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Microstratigraphy and Comparative Taphonomic Analysis of the Upper Core Shale of a Pennsylvanian Cyclothem: Keys to the Recognition of Subtle Cyclic Deposition

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ABSTRACT

The Upper Pennsylvanian Barnsdall Formation as exposed near Copan, northeastern Oklahoma, represents a low energy, prodeltaic distal shelf environment and constitutes part of the highstand phase (core shale) of the Missourian (=Kasimovian) Stanton cyclothem. Directly overlying a dark grey, phosphatic shale representing maximum highstand, an interval of green mudstone records initial regression and breakdown of water column stratification. Within this upper core shale is a diverse and abundant benthic fossil assemblage, including the highest levels of crinoid diversity recognized in the global Pennsylvanian System. Detailed microstratigraphic and comparative taphonomic analysis reveals that this lithologically monotonous succession records three cycles, each approximately 15 cm (6 in) thick. Each cycle consists of a distal portion (a thin, very time-averaged unit bearing large siderite concretions and a diverse, abundant, and well-preserved crinoid assemblage) overlain by a more proximal interval (a thicker unit bearing small siderite concretions, discrete sideritized burrows, winnowed skeletal lags, and burrowing mollusks preserved in living position). These cycles appear to be arranged into a progradational pattern, fitting the overall regressive trend of this portion of the cyclothem. This indicates that seemingly monotonous intervals may indeed be capable of revealing sea-level dynamics, although the evidence is inconspicuous and requires detailed investigation.

INTRODUCTION

The Late Pennsylvanian Midcontinent Sea was a vast but relatively shallow water body that persisted from the Middle Pennsylvanian to the Early Permian and covered a sizeable portion of the North American Craton (e.g., Algeo and Heckel, 2008). An Upper Pennsylvanian outcrop belt consisting of a series of laterally extensive, depth-related facies spanning the area from Iowa in the north to central Oklahoma in the south records deposition within this epicontinental seaway. Shallow carbonate-platform facies susceptible to occasional subaerial exposure dominate in the north as evidenced by the presence of correlatable paleosol horizons (Boardman and

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Heckel, 1989) and a geochemically and petrographically recognizable meteoric influence on carbonate diagenesis (Xiong and Heckel, 1996). Further south, carbonate-dominated open marine conditions prevailed, with a phylloid algal mound complex developed through much of southern Kansas. In contrast, the Early Pennsylvanian uplift of the Ouachitas and subsequent shedding of abundant clastic material, coupled with increased subsidence near the Arkoma Basin, resulted in the loss of extensive carbonate units near the Kansas-Oklahoma border and the development of the terrigenous detrital facies belt of Heckel (1977, 1978) in the southern midcontinent. Northern Oklahoma, therefore, is dominated by fine-grained clastics deposited at the southern margin of this epicontinental sea and in the adjacent basinal environment (Heckel, 1977, 1978; Algeo and Heckel, 2008, and references therein).

Much of the Pennsylvanian System in North America is characterized by cyclic deposition, representing fluctuations in relative sea-level driven by combined tectonic and eustatic controls (Klein and Willard, 1989; Read and Forsyth, 1989; Klein, 1990) operating on the Late Pennsylvanian Midcontinent Sea. Whereas Pennsylvanian cyclothems of the Appalachian and Illinois Basins appear to have been influenced primarily by tectonic subsidence (Klein and Kupperman, 1992), midcontinent cyclothems appear to have resulted primarily from eustatic sea-level oscillations, as indicated by numerical modeling and their position in the tectonically stable continental interior (Heckel, 1977, 1978, 1980, 1986, 1994). Cyclothem periodicity suggests that Milankovitch cyclicity, specifically orbital eccentricity, was the driving force between these eustatic sea-level changes (Heckel, 1986); these orbital perturbations resulted in the waxing and waning of Gondwanan continental glaciers, which were present throughout the Late Pennsylvanian (Crowell, 1978).

Midcontinent cyclothems, or Kansas-type cyclothems of Heckel (1977), ideally consist of five units and represent a single rise and fall of relative sea-level. An outside shale, potentially containing terrestrial facies, and an overlying middle limestone constitute a transgressive phase; a core shale, typically black or dark gray and bearing pelagic fauna and phosphate nodules, represents the maximum highstand and the development of thermohaline water-column stratification (see detailed discussion of sedimentology in Bisnett and Heckel, 1996; paleontology in Malinky and Heckel, 1998; and paleoceanography in Algeo and Heckel, 2008); finally, an upper limestone and outside shale constitute the regressive phase, which is disconformably overlain by the next cyclothem. The core shale is often used as a marker for lithostratigraphic correlation across broad portions of the midcontinent (e.g., Boardman and Heckel, 1989), as it is easily recognizable lithologically, contains a unique and distinctive fauna relative to surrounding units, and occurs in a central position within the cyclothem.

In many cases, however, the core shale portion can be divided into two lithofacies: the lower core shale, as described above, and the overlying upper core shale, which is light gray to green in color and contains a diverse benthic marine invertebrate fauna. Upper core shales were deposited during relatively high sea-level, but during initial periods of regression; as a result, water-column stratification was broken down, and increased benthic oxygenation permitted the replacement of dysaerobic faunas (*sensu* Boardman et al., 1984; Kammer et al., 1986) by normal marine faunas, while sedimentation rate and environmental energy remained low. It was this oxygenated, low energy, low turbidity environment that allowed benthic invertebrates to flourish. The low sedimentation rate and relatively slow rate of initial sea-level fall resulted in highly fossiliferous upper core shale facies throughout the midcontinent (Holterhoff, 1996).

The Upper Pennsylvanian (Missourian/Kasimovian) Stanton cyclothem constitutes the youngest cyclothemic sequence of Missourian age in the midcontinent and is represented by the Stanton Formation of the Lansing Group in Kansas, where the cyclothem was first described and is most complete (Heckel, 1986; Boardman and Heckel, 1989); however, the major disparity between carbonate-dominated, shelf lithofacies of Kansas and clastic-dominated, basinal lithofacies of Oklahoma results in the formal recognition of neither the Stanton Formation nor the Lansing Group in Oklahoma. Instead, the marine portion of the Stanton Formation in Kansas is correlated to the Barnsdall Formation of the Ochelata Group in Oklahoma (Holterhoff, 1997). The Barnsdall Formation represents the last major transgressive event of the Missourian (=Kasimovian) Stage, and in northern Oklahoma and southeastern Kansas, a complex mosaic of facies is present, including elements of a dysoxic basin (lower core shale), an oxygenated basin to distal shelf (upper core shale), and various shallow marine environments, including delta-front deposits (see detailed stratigraphic analysis in Watney et al., 1989, and summary in Holterhoff, 1997). Local and regional lithologic variation, coupled with minor structural deformation (e.g., Rascoe, 1975) can make precise stratigraphic interpretations and correlations within the Barnsdall Formation quite difficult.

A hillside exposure, approximately 9 m (30 ft) thick, within the middle portion of the Barnsdall Formation crops out roughly 4 km (2.5 mi) northeast of Copan, Washington County, northeastern Oklahoma (Fig. 1). Here, the transition from lower core shale to upper core shale facies, and eventually to regressive, shallow marine facies, is recorded (Fig. 2). The lower core shale is represented by a thin unit of dark gray, platy, phosphatic, sparsely fossiliferous shale containing a distinctly dysaerobic molluskan fauna (Boardman et al., 1984); this unit correlates to the Eudora Shale Member of the Stanton Formation in Kansas (Holterhoff, 1997). This is transitionally overlain by the upper core shale facies, represented by a green to gray, thoroughly bioturbated, densely fossiliferous mudstone containing abundant siderite concretions and a diverse benthic fauna. This facies is overlain by a thick sequence of non-fossiliferous silty sandstones and sandy mudstones representing more proximal shelf deposits, with well-sorted quartz sandstones representing proximal delta environments capping the succession.

The upper core shale facies at Copan, approximately 50 cm (20 in) in thickness, has received considerable interest from paleontologists, due primarily to the diverse and abundant crinoid fauna recovered from this geographically and stratigraphically restricted setting (Pabian, 1987; Pabian et al., 1995, 1997; Lewis et al., 1998; Thomka et al., 2010a, 2010b, 2011). To date, the deposit has produced over 1250 crinoid specimens representing 44 genera and 50 species, making this the most diverse crinoid assemblage within the global Pennsylvanian System. In addition to diversity, the crinoid fauna is renowned for its remarkable preservation, with numerous articulated cups and crowns, including specimens with complete arms (delicate feeding structures) and columns (multi-element elevation/attachment structures), intact anal sacs (delicate, multiplated, often ornate, structure used in feeding and excretion) and unbroken spines and ornamentation on skeletal structures (Fig. 3). The presence of articulated multi-element crinoid skeletons, typically preserved as isolated skeletal plates or fragmentary remains, qualifies this thin interval as a *Konservat-Lagerstätte*, reflecting the influence of unusual sedimentological and/or geochemical processes (Lewis, 1980; Donovan, 1991; Brett et al., 1997; Ausich, 2001) and worthy of special attention from paleontologists (Seilacher et al., 1985).

