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Use of fossil bryozoans as provenance indicators for dimension stones

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SUMMARY - *Use of fossil bryozoans as provenance indicators for dimension stones* - This study reviews the literature of case studies and incorporates our own research of using fossil bryozoans as provenance indicators for historic building stones. Fossil bryozoans of different ages and clades can be effectively used to determine the provenance of dimension stone from a variety of historic periods. The bryozoan case studies included in this report span their stratigraphic range from the Ordovician to the Neogene. The bryozoans came from five different orders: trepostome, cryptostome, cystoporate, fenestrate, and cheilostome. The use of these dimension stones ranged as far back as 5,000 years ago. The improved searchable online paleontologic databases allow for more efficient use of fossil bryozoans to constrain the stratigraphic and paleogeographic distribution of source rocks. Though generally underutilized in provenance studies of historic dimension stone, it is clear that if more attention was paid to bryozoans, an increased understanding of the lithologic nature of these materials could be gained by the architectural, conservation and construction sectors.

RIASSUNTO - *Uso dei briozoi fossili come indicatori di provenienza delle pietre da costruzione* - Questo studio passa in rassegna la letteratura sui casi in cui i briozoi fossili sono stati utilizzati come indicatori di provenienza per le pietre da costruzione storiche, incorporando anche le nostre ricerche. I briozoi fossili di ere diverse appartenenti a gruppi differenti possono essere utilizzati per determinare la provenienza delle pietre da costruzione utilizzate nei diversi periodi storici. Le casistiche esaminate rientrano in un ampio ambito stratigrafico che va dall'Ordoviciano al Neogene. I briozoi appratengono a cinque ordini diversi: trepostomi, criptostomi, cistoporati, fenestrati e cheilostomi. L'uso delle pietre da costruzione esaminate risale a non meno di 5.000 anni fa. I database paleontologici sempre più facilmente consultabili on-line consentono un uso più efficiente dei briozoi fossili per risalire alla distribuzione stratigrafica e paleogeografica delle rocce di origine. Sebbene siano oggi sottoimpiegati negli studi sulla provenienza delle pietre da costruzione, è chiaro che una maggiore attenzione ai briozoi consentirebbe di comprendere meglio la natura litologica dei materiali con vantaggi per settori quali l'architettura, la conservazione e la costruzione.

Key words: Fossil bryozoans, provenance, dimension stones
Parole chiave: Fossili briozoi, provenienza, dimensione pietra

1. INTRODUCTION

Provenance herein refers to the geologic source of a dimension stone. 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. The oldest and perhaps the 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 important to know the provenance of dimension stones as it assists in finding suitable replacement stone for conservation. In recent years there has been an increase in studies devoted to dimension stone conservation: determining the factors that cause stone decay (Přikryl & Smith 2005), the provenance of historic building materials (Waelkens et al. 1992; Doehne & Price 2010), their variability (Fronteau et al. 2010), and recognizing and thus reducing the problems of poor substitute stone selection (Rozenbaum et al. 2008). This has become an important aspect of the work of conservation architects and others as they attempt to find suitable replacement material that may be procured for conservation and restoration work.

Geoarcheologists and conservators use a variety of paleontologic, lithologic, geochemical, and geophysical parameters to determine the provenance of dimension stones. Methods include both destructive and non-destructive approaches such as petrographic analysis, scanning electron microscopic (i.e., SEM for imaging), X-ray fluorescence (i.e., XRF for determining chemical composition), X-ray diffraction (i.e., XRD for determining mineralogical composition), induction coupled plasma-mass spectroscopy (i.e., ICP-MS for determining isotopic composition), and laser-induced breakdown spectroscopy (i.e., LIBS for determining elemental composition) (Ray 2007; Colao et al. 2010). Due to wider availability and lower cost, most studies are still largely based on petrographic analysis (e.g., Flügel & Flügel 1997; Dreesen & Dusar 2004). However a number of studies focus on, or at least include as part of a wider study, the fossil-content of the dimension stone in an attempt to fully characterize it and determine its source. The key is to choose an approach with sufficient discriminatory ability to distinguish the various possible source localities of the original stone.

