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Preservation of Sea Anemone Burrows in Silurian (~432 Million Years Old) Carbonate Rocks of Southeastern Indiana, USA

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ABSTRACT

Preservation of trace fossils (ichnofossils) in siliciclastic environments is often quite different from preservation in carbonate environments, representing an important source of variation that must be well understood in order to enhance interpretations of paleoenvironments and paleoecology. This study focuses on *Conostichus*, a relatively common burrow constructed by solitary sea anemones. These trace fossils are generally well-preserved (i.e., they display detailed external features) in siliciclastic rocks but are typically little more than conical masses in carbonate rocks. However, certain specimens recovered from the middle Silurian Massie Formation at the Napoleon quarry of southeastern Indiana are composed entirely out of carbonate mud but nevertheless preserve delicate features on the apical disk that have only been described previously from siliciclastic deposits. Specimens displaying typical carbonate-style preservation are also present in the same interval. This is interpreted as reflecting the fine grain size of sediment that passively infilled the well-preserved burrows, in contrast to the more poorly preserved burrows, which are filled with much coarser, skeletal grains. Further, specimens that are characterized by typical carbonate-style preservation contain a zoned infill, with coarser particles around the margin, preventing casting of delicate features. This indicates that grain size is a more important factor than sediment composition in preserving *Conostichus* at this locality. It is likely that other localities are also capable of producing siliciclastic-style preservation of trace fossils in carbonate environments.

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TABLE OF CONTENTS

INTRODUCTION

Trace Fossils

Ichnology is defined as the study of ichnofossils, or trace fossils, which are the preserved evidence of organismal activities. The study of trace fossils is fundamentally different from the study of other fossil types, as trace fossils preserve the behavior of organisms rather than their physical remains. There are many different types of ichnofossils, but the most common are burrows, which represent voluntary subsurface interactions between an organism and soft, unconsolidated sediment (Ekdale et al., 1984). Burrows are highly variable and diverse, reflecting different trace-making organisms, different behaviors, and different characteristics of the sediment.

Classification of trace fossils is necessarily treated entirely separately from classification of potential trace-making organisms. This is required because a single organism can produce multiple separate traces by exhibiting different behaviors and because the exact same trace can be produced by different organisms with the same basic morphology (Bromley, 1996). Therefore, burrows and other trace fossils are identified, named, and classified based on the physical characteristics of the structure rather than the organism that was interpreted to have made the trace (Magwood, 1992). For this reason, the state of preservation of ichnofossils is crucial to accurately recognizing and interpreting these structures and using them to better understand the environments in which they are found (Savrda, 1995, 2007).

Trace Fossil Preservation

Identification and interpretation of trace fossils requires physical material that is sufficiently well-preserved to permit description of overall size, shape, and composition, as well as the presence and geometry of significant features (Bromley, 1996). Since trace fossil preservation is affected by the behavior of the organism that produced the trace, the environment in which the trace was produced, and the burial history of the sedimentary rock containing the trace, otherwise similar ichnofossils can appear significantly different owing to preservation in different settings (Savrda, 2007). Burrows are produced within the sediment, so they are most commonly preserved via infilling by a secondary, younger mass of sediment. In some cases, burrows are actively back-filled by organisms, but this leaves distinct indicators that can be recognized in the fossil record (Bromley, 1996). In contrast, burrows that were passively filled by natural processes have a preservation style that is directly controlled by the sediment that infills them. For example, a burrow that was emplaced within a quartz sand and then infilled with another layer of very similar quartz sand will be indistinct (poorly preserved) or have a low chance of recognition. Likewise, burrows that were infilled with fine sediment are more likely to preserve delicate features and details than are burrows that were infilled with coarse particles, which are poorly suited to casting of delicate or subtle features.

A related issue involves preservation of ichnofossils in carbonate environments compared to siliciclastic environments. Because the sediment is dramatically different in these two depositional regimes, the same trace fossils can appear quite different, or even be (mis)identified as unrelated structures. In many normal marine carbonate environments, all or most of the sediment is represented by bioclastic (organically precipitated skeletal) material (Tucker, 1991) and these particles can preserve burrows in ways that vary from environments where siliciclastic grains that respond to gravity and currents in similar ways are capable of preserving burrows (see Thomka et al., 2016b). Further, the rate at which burrow-filling sediments can be cemented is increased in carbonate sediment relative to siliciclastic sediment (Tucker, 1991; Savrda, 2007).

The relationship between trace fossil preservation in carbonate and siliciclastic sediments forms a central focus of this project.

