DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

Investigation of the Column Capital Volute Failure at the Jefferson Memorial, Washington, D.C.

by

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Open-File Report 96-518

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards.

1996

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ABSTRACT

An investigation into possible causes for the failure of a large portion of a column capital volute at the Jefferson Memorial was conducted to identify features that indicate if a volute might fail. All the column capitals at the memorial were examined in detail. Fracture surfaces on the broken pieces and on the remaining volute portions were examined visually, optically, and with scanning electron microscopy. Dirt and organic material on the fracture surfaces and cracks on the unbroken volutes indicate that the cracks were probably open long before the failure occurred.

Cracks are fairly common in the column capitals at the Jefferson Memorial and many of the cracks occur in the same area and orientation as the fracture planes on the broken volutes. However, not all of the cracks in the volutes indicate the presence of a potential fracture plane. In order for a crack to become a fracture plane, it must penetrate into the stone, and thus affect the integrity of the marble block. Cracks on the volutes range from surficial indentations caused by exposure of the stone to wind and rain, to openings that appear to penetrate into the stone. Inclusions of minerals other than calcite in the marble was not a factor in the failure of the volutes. Thus, cracks that are associated with a textural change in the marble are considered more significant than cracks associated with inclusions. Most likely a weakness in the stone, such as a healed shear plane, aggravated by some external factor such as vibration led to the failure. Textural changes in the marble of the volutes probably correlate with small cracks and flaws that were measured between bedding layers in the marble with ultrasonic pulse velocity. While it may not be possible to predict when (or if) a volute will fail, it is possible to establish a priority for monitoring the volutes based on the characteristics of the cracks and the marble features. Cracks on volutes that appear most likely to fail meet one of several criteria: 1- they occur on column capitals where another volute has failed; 2- they occur as an opening in a recessed area of the volute face, or 3- they extend across several features on the volute face or wrap around the edge of the volute, and extend to the back of the volute.

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INTRODUCTION

The failure, in 1990, of one of the column capital volutes at the Jefferson Memorial in Washington, D.C. posed a danger to public safety and raised concerns about the integrity of this national memorial. Both of these issues are of great concern to the National Park Service, which is responsible for the Jefferson Memorial. An investigation was undertaken to try and determine if there is an inherent characteristic of the marble, used in the column capital, which might have caused the volute failure. If the cause (or causes) of the volute failure can be identified, then it may be possible to predict other failures so that further loss can be avoided and so that the safety of visitors to the memorial can be ensured.

BACKGROUND INFORMATION

The Memorial and its Stone

The Jefferson Memorial in Washington, D.C. is located south of the Washington Monument, on the south bank of the Tidal Basin near the Potomac River. The memorial was dedicated in 1943. However, the construction of the memorial spanned a number of years: the cornerstone was laid in November 1939, the portico columns were completed in August 1940, and construction of the memorial was completed in 1942 (Warren-Findley, 1985). The memorial is a marble superstructure over concrete, but the columns and column capitals are solid pieces of marble.

All of the exterior marble at the memorial is from Danby, Vermont; it is identified by the trade name "white Imperial marble". This marble is quarried from the Shelburne formation in Vermont and it has been used in many buildings throughout the United States (McGee, 1989). The marble is predominantly composed of calcite (calcium carbonate) grains that are 0.3-0.9 mm in size and form a tightly interlocked fabric. Inclusions of dolomite, phlogopite, muscovite, chlorite, feldspar, pyrite, rutile, and apatite are typically present in the Vermont marble (McGee, 1989). The Vermont marble used for the exterior stone at the Jefferson Memorial is mostly white with some linear traces of phlogopite and muscovite that are light tan in color. Light gray diffuse traces and swirls of dolomite inclusions are also visible in some stones. Other mineral inclusions are not very common or noticeable in the columns and column capitals.

The colonnade at the Jefferson Memorial consists of an outer circle and a row of columns across the front entrance; sets of four columns stand in the doorways around the inner statue chamber. The columns are numbered following the plan in Figure 1. The Ionic capitals have intricately carved volutes and egg and dart moldings. A single block of marble, approximately 6.5 x 4.3 x 2.5 feet in size, was used for each column capital (Fig. 2). The column capitals at the memorial were laid so that the inclusions, which indicate where bedding planes would have been in the original sedimentary rock before it was metamorphosed to marble, are horizontal (approximately parallel with the ground) (Fig. 3).

Volute Failure and Removals

In May 1990, a large portion of a column capital volute was found lying on the portico of the Jefferson Memorial. During initial investigation of the column capital from which the volute had fallen, another nearby volute was accidently bumped and it also broke. Subsequently, because of concern for public safety, portions of six cracked volutes were intentionally removed (Hartman-Cox, 1990). Each of the volutes broke along a plane that was approximately horizontal. All of the broken pieces are from the lower portion of the Ionic volutes (Fig. 4). The pieces vary in size (Table 1) and proportion. On average the pieces are 18 x 8 x 5 inches in size and weigh 21 pounds; the piece from column 12 is the closest to average in size (Fig. 5).

OTHER STUDIES AT THE MEMORIAL

An initial examination of the column capitals, immediately after the discovery of the failure of the volute was made from portable scaffolding (Hartman Cox Architects, 1990). Later, a detailed visual stone-by-stone condition survey was conducted by the architecture and engineering firm Einhorn Yaffee Prescott (1995). The visual condition survey was made to provide the Park Service with a comprehensive baseline examination of the stone in the memorial. Non-destructive geophysical testing and vibration tests were made at the memorial by Olson Engineering, Inc., consultants to Einhorn Yaffee Prescott (1993; 1993a) and vibration tests were also made by Mr. Ken King, a geologist and geophysicist consultant to Hartman-Cox Architects (1994). The non-destructive geophysical tests and the vibration tests were conducted to provide baseline information about the vibration characteristics of the Memorial and to compare the visual survey observations of stone condition with testing results.

THIS STUDY

This study was begun to find out if the failure of the column capital volute could be due to an inherent characteristic of the marble used in the column capitals. One weathering feature typically found in the marble columns at the memorial, occurs where mica inclusions have weathered out leaving a groove that mimics the traces of inclusions in the marble (Fig. 6). Thus, one suspicion regarding causes of the volute failure was that it might have occurred along a plane of mineral inclusions. The volute pieces that were removed from the column capitals were examined visually and petrographically and the column capitals at the memorial were also examined to see if a characteristic of the marble could be identified as a cause of the volute failure.

Examination of the Volute Pieces

The eight pieces that were removed from the Memorial were examined visually and optically to determine if a concentration of mineral inclusions in the marble caused the volutes to fracture where they did (McGee, 1991). As part of that investigation, a few grains were removed from the fracture surfaces of the volutes so that mineral phases and features on the fracture surfaces could be confirmed using scanning electron microscopy. In only one case (column 29) was there a significant concentration of mica inclusions along the fracture plane (McGee, 1991). In all cases, only a small portion of the fracture surface appeared to be freshly broken. Most of the fracture surfaces have accumulated dirt and some organic growth; evidence that along the fracture plane, cracks had been present for some time prior to the failure of the volute (McGee, 1991). The fracture surfaces typically have a blocky, stepped appearance (Fig. 7) that resembles slickenside surfaces in geologic faults, where gradual slipping occurs along shear zones. The appearance of the fracture surface suggests that there may have been slight sliding movement of the pieces along the fracture plane for some time prior to the failure.

In-situ Examination of Column Capitals

When scaffolding at the memorial provided access to the column capitals, an examination of the column capitals was conducted as a follow up to the first examination of the volute pieces. The intent of this examination was to identify factors that might have led to the volute failure, and to determine whether the fracture planes on the portions of the volutes remaining after the removal of the pieces showed any further clues about the break. All four sides of each column capital were examined and the volutes were designated by a letter code (A,B,C,D; Fig. 2). The A and D volutes face toward the center of the building and the B and C volutes face away from the center of the building. Observations made at each column capital documented the presence of cracks and missing pieces, the weathering features, and the nature of the inclusions in that block of marble. Small samples were taken of weathered inclusions (Appendix A) and, also, of some of the light and dark alteration crusts that have accumulated on the surfaces of the marble (Appendix B). Powder X-ray diffraction, optical examination, and scanning electron microscopy were used to confirm the identification of the samples (Appendix A and B). The column capitals were photographed, as were details of some of the cracks and weathering features. Descriptive notes were made of observations at each column capital and a system was devised to classify the cracks that were found in the volutes (McGee and Woodruff, 1993). Close (approximately two to three feet away) eye-level access to the column capitals was an important element of the in situ examination of the volutes because blackened surficial alteration crusts, dirt, spider webs, and normal inclusion traces in the stone could obscure or could easily be confused with cracks.

A number of cracks, with varied characteristics, were found during the examination of the column capitals. Cracks were placed in one of three categories (Type 1, 2 or 3) to reflect their similarity with the fracture plane location in the volutes that failed (McGee and Woodruff, 1993). Crack types 1 and 2 are of greatest relevance to understanding the volute failure at the memorial. Both types indicate fine lines or linear openings in the stone; type 1 occur in the lower half of the volute and type 2 occur in the upper half of the volute, where the stone is more massive (Fig. 2). A summary of the type 1 and 2 cracks identified at all the column capitals is given in Table 2.

The crack classification system was further refined by combining it with observations about crack characteristics such as: is it open or is it a surficial indentation?, is it associated with a texture change or with an inclusion in the stone?, where is it located with respect to the carved features of the volute?, and what is the orientation and visibility of the crack? (Table 3). The characteristics listed in Table 3 were compiled from field notes and from examination of photographs of each volute at the memorial. A summary of the crack characteristics will help identify typical features of the marble in the memorial. If particular features on a volute correlate with features observed on the broken pieces, we may be able to predict which volutes might be likely to fail.

SUMMARY OF OBSERVATIONS

Fractured Volutes

In all, there are eight fractured volutes that are distributed around the memorial as shown in Fig. 1. The fracture planes of the pieces that were removed are similar to the fracture plane of the volute pieces that remain on the column capitals. Therefore, there was no preferential parting along the fracture planes that might have left a plane of inclusions on one side but not on the other. Of the eight pieces that were removed, only one (29D) has a significant concentration of mica inclusions on the fracture plane. One of the fractured volutes (13A) was previously repaired; it has holes from pins (the pin stubs are in the column capital) and dried fragments of an adhesive material on the fracture surface. All of the fracture surfaces have accumulated dirt and several have organic growth (like algae) which indicate that the crack was open for a long time before the piece was removed. Portions of many of the fracture surfaces have a blocky, stepped appearance suggesting that slight, long-term sliding movements have occurred along the fracture plane.

Cracked Volutes

Twenty-five of the 54 columns at the memorial have either a type 1 or a type 2 crack in a volute (Table 2). Cracks are more likely to occur in the lower half (type 1) of the volute than they are in the upper half (type 2) of the volute (Table 4). The cracks tend to be clustered; only five column capitals have a crack in a single volute (columns 52, 44, 41, 34, 5). Typically, if a crack occurs in one volute of a column capital, other volutes on the same capital are likely to have cracks as well (Table 2). The majority of cracks occur in the outward facing (B and C) volutes. Most of the cracks occur in column capitals that are part of the outer colonnade at the memorial (Table 4).