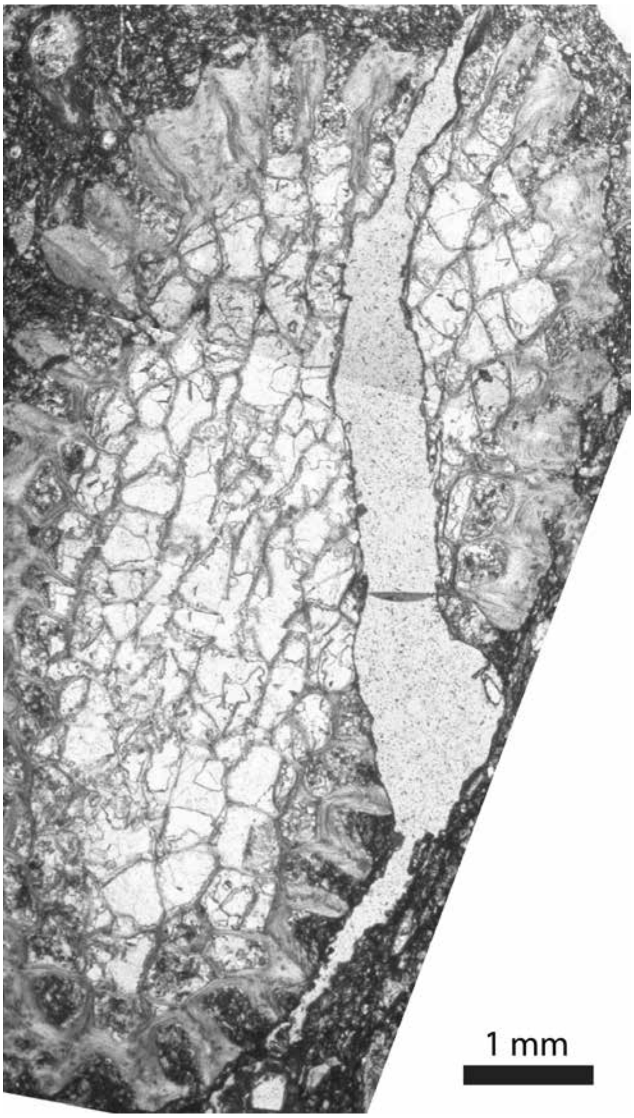

Fig. 1 - Photomicrograph of an oblique longitudinal section through the stenoporid trepostome bryozoan *Stenophragmidium crassimuralis* (Lee, 1912) found in lime mortar of a pre-Romanesque wall below floor of the Cathedral Notre Dame in Tournai, Belgium. The gray infilling is fluorescein isothiocyanate dyed epoxy resin. Provided by Gilles Mertens (KU Leuven, Belgium).
Fig. 1 - Microfotografia di una sezione longitudinale obliqua del briozoo trepostoma stenoporide Stenophragmidium crassimuralis *(Lee, 1912) trovato in un mortaio in una parete pre-romanica sotto il pavimento della Cattedrale di Notre Dame a Tournai, Belgio. Il riempimento grigio è una resina epossidica colorata con isotiocianato di fluoresceina. Reso disponibile da Gilles Mertens (KU Leuven, Belgio).*

All approaches fail unless the variation within and between replicate specimens is less than that between possible source formations (Rapp & Hill 2006).

Determining provenance is problematic with small dimension stones of valuable buildings or tombstones, so spatial variability becomes a problem. Physical properties, color, texture, and fossil content can vary within and between samples (Barton 1968). Lithic resources vary greatly in texture, color, composition, and if present, fossil content, both horizontally and vertically in a single outcrop (Meeks 2000). This variability makes tracing a stone back to an exact location of a specific outcrop essentially impossible, but it is often possible to attribute it to a particular stratigraphic formation.