Statement of Research Problem

This project focuses on *Conostichus*, a cone-shaped burrow that is relatively common in shallow marine environments from the Cambrian Period to Recent, and known from both carbonate and siliciclastic settings (Pemberton et al., 1988; Thomka et al., 2016b). Although traces and trace-makers are classified separately, *Conostichus* can be confidently attributed to solitary, soft-bodied polypoid cnidarians such as sea anemones (Chamberlain, 1971; Pemberton et al., 1988). These burrows are generally well-preserved in siliciclastic rocks, displaying a number of delicate external features including closely spaced constrictions perpendicular to the long axis of the burrow, radiating ridges parallel to the long axis of the burrow, and twelve lobes in the apical region of the burrow (Pemberton et al., 1988). In fact, all published descriptions of these features and all holotypes of recognized *Conostichus* ichnospecies come from fine-grained siliciclastic deposits (Pemberton et al., 1988). In contrast, *Conostichus* recovered from carbonate rocks generally display none of these features and are essentially little more than tapering conical masses (Thomka et al., 2016b).

The basis of this study is a collection of *Conostichus* burrows that preserve the delicate lobate structures of the apical region but are composed entirely of carbonate sediment. This is an important occurrence, as features associated with siliciclastic-style preservation are present in specimens from a carbonate setting, raising the question of whether sediment composition (carbonate vs. siliciclastic) or other characteristics are the primary controls on preservation of this trace fossil.

MATERIALS AND METHODS

Geologic and Stratigraphic Setting

The material studied here was collected from sedimentary rocks of middle Silurian age, being approximately 432 million years old (Cohen et al., 2013). This portion of Earth's history was relatively warm and tectonically stable, resulting in widespread flooding of most continents; consequently, much of the interior portion of North America was covered by an extensive shallow sea where tropical carbonate sediments, sometimes associated with reefs, accumulated in abundance (Berry and Boucot, 1970). Middle Silurian rocks in southeastern Indiana are excellent examples of this environmental setting. Such middle Silurian tropical, shallow-water carbonate rocks are well exposed at the Napoleon quarry of northern Ripley County (N39°12´31.39´´, W85°18´53.74´´; Fig. 1), which serves as the primary study site for this project. This locality is relatively important, since nearly all other middle Silurian successions in the region have been altered by dolomitization (Thomka and Brett, 2015b).

At the Napoleon quarry, Silurian units include, in ascending order, the "golden Brassield" Formation, the Osgood Formation, the Lewisburg Formation, the Massie Formation, and the Laurel Formation (Brett et al., 2012). All of these units represent relatively shallow, normal marine, storm-influenced environments (McLaughlin et al., 2008; Brett et al., 2012). The carbonate-dominated units, notably the Laurel and Lewisburg formations, are actively quarried, but the thin, mud-dominated Massie Formation is the most productive in terms of fossils, being recognized as a world-class deposit for rare and beautifully preserved echinoderms (Thomka et al., 2016a). The *Conostichus* specimens studied here were recovered from the lower 50 cm of the siliciclastic mudstone interval of the Massie Formation as well as the immediately underlying carbonate bed (Fig. 2).

