U.S. Department of the Interior
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# Colorado Yule Marble— Building Stone of the Lincoln Memorial

U.S. GEOLOGICAL SURVEY BULLETIN 2162

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# Colorado Yule Marble—Building Stone of the Lincoln Memorial

By Elaine S. McGee

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Prepared in cooperation with the
National Park Service

An investigation of differences in
durability of the Colorado Yule marble,
a widely used building stone

**U.S. DEPARTMENT OF THE INTERIOR**
**BRUCE BABBITT, Secretary**

**U.S. GEOLOGICAL SURVEY**
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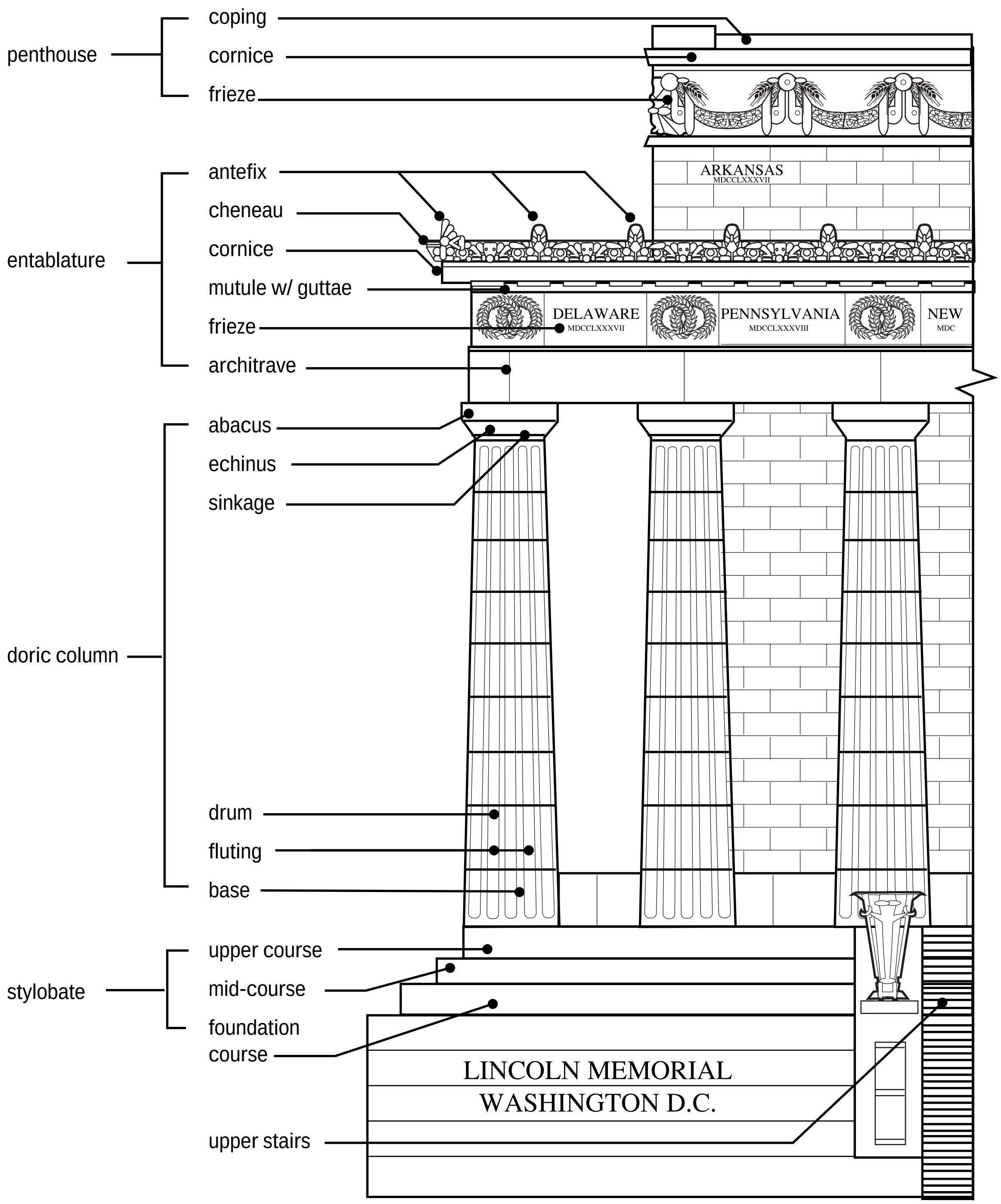
# METRIC CONVERSION FACTORS

[Both metric and customary units are used in this report. For convenience, conversion factors are provided below]

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| micrometer (µm) | 0.00003937 | inch |
| millimeter (mm) | 0.03937 | inch |
| centimeter (cm) | 0.3937 | inch |
| | **Area** | |
| square inch ($in^2$) | 6.452 | square centimeter |
| square centimeter ($cm^2$) | 0.1550 | square inch |
| | **Volume** | |
| cubic foot ($ft^3$) | 0.02832 | cubic meter |
| cubic meter ($m^3$) | 35.31 | cubic foot |
| | **Mass** | |
| ton (2,000 lb) | 0.9072 | metric ton (1,000 kg) |
| milligram (mg) | 0.00003527 | ounce avoirdupois |
| | **Mass per unit volume (density)** | |
| pound per cubic foot ($lb/ft^3$) | 16.02 | kilogram per cubic meter |
| | **Pressure** | |
| pound-force per square inch ($lb/in^2$) | 6.895 | kilopascal |
| kilogram-force per square centimeter ($kg/cm^2$) | 98.066 | kilopascal |

Temperature conversions for degrees Fahrenheit (°F) and degrees Celsius (°C) follow:

$$°C = (°F - 32)/1.8$$
$$°F = (1.8 \times °C) + 32$$




Architectural terms for parts of the Lincoln Memorial. Modified from Einhorn Yaffee and Prescott (1994).

# Colorado Yule Marble—
# Building Stone of the Lincoln Memorial

By Elaine S. McGee[1]


## ABSTRACT

The Colorado Yule marble, quarried in Marble, Colo., is a very pure white marble, and it has been widely acclaimed for its quality and purity. This marble has been used for many prominent buildings; one of the most notable is the Lincoln Memorial in Washington, D.C., built nearly 80 years ago. Although most of the marble in the memorial appears to be in very good condition, some of the stones have developed pronounced surficial roughness and show a significant loss of carved details and rounded edges compared with adjacent stones. Because adjacent blocks of marble receive nearly identical exposure to weathering agents that cause deterioration of the marble, it seems very likely that this pronounced difference in durability of adjacent stones arises from some inherent characteristic of the marble.

The Colorado Yule marble is a nearly pure calcite marble with minor inclusions of mica, quartz, and feldspar. Compositions of the calcite and the inclusion phases in the marble are typical for those phases. The calcite grains that compose the marble are irregularly shaped and range from 100 to 600 micrometers in diameter. The texture of the marble is even, with a slight preferred directional elongation that is visible when the marble is cut in certain directions. Physical tests of the marble show that its strength is comparable to that of other marbles typically used in buildings.

Variations in the durability of the marble, like those seen at the Lincoln Memorial, are not related to variations in calcite composition or to the presence of inclusions in the marble. Most likely, the variations arise from differences in the calcite grain boundaries and the degree to which the grains interlock with one another. Weak grain boundaries that permit water or solutions to penetrate into the marble and dissolve the calcite grains at their edges cause the marble to disaggregate or “sugar.” Subtle differences in texture that occur in the marble from various parts of the quarry probably cause some stones to be more susceptible to this form of deterioration. These differences may not be readily visible when the stone is freshly quarried.


## INTRODUCTION

Praised as one of the purest marbles ever quarried, and cited as a rival to the Italian and Greek marbles of classic fame, the Colorado Yule marble was selected and used for the exterior stone of the Lincoln Memorial in Washington, D.C. Built between 1914 and 1922, the Lincoln Memorial (fig. 1) is one of the most visited and treasured memorials in Washington, D.C., and it serves as a symbolic focus for many historic gatherings. Some believe that the marble, selected for the monument at the urging of the architect Henry Bacon, is integral to the effect and feeling created by the memorial (Thomas, 1993).

After nearly 80 years of exposure to rain, wind, temperature variations, moisture, and urban pollution, the stone in the Lincoln Memorial shows signs of deterioration. Characteristics of the deterioration include places that display a roughened “sugared” surface, inclusions in the marble that stand above the rest of the stone surface, and stain discoloration or blackened surficial alteration crusts. Many of these weathering features are typical for marble buildings. However, one of the most striking deterioration features of the marble at the Lincoln Memorial occurs where adjacent blocks of stone have weathered very differently. The surface of one block of stone appears rough, with loose surficial grains and softened edges on carved details, while an adjacent block has retained its smooth surface and crisp edges on carved features as seen in figure 2. Because adjacent blocks are exposed to identical conditions of weather and pollution, the difference in degree of deterioration must arise from some characteristic of the stones. Characteristics of the marble that might influence its durability include composition of the calcite, type and composition of inclusion minerals, grain size, texture, and physical properties. This study was conducted to characterize the Yule marble and to identify any characteristic(s) that might cause its variable durability.

When the Colorado Yule marble was chosen for the construction of the Lincoln Memorial, its selection was

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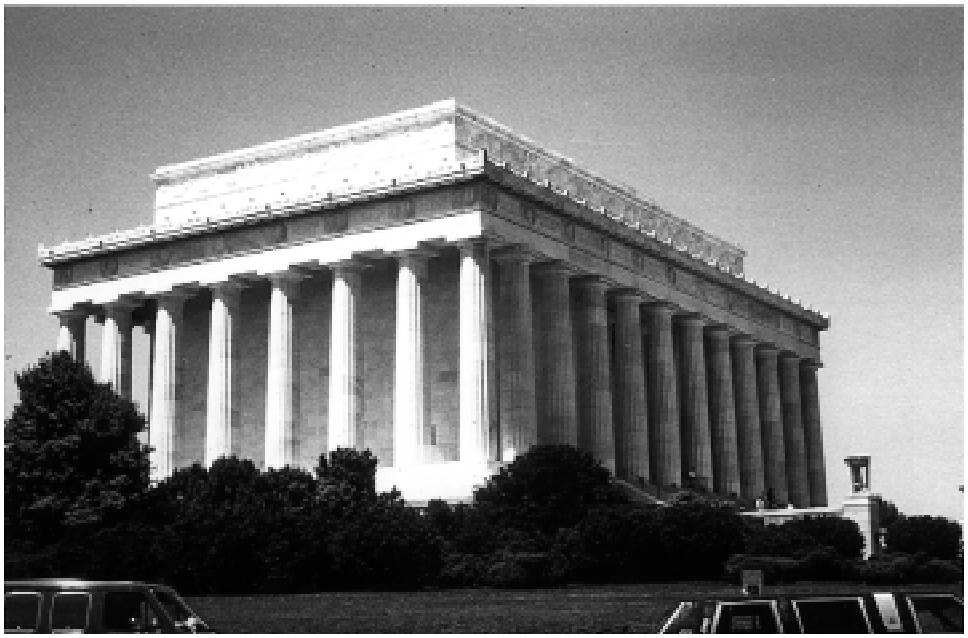

**Figure 1.** The Lincoln Memorial, Washington, D.C. (dedicated 1922). Photograph taken in 1990.

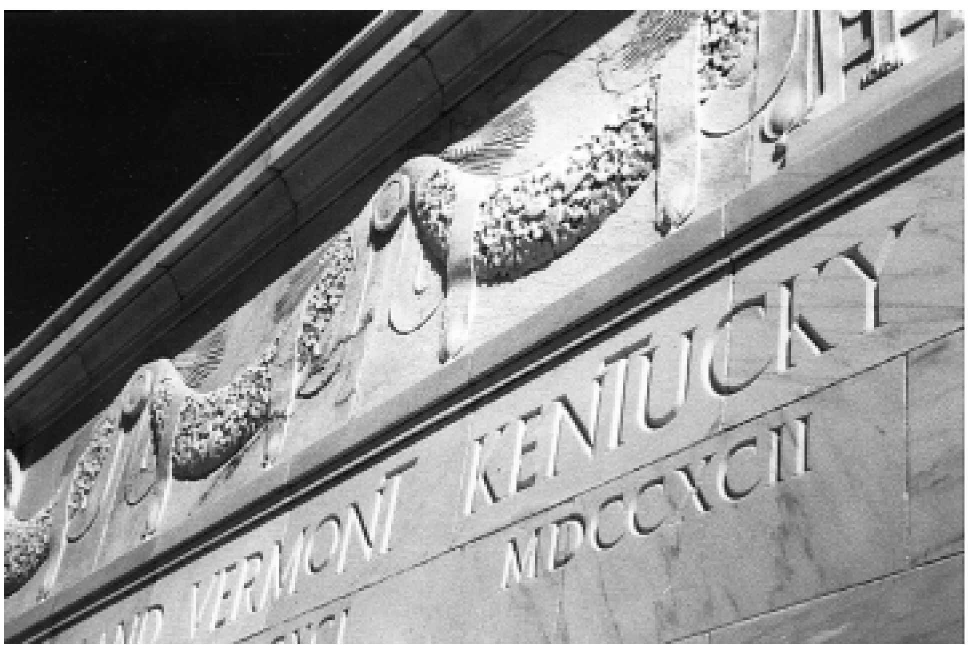


**Figure 2.** Colorado Yule marble in the penthouse wall of the Lincoln Memorial, Washington, D.C. Although the memorial gives an overall appearance of clear, white marble, some blocks (upper part of photograph) have a roughened, sugared surface, whereas adjacent blocks retain smooth surfaces and crisp edges (bottom of photograph).

controversial. The Lincoln Memorial Commission heard testimony questioning the quality and durability of the Colorado Yule marble. Questions also were raised about the recently opened quarry's ability to provide the quantity and size of the blocks of marble required for the construction of the Lincoln Memorial. Additional physical tests of the marble were made in response to these questions, and additional reviews were made of the quarry and the stone quality before the Colorado Yule marble was finally selected.

As the marble is examined today and options for the treatment and preservation of the stone are considered, it is important that characteristics of the stone be understood. Just as the mineralogical and physical characteristics of the marble have influenced the manner and degree to which the stone has weathered, these features may also influence the effectiveness of treatments that may be applied to the stone. An examination of the mineralogy and physical characteristics of the Colorado Yule marble, along with observations of the weathered features of this marble in various buildings, may help guide the selection of appropriate preservation choices for the marble in the Lincoln Memorial.

### ACKNOWLEDGMENTS

Steve Moore (National Park Service) helpfully provided copies of items from the National Archives pertaining to the marble and to the construction of the Lincoln Memorial. The study described in this report was conducted as part of a cooperative project between the U.S. Geological Survey and the Denver Service Center of the National Park Service, funded by agreement MT 2150–5–0001.

## GEOLOGIC BACKGROUND

The Colorado Yule marble is quarried near the town of Marble in Gunnison County, located in central Colorado. It has been called by the trade names Colorado Yule marble and Yule Colorado marble, but the stone comes from the Leadville Limestone of Mississippian age (Vanderwilt, 1937; Gaskill and Godwin, 1966). The marble was formed by contact metamorphism that occurred during the Tertiary period, following the intrusion and uplift of the nearby granitic Treasure Mountain dome (Vanderwilt and Fuller, 1935; Ogden, 1961). Local contact with the heat and pressure from the intrusion of hot granitic magma recrystallized the Leadville Limestone, which elsewhere in Colorado is a dark-blue stone, into a distinctive white marble (Vanderwilt, 1937).

In the vicinity of the quarry, the Leadville Limestone is separated from the overlying and underlying rocks by unconformities (Gaskill and Godwin, 1966). These unconformities may be the reason why some reports about the Colorado Yule marble (Bain, 1936b) erroneously place the age of the marble as Silurian instead of Mississippian. The indistinct nature of the boundaries of the Leadville Limestone, particularly of the lower contacts near the Treasure Mountain dome, also explains the varied thicknesses (166 ft at the quarry on Yule Creek and 239 ft about 2,000 ft southeast of the quarry; Vanderwilt, 1937) that have been reported for the marble beds of the Leadville Limestone. The Pennsylvanian Molas Formation, consisting of argillites that were metamorphosed to hornfels and quartzite, lies above the Leadville Limestone (Gaskill and Godwin, 1966). The Dyer Dolomite Member of the Devonian Chaffee Formation lies below the Leadville Limestone. The Dyer Dolomite is locally cherty; it was metamorphosed to lime silicate marble and occasional serpentine marble (Gaskill and Godwin, 1966).

The Yule marble occurs as a massive white bed, 166 to 239 ft thick, with outcrops that usually form prominent cliffs (Vanderwilt and Fuller, 1935; Vanderwilt, 1937). Its most distinctive and productive occurrence is along the west side of Yule Creek, about 2.5 miles south of where Yule Creek joins the Crystal River. The Colorado Yule marble quarry is at an elevation of 9,300 ft above sea level on the west side of Treasure Mountain along Yule Creek. About 1,400 ft above the valley formed by Yule Creek, a nearly 200-ft-thick bed of the marble is exposed for more than a mile (Lakes, 1910). The marble bed dips at an angle into Treasure Mountain; however, because the metamorphism that formed the marble obscured most traces of bedding in the marble, it has been difficult to determine the angle of dip of the marble. Lakes (1910) reported that the marble dipped 51° into the mountain; Merrill (1914) reported a dip of 35°; and Vanderwilt (1937) reported that chert bands, which are believed to be parallel to the original bedding, dip 65° southwest in a prospect tunnel a short distance south of the quarry. The quarry openings are located on the thickest portion of the bed where the exposed marble is overlain by a "heavy covering" of rock that prevented erosion and limited fracturing of the marble (Merrill, 1914). Vanderwilt (1937) reported that the entire Mississippian formation (that is, the Leadville Limestone) at the quarry is 239 ft thick. However, Vanderwilt (1937) went on to say that only 100–125 ft of this bed consists of salable white marble: the lower 100 ft is unmarketable interbedded dolomite marble, and the upper 20–40 ft of the bed is also unmarketable because it contains streaks of gray and red.

Early reports (Lakes, 1895) stressed the massive nature of the white statuary (best quality) marble beds, emphasizing that the beds could produce blocks of almost any size or thickness. Lakes (1910) declared that the size of pure statuary blocks that could be produced from this deposit was limited only by the machinery capable of handling it. In his report to the Lincoln Memorial Commission, Merrill (1914) observed that there were two principal series of joints in the marble (north 70° west, and 20° south of west) and commented that the sizes of blocks obtainable from the quarry

**Table 1**. Chemical analyses reported for the Colorado Yule marble.

[— = not reported]

| | 1 | 2 | 3a | 3b | 4 |
|---|---|---|---|---|---|
| $CaCO_3$ | 99.79 | 99.72 | 98.84 | 99.50 | 99.73 |
| $MgCO_3$ | .15 | trace | .25 | .19 | .23 |
| $FeCO_3$ | — | — | .02 | .03 | .04 |
| $MnCO_3$ | — | — | .03 | .02 | .00 |
| $SiO_2$ | .04 | .10 | .27 | .05 | — |
| $Al_2O_3$ | — | — | .05 | .03 | — |
| $Fe_2O_3$ | — | — | .28 | trace | — |
| $MnO_2$ | — | — | .06 | none | — |
| $CaSO_4$ | — | — | .08 | .09 | — |
| Fe | trace | — | — | — | — |
| MnO, FeO, $A1_2O_3$ | — | .07 | — | — | — |
| Undetermined | — | — | .12 | .09 | — |
| Total | 99.98 | 99.89 | 100.00 | 100.00 | 100.00 |

SOURCE OF DATA AND DESCRIPTION OF SAMPLES

1. Analysis of samples submitted for Lincoln Memorial Commission: (Anonymous, undated).
2. Analysis by Von Schultz and Low, Chemical Laboratory and Assay Office, Denver, Colo.: (Von Schultz and Low, 1907). Sample: "Golden Vein White Marble."
3. Analysis reported by Vanderwilt (1937, p. 160): "Made under direction of A.W. Smith, Case School of Applied Science, Cleveland, Ohio, Oct. 22, 1907." Samples: 3a, "Streak" represents the markings in the "golden vein" marble; 3b, "Clear."
4. Analysis reported by Busenberg and Plummer (1983): Magnesium determined by atomic absorption spectrophotometry, iron and manganese determined by spectrophotometry, calcium assumed to be only other cation present and calculated from known weight of the sample and charge balance considerations. Subsample (20–50 mg) of National Museum of Natural History, Smithsonian Institution, sample 77858.

would be limited only by the joints and by the occasional chert layers. Knopf (1949) described two sets of fractures or joints: one set runs N. 65° E. and dips about 80° NW.; a second set of discontinuous, en echelon joints is not easily seen, but the joints strike N. 55° W. and dip about 70° SW. Vanderwilt (1937) also described two sets of fractures, classed as "main headers" and "dry seams," that are important constraints in the quarrying of the marble, but he further stated that despite these difficulties, the quarry can produce large blocks of essentially pure-white marble.