This study reviews the use of bryozoan fossils as the discriminating parameter for two reasons. First, the evolutionary process creates species with distinct temporal and geographic distributions. As a result, fossils are often more unique in time and space and thus more useful for sourcing compared to physical or chemical parameters. Second, fossils tend to be relatively unaltered during the manufacturing of the dimension stone, so they can be more easily related back to their source rock. For example, Key et al. (2010) used the occurrence of Lower Cretaceous bivalves in stone floor pavers in an 18th century church in Virginia, U.S.A. to determine their source in the Purbeck Limestone Group in Dorset, England.

The authors searched the literature for examples of bryozoans being used as provenance indicators. Other than their own original work included here, examples from the literature are few. One reason is that bryozoan paleontologists are few. For example, the International Paleontological Association's (2011) online list includes only 43 bryozoan workers. As a result, the taxonomy and paleobiogeographic distributions of bryozoan species are not as well-known as other groups. Therefore, their utility as provenance indicators has historically been limited and underutilized by conservators. The lack of workers documenting the stratigraphic distribution of bryozoan species has similarly hampered the earlier promise of bryozoan biostratigraphy (e.g., Merida & Boardman 1967). The situation has greatly improved with centralized searchable paleobiogeographic databases (e.g., Paleobiology Database (Alroy 2000)). The goal of this project is to review the use of bryozoans as provenance indicators using the literature and the authors' own research.

2. FOSSIL BRYOZOANS IN DIMENSION STONES

There are a number of bryozoan-rich limestones both in the United States, Europe, and elsewhere that have been utilized over the centuries for dimension stone. The oldest fossil bryozoans we could find in dimension stones are from the Holston Marble (Holston Formation, Middle Ordovician, Tennessee, U.S.A) (Ulrich 1924). It is an attractive decorative stone that is more bryozoan-rich than most other dimension stones (Ruppel & Walker 1982). In Estonia, Upper Ordovician limestone was and remains a commonly used dimension stone. Bryozoan-bearing stone from Vasalemma has been used since the 13th century and was favored for use as gravestones throughout Estonia (Perens & Kala 2007) and by builders in St Petersburg and Moscow for use in staircases in public buildings and private residences (Watson 1916). Ernst (2011) exploited the presence of fossil bryozoans to source limestone slabs used to build a cellar in ~1180 AD in Lübeck, Germany. The presence of the trepostome *Monotrypa* cf. *gotlandica* Hennig, 1908 and the cystoporate *Ceramopora perforata* Hennig, 1908 contributed to constraining the source to the Middle Silurian (Wenlockian) Tofta Formation of Gotland Island.