Cracked volutes commonly have more than one crack. Eighty percent of the volutes with type 1 cracks have several cracks, and 43% of the volutes with type 2 cracks have several cracks in the same volute (Table 3). Most of the cracks are horizontal or nearly horizontal. Cracks range from shallow indentations (Fig. 8), to fine lineations or narrow linear openings (Fig. 9). Approximately 70% of the type 1 and type 2 cracks are indentations, rather than open cracks (Table 3). The rims of the volute are the most likely place for a crack to occur (Table 3), but more than half of the volutes with type 1 cracks have cracks in the recessed area of the volute face (Table 3; Fig. 10). On nearly 30% of the volutes with type 1 cracks, cracks wrap around the edge of the volute from the front to the back face (Table 3; Fig. 11). Cracks occur on the backs of volutes less frequently than on the fronts (Table 3); only two volutes have cracks on the back and have no cracks on the front of the volute (5A- type 1, 27D- type 2).

Inclusions are fairly common in the marble of the column capitals. Often the inclusions form thin linear traces that, when accentuated by weathering, resemble cracks. Because of this, an effort was made to distinguish linear weathering features from features that might indicate an impact on stone integrity. Some of the factors used to distinguish cracks from weathered inclusions were: the appearance of an inclusion trace, how deep and extensive it appears to be, whether it is open in a partly sheltered area of the volute, and whether it seems to correlate with other segments along a horizontal line. About 30% of the cracks on the volutes are associated with inclusions in the marble (Fig. 12, Table 3). Approximately half of the type 1 and type 2 cracks appear to be independent of the mica inclusions; but they occur where the texture (grain size or appearance) of the calcite changes in the marble (Fig. 13, Table 3).

One concern during the in situ examination of the column capitals was whether or if we might find loose pieces of stone that might be in danger of falling. Some small (approximately 1 - 2 square centimeter) chips were loose and crumbled when touched, but these were mostly on the egg and dart portion of the column capitals (Fig. 14), where the stone surface is heavily encrusted with blackened surficial alteration. However, no loose pieces were found associated with crack types 1 or 2. Where cracks were found that seemed like they might pose a significant risk of failure, such as on volute 10C which has a large crack that is coplanar with a fractured volute (Fig. 15), the portion of the volute below the crack did not move or feel loose when it was pulled by hand.

DISCUSSION

Although there are many cracks in the volutes at the memorial (Table 3), not all of the volutes with cracks pose a significant risk for failure. Surficial weathering of the marble and unique conditions at a few columns cause many of the cracks. Most of the cracks are located on the B and C volutes of columns around the outer colonnade, where the effects of wind and rain are most likely to accentuate weaknesses in the marble. Columns 33 to 20 face south and west which is the direction from which wind and rain are most likely to come, and the type 1 cracks on these columns are mostly surficial weathering features. The cracks are predominantly indentations on rims of the volutes (Table 3). Thus, while there are many cracks in these columns, the number of cracks by itself does not indicate that this section of columns is at serious risk. Several columns (particularly 18, 19, 44, 53, and 54) have vertical cracks, cracks that follow some of the carved features of the capital, and cracks that extend into the column shaft. These columns are roughly clustered in two areas of the memorial. Although the cracks in these columns are significant, the number of cracks, their orientations, and the way they are clustered suggests that they are not related to the type of sudden volute failure that occurred in May 1990. In order to assess which volutes might be at risk of failing, the way the volute failed in May of 1990, it is important to identify features or characteristics on the volutes that might affect the integrity of the volute.

What features might indicate failure?

Many of the features visible on the column capital volutes are characteristic of the stone and the manner in which it weathers because it is exposed to wind, rain, and temperature cycles. These typical weathering features such as: surface roughness, preferential wear around inclusions, and loss of some grains are primarily surficial features and are not likely to affect the integrity of the stone. However, while some of the cracks are undoubtedly just surficial features, some appear to penetrate into the volute along a plane that might eventually become weak enough to fail. Dirt and some organic material was found to have accumulated on the fracture surfaces of the broken volute pieces (McGee, 1991). This could have happened if a crack that penetrated into the body of the stone was open at the stone surface long before the volute failed.

Many of the cracks on the volutes are horizontal and occur in the same plane as other cracks, either in the same volute or in an adjacent volute on the same column capital. Some of the features that indicate a plane of weakness similar to the regions where the volutes fractured include: cracks on recessed areas, cracks that cross several carved areas of the volute, and horizontal cracks that are co-planar with other similar cracks. Cracks that occur on recessed portions of the volute faces may indicate where there is a weak area that penetrates into the stone because the recessed areas will be less affected by surficial weathering effects than the more exposed rims of the volutes. Cracks that cross more than one carved feature of the volute face (e.g.: through a recessed area and around a rim; or on a rim, around the edge of the volute, and extend into the back (Fig. 11)) also indicate the extent of a weak zone. A planar crack that cuts across several features shows that the weakness in that area is independent of surface exposure and is not related to the geometry (carving) of the surfaces.

The cracks in the marble show where weaknesses have been accentuated. However, specific characteristics of the marble around the cracks can also be used to identify features that may be present where the marble is weak, but where cracks haven't developed yet. While many cracks are associated with inclusion traces in the marble, these cracks tend to occur in short segments suggesting that they are not continuous over a wide area. Only one broken volute had a significant amount of mica inclusions on the fracture plane. Together, these observations suggest that the mica inclusions may not be a particularly significant indicator of risk for failure. In contrast, cracks associated with textural changes in the marble appear to extend over wider areas than the inclusions. They occur in the recessed areas of the volutes and often cross several features on the volute face. Textural changes also appear as horizontal planar features that occur on more than one volute of a column capital (see Appendix C). Because of the apparent extent of the textural change zones, cracks associated with them may be important indicators of risk for the volutes. These textural changes may be remnants from when the marble formed and represent zones where layers of the marble are poorly bonded together. Selected volutes from 13 columns were tested with ultrasonic pulse velocity (UPV) and with impact echo (IE) methods (Einhorn Yaffee Prescott, 1993) to evaluate integrity and to locate internal flaws in the stone. The UPV tests did a good job of confirming volutes with good integrity, but were not a clear indicator of problem volutes; in part because surface weathering seemed to obscure some of the results (Einhorn Yaffee Prescott, 1993). However, the UPV results did indicate that there may be extremely small cracks and flaws in the bonds between bedding layers in the stone. Flaws between bedding layers probably correspond to the planes where the marble texture changes on some of the volutes.

What Caused the Failure?

By itself, identification of particular features of the cracks on the volutes that correlate with a plane of weakness similar to the fracture plane on the broken volutes does not explain why the volute failed. Many of the volutes at the memorial have some of the same features: cracks in recessed areas, cracks where the texture of the marble changes, cracks that wrap around the rim and edge of a volute. However, the volutes have not failed, and they are not loose. Probably the volute failed after a weakness was aggravated by some external influence. An opening at the stone surface could gradually expand along a weak plane in a volute until a piece falls because the opening penetrates over most of the area that holds the piece to the rest of the capital. A sudden shock to a weakened area could cause a failure like what happened with the volute at the Jefferson Memorial. Alternatively, an accumulation of small continuous effects might cause the "sudden" failure of a volute by aggravating a weak portion, and gradually expanding along an opening until a piece falls.

Water penetrating into a crack can cause a crack to expand and grow as temperature cycles cause water to freeze and thaw, or as dissolved salts precipitate and grow in the crack. Also, through capillary action, water drawn into a crack exerts pressure at the tip of the crack, causing it to open. However, water would have to penetrate deep into the crack in order to open it enough to cause the fracture in the volute. Water penetration seems an unlikely cause for the volute failure because many of the broken volutes were from sheltered locations that are not exposed to driving rain or to water from the hoses used for cleaning the memorial. Even though moisture from humidity and fog might penetrate a crack by capillary action, in order to continue to impact the stone there would have to be a continual supply of moisture to maintain the driving pressure for capillary action to occur.

Small vibrations might also cause a crack to grow along a weak zone. The fracture faces of most of the broken volutes have a stepped appearance, suggesting that the fracture plane opened with a series of small movements that might have been caused by vibrations. Two studies were made of vibration at the Jefferson Memorial (Hartman-Cox Architects, 1994; Einhorn Yaffee Prescott, 1993a). Although the studies measured vibration in slightly different ways, both measured typical vibration frequencies for the building and for some architectural elements on the building. Both studies concluded that their measurements for vibration of the structure were within the limits that are considered safe for historic structures. However, both studies also suggested that additional vibration sources or amplification of vibration by the structure might be a cause for concern, especially for some architectural elements, like the column capital volutes. Vibration traveling from the dome of the memorial through the entablature to the volutes might be amplified by the time it reaches the volutes; but this possibility has not been investigated. Similarly, these studies were not able to assess the cumulative effect of small ("safe" levels of) vibrations on weaknesses in the marble. Monitoring that has recently been installed at the memorial (Michael Barford & Associates, Inc. and Hartman-Cox Architects, 1994) may help to develop an overall picture of the frequency and range of vibrations that reach the volutes. This information can be used to establish criteria for repairs that might be made to the volutes, and could also aid the monitoring of some of the cracks on the volutes.

PREDICTING RISK OF FAILURE

The visual examinations and the geophysical tests at the memorial provide information about the characteristics and features of the volutes and cracks at the memorial. However, an important question underlying this study is: can we predict which volutes might fail? It may not be possible to predict which, when, or if a volute will fail, however it is possible to prioritize the volutes for monitoring.

Close examination and looking for similarities and connections between features found on the volutes and cracks has helped us develop some guidelines for indicating which volutes might be at risk of failure. Type 1 cracks are probably of greater concern than type 2 cracks because if a volute were to suddenly fail along a type 1 crack, a fairly large piece of the column capital could fall. It is less likely that a type 2 crack would lead to a sudden failure because failure along a type 2 crack would extend into the main mass of stone that comprises the column capital, that rests on the column shaft, which would not be likely to fall. Since it appears the failure of the volute was probably related to a plane of weakness in the stone, and because the column capitals are single blocks of stone, special attention should be paid to column capitals where a failure has already occurred. Several capitals (e.g. columns 10, 17, and 40) have volutes with cracks that are located in the same plane as the fracture surface on an adjacent volute. If the failure is related to a planar feature that extends into the stone; cracks that occur where there is a textural (grain size change) in the marble may be significant because they probably indicate a more extensive planar feature than would be present where a crack and an inclusion trace coincide. While exposure to weathering agents typically causes deterioration of marble, the failure of the volute is a loss of greater magnitude than is typical of normal weathering, suggesting that while weathering may contribute to volute failure it is not the sole cause of the failure. Therefore, cracks that occur where weathering is not a significant factor, such as on recessed areas of the volute face or on sheltered volute faces, may be of particular importance for indicating a weakness in the stone.