The articulated crinoid fossils have been collected primarily from a horizon 5–8 cm (2–3 in) thick near the base of the upper core shale unit, although fieldwork at the Copan site has revealed that similar fossils are also present in two thin horizons above what has been termed the Main Crinoid Bed (Lewis et al., 1998). Further, recent research focusing on the taphonomy (post-mortem processes and fossilization) of crinoids recovered from

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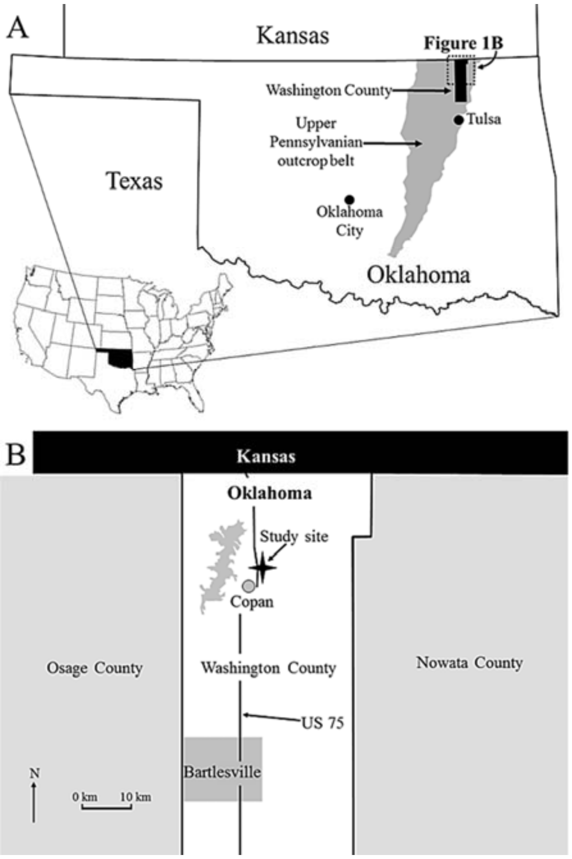

Figure 1. Location of study area, showing position of Washington County within the Upper Pennsylvanian outcrop belt of Oklahoma and the specific location of the site under investigation.

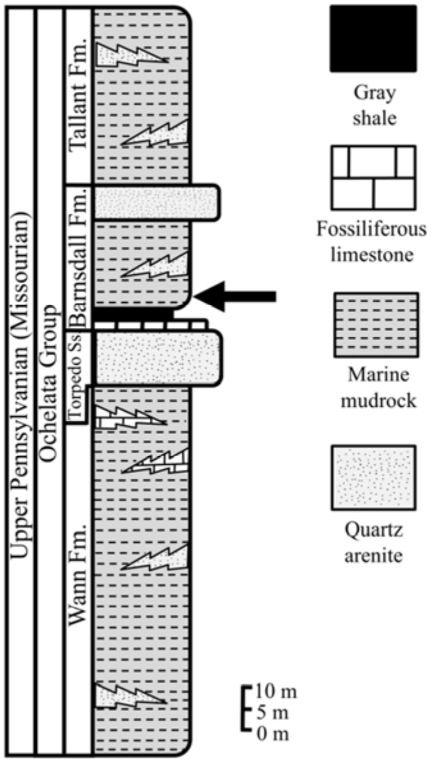

Figure 2. Generalized stratigraphy of northern Washington County, Oklahoma. The arrow marks the location of the crinoid-bearing horizon within the upper core shale facies.

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the Main Crinoid Bed (Thomka et al., 2011) and from multiple horizons throughout the upper core shale interval (Thomka et al., 2010a) has shown that crinoid skeletons do not exhibit uniform preservation, and that the distribution of taphonomic features is nonrandom with respect to interpreted paleoenvironmental parameters. Work focused on the distribution and morphology of siderite concretions throughout the upper core shale interval (Thomka, 2010) also supports the assertion that this distinctive facies, although lithologically homogeneous, may record minor paleoenvironmental fluctuations associated with the initial phases of regression in a prodeltaic distal shelf setting. Such small-scale patterns are important in (1) interpreting bioturbated mudrock facies lacking bedding planes and primary sedimentary structures; (2) further refining the biotic signature of high-frequency changes in paleoenvironmental processes; (3) understanding conditions responsible for preservation of exceptional fossil faunas; and (4) identifying minor cycles that may have sequence stratigraphic significance.

METHODS

Although the Copan site has a history of study dating to the 1940s, the early phase of investigation consisted entirely of taxonomic description of crinoid specimens recovered from the Main Crinoid Bed. It was not until the early 1990s that the upper core shale interval was examined with the goal of determining the stratigraphic context of the crinoid fauna. Emphasis was placed on documenting in-place macrofossils and identifying distinctive horizons based on faunal or sedimentologic criteria. It was during this phase of investigation that detailed field measurements and outcrop photographs were made, and bulk sediment samples in the form of mudstone blocks were collected from various horizons of the section; such materials form the basis of the study described herein.

Field measurements and photographs with precise scales were used to construct a centimeter-scale microstratigraphic section for the upper core shale interval at the study site. Important attributes noted include identity, orientation, taphonomic state, and relative abundance of fossils; size, shape, and abundance of siderite concretions; identity and abundance of any physical and biogenic sedimentary structures; and nature of contacts between identified units.

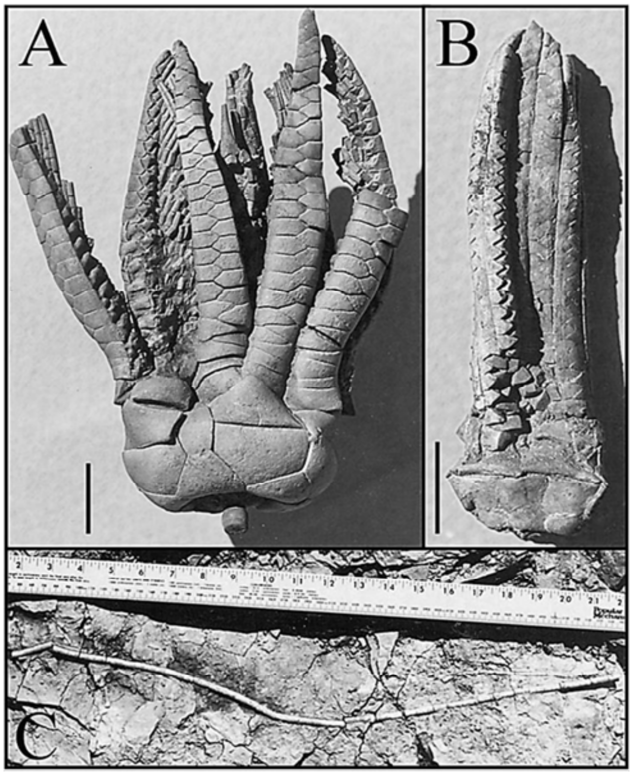

Figure 3. Examples of exceptionally preserved crinoid remains from the Copan site. (A) *Delocrinus subhemisphericus* with pinnulate arms and intact anal sac. Scale bar = 1 cm (0.4 in). (B) *Erisocrinus typus* with minor disruption of the proximal arms. Scale bar = 1 cm (0.4 in). (C) Articulated portion of column attaining nearly 50 cm (2 ft) in length.

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Lithologic samples collected from numerous horizons during fieldwork and stored at Auburn University were used for detailed fabric analysis in order to supplement field measurements and verify observations derived from fieldwork. Large mudstone slabs were coated with a thin layer of clear enamel and then cut perpendicular to presumed bedding with a tile saw. Such measures are necessary due to the very poorly indurated nature of the mudstone, as exposing the blocks to water or liquid lubricant would result in complete disaggregation. Cut faces were ground against increasingly fine grades of sandpaper until all saw marks and scratches were removed. These faces were then examined and potentially significant features were photographed and digitally magnified. The same attributes documented for horizons in the field were noted for mudstone slabs (e.g., fossil identity and distribution, and size and morphology of siderite concretions).

Mudstone samples that were too fractured or poorly indurated to yield sedimentary fabric data were disaggregated to provide data on the relative abundance and taphonomic state of fossil material throughout the section. Samples were weighed and then soaked in kerosene for one day; after this period, the kerosene was removed and an equal volume of water was added. After one day of soaking in water, the sample was typically thoroughly disaggregated and the viscous slurry was passed through 3.0, 2.0, 1.0, and 0.5 mm sieves, with all fossil material collected and retained from each size interval. This material was weighed, providing an estimate of the relative abundance and size distribution of bioclasts, and then inspected using a binocular microscope. All crinoid material was identified, counted, weighed separately, and analyzed for taphonomic indicators, including encrusting epibionts and broken faces.

RESULTS AND ANALYSIS

Microstratigraphic measurement resulted in the development of a centimeter-scale stratigraphic section for the upper core shale interval, given in Figure 4. The most striking pattern, first noted by Lewis et al. (1998), is the alternation between (1) thinner units easily recognized by the presence of abundant articulated crinoid skeletons and large siderite concretions (Main Crinoid Bed, Bed 1, and Bed 3), and (2) thicker units characterized by small siderite concretions, numerous endobenthic mollusks, and an absence of abundant articulated crinoid material (Bed 0, Bed 2, and Bed 4). Comparative taphonomic analysis, detailed fabric analysis of mudstone slabs, and data from disaggregation of samples revealed a number of further genetically significant, but subtle differences between units comprising this interval. These are manifest in varying biofacies, taphofacies (*sensu* Speyer and Brett, 1986; units defined on the basis of fossil preservation), ichnofabrics (*sensu* Savrda, 1995; holistic ichnologic/sedimentologic character of sediment or sedimentary rock), lithologic properties, and siderite concretion morphologies.

