 38.

[79] Julien, Alexis A. "The Durability of Building Stones in New York City and Vicinity," *Tenth Census of the United States*, v.10. Washington: Government Printing Office, 1884, p. 366

[80] Ibid.

[81] Merrill, George E. "The Collection of Building and Ornamental Stones in the U.S. National Museum: a handbook and catalogue," in *Annual Report of the Board of Regents of the Smithsonian Institution, showing*

Merrill's observation points to the basic texture and structure of Tuckahoe marble as key

components of its decay.   Once a dressed and finished surface was weathered, the large

grains facilitated the settling of particulate matter and the introduction of moisture and

salts to the interior of the stone.

Julien went beyond describing stone weathering to try to understand its root

causes. In the Tenth Census, he noted that the behavior of marble in urban environments

could not be explained simply by moisture content, as was commonly accepted at the

time. Rather, the peculiarities of texture as determined by metamorphism could explain

far more about marble weathering. On the bending of marble he wrote,

> …the irregular and closely contiguous grains of calcite which make up a white
> marble are united by no cement, and have apparently a very feeble coherence. It
> appears to me probable also that their contiguous crystallization has left them in a
> state of tension, on account of which the least force applied, through pressure
> from without, or of the unsupported weight of the stone, or from thermal
> expansion by heat or frost, produces a separation of the interstitial planes in
> minute rifts. Such a condition permits a play of the grains upon each other and
> considerable motion…In such cases, also, I have observed that the mutual
> attrition of the grains has been sometimes sufficient to convert their angular, often
> rhomboidal, original contours into circular outlines, the interstices between the
> rounded grains being evidently filled up by much smaller fragments and rubbed
> off particles.[82]

Later, when discussing tension and loss of cohesion between grains within a stone, Julien

refers to Tuckahoe marble:

> A crystalline building stone…is made up almost entirely of imperfect crystals of
> its constituent minerals…closely compacted together, originally with intense
> mutual pressure. Sometimes no cement intervenes…Such a condition must be
> sensitive to very slight influences, the surfaces of the grain in a building
> alternately pressed still more tightly together or separated to disruption, e.g. by
> variations of temperature…A good illustration is found in those marbles which
> seem to contain no cement in their interstices, e.g. the coarse Tuckahoe marble,
> which soon becomes seamed with cracks.[83]

---

the operations, expenditures, and conditions of the institution for the year ending June 30, 1886, Part II.
Washington: Government Printing Office, 1889, p. 380.
[82] Julien, p. 367.
[83] Ibid., p. 379.

Julien's observations highlight the primary role of microstructure in the weathering of marble. The issues he discussed in the *Tenth Census* continue to shape our understanding of stone decay. The relationship between cyclical heating and cooling and the deformation of marble at the level of the individual grain boundary is essential to the behavior of both Tuckahoe and Sheffield marbles. Julien did not mention the Tweed Courthouse in his survey, but the patterns of decay exhibited so early in the building's life are characteristic of Tuckahoe marble.

Where much has been written about Tuckahoe marble, far less is known about Sheffield marble. The quarries of Berkshire County had provided stone locally since at least the first half of the 19th century. The only other known use of Sheffield marble on a large-scale was in the Washington Monument in Washington, D.C.[84] George Merrill mentions the Sheffield quarry in connection with the quarry in Lee, Massachusetts 18 miles to the north. Lee marble had been used in the extensions to the United States Capitol and was relatively well known. Merrill writes,

> Crystalline limestones and dolomites of such a character as to assume the name of marble are now or have been in times past quarried in various towns of Berkshire County, in this state. The stones are all white or some shade of gray color, medium fine-grained in texture, and are better-adapted for general building than for any form of ornamental work...In the quarries the stone lies very massive, and it is stated cubes 20 feet in diameter could be obtained if necessary. The Sheffield quarries were opened in 1838. The rock there is massive, with but little jointing. Natural blocks 40 feet square can be obtained.[85]

It is not certain that the Berkshire marbles are in fact dolomitic, as Merrill believed. However, on the other accounts Merrill's observations are worth noting. The fine-grained texture of the Berkshire County marbles is one of their defining characteristics,

---

[84] This is based on a conversation with the owner of the former Briggs quarry, who claims to have documentation provided by the National Park Service. It is not independently verified.
[85] Merrill, p. 379.

and like the Tuckahoe marble, accessory minerals were another defining characteristic.

Merrill writes that much of the stone from the Berkshire quarries contained small crystals

of yellowish tremolite. The tremolite crystals tended to weather out of the surface within

a few years, leaving a pock-marked appearance.[86] This behavior was visible in the

exterior walls of the Capitol building even in Merrill's day.

John Strong Newberry's description of the Lee quarry was included in the Tenth

Census, and it provides more information on some of the important features of Berkshire

marble. Again like the Tuckahoe, Berkshire marble typically contained a noticeable

amount of iron and visible inclusions. He wrote,

> The Lee marble is for the most part of uniform though not brilliant white color, is
> coarser grained than the Vermont marbles, and yet finer than those of New York.
> It is a strong and durable stone but contains a little iron, by the oxidation of which
> it becomes somewhat brown on exposure. It is doubtful whether its strength and
> durability are materially impaired by this, and the change of color which it
> produces is by some architects regarded as an excellence rather than a defect. It
> usually contains a little pyrites, but it is a remarkably white marble.[87]

The existence of these four features, magnesium content, iron content, tremolite and

pyrite inclusions, and general white coloration, indicates the degree of relatedness

between Tuckahoe marble and Sheffield marble. Similar geological provenance accounts

for this relatedness. Although the Westchester and Berkshire county quarries are

separated by over 100 miles, the stone they produced during the years of their greatest

activity was strikingly similar. It is useful to remember this fact when considering the

variation in decay that manifested itself at the Tweed Courthouse over time.

While the two types of marble used in the construction of the Tweed Courthouse

derive from a single geological formation, the individual characteristics of texture, grain

---

[86] Ibid.
[87] *A Report on the Coke and Building Stone Industries in the United States*, p. 323.

boundary, grain size and grain shape unique to each type of stone have produced

observable differences that are as striking as their similarities. Despite their undeniable

relatedness, Tuckahoe and Sheffield marble exhibit distinct patterns of weathering that

derive from the idiosyncrasies of mineral composition and micromorphology. These

patterns of weathering will be discussed in the following chapters.

CHAPTER III

Previous Analysis and Cleaning

Although their formal results have never been published, several investigations of

the Tweed Courthouse marble have been performed within the past twenty years. The

first significant tests, which applied x-ray diffraction (XRD) and scanning electron

microscopy (SEM) to a group of 24 samples taken from the south side of the building,

occurred in 1981.[88] In 1989, as a preliminary step in determining a suitable method for

cleaning the exterior marble, 16 stone samples were observed under an optical

microscope, and SEM and Energy-Dispersive X-Ray Microanalysis (EDXA) were

performed.[89] Subsequent to this analysis, cleaning tests were performed and a method

was chosen for cleaning the marble. In 1991, further testing was performed in order to

determine an appropriate conservation treatment for the extensively deteriorated

marble.[90] Three drilling cores were chosen to represent the exterior marble and were

used for XRD and a wide array of laboratory tests. Finally, as part of the current

restoration, another round of surface cleaning was implemented in 2000. This took place

ten years after the first cleaning. In order to understand what is and is not already known

---

[88] *A Report on the reconstruction and improvement to the New York County Courthouse
(Tweed Courthouse).* Prepared by Ammann & Whitney, Consulting Engineers and Beyer, Blinder, Belle, Architects
and Planners. New York, February 1981.
[89] Rehabilitation and restoration of 52 Chambers Street (Tweed Courthouse), Borough of Manhattan, City of New
York, for the Department of General Services, PW-292-01. Prepared by Mesick, Cohen, Waite Architects. Albany,
1989.
[90] *Evaluation of Submitted Masonry Samples; Recommendations for Conservation Treatment. Tweed
Courthouse, 52 Chambers St., New York, NY, Project No. 9010-38 MSSC.* Prepared for Mesick, Cohen, Waite
Architects by the Stone Testing Laboratory, Masonry Stabilization Services Corporation. March 1991.

about the Tweed Courthouse marble, it is worthwhile to examine the results of these

different testing programs.

1981 Exterior Survey by Ammann & Whitney

In 1981, engineers from the firm of Ammann & Whitney consulted with the

architectural firm of Beyer Blinder Belle to produce an exterior survey of the Tweed

Courthouse for the Department of General Services, the agency that oversees New York

City's government buildings. The purpose of the report was to provide a

recommendation for the rehabilitation of the courthouse, which by the late 1970's had

become a source of concern. Figures 3.1 and 3.2 give some indication of the condition of

the building's exterior. Decaying marble on the columns and in the cornice created a

serious falling hazard for city employees and pedestrians in City Hall Park.   Ammann &

Whitney Consulting Engineers was asked to determine why the stone was failing and

what could be done to repair it. During the course of their work, vibration from a coring

drill did in fact cause a large carved leaf of a column cap to detach and fall, confirming

concerns about the extent of the decay.

Technical Report 'B'-Exterior Survey includes the findings of the chemical and

mineral analyses performed as part of this investigation. For the purposes of testing,

Ammann & Whitney took 24 marble and mortar samples from the south side of the

building. Some samples were removed from the Eidlitz addition but most were taken

from the Kellum portion of the building and all were within reach of a stepladder or open

window. Each sample was subjected to XRD and examined using SEM.

Figures 3.1 & 3.2: Discoloration on the north façade, east and west sides of the portico. May, 1989.

Ammann & Whitney were able to calculate exact proportions of constituent

minerals using XRD. This was apparently accomplished by fine-tuning the machine in

the laboratory to provide precise readings. Of the 21 marble samples tested, it was found

that 11 had a dolomite content of 76% or greater. Of those samples, the micaceous

mineral phlogopite accounted for 10% or more in 2 samples and was present as a minor

accessory mineral in the other 8. It was also found that quartz was a major component

(49%) in one sample and a minor component in 8 others. Calcite was present as an

accessory mineral in 6 of the 11 dolomitic samples.[91]

In the 10 calcitic samples, calcite content ranged from 72% to 95%. Phlogopite

was an accessory mineral in 5 samples and in 2 of those it comprised 10% of the total.

---

[91] Ammann & Whitney, pp. 15-37.

Muscovite and quartz were also present. Quartz appeared in 8 samples, and in two

samples it made up 7% and 10% of the total. A breakdown of test results is given in

Table 1.

The frequent appearance of quartz and phlogopite in both categories of stone is

significant. Ammann & Whitney concluded that the presence of micaceous phlogopite

was one reason for the patterns of deterioration visible on much of the exterior. Where

the sheety mica inclusions were close to the surface, they acted as a wick for moisture

and in freezing weather led to rapid removal of surface material.[92] This phenomenon was

discussed by Lewin and Charola in 1981.[93] Phlogopite, which originally may have been

valued for the sparkling appearance it gave to the stone, was the most likely source of the

commonly observed "pock-marking" of the surface. The significance of quartz was not

mentioned, but it may account for some lack of cohesion within the marble. The

engineers also noted iron oxide staining and attributed this to the leaching of ferruginous

minerals such as pyrite within the stone or to rusting of metal on the outside of the

building.

The most interesting outcome of the 1981 *Exterior Survey* was the new

understanding it prompted about composition of the marble used to build the Tweed

Courthouse. It had long been assumed that marble from both quarries was dolomitic. On

the contrary, tests showed that calcitic marble accounted for 1/3 or more of the exterior

stone. Based on the textural and compositional range observed by Ammann & Whitney,

it was felt that as many as seven different quarries could have provided the stone. Yet the

two broad categories drawn by the tests, calcitic and dolomitic, indicated the possibility

---

[92] Ibid., p. 12.
[93] Lewin, Seymour Z. and A. Elena Charola, "Stone decay due to foreign inclusions." Preprints of the Contributions to the International Symposium on the Conservation of Stone: Part A, Deterioration, Bologna, 1981.

of two general locations for the quarrying of the stone. Since the Westchester marbles

are widely classified as dolomitic, it is reasonable to assume that the Sheffield quarry was

the source of the calcitic marble sampled. Ammann & Whitney did not interpret their

results this way, but the patterns of decay observed prior to the two cleaning campaigns

could be explained in part by the behavior of two general types of marble deriving from

two general locations.

Supporting this observation is the detection of another mineral in the XRD

analysis performed by Ammann & Whitney. Calcium sulfate or gypsum ($CaSO_4 \cdot$

$2H_2O$) was observed in nearly half of the samples. The presence of gypsum can be

attributed in part to the sampling technique employed, which relied on surface scrapings

or included portions of surface material for use in XRD. The process of formation of

gypsum from the interaction between calcium and sulfur is well known. Sulfation is to

be expected in exterior marble subjected to an urban climate; but because magnesium is

slower to react with sulfurous compounds than calcium in solution, the occurrence of

gypsum is less common on dolomitic marble than it is on calcitic marble. This was true

in the tests performed by Ammann & Whitney. Gypsum was present in 9 of the 21

samples; of those 9 samples, 8 were calcitic marbles. In one of these 8 samples, gypsum

accounted for 12% of the total, the rest being calcite. Results of the XRD tests are

summarized in Table 3.2.

In their conclusions, Ammann & Whitney comment on the role of gypsum and the

absorption of soluble salts in the decay of exterior marble at the Tweed Courthouse:

> The other main source of ongoing decay is due to the attack of acidic air
> pollutants (oxides of sulfur and nitrogen from combustion of fossil fuels and
> automotive vehicle exhausts.) These react with the alkaline stone (dolomitic and
> calcitic marble), eroding it and producing soluble salts (gypsum) that, under the

influence of normal wet-to-dry cycling, undergo internal migration and recrystallization, and produce the characterisitc manifestations of "salt-decay."

If this is the case, it may be possible to make a finer distinction between the samples analyzed. Based on the data obtained by XRD, it could be stated that surface decay due to the recrystallization of soluble salts is more likely to be observed in the calcitic marble than in the dolomitic marble. If a connection between provenance and composition, i.e. between location (Tuckahoe, New York versus Sheffield, Massachusetts) and classification (calcitic versus dolomitic), can be confirmed, then this observation takes on greater significance for the characterization of decay mechanisms in the two types of stone used at the Tweed Courthouse. Since a piece of calcitic Sheffield marble would be more likely to have a surface formation of calcium sulfate than a piece of dolomitic

Number	Calcite	Dolomite	Phlogopite	Quartz	Gypsum	Muscovite	Location	Type
1	82%	0%	10%	minor	minor	minor	known	calcitic
2	minor	93%	minor	0%	minor	0%	known	dolomitic
3	0%	96%	minor	minor	0%	0%	known	dolomitic
4	0%	89%	10%	minor	0%	0%	known	dolomitic
5	86%	0%	0%	7%	0%	0%	known	calcitic
6	0%	51%	0%	49%	0%	0%	known	dolomitic
7	minor	76%	20%	minor	0%	0%	known	dolomitic
8	minor	90%	minor	minor	0%	0%	known	dolomitic
9	0%	96%	minor	minor	0%	0%	known	dolomitic
10	minor	92%	minor	minor	0%	0%	known	dolomitic
11	72%	0%	10%	12%	minor	minor	known	calcitic
12	95%	0%	0%	0%	minor	0%	known	calcitic
13	95%	0%	0%	0%	minor	0%	known	calcitic
14	86%	0%	0%	minor	12%	0%	known	calcitic
15	86%	0%	minor	minor	minor	minor	known	calcitic
16	minor	89%	minor	minor	0%	0%	known	dolomitic
17	94%	0%	minor	minor	0%	minor	known	calcitic
18	minor	91%	minor	minor	0%	0%	known	dolomitic
19	0%	95%	minor	0%	minor	0%	known	dolomitic
20	87%	0%	minor	minor	minor	minor	known	calcitic
21	92%	0%	minor	minor	minor	minor	known	calcitic

Table 3.1: Mineralogical constituents detected using X-Ray Diffraction. Ammann & Whitney, 1981.

Tuckahoe marble, this difference should be visually evident to some degree. And on the

dolomitic marble, a highly soluble, highly hygroscopic gypsum--epsomite

($MgSO_4 \cdot 7H_2O$)-- would be expected to form.

1989 Cleaning of the Exterior Masonry: Pre-preliminary Report
by Mesick, Cohen, Waite, Architects

Eight years after these tests, the Albany-based firm of Mesick, Cohen, Waite

Architects (MCWA) was hired by the Department of General Services to produce a

comprehensive feasibility study for the restoration of the Tweed Courthouse. The first

part of that study involved a preliminary analysis of the masonry and the execution of

small-scale cleaning tests. A few sections of scaffolding were erected on the exterior, but

samples were obtained and tests were carried out mostly on areas that could be reached at

ground level. For their laboratory analysis, MCWA consulted with the Environmental

Particulates Analysis at the Atmospheric Sciences Research Center of the State

University of New York at Albany. Testing again involved SEM, but instead of using

XRD for the identification of constituent minerals, Energy Dispersive X-Ray

Microanalysis (EDXA) was applied to each sample while in the scanning electron

microscope. EDXA identifies elements rather than mineralogical composition, and

results are not reported as percentages of the entire sample. 16 samples were taken from

the building and locations for these samples were not noted. Between 5 and 12 locations

on each sample were tested with EDXA. Averaged compositions of test locations on

Number	Mg	Al	Si	P	S	Cl	K	Ca	Fe	Location	Type
1	high	none	high	low	low	none	none	high	low	unknown	dolomitic
2	high	none	high	low	low	none	none	high	low	unknown	dolomitic
3	high	none	high	low	low	none	none	high	low	unknown	dolomitic
4	low	high	high	none	none	none	none	high	high	unknown	calcitic
5	high	none	high	low	low	none	none	high	low	unknown	dolomitic
6	v. low	v. low	low	none	none	none	v. low	high	low	unknown	calcitic
7	high	none	low	low	low	none	none	high	high	unknown	dolomitic
8	none	v. low	low	none	none	none	v. low	high	v. low	unknown	calcitic
9	none	low	high	none	none	none	low	none	low	unknown	inclusion
10	high	none	high	low	low	none	none	high	v. low	unknown	dolomitic
11	high	none	high	low	moderate	none	none	high	v. low	unknown	dolomitic
12	high	none	high	low	moderate	none	none	high	v. low	unknown	dolomitic
13	low	none	none	none	none	none	none	high	low	unknown	calcitic
14	low	low	moderate	low	low	low	low	moderate	moderate	unknown	uncertain/ calcitic
15	none	low	high	low	none	low	none	high	low	unknown	calcitic
16	high	none	high	low	moderate	none	none	high	low	unknown	dolomitic

Table 3.2: Elements detected using EDXA. Mesick, Cohen, Waite, 1989.

each sample are given in Table 3.2. Samples were also observed under an optical

microscope with photomicrographic dispersive staining capability.

The results of these tests were less precise than the 1981 tests, but they tend to

confirm the earlier findings. 9 of the samples can be characterized as dolomitic marble

based on the presence of calcium and magnesium, and 6 can be characterized as calcitic

based on the presence of calcium and the absence or very low presence magnesium.   One

sample appeared to be an inclusion of pure silicon and another sample, grouped for

simplicity with the calcitic marbles, had more silicon than calcium. Other chemicals

present were sulfur, silicon, chlorine, iron, phosphorus, and titanium.

Sulfur was present on the surface or interior of 9 of the samples. 7 of these were

dolomitic marble. Although it is impossible to infer from EDXA if this indicates the

presence of calcium sulfate, MCWA considers this to be proof of gypsum formation on

the dolomitic marble samples.[94] It could also be interpreted to mean that sulfurous particulate matter, and not gypsum, was more common on large exposed surface grains of the dolomitic marble or that magnesium sulfate ($MgSO_4$) was present.

Iron was present in 7 of the dolomitic samples and in 2 of the calcitic samples. The presence of iron is significant for weathering, although again it is impossible to say with certainty why it is present. In analysis of sample 1, MCWA writes that the iron detected in the dolomitic marble indicates the presence of hornblendes, but elsewhere the presence of iron is attributed to the deposition of fly ash on the surface of the stone. It may also be due to the presence of pyrite. Iron has been observed in Tuckahoe marble from other buildings, so this may be an accurate assumption for the dolomitic marbles. It is likely that the iron observed using EDXA is a combination of existing iron content and iron deposited in the form of fly ash or other pollution, as stated by MCWA.

Another element observed using EDXA was silicon. Silicon was detected in 11 samples and was the dominant constituent in 1 of these. This can be explained by the fact that various silicates and silico-aluminates are usually present in these marbles. Phosphorus was present as a result of a bird-proofing agent applied to many of the ledges. The chemicals sulfur and chlorine were also observed in some of the samples, indicating the presence of salts within the stone and the influence of atmospheric pollutants. Carbon particles could account for some of the surface yellowing seen in much of the stone.

The characterization of stone samples performed by MCWA for their report to the Department of General Services served the larger purpose of helping to determine a proper method of cleaning the exterior marble. 19 tests were performed on isolated areas

---

[94] *Rehabilitation and Restoration of 52 Chambers Street (Tweed Courthouse), Borough of Manhattan, City of New York, for the Department of General Services, PW-292-01.* Prepared by Mesick, Cohen, Waite Architects, Albany, 1987, Appendix B.

of the building. The difference between soiled and cleaned surfaces was, in most of the

tests, dramatic. Figures 1 and 2 show the degree of color change between soiled and

cleaned stone. They provide an inkling of the original whiteness of the Tweed

Courthouse in its earliest days. After testing everything from crushed walnut shells to

water soaking, MCWA recommended a three-step process for cleaning the building.[95]

Step one involved removal of the pigeon proofing substance using a metal scraper. Step

two involved pressure rinsing the stone with water at a pressure of 500 psi and with a fan

tip nozzle of at least 40 degrees. The third step required the brushed application of an

alkaline prewash such as Prosoco's Sureklean 766® to the surface with a dwell time of 30

to 60 minutes. Dwell time varied according to the seriousness of surface soiling. After

the appropriate dwell time, the prewash was to be rinsed off. The fourth step called for

application of an afterwash, such as Sureklean Retoration Kleaner®, which should be

pressure rinsed after 5 minutes. The final step was to test the surface for pH to ensure that

the chemicals had been thoroughly removed.

In addition to their recommendation for cleaning, MCWA also commented on the

general conditions of decay that they observed on the building. By 1989, many of the

architectural details that were most exposed to wind, rain, sun, and freezing had seriously

decayed or simply fallen off, like the abacus details of many of the capitals.[96] Areas

especially susceptible to damage and staining were the column and pilaster flutes,

window trim, and rusticated blocks on the first floor.

Because their test results corroborated the existence of two different types of marble on

the exterior of the building, MCWA observed the behavior of the marble with this in

---

[95] Ibid., p. 38.
[96] Ibid., p. 20.

mind. The "two types of marble," as MCWA called them, seemed to be weathering differently, although they did not identify the difference as deriving from the original quarry location. The stones were referred to simply as "gray" and "white."[97] Most of the façade was made up of the "dark gray" stone, and the rest was made up of "quite white" stone. In the gray stone, numerous small holes were evident where hard mineral inclusions had fallen out. This is in keeping with Julien's description of Tuckahoe marble. The holes themselves were stained yellow or brown, suggesting that the inclusions contained iron.[98] All of the stone in the Eidlitz wing was dark gray prior to cleaning. This would seem to confirm the sameness of the gray stone and the Tuckahoe marble, also indicated by the construction timeline. It was also remarked that the stone in the Eidlitz wing seemed to be in better condition than the stone in the Kellum section of the building. This suggests that the Tuckahoe is in general a more sturdy material than the Sheffield.

In contrast, the "white" blocks had relatively smooth surfaces without holes or inclusions, and dark yellow/brown stains were common in areas that were not washed by water. This may be due to surface gypsum trapping fly ash and other particles. Such a pattern is in keeping with Newberry's description of Lee marble in the Tenth Census. Some sections of both the white and gray stone were so friable that they simply turned to "marble sand" when touched.

The report to the Department of General Services also describes patterns of black crust formation on the exterior stone. In areas of the façade protected from the flow of water, particularly the moldings at the sides of the windows under lintels and segmental

---

[97] Ibid.
[98] Ibid.

Figure 3.3: Cleaning test number 10 performed on two blocks of Tuckahoe marble at the first floor level, July 1989.
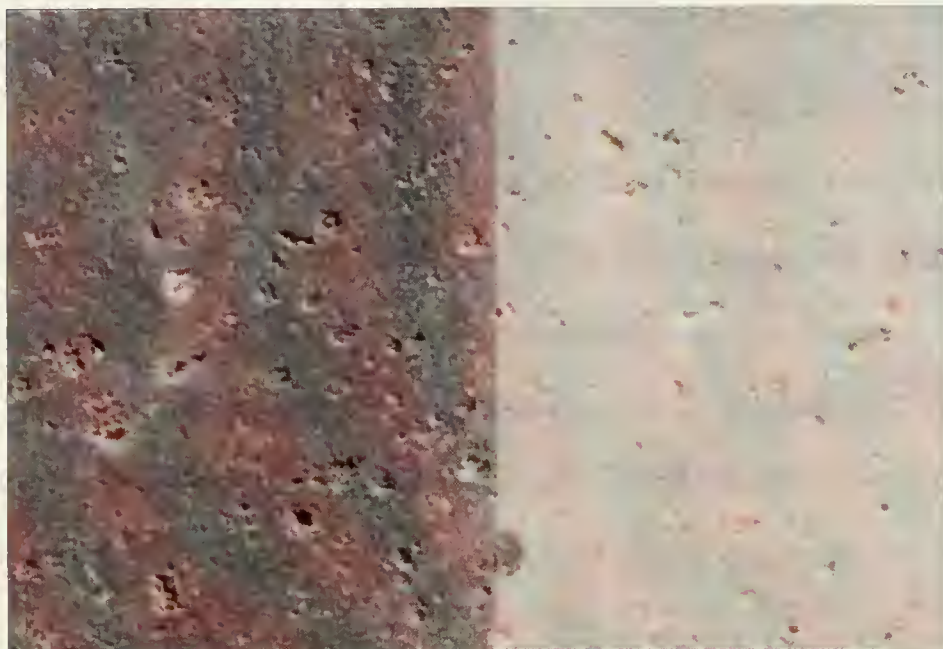

Figure 3.4: Close-up of cleaning test number 10. Gray discoloration and pock-marking are evident.

pediments, and the joints in the rusticated blocks at the first floor, gypsum crusts were

common. These crusts were extremely friable and could be removed by hand.

1991: Evaluation of Submitted Masonry Samples
by Masonry Stabilization Services Corporation

Mesick, Cohen, Waite's contract with the Department of General Services also

called for testing of possible consolidants. Since the stone would continue to decay

regardless of cleaning, it was considered important to review treatments that might at

least slow this process. MCWA hired Masonry Stabilization Services Corporation

(MSSC) of Kansas City to carry out these tests. In order to quantify how the stone would

perform before and after treatment, the Stone Testing Laboratory at MSSC analyzed

some of the traits of the stone, including hygroscopic moisture uptake, water absorption,

acid solubility, water solubility, anionic salt content, accelerated weathering, and

measurement of color change. All of these tests were performed according to ASTM

standard methods.

Following the lead of MCWA's previous report, three basic categories of stone

were created. Category 1 was labeled "white marble," category 2 was labeled "gray

marble," and a third category labelled "Type 01" was also included. It is not clear what

the term Type 01 refers to, although it must have been relatively common.

The samples themselves were cut to uniform sizes (2" diameter by 1-1/2" length)

from cores drilled to depths greater than 2 feet in the exterior walls. 6 of each type of

sample were obtained. All of the stone was recorded to be in sound condition. XRD

results are provided in Table 3.3, and the basic properties of the three substrates are summarized in Table 3.4.

MSSC also performed XRD and basic observation under an optical microscope for all of the samples. This revealed that the Type 01 samples were a white marble composed chiefly of calcite with minor amounts of dolomite.[99] It was noted that the substrate was almost pure calcite with no traces of other minerals. Minor amounts of dolomite were detected, and average grain size was observed to be 0.5mm. From this description, Type 01 matches samples of the Sheffield marble analyzed in Chapter 4.

The gray marble was characterized as a dolomitic marble composed primarily of dolomite with small amounts of calcite.[100] The crystals were large, measuring up to several millimeters in diameter. Abundant small flakes (about 0.5mm wide) of magnesian mica, or phlogopite, were present, and pyrite was noted to be abundant. Graphite and wollastonite may have been detected, but the identity of these minor

Sample	X-Ray Diffraction Mineralogical Summary		
	Major	Minor	Trace
Type 01	calcite	dolomite	none
Gray Marble	dolomite, pyrite	phlogopite, hydromica	graphite, wollastonite?, kaolinite?
White Marble	dolomite, phlogopite	calcite	pyrite, gypsum

Table 3.3: Mineralogical constituents detected using X-Ray Diffraction. MSSC, 1981.

[99] *Evaluation of Submitted Masonry Samples; Recommendations for Conservation Treatment. Tweed Courthouse, 52 Chambers St., New York, NY, Project No. 9010-38 MSSC.* Prepared for Mesick, Cohen, Waite Architects. Prepared by the Stone Testing Laboratory, Masonry Stabilization Services Corporation, March 1991, p. 13.
[100] Ibid.

accessory minerals is not certain in the XRD readout provided in MSSC's report.

Judging by the other characteristics, the gray marble is a close match for Tuckahoe

marble.

Compositionally similar to the gray marble, the white marble was described as a

white dolomitic marble comprised chiefly of dolomite and phlogopite with low amounts

of calcite.[101] The phlogopite grains were several millimeters large and oriented parallel

to each other. Pyrite was present in traces, as was gypsum. The tested samples are not

accompanied by photographs, and no locations are given for the samples, making it

impossible to visually cross-reference MSSC's results with other stone from the building.

Sample	24 Hr. Water Absorption, % Wt. ASTM C 97	Anionic Salt Content			Surface pH	Hygroscopic Moisture Uptake (48 hrs. at 94% RH)	Solubilities of Untreated Samples	
		Chloride Cl-	Sulfate SO4--	Nitrate NO3-			Water Soluble Content % Wt.	Acid Soluble Content % Wt.
Type 01	0.14%	<30 ppm	<50 ppm	<1 ppm	6.96 to 8.45	0.00% to 0.05%	2.02%	92.50%
Gray Marble	0.16%	<30 ppm	<50 ppm	<1 ppm	8.61 to 8.72	0.01% to 0.08%	0.00%	91.50%
White Marble	0.23%	<30 ppm	<69 ppm	<1 ppm	7.98 to 8.47	0.00% to 0.09%	0.00%	91.00%

Table 3.4: Basic properties of three marble types. MSSC, 1991.

---

[101] Ibid.

Figure 3.5: Tuckahoe marble balusters showing extreme degradation due to weathering. Characteristic gray discoloration and blackening from the accretion of pollutants are evident. Projecting elements of both types of marble tend to look alike because of pollution staining. Photo taken May, 1989.

Observations about Exterior Weathering

Subsequent to MCWA's testing, no further analysis was performed on marble samples from the Tweed Courthouse. Thorough cleaning was undertaken using the recommendations made by Mesick, Cohen, Waite Architects and the courthouse was returned to a state of relatively uniform whiteness, removing the most obvious visual clues of differential weathering. Cleaning was undertaken again in 1999 prior to the Economic Development Corporation's current restoration. Without being able to refer to the building itself as a general gauge of comparative weathering as it is manifested in surface discoloration and the accretion of pollutants, it is difficult to make observations on the weathering of the two types of marble. Even so, the building provides a wealth of information about the behavior of Sheffield and Tuckahoe marble.

The collection of photographs taken by MCWA as part of their work there provides the best record of the conditions of decay that existed on the building prior to cleaning. After an analysis of MCWA's photographic archive of the previous conditions on the building, the following observations were made:

1) The gray stained marble shows the characteristic properties of Tuckahoe marble: medium to large grain size, gray surface deposition of sooty pollutants and gypsum crust formation on projecting elements (See Figure 3.5.) Surface friability is often extreme. Figure 3.6 and 3.7 show that in areas where the stone is thin, it has detached from the substrate. Small iron spots are also visible on many of the elements, as shown in Figure 3.8. The graying of Tuckahoe marble is likely to be an urban phenomenon, since Tuckahoe samples on the Stone ExposureTest Wall at the National Institute of Testing and Standards in rural Maryland have not become gray in 50 years of exposure (see Figure 3.9.).

2) Reddish iron-stained marble is mixed in with the gray marble on most of the façade (see Figure 3.10.) As with the gray marble, black crusts had covered the most exposed elements of this type of stone, making it difficult to differentiate even when severely decayed. On the south façade of the east pavilion of the Kellum section, severe iron staining is visible across the entire surface (see Figure 3.11). Similar iron staining is common in a sample of stone from Lee, Massachusetts at the NIST (see Figure 3.12). In one instance, a ledge-like window hood was coated with bird-proofing material, causing moisture to be trapped inside the stone and intensifying iron staining and decay (Figure3.13.) This seems to indicate the leaching of ferruginous minerals such as pyrite. The prevalence of iron staining in this area may be attributable to the prevalence of

Figures 3.6 & 3.7: Chipped pilaster flutes to the left and a chipped rusticated basement block to the right. Many of the finer details of the Tuckahoe marble have detached due to weathering. The whiter substrate has been exposed, revealing the level of discoloration. Photos taken May, 1989.

Figure 3.8: Leaf detail with degraded surface showing exposed individual grains and iron stains. Weathering has made the surface extremely friable. Photo taken August 2000.

Figure 3.9: A smooth but slightly iron-stained sample of Tuckahoe marble in the Stone Exposure Test Wall at the NIST. After 50 years of exposure, no gray discoloration was visible. The large grains are highlighted by the reflection of the sun on the surface.

Figure 3.10: Iron-stained marble, probably Sheffield, interspersed with blocks of Tuckahoe. Iron staining may be due to the leaching out of ferruginous minerals such as pyrite. Note how the stone has been washed white in areas of rain runoff near the Tuckahoe marble while the Tuckahoe has remained a solid gray color. Photo taken May, 1989.

Figure 3.11: South facade, west end, May, 1989. Extreme staining is visible across the entire surface. This type of discoloration is typical of Lee marble, a stone quarried within 20 miles of Sheffield, MA. The south façade exhibits the worst weathering on the building.


Figure 3.12: An iron-stained sample of Lee marble in the Stone Exposure Test Wall at the NIST. Like the Tuckahoe sample, discoloration due to pollution was not noticed.

Figure 3.13: A Sheffield window header that had been covered with bituminous bird-proofing. The corner shows the effects of trapped moisture. This part of the stone could be removed merely by scraping the surface.
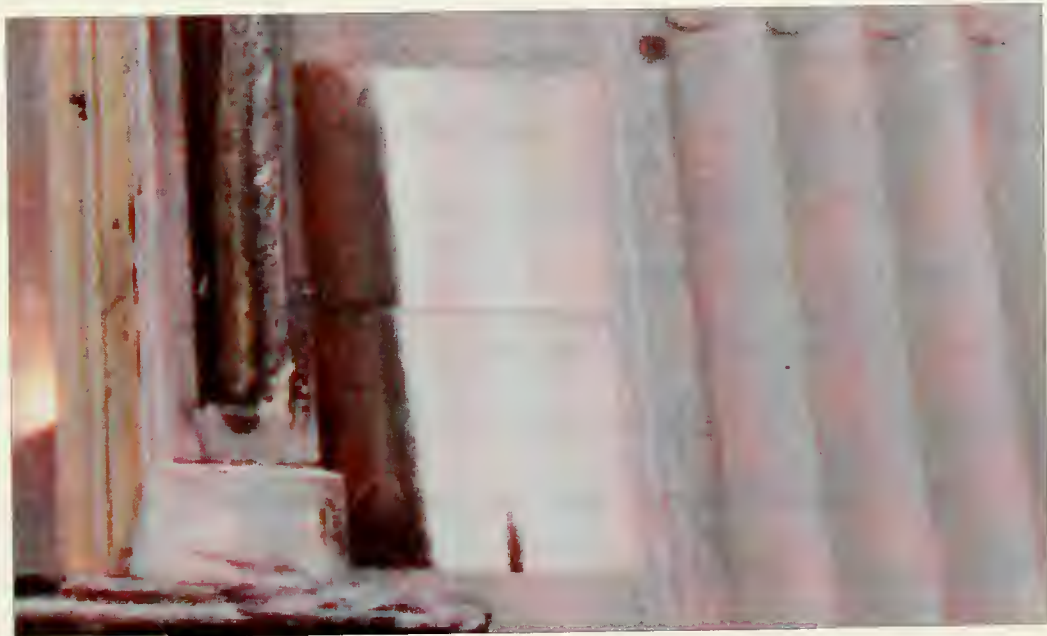
Figure 3.14: A combination of blackening and iron-staining on the left is non-existent on the right of these two blocks in the center of the photograph. The Similar to the iron-stained blocks, rain runoff appears to be washing part of the surface.
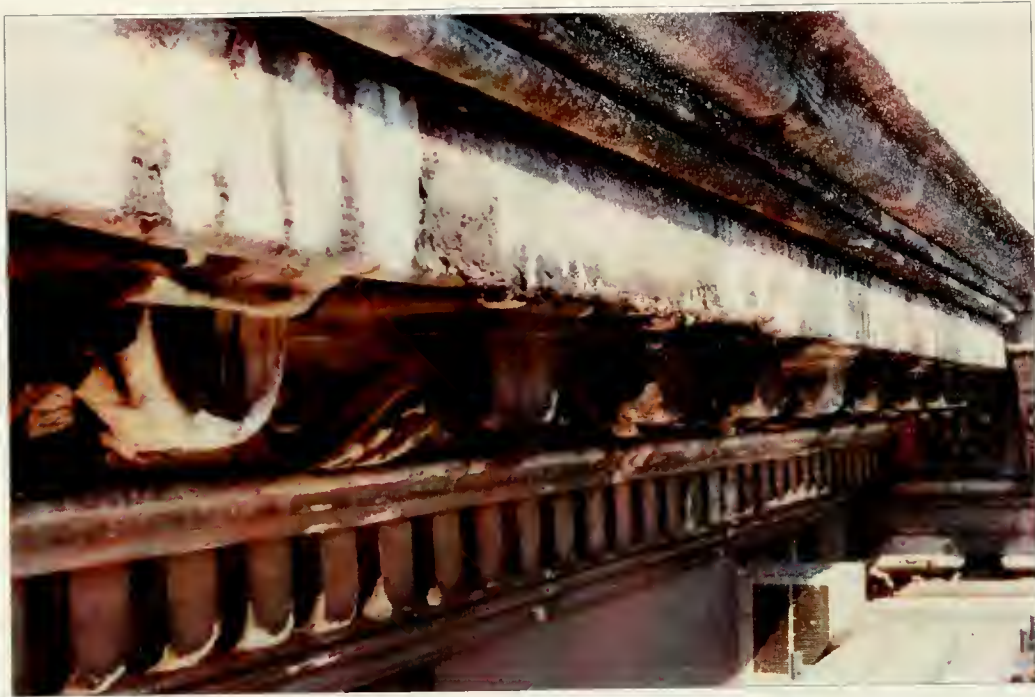
Figure 3.15: Exposed areas where moisture is likely to collect, such as the cornice, show the most intense staining and decay.

