Trilobite Taphonomy and Temporal Resolution in the Mt. Orab Shale Bed (Upper Ordovician, Ohio, U.S.A.)

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*Clay-rich units, locally termed "butter shales," contain the best-preserved trilobites in the richly fossiliferous Cincinnatian Series and likely provide the highest temporal resolution available within these rocks. Sedimentological and taphonomic evidence indicates that the 0.46-m-thick Mt. Orab "butter shale" bed of the Arnheim Formation is composed of a series of stacked event beds, each representing rapid deposition from a flow bearing fine-grained sediment, most likely associated with distal storm processes below storm-wave base. It contains sedimentary structures similar to those of distal mud turbidites, and comprises a total of at least seven, and possibly many more, alternating silt and clay couplets. These clay and silt layers are interpreted to represent the products of different energetic regimes in a series of discrete depositional events accumulated within a common depositional regime. Trilobites within individual clay beds represent census assemblages of animals alive at the same time, and evidence from sedimentology, taphonomy, and stratigraphic architecture are consistent with accumulation of the whole bed within a period from 10^1 to 10^3 years. Silt layers of the Mt. Orab events beds are interpreted to represent parautochthonous assemblages, while clay layers, although displaying reorientation of specimens, are interpreted as autochthonous assemblages. Both layers are deposited in a shallower-water environment than the comparable "*granulosa*" trilobite cluster of the Kope Formation, which represents an autochthonous assemblage with* in-situ *burial of trilobites.*

INTRODUCTION

The Cincinnatian Series (Upper Ordovician; Ohio, Kentucky, and Indiana) contains certain shale horizons that are famous for their unusually abundant and exceptionally well-preserved trilobites. These beds, commonly referred to as "butter shales," occur at numerous stratigraphic horizons throughout the Cincinnatian succession. They are composed of mudstones that contain well-preserved and articulated fossil remains that commonly include marked concentrations of articulated trilobites preserved in postures assumed during life. The exceptional preservation of trilobites in multiple butter shales offers an opportunity for a detailed analysis of morphological change through time within the Series. Accordingly, understanding the nature of butter-shale preservation, and the differences seen among butter-shale trilobite assemblages, is a critical step in realizing the potential of these deposits for evolutionary analysis. Individual event beds within the butter shales contain individuals that were alive at the same instant, affording a standard comparable to samples of live animals, by which to assess patterns of morphological variation seen in other deposits, such as limestones, occurring throughout the Cincinnatian Series. Hence, a detailed understanding of the characteristics and variability of trilobite assemblages within butter shales is a prerequisite for a more complete utilization of the Cincinnatian Series as a chronicle of evolutionary change.

Despite being well known, relatively few studies of Cincinnatian butter shales and their fossil assemblages have been published (e.g., Brandt Velbel, 1985; Schumacher and Shrake, 1997; Hughes and Cooper, 1999). Each of these studies documented different patterns of trilobite articulation and posture, but the factors responsible for these differences remain poorly understood. Furthermore, the varied trilobite assemblages of the Cincinnatian butter shales provide an opportunity to compare trilobite preservation within the Cincinnatian Series with the trilobite taphofacies of the Devonian Hamilton Group of New York (Speyer and Brett, 1986).

Previous ecological and taphonomic analyses of the fossil assemblages enclosed in the butter shales have treated each shale as a single depositional unit (Brandt Velbel, 1985; Feree, 1994; Rosenkrantz, 1999), but recent analyses have noted that these beds may contain several episodes of deposition. Based upon taphonomic analyses, Schumacher and Shrake (1997) concluded that a fossil-rich shale unit from the Waynesville Formation represented numerous separate depositional events, rather than a single large event. Contrasts between concentrations of disarticulated remains, interpreted to represent periods of low sedimentation, and the presence of distinct horizons of accumulated articulated trilobite and ostracode carcasses, representing rapid burial within the shale bed, served to mark the boundaries between event beds. In Schumacher and Shrake's (1997) study, thin-section analysis revealed a single interval of graded bedding, a characteristic of tempestite sedimentation, but did not reveal additional diagnostic sedimentary structures commonly associated with

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storm-related deposition. In contrast, Hughes and Cooper (1999) identified two distinct gradational beds in a 3-cm interval within a 15-cm shale bed that apparently was homogeneous in hand specimen. Taphonomic evidence suggested that these layers apparently represented deposition in rapid succession, most probably as different phases of a single gravity-flow event generated by storm activity. Trilobites within these beds were interpreted to represent a contemporaneous population smothered alive by storm-related deposition (Hughes and Cooper, 1999). Previous studies in the Cincinnatian Series (Brandt Velbel, 1985; Jennette and Pryor, 1993; Holland et al., 1997; Hughes and Cooper, 1999) have established that storm-related deposition was responsible for the rapid burial and exceptional preservation of organisms that are characteristic of butter shales. Nevertheless, individual butter shales vary markedly in details of trilobite size distribution, articulation state, posture, attitude, and density. For example, whereas trilobites in most butter shales in the Cincinnatian Series exhibit enrollment, Hughes and Cooper (1999) documented dorsal flexure (upward arching of thorax) in a new species of *Gravicalymene* (which they compared to *Flexicalymene granulosa*) from a butter shale in the Kope Formation. Understanding the factors that contribute to these differences between butter shales, and their relationships with depositional settings, may help to decipher differences in specimen posture.

Depositional Setting of Butter Shales within the Cincinnatian Series

Numerous authors (e.g., Hay, 1981; Kriesa, 1981; Tobin, 1982; Frey, 1987), citing evidence from sedimentary facies, sedimentary structures, and the fossil biota, have inferred that the entire Upper Ordovician exposed in the Cincinnati area represents shallow-marine, mixed siliciclastic-carbonate subtidal deposition on an extensive, gently sloping shelf. This shelf was located in a low-latitude area subject to powerful storms. The result was a stratigraphic succession in which all facies are interpreted to show some evidence of storm activity. Siliciclastic muds originated from the Taconic highlands to the east, and limestones resulted from storm processes that concentrated bioclastic material on open-shelf bottoms (Tobin, 1982).

The Arnheim Formation is characterized by alternating beds of limestone and shale and is divided into two members: the Sunset Member, which contains an informal unit called Mt. Orab butter-shale bed (hereafter referred to as the Mt. Orab bed), and the overlying Oregonia Member (Fig. 1). The Sunset Member is within the highstand systems tract of the C4 third-order cycle in the Cincinnatian Series (Holland, 1993), and is characterized by medium- to thin-bedded fossiliferous packstone and mudstone beds. These beds belong to the Mixed Packstone-Shale facies of Holland (1993), and are characterized by the presence of a wide range of storm beds, a diverse assemblage of brachiopods and bryozoans, and articulated trilobite and echinoderm remains. These strata were interpreted by Holland (1993) to have been deposited in the transition-zone environment between shoreface and offshore facies.

Conditions favoring the preservation of event beds are not random with respect to stratigraphy. Smothered-bottom deposits are recognized most frequently in the late-transgressive to mid-highstand deposits of many successions because these phases of third-order cycles represent the time in which the shelf and epicontinental seas were flooded to depths greater than wave base (Brett, 1995). Storm processes carried sediment into deeper portions of the basin, where it was protected from later reworking by all but the most powerful storms. Smothered-bottom assemblages consistently occur in the basal portions of parasequences. Trilobites of the "*granulosa*" cluster from the Kope Formation occur within the basal portion of the parasequence (Hughes and Cooper 1999, fig. 4), and the Mt. Orab bed occurs in a similar basal position within a parasequence of the Arnheim Formation (Fig. 1). These portions of parasequences represent the maximum available accommodation space and the lowest energy conditions, favoring the preservation of census assemblages.

METHOD OF INVESTIGATION

The Mt. Orab bed, near the town of Mt. Orab, Ohio (Fig. 2), is an informal unit that is locally well known for the abundant enrolled trilobites (Feree, 1994) that occur throughout its 0.46-meter thickness. It was selected for detailed analysis because the taphonomic condition of the trilobite assemblage appears to be representative of most butter shales from the Cincinnatian, and because of the availability of the site.

A one-m^2 block of mudstone (a general descriptor for the unit), 0.46-m thick, was dissected by hand at the Mt. Orab site. Every piece of fossil material, along with carbonate concretions and burrows, was recorded on a series of clear plastic pages within a horizontal grid system consisting of 20 individual squares. Information recorded *in situ* before removal of the specimen, where applicable, included height above base, orientation, attitude (upside-down, right-side-up), posture (prone, enrolled, partially enrolled), articulation, and fragmentation. Specimens were placed in plastic bags to limit the rate of drying, and later prepared with an air-abrasive unit using a combination of sodium bicarbonate and dolomite as the abrasive medium at a low pressure. Thin sections were made throughout the thickness of the Mt. Orab bed. Due to the friable nature of the mudstone when dry, 6 cm of the total thickness of the bed was lost during thin sectioning.

SEDIMENTOLOGY OF THE MT. ORAB BUTTER SHALE

At outcrop scale, the Mt. Orab bed appears to be lithologically homogenous, as is typical of all butter shales (Fig. 3). However, thin-section analysis of the Mt. Orab bed reveals at least seven repeated alternations of discrete clay and silt layers within the 0.46-m unit (Fig. 4). These layers were recognized based on the ratio of coarse- to fine-grained sediment, and their boundaries were defined by abrupt transitions from fine- and coarse-grained sediment. Each layer is characterized by a couplet consisting of a basal, quartz-dominated, silt-sized layer overlain by a thicker layer of clay. The basal layer is characterized by ~90% quartz grains, and ~10% feldspar grains encased within a carbonate cement. In several cases, the base of the quartz-silt layer is characterized by an irregular contact that cuts into the bed beneath (Fig. 4A). The silt layer

