PHOSPHATIC CONCRETIONS AND ICHNOFOSSIL PRESERVATION IN A MARINE LAGERSTÄTTE, RIPLEY FORMATION, CENTRAL ALABAMA

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Jonathan Trent Hall

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PHOSPHATIC CONCRETIONS AND ICHNOFOSSIL PRESERVATION IN A MARINE LAGERSTÄTTE, RIPLEY FORMATION, CENTRAL ALABAMA

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A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
May 11, 2006

PHOSPHATIC CONCRETIONS AND ICHNOFOSSIL PRESERVATION
IN A MARINE LAGERSTÄTTE, RIPLEY FORMATION,
CENTRAL ALABAMA

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Signature of Author

Date of Graduation

VITA

Jonathan Trent Hall, son of Noah Hall and Judy Ellenburg, was born on January 24, 1973, in Fort Ogelthorpe, Georgia. He graduated from Chattooga High School, in Summerville, Georgia, in 1992. He married Meredith Cunningham on July 20, 2001. He attended the State University of West Georgia, in Carrollton, Georgia, and graduated in May 2003 with a Bachelor of Science degree in Geology. Immediately after graduation he entered the Graduate School at Auburn University in the Fall of 2003. On June 20, 2004, he became the proud father of Harper Grace Hall.

THESIS ABSTRACT

PHOSPHATIC CONCRETIONS AND ICHNOFOSSIL PRESERVATION IN A MARINE LAGERSTÄTTE, RIPLEY FORMATION, CENTRAL ALABAMA

Jonathan Trent Hall
Master of Science, May 11, 2006
(B.S., State University of West Georgia, 2003)

122 Typed Pages

Directed by Charles E. Savrda

Phosphate concretions are common in the Upper Cretaceous Ripley Formation exposed along Dry Cedar Creek, Lowndes County, Alabama. Sedimentologic and ichnologic studies of concretions and host sediments were undertaken to investigate the origins of concretions and the role of phosphatization in trace fossil preservation.

The concretion-bearing interval is composed of bioturbated, fossiliferous, calcareous, carbonaceous mud and sandy mud. Deposition occurred on a shallow shelf between fair-weather and storm wave bases and beneath moderately oxygenated waters of relative high organic productivity. Preservation state of body fossil nuclei and textural and geochemical evidence indicate that concretions formed during very early diagenesis

at shallow substrate depths prior to significant compaction. Phosphate likely was derived from biodegradation of organic matter and precipitated near the oxic/anoxic boundary, perhaps during periods of lower sedimentation rates and/or hypoxia.

Trace fossils are poorly preserved in unmineralized Ripley sediments owing to limited textural and compositional contrast, lack of three-dimensional expression, and compactional deformation. However, trace fossils are commonly preferentially preserved on or within phosphate concretions. The preserved assemblage, reflecting the work of both deposit- and suspension-feeding organisms, represents an impoverished *Cruziana* ichnofacies. Phosphatization enhanced ichnofossil visibility by limiting compaction and by providing partial three-dimensional views of ichnofossils. Ichnofossils locally formed microenvironments favorable for phosphatization, serving as the nuclei for concretion growth. More commonly, trace fossils were preserved by collateral mineralization on the interiors and exteriors of concretions with body-fossil (e.g., crabs, ammonites, vertebrate remains) and enigmatic nuclei. Preservation is best on concretion exteriors where, owing to differential migration of mineralization fronts, trace fossils were preserved in partial relief. Because concretions provide ichnologic information that is otherwise not available from unmineralized host sediments, they represent a form of conservation-lagerstätte.

Based on observations made in this study and by previous workers, a set of terms is proposed for describing the relationships between diagenetic mineralization and trace fossil preservation. These terms refer to the relative timing of concretion growth and trace fossil production, type of mineralization, spatial relationships between concretion nuclei and preserved trace fossils, and modes of trace fossil expression relative to concretion interiors and exteriors.

ACKNOWLEDGMENTS

The author would like to thank the Gulf Coast Association of Geological Societies and the Geological Society of America for grants-in-aid that supported this research. Numerous individuals provided help that was essential to the completion of this thesis. Fellow Auburn University geology students, Olivia Buchan, John Counts, Robert Monrreal, Rick Urash, and Jamey Turner, assisted in the field. John Simms (AU Department of Geology and Geography) assisted with XRD analyses. Subscribers to Paleonet supplied valuable information regarding pertinent literature. The author's thesis committee members, especially Dr. Charles E. Savrda, provided guidance with field work, laboratory analyses, and writing. The author's family provided their love and support. The author dedicates this thesis and M.S. Degree to his wife Meredith and daughter Harper for their inexhaustible patience, encouragement, and love.

Journal style used: Palaios

Computer software used: Microsoft Word 2002, Microsoft Excel 2002, Microsoft PowerPoint 2002, Adobe Photoshop 8.0, Endnote 5

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1.0 INTRODUCTION

Fossil-lagerstätten, deposits that contain unusually abundant and/or well-preserved fossils, provide paleontological and paleoenvironmental information that is not otherwise available from "normal" sedimentary sequences. Fossil-lagerstätten can generally be placed into two categories: (1) concentration-lagerstätten, wherein fossils were concentrated by physical or biological processes; and (2) conservation-lagerstätten, in which extraordinary preservation resulted from rapid burial (obrution deposits), reducing conditions that limited biogradation (stagnation deposits), early diagenetic mineralization, and/or other processes (Seilacher, 1970; Seilacher et al., 1985). According to Allison (1988a) and Briggs (2003), early diagenesis and associated growth of pyrite, phosphate, and/or carbonates (e.g., calcite and siderite) are the most important factors in the formation of conservation-lagerstätten, particularly ones that preserve soft body parts. The timing, extent, and type of mineralization that may impact fossil preservation are governed by factors such as redox conditions, sediment organic content, sedimentation rate, salinity, and the composition of the fossil nuclei (Allison, 1988b,c).

Trace fossils have their own unique set of properties. However, they are subject to many of the same taphonomic and preservational controls that influence body fossils (e.g., rapid deposition, erosion, diagenesis, etc.). Consequently, the lagerstätte concept also is applicable to the ichnofossil record. Previous workers have recognized various types of ichnofossil-lagerstätten that include concentration-type deposits (e.g., Savrda and

King, 1993; Savrda et al., 1993) and conservation-lagerstätten related to rapid burial and/or stagnation (Savrda and Ozalas, 1993; Mangano and Buatois, 1995; de Gibert et al., 2000). However, the concept has not yet been adequately applied to early diagenetic processes and concretion growth. This is surprising given that ichnofossil preservation is commonly influenced by diagenetic precipitation of calcite (e.g., Dix and Mullins, 1987), siderite (e.g., Baird et al., 1986), dolomite (e.g., Brown and Farrow, 1978), silica (e.g., Bromley and Ekdale, 1984), pyrite (e.g., Schieber, 2002), and/or phosphate (e.g., Allison, 1988b).

The Upper Cretaceous Ripley Formation, part of the Selma Group, exposed in the Alabama coastal plain includes marine shelf deposits that contain common fossil-bearing phosphatic concretions and have been recognized as a fossil-lagerstätte (Abston et al., 1990). These concretions entomb well-preserved body fossils, most notably crabs and ammonites (Abston and Savrda, 1990; Abston et al., 1990), but also vertebrate remains (Schein, 2004). However, preliminary observations indicate that phosphate mineralization also has influenced the preservation of ichnofossils. The primary objectives of this thesis research are (1) to evaluate the ichnology of Ripley phosphate concretions and their host sediments in order to document the relationships between mineralization and trace fossil preservation; and, based on the Ripley observations and review of existing literature, (2) to develop terminology that will be of general use for describing trace fossil preservation in concretion-type conservation-lagerstätten.

2.0 STRATIGRAPHIC CONTEXT

2.1 Selma Group

The Upper Cretaceous (mainly Campanian – Maastrichtian) Selma Group crops out in a 40-to-50-km-wide, arcuate belt that extends across Alabama and then northwestward along the eastern margin of the Mississippi Embayment (Jones, 1967a; Russell and Keady, 1983; Frey and Bromley, 1985) (Fig. 1). Strata dip very gently to the south and southwest. The Selma Group unconformably overlies the Santonian Eutaw Formation and is unconformably overlain by the lower Paleocene Clayton Formation (Monroe, 1941; Copeland, 1972) (Fig. 2). Units of the Selma Group are, in ascending order, the Mooreville Chalk, Demopolis Chalk, Ripley Formation, and Prairie Bluff Chalk (Fig. 2). These strata (mainly chalks, chalky marls, clays, and sands) reflect deposition in marine shelf and shoreface environments (Monroe, 1941; Russell and Keady, 1983; Mancini et al., 1998). The chalk units in the group grade into siliciclastic units to the east and northwest (Jones, 1967b; Copeland, 1972) (Fig. 1). The Ripley Formation, the subject of the current study, is the only predominantly siliciclastic unit in the group.

2.2 Ripley Formation

2.2.1 General Stratigraphy

The Ripley Formation ranges from late Campanian to Maastrichtian in age (Mancini et al., 1995). It crops out in a belt extending from western Georgia, across

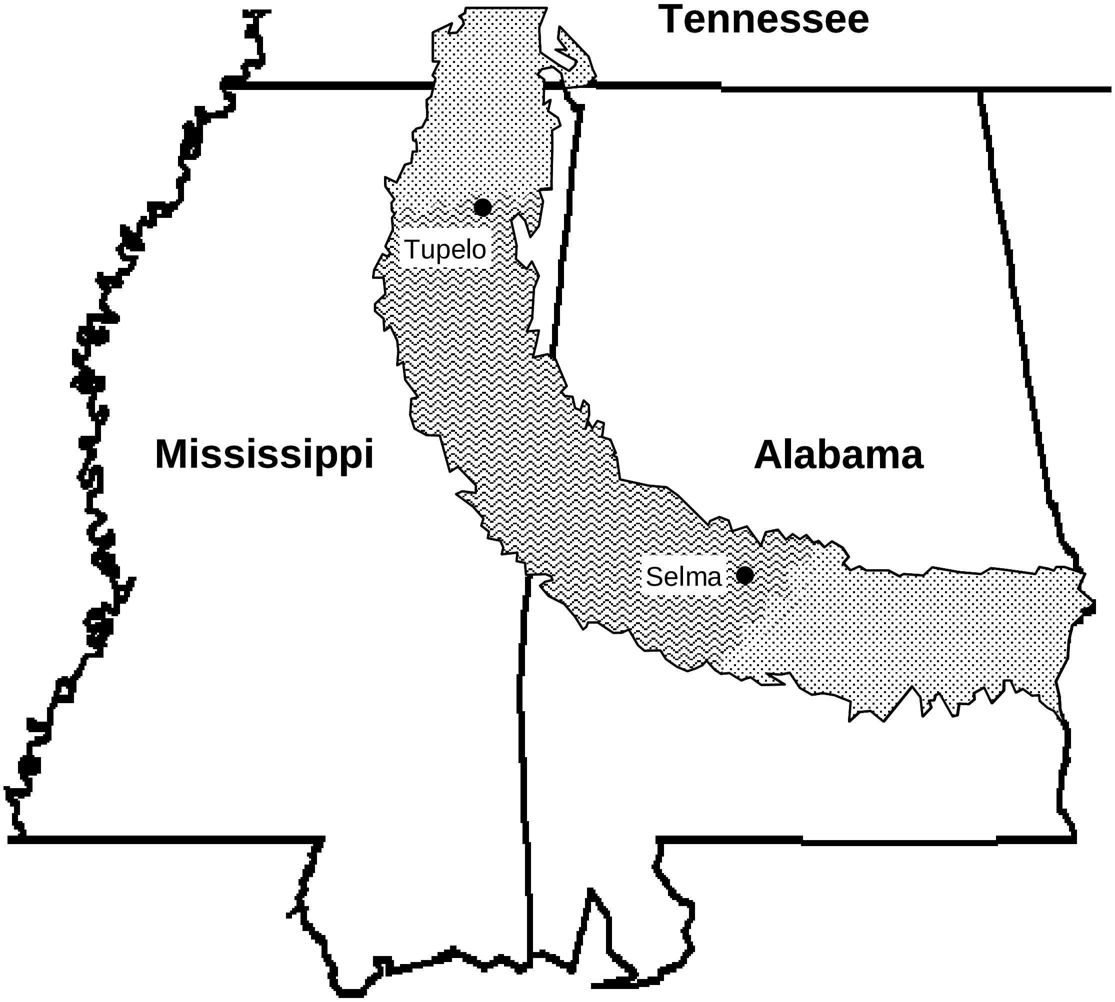

Figure 1 – Outcrop belt of the Upper Cretaceous Selma Group in eastern Gulf Coastal Plain of Alabama and Mississippi. Wavy and stippled patterns reflect chalk- and siliciclastic-dominated deposits, respectively (modified from Mancini et al., 1996).

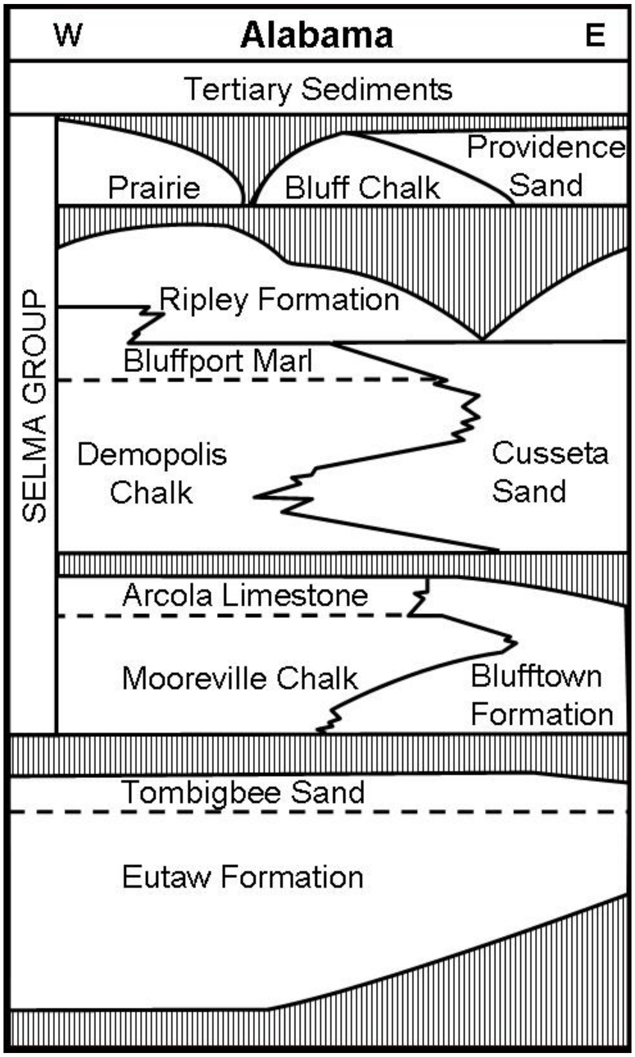

Figure 2 – Lithostratigraphy of Upper Cretaceous Selma Group exposed in Alabama outcrop belt (after LaMoreaux and Toulmin, 1960).

central Alabama (Fig. 3) and northeastern Mississippi, and into southern Tennessee (LaMoreaux and Toulmin, 1960; Copeland, 1972; King and Skotnicki, 1990). In Mississippi and Tennessee, the Ripley Formation interfingers with and grades into the McNairy Sand (Smith, 1989; Mancini et al., 1995). Like that of other units of the Selma Group, strata of the Ripley Formation dip south to southwest at approximately 7.5 m/km (King, 1994).

In western and central Alabama, including the current study area, the Ripley Formation overlies the Bluffport Marl Member of the Demopolis Chalk and is unconformably overlain by the Prairie Bluff Chalk (Copeland, 1972). In the Chattahoochee River Valley region of eastern Alabama and western Georgia, the Ripley Formation rests upon the Cusseta Sand (Skotnicki and King, 1989a,b) and is overlain by the Providence Sand (Copeland, 1972) (Fig. 2). In the outcrop belt in Alabama, the Ripley Formation varies in thickness from 10 to 76 m (Copeland, 1972; Smith, 1989). However, it may be as thick as 123 m in the shallow subsurface (Skotnicki and King, 1989a,b).

2.2.2 Sequence Stratigraphy

In their study of the Upper Cretaceous sequence stratigraphy of the Mississippi-Alabama area, Mancini et al. (1995) indicate that the Ripley Formation forms parts of two separate depositional sequences (Fig. 4). They assign the lower part of the Ripley Formation to the highstand systems tract of sequence UZAGC 4.0 and the upper part of the Ripley to the lowstand systems tract of sequence UZAGC 5.0. They link the sequence boundary/transgressive surface between sequences UZAGC 4.0 and 5.0 to a discontinuity within the Ripley.

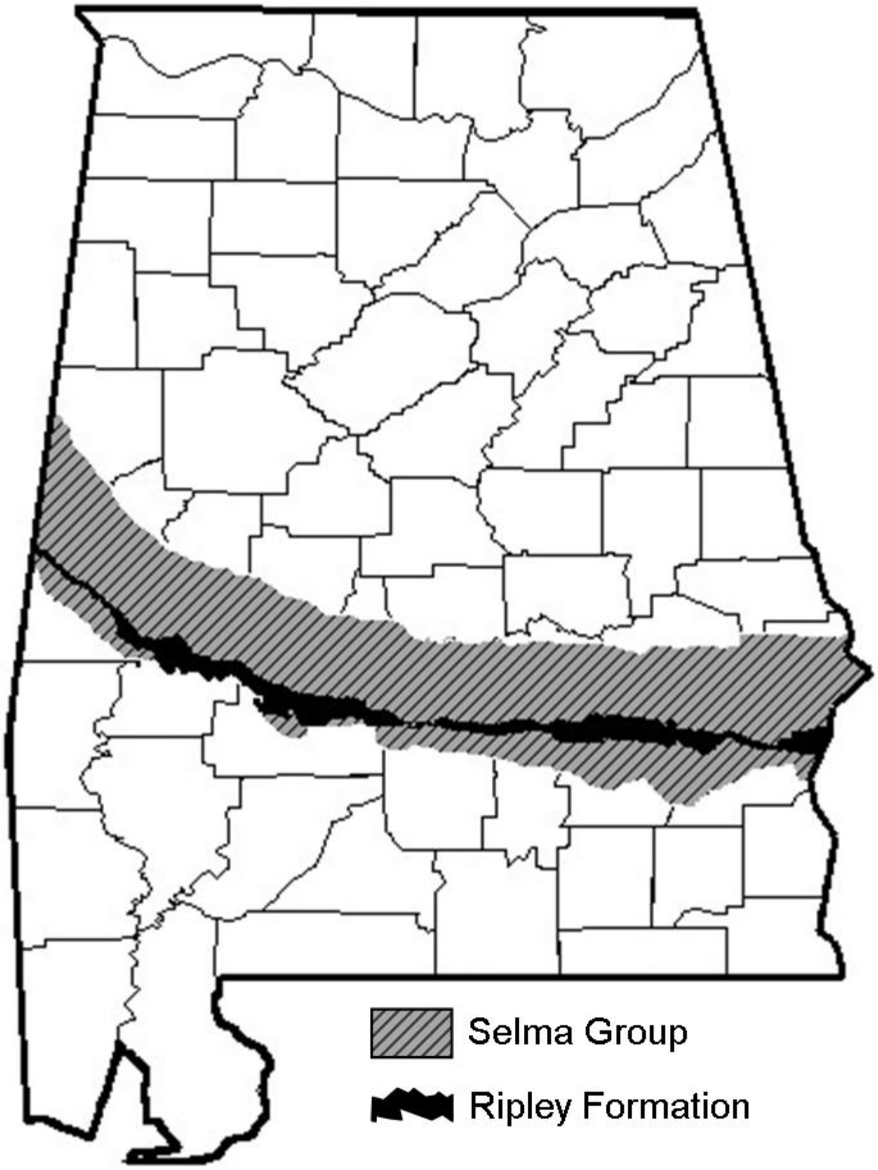

Figure 3 – Distribution of Ripley Formation (black) within Selma Group in Alabama.

