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Characteristics and Weathering Features of Sandstone Quoins at Fort McHenry, Baltimore Maryland

by

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Introduction

A major rehabilitation of Fort McHenry in Baltimore, Maryland is being planned by the National Park Service. It will include repairs to the brickwork and masonry at the Fort. Although the Fort is mostly built of brick, sandstone blocks were used in the quoins (the exterior angles of the walls; Fig. 1). Park Service records suggest that the sandstone used for the quoins may have been obtained from a quarry near Aquia Creek in Virginia. Sandstone quarried from this location was widely used for buildings in Washington, DC in the early 1800's (eg. the White House and the U.S. Capitol) but its use was discontinued in 1837 when it was found to have very poor durability (U.S. Census, 1884). Since some of the sandstone quoins at Fort McHenry are in extremely poor condition, it may be necessary to replace some stones. The Park Service has a possible source of Aquia Creek sandstone, so they wanted to find out if the original stone used in Fort McHenry was the Aquia Creek stone. On July 24, 1992 Elaine McGee (USGS) visited Fort McHenry with Tom Fields (NPS) to examine the sandstone quoins to see if they were Aquia Creek stone. The sandstone blocks were examined for general features and characteristics, details were examined by hand lens, and a few small pieces that had begun to spall off were taken for laboratory examination to determine chemical composition and mineral characteristics.

Visual Observations of the Sandstone at Fort McHenry

We visually inspected the sandstone quoins at each point around the fort. The stones blocks from ground level to just above eye level were closely examined and some were sampled. Stones above eye level were scanned to confirm that features visible there were similar to those observed on the more accessible stones. Most of the stone surfaces are rough and are covered by a hard black encrustation that obscures the features and characteristics of the underlying stone. Many of the blackened stones appeared intact and in fairly good condition. The more badly deteriorated stones were of greater interest because many show weathering features and the characteristics of the stones were more readily visible. The stone blocks were examined for color, texture, and large scale features such as sedimentary structures that might reflect the formation (and origin) of the stone. Weathering characteristics were also of importance since the Aquia Creek sandstone is noted for poor durability and therefore might have a typical weathering pattern.

The general color of the sandstone is buff with some reddish brown areas; the coloration of these areas makes the layers of the stone appear prominent. The distinctive beds (layers) visible in the stone are mostly thin horizontal layers, but in some places cross beds (layers at slightly inclined angles) are visible (Fig. 2). Rounded pebble inclusions, generally about 1 - 1.5 cm size, that form a discontinuous layer of coarser material also occur in some of the sandstone blocks that we examined at Fort McHenry (Fig. 2).

A common weathering feature of the sandstone is the spalling of thin layers. Spalled pieces are thin, normally about 2 mm thick, and they range in area from approximately one square centimeter to one by several centimeters. The natural bedding of the sandstone has also been accentuated by weathering processes that have caused the loss of weak or fine material making the layers visible in several places. The most distinctive (and probably the most detrimental) weathering feature of the sandstone blocks at Fort McHenry is the concave recession of some stone surfaces (Fig. 2). In some places, the faces of the stones are recessed nearly three centimeters, as though portions of the stone had been scooped out. The stone may have weak layers that tend to spall as moisture penetrates between the layers of the stone; this may be accentuated if the stone was positioned improperly, in an orientation that facilitates penetration of water between the layers. Alternatively, a pocket of clay or a clay rich area may have been located at or just below the surface of the stone. Such an area would tend to lose material rapidly through physical processes, like freezing and thawing or expansion and contraction of the clays as moisture hydrates and dehydrates the layers in the clay, resulting in a pronounced recession of the stone surface in that area.

Many of the sandstone blocks at Fort McHenry have blackened surficial crusts that are very tough and appear to protect (or preserve) the surface of the stone; tool marks are visible on some of the stones that have blackened crusts. Typically, the black crusts obscure both the grains and matrix in the sandstone, and the sedimentary structures (such as layering and cross beds) are not readily apparent on the black encrusted stones. While spalling of the stone surface is occurring on some of the blackened stones, the extent of spalled areas on these stones is limited. Areas of concave recession were not covered with the black encrustation, however it is not known if the blackened encrustation was present prior to the loss of material that resulted in the concave stone surface.