Out of 47 volutes with cracks, 25 volutes on 13 columns may pose a significant risk of failing (Table 5). Ten volutes on seven columns pose a lower risk of failure (Table 5), and eight volutes on five columns do not appear to pose a significant risk. The cracks identified in the latter group are all indentations, and most occur only on the rims of the volutes or are in the upper half of the volute face. Cracks on volutes that appear most at risk, meet one of several criteria: 1- they occur on column capitals where another volute has failed; 2- they occur as an opening in a recessed area of the volute face, or 3- they extend across several features on the volute face or wrap around the edge of the volute, and extend to the back of the volute. Cracks that are associated with a textural change in the marble are considered more significant than cracks associated with inclusions.

At present, a number of column capitals at the Memorial have been covered with nets that will contain small pieces of stone if they fall and may provide some protection if a volute fails. Criteria developed with observations from this study and from the other studies at the memorial were used to determine which column capitals should be netted. Column capitals that have broken volutes were netted; of those, capitals with cracks in other volutes were of special priority. Even though the cracking may arise from a different cause than the original volute failure, columns 53, 54, and 44 were netted because of the extent of cracking on the columns. Similarly, columns 18 and 19 were netted because of the large cracks that were present, and because the cracks extend through several areas of the column capital. Additional columns were selected for netting because the stone survey identified small or hairline cracks, and this study showed that the cracks are type 1, they occur along a textural change in the stone, and the cracks cross several features on the face of the volute.

SUMMARY

This study used the characteristics that were known about the volute pieces that failed as a guide to identifying specific characteristics on the cracked volutes that might indicate a potential risk of failure. Just the presence of a crack is not sufficient to indicate a failure. Cracks are very common but they may be shallow features that reflect the weathering of the stone. Cracks that indicate a weakness that extends into the stone or indicate a weakness that might be aggravated by external influences are of special concern. A primary objective of this study was to identify characteristics that can be used as clues to the possible failure of a volute. In conjunction with information learned from the stone survey, the non-destructive geophysical testing, and the vibration monitoring, this examination of the volute pieces and column capitals identified some specific characteristics that may indicate a future failure risk. The characteristics of particular importance are:

- another volute on the same column capital has previously failed;
- a horizontal crack in the lower half of the volute, especially if it is in a recessed area of the volute face, or if the crack extends around an edge or across both a raised and recessed portion of the volute surface;
- the crack is open;
- there is a change in texture or grain size in the vicinity of the crack.

Volutes which posses specific characteristics that may indicate a risk can be identified for careful monitoring or for possible preventive measures. At the Jefferson Memorial, some of these measures have been put into place already. Selected column capitals have been netted and a system has been installed to monitor vibration and crack movement at various locations around the memorial. The baseline survey of cracks and features of the stones in memorial will provide a point of comparison by which changes can be assessed. Although we may not be able to predict a failure of a volute, identification of warning symptoms and regular monitoring of those conditions can be an important part of the overall strategy for the preservation of the Jefferson Memorial.

ACKNOWLEDGEMENTS

M.E. Woodruff provided assistance during the initial field examination of column capitals and obtained the powder X-ray diffraction patterns that are discussed in Appendices A and B. Discussions with B.S. Hemingway were helpful for this study.

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Table 1. Dimensions of the eight broken volute pieces.*

Sample #	length (in.)	depth (in.)	height (in.)	weight (lbs)
40A	18.75	10.0	7.75	34
30C	14.62	3.25	2.87	6
29D	19.5	6.75	5.0	17
17A	20.5	8.37	6.56	30.75
13A	19.12	5.37	4.75	15.25
12D	19.37	8.12	5.75	22.25
10B	20.0	7.5	6.44	27
4D	18.75	5.5	4.88	16.5

* *Information from Table 1 of McGee, 1991; column numbers were changed (and re-ordered) to reflect the stone setting numbers used by the NPS Jefferson Memorial preservation project and stone survey work.*

Length, depth, and height measurements are in inches and were made perpendicular to one another. Length is measured from side to side over the fracture face, depth is from front to back across the fracture face, and height is measured across the outer face perpendicular to the lower edge and toward the center of the volute (thus, forming a portion of the volute radius). Weight is measured in pounds; the weight for 10B includes both pieces but for 40A only the single large piece was weighed.

Table 2. Types* of cracks identified on column capitals

Column #	A	B	C	D	Area
54	1		2	1	Front Portico
53	1	2	2	1	
52		2			
51					
50					
49					
48					
47					
46					
45					
44			1		
43					
42					Outer Colonnade
41			2		
40	★	2		1	
39					
38					
37					
36		1	1		
35					
34			2		
33		1	1		
32		1, 2	1, 2		
31		1	1, 2		
30		1	★ 1		
29		1	1	★	
28					
27		2	1, 2	2	
26		2	2, 1		

Table 2. *con't.*

Column #	A	B	C	D	Area
25		1	1, 2		Outer Colonnade (con't)
24					
23		1	1		
22		2, 1	1		
21		2, 1	1, 2		
20			1, 2		
19		1	2, 1		
18		1	2		
17	★		2	1	
16					Inner Colonnade
15					
14					
13	★				
12	---			★ ---	
11	---			---	
10		★	1		
9				n/e	
8	n/e			n/e	
7	n/e			n/e	
6					
5	1				
4	---			★ ---	
3	---			---	
2					
1				---	

★ This volute is partially missing.

* *Types as defined in McGee and Woodruff (1993):*

Type 1: linear opening, lower half of volute.

Type 2: fine opening at the center knob or above.

n/e Volute not examined at close range.

--- *Volute examined with binoculars, from lift placed near columns.*

Table 3. Summary of Cracks on Volutes -- Part A: Type 1 cracks.

		open?		*grain?*			*area?*				*see?*			
C #	V	open	indt	chg	incl	?? tell	back	rim	recss	edg	svrl	cplnr	hrz	3′
54	A	✓		✓			✓	✓	✓	✓	✓	✓[D]	✓	✓
54	D	✓		✓				✓	✓	✓	✓	✓[A]	✓	✓
53	A	✓		✓			✓	✓	✓	✓		✓[D]	✓	✓
53	D	✓		?			✓	✓	✓	✓		✓[A]	✓	✓
44	C	✓	?		?				✓		✓			
40[A]	D	✓		?				✓	✓	✓		✓[A]	✓	✓
36	B	✓	✓		✓			✓	✓	✓	✓		✓	?
36	C	✓	?		✓			✓		✓	✓		✓	✓
33	B	✓	✓		✓		✓	✓	✓		✓		✓	✓
33	C		✓		✓		✓	✓	✓		✓		✓	?
32	B		✓		✓			✓	✓		✓	✓[C]	✓	
32	C		✓		✓		✓	✓	✓	✓	✓	✓[B]	✓	
31	B		✓		✓			✓			✓		✓	
31	C		✓	✓					✓				✓	
30[C]	B		✓	✓				✓			✓		✓	
30[C]	C	✓	✓	✓			✓		✓		✓		✓	b
29[D]	B		✓		✓			✓	✓		✓		✓	?
29[D]	C		✓		✓			✓	✓		✓		✓	
27	C		✓	✓				✓			✓		✓	
26	C	✓	✓	✓				✓			✓			✓

Table 3-A con't.

		open?		*grain?*			*area?*				*see?*			
C #	V	open	indt	chg	incl	?? tell	back	rim	recss	edg	svrl	cplnr	hrz	3′
25	B		✓	✓				✓			✓			?
25	C		✓	✓				✓			✓		✓	?
23	B	?	✓	✓				✓	✓	✓	✓		✓	
23	C		✓	✓				✓			✓		✓	
22	B		✓	✓				✓			✓		✓	?
22	C		✓	✓	✓			✓	?		✓		✓	✓
21	B		✓	✓				✓			✓		✓	✓
21	C		✓	✓				✓	✓		✓		✓	✓
20	C		✓		?			✓	✓		✓		✓	
19	B	✓	✓	✓	?			✓	✓		✓		✓	
19	C		✓	✓	✓			✓			✓		✓	?
18	B	✓	✓	?				✓	✓		✓			
17[A]	D	?				✓		✓	✓	✓		✓[A]	✓	?
10[B]	C	✓				✓			✓			✓[B]	✓	✓
5	A	?				✓	✓						✓	✓
%'s		40%	71%	51%	31%	9%	23%	86%	63%	29%	80%	26%	89%	37%

15

Table 3. Summary of Cracks on Volutes -- Part B: Type 2 cracks.

		open?		*grain?*			*area?*				*see?*			
C #	V	open	indt	chg	incl	?? tell	back	rim	recss	edg	svrl	cplnr	hrz	3′
54	C	✓				✓		✓	✓				✓	✓
53	B	✓		?				✓	✓					✓
53	C	✓		?			✓	✓	✓	✓	✓		✓	✓
52	B		✓		?			k					✓	
41	C		✓			✓		✓					✓	✓
40^A	B	✓	✓	✓				✓	✓		✓		✓	✓
34	C	?	✓		✓			✓, k		✓	✓	✓	✓	✓
32	B	✓			✓			✓			✓		✓	
32	C		✓			✓		k					✓	✓
31	C		✓		✓			✓					✓	
27	B	✓		✓					✓					✓
27	C		✓	✓			✓			?	✓		✓	
27	D		✓		?		✓							
26	B	✓			✓			✓			✓		✓	✓
26	C		✓	✓				k					✓	✓
25	C	b?	✓	✓	b		✓	✓		✓			✓	
22	B		✓	✓				✓, k					✓	✓
21	B		✓	✓				✓, k			✓		✓	✓
21	C	✓	✓	✓	✓			✓			✓		✓	
20	C		✓	✓				✓					✓	

Table 3-B *con't.*

		open?		*grain?*			*area?*				*see?*			
C #	V	open	indt	chg	incl	?? tell	back	rim	recss	edg	svrl	cplnr	hrz	3′
19	C		✓	✓				✓, k			✓		✓	
18	C	✓			✓			✓	✓		✓		✓	
17[A]	C		✓	✓				✓					✓	
%'s		39%	70%	48%	30%	13%	17%	87%	26%	13%	43%	4%	87%	52%

Column Headings: *open?* - is the crack open or is it an indentation? *grain?* - is the crack associated with a grain change, an inclusion, or can't tell which it is? *area?* - where is the crack located with respect to the volute features? *see?* - what is the orientation and visibility of the crack; how does it relate to other cracks on the volute?

C # = column number; V = volute letter, indt = indent; chg = grain change; incl = inclusion; ?? tell = can't identify association; recss = recessed area; edg = edge, crack goes around the edge of the volute (to the back); svrl = several; cplnr = co-planar; hrz = horizontal orientation; 3′ = crack is visible from approximately 3 feet away. %'s = Percent, of all volutes, having a particular feature.

[A,B,C,D] Indicates a missing volute on this capital. (For example: 30[C] = volute C is missing.)

✓ = feature exists, ? = not certain, k = feature occurs on center knob of the volute, b = feature occurs only on the back of the volute, ✓[D] = crack is co-planar with crack (or fracture) on another volute on the capital (letter shown).