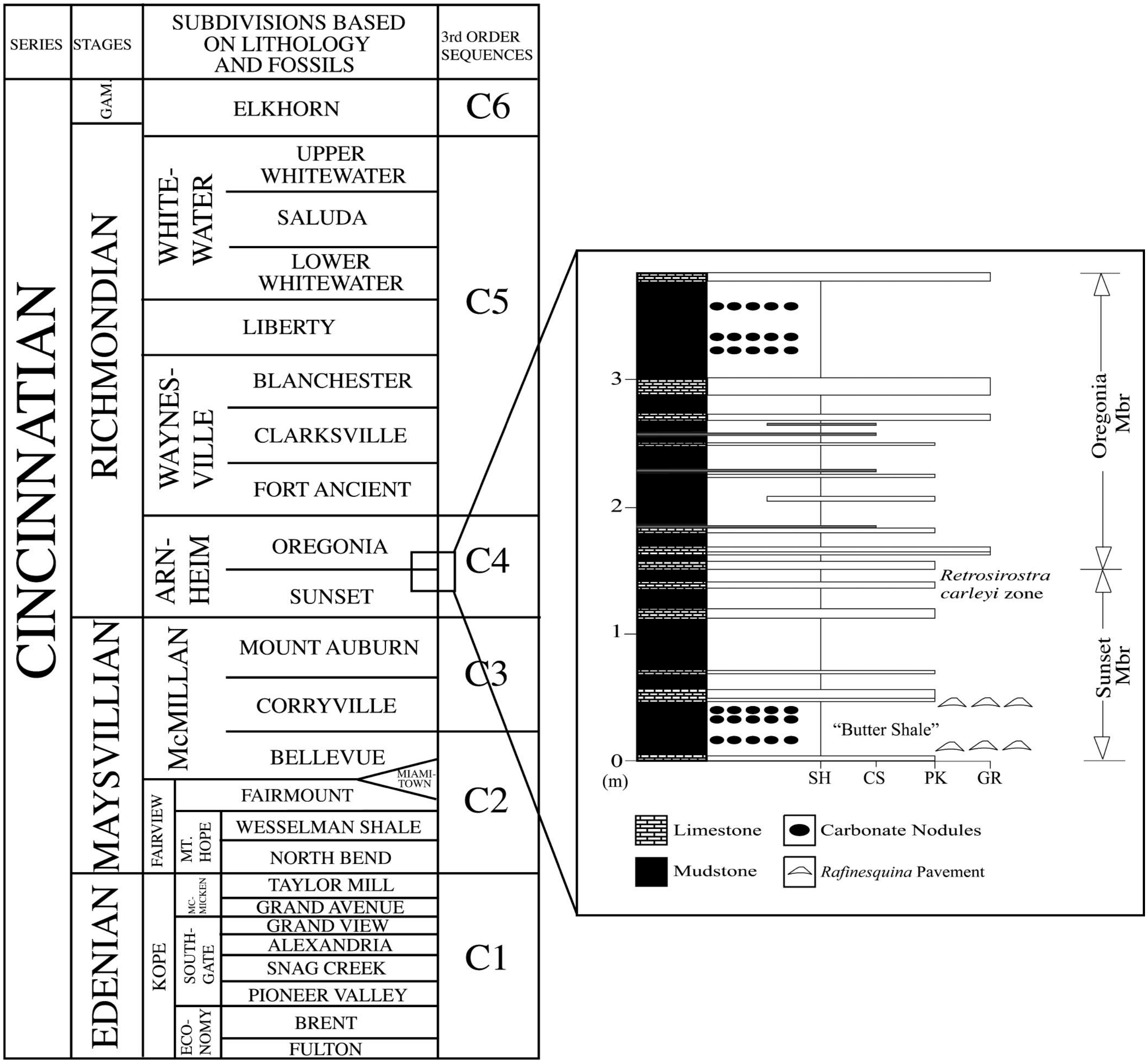

FIGURE 1—Graphic log of section containing the Mt. Orab bed (labeled "Butter Shale") within the Sunset Member of the Arnheim Formation.

appears as either a single, ungraded layer with cross sets (Fig. 4A), or as a series of finely graded layers (Fig. 4B). Division of the units into seven couplets represents a conservative estimate, based on the presence of seven distinct clay/silt transitions. Other, more minor, silt horizons interspersed within clay layers likely represent additional couplets, but these silt layers commonly form discontinuous stringers associated with fragmented skeletal debris (Fig. 4C), so their status as discrete events of silt deposition is equivocal. The silt stringers possibly result from bioturbation.

The clay component of each major couplet lacks distinct sedimentary structures, and contains varying amounts of coarse silt, ranging from pure clay to intervals containing high fractions of silt. Discrete *Chondrites* burrows are visible in outcrop as distinct, light-colored branches. In thin section, the degree of bioturbation is low—ichnofabric index ii of Droser and Bottjer (1986)—with the major basal silt layers remaining undisrupted. Dispersed silt grains that occur sporadically within the upper clay layers may suggest some mixing of silt and clay components due to bioturbation.

Disarticulated skeletal remains are concentrated predominantly in the finely graded silt layers (Fig. 4B) and the silt stringers (Fig. 4C, D), and often contain clay and silt grains within internal cavities beneath the doublure of various trilobite skeletal elements (Fig. 4E). The clay layers have a lower overall abundance of skeletal material. Where present in the clay layer, the skeletal material commonly is articulated, with internal voids of completely en-

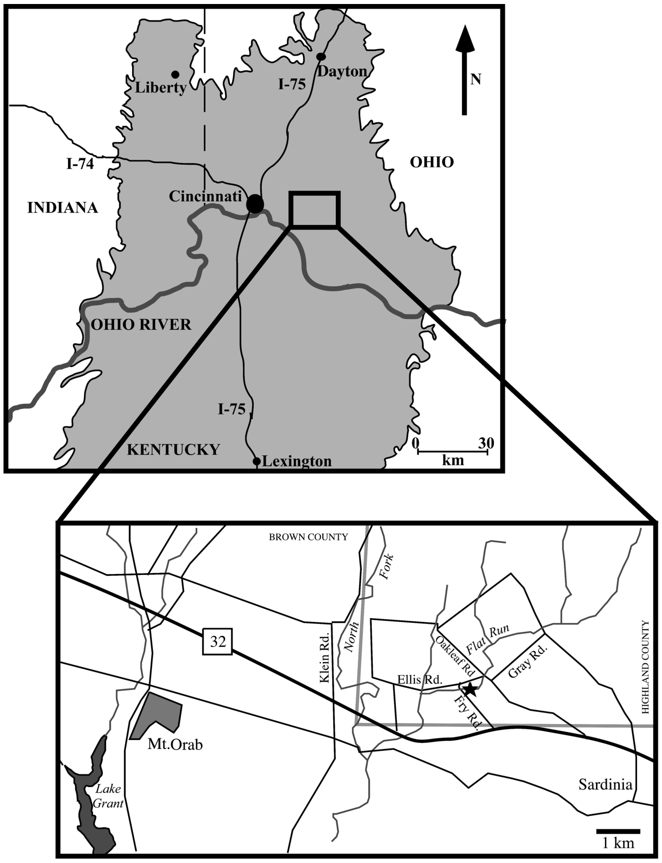

FIGURE 2—Locality map for the Mt. Orab collection site, Ohio, USA.

rolled specimens lined by pyrite (Fig. 4F), often showing secondary sparry calcite mineral precipitation (Fig. 4G, H).

Carbonate nodules occur in specific horizons throughout the 0.46-m interval. They are characterized by a slightly lighter color in hand specimen and thin section (Fig. 4I). Clay particles within the nodules have a random orientation, whereas clay particles within the mudstone show alignment parallel to bedding. This suggests that nodules formed prior to significant compaction. Deformation of silt stringers around carbonate nodules indicates that the sedimentary fabric in the clays is partly diagenetic in origin, resulting from compression around *in-situ* nodules (Fig. 4I).

The entire set of sedimentary structures associated with any one of these couplets is rarely seen in a single layer. A schematic representation of a couplet, constructed from representative layers within the Mt. Orab bed (Fig. 5), shows a distinctive gradation of structures, with the highest content of silt fractions at the base of the couplet and continual decrease of silt content upwards within it. The basal layer consists of an approximately 1-cm-thick lenticular cross-bedded silt lamina, followed by regular, thin, parallel silt laminae interbedded with muds containing disarticulated remains. Silt content decreases above this level, passing into muds containing indistinct silt lenses with disarticulated material, which become finer and thinner upwards, yielding finally to ungraded muds containing articulated trilobite remains.

TRILOBITE TAPHONOMY OF MT. ORAB BED

There is no indication that these individual couplets represent distinct taphonomic grades within a similar depositional regime. Therefore, in order to characterize the trilobite taphonomy of the Mt. Orab bed adequately, en-

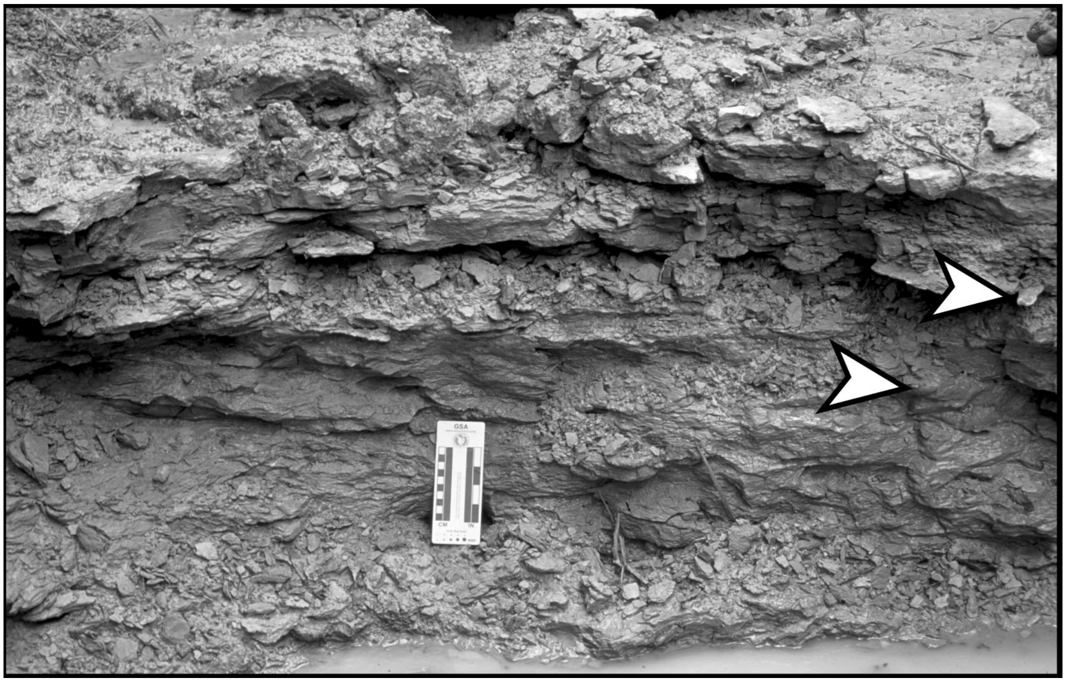

FIGURE 3—The 0.46-m-thick Mt. Orab bed. Arrows point to carbonate nodules that occur at specific horizons throughout the shale.