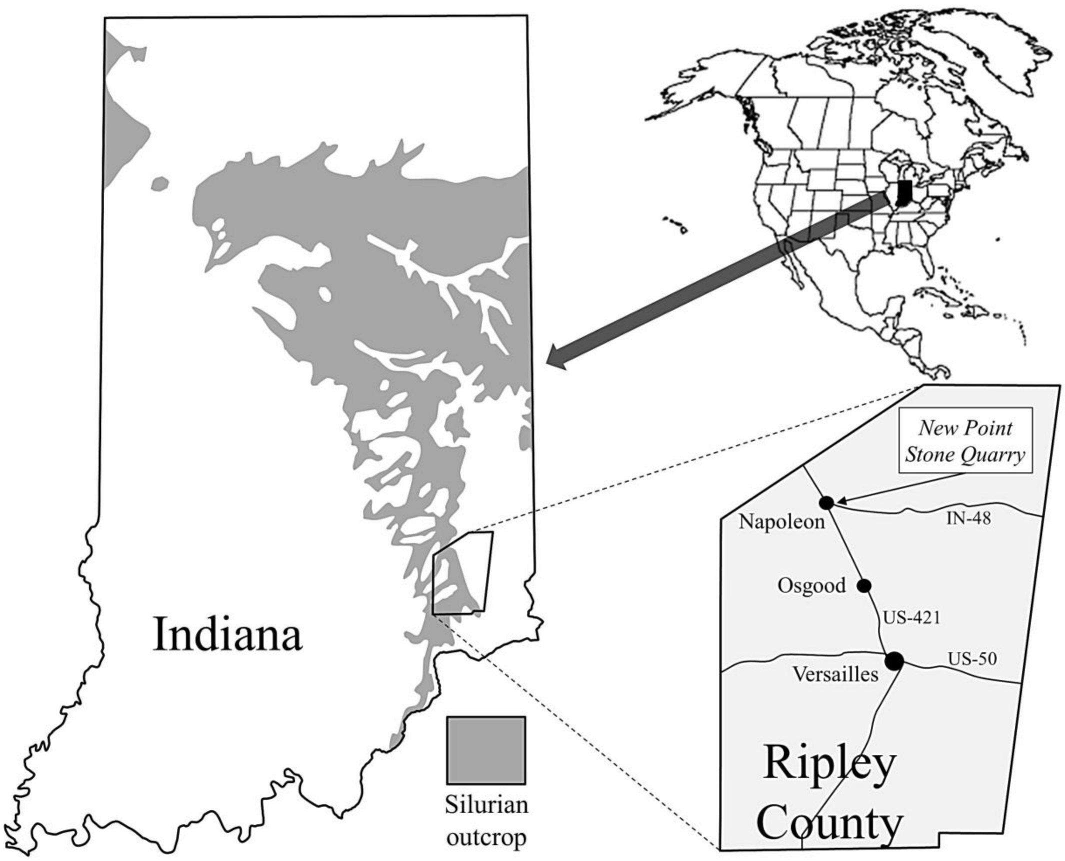

FIGURE 1: Locality of the study site, at the Napoleon quarry (New Point Stone quarry) of northern Ripley County, southeastern Indiana. From Thomka and Brett (2015a).

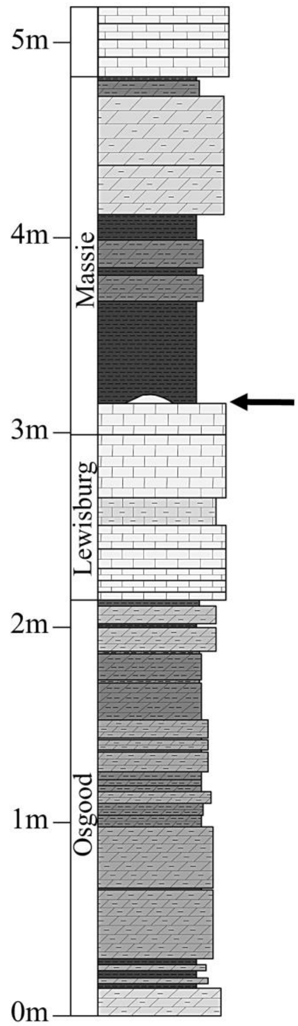

FIGURE 2: Stratigraphy of middle Silurian units at the Napoleon quarry. The specimens used in this study were collected from the lower portion of the Massie Formation mudstone, the base of which is marked by the arrow. From Thomka and Brett (2015a).

The Massie Formation mudstone is not a pure, homogeneous unit, since it contains numerous thin interbeds of muddy carbonates (Fig. 3). These thin beds were particularly rich in trace fossils relative to the finer-grained material (Thomka et al., 2016b) and produced the majority of burrows.

***Conostichus* Specimens**

The burrows analyzed in this study were collected primarily by searching spoil piles of the Massie Formation mudstone, talus piles underneath headwalls, and the quarry floor where the right interval is exposed. Many specimens were collected and donated for study by Mr. Thomas Bantel. All burrows are preserved in full relief, exposing the full dimensions of the structure and all of the infilling sediment (Ekdale et al., 1984).

Conostichus burrows from the Napoleon quarry are preserved in two different modes: carbonate-style preservation and siliciclastic-style preservation. Siliciclastic-style preservation is characterized by ornamentation on the walls of the burrow and a distinct apical disk, at the narrow end of the burrow, with multiple lobes (Fig. 4). This is the style of preservation that has been documented in previous descriptions of *Conostichus* specimens (Pfefferkorn, 1971; Pemberton et al., 1988). Carbonate-style preservation is characterized by an absence of any external features and no recognizable apical disk (Fig. 5).

Burrows displaying carbonate-style preservation were more common at the Napoleon quarry and were collected from the Massie Formation mudstone and the underlying, denser carbonate bed (Fig. 2). There were no differences between burrows displaying carbonate-style preservation in these two rock units. *Conostichus* characterized by siliciclastic-style preservation are comparatively rare at the Napoleon quarry and have only been found in the mudstone

FIGURE 3: Field photograph of the Massie Formation mudstone. The pen is pointing to one of the muddy carbonate interbeds from which most of the specimens were collected.

FIGURE 4: Specimen of *Conostichus* displaying typical siliciclastic-style preservation. There is prominent ornamentation along the burrow walls and an apical disk at the narrow end (bottom) with multiple lobes. The specimen was photographed upside-down so the apical disk could be visible. This burrow (S-1) was collected by J. Thomka from the Pennsylvanian Breathitt Formation of eastern Kentucky.

FIGURE 5: Specimen of *Conostichus* displaying typical carbonate-style preservation. Note the absence of wall ornamentation and an apical disk. This specimen was photographed in its original orientation, with the narrow end deeper into the sediment. This burrow (C-7) was collected from the Napoleon quarry.

interval.

In total, a collection of 21 *Conostichus* burrows was collected from the Napoleon quarry. These included 17 specimens displaying carbonate-style preservation and 4 specimens displaying siliciclastic-style preservation. To supplement interpretations based on this Silurian sample, two specimens displaying siliciclastic-style preservation were added from the Pennsylvanian-age Breathitt Formation of Kentucky (Fig. 4; see Greb and Chestnut, 1994).