Table 4. Summation of crack types, by volute designation[1], at the Jefferson Memorial

Entire memorial:

Type	A	B	C	D	Total #
1	3	12	16	4	35
2	0	8	14	1	23
Broken	3	1	1	3	8

Outer Colonnade: *(cols 17 - 42)*

Type	A	B	C	D	Total #
1	0	12	14	2	28
2	0	6	12	1	19
Broken	2	0	1	1	4

Inner Colonnade: *(cols 1 - 16)*

Type	A	B	C	D	Total #
1	1	0	1	0	2
2	0	0	0	0	0
Broken	1	1	0	2	4

Front Portico: *(cols 43 - 54)*

Type	A	B	C	D	Total #
1	2	0	1	2	5
2	0	2	2	0	4
Broken	0	0	0	0	0

[1] Volutes are designated A,B,C,D. Volutes A & D face toward the statue, volutes B & C face away from the statue.

Note: A volute is only tabulated once for each type of crack in this summary table. Volutes A and D of this study correspond to side A of the stone survey (Einhorn Yaffee Prescott, 1995); volutes B and C correspond to side C of the stone survey.

Table 5. Volutes that may pose a risk of failing.

C #	V	Type	Location of Feature	Crack Description	Stone Characteristic
54	A	1	outer rim & recessed - left	open	grn chg
			middle rim curve - lower	open	??
			back	open	grn chg?, ??
54	C	2	outer rim & recessed - upper right	open	??
54	D	1	outer rim & recessed - upper left	open	grn chg
53	A	1	outer rim, recessed, & back - left	open	grn chg
		2	middle rim curve	open	??
53	B	2	outer rim & recessed - upper left	open	??
53	C	2	outer rim, recessed, & back - upper left	open	grn chg?
			outer rim & recessed - upper right	open	grn chg?
53	D	1	outer rim, recessed, & back - right	open	grn chg?
44	C	1	outer recessed - lower right	open	incl?
			outer recessed - right	indent?	incl?
40[A]	B	2	outer rim & recessed - upper left	open, indent	grn chg?
			middle rim; egg & dart	open	grn chg?
40[A]	D	1	outer rim & recessed - left	open	grn chg?
			middle rim & edge	open	grn chg?
36	B	1	outer rim & recessed - lower, sides	open, indent	incl
36	C	1	outer rim & edge - lower	open	incl

Table 5 con't.

C #	V	Type	Location of Feature	Crack Description	Stone Characteristic
33	B	1	middle rim - lower	open	incl
			outer rim & recessed - side & left	open, indent	incl
			back	open?	incl
33	C	1	outer rim & recessed - lower & right	open	incl
			middle rim - lower	open	incl
			back	open	incl
32	B	1	outer rim & recessed - lower, left	indent	incl
			middle recessed	indent	incl
		2	middle rim - top	open	incl
32	C	1	outer rim, recessed, & edge - left	indent	incl
30[C]	C	1	outer recessed - right	open, indent	grn chg
			back	open	??
29[D]	B	1	middle rim - lower	indent	incl
			outer rim & recessed - lower	indent, open	incl
			inner rim curve - lower	open	??
29[D]	C	1	curve of rims - lower	open	incl
			inner rim - lower left	indent	incl
			middle rim - lower left	indent	incl?
27	B	2	middle rim & recessed - right	open	grn chg
			inner recessed - right	open	grn chg
27	C	1	middle rim - lower, left	indent	grn chg
			outer rim - sides	indent	grn chg
		2	back	indent	grn chg
18	B	1	middle recessed	open	?? (grn chg)
			outer rim & recessed	indent	grn chg?
18	C	2	inner & niddle recessed	open	incl
			inner rim & edge - left	open	incl

Table 5 con't.

C #	V	Type	Location of Feature	Crack Description	Stone Characteristic
17[A]	D	1	outer rim, edge & recessed - left	open?	??
10[B]	C	1	middle recessed - lower	open	??
			Lower Risk		
34	C	2	center knob middle rim - left outer rim - sides & edge	open (slight) indent/open? indent/open?	incl incl incl
26	B	2	middle rim - top outer rim - top	open open	incl incl
26	C	2 1	center knob middle rim lower rim	indent open indent	grn chg grn chg grn chg
23	B	1	outer recessed & rim - lower & sides	indent	grn chg
21	B	2 1	inner rim - top center knob outer & middle rim - lower	indent indent indent	grn chg grn chg grn chg
21	C	1 2	outer rim & recessed - lower right inner rim - top middle rim - top	indent indent open	grn chg grn chg incl
20	C	1	outer recessed - lower r middle rim	indent indent	incl? incl?
19	B	1	outer rim - lower outer recessed	open indent	incl? grn chg
19	C	2 1	center knob middle rim - right middle rim - lower	indent indent indent	grn chg grn chg incl
5		1	back	open?	??

Table 5 con't.

[A,B,C,D] Volute is partially missing on this capital.

C # = Column Number
V = Volute Letter
incl = inclusion trace; grn chg = grain (texture) change; ?? = can't determine

Cracks cross the volutes along a horizontal plane. Exceptions, where a crack follows the curve of a rim on the volute, are indicated with "curve" in the location description.

Column Capitals with Missing Volutes

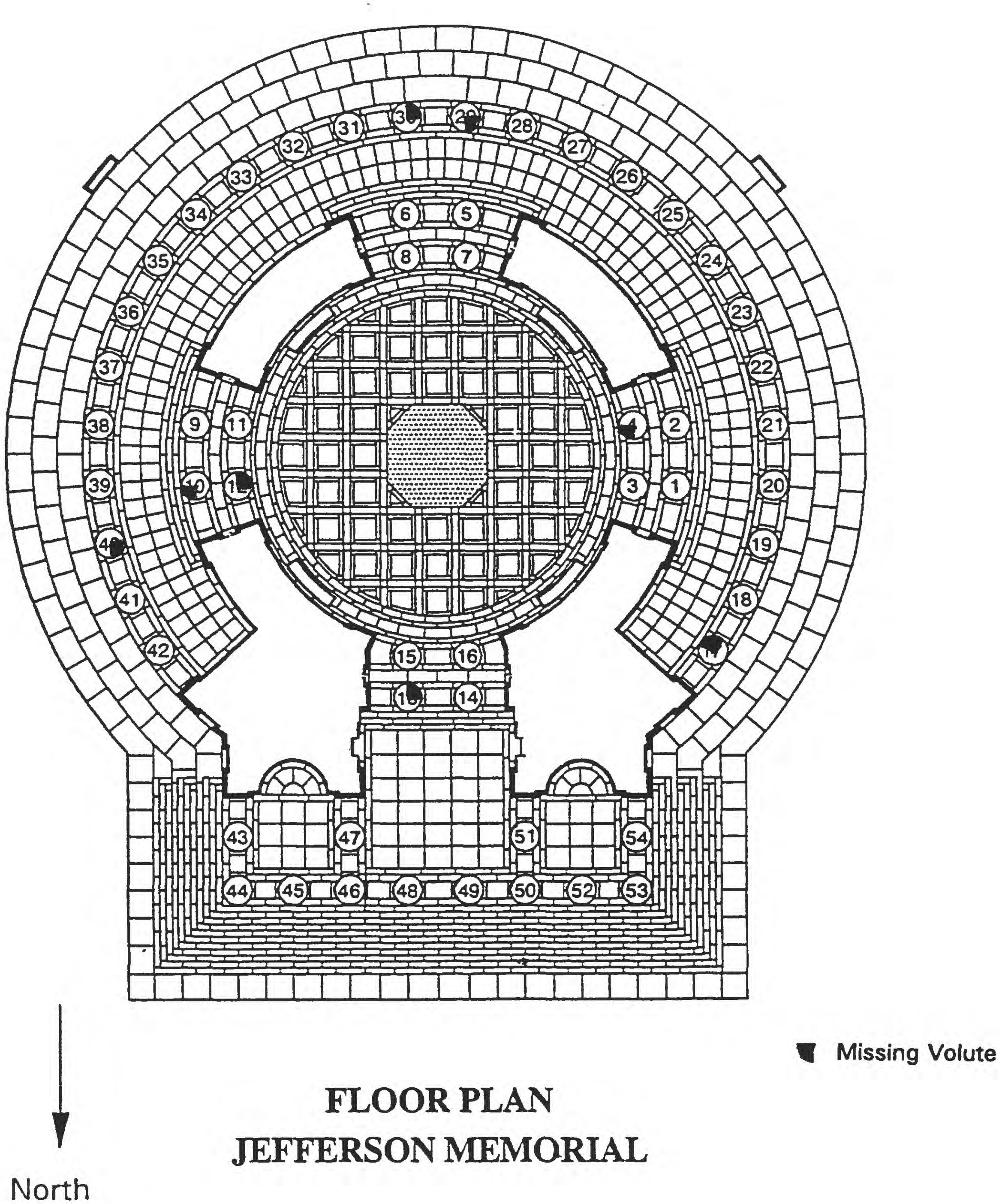

Fig. 1 Plan of Jefferson Memorial, showing column numbering and missing volutes designated by a blackened quadrant where the missing volute occurs.

