Geoheritage (2020) 12:4
https://doi.org/10.1007/s12371-020-00426-x

ORIGINAL ARTICLE

An Historical Geoarchaeological Approach to Sourcing an Eighteenth Century Building Stone: Use of Aquia Creek Sandstone in Christ Church, Lancaster County, VA, USA

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Received: 16 July 2019 / Accepted: 7 January 2020

Abstract
Historic Christ Church in Lancaster County, VA (1735), is one of America's best-preserved examples of colonial Georgian architecture. Among its many architectural highlights is the beautiful stone trim that adorns the brick church's doorways and windows. As it ages, conservation of original stone architectural elements is becoming necessary. The goal of this study is to determine the source of the exterior stones so appropriate matches can be acquired when repairs or replacement of some elements are needed. It will also help elucidate Christ Church's construction history. We compared stone samples from Christ Church's steps and keystones to samples taken from the famous Aquia Creek quarry on Government Island in Stafford County, VA, that provided the stone for America's first federal buildings (e.g., White House, Capital, Treasury). We used standard petrographic thin-section analysis to compare the samples' grain size, sorting, and mineralogy. Both stones are moderately sorted, medium sand sized, subarkose sandstones. Based on this as well as historical evidence, we suggest that the steps at the north, south, and west doors as well as the stone elements around the windows and doors of the church are made of the Cretaceous Aquia Creek sandstone quarried on Government Island. Within the quarry, the sandstone most likely came from the upper Patapsco Formation of the Potomac Group rather than the lower Patuxent Formation. This information should be kept in mind as Aquia Creek sandstone has a history of premature weathering and may require shorter term maintenance and longer term replacement.

Keywords Sourcing · Provenance · Aquia Creek sandstone · Christ Church

Introduction

Importance of Determining Provenance

Why is it important to determine the provenance of stone building material in historic buildings, especially ones as significant as Christ Church? The provenance of a dimension stone refers to its geologic source. The geologic source is usually a quarry, mine, or rock outcrop. By a dimension stone, we mean a natural rock that has been worked to a specific size and/or shape such as a building stone or tombstone.

Knowing the provenance or source of stone materials helps understand ancient trade routes (Thibodeau et al. 2018). The oldest and perhaps most famous example of determining the provenance of dimension stones comes from the 3100 B.C. Stonehenge sarsens and blue stones (Johnson 2008; Bevins et al. 2011). It is also important to know the provenance of dimension stones as it assists in finding suitable replacement stone for conservation. Identifying the source of building stones helps determine the factors that cause stone decay (Přikryl and Smith 2005; Cassar et al. 2014) and assists in recognizing and thus reducing the problems of poor substitute stone selection (Rozenbaum et al. 2008). This has become an essential component of the work of conservators as they attempt to find suitable replacement material for preservation and restoration work.

The objective of this study is to apply historical geoarchaeological sourcing techniques to determine the provenance of the exterior sandstone architectural elements in Christ Church (1735), Lancaster County, VA, USA. Based on a variety of historical and geological observations below,

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our hypothesis is that these elements are made of Aquia Creek sandstone, a Cretaceous sandstone from the Maryland-Virginia region.

Christ Church

Christ Church is registered with the U.S. National Park Service (National Historic Landmark Number 66000841), the Historic American Buildings Survey (HABS VA, 52-KILM.V, 1), and the Virginia Department of Historic Resources (ID number 051-0004). It is located in Lancaster County in the Northern Neck of Virginia in the Outer Coastal Plain physiographic province at 37°40′50.32″N latitude and 76°25′23.36″W longitude (Fig. 1). Construction began in 1730 and was completed in 1735 (Neblett 1994). Today the brick church (Fig. 1) appears much like it did nearly three centuries ago. Included in its outstanding collection of original architectural features are the subjects of this study, the exterior stone elements consisting of the steps at the north, south, and west doors (Fig. 2(a)) as well as the stone features around the windows and doors (Fig. 3).

The stone steps consist of a two-level semi ellipse with the second step forming a larger flat stoop. They are on average 4.5 m wide and 1.4 m deep (Harms and Neubauer 1992a). The west steps lead up to the main entrance of the Church and are 20 cm deeper. The steps are constructed of on average 24 individual stones. The south steps contain the fewest stones (17). With 41 stones, the west steps have the most because they comprise the largest area and presumably, they received the most wear from visitors over the years and thus have had parts of larger stones replaced by smaller stones (Fig. 2(c)).

Christ Church's builders used stone to decorate the church's soaring windows and rubbed and gauged brick doorways (Fig. 3) considered by many architectural historians as one of America's finest and best-preserved examples of colonial Georgian architecture (Gowans 1969; Loth 1986; Upton 1997; Lounsbury 2004). The 12 compass windows have stone sills with keystones and stone imposts in the rubbed-brick arches; the three small oval windows over the doors have small keystones centered top and bottom and at each side (Neblett 1994). At the doorways, stone is used in the pilasters, pedestal caps, and bases and in the keystones and imposts in the small brick arch framing the west door.

Aquia Creek Sandstone

Aquia Creek sandstone is registered with the National Building Stone Database (Mueller 2010) and was included in the earliest systematic surveys of the dimension stone industry for the US Census and the US National Museum's building stone collection (Hawes 1884; Merrill 1889, 1891). In this paper, we use the term Aquia Creek sandstone as there are two sandy stratigraphic units that outcrop along Aquia Creek: the upstream, Cretaceous, well-indurated sandstone of the Potomac Group and the downstream, Paleocene, generally unlithified sands of the Aquia Formation (Mixon et al. 2000, pl. 1). The former is the focus of this study.

Aquia Creek sandstone is also referred to as Aquia Stone, Virginia Freestone, Aquia Freestone, Colonial Freestone, Colonial Sandstone, or George Washington Stone (Lent 1925; Withington 1975). These are informal builders' terms, not stratigraphic terms. Aquia Creek sandstone is not from the Aquia Formation. The Aquia Formation of the Pamunkey Group is a clayey, silty, shelly, glauconitic fine to medium quartz sand deposited during the Paleocene epoch of the Paleogene period whose type locality is Aquia Creek in