Laboratory Observations of Sandstone Samples from Fort McHenry

A few small pieces of the sandstone at the Fort were sampled in order to examine characteristics of the stone, to compare it with stone known to be Aquia Creek sandstone, and to examine the black encrustation. Samples were taken at various points around the fort (Table 1), by prying off small spalls with fingers or a pocket knife. All the samples came off very easily, although the black crusts adhere tightly to the stone. The samples were examined with optical and scanning electron microscopy, and were analyzed by X-ray diffraction.

This sandstone is fairly evenly grained and is composed of slightly rounded to blocky grains. The grains are typically translucent to clear and encompass a range of colors: white, light and dark gray, tan, light pink, and (rarely) black. Grain size is typically 0.4 to 0.7 mm (Table 2). The cement that binds the grains in the stone is tan to yellow and sometimes red-orange in color. The cement does not react with weak acid, so it is a silica (rather than a carbonate) cement and is probably quartz or clay. There is abundant organic material and clay in the interstices of some samples and on some of the surfaces. The organic material appears to be algae but may also include some fungi. Because of the types of samples that we took (small pieces of stone pried away from the surface, that had already begun to spall off) we may see a greater than normal proportion of organic (and weathered) material.

The stone is mostly composed of quartz (SiO_2), potassium feldspar ($KAlSi_3O_8$), and kaolinite clay ($Al_4[Si_4O_{10}](OH)_8$). Abundances of the mineral phases were estimated from X-ray diffraction patterns (Table 3). Ilmenite ($FeTiO_3$) was also found, but was not detected with X-ray diffraction.

The black crust remains a puzzle. Black alteration crusts typically form on marble and limestone buildings that are exposed to sulfur dioxide pollution (McGee and Mossotti, 1992), but those crusts are composed of gypsum crystals with trapped dirt and pollutant particles. Gypsum was not detected in any of the samples taken from Fort McHenry, nor were any pollutant particles found in the samples examined to date. The black crust from the Fort McHenry samples appears to be a dark, very fine-grained to amorphous coating that has evenly and thinly covered the grains in the sandstone. It mimics the rough and uneven surface of the stone, retaining the appearance of individual grains and crystal faces that are underneath it. The crust is thin, varying from 0.03 to 0.07 mm thick, but tightly adheres to the underlying stone. Scanning electron microscopy of the blackened surface shows that even at high magnification, no crystals or particles could be discerned and the crust retains its amorphous appearance (Fig. 3). The absence of crystals at high magnification and the homogeneous, amorphous texture of the surface suggests that dissolution and reprecipitation of some phase has occurred. X-ray diffraction of two samples, selected to concentrate the black crust, showed only quartz, kaolinite (clay), and potassium feldspar to be present, and they are in proportions similar to what was detected on other samples (Table 3). Energy dispersive X-ray analysis with the scanning electron microscope indicates that the crust contains mostly silicon, some aluminum, and very minor amounts of iron, potassium, calcium, and sulfur. Even with identification of the composition and phases in the crust, it is not clear why the crust appears black or why it is tough and relatively impenetrable. It may contain some carbon, possibly from pollutant sources, that we are not able to detect with our instrumentation.

Optical microscopy, scanning electron microscopy, and X-ray diffraction analysis indicate that kaolinite clay is an important constituent of this sandstone. Clays are very fine platy minerals. Because of their crystal form, habit, and composition they are susceptible to the effects of water, and aggregates of fine clays may readily expand and contract as they become hydrated or dehydrated. In the samples from Fort McHenry, the kaolinite is probably the major constituent of the intergranular material. Optical examination, especially of the weathered surfaces, shows that the material is soft and friable and shows evidence of water penetration, by the way some intergranular material has split (opened) into thin layers. The appearance of abundant clay along with the larger scale deterioration observed in the sandstone at Fort McHenry indicate that clay, because of its susceptibility to water, is probably one of the main factors influencing the deterioration of this stone.