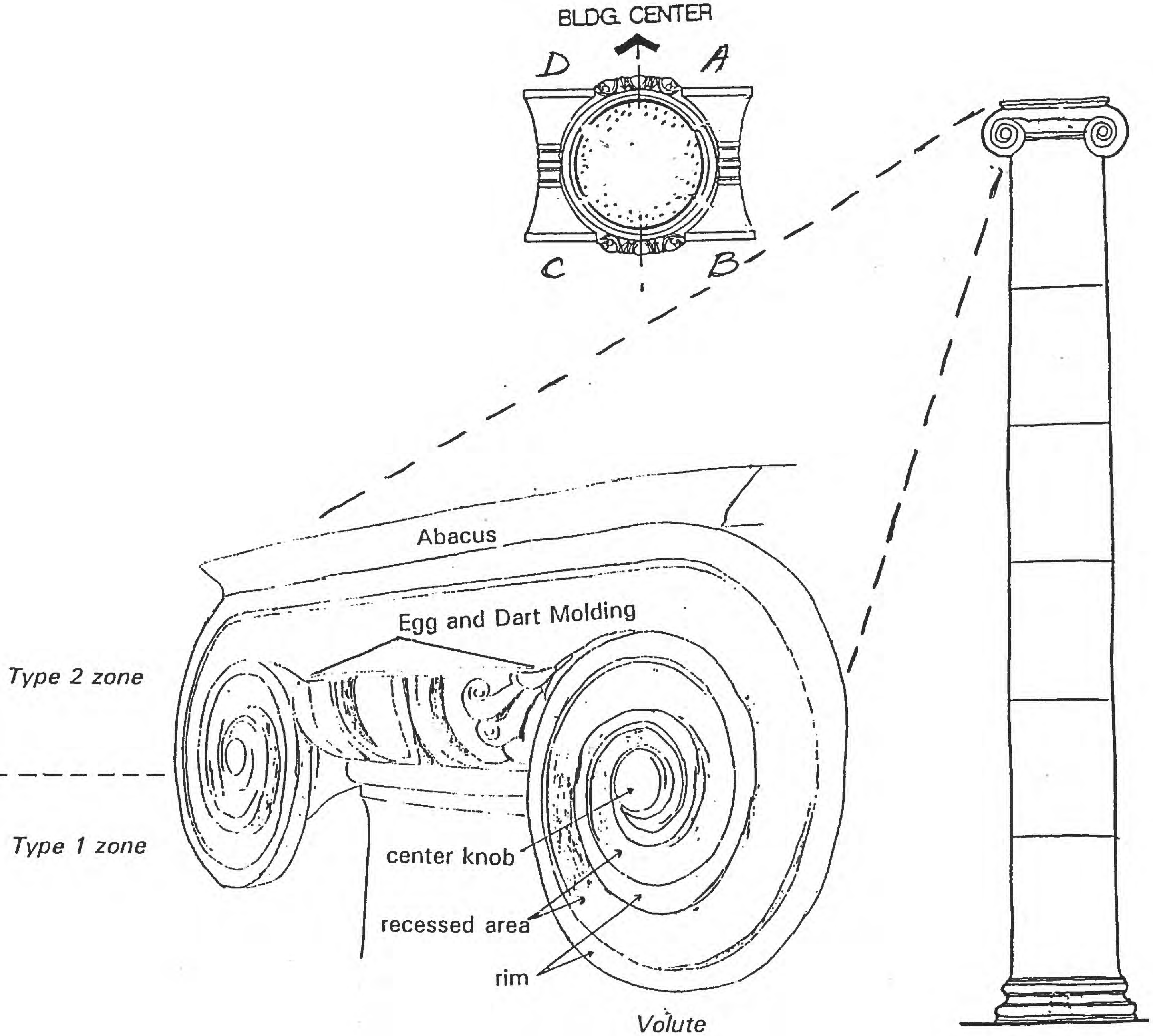

Fig. 2 Sketch of column and column capital at Jefferson Memorial

Fig. 3 Photograph of column capitals at Jefferson Memorial, showing inclusions (dark linear traces) in marble

Fig. 4 Photograph of column capital (#40) with broken volute A.

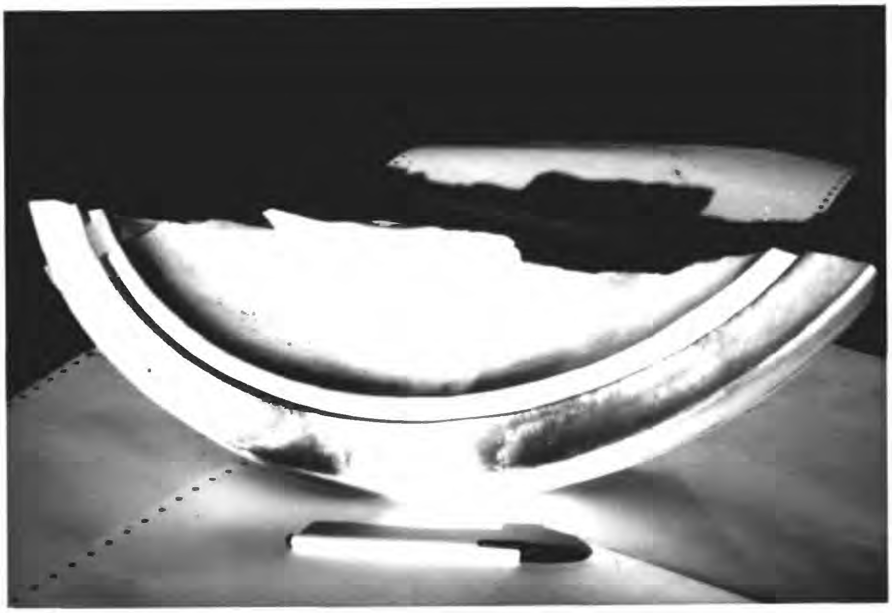

Fig. 5 Photograph of volute piece D from column 12; piece closest to average in size

Fig. 6 Column shaft at Jefferson Memorial with preferential weathering along an inclusion trace.

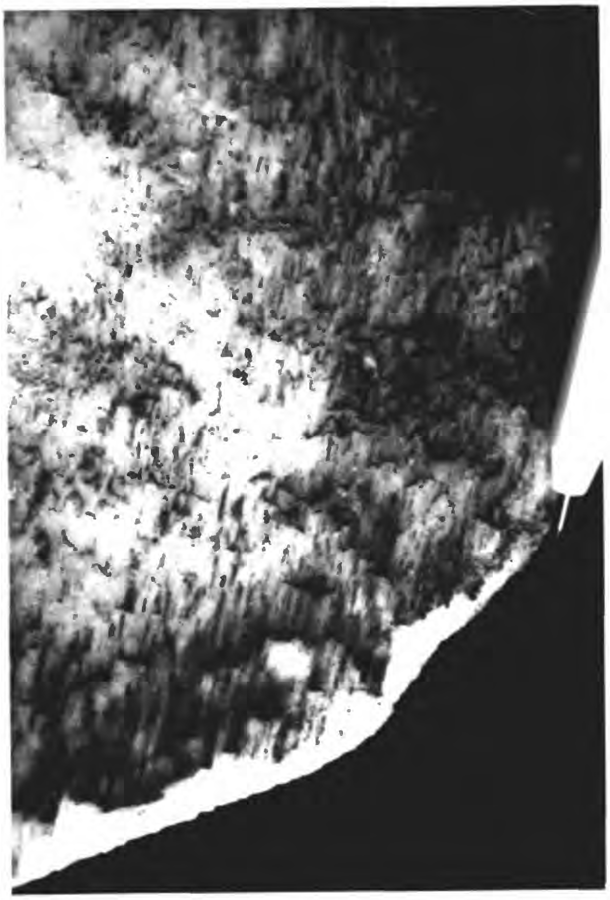

Fig. 7 Fracture plane of a volute piece, showing stepped surface with accumulated dirt; piece from volute 17A.

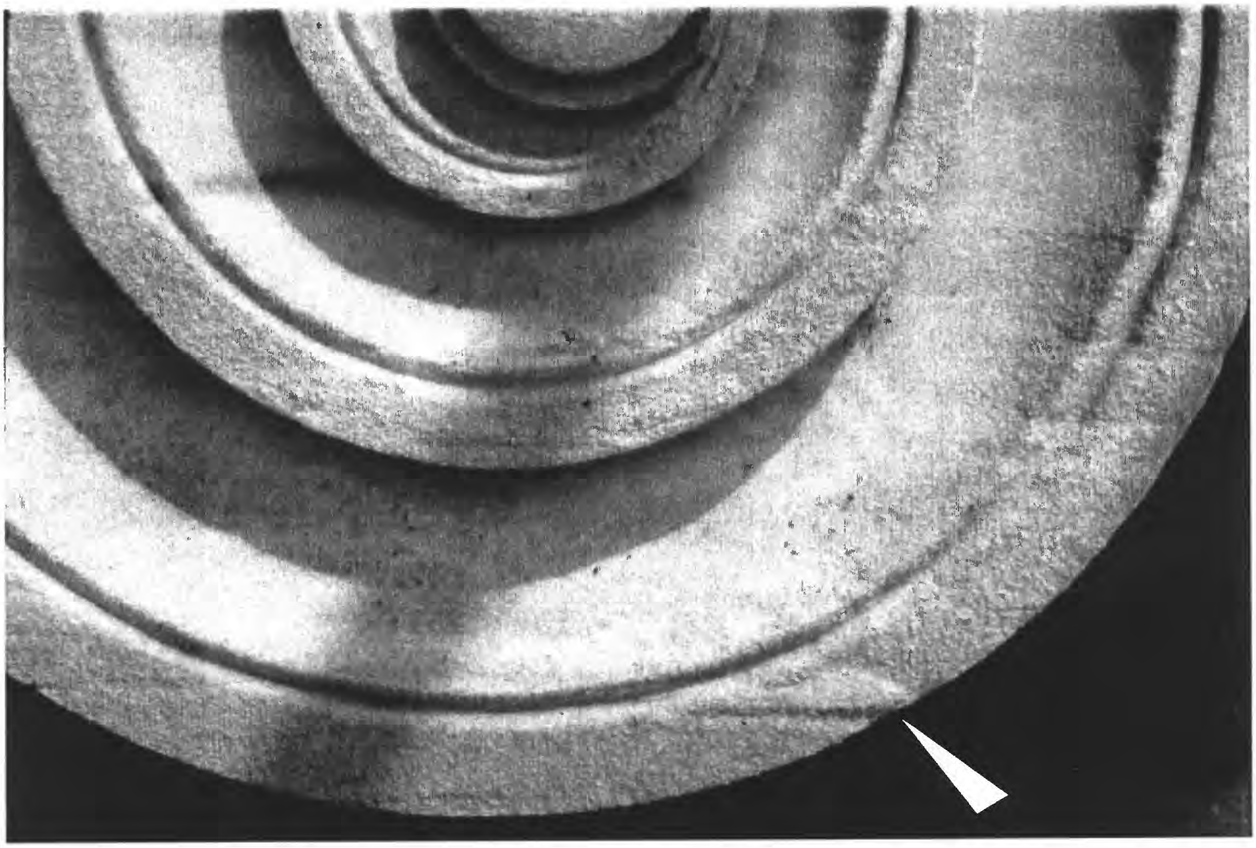

Fig. 8 Shallow indentations on a volute face, some resemble cracks; lower half of volute 21C.

Fig. 9 Some cracks form narrow, linear openings; detail of volute 40B.

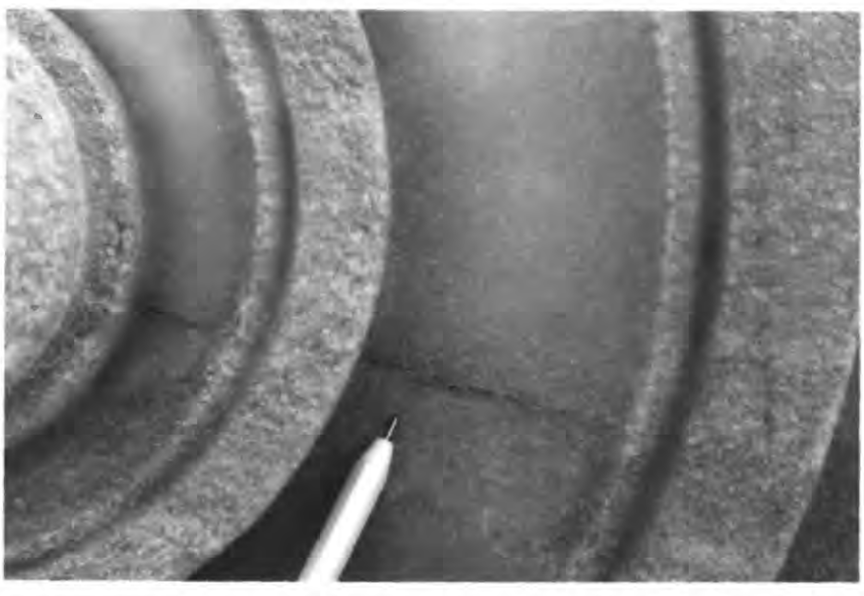

Fig. 10 Cracks that occur in recessed portions of the volute faces are probably are not the result of surface weathering effects on the stone (volute 27B).