Biofacies

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All units shown in Figure 4 are rich in fossil material, and several particularly common fossil types, including fenestrate bryozoan fronds, productid brachiopod shells, tubular sponges, and disarticulated crinoid debris, are ubiquitous throughout the section. There are, however, notable differences in the relative abundances of these skeletal components. The thinner units are dominated by a diverse assemblage of crinoids, a diverse assemblage of articulate brachiopods (particularly productids), and fenestrate bryozoans. Subordinate faunal elements include tubular sponges and regular echinoid spines, with bivalve mollusks and scaphopods as relatively rare constituents. In contrast, the thicker units are dominated by bivalve mollusks, with tubular sponges, scaphopods, inarticulate and articulate brachiopods, and fenestrate bryozoans as secondary faunal components.

The distinction between these two biofacies has significant paleoecological implications. With thinner units characterized by an epibenthic, sessile biofacies, an environment with stable, low turbidity, low sedimentation conditions must persist in order to permit suspension feeding by the abundant crinoids, articulate brachiopods,

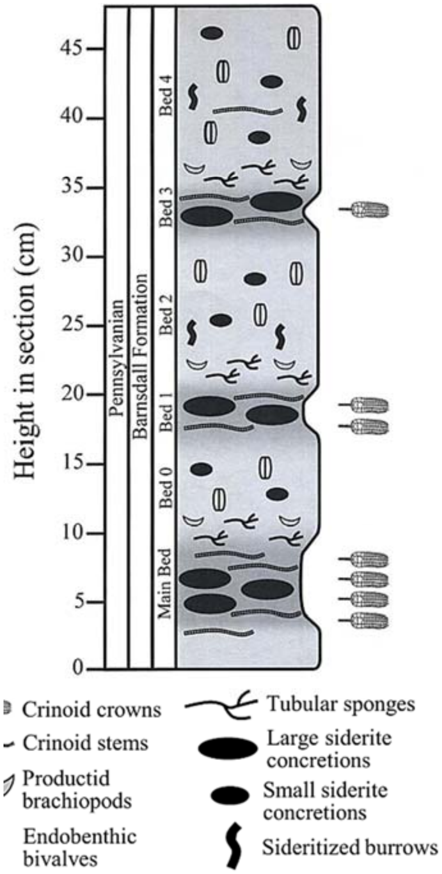

Figure 4. Microstratigraphy of upper core shale interval. Note the alternation between thinner units containing abundant articulated crinoid remains and large siderite concretions and thicker units containing abundant endobenthic bivalves and small siderite concretions.

and bryozoans. The subsequent development of a biofacies dominated by an endobenthic, vagile molluskan fauna indicates a transition to an environment less favorable to epibenthic suspension feeding. This transition commonly occurs as a result of increased sedimentation rate, which serves to inhibit dominance by epibenthic suspension feeding by interfering with particle capture apparatuses (e.g., clogging filtration fans) while simultaneously increasing the amount of particulate organic matter brought into the environment, favoring vagile deposit feeders.

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Taphofacies

Taphonomic analysis of many fossiliferous units, including *Lagerstätten*, has revealed that fossil assemblages are often composed of two distinct assemblages: the event assemblage, representing individuals preserved through episodic rapid burial events, and the background assemblage, comprising multiple generations of skeletal remains contributed to the seafloor sediment over long periods of normal sedimentation (Speyer and Brett, 1991). Consequently, these two assemblages have contrasting taphonomic signatures. The event assemblage is characterized by such features as articulated multi-element skeletons, organisms in life position, and preserved microstructural details of skeletal material; the background assemblage shows evidence of considerable time in the taphonomically active zone (the zone in which skeletal material is operated upon by physical and biological processes, generally prior to deep burial), with typical features including completely or primarily disarticulated multi-element skeletons, organisms in orientations and positions not adopted during life, skeletal elements in a generally degraded condition (corroded, abraded, and fractured), and delicate fossils or features completely destroyed (Speyer and Brett, 1986, 1991; see also Brett and Baird, 1986a).

Both assemblages are present within both the thinner and thicker units of the section under study. The event assemblage of the thinner units is dominated by articulated crinoid remains, represented by complete and partial crowns as well as long columns (see Figure 3). In addition to crinoidal material, the thinner units also contain numerous productid brachiopods retaining surface ornamentation and, in some cases, featuring attached spines and preserved in life position, as well as large fronds of fenestrate bryozoans found intact as flat-lying to slightly undulose sheets. These well preserved fossils provide evidence of rapid burial by fine-grained sediments. The background assemblage of thinner units consists of isolated crinoid ossicles representing completely disarticulated individuals, regular echinoid spines, fragments of fenestrate bryozoan zoaria, degraded and commonly broken scaphopod, brachiopod, and bivalve material, and portions of tubular sponges.

Although there is considerable similarity between the event and background assemblages in these units, a significant discrepancy is represented by the conspicuous absence of any mobile fauna within the event assemblage. Although the delicate spines and plates of regular echinoids are moderately common constituents of sediment within the thinner units, not a single intact or even partial specimen has been discovered despite their slow locomotion. Likewise, despite the presence of scaphopods and bivalves in the Main Crinoid Bed, Bed 1, and Bed 3, these organisms invariably display evidence of considerable exposure at the seafloor and are never preserved in life position. This is strong evidence that the burial events responsible for preservation of the articulated crinoids and associated fauna, although rapid, resulted in beds sufficiently thin to allow the escape of mobile fauna and only entomb stationary organisms such as crinoids, articulate brachiopods, and bryozoans. Further, fabric analysis of mudstone slabs revealed that the Main Crinoid Bed, Bed 1, and Bed 3, although stratigraphically thin, are not single-event beds, but rather represent the stacking of thin obrution (rapid burial) horizons formed over an extended period of time. The strongest evidence for this interpretation is the presence of several articulated productid brachiopods in life position, with the concave brachial valve facing upwards, separated by several millimeters of sediment (Fig. 5); a similar pattern was observed with intact fenestrate bryozoan fronds. This could not have been produced by a single episode of rapid burial, as the brachiopods are neither in the hydrodynamically stable convex-up position, which can result from reworking by relatively gentle currents in muddy substrates (Brenchley and Newall, 1970), nor are they found at the same level, as would be expected for a hydraulically sorted bed. The presence of an associated background assemblage indicates that these rapid burial events were separated by long periods of slow sedimentation, resulting in little net sediment accumulation. This is further supported by data from mudstone disaggregation, showing that the thinner units are enriched in dissociated skeletal material and separate crinoid ossicles (background assemblage material) relative to thicker units and a significantly greater proportion of encrusted skeletal grains (Fig. 6), indicating that the thinner units represent increased stratigraphic condensation.

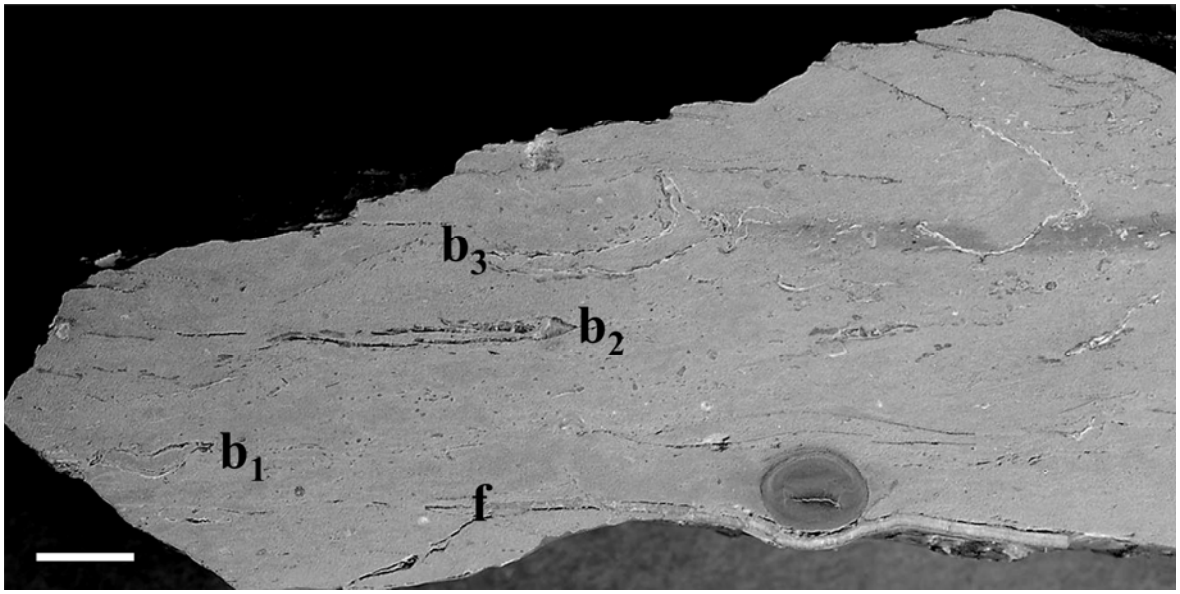

Figure 5. Sample from the Main Crinoid Bed containing articulated productid brachiopods in living position (convex side down) at three closely spaced horizons (b1, b2, and b3). This indicates that several rapid, but thin, burial events comprise the Main Crinoid Bed and other thinner units. Note also the fenestrate bryozoan frond (f) in the lower portion of the slab, which may indicate a fourth rapid burial horizon below b1. Scale bar = 1 cm (0.4 in).