Other Paleozoic bryozoan-bearing dimension stones

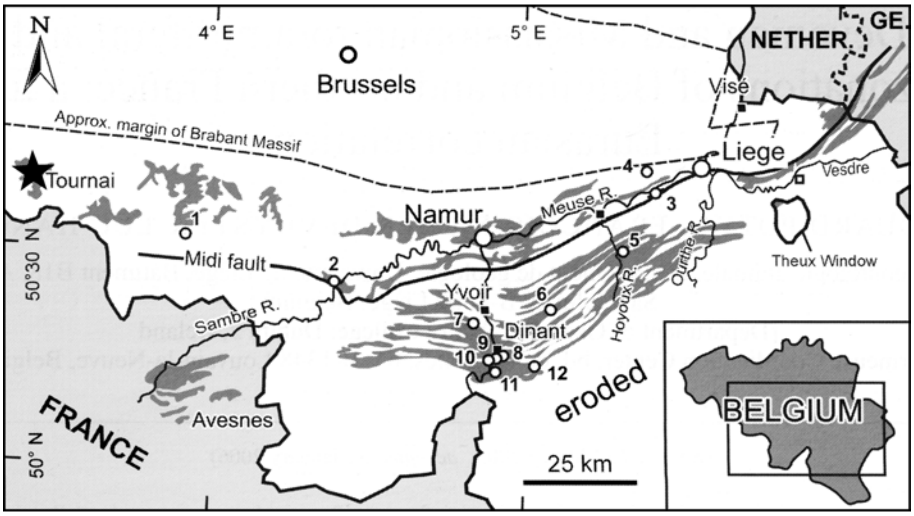

Fig. 2 - Outcrop distribution of Tournaisian and Viséan sediments (shaded areas) in southern Belgium and neighboring countries. Star indicates location of Cathedral Notre Dame in Tournai. Numbers refer to localities in Poty et al. (2006). R. = river; Nether = Netherlands; Ge. = Germany. Modified from Poty et al. (2006).
Fig. 2 - Distribuzione degli affioramenti dei sedimenti del Turnaisiano e del Viseano (aree ombreggiate) nel Belgio meridionale e nei paesi limitrofi. L'asterisco indica l'ubicazione della Cattedrale di Notre Dame a Tournai. I numeri si riferiscono alle località citate in Poty et al. (2006). R.: fiume; Nether: Olanda; Ge.: Germania.

include the Silurian Lockport Dolomite used in western New York, U.S.A. for locks on the Erie Canal, and the Devonian Grand Tower Formation of Missouri, U.S.A. that is marketed as the St Genevieve Golden Vein marble (see Hannibal & Schmidt (1992: 11, Fig. 14D) for an example of its use in Cleveland, Ohio, U.S.A.). Probably the most widely used dimension stone in North America is the Lower Carboniferous (Mississippian) Indiana Limestone (Salem Formation) (Patton & Carr 1982). It was used for buildings in all 50 U.S. states including the Empire State Building in New York (Williams 2009). It is easily recognized by its bryozoan fauna which includes characteristic colonies of the fenestellid fenestrate bryozoan *Archimedes* (Cumings et al. 1906). *Archimedes* is also diagnostic of the similarly aged Bangor Limestone of Alabama, U.S.A. (McKinney 1972) which was used in the construction of the U.S. National Gallery of Art in Washington, DC. Another *Archimedes*-bearing Mississippian limestone is the Carthage Limestone, that was quarried at Carthage, Missouri and extensively used in the US mid-west. Aside from being utilized as a dimension stone, this limestone was readily cut into paving tiles; good examples of such use are in the Field Museum of Natural History, Chicago, and the Missouri State Capitol, Jefferson City, Missouri where longitudinal sections of the calcified central spirals of *Archimedes missouriensis* Condra & Elias, 1944 can be easily seen (Nichols, 1930).

Of similar stratigraphic age, but architecturally used much earlier, is the stenoporid trepostome bryozoan *Stenophragmidium crassimuralis* (Lee, 1912) (Fig. 1). It was found below the Cathedral Notre Dame in Tournai, Belgium (Fig. 2) in the unburned mortar that survived lime kiln firing. The mortar was taken from excavations under the present day cathedral floor from a pre-Romanesque wall (Elsen et al. 2004, 2011; Mertens et al. 2009). It most likely came from the local Tournaisian Limestone (Fig. 2) as the genus *Stenophagmidium* has been reported in Belgium by Wyse Jackson (2006) who described the genus as occurring in the lateral equivalent facies to the Waulsortian facies at Furfooz buildup at St Hadelin, near Gendron-Celles, Belgium which is Lower Carboniferous (Mississippian) Tournaisian to earliest Viséan. Even though *S. crassimuralis* has only been reported from Wales and northern England (Cleary & Wyse Jackson 2007), that it occurs in the Tournaisian of Belgium is not surprising paleobiogeographically.