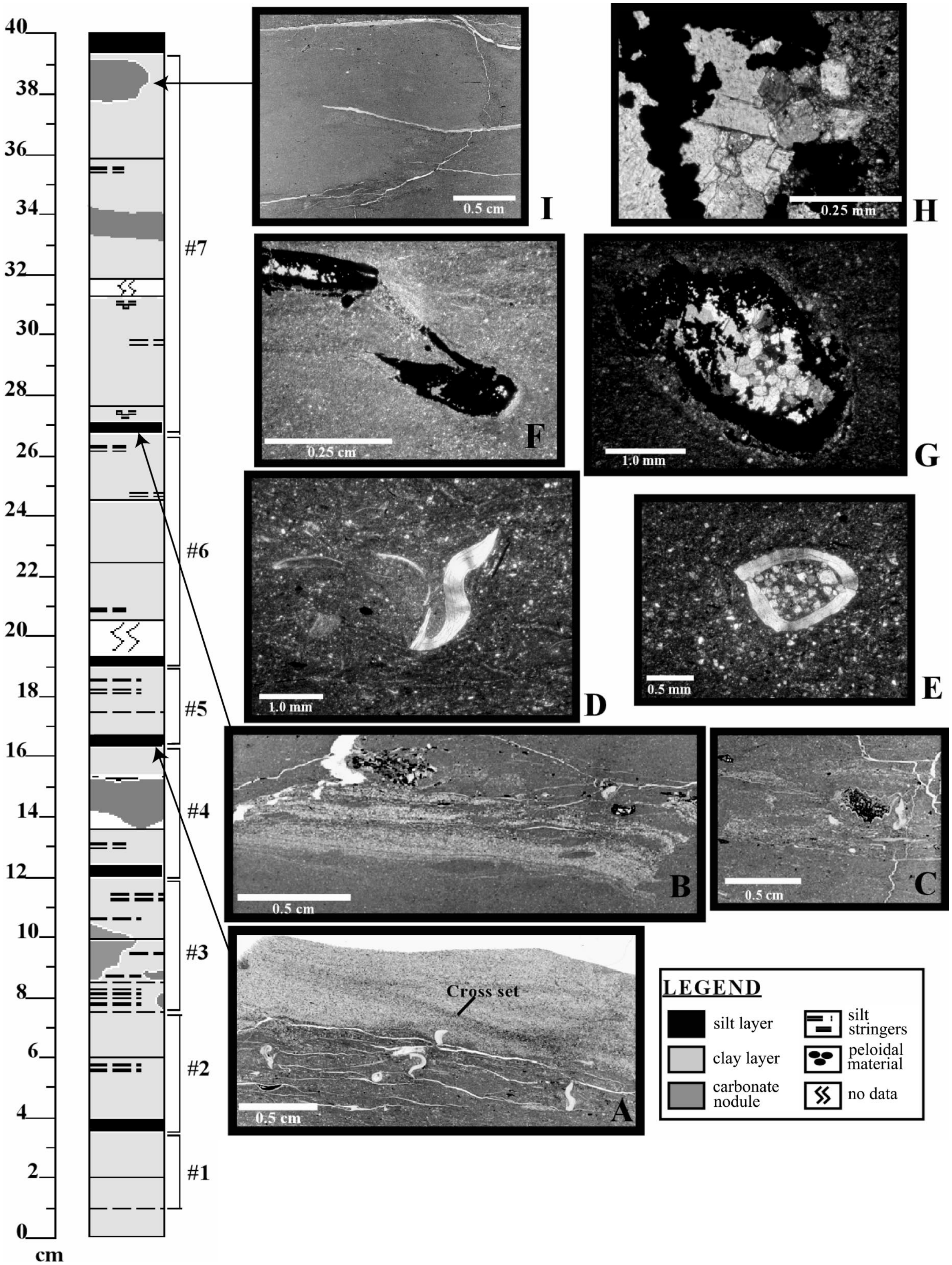

FIGURE 4—Graphic log of thin sections of the 0.46-m-thick Mt. Orab bed, showing the presence of seven identifiable couplets, numbered #1–#7. (A) Coarse-grained silt layer with ripple cross lamination and a microscoured base. (B) Series of finely graded layers. (C) Discontinuous quartz-silt stringers within clay bed; note brachiopod shell with pyrite infilling. (D) Trilobite sclerites and other skeletal debris associated with coarser silt stringers. (E) Cross-section of trilobite sclerite with infilling of clay and silt grains. (F) Trilobite thoracic pleura with pyrite infilling. (G) Cross-section of trilobite sclerite with pyrite infilling and secondary calcite mineral precipitation. (H) Close-up of calcite crystals inside sclerite. (I) Carbonate nodule (lighter color).

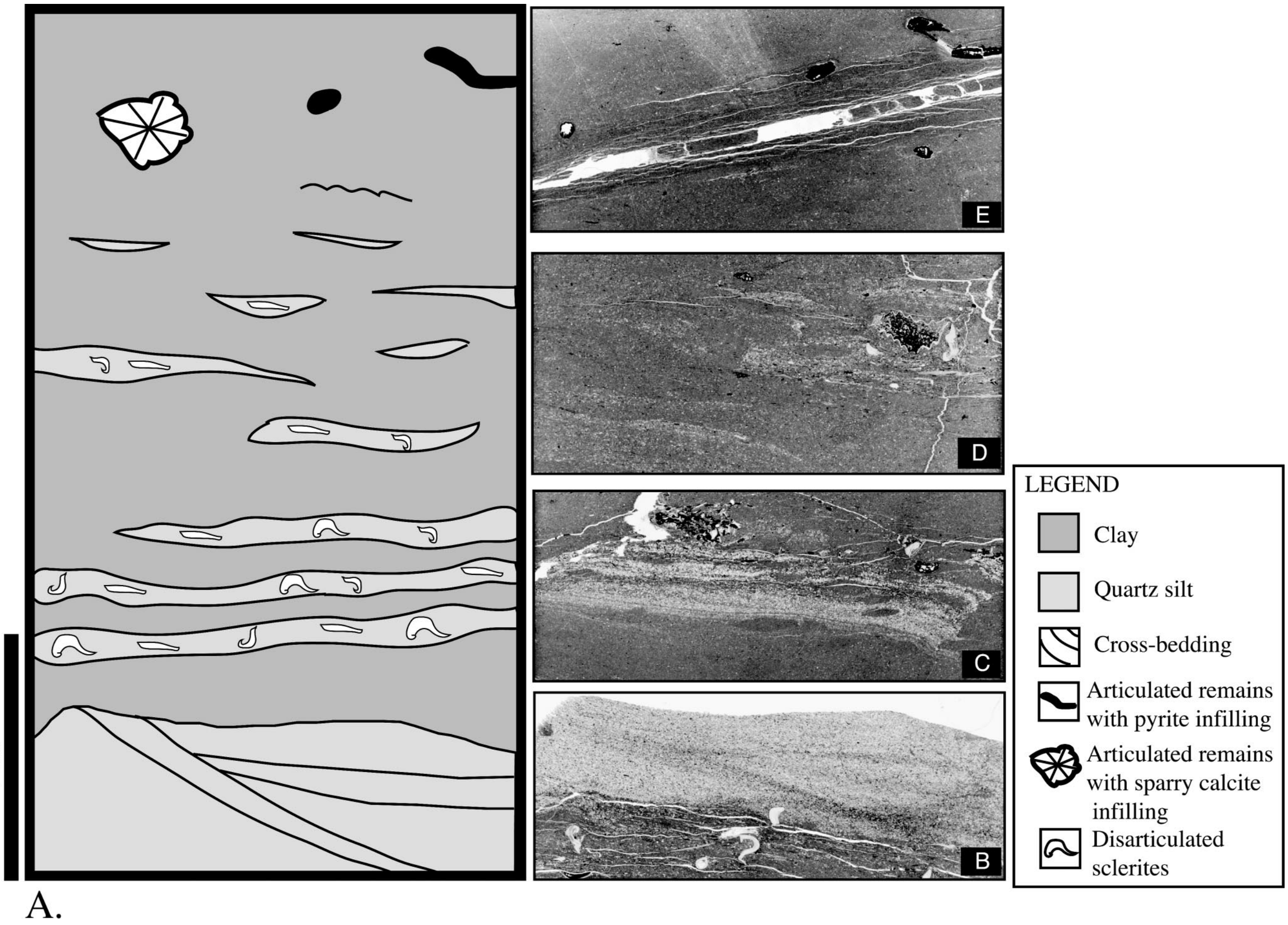

FIGURE 5—A complete sedimentary couplet reconstructed from representative layers within the Mt. Orab bed. (A) Schematic cross-section of a complete couplet. (B–E) Thin-section images of sedimentary fabrics of a complete couplet. (B) Basal quartz-silt bed with cross-ripple lamination and microscoured base. (C) Quartz-silt stringers with interlaminations of clay. (D) Isolated quartz-silt lenses with predominantly clay grains. Note internal pyritization of articulated brachiopod shell. (E) Ungraded clays with internal pyritization of trilobite thoracic pleurae (upper right) and additional unidentified skeletal remains.

able analyses with a large sample size, and provide a direct comparison with additional butter shales, the taphonomy is discussed utilizing the whole-bed approach (i.e., the trilobite taphonomy for all silt layers and all clay layers will be treated together).

Disarticulated cranidia and pygidia from the silt layers of each couplet at Mt. Orab indicate that there was no preferred orientation in the long axes of this material (Fig. 6). Disarticulated sclerites of *Flexicalymene retrorsa* show little evidence of fragmentation. On average, the percentage of individuals represented by articulated remains (carcasses) of *Flexicalymene retrorsa* within the Mt. Orab bed was 22.7% (n = 101 for completely or partly articulated individuals, carcasses, and molts for all couplets), indicating a higher proportion of individuals represented by disarticulated remains (counts based on numbers of pygidia; total disarticulated n = 328). Partially articulated exoskeletons, represented by thoracopygidia, constitute, on average, 45.5% of articulated remains (total n = 101). Disarticulated sclerites show equal ratios of convex-up and convex-down orientations (on average, 51% are convex-up; total disarticulated n = 328), as well as approximately equal ratios of cephala to pygidia (on average, 61% are pygidia; total cranidia and pygidia n = 261; Table 1).

Completely articulated, well-preserved enrolled and prone specimens of *Flexicalymene retrorsa*, all holaspids, are common within the clay layers of the Mt. Orab bed. In total, within the 1-m × 1-m × 0.46-m block, 14 such specimens were recovered, with an additional 38 specimens collected from adjacent beds. Complete specimens show a range of shape deformation, with little to no deformation recorded in the majority of specimens, and the greatest amount of deformation occurring in the few specimens preserved on their sides. Orientation measurements of articulated specimens also indicate a lack of preferred orientation along the long axes of the specimens (Fig. 6).

Fully articulated specimens of *Flexicalymene retrorsa* show a variety of postures and attitudes with respect to bedding (Table 1). Of the 52 specimens, 25 (48%) were enrolled, 23 (44%) were prone, and 4 (8%) exhibited partial enrollment, ranging from postures III to V, as defined by Babcock and Speyer (1987); 41.4% of enrolled specimens were cephalon-up, 41.4% found cephalon down, and 17.2% were found on their sides (n = 29); 52% of the 23 prone

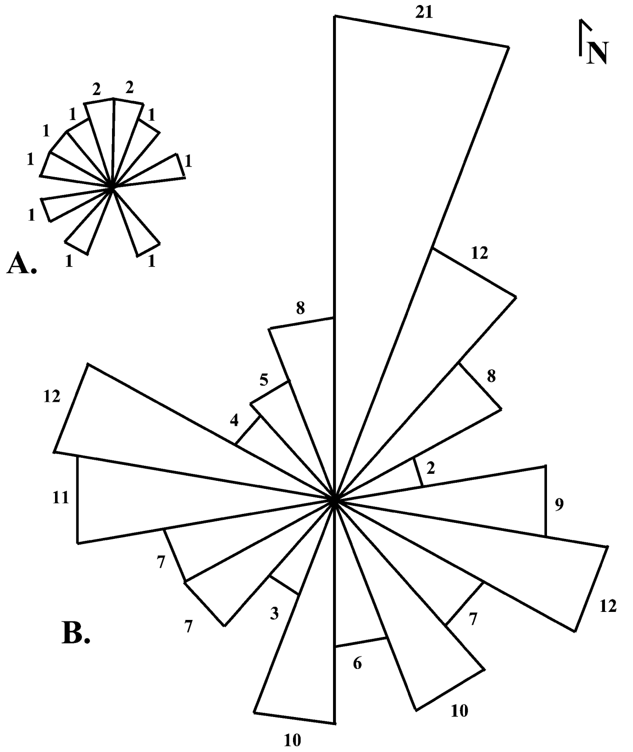

FIGURE 6—Orientation of specimens from clay-layer assemblage 6 of the Mt. Orab bed, illustrated here because this bed contains the most material for orientation measurements. All event beds show no clear preferred orientation of trilobite material. (A) Orientation of 12 *Flexicalymene* carcasses. (B) Orientation of articulated (carcasses and thoracopygidia) and disarticulated sclerites of *Flexicalymene*.

specimens were inverted. Size, as expressed by cranidial length, ranged from 3.4 mm to 14.2 mm within the survey area. Sample sizes recovered from each of the individual layers at Mt. Orab were too small to assess whether layers differ significantly in mean size, but no marked variation in trilobite size between event-bed layers was evident. Distribution of sizes for the 0.46-m interval, as represented by total cephalic length, exhibits a unimodal distribution, with the largest specimens almost four times the length of the smallest (Fig. 7).