Methods

Three main approaches were used in this study. The first approach was field collection of material and documentation of stratigraphic setting. This was primarily accomplished by J. Thomka and T. Bantel over the course of the past several years. Collection at the Napoleon quarry has produced very few specimens over the past 1.5 years, making the previously collected material the best record of *Conostichus* from the study site. All specimens were given unique identifying numbers so each could be specifically described.

The second approach was detailed analysis and description of specimens in the laboratory. This included evaluation of composition, presence or absence of important features, width and depth, any external observations about infilling material, and other notes. For burrows surrounded by some amount of rock, only the burrow dimensions were noted, but attention was paid to features of the associated material. A number of specimens were cut open with a rock saw and smoothed with increasingly fine grades of sandpaper in order to study the details of infilling sediment. For these, any patterns related to the character of internal material was noted.

The third approach involved producing petrographic thin sections of the internal structure of certain specimens. Doubly polished thin sections, ground to 20 microns with 0.3

micron grit were created of specimens S1, S2, C4, C6, C7, and C12, representing both carbonate-style and siliciclastic-style preservation examples of these ichnofossils. To make the thin sections, selected specimens were bisected via cutting by a water saw. Specimen C4 had already been bisected as part of a previous analysis. After all of the specimens were bisected, one half of each specimen was cut to the appropriate size for the thin section using the water saw. After specimens were cut to the appropriate size, they were polished using 600, 1000, 1200, and 0.3 micron grit sizes. Grits 600 and 0.3 microns used a grinding wheel, while the 1000 and 1200 grits used a grinding plate. At each stage, the specimen was ground for five minutes and then put into the sonicator for five minutes. After the specimens were polished, they air-dried overnight. Each thin section could then be viewed under a standard petrographic microscope.

RESULTS

A summary of information on the collection of *Conostichus* from the Napoleon quarry is given in Table 1. Specimens designated as Sh-x are composed of micritic carbonate material but display siliciclastic-style preservation (Fig. 6); those designated as S-x are typical burrows from siliciclastic environments (as in Fig. 4); those designated as C-x are typical burrows from carbonate environments (as in Fig. 5). All unusually well-preserved specimens from the Napoleon quarry, meaning those characterized by siliciclastic-style preservation, are quite small compared to those displaying carbonate-style preservation and are not tapered (Table 1). This suggests that these are not complete burrows, but rather isolated apical disks that became separated from the rest of the structure (Thomka et al., 2016b).

Table 1 also lists which specimens were bisected to expose infilling material. The unusually well preserved specimens were considered too valuable to be bisected, but burrows of

TABLE 1: Summary data on collection of *Conostichus* burrows studied in this project.

Specimen	***Composition***	***Cut?***	***Depth (cm)***	***Max width (cm)***	***Apical width (cm)***	***Thin section?***	***Notes***
Sh-1	Micrite	No	NA	NA	1.80	No	Apical disk only; Fig. 6
Sh-2A	Micrite	No	NA	NA	1.80	No	Apical disk only
Sh-2B	Micrite	No	NA	NA	2.00	No	Apical disk only
Sh-2C	Micrite	No	NA	NA	2.00	No	Apical disk only
S-1	Siliciclastic	Yes	2.40	3.40	1.30	Yes	Fig. 4
S-2	Siliciclastic	Yes	2.20	3.30	1.20	Yes	Fig. 10
C-1	Bioclasts	Yes	2.10	2.90	1.60	No	Abundant pyrite
C-2	Bioclasts	Yes	1.80	4.30	1.80	No	
C-3	Bioclasts	Yes	2.00	4.80	2.60	No	Abundant pyrite
C-4	Bioclasts	Yes	3.35	6.30	2.90	Yes	Fig. 7
C-5	Bioclasts	Yes	2.90	5.40	2.50	No	Abundant pyrite
C-6	Bioclasts	Yes	3.30	6.00	1.50	Yes	Abundant pyrite; Fig. 8
C-7	Bioclasts	Yes	3.50	5.50	1.70	Yes	Abundant pyrite; Fig. 5
C-8	Bioclasts	No	2.00	4.70	1.50	No	
C-9	Bioclasts	No	2.80	7.90	3.30	No	
C-10A	Bioclasts	No	1.60	3.40	1.70	No	Abundant pyrite
C-10B	Bioclasts	No	1.70	3.30	1.30	No	
C-11	Bioclasts	No	2.70	5.50	1.30	No	
C-12	Bioclasts	Yes	3.50	3.60	1.20	Yes	Abundant pyrite; Fig. 9
C-13	Bioclasts	No	2.03	3.81	1.78	No	Preserved in matrix; Abundant pyrite
C-14	Bioclasts	No	1.65	4.57	1.85	No	Preserved in matrix; Abundant pyrite
C-15	Bioclasts	No	3.30	3.81	1.52	No	Preserved in matrix; Abundant pyrite
C-16	Bioclasts	No	2.29	2.54	1.11	No	Preserved in matrix
C-17	Bioclasts	No	0.89	2.06	0.74	No	Preserved in matrix; Abundant pyrite; Finer-grained