The event assemblage in thicker units is very different from that described above. Very few articulated crinoid crowns were recovered from Bed 0, Bed 2, and Bed 4, and although some relatively long columns were observed in these horizons, they were overwhelmingly within the lower 2–5 cm (0.75–2 in) of each unit. Instead, the event assemblage is dominated by large, thin-shelled endobenthic bivalves preserved articulated and in life position (embedded vertically or subvertically), as well as scaphopods and productid brachiopods preserved in life position (Fig. 7). Some large fenestrate bryozoan fronds are present as well, although they are not as numerous as those in the Main Crinoid Bed, Bed 1, and Bed 3. The background assemblage in thicker units is fairly similar to that of the thinner units, with crinoid ossicles, tubular sponge fragments, fenestrate bryozoan fragments, and degraded and/or broken material from bivalves, scaphopods and acrotretid inarticulate brachiopods.

The presence of numerous endobenthic mollusks preserved as part of the event assemblage is very significant, as these organisms are not only mobile, but are adapted for proficiency at moving vertically through sediment. These burrowing bivalves would have been capable of escaping rapidly deposited sediment, especially the thin sediment blankets typical of the thinner units (e.g., Kranz, 1974; Peterson, 1985); the inability of the bivalves to escape the entombing sediment layer reflects a markedly increased thickness of event layers capable of entombing not only the few epibenthic organisms, but the more common endobenthic organisms as well. The orientation of these bivalves is unlikely to be the result of post-mortem reworking, as the rapid decay of the adductor muscles creates a tendency for the shell to splay open at the hinge rather than remain articulated (Allmon, 1985). Thus the thinner and thicker units are distinct not only in terms of the dominant organisms preserved but also in the nature of rapid burial events. The evidence for increased sedimentation rates and thicker burial events appear to indicate an environment closer to a sediment source area for Bed 0, Bed 2, and Bed 4.

Ichnofabrics

Ichnofabrics are essentially identical in both the thicker and thinner units, and are characterized by a lack of discrete biogenic sedimentary structures of any kind. However, the sole exception to this is the presence of rela-

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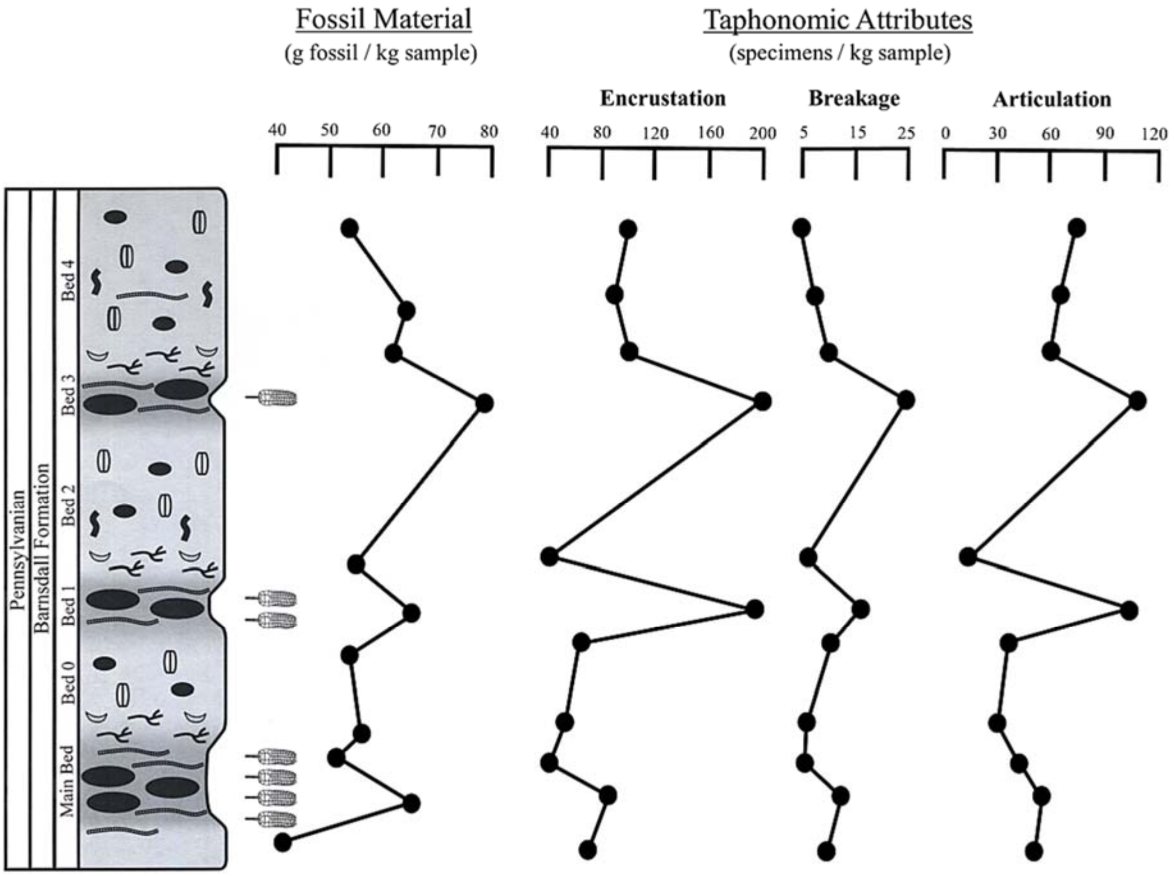

Figure 6. Summary of mudstone disaggregation. Note that the value of fossil material is given in grams of recovered fossil material per kilogram of mudstone disaggregated; the values of encrusted, broken, and articulated fragments are given in number of fragments per kilogram of mudstone disaggregated.

tively uncommon, fairly large-diameter, sideritized burrows found consistently within the lower portion of Bed 2 and the middle portion of Bed 4. Burrow morphology is difficult to ascertain, as the burrows tend to fracture into segments that weather out of the outcrop individually. Branching is observed on some specimens, and there is considerable variation in burrow orientation, with subvertical, subhorizontal, and even seemingly coiled orientations observed.

The preferential sideritization of these biogenic structures indicates a major porosity difference between burrow-filling sediment and the surrounding sediment into which the structure was emplaced. In addition, a large burrow would have been highly unstable in muddy, fluid-rich sediment such as that indicated for the environment represented by the studied section. Both of these lines of evidence indicate that these large burrows were emplaced into firm substrates. The absence of a major shift in biota or crinoid morphology, pervasive seafloor encrustation, or reworked sedimentary material suggests that this firm substrate was unlikely to have been exposed at the sediment-water interface; instead, only the upper portion of the fluid-rich mixed layer may have been removed, permitting the deepest bioturbators to encounter partially de-watered, stiff mud that was normally too deep for excavation, creating a concealed firmground (*sensu* Bromley, 1990). Thus, minor episodes of sediment removal occurred during deposition of the thicker units, suggesting episodic increases in energy that did not occur during deposition of the thinner units.

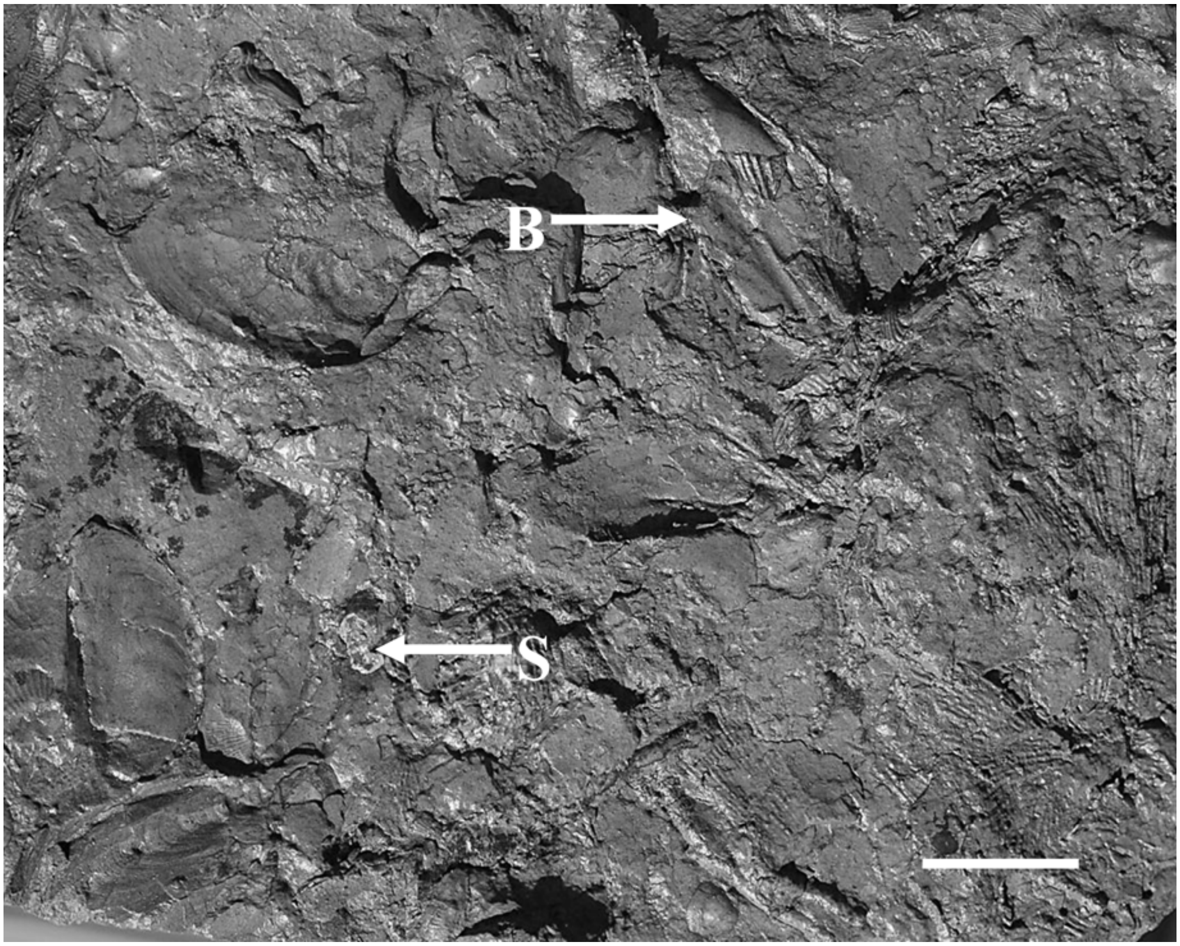

Figure 7. Mollusk-dominated event assemblage from Bed 2, typical of the thicker units. The "S" marks a scaphopod in living position and the "B" marks an articulated thin-shelled bivalve in living position. The presence of these efficient burrowers in living position indicates a thick, rapidly deposited sediment layer. Scale bar = 1 cm (0.4 in).