Sheffield stone and to the microclimate of this section of the building.

3) Elsewhere, the same type of stone appears to be an "unstained" white color. The white is often side by side with black staining on the same piece of stone. This may simply be a less iron rich version of the previously described stone. A factor that appears to affect the relative cleanness of all of the exterior stone at the Tweed Courthouse is the amount of runoff across the surface of the building (see Figure 3.14). In the case of the white stone, areas that are regularly washed by rainwater seem to be cleaner than other areas where moisture may linger and not evaporate, like the cornice area shown in Figure 3.15. Unwashed locations are prime for the conversion of sulfurous particulates into gypsum and the initial migration of soluble salts into the stone.

4) Visual distinction between what appear to be the Sheffield and Tuckahoe blocks, based on the observed weathering properties, was easily made prior to cleaning.

Both are mixed randomly, and even close proximity did not make the weathering more uniform. Figure 3.16 shows the typical juxtaposition.

5) Gypsum formation in especially exposed areas of the balustrade and cornice, produced hardened surface crusts beneath which water infiltration and freeze-thaw cycling continued to act on sound stone. This is evident in Figure 3.17. Both types of stone seem to have been affected by this phenomenon in very exposed locations.

Drawing on the facts of the Tweed Courthouse's construction, the historic accounts of both types of stone, and the observations of testing in the past 25 years, general characterizations of the Tuckahoe and Sheffield marble can be made. The Tuckahoe can be expected to weather to a dull gray, crack and break off in especially fine detailing, and exhibit pocking and iron staining in some areas. When the original dressed and finished surface of ornamental stone has weathered a few millimeters, the large grains become exposed and extremely friable. This characteristic texture is visible in Figure 3.2. The finer-grained Sheffield marble can be expected to acquire a reddish hue or extreme blackening when it weathers. In areas where the surface of the Sheffield stone is washed by water, especially by runoff from the magnesium rich Tuckahoe, the stone may stay closer to its original pure-white color. When the surface is eroded, the loosely crystalline stone often turns to marble sand. Both types of marble are susceptible to formations of gypsum crust, but the calcitic Sheffield is more likely to suffer from serious decay due to calcite's faster reaction rate with airborne pollutants.

The photographic record makes it clear that the earlier, obvious signs of differential weathering are no longer there to assist in the identification of Sheffield and Tuckahoe marble in their various locations on the building. That pronounced differences

Figure 3.16: This photograph illustrates the juxtaposition of different stone types that is clear today but which was not obvious at the time of construction. Iron-stained blocks in the wall, probably Sheffield marble, are visually distinguishable from the gray, discolored stone, which is probably Tuckahoe. The window jambs both appear to be Tuckahoe, although the one on the left is significantly more chipped and discolored.

Figure 3.17: A modillion appears to be splitting at the seams due to continued freeze/thaw cycling beneath a hard surface crust of gypsum. Note the semicircular patterns of brownish and blackish iron deposits due to the diffusion of iron leachates and other atmospheric pollutants.

in weathering did exist between certain types of stone on the exterior of the courthouse was not in doubt in previous rounds of analysis. However, the differences in weathering were not attributed to different quarry origins for the Tweed marbles. Neither Ammann & Whitney nor Mesick, Cohen, Waite went so far as to characterize the observed behavior as being indicative of Tuckahoe or Sheffield marble. While the purpose of their work was not to come to any conclusion on this point, their data leave the door open for further investigation.

With the wealth of high technology now available for the analysis of building materials, more traditional analysis is often neglected. Along with some cursory optical microscopy, the most advanced analytical tools available at the time, SEM, XRD, and EDXA, were applied to marble specimens from the Tweed Courthouse. Surprisingly, the characteristics of Tuckahoe and Sheffield marble have not been investigated extensively

using thin section microscopy. The only known thin section analysis of Tuckahoe marble

was performed by Matero and Tagle (1995), and thin section has never been used with

Sheffield marble. This method of investigation can yield a great deal of information about

the composition and behavior of stone. For that reason, thin section microscopy was used

in the laboratory research phase of this project to characterize the basic properties of the

Tweed Courthouse marbles. The results of this investigation will be discussed in Chapter

4. Thin section analysis may not entirely explain the differential weathering of marble

observed at the Tweed Courthouse in the past, but it will help to characterize the

microstructures of Tuckahoe and Sheffield marble. These parameters can offer insight

into the weathering behavior of the stone as it has been documented in the more than 120

years of the courthouse's existence.

CHAPTER IV

Analysis and Observations

Rationale for Testing Program

Marble has spawned a long history of investigation. Historians, archaeologists, geologists, engineers, and, more recently, fine arts and architectural conservators have all taken an interest in researching the structure, composition, and behavior of the "noblest" of building materials. As a result of this interest, there is no lack of published material on a number of topics related to marble, including its mechanisms of decay.

One area of marble research has focused consistently on primary causes of decay. Geologists and engineers have prompted the larger part of the dialogue on this topic to date. At least since 1884, with the publishing of the *Tenth Census* and its report on building stones in the United States, observers have speculated on the mechanisms responsible for the initial deterioration of marble.[102] Alexis Julien believed that the crystalline structure of marble, in which grains are not held together by any kind of cement but rather by extreme tension, was susceptible to very slight variations in temperature. He surmised that heating and freezing cycles could cause the grains to slide past each other, wearing down the original intergranular cohesion on a microscopic level. Once this had been accomplished, the stone was vulnerable to other decay mechanisms. Julien placed the effects of temperature ahead of other factors in trying to explain the first stages of structural breakdown.

---

[102] Julien's observations in "The durability of building stones in New York City and vicinity" are discussed in Chapter II.

In 1919, David Kessler, a researcher at the Bureau of Standards in Washington, D.C., observed that heating may cause permanent deformation in marble.[103] Once a marble sample had been exposed to repeated heating, its actual dimensions appeared to change inalterably. Widhalm, Tschegg, and Eppensteiner recount the history of research on the effects of thermal deformation of marble since that time.[104] They write that Rosenholtz and Smith arrived at similar conclusions in 1949, as did Thomasen and Ewart in 1984, Monk in 1985, and Wilson in 1989. However, the general opinion among these scientists held the presence of moisture to be an important factor in determining thermal alteration. The permeability of thin marble slabs, and hence their capacity for water absorption, was thought to be a controlling variable in thermal deformation.

Widhalm, et al. write that a secondary factor considered by Rosenholtz and Smith was the thermal anisotropic behavior of calcite. Dreyer in 1974 and Samen in 1991 also took this factor into account. Stiny in 1935, Neumann in 1964, and deQuervain in 1967 concluded that thermal anisotropy of calcite grains was actually the most important determinant of the loosening of grain boundaries in marble after thermal cycling.[105]

An explanation of the extreme thermal anisotropy of calcite is important in understanding the breakdown of marble. When heated, calcite does not expand uniformly in all directions. The linear coefficient of thermal expansion is $\alpha = (1/t)(dl/dt)$, where l=length, t= temperature, and the change in both is indicated by d.[106] Materials like glass and cubic crystalline solids are isotropic. When a material has a lower crystallographic symmetry due to the preferred orientation or texture of the individual

---

[103] Kessler, D.W. "Physical and chemical tests on the commercial marbles of the United States," *Technologic Papers of the Bureau of Standards,* Government Printing Office: Washington, 1919.
[104] Widhalm, Clemens, Elmar Tschegg, amd Walter Eppensteiner. "Anisotropic thermal expansion causes deformation of marble claddings." *Journal of Performance of Constructed Facilities*, Feb. 1996, p. 5.
[105] Ibid, p. 5.
[106] Ibid., p. 7.

grains, it may be anosotropic.[107] Widhalm et al. consider the direction of trigonal calcite

monocrystals within a polycrystalline marble to be the chief determinant of deformation

in marble slabs. The preferred orientation, or texture, of marble, as dictated by the

layering of grains during the formation of sedimentary limestone and the processes of

metamorphosis, in conjunction with the anisotropy of calcite, largely determines the early

loosening of grain boundaries leading to decay. In calcite, anisotropy is expressed as a

comparison of thermal expansion in two directions: parallel ($\alpha\| = +26.10^{-6}\,K^{-1}$) and

perpendicular ($\alpha\bot = -6.10^{-6}\,K^{-1}$) to an imaginary c-axis through the center of a crystal.

[108]These demonstrate the directional difference in expansion and contraction when a

calcite crystal is heated.

Based on their experimental measurements, Widhalm et al. concluded that: 1)

residual dilatation (permanent deformation) occurs after heating; 2) the first round of

heating is the most important for dilatation; 3) the direction of expansion is dependent on

the crystallographic preferred orientation (texture); and 4) water absorption capacity

increases with the number of heating cycles. Thermal anisotropic expansion of calcite,

therefore, is believed to the first step in the breakdown of calcitic marbles. Significantly,

the temperature variations leading to a breakdown of cohesion along grain boundaries do

not have to be great. Normal seasonal and day-night differences in temperature, even in

temperate climates, are sufficient for this to occur.[109]

Like Julien, Siegesmund et al. concluded that the major effect of thermal

dilatation is a reduction of cohesion along grain boundaries and the formation of inter as

---

[107] Ibid., p. 7.
[108] Widhalm et al., p. 35.
[109] Siegfried Siegesmund, Thomas Weiss, Axel Vollbrecht, and Klaus Ullemeyer. "Marble as a natural building material: rock fabrics, physical and mechanical properties." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, p. 247.

well as transgranular (intragranular) cracking.[110] They expand on Widhalm's analysis by

considering two-phase marbles that may be composed of calcite and its close cousin,

dolomite. Dolomite has a high thermal coefficient α, meaning that it readily expands

when heated. The experimental linear coefficient of thermal expansion in dolomite was

reported as follows: α minimum equals $11.9 \times 10^{-6} K^{-1}$, while α maximum equals 13.8×10^{-6}

K^{-1}.[111] For calcite, α minimum is $2.4 \times 10^{-6} K^{-1}$, and α maximum is $6.7 \times 10^{-6} K^{-1}$, smaller

than dolomite. Additionally, the degree of anisotropy in dolomite is small, meaning that

it expands more or less equally in all directions. In contrast, calcite is highly anisotropic,

as shown above.[112] Consequently, the calcite to dolomite ratio of a marble can affect

property changes. Siegesmund et al. reported that the interdependence between the

coefficient of thermal expansion and the calcite content per volume appeared to be

linear.[113] The more calcite present in a marble sample, the lower the overall observed

thermal expansion. Likewise, the more dolomite, the greater the overall observed

thermal expansion. However, one would expect anisotropic thermal expansion to be

greater in marbles with a higher calcite content.

Widhalm et al. consider texture, shape fabric, and microcracks to be the

controlling variables of thermal dilatation, and these are additionally controlled by the

mineralogical composition of the marble. They also found a correlation between grain

size and the formation of microcracks. Marbles with a larger grain size exhibited

---

[110] Siegfried Siegesmund, Klaus Ullemeyer, Thomas Weiss, Elmar K. Tschegg. "Physical weathering of marbles caused by anisotropic thermal expansion." *International Journal of Earth Sciences*, 2000, v. 89, p. 177. A 1986 article by Reeder and Markgraf provides a thorough discussion of the opposite thermal expansion behaviors of calcite and dolomite. See Richard J. Reeder and Steven A. Markgraf, "High temperature crystal chemistry of dolomite," *American Mineralogist*, 1986, v. 71, pp. 795-804.

[111] Ibid., p. 178.

[112] Ibid., p. 178.

[113] Ibid., p. 178.

cracking at significantly lower temperatures than fine-grained marbles.[114] Conversely, only the finer-grained marbles seemed to undergo plastic, thermally-induced bowing.

An additional parameter of thermal deformation of marble considered by Siegesmund et al. was grain boundary geometry as determined by recrystallization processes. In their analysis, fracture strength appeared to correlate with grain boundary geometry. Straight or slightly curved grain boundaries were characterized as showing weakening phenomena at lower tensile, compressive, or shear stresses than grains with interlocking or strongly curved grain boundaries.[115] Thomas Weiss et al. also found that straight grain boundaries were less resistant to crack propagation than interlocking or curved grain boundaries.[116] Tschegg et al. (1999) saw a correlation between the ability to withstand thermal deformation and the observable properties of grain orientation and grain size. [117] In their experiments, finer-grained marbles with a low degree of grain-orientation, like Carrara marble, were more susceptible to thermal deformation than larger grained-marbles with a more distinct orientation, such as the Hartensteiner marble.

Clearly, much of the most interesting research into the primary causes of marble decay has focused on thermal anisotropy of constituent minerals and the related breakdown of cohesion along grain boundaries. The quantification of rock fabrics has shown to be very useful in understanding the weathering of marbles, and it is an approach that is worth taking in a study of marble from the Tweed Courthouse. Microstructure is as important to the processes of weathering as mineralogical composition.

---

[114] Ibid., p. 180.
[115] Ibid., pp. 180-181.
[116] Thomas Weiss, Bernd Leiss, Heidrun Opperman, and Siegfried Siegesmund. "Microfabric of fresh and weathered marbles: implications and consequences for the reconstruction of the Marmorpalais, Potsdam." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, p. 329.
[117] Elmar K. Tschegg, Clemens Widhalm, and Walter Eppensteiner. "Ursachen mangelnder Formbeständigkeit von Marmorplatten." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp. 283-297.

The current body of research suggests the following parameters for investigation:

1) Characterization of constituent and accessory minerals and their interaction

2) Characterization of the microcrack population, especially inter and intragranular cracking

3) Analysis of preferred orientation and its relation to thermal deformation

4) Analysis of grain dimensions and grain size distribution

5) Analysis of grain boundary geometry

6) Observations about mechanisms of decay

Testing Program

As discussed in Chapter III, microscopic thin section analysis is a powerful tool for the characterization of basic stone properties. Surprisingly, this method has never been used at the Tweed Courthouse. Because of the amount of information it can provide, microscopic thin section was chosen as the primary method of analysis for the investigation of Tuckahoe, Sheffield, and Cherokee marbles used in the construction and restoration of the Tweed Courthouse exterior. By observing a sample of stone sliced to a thickness of 1 micron, some of the most important questions about the weathering behavior of a stone can be answered. This is especially true when correlated with patterns of field-observed weathering phenomena. Features that can be differentiated and quantified are: the general mineralogical composition and the ratio of different minerals to one another; grain size, shape, distribution, perimeter, and boundary; microcrack population; and the existence of surface pollutants or biological growth.

As part of the process of creating thin section slides, each sample was vacuum-impregnated with blue dye to highlight the microcrack population, and half of each slide

was stained to indicate the presence or absence of calcite, the dominant mineralogical constituent of most marble. What remained of the original sample was retained for comparison with the thin section slide.

The original samples were also analyzed to understand the differences in fracturing between fresh and weathered marble. Grimm observed a relationship between the degree of weathering and the amount of intracrystalline cracking in marbles.[118] Fresh marbles tended to have subvalent to prevalent granular cohesion (20%-100% intragranular fracturing), while weathered marbles tended to have subvalent granular cohesion (0%-70% intragranular fracturing). He concluded that weathered marble usually has a higher degree of intergranular cracking than fresh marble because of loss of cohesion along grain boundaries.[119] More weather-resistant marbles were characterized by a higher degree of intragranular cracking. Observed differences in granular cohesion between weathered and unweathered marble can be an indicator of the material's resistance to weathering.

Augmenting a visual analysis of the thin section slides, computer-aided analysis of the slides using Bioquant® software was performed. Bioquant® is a Windows-based application designed to perform quantitative analysis on organic matter such as cell tissue for biological and pharmaceutical research. It has not been used widely for building materials research. This software was selected by the Architectural Conservation Laboratory at the University of Pennsylvania for microstructural analysis of porous building materials at Mesa Verde National Park as part of a research grant from the National Park Service. By applying Bioquant® to marble in thin section, it was hoped

---

[118] Wolf-Dieter Grimm, "Beobachtungen und überlegungen zur Verformung von marmorobjekten durch gefügeanflockerung." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp. 199-201.

[119] Grimm, p. 202.

that some of the analysis traditionally performed by the researcher, such as calculation of individual grain size, shape factor, and perimeter, could be performed by the computer. The first step of this process involved making images of the thin section slides readable by the software. Photomicrographs of each slide were scanned into the computer, and the photos were imported into Adobe Photoshop®. The grain boundary geometries in a 1 square cm area of the slide were then "hand drawn" in Photoshop®. After this, the 1 cm square images were opened in Bioquant®, and four parameters for analysis were set: grain area, average diameter in a grain, perimeter, and Paris factor. Applying these parameters to the images provided data almost instantaneously. The data were then copied to Excel® to calculate grain size distribution, gradation coefficient, and inequality grade.

Paris factor, also known as shape factor, defines the irregularity of the grain boundaries. According to Weiss et al., it is equivalent to the ratio between circumference and a convex envelope of a grain: "for regular, smooth grain boundaries the Paris factor approximates the value of 1. The more the grain boundaries are irregular, the lower the Paris factor."[120] The equation for Paris factor, calculated in Excel® rather than Bioquant®, is $4\pi (F/U^2)$, where F=surface and U=perimeter. Including two additional parameters discussed by Grimm (1999), gradation coefficient $(So=\sqrt{d75/d25})$ and inequality grade $(U=d60/d10)$ were calculated where d is the diameter of a specified percentage of the grains in a sample.[121] In general, the higher the "toothing factor" of interlocking grain boundaries, and the more irregular the grain boundaries, the stronger the grains cohere to one another. This can be an indicator of resistance to mechanical decay.

---

[120] Weiss et al., p. 317.
[121] Grimm, pp. 199-201.

Like Paris factor, gradation coefficient and inequality grade relate to the degree of mechanical resistance in a stone sample. Marbles with smaller grains tend to fracture more easily than those with larger grains.

As a complementary approach to the thin section and Bioquant® analyses, Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-Ray Diffraction (XRD) were also applied to samples of the two stones. The information gained by cross-referencing scanning electron micrographs, elemental data from EDS, and mineralogical data from XRD with information from thin section analysis and Bioquant® was useful in confirming the final conclusions.

Gathering and Selection of Samples for Analysis

Samples that were processed for thin section slides were gathered from a handful of sources. Most of the stone was collected on site. During the course of replacement, the most severely weathered exterior stone was removed and discarded. Drilling cores, abacuses on the capitals, dumpsters on the scaffolding, and an assortment of other locations accounted for most of these specimens. Therefore, a general location of each sample piece is known, but the exact origin of each piece from a location on the building is not usually known. Understandably, it is not possible to know the original position of the stone in the quarry from which it was removed, either. This information, especially any details about layering and each sample's relation to other strata in the quarry, would be helpful for the kind of petrographic analysis that is being done as part of this research. Some of this information can be inferred from the visible signs of layering in the samples, but it has not been included in the current analysis.

Other stone, especially the replacement Georgia Cherokee, was taken from new blocks delivered to the site. Some pieces of the stone were detached during handling or were removed during the setting of the new cornice, which is composed entirely of the Cherokee marble. Some stone was also taken from blocks of salvaged stone from the building itself. The decayed cornice provided much of the dutchman material for the lower, more visible areas of the building.

A few samples of stone also derive from the actual Briggs quarry in Sheffield, Massachusetts. Large blocks have remained on the quarry site since the last century and these were purchased, shipped, finished, and dressed for use as replacement stone. Consequently, the weathering of the Sheffield marble, particularly in the lower, more visible areas of the building where it is being used again, will be a significant factor in the future behavior of the exterior stone.

A matrix of the samples collected is provided in the Appendix 2. Each piece has been assigned a number and any relevant information about it has been included. Some samples have had thin section slides made from them, but most have not. The general location of each sample on the building has been provided in the matrix. General calcite content is given, and each sample has been labeled weathered or fresh. It is also noted if SEM or XRD has been performed, and if a thin section slide has been made from the sample.

The selection of thin section slides for comparison was based on a positive identification of each as deriving from either the Tuckahoe area of Westchester County, New York or the Sheffield quarry in Massachusetts. It was essential that the identification of each be accurate. This main criterion narrowed the number of useable thin section slides considerably. The slides themselves have been numbered based on the

matrix identification number plus a single-letter prefix, "T", "S", or "G" to denote the likely origin as either Tuckahoe, Sheffield or Georgia Cherokee.

Tuckahoe samples derive from locations on the building that historically have been characterized as being built of Tuckahoe marble. The Eidlitz wing and the North Portico of the Kellum section of the building were the primary sources of Tuckahoe marble for these purposes. Another important criterion was visual similarity between samples of Tuckahoe taken from these areas. Sample number 8, labeled T-8 in thin section, is part of a drilling core taken from the cornice. Its textural and mineralogical properties are a close match for samples taken from the areas of the building known to have been built with Tuckahoe marble. T-8 was the best approximation for a recently quarried sample, since the Tuckahoe quarries have not been open since the early decades of the 20th Century.

Likewise, Sheffield samples were taken only from areas known to have been built with a mixture of Sheffield and Tuckahoe. Samples of stone from the Briggs quarry, one of which is numbered 15 in the matrix and S-15 in thin section, were used to match samples from the building for comparison. One block of stone from the building, 38 in the matrix and S-38 in thin section, is analyzed as fresh Sheffield, because it was large enough that an area with no decay could be obtained several centimeters beneath the surface. S-36 and S-37 are exact textural and mineralogical matches for the S-15 sample from Sheffield and are treated as weathered samples of the stone.

All Georgia Cherokee samples derive from blocks of the stone shipped to the site. Their identity was easier to ascertain than that of the other two types of stone.

The final selection of samples used in this analysis will provide more uniformity within a marble type grouping than may actually exist on the building. The observations

are not intended to characterize the materials on the building per se. Rather, they are

intended to broadly characterize some of the qualities of fresh and weathered marble

from the Tuckahoe quarries in New York and the Sheffield quarry in Massachusetts.

Characterization of Samples

Figure 4.1: A fresh Tuckahoe surface from sample Number 8.

Fresh Tuckahoe

Thin section analysis of fresh Tuckahoe marble was limited to slide T-8, which

was taken from sample 8, a drilling core found at the cornice on the south end of the east

façade. The core was drilled to make room for a large anchor installed to secure the new

cornice stones. Figure 4.1 shows a typical cut surface of the sample.

Mineralogical Characterization: A cursory visual inspection of sample 8 shows

that the fresh Tuckahoe marble is a very white, medium-grained stone with some light

brown inclusions. Staining on the T-8 thin section slide produced a pale rose color, indicating that the dominant mineralogical constituent is probably dolomite. Upon closer inspection, many small flecks of calcite, stained a darker red color, are scattered throughout the sample (see Figures 4.2 and 4.3.) This pattern is repeated in all of the weathered Tuckahoe samples from the Kellum and Eidlitz sections of the building. Calcite and dolomite are difficult to differentiate in the absence of staining or laboratory testing, and the combination of the two in such a uniform mixture was not expected based on previous analysis. This combination may affect some of the properties seen in the weathered samples.

In addition to the primary component dolomite and the secondary component calcite, numerous other accessory components were evident in thin section. The presence of phlogopite and tremolite was noted, as was the presence of a number of other minerals that could not be easily identified. On a microscopic level, the fresh Tuckahoe is very heterogeneous for a stone that appears to be uniform. Figures 4.2, and 4.5 show typical views in thin section.

Structural Characterization: The structure of the fresh Tuckahoe sample is not uniform, and the grain fabric is irregular. Some areas are highly crystalline with interlocking grain boundaries, composed mostly of dolomite and calcite, while others are characterized by a random mixture of minerals and grain sizes and varied grain boundary shapes. The grain boundaries in the uniform areas are angular but not interlocking. Boundary interfaces are generally linear. Figures 4.2 and 4.4 show the compact structure of the sample with characteristic pockets of mixed inclusions.

The grains also have a distinct degree of preferred orientation. This is common in Tuckahoe marble, which often contains layers along which the stone will tend to break.

Sample T-8 was cut to demonstrate this type of layering. Figure 4.4 shows the transition between a layer of mixed minerals and a more purely uniform layer of dolomite, calcite, and a few inclusions.

Microcracking: The fresh sample had very little microcracking. Vacuum impregnation of the thin section sample with blue dye did not reveal significant loss of cohesion along grain boundaries or fracturing across grains. Figure 4.6 shows the surface of the fresh stone in the upper portion of the photo and no visible fractures. The surface of the core seems relatively impervious to moisture penetration.

Surface Fracturing: An idea of grain cohesion can be gathered by comparing the amount of inter and intragranular cracking in different stones. For this investigation, surface fracturing was investigated by looking at a fractured surface under a stereomicroscope (Figure 4.7). In the fractured surface of sample 8, intragranular cracking, obvious by the jagged cleavage across the stone, predominated. Intragranular cracks accounted for about 70% of the cracking, and intergranular cracks accounted for about 30 %. These percentages were cross-referenced by counting the number of inter versus intragranular cracks in 50 grains on the thin section slide. The slide analysis yielded a similar breakdown of 60% intragranular to 40% intergranular cracks. The percentage of intragranular cracks observed, around 60%, would place it in the category of prevalent to equivalent granular cohesion according to Grimm (1999).

Bioquant® Analysis: Analysis of the fresh Tuckahoe thin section slide using Bioquant® showed that 1 square cm contained 207 individual grains. The digitized image of grain boundary outlines in 1 square cm of sample 8 is seen in Figure 4.8. The average grain perimeter was 2.35 mm, the average grain diameter was 0.52 mm, and the average grain area was 407, 500 square microns. The Paris factor was calculated to be 0.53 in

comparison to a perfect convex grain envelope of 1. Additional calculations made with the data obtained from Bioquant® showed that 62% of the grains were between 300 and 1180 microns in diameter. The distribution was even between 150-300, 300-600, and 600-1800 microns in diameter. 26% were smaller than this, while 12% were larger. The gradation coefficient was calculated to be 2.28 and the inequality grade was calculated to be 5.1.

An individual summary of results for T-8 is provided in Table 4.1. A summary of all Bioquant® data and related results for tested samples is given in Appendix 3.

Decay Mechanisms: Although T-8 shows no traces of decay, it has some characteristics worth noting for discussion of the weathered samples. Foremost among these is the heterogeneous mixture of minerals already discussed. Phlogopite, tremolite, and iron minerals, among others, have been observed in the past in Tuckahoe marble and these are in abundance in thin section slide T-8. Calcite, visibly indistinct from dolomite without staining, could also be a factor in the decay of fresh Tuckahoe marble. The different properties of these minerals, including coefficients of thermal expansion and water absorption capacities, contribute to create a relatively unstable marble.

Tuckahoe's acceptable but not outstanding performance as an exterior cladding could derive from the interaction of texture and mineralogical composition. Tschegg et al. (1999) characterized large-grained marbles with strong preferred grain orientation as more resistant to thermal deformation than fine-grained marbles with weak grain orientation. Fresh Tuckahoe marble has larger than average grain size and a distinct preferred orientation. This is offset by the presence of micaceous inclusions that compromise cohesion along the grain boundaries. A marble without the diverse behavior of these inclusions may perform better. Conversely, a marble without as many

inclusions but also without a distinctly preferred grain orientation may not perform as

well as Tuckahoe marble.   On the surface at least, the combination of various minerals

would seem to facilitate decay (see Figure 4.4).

Figure 4.2: A typical view of fresh Tuckahoe marble from thin section slide T-8. Red stained calcite is interspersed with dolomite. The structure appears uniform and crystalline at the top of the photomicrograph. In the lower left, the structure appears more conglomerated. 5x magnification, cross-polarized light.
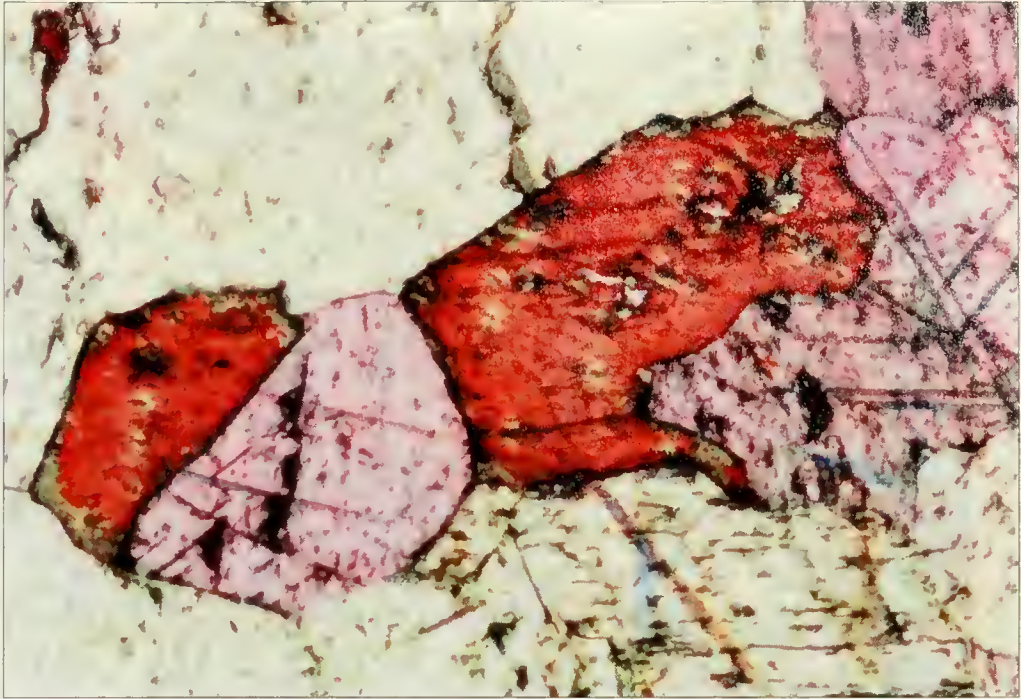
Figure 4.3: Calcite and dolomite distinguished by calcite staining. Lamellar twinning can be seen in crystals to the right of the photomicrograph. The structure is very compact and uniform in some areas but less so in others. The grain boundary shows no separation between crystals. 10x magnification, cross-polarized light.
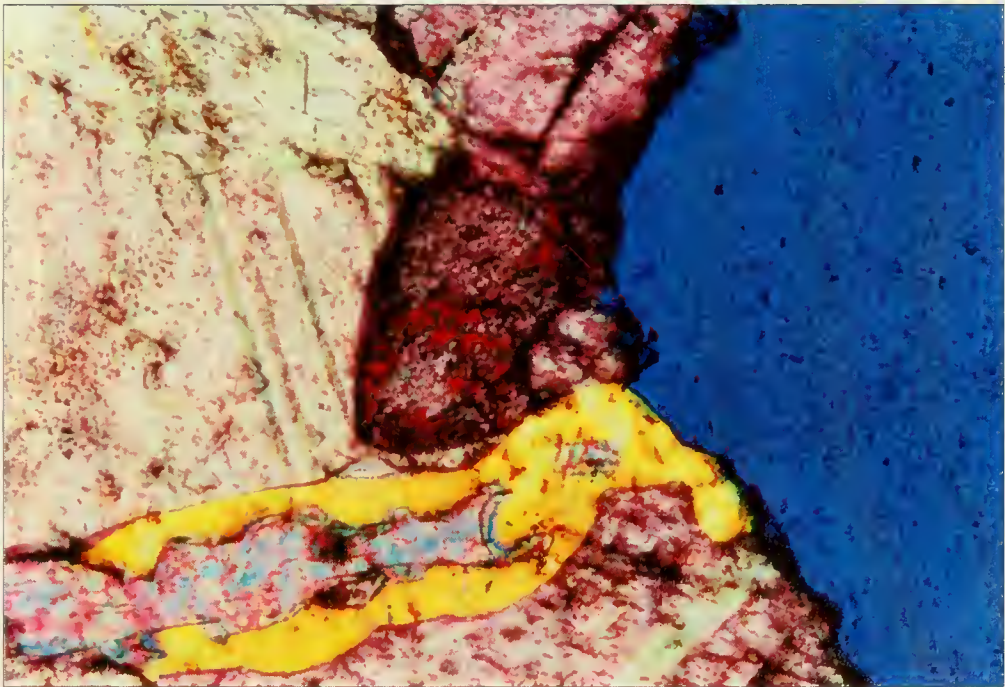
Figure 4.4: Dolomite, red-stained calcite, and phlogopite at the surface of the fresh Tuckahoe sample on slide T-8. Different expansion behavior during thermal cycling will probably cause surface pitting.This image is an interesting contrast to Figure 4.19, a similar but weathered surface. 20x magnification, cross-polarized light.
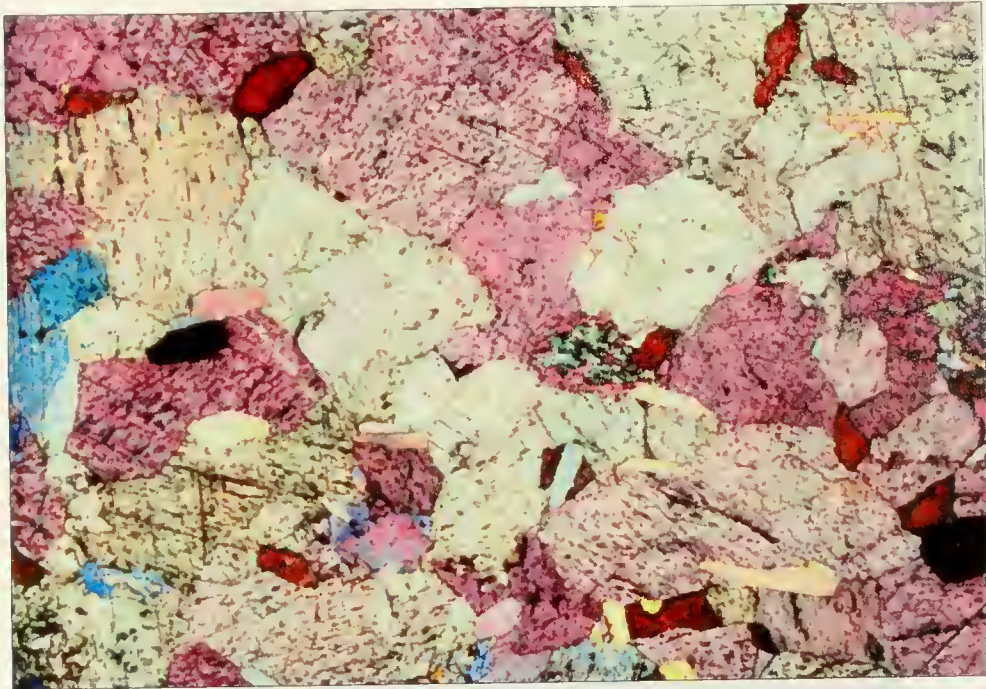
Figure 4.5: Numerous inclusions are seen in the lower half of the picture. The green inclusion appears to be tremolite, while the numerous oblong inclusions are phlogopite. The variety of minerals creates a heterogeneous structure. 5x magnification, cross-polarized light.
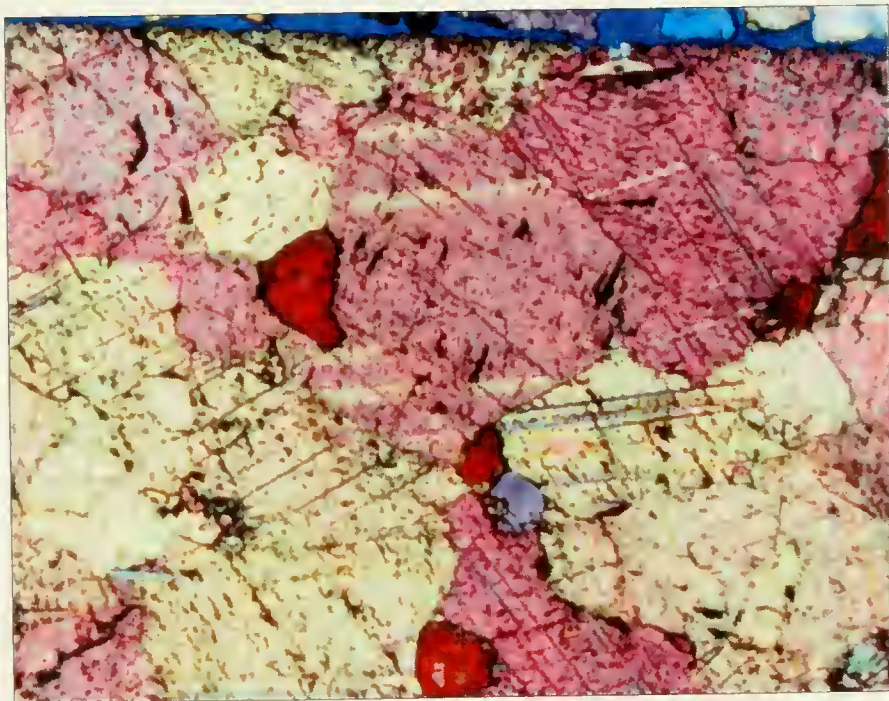
Figure 4.6: An absence of microcracking is evident in this photomicrograph of slide T-8. Vacuum impregnation with blue dye did not reveal any fractures. The clean surface is seen in the upper portion of the photomicrograph bordered by the blue dye. Close-up of 5x magnification, cross-polarized light.

Figure 4.7: A fractured Tuckahoe surface from sample 8 seen in raking light. Intragranular cracking is more common than intergranular cracking.   7.5x magnification, fiber-optic illumination.
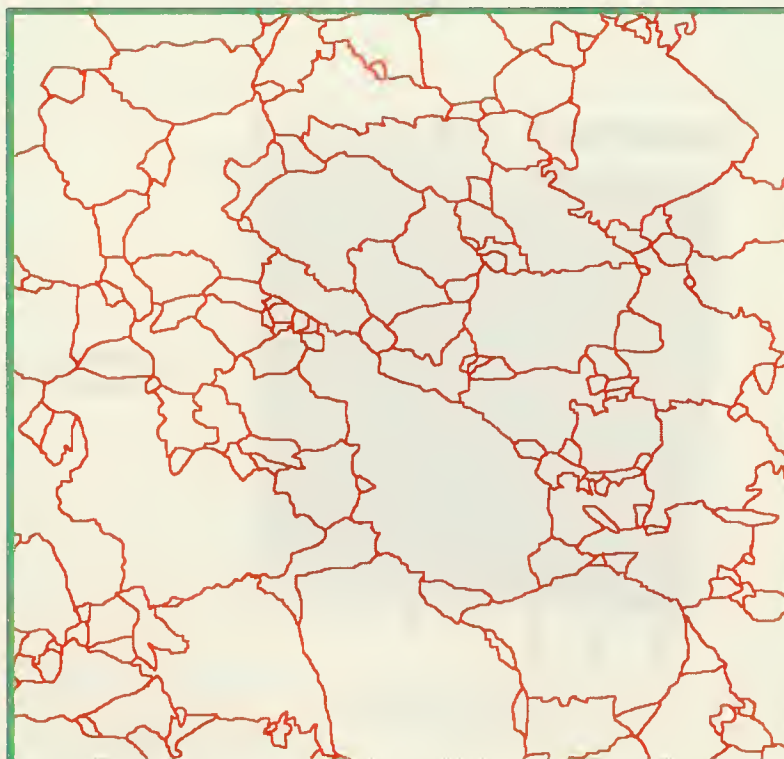
Figure 4.8: Digitized grain boundary image of 1 square cm of Tuckahoe slide T-8.