FIGURE 6: A specimen composed entirely out of micrite that preserves all twelve lobes of the apical region, a distinctive feature of *Conostichus*, but only previously known from siliciclastic sediments (as in Fig. 4). All specimens preserved in this style consist only of isolated apical disks. This burrow (Sh-1) was collected from the Napoleon quarry.

the other preservational styles were inspected. *Conostichus* burrows characterized by siliciclastic-style preservation display no internal patterns, in contrast to some previous reports of this trace fossil (Pfefferkorn, 1971; Pemberton et al., 1988). Specimens displaying carbonate-style preservation, however, generally display a distinctly zoned fill, with an outer, coarser-grained margin surrounding an inner, finer-grained internal area (Fig. 7). There is no consistency in the size, shape, composition, or orientation of particles in either zone aside from the general difference in coarseness, suggesting that this does not represent active filling by the trace-making anemone (Bromley, 1996). Instead, this may represent some form of a graded fill (Thomka et al., 2016b).

Thin sections show that sediment infilling is very different between specimens displaying siliciclastic-style preservation and carbonate-style preservation. Sediments infilling burrows characterized by carbonate-style preservation at the Napoleon quarry consist of bioclastic particles, most commonly crinoid plates, trilobite pieces, ostracod valves, bryozoan fragments, and more rare coral and mollusk remains (Fig. 8). The precise size range and relative abundances of bioclasts vary between the thin sections of these burrows, but the dominant skeletal grains remain consistent. Where visible, the boundary between the coarser outer zone and the finer inner zone is not sharp, but is clearly recognizable by a decrease in average size of fossil debris (Fig. 9). In contrast, *Conostichus* specimens preserved via infilling by siliciclastic particles have sedimentary fills consisting nearly entirely of angular quartz grains (Fig. 10). No skeletal grains are identifiable in any of the thin-sections of burrows displaying siliciclastic-style preservation. The significant different in average grain size between these burrows and those collected from the Napoleon quarry is obvious in spite of the variety of sedimentary particles present within the various burrows.

FIGURE 7: Sedimentary infill of a *Conostichus* specimen (C-4) characterized by typical carbonate-style preservation. There is a zoned infill, with a coarser and slightly darker outer rim and a finer and slightly lighter inner core. This pattern is consistently observed in the infilling material of specimens collected from the Napoleon quarry that display this style of preservation.