Lithologic Properties

A remarkable degree of similarity is observed in grain size and composition between the thinner and thicker units. Seemingly, this fairly calm environment was far enough from sources of clastic sediment to be affected only by relative sedimentation rates, without any appreciable changes in grain size, even in event layers. One notable difference in macroscopic lithologic properties exists between the thinner and thicker beds, however. The thinner beds, although rich in skeletal material, do not contain any distinct skeletal lags or sharply defined fossil concentrations, while the thicker units are host to numerous thin, sharply based, densely packed skeletal horizons (Fig. 8). These appear to represent lags resulting from winnowing of fine-grained sediment during periods of increased current velocity. Lag horizons are relatively common in mud-dominated shelf sequences and are frequently generated by increased energy associated with distal storm events (Aigner, 1985; Brett and Allison, 1998).

Siderite Concretion Morphology

Despite the ubiquitous occurrence of siderite in the Copan section (Fig. 4), concretion morphologies are variable and are distributed nonrandomly throughout the microstratigraphic section. Four siderite concretion morphologies were recognized by Thomka (2010): (1) large concretions lacking a distinct fossil nucleus; (2) small concretions, commonly enclosing a single fossil nucleus; (3) large-diameter sideritized burrows; and (4) small concretions very locally nucleated around sites of soft tissue on macrofossils but not enclosing the fossil. The first three morphologies have important implications for interpreting the section.

Large siderite concretions occur within the thinner units and are, in fact, essential to locating these horizons in the field (Lewis et al., 1998). Lengths of up to 25 cm (10 in) and diameters of 15 cm (6 in) for single concretions are observed consistently. Concretions are generally fossiliferous and contain a fossil assemblage identical to that of the surrounding mudstone. Interestingly, despite containing abundant skeletal material, large concretions do not appear to contain a distinct skeletal nucleus that initiated and localized siderite precipitation; instead, fossils are scattered throughout the concretion and appear to have been preserved incidentally as the concretion grew and incorporated surrounding sediment. Although these concretions are characterized by interesting inter-

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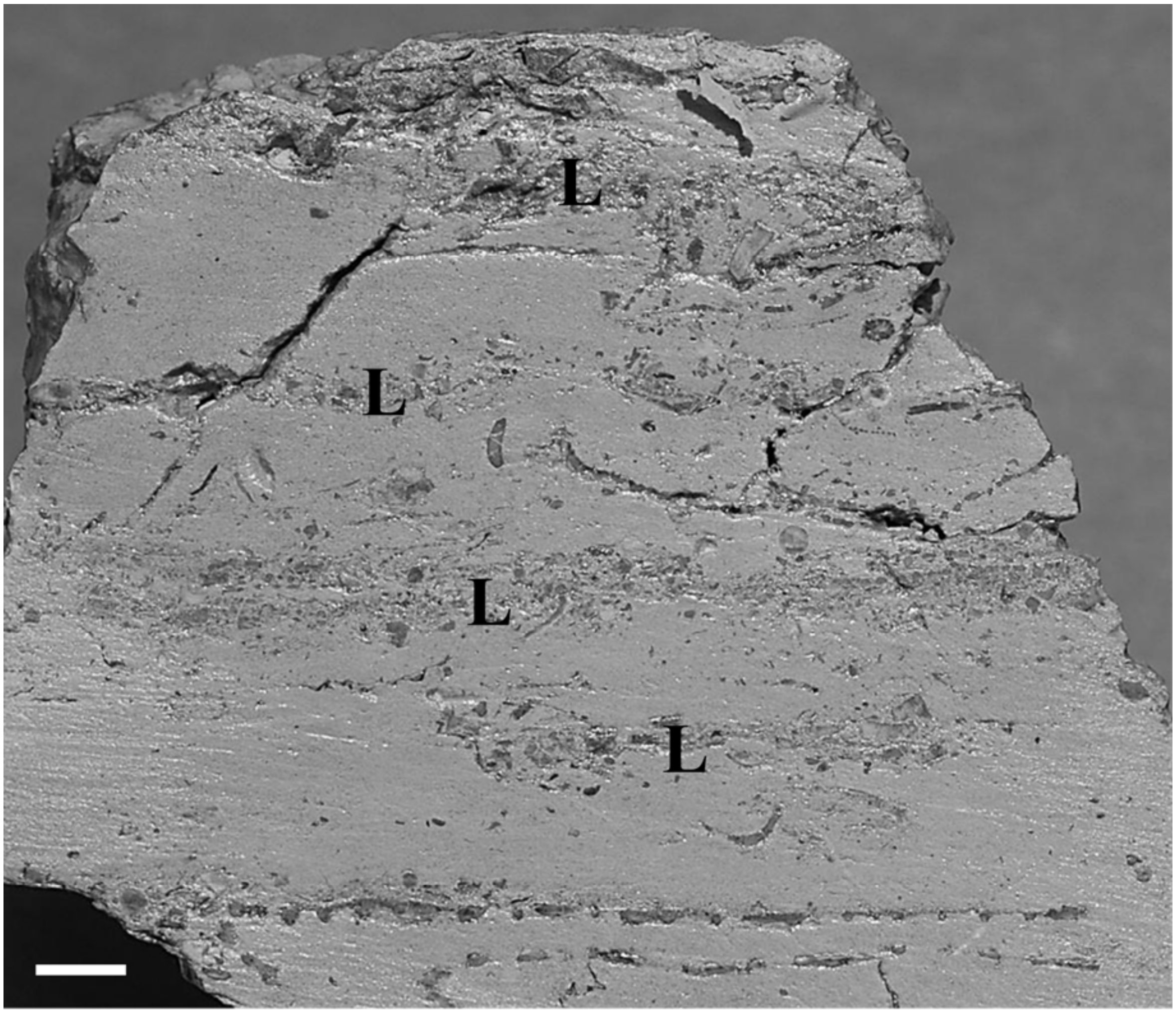

Figure 8. Winnowed skeletal lag horizons (L) in a mudstone slab from the lower portion of Bed 2. These represent repeated episodic higher-energy events. Scale bar = 1 cm (0.4 in).

nal fabrics indicating early diagenesis, the most paleoenvironmentally relevant aspect of the large siderite concretions is simply their large size. Because concretions need time to grow, precipitation of large concretions requires considerable time within a stabilized zone of alkalinity enriched in ferrous iron and bicarbonate. Such requirements exist only in a narrowly restricted subsurface zone. Because redox boundaries migrate with vertical sediment accretion or erosion, siderite concretions of this size require static and stable redox boundaries for an extended period of time, likely hundreds to a few thousand years (Raiswell, 1987), reflecting little net sediment accumulation or removal. Thus, the occurrence of such large siderite concretions and their restriction to only the three units bearing articulated crinoids can only result from sediment starvation operating during deposition of the thinner units.

Smaller siderite concretions are found concentrated within the thicker units. Typical diameters range from 2 to 4 cm (0.75–1.5 in), and shapes are generally similar to those of the large concretions. No evidence of post-formational exposure was detected in these concretions despite their co-occurrence with evidence for occasional winnowing and erosion. Small concretions frequently contain a recognizable skeletal nucleus, most commonly endobenthic bivalves. Fossil nuclei are generally well preserved, with bivalves containing both articulated valves and sometimes found in living position. The occurrence of articulated bivalves at the center of small concretions indicates that the decay of soft tissue generated the ionically reactive, reducing microenvironment required for concretion formation (e.g., Allison, 1988); this is interpreted to indicate rapid burial under a thick sediment layer, as the burial event had to be sufficiently thick to immediately place the bivalve below the near-surface oxic and taphonomically active zone. More importantly, the size of these concretions indicates that insufficient time was spent within the zone of siderite-forming conditions to produce concretions as large as those within the thinner beds. This indicates more transient redox boundaries, reflecting relatively rapid changes in the position of the sediment-water interface. Coupled with the paleontologic and stratinomic evidence described above, the stratigraphic occurrence of this siderite morphology indicates considerably higher sedimentation rates in the thicker units relative to the thinner units.

The implications and significance of large sideritized burrows has been discussed previously, but the stratigraphic occurrence is worth re-emphasizing: these structures, which appear to indicate minor erosive events, occur only in the thicker units (specifically Bed 2 and Bed 4). These units seemingly represent an environment where episodic events were energetic enough to remove at least some of the uppermost, fluid-rich sediment. The absence of these features in the thinner units suggests that rapid burial events were not as energetic as those of the thicker units.