Feree's (1994) study provided a larger-scale look at the taphonomy of complete trilobites within the Mt. Orab assemblage, but treated the entire 0.46-m interval as one homogenous unit. His analysis considered 29 m^2 and 605 specimens of *Flexicalymene*. Of the articulated remains, 54% were prone, 28% were enrolled, and 18% were considered molts (Table 1). The cephalon was uppermost in 46% of the enrolled specimens. Of the prone specimens, 77% were inverted. These results concur with this smaller-scale study, with only small differences in the proportions of different trilobite postures and attitudes.

INTERPRETATION OF THE MT. ORAB BED

The silt/clay couplets are the characteristic sedimentary package within the Mt. Orab bed. The proposed schematic complete sequence for these couplets is similar to those constructed for distal mud turbidites (e.g., Einsele and Seilacher, 1991; Piper and Stow, 1991). Mud tempestites often are associated with a high degree of bioturbation, which destroys primary sedimentary structures and makes recognition of these deposits in the fossil record difficult. In the Mt. Orab bed, bioturbation has been limited, and silt laminae associated with these thin deposits commonly are preserved. While mud tempestites are initiated by storm processes, they are interpreted as mud-laden gravity deposits that travel downslope beyond storm wave base, acquiring characteristics of a turbidity flow (Brett and Seilacher, 1991).

Sedimentological features alone do not indicate whether the components of the couplets observed in the Mt. Orab bed, namely the basal silt layer and the upper clay layer, are (1) different phases of a single depositional event; (2) representatives of different phases of a similar depositional process, but not deposited during the same event; or (3) deposition resulting from two distinct processes, possibly a rapid influx of coarser-grained sediment, represented by the basal layer, followed by normal background sedimentation associated with deposition of fine-grained clays. The lack of sedimentary structures in the clay layers, resulting in an ungraded appearance, makes interpretation of the genesis of these layers difficult based on sedimentological criteria. However, different taphonomic attributes of trilobites with the different types of layers in the Mt. Orab bed can provide additional insight into the depositional processes associated with these deposits.

Silt Layers

Thin-section analysis of the Mt. Orab bed has revealed sedimentary structures within the silt layers that can be interpreted to represent lateral transport of sediments. These include micro-scours at the bases of the silt layers and ripple-formed cross-bedding in thicker silt layers, both indicating that energy was sufficient for tractive transport of silt. The source of this coarser-grained material is unclear. It could be the *in-situ* concentration of coarser sediment fractions reworked from local beds or fresh input from an extrinsic source.

Additional evidence of transport is provided by the disarticulated sclerites found within these layers. Isolated and disarticulated sclerites suggest the absence of organic tissues holding the exoskeleton together at the time of burial. Because all sclerites were articulated during the life of the animal that bore them, there must have been an interval between their being freed from binding by organic tissues (in either an exuvium or carcass) and their emplacement in the silt layer. Complete infilling of all void spaces of skeletal elements with clay and silt grains and subsequent post-burial diagenetic alteration of the infillings confirm that these voids were devoid of tissue at the time of burial. The absence of fragmentation and abrasion in these disarticulated sclerites suggests that predation or scavenging may not have been a significant factor (Babcock, 2003), and that the residence time of disarticulated sclerites within the portion of the sea floor subject to reworking was relatively short.

Orientation data and the ratios of disarticulated sclerites also may provide insight into the depositional dynamics of these layers because some modeled dissociated cephala and pygidia have distinctive hydrodynamic behaviors (Hesselbo, 1987; Speyer, 1987). Disarticulated sclerites

TABLE 1—Comparative trilobite taphonomic data from butter shales in the Cincinnatian Series. Taphonomic data from Brandt Velbel (1985) are taken from frequency histograms because raw data were not provided. Size-range data for Brandt Velbel (1985) and Hughes and Cooper (1999) were standardized to cephalic length (mm), based upon relative proportions of trilobite body segments, as measured by numerous specimens of *Flexicalymene*. N = number of specimens; ENR = enrolled; PR = prone; PART ENR = partially enrolled; FLEX = flexure; CEPH UP = cephalon up; CEPH DOWN = cephalon down; SIDE = sideways; RSU = right-side up; INV = inverted; INCL = inclined; CONV UP = convex up; CONV DOWN = convex down; CR = cranidium; PY = pygidium.

	Trilobite taphonomy						Attitude			
		Posture					Enrolled			
Study	Size range (Sagittal cephalic length)	N	ENR (%)	PR (%)	PART ENR (%)	FLEX	N	CEPH UP (%)	CEPH DOWN (%)	SIDE (%)
This study	3.4–14.2 mm; no size segregation	52	48	44	8	partial to full enrollment	29	41.4	41.4	17.2
Hughes and Cooper (1999)	8.0–12.75 mm; size consistency within taxa	37	0	97	3	dorsal and ventral flexure (50% of specimens) torsion	0			
Schumacher and Shrake (1997)	no data	15	40	60	0	partial to full enrollment	6	100	0	0
Ferree (1994)	no data	788	27.7	65.5	6.9	partial to full enrollment partial to full enrollment	272	46	54	no data
Brandt Velbel (1985)	<5.86 mm–>11.7 mm varying size range at all localities	A: 14	30	65	5	A: 27	55	40	5	
		B: 10	10	90	0	B: 54	40	55	5	
		C: 12	15	60	25	C: 12	70	25	5	
		D: 5	0	100	0	D: 6	90	10	0	

that settled from a suspension cloud after rapid deposition often exhibit concave-up orientations (Speyer, 1987). In contrast, persistent surface currents resulted in sclerites with a hydrodynamically stable concave-down orientation (Speyer, 1991). Similar results were obtained by Lask (1993) who utilized a model of the dorsal cephalic shield (i.e., cranidium with attached free cheeks) in his experiments rather than an isolated cranidium. This makes interpretation of the applicability of these results to field studies difficult because isolated dorsal cephalic shields are rarely found articulated in the field. The approximately equal proportion of concave-up and concave-down sclerites within these layers does not support high-velocity current transport or reworking of skeletal material under agitated conditions. Speyer and Brett (1986) suggested that equal proportions of concave-up and concave-down sclerites represent deep, intrastratal bioturbation. The preservation of original sedimentary fabric in these mudstones indicates that overall bioturbation was quite low; therefore, extensive bioturbation is not a plausible explanation for the trilobite sclerite orientations seen in these layers. It is more likely that the attitudes exhibited by the disarticulated cranidia and pygidia within the silt layers result from settling in the absence of a persistent surface current during the interval between settling and final burial. The shapes of different sclerites can result in strikingly different hydrodynamic behaviors (Hesselbo, 1987) and consequent shape-related sorting. The cephalic/pygidial ratios

TABLE 1—Continued.

	Trilobite taphonomy								
	Attitude				Disarticulated remains				
	Prone								
Study	N	RSU (%)	INV (%)	INCL (%)	N	CONV UP (%)	CONV DOWN (%)	N (CR & PYG)	% CR; % PYG
This study	23	48	52	N/A	328	51	49	261	39%; 61%
Hughes and Cooper (1999)	37	32	54	14	0				
Schumacher and Shrake (1997)	9	66	33	0				18	39%; 61%
Ferree (1994)	516	23	77	N/A					
Brandt Velbel (1985)	Attitude data for enrolled and prone specimens of *Flexicalymene* are included in the enrolled section.							A: 41 B: 6	41.5%; 58.5% 33%; 66%

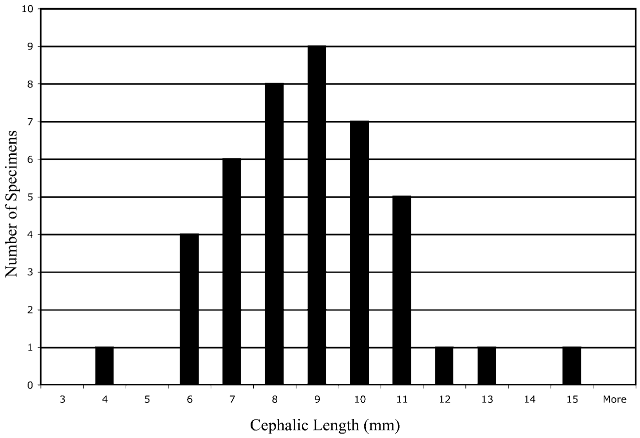

FIGURE 7—Size-frequency distribution of 43 specimens of *Flexicalymene retrorsa* from all Mt. Orab couplets, sizes range from 3.4 mm to 14.2 mm in cephalic length. Size-frequency plot shows a normal distribution. Size-frequency plots for each event bed were not possible due to low sample numbers.

of disarticulated *Flexicalymene retrorsa* sclerites show a departure from the 50:50 ratio expected from an unsorted assemblage (Speyer, 1987), suggesting some degree of shape sorting. However, the lack of fragmentation and abrasion of the sclerites argues against strong persistent currents as the sorting agent.

Sedimentological and taphonomic evidence indicates that transport of silt and disarticulated trilobite remains, while at relatively low energies, was responsible for deposition of this basal portion of the couplet. Entrainment of skeletal debris during deposition indicates that the material within the silt layers is parautochthonous, representing the mixing of disarticulated material, perhaps derived locally, into the silt layer.

Clay Layers

The manner of deposition of the clay layers is difficult to ascertain because they appear ungraded in thin section. However, taphonomic evidence, such as the presence of articulated, multi-element skeletons, can provide further insight into the depositional processes associated with rapid burial in the stratigraphic record.

Pyritization of several *Flexicalymene retrorsa* exoskeletons in the form of localized patinas, pyrite infilling of skeletal remains, and the presence of carbonate nodules suggests that early (pre-compaction) diagenesis occurred within the Mt. Orab bed, possibly triggered by the burial and decay of organic remains. Anaerobic decay of freshly buried organic matter (such as in trilobite carcasses) may have generated concentrations of ammonia, locally raising pH levels of the surrounding sediment and creating a microenvironment for the localized precipitation of interstitial carbonate cements (Brett et al., 1993). In addition, the concentration of decaying organic material in dispersed, discrete patches within sediments, in the presence of reactive microbial biofilms (Borkow and Babcock, 2003), immobilizes reduced sulfur at or near sites of bacterially mediated organic decomposition (Dick and Brett, 1993). Reactive iron introduced into the sediment in the form of iron hydroxides becomes reduced under anoxic conditions, resulting in the formation of early diagenetic pyrite (Dick and Brett, 1993). The presence of pyrite in void spaces and on the outer surface of skeletal remains as thin pyrite crusts indicates the formation of a chemical microenvironment around the carcasses due to the localized concentration of decaying organic material.