In 1930, the Colorado Yule marble was selected for the Tomb of the Unknown Soldier (in Arlington National Cemetery) because it was the only quarry that could provide a solid block of marble of the dimensions required (Vandenbusche and Myers, 1991). When the 56-ton block of white statuary marble was removed from the Colorado Yule marble quarry for the Tomb of the Unknown Soldier, it was the largest single piece of marble ever quarried (Through the Ages, 1931).

## QUALITY OF THE MARBLE

Two of the most remarkable characteristics of the Colorado Yule marble deposit are its quality and purity. Lakes (1910) reported that the statuary marble from the Colorado Yule deposit has "the same fine texture as the best grade Italian." Vanderwilt (1937) compared the statuary Yule marble to the Pentelic marble of Greece. Even today, the Colorado Yule statuary marble is praised, and its quality is compared with that of the world-renowned Carrara marble from Italy (Roberts, 1992; Compressed Air Magazine, 1993; Klusmire, 1993). The even grain size and lack of inclusions are the reasons the Yule marble is praised as fine and pure. Chemical analyses of the marble (table 1) confirm its purity and show that it is composed mostly of calcium carbonate (98.8–99.8 weight percent).

Vanderwilt (1937) described the Leadville Limestone as pure calcite marble and reported that metamorphic minerals (that is, noncalcite inclusions) are lacking over large areas. Although the marble was formed by contact metamorphism, and thus might show different characteristics close to the intrusion that caused the metamorphism, typical contact metamorphic silicate minerals did not form where the "marbleized" Leadville Limestone came into contact with the intrusive granite (Vanderwilt, 1937). The intrusive contact exhibits relatively few metamorphic effects (Vanderwilt, 1937). Although the formations near the Treasure Mountain dome were metamorphosed by the intrusion,

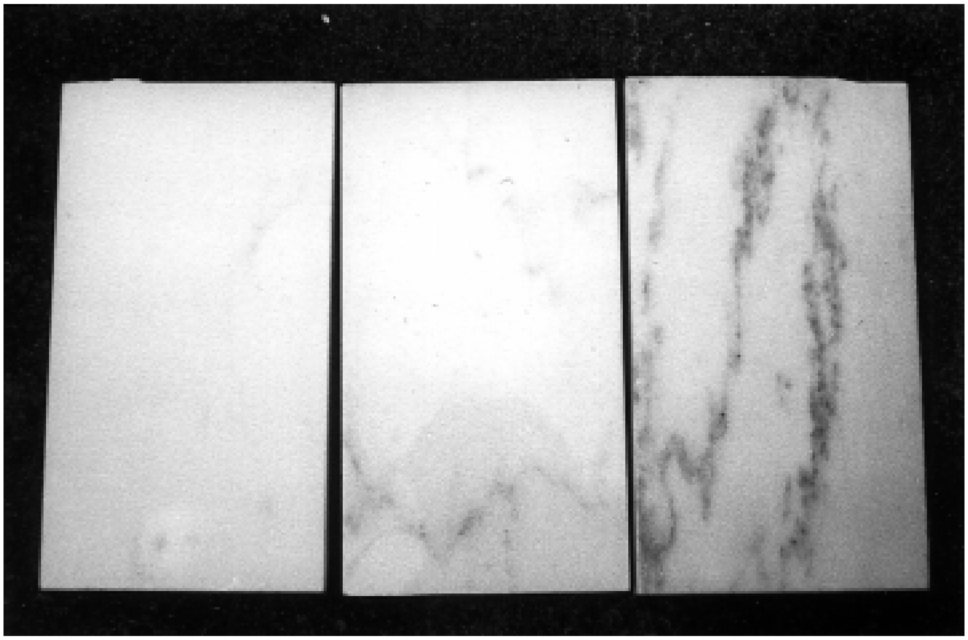

**Figure 3.** Slabs of three grades of the Colorado Yule marble marketed in 1992. Note how the appearance and abundance of inclusions in the samples vary with the grade. From left to right, the grades are Snowmass Statuary, Colorado Golden Vein Select, and Colorado Golden Vein.

proximity to the dome probably had less influence on the development of metamorphic minerals than structural and permeability conditions along joints and contacts of various formations (Vanderwilt, 1937). Where the marble is in direct contact with the intrusive granite, the most consistent change in the marble is that it becomes extremely coarse grained; the grain size in the contact zone is 1.0–2.0 cm, whereas the average grain size in the main body of marble is 2.0 mm (Bain, 1936a; Vanderwilt, 1937). Impurities in the marble from the Yule quarry and variations in quality are most common along joints in the stone (Merrill, 1914; Vanderwilt, 1937).

Nodules of gray chert and bodies of "lime" are the two main imperfections that have been encountered and that have caused some problems in quarrying the Colorado Yule marble. Merrill (1914) described lenticular masses of a dense structure with a water-blue tint that were unpredictably encountered in quarrying, but he reported that they could be avoided by judicious quarrying. Vanderwilt (1937) described two types of "lime" that were avoided by the quarrymen because of their color and because of the fractures that the bodies contain. One of the types of "lime" forms irregular masses from a few inches to several feet across that are slightly elongated parallel to the bedding. These masses consist of fine-grained dolomite mixed with calcite-filled fractures (Vanderwilt, 1937). The second type of "lime" is also gray but has a tabular form with well-defined boundaries parallel to the bedding; cross sections of these bodies are lenticular, and the dimensions may be as large as 4 ft in length and 1 ft in thickness (Vanderwilt, 1937). These lime bodies have rims consisting of fine quartz, calcite, tremolite, and possibly diopside with some local concentrations of sphalerite along the borders (Vanderwilt, 1937).

## GRADES OF THE MARBLE

The most celebrated samples of the Colorado Yule marble are pure white, with no apparent variation in mineral content or in grain size. However, the Colorado Golden Vein grade of the Yule marble, which contains inclusions that appear as fine lines of golden veining, is also well known. The Yule marble is classified into grades by the quarry to reflect stone quality and the amount of inclusions in the stone. Grade names change with time; in 1992, four grades of Yule marble were marketed for use in buildings. From highest grade to lowest, these are Snowmass Statuary Select (SSS), Snowmass Statuary (SS), Colorado Golden Vein Select (GV select), and Colorado Golden Vein (GV); the last three grades are shown in figure 3. A "select" designation indicates fewer inclusions and better quality. The Snowmass Statuary grades contain very few inclusions and are nearly pure white with an even grain. The Colorado Golden Vein grades are also predominantly white but contain inclusions that occur as thin linear streaks or as clouds of gold-bronze, tan, or gray (fig. 3). Vanderwilt (1937) described five grades of marble: statuary marble, veined or

**Table 2**. Polished thin section samples of the Colorado Yule marble examined for mineralogic and petrologic characteristics.

[Trade names used are from 1992; names of grades currently marketed may differ. EYP=Einhorn Yaffee and Prescott; NPS=National Park Service. Sample numbers show how many thin sections were examined but are not used in the rest of the report because only representative and averaged data are given]

| Sample type | Description | Sample number | Source of material sectioned |
|---|---|---|---|
| SSS | Snowmass Statuary Select grade | SSS | Slab obtained by David Coe, EYP, from Colorado Yule Marble Company in 1992 as part of his work for NPS on the "Lincoln Memorial Stone Survey" (EYP, 1994). Thin sections were cut from these samples with permission of EYP and NPS. |
| SS | Snowmass Statuary grade | SS–1 | Ditto. |
| CGVS | Colorado Golden Vein Select grade | CGVS–1<br>CGVS–2 | Ditto. |
| CGV | Colorado Golden Vein grade | CGV–1<br>CGV–2 | Ditto. |
| GV | Colorado Golden Vein grade | GV1–1<br>GV2–1 | Samples given to E.S. McGee by Colorado Yule Marble Company in 1993. |
| LMP | Pieces removed from Lincoln Memorial during renovation; possibly from stylobate steps; possibly in mid-1970's. | LMP1–1<br>LMP2–1 | Samples given to E.S. McGee by NPS as part of cooperative work. |
| LM0713 | Piece that broke from a badly weathered antefix on the Lincoln Memorial. | LM0713–1 | Ditto. |
| CYMR | Piece of marble collected from the quarry dump pile because of its badly disaggregated condition. | CYMR–1<br>CYMR–2 | Sample collected by E.S. McGee from refuse pile at Yule marble quarry. |

second statuary marble, golden-vein marble, bottom-base stock, and crystal grade. The grade designations used in this study appear to correspond to four of Vanderwilt's descriptions; however, there is no current grade specified that corresponds to the bottom-base stock grade described by Vanderwilt.

## MINERALOGIC AND PHYSICAL CHARACTERISTICS

Characteristics of marbles such as their texture, grain size, color, and inclusions influence the quality and the durability of the stone. Although pure-white, even-textured marbles are sought after and praised, most marbles also contain some mineral inclusions within the calcite matrix that give the marble a characteristic appearance. Merrill (1914) described the pure whiteness and compact crystallization of the Colorado Yule marble, but he also noted the presence of chert bands in the marble and described two types of colored veins: a dark streak that he attributed to original organic matter and a yellow veining that he attributed to penetration of iron or manganese oxide solutions along lines of strain. Bain (1936b) reported that the veining in the Colorado Yule Golden Vein marble is predominantly quartz with small amounts of iron- and magnesium-bearing amphiboles, the latter giving the veins their characteristic color. Vanderwilt (1937) listed dolomite, chert, diopside, quartz, sphalerite, and a small amount of fuchsite as inclusions in the Colorado Yule marble. Many of the reported mineral inclusions in the marble appear to be minor constituents or are constituents of zones of the marble that have not been routinely quarried. An example is fuchsite, which was reported by Merrill (1914) from an occurrence in the cliff face between quarries number 2 and 3 (see app. B for quarry description).

For this study of the Colorado Yule marble, polished thin sections were made from samples of all four grades of the marble, from several pieces of stone previously removed from the Lincoln Memorial, and from a sample collected at the Yule marble quarry dump pile (table 2). More sections were made from the Colorado Golden Vein grade stone than any other in order to observe the largest variety of inclusion phases present in the marble. The available samples from the Lincoln Memorial were examined and compared with samples currently quarried to look for similarities between older and newer quarried stone. The disaggregated sample from the quarry dump pile was selected because it was a rare crumbly piece; it was examined to see if any characteristics could be identified that explain its lack of durability compared to most typical samples of Yule marble.

The polished thin section samples were examined by using optical and scanning electron microscopy to characterize the texture and grain size of the samples. Mineral phases in the samples were identified with qualitative energy-dispersive X-ray analysis on the scanning electron microscope. Calcite and some inclusion phases were analyzed quantitatively by using a JEOL JXA–8900

**Table 3**. Inclusion samples collected at the Lincoln Memorial.

[Attribute: portion of the memorial from which the sample was collected.
Field description: appearance of the sample in the memorial, includes observations made by E.S. McGee while sampling in 1990–93.
Phases: alt = alteration, ap = apatite, biot = biotite, Ca-fsp = calcium feldspar, cc = calcite, dol = dolomite, fs = feldspar, K-fsp = potassium feldspar, mix = mixture, mus = muscovite, pyr = pyrite, qtz = quartz.
Phases were identified with energy-dispersive X-ray analysis on a scanning electron microscope or with powder X-ray diffraction]

| Sample number | Attribute | Field description | Phases |
|---|---|---|---|
| LM00713–3 ---------------- | Antefix | Inclusion, pried off | Ca-fsp. |
| LM00713–4 ---------------- | Parapet | Inclusion, raised; pried off | K-fsp, Ca-fsp. |
| LM10820–1 ---------------- | Penthouse wall | Dark-gray inclusion streak, raised, with pyr | K-fsp, mus, pyr, Ca-fsp. |
| LM10820–2 ---------------- | Penthouse wall | Yellowish-orange vein fill; scraped easily | Dol? fluffy coating. |
| LM10820–3 ---------------- | Parapet | Pried raised fs? inclusion off | K-fsp. |
| LM10916–2 ---------------- | Attic wall | Raised inclusion with dark edges; pried off | K-fsp, pyr, alt. |
| LM10916–4 ---------------- | Attic wall | White, raised area chalky under; came off easily | Qtz, cc. |
| LM10916–5 ---------------- | Attic wall | Chalky white area; fine powder, scraped easily | Cc, qtz. |
| LM10916–6 ---------------- | Parapet wall | Pinkish-tan grains with fungus “inclusion” area | Organic + qtz? + mix. |
| LM20603–1 ---------------- | Column | White area, center large inclusion; hard, scraped | Cc, qtz. |
| LM20603–2 ---------------- | Column | Rim of large inclusion (603–1); hard to pry out | Qtz, cc. |
| LM20603–3 ---------------- | Column | Rusty-black in raised grayish-brown inclusion; hard to remove. | Pyr, biot?, ap?, Ca-fsp? |
| LM20603–4 ---------------- | Column | Raised, rusty inclusion; pried pieces easily, left shiny/metallic film under. | Sphalerite, cc, alt. |
| LM20603–5 ---------------- | Column | Yellowish, soft, fills vein which follows crack | Dol, alt? |

electron microprobe (app. A). The compositions of the main constituents of the marble were determined in order to compare them with the compositions of typical minerals in marble; variations in composition or unusual characteristics might influence the marble durability.

Samples of weathered inclusion minerals were collected at the Lincoln Memorial and were analyzed to identify the phases (table 3). Typically, I collected these samples because they appeared significantly different from the surrounding stone. They were collected by scraping or prying small (usually a few grains to less than 0.5 $cm^2$ area) pieces away from the matrix, or they were collected where a small piece of stone (less than 2 cm long) crumbled or broke when it was touched. These samples were examined optically and were analyzed by using the scanning electron microscope with qualitative energy-dispersive X-ray analysis. Where there was sufficient material, some samples were also analyzed by using powder X-ray diffraction.

## GRAIN SIZE AND TEXTURE

The grain size and texture of marble influence both its appearance and its durability. Qualities that are often sought in marble are an even texture, a homogeneous appearance, and a luminous surface that polishes well. Fine-grained marbles have a homogeneous appearance and may take a polish better than some coarser grained marbles. Similarly, marbles with tightly joined calcite grains may appear more luminous when polished and may prove to be more durable than marbles that have large or loosely bonded grains.

The fabric and texture of the Colorado Yule marble have been widely studied and examined. Early reports of the marble described its fine texture and fine crystallization (Lakes, 1910). The grain size of the Yule marble is reported as 2,000–3,000 grains to the square centimeter (Vanderwilt, 1937, quoted Bain, 1936a, written commun.). Knopf (1949) reported grain sizes in the marble as 0.5–1.5 mm, and Thill and others (1969) reported an average grain size of 0.4 mm for the sample they studied. The edges of the calcite grains in the Colorado Yule marble are deeply crenulated (irregularly and minutely notched and scalloped) (Bain, 1936b); these crenulations are believed to account for the resistance to weathering of the marble. Bain (1936b) also reported that the calcite crystals in the Yule marble are aligned so that the long axes of the grains are essentially perpendicular to the principal veining in the deposit. From a geographically oriented block of marble, Knopf (1949) examined calcite grain dimensions in thin sections cut with respect to the grain (texture) of the marble. Calcite grains are distinctly elongated in sections cut normal to the strike and dip vectors of the grain (longer to shorter axis: 1.8:1) and in sections cut parallel to the strike and normal to the dip vectors (longer to shorter axis: 3:1), but they are nearly equidimensional in samples cut parallel to the strike and dip vectors of the grain (Knopf, 1949).

As the major constituent of the marble, calcite grains determine texture and fabric characteristics of the stone. In the samples studied for this report, the calcite grains are irregularly shaped, and they are generally equidimensional to slightly elongated with irregular edges (fig. 4). Some of

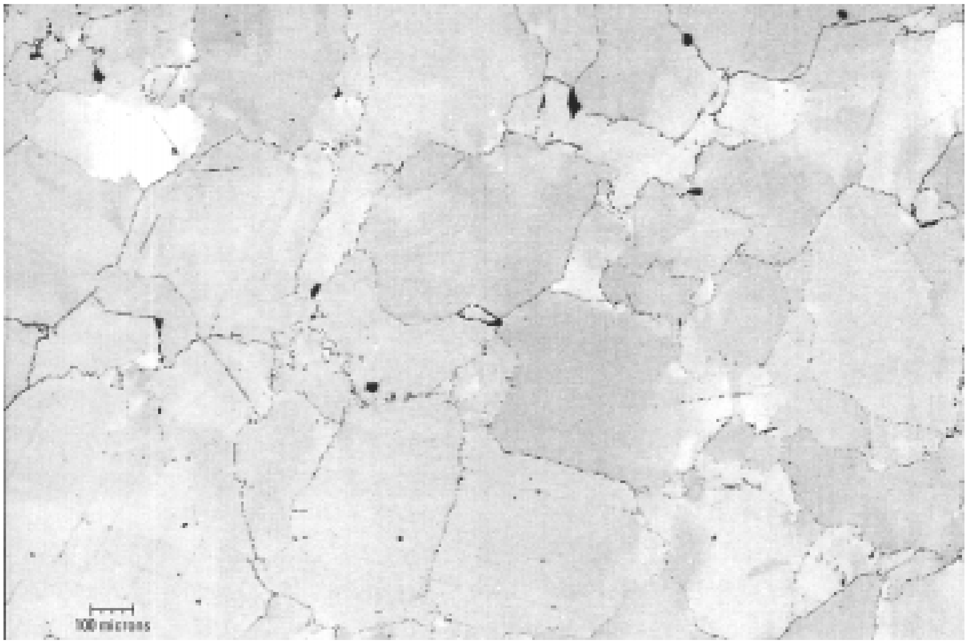


**Figure 4.** Backscattered electron image of a polished thin section showing calcite texture in the Snowmass Statuary Select sample of the Colorado Yule marble. The irregular shapes of the grains and the range of grain sizes in one area are fairly typical of this marble. “Micron” is another name for micrometer.

the grains meet at 120° angles, indicating that parts of the marble are well recrystallized.