Aquia Creek Sandstone

The Aquia Creek sandstone is a light gray and buff sandstone, that is soft and friable (Lent, 1925; Merrill, 1889). It was quarried from the late 1700's to the early 1800's in Stafford county, Virginia along the Potomac River, about 40 miles south of Washington, D.C., where Aquia Creek joins the Potomac. The stone quarried there was commonly called Aquia Creek sandstone or Virginia freestone, but the names "Colonial sandstone" or "George Washington sandstone" may also have been used for it (Lent, 1925; Withington, 1975). The modern name for the geologic formation from which this sandstone was quarried, is the Potomac Group, and it is of lower Cretaceous age.

Latrobe (1809) describes the sandstone from the vicinity of Aquia Creek as varying in color from white to dark rust, and comments that the stone is stratified with layers of clay or pebbles between the sand layers. The pebbles are quartz, sandstone and granite (Latrobe, 1809). Latrobe (1809) also notes that clay nodules in the stone range from "the size of a pea, to many inches in diameter", nodules of iron stain the stone, and pyrite in the stone effloresces in the air and causes localized deterioration. Modern descriptions of the formation are similar, and describe it as light gray to pinkish gray color, a medium to coarse grained feldspar-rich sandstone mixed with clay and having a clay cement (Mixon et al., 1972). Typical sedimentary features of the Potomac Group include: cross bedding, quartz and clay-pebble conglomerates, and boulder sized clay fragments that may reach as much as 2 - 3 feet in maximum dimension (Mixon et al., 1972).

Aquia Creek sandstone used in the Capitol Gatehouse now located at the corner of 17th Street and Constitution Avenue in Washington, D.C., shows many of the typical features described above. The stone is generally light buff or gray in color with occasional bands of red orange staining that seem to accentuate the layers in the stone. Layers and some zones rich in rounded pebble inclusions (approximately 1 to 3 cm diameter) are distinctive features of the stone. Microscopic examination shows that the stone is composed of nearly equigranular grains that average 0.5 mm in size (Table 2). The stone has a mixture of clear, white, light and dark gray, light pink, and a few black grains cemented by a soft tan matrix. The cement is friable and soft in some places, and it does not react with weak acid, indicating that it is a silica or more likely, silica plus clay cement. The stone is predominantly quartz, feldspar, and kaolinite, with minor ilmenite and some gypsum (Table 3). The minor gypsum is probably a recent weathering product. Weathering features of this stone include: accentuation of original bedding layers by loss of intergranular material, hollows where rounded pebbles have fallen out, and loss of thin layers of material by spalling. In some places the outer surface of blocks are bowed out (up to 1 cm) where a new spall is developing.

The quarry at Aquia Creek was acquired by the U.S. government in 1791 so the stone could be used in the construction of federal buildings in Washington D.C. (U.S. Census, 1884). Stone from the quarry was used in a number of important buildings including the White House, the center portion of the U.S. Capitol, and the original portion of the Treasury building (U.S. Census, 1884; Carr, 1950). However, its use was discontinued in about 1837 because the stone was found to have very poor durability (Watson, 1907). Latrobe (1809, p289) described the poor quality of the Aquia Creek stone:

> "The quality of the stone, as a building material, is also in other respects various. Of the stone most even in its grain and texture, most pleasant to work, and of the most durable appearance, a great part cracks and falls to pieces, on exposure to the sun and air, especially if rapidly dried, after being taken from the quarry. Sometimes contrary to all expectation, the frost tears it to pieces. --- All of it expands when wet, and contracts in drying. This property it seems never to lose. When buried in the walls of a heavy building, it is controuled [*sic*] by the incumbent weight, but those blocks that are more at liberty, either at one or both ends, are subject to this variation of size; and the joints of the work open and shut, according to the dryness or humidity of the weather."