BIOQUANT ANALYSIS: SUMMARY OF DATA

T-8 Fresh Tuckahoe Marble	
Average Grain Area (square microns)	407,500
Average Grain Diameter in Sample (microns)	522
Average Grain Perimeter (microns)	2,345
Average Grain Paris Factor	0.53
Number of Grains in 1 Square cm	207
Gradation Coefficient (So=$\sqrt{d75/d25}$)	2.28
Inequality Grade (U=d60/d10)	5.10

GRAIN SIZE SUMMATION

Sieve Number	Size (microns)	Number of Grains	Percent
200	0-75	15	7.25%
100	75-150	38	18.36%
50	150-300	43	20.77%
30	300-600	44	21.26%
16	600-1180	42	20.29%
8	1180-2360	24	11.59%
	>2360	1	0.48%
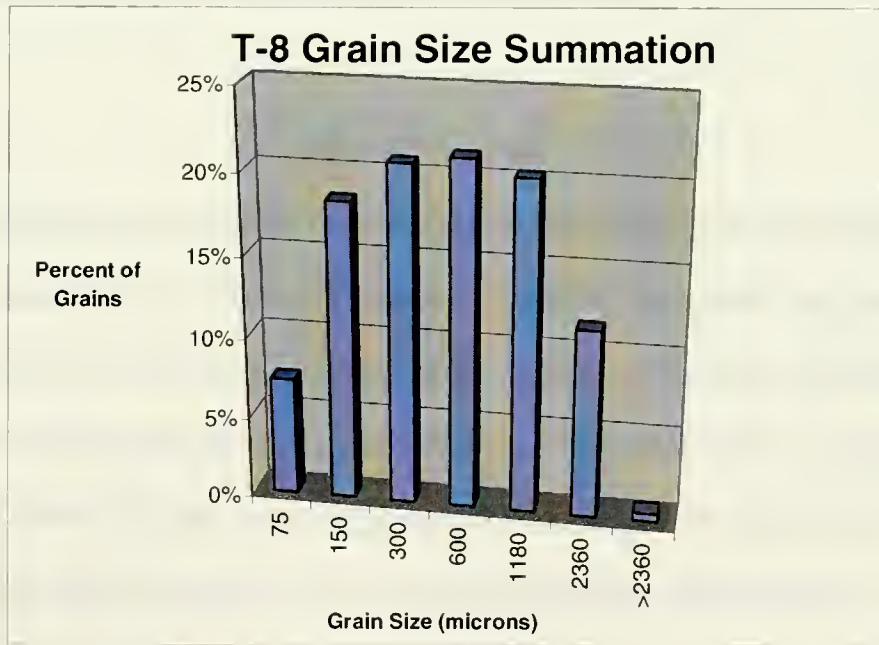
Table 4.1 Summary of Bioquant[®] data and related measurements for slide T-8.
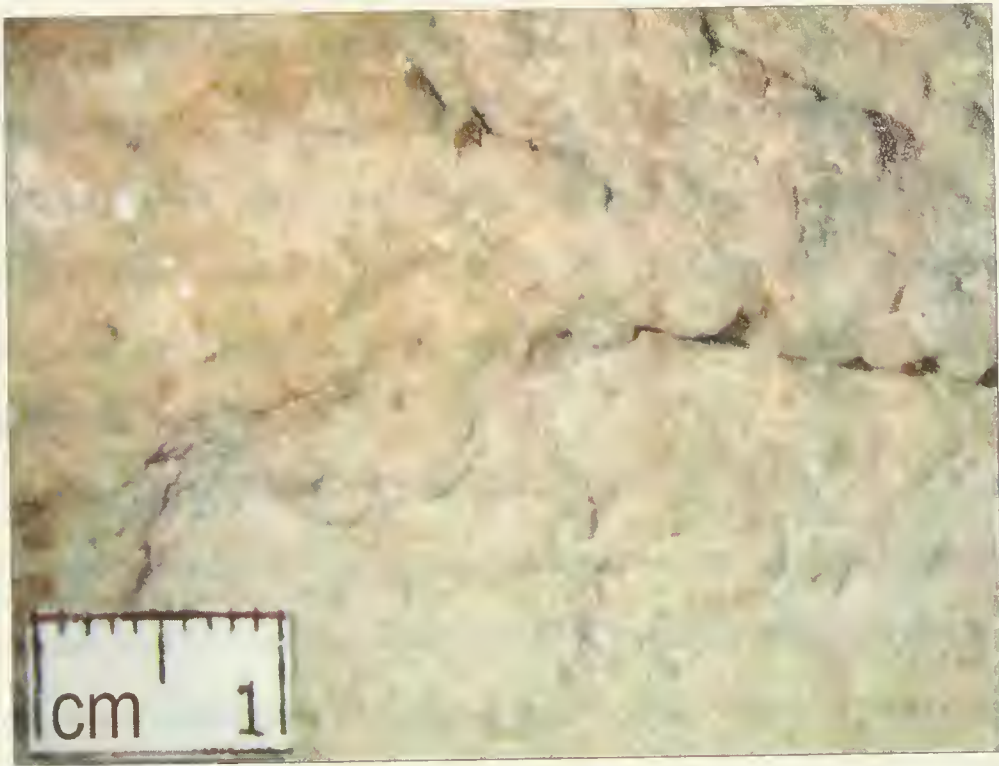
Figure 4.9: Sample 1, a typical weathered Tuckahoe surface. Individual grains have been exposed and rounded. The original white color has turned to a yellowish brown.

Weathered Tuckahoe

Thin sections of several stone samples were classified with relative certainty as weathered Tuckahoe marble. Those that will be referred to in this section were taken from the North Portico of the Kellum section of the building and the Eidlitz section of the building, both of which are believed to have been built of Tuckahoe marble. A typical sample of weathered Tuckahoe is seen in figure 4.9. This sample was taken from an abacus on a capital in the North Portico. The exposed grains are rounded and the surface has turned to a yellowish brown color.

Mineralogical Characterization: The thin section samples analyzed are identical to the fresh sample in mineralogical composition. Figures 4.10 and 4.11 show a piece of finer-grained Tuckahoe from the Eidlitz wing. Figure 4.12 shows another sample from the North Portico. They are predominantly made up of dolomite with uniformly distributed calcite grains together with phlogopite and tremolite. As shown in sample 1, in Figure 4.13, pyrite was seen in addition to other minerals. Slide T-1B was analyzed using Bioquant®. It also contains calcite along with the predominant dolomite and phlogopite inclusions.

Structural Characterization: The structure of the observed weathered Tuckahoe samples is identical to that of the fresh samples. Like the fresh sample, the occasionally composite nature of the weathered samples often conveyed little uniform structure. However, there was greater variation in grain size and grain boundary geometry. Some of the samples were characterized by straight but moderately angular grain boundary geometry, while others have an amoebic grain boundary. In most samples, the dominant grain size was in the medium range, but within and across samples, there was a high degree of variation. In slide T-4, the grain size was smaller than any other Tuckahoe sample and the grains were considerably rounder (see Figure 4.10). On slide T-1B, seen in Figure 4.12, the grain size is more like the fresh Tuckahoe sample. Some of the grains in all of the weathered samples were so small that they were impossible to observe.

Preferred orientation of the grains was distinct in many of the samples. In slide T-12B, the grains are preferentially oriented vertically in the image, but in slide T-4 the grains show a looser horizontal orientation relative to the image. In general, the weathered Tuckahoe samples are characterized by some degree of preferred orientation, medium grain size, and straight but angular grain boundary geometry.

Microcracking: The microcracking seen in the weathered Tuckahoe thin section slides is characterized by a large amount of opening between and within grains. Intra and intergranular cracking were observed in the fresh sample, and they seem to proliferate after weathering with intragranular cracking becoming notably more prevalent. The degree of intragranular cracking correlates to the strength of cohesion between grains. The more crystalline and angular the grain boundary, and the more tightly cohered the grains, the more likely it is that a fracture will break through the grain and not around it. This is also a function of grain size, as described by Widhalm et al. (1996). Larger grained marbles are less susceptible to intergranular cracking than finer grained marbles. Some areas of the slides are so intensely cracked that it is difficult to imagine how they originally appeared (Figure 4.12). Intragranular cracking is evident to a high degree in T-1A, a larger-grained sample, as shown in Figure 4.15. This behavior was seen in most of the weathered Tuckahoe samples except for the finer-grained T-4, seen in Figure 4.10, which showed almost exclusive intergranular cracking. The prevalence of intragranular cracking in the larger-grained samples and the prevalence of intergranular cracking in the finer-grained samples confirms observations made by Widhalm et al.

Surface Fracturing: By analyzing the fractured surface of sample 1 under the stereoscope, it was observed that roughly 40% of the cracking was intragranular, indicating subvalent to equivalent cohesion. The analyzed surface is seen in Figure 4.22. However, this did not appear to be the case deeper into the stone where the stone was not as weathered. A count of inter and intragranular cracking of 50 grains at a greater depth on thin section slide T-1A produced a breakdown of roughly 30% intergranular to 70% intragranular cracking, indicating prevalent to equivalent grain cohesion. As expected, intragranular cracking predominated in the deeper areas of the weathered Tuckahoe,

which were slightly less weathered. The percentage of intragranular cracks observed overall, around 40%-50%, would place it in the category of equivalent granular cohesion according to Grimm (1999). On the building itself, the areas of weathered Tuckahoe marble are degraded enough that they can be broken off with a minimum of force. Loose individual grains can be scraped from the surface like sand.

Bioquant[®] **Analysis:** As was done with the fresh sample, grain boundaries in 1 square cm of thin section slide T-1B were drawn and digitized in order to calculate a set of parameters in Bioquant[®]. The digitized image of grain boundary outlines in 1 square cm of sample 1 is presented in Figure 4.23. 145 individual grains were calculated in 1 square cm. The average grain perimeter was 3.04 mm, the average grain diameter was 0.59 mm, and the average grain surface area was 590,318 square microns. The Paris factor was calculated to be 0.46 in comparison to a perfect convex grain envelope of 1, the lowest of the marbles. Additional calculations made with the data obtained from Bioquant[®] showed that 56% of the grains were between 600 and 2,360 microns or greater in diameter. However, 44% of the grains were smaller than 600 microns. The largest single diameter category was 600 microns, which accounted for 23% of the whole. 18% of the grains were 75 microns wide or smaller. The gradation coefficient was calculated to be 2.76 and the inequality grade was calculated to be 10.70.

These measurements are close to the measurements made for T-8, the fresh sample. Average grain area, however, was nearly twice as large as the fresh sample and the Paris factor was significantly lower, reflecting the unusual grain boundary geometry, which may be the result of recrystallization. Grain size distribution was not as even as in the fresh sample. An individual summary of results for T-1B is provided in Table 4.2,

and a summary of all Bioquant® data and related results for tested samples is given in

Appendix 3.

Decay Mechanisms: Several factors were observed to have some bearing on the

extreme, intragranular microcracking of the weathered Tuckahoe samples. Iron content,

surface gypsum formation and recrystallization, as well as the behavior of accessory

minerals were considered to be important.

Figure 4.16 shows etching, cracking, and iron staining on the surface grains of T-

1B. Particularly near the exposed weathered surfaces, iron staining was more

pronounced. The source of the iron staining could not be traced to any specific inclusions

in the marble. Rather, the iron seemed to originate from the dolomite crystals themselves

(see Figure 4.17). This may be explained by the chemical makeup of the Tuckahoe

sample, which was analyzed using XRD and will be discussed at the end of the chapter.

The characteristic jagged etching pattern of weathered dolomite was observed on the

exposed edge of sample T-1B. When observed under high magnification, the upper

portions of the weathered surface grains seemed to have taken on a sponge-like structure

due to gypsum formation.

This salt was also observed to have crystallized in the pores created by the

microcracks, further accelerating cracking below the surface of the stone. This occurs

when airborne pollutants land on the stone surface and convert calcium to gypsum in the

presence of moisture. Figure 4.18 shows a typical layering of pollutant deposition on a

Tuckahoe surface. After repeated absorption of water into the substrate, gypsum

crystallizes within the pores of the weathered marble, as seen in Figure 4.19 and 4.21. In

the same photomicrograph, iron spots are also seen on individual dolomite crystals. The

same is seen in Figures 4.20 and 4.21closer to the weathered surface. Microcracks

emanating from a calcite crystal wedged between two dolomite crystals harbor recrystallized salts.

The opposite thermal dilatation behavior of calcite and dolomite is one possible reason for microcracking at this location and elsewhere in the Tuckahoe marble. While dolomite is quicker to expand, its anisotropy is low. As Siegesmund et al. (1999) noted, in a pure dolomitic marble, the thermal expansion coefficient is large while the degree of anisotropy is small. Calcite, on the other hand, is slower to expand but is highly anisotropic. This may explain why some microcrack networks in the weathered Tuckahoe samples seem to be connected by nodes of calcite. A random but distinct distribution of calcite crystals within the largely dolomitic marble could contribute to early microcracking.

The action of mineral inclusions within the stone is a major source of surface decay. As explained by Lewin and Charola, platy or fibrous inclusions occurring at or just below the surface trap liquid water.[122] Immense interlaminar pressure is built up in the micaceous phlogopite by the absorption of water during freeze thaw cycling. This pressure causes the inclusion to expand and eject any surface material above it. In this way, inclusions within 1-3 millimeters of the surface are capable of swelling and bursting in this way. Phlogopite and tremolite were evident in all of the Tuckahoe samples, and they are noted in Figures 4.13, 4.14, and 4.23. Their presence in this and other samples is undoubtedly responsible for some of the initial surface decay of Tuckahoe marble.

---

[122] Seymour Lewin and A. Elena Charola, "Stone decay due to foreign inclusions." *The Conservation of Stone II: Preprints of the Contributions to the International Symposium, Bologna, 27-30 October 1981, Part A: Deterioration.* Bologna, 1981, p.210.
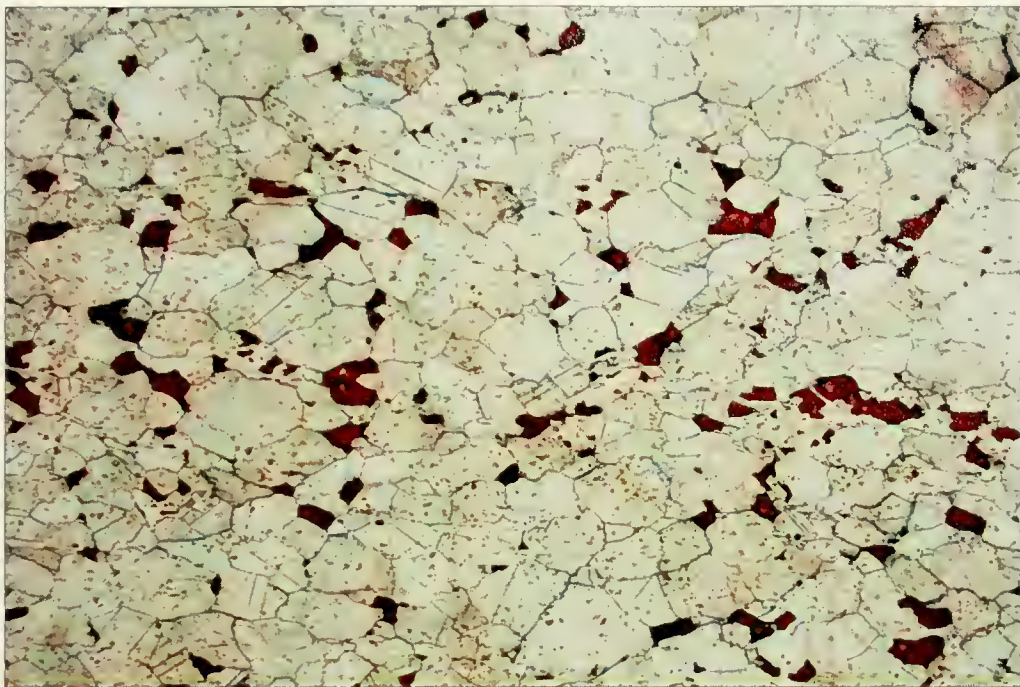
Figure 4.10: Thin section slide T-4 from the Eidlitz wing. Calcite is interspersed with dolomite. The grains are much finer and rounder, and fewer inclusions are seen in this sample than in the fresh sample. Grains are oriented more or less horizontally. Intergranular cracking is indicated by the vacuum impregnated blue dye. 1.25x magnification, plane polarized light.
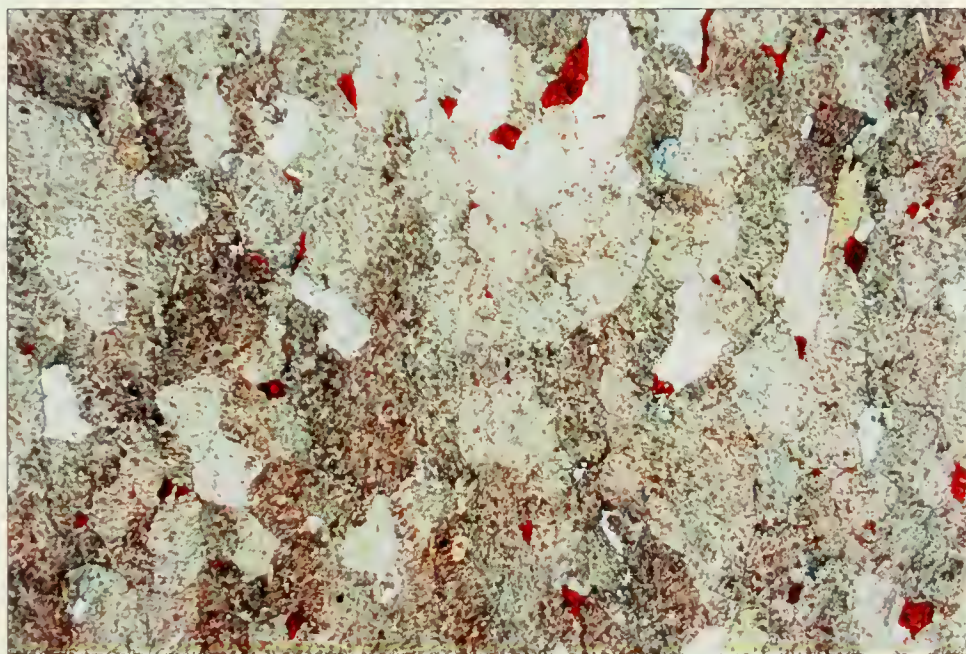
Figure 4.11: Thin section slide T-12B from the Eidlitz Wing. Again, calcite is interspersed with dolomite. Grains show a more or less vertical orientation relative to the photomicrograph. 1.25x magnification, cross-polarized light.
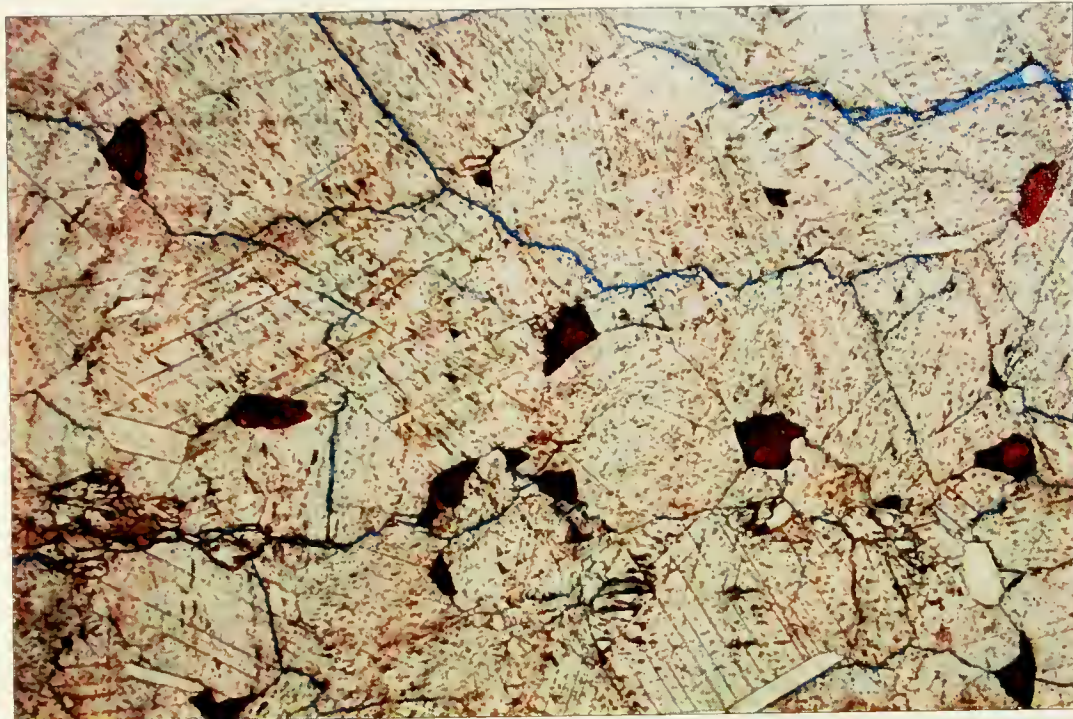
Figure 4.12: Thin section slide T-1B. Red-stained calcite is scattered throughout, and oblong phlogopite inclusions are visible in the lower right. Cracking, seen in blue, seems to emanate from and connect the calcite grains. 5x magnification, plane-polarized light.
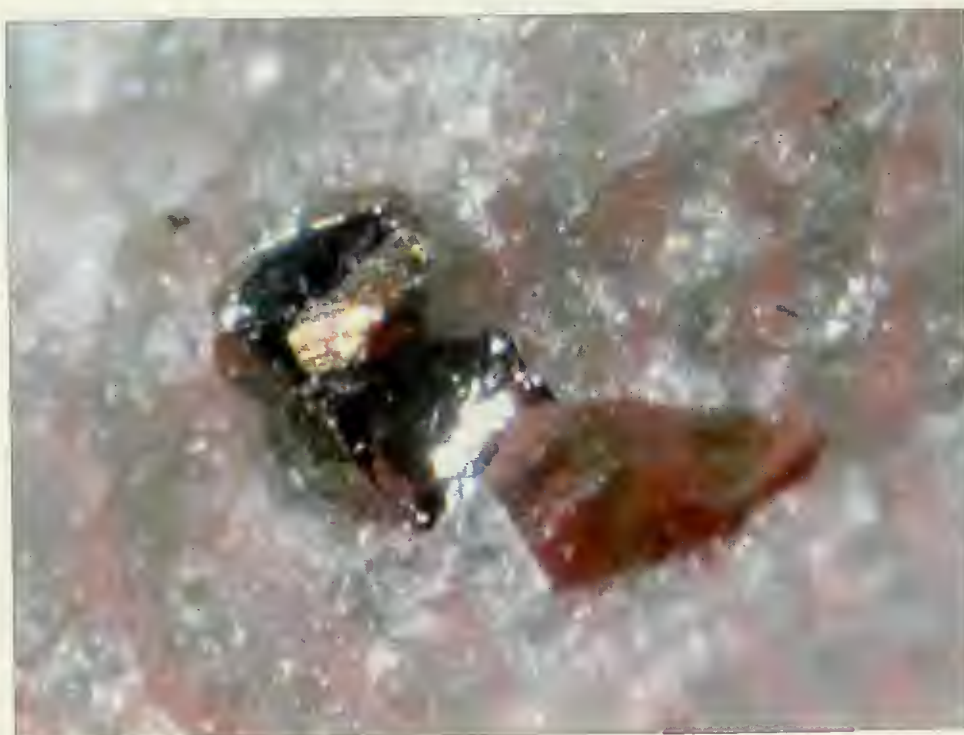
Figure 4.13: Pyrite (left) and phlogopite (right) in a fractured surface of sample 1 seen under a stereomicroscope. 38x magnification, fiber-optic illumination.

Figure 4.14: Slide T-1A, a typical weathered specimen with extensive microcracking. Crack networks are highlighted by vacuum-impregnated blue dye. Oblong phlogopite inclusions are visible at the center of the image. The exposed weathered surface is at the bottom of the picture. Photomicrograph is 1 cm wide, slide is unstained for calcite. 1.25x magnification, plane-polarized light.

Figure 4.15: Intragranular cracking below a weathered surface in thin section slide T-1B, taken from an abacus on the North Portico. The original grain boundary is shown in yellow, cracks are indicated by the presence of blue dye, and intragranular cracks are indicated by red arrows. 50x magnification, cross-polarized light.
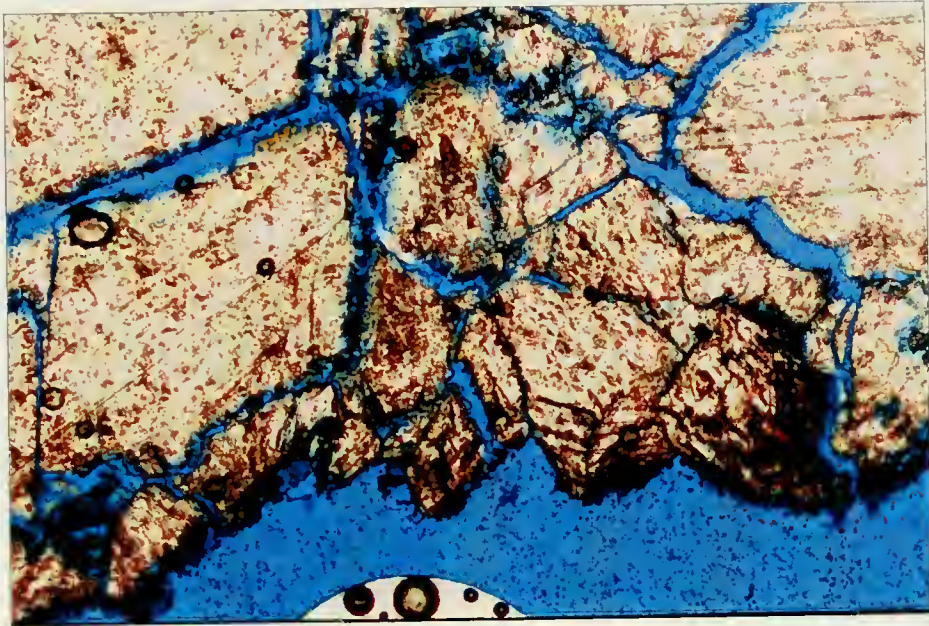
Figure 4.16: Heavy etching, cracking, and iron staining of surface grains, slide T-1B. The weathered surface is bordered by the blue dye matrix. 5x magnification, plane polarized light.
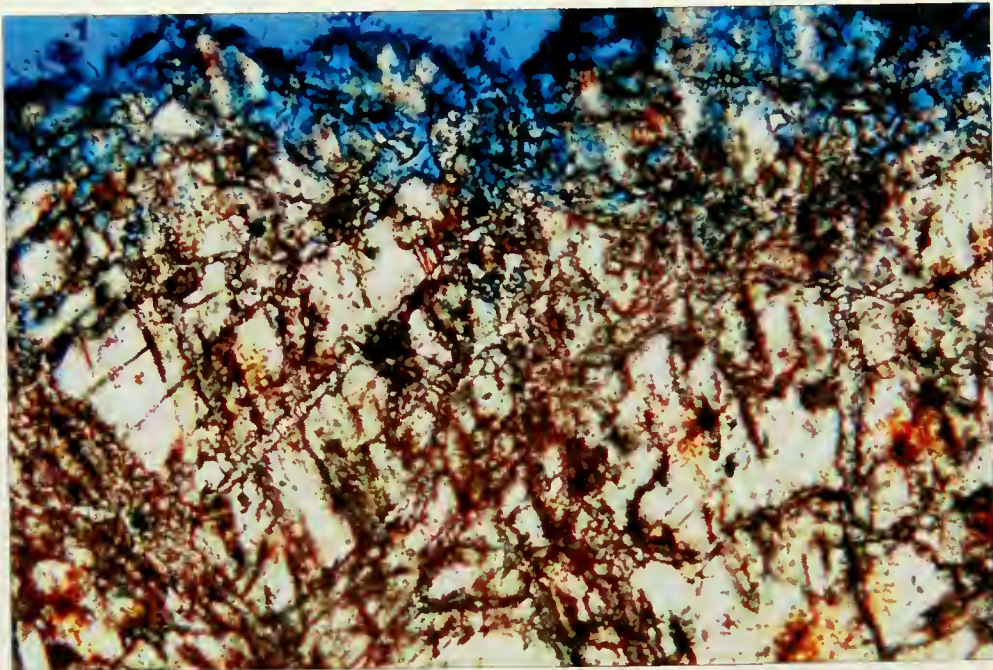
Figure 4.17: Iron staining and acid etching of surface dolomite crystals on slide T-1B. The surface appears at the top of the slide. Reddish iron spots seem to originate in the dolomite crystals themselves. Weathering has created an almost sponge-like structure in the exposed grains 20x magnification, plane polarized light.
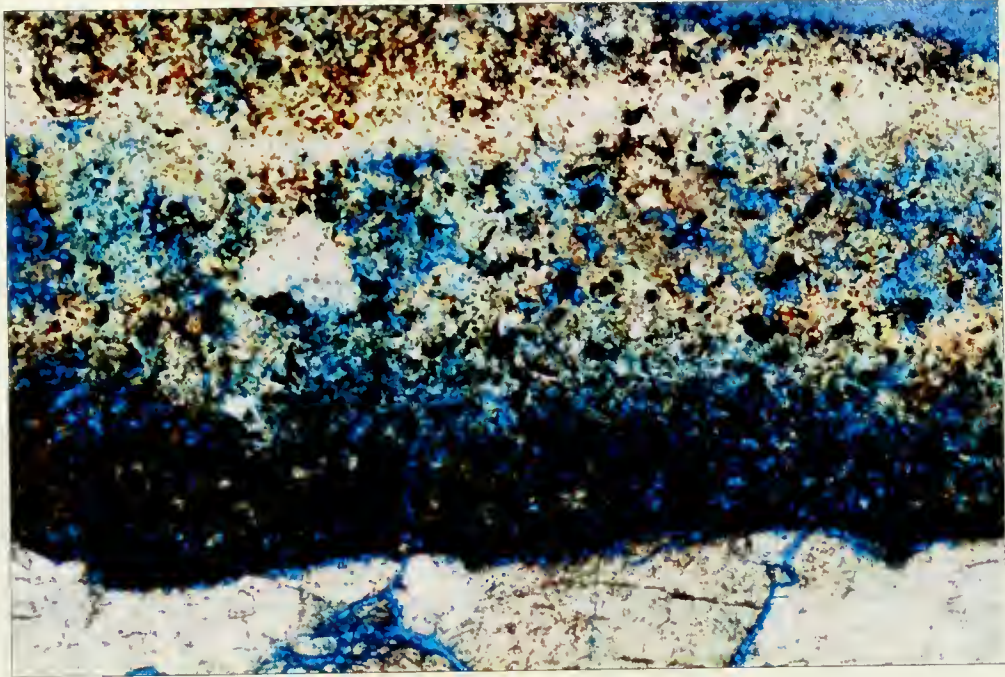
Figure 4.18: Layers of sulfurous pollution have formed a crust 1mm thick on this surface, from slide T-17. A combination of thermal expansion and infiltration by soluble salts probably leads to the surface decay of Tuckahoe marble. The substrate is seen at the bottom and the blue dye matrix is seen at the top. 5x magnification, plane-polarized light.
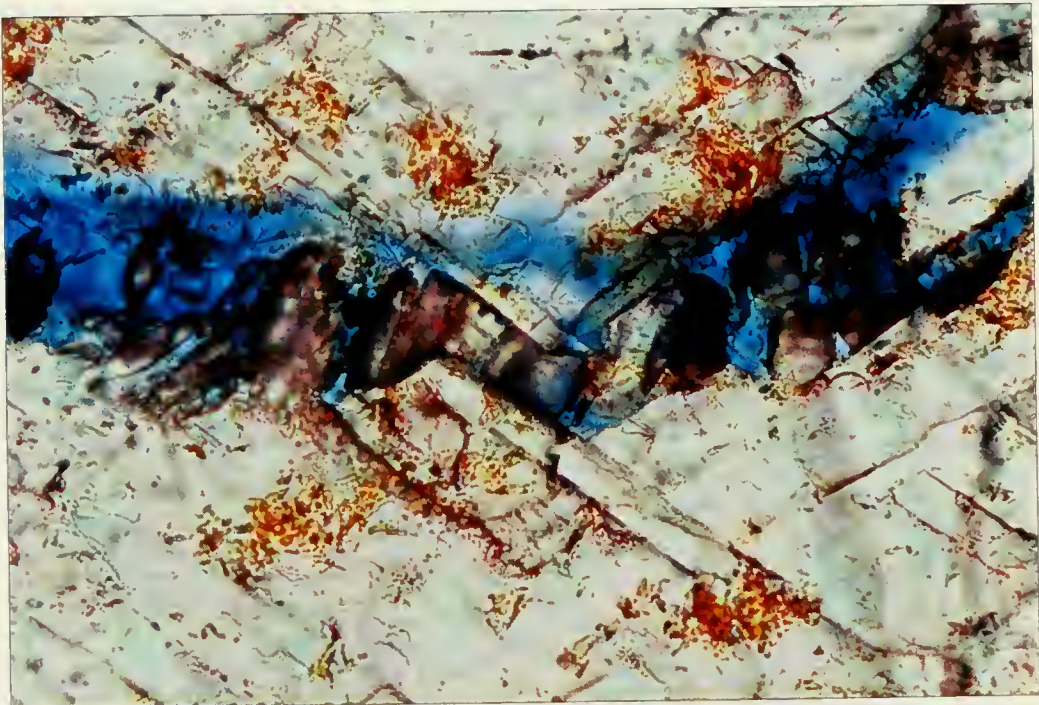
Figure 4.19: Gypsum recrystallization within microcracks, slide T-1B. Due to its relative higher solubility, it has penetrated the stone and recrystallized, creating additional pressure in the openings. Iron spots are also visible. The rhombohedral structure of the dolomite grains is seen in the translucent cross-hatching patterns. 40x magnification, plane-polarized light.
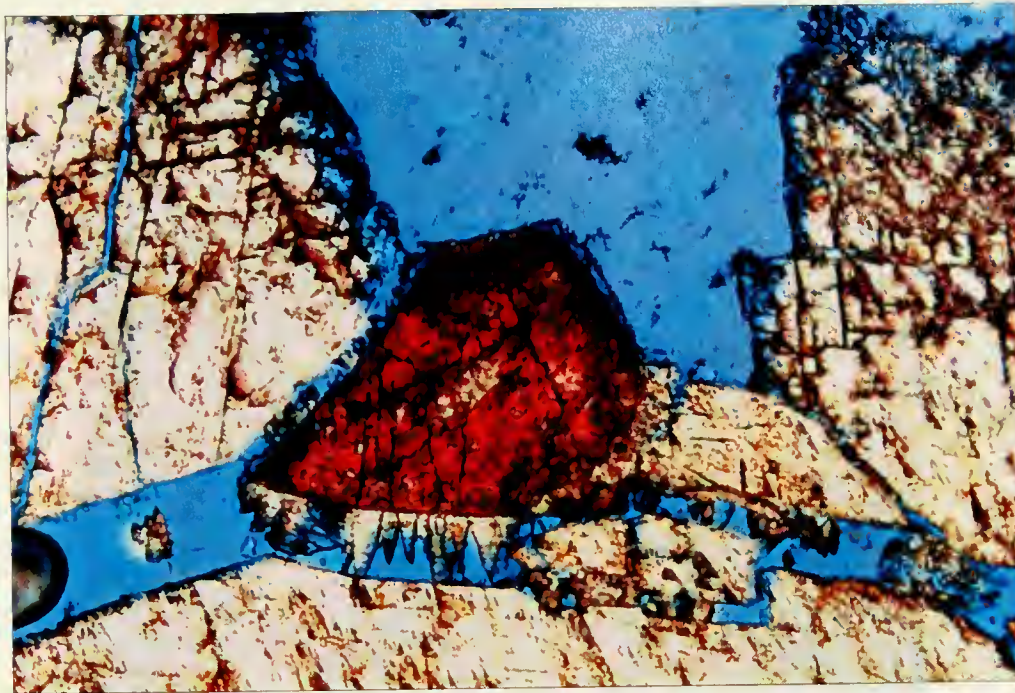
Figure 4.20: A surface grain of calcite wedged between two surface grains of dolomite, slide T-1B. The etching of dolomite beneath the calcite grain has created a saw-toothed pattern. Recrystallized salts are also seen. Thermal dilatation is the most probable cause of the microcracking surrounding the calcite grains. The space above the calcite grain may have held an ejected dolomite grain. 20x magnification, plane-polarized light.
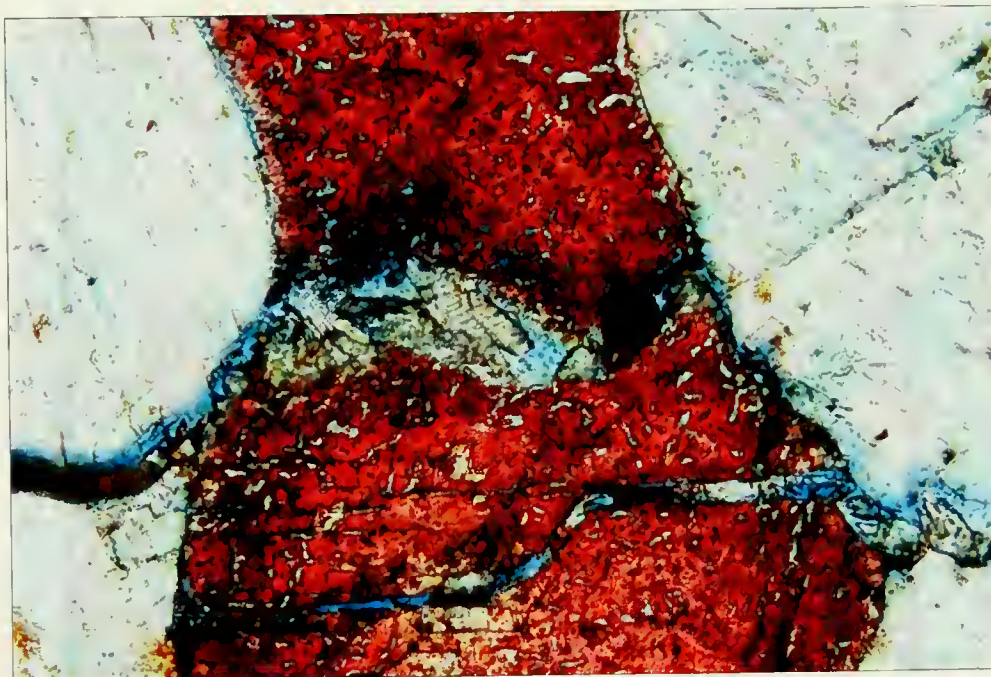
Figure 4.21: Recrystallization of calcite or salts in microcracks, slide T-1B. A red stained calcite grain is seen in the center of the photo surrounded on either side by white dolomite grains. Gypsum appears in a dolomite crack to the bottom right. 40x magnification, plane-polarized light.