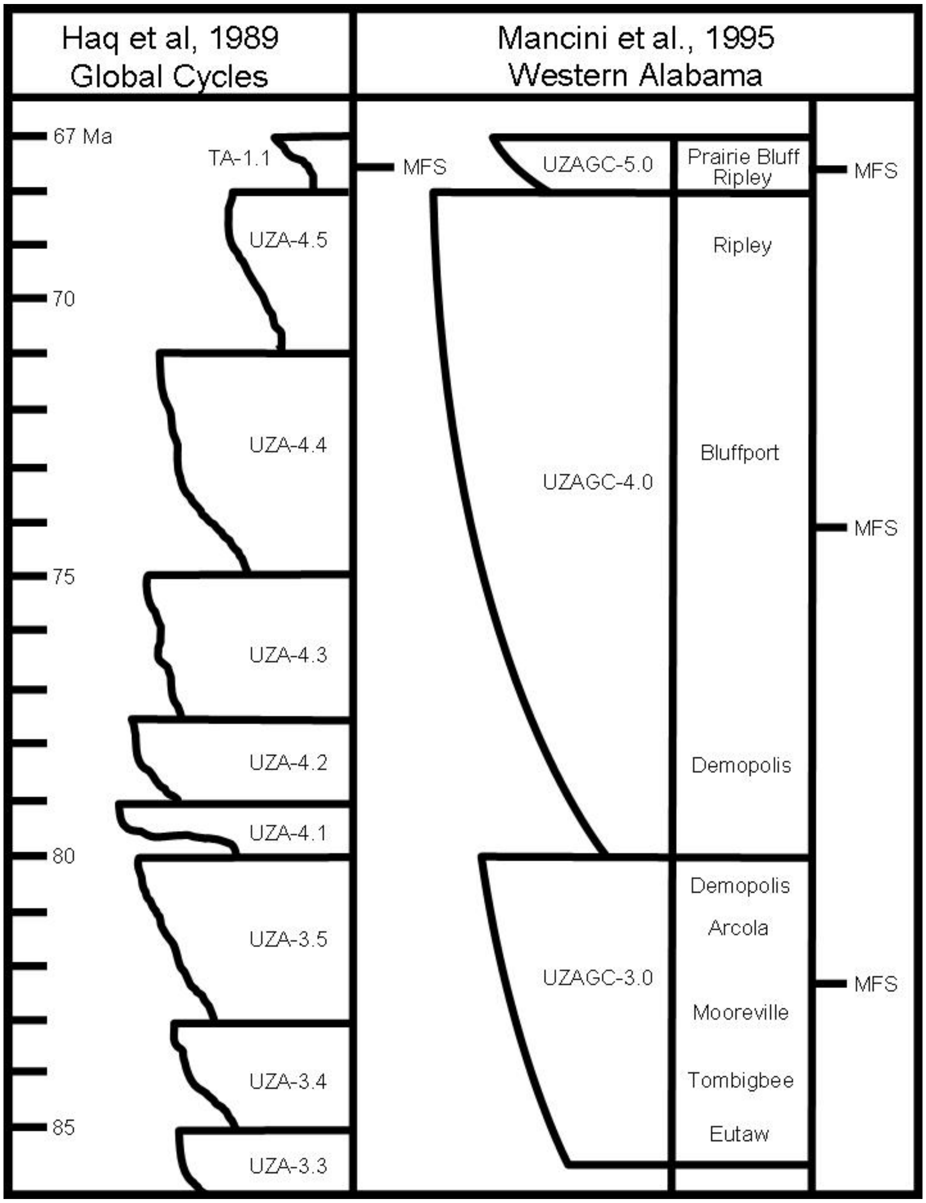

Figure 4 – Sequence stratigraphic interpretation for Upper Cretaceous strata in western Alabama based on Mancini et al. (1995) versus global cycles chart of Haq et al. (1988) (modified from Mancini et al., 1995). MFS = Maximum flooding surface.

Working mainly in eastern Alabama and at a different scale, Skotnicki and King (1989a,b; King and Skotnicki, 1990; King, 1993a,b; 1994) indicate that the Ripley Formation embodies two complete depositional sequences (their sequences 10 and 11) that are bounded by stratigraphic breaks caused by sea-level fluctuations (Fig. 5). They place sequence boundaries at the low-relief erosional contact between the Ripley and underlying Demopolis Chalk/Cusseta Sand, at a low-relief erosional discontinuity within the Ripley (boundary between genetic packages 1 and 2, Fig. 4), and at the high-relief erosional contact between the Ripley and the overlying Prairie Bluff Chalk/Providence Sand.

2.2.3 Lithologies and Depositional Facies

The Ripley Formation is heterolithic. According to earlier workers (e.g., LaMoreaux and Toulmin, 1960; Copeland, 1972), this unit is characterized by calcareous, micaceous, fossiliferous clays; fine- to medium-grained, calcareous, micaceous, glauconitic sandstones; and medium- to coarse-grained, sandy glauconitic limestones. These earlier workers recognized that Ripley sediments accumulated in shallow marine environments, but little attention was given to specific depositional facies.

King (1993a,b, 1994) recognized in Upper Cretaceous rocks of the eastern coastal plain two major facies associations: (1) a paralic facies association that includes barrier island, lagoon-marsh, lower shoreface, and sandy inner-shelf facies; and (2) a shelfal facies association that includes clayey inner-shelf facies and marly mid-shelf facies. Both of these associations are represented in the Ripley Formation. Skotnicki and King (1989a; King and Skotnicki, 1990) recognized six depositional facies within the Ripley Formation. These facies, summarized in Table 1, include back-barrier through shelf

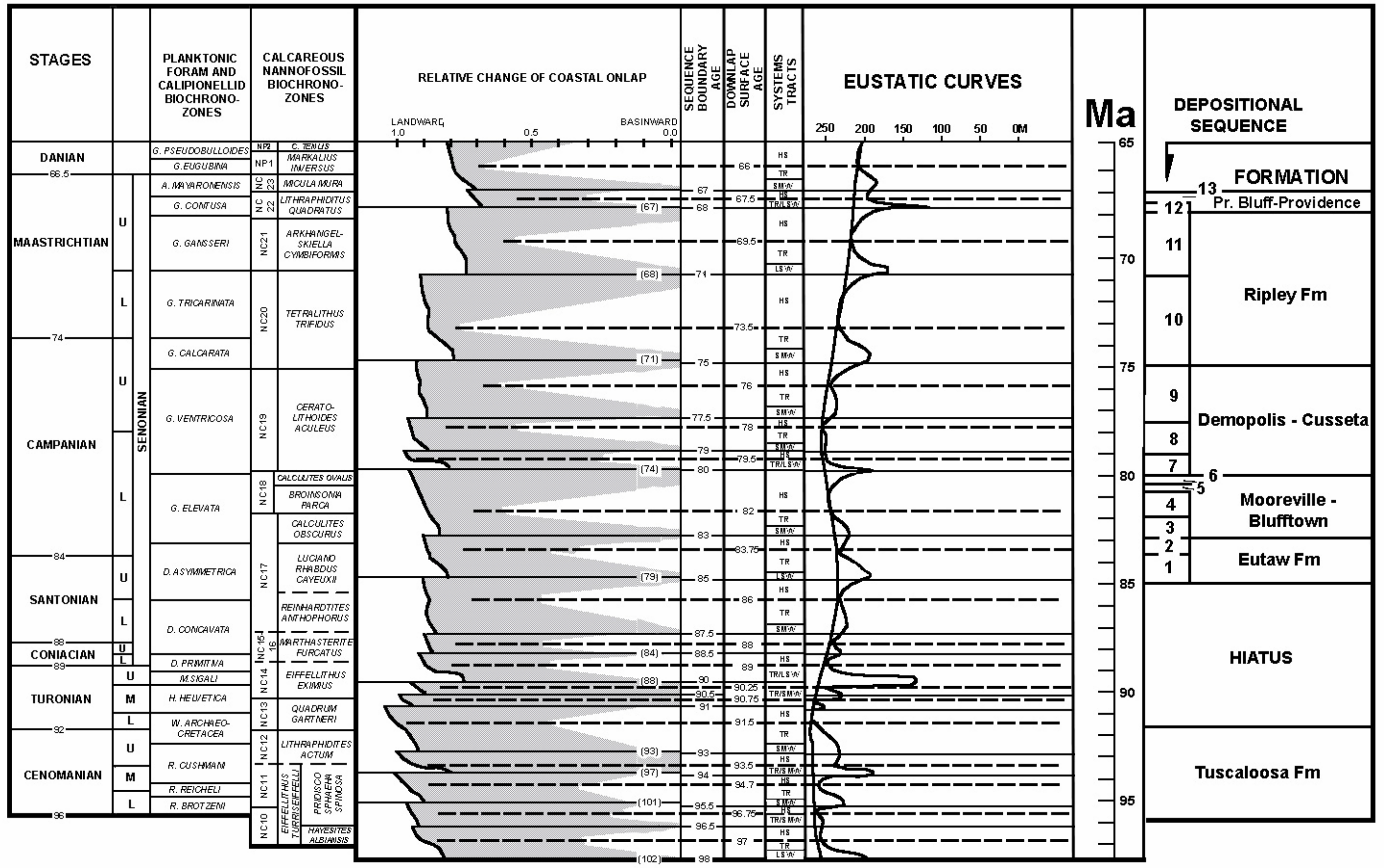

Figure 5 – Correlation between Upper Cretaceous Ripley Formation depositional sequences of King (1994) and chronostratigraphy, biochronostratigraphy, and eustatic sea-level curves (from King, 1994).

Table 1 – Depositional Facies in the Ripley Formation (after Skotnicki and King, 1989b).

	Lithology	Sedimentary structures	Body Fossils	Ichnology	Interpretation
Facies 1	Brown to orange-brown, micaceous, medium- to coarse-grained sand; abundant quartz gravel	Planar cross-stratification, trough cross-stratification, interbedded laminated-scrambled sequences; Coarsening upwards		*Ophiomorpha*	High energy shoreline sedimentation (barrier-shoreline/tidal inlet)
Facies 2	Black, carbonaceous, siltstone, fissile; Light brown, micaceous, slightly sandy siltstone, commonly bioturbated	Hummocky cross-stratified sand common in light brown siltstone; Coarsening upwards trend	Plant debris and impressions; bivalve molds and impressions	*Planolites* and *Teichichnus*	Back-barrier deposits (lagoon and marsh sediments)
Facies 3	Numerous discrete highly micaceous fine-sand beds	Planar laminations and hummocky cross-stratification; Interbedded with Facies 2	Small, streamlined bivalves molds and impressions similar to facies 2	Isolated to extensive vertical burrows	Back-island storm sands
Facies 4	Tan to red-gray, slightly sandy, micaceous, fissile, silty claystone	Thin planar laminations, with rare ripple cross-lamination	Absence of body fossils and plant material	Little to no bioturbation	Back-island sediment (sediment starved tidal flat or lagoonal setting)
Facies 5	Glauconitic, micaceous, slightly calcareous, fine to medium-grained clayey sand; some indurated layers	Rare planar laminations; coarsening upwards cycles	*Exogyra costata, Exogyra cancellata,* various ostreids, *Anomia, Gryphea,* turitellids, and shark teeth	*Thalassinoides* and *Teichichnus*	Lower shoreface of barrier-island system
Facies 6	Micaceous, glauconitic, slightly sandy to silty calcareous clay and clayey marl	Homogeneous mixing	*Anomia*, bivalve; calcareous nannofossils and planktonic foraminifera	Extensive bioturbation, but no distinct trace fossils	Shelf (inner-shelf) environment seaward of facies 5

environments. The spatial distribution of facies in central and eastern Alabama indicate a general westward deepening, where as vertical facies changes reflect temporal sea-level fluctuations (Fig. 6). The concretion-bearing strata addressed in the current study represents the shelf facies (facies 6) of Skotnicki and King (1989).

2.2.4 Ripley Formation Ichnology

Relatively little work has been done on the ichnology of the Ripley Formation. Wheatcroft (1986) discussed numerous ichnofossils and associated ichnocoenoses in the Ripley Formation in the Chattahoochee River Valley area of Alabama and Georgia. He describes *Ophiomorpha*, *Cylindrichnus*, *Palaeophycus*, *Planolites*, *Rosselia*, *Skolithos*, *Teichichnus*, and various unnamed structures. His observations were restricted to marginal and shallow marine facies; shelf deposits comparable to those addressed in the current investigation were not included in his study.

In their studies of the Ripley Formation of eastern and central Alabama, Skotnicki and King (1989) employed trace fossils with sedimentologic evidence to delineate their six depositional facies (Table 1). They recognized *Ophiomorpha*, *Planolites*, *Teichichnus*, and “isolated, extensive, vertical burrows” in various barrier and back-barrier facies (facies 1-3), and *Thalassinoides* and *Teichichnus* in lower shoreface deposits (facies 5). These authors recognized extensive bioturbation in their shelf facies (facies 6), but they were unable to identity distinct trace fossils. Trace fossils preserved in association with the phosphatic concretions examined in the current study provide the opportunity to better evaluate the ichnology of Ripley shelf deposits.

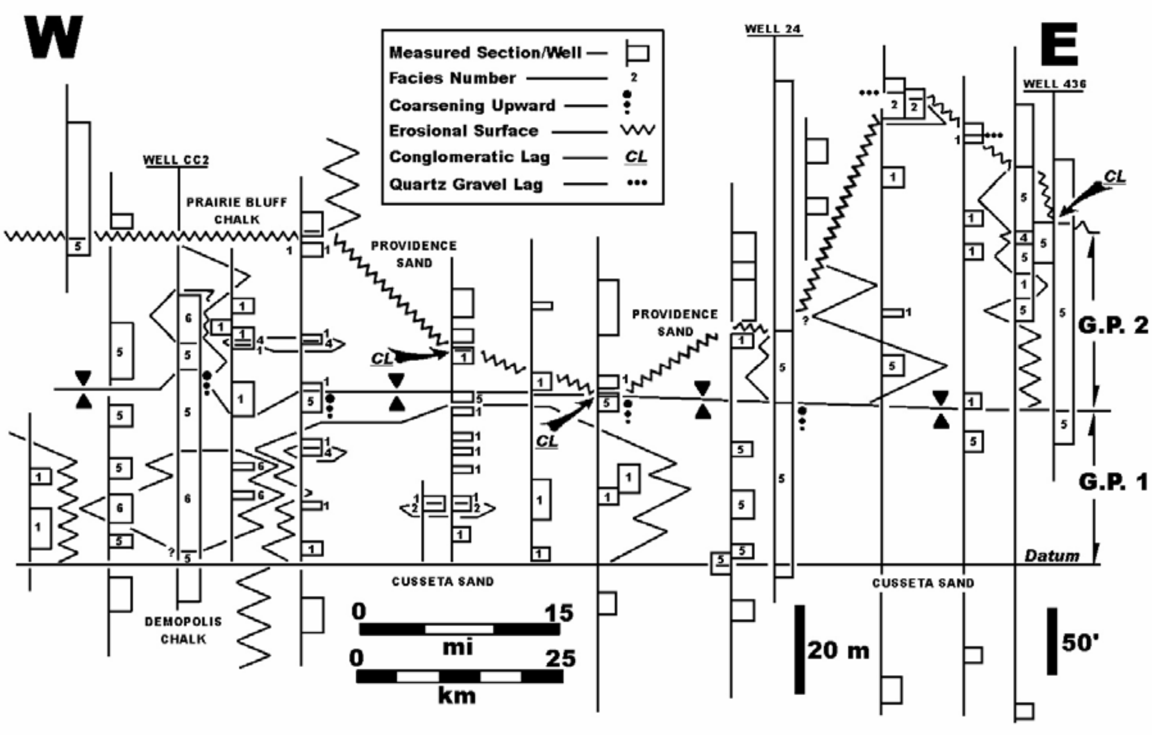

Figure 6 – Facies distribution in Ripley Formation, west-central to eastern Alabama. G.P. = genetic package; Facies number(s): 1= barrier-island shoreface and tidal inlet; 2= back-barrier (lagoon and marsh); 3= storm-influenced lagoon; 4= tidal flat or lagoon; 5= lower shoreface; 6= inner-shelf (from King and Skotnicki, 1990).

2.2.5 Ripley Concretions

Considering their potential role in fossil preservation, phosphatic concretions in the Ripley Formation in Alabama have received surprisingly little attention, at least in print. To date, abundant concretions have been described only from Lowndes County, central Alabama, where shelf deposits of Ripley Formation are exposed along Dry Cedar Creek. Two published abstracts (Abston and Savrda, 1990; Abston et al., 1990) briefly describe modes of occurrence and abundance of body fossils entombed within concretions from the Dry Cedar Creek locality. Schein (2004) later described the skull of a teleost fish (*Enchodus*) preserved within a phosphatic concretion collected from that same location.

Abundant phosphatic concretions likely occur within the same facies at other localities. However, evidence of other occurrences is limited to vague anecdotal information provided by individuals with passing interest in geology and/or fossils. For this reason, the current investigation focuses solely on the Dry Cedar Creek locality.

3.0 LOCATION AND METHODS

This study focused on Ripley sediments exposed along Dry Cedar Creek, east of highway 7 in Lowndes County, central Alabama (Fig. 7A), along which Abston and others (Abston and Savrda, 1990; Abston et al., 1990) recognized an abundance of both *in situ* and reworked, fossil-bearing concretions. Specifically, the current work focused on a ~3-km-long east-west segment of Dry Cedar Creek and the proximal part of a tributary that flows into that segment from the south (Fig. 7B). Strata with *in situ* concretions are exposed intermittently in cut-banks and, rarely, on the channel bed. The creek bed is commonly floored by Holocene sand sheets and/or gravelly midstream and point bars containing rare to abundant reworked concretions. This study included investigations of both Ripley exposures and Holocene bar deposits.

3.1 Field Investigations

The distributions of Ripley exposures, stream bars, and phosphatic concretions in the study area were mapped with the aid of a Garmin handheld GPS unit. All substantial bank exposures (>50 cm high) were located and measured using a tape and/or Jacobs' staff; presence/absence of *in situ* phosphatic concretions in each of these exposures was noted. The distribution of channel-floor exposures and associated *in situ* concretions was also mapped. Point and midstream bars were located and categorized on the basis of their relative sizes (areal coverage) and abundances of allochthonous concretions.

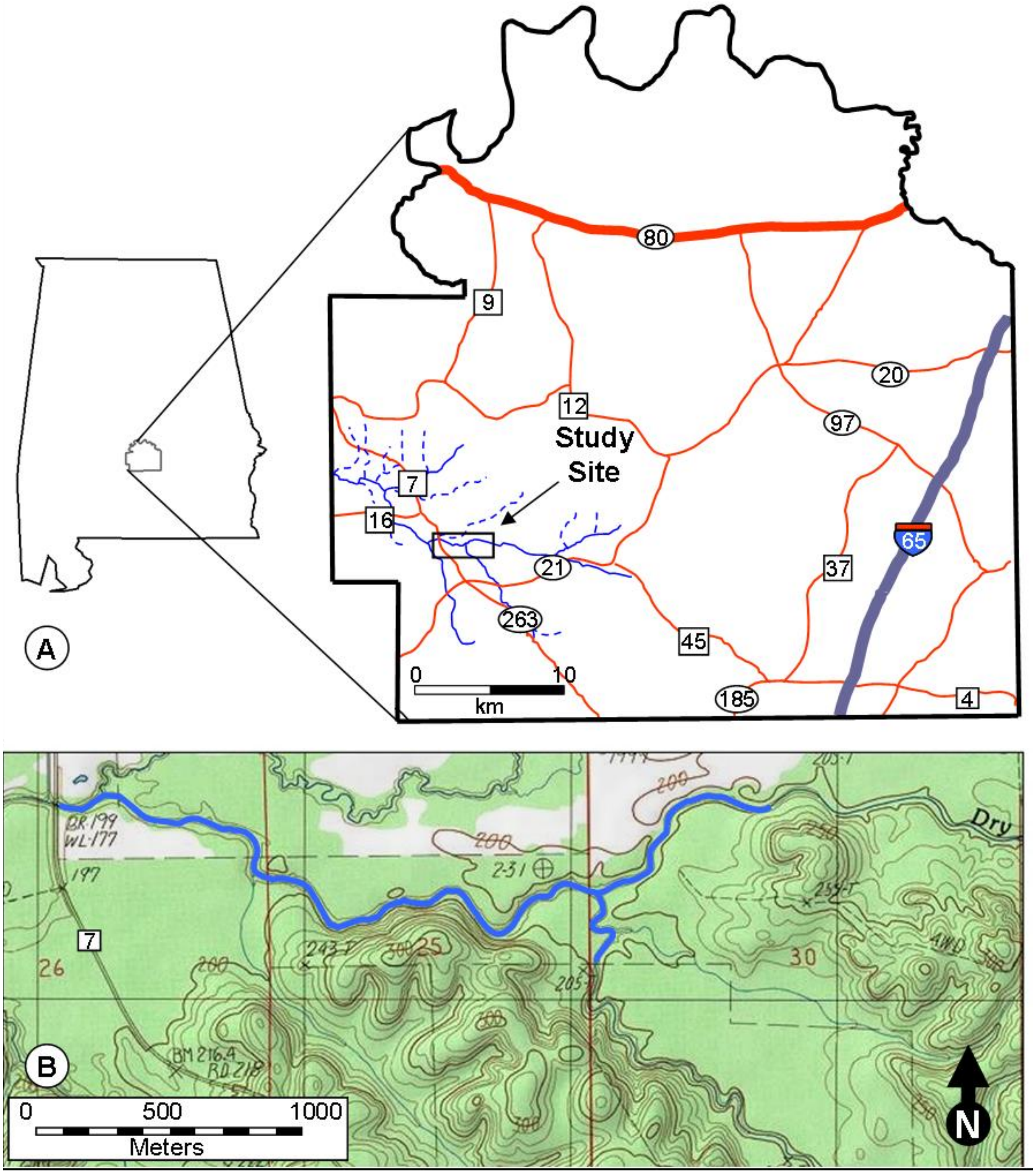

Figure 7 – Location of the study area. (A) Generalized map of study locality in Lowndes County, central Alabama. (B) Detailed topographic map of the study area. Blue line indicates transect on Dry Cedar Creek along which Ripley exposures and midstream and point bars were studied (from USGS 7.5-minute, Braggs quadrangle).