The calcite is varied in size, ranging from about 50 to 1,000 micrometers in the longest dimension. In four to eight randomly chosen areas of each polished thin section, the average calcite grain is about 300 micrometers in diameter (fig. 5). The calcite grain sizes in the four grades of marble, in several samples from the Lincoln Memorial, and in a crumbling piece of marble obtained from the quarry dump pile are compared in table 4. Because the average calcite grain sizes are so similar, the distribution of grain sizes in the samples was plotted (fig. 6) to see whether there are any textural differences among the samples. Most of the calcite grains in the graded samples are between 100 and 600 micrometers in diameter (fig. 6*A*). The four graded samples have fairly similar grain size distributions, but the Snowmass Statuary has a less pronounced peak between 200 and 300 micrometers. The grain sizes vary more widely in the Snowmass Statuary grade than in the other grades. The grain-size distribution patterns for the samples from the Lincoln Memorial and from the quarry dump are also similar to the patterns for the graded samples (fig. 6*B*). The Colorado Golden Vein Select grade samples are most similar to the stylobate(?) pieces from the Lincoln Memorial (LMP–1 and LMP–2) (fig. 7). In contrast, the texture of the sample from a crumbling antefix at the memorial is very similar to the texture of the Colorado Golden Vein grade samples (lowest grade) and of the disaggregated sample from the quarry dump (fig. 8).

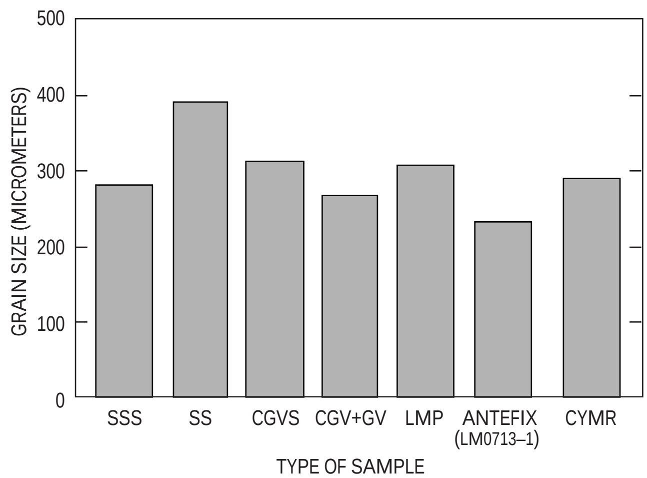


**Figure 5.** Average calcite grain sizes in longest dimension measured for each type of Colorado Yule marble sample. Sample types are explained in table 2; grain size ranges are given in table 4.

## MINERAL PHASES AND COMPOSITIONS

Acid dissolution and staining tests described by Knopf (1949) showed that the Colorado Yule marble is practically a pure calcite marble with very few inclusions of other minerals. Whole-rock chemical analyses of the marble given in table 1 demonstrate the purity of the marble. Thill

**Table 4.** Calcite grain sizes (in micrometers) in Colorado Yule marble samples.

[Avg = average, Min = minimum, Max = maximum, # grns = number of grains. Grain sizes were measured on scanning electron microscope images]

| Type of sample (table 2) | Avg | Min | Max | # grns |
|---|---|---|---|---|
| Snowmass Statuary Select (SSS) --------- | 281 | 52 | 971 | 358 |
| Snowmass Statuary (SS) ------------------- | 389 | 63 | 1180 | 288 |
| Colorado Golden Vein Select (CGVS)--- | 311 | 58 | 1006 | 386 |
| Colorado Golden Vein (CGV+GV) ------ | 264 | 44 | 738 | 271 |
| Lincoln Memorial pieces (LMP)--------- | 305 | 62 | 1039 | 550 |
| Lincoln Memorial antefix (LM0713) ---- | 230 | 52 | 719 | 230 |
| Quarry dump (CYMR)-------------------- | 289 | 46 | 1390 | 508 |

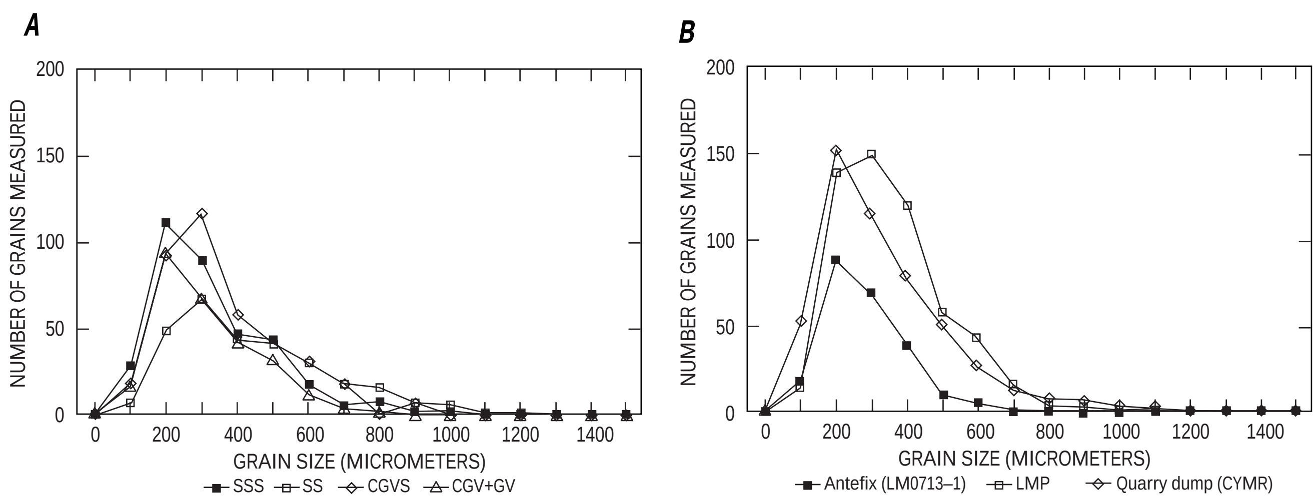


**Figure 6.** Calcite grain size distribution in the Colorado Yule marble in (*A*) graded samples and (*B*) samples from the Lincoln Memorial and from the Colorado Yule quarry dump. Sample types are explained in table 2; grain size data are given in table 4.

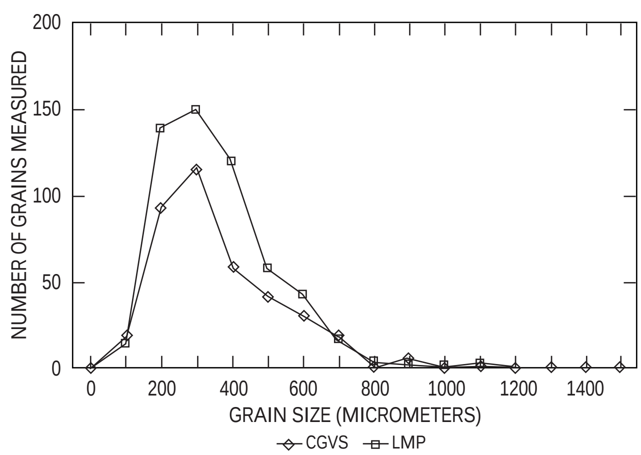


**Figure 7.** The calcite grain size distribution for the Colorado Golden Vein Select grade sample (CGVS from fig. 6*A*) is similar to the grain size distribution for the Lincoln Memorial pieces (LMP from fig. 6*B*).

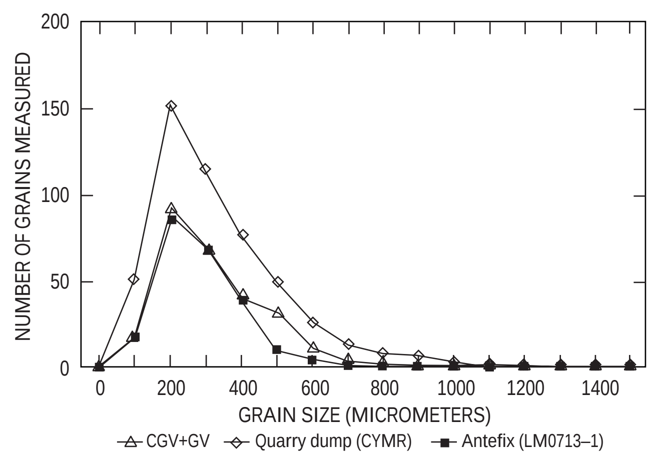


**Figure 8.** The calcite grain size distributions for the Colorado Golden Vein grade (CGV + GV from fig. 6*A*), the Lincoln Memorial antefix (from fig. 6*B*), and the quarry dump samples (from fig. 6*B*) are similar to one another.

and others (1969) reported that a 1,000-point-count modal analysis of the Yule marble showed it to be 99 percent calcite and 1 percent accessory minerals by volume. The accessory minerals reported by Thill and others (1969) differ slightly from the inclusion phases identified in the samples for this study. However, Thill and others did not provide any more details about the sample or about the methods used for mineral identification.

Samples examined for this study—in hand specimen and in thin sections made from recently quarried samples of the marble and from pieces in the Lincoln Memorial—show that the Yule marble is predominantly composed of white calcite. The most common inclusion in the marble is quartz. Minor inclusions include muscovite, phlogopite, feldspar, pyrite, sphene, apatite, zircon, and rutile. In inclusion-rich samples of the marble, such as those from the Colorado Golden Vein Select and Colorado Golden Vein grades, the inclusions commonly occur in clusters (fig. 9) and, with the exception of some quartz grains, are finer grained than the calcite.

The calcite ($CaCO_3$) in the Yule marble is nearly pure calcium carbonate (table 5). It does not vary significantly among the four grades of marble (table 6). The compositions of the calcite grains in samples from the antefix, stylobate(?), and quarry dump are also very similar to the compositions in the graded marble samples. Minor constituents determined in the calcite include MgO, MnO, FeO, and SrO; all are present in amounts less than 0.5 weight percent (tables 5 and 6). There is no correlation between the grade of the marble and the presence or amount of the minor constituents in the calcite.

Quartz ($SiO_2$) is the most abundant inclusion in these samples of the Yule marble. The quartz occurs as rounded grains in clusters with other phases or in clusters of quartz grains (fig. 10). The quartz grains range in diameter from 7 to 400 micrometers. Electron microprobe analyses of quartz inclusions in samples of the Yule marble show that the quartz is nearly pure $SiO_2$ (tables 7 and 8). Quartz in the Colorado Golden Vein samples appears to be purer than quartz in the Colorado Golden Vein Select samples (table 8). However, this slight trend may arise because the quartz grains analyzed in the Select grade sample are smaller and commonly occur with other (usually mica) phases, whereas the quartz grains analyzed in the standard Golden Vein samples are generally larger, more isolated grains. Weathered quartz inclusions occur as rounded, translucent gray grains that may be slightly raised compared to the surrounding calcite (fig. 11*A*). Some quartz inclusions form lines or veins, where they appear as clusters of small rounded grains (fig. 11*B*). Vanderwilt (1937) reported that the crystal grade of the Yule marble was not marketed after 1936 because it contained a quantity of chert that occurred in thin streaks; by that time, studies had shown that the chert weathered to an unacceptable, dark-gray color. It is probable that some of the quartz that occurs as distinct, dull-gray, rounded grains in the stone at the Lincoln Memorial corresponds to the chert described by Vanderwilt.

Mica inclusions occur as thin gold to brown lines and streaks, and they also occur with quartz in clouds of gray mixed with brown. Individual, isolated grains of mica are rare in the Colorado Golden Vein and Colorado Golden Vein Select samples. The mica grains range from 10 to 151 micrometers in the longest dimension; they average about 50 micrometers in length. Rare inclusions of mica in the Snowmass Statuary grades occur in thin lines or as small clusters of two to three grains.

Most of the mica grains in the Yule samples of this study are muscovite, but some phlogopite has also been found. Muscovite in the samples is close to the ideal composition for muscovite—$K_2Al_4Si_6Al_2O_{20}(OH,F)_4$— but it contains small amounts (typically 0.5–2.0 weight percent) of MgO (tables 7 and 8). Trace amounts of a calcium oxide component detected in the muscovites (tables 7 and 8) may come from simultaneous analysis of the adjacent calcite. A comparison of muscovites in the two grades of Colorado Golden Vein samples shows that muscovites in the Golden Vein samples contain slightly higher amounts of MgO, CaO, and $Na_2O$ than muscovites in the Golden Vein Select grade samples (table 8).

Mica inclusions in the marble at the Lincoln Memorial do not have any distinctive weathering features. On a small scale, the area around inclusion streaks may be rougher with more relief in the calcite because of the loss of small flakes of mica. However, for the most part, the weathering of the mica inclusions at the Lincoln Memorial is not as noticeable as the weathering of other, larger, more isolated inclusion phases such as feldspar and quartz.

Feldspar inclusions are present in the Colorado Golden Vein samples. They are intergrown in clusters with muscovite, quartz, and sphene (fig. 9), but they are not major constituents of these samples. Typical feldspar grains in the polished sections studied are from 20 to 80 micrometers in length; however, there are some rather large (1.5–3.5 cm) feldspar inclusions at the Lincoln Memorial (fig. 12*A*). Potassium-, sodium-, and calcium-bearing feldspars have all been found in the samples (tables 7 and 8). Calcium feldspar occurs as larger grains and appears to be slightly more abundant than the other two feldspars, but this relative abundance has not been determined statistically. In addition to its size, weathered feldspar is quite noticeable in some areas of the Lincoln Memorial (fig. 12*B*) because it is typically white to gray and is raised relative to the surrounding calcite. Weathered feldspar appears blocky, and gray feldspar grains are less translucent than quartz inclusions. Although some feldspar occurrences stand out, feldspar is a less common inclusion than quartz in the Lincoln Memorial stone.

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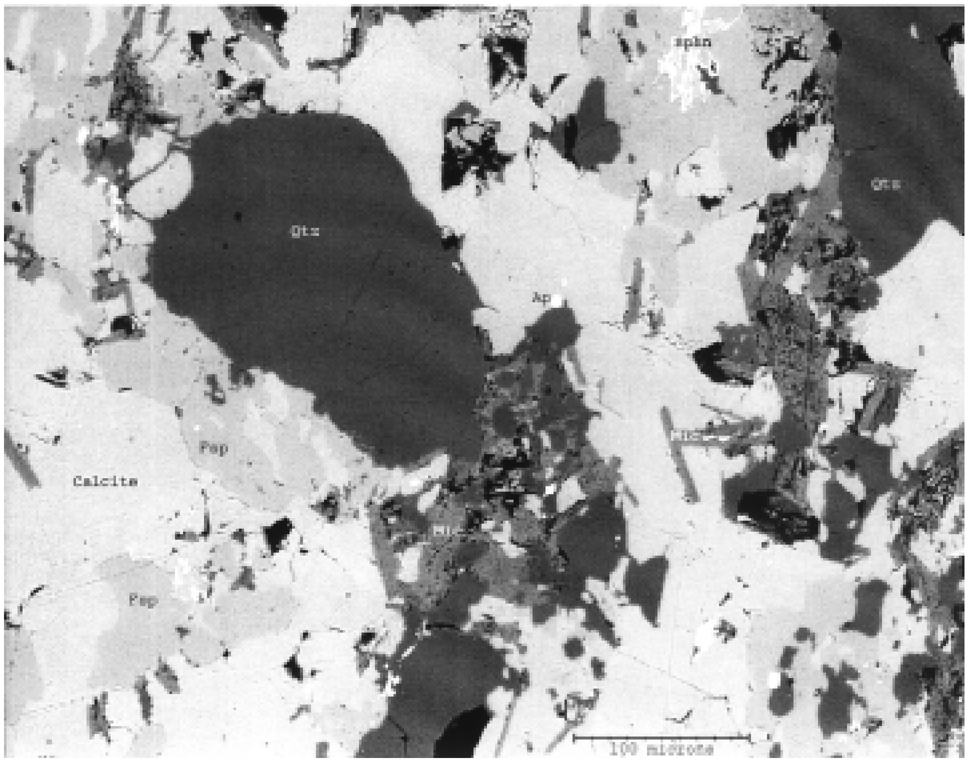



**Figure 9.** Backscattered electron image of an inclusion cluster in a polished thin section of the Colorado Golden Vein sample of the Colorado Yule marble. This image shows the mineral phases as shades of gray that reflect their average atomic weight. Ap = apatite, Fsp = feldspar, Mic = mica, Qtz = quartz, Sphn = sphene.

**Table 5**. Representative microprobe analyses of calcite in Colorado Yule marble samples.

[SSS = Snowmass Statuary Select; SS = Snowmass Statuary; CGVS = Colorado Golden Vein Select; CGV+GV = Colorado Golden Vein; LM0713 = sample from crumbling antefix at Lincoln Memorial; LMP = piece from stylobate(?) at Lincoln Memorial; CYMR = crumbling piece of poor-quality marble from quarry dump. Carbon dioxide ($CO_2$) was determined by difference and stoichiometry]

| | SSS | SS | CGVS | CGV +GV | LM0713 | LMP | CYMR |
|---|---|---|---|---|---|---|---|
| **Major oxides in weight percent** | | | | | | | |
| CaO------ | 55.60 | 56.55 | 55.83 | 55.99 | 55.90 | 55.68 | 55.96 |
| MgO----- | .05 | .06 | .08 | .08 | .07 | .06 | .03 |
| MnO----- | .00 | .02 | .03 | .05 | .07 | .10 | .14 |
| FeO ------ | .00 | .00 | .02 | .03 | .01 | .06 | .01 |
| SrO ------ | .00 | .03 | .00 | .00 | .04 | .00 | .01 |
| $CO_2$ ------ | 44.35 | 43.35 | 44.03 | 43.85 | 43.91 | 44.10 | 43.85 |
| **Number of atoms** | | | | | | | |
| Ca-------- | 0.988 | 1.015 | 0.995 | 1.000 | 0.998 | 0.992 | 0.999 |
| Mg------- | .001 | .001 | .002 | .002 | .002 | .002 | .001 |
| Mn------- | .000 | .000 | .000 | .001 | .001 | .001 | .002 |
| Fe -------- | .000 | .000 | .000 | .000 | .000 | .001 | .000 |
| Sr -------- | .000 | .000 | .000 | .000 | .000 | .000 | .000 |
| C --------- | 1.005 | .992 | 1.001 | .999 | .999 | 1.002 | .999 |
| Sum---- | 1.995 | 2.008 | 1.999 | 2.001 | 2.001 | 1.998 | 2.001 |

**Table 6**. Compositions of calcite in Colorado Yule marble samples.

[Avg = average, Min = minimum, Max = maximum, Sdv = standard deviation. Number in parentheses is the number of electron microprobe analyses of the sample. Compositions are in weight percent]

| | Snowmass Statuary Select, SSS (25) | | | | Snowmass Statuary, SS (17) | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg | Min | Max | Sdv | Avg | Min | Max | Sdv |
| CaO --------- | 56.28 | 55.37 | 56.79 | 0.361 | 56.43 | 55.64 | 56.82 | 0.303 |
| MgO -------- | .06 | .01 | .09 | .019 | .06 | .01 | .12 | .026 |
| MnO -------- | .03 | .00 | .14 | .041 | .02 | .00 | .12 | .033 |
| FeO --------- | .02 | .00 | .16 | .042 | .02 | .00 | .05 | .020 |
| SrO --------- | .00 | .00 | .03 | .007 | .01 | .00 | .04 | .012 |
| $CO_2$ --------- | 43.60 | 43.05 | 44.44 | .366 | 43.47 | 43.08 | 44.35 | .315 |
| | Colorado Golden Vein Select, CGVS (49) | | | | Colorado Golden Vein, CGV+GV (64) | | | |
| | Avg | Min | Max | Sdv | Avg | Min | Max | Sdv |
| CaO --------- | 56.32 | 54.92 | 56.82 | 0.393 | 56.15 | 55.12 | 56.83 | 0.456 |
| MgO -------- | .06 | .01 | .11 | .022 | .11 | .01 | .33 | .052 |
| MnO -------- | .06 | .00 | .41 | .096 | .06 | .00 | .40 | .076 |
| FeO --------- | .02 | .00 | .21 | .040 | .04 | .00 | .16 | .043 |
| SrO --------- | .01 | .00 | .08 | .020 | .01 | .00 | .07 | .017 |
| $CO_2$ --------- | 43.52 | 43.04 | 44.64 | .355 | 43.64 | 43.07 | 44.63 | .446 |
| | Lincoln Memorial antefix, LM0713 (24) | | | | Lincoln Memorial stylobate(?), LMP (39) | | | |
| | Avg | Min | Max | Sdv | Avg | Min | Max | Sdv |
| CaO --------- | 55.82 | 54.82 | 56.84 | 0.612 | 56.31 | 55.52 | 56.81 | 0.412 |
| MgO -------- | .08 | .01 | .13 | .032 | .05 | .02 | .09 | .017 |
| MnO -------- | .03 | .00 | .12 | .042 | .08 | .00 | .37 | .110 |
| FeO --------- | .02 | .00 | .18 | .040 | .02 | .00 | .14 | .033 |
| SrO --------- | .02 | .00 | .07 | .023 | .01 | .00 | .07 | .019 |
| $CO_2$ --------- | 44.03 | 43.08 | 44.88 | .565 | 43.52 | 43.06 | 44.41 | .372 |
| | Quarry dump, CYMR (43) | | | | | | | |
| | Avg | Min | Max | Sdv | | | | |
| CaO --------- | 55.77 | 55.15 | 56.63 | 0.420 | | | | |
| MgO -------- | .05 | .02 | .13 | .020 | | | | |
| MnO -------- | .06 | .00 | .22 | .072 | | | | |
| FeO --------- | .03 | .00 | .17 | .041 | | | | |
| SrO --------- | .01 | .00 | .12 | .022 | | | | |
| $CO_2$ --------- | 44.07 | 43.16 | 44.79 | .407 | | | | |