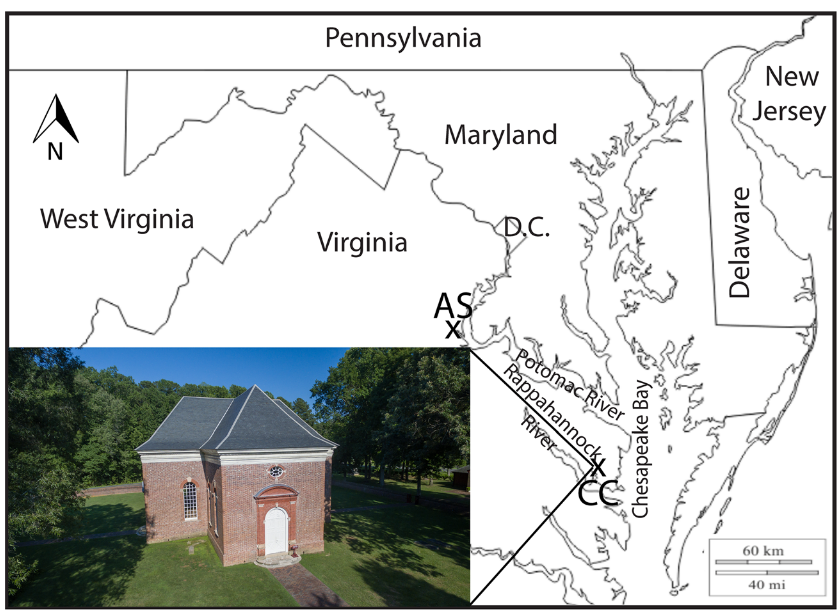

Fig. 1 Map showing location of Christ Church (CC and insert) relative to the Aquia Creek sandstone quarry on Government Island (AS). D.C. = federal capital of Washington, District of Columbia. Photograph by Charles R. Lawson

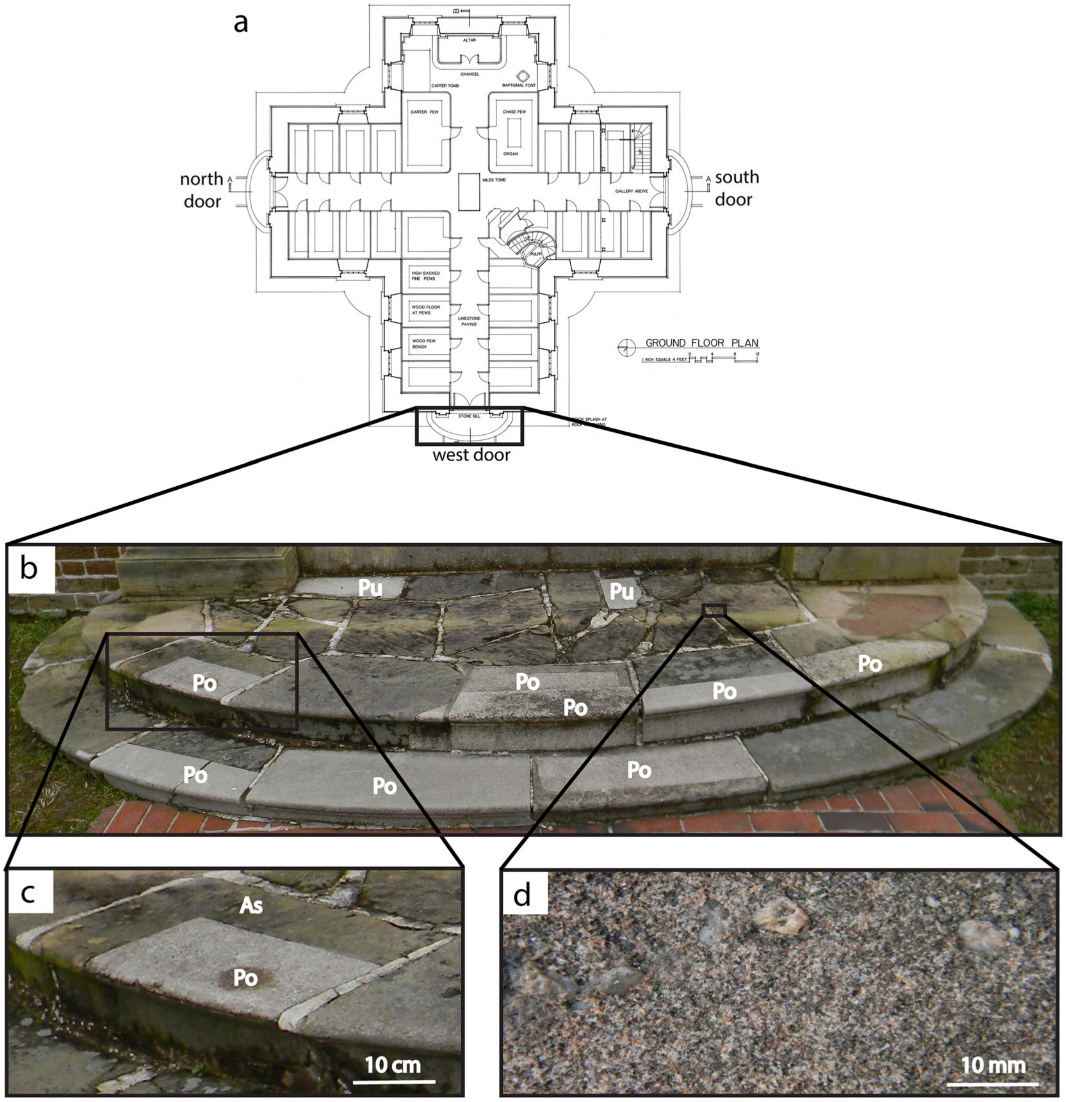

Fig. 2 Christ Church ground floor plan (a) modified from Evans et al. (1983). Stones steps of west entrance to Christ Church (b). Aquia Creek sandstone step showing part of the step that was replaced by Portland stone (c). Close up view of Aquia Creek sandstone step showing sediment grains (d). Pu = Purbeck stone, Po = Portland stone, Unlabeled or As = Aquia Creek sandstone

Stafford County, downstream from where Aquia Creek sandstone was quarried (Mixon et al. 2000, 2005; Powars et al. 2015). Thus, the Aquia Formation is not the same age or lithology of the focus of this study, the Aquia Creek sandstone.

Aquia Creek sandstone is part of the Potomac Group, a Cretaceous package of two to three formations. From oldest to youngest, they are the Patuxent and Patapsco formations with some recognizing an Arundel Fm. between the two. Some authors demote the Potomac Group to formation status with the Patuxent and Patapsco becoming members. Based on pollen and macro-plant fossils, the Patapsco Fm. was deposited in the Albian-Cenomanian stages of the Lower-Upper Cretaceous, ~110–97 Ma. The sediments were deposited in a meandering fluvial-deltaic system with channel, point bar, overbank, and floodplain facies resulting in vertical and lateral sedimentologic variation. The most common lithology is an oxidized, silica-cemented, moderately well to poorly sorted, fine to coarse, feldspathic quartz sand with occasional gravels and clay rip up clasts. It is typically gray or tan, sometimes with streaks or shades of red, yellow, or buff (Glaser 1969; Doyle and Robbins 1977; Powars and Bruce 1999; Powars 2000; Mixon et al. 2005; Mueller 2010; Jud 2015; Powars et al. 2015; Miller et al. 2017).