Additional secondary calcite precipitation within these voids indicates that sediment did not penetrate completely all voids left after soft-tissue decay. Penetration presumably was inhibited by the presence of tissue at the time of burial. Although the mechanisms by which clay-sized sediment can be deposited rapidly are contested, the degree of articulation of trilobites within the clay layers of the Mt. Orab bed suggests that burial had to be rapid. The multielement exoskeleton of trilobites could be preserved intact only if individuals were buried rapidly (usually within hours to weeks), as demonstrated by actualistic experiments on decay processes within arthropods (Plotnick, 1986; Babcock et al., 2000). It seems unlikely that gradual settling of clay grains from suspension would have resulted in the quality of preservation observed because clay-settling rates are too low. Rapid burial may occur if the suspended clays flocculated or were within a dense suspension cloud (Brett et al., 1993).

It is difficult to constrain the amount of transport of the skeletal elements associated with the deposition of these layers. The chaotic arrangement of trilobites within each of the clay assemblages is the clearest evidence for some level of transport or minor reorientation during emplacement. The articulated specimens in the Mt. Orab bed, as well as in other Cincinnatian butter shales (Brandt Velbel, 1985), exhibit of a variety of attitudes with respect to bedding (Table 1). The lack of bioturbation in these beds suggests that these positions were not the result of trilobites living and burrowing into the mud, and therefore indicates that the pre-disturbance position of these specimens was disrupted, possibly during the burial event.

The rare occurrence of intact molt ensembles in the clay-layer assemblages provides evidence to the contrary. Thoracopygidia indicate the lack of a substantial period of disarticulation, with burial occurring relatively quickly after formation. Disarticulation of the cephalon from the rest of the animal suggests an element of transport, but this configuration also may reflect the disturbance of the exuvium after molting. Although this cannot exclusively rule out transport in deposition of the clay layers (see Cisne, 1973), articulation of the sclerites of the thorax and pygidium suggests that if transport occurred, the energy associated with deposition must have been low. However, sclerites that were disarticulated, yet remain in close association within the clay layers, suggest the absence of any transport.

This dichotomy of pattern suggests that depositional energy either was low enough not to disrupt these molt configurations and still high enough to result in minor reorientation of carcasses in the layer, or that there may be a mix of transported individuals with individuals that were living and molting at the final site of deposition. Another alternative might be that different clay layers have different taphonomic properties. While this could be true, any differences between clay layers would be subtle because none was observed in outcrop. Therefore, because the associated molt configurations provide the most compelling

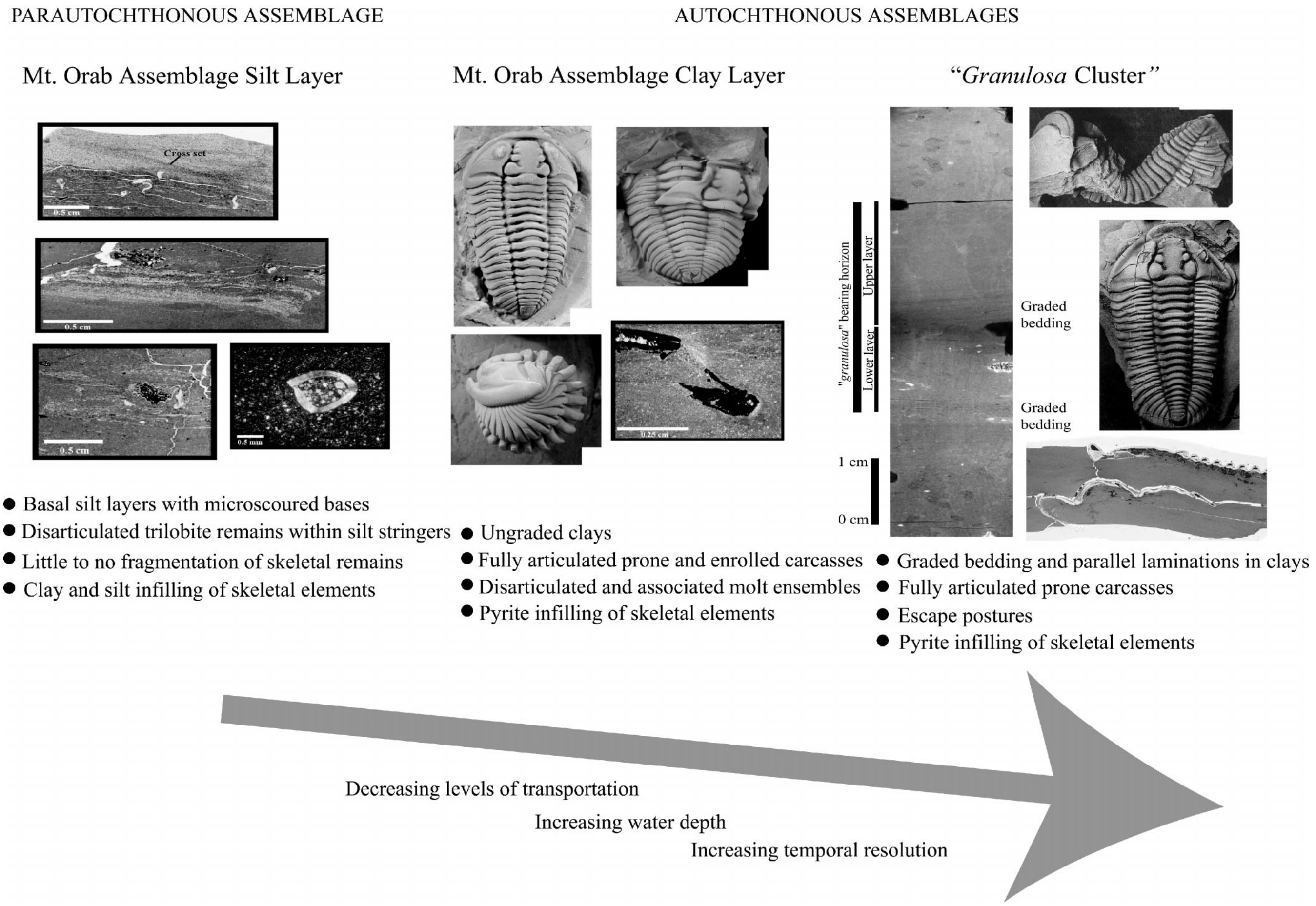

FIGURE 8—Sedimentologic and taphonomic indicators of degrees of transport, water depth, and temporal resolution in distal mud tempestites of the Cincinnatian Series. Trilobites within the silt portion of a couplet represent a parautochthonous assemblage, as indicated by the sedimentologic indicators of tractive transport and the degree of disarticulation of trilobite remains. The clay-layer assemblage represents an autochthonous assemblage with reorientation of specimens during emplacement, as indicated by the chaotic orientation of trilobites within these layers. The ''*granulosa*'' cluster from the Kope Formation (images from Hughes and Cooper, 1999) also is an autochthonous assemblage with *in-situ* burial, as indicated by the degree of articulation and prone posture of the trilobites.

evidence for the lack of significant transport, indicating that these trilobite assemblages were most likely formed *in situ,* these assemblages are considered autochthonous (Fig. 8).

DISCUSSION

Sedimentological analysis of the Mt. Orab bed indicates that butter shales in the Cincinnatian Series can comprise multiple episodes of deposition. Previous studies (Brandt Velbel, 1985; Feree, 1994; Rosenkrantz, 1999) have treated butter shales as single beds, which could confound the interpretations of these studies by compounding information from multiple, separate events. However, although the sample sizes from each couplet at Mt. Orab are small, there is no evidence of marked variation in either the morphological or taphonomic characteristics of the trilobites between any of the couplets within the bed. The Mt. Orab bed thus represents a distinctive facies rich in articulated trilobites and other fossils composed of multiple episodes of deposition, with each providing a similar record.

Depositional Dynamics of the Mt. Orab Event-Bed Layers

The sedimentological and taphonomic evidence presented above is consistent with the tempestite depositional model of Miller et al. (1988), whereby fine-grained sediment below storm wave base is suspended during the passing of a storm, carried basinward, and deposited rapidly in deeper water as broad sheets, thinning in distal settings. Distal portions of the flow often are associated with settling of mud from a fine-suspension cloud (Miller et al., 1988).

The presence of intact thoracopygidia (Fig. 9N) and additional sclerite configurations likely associated with molting (Fig. 9L) challenge the idea that both the silt and clay layers were deposited during a single event. Tractive transport is evident in the basal silt layers that contain disarticulated sclerites. This contrasts with the articulated material in the clay layers, and it is unlikely that configurations associated with molting would remain intact during transport unless deposition occurred while the articulating membranes connecting sclerites within these molts were still intact. While transport might be possible