After general mapping, several Ripley exposures were selected for more detailed field examination. Field studies focused on vertically extensive exposures that contained obvious *in situ* concretions. General lithologies and sedimentary structures, fabrics, and textures were described and photographically documented. *In situ* concretions and small block samples of sediments immediately above and below them were collected wherever possible for laboratory studies. Two cut-bank exposures were sampled extensively for more detailed sedimentologic and ichnologic studies in the laboratory. One sample set (sample set 1) consisted of a continuous series of large (up to 8000 cm^2) block samples representative of an ~1-m-thick concretion-bearing interval. The second set (sample set 2) consisted of twelve smaller block samples (~1,000 cm^3 each) extracted at ~20-cm intervals throughout an ~2.5-m-thick concretion-bearing exposure.

Reworked concretions occurring on midstream and point-bar surfaces were examined, and representative specimens were collected for later study. Preference in sampling was given to those concretions that exhibited evidence of ichnofossils in their overall form or on exterior surfaces, and to those that reflected exceptional preservation of body fossils.

3.2 Sedimentologic Studies

Laboratory studies of sediment samples were performed to better characterize the concretionary-bearing strata and to aid in the interpretation of depositional and diagenetic conditions that led to phosphate concretion growth. These studies included various textural and compositional analyses as described below. All procedures were performed at Auburn University with the exception of petrographic thin-section preparation and whole-rock analyses, which were contracted out to commercial laboratories.

3.2.1 Textural Analysis

Sand contents of 21 representative samples (9 and 12 samples from sample sets 1 and 2, respectively) were determined by wet-sieving. Small (~5 to 10 g) subsamples were removed from each sample and then dried and weighed. Each subsample was disaggregated in distilled water for 24 hours and wet-sieved through a 4Φ (63 micron) screen to separate sand- and mud-sized fractions. Sand fractions were dried, weighed, and stored for further investigation. Sand percentages were determined by dividing the weight of sand by the original dry subsample weight.

3.2.2 Petrographic Analyses

Standard petrographic thin sections were commercially prepared (by Wagner Petrographic) from five representative subsamples extracted from sample set 1. Following general description, each thin section was subjected to point-count analysis (using 300+ points) in order to quantify the relative abundance of clastic and allochemical framework grains, matrix material, and early diagenetic constituents. Additional general petrographic observations of sediment texture and composition were made from 12 oversized (2x3") thin sections prepared from sediment blocks from sample set 2 (see below). Significant features observed in thin sections were documented via digital photography.

3.2.3 Carbonate and Organic Carbon Analyses

Analyses of carbonate and organic carbon content were performed on the same 21 samples employed in textural analysis using a combination of acid digestion and LECO combustion techniques. Samples weighing ~ 2 g each were dried in an oven at ~85° C for 24 hours and then powdered using a mortar and pestle. After homogenization, ~ 0.25 g subsamples were weighed and digested in dilute (10%) HCl. Insoluble residues were filtered through pre-weighed, carbon-free, borosilicate glass filters. Filters and residue were oven dried for 24 hours at ~85° and then weighed. Carbonate contents (wt%) were determined by weight loss upon acid digestion. Filters and residues were then combusted in a LECO C/S 200 carbon-sulfur analyzer wherein weight percent organic carbon was determined by infrared detection of evolved CO_2.

3.2.4 Whole-Rock Analyses

Four sediment samples were subjected to whole-rock geochemical analyses. Two of these, DCC-SS1 and DCC-SS12, represent the lowermost and uppermost samples, respectively, of sample set 2. The other two (DCC-Su1 and DCC-056s) represent sediment samples collected immediately adjacent to *in situ* concretions within other cut-bank exposures. After powdering with a mortar and pestle, ~5-g subsamples were sent to ACME Analytical Laboratories, LTD, where ~0.2 g of material were analyzed via ICP-emission spectrometry following $LiBO_2$ fusion and digestion in dilute nitric acid. Data included concentrations of major elements (reported as oxide equivalents) and selected minor elements (e.g., Ba, Ni, Sr, Zr, Y, Nb, Sc; reported in ppm).

3.2.5 Ichnofabric Studies

Owing in part to the low degree of induration and weathering of Ripley sediments, ichnofossils and ichnofabrics commonly were difficult to observe in field exposures. Hence, ichnologic studies of unmineralized sediments focused on sample blocks extracted from cut-bank exposures. Block samples were cut to produce serial slabs normal to bedding. Slabs were examined under a binocular microscope to describe general ichnofabrics and, where possible, to identify discrete ichnofossil forms.

Seventeen slabs cut from separate samples (five from sample set 1, twelve from sample set 2) were used to prepare oversized thin sections that were used to make additional ichnological observations. Significant aspects of ichnofabric recognized on slab surfaces and in thin sections were documented via digital photography.

3.3 Concretion Studies

A total of 170 concretion specimens were collected from the Dry Cedar Creek study location. Owing to the relative scarcity of *in situ* concretions, the majority of these specimens are allochthonous concretions collected from midstream and point-bar surfaces.

In the laboratory, concretions were systematically described and digitally photographed from various angles. After documentation, concretions were placed into one of three broad categories based on gross morphology and inferred fossil nuclei: (1) type 1 concretions, which contain obvious body-fossil nuclei; (2) type 2 concretions, which contain enigmatic nuclei; and (3) type 3 concretions, which appear to have nucleated in or around large burrows. As with the unmineralized sediments, concretions of various types were serially sliced with a rock saw, and resulting subsamples were subjected to a variety of analyses to characterize composition and fabrics.

3.3.1 Ichnologic Analysis

Ichnologic observations initially focused on discrete traces and other aspects of ichnofabric expressed on the exteriors of concretions. Individual traces were digitally photographed, systematically described, and, where possible, identified to the ichnospecies and/or ichnogenus level. Following description of concretion exteriors, numerous representative concretions were systematically sliced in various orientations, and fresh slab surfaces were polished. Seventeen slab samples cut from concretions were used to prepare thin sections. Polished slab surfaces and thin sections were examined under binocular and petrographic microscopes, respectively, to describe ichnofossils and ichnofabrics in concretion interiors.

3.3.2 Textural and Compositional Analyses

Subsamples of representative concretions were subjected to several analytical procedures to assess composition and textures. These included x-ray diffraction and ICP analyses and general petrographic studies.

X-ray diffraction analysis was performed on 3 subsamples extracted from type 2 concretions. Small (~3 g) subsamples were finely ground with a mortar and pestle, and a portion of the powder was analyzed using a Siemens D5000 X-Ray diffractometer housed in the Agronomy and Soils laboratory at Auburn University. Samples were run from 2 to 80 degrees 2Θ operating at 40 kV and 30 mA.

Sixteen subsamples taken from ten separate concretions were subject to whole-rock geochemical analysis via ICP-emission spectrometry following the same procedures used for analyses of sediment (see section 3.2.4). Eleven of these represent multiple subsamples (2 or 3) taken from five concretions. These were analyzed to assess compositional differences between cores (nuclei) and outer regions of concretions. Three subsamples were selected to examine potential relationships between concretion color and chemical composition. The remaining two subsamples were selected in order to compare the composition of concretions with that of immediately adjacent sediments.

Mineralogy and textures of concretions were assessed via general petrographic observations of the 17 thin sections prepared for the ichnofabric analyses discussed above. A fewer number of thin sections (9) were subjected to point-count analysis (300+ points) to quantify the relative abundance of detrital and diagenetic constituents.

4.0 DISTRIBUTION OF RIPLEY EXPOSURES, STREAM BARS, AND CONCRETIONS

4.1 Ripley Exposures

The vertical extent of Ripley Formation exposures in the study area is highly variable (0 to 6 m). Where present, cut-bank exposures of the Ripley Formation along the Dry Cedar Creek transects were ranked into four groups based on relative thickness of exposed strata: (1) group 1- 0.5 to 1.0 m thick; (2) group 2- 1.0 to 2.0 m thick; (3) group 3- 2.0 to 3.0 m thick; and (4) group 4- greater than 3 m thick (up to 6 m). The distribution of cut-bank exposures is depicted in Figure 8B.

Although low cut banks (groups 1 and 2) occur intermittently along the study transects, laterally extensive, higher cut banks exposing thicker sequences (groups 3 and 4) of Ripley Formation are restricted to the central part of the main transect where Dry Cedar Creek is bounded on its southern margin by a relative high bluff (Fig. 8B). This central area is the only place along the transect where relatively extensive stream-bed exposures of the Ripley occur during periods of normal water levels (Fig. 8C). *In situ* phosphatic concretions are observed in many of the cut-bank and stream-bed exposures, but they are most apparent in the central part of the transect (Fig. 8B, C). Concretions appear to be scattered throughout the vertical extent of the Ripley exposures. However, observations made of more laterally and vertically extensive exposures suggest that concretions may be concentrated within several horizons.

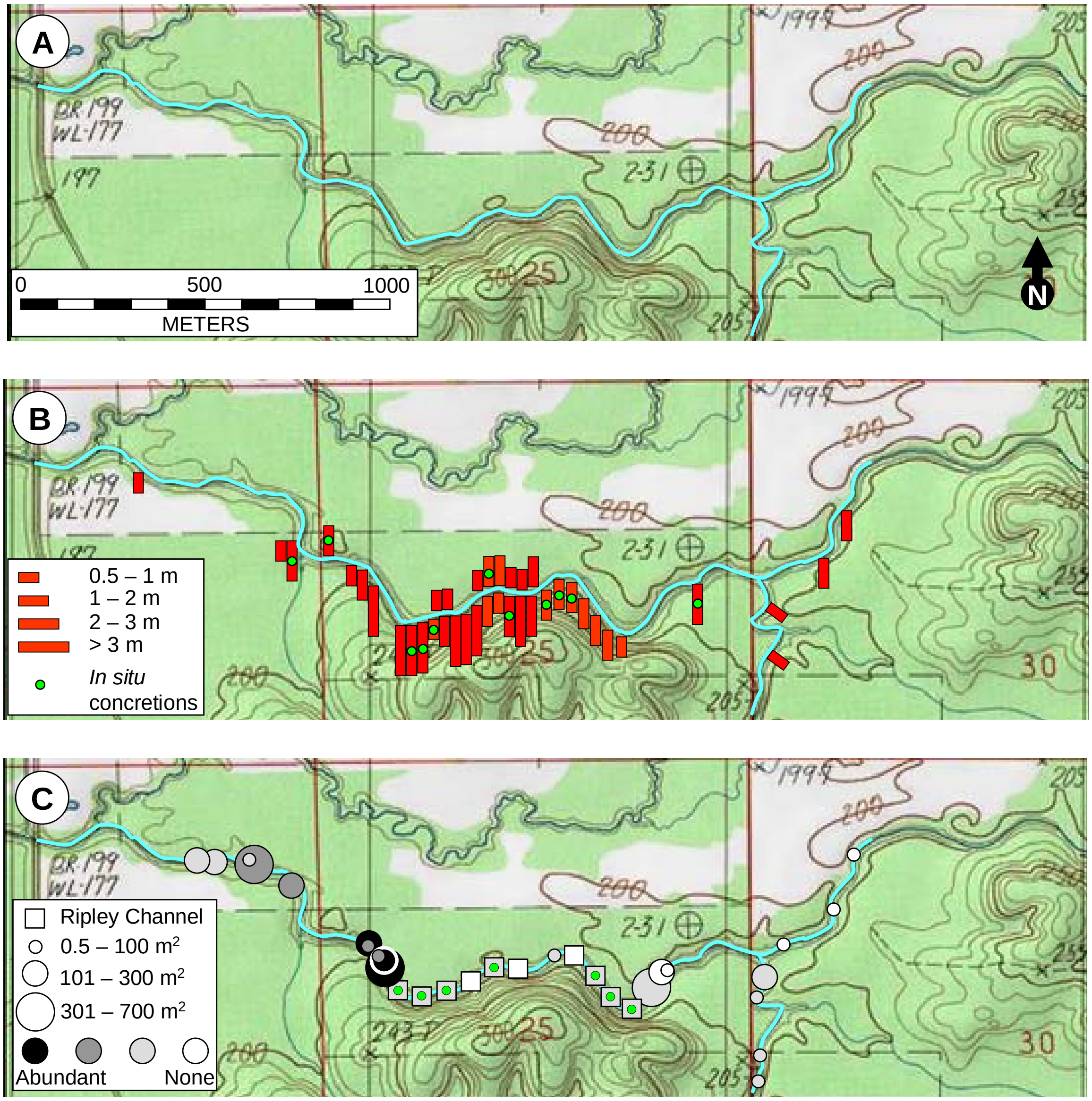

Figure 8 – Maps of study area showing general topography (A), distribution of cut-bank exposures of the Ripley Formation (B), and distribution of Ripley channel exposures and modern midstream and point bars (C). In B, bar lengths reflect relative heights of cut-bank exposures, while green dots indicate the presence of *in situ* phosphatic concretions. In C, squares indicate areas where Ripley muds are exposed on the stream floor; green dots indicate presence of *in situ* concretions. Circles in C indicate position and relative size of bars; shading of circles reflects relative abundance of concretionary material in bars (from USGS 7.5-minute, Braggs quadrangle).

4.2 Stream Bars

Point bars and midstream bars occur intermittently along studied transects (Fig. 9A,B). These bars generally are dominated by relatively flat, imbricated, pebble- and cobble-sized clasts of Ripley Formation muds (Fig. 9C). Tops of bars typically are winnowed and relatively free of finer sediment, whereas a quartzose sand matrix commonly fills interstices between clasts in bar flanks and below bar surfaces.

Bars along the study transect were placed into one of three categories based on areal extent: (1) small bars- <100 m^2; (2) medium bars- 100 to 300 m^2; and (3) large bars- 300 to 700 m^2. All bars also were categorized based on the presence/absence and visually estimated relative abundance of allochthonous concretions exposed on their surfaces. Concretions were recognized as absent or rare (<1 concretion/m^2), common, or abundant (10 or more concretions/m^2; e.g., Fig. 9D).

The distribution of stream-bar categories are depicted in Figure 8C. There are no obvious relationships between bar size and position along the transect. However, concretion abundance is greatest just downstream from the thicker bluff exposures of the Ripley and progressively decreases downstream (westward). Upstream (eastward) of the bluff exposures, concretions are rare to absent (Fig. 8C). The relationships shown in Figures 8B and C strongly indicate that most of the allochthonous concretions in the study area were derived from the interval of Ripley exposed in the central part of the transect rather than from upstream.

Figure 9 – Representative views of point bars (A) and midstream bars (B) distributed along studied section of Dry Cedar Creek. (C) Point bar with imbricated clasts of Ripley mud and concretions. (D) Abundance of concretionary material (outlined in white) that accumulated as allochthonous clasts on a point bar. Scale bar = ~1 meter.

5.0 RIPLEY SEDIMENTS

5.1 General Field Observations

The Ripley Formation sediments exposed on stream beds and in cut banks (Fig. 10A,B) appear relatively homogeneous throughout the study area. Strata, which typically exhibit blocky weathering, are medium to dark gray, sandy, quartzose, micaceous, slightly glauconitic, carbonaceous and calcareous, fossiliferous muds (Fig. 10C). Common invertebrate fossils include various bivalve and gastropod mollusks with original shell material preserved (Fig. 10D). Strata are generally intensely bioturbated. However, with localized exceptions (e.g., Fig. 10E), discrete ichnofossils are difficult to discern on outcrop surfaces owing to limited compositional and textural contrast between burrow fills and ambient sediments. No discrete bedding or other physical sedimentary structures are manifest on outcrop surfaces. However, carefully cleaned outcrop surfaces (and thin sections described below) locally reveal highly biogenically disturbed remnants of what appear to have been discrete laminated or cross-laminated silts and/or sands (Fig. 10F).

5.2 Textural Analyses

Results of textural analyses of a total of 21 sediment samples from sample sets 1 and 2 are summarized in Table 2. All samples are dominated by the mud fraction. Sand contents are variable but generally low, ranging from 1.5% to 16%. Based on the textural classification scheme of Folk (1958), most samples represent muds (<10% sand) while

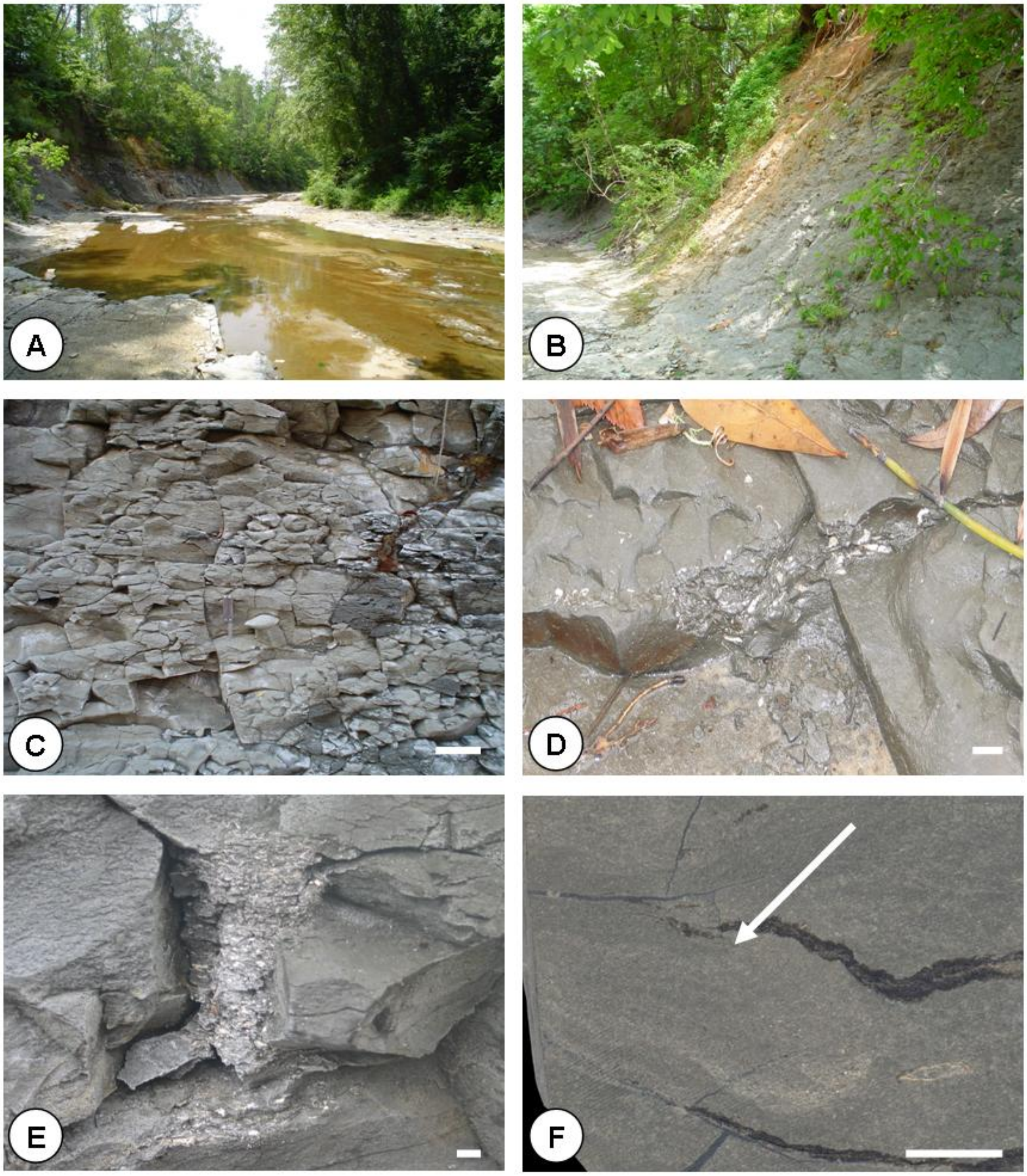

Figure 10 – Ripley Formation exposed in (A) stream beds and (B) cut banks. (C) Blocky weathering in a cut bank (scale bar is ~ 10 cm). (D) Close up of invertebrate fossil material (scale bar is ~1 cm). (E) Rare example of discrete ichnofossil (*Diopatrichnus?*) within Ripley sediments (scale = ~1 cm). (F) Faint, biogenically disturbed laminae or cross laminae (arrow; scale = ~5 mm).

Table 2 – Sand, carbonate, and organic carbon contents for sample sets 1 and 2. Shaded fields indicate intervals of sandier mud.

	Sample #	Height in Section (cm)	% Sand	% $CaCO_3$	% Organic Carbon
Sample Set 1	SamS1-9	9	8.16	25.50	1.41
	SamS1-8	8	8.30	25.57	1.35
	SamS1-7	7	6.52	27.20	1.42
	SamS1-6	6	6.98	26.49	1.39
	SamS1-5	5	9.95	24.72	1.38
	SamS1-4	4	10.95	25.41	1.44
	SamS1-3	3	12.12	23.70	1.25
	SamS1-2	2	15.09	19.99	1.27
	SamS1-1	1	9.87	19.73	1.47
Sample Set 2	SamS2-12	230	5.37	20.25	1.32
	SamS2-11	210	3.35	18.99	1.37
	SamS2-10	190	2.48	19.91	1.45
	SamS2-9	170	2.97	19.14	1.28
	SamS2-8	150	1.49	18.66	1.12
	SamS2-7	130	1.81	20.00	1.44
	SamS2-6	110	4.19	20.11	1.29
	SamS2-5	90	10.84	19.47	1.12
	SamS2-4	70	15.77	17.28	1.09
	SamS2-3	50	4.09	28.17	1.36
	SamS2-2	30	6.87	19.15	1.36
	SamS2-1	10	3.88	26.14	1.37

only five samples represent sandy muds. Based on the relative position of individual samples within vertical sample profiles (Table 2), it appears that sandier muds occur in discrete intervals of the Ripley Formation. The character of the mud and sand fractions as assessed in thin sections is described below.