Mesozoic fossil bryozoans have been reported from dimension stones throughout Europe. In England many Mesozoic carbonate-rich yellow to buff-colored sandstones have been used for building particularly since the 1600s. Superficially these can appear very similar, but recent paleontological and mineralogical studies have demonstrated that they can be moderately easily distinguished from each other (Lott & Cameron 2005). For example in the Kentish Ragstone (Hythe Beds; Lower Cretaceous, Aptian), the Ragstone Beds can be distinguished from the Hassock Beds on account of the former containing bryozoans. Similarly among the glauconitic sandstones, the Bargate Stone (Sandgate Formation; Lower Cretaceous, Aptian) contains echinoid and bryozoans fragments whereas the Folkestone Stone (Lower Cretaceous, Aptian) does not (Lott & Cameron 2005). This has implications for conservation and restoration efforts. In Belgium the bryozoan-rich Upper Cretaceous Maastricht Limestone (Voigt 1981) was used in the 13th century basilica in Tongeren (Saiz-Jimenez et al. 1990).

Elsewhere in archeological studies, bryozoans have proved to be useful in historic provenance determination. For example a number of the buildings at Sagalassos in southwest Turkey, including the fountain house, that date from the late Hellenistic period (323-146 BC), have been shown to be constructed of a fossil-rich, bryozoan-bearing Mesozoic limestone that was quarried locally (Degryse & Waelkens 2008). Other local limestones lack bryozoans, and fossil evidence has been utilized in an effort to locate precisely the quarries from where the different stone types originated.

Cenozoic fossil bryozoans have also been reported from dimension stones. The famous Danian bryozoan limestone of Denmark (Bjerager & Surlyk 2007) was used extensively as a building stone from Copenhagen, Denmark to Rostock, Germany (Kienel et al. 1993, Ansorge & Schafer 1994). Perhaps the bryozoan-rich limestone most used as a building material is Oamaru Stone from the Late Eo-