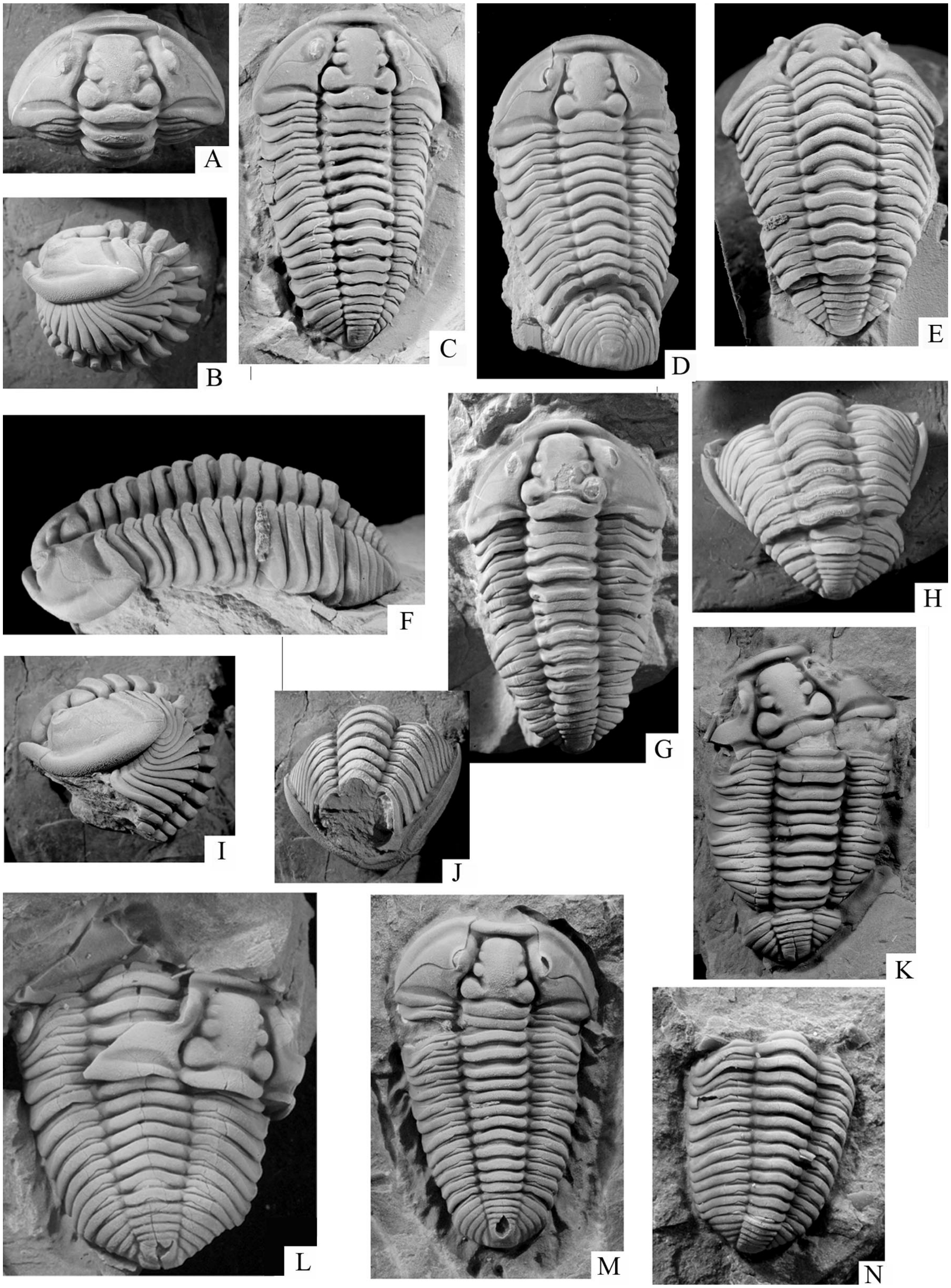

FIGURE 9—Various sclerite configurations exhibited by articulated specimens of *Flexicalymene retrorsa* from the Mt. Orab bed, Ohio. All specimens were coated with ammonium chloride sublimate prior to photography. (A, B) Dorsal and lateral views of completely articulated, enrolled specimen (MO-039 ×1.39). (C) Dorsal view of complete prone specimen (MO-063 ×1.14). (D) Dorsal view of prone specimen with disarticulated and slightly rotated 13th thoracic segment and pygidium (Feree #484 ×1.14). (E, F) Dorsal and lateral views of prone specimen with disarticulated pygidium and rotated 13th thoracic segment (Feree #45 ×2.12 and ×2.51, respectively). (G) Dorsal view of prone specimen with telescoping 7th thoracic segment (Feree #529 ×1.14). (H) Enrolled specimen with disarticulation and slight rotation of the pygidium (MO-128 ×1.45). (I, J) Lateral and posterior views of enrolled specimens with missing pygidium (MO-066 ×1.43 and ×1.29, respectively). (K) Dorsal view of specimen with missing librigena, disarticulated and rotated cranidium from the thorax, and disarticulated pygidium (Feree #108

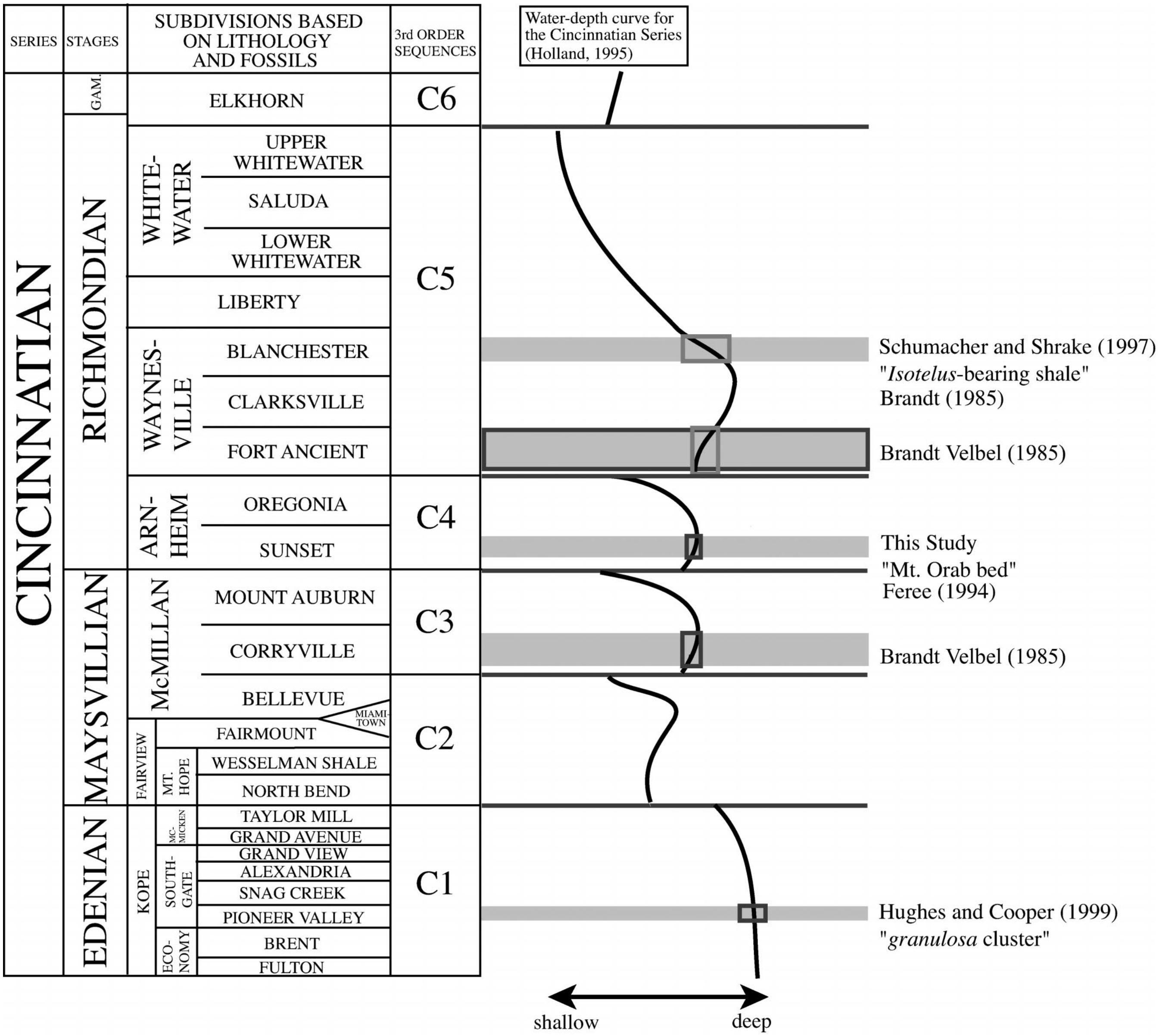

FIGURE 10—Water-depth profile of butter shales in previous studies of sedimentology. Exact stratigraphic position of each study shale within formations is unknown; gray rectangles bracket known stratigraphic interval in which study shales occur. The butter shale of the ''*granulosa*'' cluster represents deposition and preservation of articulated trilobites within the deepest water depth of all previous studies of butter shales in the Cincinnatian Series. The water-depth curve is from Holland (1995).

for thoracopygidia, it is most unlikely in cases where the disarticulated sclerites that apparently belong to a single individual remain associated. Therefore, the articulated remains in the upper clay layer indicate burial under lower energy conditions than those indicated by the erosive bases and cross-ripple lamination of the basal silt layers. Therefore, these stacked events are interpreted to represent different depositional events of different energetic intensity resulting from a similar depositional process. Such variations may represent variations in storm intensity or minor changes in base level. At this point, there is no compelling evidence to suggest that at this centimeter scale, these variations could be attributed to changes in water depth.

←

×1.14). (L) Dorsal view of specimen with cranidium disarticulated from thorax and missing librigena; note the inverted librigena (MO-012 ×1.57). (M) Dorsal view of prone specimen with disarticulation of cephalon and 1st thoracic segment from the thorax (MO-033 ×1.14). (N) Dorsal view of thoracopygidium (Feree #58 ×1.78).

Mt. Orab Taphofacies

In their study of the Devonian Hamilton Group of New York State, Speyer and Brett (1986) defined a series of trilobite taphofacies applicable to that region. The Mt. Orab bed is most comparable to their taphofacies 4B, but differs from it in the higher percentage of disarticulated trilobite remains. Indeed, the taphonomy of trilobites in the silt layers at Mt. Orab does not compare directly with any single taphofacies described by Speyer and Brett (1986). This may be due, in part, to the different setting and fauna of the Hamilton Group, and to differences in the scale at which the analyses were conducted.

While Speyer and Brett's (1986) focus was on large-scale spatial trends among broadly defined taphofacies, this study of trilobite taphonomy within the Mt. Orab butter-shale bed has revealed that distinct trilobite taphofacies also can occur as stacked microfacies at a higher stratigraphic resolution within a similar environmental setting.

Identification of Molts and Carcasses

Fully articulated and enrolled trilobites within the Mt. Orab bed apparently were alive at least for some portion of the events that led to their burial. Fully enrolled specimens from Mt. Orab show no evidence of telescoping of the thorax or rotation of the pygidium, criteria that have been used previously to relate them to exuviae or to invoke post-mortem disturbance (Brandt Velbel, 1993). The presence of *in-situ* librigenae and hypostomes in these animals is strong evidence that these specimens represent carcasses (Fig. 9A–C) because these sutures must have opened during exuviation. Specimens exhibiting partial enrollment have been interpreted to represent either individuals that were buried in this state, completely enrolled carcasses that partially unrolled, possibly due to tissue decay, or as exuviae (Brandt, 1993). Most partially enrolled specimens within the Mt. Orab bed are fully articulated, with librigenae in place, and are considered here to be carcasses. While the dorsal cephala are intact, several specimens exhibit dislocation between the thorax and pygidium (Fig. 9D–F). Post-mortem disturbance of a carcass, possibly during soft-tissue decay as outlined by Speyer (1987), is the most parsimonious explanation for these specimens.

While most prone specimens are preserved in perfect condition, a few show evidence of minor disarticulation among sclerites, including slight rotation of an articulated cranidium with respect to the rest of the exoskeleton, missing librigenae or pygidia in an otherwise intact animal, and/or slight telescoping of thoracic segments. Forms interpreted as exuviae show separation and rotation of sclerites. However, dissociation of sclerites does not necessarily imply ecdysis (Brandt, 1993). In several specimens, the absence of librigenae in an otherwise intact animal suggests that these were molts. Such a pattern commonly is interpreted as a molt configuration in other trilobites (e.g., Henningsmoen, 1975), and is consistent with functional arguments because the sole apparent function of the dorsal sutures was to facilitate molting. However, other specimens show intact cephala, with disruption represented by telescoping of thoracic segments (Fig. 9G) and/or dislocated pygidia (Fig. 9H–J) occurring in the trunk of the animal. Prone specimens with intact cephala but dislocated or missing posterior sclerites are interpreted as carcasses, with taphonomic disturbance resulting from post-mortem decay processes (Speyer, 1987), scavenging (Babcock, 2003), or physical disruption, possibly by low-energy transport, bioturbation, or compaction of sediments. These cannot be interpreted with confidence as molt configurations, and so are not taken to indicate evidence of a wide variety of molt configurations in these trilobites (cf., Brandt, 2002).

Some prone specimens show sclerite configurations consistent with previous interpretations of molting patterns in *Flexicalymene retrorsa*. These include disarticulated librigenae coupled with rotation of the cranidium with respect to the rest of the animal (Fig. 9K) and, sometimes, inversion of the free cheeks (Fig. 9L). These specimens might represent disturbed carcasses, but their configurations also are consistent with inferred molting behavior. Because the juncture between the cephalon and thorax usually is the first to break in an intact exuviae, it also may be argued that rotation and dislocation of the cranidium away from the thorax (Fig. 9M) did not play an original role in ecdysis, and simply reflects disturbance before or during burial (Whittington, 1990).