5.3 Petrography

General petrographic observations and point-count analyses (Table 3) indicate that the Ripley sediments exposed at Dry Cedar Creek are composed of (1) clay- and fine silt-sized mud (54-62%), representing an admixture of unidentifiable phyllosilicates and micritic calcite; (2) coarser silt- and sand-sized detrital grains that include quartz (16-20%), micas (5-10%), and rare feldspars (<1%); (3) skeletal carbonate grains (2-11%); and (4) authigenic constituents, including phosphate (3-8%), pyrite (2-4%), and glauconite (1-2%) (Figs. 11 and 12).

Detrital quartz grains (e.g., Fig. 11A, B) are typically angular to subangular, monocrystalline, and nonundulose, although rare semicomposite undulose grains are observed. Quartz grains range in size from 20 μ (silt) to 0.25 mm (fine sand). Quartz is generally randomly distributed through the sediment but locally is concentrated in what appear to be burrow fills and in biogenically disrupted silt or sand lenses and layers. Quartz grains coated with glauconite are common.

Micas (e.g., Fig. 11B, C) are dominated by muscovite, but rare biotite is observed. These grains appear either as long, slender laths or thick, polygonal grains ranging in length from 0.1 to 0.5 mm (very fine to medium sand). Micas typically are randomly distributed throughout the finer mud matrix and display no preferred orientation.

Table 3 – Relative abundance of constituent minerals of Ripley Formation sediment (shaded area) and concretion samples based on point counts.

			Minerals							
			Mud Matrix	Quartz	Mica	Carbonate	Feldspar	Phosphate	Pyrite	Glauconite
			%	%	%	%	%	%	%	%
Samples	Sediment	DC1A/1+	62.33	16.00	10.00	2.33	0.00	4.67	3.67	1.00
		DC1A/1-	60.33	20.00	4.67	8.00	0.33	3.33	2.00	1.33
		DC1A/2A+	54.00	19.67	6.67	10.67	0.67	5.33	1.67	1.33
		DC1A/2B+	54.33	18.67	5.33	10.33	0.33	6.00	2.67	2.33
		DC1A/3+	57.67	16.00	7.00	7.33	0.00	8.67	2.33	1.00
	Concretions	B2	73.00	8.67	1.33	11.67	0.33	2.67	1.33	1.00
		BLT1	84.00	3.33	1.00	9.00	0.00	1.67	0.67	0.33
		BLT2	80.00	4.33	1.33	10.00	0.00	2.67	1.00	0.67
		DBLT1	66.67	10.67	1.00	14.00	0.00	5.33	1.00	1.33
		A4.2	77.33	6.00	3.33	11.00	0.00	1.67	0.67	0.00
		A26.1	70.67	9.33	5.33	8.67	0.00	3.00	1.00	2.00
		A47	79.33	6.00	3.33	7.33	0.00	2.33	0.67	1.00
		A62.1	75.33	8.33	6.67	6.00	0.00	1.00	1.00	1.67
		A63.1	80.67	5.33	3.67	4.33	0.00	4.00	0.67	1.33

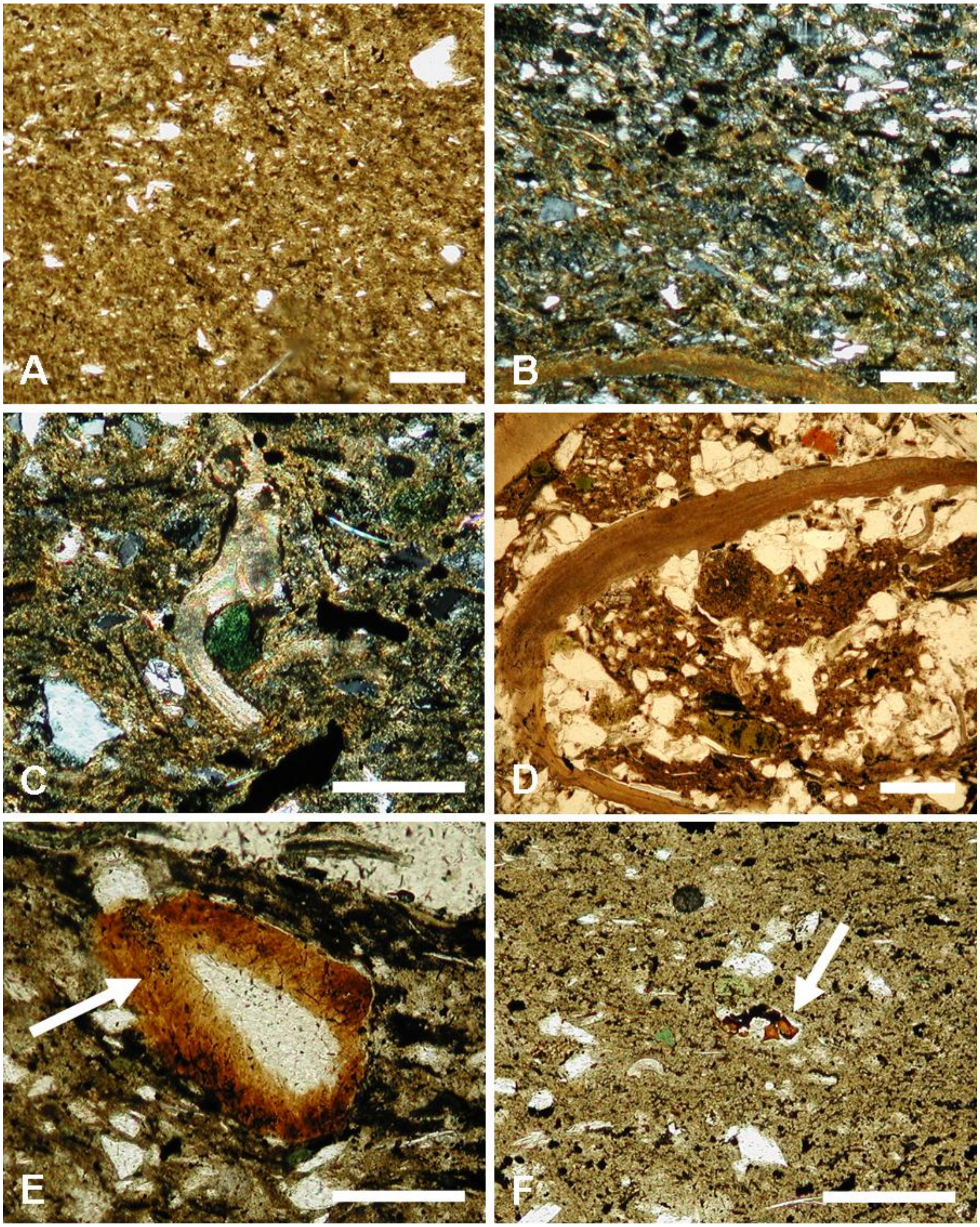

Figure 11 – Thin-section photomicrographs of Ripley sediments. All scale bars are ~0.25 mm. (A) Fine-grained mud with randomly distributed detrital grains (plane-polarized light). (B) Silt- and sand-sized detrital quartz, micas, and feldspars concentrated in burrow fill, upper right part of view (cross-polarized light). (C) Calcite skeletal fragment, glauconite, and pyrite (cross-polarized light). (D) Partially phosphatized skeletal elements concentrated in a burrow fill (plane-polarized light). (E,F) Examples of primary biogenic skeletal phosphate (arrows) in fine-grained sediment (plane-polarized light).

Rare feldspar grains are mainly plagioclase. They are coarse silt-sized, subangular, and commonly highly altered.

Carbonate skeletal grains (Fig. 11C, D) are mainly fragments of mollusks and whole or fragmented foraminifera. Although skeletal material often occurs as individual fragments randomly distributed within the sediment, they also locally appear to be concentrated in burrow fills. Skeletal grains typically range from 0.5 to 3.0 mm in apparent maximum dimension. Many of these grains appear to be partially phosphatized (Fig. 11D).

Readily identifiable phosphatic grains are typically orange-brown to dark brown (Fig. 11E, F). Although some are primary biogenic phosphate (e.g., fish vertebra; Fig. 11E, F), most appear to have formed as replacement products of carbonate shell fragments (Fig. 11D) or other organic constituents.

Pyrite occurs throughout most sediment samples (Figs. 11, 12), but appears to be locally concentrated in and around organic detritus. Pyrite occurs as irregular masses and framboids ranging in size from 0.1 to 0.5 mm (Fig. 12A, B).

Glauconite grains (Fig. 12C, D, E, F) are randomly scattered throughout sediment samples. Glauconite occurs as distinct, irregular, rounded, tabular, or vermicular grains, and as coatings on detrital quartz, mica, and feldspar grains.

5.4 Carbonate and Organic Carbon Contents

Carbonate and organic carbon contents, presented in Table 2, are relatively consistent within and between the two sample sets. Carbonate contents range from 17 to 28%, reflecting the presence of both skeletal carbonate grains and micritic carbonate admixed in the matrix. Organic carbon contents are relatively high, ranging from 1 to

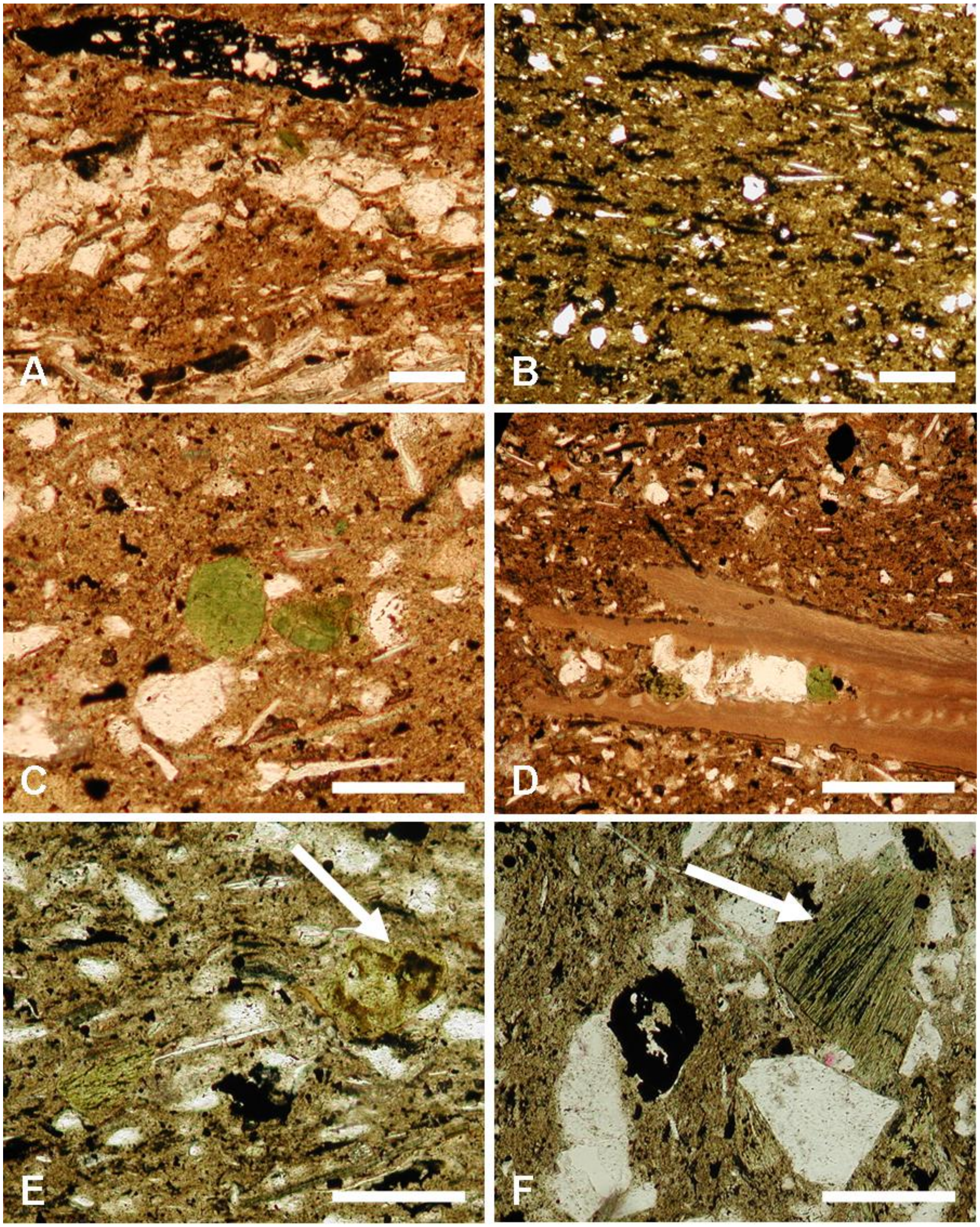

Figure 12 – Representative thin-section photomicrographs of authigenic constituents in Ripley sediments. All scale bars are ~0.25 mm and all views are in plane-polarized light. (A) Relatively large pyrite mass. (B) Locally abundant framboids and elongated masses of pyrite within muddy sediment. (C) Rounded and cracked grains of glauconite. (D) Glauconite grains in partially phosphatized skeletal fragment. (E) Glauconite grain with phosphatic core (arrow). (F) Partially glauconitized mica grain (arrow).

1.5%. Organic carbon content generally varies in proportion to carbonate content and inversely with sand content (Fig. 13).

5.5 Whole-Rock Analyses

Data from whole-rock analyses of four sediment samples are reported in Table 4. As expected for calcareous siliciclastic mudrocks, silica and aluminum are the dominant components of all samples, reflecting the abundance of quartz, clay minerals, and other aluminosilicates, while calcium concentrations are moderate and vary inversely with silica concentrations. Fe contents are also relatively high. Although some Fe likely is associated with siliciclastic minerals and glauconite grains, Fe contents likely reflect the abundance of authigenic sedimentary pyrite. Concentrations of other major elements (e.g., Mg, K, Ti) and several trace elements (Ba, Ni, Zr, Nb, and Sc) likely reflect the contribution of these components in siliciclastic minerals. Notably, phosphate concentrations in the sediment samples are very low (<0.11 weight % P_2O_5)

5.6 Interpretation

The Ripley Formation exposed along Dry Cedar Creek is most similar to facies 6 of Skotnicki and King (1989). The dominance of clastic and carbonate mud reflects deposition in a generally quiet-water shelf setting. However, the common occurrence of coarser admixed sand and rare vestiges of laminated or cross-laminated sands suggests that bottom currents periodically influenced the seafloor. This is taken to indicate that deposition occurred above storm-wave base.

Nearly complete bioturbation and the abundance of benthic invertebrate fossils indicate that the seafloor was at least moderately well oxygenated during deposition. However, organic carbon contents are unusually high for bioturbated marine shelf

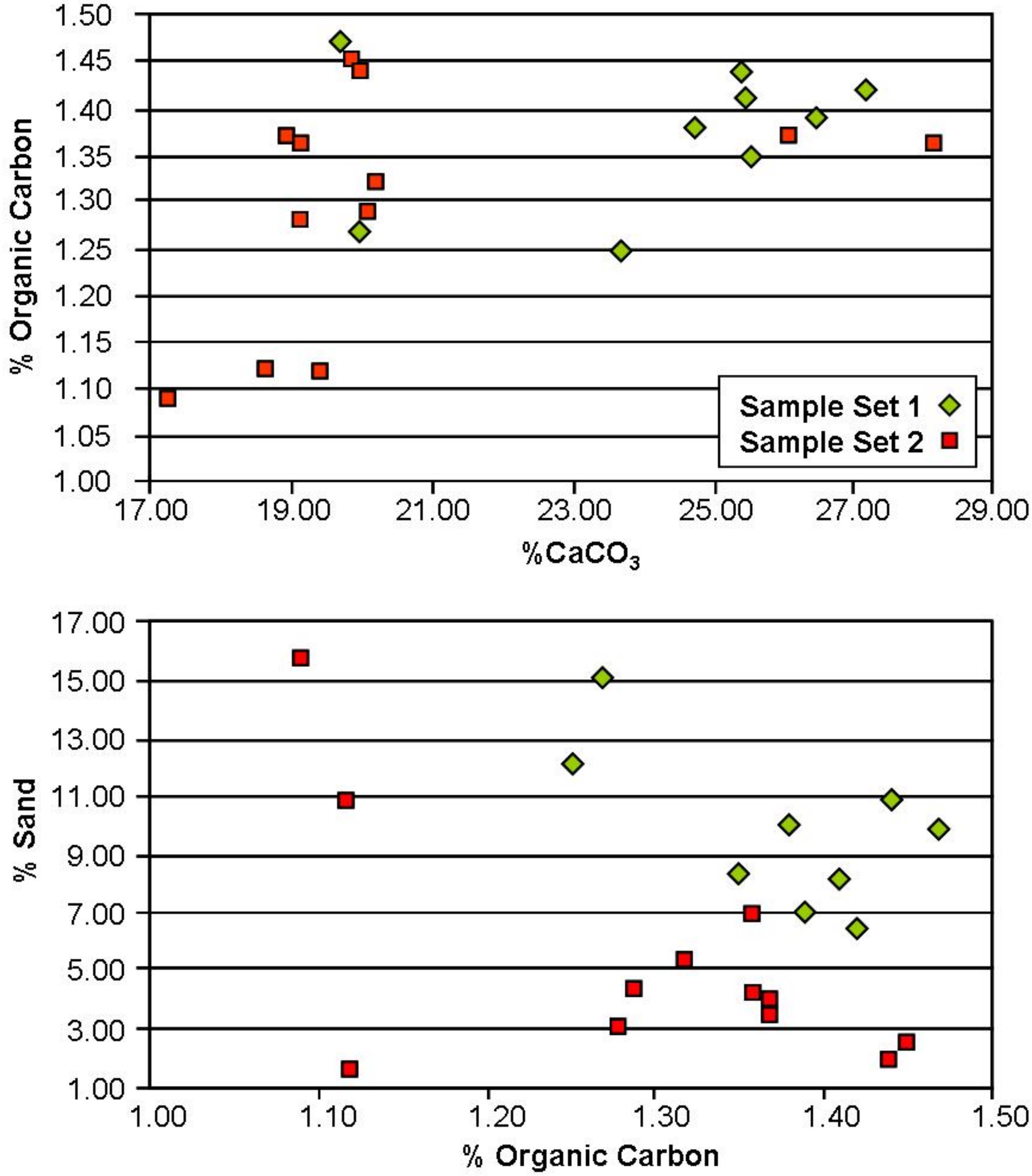

Figure 13 – Relationships between organic carbon, carbonate, and sand content.

Table 4 – Major and trace element composition of sediment and concretion samples.

				Elements															
				SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Ba	Ni	Sr	Zr	Y	Nb	Sc
		Sample	**Description**	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Sediment	SS-056s	Sediment adjacent to *in situ* concretion	42.97	14.87	5.32	1.81	13.03	0.30	1.94	0.68	0.11	307	38	764	191	19	13	12
		SS01	Bottom sample set 2	40.61	15.31	5.43	1.93	14.26	0.27	1.87	0.68	0.09	278	36	859	159	19	12	13
		SS12	Top sample set 2	45.13	15.73	5.39	1.93	10.83	0.26	1.96	0.73	0.09	300	37	660	183	20	14	13
		SS-Su1	Sediment adjacent to *in situ* concretion	49.24	15.49	5.36	1.97	8.57	0.31	1.98	0.75	0.06	323	37	640	223	21	12	13
Concretions	**Type 1**	Su1Con	*In situ* concretion	10.98	3.61	1.49	0.46	42.54	0.64	0.47	0.19	30.51	178	14	4545	85	21	5	4
		A35/am	Ammonite shell	9.36	2.97	1.42	0.40	44.50	0.59	0.42	0.17	31.20	159	5	3465	99	9	5	3
		A35/sh	Shell hash surrounding ammonite shell	18.98	4.35	1.95	0.52	38.04	0.65	0.86	0.28	26.21	248	5	3044	165	34	5	5
	Type 2	A2/a	Transect (center)	9.75	3.07	1.46	0.40	43.66	0.60	0.40	0.14	30.95	159	5	3470	62	22	5	4
		A2/b	Transect (middle)	8.00	2.70	1.39	0.36	44.70	0.61	0.36	0.13	32.26	172	5	3602	67	17	5	4
		A2/c	Transect (outer)	8.69	3.03	1.47	0.37	44.14	0.56	0.41	0.16	30.95	170	5	3714	71	48	5	5
		A4	Diffuse sample from center	9.81	3.73	1.51	0.47	43.19	0.49	0.47	0.18	28.80	149	5	3390	54	35	5	4
		A5/a	Diffuse sample - core	10.93	3.65	1.63	0.41	41.96	0.55	0.53	0.20	31.46	186	5	3353	84	81	5	6
		A5/b	Red region	9.46	3.09	3.38	0.40	42.08	0.60	0.45	0.16	31.31	169	5	3262	89	17	5	4
		A23/a	Black (inner) region	7.43	2.66	1.37	0.35	45.14	0.55	0.36	0.15	32.27	160	5	3861	102	45	5	6
		A23/b	Light (outer) region	10.16	3.71	1.69	0.47	43.06	0.49	0.49	0.20	29.35	147	9	3525	73	59	5	5
		A26/a	Transect - (center)	11.23	4.21	1.92	0.50	41.68	0.54	0.50	0.20	28.76	175	5	3301	53	10	5	4
		A26/b	Transect - "weathering rind"	11.05	4.03	2.11	0.47	41.41	0.54	0.54	0.21	30.66	180	5	3360	76	62	5	5
		A27	Diffuse sample	9.15	3.06	1.45	0.40	43.65	0.60	0.42	0.16	31.81	164	5	3731	72	19	7	4
		056Con	*In situ* concretion	15.50	4.07	1.63	0.50	40.23	0.63	0.64	0.22	27.47	199	22	3673	113	27	5	4
		A63	Diffuse sample	9.78	4.03	1.70	0.39	42.34	0.54	0.40	0.18	31.55	226	5	3117	60	141	5	3

deposits. The accumulation of substantial organic matter in oxygenated sediments likely resulted from high organic productivity above the Ripley shelf. The abundant organic matter facilitated development of sulfidic conditions in pore waters, leading to the precipitation of abundant authigenic Fe sulfides.