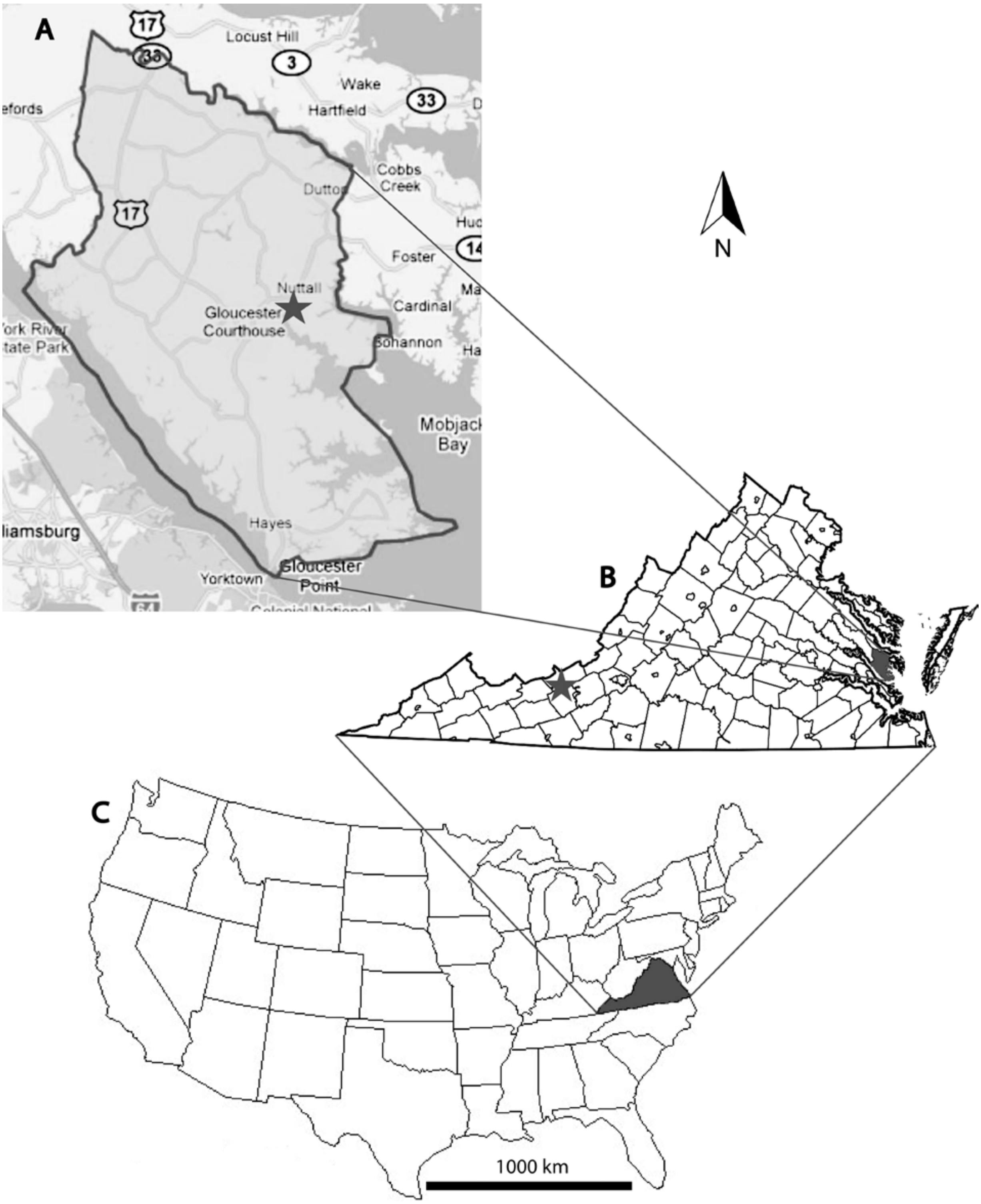

Fig. 3 - Location map of Ware Church (star) in Gloucester County (A), Virginia (B), U.S.A. (C). The nearest Mississippian aged limestone outcropping in Virginia indicated by the star in B is 460 km west.
Fig. 3 - Ubicazione della Ware Church (asterisco) a Gloucester County (A), Virginia (B), U.S.A. (C). I calcari di età mississipiana più vicini affioranti in Virginia indicati con un asterisco in B, si trovano 460 km a ovest.

cene to the Early Oligocene Ototara Limestone from Otago, New Zealand (Cooper 1966, Christie et al. 2001). First used in the mid-nineteenth century particularly in the cities of Christchurch, Oamaru and Dunedin, this material is still quarried today. The Miocene bryozoan limestones that crop out at numerous localities in Moravia, southeast Czech Republic contain multiple bryozoan species (Zagorsek 2010a, b). A number of these limestones have been exploited for