Occurrences of isolated thoracopygidia have been interpreted to represent biological configurations left *in situ* following molting rather than the product of separation of cephalon and trunk during transport (Speyer, 1991). Thoracopygidia within the Mt. Orab bed are interpreted as molt exuviae (Fig. 9N) according to this model. These configurations thus may represent partial exuviae rather than carcasses. If they were the products of molting, they likely were bound originally by articulating membranes (Whittington, 1990) and their intact preservation may suggest preservation prior to the decay of these membranes.

Comparison with other Cincinnatian Butter Shales

In most features, the Mt. Orab bed appears representative of typical Cincinnatian butter shales, but detailed comparisons reveal differences that could bear on the interpretation of these beds. The coarse-sediment fractions, represented by silt, and the delineation of couplets based on the presence of these coarse layers distinguish the Mt. Orab bed from all previously studied Cincinnatian butter shales (Table 2). In addition, upward-fining grain sizes and parallel laminations—characteristic sedimentary features found in other butter shales (Brandt Velbel, 1985; Schumacher and Shrake, 1997; Hughes and Cooper, 1999)—are absent from the Mt. Orab bed.

Despite these minor sedimentological differences, trilobite taphonomic patterns are similar among all butter shales, although the "*granulosa*" cluster forms an outlier from all other occurrences (Table 1). Trilobites in the butter shales of stratigraphic horizons from the Corryville, Arnheim, and Waynesville formations all show varying degrees of enrollment postures (partial to full enrollment), representing what is inferred to be the typical response of trilobites to adverse environmental conditions. Inversion and flexure of specimens from the "*granulosa*" bed (Kope Formation) are interpreted to indicate vigorous movements by the trilobites in an attempt to escape after rapid burial. This indicates an interesting contrast between the

TABLE 2—Comparison of various stratigraphic, sedimentologic, and faunal aspects of Cincinnatian butter shales compiled from several studies.

Study	Stratigraphic position	Sedimentary structures	Diagenetic features	Trace fossils
This study	Sunset Member Arnheim Formation	basal portion of bed with microscoured base and cross-ripple lamination; upper portion of bed with quartz stringers and ungraded muds	carbonate nodules; pyrite patches on skeletal remains; void-filling pyrite	*Chondrites*
Hughes & Cooper (1999)	Southgate Member Kope Formation	2 units: upward-fining grain size in lower and upper units; parallel laminations in upper unit	pyrite-filled tubes; void-filling pyrite; pyrite patches on exoskeletons	horizontal traces; pyritized tubular burrows
Schumacher & Shrake (1997)	Blanchester Member Waynesville Formation	upward-fining grain size	carbonate nodules; pyrite patinas on outer surface of fossils	*Chondrites Rusophycus* horizontal traces
Ferree (1994)	Sunset Member Arnheim Formation		carbonate nodules; pyrite patches on skeletal remains	*Chondrites*
Brandt Velbel (1985)	A—Ft. Ancient Member Waynesville Formation B—Blanchester Member Waynesville Formation C—Corryville Formation D—Corryville Formation	upward-fining grain size		*Chondrites Rusophycus*

TABLE 2—Continued.

	Degree of bioturbation	Faunal diversity	Spatial distribution of articulated trilobites	Orientation of articulated trilobites
This study	low (ichnofabric index ii)	*Flexicalymene* *Isotelus* *Rafinesquina* *Zygospira* *Modiolopsis* Bryozoans Crinoids Lingulid		lack of preferred specimen orientation
Hughes & Cooper (1999)	low (ichnofabric index ii)	*Flexicalymene* *Isotelus* *Primaspis* *Ceraurus* *Zygospira* *Ectenocrinus* Bivalves	spatial restriction of trilobite positions (“cluster”)	lack of preferred specimen orientation
Schumacher & Shrake (1997)	sparse/low	*Flexicalymene* *Isotelus* *Leptaena* *Orthodesma* *Zygospira* Graptolites Chitinozoans Scolecodonts Ostracods		predominantly north orientation
Ferree (1994)	low	same as current study (see above)		
Brandt Velbel (1985)	low	*Flexicalymene* *Isotelus* *Zygospira* *Modiolopsis* *Ambonychia* *Lingula* *Onniella* Crinoids	cluster of two or more rather than single occurrences	roughly NE–SW orientation

autochthonous assemblage of the "*granulosa*" cluster of the Kope Formation (Hughes and Cooper, 1999) and the autochthonous trilobite assemblage in the Mt. Orab clay layers. While autochthonous assemblages preserve individual spatial relationships due to *in-situ* burial, it is clear that the autochthonous assemblages of the Mt. Orab clay layers have had some degree of reorientation and disruption of the original spatial and behavioral relationships of individual trilobites. The question then becomes to what degree trilobite stance and posture is a reflection of the dynamics of burial associated with different conditions of mud-tempestite deposition.

Inversion is a common occurrence in trilobite clusters (e.g., Speyer and Brett, 1985; Hickerson, 1997), yet the reasons for such occurrences remain unclear. Suggested explanations include molting posture, post-mortem reorientation of specimens, possibly due to the release of decay gases or bioturbation, scavenging, settling of carcasses after transport and/or transport-mediated inversion due to current dynamics, behavioral responses to burial or pre-burial disturbances, or simply taphonomic artifact (Speyer and Brett, 1985; Speyer, 1987). Prone trilobites in both the "*granulosa*" cluster and the Mt. Orab clay-layer assemblages exhibit inversion, yet if inversion were related to transport, a low percentage of specimens exhibiting inversion in the autochthonous assemblage would be expected. However, inverted specimens comprise the majority of postures in the "*granulosa*" cluster. Although transport may provide a likely means of inverting exoskeletons, it does not explain inversion in autochthonous clusters. Behavioral responses to pre-burial disturbance, inversion associated with molting behavior, or inversion due to release of decay gases slightly before burial are scenarios discussed by Hughes and Cooper (1999). Because inversion is a common phenomenon found in assemblages with varying burial scenarios, inversion of prone individuals as a behavioral response to rapid burial is considered as the most likely scenario.

Most trilobite smothered-bottom assemblages have been interpreted as specific behavioral aggregations associated with spawning or synchronous molting (Speyer and Brett, 1985; Hickerson, 1997; Karim and Westrop, 2002), often characterized by monospecific clustering and relatively restricted size ranges of specimens. While specimens from other butter shales exhibit no apparent size-sorting, the "*granulosa*" bed of the Kope Formation contains a spatially localized, dense aggregation of trilobites that show specific size segregation (Table 1). Based upon these features, the "*granulosa*" cluster also has been interpreted to represent a congregation of trilobites assembled for a specific biotic function (Hughes and Cooper, 1999). This clustering, defined as an assemblage with spatial restriction and a relatively high concentration of individuals (Hughes and Cooper, 1999), is in marked contrast with the trilobite assemblages of the Mt. Orab clay layers. When all beds are combined, trilobite specimens exhibit a unimodal size distribution, with a broad range (Fig. 7) and low densities, suggesting that the Mt. Orab mudstone taphofacies may permit an estimate of normal densities and size distributions within a population of *Flexicalymene retrorsa*.

The wide range of exoskeletal sizes, relatively low density of specimens, and the presence of numerous enrolled or partially enrolled specimens (as opposed to the dorsally flexed posture in the "*granulosa*" example) suggest differences in the nature of the trilobite assemblages of the "*granulosa*" bed and those at Mt. Orab. The enrolled postures at Mt. Orab may reflect minor transport and reorientation of live trilobites within storm-induced flows, in contrast with the "*granulosa*" cluster, which is a deeper-water, autochthonous assemblage with *in-situ* burial of trilobites. These differences aside, the quality of preservation and degree of articulation of the trilobites in the Mt. Orab bed (and the "*granulosa*" cluster) suggest that they represent populations of trilobites that were alive at the time of the initiation of events that led to their burial.

The increase in coarse-sediment fraction, evidence of tractive transport, and disarticulated shell and sclerite lags within basal silt layers suggest that the Mt. Orab layers are shallower-water representatives of tempestite deposition than the "*granulosa*" cluster of the Kope Formation (Fig. 10). Published water-depth curves for the Cincinnatian Series (Holland 1993; 1995), as well as faunal analyses (Holland, 1997), provide independent support for such a conclusion. The Kope Formation was deposited within the offshore zone, whereas the Arnheim Formation was deposited within the transition zone between shoreface and offshore environments (Holland, 1997).

Patterns of flexure within trilobites have been suggested to correlate with proximality, with enrollment behavior more likely to occur in shallower-water environments (Chatterton and Ludvigsen, 1998). Hughes and Cooper (1999) noted that enrollment is more typical of later deposits in the Cincinnatian Series, and is associated with a slightly coarser matrix and possibly a more-oxygenated setting. The patterns of flexure in trilobites within the Mt. Orab bed and other previously studied butter shales are consistent with this suggestion, where a higher proportion of trilobites exhibit full or partial enrollment than prone specimens.

TEMPORAL RESOLUTION IN THE CINCINNATIAN SERIES

Because processes of skeletal accumulation occur at different rates and vary among environments, careful attention to taphonomic features permits estimation of the relative order of temporal magnitude represented within different sedimentary units (Brett and Baird, 1993). Timescales spanning several orders of magnitude are represented by the various strata within the Cincinnatian Series (Table 3). The preservation of abundant articulated exoskeletons in Cincinnatian butter shales suggests a high degree of temporal resolution. In this section, constraints on estimates of the degree of time-averaging in various Cincinnatian beds are considered in order to place butter-shale horizons in their temporal context within the Series. With the exception of individual event beds, it is difficult to place firm constraints on the amounts of time represented in beds, although the combination of evidence from various approaches, when viewed collectively, can be used to define reasonable estimates of depositional intervals over which beds accumulated.

In the literature, single-event fossil beds have been considered to constitute the record of intermittent short-term processes, spanning minutes to a few days (Brett and Baird, 1993). Estimates of how much time is distributed

TABLE 3—Scales of temporal resolution within beds of the Cincinnatian Series. Taphonomic and sedimentological criteria are from Kidwell (1993) and Brett (1995). The above attributes provide a framework for assessing the temporal context of various assemblages and should not be viewed as definitive under all environmental and stratigraphic conditions. The above criteria do allow for an ordinal ranking of temporal resolution within beds of the Cincinnatian Series. Frag. = fragmentation; Sk. Diss. = Skeletal dissolution; Corr. = Corrosion.