Latrobe's description suggests that durability problems with this sandstone are caused by the typical response of clay to changes in moisture in the stone. The presence and abundance of clay and the clay nodules were later (U.S. Census, 1884, p358) specifically indicated as causing the poor durability of the Aquia Creek sandstone:

> "An examination of the buildings constructed of the Aquia Creek sandstone show that numerous clay-holes have appeared, caused by the disintegration of portions of the rock from exposure to the atmosphere. Experience with this stone has proved that within a few years, unless constant attention is given to it by filling the clay-holes and covering with a coat of paint, the stone becomes flimsy and unpresentable."

Summary

The stone used in the quoins at Fort McHenry is most likely Aquia Creek sandstone. The general appearance and sedimentary features, the mineralogical characteristics, and the weathering of the stone at Fort McHenry are similar to literature descriptions of the Aquia Creek sandstone. In addition, visual comparisons between the Fort McHenry stone and stone known to be Aquia Creek sandstone confirm the similarities in large and small scale features. Sedimentary structures such as layering, cross beds, included pebbles, and the manner in which the pebbles occur in the stone are present in both the Fort McHenry and the Aquia Creek sandstones and appear typical in both. Evidence of clay pockets, the tendency of the stone to spall, and the general coloration and weathering surface are all typical of the Aquia Creek sandstone and are readily apparent in the stone at Fort McHenry.

Mineralogical characteristics including the nature, diversity, size, shape and sorting of the grains in the stone at Fort McHenry are quite similar to these characteristics in the Aquia Creek sandstone. On a microscopic scale, the grains have the same general size and shape. The cement of both stones is a clay composition, and the mixture of grains that make up the stone (mostly quartz, feldspar and clay) is similar.

Available historical information also suggests that it is quite likely that the stone used at Fort McHenry was from the Aquia Creek quarries. The United States government purchased the quarries to use the stone for construction of federal buildings. Transportation of stone for building was a problem, especially in the late 1700's and early 1800's, and typically local stone was used for construction when it was available. However, both the quarry and the fort are located so that water transportation of the stone from the quarry to the fort site would not have been very difficult. In addition, there is no mention in the literature that any more local sources of sandstones with characteristics similar to those found in the stone at Fort McHenry were used for building (Merrill and Mathews, 1898) in Baltimore and its vicinity.

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Figures

Figure 1. Sketch of the top view of a bastion at the fort, to identify the parts examined and sampled.

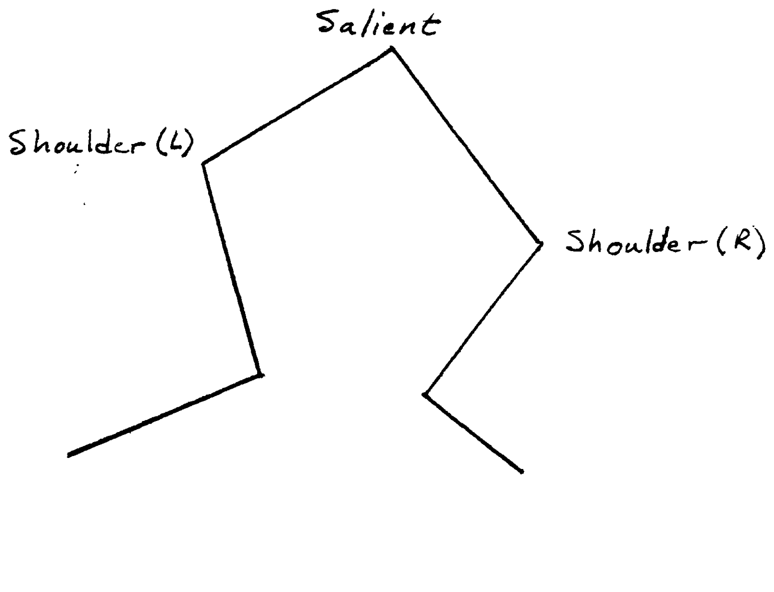

Figure 2. Sketch of sedimentary features typically found in the sandstone quoins at Fort McHenry. A. Thin horizontal bedding plane layers. B. Cross beds form slight angles from the horizontal where grains were laid by wind or water. C. Pebble inclusions form discontinuous layers of unusually coarse grains mixed with the normal grain sizes. D. Concave recession forms scooped out areas on the faces of some blocks. The recessed areas were probably formerly occupied by clay nodules that succumbed to physical weathering processes such as freeze - thaw or hydration and dehydration.