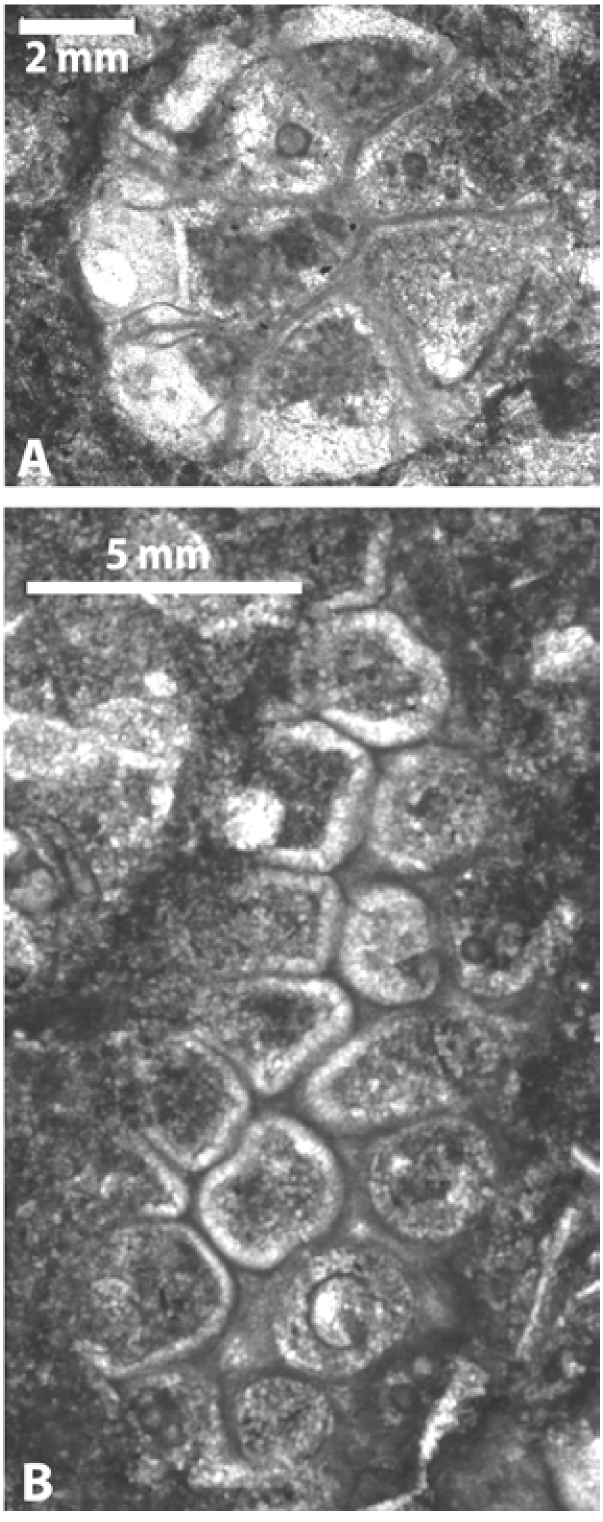

Fig. 4 - Photomicrographs of (A) transverse and (B) tangential sections through the arthrostylid cryptostome bryozoan *Pseudonematopora* from the Lower Carboniferous, Lower to Middle Mississippian, Tournaisian to Viséan stages of Western Europe. It was found in a tombstone from the cemetery of Ware Church in Gloucester County, Virginia, U.S.A. (Fig. 3).

Fig. 4 - Microfotografie della sezione trasversale (A) e tangenziale (B) del briozoo criptostoma artrostilide Pseudonematopora *dei piani Turnaisiano-Viseano del Mississipiano Inferiore-Medio, Carbonifero Inferiore, dell'Europa occidentale. E' stato trovato in una lapide tombale del cimitero di Ware Church, a Gloucester County, in Virginia, U.S.A. (Fig. 3).*

dimension stone over several centuries. Among them are those used for the Austerlitz memorial at Mohyla míru near Brno, that commemorates the battle of 1805 when Napoleon defeated the joint Russian and Austrian forces. This stone was quarried 100 m from the location of the memorial (K. Zagorsek pers. comm., 11 June 2012). Similar bryozoan-rich limestone was used for the construction of the impressive classical Reistna Colonnade near Valtice erected between 1817 and 1823. Rozenbaum et al. (2008) used the presence of fossil bryozoans in dimension stones to ascertain that the best replacements for use in an historic building renovation near Paris were from Middle Eocene Lutetian limestones in France. Finally, in Spain the crypt of the cathedral at Almudena begun in the 1880s is partially constructed of Upper Miocene cheilostome bryozoan-bearing Novelda Stone from Alicante (Fort et al. 2002; Ascaso et al. 2004). In southern Spain, the bryozoan-rich Upper Miocene (Tortonian) Santa Pudia Limestone was used for the historic buildings in Granada, such as the cathedral, the palace of Carlos V in the Alhambra, and the Royal Hospital (Vázquez et al. 2013). The youngest fossil bryozoans we could find in dimension stones are from the Pliocene of Europe. In Austria the monument Dreifaltigkeits-säule (Trinity Column) at Ernstbrunn, is carved from the bryozoan-rich Celleporen-Kalk (Pliocene) (Suess 1862). Locally in Suffolk, England during the 1800s, the upper part of the Coralline Crag that contains a rich Pliocene bryozoan fauna (Busk 1859) was utilized as a building material (Kelly 1879).