Figure 4.22: A fractured surface of sample 1. Intergranular cracking is more common in the weathered sample than in the fresh sample. Brown flecks of phlogopite are visible in the cracks. 7.5x magnification, fiber-optic illumination.

Figure 4.23: Digitized grain boundary image of 1 square cm of Tuckahoe slide T-1B.

BIOQUANT ANALYSIS: SUMMARY OF DATA

T-1B Weathered Tuckahoe Marble	
Average Grain Area (square microns)	590,318
Average Grain Diameter in Sample (microns)	586
Average Grain Perimeter (microns)	3,046
Average Grain Paris Factor	0.46
Number of Grains in 1 Square cm	145
Gradation Coefficient (So=√d75/d25)	2.76
Inequality Grade (U=d60/d10)	10.90

GRAIN SIZE SUMMATION

| *Sieve Number*	*Size (microns)*	*Number of Grains*	*Percent*
200	0-75	26	17.93%
100	75-150	22	15.17%
50	150-300	18	12.41%
30	300-600	33	22.76%
16	600-1180	25	17.24%
8	1180-2360	19	13.10%
	>2360	4	2.76%
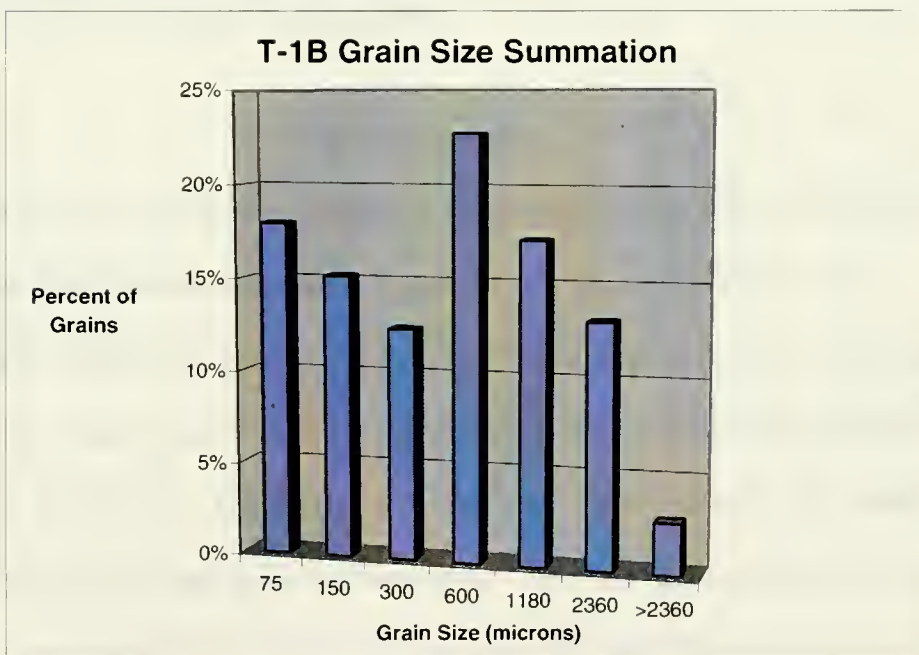
Table 4.2: Summary of Bioquant® data and related measurements for slide T-1B.
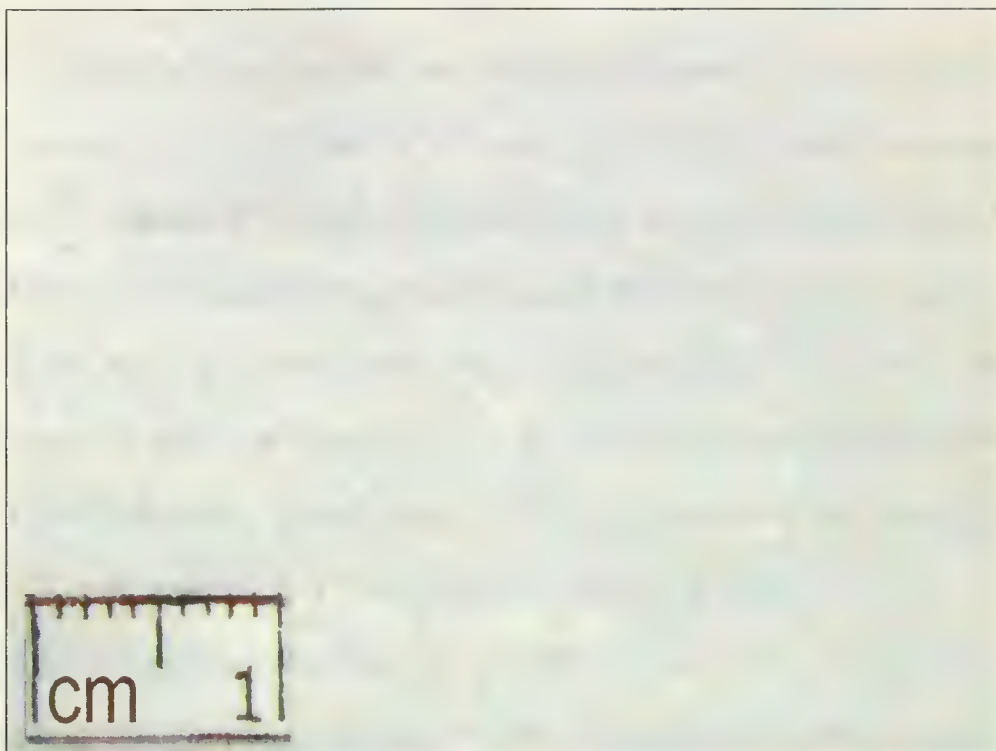
Figure 4.24: A fresh Sheffield surface from sample 38. The sample is characterized by fine-grained "filler" grains between the larger grains.

Fresh Sheffield

The block of fresh Sheffield marble in Figure 4.24 is very white and comparable

in color to the fresh Tuckahoe sample in Figure 4.1. As discussed in the section

"Gathering and Selection of Samples for Analysis," identification of Sheffield marble

was made by a visual comparison of a block of stone from the defunct Sheffield quarry to

samples from the building. This produced several very close matches for the weathered

stone and one very close match for the fresh stone. The fresh Sheffield samples used for

this analysis were gathered from the Kellum section of the building and the quarry. Thin

sections slides were then made from these.

Mineralogical Characterization: One of the interesting findings of this research relates to the composition of the Sheffield marble. In the range of samples picked as close matches with the quarry sample, there was strong uniformity of composition. Unlike the dolomitic Tuckahoe samples, all of the Sheffield thin section slides stained highly red for the presence of calcite. This suggests that the calcitic marble samples analyzed in previous rounds of testing derive from the Sheffield quarry. The most prominent inclusions seen in the fresh Sheffield samples were round silica grains. Silica was interspersed regularly throughout all of the Sheffield samples and generally forms along the grain boundaries. As a percentage of the total composition, silica was not great. Figure 4.25 shows a typical view with a regular distribution of silica.

Structural Characterization: Comparing the samples in hand, without the help of a microscope, the structural differences between Tuckahoe and Sheffield marble are readily visible. The grain is noticeably finer in the Sheffield samples than in the Tuckahoe samples. A large amount of very fine, almost powdery grains seems to be mixed in with the larger but still fine grains, making the grain fabric somewhat irregular. At the visual level, the powdery material would not seem to be highly crystalline or to possess strong cohesion between grains.

Sample 38 did not seem to exhibit a strong preferred orientation. Vague bands of layering approximately 0.5 cm thick were observed at the macroscopic level. Viewed under the polarized light microscope, thin section S-38 can be characterized as having a low preferred orientation. Some microcracks produced during the preparation of the thin section slide broke across the sample in a uniform direction, indicating that there was some preferred orientation of the grains (see Figure 4.26). Other samples were characterized by a noticeably irregular grain fabric.

Crystallization of calcite seems to be the main determinant of grain shape. The calcite crystals have a roughly hexagonal outline. This was seen in the SEM images obtained from Sheffield samples. Consequently, the grain boundary geometry in the fresh Sheffield samples tends to be angular but straight. The grain-to-grain contacts tend to be smooth and not overly convoluted or crystallized, unlike those in slide T-1B. On the whole, the grain shapes of the fine-grainedTuckahoe and the fresh Sheffield were similar.

Microcracking: Microcracks in the fresh Sheffield samples were more common than microcracks in the fresh Tuckahoe samples. This would seem to indicate a weaker overall structure. Even in the fresh sample slide, number S-38, microcracks were observed, probably as a result of thin section preparation (see Figure 4.26). One of the most distinct differences between Tuckahoe and Sheffield marble overall is the ratio of intergranular to intragranular cracking. Intergranular cracking was by far more common than intragranular cracking. According to Widhalm et al. (1996), the stone's medium to fine grain size may partially explains this. The lack of interlocking grain boundaries probably also contributes to this phenomenon. Smaller grains with low crystalline cohesion are more susceptible to cracking between grains and in general. Both of these factors are partially mitigated by the presence of a degree of preferred grain orientation, which directs fracturing along the bedding planes.

Surface Fracturing: By analyzing a fractured surface of sample 38 under the stereoscope, it was observed that roughly 60% of the cracking was intergranular. The analyzed surface is seen in Figure 4.27. Analyzing 50 grains further below the surface of the thin section slide, the breakdown was closer to 80% intergranular cracks to 20% intragranular cracks. This was expected based on the observations about microcracking and structural characterization. The percentage of intergranular cracks was generally

about 60%, very different from the fresh fractured Tuckahoe surface. The percentage of intragranular cracks observed, around 40%, would place it in the category of equivalent granular cohesion according to Grimm (1999).

Bioquant® Analysis: The grain boundaries in 1 square cm of thin section slide S-38 were hand-drawn and digitized in order to calculate the set of parameters previously discussed. 449 individual grains were calculated in 1 square cm, more than double the same number for the Tuckahoe samples. The digitized image of grain boundary outlines in 1 square cm of sample 1 is shown in Figure 4.28. The average grain perimeter was 1.55 mm, a little more than half the size of the Tuckahoe samples. The average grain diameter was 0.36 mm, or 69% of the fresh Tuckahoe diameter. The average grain surface area was 41% of the Tuckahoe, or 168,726 square microns. The Paris factor was calculated to be 0.58, which is very close to that calculated for the fresh Tuckahoe. Additional calculations for grain size distribution made with the data obtained confirmed observations about the thin section. 82% of the grains were less than 600 microns in diameter. 52% of the grains were 300 microns in diameter or smaller. The largest category was 600 microns, which accounted for 30% of the number of grains counted. Only 2% of the grains were 2,360 microns wide or wider. The gradation coefficient was calculated to be 1.75, and the inequality grade was calculated to be 5.60.

An individual summary of results for S-38 is provided in Table 4.3, and a summary of all Bioquant® data and related results for tested samples is given in Appendix 3.

Decay Mechanisms: Slide S-38 is considered a fresh sample of Sheffield marble and therefore no decay was observed. Nevertheless, the existence of microcracking even in the fresh sample indicates a vulnerability to weathering phenomena. Figure 4.26

shows clean intergranular cracking through the center of S-38. This fact will be useful in

understanding decay in the weathered samples.
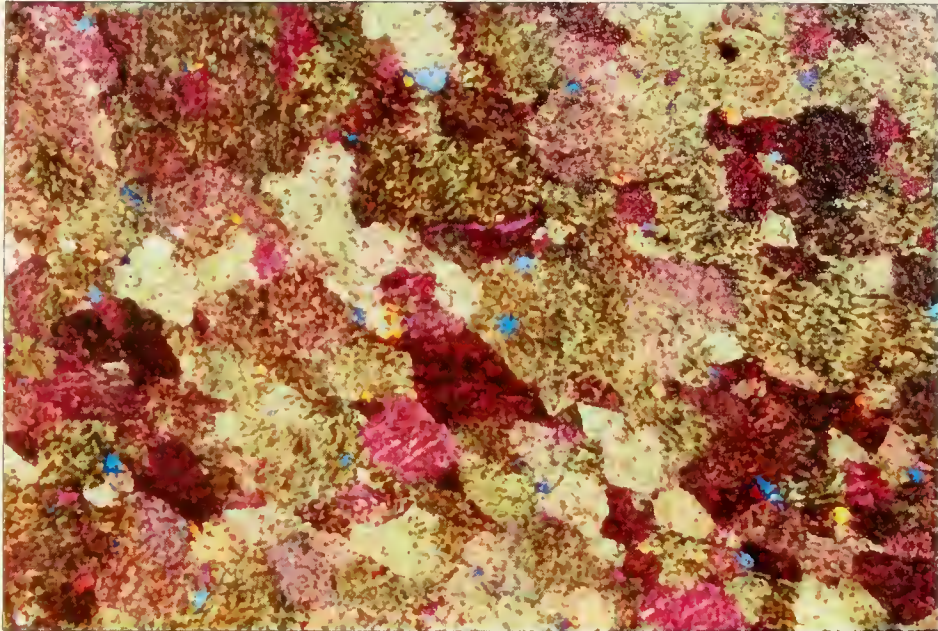
Figure 4.25: Typical view of fresh Sheffield grains from slide S-38 in cross-polarized light. Calcite is seen throughout, and silica is seen distributed regularly in blue and orange. 1.25x magnification, unstained for calcite.
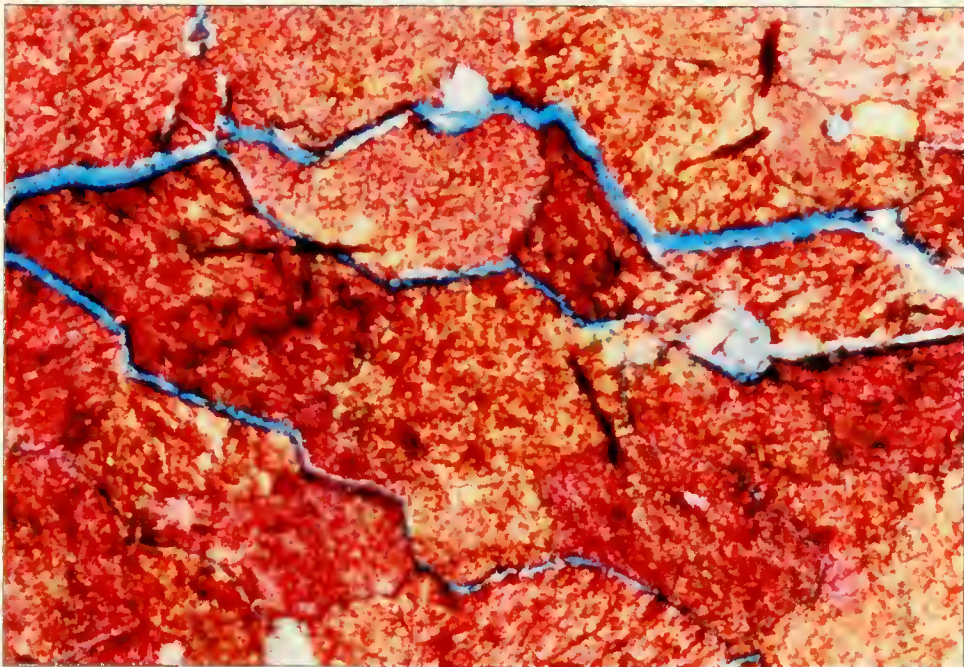
Figure 4.26: Intragranular cracking seen on fresh slide S-38. Cracking appears to propagate parallel to the bedding plane in this case. 5x magnification, plane-polarized light, stained for calcite.
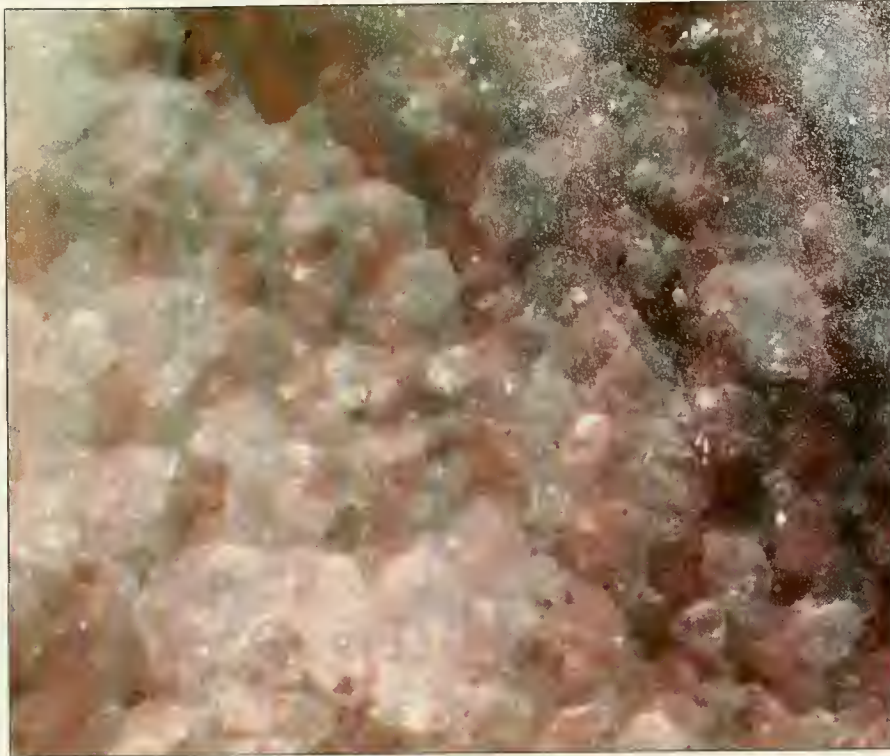
Figure 4.27: A typical fresh fractured Sheffield surface from sample 38. 7.5x magnification, fiber optic illumination.
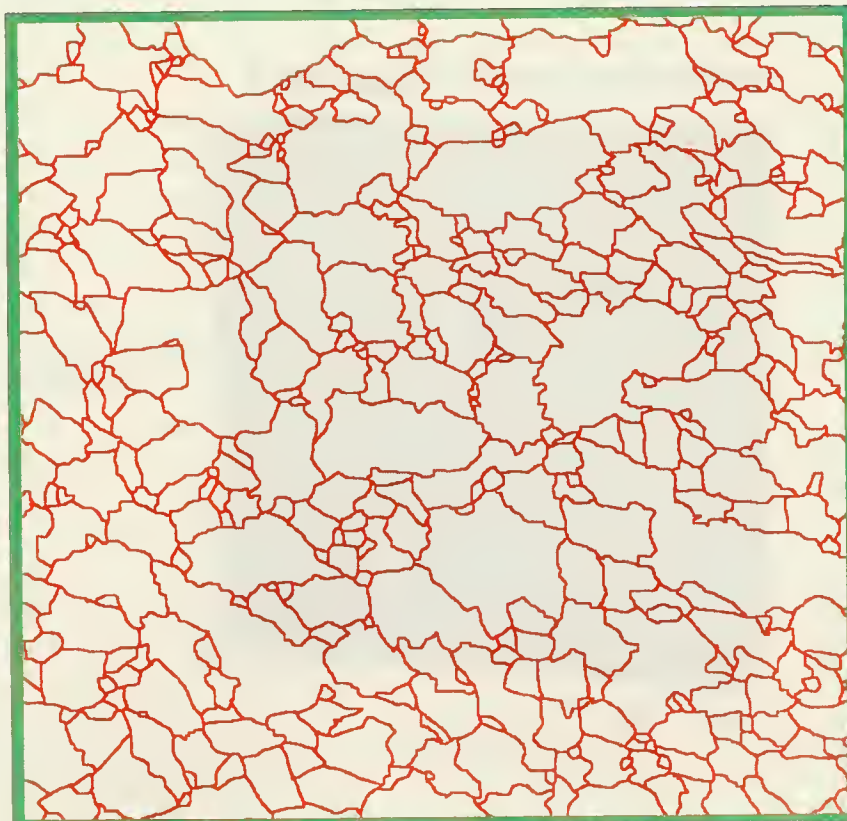
Figure 4.28: Digitized grain boundary image of 1 square cm of slide S-38.

BIOQUANT ANALYSIS: SUMMARY OF DATA

S-38 Fresh Sheffield Marble	
Average Grain Area (square microns)	168,726
Average Grain Diameter in Sample (microns)	358
Average Grain Perimeter (microns)	1,548
Average Grain Paris Factor	0.58
Number of Grains in 1 Square cm	449
Gradation Coefficient (So=√d75/d25)	1.75
Inequality Grade (U=d60/d10)	5.60

GRAIN SIZE SUMMATION

Sieve Number	Size (microns)	Number of Grains	Percent
200	0-75	48	10.69%
100	75-150	81	18.04%
50	150-300	104	23.16%
30	300-600	135	30.07%
16	600-1180	71	15.81%
8	1180-2360	10	2.23%
	>2360	0	0.00%
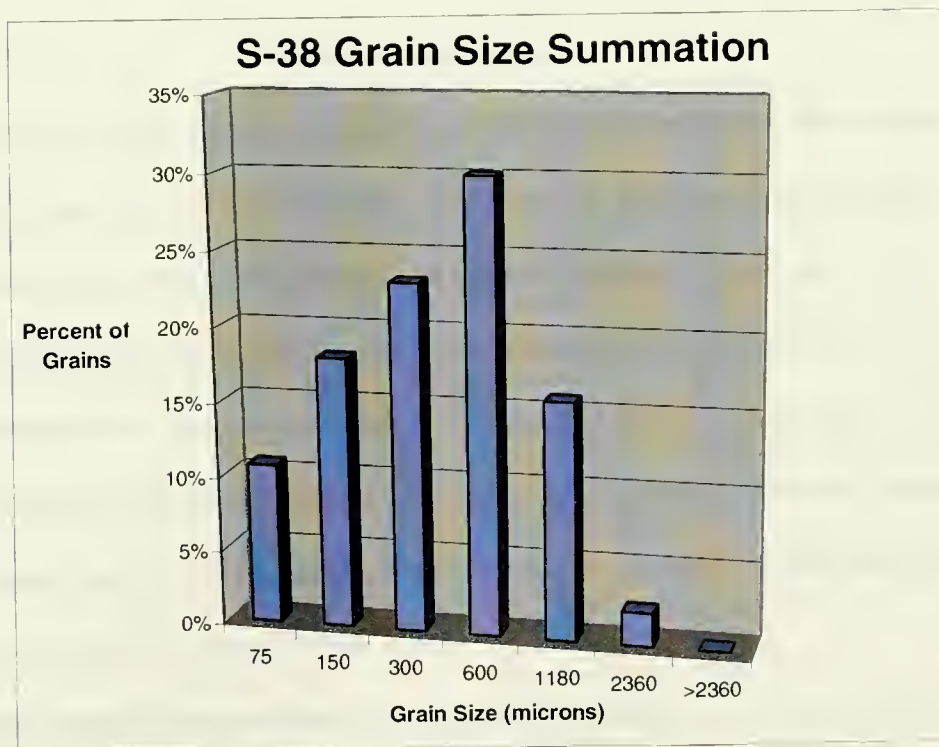
Table 4.3: Summary of Bioquant® data and related measurements for slide S-38.
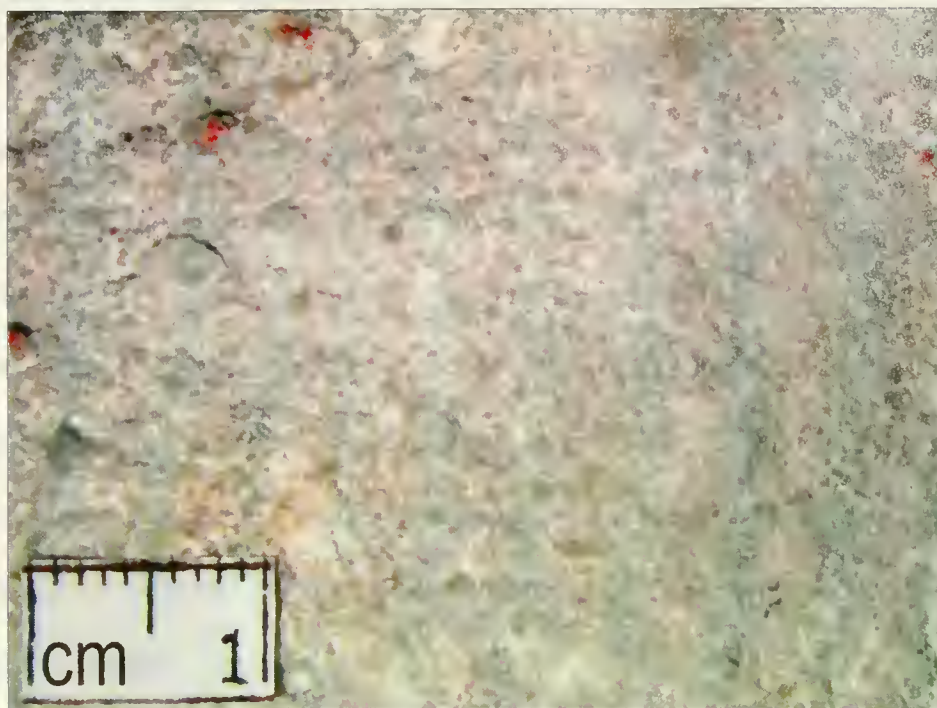
Figure 4.29: A typical weathered Sheffield surface from sample 37. Exposed surface grains have been rounded. T he original white color has changed to a darker color than the weathered Tuckahoe.

Weathered Sheffield

Thin section slides for the weathered Sheffield marble were made from samples found on the Kellum section of the building. They were all medium to fine-grained, yellow to brownish in color, and demonstrated extreme friability. To a depth of up to several centimeters, individual grains could be scraped from the surface like sand. S-36 and S-37 are taken from window surrounds at the west end of the south elevation. They closely resembled the quarried sample, S-15. S-15 is also considered because it presents different weathering phenomena, namely biological decay. A typical weathered surface rounded exposed grains is seen in Figure 4.29.

Mineralogical Characterization: The weathered samples are mineralogically identical to the fresh sample, S-38. All weathered slides stained dark red for the

presence of calcite. Like the fresh sample, silica grains were mixed regularly throughout. The silica grains were uniformly distributed along the grain boundaries and were often found in bands within the stone, as seen in Figure 4.32. Other mineral inclusions were not observed to exist in significant amounts.

Structural Characterization: Again like the fresh sample, the structure of the weathered slides is characterized by a relatively fine grain size, low preferred orientation, and angular but straight grain boundaries, as seen in Figure 4.34. The very fine size of a large percentage of grains and the lack of strong cohesion between them contribute to a noticeably weak structure. Figures 4.30 and 4.31 show the characteristic structure of the weathered Sheffield.

Microcracking: Intergranular microcracking was to be expected based on the previously described structural characteristics. Extreme microcracking was seen in all of the weathered samples. Intergranular cracking dominated while intragranular cracking was seen only to a small degree. Figures 4.31, 4.33, and 4.34 show the degree of cracking near the surface of a weathered Sheffield sample.

Surface Fracturing: By analyzing a fractured surface of sample 37 under the stereoscope, it was observed that roughly 80% of the cracking was intergranular, more than the fresh surface. The analyzed surface is seen in Figure 4.35. Analyzing 50 grains further below the surface of the thin section slide, the breakdown was again about 80% intergranular cracking to 20% intragranular cracking. This was expected based on the observations about microcracking and structural characterization. The small gain size and lack of strong intergranular cohesion seem to determine the fracturing behavior in both weathered and fresh samples. The percentage of intragranular cracks observed,

around 20%, would place it in the category of low granular cohesion according to Grimm (1999).

Bioquant® Analysis: Slide S-15, taken from the quarry sample, was chosen to be analyzed in Bioquant®. Because its identity was certain, it provided a good control for the other samples taken from the building. The digitized image of grain boundary outlines in 1 square cm of sample 1 is seen in Figure 4.36. Much like the fresh sample, 410 individual grains were calculated in 1 square cm. The average grain perimeter was 1.47 mm, very close to the fresh sample. The average grain diameter was 0.35 mm. The average grain surface area was 191,383 square microns. The Paris factor was calculated to be 0.56. These measurements were very close to the measurements taken from the fresh sample. Additional calculations for diameter made with the data obtained were also close. 80% of the grains were 600 microns in diameter or less. 52% of the grains were 300 microns in diameter or smaller. The largest category was between 300 and 600 microns, which accounted for 28% of the number of grains counted. 4% of the grains were between 1,180 and 2,360 microns wide or wider. The gradation coefficient was calculated to be 1.91 and the inequality grade was calculated to be 4.70.

An individual summary of results for S-15 is provided in Table 4.4. A summary of all Bioquant® data and related results for tested samples is given in Appendix 3.

Decay Mechanisms: Several factors are considered to have some bearing on the extreme intergranular microcracking of the weathered Sheffield samples. The thermal anisotropy of calcite, a basic structural inability to resist thermal deformation, and the resulting capillary porosity are considered major mechanisms of Sheffield marble decay. The presence of silica inclusions is also considered to have some influence on the weathering of the marble.

The thermal deformation of calcitic marble has been discussed earlier in this chapter. The behavior of heated calcite crystals in a polycrystalline matrix should be considered one of the primary factors affecting surface weathering. Preferred grain orientation within a polycrystalline matrix can also influence weathering properties. Tschegg et al. (1999) modeled the relationship between the grain configuration in a calcitic marble and the observed deformation or damage. In their analysis, increased random orientation correlated to increased damage due to thermal deformation. This may contribute to the pervasive structural disintegration of the weathered Sheffield with its random orientation of grains. Figure 4. 38 shows the orientation of grains in slide S-15, frequently at 45'or 90' angles to each other.

The initial loosening of the surface grains due to day/night thermal cycling makes the substrate more vulnerable to other mechanisms of decay. Figure 4.37 shows a surface calcite grain detaching from sample S-37. This type of surface opening permits infiltration of salts in solution, which will contribute to further structural breakdown. On the south side of the building, where samples 36 and 37 were located, the amount of daily sunlight exposure is higher than any other place on the building. The samples taken from this area have been exposed to daily thermal cycling for over 115 years.

Surface deposition of sulphuric compounds in precipitation etches the surface grains and introduces secondary mechanisms of decay into the substrate. Figure 4.38 gives some idea of a typical etched surface with numerous fine microcracks that facilitate capillary absorption of water. The extremely porous and stained state of these and other pieces of stone on the south facade is the chief reason for their current replacement. After the heated, exposed surface creates fine openings between grains, capillary

absorption is powerful enough to bring salts deeper into the interior of the stone. The

presence of silica and other inclusions also probably affects the formation of microcracks.

Another type of decay was seen in the weathered sample taken from the Sheffield

quarry. Figure 4.39 shows colonization of the surface by biological growth. Unlike the

samples from the building, the quarry samples had little evidence of pollution. A fine,

dark layer of fungus covered the surface instead. In thin section, acid breakdown of

calcite by microbial communities has created rounded holes in the surface. A porous

structure was seen to a depth of 2+ mm. The difference between this sample and the

surface that have weathered in New York City points out the importance of regional,

local and even micro-climate in the weathering of exterior stone.
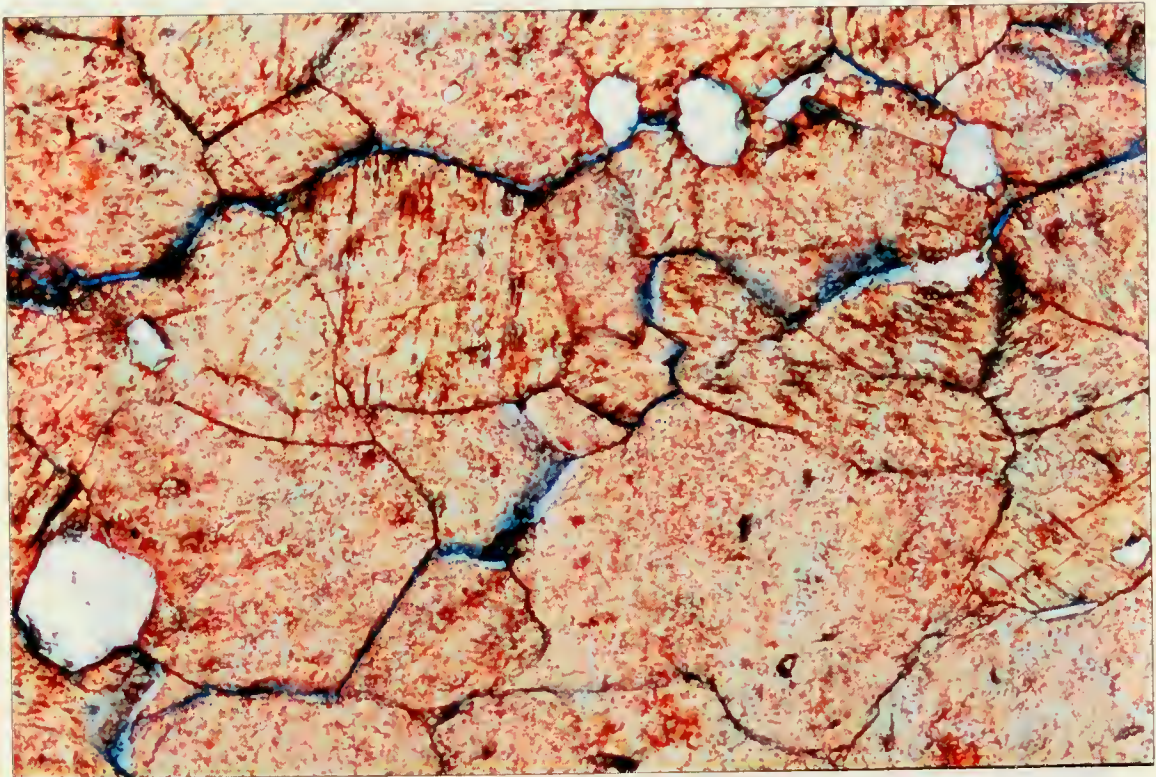
Figure 4.30: Calcite with occasional silica (white) along the grain boundaries on slide S-15. Note red staining for calcite. 5x magnification, plane-polarized light, stained for calcite.
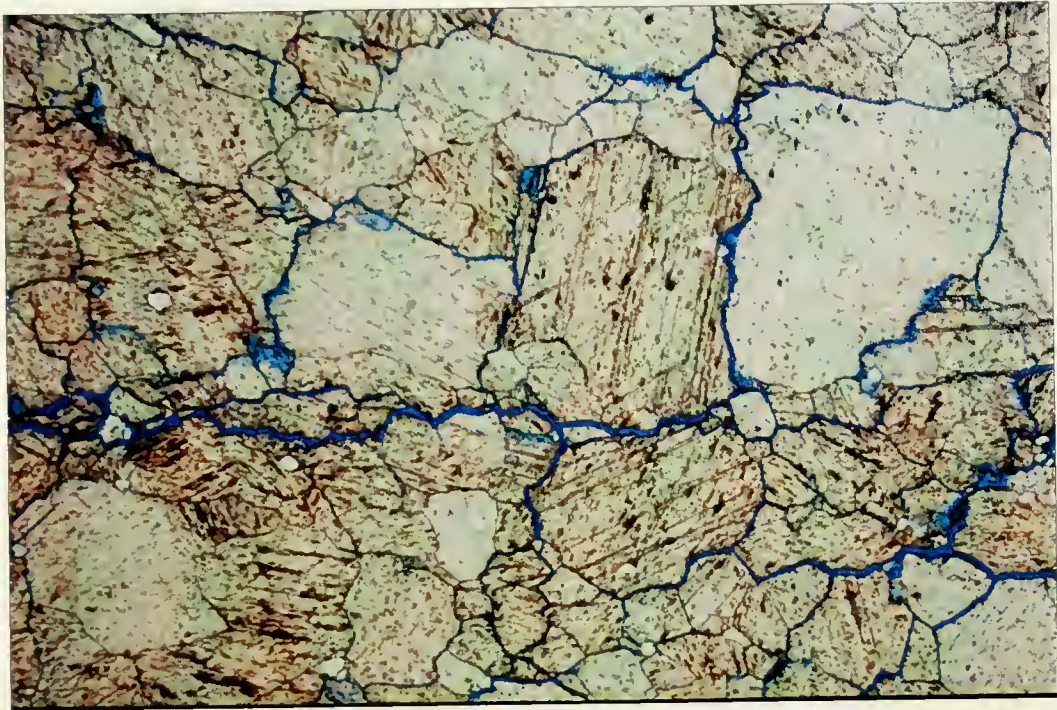
Figure 4.31: Even in the quarry sample S-15, intense microcracking was seen. Notice the jumbled of grain sizes and the lack of preferred orientation. Cracks are indicated by the vacuum-impregnated blue dye. 5x magnification, plane-polarized light.