Aquia Creek Quarries

The original Aquia Creek quarry is located at the head of the tidewater on Aquia Creek in Stafford County in the Outer Coastal Plain physiographic province at 38°26′58.78″N latitude and 77°22′48.49″W longitude (Fig. 1). It is known as the Public Quarry at Government Island and is registered with the

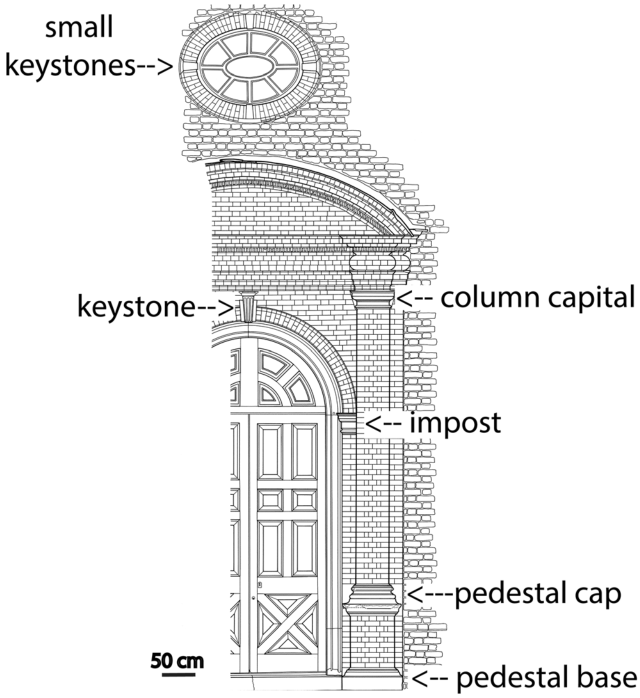

Fig. 3 Christ Church west entrance half elevation and profile modified from Harms and Neubauer (1992b). Aquia Creek sandstone architectural elements are labeled

U.S. National Park Service (National Historic Landmark Number 03000457) and the Virginia Department of Historic Resources (ID number 089-0103).

The Brent family, originally from Maryland, operated the Aquia Creek quarries on a small scale beginning in the late 1600s for tombstones, doorsteps, and foundation stones (Table 1; Conner 2005; Seale 2017). Aquia Creek sandstone tombstones from this time are common in Stafford County, VA, and St. Mary's County, Maryland (Conner 2005; Mackie III 1988; Crowell and Mackie III 1990). In 1791, the federal government purchased Brent's Island (a.k.a., Wigginton's Island) in Aquia Creek to allow larger scale extraction of stone for the new buildings in the new federal capital (Table 1; Seale 2017). The quarry on the island became known as Public Quarry and the island (actually a peninsula) became known as Government Island. This quarry was one of the big five quarries along Aquia Creek. These were large commercial ventures that produced considerable quantities of sandstone that was used in the construction of buildings in Washington, DC and elsewhere (Table 1). The other four quarries in this group were Gibson's (located right across Aquia Creek from the "island"), Rock Rimmon (~ 1 km downstream and across the creek), Mt. Pleasant, and Robertson's (~ 2–3 km inland from the creek).

Christ Church is 120-km straight line distance from the Aquia Creek quarries (Fig. 1). The cut stones were probably not transported over land due to their weight (density averages 2 g/cm^3; Hockman and Kessler 1957) and poor land-based transportation infrastructure at that time. For example, the Aquia Creek sandstones quarried for the buildings in Washington, DC in the 1790s were not transported by land, but by boat 64 km (40 mi) up the Potomac River (Nelson 1992; Conner 2005; Seale 2017). The distance by boat down Aquia Creek, down the Potomac River, and the Chesapeake Bay then up the Rappahannock River to Carters Creek near Christ Church is at least 200 km (125 mi) (Fig. 1).

Materials and Methods

First, we surveyed the literature for mentions of Aquia Creek sandstone being used in buildings, including in any architectural elements in Christ Church. Unfortunately, few reports of Aquia Creek sandstone use involve a thorough petrologic analysis to confirm the stone was actually Aquia Creek sandstone. In these reports, like most, identification was probably either assumed or based on a gross superficial similarity in general appearance to other known uses of the stone.

Second, we sampled stones from Christ Church and the Aquia Creek quarry. The standard method for classifying sandstones uses petrographic thin sections (Krumbein and Pettijohn 1938). This requires a destructive process involving cutting out a ~ 2-cm^3 stone sample. As the stone steps are still used by visitors today and Christ Church is a National Historic Landmark, we wanted to avoid defacing the steps during our sampling. Therefore, we chose to use samples in the church museum's archives that came off the building by weathering or during previous restoration work. Some of the stone steps have been replaced over the years as almost 300 years of exposure to weathering and visitor foot traffic has worn them down. The different colors of the stones in the steps (Fig. 2(b)) may be partly attributed to replacement over the years. Black and white photographs taken on 25 April 1937 show the steps in the north and west doors consisting of larger stone blocks compared with the smaller piecemeal arrangement seen today (Fig. 2(b)). Maintenance records for the church indicate all three stone entrance ways were dismantled, new foundations built, and the original stones re-laid in the latter half of the 1900s (Neblett 1994). At some time, all three door sills were replaced with concrete (Neblett 1994). Two plinths under the pedestal bases of the west door were refaced with concrete, likely in the 1920s (Neblett 1994).

From the Christ Church's museum archives, we found three samples of stone steps (CC1 to CC3) and one sample of a keystone (CC4) that had the same general color, lithology, and carved shapes of the existing steps (Fig. 2(d)) and keystones. From the original quarry on Aquia Creek (i.e., on Government Island), we took fives samples (AS1–AS5). As the quarry is of historic importance, part of a county park and on the National Register of Historic Places and the Virginia Landmarks Register (Hansen 2002), our samples were

Table 1 Major architectural structures (e.g., not tombstones) that used Aquia Creek sandstone in their construction arranged by year