6.0 CONCRETIONS

As previously indicated, concretions collected from Ripley exposures and from stream bars were categorized as one of three types based on general morphology and inferred nuclei. Type 1 concretions are those that clearly nucleated in or around body fossils. Type 2 concretions are irregular, mineralized sediment masses containing no obvious nuclei. Type 3 concretions are those that appear to have nucleated on or around large burrows. The general characteristics of each of these concretion types are described below.

6.1 Type 1 Concretions

Exteriors of type 1 concretions are relatively uniform in color, most commonly moderate, pale, and dark yellowish brown (10YR 5/4, 6/2, 4/2). Interiors of concretions as viewed on cut or fractured surfaces are typically darker (mainly dark yellow brown, 10YR 4/2 to dark gray, N3); some are zoned, with the darkest colors towards concretion cores.

Type 1 concretions nucleated on various invertebrate and vertebrate fossils. Some type 1 concretions represent simple internal molds (e.g., phosphatic steinkerns of ammonites). For others, concretion growth included phosphate replacement and permineralization of skeletal material but did not extend beyond the outer margins of fossil nuclei. More commonly, mineralization advanced some distance (0.1-4 cm) beyond body fossil exteriors to form mummy concretions (Mundlos, 1975) that reflect at least the gross shape of the entombed fossil. Invertebrate nuclei include, in order of decreasing abundance, crabs, ammonites, and other mollusks. Vertebrate nuclei are less common and include fish and reptilian remains and isolated, unidentified bone fragments.

Crab-bearing concretions are very abundant; in an earlier study, approximately 10% of the ~800 concretions collected on a 14-m^2 point-bar surface had crab nuclei (C.E. Savrda, personal communication, 2004). These concretions are mostly mummy concretions wherein mineralization extended typically 2 to 4 cm beyond the body fossil. Shapes of concretions clearly reflect the position of the chelae and proximal parts of walking legs (parts of which are exposed on concretion margins) and indicate that crab remains (dead crabs or molts) generally had not disarticulated prior to mineralization (Fig. 14A, B). Sizes of crab-bearing concretions vary significantly depending on the size of entombed crabs; concretion widths vary from 8 to 30 cm, heights from 5 to 13 cm, and thicknesses from 1 to 5 cm. When broken or cut, concretion interiors commonly reveal fractures that crudely define the original position of the chitinous exoskeleton. Some internal fractures are open, while others are filled with pyrite.

Concretions that nucleated in or on ammonites (e.g., Fig.14C) are discoidal (diameters 10-30 cm), with the exception of the less common examples that grew on straight-shelled forms (*Baculites*). Some of these concretions are simple internal molds, while others are mummy concretions wherein mineralization extended a few millimeters to 1 cm beyond the ammonite shell. In both cases, ammonites are only weakly compressed. In most mummy concretions, original ammonite shell material is moderately to well preserved.

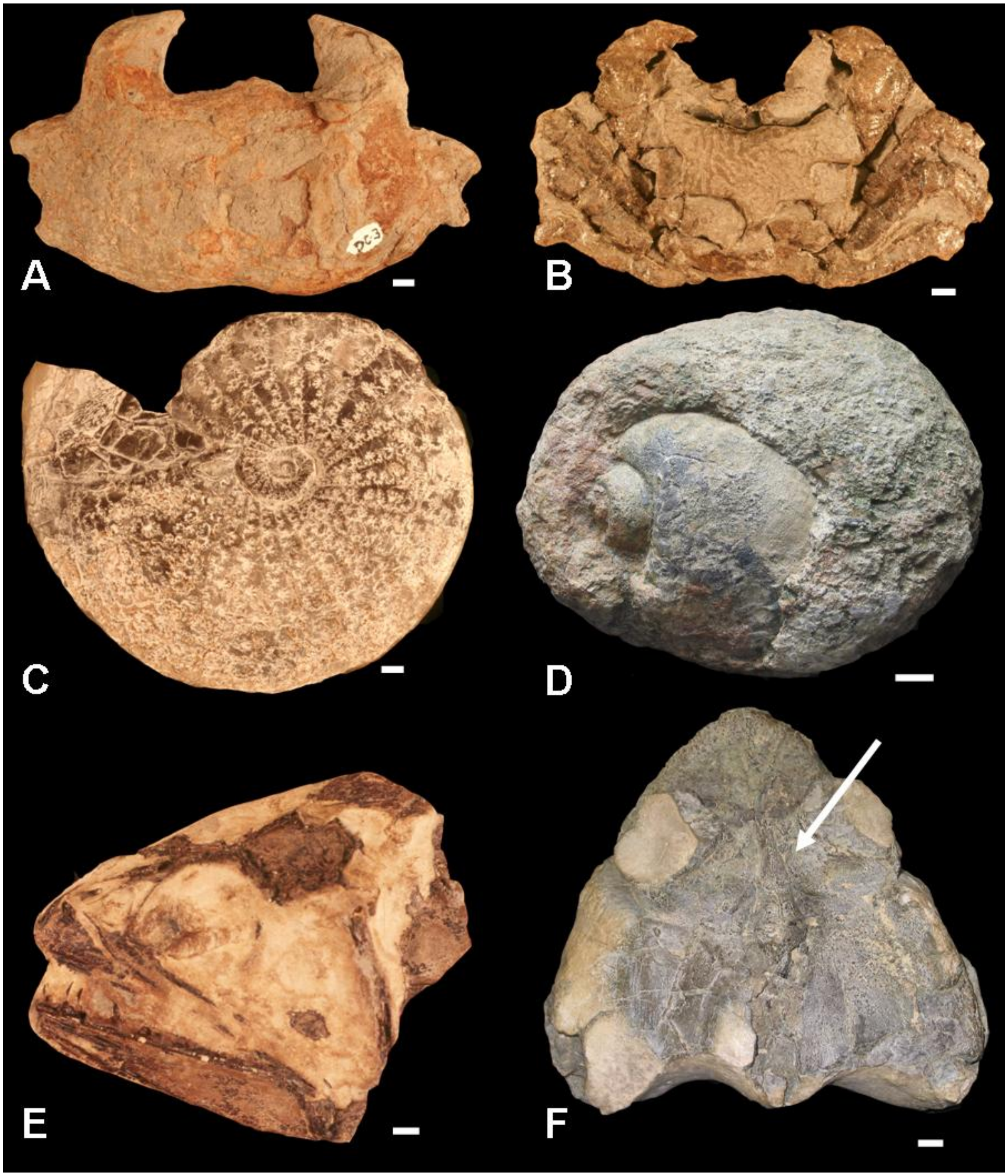

Figure 14 – Examples of type 1 concretions, which nucleated within or around body fossils. All scale bars are ~1 cm. (A) Type 1 concretion with overall shape reflecting that of entombed crab. (B) Semi-prepared crab-bearing concretion showing chelae and legs. (C) Ammonite mold showing detail of original shell exterior. (D) Large gastropod preserved as internal mold within type 1 concretion. (E) Phosphate-cemented fish (*Enchodus*) skull. (F) Dorsal view of fossil sea turtle skull (arrow indicates phosphatic cast of braincase).

The extent to which concretions nucleated on or in other types of mollusks is not clear. Some mummy concretions nucleated on gastropods or previously formed gastropod steinkerns (Fig. 14D). Concretions that crudely resemble bivalve mollusks are abundant. However, examination of the interiors and exteriors of these concretions reveal no definitive evidence that these are steinkerns or mummy concretions formed in or around bivalves.

Concretions that nucleated on vertebrate remains are rare but generally show spectacular preservation. Examples include concretions that preserve partly compressed but relatively well-articulated skulls of a fish (Fig. 14E; *Enchodus*; Schein, 2004) and a sea turtle. The latter includes a phosphatic cast of the turtle's braincase (Fig. 14F).

One of the collected type 1 concretions has compound nuclei (Fig. 15). In this sample, growth of phosphate from two adjacent body fossils (a crab and a bone fragment) coalesced, resulting in mineralization of intervening host sediments. Host sediments in this case included cross-stratified, fine- to medium-grained sands that probably reflect storm deposition on the shelf.

6.2 Type 2 Concretions

Type 2 concretions are highly variable in shape (Fig. 16). In gross form, most are crudely discoidal or bladed; maximum projection areas generally are or appear to have been bedding parallel. Long and short axes of concretions range up to 28 cm and 8 cm, respectively. In detail, type 2 concretions commonly exhibit irregular protrusions and pockets, some which are related to body fossils or burrows (Figs. 16A-D).

Exteriors of type 2 concretions tend to exhibit some color variation. Juxtaposition of two or more colors (mostly pale and moderate yellowish brown, 10YR 6/2 and 5/4;

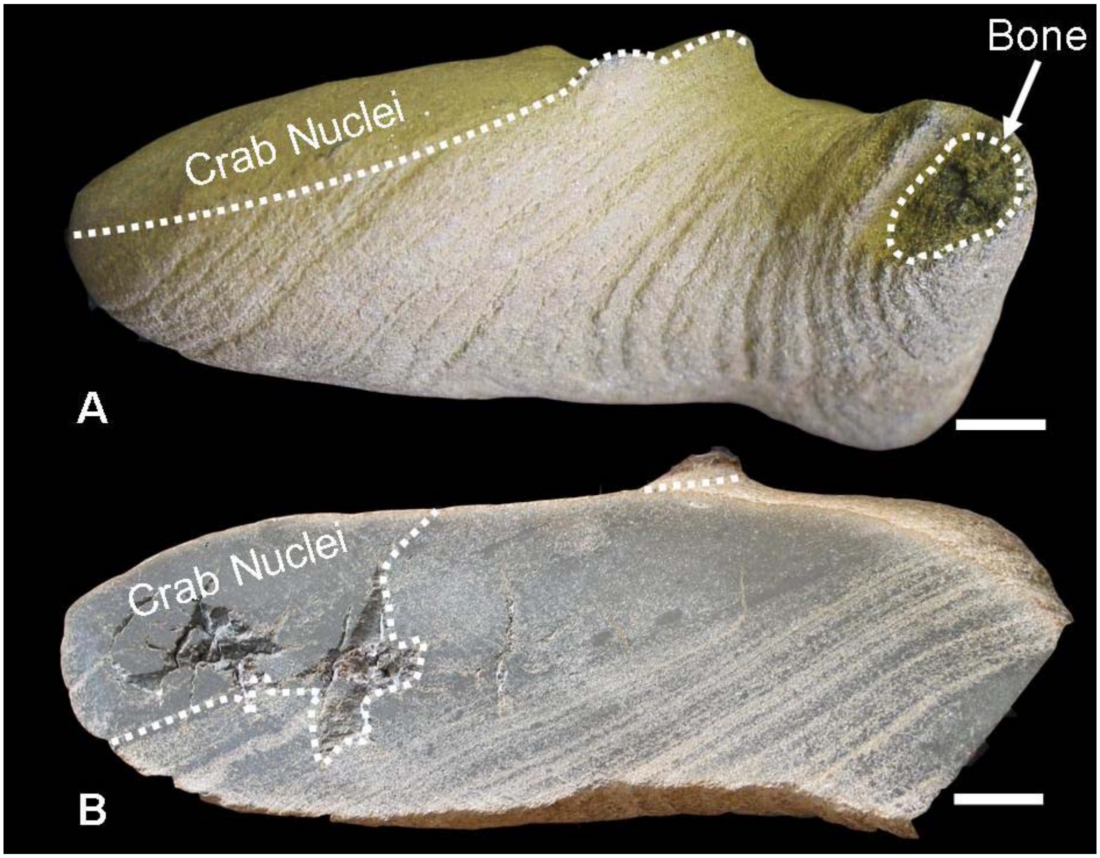

Figure 15 – Type 1 concretion with compound nuclei (bone fragment and crab). All scale bars are ~1cm. (A) External view of concretion. (B) Cross-sectional view of concretion. Mineralized sands between nuclei exhibit well developed cross-stratification.

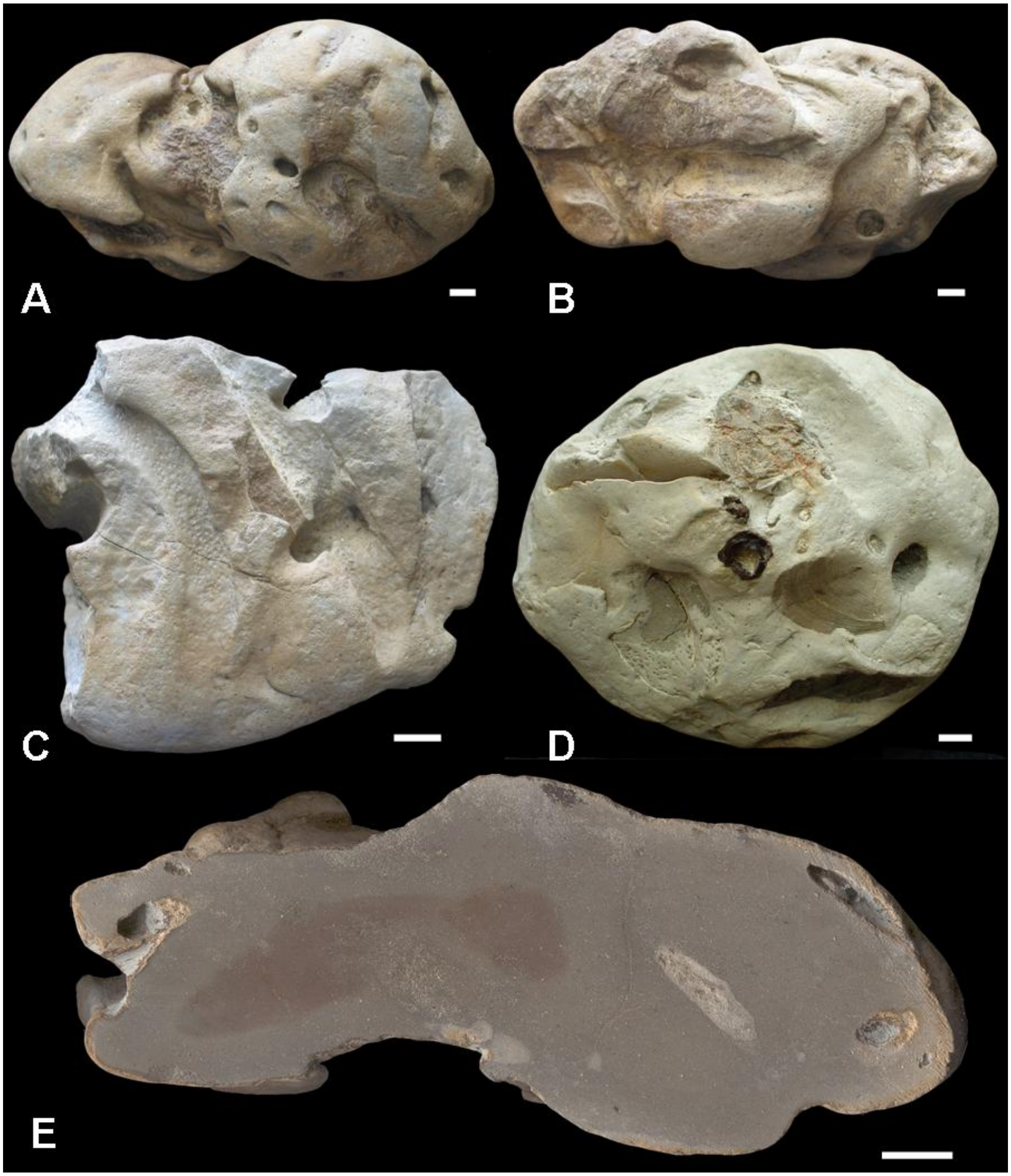

Figure 16 – Examples of type 2 concretions. All scale bars are ~1 cm. (A-D) Variably shaped concretions with external irregularities reflecting burrows and body fossils within mineralized sediments. (E) Interior of slabbed concretion showing crude color zoning and burrow-related color mottling.

grayish orange, 10YR 7/4; light olive gray, 5Y 6/1; and very pale orange, 10YR 8/2) reflects primary compositional and textural differences within the mineralized sediment. Many of the differences related to bioturbation.

Concretion interiors viewed on cut or broken surfaces tend to be darker than exteriors (e.g., light olive gray, 5Y 6/1; medium dark gray, N4; and dark reddish brown, 10YR 4/2). Many exhibit crude concentric color zoning, with darker colors towards the concretion core, and irregular color mottling associated with burrowing (Fig. 16E).

6.3 Type 3 Concretions

Type 3 concretions include vertical, cylindrical to subcylindrical masses (Fig. 17A), some of which exhibit slickensides associated with differential compaction, and horizontal to subhorizontal, elongate, cylindrical or flattened masses (Fig. 17B,C). These concretions typically are pale yellowish brown (10YR 6/2). Type 3 concretions range up to 50 cm in maximum length and up to 15 cm in diameter. Because type 3 concretions are inferred to have nucleated within burrows, they are described in greater depth later in section 7.2.3.

6.4 Concretion Composition and Textures

X-ray diffraction analyses of three representative type 2 concretions confirm that they are phosphatic. The dominant mineral constituent is carbonate fluorapatite. Other mineral components recognized in diffractograms include detrital quartz and early diagenetic pyrite (Fig. 18).

Data from whole-rock ICP analyses of sixteen concretion samples are reported in Table 4. Relative to unmineralized sediment samples, concretions are characterized by considerably lower silica and aluminum contents and higher phosphate and calcium

Figure 17 – Representative samples of type 3 concretions. All scale bars are ~1 cm. (A) Phosphatized cylindrical vertical burrow. (B) Phosphatized large, horizontal burrow. Phosphatization extended beyond burrow walls into adjacent sediments. (C) Relatively large phosphatized burrow flattened parallel to bedding.