Figure 4.32: Silica inclusions sometimes appear in bands. Here they are gathered in the center and bottom of the slide, S-36. 1.25x magnification, plane-polarized light, stained for calcite.
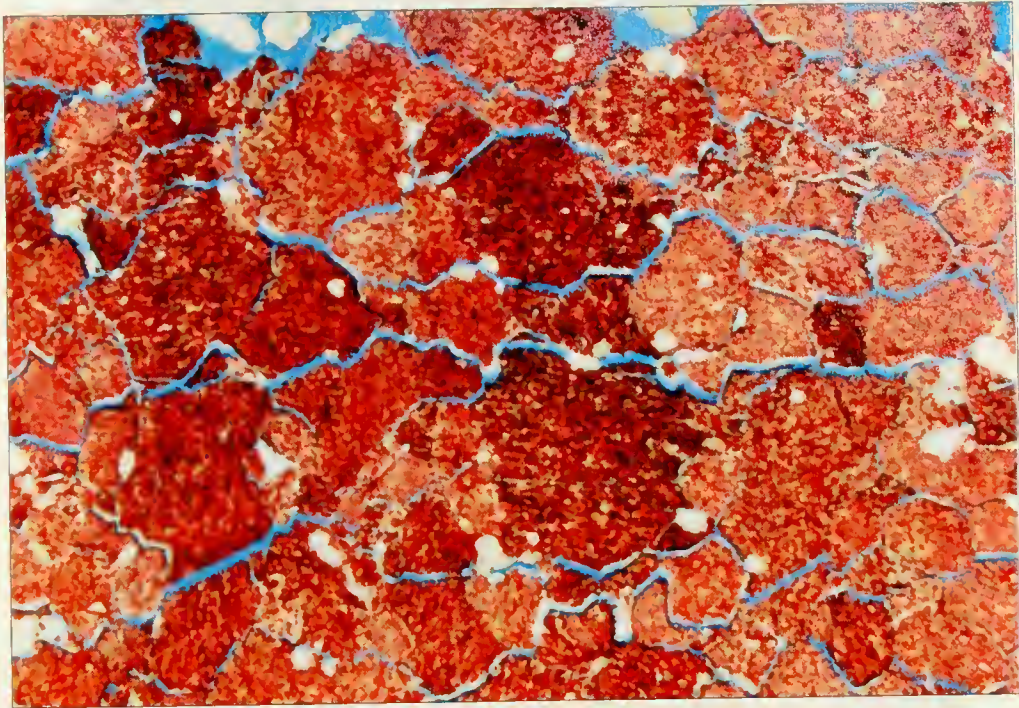
Figure 4.33: Extreme surface friability on slide S-37. The surface is bordered by blue above. Note the predominance of intergranular cracking and siliceous inclusions. 5x magnification, plane-polarized light, stained for calcite.
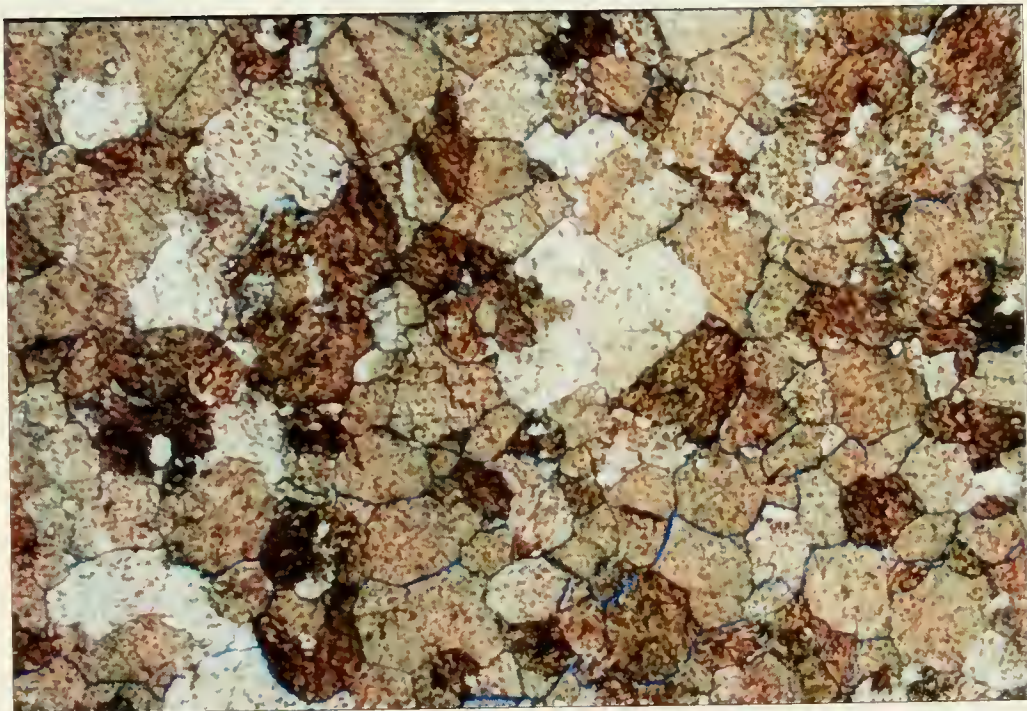
Figure 4.34: More extensive intergranular cracking in slide S-37. 1.25x magnification, cross-polarized light, unstained for calcite.
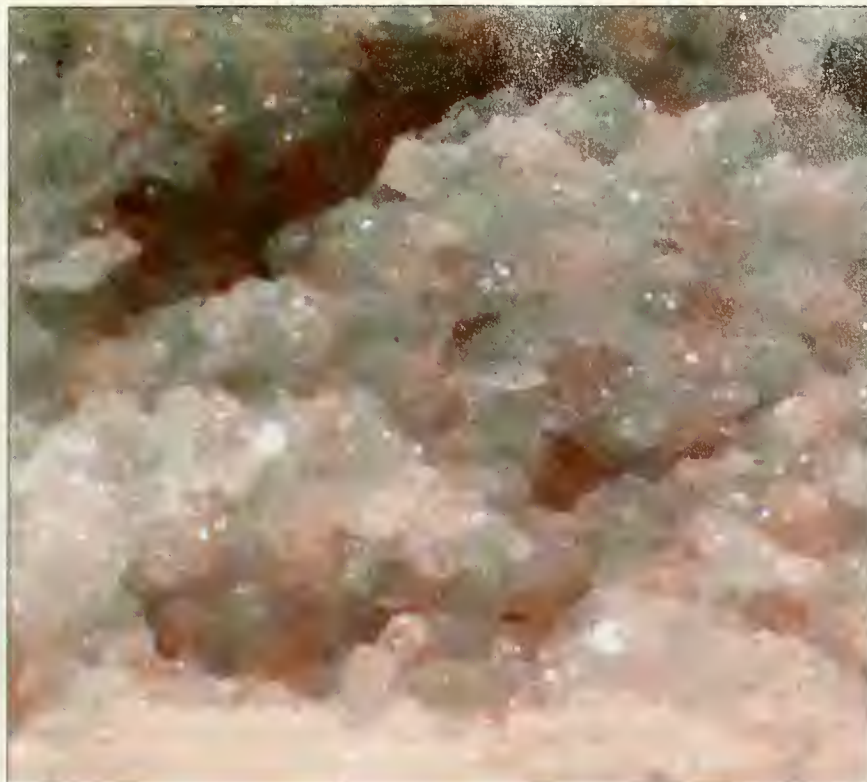
Figure 4.35: A typical fractured, weathered Sheffield surface from sample 37. 7.5x magnification, fiber optic illumination.
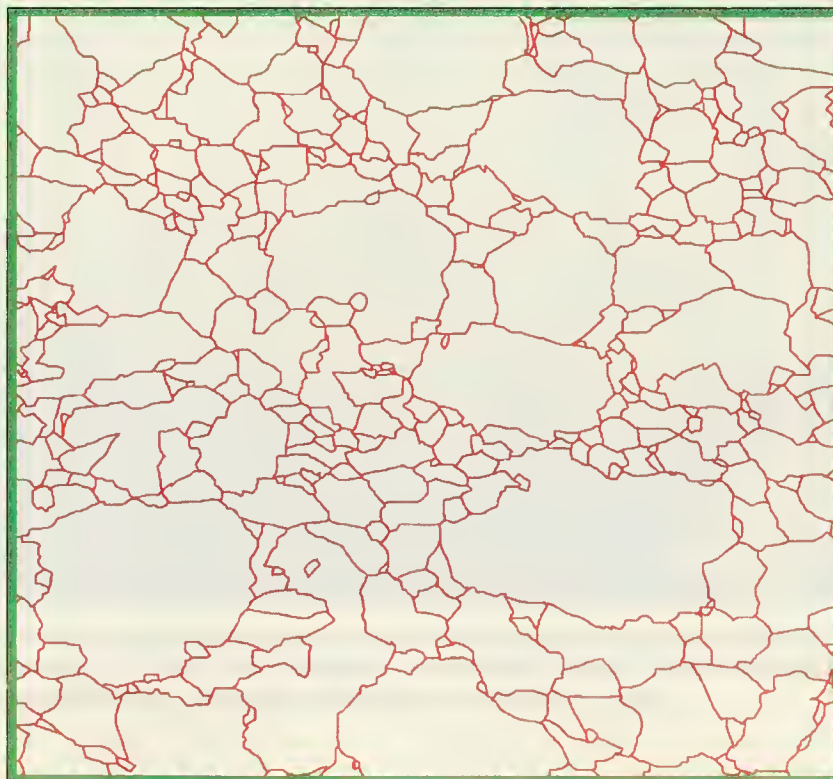
Figure 4.36: Digitized grain boundary image of 1 square cm of slide S-15.
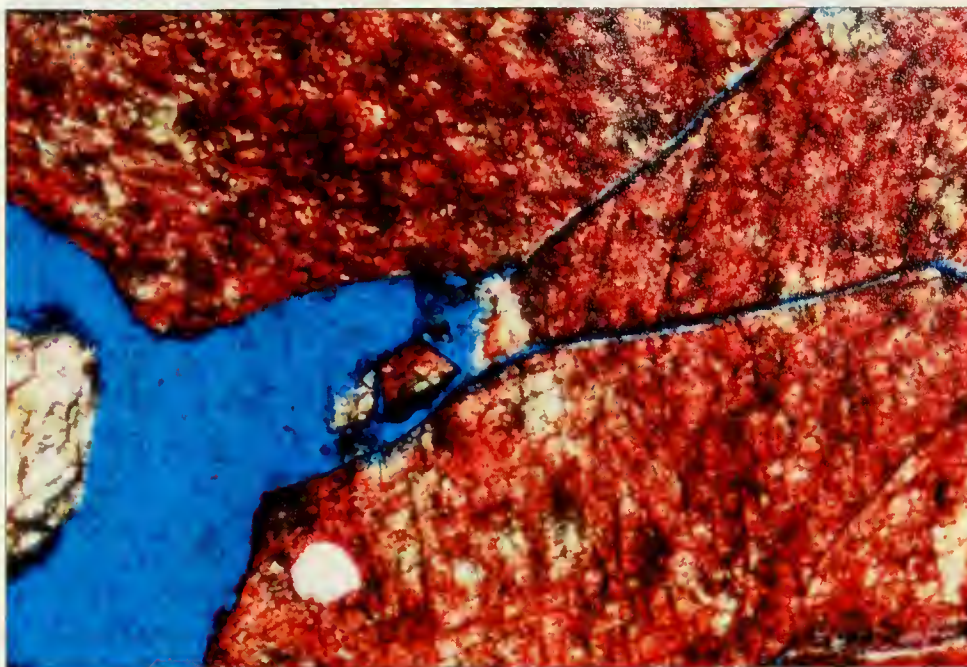
Figure 4.37: A surface grain detaching from the substrate on slide S-36. Thermally-induced deformation causes surface grains to fall off, opening microcracks that facilitate moisture penetration. 10x magnification, plane polarized light, stained for calcite.
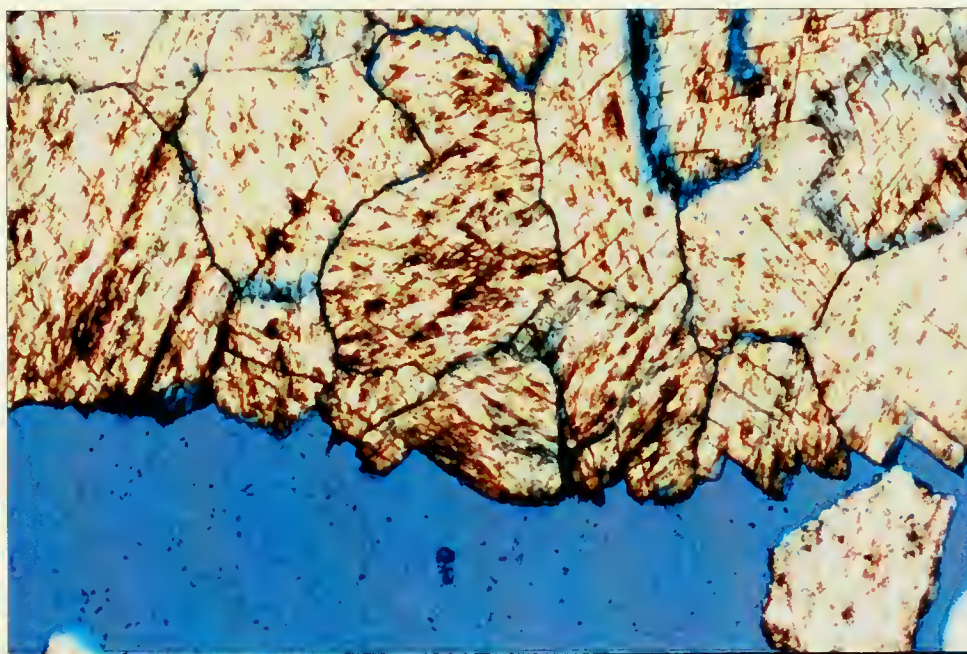
Figure 4.38: Etched surface grains oriented at various angles to one another on slide S-15. The random orientation of grains may contribute to thermally-induced surface damage in Sheffield marble. 5x magnification, plane-polarized light, unstained for calcite.
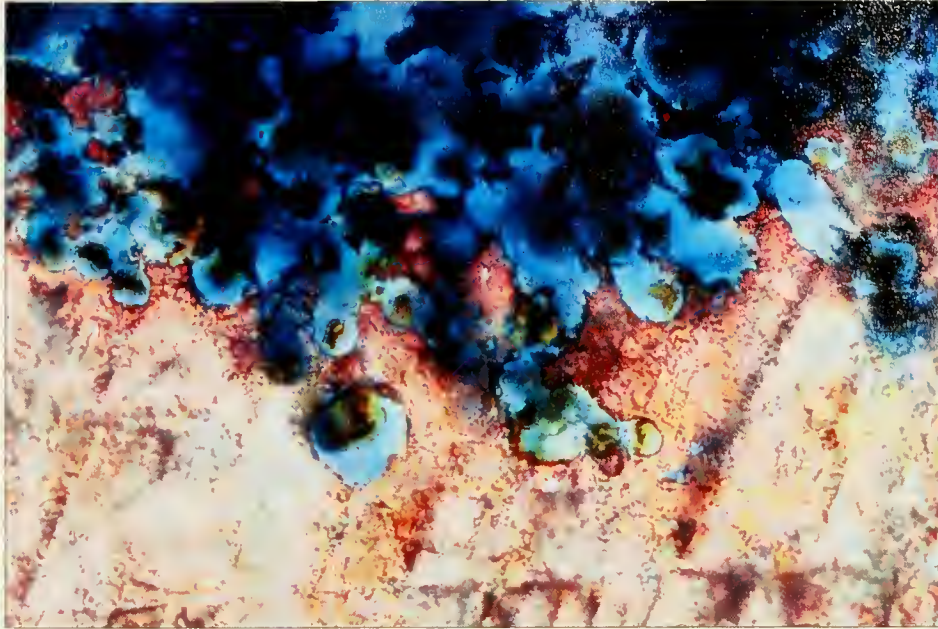
Figure 4.39: Biological growth on the surface of the quarry sample, slide S-15. Fungi have digested the first 2 mm of the surface, creating a porous substrate. 20x magnification, plane-polarized light, stained for calcite.

BIOQUANT ANALYSIS: SUMMARY OF DATA

S-15 Weathered Sheffield Marble	
Average Grain Area (square microns)	191,383
Average Grain Diameter in Sample (microns)	349
Average Grain Perimeter (microns)	1,471
Average Grain Paris Factor	0.56
Number of Grains in 1 Square cm	410
Gradation Coefficient (So=√d75/d25)	1.91
Inequality Grade (U=d60/d10)	4.70

GRAIN SIZE SUMMATION

Sieve Number	Size (microns)	Number of Grains	Percent
200	0-75	2	10.69%
100	75-150	0	18.04%
50	150-300	11	23.16%
30	300-600	21	30.07%
16	600-1180	31	15.81%
8	1180-2360	26	2.23%
	>2360	1	0.00%
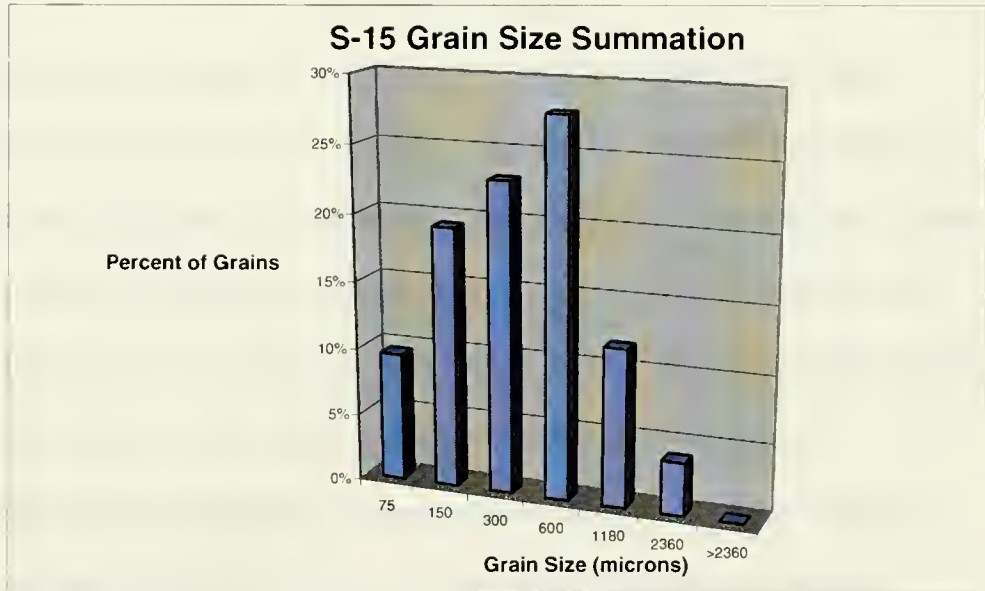
Table 4.4: Summary of Bioquant[®] data and related measurements for slide S-15.

Figure 4.40: A typical fresh Cherokee surface from sample 36.

Fresh Cherokee

The stone that is being used to replace the weathered marble at the Tweed

Courthouse is texturally similar to the Tuckahoe marble and compositionally similar to

the Sheffield marble. As such, it offers an interesting contrast to both. The two Cherokee

thin section slides, G-26 and G-29, were taken from blocks of recently quarried stone.

The highly crystalline surface of sample 26 is seen in Figure 4.40. The Cherokee marble

exemplifies the importance of petrofabric and microstructure to weathering.

   .   **Mineralogical Composition:** Staining of both slides revealed the Cherokee

marble to be almost purely calcitic. In thin section slide G-26, silica grains were

observed to occur only rarely along the calcite grain boundaries. In thin section G-29,

silica grains were observed to occur in larger amounts, but they still accounted for only a

small percentage of the overall composition. Figure 4.41 shows a typical section with

calcite next to silica grains.

Structural Characterization: The Cherokee samples are highly crystalline and

are characterized by uniformity. Grains are all medium to large, with straight, strongly

adhered grain boundaries. No preferred orientation of the texture was noted. The large

grain size, as will be shown in the explanation of the Bioquant® analysis, is a factor that

contributes greatly to the stone's documented resistance to weathering. Despite a lack of

any noticeable preferred orientation, the large grain size, straight, angular grain

boundaries, and extremely fine, almost fused grain-to-grain contacts seem to give the

Cherokee a very strong texture. Figure 4.42 shows a typical section with large grain size

and clean grain-to-grain contacts.

Microcracks: At low magnification, the degree of microcracking in the Cherokee

samples appeared to be low. However, at higher magnification, fine microcracking was

indeed observable. Whether pre-existing due to recrystallization or resulting from

quarrying processes, the microcracks were generally intragranular, as would be expected

in a stone with large grains and strong intergranular cohesion. Figure 4.43 shows the type

of microcracking common in the fresh Cherokee samples.

Surface Fracturing: By analyzing a fractured surface of sample 29 under the

stereoscope, it was observed that roughly 40% of the cracking was intergranular. The

analyzed surface is seen in Figure 4.44. By looking at grains further below the surface

of the thin section slide, the breakdown was closer to 75% intragranular cracking to 25%

intergranular cracking. This was expected based on the observations about structural

characterization. The large grain size and strong intergranular cohesion seem to

determine the fracturing behavior in the fresh sample. The percentage of intragranular

cracks observed, around 70%, would place it in the category of high to equivalent granular cohesion according to Grimm (1999).

Bioquant® Analysis: Thin section G-29 was chosen to be analyzed in Bioquant®. The digitized image of grain boundary outlines in 1 square cm of sample 29 is given in Figure 4.45. The Cherokee proved to be the largest-grained, most uniform of the marbles from the Tweed Courthouse. Only 91 individual grains were calculated in 1 square cm. The average grain perimeter was 4 mm, significantly larger than the Tuckahoe. The average grain diameter was 0.94 mm, again larger than the Tuckahoe. The average grain section area was 977,018 square microns. Interestingly, the Paris factor was calculated to be 0.57, close to both Sheffield measurements. Additional calculations for grain size made with these data showed relative uniformity. 86% of the grains were larger than 600 microns in diameter. 30% of the grains were larger than 1,180 microns in diameter. The largest category was for grains between 600 and 1,180 microns in diameter, which accounted for 34% of the grains counted. 4% of the grains were 2,360 microns wide or wider. The gradation coefficient was calculated to be 1.87, and the inequality grade was calculated to be 4.10.

An individual summary of results for G-29 is provided in Table 4.5. A summary of all Bioquant® data and related results for tested samples is given in Appendix 3.

Decay Mechanisms: Very little decay was seen at low magnification. However, at higher magnification, etching of calcite was observed, as was incipient microcracking. The etching and microcracking mirrored the rhombohedral molecular structure of calcite. Figures 4.46 and 4.47 give some idea of how the weathering of Cherokee marble would progress in typical conditions of exposure. A block of Cherokee marble in the Stone Exposure Test Wall at the National Institute of Standards and Technology showed very

little degradation after more than 50 years of exposure. Because of the large, very

crystalline grains, there is relatively low porosity per volume of stone. The large polished

surfaces of the grains equate to a low specific surface for moisture absorption and acidic

decay.

Figure 4.41: Crystalline calcite grains (red and orange) and silica inclusions (blue, purple, white, yellow). The silica occurs occasionally in the Cherokee marble. An unusually dense concentration is seen here. The silica forms both along the grain boundaries and within the calcite grains. 1.25x magnification, cross-polarized light, stained for calcite.
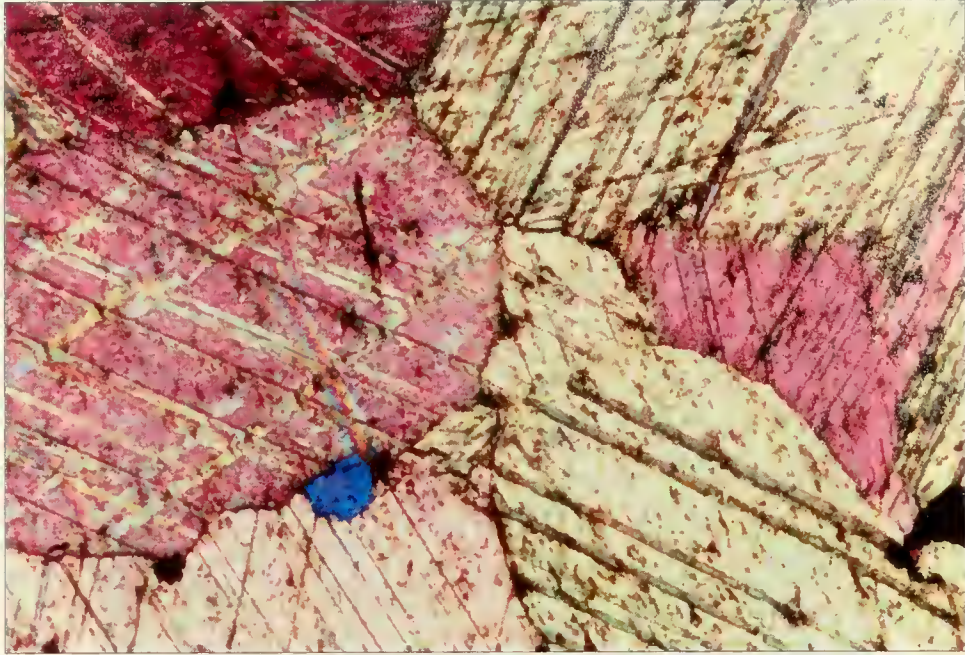
Figure 4.42: Highly crystalline calcite grains in slide G-26. Note highly angular, fused grain boundaries. A siliceous inclusion, seen in blue occurs along the grain boundary towards the bottom of the photomicrograph. Twinning of calcite is also seen. 50x magnification, cross-polarized light, unstained for calcite.
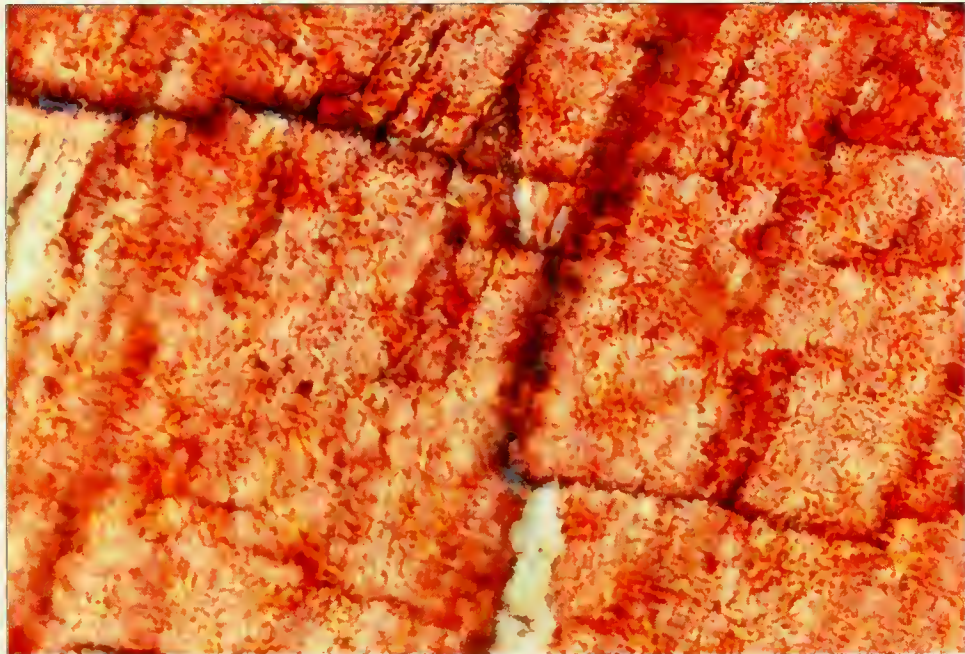
Figure 4.43: Microcracking in fresh Cherokee slide G-29 seen at high magnification. Fractures follow the rhombohedral mineralogical structure of calcite. 40x magnification, plane-polarized light, stained for calcite.

Figure 4.44: A typical fractured surface of Cherokee marble from sample 29. 4x magnification, fiber-optic illumination.
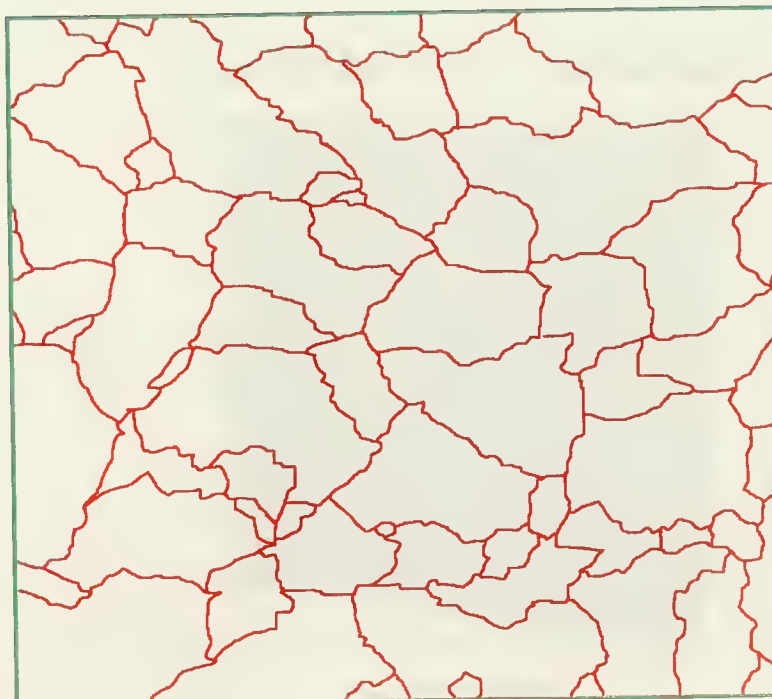
Figure 4.45: Digitized grain boundary image of 1 square cm of slide G-29.

BIOQUANT ANALYSIS: SUMMARY OF DATA

G-29 Fresh Cherokee Marble	
Average Grain Area (square microns)	977,018
Average Grain Diameter in Sample (microns)	943
Average Grain Perimeter (microns)	3,970
Average Grain Paris Factor	0.57
Number of Grains in 1 Square cm	91
Gradation Coefficient (So=√d75/d25)	1.87
Inequality Grade (U=d60/d10)	4.10

GRAIN SIZE SUMMATION

Sieve Number	Size (microns)	Number of Grains	Percent
200	0-75	2	2.20%
100	75-150	0	0.00%
50	150-300	11	12.09%
30	300-600	21	23.08%
16	600-1180	31	34.07%
8	1180-2360	26	28.57%
	>2360	1	1.10%
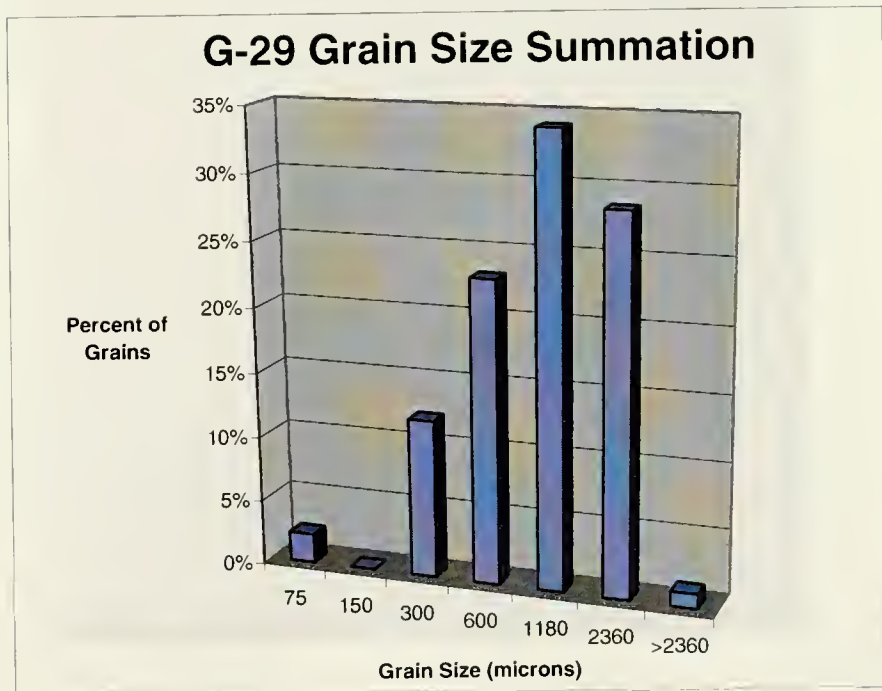
Table 4.5: Summary of Bioquant® data and related measurements for slide G-29.
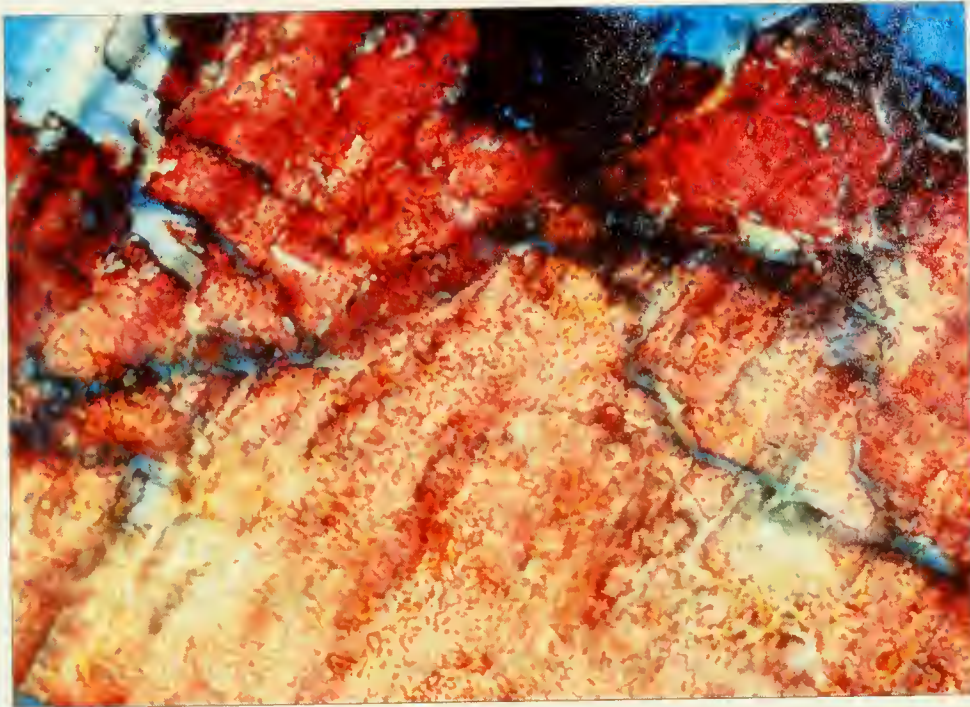
Figure 4.46: Microscopic decay of fresh Cherokee sample number 26. Microcracking of surface grains gives some idea of what might happen on a larger scale when the replacement stone weathers. 40x magnification, plane polarized light, stained for calcite.

Figure 4.47: A block of Georgia Cherokee marble at the NIST Stone Exposure Test Wall in Gaithersburg, MD. After 50 years of outdoor exposure, the Cherokee block shows surface decay of less than a few microns. No staining from pollution was observed. The block is 2 ft. tall.

Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) was applied to weathered and freshly fractured surfaces of Tuckahoe and Sheffield marble from the Tweed Courthouse as a complement to thin section analysis. As with the samples chosen for thin section, the samples used for SEM were picked because their identities were known. Sample 1 from the North Portico of the Kellum Section of the Courthouse was the source of the Tuckahoe images, and samples 36 and 37 from the south façade were the sources of the Sheffield images. Both have been positively identified in the previous section of this chapter. The results of this analysis confirmed observations about microcracking and surface etching. In the case of the Tuckahoe sample, intragranular and intergranular cracking were seen on the fractured surfaces and large amounts of gypsum were seen on the weathered surface. In the case of the Sheffield sample, intergranular cleavage was seen and etching of surface calcite grains was also seen.

Figure 4.48 shows the surface of the sample covered by platy gypsum crystals to such a degree that the marble grains themselves are not visible. The formation of calcium sulfate crystals on the surface is mirrored in the pores of the stone, where salt crystallization acts to further degrade the structure of the stone. Gypsum crystallization within the pores of the Tuckahoe marble has been shown in Figures 4.19 and 4.21.

On the fractured face of the same sample, characteristic intragranular and intergranular cleavage are evident, also confirming the previous observations. Figure 4.49 shows this type of surface fracturing, common in the Tuckahoe. Energy Dispersive

Spectroscopy (EDS) showed the primary constituents of the crystals to be calcium and magnesium with sulfur also detected. Sulfur would be expected given the prevalence of gypsum on the weathered surface of the sample.

A typical Tuckahoe inclusion is seen in Figure 4.50. A large dolomite crystal is surrounded by partial intragranular cleavage. The crystal is bordered on the bottom right by a micaceous phlogopite inclusion.

The previous observations about the Sheffield marble were also supported by SEM analysis. A clear predominance of intergranular cleavage is seen on a fractured surface in Figure 4.51. Fine cleavage is seen between very distinct calcite crystals, and very little intragranular cleavage is visible in the same image. The fine cleavage planes create a strong capillary absorption capacity in the stone. On the weathered surface, both etching of calcite grains (Figure 4.52) and an accretion of fine pollution or sediment (Figure 4.53) were visible. EDS confirmed that the primary constituents of the grains were calcium and oxygen. Appendix 3 contains the EDS readings.

X-Ray Diffraction

As with the previous analyses, samples were carefully chosen based on their known identity as either Tuckahoe or Sheffield marble. Two samples were picked for each category by visual comparison alone. Additionally two samples of Cherokee were chosen and another marble of unknown identity was also chosen. This marble was included because it was noticed to occur frequently on the building and could not be categorized easily as Sheffield or Tuckahoe based on a visual comparison. These samples were then pulverized and prepared for X-Ray Diffraction. The results generally

confirmed what had been observed in thin section analysis but also revealed something about the Tuckahoe's composition.

The two Tuckahoe samples, 1 and 22, both from the North Portico, had interesting results. In sample 1, the characteristic peak for dolomite was observed to be double. Due to careful calibration, it was possible to determine that these corresponded to two varieties of dolomite (JCPDS# 36-0426 and #11-0078) containing different amounts of iron, 0.44% and 0.22% respectively, expressed as FeO. The increase in iron content shifts the dolomitic peak (d=0.288) to higher d-spacing reading (d=0.91) for the case of ankerite [$Ca(Fe,Mg)(CO_3)_2$] (JCPDS#4-0586) with an FeO content of 19.15%. In sample 22, the intensity of these peaks was inverted, while in the common sample 41 they were almost identical to Tuckahoe sample 1. This would help to explain the iron spotting observed on the dolomite crystals themselves. A variable iron content may be characteristic of the Tuckahoe dolomite. The two Sheffield samples were identical, composed entirely of calcite. The Cherokee, as expected, was entirely calcitic. Test results and information about mineralogical identification are provided in Appendix 3.

The Sheffield samples, 14 and 32, were identical. They were composed entirely of calcite, except for a small peak at 26.7 in sample 14. Cherokee, as expected, was entirely calcitic. Test results and information about mineralogical identification are provided in Appendix 4.

Figure 4.48: Gypsum encrusted surface of sample 1. 100x magnification, JEOL 6400 Analytical SEM.
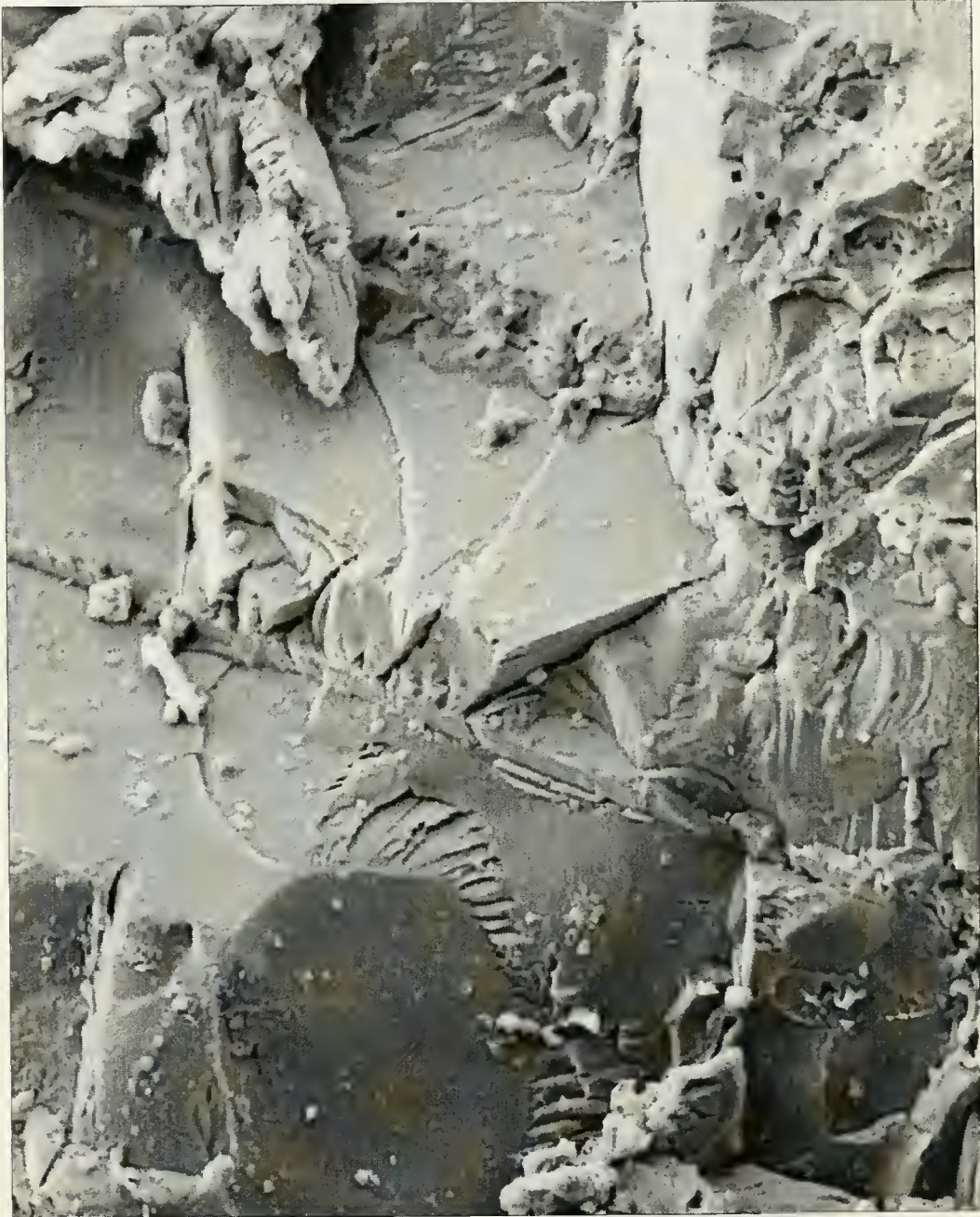
Figure 4.49: A fresh fractured Tuckahoe surface from sample 1. Jagged intragranular cleavage is seen to the right and top of the image and straight intergranular cleavage is seen in the center. 100x magnification, JEOL 6400 Analytical SEM.

