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Unusual preservation of the trace fossil *Conostichus* in middle Silurian carbonate facies of Indiana, USA

James R. Thomka^{1*}, Thomas E. Bantel², and Marissa J. Tomin¹

¹*Department of Geosciences, University of Akron, Akron, Ohio 44325, USA;*

jthomka@uakron.edu, mjt70@zips.uakron.edu

²*Dry Dredgers, P.O. Box 210013, Cincinnati, Ohio 45221, USA; tebantel@cinci.rr.com*

***Corresponding author (J. R. Thomka)**

Department of Geosciences

114 Crouse Hall

University of Akron

Akron, Ohio 44325, USA

E-mail: jthomka@uakron.edu

Telephone: +1-630-935-2983

Fax: 330-972-7611

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Abstract: The long-ranging, plug-shaped ichnofossil *Conostichus*, attributed to solitary polypoid cnidarians, is most commonly described in the Paleozoic from fine-grained siliciclastic sediments, with few descriptions from carbonate settings. The few described examples of putative *Conostichus* preserved in carbonate sedimentary rocks of Paleozoic age are essentially conical masses lacking recognizable external radial or longitudinal structures. Herein, we describe the occurrence of well-preserved examples of this ichnogenus within middle Silurian (Wenlock: Sheinwoodian) carbonate sedimentary rocks of the Massie Formation from southeastern Indiana, USA. These specimens represent isolated apical discs of *Conostichus* with prominent radiating physal impressions displaying duodecimal symmetry. Interestingly, well-preserved specimens co-occur with relatively poorly preserved (“typical carbonate”) specimens. The factors responsible for this unusual taphonomic state are unclear, but the most likely explanation is that exceptionally preserved specimens represent burrows that were somehow infilled, at least in their apical terminations, with fine-grained carbonate sediment, enhancing preservational fidelity. In contrast, other burrows had their apical regions passively filled with larger carbonate particles that could not preserve fine details. This occurrence indicates that early Paleozoic carbonate sediments are capable of preserving *Conostichus*, and potentially other ichnofossils, in similar modes to later Paleozoic siliciclastic deposits.

KEYWORDS: ichnology, Wenlock, trace fossil taphonomy, *Conostichus*

Introduction

Conical sedimentary structures of both biotic and abiotic origin are common throughout the Phanerozoic stratigraphic record (Buck and Goldring 2003; Joeckel 2008). As thoroughly reviewed by Pemberton et al. (1988), most biogenically generated sedimentary structures characterized by a conical or plug-like shape can be classified as the common ichnogenera *Conostichus*, *Bergaueria*, *Conichnus*, *Dolopichnus*, and *Astropolichnus*; additional potentially conical ichnogenera include *Monocraterion*, *Rosselia*, *Lingulichnus*, and *Pentichnus*. Study of these and related structures poses a unique suite of challenges, including issues that arise from preservation of material that does not permit ready identification, differentiation, or interpretation of ichnotaxa. The relatively common ichnogenus *Conostichus* exemplifies this problem, as differentially preserved specimens may be misidentified (e.g., identified as *Bergaueria*; see examples described in Pemberton et al. 1988) or go unrecognized as trace fossils (e.g., viewed as body fossils; Branson 1961, 1962).

Although *Conostichus* has been discovered in sedimentary units as old as Upper Cambrian (Mangáno et al. 1996; Poiré et al. 2003), this ichnogenus was originally described from, and has been most commonly reported from, Upper Carboniferous (Pennsylvanian) strata of eastern and midcontinental USA (Lesquereux 1876; Pemberton et al. 1988). Specimens in these settings are preserved within siliciclastic deposits representing paralic to shallow marine environments (e.g., Lesquereux 1876, 1883; Marple 1956; Branson 1960, 1961, 1962; Pfefferkorn 1971; Hakes 1976; Miller and Knox 1985; Martino 1989; Greb and Chestnut 1994), which is true for *Conostichus* outside of the USA as well (e.g., Seilacher 1983; Mangáno et al. 1996). Traces from these units are preserved via infilling by fine-grained sediments (Pfefferkorn 1971), resulting in casting of such delicate features as radiating physal impressions, transverse

constrictions, and rugose adjustment laminae (Pemberton et al. 1988). These features allowed *Conostichus* to be readily recognized as the product of burrowing by solitary polypoid actinarian cnidarians (Chamberlain 1971; Pemberton et al. 1988; Lech 2009; see also Shinn 1968; Frey 1970; Curran and Frey 1977).