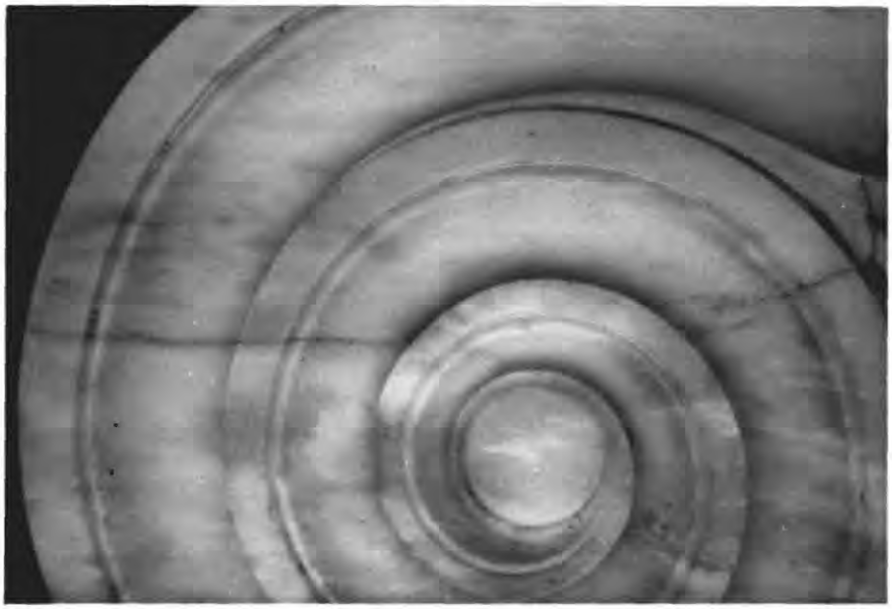

Fig. 11 Photograph of a crack on volute 53C that extends across a rim and a recessed area of the volute face.

Fig. 12 Crack associated with inclusions in the marble on volute 18C.

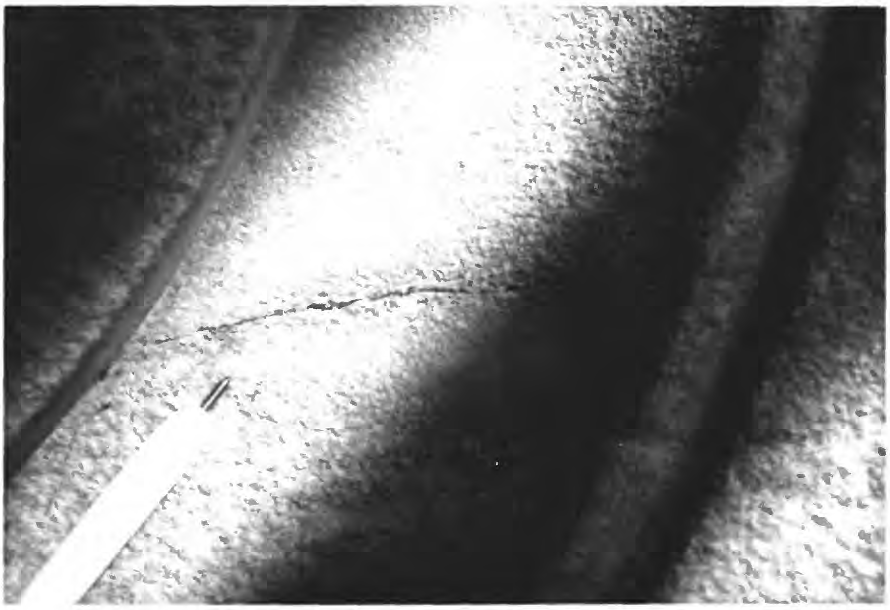

Fig. 13 Photograph of grain size (textural) change associated with a crack in volute 30C.

Fig. 14 Portions of the egg and dart trim (on column 19; A-D side) have broken off, revealing sugaring marble under the black surficial crust.

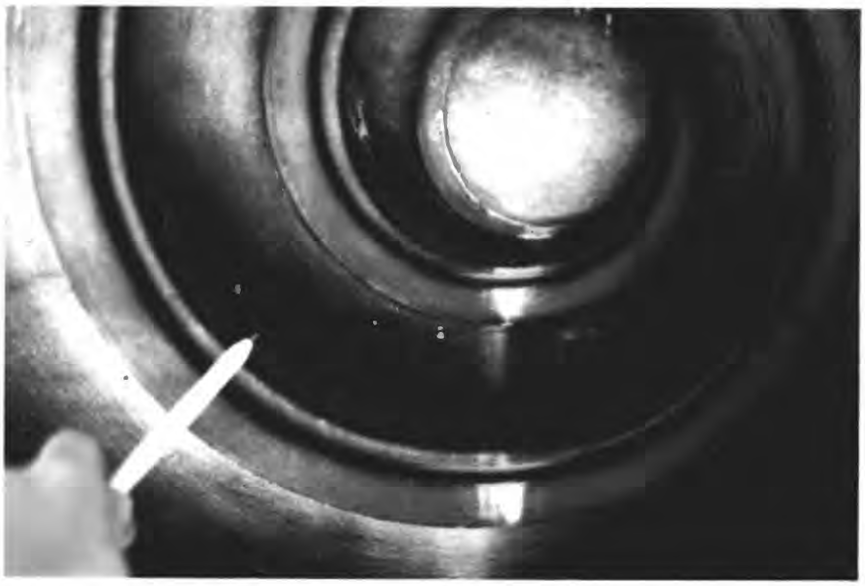

Fig. 15 The crack in volute 10 C is horizontal, in the recessed portion of the lower part of the volute, and it is co-planar with the fracture face in the adjacent, broken volute (10B).

APPENDIX A. Inclusions

Mineral inclusions in the marble at the Jefferson Memorial are of potential interest to the problem of the volute failure because of questions about whether a plane of mineral inclusions might have coincided with and perhaps caused the failure of the volute. Marble is predominantly composed of the mineral calcite (calcium carbonate, $CaCO_3$), but it also typically contains inclusions of other minerals that have different properties from the calcite. Mineral inclusions of dolomite, phlogopite, muscovite, chlorite, feldspar, pyrite, rutile, and apatite are typically present in the Vermont marble (McGee, 1989). Inclusions in the marble used in the Jefferson Memorial occur in clusters and streaks; mica and dolomite inclusions are the most readily visible inclusions. Mica (phlogopite and muscovite) inclusions appear as tan colored linear streaks; dolomite inclusions appear as light gray clouds and streaks.

Mica inclusions were of particular interest in our examination of the stone at the Jefferson Memorial because in many places, particularly on the columns, micas seem to weather preferentially by spalling off in layers or by leaving thin linear grooves in the marble (see Fig. 6). Because it was important to distinguish cracks from inclusions, and because we were looking for features that might explain the cracks, we examined some of the inclusions we found in the columns and column capitals. One feature of particular note is that some inclusions are recessed (lower than the surrounding calcite), some are raised (higher than the surrounding calcite), and some have no noticeable difference in the surface around an inclusion. We sampled some of the recessed and raised inclusions and some that were associated with cracks, to identify the inclusion mineral and to determine if there is a connection between the relative surface weathering and the type of inclusion. Samples were obtained by scraping or prying a few grains of the inclusion with the blade of a pocket knife. In some cases, the stone was spalling (splitting into thin layers) near an inclusion, so it was possible to pry off a small (less than one square centimeter) sample of the stone. The samples were examined with an optical microscope and identities of some of the phases were confirmed using powder X-ray diffraction and (or) the scanning electron microscope.

Seventeen samples were examined to identify inclusions in the marble (Table A-1). Most samples are mixtures of several mineral inclusions. The most common inclusions are pyrite, muscovite, and phlogopite. Three samples (JM501-2, JM501-1, and JM429-1) were specifically collected to investigate inclusion traces in the column capitals that appeared raised or recessed compared to the surrounding calcite (see field description column in Table A-1). Several small pieces that were spalling (flaking off in a layer) were also removed for examination and identification of their minerals. There are no unique minerals or special combinations of minerals in any of these samples that had specific weathering features of raised or recessed compared to the surrounding calcite. So, there does not appear to be any correlation between the mineral phases and whether an inclusion trace appears to be more or less resistant compared with the surrounding stone. The orientation of the inclusion with respect to the stone surface and the specific exposure of the stone surface to weathering agents must play a significant role in determining how an inclusion weathers relative to the marble surface.

Table A-1. Inclusion Samples from the Jefferson Memorial

SAMPLE#	ATTRIBUTE	#	AREA	FIELD DESCRIPTION	PHASES PRESENT
JM501-3	column	41	top drum (AD)	broad incl. area; flat incl. plane	cc,py,mus
JM518-2	column	40	top drum (CD)	soft; pried off	cc,py,mus,ap
JM317-1	column	29	2nd drum down	spalled area	cc,py,mus,cordierite?
JM602-1	column	26	top drum	raised blk dots, hard to scrape	cc,py
JM602-4	column	26	bottom drum, top	spall piece, has light crust; area along incl. traces	cc,py,mus,qtz,ap
JM701-1	column	25	top drum, C-D side	several small pieces pried fr. pitted areas, some w/ incl.	cc,mus,py,phl?,??
JM908-1	column	19	lower drum	yellowish, beige blocky incl. stands above surface, pried off	cc,mus,py,phl,qtz
JM501-2	echinus	41AD	above e&d	recessed, horizontal	cc,phl,py
JM317-2	capital	28BC	annulet ?	spalled area	cc,py,mus,phl
JM501-1	volute	41B	face	raised incl. trace	cc,phl
JM429-5	volute	29D	fracture face	spall fr. fracture surface	cc,phl
JM429-1	volute	28B	back	raised incl. trace	cc,py,mus,phl
JM625-1	volute	26C	back	broad, raised incl., pried off easily; soft, crumbly pieces	cc,mus,py
JM602-2	volute	26B	middle rim, top	spall piece, split on incl. plane	cc,mus,py
JM814-1	volute	21A	back	area of incl. trace, beginning to spall; touched & piece fell off	cc,mus,phl
JM722-1	stylobate		east side	green incl. sample pried out, organic material underneath	cc,??talc?chl? diop?chl?
JM429-9	stylobate		east side, bottom step	raised incl. w/ blk(organic?) ard. it	cc,py,mus,phl

Architectural feature (ATTRIBUTE) and specific column number (#) indicate where the samples were collected. The inclusion phases were identified with optical and scanning electron microscopy (with energy dispersive analysis) and with powder X-ray diffraction.
Abbreviations: incl. = inclusion; fr. = from; w/ = with; blk = black; ard. = around; e&d = egg & dart trim

Phase abbreviations: cc = calcite; py = pyrite; mus = muscovite; ap = apatite; qtz = quartz; phl = phlogopite; chl = chlorite; diop = diopside

calcite = $CaCO_3$, pyrite = FeS_2, muscovite (mica) = $K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$, apatite = $Ca_5(PO_4)_3(OH,F,Cl)$, quartz = SiO_2, phlogopite (mica) = $K_2(Mg,Fe)_6[Si_6Al_2O_{20}](OH,F)_4$, chlorite = $(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$, diopside = $Ca(Mg,Fe)Si_2O_6$, talc = $Mg_6Si_8O_{20}(OH)_4$, cordierite = $Al_3(Mg,Fe)_2Si_5AlO_{18}$Table A-1. Inclusion samples from the Jefferson Memorial

APPENDIX B. Alteration Crusts and Discolorations

During examination of the column capital volutes at the Jefferson Memorial, surficial discolorations of the marble were investigated to identify what they were. Identification of the surficial discolorations could help us understand factors that might affect the volutes, or it might indicate if the discolorations are influencing the deterioration of the marble. The predominant type of surficial discoloration on the column capitals is black or light tan surficial alteration crusts that can easily be scratched with a fingernail. A more resistant second discoloration, mainly found on the column shafts, ranges from bright yellow to dark pink, but it only occurs on columns 44, 53, and 54.