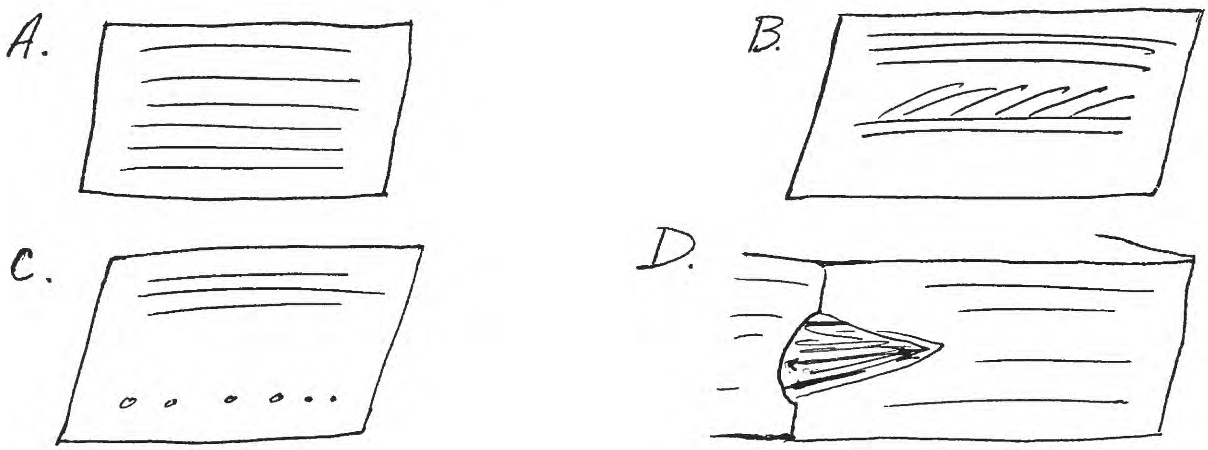

Figure 3. Scanning electron photomicrograph of a blackened crust, sample 724 - 1. Even at high magnification (scale bar, lower right) no crystals or grain structure can be seen, suggesting the crust formed by dissolution and reprecipitation.