Unfortunately, preservation of *Conostichus* in carbonate sedimentary rocks differs markedly from those recovered from siliciclastic deposits, which include the type specimens of all recognized ichnospecies (Pemberton et al. 1988). Carbonate sediments, particularly those dominated by common Paleozoic bioclasts such as crinoid columnals (see Lowenstam 1957; Ausich 1997), are commonly too coarse-grained to preserve fine morphological details. Moreover, a high proportion of Paleozoic carbonates were subjected to diagenetic alteration that obscured primary features of enclosed fossils. Hence, *Conostichus* has not been reported commonly in early to middle Paleozoic carbonate strata, nor have assemblages been described in detail, likely owing largely to taphonomic factors.

Here, we describe an occurrence of atypically preserved middle Silurian *Conostichus* from argillaceous carbonate sediments. This assemblage is unique in that specimens display morphological details typically observed only in siliciclastic environments and generally in younger deposits. Exceptional preservation is evidently the result of unusual taphonomic processes that permitted siliciclastic-style preservation in a carbonate environment.

Locality, stratigraphic setting, and previous ichnological studies

The specimens studied here were recovered from the New Point Stone quarry just east of Napoleon, Indiana (N39°12'31.39'', W85°18'53.74''; Fig. 1A). This site exposes a relatively condensed, carbonate-dominated middle Silurian succession deposited in upper to middle ramp

settings in close proximity to the proto-Cincinnati Arch (McLaughlin et al. 2008; Brett et al. 2012). The Silurian stratigraphy of this quarry, recently summarized by Thomka and Brett (2015a, 2015b), comprises, in ascending order, the Aeronian “golden Brassfield” Formation (see Brett et al. 2014), the Telychian-Sheinwoodian Osgood Formation, and the Sheinwoodian Lewisburg, Massie, and Laurel formations (Fig. 1B).

Conostichus is present in the Massie Formation (Fig. 1B), which is composed of three lithofacies: a basal skeletal packstone-grainstone, a thicker overlying interval of fossiliferous siliciclastic mudstone with skeletal wackestone (biomicrite) interbeds, and an uppermost interval of dense, poorly fossiliferous, silty packstones. The majority of burrows are found in the lower decimeter of the mudstone lithofacies (Fig. 1B), present within the carbonate interbeds. The carbonates that are interbedded within the siliciclastic mudstone lithofacies of the Massie Formation have two origins: generally thinner, graded beds with sharp, erosional bases represent storm beds, whereas more substantial, ungraded but also sharp-based beds with higher proportions of micrite and a more concretionary texture represent sediment-starved small-scale transgressive intervals. Specimens recovered from both types of these beds are generally preserved hypichnially or endichnially, the latter typically having weathered free from surrounding matrix in spoil piles or the exposed quarry floor. A smaller number of *Conostichus* specimens was collected from the basal carbonate lithofacies of the Massie Formation (Fig. 1B); these specimens are morphologically identical to those recovered from the mudstone lithofacies, but are embedded tightly within the surrounding dense bioclastic material. For a more detailed description of the Massie Formation basal carbonate lithofacies, see Thomka and Brett (2014, 2015a); for a more detailed description of the lower mudstone lithofacies, see Thomka and Brett (2015b) and Thomka et al (2016).

Previous studies of trace fossils from this interval of the Napoleon quarry focused primarily on hard-substrate ichnofaunas, particularly parasitic embedment structures in diploporite echinoderms (Paul 1971; Brett 1985; see also Frest et al. 1977, which does not specifically mention localities bearing parasitized echinoderms) and *Trypanites* borings in large crinoid pluricolumnals and calyxes (Thomka and Brett 2014, 2015b). Burrows described from the lower Massie Formation consist of pre-omission firmground *Thalassinoides* from the basal carbonate lithofacies (Thomka and Brett 2015a) and thin, meandering pascichnia (*Gordia* isp.?) in areas surrounding microbiohermal buildups (Thomka and Brett 2015b). The current description represents the first detailed study of softground trace fossils found within the mudstone lithofacies of the Massie Formation.

Preservation of *Conostichus*

Specimens can be classified as belonging to one of two primary taphonomic categories: those displaying carbonate-style preservation and those displaying siliciclastic-style preservation. Carbonate-style preservation, shown in Figure 2, is characterized by a tapering, conical shape with no discernable wall ornamentation (though some relatively well-preserved representatives may display subtle, barely recognizable radial structures on the walls, as in Fig. 2B). Traces preserved in this style vary considerably in size, with the smallest specimens being roughly the same diameter as the exceptionally preserved specimens described below and the largest specimens exceeding 5 cm in diameter at the widest end (Figs. 2A-B). Burrows that were cut open to expose sedimentary infill consistently show a pattern of relatively coarse bioclastic grains along the bottom and sides of the structure, with finer particles (smaller bioclasts, siliciclastic mud, and micrite) in the interior (Fig. 2C). No semblance of laminae, chevron-

shaped or otherwise (cf. Pfefferkorn 1971; Pemberton et al. 1988), are preserved within specimens characterized by carbonate-style preservation (Fig. 2C).