Samples were collected by scraping the stone surface with the blade of a pocket knife. Less than 0.5 g of material was typically collected. In a few cases, small encrusted pieces (approximately one square centimeter in size) were collected because they broke off when touched. These samples consist of crumbling marble with an adhered dark or light surficial crust. The samples were examined with an optical microscope and analyzed with powder X-ray diffraction. Some samples were also examined with the scanning electron microscope.

Alteration Crusts

Black or light tan surficial alteration crusts are present on most column capitals at the Jefferson Memorial. The crusts are especially noticeable on the inward facing volutes of the outer colonnade and on the outward facing sides of the inner colonnade column capitals (Fig. B-1). Although the distribution of the crusts differs, on many volutes the crusts are darkest at the bottom half of the volute, and the tan crusts are located in the recessed portions at the top of the volute face. Dark and light crusts were scraped from several ares on the column capitals (volutes, egg and dart trims, and the scrolls). The samples, analyzed with X-ray diffraction, contain calcite, gypsum, $\pm$ quartz, $\pm$ micas (muscovite or phlogopite) (Table B-1), but they are predominantly composed of gypsum. The proportions of the phases vary because the crusts actually consist of a network of gypsum crystals that have trapped dirt particles (especially quartz grains) and some pollutant particles (Fig. B-2).

Gypsum alteration crusts are typically found on marble building surfaces (Amoroso and Fassina, 1983). The crusts form when the calcite ($CaCO_3$) in the marble reacts with moisture and sulfur dioxide air pollution to form gypsum ($CaSO_4 \cdot 2H_2O$). Because gypsum is soluble in water, it tends to accumulate in areas that are sheltered from rain or washing. Thus, the distribution of the accumulated crusts show which areas of the building have been most sheltered from water.

For this study, the crusts are mostly of concern because they obscure surface features of the marble. They are useful however, because their presence shows that a particular area of the column capital has not been exposed to much washing from water. In addition to disfiguring the memorial, the crusts may cause problems because the marble under the crusts tends to disaggregate. Despite the relatively young age of this memorial, where the blackened stone is chipped, the freshly exposed stone crumbles easily when it is touched (Fig. 14).

Bright Discoloration

A bright pink and yellow discoloration near the top of column 43, on the front portico, is easily visible from the east side of the memorial (Fig. B-3). Similar, less visible, small areas of this stain are located elsewhere near the top of column 43 and on columns 53 and 54. The stain first appears as a light yellow color; with time it changes to a darker yellow and then to pink. It appears more pronounced in warm humid weather. Close examination of the stain on the column shows that it appears to be concentrated just below the stone surface, and X-ray diffraction analysis of samples scraped from the discolored area found only calcite. Because the bright discoloration occurs on columns where there may be excess moisture from the roof, and because the stained area appears to change in size with time and humidity, it was suggested that the stain might be of biologic origin. A sample was collected and cultured, and a filamentous bacteria was found in it (written communication to A. Donald, DCS-NPS, 10/31/95). David Kemnitzer (Einhorn, Yaffee, and Prescott; oral communication) identified a micrococcus roseolous bacteria in a similarly stained area at the Arlington Memorial Amphitheater. It appears that the bright discoloration at the Jefferson Memorial is probably the same type of bacteria.

While some organisms can cause stone deterioration, the main effect of this bacteria appears to be that it disfigures the marble. So, except that it indicates places where the stone retains moisture, these bright discolorations do not seem to be of importance to the column capital integrity or to the volute failures.

Reference cited:

Amoroso, G.G. and Fassina, V., 1983, Stone Decay and Conservation. Materials Science Monographs, 11, Elsevier, New York, 453p.

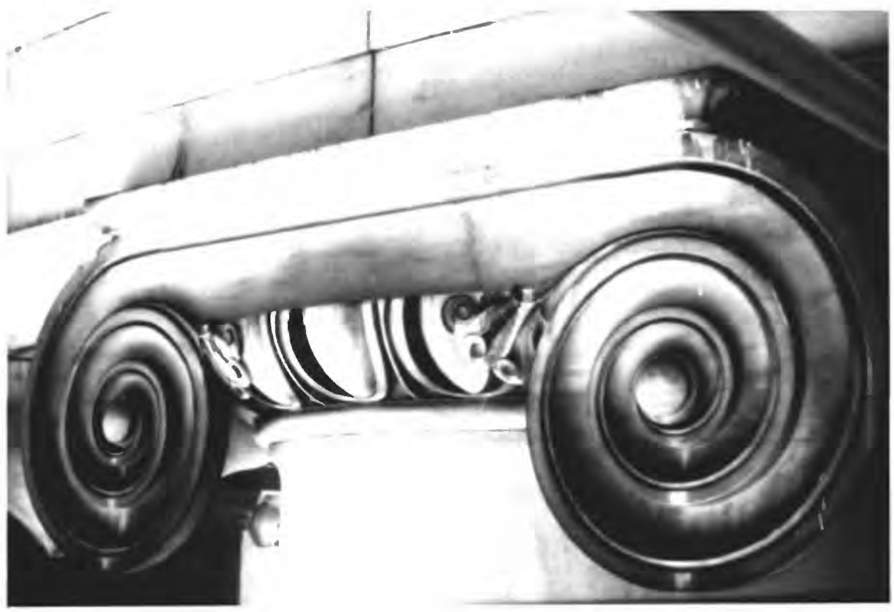

Fig. B-1. Volutes B and C on column 8 show the typical distribution of blackened surficial crusts on a sheltered column capital.

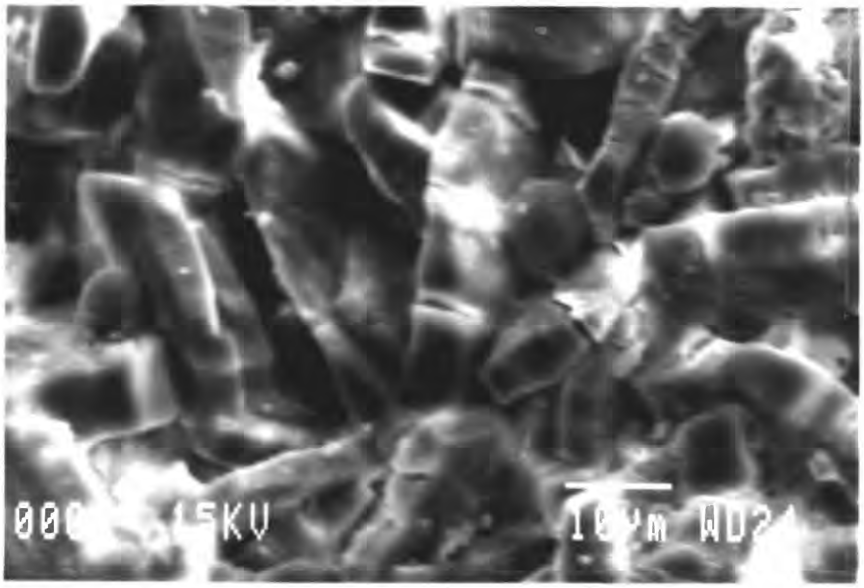

Fig. B-2. Scanning electron micrograph of elongate gypsum crystals that form a network on the marble surface. The openings between the crystals trap dirt and pollutant particles (smooth round spheres) which make the crust appear black.

Fig. B-3. The bright pink/yellow stain is visible on the side, near the top of column 43 (center of photo) even from some distance away.

Table B-1. Analyses of crust samples

Dark Crusts

SAMPLE#	ATTRIBUTE	#	AREA	FIELD DESCRIPTION	PHASES
JM1014-5	volute	43A	outer rim R	gray material, tightly adherent	cc,gyp
JM501-4	volute	41A	inner recessed, lower R edge	soft, scraped off easily; sample fine & powdery	gyp,cc,qtz,wed?
JM501-5	egg&dart	41A	top curve of palmette	adherent, did not scrape easily; fine powder sample	gyp,cc,qtz
JM610-2	volute	39C	outer recessed, top edge	scrape fine blk powder	gyp,cc,qtz
JM429-4	scroll	28AB	middle ridges		gyp,qtz,cc
JM826-2	volute	20B	back	blk specks, scraped easily	gyp,qtz
JM916-3	volute	19D	lower outer rim	blistered crust	gyp,cc,qtz
JM916-2	volute	19A	outer recessed, L side	raised lumps, white under	cc,gyp,qtz

Light Crusts

SAMPLE#	ATTRIBUTE	#	AREA	FIELD DESCRIPTION	PHASES
JM1014-6	egg&dart	43A	palmette	drip from joint above	cc
JM325-1	volute	41A	inner recessed, top		gyp,cc,phl,sph?
JM527-1	volute	39A	top	scraped easily; fine powder	gyp,cc,qtz,mus
JM429-2	column	28	top drum (AB)	soft efflorescence; wide area	gyp,cc,qtz

Table B-1 *con't. -- Light Crusts*

SAMPLE#	ATTRIBUTE	#	AREA	FIELD DESCRIPTION	PHASES
JM429-3	column	28	top drum (AB)	adherent; shallow, diffuse yellow efflorescence	cc,gyp,sph?
JM1104-2	volute	17D	outer recessed, upper L	scraped off easily	gyp,cc,mus,qtz
JM30106-1	ceiling		portico ceiling, nr col 50	scraped easily; fine powder	cc,gyp,qtz

Stains

SAMPLE#	ATTRIBUTE	#	AREA	FIELD DESCRIPTION	PHASES
JM1014-2	volute	43D	outer rim & recessed lower L	pink; sugared surface, scrapes easily	cc
JM30119-1	column	43	top drum (BC)	lg patch bright yellow	cc

Architectural feature (ATTRIBUTE) and specific column number (#) indicate where the samples were collected. The phases were identified with X-ray diffraction analysis.