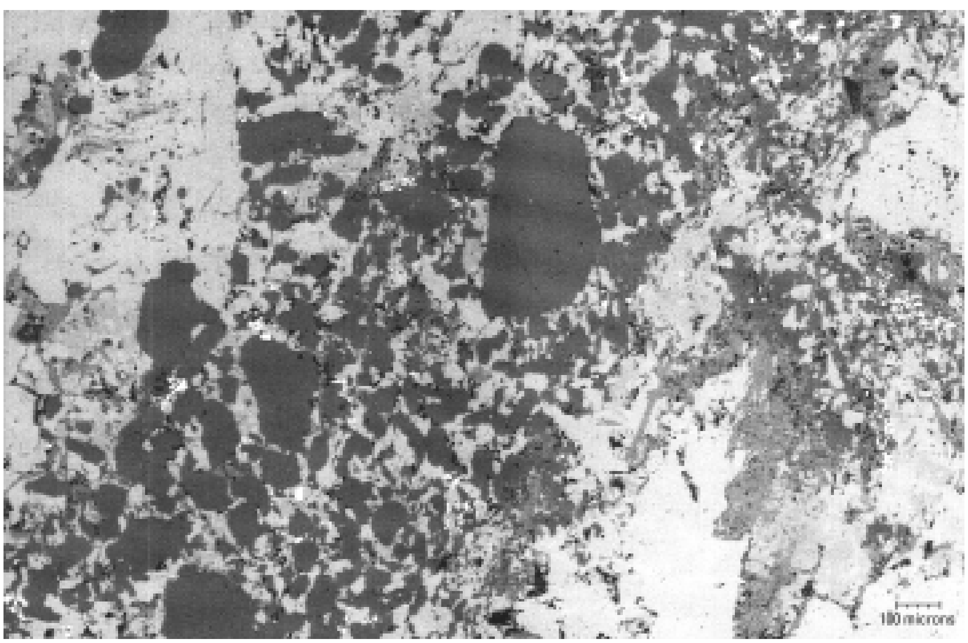



**Figure 10.** Backscattered electron image of clusters of quartz inclusions in a polished thin section of the Colorado Golden Vein sample of the Colorado Yule marble. This image shows the mineral phases as shades of gray that reflect their average atomic weight. Dark gray = quartz, medium dark gray = mica, medium light gray = feldspar, lightest gray = calcite, white = oxides and (or) sulfides.

**Table 7.** Representative microprobe analyses of inclusion minerals in Colorado Yule marble samples.

[GV = Colorado Golden Vein grade; CGVS = Colorado Golden Vein Select grade; SS = Snowmass Statuary grade; LMP = Lincoln Memorial stylobate(?) piece; calc = calculated; cat = cation; fsp = feldspar (K-rich, Na-rich, or Ca-rich); ox = oxide. Totals may appear inexact because of rounding]

Quartz

| | GV | CGVS |
|---|---|---|
| **Major oxides and F, in weight percent** | | |
| $SiO_2$ | 99.40 | 98.82 |
| $Al_2O_3$ | .00 | .00 |
| CaO | .01 | .10 |
| $K_2O$ | .00 | .01 |
| $Na_2O$ | .00 | .00 |
| MgO | .00 | .00 |
| FeO | .01 | .07 |
| BaO | .03 | --- |
| MnO | --- | .03 |
| $TiO_2$ | --- | .01 |
| F | --- | .00 |
| Total | 99.46 | 99.05 |
| **Number of atoms** | | |
| Si | 3.999 | 3.996 |
| Al | .000 | .000 |
| Ca | .001 | .004 |
| K | .000 | .001 |
| Na | .000 | .000 |
| Mg | .000 | .000 |
| Fe | .000 | .002 |
| Ba | .000 | --- |
| Mn | --- | .001 |
| Ti | --- | .000 |
| F | --- | .000 |
| Sum | 4.001 | 4.004 |

Muscovite (mica)

| | GV | CGVS |
|---|---|---|
| **Major oxides and F, in weight percent** | | |
| $SiO_2$ | 47.35 | 46.47 |
| $Al_2O_3$ | 36.12 | 36.52 |
| MgO | .48 | .39 |
| CaO | .21 | .19 |
| FeO | .06 | .02 |
| MnO | .04 | .00 |
| $TiO_2$ | .15 | .17 |
| $K_2O$ | 9.81 | 10.32 |
| $Na_2O$ | .22 | .20 |
| F | .00 | .02 |
| Total | 94.43 | 94.28 |
| **Number of atoms** | | |
| Si | 6.269 | 6.187 |
| Al | 5.629 | 5.724 |
| Mg | .094 | .076 |
| Ca | .030 | .028 |
| Fe | .007 | .002 |
| Mn | .005 | .000 |
| Ti | .014 | .017 |
| K | 1.653 | 1.749 |
| Na | .057 | .051 |
| F | .000 | .008 |
| OH calc | 4.000 | 3.992 |
| $H_2O$ calc | 4.532 | 4.497 |
| F=O | .000 | .008 |
| Ox sum | 98.97 | 98.77 |
| Cat sum | 13.757 | 13.834 |

Feldspar—GV

| | K-fsp | Na-fsp | Ca-fsp |
|---|---|---|---|
| **Major oxides and F, in weight percent** | | | |
| $SiO_2$ | 64.96 | 67.61 | 49.68 |
| $Al_2O_3$ | 18.65 | 20.59 | 32.61 |
| CaO | .08 | 1.01 | 14.88 |
| $K_2O$ | 15.56 | .18 | .09 |
| $Na_2O$ | .53 | 11.38 | 2.92 |
| MgO | .00 | .04 | .01 |
| FeO | .02 | .00 | .01 |
| BaO | .16 | .02 | --- |
| MnO | --- | --- | .04 |
| $TiO_2$ | --- | --- | .03 |
| F | --- | --- | .06 |
| Total | 99.96 | 100.83 | 100.30 |
| **Number of atoms** | | | |
| Si | 2.997 | 2.942 | 2.260 |
| Al | 1.013 | 1.055 | 1.746 |
| Ca | .004 | .047 | .724 |
| K | .914 | .010 | .005 |
| Na | .047 | .958 | .257 |
| Mg | .000 | .003 | .001 |
| Fe | .001 | .000 | .000 |
| Ba | .003 | .000 | --- |
| Mn | --- | --- | .000 |
| Ti | --- | --- | .001 |
| F | --- | --- | .008 |
| Sum | 4.978 | 5.015 | 5.005 |

Pyrite

| | GV | CGVS | SS | LMP |
|---|---|---|---|---|
| **Elements, in weight percent** | | | | |
| Fe | 46.80 | 46.59 | 46.13 | 46.58 |
| Co | .08 | .15 | .33 | .10 |
| Ni | .08 | .31 | .23 | .07 |
| Cu | .00 | .01 | .04 | .00 |
| Zn | .00 | .00 | .00 | .00 |
| Pb | .14 | .22 | .36 | .13 |
| S | 53.85 | 53.90 | 53.59 | 53.84 |
| Total | 100.95 | 101.17 | 100.67 | 100.71 |

| | Sphalerite | Galena | |
|---|---|---|---|
| | GV | GV | LMP |
| **Elements, in weight percent** | | | |
| Fe | 2.50 | 3.15 | 0.08 |
| Co | .00 | .01 | .01 |
| Ni | .02 | .04 | .01 |
| Cu | .02 | .09 | .02 |
| Zn | 63.44 | .00 | .00 |
| Pb | .03 | 81.34 | 86.49 |
| S | 32.52 | 14.21 | 13.49 |
| Total | 98.53 | 98.84 | 100.10 |

**Table 8**. Compositions of inclusion minerals in Colorado Yule marble samples.

[Avg = average, Min = minimum, Max = maximum. CGVS = Colorado Golden Vein Select grade; SS = Snowmass Statuary grade; LMP = Lincoln Memorial stylobate(?) piece. Number in parentheses is the number of electron microprobe analyses of the sample. Ranges are not shown for small groups of analyses. Dashes (---) indicate not analyzed]

Feldspars: Colorado Golden Vein

| | K-fsp (3) | Na-fsp (2) | Ca-fsp (7) |
|---|---|---|---|
| $SiO_2$ | 64.56 | 68.07 | 50.99 |
| $Al_2O_3$ | 18.84 | 20.61 | 31.26 |
| CaO | .21 | .99 | 13.46 |
| $K_2O$ | 15.34 | .14 | .60 |
| $Na_2O$ | .55 | 11.41 | 3.17 |
| MgO | .00 | .03 | .01 |
| FeO | .02 | .00 | .01 |
| BaO | .16 | .04 | --- |
| MnO | --- | --- | .02 |
| $TiO_2$ | --- | --- | .01 |
| F | --- | --- | .04 |

Quartz

| | Colorado Golden Vein (10) | | | Colorado Golden Vein Select (6) | | |
|---|---|---|---|---|---|---|
| | Avg | Min | Max | Avg | Min | Max |
| $SiO_2$ | 99.30 | 98.28 | 99.95 | 98.43 | 98.19 | 98.82 |
| $Al_2O_3$ | .02 | .00 | .06 | .16 | .00 | .47 |
| CaO | .04 | .00 | .14 | .12 | .02 | .20 |
| $K_2O$ | .00 | .00 | .01 | .05 | .00 | .13 |
| $Na_2O$ | .00 | .00 | .01 | .00 | .00 | .00 |
| MgO | .00 | .00 | .01 | .01 | .00 | .02 |
| FeO | .01 | .00 | .04 | .03 | .00 | .07 |
| BaO | .02 | .00 | .05 | .00 | .00 | .00 |
| MnO | --- | --- | --- | .02 | .00 | .06 |
| $TiO_2$ | --- | --- | --- | .04 | .00 | .18 |
| F | --- | --- | --- | .04 | .00 | .10 |

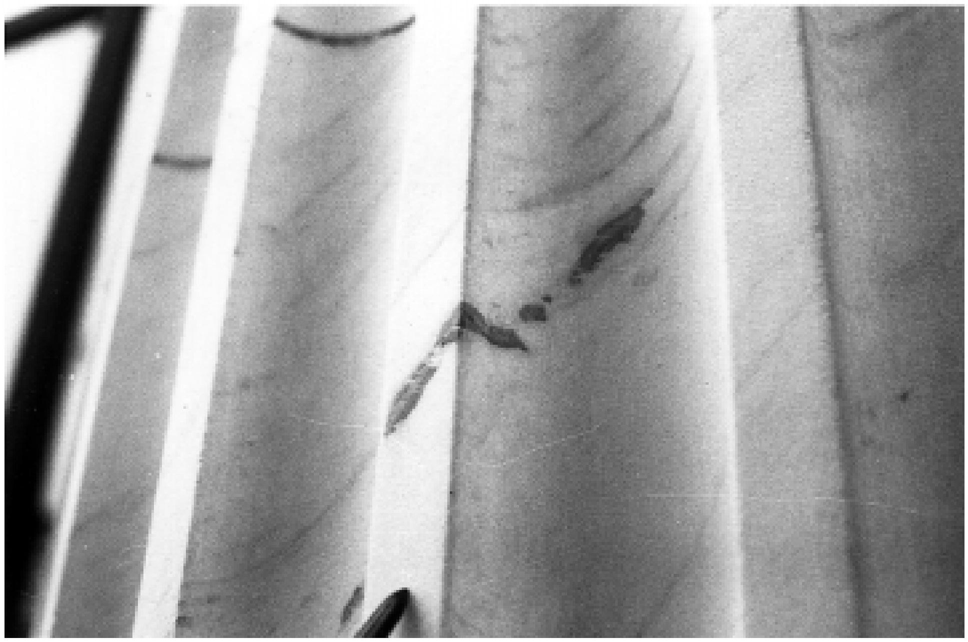
Muscovites (micas)

| | Colorado Golden Vein (42) | | | Colorado Golden Vein Select (16) | | |
|---|---|---|---|---|---|---|
| | Avg | Min | Max | Avg | Min | Max |
| $SiO_2$ | 47.56 | 45.68 | 51.43 | 47.15 | 46.28 | 48.04 |
| $Al_2O_3$ | 35.85 | 28.51 | 37.66 | 37.12 | 36.15 | 38.19 |
| MgO | .98 | .30 | 3.07 | .41 | .15 | .61 |
| CaO | .29 | .04 | 1.15 | .19 | .05 | .39 |
| FeO | .09 | .00 | .27 | .02 | .00 | .06 |
| MnO | .01 | .00 | .05 | .01 | .00 | .04 |
| $TiO_2$ | .09 | .00 | .37 | .07 | .00 | .17 |
| $K_2O$ | 9.91 | 8.50 | 10.70 | 10.06 | 9.53 | 10.43 |
| $Na_2O$ | .22 | .02 | .91 | .17 | .12 | .31 |
| F | .07 | .00 | .25 | .06 | .00 | .21 |

Pyrites

| | Colorado Golden Vein (35) | | | CGVS (3) | SS (3) | LMP (17) | | |
|---|---|---|---|---|---|---|---|---|
| | Avg | Min | Max | Avg | Avg | Avg | Min | Max |
| Fe | 46.92 | 45.08 | 47.82 | 46.28 | 46.57 | 47.06 | 46.38 | 47.75 |
| Co | .13 | .05 | .68 | .31 | .22 | .09 | .06 | .13 |
| Ni | .15 | .00 | .54 | .26 | .12 | .06 | .00 | .16 |
| Cu | .01 | .00 | .05 | .00 | .02 | .02 | .00 | .06 |
| Zn | .01 | .00 | .07 | .00 | .00 | .00 | .00 | .02 |
| Pb | .21 | .00 | 1.40 | .27 | .29 | .12 | .00 | .37 |
| S | 54.00 | 53.20 | 54.47 | 53.79 | 53.63 | 53.85 | 53.58 | 54.25 |

A



B

**Figure 11.** Weathered quartz inclusions in the Colorado Yule marble. *A*, Typical occurrence of large, fairly isolated quartz grains (in the Colorado National Bank, Denver, Colo.). *B*, Small quartz grains may be clustered, appearing as a vein in the marble (darker gray areas at the lower right of the photograph; in the Lincoln Memorial, Washington, D.C.).

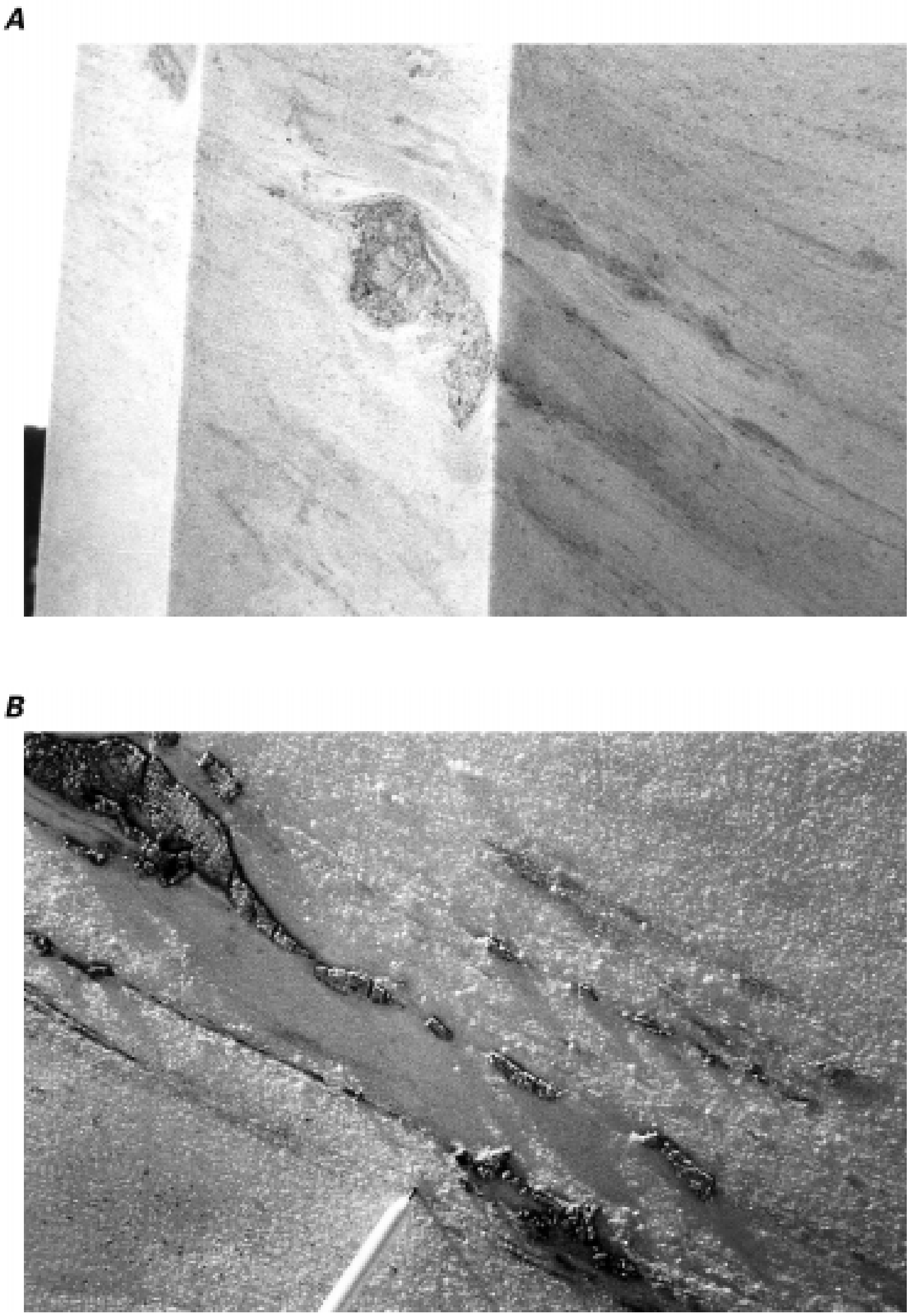



**Figure 12.** Large feldspar inclusions at the Lincoln Memorial (*A*) in a column shaft and (*B*) on the roof parapet; note how the feldspar stands above the surrounding calcite.