Figure 4.50: Sample 1 surface with a distinct dolomite grain, center, adjoining a micaceous phlogopite inclusion, right. 50x magnification, JEOL 6400 Analytical SEM.

Figure 4.51: Distinct calcite crystals on a fractured Sheffield surface from sample 37. Fine cleavage planes can be seen between grains. 100x magnification, JEOL 6300FV Field Emission HRSEM.
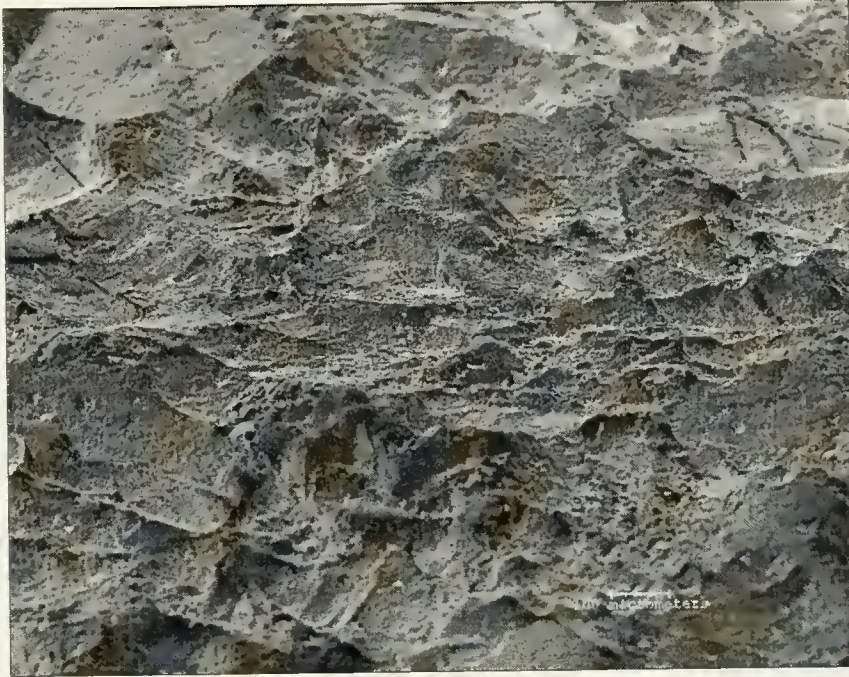
Figure 4.52: Etching of calcite grains on a weathered Sheffield surface from sample 36. Note the outline of an individual calcite crystal in the upper left hand of the image. 100x, JEOL 6300FV Field Emission HRSEM.
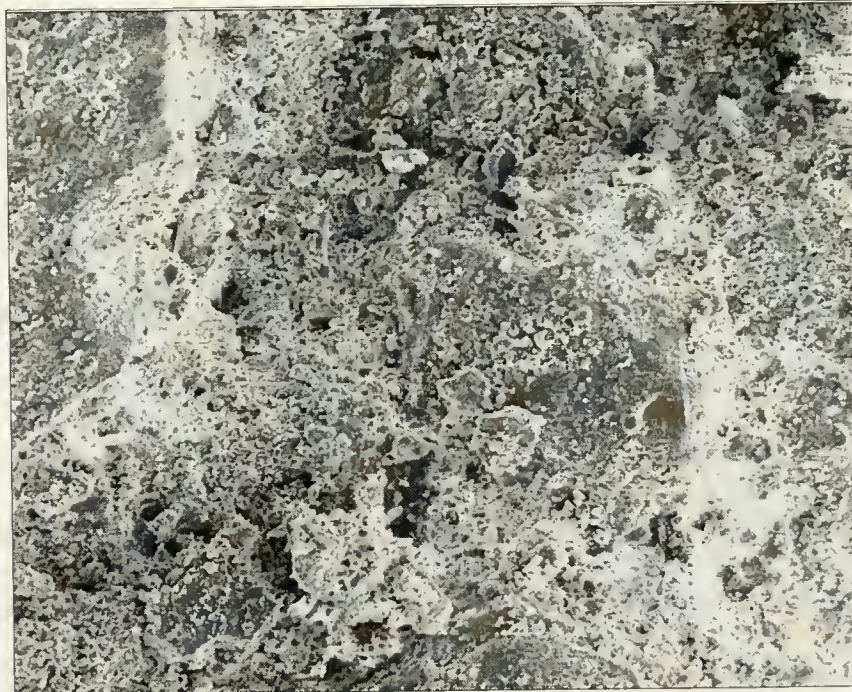
Figure 4.53: Accretion of pollutants or fine sediment on the weathered surface of sample 36. The vague outline of a coated individual crystal can be seen in the center of the image. 100x magnification, JEOL 6300FV Field Emission HRSEM.

Comparison of Characterizations

Finally, by comparing some of the observations made, it is possible to discuss the findings across the three stone types. Figures For instance, the average Paris factor of the Tuckahoe grains, 0.495, makes them the least circular in shape. The angularity and irregular boundaries of the Tuckahoe grains could translate into a higher toothing factor between grains, and hence a higher degree of intragranular cohesion. This is seen in the Tuckahoe's grain cohesion categorization, equivalent to prevalent cohesion. Grain cohesion, a corollary of intra versus intergranular cracking is also affected by grain size. In the case of the Tuckahoe, the predominant grain size interval of 0.6 to 1.2 mm may relate to the amount of intragranular cracking seen. On the other hand, the high gradation coefficient and inequality grade may negatively influence the performance of the marble. The more inequally graded the grains are, the less likely it is that the marble will weather uniformly.

In the case of the Sheffield, the smaller predominant grain size interval (0.3-0.6mm), higher average Paris factor (0.57) and lower gradation coefficient could contribute to the equivalent to subvalent granular cohesion seen in both fresh and weathered samples. The more distinct roundness of the grains, and hence the lower toothing factor, together with a small grain size would seem to make the Sheffield more susceptible to weathering than the Tuckahoe. This would also seem to be compounded by the anisotropic thermal expansion behavior of calcite, at least in areas of the building exposed to sunlight on a regular basis. Nevertheless, mineralogical content is an important controlling factor, as discussed previously. In reality, Tuckahoe and Sheffield

may weather equally well or poorly, despite the differences between these observed factors, because of their very different mineralogical compositions.

The highest gradation coefficient, 2.52, was noted in the Tuckahoe samples. As seen in the thin section slides, the Tuckahoe had a large number of medium grains but also a large number of smaller grains that contributed to a varied microstructure. The heterogeneous mix of grain sizes may contribute to different thermal expansion/ contraction behaviors. Because the grain sizes are more diverse, a greater specific surface is available on which acids can react. This could help to explain the stone's observed breakdown and friability, at least in the samples observed at the courthouse.

The Cherokee turned out to be similar to the Sheffield in two categories: Paris factor and gradation coefficient. It was also closer to the Sheffield than the Tuckahoe in the category of inequality grade. Since it is compositionally so close to the Sheffield, it brings out several interesting points. Both the Sheffield and Cherokee are calcitic marbles, yet the Cherokee is noticeably more durable and is characterized by strong grain to grain cohesion in the fresh sample. The general gradation of grains between the two is almost identical. The main differences are the degree of crystallization, noticeably higher in the Cherokee, and the larger predominant grain size interval. These differences may largely explain the differences in durability between the two.

Looking at the Tuckahoe, the lower average Paris factor would seem to predict better weathering than the Cherokee. Again, however, composition, gradation coefficient, and a high inequality grade seem to intersect with Paris factor to influence actual weathering behavior. In the Cherokee, lower specific surface makes moisture absorption more difficult

Grain Size Distribution
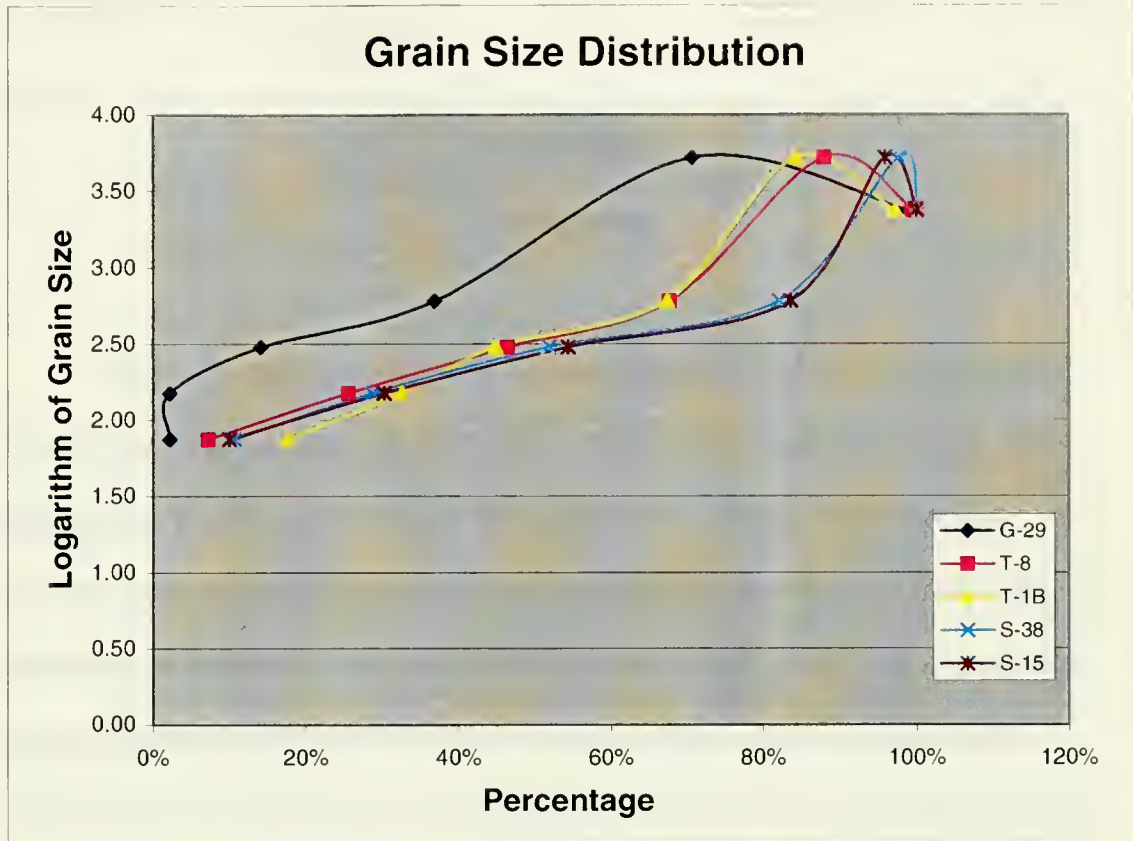
Table 4.6: Comparison of Grain Size Summation for the five marble types: G-29 Cherokee Fresh; T-8 Tuckahoe Fresh; T-1B Tuckahoe Weathered; S-38 Sheffield Fresh; and S-15 Sheffield Weathered. Grain sizes have been converted to logarithms of the actual grain sizes. Both Sheffield curves correspond to each other, as do both Tuckahoe curves. The Cherokee curve is noticeably distinct from the rest.

COMPARISON OF DATA

Marble Type	Gradation Coefficient (So)	Inequality Grade (U)	Paris Factor	Grain Cohesion	Predominant Grain Size Interval
Tuckahoe Fresh	2.28	5.1	0.53	equivalent to prevalent	0.6-1.2 mm
Tuckahoe Weathered	2.76	10.9	0.46	equivalent	0.6-1.2 mm
Sheffield Fresh	1.75	5.6	0.58	equivalent	0.3-0.6 mm
Sheffield Weathered	1.91	4.7	0.56	subvalent	0.3-0.6 mm
Cherokee Fresh	1.87	4.1	0.57	equivalent to prevalent	1.2-2.4 mm

Table 4.7: Comparison of gradation coefficient, inequality grade, Paris factor, grain cohesion, and predominant grain size interval across marble type.

CHAPTER V

Conclusion

The observations made through thin section analysis of fresh and weathered Tuckahoe and Sheffield marble add to the previous observations about them. The juxtaposition of these two stones on the exterior of the Tweed Courthouse has provided architects and conservators in the past with an opportunity to look at the differential weathering of two superficially similar types of stone. In this instance, a relatively fundamental analytical tool, microscopic thin section, has been used to characterize the microstructure and breakdown of the two stones. This approach was suggested by the simple fact that thin section had never been applied in an extensive study of the Tuckahoe or Sheffield marbles and that it might yield useful information about each material's resistance to weathering. Sheffield marble has never been the subject of conservation analysis, making some sort of investigation into its behavior all the more worthwhile. The results of this study suggest that thin section was a useful method for understanding the makeup, behavior, and primary causes of decay of the Tweed Courthouse marbles.

An interesting result of this research relates to the origin and mineralogical composition of the two types of marble used at the Tweed Courthouse. Historical records indicate that two quarries, or at least two distinct quarrying areas, provided exterior stone for the building. It has also been assumed in historical accounts that

both types of marble were dolomitic. Testing by Ammann & Whitney and Mesick, Cohen, Waite has suggested that there were perhaps as many as seven different quarries based on observed compositional and mineralogical characteristics of the Tweed marble. This included an almost purely calcitic marble that may comprise as much as 30% of the exterior stone. The current research reconciles the previous accounts to some degree.

Using samples carefully chosen from the exterior based on likely quarry origin, several important observations were made. First, it was confirmed that the Tuckahoe marble is indeed dolomitic. This was expected based on historic accounts and past analysis. Relative uniformity among the samples in thin section staining and XRD confirmed this general characterization of the Tuckahoe. Second, using a sample of marble recently taken from the Sheffield quarry as a benchmark, the Sheffield samples were identified as being highly calcitic rather than dolomitic. This was not expected. Again, relative uniformity among the samples in thin section staining and XRD confirmed the mineralogical characterization of the Sheffield. This finding points out the possibility that the Sheffield quarry could be the source of all of the calcitic marble seen on the exterior of the Tweed Courthouse. The Georgia Cherokee replacement stone was confirmed to be highly calcitic as well.

In addition to confirming the Tuckahoe's dolomitic composition and the presence of phlogopite and tremolite inclusions that affect surface weathering, it was also found that calcite grains occur regularly in the Tuckahoe samples. Due to the opposite thermal expansion behaviors of calcite and dolomite, this may be a determinant of weathering behavior in the Tuckahoe marble. On a structural level, the moderate to large grain size and moderately interlocking grain boundaries in the

fresh samples would seem to predict low potential for thermal degradation. The

marble Tuckahoe's mineralogical composition, heterogeneous grain size distribution

and structure, and relative grain roundness would seem to additionally control these

factors. Taken together, moderate to high potential for thermal degradation would be

predicted in areas of the building that are exposed to regular thermal cycling. This in

fact appeared to be the case with the weathered samples.

On the thin section slides, many of the weathering phenomena that have been

observed in the past were made vividly clear. The degree of gypsum crystallization

within the microcracks, a factor that is known to accelerate decay, was well illustrated

by photomicrographs of the weathered Tuckahoe. The presence of gypsum in the

substrate derives from the layering of fine particulate pollution on the stone's surface.

Calcium sulfate, formed from sulfurous pollution in the presence of water and drawn

into the microcracks by capillary absorption, results in the presence of gypsum. EDS

applied during SEM confirmed that the surface crystals were largely composed of

sulfur and calcite.

The unusual iron spotting of the dolomite, observed occurring on the dolomite

grains themselves rather than within the stone pores, was also well illustrated by

photomicrography, as were surface etching and the breakdown of the dolomite grains

by sulfation. The shifting of the main peak in XRD seemed to confirm that the

Tuckahoe dolomite crystals have some iron content, an observation that is worth

noting since iron staining of the Tuckahoe is usually attributed to the presence of

pyrite inclusions. These primary mechanisms of decay manifest themselves on the

macroscopic level in extreme friability and discoloration, the dominant features of

weathered Tuckahoe.

The Sheffield's highly calcitic composition was the first and most obvious observation made, and it helps to explain some of the weathering phenomena seen in this type of marble. Because calcium carbonate is quicker to form calcium sulfate than magnesium carbonate is, black crusts of sulfurous pollution may be more commonly observed on the Sheffield blocks. It was also noted that grains of silica commonly occurred along the grain boundaries. Weak cohesion created by the low toothing factor between the silica grains and the calcite grains could contribute to the breakdown of the stone. This may be exacerbated by differential coefficients of thermal expansion and different anisotropic thermal expansion behaviors, contributing to deterioration, although these were not measured in this research.

Other factors relating more strongly to microstructure seemed to be at work in the weathering of the Sheffield marble. For one, a large amount of intergranular cracking was observed even in the fresh Sheffield samples. The comparatively small grain size, straight grain boundaries, and relative roundness of the grains also predicted a strong potential for thermal degradation and microcracking in areas exposed to regular thermal cycling. The thermal anisotropic behavior of calcite, which controls the degree of damage due to thermal expansion, is an important factor in the early stages of decay. This appeared to be relevant in the weathered samples taken from the south façade, which were characterized by a large amount of porosity due to intergranular microcracking and the subsequent loss of grain to grain cohesion. The capillary absorption capacity of the Sheffield resulting from this should be considered a major determinant of weathering. As seen in the SEM images, clean cleavage planes between individual crystals on the surface provide a direct entry for moisture and salts in solution.
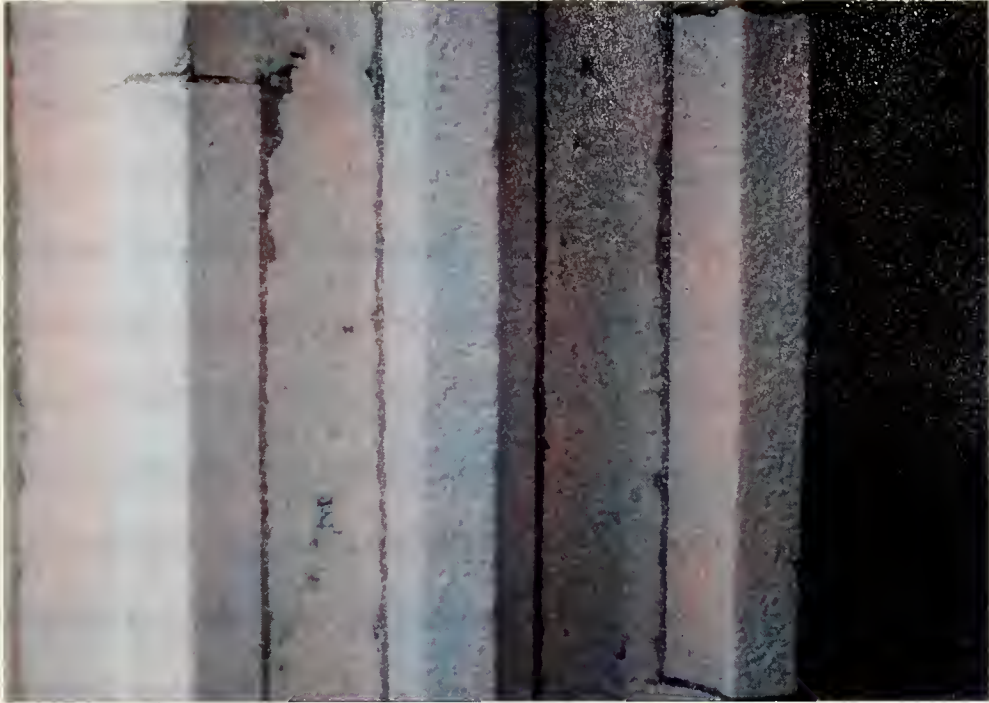
Figure 5.1: Dutchman repairs to column flutes on Brooklyn City Hall. The one on the right is a closer match with the original Tuckahoe. After these repairs were made, extensive retooling was done to reduce the starkness of the contrast between the two types of marble.
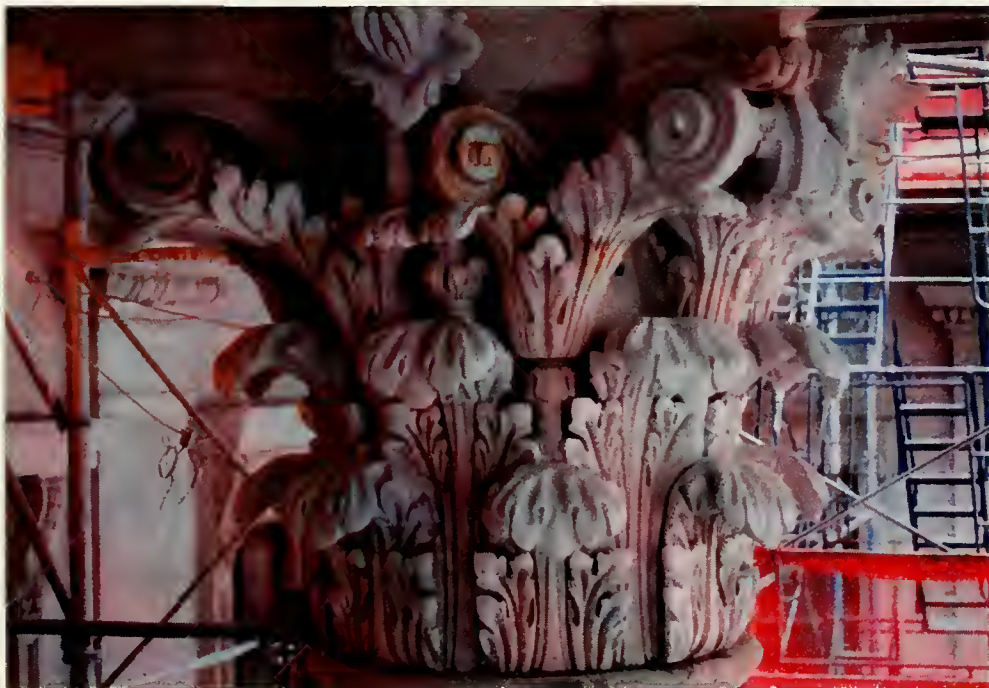
Figure 5.2: Cherokee replacement abacuses on a Tuckahoe capital. Although the difference between the two types of marble is noticeable and will become more distinct as the stone weathers, the mixture of Cherokee with the Tuckahoe and Sheffield has been limited to areas of the building where it will not be as noticeable.

The introduction of Georgia Cherokee marble as a replacement stone adds another dimension to the differential weathering patterns of the past. Superficially similar to the Tuckahoe in grain size and general color, at least when the Tuckahoe has been cleaned, the Cherokee would seem to be a logical replacement. However, its greater durability and tendency not to discolor over time point out potential problems for the future. In planning the replacement of stone at the Tweed Courthouse, care is being taken to minimize this type of contrast. The architect overseeing the project originally specified that Cherokee replacement stone should be used mostly above the first floor and in the area of the cornice, out of normal viewing range. Due to a limited quantity of salvage and Sheffield quarried stone, the Cherokee is being used more and more on the lower parts of the building.

Recent dutchman repair work done on columns at Brooklyn City Hall gives some indication of how the Cherokee will weather next to the Tuckahoe. Cherokee dutchman pieces were inserted into damaged pilaster flutes, and the resulting contrast was stark. When the Tuckahoe began to show discoloration, the contrast became even more pronounced. Additional tooling work was done to make the two stones appear more compatible. Figure 4.54 shows the difference between the Cherokee and the original Tuckahoe marble at Brooklyn City Hall.

Elsewhere, the replacement of deteriorated exterior stone with a mixture of stone from the building and from the Sheffield quarry can be expected to produce familiar patterns of weathering. The reuse of this material raises a difficult question for conservators, that is, whether two stones with such a long history of repair problems and aesthetic incompatibility should be reused at all.

Such a large building with such a variety of conservation issues offers many opportunities for further research. Future testing could help to refine the data gathered in this analysis. One possibility for analysis related to this study would involve collection of fresh stone samples cut and quantified based on the their locations within the quarries. Careful notation of each sample's preferred orientation relative to the crystallographic x, y, and z axes would go a long way to producing more definitive data about microstructure and weathering. This approach has been used by geologists studying the behavior of marble as a building stone and has provided information that can be compared reliably across stone types. Given the nature of the samples used for this research, such measurements were not possible.

Something that was not done in thin section analysis for this research is dot mapping in SEM of specific elements in the slides. Dot mapping could refine an understanding of the phenomena observed in thin section, such as iron staining, salt crystallization within pores, and the mineralogical identity of inclusions.

Although there is little chance that such a program could be implemented at the Tweed Courthouse any time in the near future, testing for an appropriate consolidation treatment would also be an interesting area of research. The possibility of applying a barium hydroxide urea treatment to the stone has been explored in the past. A survey of consolidation treatments would broaden the range of options for dealing with the very friable weathered marble at the Tweed Courthouse.

Another type of analysis that could be worthwhile is a façade by façade breakdown of stone types correlated to their degrees of deterioration. Mapping decay relative to position on the building and stone type would yield useful information about weathering as it is controlled by microclimate. Sufficient historical information

exists that such a project should be possible. This may be a suitable application for

Geographic Information Systems.

As the Tweed Courthouse ends its 140th year, the question of how to approach

its stabilization for the future has become central. Although the courthouse is a

building of broad historical scope and grandeur, any approach to its conservation and

repair must begin and end with an understanding of it on the most minute scale. A

failure to comprehend the fundamental mechanisms of weathering will lead to a

failure to find an appropriate treatment. This thesis has attempted to contribute to the

body of knowledge about the Tweed Courthouse by exploring the relationship

between microstructure, composition, and decay of the exterior marble. It is hoped

that it will assist in any future efforts at restoration or repair.
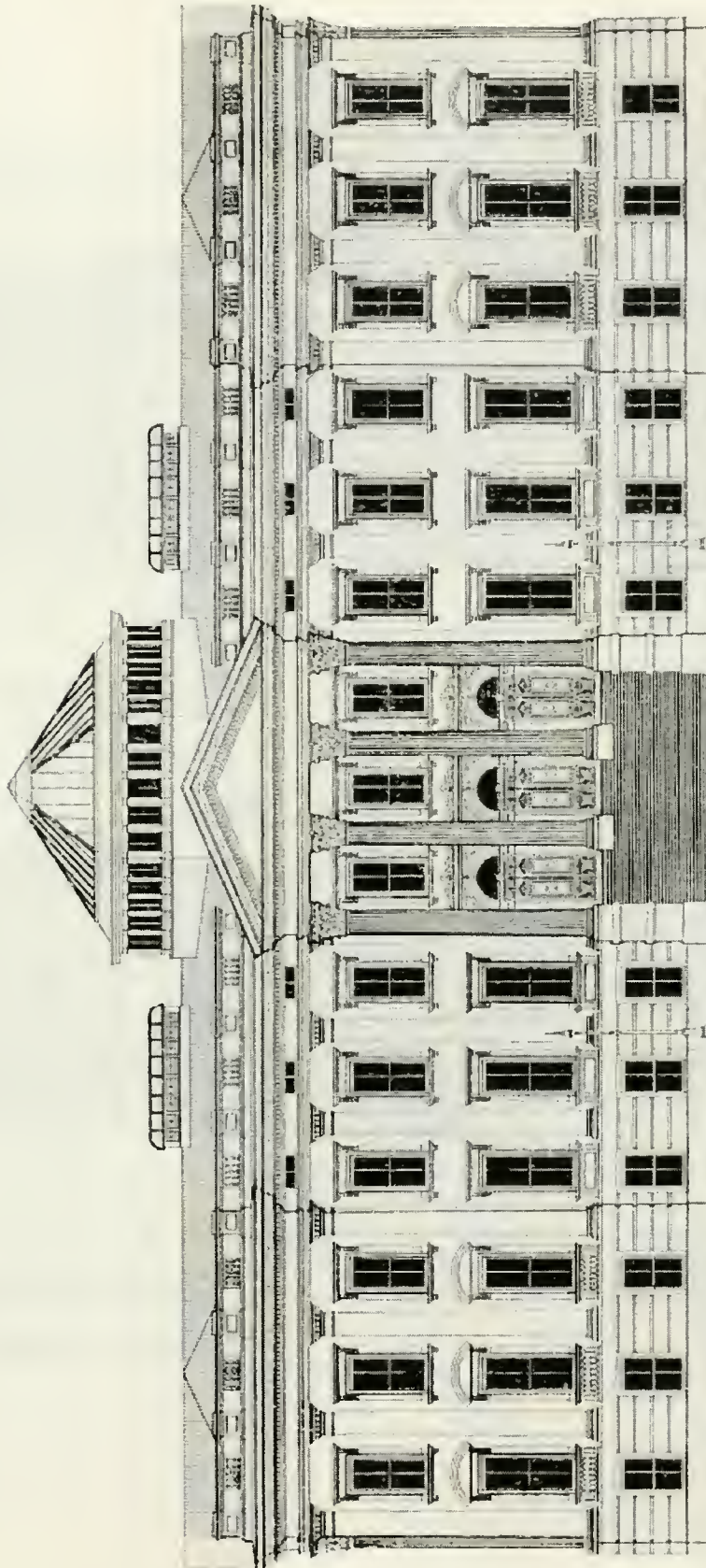
NORTH ELEVATION
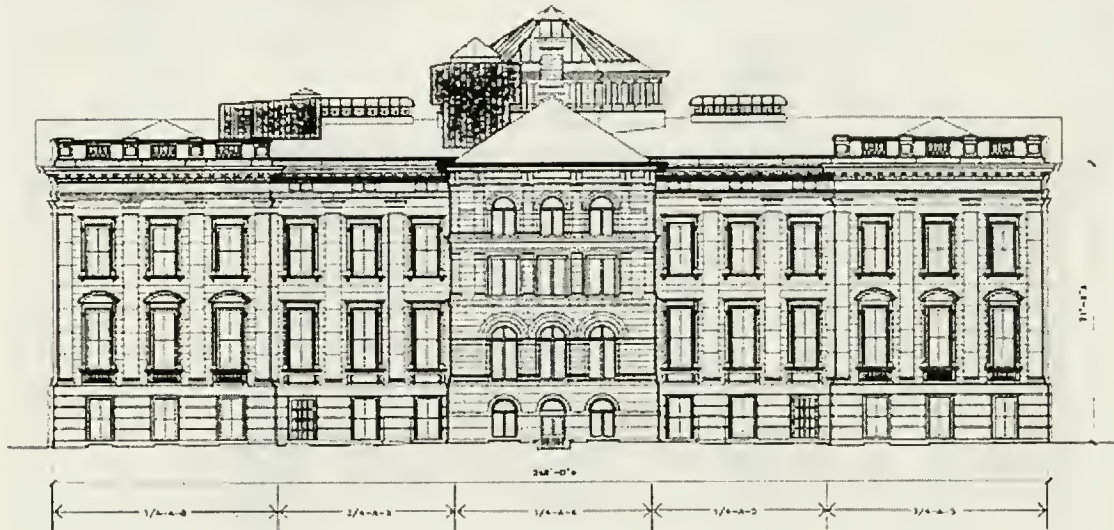
1 SOUTH ELEVATION
A-1 SCALE : 1/16" = 1'-0"
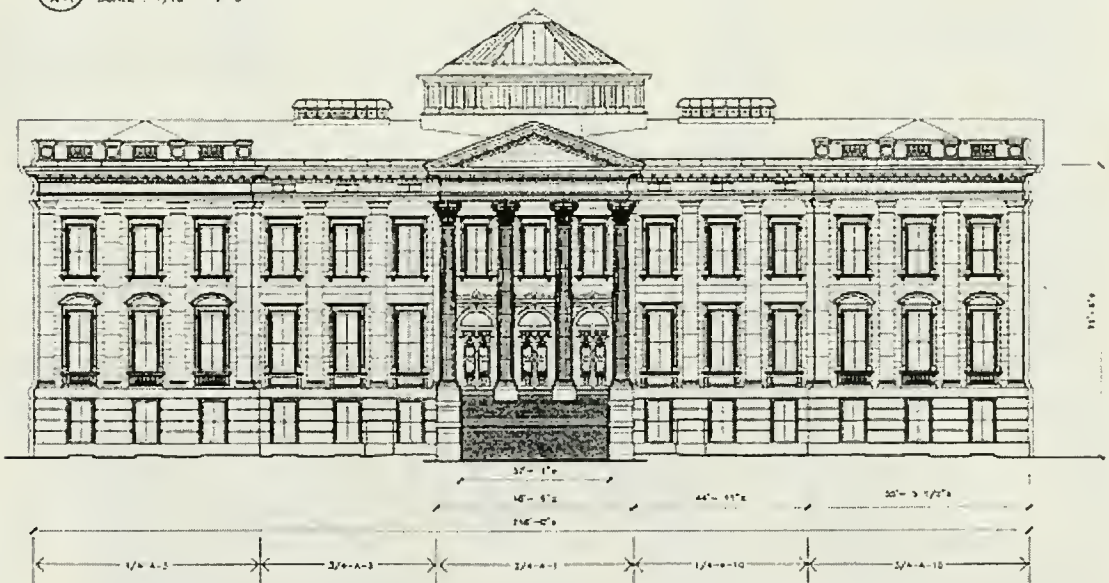
3 NORTH ELEVATION
A-1 SCALE : 1/16" = 1'-0"
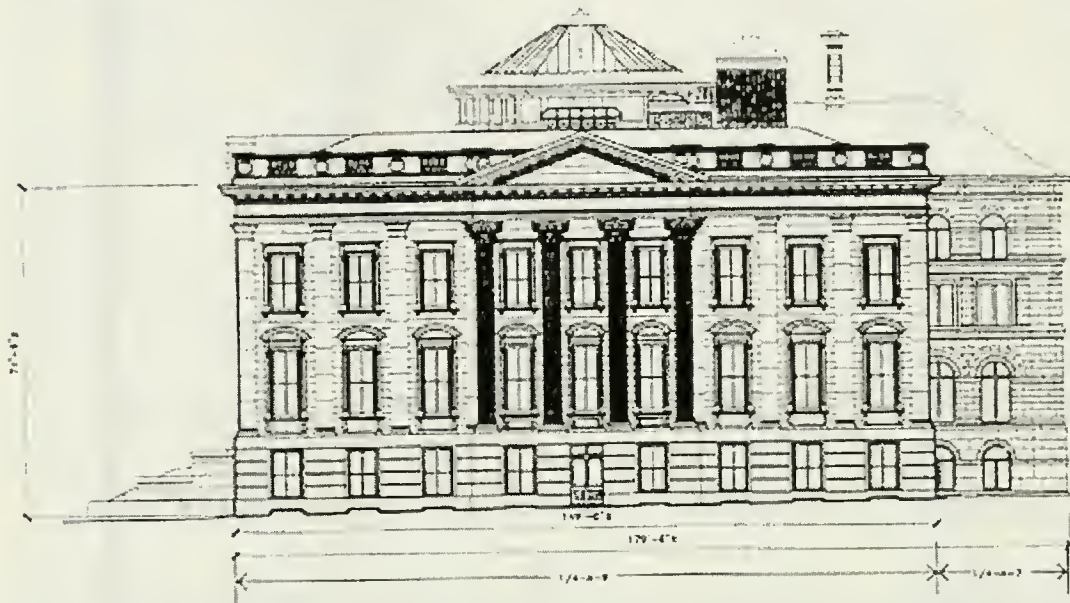
2/A-1 WEST ELEVATION
       SCALE : 1/16" = 1'-0"
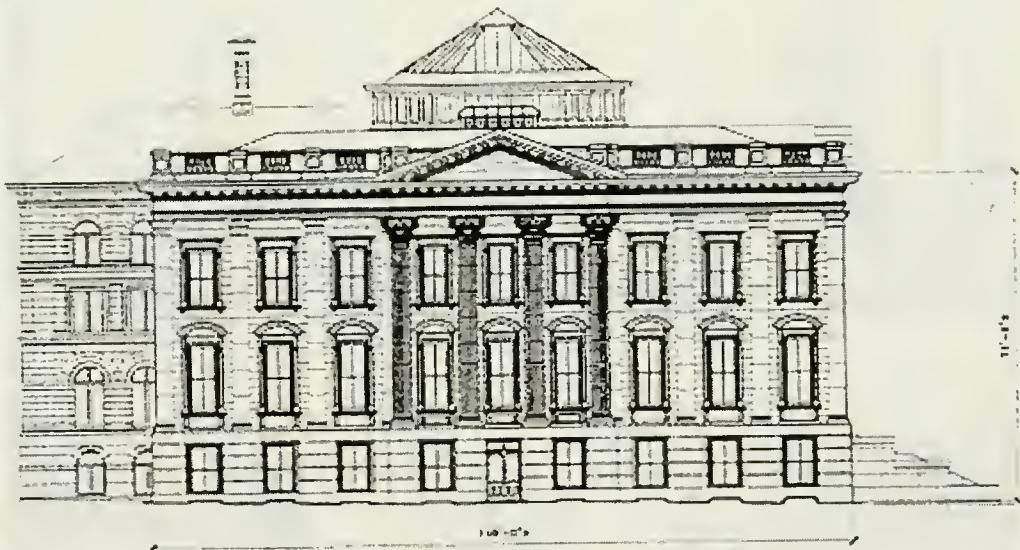
4/A-1 EAST ELEVATION
       SCALE : 1/16" = 1'-0"