Building	Approximate year of construction	Location	Architecturally where Aquia Creek sandstone is used	Reference(s)
Nelson House	1730	Yorktown, VA	Quoins and window trim	Conner 2005
Christ Church	1735	Irvington, VA	Door steps, frontispieces, surrounds, and keystones	Neblett 1994; Lounsbury 2004; this study
Sabine Hall	1742	Warsaw, VA	Lintels, keystones, and for the central windows	Neblett 1994
Cleve Plantation	1746	King George Co., VA	Quoins	Mooney 2008
Carlyle House	1753	Alexandria, VA	Walls	Neblett 1994; Scott 1998; Conner 2005; Maloney 2012; Seale 2017
Aquia Church	1755	Stafford, VA	Quoins, window keystones, and door lintels	Studebaker 1959; McKee 1973; Sweet 1990; Webb and Sweet 1992; Neblett 1994; Upton 1997; Jones 2002; Conner 2005; Maloney 2012
Johnston-Vowell House	1757	Alexandria, VA	Flat arches with keystones	Stanton 2019
Mount Vernon	1757	Mount Vernon, VA	Main house doorsteps, piazza walkways, greenhouse keystone, grist mill	Studebaker 1959; Schlesinger 1981; Webb and Sweet 1992; Scott 1998; Jones 2002; Conner 2005; Maloney 2012; Mountford 2012; Seale 2017
Gunston Hall	1758	Fairfax Co., VA	Quoins, chimney caps, keystones to the flat arches	Studebaker 1959; Schlesinger 1981; Scott 1998; Jones 2002; Conner 2005; Maloney 2012; Seale 2017
1st Town Hall/Market House	1763	Fredericksburg, VA	Ground floor arches	Millar 2014
Mount Airy	1764	Richmond Co., VA	Quoins, architraves, horizontal bands, window trim, entrance pavilions, and pedestals at the top of terrace steps that support a pair of stone urns	Neblett 1994; Scott 1998; Jones 2002; Wells 2003; Lounsbury 2004; Conner 2005
Williams Ordinary	1765	Dumfries, VA	Quoins and door trim	Conner 2005
Mannsfield	1766	Spotsylvania Co., VA	Quoins and surrounds for the doors and windows	Barnette 1936
Christ Church	1773	Alexandria, VA	Quoins and window keystones	Studebaker 1959; Webb and Sweet 1992; Scott 1998; Jones 2002; Conner 2005; Maloney 2012; Seale 2017
Cape Henry Lighthouse	1773	Virginia Beach, VA	Windows, door trim, and foundation	Studebaker 1959; Webb and Sweet 1992; Conner 2005
Pohick Church	1774	Ft. Belvoir, VA	Quoins, door frames, facing, and steps	Studebaker 1959; Webb and Sweet 1992; Scott 1998; Conner 2005; Maloney 2012
Kenmore Plantation	1775	Fredericksburg, VA	Front portico and rear steps facing Rappahannock River	Conner 2005
Dalton-Herbert House (a.k.a., Wise's tavern)	1777	Alexandria, VA	Front doorway	Stanton 2019
Masonic Cemetery	1784	Fredericksburg, VA	Perimeter wall and tombstones	McCarthy and Ginell 2001; Seale 2017
Jonah Thompson Houses	1790	Alexandria, VA	Arched doorways, flat arches with keystones	Sutton 1959; Stanton 2019
Murry-Craik House	1790	Alexandria, VA	Flat arches with keystones	Stanton 2019
Gen. Daniel Roberdeau House	1790	Alexandria, VA	Flat arches with keystones	Stanton 2019
Edmund J. Lee House	1791	Alexandria, VA	Front steps	Stanton 2019
DC boundary	1791	Washington, DC	Boundary stones	Carr 1950; Terman and Terman 1972; Withington 1975; McGee 1994; McCarthy and Ginell 2001; Robbins and Welter 2001; Conner 2005; Maloney 2012; Seale 2017
White House	1792	Washington, DC	Walls and architectural details around the front entrance and stables; fence capping	Carr 1950; Hockman and Kessler 1957; Studebaker 1959; Sweet 1990; Nelson

Table 1 (continued)

Building	Approximate year of construction	Location	Architecturally where Aquia Creek sandstone is used	Reference(s)
				1992; Scott 1998; Withington 1998; Robbins and Welter 2001; Jones 2002; Conner 2005; Seale 2008, 2017; Mountford 2012; Aloiz et al. 2016
U.S. Capitol	1793	Washington, DC	Interior and exterior walls; columns in crypt	Carr 1950; Hockman and Kessler 1957; Studebaker 1959; Campioli 1971; Clifton 1987; Sweet 1990; Office of the Architect of the Capitol 1998; Scott 1998; Withington 1998; Allen 2001; Robbins and Welter 2001; Jones 2002; Conner 2005; Mountford 2012; Hannibal and Bolton 2015; Livingston et al. 2015; Aloiz et al. 2016; Seale 2017
Potts-Fitzhugh House	1795	Alexandria, VA	Steps	Bailey and Lee 1975
Fort McHenry	1798	Baltimore, MD	Quoins	McGee and Woodruff 1992; Hannibal and Bolton 2015
Octagon House	1799	Washington, DC	Stone trim in horizontal bands and plaques	Conner 2005
Vowell-Snowden-Black House	1800	Alexandria, VA	Foundation, front stoop and steps	Bailey and Lee 1966; Stanton 2019
Riversdale Mansion	1802	Riverdale, MD	Porch columns	Riversdale House Museum 2019
Arlington House	1802	Arlington, VA	Window sills	Studebaker 1959; Arnest III and Sligh 1985
Woodlawn Plantation	1805	Mount Vernon, VA	Window sills and lintels, doors, and basement coping	Conner 2005
Congressional Cemetery	1812	Washington, DC	Cenotaphs	Conner 2005; Seale 2017
Stone Warehouse	1813	Fredericksburg, VA	Walls and columns	Webb and Sweet 1992
Monumental Church	1814	Richmond, VA	Walls and columns	Webb and Sweet 1992; Conner 2005
2nd Town Hall/ Market House	1816	Fredericksburg, VA	Foundation	Schemmer 2016
Thomas Lawrason/ Lafayette House	1816	Alexandria, VA	Flat window arches with fluted keystones, elliptical arched stone porch and doorway	Jay 2014; Stanton 2019
Basilica of the Assumption	1821	Baltimore, MD	Large, rectangular panels on the upper sides of the building and two smaller blocks above the two front doors that flank the larger main front door of the Basilica	Hannibal and Bolton 2015
Wye House cemetery	1825	Eastern Shore of MD	Monuments belonging to Col. Edward Lloyd (d. 1796) and his wife Elizabeth Lloyd (d. 1825)	Rude and Eisenberg 1995
U.S. Capitol	1826	Washington, DC	East front portico columns	Studebaker 1959; McCarthy and Ginell 2001; Conner 2005; Jordan 2012; Livingston et al. 2015; Aloiz et al. 2016; Seale 2017
U.S. Capitol	1828	Washington, DC	Gate/guardhouses and gateposts	Hockman and Kessler 1957; Black et al. 1993; Withington 1998; Robbins and Welter 2001; Jones 2002; Conner 2005; Livingston et al. 2015; Aloiz et al. 2016; Seale 2017
Chesapeake and Ohio Canal Locks nos. 1–7	1828	Georgetown, DC to Bethesda, MD	Dressing on lock walls	Withington 1998; Robbins and Welter 2001; Jones 2002; Conner 2005; Southworth et al. 2008
Wisconsin Avenue Bridge over the Chesapeake and Ohio Canal	1831	Georgetown, DC	Barrel and walls	Conner 2005; Withington 1975, 1998; Livingston et al. 2015

Table 1 (continued)