Abbreviations: R = right; L = left; blk = black; nr = near; lg = large

Phase abbreviations: cc = calcite; gyp = gypsum; qtz = quartz; mus = muscovite; phl = phlogopite; sph? = sphene?; wed? = weddellite? (? indicates uncertain identification)

calcite = $CaCO_3$, gypsum = $CaSO_4 \cdot 2H_2O$, quartz = SiO_2, muscovite = $K_2Al_4Si_6Al_2O_{20}(OH,F)_4$, phlogopite = $K_2(Mg,Fe)_6Si_6Al_2O_{20}(OH,F)_4$, sphene = $CaTiSiO_5$, weddellite = $CaC_2O_4 \cdot 2H_2O$

APPENDIX C. Preferential Weathering on Outward Facing Volutes

All of the marble surfaces at the Jefferson Memorial that are exposed to rain and wind have developed a roughened (sugared) surface that is typical of the manner in which marble weathers. However, some of the column capitals on the outer circle of the colonnade have distinctive horizontal bands that appear gray in color and are slightly raised and rougher compared with the surrounding buff colored stone (Fig. C-1). A more resistant zone in the stone might typically form where there is a concentration of minerals that are slightly more resistant to weathering than the calcite that predominantly composes the marble. To find out if a mineralogical variation in the stone was the cause of the banding, we scraped some grains from the distinctive gray and buff bands on three column capitals (numbers 30, 29, and 28). One of the volutes that was sampled (30C) has a fracture plane near the transition between the gray and buff zones. Because the bands occur across the whole block of stone and they are horizontal, similar to the planes of the fractured volutes, some feature of the bands might provide a clue about the volute failure.

We examined grains from the buff and gray areas optically and with the scanning electron microscope, and we analyzed the samples with powder X-ray diffraction to determine what might cause the difference in appearance (color and resistance) of these zones in the marble. There is no significant difference in mineralogy between the buff and gray layers. Most of the samples consist only of calcite. Three samples contained some quartz, but two of the three samples with quartz are from the buff zone and one is from the gray zone, so presence of quartz does not appear to correlate with the different zones. Because the mineral assemblage did not provide a clue to any differences, we examined the samples and the bands again, and noticed that there appeared to be a slight difference in grain size between the bands. Although the grain size ranges for the calcite from the gray and buff bands overlap, the grains from the gray zone are smaller on average than the grains from the buff zones (Fig. C-2). The gray and buff zones on the column capitals appear to indicate a difference in texture or grain size that correlates with a different resistance of the marble and results in bands of contrasting appearance.

The textural change revealed by the bands is horizontal and appears to be extensive; it is continuous and visible across the two outward facing volutes on the column capitals where it occurs. However, the textural change is not visible on the sheltered sides of the column capitals where the stone surface has not been roughened by weathering and details of the marble are partially obscured by surficial alteration crusts. Cracks in some column capitals (eg. 33B, 32C, 30C, 27B) are associated with textural changes in the marble that are similar to the textural change on the column capitals with the bands of buff and gray stone. It seems that such a textural change indicates that there are horizontal planes in the marble that may differ in strength and might contribute to the failure of a volute in the right situation. Two of the column capitals where the banding was quite noticeable (#29 and 30) have broken volutes, suggesting a correlation between the bands and a weakness in the stone. However, on column 29 there is also a significant concentration of phlogopite inclusions on the fracture plane so in this case it is unclear whether the texture, the inclusions, or both influenced the failure of the volute.

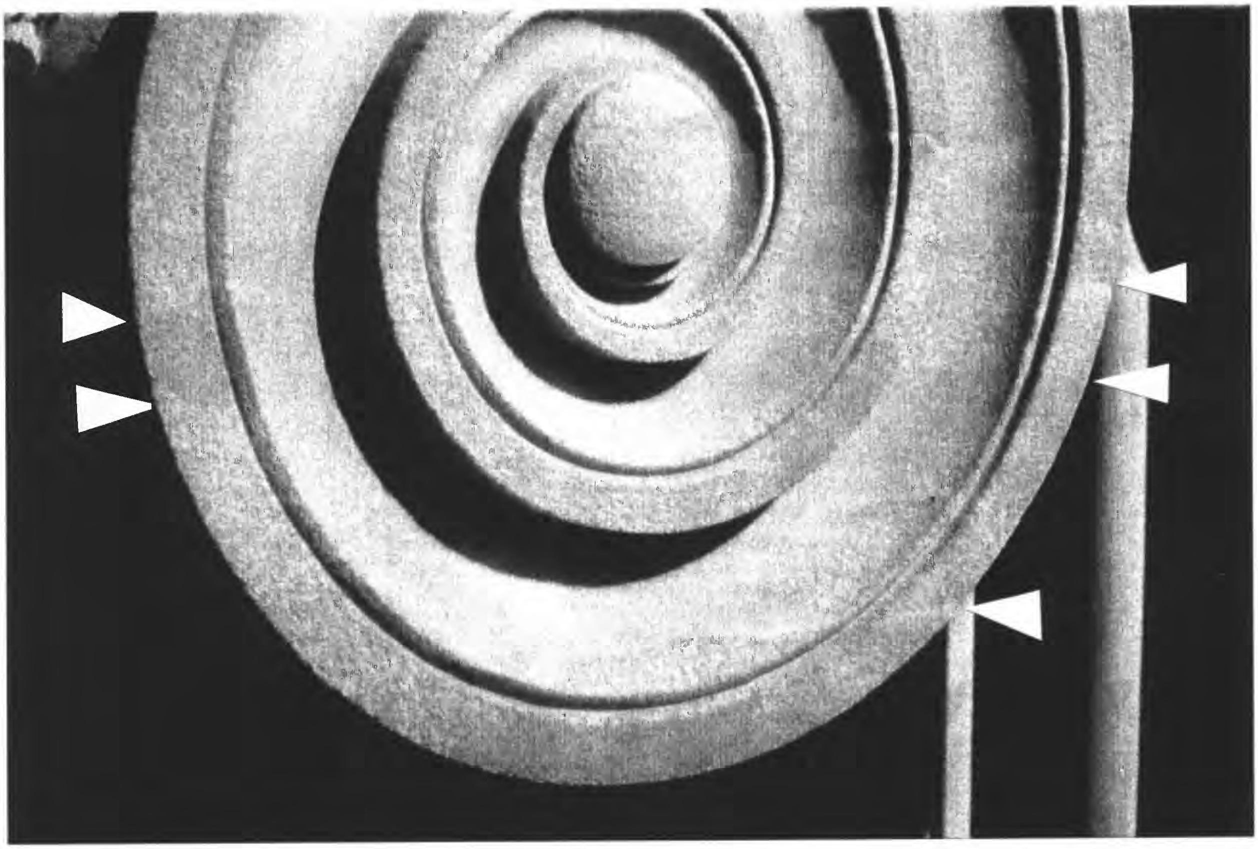

Fig. C-1 Volute 30B has buff and gray bands that appear to have differing surface textures.

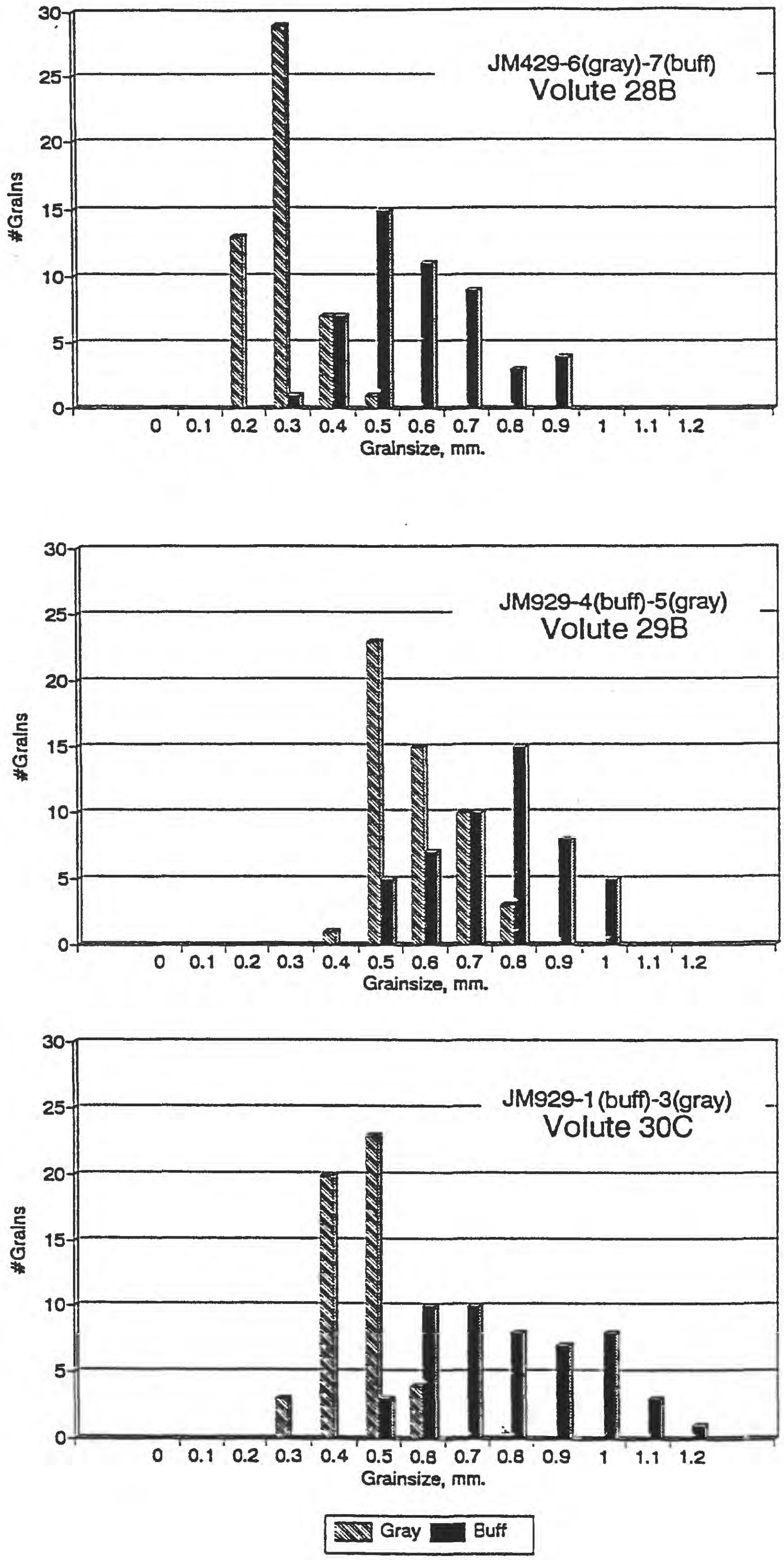

Fig. C-2 Grain size distributions for buff and gray bands from columns 28, 29, and 30.