Pyrite, sphene, apatite, rutile, zircon, and sphalerite all occur as minor inclusions in the marble. With the exception of pyrite, which ranges in size from about 20 to 160 micrometers, these inclusions are small (typically about 10 micrometers). Rutile, zircon, and apatite are minor inclusions visible in polished sections of the marble but not noticeable on weathered surfaces in buildings. Apatite is the most common of these minor inclusions; it occurs as part of the inclusion-rich clusters in the Colorado Golden Vein samples, along with quartz, mica, and occasional feldspar (fig. 9). Sphene, which is mostly noticeable in thin sections of the marble, also occurs in the clusters of quartz, mica, and feldspar in the Golden Vein samples (fig. 9). Typically, pyrite and sphalerite inclusions occur in small groups of a few isolated grains (fig. 13). The composition of the pyrite in the samples studied is variable but within the usual range for this sulfide (tables 7 and 8). At the Lincoln Memorial, where they have weathered, sphalerite and pyrite are quite noticeable compared to the surrounding white calcite. The exposed sphalerite surfaces have a reddish-brown rusty appearance (dark grain in fig. 13), the pyrite has a golden-metallic appearance, and both of these inclusions are raised compared to the surrounding calcite.

## PHYSICAL CHARACTERISTICS

Results from a number of physical tests of the Colorado Yule marble have been reported in the literature (table 9). Initially, tests were conducted on the marble as part of the selection process for marbles submitted to the Lincoln Memorial Commission (Stratton, 1913b; Bureau of Standards, 1914a). Additional tests were conducted on the Yule marble after questions about its quality and durability were raised when it was selected for use in the Lincoln Memorial (Bureau of Standards, 1914b). Later, because of its purity and homogeneous texture, the Yule marble was used in a number of experiments, especially those conducted to understand physical properties of rocks (Balsley, 1941; Knopf, 1949; Griggs and Miller, 1951; Rosenholtz and Smith, 1951).

For discussion, the physical tests conducted on the Yule marble can be divided into three categories: general physical characteristics, strength characteristics, and weathering or durability characteristics. General physical characteristics describe attributes of the marble including the weight, hardness, specific gravity, porosity, absorption, and coefficient of thermal expansion (table 9*A*). Strength characteristics are determined by various loading tests that are applied to the stone to see how well the stone withstands applied forces (table 9*B*). Weathering or durability characteristics are determined by tests conducted to assess the long-term durability of the stone when it is exposed to environmental conditions such as temperature changes and pollutants (table 9*C*). Because the tests reported in table 9 were performed in slightly different manners (see notes in the table), direct comparison of the test results is difficult. However, the results do give a general picture of the stone's characteristics.

Of great interest in this study is how the Yule marble compares with other marbles. A second important aspect is whether the tests might have indicated a weakness that we now see in the long-term durability of the marble. The Lincoln Memorial Commission had the Bureau of Standards perform a number of tests on the candidate stones (Bureau of Standards, 1914a). Comparisons of physical properties of dimension stone have also been reported in the literature (Kessler, 1919; Griffith, 1937). Unfortunately, the Yule marble was not among the 50 marbles tested by Kessler, and, although Griffith included the Yule marble, he did not have results for strength or durability tests of the Yule. To see how the Yule compares with other marbles being quarried and used in 1914, average physical measurements for the Yule marble are compared in table 10 with measurements for commercial marbles tested by Kessler (1919). Measurements made on some of the chief competitors of the Yule, marbles from Vermont, Georgia, and Alabama, are also shown in table 10.

The general physical properties of the Yule marble are similar to those of other marbles, but both the compressive strength and the transverse strength of the Yule are lower than those properties in most of the other marbles tested (table 10). The low strength values on the Yule may arise because the tests on the Yule did not specify whether they were made with the grain or perpendicular to the grain of the marble. Even allowing for the uncertainty of the grain direction, the Yule appears to have lower strengths than most other marbles. However, the strength values for the Yule marble are not unreasonably low. For ordinary uses, stone that has a compressive strength of 5,000 $lb/in^2$ is satisfactory (Bowles, 1939). In its report to the Lincoln Memorial Commission, the Bureau of Standards concluded that none of the marbles tested for the commission were structurally unsound (Bureau of Standards, 1914a). Kessler (1919) pointed out that even though few stones have compressive strengths that are too low, other factors in a structure, such as uneven loads, expansion of water in pores during freezing, and vibrations, may reduce the strength of the stone. The strength values of the Yule marble are likely to be significant to the Lincoln Memorial only if they influence the durability of the marble.

Several tests by the Bureau of Standards (1914a) and by Merrill (1915) manipulated samples of marble to determine if a prediction might be made about the durability of the marble. In these tests, loss of strength was evaluated after the marble was subjected to cycles of freezing, depth of penetration of a staining solution was estimated, and weight loss was measured after the marble was suspended in an acid solution for an extended period (table 9*C*). Compared with the other marbles tested, the Yule showed a

**Figure 13.** Sphalerite inclusion (dark grain) at the Lincoln Memorial occurs as an isolated grain with a rusty-brown surface. On weathered surfaces, sphalerite stands higher than the surrounding calcite.

**Table 9**. General physical characteristics, strength characteristics, and durability characteristics of the Colorado Yule marble.

[Dashes (---) indicate no data available]

**A. General Physical Characteristics**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Weight (lb/ft$^3$) ----------------------- | 168.7 | 170 | --- | --- | --- | --- | --- | 169.2 |
| Hardness (Shore number)---------- | 38.3 | --- | --- | --- | --- | --- | --- | --- |
| Specific gravity--------------------- | --- | --- | 2.711 | --- | --- | --- | --- | 2.714 |
| True specific gravity ---------- | 2.72 | --- | --- | --- | --- | --- | --- | --- |
| Apparent specific gravity ---- | 2.70 | --- | --- | --- | --- | --- | --- | --- |
| Porosity (percent)------------------ | * | --- | --- | 0.15 | --- | --- | --- | --- |
| Absorption (percent) --------------- | 0.19 | 0.103 | 0.067 | --- | 0.061 | 0.072 | 0.13 | 0.16 |
| Coefficient of thermal expansion - | 38 | --- | --- | --- | --- | --- | --- | --- |

SOURCE OF DATA

1. Griffith (1937, table 1, p. 12): * Griffith reported pores = 0.45 percent and solids = 99.5 percent. The coefficient of thermal expansion was determined from room temperature to 212°F on a sample 1/2 inch square by 4 inches long.
2. Bureau of Standards (1914a): Weight was given in description of samples, p. 2. Absorption was measured on 2-inch-square pieces cut from the sample slabs; the value above is the average of eight total test results; the range of values was 0.086 to 0.123 percent. For comparison, absorption values are presented as percentages; referenced source reported them as a ratio (for example, 0.00103).
3. Merrill (1914, p. 16): Specific gravity test information was provided with analysis of sample made by A.W. Smith, Case School of Applied Science, Cleveland, Ohio, October 22, 1907. Absorption tests are reported from Bureau of Standards test No. 14234 dated November 3, 1913; the value above is the average of results of three tests on 3-inch cubes; the range of absorption ratios was 0.00061 to 0.00076. For comparison, absorption values are presented as percentages; referenced source reported them as a ratio (for example, 0.00103).
4. Knopf (1949, p. 440): No information was provided about how porosity data were obtained.
5. Stratton (1913b): The absorption ratio was obtained by the Bureau of Standards on five samples by using 3-inch cubes. Ratio range of 0.00061 to 0.00076 was reported, but no other values or average was reported.
6. Stratton (1913a, includes Bureau of Standards certificate for Colorado Yule marble, Test No. 14374, November 11, 1913): Absorption tests on 3-inch cubes yielded ratios of 0.00072 and 0.00075.
7. Vanderwilt (1937, p. 162): In addition to showing data that were published elsewhere (for example, Merrill, 1914), Vanderwilt reported the average result from absorption tests made on three polished 2-inch cubes.
8. Colorado Yule Marble Company (1996): The information sheet states that all tests were performed to American Standards of Tests and Measurements [sic] criteria.

**Table 9.** General physical characteristics, strength characteristics, and durability characteristics of the Colorado Yule marble—Continued.

## B. Strength Characteristics

[In the literature cited below, different terms are used for some of the tests. These include the following: crushing strength = ultimate strength, compressive strength; modulus of rupture = transverse test, cross-breaking test; modulus of elasticity = Young's modulus]

| | 1 | 2 | 3a | 3b | 4a | 4b | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Crushing strength (lb/in$^2$)---- | 6,694 | 10,195 | 6,760 | 10,735 | 4,220 | 8,000 | 7,550 | 9,785 | 7,600 | 14,847 |
| Modulus of rupture (lb/in$^2$)-- | --- | 1,030 | --- | --- | --- | --- | 1,244 | --- | 1,200 | 1,374 |
| Modulus of elasticity (multiply each result by $10^5$; units are in footnotes)---------------- | --- | --- | 86.7[a] | 56.4[a] | 4.01[b] | 3.84[b] | --- | --- | --- | --- |

[a] Modulus of elasticity values in columns 3a and 3b are in pounds per square inch (lb/in$^2$), as reported by Lepper (1949).

[b] Modulus of elasticity values in columns 4a and 4b are in kilograms per square centimeter (kg/cm$^2$), as reported by Knopf (1949). A conversion indicates that $4.01\times10^5$ kg/cm$^2$ $\simeq 57\times10^5$ lb/in$^2$ and that $3.84\times10^5$ kg/cm$^2$ $\simeq 55\times10^5$ lb/in$^2$.

SOURCE OF DATA

1. Stratton (1913b): The above value is the average of results obtained by the Bureau of Standards for "ultimate strength" of two samples (6,256 and 7,133 lb/in$^2$); tests were made on 3-inch cubes.
2. Merrill (1914, table on p. 16): Compression test and cross-breaking test data were supplied by Milo S. Ketcham, C.E., Dean, University of Colorado. Four samples were tested in each test. Compression (crushing strength) was measured on 2-inch cubes; the range of values was 9,630 to 10,990 lb/in$^2$. Cross-breaking strength (modulus of rupture) was measured on samples 6×2×2 inches; the range of values was 970 to 1,100 lb/in$^2$.
3. Lepper (1949, p. 573): Tests were made on four samples 1×1×2 inches. Results shown are averages for two types of measurements: a–Load applied parallel to the grain of the marble (crushing strength = 5,810 and 7,710 lb/in$^2$; modulus of elasticity = $83.4\times10^5$ and $90.0\times10^5$ lb/in$^2$); b–Load applied perpendicular to the grain of the marble (crushing strength = 11,120 and 10,350 lb/in$^2$; modulus of elasticity = $54.2\times10^5$ and $58.5\times10^5$ lb/in$^2$). Grain is the plane of easiest splitting; the grain direction coincides with the longest axis of ellipsoidal calcite grains in the marble.
4. Knopf (1949, p. 440–441): Data were reported from other sources, but no published references were given. Crushing strength: a–From Griggs and Bell on a cylinder 1 inch×1/2 inch with length parallel to the grain of the calcite; b–Quote from Bain, "in a direction normal to the 'grain' the strength could be 8000 psi [lb/in$^2$]." Modulus of elasticity (Young's modulus) results were quoted from Bain data with no information about sample size: a–Force parallel to veining; b–Force perpendicular to veining.
5. Bureau of Standards (1914a): Twelve samples were measured in the tests; average measurements are shown above. Crushing tests were made on 2-inch-square pieces cut from the slabs (height approximately 0.9 inch); the range of values was 6,887 to 7,893 lb/in$^2$. Modulus of rupture tests (transverse tests) were made on 12 samples, 14×2 inches, cut from the slabs, with a span of 10 inches in the tests; the range of values was 1,130 to 1,350 lb/in$^2$.
6. Bureau of Standards (1914b): Load was measured on the bed faces of eight 9-inch cubes; three cubes were polished, and five were unpolished. The range of values obtained was 8,557 to 10,842 lb/in$^2$; there is no particular correlation between strength and whether the sample was polished.
7. Vanderwilt (1937, p. 161): Vanderwilt cited data supplied by the National Bureau of Standards in connection with the Lincoln Memorial from a letter to G.F. Loughlin (U.S. Geological Survey) dated May 26, 1936. Crushing tests (compressive strength tests) were made on pieces 2×2×7/8 inch (load applied to 2-inch-square faces); reported value is average of 12 test results. Modulus of rupture tests were made on pieces 12×2×7/8 inch; the reported value is the average of four test results.
8. Colorado Yule Marble Company (1996): The information sheet states that all tests were performed to American Standards of Tests and Measurements [sic] criteria.

## C. Durability Characteristics

Loss of Crushing Strength after Freezing (Bureau of Standards, 1914a):

Two-inch-square samples from test slabs were treated, and crushing strengths before and after treatment were compared. Treatment: alternate freezing (16 hr) and boiling (8 hr) for 9 successive days. Twelve samples were tested, and average loss of strength in crushing tests was 10.9 percent.

Stain Penetration (Bureau of Standards 1914a):

Four samples, about 1 inch square by 2 inches high, were dried, coated with paraffin 1/2 inch above the base, and placed in a dish with a highly colored aqueous solution of eosin, about 1/8 inch deep. After 7 days, an estimate was made of how high the stain had risen in the four samples. Out of 12 samples, the 4 Yule marble samples were rated as 4, 7, 8, and 10 on a scale where 12 was the greatest penetration and 1 the least. A value for the four Yule marble samples tested was reported as 1.25 inches.

Weight Loss in Carbonic Acid (Merrill, 1915):

One-inch cubes of marble with smoothed (but not polished) sides were suspended by threads in water kept acid by a carbonic acid stream. Some samples were weighed after 70 days, and other samples were weighed after 3 months. For the two time periods, the Yule marble samples experienced 0.0097 and 0.019 percent weight loss, respectively. The average weight loss for all marbles tested was 0.0083 and 0.0142 percent for the two time periods.

Thermal Expansion (Rosenholtz and Smith, 1949):

Thermal expansion of three orientations of samples was measured from 20°C to 700°C. The elongation determined for each type of sample is given below:

| *Orientation* | *Elongation (percent)* |
|---|---|
| Parallel maximum concentration of c-axes of calcite (E-W) ---------------------------------------------------- | 1.02 |
| Perpendicular maximum concentration of c-axes of calcite (N-S)--------------------------------------------- | .50 |
| Perpendicular maximum concentration of c-axes of calcite (vertical)----------------------------------------- | .71 |

**Table 10.** General physical characteristics, strength characteristics, and durability characteristics of commercial marbles tested by Kessler (1919) compared with average values for the Colorado Yule marble (from table 9) and with data for five marbles tested for the Lincoln Memorial Commission (Bureau of Standards, 1914a).

[Min=minimum; Max=maximum; Avg=average calculated for this report. Dashes indicate no data available]

| Marble | | Weight (lb/ft$^3$) | Specific gravity | | Porosity (percent) | Absorption (weight percent) |
|---|---|---|---|---|---|---|
| | | | Apparent | True | | |
| **Ranges and averages calculated from data given by Kessler (1919)** | | | | | | |
| Entire set of 50 marbles | Min | 165.2 | 2.643 | 2.718 | 0.40 | 0.016 |
| | Max | 178.9 | 2.863 | 2.879 | 2.09 | .452 |
| | Avg | 171.3 | 2.740 | 2.760 | .61 | .113 |
| Vermont marbles-------- | Min | 168.8 | 2.700 | 2.721 | .40 | .030 |
| | Max | 177.7 | 2.844 | 2.739 | .77 | .201 |
| | Avg | 170.7 | 2.731 | 2.727 | .51 | .119 |
| Georgia marbles -------- | Min | 169.1 | 2.705 | 2.722 | .40 | .085 |
| | Max | 170.4 | 2.726 | 2.742 | .84 | .131 |
| | Avg | 169.8 | 2.716 | 2.731 | .54 | .104 |
| Alabama marbles ------- | Min | 169.9 | 2.718 | 2.732 | .44 | .059 |
| | Max | 170.1 | 2.721 | 2.733 | .51 | .079 |
| | Avg | 170.0 | 2.720 | 2.733 | .48 | .069 |
| **Individual values from Kessler (1919)** | | | | | | |
| Dorset, Vt------------------- | | 169.2 | 2.708 | -- | -- | 0.134 |
| Etowah, Ga ----------------- | | 170.4 | 2.726 | 2.737 | 0.40 | .095 |
| Amicalola, Ga-------------- | | 169.9 | 2.719 | 2.742 | .84 | .085 |
| Alabama -------------------- | | 170.1 | 2.721 | 2.733 | .44 | .059 |
| **Data averaged from table 9** | | | | | | |
| Yule------------------------- | | 169 | 2.71 | -- | 0.45* | 0.104 |
| **Marbles tested for the Lincoln Memorial Commission (Bureau of Standards, 1914a)** | | | | | | |
| East Dorset, Vt------------- | | -- | -- | -- | -- | 0.103 |
| Tate, Ga --------------------- | | -- | -- | -- | -- | .107 |
| Amicalola, Ga-------------- | | -- | -- | -- | -- | .102 |
| Alabama -------------------- | | -- | -- | -- | -- | .093 |
| Yule------------------------- | | -- | -- | -- | -- | .103 |

greater loss in strength, about the same amount of stain penetration, and slightly greater weight loss after exposure to carbonic acid (tables 10 and 9*C*). None of the marbles submitted to the Lincoln Memorial Commission varies significantly from the others in the test results.

## SELECTION OF THE YULE MARBLE FOR THE LINCOLN MEMORIAL

The selection of a white marble to be used for the exterior of the Lincoln Memorial was a competitive process. Companies submitted samples of marble and bids to the Lincoln Memorial Commission, which was charged with making a selection. Five marbles were submitted for consideration for the exterior of the memorial (Bacon, 1913): Cherokee marble from Georgia, Dorset White marble from Vermont, Southern marble from Georgia, Amicalola marble from Georgia, and Colorado Yule marble from Colorado. However, Henry Bacon, the architect of the memorial, thought only three were worthy of consideration, and he preferred the Colorado Yule because it was "immeasurably superior" to the other marbles (Bacon, 1913).