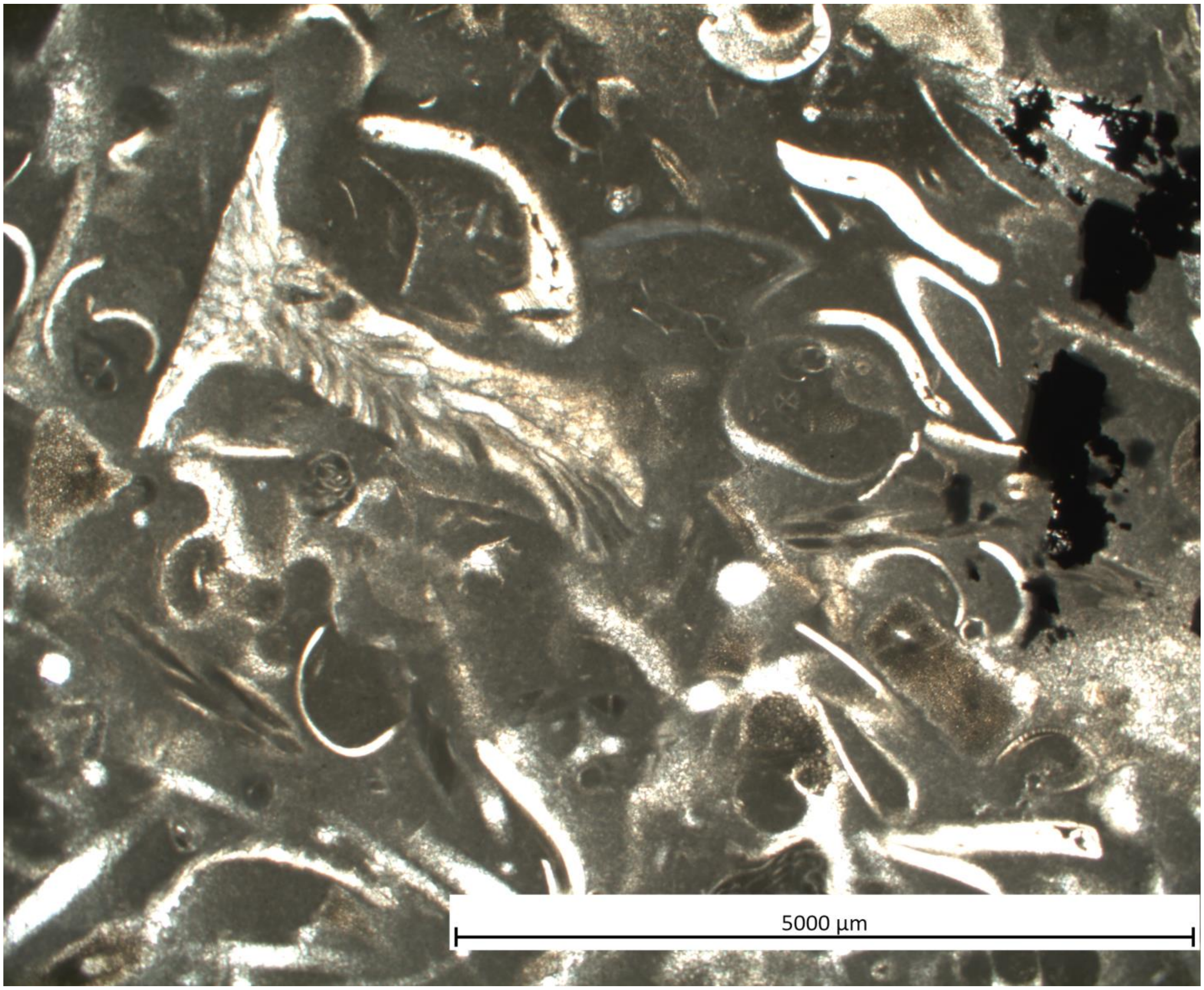

FIGURE 8: Thin section under cross-polarized light showing typical infilling material of a burrow from the Napoleon quarry that is characterized by carbonate-style preservation (C-6). A variety of skeletal grains are present, producing a coarse-grained sediment.