DISCUSSION

Implications for Genesis of Deposit

There is abundant evidence that the thinner units (Main Crinoid Bed, Bed 1, and Bed 3) represent periods of sediment starvation punctuated by rapid burial events. This evidence includes (1) the dominance of the fossil assemblage by epibenthic suspension feeders, which require low turbidity and sedimentation; (2) the prominent background assemblage, representing generations of individuals that lived, died, disarticulated, and contributed their skeletal remains to the seafloor sediment over a long period; (3) the thorough biogenic mixing of sediment such that no distinct physical or biogenic sedimentary structures remain; (4) the enrichment in fossil material relative to thicker units without any evidence of bioclast transport; (5) the abundance of encrusted skeletal grains, which indicate periods of exposure of skeletal material at the sediment-water interface under conditions of relatively low sedimentation; and (6) the presence of very large siderite concretions, which can only form through considerable residence time within a narrowly defined subsurface redox zone. The articulated state of crinoids and associated fauna indicate that this period of sediment starvation was episodically interrupted by rapid burial events; however, the absence of mobile fauna, winnowed shell lags, or firmground perforations shows that these depositional events, although rapid, deposited only a thin burial layer and were not accompanied by major increases in energy. Thus, the remarkable diversity and abundance of articulated crinoid specimens in the thinner units reflects the stacking of thin obrution layers, undiluted by background sedimentation, which allowed successive crinoid thanatocoenoses (death assemblages) to become telescoped together as a result of stratigraphic condensation and intense compaction.

The thicker units, in contrast, show evidence of deposition under higher sedimentation and energy conditions. Evidence for this interpretation includes (1) dominance by endobenthic mollusks, including deposit feeders, which are more tolerant of turbidity; (2) numerous endobenthic bivalves preserved articulated and in living position, which indicate much thicker individual burial events relative to the thinner units; (3) large-diameter sideritized burrows, which provide evidence of occasional erosive events to allow bioturbation in firmer substrates; (4) thin winnowed shell lags, produced by episodic reworking of the seafloor; (5) decreased abundance of skeletal material despite increased stratigraphic thickness; (6) decreased number of encrusted skeletal grains, suggesting decreased exposure time at the seafloor; and (7) small siderite concretions, indicating transient redox boundaries and, therefore, enhanced migration of the sediment-water interface.

Although the entire section under study reflects relatively deep water, low energy environments on a regional scale, there is clearly a marked difference between the thinner and thicker units that influenced biofacies, taphofacies, ichnofabrics, lithologic properties, and siderite concretion morphologies. While it may be problematic to interpret the thicker units as shallower in terms of absolute water depth, the higher sedimentation rate, increased event-bed thickness, and increased intensity of physical seafloor disturbance at least argues for an interpretation of the thicker units as representing a more proximal environment than the thinner units. Thus, each transition from underlying thin unit to overlying thick unit appears to represent an episode of minor shoaling upward, in that absolute water depth may not appreciably shift, but position along an onshore-offshore sedimentation and tempestite proximality gradient is changed. The overlying transition from thicker unit to thinner unit (from Bed 0 to Bed 1, for example) represents a flooding event and consequent return to more distal conditions.

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Anatomy of a Cycle

The three thin cycles detected within the upper core shale of the Barnsdall Formation are relatively simple and, as described above, consist of alternations between underlying distal facies and overlying more proximal facies. Although the thinner units are characterized by the presence of numerous articulated crinoid crowns and large siderite concretions, these elements are actually concentrated primarily in the lower portion of the units, with the upper portion dominated by disarticulated crinoid debris and fenestrate bryozoan material. The increased concretion size most likely reflects the longer span of time earlier-formed concretions spent within the zone of siderite-forming conditions compared to later concretions, and the greater number of articulated crowns at the base of thinner units may reflect damage imparted by later storm events on overlying sediment. Scattered crowns and cups do occasionally occur in the upper parts of the horizons, however, and column segments ranging in length from short pluricolumnals to long, nearly complete columns, as well as articulate brachiopods, are common throughout each thin unit. Directly above this zone, at the very base of the overlying thicker beds, is a 1–4 cm (0.5–1.5 in) horizon very rich in tubular sponges. Overlying this zone is a 3–5 cm (1–2 in) layer of tubular sponges and productid brachiopods, both in life and overturned orientations, and in varying degrees of completeness. Above this zone is a thick interval dominated by endobenthic mollusks; this zone is also host to the majority of winnowed shell lags and sideritized burrows. Interestingly, the repeated occurrence of the distinct succession of characteristic zones at the transition between thinner and thicker units may indicate that the tubular sponges thrived in some sort of ephemeral intermediate interval between the crinoid/brachiopod/bryozoan fauna dominant in the thinner units and the molluskan fauna of the thicker units. Perhaps, these sponges were more tolerant in substrate preference or turbidity resistance than the other organisms. The upper 3–5 cm (1–2 in) of the thicker units contain more articulated crinoid columns than the middle, possibly reflecting either sampling from the base of overlying thinner units where microstratigraphic relationships were unclear or some sort of environmental/ecological transition zone between thicker and thinner units.

Nature of Cyclicity

While the shift from the Main Crinoid Bed to Bed 0 represents a single episode of minor shoaling, the subsequent shift from Bed 0 to Bed 1 and consequent return to conditions similar to those of the Main Crinoid Bed are more intriguing. The geographic limits of the area containing articulated crinoid remains were tested during fieldwork, resulting in the tentative conclusion that the *Lagerstätte* interval appears to be laterally restricted at all horizons (Lewis et al., 1998); further, regional stratigraphic studies by Holterhoff (1996, 1997) have failed to locate similar *Lagerstätten* in correlative portions of the Barnsdall Formation. Following the first episode of shoaling upward, why was the same distal facies, characterized by numerous articulated crinoids, re-established not once, but twice in the same laterally restricted zone? One would intuitively expect the articulated crinoid-bearing facies to migrate away from the same geographically localized site once conditions became less hospitable to diverse crinoid assemblages, yet the Copan site is host to three horizons in the same laterally restricted area that are distinct relative to adjacent and sub/superjacent horizons in terms of fossil content and preservation. A possible, although speculative, explanation centers on some sort of submarine topographic depression that served to funnel nutrients and promote steady current flow, but also funnel sediment during storm events; this would lead to repeated rapid burial followed by rapid re-colonization by epibenthic fauna, particularly suspension feeders dependent on the locally increased current. Such a scenario was documented by Ausich et al. (1979) and Kammer (1985) in the Mississippian Borden Delta complex of Indiana and Kentucky: in addition to promoting rapid re-establishment of crinoid communities following burial events, the diversity of prodeltaic crinoid communities was increased by the ready availability of suspended nutrients. Although no evidence for such a feature has been detected within the Barnsdall Formation, such a mechanism may help to explain some currently unexplained aspects of crinoid paleoecology (e.g., diversity of arm morphologies) and taphonomy (e.g., repeated occurrence of articulated crinoids in the same laterally restricted area at multiple horizons) within the Copan deposit.

Each individual cycle records an initial period of sediment starvation punctuated by thin rapid burial events, which is then overlain by the sponge-rich transition zone and the thicker, molluskan-dominated units. This thicker unit is rather abruptly overlain by another thinner unit. Thus, the overall pattern represented by each cycle is one of gradual shoaling, followed by rapid flooding. There are three such cycles observed within the studied section, and the stacking pattern of these cycles appears to represent a longer-term pattern. The stratigraphic thickness, crinoid diversity, and crinoid specimen abundance decreases successively from the Main Crinoid Bed to Bed 1, and from Bed 1 to Bed 3. Likewise, bed thickness increases upsection within the thicker units, and sideritized burrows (indicating minor erosive episodes) are observed in Bed 2 and Bed 4, but not in Bed 0. Collectively, these trends suggest that less time was spent in the more distal portion of each successive cycle, with fewer rapid burial events occurring during sediment starved periods in higher cycles compared to the underlying thin units. Longer time spans and possibly increasing energy conditions characterized the more proximal portion of higher cycles. This distinctly progradational pattern of cycle stacking indicates that regression during deposition of the upper core shale interval occurred not in a single episode, but rather in several phases interrupted by minor flooding events (phased regression). Such a pattern has been documented by Felton and Heckel (1996) in the regressive limestone member of the Dennis cyclothem. The extension of phased regression into the upper core shale facies provides further evidence that sea-level fluctuations associated with Pennsylvanian cyclothems are complex and vary on numerous scales; if small-scale sea-level shifts are related to minor glacio-eustatic fluctuations, this would add credence to recent comparisons between the dynamics of Late Pennsylvanian and Pleistocene glaciation and glacio-eustacy (e.g., Fielding et al., 2008).

Interpreting the cause of these cycles is difficult given their subtlety and the lithologic homogeneity of the Barnsdall Formation, which impedes regional identification of thin horizons surrounded by sediment of nearly identical character (Holterhoff, 1997). Further, recognition of these small cycles are dependent to a large extent on comparative taphonomy of articulated and partially articulated crinoids, which are not characteristic of the entire Barnsdall Formation and may be restricted to local occurrences such as the Copan site; hence, the same processes may have operated on the seafloor regionally but are unrecognizable at sites containing different taphofacies. Given the strong deltaic influence, it is likely that this cyclicity reflects an autocyclic mechanism such as delta lobe switching: in this model the sediment starved periods indicate sediment shutoff related to lobe abandonment and the more proximal microfacies is associated with sediment input from the activated lobe. The progradational stacking pattern of these minor autogenic cycles would reflect the overall progradation of the delta.