In 1913, the Colorado Yule marble was relatively unknown because the quarry had only recently opened and, in contrast to the marbles from Georgia and Vermont, the Yule had been used in only a few buildings. Objections to the selection of the Colorado Yule marble for the Lincoln Memorial centered on three main issues: (1) whether the relatively new (and remote) quarry would be able to provide the quality and quantity of stone that would be required; (2) whether the marble was sound and acceptable for exterior use; and (3) whether this relatively unknown marble was as durable as other, better known marbles. Copies of letters

**Table 10.** General physical characteristics, strength characteristics, and durability characteristics of commercial marbles tested by Kessler (1919) compared with average values for the Colorado Yule marble (from table 9) and with data for five marbles tested for the Lincoln Memorial Commission (Bureau of Standards, 1914a)—Continued.

| Marble | | Compressive strength (lb/in²) | | Transverse strength (lb/in²) | | Change in compressive strength after freezing (percent) | | Stain penetration (inches) |
|---|---|---|---|---|---|---|---|---|
| | | On bed | On edge | Perpendicular to grain | Parallel to grain | On bed | On edge | |
| **Ranges and averages calculated from data given by Kessler (1919)** | | | | | | | | |
| Entire set of 50 marbles | Min | 9,058 | 7,850 | 322 | 607 | -- | -- | -- |
| | Max | 50,205 | 44,470 | 4,948 | 3,670 | -- | -- | -- |
| | Avg | 16,663 | 15,418 | 2,186 | 1,666 | –6.1 | –6.4 | -- |
| Vermont marbles | Min | 9,058 | 7,850 | 322 | 618 | -- | -- | -- |
| | Max | 50,205 | 44,470 | 2,719 | 1,858 | -- | -- | -- |
| | Avg | 15,763 | 14,891 | 1,730 | 1,360 | –11.3 | –12.7 | -- |
| Georgia marbles | Min | 10,144 | 9,244 | 1,266 | 624 | -- | -- | -- |
| | Max | 11,945 | 11,908 | 1,596 | 1,346 | -- | -- | -- |
| | Avg | 11,123 | 10,295 | 1,455 | 1,106 | –6.4 | –14.2 | -- |
| Alabama marbles | Min | 14,744 | 11,456 | 2,170 | 1,740 | -- | -- | -- |
| | Max | 17,787 | 11,515 | 3,442 | 1,740 | -- | -- | -- |
| | Avg | 16,266 | 11,486 | 2,806 | 1,740 | 7.25 | 29.95 | -- |
| **Individual values from Kessler (1919)** | | | | | | | | |
| Dorset, Vt | | 9,245 | 7,850 | 1,642 | 934 | –5.6 | –9.5 | -- |
| Etowah, Ga | | 11,545 | 10,194 | 1,520 | 1,226 | –10.6 | –15.2 | -- |
| Amicalola, Ga | | 11,012 | 9,922 | 1,596 | 990 | 23.6 | –13.4 | -- |
| Alabama | | 17,787 | 11,515 | 3,442 | 1,740 | –5.3 | 16 | -- |
| **Data averaged from table 9** | | | | | | | | |
| Yule | | 7,950 | -- | 1,200 | -- | –10.9 | -- | 1.25 |
| **Marbles tested for the Lincoln Memorial Commission (Bureau of Standards, 1914a)** | | | | | | | | |
| East Dorset, Vt | | 10,187 | -- | 1,436 | -- | –5 | -- | 1.25 |
| Tate, Ga | | 11,296 | -- | 1,179 | -- | –11.6 | -- | 1.85 |
| Amicalola, Ga | | 8,801 | -- | 1,419 | -- | –8.3 | -- | 1.2 |
| Alabama | | 11,882 | -- | 2,040? | -- | 0 | -- | .6 |
| Yule | | 7,550 | -- | 1,244 | -- | –10.9 | -- | 1.2 |

*From Griffith (1937); similar (derived same way?) to porosity values of Kessler (1919).

from customers who had used the Yule marble were sent to members of the Lincoln Memorial Commission by the Colorado Yule Marble Company to show that the company had provided quality stone in a timely fashion (Manning, 1913b). A statement about the marble's purity, from a Denver chemical laboratory and assay office, was also submitted to the commission to attest that the marble was likely to resist discoloration or disintegration from weathering (Von Schultz and Low, 1907; Manning, 1913a).

Because of reports of cracks (rifts) in two buildings where the Yule marble had been used in exterior work, in the Cheesman Memorial and the Post Office in Denver (The Financial World, 1913), a large portion of the testimony in a hearing held by the Lincoln Memorial Commission focused on the issue of the integrity of the marble (Lincoln Memorial Commission, 1913). To address concerns about the Yule marble, a geologist, George P. Merrill, was sent by Colonel W.W. Harts (Engineer Officer in charge of Public Grounds, overseer of the Lincoln Memorial project) to the quarry in Colorado to examine the stone and assess whether the quarry would be able to produce the quality and quantity of marble needed for the project. Merrill reported to Colonel Harts that the quarry "can be made to yield stone of good quality of the desired size and in quantity" (Merrill, 1913a,c). Merrill also stated that the chief defect, small rifts, was limited to certain beds and "can be averted if inspection is sufficiently severe" (Merrill, 1913b,c).

After consideration of the testimony and review of Merrill's report, the Lincoln Memorial Commission recommended that the Yule marble be used for the memorial (Vale, 1913). However, because of controversy about the choice, the selection of the Yule marble for the Lincoln

Memorial was not finalized for several months (Vale, 1914b; McCollum, 1993). Secretary of War Lindsley Garrison, the authorizing official, delayed announcing that a contract would be made until he had heard additional testimony regarding the proposed marble selection, received testing results from the Bureau of Standards, and received a recommendation on the marble selection from the Fine Arts Commission (French, 1914; Redfield, 1914; Vale, 1914a; McCollum, 1993). An integral part of the decision to use the Yule marble was the requirement that all of the marble was to be carefully inspected before it was accepted for installation in the memorial (Lincoln Memorial Commission, 1913; Taft, 1913).

## COLORADO YULE MARBLE IN THE LINCOLN MEMORIAL

The Colorado Yule marble was used for all of the exterior marble at the Lincoln Memorial. Many of the marble blocks were quite large. For example, the column drums were cut from blocks of marble that weighed 35 tons each (Kirsch, 1915), and there are 12 drums in each column of the memorial. All of the marble used in the memorial was fabricated and carved in Marble, Colo., before it was shipped to the Lincoln Memorial. The marble pieces were inspected at the quarry by a superintendent of the Yule Marble Company to make sure that all the stones that were shipped conformed to the specifications (Baird, 1914a). Although the government would not inspect the pieces at the quarry prior to shipping (Harts, 1914a,b), when the marble pieces arrived at the Lincoln Memorial, a government representative inspected the pieces as they were uncrated and put into storage (Baird, 1914b). At the beginning of the project, Colonel Harts (1914a) listed six general criteria that could cause rejection of a stone: (1) failure to meet color or veining requirements; (2) flaws that would result in structural weakness or defect of appearance; (3) repairs, patches, or concealment of defects; (4) improper quarrying so the stone does not lie on natural quarry beds; (5) improper matching of adjacent stones, so that appearance is affected; and (6) incorrect dimensions.

The high standards set for the quality of the marble and the large quantity of stone required for the Lincoln Memorial project were a challenge for the Colorado Yule Marble Company. Even at the start of the job, the company was aware of the very high standards that Harts and Manning were setting for the stone to be used in the memorial. In June 1914, Manning (Colorado Yule Marble Company) wrote that he was setting a standard for the marble that “will require us to take out of our quarries about 80,000 cubic feet of stock a month in order to ship 12,000 to 15,000 feet of finished material on the Lincoln Memorial job” (Manning, 1914). When some of the stones shipped to Washington were rejected, the George Fuller Company wrote to Colonel Harts about the difficulty of obtaining perfect stones of such large sizes, stating “... it is practically impossible to get marble, especially in large sizes, that does not show any seams” (Baird, 1914d). Harts reminded the Fuller Company that stones were rejected only if they did not meet the contract specifications (Harts, 1914d). Harts also later reiterated his position that “... the contract does not specify that the marble furnished shall be the best which any particular quarry may be capable of producing, but that it shall be equal to a certain standard established before the contract was entered into” (Harts, 1915).

Many stones were rejected at the quarry. Sometimes less than 10 percent of the stone that was quarried was shipped to the Lincoln Memorial job site (Manning, 1915a). Manning also wrote (1915a) that the Colorado Yule Marble Company had quarried six times for cheek pieces and was able to ship only four out of six pieces. Apparently, Manning felt that some of this high rejection rate was unnecessary because of the very high standards that were set. He wrote to Baird “... we are throwing out many blocks which should in my opinion go into the contract, but which would be criticized if we shipped them” (Manning, 1915a). Even a representative of the construction company reported back from a visit to the quarry that “for every block that is shipped four are thrown out” (Butler, 1915).

There were three main reasons for the difficulties encountered and the high rejection rate of stones that were quarried: the sizes required, the presence of flint (chert) layers in the marble beds, and the nature of the flaws in the marble. Many of the pieces required for the memorial were large, particularly the column drums, the stylobate pieces, and the architrave pieces. Their size meant that very large blocks of good marble were needed. In addition, it was not always possible to get all the large pieces from a particular section of the quarry. Manning (1915a,b) reported quarrying in several different areas for drum pieces and stylobate pieces. Another difficulty posed by the sizes was that some pieces, such as the stylobate blocks, required special dimensions, and no other pieces could be cut from blocks that had failed as sources of stylobate pieces (Manning, 1915a). Further problems were encountered because in some areas of the quarry, thick flint layers had to be removed to get to good-quality marble (Butler, 1915). In addition, the quarrymen encountered “... cutters and the blue coloring matter which comes in spots here and there through the layers that are absolutely statuary marble” (Manning, 1915a). Even once the necessary sizes of quality marble were obtained, the stone might be rejected. Cracks and seams in the marble were the main reason for rejection of the stones. However, many of the cracks were not visible until the stone was cut and a smooth face had been put on it (Butler, 1915).

Despite attempts to inspect the stone in Colorado and to find stones of the very best quality, some stones that were shipped were rejected (app. B). The main problem encountered in the stones was the presence of cracks, but other problems mentioned in the inspections included excessive veining, sand pockets, and surficial discoloration (Baird, 1914b,c; Harts, 1914c). Stones that had veining that exceeded the veining in the samples originally submitted to the Lincoln Memorial Commission were rejected (Baird, 1914b). In at least one case, a stone step with "considerable blue" was accepted, but the Colorado Yule Marble Company was warned that no other stones with that much blue would be accepted in the future (Baird, 1914c). While some stones were rejected, others were conditionally accepted or modified and used even though they contained minor flaws (app. B). The inspection team decided that stones with open seams on exposed faces would be rejected, as would stones where the seams might cause a spall that would affect the appearance of the stone (Harts, 1914c). However, a stone with a seam was considered acceptable if the seam did not extend to (or close to) the face of the stone. Some stones with seams were conditionally accepted as long as the seams did not increase in size or appear to be a more severe defect before final completion of the building (Harts, 1914c). Attempts were also made to accommodate stones with localized defects. Where it was possible, a stone with a cracked end or corner might be cut and used if it was possible to modify the lengths of surrounding stones or to adjust the joint patterns (Baird, 1914c; Harts, 1914c). Manning's (1915a) correspondence from Colorado describes efforts made by the Colorado Yule Marble Company to obtain replacement stones for some of the rejected pieces.

Unfortunately, few records have been found that document details of the construction of the superstructure of the memorial. A fire destroyed the construction field office in February 1917 (Warren-Findley, 1985), but it is not known whether records of the construction were lost in the fire. The last stones for the exterior of the Lincoln Memorial were shipped from Marble, Colo., on June 8, 1916 (Vandenbusche and Myers, 1991). The exterior marble work on the memorial was completed in February 1917, and the memorial was dedicated on May 30, 1922 (Warren-Findley, 1985). The beauty of the memorial was praised in reviews after its dedication (Cram, 1923), although the marble in the memorial was rarely singled out for comment (Thomas, 1993).

## DURABILITY OF THE MARBLE

One of the concerns that was raised about using the Colorado Yule marble for the Lincoln Memorial was that no one knew whether it would prove to be a durable stone. In an effort to address that issue, prior to the selection of the marble for the Lincoln Memorial, laboratory tests for durability were performed by the Bureau of Standards on the five marbles submitted for consideration by the Lincoln Memorial Commission (table 10). The Bureau of Standards (1914a) concluded that resistance of the marbles to weathering would be best determined by a comparison of structures made of the marbles. The other marbles that were proposed for the memorial had been used in a number of buildings, and so it was possible to anticipate how those marbles might appear years after the memorial was built. However, when the Lincoln Memorial was being built, the Yule marble was a new and relatively unknown marble; few buildings had used the Yule marble. Now, more than 70 years since its construction, it is possible to examine the condition of the Yule marble in the Lincoln Memorial and see how well it has withstood the impact of weathering agents over time.

Stone on the exterior of buildings is exposed to the weathering effects of wind, rain, temperature cycles, and urban pollution. Although all stone weathers (or deteriorates) because of chemical, physical, and biologic effects, variations in the characteristics of the stone can influence the degree or rate of deterioration. Marble is particularly susceptible to deterioration in urban environments because it is composed primarily of calcite, which dissolves in weak acid. Sulfuric and nitric acids can form from the reaction among water, oxygen, and urban air pollutants such as sulfur dioxide and the nitrogen oxides. Typically, marble that is exposed to weathering agents and urban pollutants is subject to deterioration (Amoroso and Fassina, 1983; McGee, 1991). It loses sharp edges, details of carved features are softened, and the surface of the marble develops a granular, sugary texture because of dissolution along calcite grain edges at the surface of the stone. In areas where the stone surface is sheltered from rain and washing, marble may develop a blackened surficial crust of gypsum alteration plus dirt particles that disfigures the marble (Amoroso and Fassina, 1983). Eventually the marble underneath the black surficial crusts will disaggregate, and pieces of the stone will be lost (Camuffo, Del Monte, and Sabbioni, 1983).

### CONDITION OF THE MARBLE IN THE LINCOLN MEMORIAL

The marble in the Lincoln Memorial has deterioration features that are typical for marble used in buildings. Although some cracks exist in the marble of the Lincoln Memorial, few of the cracks resemble the "rifts" that were of such concern in the Cheesman Memorial (The Financial World, 1913; Bain, 1936a). On the upper areas of the Lincoln Memorial on the penthouse walls and along the entablature, in particular on the cheneau and antefixae, exposed surfaces of the marble have a sugary texture, and some stones show differential wear on the exposed surfaces, where the marble surface has weathered unevenly (fig. 14). Inclusions of quartz or feldspar, particularly in some of the stones around the roof entablature, stand higher than the surface of the calcite grains because they are more resistant to weathering (fig. 12*B*). The column shafts also show a differential weathering of inclusions or a localized pronounced

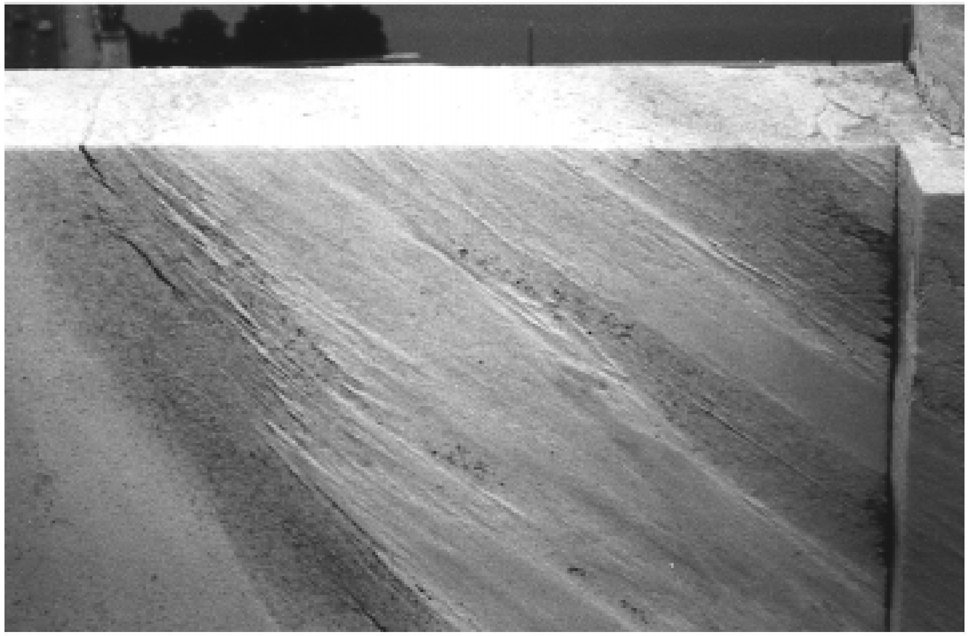


**Figure 14.** Differential wear on a cheneau piece along the roof at the Lincoln Memorial.

variation in stone quality, where there are chalky white areas in the marble (fig. 15).

There are very few black surficial alteration crusts at the Lincoln Memorial. This lack of crusts may be because the ornamentation on the memorial is simple with classical lines, so that most surfaces of the marble are washed by rain, and there are few areas where the carving provides recessed and sheltered surfaces in which surficial gypsum is likely to accumulate. Gypsum accumulation might also be slowed in many areas of the building because the National Park Service regularly washes accessible surfaces of the building. The main area where black crusts are visible at the memorial is on the guttae, on the cornice underside of the roof entablature. In this sheltered and relatively inaccessible area, many of the encrusted guttae are crumbling and falling apart (fig. 16).

Another characteristic surficial weathering feature on some stones in the Lincoln Memorial is a slight yellowish-orange surficial discoloration that is most visible on some of the antefixae and in the penthouse (fig. 17). Some of this discoloration may be a natural “antiquing” that is fairly typical of marbles, because as the calcite weathers, dirt adheres to the roughened surface (Bain, 1936a). In areas where the yellowish-orange discoloration is concentrated, bacteria may be growing on or between the calcite grains below the structure’s surface. Alternatively, some of the orange surficial discoloration may have developed during shipment to the memorial site (app. B).

A detailed visual survey conducted at the memorial in 1991–92 documented the condition of the stones in the memorial (Einhorn Yaffee and Prescott, 1994). When the baseline condition information from the visual survey is analyzed, it will be possible to describe the distribution and amount of the deterioration features at the memorial. This information will then be used in conjunction with an understanding of deterioration processes to develop plans for preservation and routine maintenance at the memorial.

One striking feature of the condition of the marble in the Lincoln Memorial is that while some blocks of stone appear to show little or no signs of deterioration at all, adjacent blocks show mild to severe deterioration (figs. 17 and 18). Stones that have withstood weathering are clear white and hard and retain crisp, well-defined edges on corners and carved features. In contrast, stones that have weathered poorly have pronounced surficial sugaring; they may show surficial cracks and a slight surficial discoloration; and in some cases, particularly where the stone has been carved, they appear to be badly crumbling. The presence of inclusions in a block of marble is not correlated with the degree of deterioration of the stone. This contrast in overall stone condition occurs in several places at the memorial but is most noticeable along the roof entablature and on the penthouse walls (figs. 2 and 17).

**Figure 15**. Chalky white inclusion on a column shaft at the Lincoln Memorial.

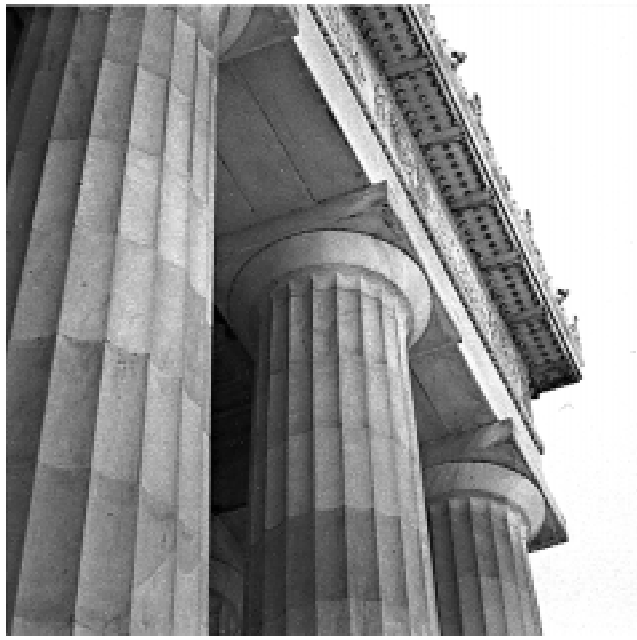
A puzzling aspect of this contrast in stone integrity is that stones which have had identical exposure to weathering agents show such a significant difference in durability. Because the deteriorated stones occur on all sides of the building, it appears that exposure to microclimatic effects around the building is not an adequate explanation for the variability in the stone surfaces. Similarly, because of the distribution of the affected stones and because there are no visible unique characteristics of the stones other than the sugared surface, it seems unlikely that salts moving in the stone or accumulating on the stone surface are the cause of the variations.

Although tooling of stone surfaces may cause minor variations in the stone that weaken the stone or make the surface more susceptible to weathering (Alessandrini and others, 1979), this seems an unlikely explanation for the stones at the Lincoln Memorial. All of the stones at the Lincoln Memorial were finished at the Yule fabricating facility in Marble prior to shipping to the memorial. If finishing of the stone caused the surficial variations, then the variations would not be distributed randomly around the memorial. Instead, the badly sugared surfaces would be restricted to stones with specific types of carved features, or to stones processed during a limited period of time when the usual stone handling procedures were not followed. Although the variable stones are most noticeable on the penthouse walls and on the roof entablature, variations in the surface roughness are found all over the building (Einhorn Yaffee and Prescott, 1994) on many types of architectural features, and it seems unlikely that a change in stone procedures at the fabricating plant could have affected the stones in such a random fashion. It seems more likely that the difference in integrity arises from some characteristic feature of the stone, which is probably an inherent feature of the marble.