Building	Approximate year of construction	Location	Architecturally where Aquia Creek sandstone is used	Reference(s)
Fort Monroe	1834	Hampton, VA	Main sally port walls	Webb and Sweet 1992; Conner 2005
Old U.S. Patent Office	1836	Washington, DC	Walls and interior columns of the original south wing	Johnson 1851; Carr 1950; Hockman and Kessler 1957; Sweet 1990; Withington 1998; Robbins and Welter 2001; Jones 2002; Conner 2005; Mountford 2012; Livingston et al. 2015; Aloiz et al. 2016; Seale 2017
Old U.S. Treasury	1846	Washington, DC	Original walls	Hockman and Kessler 1957; Sweet 1990; Withington 1998; Robbins and Welter 2001; Jones 2002; Conner 2005; Mountford 2012; Seale 2017
Stone wall along Sunken Road	1862	Fredericksburg, VA	Civil War battle site	Flora and Sherwood 2001
Cemetery Lodge, Fredericksburg National Military Cemetery	1880	Fredericksburg, VA	Walls	Webb and Sweet 1992
National Cathedral	1920	Washington, DC	Walls surrounding the Bishop's Garden and 51 steps leading to the south transept entrance, known as Pilgrim Steps	Washington National Cathedral 2017
Harkness Hall, Yale University	1927	New Haven, CT	Exterior walls	Klein 2003
Joslyn Art Museum	1927	Omaha, NE	Interior walls of the Storz Fountain Court	Joslyn Art Museum 2013
Old Planters National Bank	1927	Fredericksburg, VA	Foundation, cornice, quoins, as well as window surrounds, and door trim	Wrenn 2003
Number:	53			
Minimum:	1730			
Mean:	1803			
Maximum:	1927			
Standard deviation:	47			

restricted to float samples collected at the surface away from the public trail. Samples were selected to maximize lithologic variation. A ~2-cm^3 block was cut from each sample which was then vacuum-impregnated with epoxy resin for thin sectioning. The repository for all thin sections and remnants is the Historic Christ Church museum archives.

The thin sections were digitized (Fig. 4) on a high-resolution scanner. Grain size was determined for each grain intersected by a line drawn perpendicular to bedding across each thin section. This was to maximize stratigraphic variation in lithology. We measured the maximum diameter of each grain to best characterize grain diameter in thin section views that do not necessarily pass through the centers of the grains. Grain diameter was measured to the nearest 10 µm using ImagePro Express 5.0 image analysis software (Media Cybernetics 2004) running on a Nikon Eclipse E400 POL

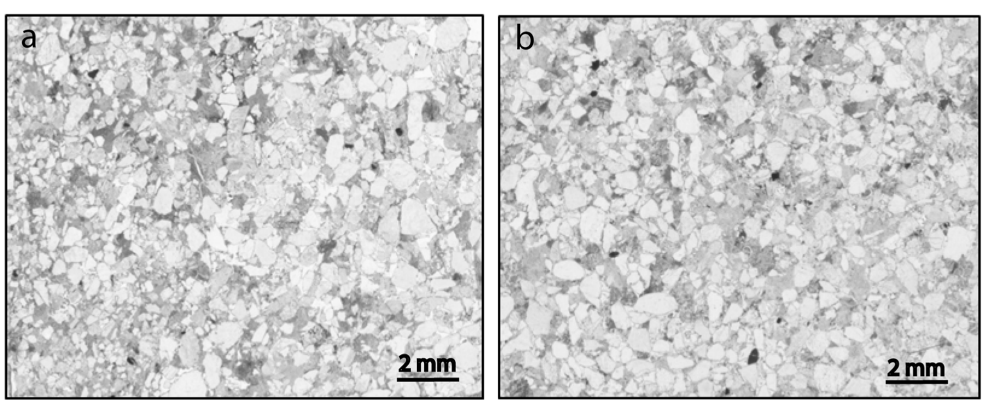

Fig. 4 Photomicrographs in plane light of thin sections comparing grain size, sorting, and shape between Christ Church stone steps ((a), sample CC1) and Aquia Creek Government Island quarry ((b), sample AS4). Both are moderately sorted coarse sandstones. Lighter grains are quartz and darker grains are feldspar, rock fragments, or heavy minerals

microscope. Grain size descriptive statistics were determined using the standard geometric method of moments in GRADISTAT (Blott and Pye 2001). We determined grain mineralogy for each grain whose diameter was measured using the same polarizing petrographic microscope. The percentages of grains that were quartz (Q), feldspar (F), or rock fragment (R) were calculated for use in a standard Q:F:R ternary diagram using Folk's (1974) sandstone classification. We also characterized the samples by color, grain roundness, matrix, heavy mineral content, and cements. Color was determined on weathered and unweathered surfaces using the standard Munsell (2009) rock color classifications. Grain roundness was determined using the standard Powers (1953) roundness scale. The composition of the matrix, heavy minerals, and cements was determined using the same polarizing petrographic microscope.

Results

Of the 53 uses of Aquia Creek Sandstone in buildings documented in the literature, the earliest we could find was 1730 when it was used in the Nelson House in Yorktown, VA (Table 1). Christ Church was the second oldest use of Aquia Creek sandstone (Fig. 5). Use peaked in the 1790s (Fig. 5) with the construction of the White House and US Capital in Washington, DC (Table 1). By 1880, Aquia Creek sandstone was no longer being used due to deterioration concerns. There was a short-lived rebirth from 1925 to 1930 with the George Washington Stone Corp. producing a product called Colonial Freestone from the Mt. Pleasant and Rock Rimmon quarries, but they closed in 1931 (Table 1; Conner 2005; Mountford 2012).

In the four thin sections from Christ Church, 95 grains were analyzed (Table 2). They ranged in size from 110 to 1570 μm

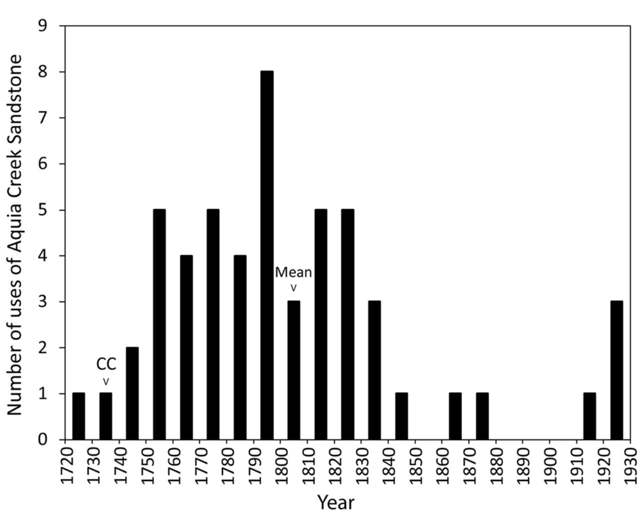

Fig. 5 Timeline of documented uses of Aquia Creek sandstone from Table 1. Note that Christ Church (CC) is the second oldest

($\bar{x}$ = 478 μm; σ = 1.63 μm). This represents a moderately sorted medium sandstone (Fig. 6). Based on the relative frequency of quartz, feldspar, and rock fragment grains, a standard Q:F:R (%Quartz:%Feldspar:%Rock Fragment) ternary diagram (Fig. 7) shows that mineralogically the four samples from Christ Church include two subarkoses, one sublitharenite, and one quartzarenite. Based on the mean relative frequency of quartz (90.0%), feldspar (5.6%), and rock fragment grains (4.4%), the Christ Church samples are on average subarkoses (Table 2; Fig. 7).