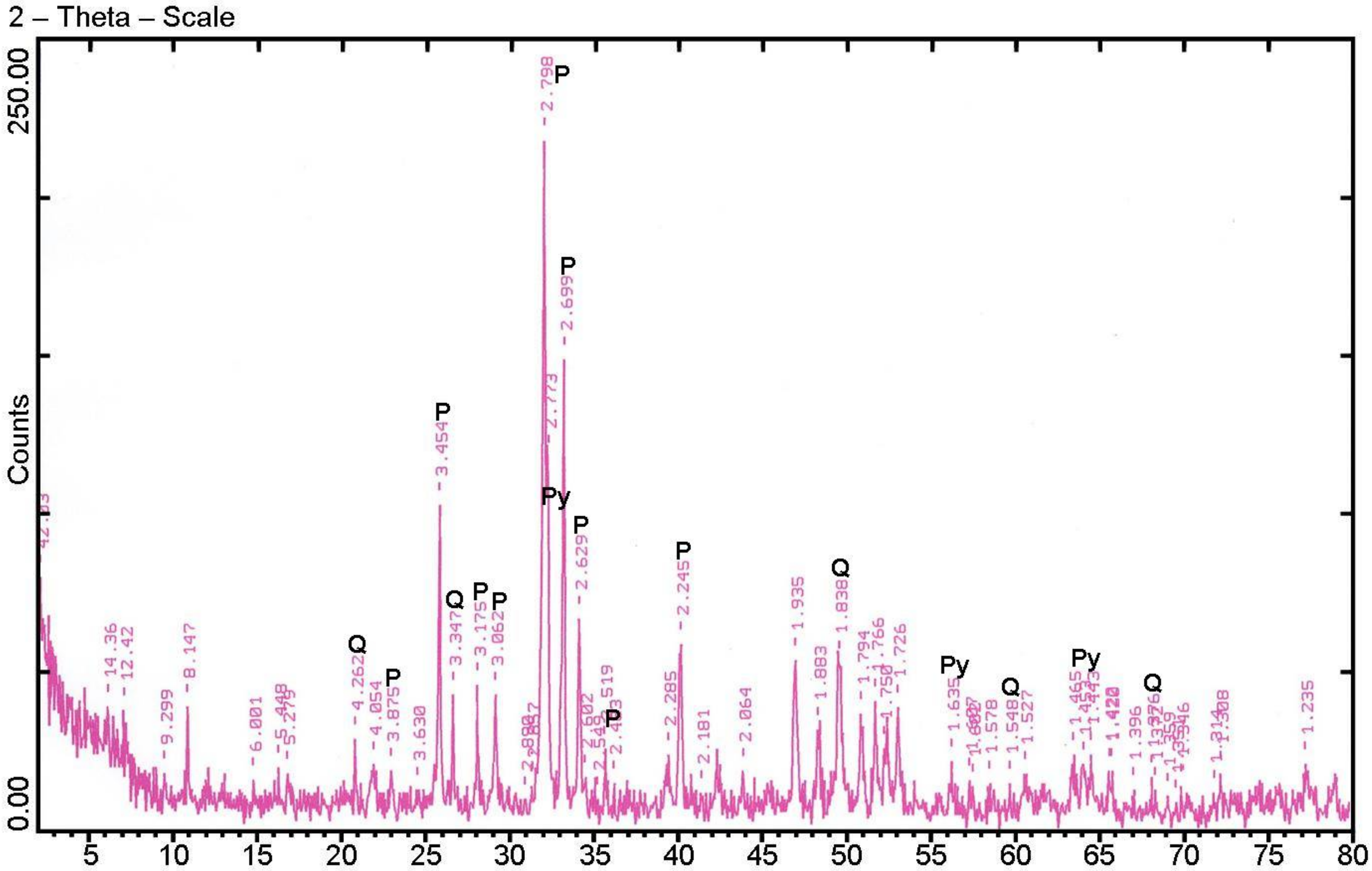

Figure 18 – X-ray diffractogram from analysis of type 2 concretion. P, Q, and Py indicate peaks for carbonate fluorapatite, quartz, and pyrite, respectively.

contents. Elevated calcium contents could be related in part to higher amounts of carbonate in the original sediment. However, most of the calcium likely resides in the carbonate fluorapatite. Other elements, particularly Sr and Na, are more abundant in concretions, indicating that these elements also likely were incorporated into the phosphate. Iron (Fe) concentrations are notably lower in concretions than in unmineralized sediments. This probably reflects the relative scarcity of authigenic sedimentary pyrite in the concretions (see below).

Based on the data available, there appears to be no systematic variation in composition between concretion cores and outer margins. In two concretions for which multiple analyses were made, weight % P_2O_5 decreases slightly from darker core areas to lighter margins (e.g., Fig 19A,B). In a third concretion, P_2O_5 contents in perceived core and margin areas are virtually identical (Fig 19C). In the fourth concretion, P_2O_5 content is actually slightly higher in the marginal rind than in the core (Fig. 19D).

General petrographic observations (Fig. 20) and point-count analyses (Table 3) of thin sections reveal significant compositional differences between concretions and unmineralized sediments. Concretions contain a much larger mud fraction (70-84%), which has been infiltrated by and/or replaced by phosphate, and more skeletal carbonate grains (4-14%), which are typically better preserved and less fragmented than those in unmineralized mud. In contrast, silt- and sand-sized detrital minerals, including quartz (3-11%), micas (1-7%), and feldspars (<1%), and authigenic components (pyrite, 0-1%; glauconite, 0-2%) are less abundant in concretions.

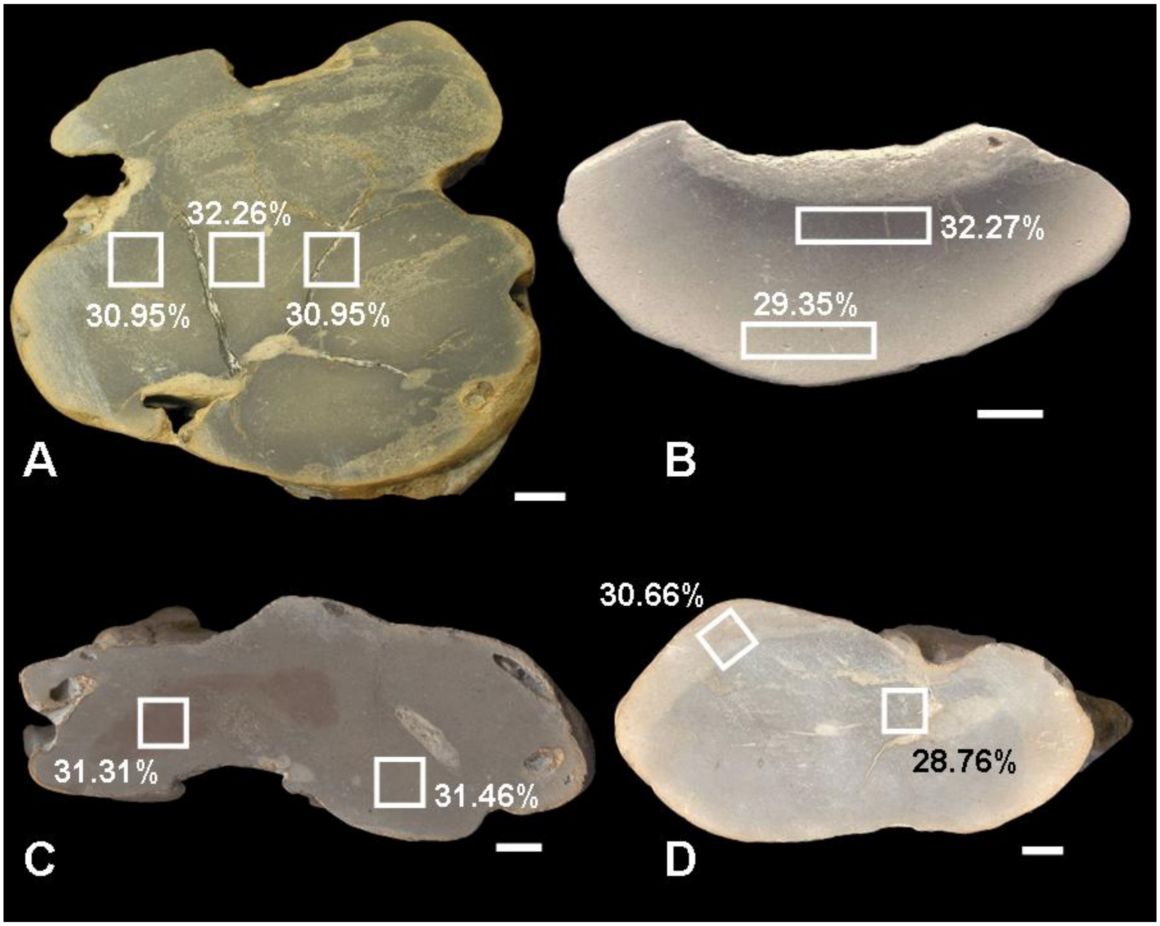

Figure 19 – Variation in phosphate contents within individual concretions. All scale bars are ~1 cm.

Figure 20 – Representative thin-section photomicrograph of Ripley concretion showing fine-grained phosphatized muddy matrix with randomly distributed detrital grains (mainly quartz and muscovite) and skeletal components (e.g., foramnifer; arrow) (plane-polarized light). Scale bar = ~0.25 mm.

6.5 Interpretation

Evidence indicates that phosphate mineralization occurred fairly rapidly during very early diagenesis at very shallow depths below the sea floor. The generally high degree of skeletal articulation of common crabs and rare vertebrate remains indicates that concretion growth began prior to significant biochemical degradation and physical/biological reworking. Similarly, the undistorted condition of most body fossils (e.g., crabs, ammonites) indicates that concretion growth preceded significant sediment compaction. Mineralization prior to compaction is also reflected in the relative abundances of silt- and sand-sized detrital grains in unmineralized sediment versus concretions. Higher relative abundances in unmineralized sediment is likely a product of compaction of the fine-grained matrix therein. Also, the lack of significant compositional variations between concretion cores and margins further suggests that concretion growth was virtually complete prior to compaction. If concretion growth occurred slowly and was in part contemporaneous with burial and compaction, phosphate contents would likely decrease outward from concretion interiors.

Growth of carbonate fluorapatite in Ripley sediments requires that pore waters were at least periodically supersaturated with respect to phosphate (Balson, 1980; Benmore et al., 1983). Dissolved phosphate could have been imported via the upwelling of nutrient-rich waters. However, previous studies (e.g., Brett and Baird, 1986; Allison, 1988a,b) indicate that the phosphate found in early diagenetic nodules and concretions is more likely derived in place from the decay of abundant organic matter (the accumulation of which may or may not be linked to upwelling). Numerous authors (Benmore et al., 1983; Coleman, 1985; Briggs and Wilby, 1996; Briggs 2003) also emphasize the importance of lower pH levels, which can result from the decay of organic matter, as a major contributing factor in the preferential precipitation of phosphate.

In addition to abundant organic matter, substantial early diagenetic phosphatization in substrates also requires particular pore-water redox conditions and slow sediment-accumulation rates. Phosphatization is apparently limited to substrate horizons that are at or near the oxic/anoxic boundary (Baturin, 1970; Baird, 1978; Balson, 1980; Krajewski, 1984; Brett and Baird, 1986; Allison, 1988a,b,c). Oxidation of organic matter produces phosphate ions that under oxic conditions initially accumulate via absorption on ferric hydroxides. At the oxic-anoxic transition, ferric hydroxide reduction liberates phosphate to pore waters, while sulfur oxidation lowers pore-water pH, favoring precipitation of phospate gels or soaps (Baturin, 1970; Coleman, 1985; Allison, 1988a). Relatively slow sedimentation rates favor sustained phosphatization by increasing the residence time of sediments at the oxic/anoxic transition (Coleman, 1985; Brett and Baird, 1986; Allison, 1988b,c).

Although the nuclei of type 2 concretions in the Ripley Formation are enigmatic, concretion types 1 and 3 clearly reflect preferential nucleation sites. This is not unusual. Phosphate precipitation occurs most readily on original phosphatic substrates (e.g., bone, teeth, crustacean carapaces) and in other semi-enclosed microenvironments that are more organic rich and porous (e.g., infills of shells and burrows, fecal pellets, etc.) than surrounding sediments (Krajewski, 1984).

The apparent restriction of phosphate concretions to particular horizons in the Ripley Formation may be related to differences in the distribution of favorable nuclei for phosphatization. Alternatively, this may reflect temporal changes in environmental regime. Phosphate mineralization may have occurred only periodically in association with brief periods of hypoxia (when the oxic-anoxic transition was positioned at high levels in the substrate) and/or during phases of reduced sediment influx.

7.0 ICHNOLOGY

7.1 Unmineralized Sediments

As previously noted, Ripley Formation sediments exposed at Dry Cedar Creek typically are extensively bioturbated. However, distinct ichnofossils are poorly represented due in part to weathering and limited compositional/textural contrast between burrow fills and host sediments. The only moderately well-preserved ichnofossil readily (albeit rarely) observed in outcrop is *Diopatrichnus*.

Bioturbation features are better manifested on freshly slabbed surfaces of sediment samples and in thin sections thereof. These surfaces often display mottling of clay-dominated sediments and coarser silt- and sand-sized detrital material. The latter is commonly concentrated in what appear to be burrow fills (Figs. 21A,B). However, distinct biogenic structures are relatively rare. The only distinct structures observed on slab surfaces are *Chondrites* and larger unidentified horizontal to subhorizontal burrows.

7.1.1 *Diopatrichnus*

Diopatrichnus are vertical to subvertical, more or less cylindrical shell-lined burrows (Kern, 1978). Those in the Ripley Formation (see Fig. 10E) are relatively large, ranging up to 12 cm in length and 6 cm in diameter. Their visibility in outcrop is enhanced by differential erosion and weathering of their relatively thick shell linings, which are composed predominantly of mollusk (mainly pelecypod) fragments.

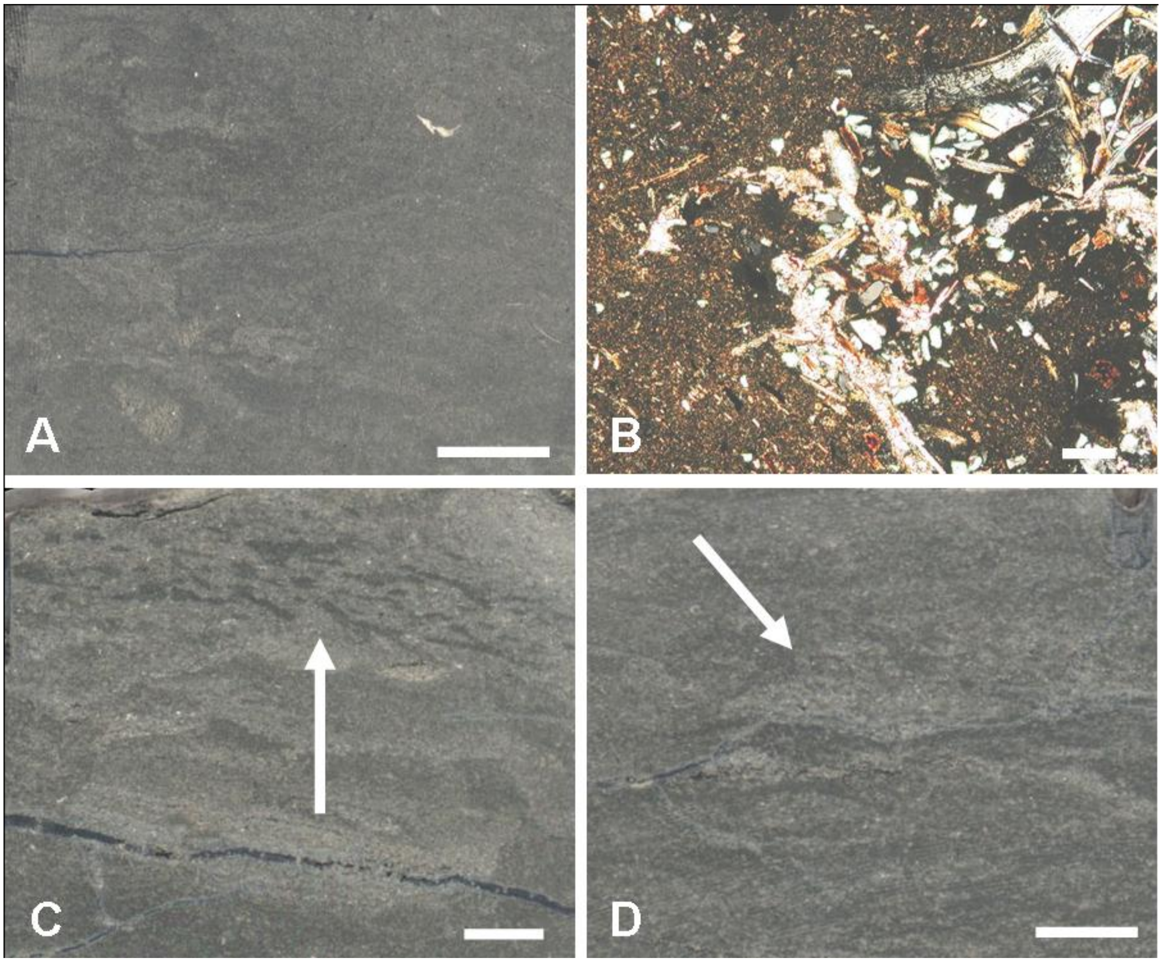

Figure 21 – Representative views of biogenic fabrics as viewed on vertical slab surfaces and in thin sections of unmineralized sediment. (A) Slab surface showing diffuse burrow-related mottling. (B) Thin-section photomicrograph (cross-polarized light) of burrow (right side). Detrital grains and skeletal fragments are concentrated in burrow fill. (C) Cross-sectional view of *Chondrites* (arrow). (D) Unidentified horizontal burrow expressed as a lenticular mass (arrow). Scale bars in A, C, and D are ~5 mm long. Scale bar in B is ~0.25 mm long.

Diopatrichnus generally is interpreted as a dwelling structure (dominichnion) produced by suspension-feeding marine annelids (Kern, 1978; de Gibert, 1996).

7.1.2 *Chondrites*

Chondrites are regularly branched networks of relatively small (less than a few mm), smooth-walled burrows of constant diameter (Howard and Frey, 1984). On Ripley slab surfaces, *Chondrites* appear as clusters of small circles (~1 mm in diameter) and ellipsoids (~1x5 mm) (Fig. 21C). These burrow systems are most obvious where passively emplaced burrow fills contrast with host sediment. Typically, burrows are filled with medium- to dark-gray, fine-grained clays that contrast with light-gray, siltier sediments into which they were emplaced . *Chondrites* is traditionally interpreted as a deposit-feeding structure (fodinichnion) constructed by vermiform animals of unknown affinity (Bromley and Ekdale, 1984).

7.1.3 Horizontal to Subhorizontal Burrows

Structures referred to here as horizontal to subhorizontal burrows appear on slab surfaces as lenticular masses (Fig. 21D) oriented parallel or subparallel to bedding. Long and short axes of lenses range up to 3 cm and 0.5 cm, respectively. The lenticular expression of these burrows mainly reflects the oblique intersection between burrow axes and slab surfaces. However, these burrows commonly exhibit ovate cross sections that likely result from sediment compaction. Burrows have sharp to diffuse, unlined walls and contain apparently structureless fills that are typically slightly coarser than host sediments. These structures could represent relatively simple forms (e.g., *Planolites*) or parts of more complex branching burrow systems (e.g., *Thalassinoides*). However, lack of three-dimensional views precludes an ichnotaxonomic assignment for these structures.

7.2 Type 1 Concretions

A variety of ichnofossils are preserved on or within type 1 concretions. Some of these traces were emplaced within sediments that filled fossil cavities and are preserved on steinkern exteriors. However, the majority of trace fossils were preserved as mineralization fronts extended beyond the margins of fossil nuclei and differentially invaded bioturbated host sediments (mummy concretions). Trace fossils recognized on or within type 1 concretions include *Chondrites*, *Thalassinoides*, *Ophiomorpha*(?), unidentified vertical to subvertical burrows, and apparent biogenic "skid marks." Although most ichnofossils were emplaced prior to phosphatization, the latter structures appear to reflect responses to incipient cementation within the benthic boundary layer.

7.2.1 *Chondrites*

Branched networks of relatively small burrows assigned to *Chondrites* are expressed in positive and negative relief on exteriors of several of the collected ammonite steinkerns. They appear as radiating, regularly branched, straight to slightly curved, horizontal to vertical, narrow (~1 mm), cylindrical burrow segments (Fig. 22). The lengths of individual burrow segments range up to 2 cm. Axes of burrows generally conform to the curved surfaces of the host steinkern. *Chondrites* are locally common in steinkern interiors. As in unmineralized sediments, *Chondrites* appear on steinkern slab surfaces as isolated, small (diameter ~1 mm) circles and ellipsoids or tight clusters thereof. Burrow fills typically are composed of medium- to light-gray clay that contrasts with the darker gray phosphatic matrix of the host concretions. The morphology and distribution of these *Chondrites* indicate that they were emplaced prior to ammonite shell destruction and mineralization of the sediment infill.

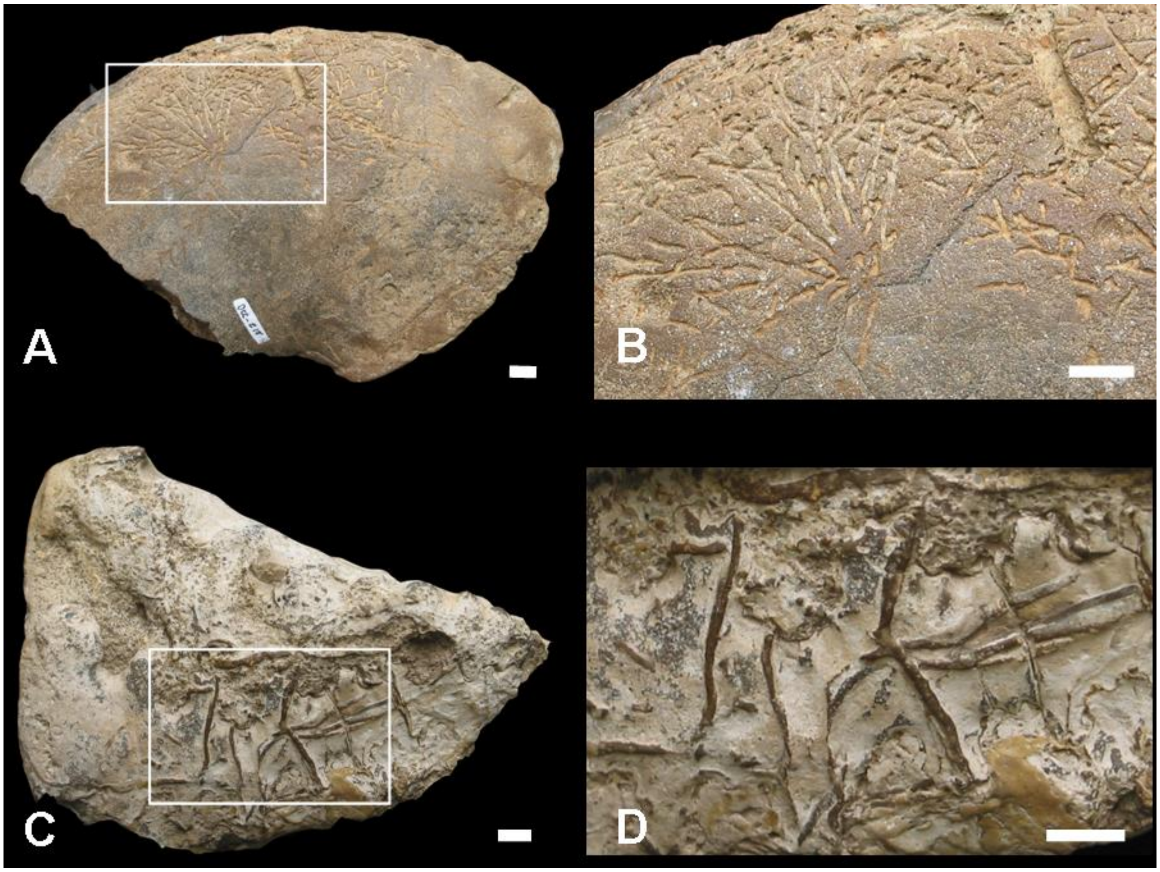

Figure 22 – *Chondrites* preserved in relief on ammonite steinkerns. All scale bars are ~5 mm; white outlines indicate areas of magnification. (A,B) Regular and magnified view of ammonite steinkern with abundant, radiating *Chondrites* preserved in negative relief. (C,D) Regular and magnified view of ammonite steinkern with *Chondrites*(?) preserved in positive relief.