## VARIATIONS IN THE YULE MARBLE

One element of this study was to examine the characteristics of the marble to see whether any specific characteristics of the marble might correlate with its durability and its tendency to stay intact. Because we did not want to take samples from the Lincoln Memorial, the stone was examined in situ on the building. Graded samples of the Yule marble were obtained from the Colorado Yule Marble Company. For comparison, a sample of disaggregated marble was collected near the dump pile at the Yule quarry, and a few broken pieces of marble that were found at the Lincoln Memorial were also examined (table 2). The composition of calcite in the various samples does not vary significantly (tables 5 and 6) and does not correlate with grade or type of sample. The type and composition of inclusions in the samples also do not correlate with the type of sample (tables 7 and 8). So it seems that neither composition nor the presence of inclusions explains the significant variation in durability observed in the Yule marble.

A



B

**Figure 16.** Blackened surficial alteration crusts accumulate on the underside of the roof entablature at the Lincoln Memorial. *A*, Black surficial alteration crusts accumulate in areas that are sheltered from washing and rain. *B*, Detail of the guttae under the roof entablature showing that many are disaggregating. A portion of black surficial alteration crust is still visible on the side of the crumbling gutta near the center of the photograph. The rest of the blackened surface on these guttae fell off when they were touched during examination of the area.

**Figure 17.** Orange surficial discoloration on the penthouse at the Lincoln Memorial looks darker gray in block at center of photograph. Note the difference in surficial integrity of the discolored stone compared with the other stones. However, orange discoloration and surficial roughness are not always correlated (see fig. 18).

Grain size and shape have been identified as key factors in stone durability (Dale, 1912). The calcite grains in a marble interlock to form a network of crystals; therefore, the grain boundaries in marble are likely to be weak points where dissolution can occur (fig. 19). Dale (1912) suggested that although fine-textured marbles present more surface area for rain water to react with the calcite, a coarse-grained, loose-textured marble may allow water to move more rapidly along the grain boundaries and speed deterioration of the marble. The width of the grain boundaries also influences the rate of deterioration. If the openings are very small, water cannot easily penetrate, but slightly wider openings allow water to penetrate and dissolve the marble along the grain edges. However, once the grain width boundary expands, dissolution of the boundaries may be less effective in widening the openings, and the weathering rate may decrease (Bain, 1941). So as time passes, the effect of water penetration in marble along grain boundaries will change.

Bain (1941) also observed that the width of grain openings is not the only factor that influences marble durability. Thin sections of marble examined with the optical microscope show that smooth-grained marbles have distinct grain boundaries compared to irregularly grained marbles (Bain, 1941). Bain (1936b) stated that deeply crenulated grain boundaries may account for the weathering resistance of some marbles because the spaces between grains must be widened enough to free adjoining crystals (fig. 19). By measuring the grains per square centimeter and the length of con-

**Figure 18.** Close examination of a column shaft at the Lincoln Memorial shows a stone with a rough, sugared surface adjacent to a stone that has retained a smooth, nearly new appearing surface finish. The rough surface is not discolored.

tact of the grains (centimeter per square centimeter), Bain (1936b, 1941) devised a coefficient of irregularity for marbles. He defined the coefficient as the length of contact between grains on a surface divided by the square root of the number of grains exposed on that surface. He used the coefficient to indicate which marbles might be more resistant to weathering. According to Bain, the coefficient of irregularity for marbles is typically 1.8, but it may range from highly irregular (deeply crenulated) (2.1) to nearly smooth boundaries (1.65).

Another factor that can influence the resistance of the calcite grains to dissolution is orientation of the crystals. Marble blocks cut so the exposed faces parallel the basal face of the calcite crystals may be more weather resistant because the basal faces of the calcite crystals are less soluble than the prism edges (Bain, 1941).

Most features of the texture and crystal grains of the Yule marble seem to indicate that it should be resistant to weathering. The grains in samples examined in thin sections appear to be tightly interlocked, they are fairly angular, and there is a mixture of grain sizes in many areas of the samples (fig. 4). Bain (1941) gave the coefficient of irregularity for four Yule marble samples as 2.06, 2.00, 1.95, and 1.91. All the values are above the typical value of 1.8, indicating that the marble samples would be likely to be resistant to weathering. In some samples of the Yule marble, the calcite grains appear to be slightly elongated. One of the special characteristics of the Yule marble is the preferred orientation of the marble grains observed if the stone is cut in certain directions (Knopf, 1941). This preferential orientation

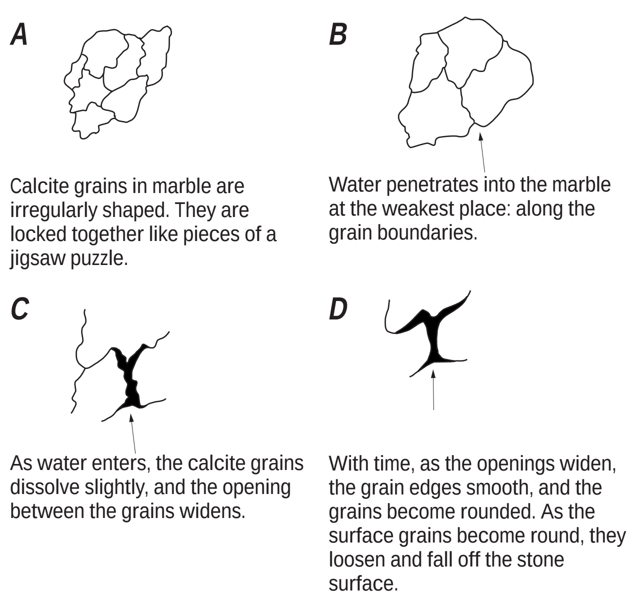



**Figure 19**. Sketch of calcite grain boundaries in marble and the progressive change that occurs along grain boundaries when water penetrates into the marble. Arrows show the entry point for water into the marble.

may also account for some of the weather resistance of some of the blocks of marble in the Lincoln Memorial.

Unfortunately, it is difficult to determine what the width and amount of crenulation of the calcite grain edges were on the stones that have weathered poorly at the Lincoln Memorial. The process of weathering widens the openings between grains and smooths the grain boundaries so that it is impossible to determine the original grain characteristics. In two of the less intact samples of this study, the thin sections from the antefix and from the crumbling quarry sample, the textures are more uniform than in the thin sections from the fresh, graded marble samples. The grain sizes of the grades and types of Yule marble samples in this study do not vary significantly (table 4), and the calcite grains in the graded samples have more irregular shapes and a wider range of grain sizes in a particular field of view compared with the antefix and quarry samples. However, it is impossible to determine whether the antefix and quarry samples were more homogeneous or had more rounded grains than the typical sample before they began to deteriorate.

Bain (1936a) and Vanderwilt (1937) both pointed out that marble from the Yule quarry varies depending on the part of the quarry that it is from. Bain (1936a) identified three areas—the east side, the bench, and the west side—that show distinct differences in integrity of the stone. Vanderwilt (1937) described the east-side marble as a relatively coarser grained, soft stone, with a high ratio of absorption (has a tendency to absorb moisture). He stated that the marble from the east side is not suitable for exterior work because it crumbles readily, and the polished surfaces lose their smoothness after a few years of exposure. After the Yule quarry was reopened in 1990, the company found that marble from the east section of the quarry was softer than marble from other areas of the quarry (Reis, 1994). In contrast, the marble from other portions of the quarry appears sound. Bain (1936a) described the west-side marble as very well preserved; the bench marble is intermediate in quality.

Because of the nature of this marble deposit, it seems entirely possible that there might be variations in the characteristics of this marble, depending on its location in the quarry. The deposit was formed from contact metamorphism, meaning that a local rather than a regional heat source caused the original limestone to recrystallize to form marble. Thus, the amount and degree of metamorphism within the marble body might have varied across the deposit depending on its proximity to the granite intrusion (the heat source) that caused the stone to recrystallize. Grain size, degree of recrystallization of the calcite, and types of inclusions other than the calcite that are present in the marble are features that vary with the amount of heat and pressure that the marble experienced during metamorphism. Vanderwilt (1937) and Bain (1936a) both reported that there are grain size variations in the marble body and that the marble that is in direct contact with the granite is very coarse grained. Both reports also describe inclusions, such as bodies of "lime," some garnet, and dolomite, that are present in some areas of the marble body but absent from others.

It seems quite likely that some of the variation in deterioration of the stones at the Lincoln Memorial may be because the stones were taken from different parts of the quarry. Merrill (1914) and Vanderwilt (1937) both reported that, at the Yule quarry, impurities and variations in quality were encountered along joints in the stone. Butler's correspondence (1915) from the quarry indicates that several fairly thick layers of flint and lime were removed in order to obtain pieces for the Lincoln Memorial. To supply large blocks that met the sample standards and to replace stones that failed in cutting or were rejected at final inspection, several different areas of the quarry were used (Manning, 1915a,b). Unfortunately, we do not know where specific stones came from in the quarry. However, some of the distinctive features of the marble are present only in some areas of the memorial, suggesting that certain characteristics were typical of the areas used for that particular stone size. For example, a number of the column drums have broad flat areas that appear as chalky white inclusions (fig. 15). This particular feature is not seen on any of the other areas of the building, such as walls, steps, and cheneau. In addition, some location information can be interpreted by considering the sizes of the stones and comments in the fragments of remaining correspondence (app. B).

Because the stones were all inspected prior to acceptance, one would anticipate that there should be little variation in the quality and characteristics of the marble in the Lincoln Memorial. However, the primary focus of the inspections was to find stones that fell within the established standards for veining and to reject stones with cracks or seams that might become cracks (Harts, 1914a; Baird, 1914b). The stones that now show significant differences in deterioration at the Lincoln Memorial most likely would have met the inspection criteria, because most do not contain significant inclusions; cracks in these stones are rare. The primary characteristic of the more deteriorated stones is extreme sugaring of the surface and pronounced rounding of edges and carved features. It is possible that even though the stones were carefully inspected, features that might have indicated that some stones would tend to sugar more than others may have been overlooked because that was not of primary concern in the inspections. Alternatively, it may have been difficult to identify these stones when the memorial was being built because the features that would indicate future extreme sugaring may have been too subtle to see before significant stone exposure occurred.

If variations in the integrity of the Yule marble are a typical feature of the marble, then it is likely that they would have appeared in other buildings. However, once the variable stone integrity was recognized at the Lincoln Memorial, and if a characteristic that caused the variable integrity was identified and could be avoided, then younger buildings should show more uniform deterioration than the Lincoln Memorial. By examining buildings with exterior Yule marble, it may be possible to determine whether variable durability is a common feature. It may also help to determine whether the problem was restricted to stone quarried at a specific time or from a specific part of the quarry.

## CONDITION OF YULE MARBLE IN OTHER BUILDINGS

In contrast to the situation faced by the Lincoln Memorial Commission, it is now possible to examine the general deterioration features of the Yule marble in a number of buildings of varied ages. The Lincoln Memorial is probably the most prominent building, nationwide, in which the Colorado Yule marble was used. However, between 1905 and 1940, the Colorado Yule was used on the exterior and interior of many important buildings and monuments built throughout the United States (fig. 20; table 11), and it has also been used nationally and internationally for many small jobs such as private grave markers. Extensive lists of structures that used the stone are provided by several authors (Vanderwilt, 1937; Holmes, 1991; Vandenbusche and Myers, 1991; McCollum, 1993); however, some of these buildings have changed names or have been taken down. Some specific examples of structures that use the Yule marble are given in table 11. The conditions of buildings built about the same time as the Lincoln Memorial are of particular interest because some of the stone quarried in 1914–16 that could not be used for the Lincoln Memorial was used in other, smaller jobs (Manning, 1915a,b).

Six buildings in Denver have Colorado Yule marble on the exterior (table 12), and, with the exception of the Cheesman Memorial, they are all located in downtown Denver. The Cheesman Memorial is close to the downtown area, but it is in a park on a small hill; it is also the oldest building (1908) using the Yule stone. The construction dates for the buildings in Denver reflect the history of the Yule quarry (app. C), as most were built in two time periods: 1914–16 and 1930–36 (table 12). One advantage of examining several buildings in the same city is that climate influences on the buildings should be similar, so variations in deterioration in the buildings are likely to reflect differences in age of the buildings and variability of the stone.

In 1993, I visited Denver to examine some of the buildings that have Yule marble on the exterior. The main purpose of the visit was to gather an overall impression of the condition of the marble in the Denver buildings so as to make comparisons with the condition of the marble in the Lincoln Memorial. Another goal was to see if the variations in the marble and in the inclusions at the Lincoln Memorial appear to be typical of the Yule marble in other structures.


**Figure 20.** Locations in the United States where the Colorado Yule marble has been used for notable buildings and major structures.

**Table 11.** Notable examples of structures that used the Colorado Yule marble.

[Sources that list buildings using Yule marble: Vanderwilt, 1937; Holmes, 1991; Vandenbusche and Myers, 1991; McCollum, 1993; Murphy, 1993. ---, no date information]

| Building | Location | Date completed | Marble position |
|---|---|---|---|
| Colorado State Capitol Building ---- | Denver, Colo --------------------------- | 1895 | Interior |
| Cheesman Memorial------------------ | Denver, Colo --------------------------- | 1908 | Exterior |
| Cuyahoga County Court House ----- | Cleveland, Ohio ----------------------- | 1912 | Interior |
| U.S. Post Office[1]----------------------- | Denver, Colo --------------------------- | 1914 | Exterior |
| Colorado State Museum Building[2]-- | Denver, Colo --------------------------- | 1916 | Exterior |
| Lincoln Memorial --------------------- | Washington, D.C ---------------------- | 1916 | Exterior |
| First National Bank ------------------- | Portland, Oreg ------------------------- | 1916 | Exterior |
| U.S. Customs Building --------------- | Denver, Colo --------------------------- | 1931 | Both |
| Tomb of the Unknowns--------------- | Arlington National Cemetery, Va --- | 1931 | Exterior |
| Merritt Building ----------------------- | Los Angeles, Calif--------------------- | ---- | Both |
| Providence County Courthouse ----- | Providence, R.I ------------------------ | ---- | Interior |

[1] Now houses Federal courtrooms. [2] Now houses the State administration.

**Table 12.** Buildings in Denver, Colo., with exterior Colorado Yule marble.

[Dates from Vanderwilt (1937) or from cornerstones]

| Building | Address | Date completed |
|---|---|---|
| Cheesman Memorial ------------------------------------------------------------ | Cheesman Park---------- | 1908 |
| U.S. Post Office (now houses Federal courtrooms)--------------------------- | 18th & Stout Street ----- | 1914 |
| Colorado National Bank ------------------------------------------------------- | 730 17th Street ---------- | 1914 |
| Colorado State Museum Building (now houses the State administration)- | 200 E. 14th Avenue ----- | 1916 |
| U.S. Customs Building --------------------------------------------------------- | 19th & Stout Streets ---- | 1931 |
| State Capitol Annex (now houses State Department of Resources; Capitol Complex Facilities)--------------------------------------------------- | 14th & Sherman--------- | 1930's |

The general condition of the Yule marble in the buildings in Denver is very similar to the condition of the marble at the Lincoln Memorial. When buildings made of Yule marble are viewed as a whole, they appear in good condition, and the stone is white and unblemished (figs. 1 and 21). Even from a close view, the marble is clear and nearly white, and the edges and surfaces appear to retain much of their original crispness. The inclusions are relatively subtle and show no appreciable difference in their weathering compared to the rest of the stone. There is little surficial blackening of the stone. However, I have no information about the cleaning or maintenance of the buildings in Denver.

At the time of my examination, the Denver Post Office building was undergoing a major renovation; it had been cleaned with a high-pressure water spray that had removed all or most of any blackened surficial crusts (fig. 22). It appears that the slight orange discoloration seen in some stones at the Lincoln Memorial may be typical of the Yule marble because some of the stones in the Denver buildings also have a similar orange discoloration. A pronounced reddish-orange stain at the Denver Post Office apparently resisted poultice treatments during the cleaning of that building (conversation with one of the workers at the site) (fig. 23).

Close examination of some of the stones in various buildings shows that their condition is similar to the condition of the marble at the Lincoln Memorial. There are variations in the surface textures of adjacent stones in several of these buildings (fig. 24), similar to that seen at the Lincoln Memorial. However, the effect is most noticeable at the Cheesman Memorial, where stones that retain crisp tooling marks are adjacent to stones with very sugared surfaces (fig. 25). Some of the stones in the buildings have slightly grayed “chert” inclusions like some of the stones at the Lincoln Memorial, but they are relatively uncommon. However, I did not see any of the shallow chalky white inclusion areas like those on the columns at the Lincoln Memorial. This observation suggests that those inclusions were restricted to the area of the quarry used for the column drums, and they could not be completely avoided when the drums were quarried because of the large sizes needed for those stones. Few (if any) of the stones in the Denver buildings are as large as many of the stones in the Lincoln Memorial. The “rifts” or surficial cracks in the Cheesman Memorial, of such concern during the hearing of the Lincoln Memorial Commission, are still visible on many of the stones in the Cheesman Memorial (fig. 26). However, I did not see this type of crack on any other building. It seems likely, as Manning implied at the hearing (Lincoln Memorial Commission, 1913), that this feature was present only in some of the top layers of the marble. It is also likely that inspections of the stone on subsequent projects successfully avoided this problem.

Overall, there are no significant differences in the condition of the marble in buildings of the two age groups (circa 1914 and circa 1930) or in the climate settings of Washington, D.C., and Denver. Some blocks of marble seen closeup have weathered so they are no longer pure white, but their discoloration seems reasonable for the “antiquing of marble” that might be expected on an older building. Inclusions are present in the marble but are not particularly noticeable on the buildings unless close inspection is made. Most significantly, visible variations in surface sugaring of the marble are present in all of the buildings examined. However, the variations are noticeable mostly only upon close examination; the sugaring and softening of the surface is not particularly visible from a distance of more than 10 ft. Differences in climate, particularly cycles of moisture and temperature that the marble experiences in Washington, D.C., have not had a significant effect on the weathering of the Yule marble. There are no marked differences in the general state of the marble in buildings in the two cities. Similarly, there is no significant difference in the weathering of the marble in the Denver buildings of different ages; thus, a 10- to 20-year difference in length of exposure, independent of climate, does not appear to correlate with specific deterioration of the marble.

## SUMMARY

Ever since its discovery, the Colorado Yule marble has been praised for its quality and appearance. It was selected for the Lincoln Memorial specifically because of its aesthetic attributes and the quality that it would bring to the memorial. Although there have been concerns about variations in the marble and about the long-term durability of the marble, overall, the early praise for the quality of the marble was well founded.

The marble is nearly pure calcite. The irregularly shaped calcite grains are equidimensional to slightly elongate, and while they range in size, most have diameters of between 100 and 600 micrometers. Physical tests of the Yule marble do not show any significant weaknesses; the results for the Yule marble are similar to typical results for other marbles. As a natural material, the marble is heterogeneous. It contains inclusions of quartz, mica, and feldspar, but the inclusions are present only in minor amounts and they are unevenly distributed. The predominant inclusion is mica, which occurs as thin traces and does not weather significantly differently from the rest of the marble. In a few older buildings where the Yule marble is used on the exterior, large inclusions of quartz or feldspar have weathered to form noticeable, slightly gray, more resistant features that stand out compared to the surrounding marble. However, specific defects such as quartz inclusions and surficial cracks in the marble are not present in more recent buildings; apparently the defects were avoided once they were recognized in early buildings that used the Yule marble.