In the five thin sections from the Aquia Creek quarry, 240 grains were analyzed (Table 2). They ranged in size from 80 to 6270 μm ($\bar{x}$ = 434 μm; σ = 1.74 μm). This represents a moderately sorted medium sandstone (Fig. 6). Based on the relative frequency of quartz, feldspar, and rock fragment grains, a Q:F:R ternary diagram (Fig. 7) shows that mineralogically the five samples from Aquia Creek quarry include two subarkoses, one sublitharenite, one quartzarenite, and one lithic arkose. Based on the mean relative frequency of quartz (87.3%), feldspar (7.5%), and rock fragment grains (5.2%), the Aquia Creek quarry samples are on average subarkoses (Table 2; Fig. 7).

Ideally, more grains would have been measured as the standard number is 300 (Krumbein and Pettijohn 1938). Due to the historically important nature of the source of the samples from both the church and the quarry, we were limited to just a few small samples. Were enough grains measured to characterize the grain size distribution of these two populations? To answer this, we employed an approach similar to rarefaction analysis that is often used to determine if enough individuals have been collected to determine the biodiversity of a location (Gotelli and Colwell 2001). The grains were randomly sorted, and the cumulative mean grain size was calculated starting with the inclusion of just one grain and ending with all 335 grains. A stable mean (i.e., medium sand) was achieved after 69 grains. Because the number of grains measured in each population (i.e., 95 and 240) is at least 38% more than this amount, the calculated mean grain sizes are considered robust.

To determine if the grain sizes were different between the Christ Church samples and the Aquia Creek quarry samples, we did a *t* test to compare the means. The results show no significant difference between the mean grain sizes of the two groups of samples ($P = 0.666$). Not only are the Christ Church sandstones and the Aquia Creek quarry sandstones indistinguishable in grain size, sorting, and mineralogy (Table 2), they also both have the same distinctive bimodal distribution (Fig. 6). Fluvial-deltaic sediments such as these often have a bimodal distribution (Sambrook Smith 1996; Sambrook Smith et al. 1997).

The unweathered surfaces of the Christ Church samples ranged from white (hue 5 Y 8/1) to very pale brown (hue 10 YR 8/2) with light gray (1 for gley 7/N) being the most common. The weathered surfaces ranged from gray (hue 10 YR

Table 2 Grain size distribution summary statistics and lithology of the Christ Church (CC) versus Aquia Creek quarry (AS) samples. Grain size statistics calculated using the geometric method of moments in Gradistat (Blott and Pye 2001)

Thin section	Number of grains analyzed	Mean grain size (μm)	Grain size	Grain size standard deviation (μm)	Sorting	% quartz grains	% feldspar grains	% rock fragment grains	Lithology (Folk 1974)
CC1	26	503	Coarse sand	1.92	Moderately sorted	92	0	8	Sublitharenite
CC2	22	483	Medium sand	1.50	Moderately well sorted	90	5	5	Subarkose
CC3	21	424	Medium sand	1.71	Moderately sorted	100	0	0	Quartzarenite
CC4	26	499	Medium sand	1.31	Well sorted	80	16	4	Subarkose
	Mean:	478	Medium sand	1.63	Moderately sorted	90.0	5.6	4.4	Subarkose
AS1	71	361	Medium sand	1.55	Moderately well sorted	86	9	5	Subarkose
AS2	39	555	Coarse sand	1.48	Moderately well sorted	89	8	3	Subarkose
AS3	70	314	Medium sand	1.53	Moderately well sorted	89	5	6	Sublitharenite
AS4	28	672	Coarse sand	1.74	Moderately sorted	70	19	11	Lithic arkose
AS5	32	680	Coarse sand	1.63	Moderately sorted	100	0	0	Quartzarenite
	Mean:	434	Medium sand	1.74	Moderately sorted	87.3	7.5	5.2	Subarkose

6/1) to pinkish gray (hue 7.5 YR 7/2) with the latter being the most common. The unweathered surfaces of the Aquia Creek quarry samples ranged from light gray (1 for gley 7/N) to light yellowish brown (hue 10 YR 6/4) with the former being the most common. The weathered surfaces ranged from pinkish gray (hue 7.5 YR 7/2) to reddish brown (hue 5 YR 5/4) with the former being the most common. Therefore, the colors of these sandstones are similar, but the Aquia Creek quarry samples are slightly more variable and browner. Others have also

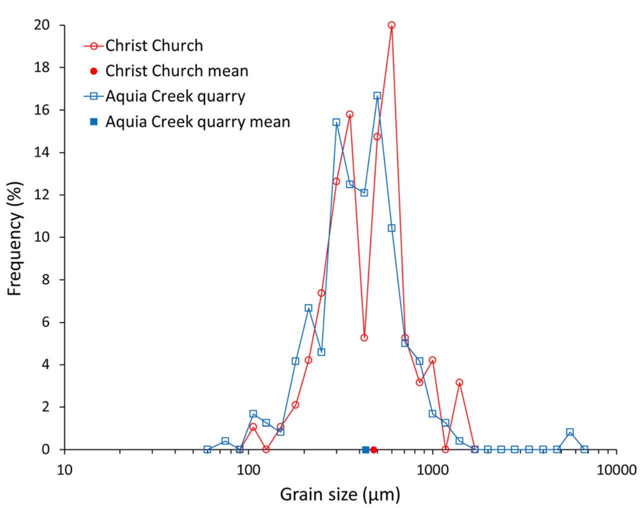

Fig. 6 Grain size distributions of sandstones from Christ Church and Aquia Creek quarry showing the moderately sorted bimodal distribution of each and the almost identical medium sand mean grain sizes