MATRIX OF SAMPLES

Sample Number	Location	Description	Identification	Certainty	Thin Section	Slide Number	Calcite Staining	Other Tests
1	N portico, column 2 from west	leaf detail from capital	Tuckahoe	high	yes	T-1A, T-1B, T-1C	pale pink, red flecks	SEM, EDS, XRD
2	N portico, column 1 from west	leaf detail from capital	Tuckahoe	high	no			
3	E elevation, S end, cornice	boring cylinder, interior staining	Sheffield	high	yes	T-3	pink, red flecks	
4	E elevation, N end, cornice	boring cylinder, ferrous streaks	Sheffield	high	yes	T-4	pale pink	
5	E elevation, S end, cornice	boring cylinder, green flecks	Tuckahoe	medium	no			
6	E elevation, S end, cornice	boring cylinder, tallest	Tuckahoe	medium	no			
7	E elevation, N end, cornice	boring cylinder, yellow staining	Sheffield	medium	no			
8	E elevation, S end, cornice	boring cylinder, some ferrous streaks	Sheffield	high	yes	T-8	pink, red flecks	
9	W pediment attic level	bedding mortar	NA	NA	no			
10	W pediment attic level	brick and salt samples	NA	NA	no			
11	E façade, cornice, Eidlitz wing	carving sample	Tuckahoe	high	yes	T-11	pink, red flecks	
12	NE corner, chimney, Eidlitz wing	chimney block	Tuckahoe	high	yes	T-12A, T-12B	pink, red flecks	
13	Sheffield, MA	quarry sample, biogrowth	Sheffield	high	no			XRD
14	Sheffield, MA	quarry sample, light biogrowth	Sheffield	high	yes	S-15	dark red	
15	Sheffield, MA	quarry sample, biogrowth	Sheffield	high	yes	T-16	pink, red flecks	
16	W pediment, exterior	pyrite inclusions	from Tuckahoe	high	yes	T-17	pink, red flecks	
17	E Eidlitz/ S. Kellum	gypsum crust	Tuckahoe	high	no			
18	W. pediment, attic level, interior	gypsum crust	Tuckahoe	medium	no			
19	SE façade, balustrade level	micaceous inclusions	from Tuckahoe	NA	no			
20	NE façade, balustrade level	unknown inclusions	from Tuckahoe	NA	yes	T-20	pink, red flecks	
21	N portico, W side, cymatium	staining inside of stone	Tuckahoe	high	yes	T-21	pink, red flecks	XRD
22	N portico, column 1 from west	large grain with brown inclusions	Tuckahoe	high	no			
23	N portico, column 1 from west	brown inclusions	tremolite	medium	no			
24	N portico, W side, cymatium	mica	mica	medium	no			
25	Scaffolding	white/ gray large crystals	Cherokee	high	yes	T-25	pink, red flecks	
26	Scaffolding	white/ gray large crystals	Cherokee	high	yes	G-26	dark red	
27	Scaffolding	white/ gray large crystals	Cherokee	high	no			
28	Scaffolding	white/ gray large crystals	Cherokee	high	no			
29	Scaffolding	white/ gray large crystals	Cherokee	high	yes	G-29	dark red	
30	N side, W pavilion, E window	profile, blue veins	Sheffield	low	no			
31	W side, S end	large grains, 1/2 square piece	Tuckahoe	low	no			XRD
32	SE corner plaster cap	fine-grained, amber stained	Sheffield	high	no			
33	Farmers & Mechanics Bank	v fine-grained sandy flakes	Lee	high	no			
34	S façade, W side, 3rd Fl window	fine-grained, sandy, micaceous layering	Sheffield	high	no			
35	S façade, W side, 3rd Fl window	larger grain, few inclusions, ferrous staining	Sheffield	high	no			
36	S façade, W side, 3rd Fl window	larger grain, few inclusions, ferrous staining	Sheffield	high	yes	S-36	dark red	SEM, EDS
37	S façade, W side, 3rd Fl window	larger grain, few inclusions, ferrous staining	Sheffield	high	yes	S-37	dark red	SEM
38	S façade, W side, 3rd Fl window	white, rectangular, tooled surface	Sheffield	high	yes	S-38	dark red	
39	N façade, W side, Right of portico	curved detail piece	Tuckahoe	low	no			
40	N façade, W side, Right of portico	curved detail piece	Tuckahoe	low	no			
41	N façade, W side, Right of portico	discarded sample, probably weathered	Sheffield	low	no			
42	N façade, W side, Right of portico	discarded sample	Sheffield	low	no			
43	N façade, Intersection N pavilion and recess	weathered discarded sample	Sheffield	low	no			
44	N façade, Intersection N pavilion and recess	freshly quarried large detail	Sheffield	low	no			

BIOQUANT ANALYSIS: SUMMARY OF DATA

S-38 Fresh Sheffield Marble

Average Grain Area (square microns)	168,726
Average Grain Diameter in Sample (micr	358
Average Grain Perimeter (microns)	1,548
Average Grain Paris Factor	0.58
Number of Grains in 1 Square cm	449
Gradation Coefficient (So=√d75/d25)	1.75
Inequality Grade (U=d60/d10)	5.60

S-15 Weathered Sheffield Marble

Average Grain Area (square microns)	191,383
Average Grain Diameter in Sample (micr	349
Average Grain Perimeter (microns)	1,471
Average Grain Paris Factor	0.56
Number of Grains in 1 Square cm	410
Gradation Coefficient (So=√d75/d25)	1.91
Inequality Grade (U=d60/d10)	4.70

T-1B Weathered Tuckahoe Marble

Average Grain Area (square microns)	590,318
Average Grain Diameter in Sample (micr	586
Average Grain Perimeter (microns)	3,046
Average Grain Paris Factor	0.46
Number of Grains in 1 Square cm	145
Gradation Coefficient (So=√d75/d25)	2.76
Inequality Grade (U=d60/d10)	10.90

T-8 Weathered Tuckahoe Marble

Average Grain Area (square microns)	407,500
Average Grain Diameter in Sample (micr	522
Average Grain Perimeter (microns)	2,345
Average Grain Paris Factor	0.53
Number of Grains in 1 Square cm	207
Gradation Coefficient (So=√d75/d25)	2.28
Inequality Grade (U=d60/d10)	5.10

G-29 Fresh Cherokee Marble

Average Grain Area (square microns)	977,018
Average Grain Diameter in Sample (micr	943
Average Grain Perimeter (microns)	3,970
Average Grain Paris Factor	0.57
Number of Grains in 1 Square cm	91
Gradation Coefficient (So=√d75/d25)	1.87
Inequality Grade (U=d60/d10)	4.10

BIOQUANT ANALYSIS: GRAIN SIZE SUMMATION

Data Set Name: S-38

Sieve Number	Size (microns)	Number of Grains	Percent
200	75	48	10.69%
100	150	81	18.04%
50	300	104	23.16%
30	600	135	30.07%
16	1180	71	15.81%
8	2360	10	2.23%
		0	0.00%

S-38 Grain Size Summation

Data Set Name: S-15

Sieve Number	Size (microns)	Number of Grains	Percent
200	75	39	9.51%
100	150	79	19.27%
50	300	94	22.93%
30	600	114	27.80%
16	1180	48	11.71%
8	2360	16	3.90%
		0	0.00%

S-15 Grain Size Summation

Data Set Name: T-8

Sieve Number	Size (microns)	Number of Grains	Percent
200	75	15	7.25%
100	150	38	18.36%
50	300	43	20.77%
30	600	44	21.26%
16	1180	42	20.29%
8	2360	24	11.59%
		1	0.48%

T-8 Grain Size Summation
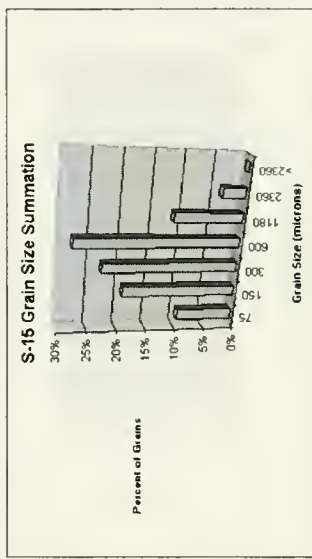
Data Set Name: G-29

Sieve Number	Size (microns)	Number of Grains	Percent
200	75	2	2.20%
100	150	0	0.00%
50	300	11	12.09%
30	600	21	23.08%
16	1180	31	34.07%
8	2360	26	28.57%
		1	1.10%

G-29 Grain Size Summation

Data Set Name: T-1B

Sieve Number	Size (microns)	Number of Grains	Percent
200	75	26	17.93%
100	150	22	15.17%
50	300	18	12.41%
30	600	33	22.76%
16	1180	25	17.24%
8	2360	19	13.10%
		4	2.76%

T-1B Grain Size Summation

BIOQUANT ANALYSIS: GRAIN SIZE DISTRIBUTION

Data Set Name: S-38

Sieve Number	Grain Size (microns)	Number of Grains	Percent	Log
200	75	48	10.69%	1.875
100	150	81	28.73%	2.176
50	300	104	51.89%	2.477
30	600	135	81.96%	2.778
16	1180	71	97.77%	3.720
8	2360	10	100.00%	3.373
	>2360	0	100.00%	3.380
		449		

S-38 Grain Size Summation
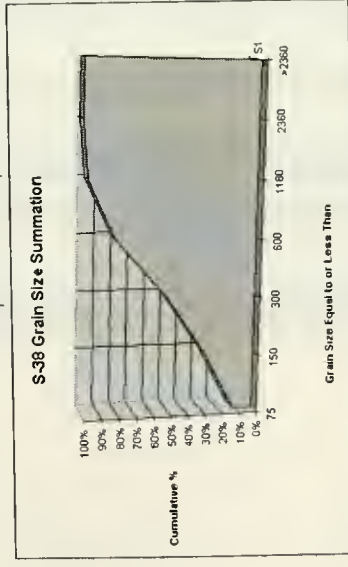
Data Set Name: S-15

Sieve Number	Grain Size (microns)	Number of Grains	Percent	Log
200	75	39	10.00%	1.875
100	150	79	30.26%	2.176
50	300	94	54.36%	2.477
30	600	114	83.59%	2.778
16	1180	48	95.90%	3.720
8	2360	16	100.00%	3.373
	>2360	0	100.00%	3.380
		390		

S-15 Grain Size Summation
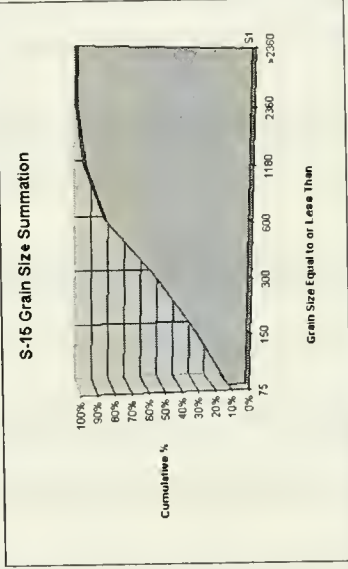
Data Set Name: T-8

Sieve Number	Grain Size (microns)	Number of Grains	Percent	Log
200	75	15	7.25%	1.875
100	150	38	25.60%	2.176
50	300	43	46.38%	2.477
30	600	44	67.63%	2.778
16	1180	42	87.92%	3.720
8	2360	24	99.52%	3.373
	>2360	1	100.00%	3.380
		207		

T-8 Grain Size Summation
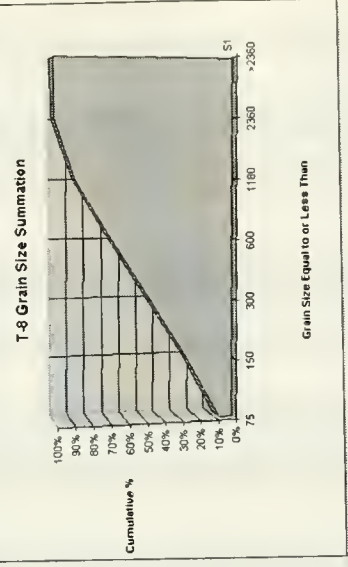
Data Set Name: T-1B

Sieve Number	Grain Size (microns)	Number of Grains	Percent	Log
200	75	26	17.69%	1.875
100	150	22	32.65%	2.176
50	300	18	44.90%	2.477
30	600	33	67.35%	2.778
16	1180	25	84.35%	3.720
8	2360	19	97.28%	3.373
	>2360	4	100.00%	3.380
		147		

T-1B Grain Size Summation
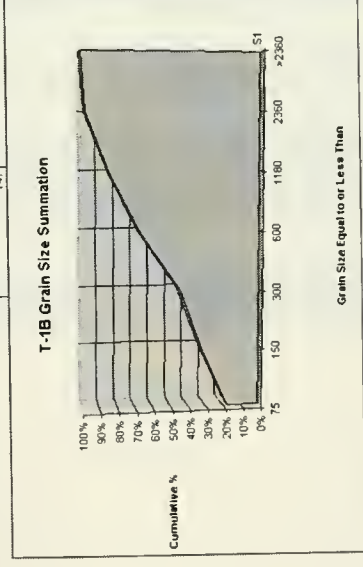
Data Set Name: G-29

Sieve Number	Grain Size (microns)	Number of Grains	Percent	Log
200	75	2	2.17%	1.875
100	150	0	2.17%	2.176
50	300	11	14.13%	2.477
30	600	21	36.96%	2.778
16	1180	31	70.65%	3.720
8	2360	26	98.91%	3.373
	>2360	1	100.00%	3.380
		92		

G-29 Grain Size Summation

BIOQUANT ANALYSIS: RAW DATA

Data Set Name: S-38				Data Set Name: S-15				Data Set Name: T-1B				Data Set Name: T-8				Data Set Name: G-29			
Area A2	Average Diameter P4	Perimeter P1	Shape Factor P2	Area A2	Average Diameter P4	Perimeter P1	Shape Factor P2	Area A2	Average Diameter P4	Perimeter P1	Shape Factor P2	Area A2	Average Diameter P4	Perimeter P1	Shape Factor P2	Area A2	Average Diameter P4	Perimeter P1	Shape Factor P2

48795.23	249.26	979.19	0.64	5572069	206.36	1424.13	0.95
17361024	470.16	1094.05	0.61	4376271	746.46	3253.08	0.52
299469.99	617.49	2459.37	0.62	441035.39	749.36	3096.19	0.58
7251.68	96.08	366.92	0.68	1996.65	50.29	181.59	0.76
1010407	113.63	407.17	0.77	7568.17	98.16	384	0.64
33657162	644.83	3538.23	0.59	30460024	622.97	2577.23	0.58
837631	326.57	1124.63	0.83	5249.72	82.13	278.28	0.86
9586.97	110.48	396.44	0.77	8913417.9	1065.31	3915.22	0.73
3384459	208.02	754.23	0.75	259115.39	574.38	2427.29	0.56
28615.1	190.54	673.63	0.79	1702.84	46.56	165.67	0.55
33001.31	204.96	944.26	0.47	30085.5	195.71	683.89	0.62
15548.1	140.7	481.28	0.94	2130009	184.99	650.68	0.81
1044734	115.33	493.71	0.84	289766.5	607.41	2708.16	0.63
27000.18	185.56	753.49	0.6	162337.35	454.64	1917.33	0.5
291911	192.79	749.99	0.65	349366.87	696.95	2788.48	0.56
13151.36	129.4	543.08	0.56	167445.9	146.01	535.25	0.56
2642.56	59.01	207.57	0.77	206894.98	513.25	1733.04	0.73
660368	104.66	865.34	0.14	4257.1	73.62	324.9	0.87
6145	88.6	143.16	0.04	1158397.68	384.13	1378.33	0.51
368.73	21.67	180.29	0.14	1049138.2	366.49	2127	0.77
1031607	117.35	509.3	0.52	293267	375.21	1318.59	0.62
1936831	157	683.33	0.52	1115757	270.17	1303.87	0.76
2663001	190.96	724.71	0.89	5733892	272.61	979.19	0.75
2913803.99	533.9	2292.22	0.64	5636895.5	61.11	961.32	0.82
2915423	609.26	2627.06	0.53	6811.36	93.13	474.08	0.79
12290991	395.59	1579.69	0.62	26772.42	184.63	752.63	0.38
347835	210.45	789.13	0.79	23082.93	171.44	636.87	0.59
71717.93	302.18	1124.63	0.71	13014.48	123.68	454.12	0.62
19604.13	157.99	856.45	0.34	17312.2	148.47	593.99	0.73
1167459.7	1219.2	5167.87	0.55	6149.14	98.49	315.68	0.62
1290.56	40.54	174.81	0.53	12960.5	128.46	475.44	0.72
12475.36	126.03	530.09	0.56	3233502.7	641.64	2395.11	0.73
576.77	65.76	444.7	0.37	732410.12	966.68	4479.53	0.46
21613707	524.59	2499.16	0.44	7719538	376.84	1460.02	0.66
11147928	376.75	1683.64	0.49	51274.38	382.08	1403.33	0.73
23770776	550.14	2843.52	0.37	13402203	129.39	579.02	0.49
576.77	85.76	30379	0.79	132916.07	448.77	2463.41	0.33
74975.04	61.48	1717.79	0.67	350630.3	165.52	167.35	0.56
13575.06	308.97	2393.35	0.75	1811.36	668.22	2434.31	0.74
3087917	686.24	6899.97	0.56	128753.57	93.13	599.77	0.54
40437.36	226.91	1800.84	0.46	95463.61	404.89	1630.68	0.6
11639568	384.97	2060	0.72	261291.24	346.62	1236.12	0.71
28847236	527.42	630.19	0.29	2270.45	576.79	2024.32	0.8
2163274	165.96	246.63	0.79	8514.2	53.77	206.37	0.68
24790928	561.63	295.11	0.48	249663	104.12	358.08	0.63
1286972	135.96	515.17	0.52	24560057	176.97	660.27	0.71
11130347	377.48	1438.02	0.6	525688.82	583.16	2789.99	0.4
15626667	448.67	1769.47	0.63	221653.92	258.79	1120.5	0.53
648731.27	835.86	5039.92	0.62	61461.42	531.24	2145.29	0.61
411749	72.41	291.84	0.27	460300.4	279.81	1000.39	0.67
16659.4	153.72	849.4	0.66	609605.69	229.45	683.38	0.76
1002330.3	357.24	1324.8	0.32	61036.82	881.16	4642.47	0.36
1106.19	37.53	252.14	0.72	67991.14	279.59	1074.97	0.67
234080.83	546.06	5512.66	0.22	15703.96	271.73	1107.69	0.59
20833.23	162.87	572.46	0.43	36989.45	141.4	460	0.93
27470364	591.41	2217.98	0.8	21474.7	217.02	768.35	0.79
1640893	144.81	634.87	0.57	748303.79	156.36	640.08	0.66
5782911	271.36	1017.7	0.51	7945.58	976.1	3676.8	0.7
38850692	700.6	3070.65	0.7	1193397.96	100.59	456.59	0.48
1047806.68	165.25	1451.21	0.63	4067.89	389.68	1656.22	0.55
6438198	286.08	1119.53	0.64	3676.65	71.97	241.82	0.87
514378	255.92	1240.65	0.38	194123.68	216.18	829.39	0.67
3687297	216.68	994.66	0.47	207936.6	497.16	2095.1	0.56
11516658	382.93	1609.33	0.56	1298028	125.13	1915.37	0.71
16654292	460.49	2392.62	0.37	348614.45	666.14	403.77	0.66
11786566	377.27	1329.27	0.8	415114.39	727.01	2766.85	0.57
5346.58	82.51	354.78	0.53	804119	101.18	3032.91	0.57
1636157	146.96	736.04	0.39	35097.41	211.29	304.58	0.68
33247.13	205.75	1199.19	0.29	14747.7	156.36	697.64	0.66
52543.96	258.66	1118.46	0.53	13717.32	132.16	466.51	0.8
1352009	131.2	485.26	0.72	1910964	155.98	679.68	0.52
737.46	30.54	126.44	0.58				

521113.0	257.59	929.43	0.76
5229.16	258.05	1134.36	0.51
21755.05	166.43	576.42	0.82
210421.76	517.61	1949.86	0.7
26281.38	578.43	2206.6	0.68
76396.46	989.73	4564.44	0.47
100048.66	356.91	1445.29	0.6
99567.02	356.03	2091.86	0.15
4123.27	229.14	871.18	0.68
37610.43	218.83	843.12	0.66
2636.17	173.34	868.29	0.39
2806.93	59.99	209.1	0.61
67213.82	935.09	3842.59	0.57
3939.62	223.96	867.73	0.66
56062.21	272.64	2166.34	0.16
46221.4	243.38	879.33	0.75
1597.83	45.1	215.45	0.43
36991.15	586.23	2923.11	0.4
16353.83	456.31	1823.34	0.62
44149.38	749.75	2770.55	0.52
62124.12	889.38	3610.8	0.63
26732.9	164.49	721.33	0.65
13308.45	128.8	523.61	0.6
3933.12	70.77	297.08	0.56
325.11	64.4	233.25	0.75
1196.372	123.52	492.06	0.62
56836.3	273.93	1036.37	0.69
79952.69	319.06	1135.1	0.7
144234.77	429.54	202572	0.44
175330.98	472.48	1889.54	0.61
10324.43	114.65	419.32	0.74
8234.56	102.4	379.01	0.72
4013.08	226.04	843.68	0.71
25442.36	179.98	799.82	0.5
5361.13	67.12	424.43	0.42
737.45	50.64	126.44	0.58

Z16972.RAW
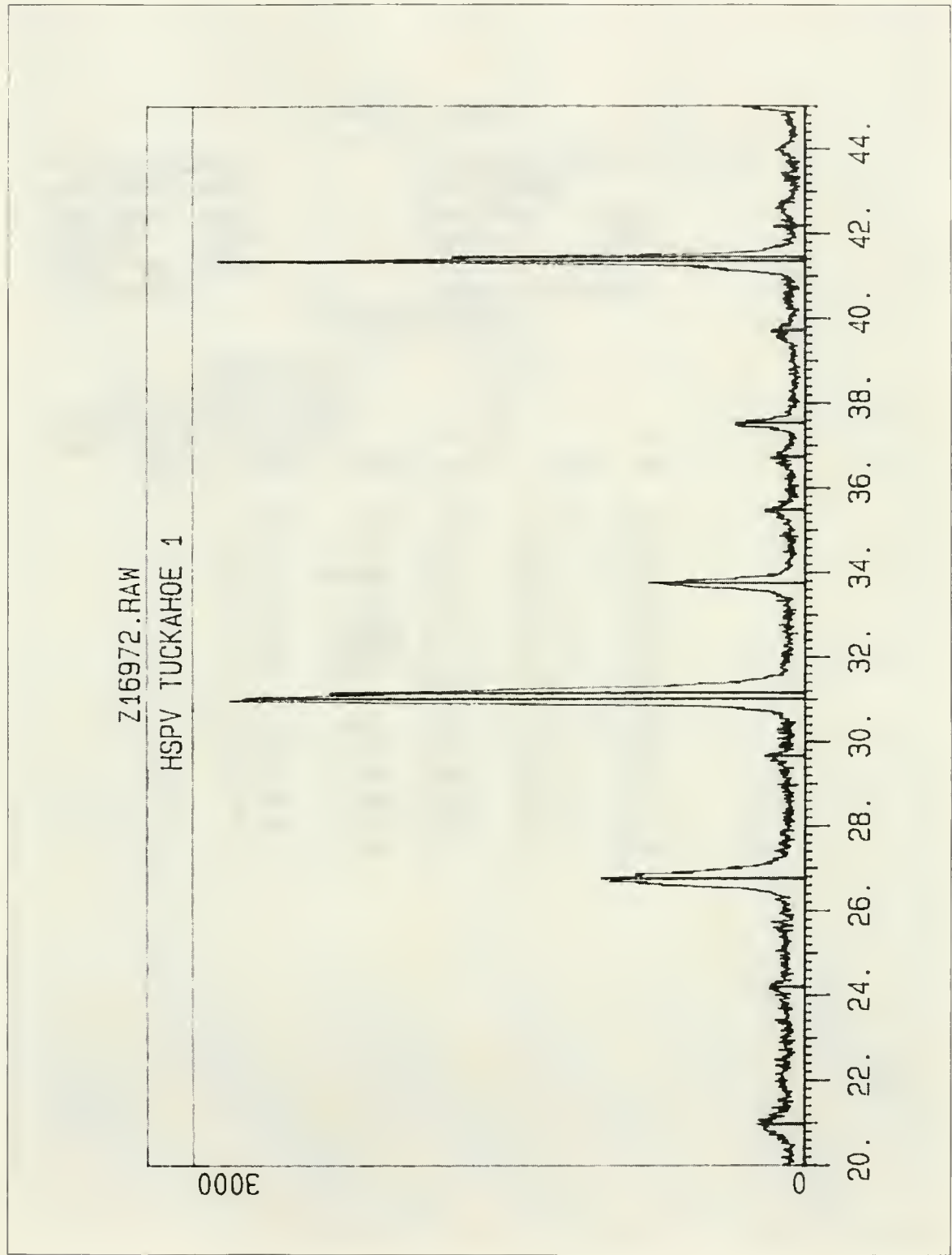
HSPV TUCKAHOE 1

PEAKS FILE LISTING

DATA FILE: 116972.PKS   COLLECTED ON 13-MAR-01 AT 10:29:13
SAMPLE IDENTIFICATION: HSFV TUCKAHOE 1
START 2THETA: 20.000   STOP 2THETA: 45.000
STEP SIZE: 0.020   SCAN SPEED: 5.000
COUNTING TIME: 5.000
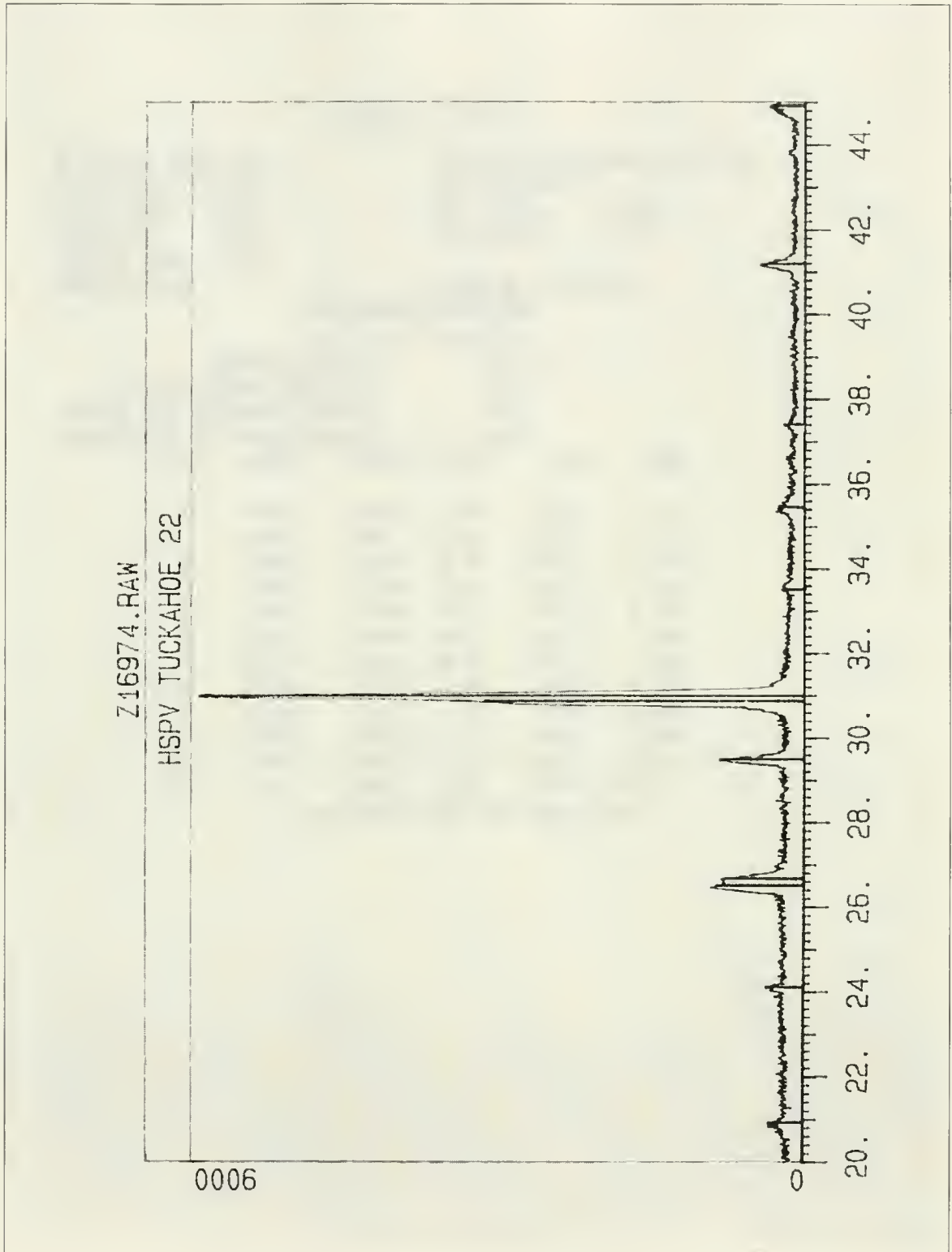PEAKS FOUND ON: 13-MAR-01 AT 11:42:42
                      PEAK FINDING PARAMETERS

            THRESHOLD VALUES: 0.0, 0.0
        RELATIVE CUTOFF INTENSITY: 0.0
    TYPICAL FULL WIDTH-HALF MAXIMUM: 0.00
    MINIMUM FULL WIDTH-HALF MAXIMUM: 0.00

        PEAK   2-THETA   D-SPACE   I(REL)   I(CPS)   FWHM

          1   20.960   4.2384   6.50   187.0   0.040
          2   24.191   3.6792   6.08   175.0   0.320
          3   26.715   3.3328   34.73   1000.0   0.122
          4   29.652   3.0129   6.95   200.0   0.200
          5   31.000   2.8848   94.20   2712.0   0.040
          6   31.140   2.8722   81.04   2333.0   0.200
          7   33.750   2.6559   26.78   771.0   0.101
          8   35.171   2.5308   6.95   200.0   25.000
          9   36.716   2.4478   5.94   171.0   0.128
         10   37.527   2.3967   12.02   346.0   0.302
         11   39.708   2.2700   5.80   167.0   0.180
         12   41.340   2.1840 100.00   2879.0   0.120
         13   41.440   2.1790   60.19   1733.0   0.120
         14   42.171   2.1429   5.35   154.0   0.040

Z16974.RAW

HSPV TUCKAHOE 22

0006

PEAKS FILE LISTING

DATA FILE: I16974.PKS   COLLECTED ON 13-MAR-01 AT 10:43:53
SAMPLE IDENTIFICATION: HSPV TUCKAHOE 22
START 2THETA: 20.000   STOP 2THETA: 45.000
STEP SIZE: 0.020   SCAN SPEED: 5.000
COUNTING TIME: 5.000
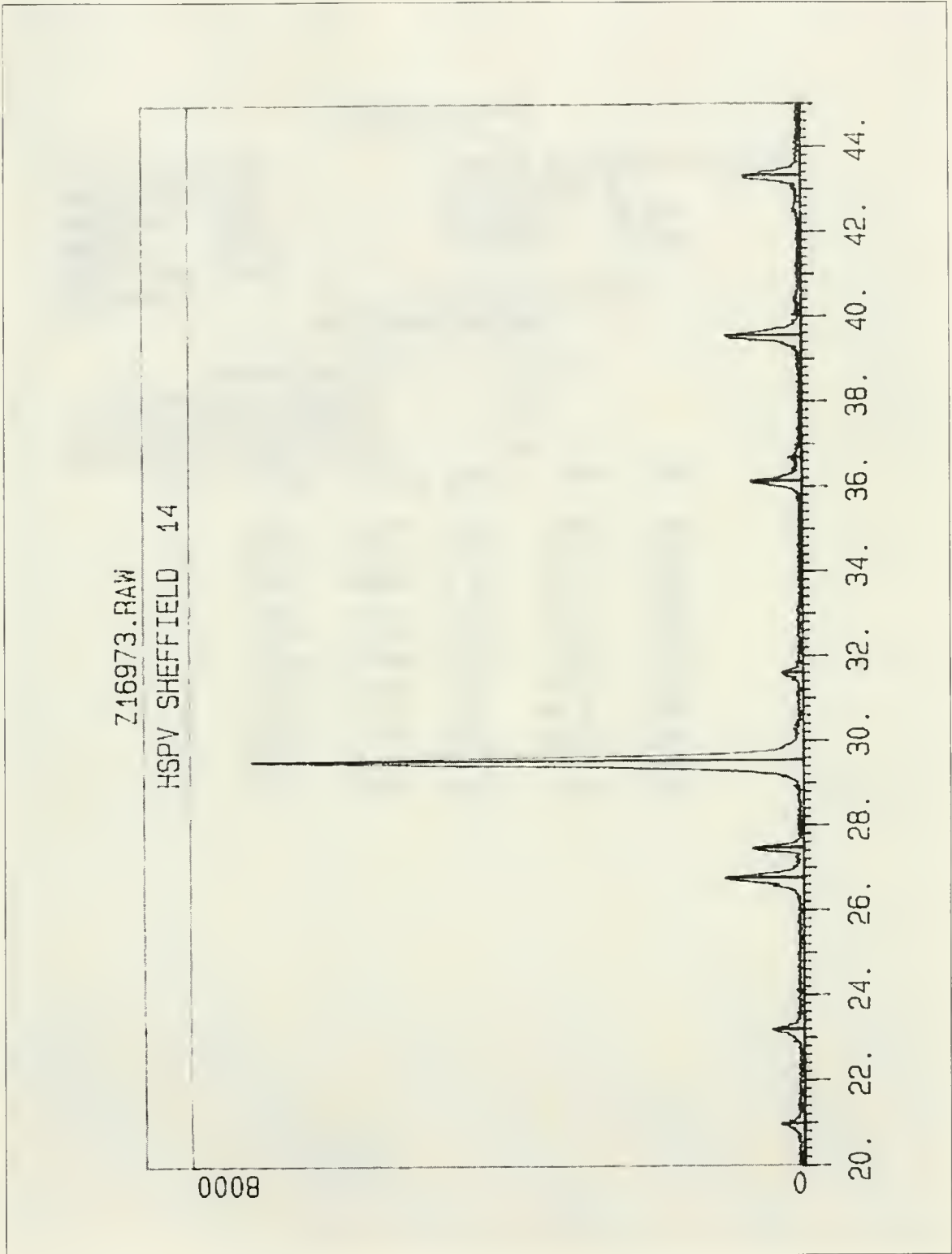PEAKS FOUND ON: 13-MAR-01 AT 12:01:23

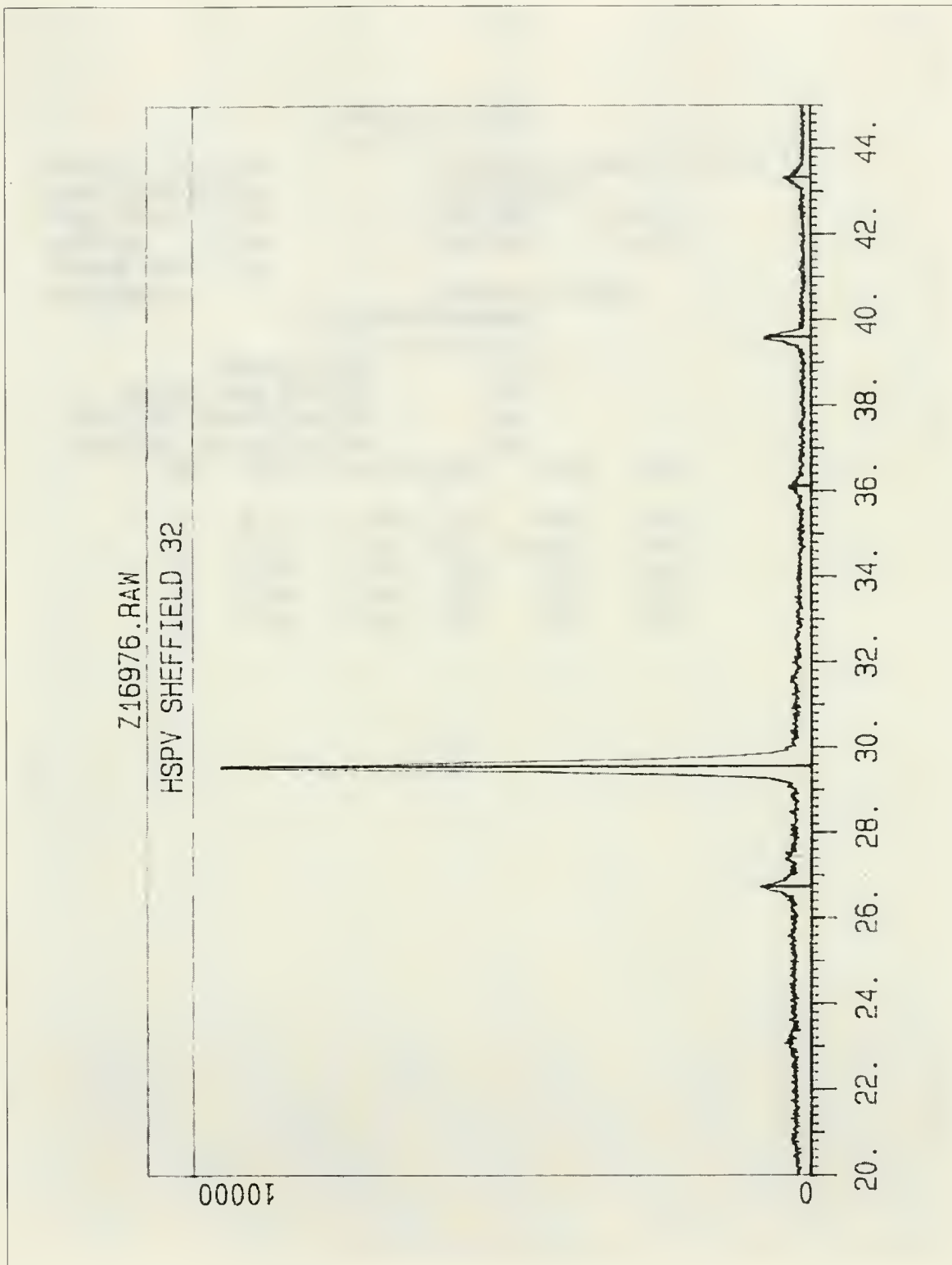PEAK FINDING PARAMETERS

         THRESHOLD VALUES: 0.0, 0.0
     RELATIVE CUTOFF INTENSITY: 0.0
 TYPICAL FULL WIDTH-HALF MAXIMUM: 0.00
 MINIMUM FULL WIDTH-HALF MAXIMUM: 0.00

PEAK	2-THETA	D-SPACE	I(REL)	I(CPS)	FWHM
1	20.917	4.2471	5.56	521.0	0.324
2	24.099	3.6930	6.38	567.0	0.294
3	26.500	3.3636	14.58	1296.0	0.305
4	26.660	3.3438	13.13	1167.0	0.040
5	29.485	3.0295	14.11	1254.0	0.208
6	30.860	2.8976	53.12	4721.0	0.120
7	30.979	2.8867	100.00	8887.0	0.248
8	33.500	2.6750	3.52	313.0	0.140
9	35.440	2.5329	4.35	387.0	25.000
10	37.400	2.4046	3.47	308.0	0.260
11	41.178	2.1923	7.45	662.0	0.010
12	44.903	2.0187	5.82	517.0	0.260