*A*

*B*

*C*

**Figure 21.** Structures with exterior Colorado Yule marble generally appear to be in very good condition. *A*, Cheesman Memorial, Denver, Colo. (built 1908). *B*, Colorado State Museum, Denver, Colo. (built 1916). *C*, Tomb of the Unknowns, Arlington, Va. (1931).

**Figure 22.** Cleaning at Denver Post Office in 1993. The workers had not yet removed the blackened surficial discoloration on the sides of the three column capitals on the left side of the photograph.

**Figure 23.** Reddish-orange stain at Denver Post Office (dark area at center of photograph) after several cleaning attempts in 1993.

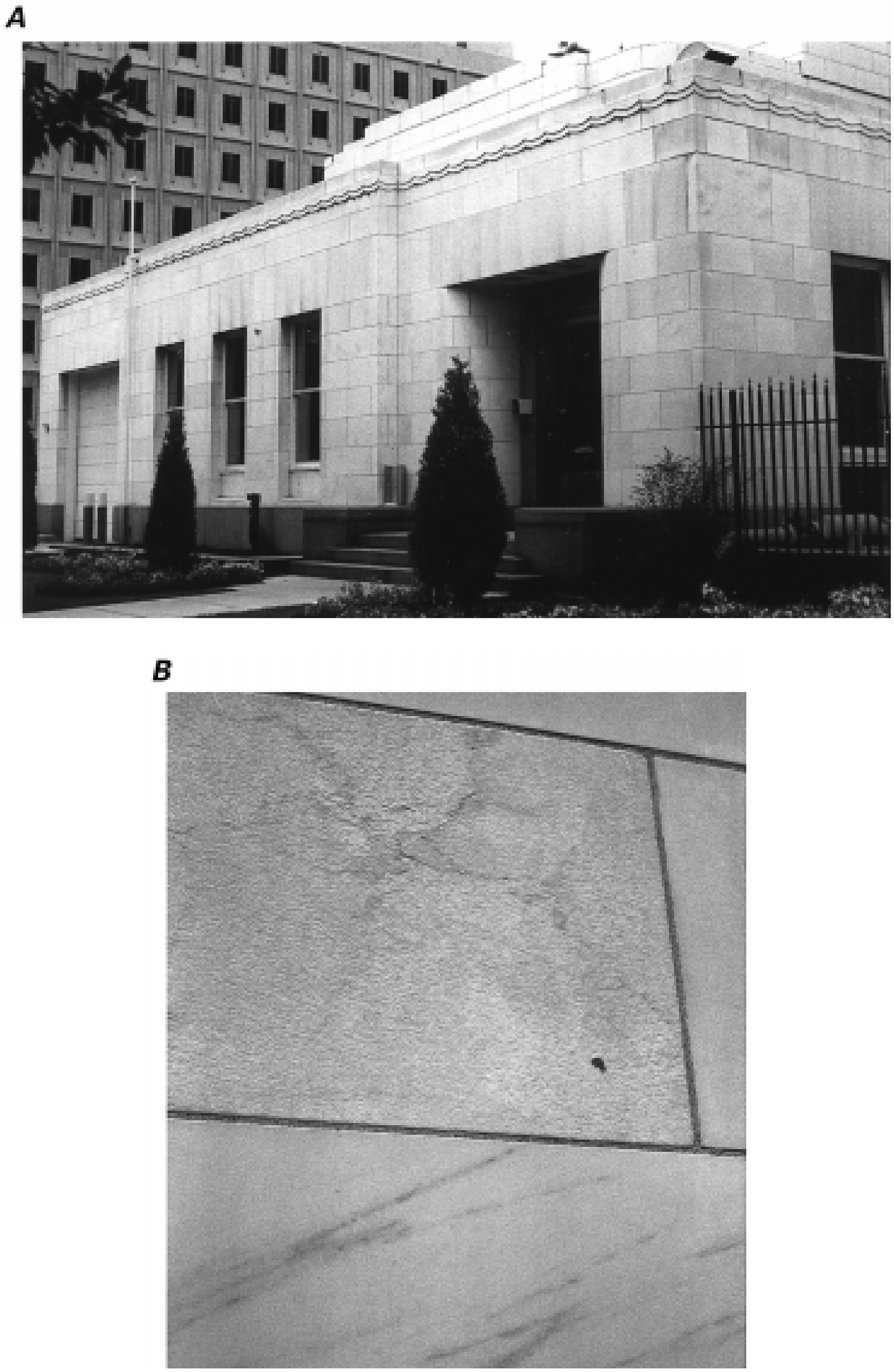


**Figure 24.** At the State Capitol Annex Building in Denver, there are variations in surficial integrity in some blocks of marble. ***A*,** The State Capitol Annex Building (built in 1930's). *B*, Some blocks have a very rough sugared surface, whereas adjacent stones retain a smooth, finished surface. Photograph is a detail of the 5th and 6th course from the ground, near the right front corner of the building.

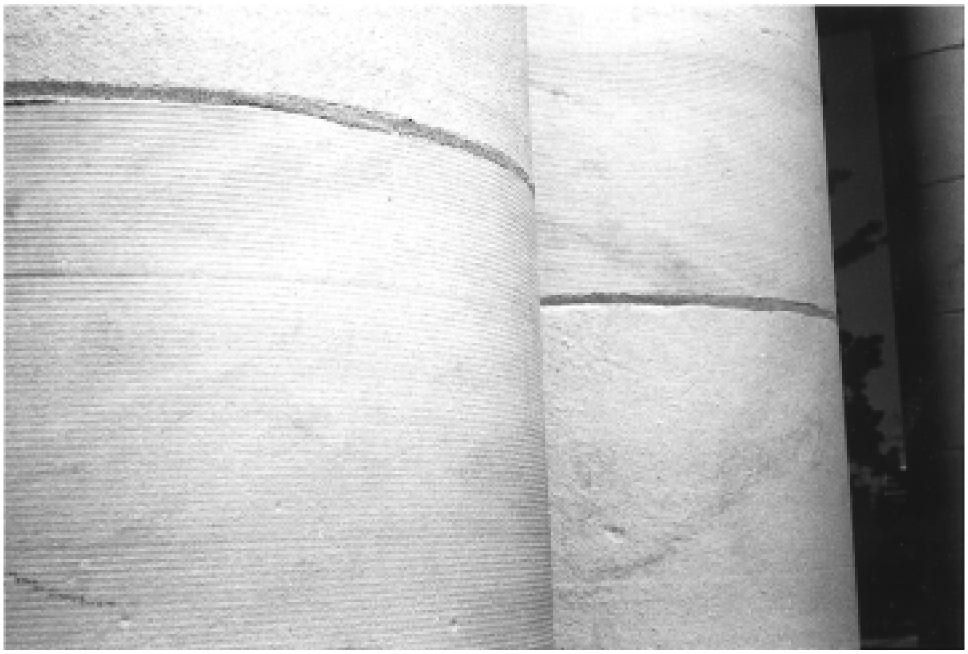


**Figure 25.** Detail at the Cheesman Memorial, Denver, Colo. Three column drums retain original tooling marks, but a fourth stone has a rough sugared surface with no trace of the original finish. The mortar layer is approximately 7 mm thick.

**Figure 26.** Rifts or surficial cracks in the marble at the Cheesman Memorial, Denver, Colo.

With time and exposure, the Yule marble remains remarkably white and solid. Buildings of Yule marble and many blocks of marble in three Colorado areas—in the quarry dump, along the Crystal River, and at the site of the abandoned finishing plant at Marble, Colo.—appear nearly pristine. However, when closely examined, one characteristic feature of this marble is the heterogeneous manner in which some of it has deteriorated. In buildings in Washington, D.C., and in Denver, some surfaces of the marble retain a crisp, nearly new appearance while adjacent surfaces soften and disaggregate with severe sugaring of the calcite grains. The varied durability of the marble does not appear to be related to the composition of the calcite or the inclusions. The composition of the nearly pure calcite grains does not vary significantly in various grades and samples of the marble. The badly deteriorated stones do not contain more distinct inclusions than their more resistant neighbors, and because the contrasts in durability occur in adjacent stones, the differences are not due to exposure of the stones to specific, local weathering.

Variation in texture and grain size is a characteristic of the Yule marble deposit. The deposit was formed by contact metamorphism, and so some portions of the marble body were closer to the intruding heat source that caused the original limestone body to recrystallize. Thus, some portions of the marble could have been more extensively recrystallized than other portions, and the heterogeneous durability of the marble may reflect subtle differences in the resulting texture of the marble. The pronounced surficial sugaring that distinguishes the less resistant blocks suggests that the problem may arise because of some characteristic weakness along the grain boundaries in the marble. Weaknesses along grain boundaries would be likely if the original grain boundary widths were wide enough for water to penetrate easily or if the original calcite grains were rounded. Alternatively, in resistant blocks, calcite grains may be aligned with the face of the block, so that water is less able to penetrate along weak grain boundaries. If samples of resistant and disaggregating stones at the Lincoln Memorial were collected so that the texture and grain boundary characteristics could be examined, it might be possible to clarify the role of grain boundary characteristics in relation to the variations in durabilty that we see at the memorial.

Although the stones with pronounced weathering are very distinctive on close examination, they constitute a relatively minor proportion of stones in an entire building (Einhorn Yaffee and Prescott, 1996?). Thus, although they do not present the ideal appearance, the badly deteriorated surfaces do not impair the overall structural integrity of the building. However, the rate of deterioration may be a concern in the long term. Where the stone of poor durability is decoratively carved or where it may be further weakened because it is exposed to direct and continual impact of weathering agents, such as along a roof parapet, its future integrity may be a concern. If steps are taken to synthesize knowledge of the marble characteristics with an understanding of deterioration processes, specifically those that have been identified at the Lincoln Memorial, the National Park Service will be well prepared to develop an effective and timely preservation approach for the Lincoln Memorial.

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# APPENDIXES A–C

# APPENDIX A. MICROANALYTICAL TECHNIQUES

Both electron microprobe analysis and scanning electron microscopy (SEM) with energy-dispersive X-ray analysis (EDAX) are useful microanalytical techniques. The particular advantages of these techniques are that a sample (polished thin section, grain mount, or small chip) can be analyzed nondestructively and that very small areas (~1 micrometer in diameter) can be selected and analyzed while the sample is examined. The ability to analyze a small area is especially useful for samples containing very small grains or for samples having compositional zonation.

In both electron microprobe analysis and scanning electron microscopy, a beam of electrons is focused on or rastered across the surface of a conductively coated sample. When the electron beam interacts with the sample, secondary electrons, backscattered electrons, and X-rays are generated. The secondary electrons and backscattered electrons are detected so that an image of the sample is produced. Secondary electron images generally show surface features and topography of the sample. Backscattered electron images provide compositional information because the various gray levels in the image reflect variations in the average atomic number across the sample.

The X-rays that are generated by the electron beam interaction with the sample also provide compositional information. If an energy-dispersive X-ray spectrum is collected, then the energy levels for all of the X-rays generated are displayed. However, if a wavelength spectrometer is used to detect the X-rays, it is tuned to measure the X-rays for one specific wavelength, for a specific element. Quantitative analyses are made by measuring the X-rays from standards of known composition so that the X-rays from the sample of unknown composition can be calibrated.

In this study, the scanning electron microscope (JEOL JSM–840 with a Princeton Gamma Tech (PGT) energy-dispersive X-ray detector) was used to examine samples and to provide qualitative analysis of the mineral phases. The electron microprobe (JEOL JXA–8900) was used for quantitative analysis of the major mineral phases in the samples. Standards of known compositions, similar to the minerals being analyzed, were used to analyze calcite, mica, quartz, feldspar, and sulfides (pyrite, sphalerite, and galena):

- Calcite was analyzed at 12 kV accelerating voltage with a beam current of $1\times10^{-8}$ amps, using a rastered beam and the Phi-Rho-Z correction method (Pouchou and Pichoir, 1991).
- Mica, quartz, and feldspar were analyzed by using 15 kV accelerating voltage with a beam current of $2\times10^{-8}$ amps, using a focused beam and the ZAF correction method for oxides (Armstrong, 1995).
- Sulfides were analyzed at 25 kV accelerating voltage with a beam current of $2\times10^{-8}$ amps, using a focused beam and the ZAF correction method for metals (Armstrong, 1995).

Analyses were judged to be of good quality if the oxide total was between 98.0 and 102.0 and if the stoichiometry was correct for the phase being analyzed. However, the check for a good oxide total for the mica and calcite was made after water and $CO_2$ were determined by difference with a check on stoichiometry for micas and calcite, respectively.

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# APPENDIX B. INFORMATION ABOUT THE QUARRYING AND INSPECTION OF STONE FOR THE LINCOLN MEMORIAL

Unfortunately, only scanty information is available about the quarrying and the rejection of stones during construction of the Lincoln Memorial. However, information of that sort may be useful when the durability of the stones in the Lincoln Memorial is evaluated. Stones quarried from one particular portion of the quarry may possess similar characteristics that become visible years later as the stone weathers in the building. If it is known that stones with a specific characteristic all come from one part of the quarry, it is easier to narrow the problem down because it may be closely related to a characteristic of the stone and less influenced by exposure or something that has been done to the stone in the building. Likewise, any descriptions or questions about flaws that arose during inspection of the stones might correspond to problems that we can see now in the stones.

## QUARRYING REPORTS

Information about which parts of the Yule quarry were used for the stone in the Lincoln Memorial might aid in understanding and correlating the observed variations in durability of the marble. Several portions of the marble deposit were used in quarrying operations; the openings were designated as quarry numbers 1 through 4. During the construction of the Lincoln Memorial, all quarrying operations were directed at obtaining stone for the Lincoln Memorial project, so it is possible that stone was taken from all portions of the quarry. However, most of the stone for the Lincoln Memorial may have come from quarries number 1 and 2. Correspondence from 1915, during the construction of the Lincoln Memorial (Manning, 1915a,b), indicates that quarries number 1 and 2 were being used to obtain large pieces for the stylobate courses and drum blocks. Portions of both quarries were used for drum blocks, cheek pieces were obtained from quarry number 2, and while they tried to get pieces for the stylobate from quarry number 1, they failed (correspondence from Manning, 1915a).

Blocks quarried for the stylobate that failed, presumably because some flaw showed up as they began finishing the stone, were used for the GG, WW, and PP courses and for the architrave (Manning, 1915a). A few blocks that failed for the stylobate and architrave were used for the frieze and carved courses (Manning, 1915b). Similarly, blocks for the column drums were cut to meet the largest sizes needed (at the base of the columns) and then cut down for smaller drum courses if flaws appeared during the finishing. Butler's letter (1915) describes how a block that was cut for an AB drum was cut for a GH and then for a KL drum. If the stone designations used in this correspondence are the same as those used in the stone setting and recent stone condition survey at the memorial, it may be possible to examine particular stones for similarities in texture or inclusions. Comparisons of some of the stones from the areas and courses mentioned may also show some similarities in their condition at the Lincoln Memorial and help show whether any specific characteristics of the marble might have been restricted to certain areas of the deposit or if they occur randomly.

## INSPECTIONS

All of the stone was checked before it left the Yule marble finishing plant to make sure that it met the dimensions needed (Baird, 1914a). In addition, the stone was inspected after delivery at the Lincoln Memorial site after it was uncrated (Baird, 1914b) to determine whether it met criteria pertaining to quality, appearance, and proper dimensions (Harts, 1914a). Correspondence, preserved in the archives, from September 1914 indicates that some specific stones were identified as having problems when they were inspected. Six or seven stones were rejected, four stones were tentatively accepted, and three stones would be used if they could be modified. The stones and descriptions (Baird, 1914c; Harts, 1914b) were as follows:

- rejected:
  - AD 39 west—column base; cracks from fluting to edge and on face
  - AC 33 north—*[no specifics given]*
  - AC 54 south—open crack on face and corner off
  - AC 27 north—open crack on the vertical face
  - AC 52 west—open crack on face and spalled
  - AD 37 west—column base; open crack from fluting to edge and at corner
  - AB 54 west—sand pockets *[Harts, 1914b, listed this as AC, not AB]*
- tentatively accepted:
  - AC 16 north—closed crack, vertical face
  - AC 36 west—closed cracks, horizontal face; accepted if stone placed on north front
  - AC 32 west—closed cracks, vertical face
  - AB 33 west—closed crack, horizontal face
- stones to be modified:
  - AC 44 west—broken corner; use if cut 2 inches off
  - AB 56 south—crack at corner; use if cut 3 1/2 inches off
  - AC 33 west *[no specifics given]*

The stones that were tentatively accepted could be rejected if, by the conclusion of the construction, the cracks had opened or gotten worse. The stones to be modified would be used if an acceptable change in the joining plans was submitted. Two of the stones are specifically identified as column bases; the others are probably from the stylobate course because they were described as large stones and the numbering of the stones is like that used in the stone setting plans for the stylobate. The numbers used for the stones here may be the same as those used in the information we have now for the stone settings. If so, it might be possible to examine their condition as documented in the recent stone condition survey (Einhorn Yaffee and Prescott, 1994) to see if the flaws identified nearly 70 years ago are still apparent.

## DISCOLORATION

Another interesting piece of information in the archive's correspondence that may relate to the present condition of some of the marble at the Lincoln Memorial describes some surficial discoloration on two stones. During an inspection of the marble in July 1914, two stones showed a yellowish discoloration that workers were unable to remove from the stone (Baird, 1914b) even after washing. Baird and a group of people (Bacon, Harts, Gillan, O'Connor, and Kennedy) suspected that the discoloration might be from cinders on the surface of the marble that had reacted with rain. There is no further mention of this issue in later correspondence, and the Colorado Yule Marble Company may have tried to avoid future problems with discoloration by careful boxing and loading of the stone prior to shipment (Baird, 1914b). Today, some of the stones in the Lincoln Memorial, particularly some of the antefix stones on the roof entablature, have a light-orange coloration. It is possible that, rather than being an inherent characteristic of the stone, some of that surficial discoloration might instead be a residue of very fine particles of iron (from cinders?) that rusted on the surface and lodged in the intergranular spaces of the marble surfaces. Although some discoloration like this is present on other buildings that used Yule marble, it may not cover as many stones in those buildings as it does in the Lincoln Memorial.

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## APPENDIX C. BRIEF HISTORY OF THE YULE QUARRY

Although the Colorado Yule marble deposit was first reported in 1882 (Vanderwilt, 1937), a producing quarry operation was not established at the deposit until 1906 (Manning, 1914). Samples of the Colorado Yule marble exhibited at the Colombia Exposition in 1893 brought much attention to the quality and purity of the marble. The Colorado-Yule Company's first large contract, for the Cuyahoga County court house in Cleveland, Ohio, was obtained in 1907 (Vandenbusche and Myers, 1991). The company made major improvements to its operation and finishing plant to help it handle the work necessary to fulfill its contract to provide the marble for the Lincoln Memorial in Washington, D.C. However, almost immediately after completing that high-profile contract in 1917, the quarry went into bankruptcy and ceased operations because of financial problems, natural disasters, and the loss of skilled laborers during World War I (Vandenbusche and Myers, 1991). The quarry was reopened in 1922 (Vanderwilt, 1937), but it closed again in 1941 when marble was declared nonessential to the war effort, and much of the machinery and equipment was sold for scrap metal (Vandenbusche and Myers, 1991).

In 1990, the Yule quarry reopened (McClean, 1990; Klusmire, 1993). The Colorado Yule Marble Company is currently operating the quarry and producing dimension stone for large projects, such as the interior of the new Denver airport (Klusmire, 1993). In 1992, the quarry shipped 1,000 cubic meters of marble; it will produce about 7,080 cubic meters at full production (Peterson and Cappa, 1994). The U.S. Bureau of Mines 1992 Annual Report for Colorado predicts that at the present rate the quarry could last 300 years (Peterson and Cappa, 1994).

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