An interesting alternative model for the genesis of these cycles is based on an allocyclic mechanism, where each cycle is treated as a parasequence. Although incredibly thin as a result of low sedimentation, cycles appear to represent a timespan of several hundred to a few thousand years and are arranged into a stacking pattern reflecting the broader trend of this portion of the cyclothem. Based on cycle thinness, one might interpret these cycles as beds or bedsets of Van Wagoner et al. (1990). However, (1) bedsets typically represent a considerably shorter span of time than that interpreted for the Copan cycles based on taphonomic evidence and inferred from concretion size and (2) beds and bedsets are typically simple internally and recognized by such features as normal grading (e.g., Taylor and Macquaker, 2000), while these cycles are more complex and represent facies shifts, although minor ones at best. Decimeter-scale parasequences in homogeneous mudstones have been described by Macquaker et al. (1998) from the Jurassic of eastern England, demonstrating that in distal successions, parasequences can be remarkably thin, and their expression inconspicuous. Studies of deposits with greater outcrop availability by Brett and Baird (1986b, 1996) and Elder et al. (1994) have resulted in the correlation of decimeter-scale distal cycles similar to those described here with thicker cycles more typical of “classic” parasequences deposited in more proximal environments. In addition, research on the Silurian Rochester Shale of New York and Ontario has documented stacking of thin obrution horizons above marine flooding surfaces during periods of resultant sediment starvation (Taylor and Brett, 1996; Brett and Taylor, 1997) in a scenario very close to that proposed for the Copan deposit and indirectly supportive of the parasequence interpretation.

In spite of the possibility that stratigraphically condensed intervals such as the upper core shales of Pennsylvanian cyclothems may permit the delineation of thin, distal parasequences, the inability to correlate flooding surfaces regionally limits the value of this model. An autocyclic mechanism for such small cycles should remain the null hypothesis unless regional surfaces can be documented; however, the issue of the expression of parasequences in similar condensed settings is intriguing and should receive further study.

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CONCLUSIONS

The upper core shale interval of the Upper Pennsylvanian Stanton cyclothem exposed near Copan, Washington County, Oklahoma represents a low-energy, oxygenated, muddy, prodeltaic distal shelf setting bordered to the north by shallower, carbonate-dominated environments, and to the south by deltaic wedges fed by the Ouachitas. The abundant and diverse macrofaunal assemblage associated with this environment is made possible by the breakdown of water column stratification following initial regression; as a result, the fossiliferous facies is located stratigraphically above dysoxic gray shale facies representing highstand and below poorly fossiliferous mudrocks and sandstones representing shallower facies reflecting deltaic progradation.

This section contains abundant articulated crinoids, restricted to three thin horizons separated from each other by thicker units that contain very few articulated crinoid remains that are instead dominated by endobenthic bivalves commonly preserved in life position. The thin units contain abundant large siderite concretions, while the thicker units contain siderite concretions of considerably smaller size. In addition, the thicker units contain discrete sideritized burrows and winnowed shell lags, both of which are absent from the thinner units. Thinner units are enriched in disarticulated skeletal material compared to thicker units, and a considerably higher proportion of separated crinoid ossicles are encrusted. Taphonomic, paleoecologic, and sedimentologic evidence demonstrates that the thinner units correspond to sediment starved conditions, while the thicker units represent periods of increased sedimentation. Further, rapid burial events in the thin units were evidently very thin and not associated with significant increases in energy, while burial events in the thicker units were much thicker and accompanied by stronger bottom currents. Collectively, these data indicate that the thin units represent a more distal environment relative to the more proximal environment of the thicker units.

Three cycles, each approximately 15 cm (5 in) thick, are expressed as alternations between proximal and distal units. The upward shift in biofacies, taphofacies, concretion morphologies, and sedimentary structures from thinner to thicker units is equated with a pattern of minor shoaling. During the following flooding event, the proximality gradient shifted landward and the more distal, sediment starved environment was re-established. These three cycles are arranged into a progradational stacking pattern with fewer rapid burial events occurring in successive thinner units. This is evidenced by upward decreases in the thickness of thinner units, number of articulated crinoid specimens, and diversity of crinoid taxa; in addition, the thickness of successive thicker units increases upwards and sideritized burrows occur in the upper two thicker beds but not Bed 0. Consequently, these cycles represent phased regression and indicate that the regression observed in the upper portion of the Stanton cyclothem occurred through a series of minor regressive episodes punctuated by minor flooding episodes. The nature of these cycles is difficult to ascertain, as their detection is dependent to a large extent on the occurrence of articulated crinoids, which are not characteristic of the majority of the Barnsdall Formation regionally. These may represent the product of autogenic processes related to delta lobe switching; yet, an interesting and controversial interpretation of these cycles as the distal expression of parasequences is also possible. However, until these small, subtle cycles are found in coeval strata or other regional evidence for an allocyclic mechanism is reported, this remains merely a stimulating postulate.

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Aigner, T., 1985, Storm depositional systems: Dynamic stratigraphy in modern and ancient shallow-marine sequences: Lecture Notes in Earth Sciences, v. 3, 174 p.

Algeo, T. J., and P. H. Heckel, 2008, The Late Pennsylvanian Midcontinent Sea of North America: A review: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 268, p. 205–221.

Allison, P. A., 1988, The role of anoxia in the decay and mineralization of proteinaceous macro-fossils: Paleobiology, v. 14, p. 139–154.

Allmon, R. A., 1985, “Butterflied” bivalves as paleoenvironmental indicators: Geological Society of America Abstracts with Programs, v. 17, p. 512.

Ausich, W. I., 2001, Echinoderm taphonomy, *in* M. Jangoux and J. M. Lawrence, eds., Echinoderm studies, v. 6: A. A. Balkema, Rotterdam, The Netherlands, p. 171–227.

Ausich, W. I., T. W. Kammer, and N. G. Lane, 1979, Fossil communities of the Borden (Mississippian) delta in Indiana and northern Kentucky: Journal of Paleontology, v. 53, p. 1182–1196.

Bisnett, A. J., and P. H. Heckel, 1996, Sequence stratigraphy helps to distinguish offshore from nearshore black shales in the Midcontinent Pennsylvanian succession, *in* B. J. Witzke, G. A. Ludvigson, and J. Day, eds., Paleozoic sequence stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, Boulder, Colorado, p. 341–350.

Boardman, D. R., II, and P. H. Heckel, 1989, Glacial-eustatic sea-level curve for early Late Pennsylvanian sequence in north-central Texas and biostratigraphic correlation with curve for midcontinent North America: Geology, v. 17, p. 802–805.

Boardman, D. R., II, R. H. Mapes, T. E. Yancey, and J. M. Malinky, 1984, A new model for the depth-related allogenic community succession within North American Pennsylvanian cyclothems and implications for the black shale problem, *in* N. J. Hyne, ed., Limestones of the Mid-Continent: Tulsa Geological Society Special Publication 2, Oklahoma, p. 141–182.

Brenchley, P. J., and G. Newall, 1970, Flume experiments on the orientation and transport of models and shell valves: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 7, p. 185–220.

Brett, C. E., and P. A. Allison, 1998, Paleontological approaches to the environmental interpretation of marine mudrocks, *in* J. Schieber, W. Zimmerle, and P. S. Sethi, eds., Shales and mudstones I: Basin studies, sedimentology, and paleontology: *E. Schweizerbart’sche Verlagsbuchhandlung*, Stuttgart, Germany, p. 301–349.

Brett, C. E., and G. C. Baird, 1986a, Comparative taphonomy: A key to paleoenvironmental interpretation based on fossil preservation: *Palaios*, v. 1, p. 207–227.

Brett, C. E., and G. C. Baird, 1986b, Symmetrical and upward shallowing cycles in the Middle Devonian of New York state and their implications for the punctuated aggradational cycle hypothesis: Paleoceanography, v. 1, p. 431–445.

Brett, C. E., and G. C. Baird, 1996, Middle Devonian sedimentary cycles and sequences in the northern Appalachian Basin, *in* B. J. Witzke, G. A. Ludvigson, and J. Day, eds., Paleozoic sequence stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, Boulder, Colorado, p. 213–241.

Brett, C. E., and W. L. Taylor, 1997, The *Homocrinus* beds: Silurian crinoid *Lagerstätten* of western New York and southern Ontario, *in* C. E. Brett and G. C. Baird, eds., Paleontological events: Stratigraphic, ecological, and evolutionary implications: Columbia University Press, New York, New York, p. 181–223.

Brett, C. E., H. A. Moffat, and W. L. Taylor, 1997, Echinoderm taphonomy, taphofacies, and *Lagerstätten*, *in* J. A. Waters and C. G. Maples, eds., Geobiology of echinoderms: Paleontological Society Special Papers 3, Boulder, Colorado, p. 147–190.

Bromley, R. G., 1990, Trace fossils: Biology and taphonomy: Special Topics in Palaeontology, v. 3, 280 p.

Crowell, J. C., 1978, Gondwanan glaciation, cyclothems, continental positioning, and climate change: American Journal of Science, v. 278, p. 1345–1372.

Donovan, S. K., 1991, The taphonomy of echinoderms: Calcareous multi-element skeletons in the marine environment, *in* S. K. Donovan, ed., The processes of fossilization: Columbia Press, New York, New York, p. 241–269.

Elder, W. P., E. R. Gustason, and B. B. Sageman, 1994, Correlation of basinal carbonate cycles to nearshore parasequences in the Late Cretaceous Greenhorn seaway, Western Interior U.S.A.: Geological Society of America Bulletin, v. 106, p. 892–902.

Felton, R. M., and P. H. Heckel, 1996, Small-scale cycles in Winterset Limestone Member (Dennis Formation, Pennsylvanian of northern Midcontinent) represent 'phased regression,' *in* B. J. Witzke, G. A. Ludvigson, and J. Day, eds., Paleozoic sequence stratigraphy: Views from the North American craton: Geological Society of America Special Paper 306, Boulder, Colorado, p. 389–397.