7.2.2 *Thalassinoides*

Thalassinoides are relatively large branching networks of straight to sinuous, smooth-walled burrows (Ehrenberg, 1944). Distinct biogenic structures tentatively assigned to *Thalassinoides* are preserved in negative or positive relief on exteriors of steinkerns (Fig. 23) and crab-bearing mummy concretions (Fig. 24A,B). They appear as horizontal to subhorizontal, branched, cylindrical to subcylindrical burrows (Figs. 23 and 24A,B) with Y-shaped branch junctures. Burrow diameters, which range from 0.5 to 2.0 cm, are relatively constant within individual burrow systems, although branch junctures may be enlarged. Where observed, burrow walls appear to be smooth and unornamented. *Thalassinoides* is normally regarded as a dwelling and/or deposit-feeding structure produced by decapod crustaceans.

7.2.3 *Ophiomorpha*(?)

Ophiomorpha, normally attributed to decapod crustaceans, are simple to complex branching burrow systems with discoidal, ovate, mastoid, bilobate, or irregular peloidal linings (Frey et al., 1978). Structures tentatively assigned to *Ophiomorpha* are locally preserved on exteriors of some type 1 concretions. These appear as relatively large (~1 cm diameter), lined burrow segments that obliquely intersect surfaces of crab-bearing mummy concretions (Fig. 24C,D). Linings are thin (~1.5 to 2 mm) and exhibit smooth interior walls and mammalate exteriors. Where well defined, peloids in linings average ~1 mm in maximum dimension. Evidence for branching is absent in the limited views provided on concretion exteriors and slab surfaces.

Parts of an *Ophiomorpha*-like structure are preserved in negative relief on the exterior of one ammonite steinkern (Fig. 23). In this sample, pelleted linings are

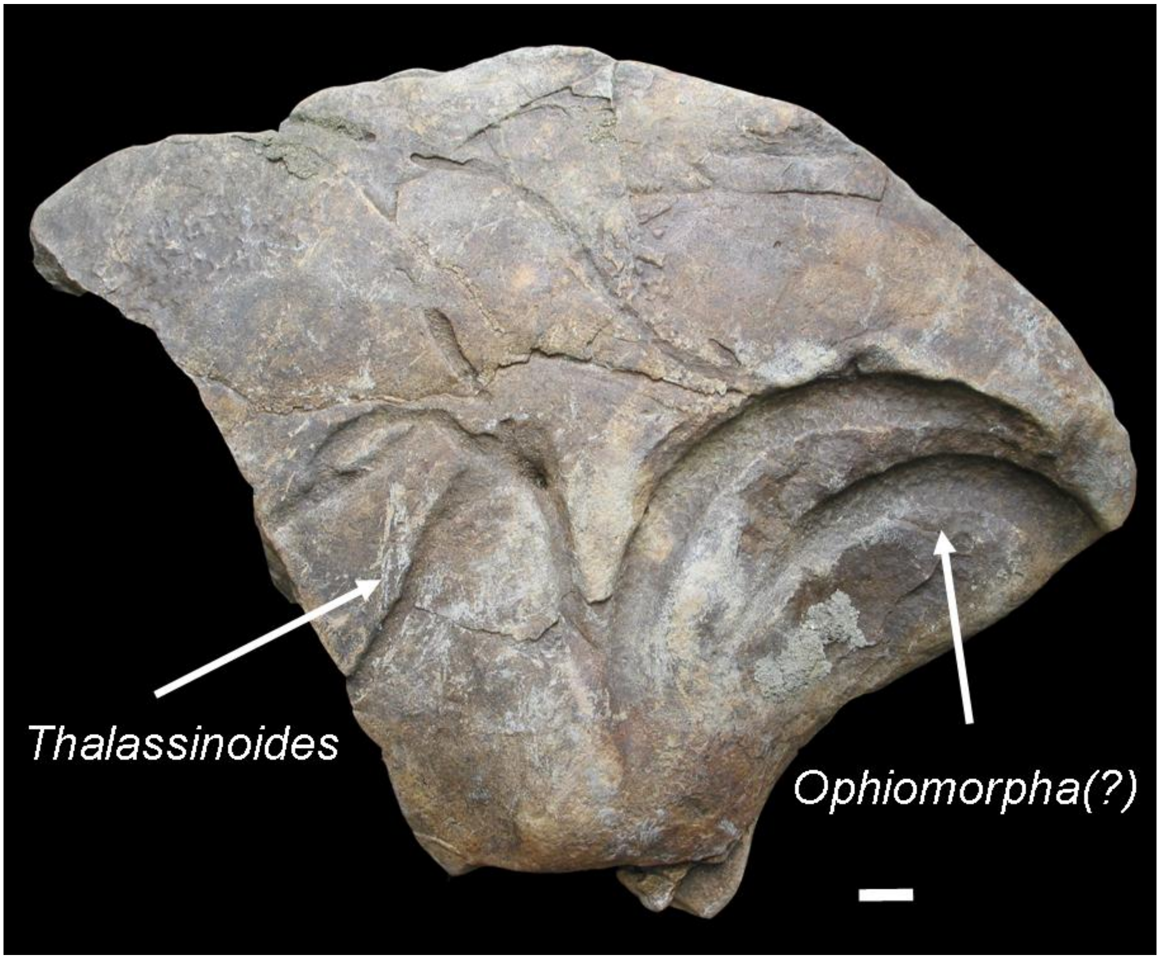

Figure 23 – Ammonite steinkern with branched burrow segments (*Thalassinoides*) and peloid-lined, curved burrow segments (*Ophiomorpha?*) expressed in negative relief. Scale bar is ~1 cm.

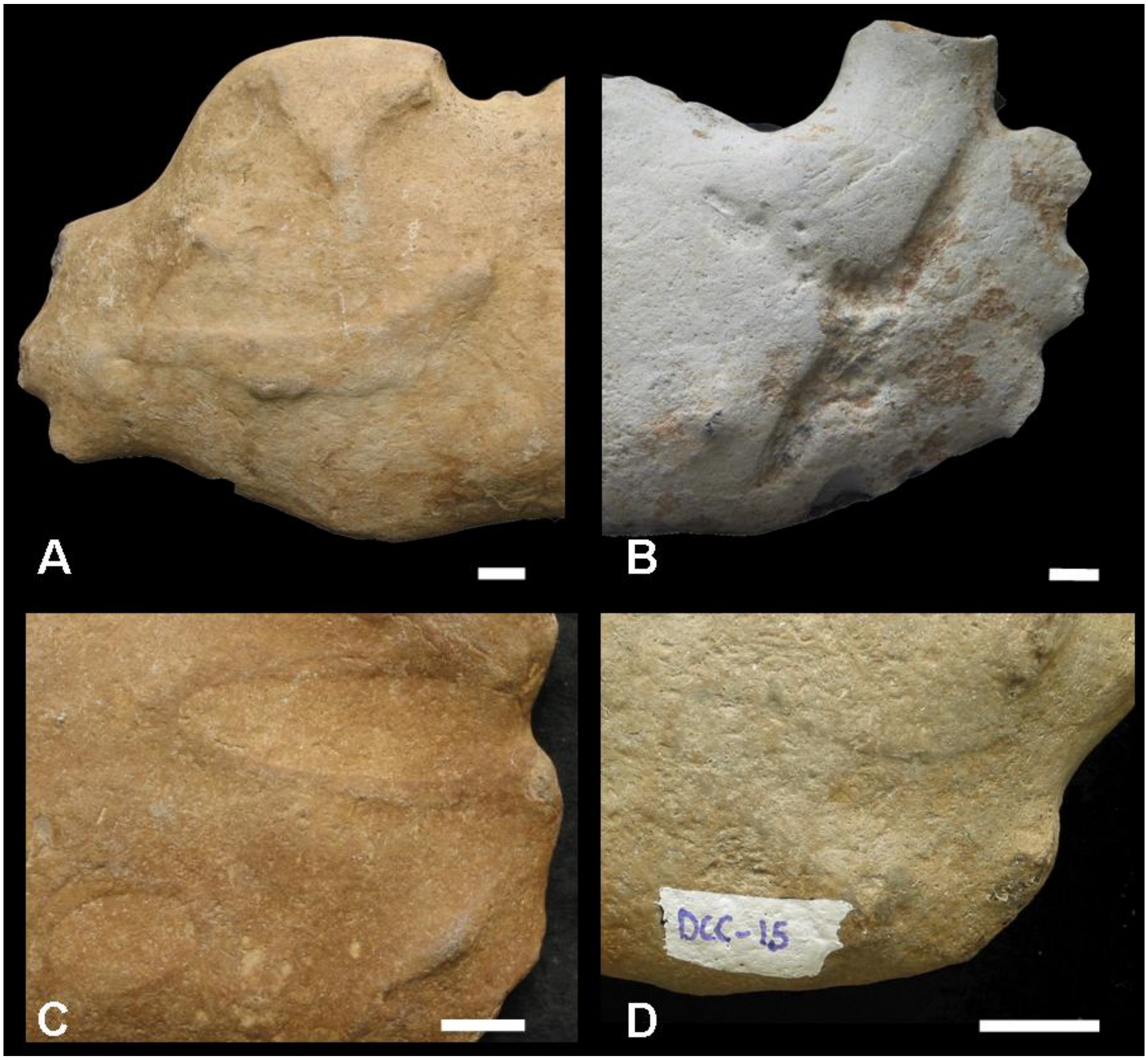

Figure 24 – Representative photographs of ichnofossil-bearing concretions. All scale bars are ~1 cm. (A,B) *Thalassinoides* expressed on exterior of concretions in positive and negative relief, respectfully. (C,D) Pellet-lined burrow segments assigned to *Ophiomorpha*.

expressed as external molds of small (~1 mm), mastoid peloids. These *Ophiomorpha*-like structures are manifest as a nested pair of strongly curved burrow segments. Burrow diameters are ~1 cm, and remain constant through both segments. There is no indication of branching or interpenetration between the segments. Rather, segments are positioned on slightly different horizontal planes, suggesting that these features are part of a helicoidal burrow. Overall morphology of this structure may reflect stenomorphism associated with burrow emplacement within the confining space of the ammonite shell interior.

7.2.4 Unidentified Vertical to Subvertical Burrows

Structures presumed to be vertical to subvertical burrow segments are common on exteriors of crab-bearing concretions. These appear as small (up to 1 cm), circular to irregularly ovate, low-relief protrusions (Fig. 25), a few of which are distinctly cylindrical. Three-dimensional geometry of these structures is unclear, precluding even tentative ichnotaxonomic assignment. However, some of these structures may represent vertical segments of *Thalassinoides* burrow systems.

7.2.5 “Skid Mark” Structures

Biogenic features referred to informally as “skid mark” structures (Fig. 26) are exceedingly rare; they have been observed only on one or two crab-bearing mummy concretions. Nonetheless, they are noteworthy in that they may reflect burrowing by a trace maker contemporaneous with concretion growth. These structures appear as narrow (~1 cm), elongate (~3 cm) furrows bordered by narrow (2-3 mm) lateral mounds and, at one end, an irregular terminal pile. The character of this structure suggests that the trace maker diverted its path when it encountered mineralized sediment. The lateral mounds

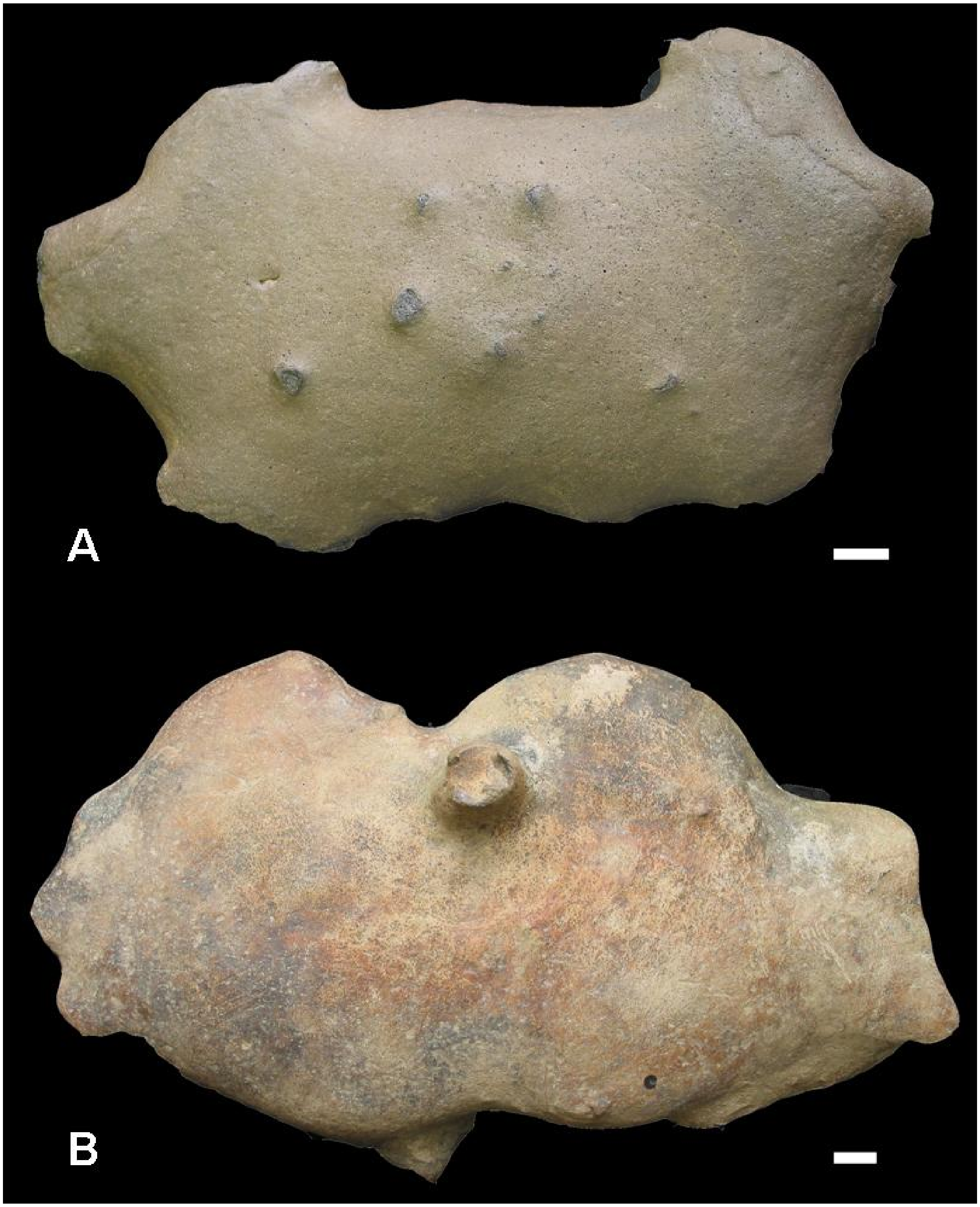

Figure 25 – Crab-bearing type 1 concretions with protrusions on exteriors. All scale bars are ~ 1 cm. (A) Small, rounded and flattened bulges. (B) Relatively large, cylindrical protrusion.

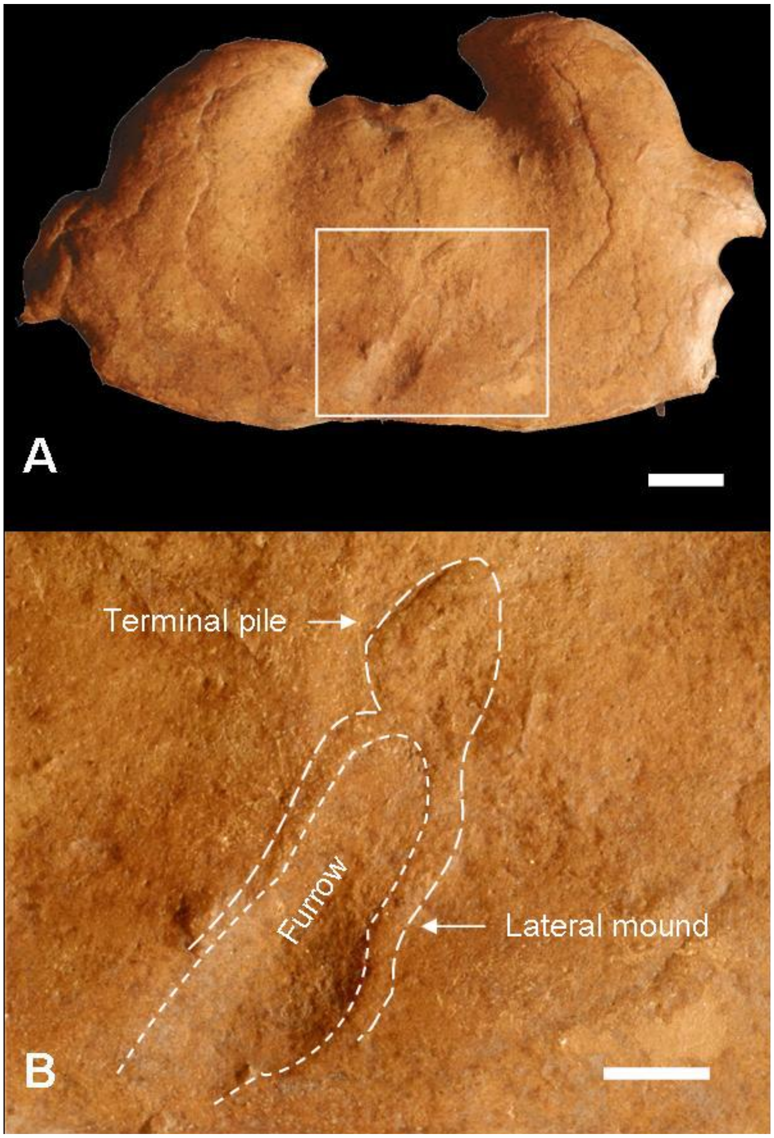

Figure 26 – (A) Normal and (B) magnified view of “skid mark” structure on exterior of type 1 concretion. All scale bars are ~1 cm.

and terminal pile may reflect the displacement of incipiently phosphate-cemented sediment on the upper surface of the growing concretion.

7.3 Type 2 Concretions

Ichnofossils are particularly well expressed on the exteriors of type 2 concretions. Burrows or particular components of burrows (e.g., linings, backfill, etc.) commonly are preserved in relief. This reflects differential migration of mineralization fronts associated with textural or compositional heterogeneities among ichnofossils and host sediments. Owing to the limited size of type 2 concretions, most biogenic structures preserved on their exteriors represent only parts of larger burrow systems. Structures observed include *Thalassinoides* and *Thalassinoides*-like structures, *Ophiomorpha*, *Chondrites*, unidentified backfilled burrows, and spreiten(?).

7.3.1 *Thalassinoides* and *Thalassinoides*-like Structures

Thalassinoides and *Thalassinoides*-like structures are commonly preserved in negative relief on concretion exteriors. *Thalassinoides* (Fig 27A,B) appear as branched networks of narrow (1-2 cm), horizontal to vertical, straight to gently curved, unlined, smooth-walled burrows. Branch junctures, at which burrow diameters are commonly slightly enlarged, are Y- or T-shaped.

Thalassinoides-like structures (Fig. 27C,D) refer to burrows with relatively larger diameters (2-4 cm). The walls of these structures are generally more poorly defined due to irregular mineralization. Moreover, owing to the large size of these burrows relative to host concretions, branching is either not observed or only weakly expressed. Hence, assignment of these structures to *Thalassinoides* is tenuous.