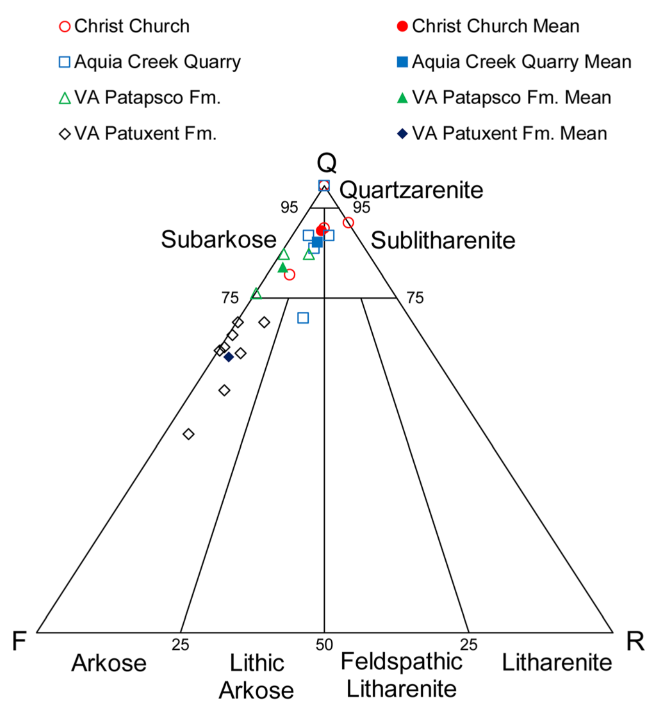

Fig. 7 QFR (%Quartz:%Feldspar:%Rock Fragment) triangular sandstone classification comparing sandstones from Christ Church and the Aquia Creek quarry to the Patapsco and Patuxent Formations of the Potomac Group in Virginia. Data for the latter two come from Glaser (1969). Sandstone classification based on Folk (1974)

reported fresh surfaces of Aquia Creek sandstone as being white to light gray with occasional stains of brownish yellow (Hockman and Kessler 1957; Mixon et al. 2005). In contrast, weathered surfaces have been described like ours as light gray to medium gray to pinkish gray (McGee and Woodruff 1992; Mixon et al. 2005). Conner (2005) attributed the redder colors to the presence of iron oxide cements, and the grayer colors to silica cement.

Roundness of the sand grains was variable and ranged from sub-angular to sub-rounded in both the Christ Church and Aquia Creek quarry samples. Others have reported similar grain roundness in the Aquia Creek sandstone (Hockman and Kessler 1957; McGee and Woodruff 1992; Black et al. 1993; Robbins and Welter 2001). Glaser (1969) noted the quartz grains were more angular than the feldspar and rock fragment grains.

The matrix of both the Christ Church and Aquia Creek quarry samples was indistinguishable. They were both a clay-silt matrix. Glaser (1969) and Obermeier (1984) attributed the matrix of the Aquia Creek sandstone to weathered rock fragments and authigenic kaolinite derived from weathering of the feldspar grains after deposition.

Using Glaser's (1969) heavy mineral identification criteria, we were able to identify the main heavy mineral species. As they form < 7 wt% of the grains in the Virginia part of the Potomac Group's outcrop belt (Glaser 1969), they were rare in our thin sections. The most common heavy mineral species in both the Christ Church and Aquia Creek quarry samples were zircons, undifferentiated opaques, and possibly staurolites. Glaser (1969) interpreted the presence of these heavy minerals as indicative of a provenance in the Piedmont immediately to the west.

The cements of both the Christ Church and Aquia Creek quarry samples were variable and thus indistinguishable. Some were well cemented and more silica-based, whereas others were poorly cemented and more clay-based. Iron oxide cements were also present throughout. Silica-based cements are the most commonly reported in the Aquia Creek sandstone (McGee and Woodruff 1992; McGee 1994; McCarthy and Ginell 2001; Robbins and Welter 2001). Hockman and Kessler (1957) and Aloiz et al. (2016) described this cement as a secondary amorphous silica. Clay matrix cementation (McGee and Woodruff 1992) is more common in the Virginia part of the Potomac Group (Glaser 1969). Obermeier (1984) suggested it was a kaolinite cement that was derived from weathering of the feldspar. Iron oxide cements were first noted by Latrobe (1809) who designed the U.S. capital and who originally chose to use Aquia Creek sandstone in its construction. Glaser (1969) attributed the iron oxide cements to hematite or limonite. Regardless of the type of cementation, the Aquia Creek sandstone is infamous for its weak cementation (Withington 1975; McCarthy and Ginell 2001; Robbins and Welter 2001).

Can we determine if the Aquia Creek quarry samples came from the younger Patapsco Fm. or the older Patuxent Fm. of the Potomac Group? To answer this, we plotted our Q:F:R data with that published by Glaser (1969) from the Patapsco and Patuxent formations of Virginia (Fig. 7). Both our Christ Church and Aquia Creek quarry samples are more quartz-rich than Glaser's (1969) more feldspar-rich arkosic samples from the Patuxent Fm. The mean lithologies of the Christ Church, Aquia Creek quarry, and Glaser's (1969) samples from the Patapsco Fm. of Virginia are all subarkoses (Fig. 7). This suggests the stone samples from Christ Church came from the Aquia Creek sandstone quarried along Aquia Creek, and that the quarry was exploiting the Patapsco Fm. of the Potomac Group.

Discussion

The decline of Aquia Creek sandstone use after 1840 (Fig. 5) may have been in response to some of Aquia Creek sandstone's poor durability, partly in response to weak cementation, that has led to maintenance and preservation problems (Seale 2008, 2017; Livingston et al. 2015). Most federal buildings using the stone (e.g., the White House) were painted white within 5 years of completion, in part as a preservation measure (Livingston et al. 2015). Aquia Creek sandstone was largely abandoned for use in favor of various types of white marble, which by then were more readily available because of the development of the railroads (Livingston et al. 2015).

It has been known for a long time that Aquia Creek sandstone is variable and unpredictable in terms of its durability (Latrobe 1809). Some layers are very competent, whereas others weather quickly (Nelson 1992). This has been attributed to a variety of lithologic factors including weak cementation, inclusion of clay rip up clasts, low compressive strength, moderate to high absorption and porosity, and a low modulus of elasticity (Johnson 1851; Hockman and Kessler 1957; Sykes and Grisafe 1986; Clifton 1987; McGee and Woodruff 1992; McCarthy and Ginell 2001; Aloiz et al. 2016).

Despite this, it was the building stone of choice for the growing U.S. capital city for three reasons: (1) At the time, it was the closest (Fig. 1) freestone available in commercial quantities (Latrobe 1809; Scott 1998; Withington 1998). A freestone is a stone that can be worked free of the quarry from any angle or direction without splitting because the grains or bedding do not impede with its extraction or shaping. As such, it is excellent for coarser working and finer carving in any direction without breaking (Nelson 1992; Hannibal and Bolton 2015). (2) The poor road transportation network at the time dictated that stone had to be obtained from local quarries near water transportation, and Aquia Creek sandstone blocks were readily moved to Washington, DC by boat up the

Potomac River (Fig. 1) (Seale 2008; Livingston et al. 2015). (3) It is one of the few well-lithified sedimentary rocks in the coastal plain on which Washington, DC sits (Hawes 1884; Robbins and Welter 2001; Livingston et al. 2015). Due to the young age (< 66 Ma) and shallow burial of the exposed Cenozoic coastal plain sediments, they are essentially unlithified (Wentworth 1930).