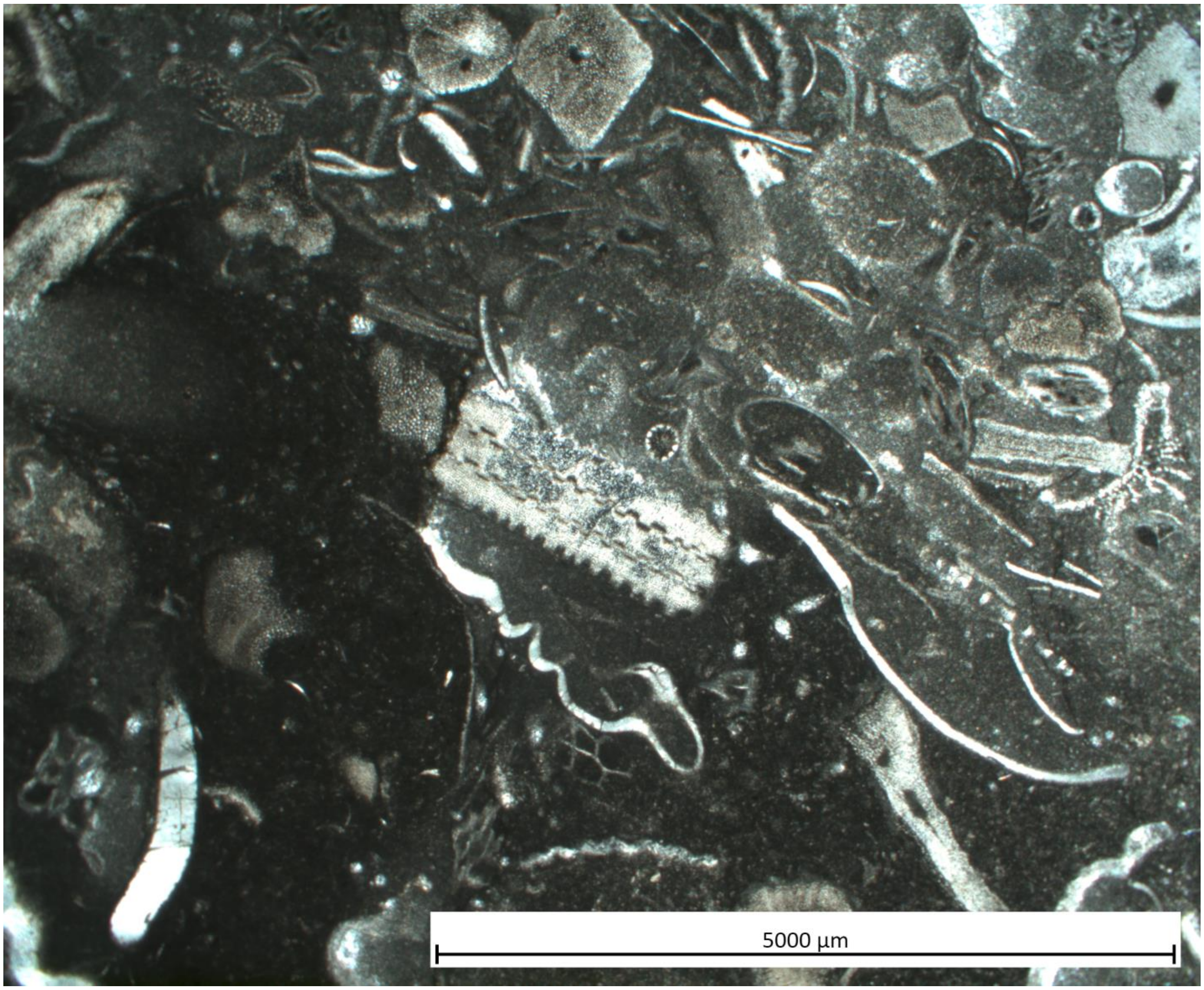

FIGURE 9: Thin section under cross-polarized light of a burrow from the Napoleon quarry displaying carbonate-style preservation (C-12). The coarser outer zone is present to the upper right of the image and the finer inner is present to the lower left. This zonation is also shown in Figure 7.

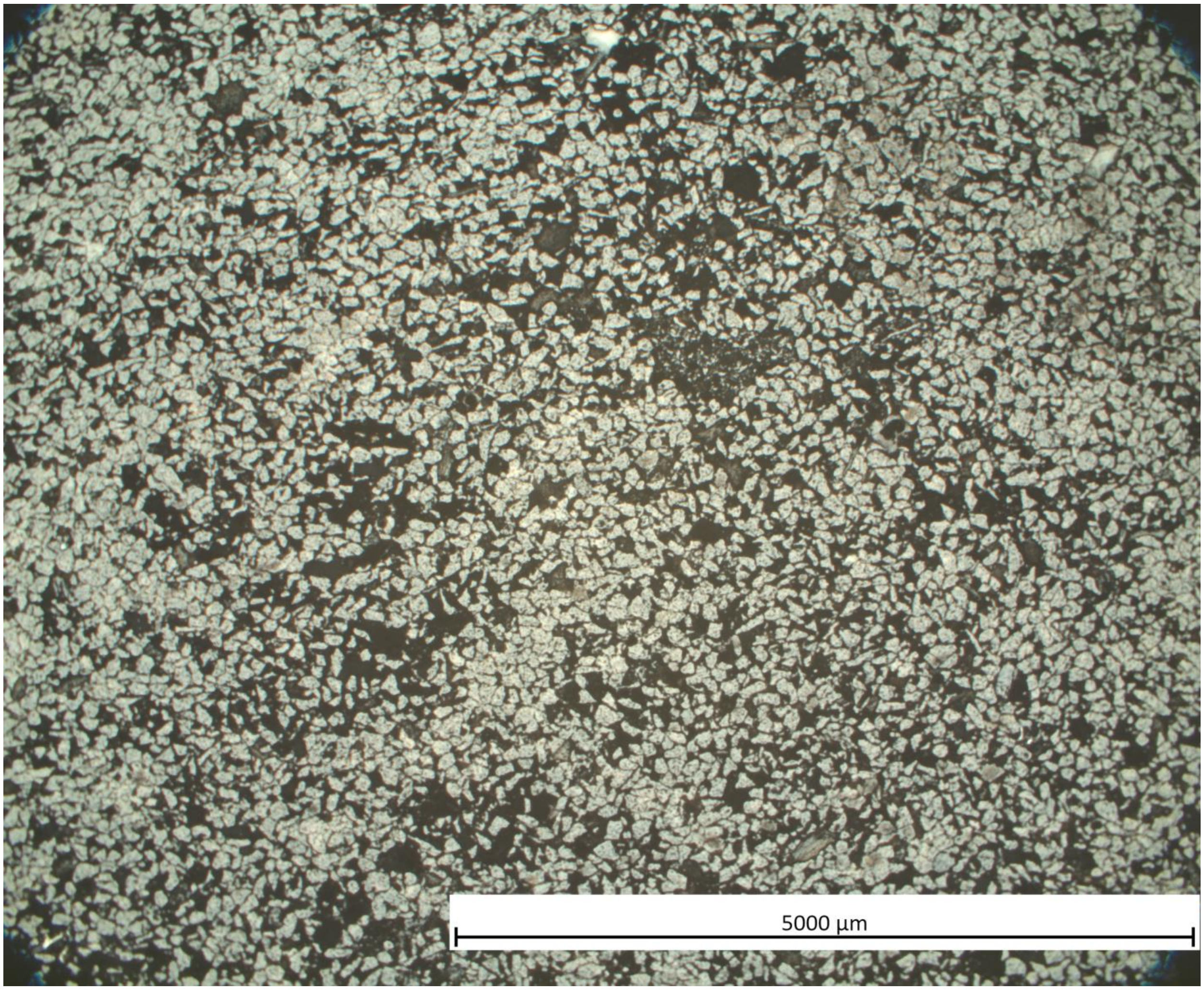

FIGURE 10: Thin section under reflected light showing sedimentary infill of a burrow characterized by typical siliciclastic-style preservation (S-2). Infilling material consists nearly entire of angular quartz silt grains, producing a sediment that is significantly finer than that shown in Figures 8-9.