In addition to these examples of fossil bryozoans being used to determine the source of building stones, bryozoans have also been used to constrain the source of smaller carved stones. Bryozoans were used to determine the source of the 17th century Ellington Stone. The Ellington Stone is a limestone slab discovered sometime between 1907 and 1920 in what is now Ellington Township, Illinois, U.S.A. The date 1671 along with Jesuit symbols are carved on one side of the slab. If not a hoax (Wisseman 2007a), it would push back two years the date of French exploration down the Mississippi River before the 1673 Jolliet-Marquette expedition (Steck 1974; Wisseman 2007b). A cursory analysis by the Illinois Geological Survey staff attributed the fenestrate bryozoans preserved in the slab to the Warsaw Limestone from western Illinois (Wisseman 2007a,b). By comparing the bryozoans with Snyder's (1991) monograph on North American Lower Carboniferous (Mississippian) fenestrates, we can confirm this stone contains fenestellid bryozoans from the Warsaw Limestone from the Viséan (Meramecian) Stage. The bryozoan-rich facies of the Warsaw Limestone has an outcrop distribution (Snyder 1991, Fig. 1) that includes Ellington Township where the stone was found. Thus the bryozoan fossils help support the claim that the stone is not a hoax, though the perpetrators of a hoax could have obtained the stone locally.

Finally we used the presence of a fossil bryozoan to help the historians of the 17th century Ware Church (Gloucester County, Virginia, U.S.A., Fig. 3) constrain the source of the black limestone tombstone of Edward Porteus (1642-1696) (Brown 2011). We found the arthrostylid cryptostome bryozoan *Pseudonematopora* preserved in the tombstone (Fig. 4). The biostratigraphic range of the genus is the Lower Carboniferous, Lower to Middle Mississippian, Tournaisian to Viséan stages (Wyse

Jackson 1996; Alroy 2000). There are no candidate limestones in the local area (Fig. 3B), and the genus' paleobiogeographic distribution is restricted to Canada, Western Europe (i.e., United Kingdom and Ireland), Kazakhstan, and Mongolia (Wyse Jackson 1996; Alroy 2000). As most of the finished goods in colonial America at the time were shipped from Europe to Virginia (Pecoraro & Givens 2006), the tombstones' provenance is likely Western Europe. Within Western Europe it was most likely quarried in Belgium as that is within the paleobiogeographic distribution of the genus, and Belgium has a long history of exporting their local Lower Carboniferous black limestone (Fig. 2) tombstones (Storemyr et al. 2007).

3. DISCUSSION AND CONCLUSIONS

The previous case studies reveal two drawbacks of using fossil bryozoans as provenance indicators. First is the stratigraphic and geographic distributions of fossil bryozoans are incompletely known. Many more faunas need to be described globally. Second is the need for thin sectioning for proper identification of fossil bryozoans. Bryozoans often fragment easily (e.g., Smith 1995) which can make them small enough to be found in small dimension stones, like a microfossil. But these small fragments typically require thin sectioning for proper identification. Geoarcheologists and conservators have to balance the benefits of determining the source of the stone with the cost of the destructive process of thin sectioning. For example, in the case above of sampling the 17th century tombstone, we were only allowed to take a small sample on the bottom of the side of the stone that was not visible to the public.

Fossil bryozoans from throughout their stratigraphic range can be found in dimension stones. Though most fossil bryozoans are incidental in these, the bryozoans are still useful for determining their provenance. Improved searchable online paleontologic databases allow for more efficient use of fossil bryozoans to constrain the stratigraphic and paleogeographic distribution of source rocks. Though underutilized in provenance studies of dimension stone, it is clear that if more attention was paid to bryozoans, an increased understanding of the lithologic nature of these materials could be gained by the architectural, conservation and construction sectors. This would aid in selection of suitable lithologically and chronologically closely-matched stone required for conservation and restoration projects in the future, which in turn could reduce long-term problems associated with ill-judged restoration.

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