We could find only three colonial era examples of Cenozoic-lithified sedimentary rocks being used around the Chesapeake Bay. Weakly iron-cemented Neogene sandstones were used to build the walled cellars and foundations of some early structures in Maryland and Virginia including Middleham Chapel at St. Peter's Episcopal Church in Lusby, MD (Carson et al. 1981; Brown 1998), Northern Neck outcrops of the Neogene Choptank sandstone were supposedly used to make the walls of the Menokin and Mount Airy Plantations in Richmond Co., VA (Lounsbury 2004), and weakly cemented mollusk-rich marls from the Neogene Yorktown Fm. were used to make gravestones in York, Co., VA, and the foundation of Grace Episcopal Church in Yorktown, VA (Butler III 1998). Thus, there are effectively no local outcrops of competent rock and thus no source of building stone near the Christ Church. The closest is the Aquia Creek quarry on Government Island in Stafford County, VA (Dicken et al. 2005).

Christ Church (1735) is the first documented use of Aquia Creek sandstone for doorsteps (Table 1). In addition to the more common use for construction walls, stone trim, and quoins, Aquia Creek sandstone was also used for the doorsteps of other important buildings including Mount Vernon (1757), Pohick Church (1774), Kenmore Plantation (1775), the Dalton-Herbert House (1777), the Edmund J. Lee House (1791), the Potts-Fitzhugh House (1795), and the Vowell-Snowden-Black House (1800) (Table 1). Not even halfway through the history of Aquia Creek sandstone use (1803), its application in steps ceased. After this point, it was mainly used in construction walls (Table 1). Perhaps this was because the stone did not stand up to weathering from the elements and foot traffic.

Most of the window sills, keystones, capitals, imposts, pedestal bases, and cornices, as well as step stones, at Christ Church are made of Aquia Creek sandstone. The first window sill to the right (south) of the west door was replaced by Indiana oolitic limestone in the 1960s (Neblett 1994). The steps leading up to the north, south, and west doors are built with a total of 91 stones. Of these, 78% are Aquia Creek sandstone, 19% are Portland stone, and 3% are Purbeck stone. Portland stone is a Jurassic limestone commercially quarried in southern England for use as a dimension stone (Hughes et al. 2013; Godden 2016). It was used at other colonial buildings around the Chesapeake Bay (Nelson 1992; Lounsbury 2004). Purbeck stone is a Cretaceous limestone imported from southern England and used to pave the floor of the Christ Church (Key Jr et al. 2010). The highest diversity of stones is at the west door which has two Purbeck stones, eight Portland stones, and 31 Aquia Creek sandstones (Fig. 2(b)). The Portland stones are probably newer replacements based on the following four independent pieces of evidence: (1) the majority (78%) of the stones are made of Aquia Creek sandstone so it is more likely they are the originals, (2) the church's archives include photographs of Portland stone being used to repair some of the step stones, (3) most of the Portland stones have clearly been laid within a larger Aquia Creek sandstone block that was cut out (Fig. 2(c)), and (4) the Portland stone steps have vertical fluting that is absent in the Aquia Creek sandstone steps. Nor do we think the use of Purbeck in the steps was original. In a structure of such high quality and craftsmanship, it is unlikely masons would have used a few odd Purbeck or Portland stones in the original steps, as they would have sought a uniform look with the Aquia stone. The Purbeck pieces probably date from preservation initiatives undertaken in the early twentieth century, perhaps when the concrete sills were installed at the doorways.

The first historical reference to the stone in Christ Church comes from the Hon. Wm. A. Jones (Townsend 1904) who suggested the stone sills and steps might be imported, but he did not say from where. Waterman (1945) was the first to assert that the elliptical steps, pedestals, pilaster caps, and bases as well as the imposts and keystones were all made of Portland stone imported from England. Portland stone is an oolitic limestone (Hughes et al. 2013; Godden 2016) grossly similar in texture to Aquia Creek sandstone but mineralogically completely different. Webb and Sweet (1992) correctly reported that the doorway ornamentation and window keystones are sandstone, but they incorrectly report the entry steps are made of granite. Evans et al. (1983) did no analyses but promulgated the idea that at least the west entrance steps were Portland stone. Harms and Neubauer (1992b, c) and copied by Neblett (1994) were the first to identify some of the church's stone as sandstone, but they do not explicitly call it Aquia Creek sandstone. These include the keystone, capitals, imposts, bases, and caps of the west entrance (Harms and Neubauer 1992b); the capitals and bases of the north and south entrances (Harms and Neubauer 1992c); and the small keystones of the three elliptical windows above the north, south, and west entrances (Harms and Neubauer 1992b), as well as the keystones, imposts, and sills of the 12 larger vertical windows (Harms and Neubauer 1992c). Neblett (1994) went so far as to have a piece from a window sill on the south wall be petrographically analyzed in 1993 by Wayne Newell of the U.S. Geological Survey. It was found to be a quartz sandstone with some feldspar grains and a kaolin clay matrix (Neblett 1994), just like Aquia Creek sandstone. Unfortunately, Neblett (1994) continued the erroneous idea that the steps were Portland stone. Finally, Buck et al. (2003) reported that the frontispieces were accentuated by sandstone, probably from the Aquia Creek quarry, but they did no lithologic analyses.

Conclusions

The historical evidence, grain size data, and mineralogical data support our hypothesis regarding the origin of the exterior stone architectural elements of Christ Church in Lancaster Co., VA. It is most likely that the steps at the north, south, and west doors as well as the stone pieces around the windows and doors are made of the Cretaceous Aquia Creek sandstone, possibly quarried on Government Island. Within the quarry, the sandstone most likely came from the upper Patapsco Fm. of the Potomac Group rather than the lower Patuxent Fm. This information should be kept in mind as Aquia Creek sandstone has a history of premature weathering and may need to be replaced in the future. The differential weathering of the various stone elements (e.g., steps versus windows versus doors) is a function of depositional variation in the original sediments, in particular the clay content. This needs to be considered when looking for replacement stone.

Acknowledgments Camille Wells (freelance colonial architectural historian and writer) helped with finding other colonial buildings that incorporated Aquia Creek sandstone. Jerrilynn Eby MacGregor (freelance historian for Stafford Co., VA) helped with understanding the history of the Aquia Creek quarries. Raymond Cannetti (master historic brick and stone mason) helped with answering questions regarding colonial masonry and building stones. Kevin Key (University of Dallas) helped with field sampling on the Middle Peninsula and Virginia Peninsula. Janet Douglas and Carol Grissom (Smithsonian Institution), and Emily Aloiz (John Milner Associates Preservation) and Richard Livingston (University of Maryland) helped with field sampling on Government Island. This manuscript was greatly improved by the reviews of Joe Hannibal (Cleveland Museum of Natural History) and two anonymous reviewers.

Funding Information This research was made possible by a Franklin Research Grant from the American Philosophical Society and a Sabbatical Support Grant from Dickinson College's Research and Development Committee.

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