DISCUSSION

Model for Preservation

The most important factor in controlling preservation of *Conostichus* appears to be grain size rather than grain composition. This means that siliciclastic-style preservation, with delicate external features retained, is not restricted to siliciclastic environments, but can instead occur in any setting where fine-grained sediment can passively infill burrows. The reason that relatively well-preserved examples of these trace fossils are rare in carbonate environments is related to the most common particles that were capable of infilling burrows, specifically the abundance of bioclastic material (Tucker, 1991). Skeletal elements such as crinoid ossicles and trilobite segments are relatively large, very common in Paleozoic marine environments, and unusually low in density, making them ideal candidates for material that would have easily been swept into open burrows, even with relatively gentle currents (Thomka and Brett, 2015b). Despite being readily transported, these particles are still too large to preserve fine details of burrow exteriors, resulting in typical carbonate-style preservation. In situations where fine sediment—either siliciclastic or micritic—can infill burrows, quality of preservation will increase.

The zonation observed in specimens displaying carbonate-style preservation (Fig. 7) is an important part of *Conostichus* preservation at the Napoleon quarry. Because the coarser particles are distributed around the exterior of the burrow, it is possible that these represent normally graded fills. Mucous secreted by the sea anemone may have also helped in permitting sediments to stick to the walls of burrows. There is abundant evidence for storm deposition in the interval from which this sample was collected (Thomka and Brett, 2015b; Thomka et al., 2016a) and this seems the most likely cause of episodic, rapid sedimentation. Hence, during intervals of increased environmental energy (likely storms), relatively large but low-density bioclastic particles were easily transported into open burrow systems.

Broader Implications

In general, the quality of fossil preservation increases with rate of burial: in nearly all instances, organismal remains or traces that are rapidly buried are better preserved than those that were not. This is why event sedimentation, related to storms, turbidity currents, ashfalls, and other processes, is so important to controlling patterns in the fossil record. The model for preservation of *Conostichus* described in this study is somewhat contradictory to this logic, as specimens that are more well-preserved are not necessarily associated with rapid burial. Because episodic high-energy events in the carbonate environment represented by the study interval produced graded fills in open burrow systems. This led to large but low-density bioclastic particles being introduced into burrows; these sediments were too coarse to permit casting of delicate details in the apical region or external margins of these structures. There is insufficient evidence to determine whether the specimens composed of micritic carbonate sediment but displaying siliciclastic-style preservation (Fig. 6) were infilled during quiet periods in between storm events or whether these represent the result of more unusual situations.

Another potential influence on preservation of *Conostichus* in the Massie Formation at the Napoleon quarry is the location of burrows relative to carbonate buildups. The surface separating the basal carbonate bed of the Massie Formation and the overlying mudstone interval (Fig. 2) serves as substrate for growth of microbioherms, which are small, mounded, patch reef-like buildups (Thomka and Brett, 2015b). The presence of these features influenced sedimentation patterns and fossil preservation at the Napoleon quarry in numerous ways, including generating rings of muddier sediment surrounding microbioherms, perhaps because of sediment baffling; both siliciclastic mud and micrite are elevated in these areas (Thomka and Brett, 2015b). It is possible that the unusually well-preserved specimens composed of micrite (Fig. 6) represent burrows that were emplaced in sediment near microbioherms and infilled by the micrite that was shed from these buildups. Since the specimens used in this study were collected largely from spoil piles, it is impossible to determine their original position and ongoing work will attempt to locate *Conostichus* burrows that in place. Nevertheless, it is worth mentioning that the presence of microbioherms at the Napoleon quarry may have controlled or affected sedimentation patterns in a previously unrecognized way. Further, the small number of *Conostichus* specimens displaying unusual preservation may be due to the specific sub-environment where they can be produced.

The major difference between *Conostichus* in siliciclastic and carbonate environments is an excellent example of one the main issues in understanding the trace fossil record. Because trace fossils must be recognized and correctly identified in order to provide information on the community of organisms that occupied an environment as well as the environment itself, variations in in trace fossil preservation between siliciclastic and carbonate deposits must be recognized and described. As a result, the better that factors that control ichnofossil preservation are understood, the more accurately paleontologists are able to compare and interpret sedimentary deposits and identify the trace fossils within them (see Savrda, 2007).

Continued work on this issue must include expanding this case study to other localities to test whether grain size is a more important factor than grain composition in other settings. These studies should include both siliciclastic and carbonate deposits. Additional specimens of *Conostichus* from the Napoleon quarry that retain delicate features but are composed of carbonate sediments will undergo petrographic analysis. In addition, study of *Conostichus* preservation in carbonate environments will focus on the potential role of diagenesis in controlling which features are retained, specifically determining whether infilling sediment was cemented together very quickly relative to the timing of that process in other burrows.

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