Conostichus displaying siliciclastic-style preservation are more similar to specimens figured in published literature (i.e., those typically reported from Carboniferous deposits; see Pemberton et al. 1988). These retain physal impressions in the apical region, with or without transverse constrictions and longitudinal ridges along the exterior wall of the burrow (Fig. 3C). Although this mode of preservation has not previously been reported from carbonate settings (see Fig. 2), a few specimens from the study site bear radiating, duodecimally symmetrical physal impressions (Fig. 3A-B). Interestingly, all currently known specimens characterized by retention of these seemingly delicate features are small (~1.5 cm in diameter) and short (less than 2 cm in height), with no recognizable tapering (Fig. 3A). There is no evidence of erosional truncation of the upper portions of these burrows. Although it is theoretically possible that these represent burrows that were shallowly emplaced, there is not a realistic mechanism that would lead to preferential preservation of external features in shallow structures over deeper structures. A better explanation is that these specimens represent isolated apical discs separated from the upper portion of the burrow. No upper portions of incomplete *Conostichus* were discovered that retain ornamentation; hence, it is unknown whether *Conostichus* displaying siliciclastic-style preservation in the Massie Formation are capable of preserving other external features.

Specimens retaining physal impressions are composed entirely of fine-grained carbonate sediment, with no component of macroscopic bioclastic particles (Fig. 3A). These traces were too small and too valuable to be prepared for thin-section analysis, but examination under an optical microscope suggests little to no dilution by siliciclastic particles. Hence, this occurrence represents an unusual ichnotaphonomic juxtaposition, with carbonate sediments preserving

Conostichus with readily altered or destroyed features.

Discussion

The most likely explanation for the preservation of delicate, siliciclastic-style features in carbonate sedimentary rocks is that the well-preserved specimens represent burrows that managed to become infilled by fine-grained carbonate material rather than the dominant sedimentary fill, namely, coarse-grained bioclastic material. Hence, the micritic sediment would have preserved the fine details of the apical region of the burrow in the same way that siliciclastic muds commonly casted features of *Conostichus* in upper Paleozoic paralic environments. It is evident that preservation of fine details in conostichoid burrows is dependent primarily on the grain size of infilling sediment; this is a more important factor than sediment composition.

Evidence for event sedimentation is common within the lower portion of the mudstone lithofacies of the Massie Formation (Thomka and Brett 2015b; Thomka et al. 2016). This is also true for stratigraphically equivalent and lithologically similar intervals in the lower Rochester Shale of western New York, with abundant evidence indicating the prominent role of storm deposition in these units (Brett 1983; O'Brien et al. 1994; Brett and Taylor 1997). The influence of storms may account for the lack of fine details characteristic of carbonate-style preservation: the abundance of coarse, but low-density, carbonate bioclasts such as pelmatozoan columnals would have readily been incorporated into graded beds during episodes of increased current velocity. Hence, the skeletal material comprising the “coarse-grained rim” of specimens characterized by carbonate-style preservation (Fig. 2C) was probably introduced during high-energy events. This is supported by the occurrence of *Conostichus* displaying carbonate-style

185 preservation at the bases of storm beds.

186 Because of the relationship between storm events and carbonate-style preservation, event
187 sedimentation does not appear to be an absolute necessity for exceptional preservation of
188 *Conostichus*. The well-preserved specimens (i.e., those characterized by siliciclastic-style
189 preservation; Fig. 3A) may represent instances where *Conostichus* was passively infilled under
190 quiescent background conditions. Since the specimens displaying the most well-developed
191 siliciclastic-style preservation were recovered from spoil piles, it is uncertain but possible that
192 these were derived from the carbonate interbeds (i.e., those that are not storm beds) in the
193 mudstone lithofacies of the Massie Formation. Whether early diagenetic cementation of fine-
194 grained sediment also played a role in enhancing preservation is unclear, but may have
195 contributed to some degree in facilitating siliciclastic-style preservation.

196 Brett and Allison (1998, p. 322) suggested that the abundance of echinoderm ossicles in
197 putative *Conostichus* reflects disruption of buried, previously articulated skeletons during
198 burrowing, followed by concentration and reorientation of skeletal grains within the burrow.
199 This interpretation implies that the disparity in preservational styles observed in this study
200 reflects slightly differing behaviors by the burrowing cnidarian rather than purely depositional
201 processes. Although it is possible that ethological differences account for the preservational
202 variability among *Conostichus* from the lower Massie Formation, we see no evidence that the
203 “coarse-grained rim” represents the result of an active filling process (i.e., there is no true mantle
204 within these specimens). The absence of preferred orientations or preferred bioclast size and/or
205 shape, and the compositional variation from specimen to specimen is far more suggestive of a
206 passive physical process than an active biological process.