APPROX. TIME SCALE	Assemblage	Disarticulation	Frag.	Reorientation	Abrasion	Sk. Diss.	Corr.	Sedimentary Structures	Diagenetic Overprint	3^{rd} Order	Parasequence	
	Census		absent	*in situ*	absent	absent	absent	obrution deposits; graded bedding	carbonate nodules and pyrite formation related to organic decay	late transgressive –mid-highstand	base of parasequence above MFS	
Days	autochthonous	intact molt exuviae and carcasses										"*granulosa*" bed
10^1	parautochthonous	disarticulated molt exuviae										Mt. Orab bed
	Within-habitat time-averaged		low-high	*in situ*	very low	very low	very low	laterally traceable on outcrop scale; sharp, scoured bases; gutter casts; sediment infillings; homogeneous matrix; internal grading	spar-filled geopetal infillings	mid-highstand	mid-top of parasequence	packstones and grainstones
10^2	parautochthonous; fossils match surrounding background sediments	intact but disarticulated exuviae and carcasses		shells in unstable, oblique, and edgewise orientations								
10^3 10^4	allochthonous; fossils do not match surrounding background sediments	aggregated sclerites		nested stacking of concavo-convex shells								
10^5 10^6	**Environmentally condensed**	aggregated sclerites	high	high	high	very low	high	erosive and sharp base; amalgamation; heterolithic matrix; internal lenses of finer-grained sediment; laterally traceable on regional scale	nodules and/or tabular layers of cemented concretionary carbonate	stratigraphically condensed intervals (TST) associated with discontinuity or flooding surface	top of parasequence (cycle caps)	amalgamated grainstones
	Biostratigraphically condensed	aggregated sclerites	very high	very high	low-high	very high	very high	lacking bedding features; loosely packed and dispersed fabrics	sedimentary phosphorite; fossil steinkerns	early transgressive systems tract; sequence-bounding discontinuities		

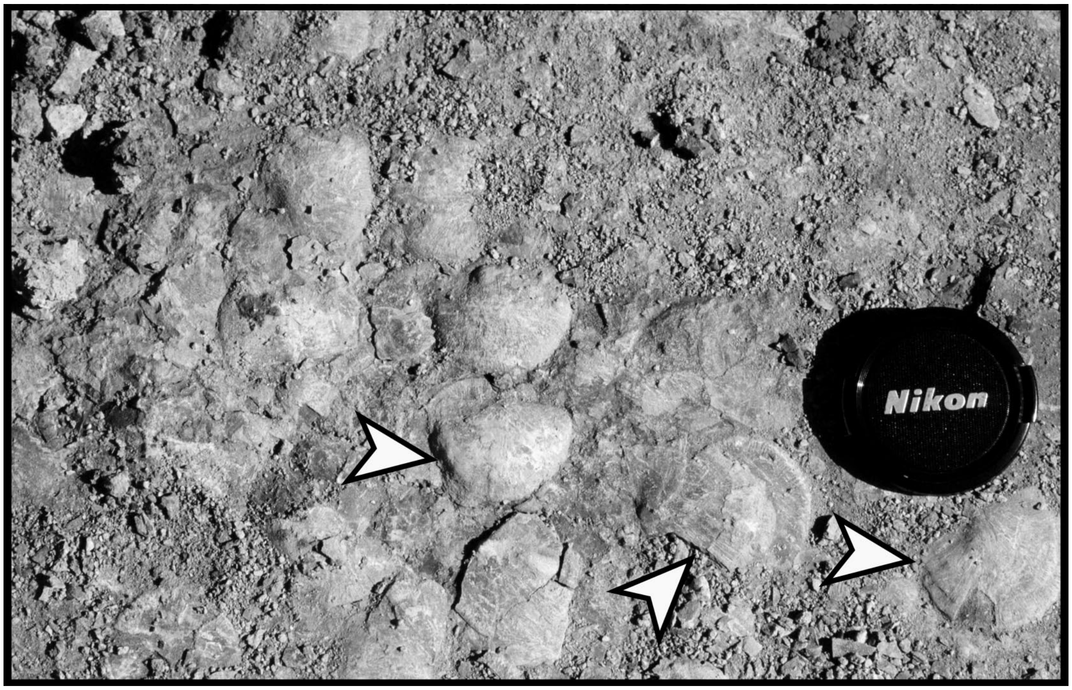

FIGURE 11—*Rafinesquina* valves found within the Mt. Orab bed. These pavements of flat-lying valves are found in the basal portion of the shale, and have been exposed over tens of meters at the site. The valves are found disarticulated, but mainly unfragmented. Arrows point to disarticulated, but complete, *Rafinesquina* valves. Lens cap is ~2.8 cm across.

within these butter shales should include not only the amount of time represented by the stacked individual event beds, but also the time recorded between rapid influxes of sediment, represented by background sedimentation or by intervals of no deposition.

Given that the genesis of the clay and silt component of each event-bed couplet within the Mt. Orab bed is derived from distinct depositional events, with unique taphonomic signatures, discussion of the amount of time represented by each portion of the couplet must be considered independently. As noted previously, the exceptional preservation and degree of articulation of trilobite specimens within the Mt. Orab clay-layer assemblages indicate that these specimens were buried rapidly. A temporal resolution of hours to days has been attributed to other similar event-bed deposits possessing a high degree of articulated remains (Hughes and Cooper, 1999; Behrensmeyer et al., 2000). Even if the clay layers contain exuviae in addition to the carcasses of animals killed during burial, the rapid decay of articulating membranes in exuviae of modern arthropods, which can take up to three or four weeks (Babcock et al., 2000), suggests that all specimens must have been contemporary in a biological sense.

The amount of time represented within the silt layers is more difficult to ascertain. While in certain depositional settings there may be no significant correlation between taphonomic condition and age (Carroll et al., 2003), the taphonomic signature of trilobite material within the silt layers suggests that these remains had at least enough time to become disarticulated and transported prior to burial. Previous studies have shown that age ranges of up to 10^3 years for shell material can occur in surficial deposits in nearshore environments (Kowalewski et al., 1998; Flessa et al., 1993; Carroll et al., 2003). It is therefore plausible that the trilobite sclerites entrained within the silt layers of the event deposits are considerably time-averaged, although there is no evidence suggesting such a conclusion. However, the good state of preservation and low density of the remains, the lack of a preservational gradient among the disarticulated remains, and the thickness of the silt beds (centimeter scale) are all congruent with the interpretation of a bed that was deposited rapidly.

The presence of epifaunal suspension-feeding brachiopods and bryozoans provides additional information on the sedimentation rate within portions of the Mt. Orab bed. Within the Mt. Orab bed, the presence of a single *Rafinesquina* pavement (Fig. 11) consisting of similar-sized, disarticulated but unfragmented valves extending tens of meters from the study quadrant at the same horizon within the shale, and the presence of *Zygospira*, suggest that low background sedimentation rates between periods of rapid mud deposition allowed populations of brachiopods to develop (Schumacher and Shrake 1997). Although it is difficult to obtain information on the growth rates of ancient brachiopods, analysis of annual growth rate in *Terebratalia* shows a range of shell growth from 0–7.6 mm per year (Thayer, 1977). If at least broadly comparable, this suggests that development of the population of *Rafinesquina* may have occurred over a few years at most, and thus, at this horizon, the seafloor apparently remained undisturbed for an interval of that duration. There is only one such layer within the Mt. Orab bed. Therefore, the Mt. Orab bed may be characterized by relatively rare periods of low background sedimentation, possibly representing a temporal scale of a few years, interrupted by influxes of sediment that rapidly buried benthic organisms. Although the exact number of depositional events that constitute the Mt. Orab bed is unknown because of the possibility that later episodes of deposition involved erosion of previous ones, the entire 0.46-m thickness of the Mt. Orab bed may represent an amount of time on the order of 10^1 to 10^3 years.

A wide spectrum occurs among limestone deposits of the Cincinnatian Series, which display a variety of taphonomic grades and degrees of amalgamation. Several lines of taphonomic evidence, such as the low degree of articulation, high degree of abrasion of fossil material, density of fossil material, thickness, and degree of lateral persistence, point to substantial reworking and time enrichment of these storm beds (Algeo and Brett, 1999). Some limestone beds, such as packstones, with low levels of comminution and good fossil preservation, indicate shorter intervals of reworking, while other amalgamated beds, such as thick grainstones, may indicate substantial periods of reworking.

An important aspect of the Cincinnatian Series is the wide spectrum of degrees of time averaging represented within the succession, with the "*granulosa*" cluster and Mt. Orab bed representing the most-rapidly deposited end-member, and amalgamated grainstones (cycle caps) representing the least-rapidly deposited end member (Algeo and Brett, 1999; Table 3). This, coupled with ongoing studies of depositional architecture, provides a detailed anatomy of how time is recorded within shelf strata (Holland, 1993; Holland and Patzkowsky, 1996; Holland et al., 1997). This variety, coupled with the highest temporal resolution being comparable to that in populations of living organisms and the abundant fauna, makes the Cincinnatian an excellent study system for accessing morphological change in stratigraphic context.

CONCLUSIONS

The Mt. Orab bed presents the opportunity for detailed analyses of the nature of deposition of the world-famous trilobite-rich shales of the Cincinnatian Series, and for dissection of an exceptional trilobite record at the highest temporal resolution available within the Cincinnatian Series.

Sedimentological and taphonomic evidence indicate that the Mt. Orab bed is a series of stacked event-bed layers that form couplets, representing rapid burial by mud-laden flows most likely associated with distal storms. Features, such as microscours at the base of some couplets and the presence of cross-ripple lamination in basal quartz-silt laminae, indicate tractive transport of coarser-grained sediment, characteristic of the silt portions of couplets. The occurrence of articulated exoskeletons and molt ensembles with associated but disarticulated sclerites within the clay-rich upper layers of these couplets suggests that these stacked components correspond to different phases of the same depositional process, but not a single depositional event. A composite model of a couplet contains sedimentary structures similar to distal mud turbidites, which may form under similar flow dynamics associated with the deposition of fine-grained sediments during a mud-laden gravity flow below storm wave base.

There is no evidence of marked variation in taphonomic characteristics of the trilobite faunas between each couplet. Size, posture, and position of individuals are similar in each, and apparent taphonomic continuity of shale beds is justifiable after detailed examination. The silt component of the couplets from the Mt. Orab bed of the Arnheim Formation are interpreted here to represent parautochthonous assemblages, while the clay component is interpreted as an autochthonous assemblage with some minor degree of disturbance resulting from burial. Both reflect tempestite deposition in a shallower-water environment, in contrast with the "*granulosa*" cluster of the Kope Formation (Hughes and Cooper, 1999), which represents an autochthonous assemblage with *in-situ* burial of trilobites in a deeper-water environment. The presence of *Rafinesquina* pavements and other epifaunal suspension-feeding brachiopods suggests that low background sedimentation allowed for the development of an epifaunal community between periods of rapid mud deposition.

Based upon the good state of preservation, the low density of the remains, the lack of a preservational gradient among the disarticulated remains, and thickness, the silt layers are interpreted to have been deposited relatively rapidly. The exceptional preservation and degree of articulation of trilobite specimens within the Mt. Orab clay-layer assemblages indicate that these specimens were buried rapidly, and therefore can be classified as census assemblages (Kidwell, 1993), which have high spatial and compositional fidelity and a temporal resolution of hours to days (Behrensmeyer et al., 2000). Although the exact number of depositional events that constitute the Mt. Orab bed is unknown because of the possibility that later episodes of deposition involved the erosion of previous ones, the entire 0.46-m thickness of the Mt. Orab bed may represent 10^1 to 10^3 years.

Articulated trilobites within these event-bed layers provide the opportunity to assess morphological variability at the maximum temporal resolution of the Cincinnatian Series. For studies of microevolution, establishing this high-resolution base level from layers within an individual bed is necessary for the comparison of morphology in a series of scaled temporal resolutions, represented by individual beds and stacked packages of beds, throughout the succession.

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