Fielding, C. R., T. D. Frank, and J. L. Isbell, eds., 2008, Resolving the Late Paleozoic ice age in time and space: Geological Society of America Special Paper 441, Boulder, Colorado, 354 p.

Heckel, P. H., 1977, Origin of phosphatic black shale facies in Pennsylvanian cyclothems of midcontinent North America: American Association of Petroleum Geologists Bulletin, v. 61, p. 1045–1068.

Heckel, P. H., 1978, Field guide to Upper Pennsylvanian cyclothemic limestone facies in eastern Kansas: Kansas Geological Survey Guidebook Series 2, Lawrence, 79 p.

Heckel, P. H., 1980, Paleogeography of eustatic model for deposition of midcontinent Upper Paleozoic cyclothems, *in* T. D. Fouch and E. R. Magathan, eds., Paleozoic paleogeography of the west-central United States: Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists, West-Central United States Paleogeography Symposium 1, Denver, Colorado, p. 197–215.

Heckel, P. H., 1986, Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along midcontinent outcrop belt, North America: Geology, v. 14, p. 330–334.

Heckel, P. H., 1994, Evaluation of evidence for glacio-eustatic control over marine Pennsylvanian cyclothems in North America and consideration of possible tectonic effects, *in* J. M. Dennison and F. R. Ettensohn, eds., Tectonic and eustatic control on sedimentary cycles: Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology 4, Tulsa, Oklahoma, p. 65–87.

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Holterhoff, P. F., 1996, Crinoid biofacies in Upper Carboniferous cyclothems, midcontinent North America: Faunal tracking and the role of regional processes in biofacies recurrence: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 127, p. 47–81.

Holterhoff, P. F., 1997, Filtration models, guilds, and biofacies: Crinoid paleoecology of the Stanton Formation (Upper Pennsylvanian), midcontinent, North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 130, p. 177–208.

Kammer, T. W., 1985, Basinal and prodeltaic communities of the Early Carboniferous Borden Formation in northern Kentucky and southern Indiana (U.S.A.): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 49, p. 79–121.

Kammer, T. W., C. E. Brett, D. R. Boardman II, and R. H. Mapes, 1986, Ecologic stability of the dysaerobic biofacies during the late Paleozoic: *Lethaia*, v. 19, p. 109–121.

Klein, G. D., 1990, Comments on sedimentary-stratigraphic verification of some geodynamic basin models: Examples from a cratonic and associated foreland basins, *in* A. T. Cross, ed., Quantitative dynamic stratigraphy: Prentice Hall, Englewood Cliffs, New Jersey, p. 503–518.

Klein, G. D., and J. B. Kupperman, 1992, Pennsylvanian cyclothems: Methods of distinguishing tectonically induced changes in sea level from climatically induced changes: Geological Society of America Bulletin, v. 104, p. 166–175.

Klein, G. D., and D. A. Willard, 1989, Origin of the Pennsylvanian coal-bearing cyclothems of North America: Geology, v. 17, p. 152–155.

Kranz, P. M., 1974, The anastrophic burial of bivalves and its paleoecological significance: Journal of Geology, v. 82, p. 237–265.

Lewis, R. D., 1980, Taphonomy, *in* T. W. Broadhead and J. A. Waters, eds., Echinoderms: Notes for a short course: University of Tennessee Studies in Geology 3, Knoxville, p. 27–39.

Lewis, R. D., P. F. Holterhoff, D. Mosher, and R. K. Pabian, 1998, Taphonomy of a crinoid *Lagerstätte* deposit, Barnsdall Formation (Upper Pennsylvanian), northeastern Oklahoma: Geological Society of America Abstracts with Programs, v. 30, p. 31.

Macquaker, J. H. S., R. L. Gawthorpe, K. G. Taylor, and M. J. Oates, 1998, Heterogeneity, stacking patterns, and sequence stratigraphic interpretation in distal mudstone successions: Examples from the Kimmeridge Clay Formation, U.K., *in* J. Schieber, W. Zimmerle, and P. Sethi, eds., Shales and mudstones I: Basin studies, sedimentology, and Paleontology: *E. Schweizerbart'sche Verlagsbuchhandlung*, Stuttgart, Germany, p. 163–186.

Malinky, J. M., and P. H. Heckel, 1998, Paleoecology and taphonomy of faunal assemblages in gray "core" (offshore) shales in midcontinent Pennsylvanian cyclothems: *Palaios*, v. 13, p. 311–334.

Pabian, R. K., 1987, A Late Pennsylvanian (Missourian) echinoderm fauna from northeastern Oklahoma: Proceedings of the Nebraska Academy of Sciences, v. 97, Lincoln, p. 48.

Pabian, R. K., D. Mosher, R. D. Lewis, and P. F. Holterhoff, 1995, Crinoid assemblage from the Barnsdall Formation, Late Pennsylvanian (Missourian), Washington County, Oklahoma: Geological Society of America Abstracts with Programs, v. 27, p. 78.

Pabian, R. K., D. Mosher, R. D. Lewis, and P. F. Holterhoff, 1997, Prey-predator, parasitic, and commensal relationships with Late Pennsylvanian crinoids and associated fauna from the Barnsdall Formation (Late Pennsylvanian, Missourian/Virgilian) of northeastern Oklahoma: Proceedings of the Nebraska Academy of Sciences, Lincoln, v. 107, p. 49.

Peterson, C. H., 1985, Patterns of lagoonal bivalve mortality after heavy sedimentation and their paleoecological significance: Paleobiology, v. 11, p. 139–153.

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Rascoe, B., Jr., 1975, Tectonic origin of preconsolidation deformation in Upper Pennsylvanian rocks near Bartlesville, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 59, p. 1626–1638.

Read, W. A., and I. H. Forsyth, 1989, Allocycles and autocycles in the upper part of the Limestone Coal Group (Pendleian E1) in the Glasgow-Stirling region of the Midland Valley of Scotland: Geological Journal, v. 24, p. 121–137.

Savrda, C. E., 1995, Ichnologic applications in paleoceanographic, paleoclimatic, and sea-level studies: *Palaios*, v. 10, p. 565–577.

Seilacher, A., W. E. Reif, and F. Westphal, 1985, Sedimentological, ecological, and temporal patterns of fossil *Lagerstätten*: Philosophical Transactions of the Royal Society of London, v. 311, U.K., p. 5–23.

Speyer, S. E., and C. E. Brett, 1986, Trilobite taphonomy and Middle Devonian taphofacies: *Palaios*, v. 1, p. 312–327.

Speyer, S. E., and C. E. Brett, 1991, Taphofacies controls: Background and episodic processes in fossil assemblage preservation, *in* P. A. Allison and D. E. G. Briggs, eds., Taphonomy: Releasing the data locked in the fossil record: Plenum Press, New York, New York, p. 502–541.

Taylor, K. G., and J. H. S. Macquaker, 2000, Spatial and temporal distribution of authigenic minerals in continental shelf sediments: Implications for sequence stratigraphic analysis, *in* C. R. Glenn, L. Prévôt, and J. Lucas, eds., Marine authigenesis: From global to microbial: Society of Economic Paleontologists and Mineralogists Special Publication 66, Tulsa, Oklahoma, p. 309–323.

Taylor, W. L., and C. E. Brett, 1996, Taphonomy and paleoecology of echinoderm *Lagerstätten* from the Silurian (Wenlockian) Rochester Shale: *Palaios*, v. 11, p. 118–140.

Thomka, J. R., 2010, Modes of occurrence of siderite in the Upper Pennsylvanian Barnsdall Formation, northeastern Oklahoma: Relationships to fossil preservation and implications for depositional dynamics: Journal of the Alabama Academy of Science, v. 81, p. 110.

Thomka, J. R., D. Mosher, R. D. Lewis, R. K. Pabian, and P. F. Holterhoff, 2010a, Taphonomy of disarticulated crinoids from the Upper Pennsylvanian Barnsdall Formation, northeastern Oklahoma: Geological Society of America Abstracts with Programs, v. 42, p. 65–66.

Thomka, J. R., R. D. Lewis, D. Mosher, P. F. Holterhoff, and R. K. Pabian, 2010b, Genesis of a crinoid *Lagerstätte* in the Upper Pennsylvanian Barnsdall Formation of northeastern Oklahoma: Geological Society of America Abstracts with Programs, v. 42, p. 511.

Thomka, J. R., R. D. Lewis, D. Mosher, R. K. Holterhoff, and R. K. Pabian, 2011, Genus-level taphonomic variation within cladid crinoids from the Upper Pennsylvanian Barnsdall Formation, northeastern Oklahoma: *Palaios*, v. 26, p. 377–389.

Van Wagoner, J. C., R. M. Mitchum, K. M. Campion, and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, core and outcrop: American Association of Petroleum Geologists Methods of Exploration 7, Tulsa, Oklahoma, 55 p.

Watney, W. L., J. A. French, and E. K. Franseen, 1989, Sequence stratigraphic interpretation and modeling of cyclothems: Kansas Geological Society 41st Annual Field Conference Guidebook, Lawrence, 211 p.

Xiong, B., and P. H. Heckel, 1996, Cementation patterns and diagenesis in the Stanton Limestone/cyclothem (Missourian, Upper Pennsylvanian) in the northern Midcontinent, *in* B. J. Witzke, G. A. Ludvigson, and J. Day, eds., Paleozoic sequence stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, Boulder, Colorado, p. 373–387.

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