207 It is well established that taphonomic processes are key factors in controlling the

perceived diversity and ichnotaxonomic identity of trace fossils (MacNaughton and Pickerill 2003; Savrda 2007). Moreover, an understanding of the underlying controls on variable trace fossil preservation permits more accurate interpretation of the relative influence of taphonomic, as opposed to ethologic, patterns that govern trace fossil diversity, abundance, and lithofacies relationships (Archer 1984). The Silurian *Conostichus* assemblage described here represents an illustrative case study of the significance of variable preservational histories in imparting dramatically different physical properties to trace fossils recovered from a single stratigraphic unit. This is significant not only in addressing how exceptionally well-preserved trace fossils and more typical representatives of the same ichnotaxon can be documented from the same interval, but also in understanding the major differences in ichnofossil preservational patterns observed between siliciclastic and carbonate regimes.

Conclusions

Well-preserved specimens of the trace fossil *Conostichus* (i.e., those characterized by distinct physal impressions) are present in carbonate sedimentary rocks within the middle Silurian Massie Formation of southeastern Indiana, USA. This occurrence is unusual because *Conostichus* in carbonates are generally lacking in any recognizable internal detail, being characterized only by a conical shape and a homogeneous or crudely graded fill. The specimens described here are more similar to “typical” *Conostichus* described from Upper Carboniferous siliciclastic deposits, which preserve fine internal structures. The exact taphonomic factors that led to siliciclastic-style preservation of *Conostichus* in carbonate sediments are not entirely clear, but most likely involve instances where fine-grained carbonate particles, rather than coarser bioclasts, infilled the bases of cavities. This led to casting of fine details of the apical region,

potentially coupled with rapid cementation of sedimentary fill. Thus, this occurrence represents a setting where early-middle Paleozoic carbonate sedimentary rocks were capable of preserving *Conostichus* in a mode otherwise primarily encountered in siliciclastic deposits, including those from which type ichnospecies have been described.

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415 **Fig. 1.** Geographic and stratigraphic setting of *Conostichus* specimens studied. (A) Location of
416 the New Point Stone quarry, just east of the town of Napoleon in southeastern Indiana, USA.
417 Ripley County, within which the study site is located, is represented by the irregular polygon.
418 Modified from Thomka and Brett (2014a). (B) Photograph of the quarry wall with labeled
419 formation-scale stratigraphic units (lithostratigraphic nomenclature follows Brett et al. 2012).
420 Most specimens were recovered from the base of the mudstone lithofacies of the Massie
421 Formation, marked by the black stars; a smaller number of specimens was recovered from the
422 underlying carbonate lithofacies, marked by the white star. Scale bar = 1 m.

423
424 **Fig. 2.** Examples of carbonate-style preservation of *Conostichus*, common to most Paleozoic
425 carbonate units, including the Massie Formation of southeastern Indiana. Note the absence of
426 physal impressions, transverse constrictions, and longitudinal ridges. (A) Typical, relatively
427 large specimen with a well-developed tapering form. (B) Specimen with faint radiating
428 structures, possibly corresponding to very minor radiating ridges. (C) Vertical cross-section
429 showing infill of burrows. Note that sedimentary fill can be roughly divided into two zones, a
430 coarse-grained rim (*cgr*) and a finer-grained core (*fgc*). The presence of this coarse-grained rim
431 seemingly precludes preservation of fine details in carbonate-style preservation of this
432 ichnogenus. All scale bars = 1 cm.

433
434 **Fig. 3.** Unusually preserved *Conostichus* from carbonate interbeds within the lower mudstone
435 lithofacies of the Massie Formation of southeastern Indiana. (A) Exceptionally well-preserved
436 specimen displaying prominent radiating physal impressions. This is typical of siliciclastic-style
437 preservation and is otherwise not observed in carbonate units (compare with Figure 2). Scale bar

438 = 0.5 cm. (B) Traced outline of the specimen in Fig. 3A with the twelve lobes labeled; this
439 demonstrates the duodecimal symmetry characteristic of this ichnogenus, but generally
440 documented only from siliciclastic-style preservation. (C) An example of typical siliciclastic-
441 style preservation, from a paralic deposit in the Pennsylvanian Breathitt Formation of eastern
442 Kentucky, USA. Note the presence of fine details not present on specimens in Figure 2. Also
443 note that the specimen in Figure 3A likely corresponds only to the terminal apical disc of this
444 specimen. Scale bar = 1 cm.

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101x57mm (300 x 300 DPI)

195x444mm (300 x 300 DPI)

127x189mm (600 x 600 DPI)