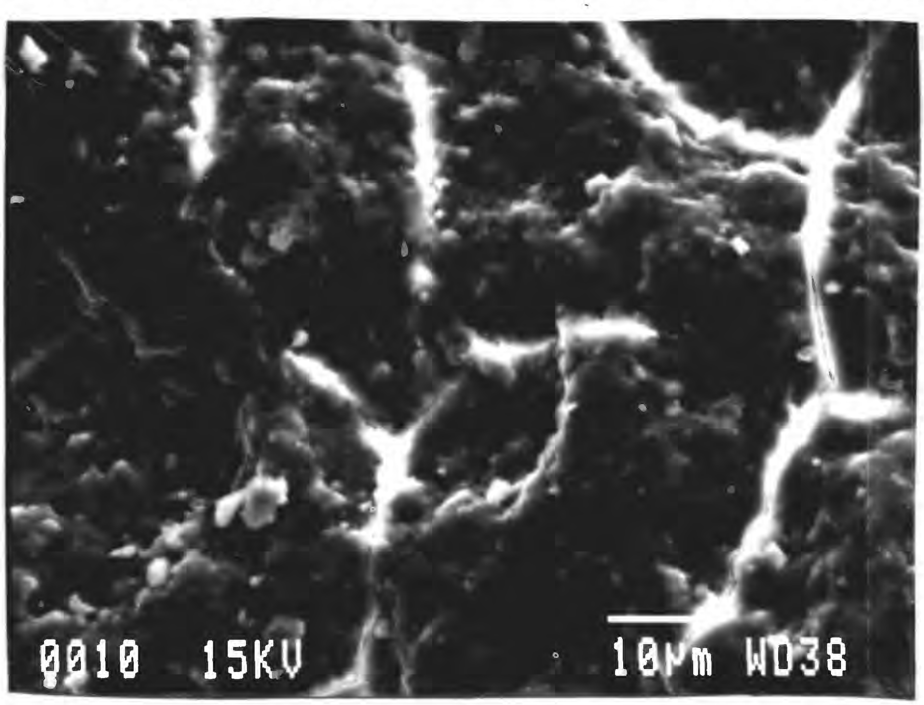

Table 1. Sample locations and brief description

Sample No.	Location	Description
724 - 1	II-L-6	Several small pieces of white to gray stone with black encrustation; one piece is 6 x 3 x 1 mm, rest are 2 - 3 mm aggregates of grains
724 - 2	III-S-7	Tan to light brown pieces, spalled off; 22 x 11 x 2 mm, 14 x 7 x 1 mm, 12 x 6 x 2 mm
724 - 3	IV-R-6	Light tan to beige spall pieces plus small grains; larger pieces are 24 x 18 x 2 mm and 12 x 9 x 2 mm
724 - 4	V-R-7	Large spall piece plus several smaller ones, white to tan stone with extensive black to brown encrustation; pieces are 48 x 18 x 2 mm, 13 x 10 x 2 mm, and 9 x 5 x 2 mm
724 - 5	--R-4	One large piece with several smaller aggregates of grains, tan to beige stone with orange to red zones that form streaks; largest piece is 20 x 10 x 2 mm
Aquia creek	Cap Gthse	White to light gray or beige, friable spall pieces, three are approx. 20 x 15 x 2-3 mm

Location Key: *Bastion number - shoulder* (Left or Right) *or salient* (S) - *stone number* (from the top).

Sample number 724-5 was taken from a separate structure near the front entrance to the fort and does not have a bastion number.

The Aquia Creek sample is a spall piece from the Capitol Gatehouse (Cap Gthse) located at 17th Street and Constitution Avenue, NW, in Washington, DC.

Table 2. Grain sizes

Sample No.	range (mm)	avg. (mm)
724 - 1	.53 - 1.07	.69
724 - 2	.17 - .57	.39
724 - 3	.33 - .67	.48
724 - 4	.33 - .67	.51
724 - 5	.33 - .67	.48
Aquia Crk	.33 - 1.0	.53

Grains were randomly selected for measurement using the optical microscope. The longest dimension of the grain was measured and tabulated. Ten to twenty easily distinguished grains were measured on each sample.

Table 3. Estimated abundances of mineral constituents from X-ray diffraction

Sample No.	Quartz	Feldspar	Kaolinite	Other
724 - 3	78%	15%	7%	
724 - 5	60%	30%	10%	
724 - 1	75%	15%	10%	
724 - 4	75%	15%	10%	
Aquia Crk	60%	15%	5%	Gypsum 20%

Sample 3 was selected to represent the average sample, most similar in appearance to the Aquia Creek sample that we had. Sample 5 was selected because it contained more of the red-orange coloration in the intergranular areas. Samples 1 and 4 were selected to include as large a proportion as possible of the black surficial encrustation. We estimate that black crust composed at least 70% of sample 4, that was analyzed.

Gypsum was found in the Aquia Creek sample but was not detected on any of the samples from Fort McHenry. Small grains of gypsum were found as alteration grains on the Aquia Creek sample when it was examined with scanning electron microscopy. Since this stone does not contain any calcium carbonate (either as grains or in the cement) the presence of gypsum is puzzling. However, this sample has had an exposure history that probably differs significantly from that experienced by the Fort McHenry samples, that may explain the slight difference in phases detected by X-ray diffraction. The Aquia Creek sample was taken from the Capitol Gatehouse building now located at the corner of 17th Street and Constitution Avenue in northwest Washington, DC. The gatehouse was originally located at the west entrance to the Capitol, from 1828 until 1874; in 1880 it was reconstructed at its present site.