∤ - peak FWHM is less than step width

Z16973.RAW

HSPV SHEFFIELD 14

PEAKS FILE LISTING

DATA FILE: 816973.PKS   COLLECTED ON 13-MAR-01 AT 10:43:46
SAMPLE IDENTIFICATION: HSPV SHEFFIELD 14
START 2THETA: 20.000   STOP 2THETA: 45.000
STEP SIZE: 0.020   SCAN SPEED: 5.000
COUNTING TIME: 5.000
PEAKS FOUND ON: 13-MAR-01 AT 11:43:46

PEAK FINDING PARAMETERS

                 THRESHOLD VALUES: 0.0, 0.0
          RELATIVE CUTOFF INTENSITY: 0.0
      TYPICAL FULL WIDTH-HALF MAXIMUM: 0.00
      MINIMUM FULL WIDTH-HALF MAXIMUM: 0.00

PEAK	2-THETA	D-SPACE	I(REL)	I(CPS)	FWHM
1	20.966	4.2373	4.26	308.0	0.166
2	23.181	3.8372	5.77	417.0	0.197
3	26.748	3.3330	14.35	1037.0	0.168
4	27.466	3.2474	2.66	192.0	0.040
5	27.461	3.2480	9.29	671.0	0.160
6	29.530	3.0250	100.00	7225.0	0.207
7	31.592	2.8321	3.81	275.0	0.280
8	36.113	2.4873	9.51	687.0	0.186
9	36.659	2.4514	2.42	175.0	0.047
10	39.543	2.2791	13.84	1000.0	0.229
11	43.312	2.0891	10.55	762.0	0.262

Z16976.RAW

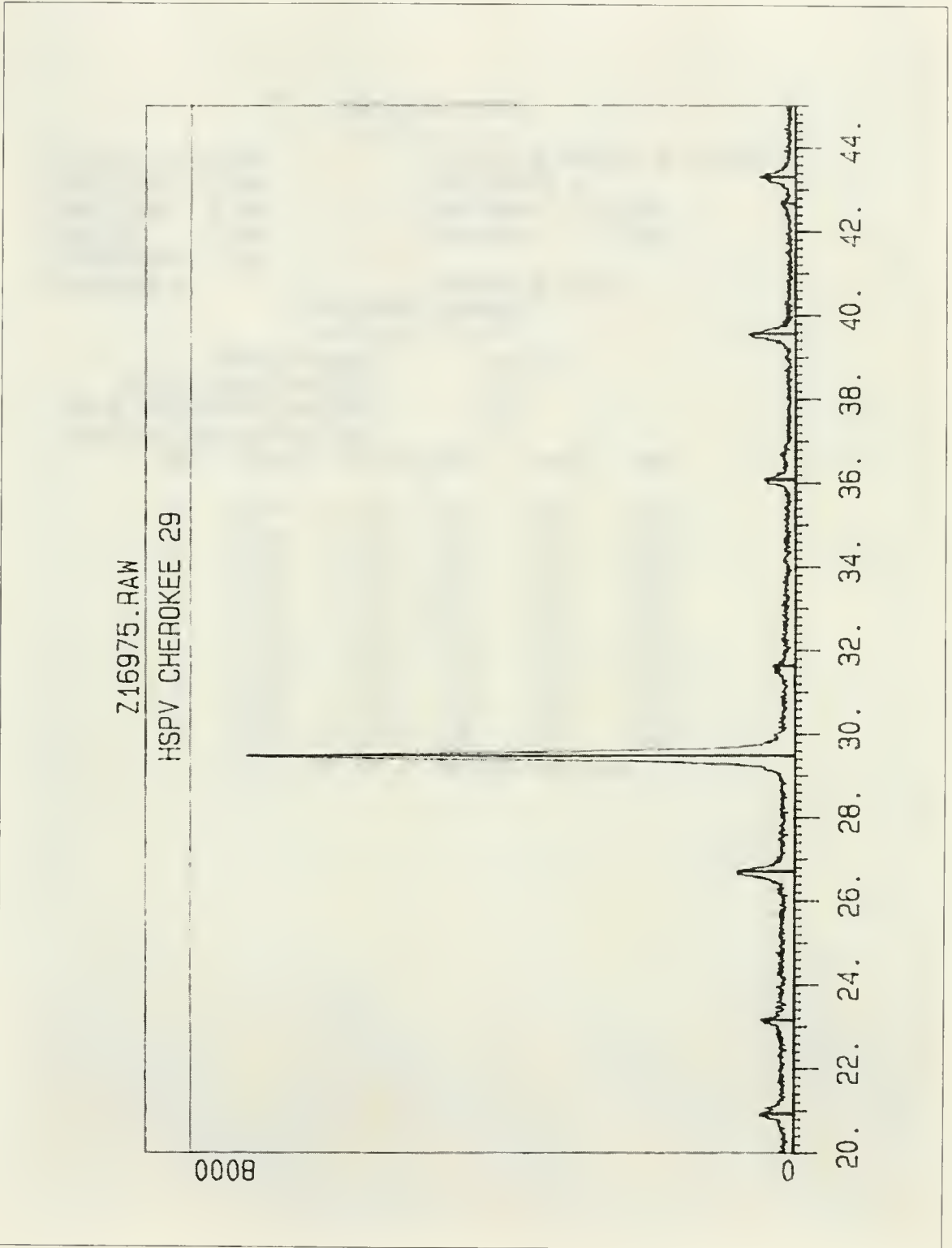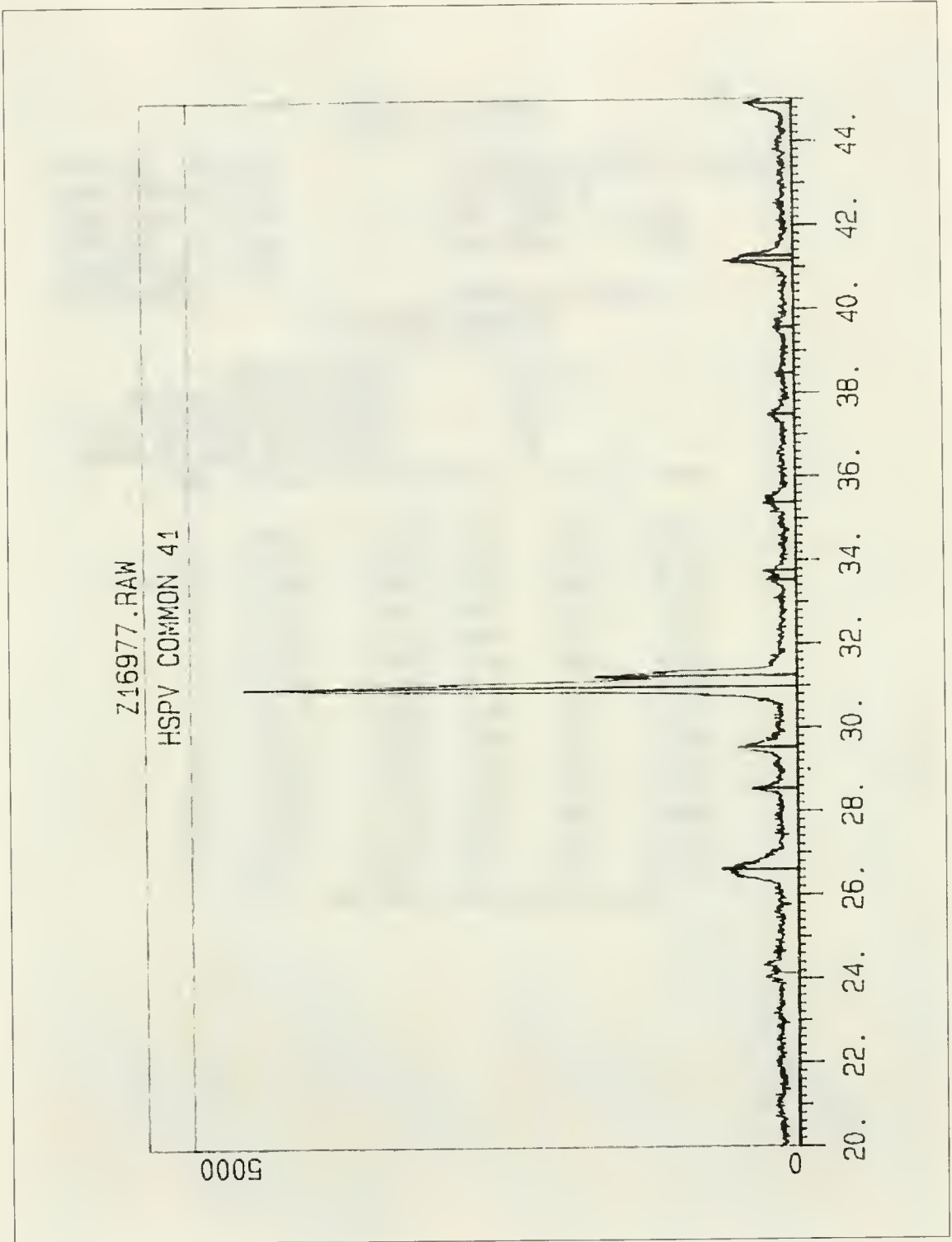HSPV SHEFFIELD 32

PEAKS FILE LISTING

DATA FILE: 116976.PKS COLLECTED ON 13-MAR-01 AT 10:43:57
SAMPLE IDENTIFICATION: HSPV SHEFFIELD 32
START 2THETA: 20.000 STOP 2THETA: 45.000
STEP SIZE: 0.020 SCAN SPEED: 5.000
COUNTING TIME: 5.000
PEAKS FOUND ON: 13-MAR-01 AT 13:24:42

PEAK FINDING PARAMETERS

THRESHOLD VALUES: 0.0, 0.0
RELATIVE CUTOFF INTENSITY: 0.0
TYPICAL FULL WIDTH-HALF MAXIMUM: 0.00
MINIMUM FULL WIDTH-HALF MAXIMUM: 0.00

PEAK	2-THETA	D-SPACE	I(REL)	I(CPS)	FWHM
1	26.721	3.3362	8.63	825.0	0.403
2	29.546	3.0234	100.00	9558.0	0.238
3	36.100	2.4881	3.84	367.0	1.623
4	39.590	2.2765	8.02	767.0	0.275
5	43.320	2.0887	4.53	435.0	0.100

Z16975.RAW

HSPV CHEROKEE 29

PEAKS FILE LISTING

DATA FILE: I16975.PKS COLLECTED ON 13-MAR-01 AT 10:43:55
SAMPLE IDENTIFICATION: ESPV CHEROKEE 29
START 2THETA: 20.000 STOP 2THETA: 45.000
STEP SIZE: 0.020 SCAN SPEED: 5.000
COUNTING TIME: 5.000
PEAKS FOUND ON: 13-MAR-01 AT 13:15:39

PEAK FINDING PARAMETERS

THRESHOLD VALUES: 0.0, 0.0
RELATIVE CUTOFF INTENSITY: 0.0
TYPICAL FULL WIDTH-HALF MAXIMUM: 0.00
MINIMUM FULL WIDTH-HALF MAXIMUM: 0.00

PEAK	2-THETA	D-SPACE	I(REL)	I(CPS)	FWHM
1	20.919	4.2467	6.20	450.0	0.010
2	23.149	3.8424	6.14	446.0	0.247
3	26.692	3.3399	4.02	292.0	0.080
4	26.694	3.3395	10.50	762.0	0.380
5	29.478	3.0302	100.00	7258.0	0.200
6	31.621	2.8296	3.95	287.0	0.498
7	36.072	2.4900	5.68	412.0	0.138
8	39.550	2.2787	8.56	621.0	0.272
9	42.660	2.1195	2.65	192.0	0.280
10	43.295	2.0898	6.65	483.0	0.267

f - peak FWHM is less than step width

Z16977.RAW

HSPV COMMON 41

PEAKS FILE LISTING

DATA FILE: S16977.PKS   COLLECTED ON 13-MAR-01 AT 10:43:59
SAMPLE IDENTIFICATION: USPV COMMON 41
START 2THETA: 20.000   STOP 2THETA: 45.000
STEP SIZE: 0.020   SCAN SPEED: 5.000
COUNTING TIME: 5.000
PEAKS FOUND ON: 13-MAR-01 AT 13:33:01

PEAK FINDING PARAMETERS

THRESHOLD VALUES: 0.0, 0.0
RELATIVE CUTOFF INTENSITY: 0.0
TYPICAL FULL WIDTH-HALF MAXIMUM: 0.00
MINIMUM FULL WIDTH-HALF MAXIMUM: 0.00

PEAK	2-THETA	D-SPACE	I(REL.)	I(CPS)	FWHM
1	26.600	3.3512	13.86	633.0	0.373
2	28.535	3.1281	8.21	375.0	0.010
3	29.524	3.0256	10.77	492.0	0.276
4	30.974	2.8872	100.00	4567.0	0.229
5	31.240	2.8632	36.50	1667.0	0.260
6	33.520	2.6735	4.20	192.0	0.040
7	33.749	2.6558	6.02	275.0	0.139
8	35.378	2.5372	5.93	271.0	0.300
9	37.480	2.3996	4.84	221.0	0.260
10	38.460	2.3407	3.37	154.0	0.140
11	39.560	2.2781	3.74	171.0	0.250
12	41.140	2.1942	10.58	483.0	0.040
13	41.260	2.1881	9.02	412.0	0.060
14	44.891	2.0192	8.67	396.0	0.240

\# - peak FWHM is less than step width

Color: light yellowish brown
Specimen from Theater Springs AR, USA. CAS d. 16389-66-1
Chemical analysis by EDS at University at North Dakota, ND, USA.
(wt %) CaO 30.19, MgO 21.10, FeO 0.44, MnO 0.11, C 02 47.18, SrO 0.17, Al2 O3 0.13, SiO2 0.17 (chiefly from traces of quartz and plagioclase) Ca (Mg0.977 Fe0.011 Sr0.005 Mn0.005 Ca0.004) (C O 01)2 Optical data on specimen from Hairy Hass Township, Ontario, Canada Colcite group, dolomite subgroup. Silicon used as an internal stand. 25C hkl0 To replace 11-76 Mol 184.40
Volume(LD) 320.00

Color: light yellowish brown

Specimen from Baxter Springs, AR USA CAS #: 16389-66 +

Chemical analysis by EDS at University of North Dakota ND. BHA (wt%) CaO 30.16, MgO 21.10, FeO 0.44, MnO 0.11 C 02 47.18, Na2 0.17, Al2 03 0.13, Si 02 0.17 (chiefly from traces of quartz and plagioclase) Ca (Mg0.977 Fe0.011 Na0.005 Mn0.003 Ca0.004) (C O3)2. Optical data on specimen from Haley Haas Township, Ontario. Canada. Calcite group, dolomite subgroup. Silicon used as an internal stand 25C BHJ0 To replace 11-78 Vol 11140

Volume[CD] 423.00

Dolomite

Ref Howie, Broadhurst, Am Mineral, 43, 1210 (1958)

Ref Ibid

Ref Ibid

Color Colorless, white
Specimen from Haley Ross Township, Ontario, Canada CAS ?
16309-88-1 Analysis (wt %): SiO2 0.12, FeO 0.22, MgO 21.12, CaO
41.27, C 02 47.22. H2 O 0.02. Calcite group dolomite subgroup
PSC hR10 Deleted by 36-426. Plus ? lines to 0.821. Mwl
101.40 Volume[CD] 321.14

X-RAY: 0 - 20 keV   Window : None
Live: 60s Preset: 60s Remaining: 0s
Real: 96s   38% Dead

S

C
a

M
g

C
a
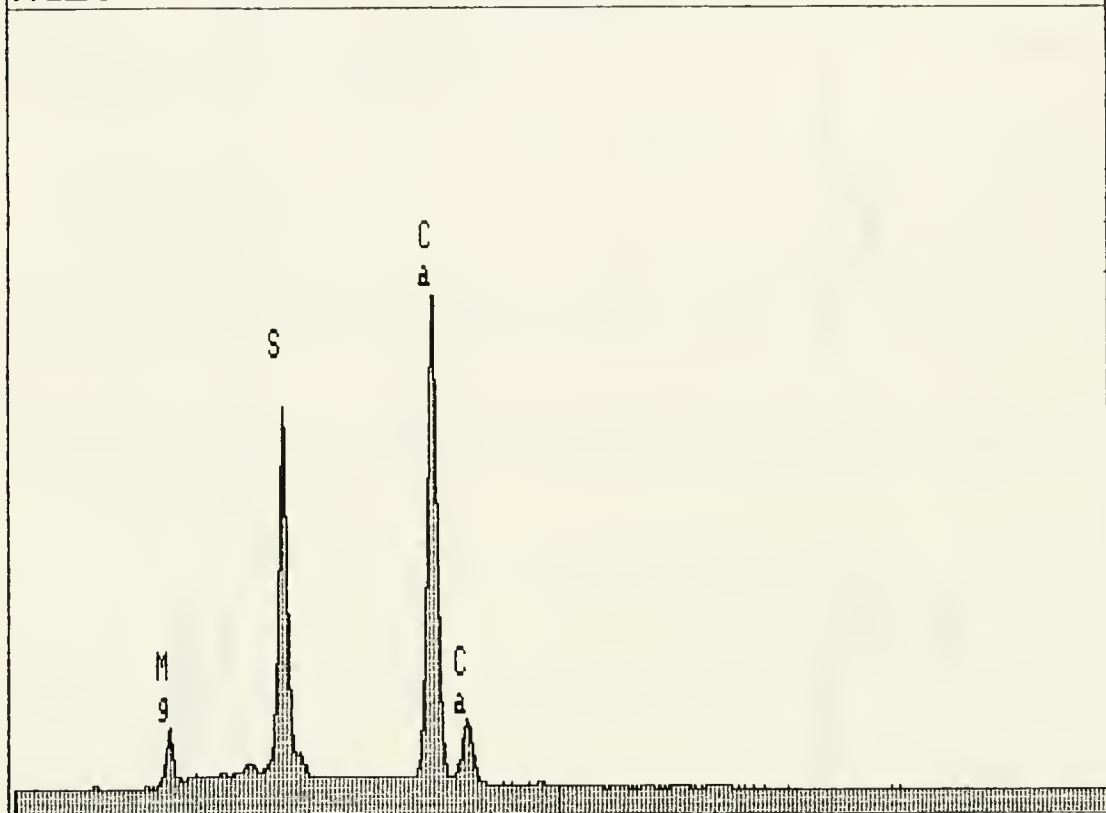
4.863   keV   10.0 >
FS= 16K OS= 512   ch   253=   164   cts
MEM1:

138 FS

✓ shefield01001

Ca

O

Ca

keV

0.0   5.0   10.0   15.0   20.0
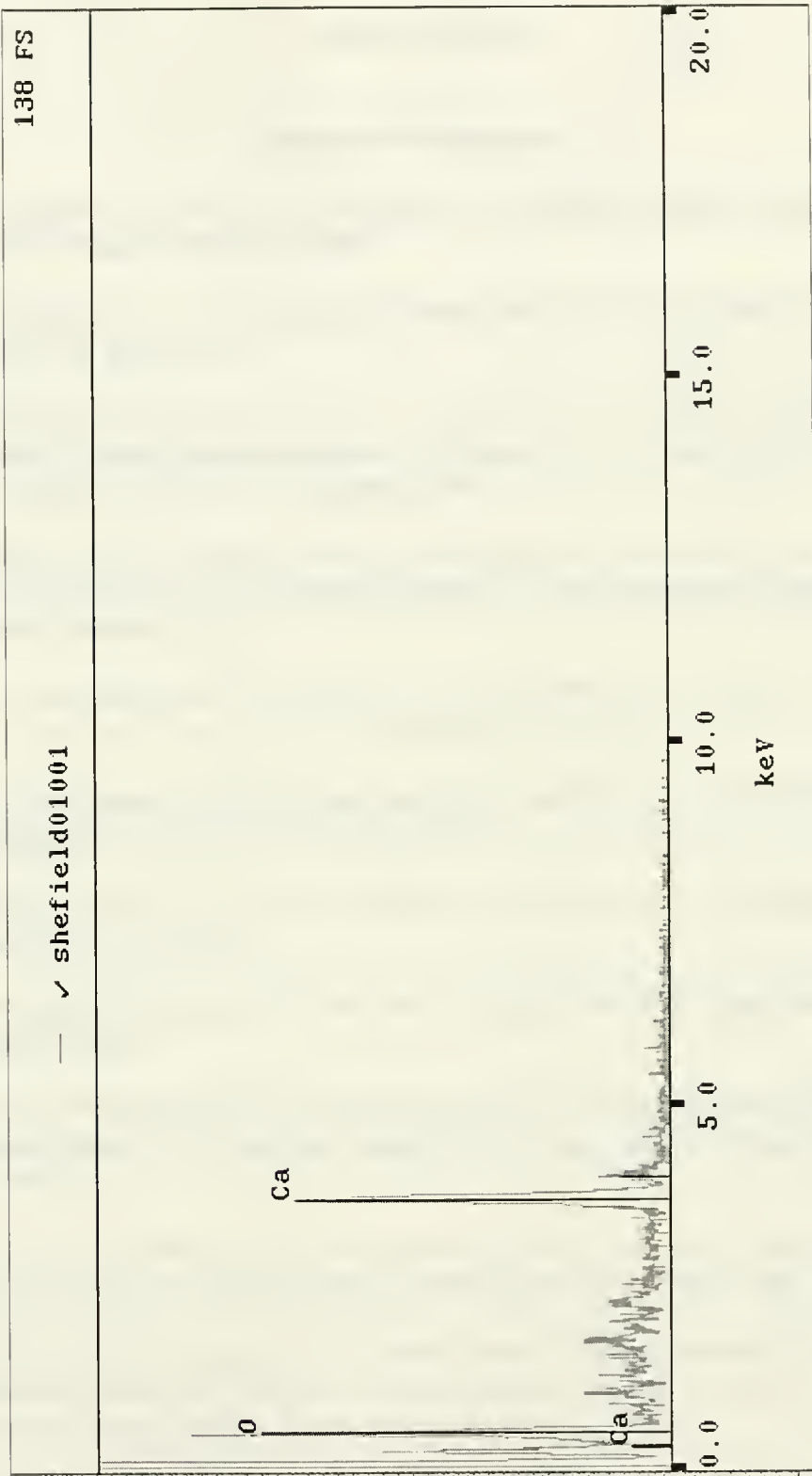
BIBLIOGRAPHY

Historical Background

Brooklyn's City Hall: Appendix: A Study Report by Conklin & Rossant. Prepared by Conklin & Rossant Architects, 1980.

Callow, Alexander B., Jr. "The house that Tweed built," *American Heritage*, October 1965, Vol. 16, pp. 65-68.

Design alternatives for the marble palace: rehabilitation and restoration of 280 Broadway & related design alternatives, Volumes 1 & 2. Prepared by Beyer, Blinder, Belle Architects & Planners. September, 1990.

Doyle, Margaret Anne. *The preservation of municipally owned buildings: the Tweed Courthouse, a case study.* Unpublished Master's Thesis, School of Architecture, Columbia University, 1978.

Harper's Weekly Magazine, vol. 14 (Nov. 19, 1870), p. 739; vol. 15 (Aug. 12, 1871), p. 14; vol. 15 (Oct. 7, 1981), p. 931; vol. 16 (Jan. 6, 1872), p. 13.

Linton, William James. *The house that Tweed built; dedicated to every true reformer (Republican or Democrat).* Cambridge, 1871.

Lynch, Dennis Tilden. *"Boss" Tweed; the story of a grim generation.* Boni and Liveright: New York, 1927.

Mather, William. *Geology of New York: Part 1.* Albany: Carroll & Cook, printers to the Assembly, 1843.

Newland, D.H. "The mining and quarry industry of New York state," *New York State Museum*, Bulletin 112, Economic Geology 16. Albany: New York State Education Dept, 1907.

Newland, D.H. "The Mining and Quarry Industry of New York State," *New York State Museum, Bulletin 142.* Albany: New York State Education Dept., 1909.

Rehabilitation and restoration of 52 Chambers Street (Tweed Courthouse), Borough of Manhattan, City of New York, for the Department of General Services, PW-292-01. Prepared by Mesick, Cohen, Waite Architects. Albany, 1987.

A Report on the reconstruction and improvement to the New York County Courthouse (Tweed Courthouse). Prepared by Ammann & Whitney, Consulting Engineers and Beyer, Blinder, Belle, Architects and Planners. New York, February 1981.

Smock, John Conover. *Building stone in the state of New York.* New York: C. Van

Benthuysen & Sons, 1888.

Torres, Louis. *Tuckahoe marble : the rise and fall of an industry in Eastchester, New York, 1822-1930.* Harrison, N.Y., Harbor Hill Books, 1976.

Tweed Courthouse, 52 Chambers Street, Borough of Manhattan. Designation List 172 LP-1437. New York City Landmarks Preservation Commission, October 16, 1984.

Tweed Courthouse, 52 Chambers Street, Borough of Manhattan, New York, NY: Feasibility Study Prepared for the Department of General Services, the City of NewYork, Kenneth J. Knuckles, Commissioner. Prepared by Mesick, Cohen, Waite Architects, Albany,1991.

The Tweed Courthouse Historic Structure Report. Joan Olshansky, Project Director, New York City Landmarks Preservation Commission, 1979.

Urquhart, Gordon Ross. *The Architectural History of the Westchester Marble Industry.* Unpublished Master's Thesis, School of Architecture, Columbia University, 1986.

Marble Weathering and Analysis

Alberti, S. A. et al. "CastelManiace, Syracuse (Sicily): the deterioration of the marble of the monumental portal and window." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 2, pp. 649-660.

Ausset, P. et al. "Early mechanisms of development of sulphated crusts on carbonate stone." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 1, pp.329-338.

Bede, E. A. "Characterization of surface morphology of carbonate stone and its effect on surface uptake of SO_2." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 1, pp. 303-312.

Beloyannis, Nicholas, and Dascalakis, Stylianos. "Marine deterioration of marbles from the Cyclades; the case of the marble statues in Delos and Naxos." *Proceedings of the 1st International Symposium on the Conservation of Monuments in the Mediterranean Basin.* Bari,1989, pp. 189-193.

Bortz, S.A., Erlin, B., and Monk, C.B., Jr. "Some field problems with thin veneer building stones." *New stone technology, design, and construction for exterior wall systems, ASTM STP 996*, B. Donaldson, ed. Philadelphia: ASTM, 1988. pp. 11-31.

Campanella, L. et al. "Instrumental chemical analysis of the more common marbles

historically used for decorative purposes or to create works of art." *Proceedings of the 9th international congress on deterioration and conservation of stone*. New York: Elsevier, 1989, v. 1, pp. 543-552.

Chang, C.T., P. Monteiro, K. Nemati, and K. Shyu. "Behavior of marble under compression." *Journal of Materials in Civil Engineering*, Vol. 8, No. 3, August 1996, pp. 157-170.

Chute, Newton E. "Structural and mineralogical features of the Stockbridge marble and Berkshire schist near Adams, Massachusetts." *Economic Geology in Massachusetts*. Amherst: University of Massachusetts Graduate School, pp. 169-179.

Cohen, Julie Mark, and Paulo J. M. Monteiro. "Durability and Integrity of Marble Cladding: A State-of-the-Art Review." *Journal of Performance of Constructed Facilities*, v. 5, no. 2, May 1991, pp. 113-124.

Evaluation of Submitted Masonry Samples; Recommendations for Conservation Treatment. Tweed Courthouse, 52 Chambers St., New York, NY, Project No. 9010-38 MSSC. Prepared for Mesick, Cohen, Waite Architects by the Stone Testing Laboratory, Masonry Stabilization Services Corporation. March 1991.

Feddema, Johannes J. "Air pollution effects on marble weathering in Philadelphia, Pennsylvania." *Publications in Climatology/ Laboratory of Climatology*. Newark: University of Delaware, 1986, v. 39, n. 1.

Franzini, Marco. "Stones in monuments: natural and anthropogenic deterioration in marble artifacts." *European Journal of Mineralogy*, Stuttgart, 1995, 7: 735-743.

Garzonio, C. A. et al. "Analyses of the physical parameters correlated to bending · phenomena in marble slabs." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone*. New York: Elsevier, 1989, v. 1, pp. 89-98.

Gauri, K. Lal, Niraj P. Kulshreshtha, Adinarayana R. Punuru, and Ahad N. Chowdhury. "Rate of decay of marble in laboratory and outdoor exposure." *Journal of Materials in Civil Engineering*, Vol. 1, No. 2, May 1989, pp. 73-85.

Giorgio, Rodorico and Piero Baglioni. "New results in the application of innovative experimental techniques for investigation of stone's decay processes." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone*. New York: Elsevier, 1989, v. 1, pp. 587-594.

Grimm, Wolf-Dieter. "Beobachtungen und überlegungen zur Verformung von marmorobjekten durch gefügeanflockerung." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp. 195-235.

Gross, Christian J., Klaus Weber, Axel Vollbrecht, and Siegfried Siegesmund.

"Cathodoluminscence and electron microprobe study of dolomite marbles from Namibia: evidence for hydrothermal alteration." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150/2, pp. 333-357.

Guidetti, V. and M. Uminski. "Ion exchange resins for historic marble desulfatation and restoration." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 2, pp. 327-334.

Herz, Norman. "Petrofabrics and classic archaeology." *American Journal of Science*, New Haven, 1954, v. 253, pp. 299-305.

Julien, Alexis A. "The durability of building stones in New York City and vicinity," *Tenth Census of the United States*, v.10. Washington: Government Printing Office, 1884. pp.

Kessler, David W. "Physical and chemical tests on the commercial marbles of the United States," *Technologic Papers of the Bureau of Standards.* Government Printing Office: Washington, 1919.

Kessler, David W. and R.E. Anderson. "Stone exposure test wall." National Bureau of Standards Building Materials and Structures Report 125. Department of Commerce, 1949.

Kocks, U.F. *Texture and Anisotropy: Preferred Orientations in Polycrystals and Their Effect on Material Properties.* Cambridge: Cambridge UP, 1998.

Kulshreshtha, Niraj P., Adinarayana R. Punuru, K. Lal Gauri, "Kinetics of reaction of SO_2 with marble." *Journal of Materials in Civil Engineering*, Vol. 1, No. 2, May 1989, pp. 60-72.

Lewin, Seymour Z. and A. Elena Charola. "Stone decay due to foreign inclusions." *Preprints of the Contributions to the International Symposium on the Conservation of Stone: Part A, Deterioration.* Bologna, 1981.

Lindborg, Ulf et al. "Thermal stress and weathering of Carrara, Pentelic, and Ekeberg marble." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 1, pp. 109-118.

Lorenz, Heinz G. and Hermann Wolf Ibach. "Marmorknoservierung durch die IBACH volltränkung: qualitätskontrolle und optierung durch mikroskopische und petrophysikalische untersuchungen." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp. 397-406.

Malagodi,M et al. "Effects of combined application of biocides and protectives on marble." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 2, pp. 225-234.

Masonry: Repointing Masonry; Exterior Cleaning of Historic Masonry Buildings; Moisture Problems in Historic Masonry bBuildings. Division of Design and Construction Management, Landmarks Program, New York City. 1981.

Matero, Frank G. and Alberto Tagle. "Cleaning, iron stain removal and surface repair of architectural marble and crystalline limestone: the Metropolitan Club." *Journal of the American Institute for Conservation* 1995, v. 34, no. 1, Spring, pp 49-68.

McGee, Elaine S. "Influence of microclimate on the deterioration of historic marble buildings." *Association for Preservation Technology Bulletin*, 1991, v.23, n.4, pp. 37-42.

Merrill, George E. "The collection of building and ornamental stones in the U.S. National Museum: a handbook and catalogue," in *Annual Report of the Board of Regents of the Smithsonian Institution, showing the operations, expenditures, and conditions of the institution for the year ending June 30, 1886, Part II.* Washington: Government Printing Office, 1889.

Mitchell, David J. et al. "The influence of building orientation on climate weathering cycles in Staffordshire, U.K." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 1, pp.357-366.

Monk, C.B., Jr. "The rational use of masonry." *Proc., Third North Am. Masonry Conf., Cost. Res. Ctr.* Arlington: University of Texas, 1985.

Nesse, William D. *Introduction to Optical Mineralogy: Second Edition.* New York: Oxford UP, 1991.

Poschlod, Klaus. "Pore structure and properties of marbles." *Proceedings of the 1st International Symposium on the Conservation of Monuments in the Mediterranean Basin.* Bari, 1989, pp. 259-262.

Reddy, Michael. "Acid rain and air pollution effects on carbonate-stone: dissolution-runoff experiments. *Proceedings of the 1st International Symposium on the Conservation of Monuments in the Mediterranean Basin.* Bari, 1989, pp. 359-363.

Reeder, Richard J., and Steven A. Markgraf. "High-temperature crystal chemistry of dolomite." *American Mineralogist*, 1986, v. 71, pp. 795-804

Rehabilitation and restoration of 52 Chambers Street (Tweed Courthouse), Borough of Manhattan, City of New York, for the Department of General Services, PW-292-01. Prepared by Mesick, Cohen, Waite Architects, Albany, 1987.

A Report on the Reconstruction and Improvement to the New York County Courthouse (Tweed Courthouse). Prepared by Ammann & Whitney, Consulting Engineers and Beyer, Blinder, Belle, Architects and Planners, New York, February 1981.

Rohatsch, A. et al. "Physical properties of fine-grained marble before and after treatment." *Proceedings of the 9th international congress on deterioration and conservation of stone.* New York: Elsevier, 1989, v. 2, pp 453-458.

Rosenholtz, J.L., and D.T Smith. "Linear thermal expansion of calcite, var. Iceland spar, and Yule marble." American Mineralogist, v. 34, pp. 846-854.

Sabbioni, Christina et al. "Analytic methodologies for carbon compound identification: Leaning Tower and Baptistery of Pisa." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 1, pp.383-390.

Schmid, J., M. Ambuhl, D. Decrouez. S. Muller, and K. Ramseyer. "A quantitative fabric analysis approach to the discrimination of white marbles." *Archaeometry,* 1999, v. 41, pp. 239-252.

Searle, David E. et al. "The effects of coal and diesel particulates on the weathering loss of two major building stones in the United Kingdom-A comparative microcatchment study." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier. v. 1, pp.391-400.

Sheremeti-Karabashi, Florife and Rolf Snethlage. "Determination of structural anisotropy of Carrara marble with ultrasonic measurements." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v.1, pp. 247-254.

Sherwood, Susan I. and Donald A. Dolske. "Acidic deposition and marble monuments at Gettysburg National Military Park." *Association for Preservation Technology Bulletin,* 1995, v.23, n.4, p.52-57.

Siano, S. et al. "Integration of laser with conventional techniques in marble restoration." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier. v. 2, pp. 569-576.

Siegesmund, S., A. Vollbrecht, K. Ullemeyer, T. Weiss, and R. Sobott. "Anwendung der geologischen gefügekunde zur characterisierung natürlicher werksteine-fallbeispiel: Kauffunger marmor." *Internationale Zeitschrift für Baunistandsetzen,* Stuttgart, 1997, v. 3, pp. 269-292.

Siegesmund, S. and R. Snethlage. "Control of marble weathering by thermal expansion and rock fabrics." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier, 1989, v. 1, pp. 205-214.

Siegesmund, Siegfried, Thomas Weiss, Axel Vollbrecht, and Klaus Ullemeyer. "Marble as a natural building material: rock fabrics, physical and mechanical properties."

Zeitschrift der Deutschen Geologischen Gesellschaft, Stuttgart, 1999, v. 150, pp. 237-257.

Siegesmund, Siegfried, Klaus Ullemeyer, Thomas Weiss, Elmar K. Tschegg. "Physical weathering of marbles caused by anisotropic thermal expansion." *International Journal of Earth Sciences*, 2000, v. 89, pp. 170-182.

Siegesmund, Siegfried. "The significance of rock fabrics for the geological interpretation of geophysical anisotropies." *Geotektonische Forschungen* 85: 1-123. 1996.

Smith, Laird M. "Moisture problems in historic masonry walls: diagnosis and treatment." Washington, D.C.: U.S. Dept. of the Interior, 1980.

Snethlage, Rolf, Hans Ettl, and Ludwig Sattler. "Ultraschallmessungen an PMMA-getränkten Marmorskulpturen." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp 387-396.

Sterflinger, Katja, Wolfgang E. Krumbein, and Jürgen Rullkötter. "Patination of marble , sandstone and granite by microbial communities." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp. 299-311.

Thomasen, S.E., and C.S. Ewart. "Durability of thin-set marble." *Proceedings of the Third International Conference on Durability of Building Materials and Components*, Philadlephia: ASTM, 1984.

Tschegg, Elmar K., Clemens Widhalm, and Walter Eppensteiner. "Ursachen mangelnder Formbeständigkeit von Marmorplatten." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp. 283-297.

Waite, John G. and Roger J. Cheng. "A case study of the cleaning and conservation of marble at the Schenectady, New York, City Hall." *Special Technical Publications 935, American Society of Testing and Materials.* ASTM: Philadelphia. 1987.

Weiss, Norman R. "Development and assessment of a conversion treatment for calcareous stone." *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone.* New York: Elsevier. v. 1, pp. 533-540.

Weiss, Thomas, Bernd Leiss, Heidrun Opperman, and Siegfried Siegesmund. "Microfabric of fresh and weathered marbles: implications and consequences for the reconstruction of the Marmorpalais, Potsdam." *Zeitschrift der Deutschen Geologischen Gesellschaft*, Stuttgart, 1999, v. 150, pp. 313-332.

Widhalm, Clemens, Elmar Tschegg, amd Walter Eppensteiner. "Acoustic emission and anisotropic thermal expansion when heating marble." *Journal of Performance of Constructed Facilities*, Feb. 1997, pp. 35-40.

Widhalm, Clemens, Elmar Tschegg, amd Walter Eppensteiner. "Anisotropic thermal

expansion causes deformation of marble claddings." *Journal of Performance of Constructed Facilities*, Feb. 1996, pp. 5-10.

Wilson, F. "The perils of using thin stone and safeguards against them." *AIA Journal*, v.78 (2), pp. 96-97

Winkler, E.M. "Technical Note: Properties of Marble as Building Veneer," *International Journal of Rock and Mechanical Mineralogical Science & Geomechanical Abstracts,* v. 33 (2) pp. 215-218,1996.

Winkler, Erhard M. "Weathering of crystalline marble at the Field Museum of Natural History, Chicago." *Association for Preservation Technology Bulletin*, 1991, v.23, n.4, pp.43-47.

Yerrapragada, Srinivas S., Surendra R. Chirra, John H. Jaynes, S. Li, Jayanta K. Bandyopadhyay, K. L. Gauri. "Weathering rates of marble in laboratory and outdoor conditions." *Journal of Environmental Engineering*, Vol. 122, No. 9, September 1996, pp. 856-863.