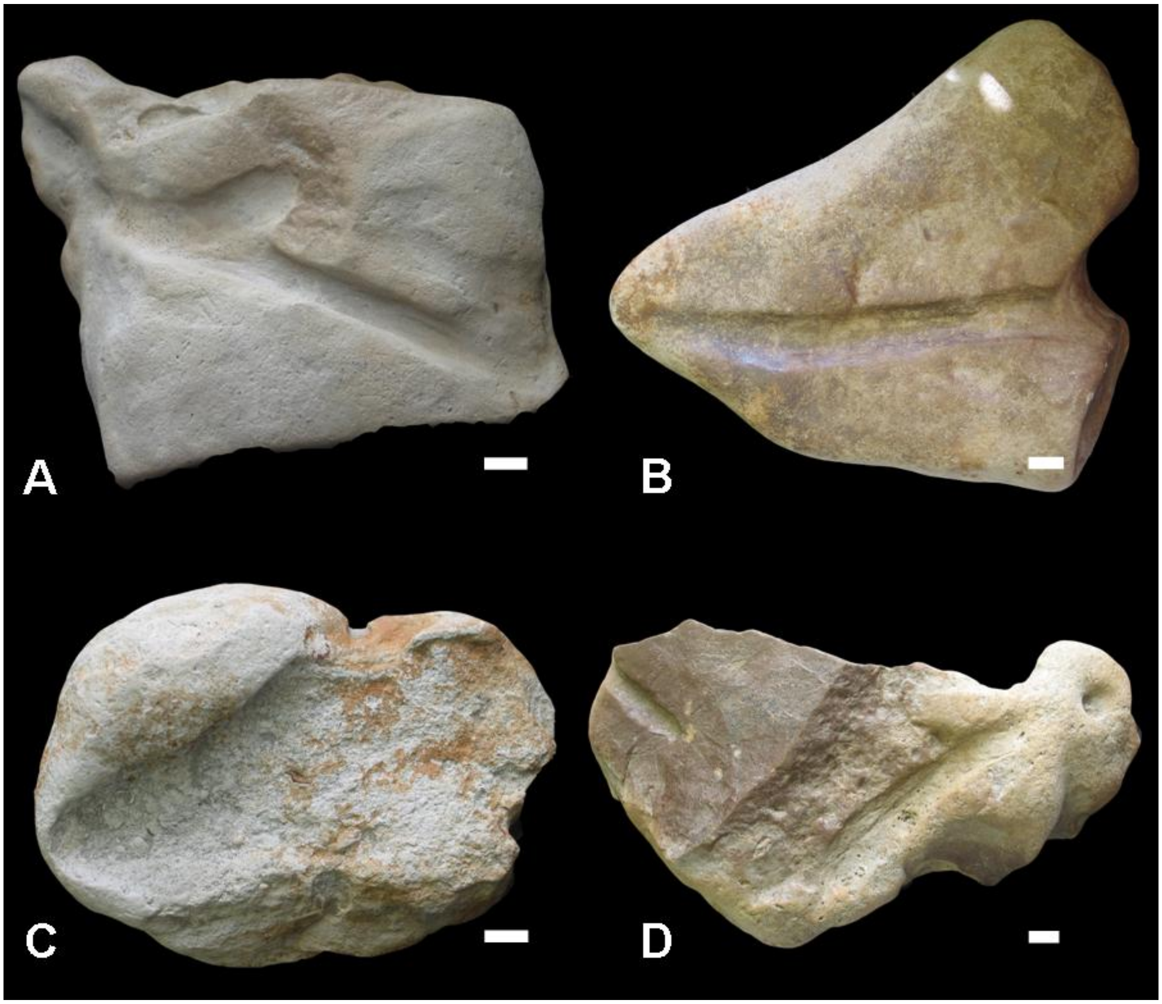

Figure 27 – *Thalassinoides* (A,B) and *Thalassinoides*-like burrow segments (C,D) expressed on exteriors of type 2 concretions. All scale bars are ~1 cm.

7.3.2 *Ophiomorpha*

Two morphotypes of *Ophiomorpha* are observed on type 2 concretion exteriors. Morphotype 1, the most common form, is manifest as vertical to horizontal, straight to slightly curved, peloid-lined burrow segments (Fig. 28). Branching, when observable, generally occurs at acute angles. Burrow diameters range from 1 to 2 cm and appear to remain constant throughout individual burrow systems. Burrow linings are composed of regularly distributed, small (~1 mm), ovoid and/or discoid peloids that are most commonly expressed as external molds. In some examples, long axes of peloids clearly are aligned perpendicular to the burrow axis (Fig. 28C,D), which is generally diagnostic of the ichnospecies *O. annulata*.

Structures referred to as *Ophiomorpha* morphotype 2 appear as horizontal to subhorizontal, strongly curved to meandering, peloid-lined burrows (Fig. 29A,B,C) reminiscent of the helicoidal(?) *Ophiomorpha*(?) observed on the ammonite steinkern described above (section 7.2.3). Branching has not been observed in this morphotype. Burrows are relatively uniform in diameter (1 to 2 cm) and are regularly to irregularly lined with small (~1 mm), ovoid and/or mastoid peloids. As in the linings for morphotype 1 burrows, peloids are most commonly preserved as external molds (Fig. 29C,D).

7.3.3 *Chondrites*

Chondrites burrow networks are similar to those seen in type 1 concretions. On type 2 concretion exteriors, they typically are expressed in negative relief as small (~1 mm) circles and ellipsoids. Characteristic branching is clearly expressed only on broken and slab surfaces (Fig. 30A).

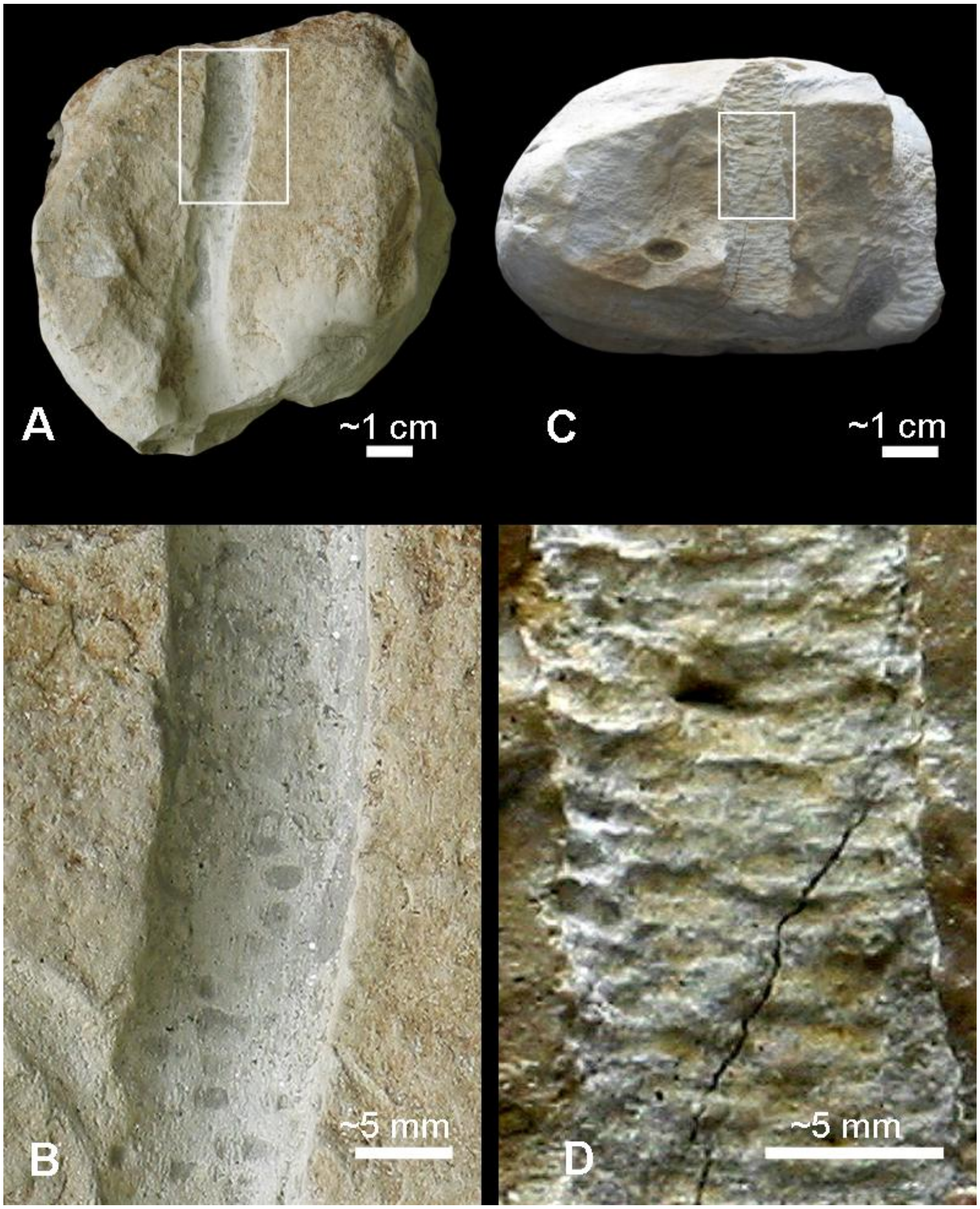

Figure 28 – Straight to slightly curved *Ophiomorpha* morphotype 1 preserved on exteriors of type 2 concretions. (A,B) Normal and magnified views of slightly curved, horizontal burrow segment with distinct cross-sectional views of ovoid peloids in wall lining. (C,D) Normal and magnified views of straight, vertical burrow segment with distinct external molds of elongate peloids oriented normal to the burrow axis.

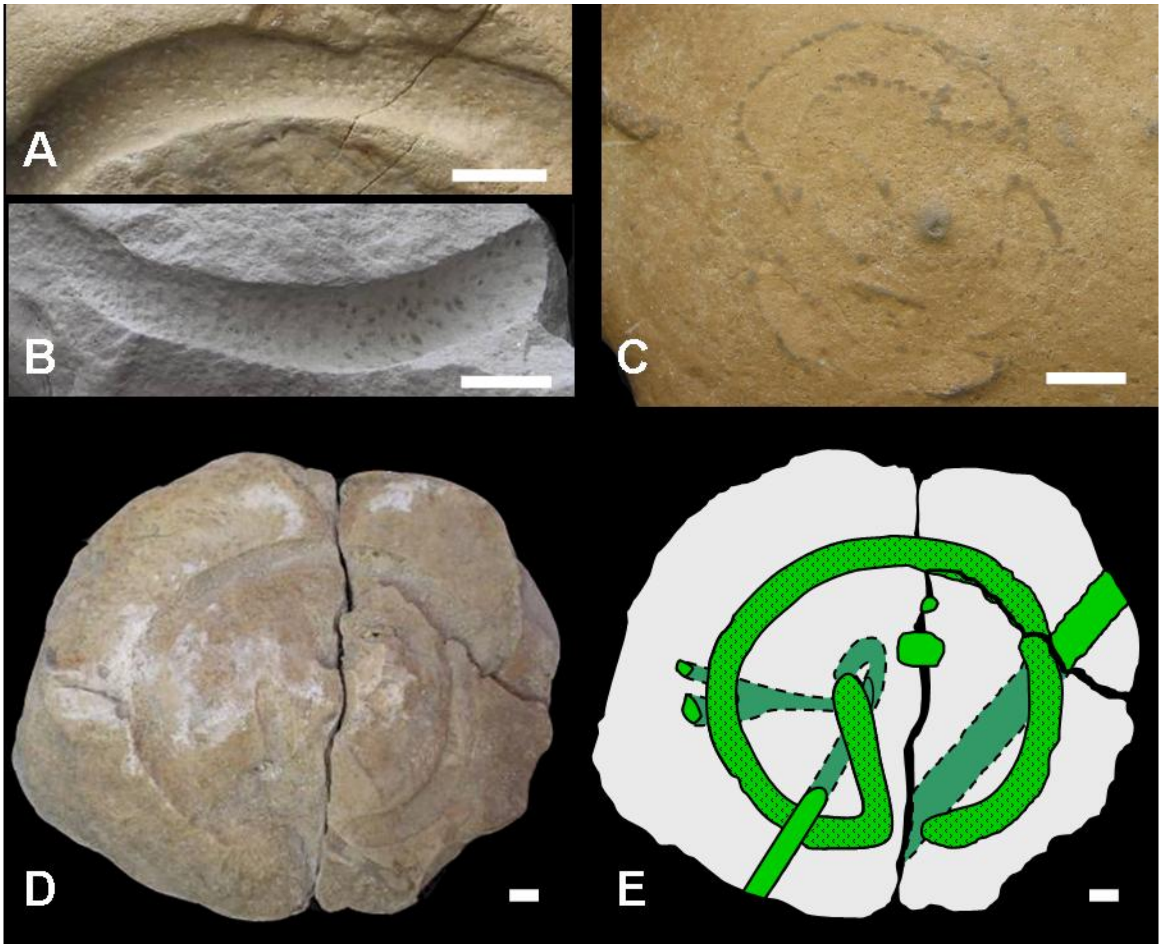

Figure 29 – *Ophiomorpha* morphotype 2 on type 2 concretion exteriors. All scale bars are ~1 cm. (A,B) Curved segments with mastoid to ovoid peloids expressed mainly as external molds. (C) Sinuous pellet-lined trace. (D) Semicircular *Ophiomorpha* preserved in negative relief with external molds of mastoid peloids. (E) Schematic showing *Ophiomorpha* in D (solid lines; stippled, light green), as well as *Thalassinoides*(?) observed in concretion interiors (dashed lines; dark green).

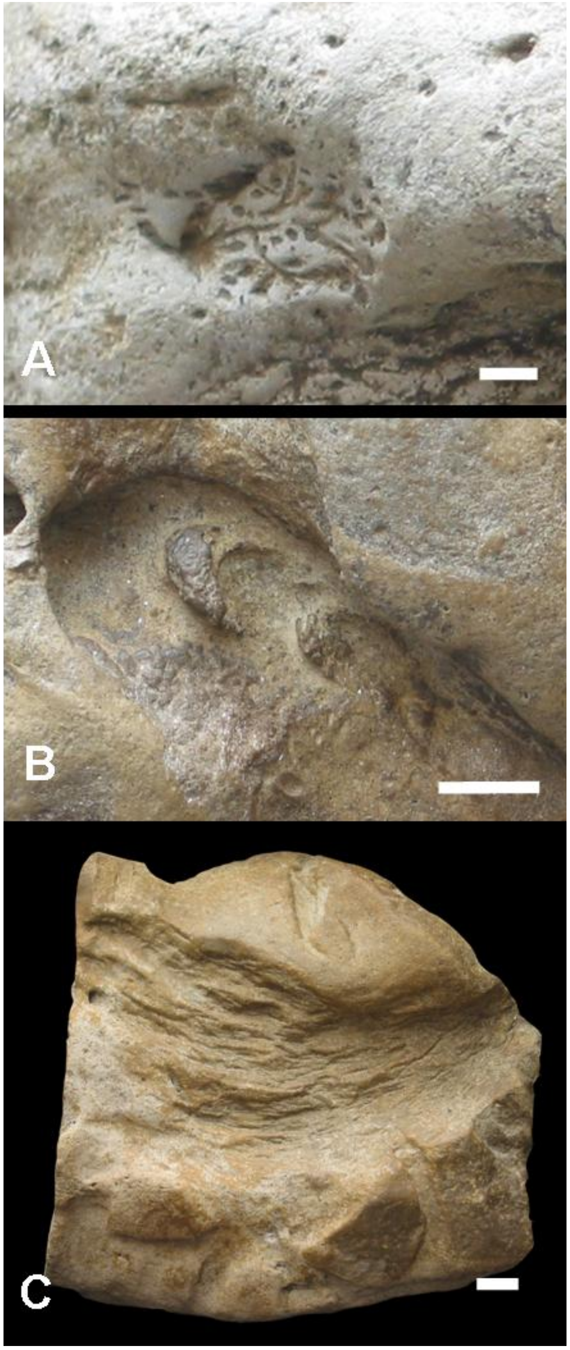

Figure 30 – *Chondrites*, back-filled burrows, and spreite(?) preserved on or in type 2 concretions. (A) *Chondrites* in concretion interior. (B) Unidentified meniscate back-filled burrow. (C) Spreiten-like structure (*Zoophycos*?). Scale bars are ~1 cm.

7.3.4 Unidentified Back-filled Burrows

Unidentified back-filled burrows are rarely preserved on concretion exteriors. These appear as relatively large (~2 cm diameter), subhorizontal, straight, cylindrical to subcylindrical, apparently unbranched structures containing meniscate backfill (Fig. 30B). Individual backfill packets range from 0.2 to 1.0 cm in thickness. Overall, these structures are preserved in negative relief. However, some backfill packets were preferentially mineralized; hence they project in positive relief.

Without adequate three-dimensional views of these structures, confident ichnotaxonomic assignment cannot be made. However, the nature of the backfill suggests that these structures were produced by a deposit-feeding organism.

7.3.5 Spreiten(?) Structures

Structures potentially representing spreiten are exceedingly rare. These are manifest in negative relief on concretion exteriors as horizontal to subhorizontal, lobe-shaped packages of gently curved laminae (Fig. 30C). Lobe widths taper from a maximum of 6.5 cm to 1.5 cm. These structures could represent portions of the fodinichnion *Zoophycos*. However, given the limited views available, identification is tenuous.

7.4 Type 3 Concretions

Type 3 concretions represent those that nucleated in or around relatively large burrows. In some cases, mineralization was confined to burrow fills, while in others, phosphatization extended well beyond burrow walls into host sediments (mummy concretions). Mineralized burrows include horizontal to subhorizontal and vertical forms.

7.4.1 Horizontal to Subhorizontal Forms

Horizontal to subhorizontal forms include large, straight to weakly curved, apparently unbranched burrows with ovate cross-sections (Fig. 31). Concretion lengths, reflecting minimum burrow lengths, range up to 55 cm. Burrow widths typically are on the order of 8 to 10 cm but range up to 15 cm. Burrow fills typically include phosphatized mud. However, most of these large burrows are at least partially filled with phosphatized molluscan shell hash admixed with silt- and sand-sized detrital grains and rare clasts of host sediment (Fig. 31B,C). Although mineralization was largely restricted to burrow fills, phosphatization locally extended a few millimeters beyond the original burrow walls. These larger structures likely represent the burrows of decapod crustaceans, possibly crabs.

Other horizontal to subhorizontal forms include smaller diameter burrows that are more heavily encased in phosphate (mummy concretions). These burrows, which exhibit ovate cross sections, range from 3 to 5 cm in width. Phosphatization extended up to 2 cm beyond burrow walls into the host sediment. Branching is not directly observed. However, localized widening near the ends of some concretions suggests mineralization of branch junctures (Fig. 32). If truly branched, these forms could be assigned to *Thalassinoides*. *Chondrites* (Fig. 32) and other, unidentified biogenic structures locally are observed within the fills of these burrows and in the mineralized sediments that surround them.

7.4.2 Vertical Forms

Phosphatized vertical burrows are relatively rare. Those that were collected for this study generally appear as unbranched cylindrical shafts ranging from 1 to 2 cm in

Figure 31 – Representative type 3 concretions. All scale bars are ~1 cm. (A) Large phosphatized burrow (plan view). (B) Cross-sectional view of large burrow showing phosphatized shell-hash infill. (C) Close-up of well-defined external molds and casts of phosphatized shell-hash in burrow fills.

Figure 32 – Horizontal to subhorizontal, bulbous mummy concretion that nucleated on relatively large burrow. Enlarged portions of concretion suggest branching. Mineralized host sediments contain *Chondrites* (arrows). Scale bar is ~1 cm

diameter and 3 to 6 cm in length (Fig. 33). All of these burrows occur in mummy concretions wherein mineralization extended 0.5 to 2 cm beyond the burrow walls. Concretion exteriors typically exhibit well-developed longitudinal slickensides reflecting early mineralization and differential compaction (Fig. 33C).

One of these burrows is characterized by what appears to be a poorly preserved phosphatized shell lining and by a concave-up, meniscate fill that is manifested in transverse view as concentric laminae (Fig. 33B). This structure may reflect the preferential phosphatization of *Diopatrichnus* similar to that observed in unmineralized sediment (see section 7.1.1).

Others of the mineralized vertical burrows are characterized by homogeneous to irregularly mottled fills. Although these structures may represent a separate unidentified ichnotaxon, they could represent preferentially mineralized vertical shafts of larger, more complex burrow systems such *Thalassinoides*.

7.5 Interpretation

The trace fossil assemblage recognized in unmineralized sediments and concretions of Ripley Formation at Dry Cedar Creek is of low to moderate diversity. Identified ichnofossils represent a variety of behavioral and trophic classes. *Chondrites* and *Thalassinoides* represent dwelling/feeding structures (fodinichnia) produced by deposit-feeding worms and crustaceans, respectively. Unidentified backfilled burrows and spreiten(?) also likely are pascichnia or fodinichnia produced by vagile or sessile deposit-feeding organisms. In contrast, *Diopatrichnus* and *Ophiomorpha* normally are interpreted as dwelling structures (dominichnia) produced by suspension-feeding worms and crustaceans, respectively.

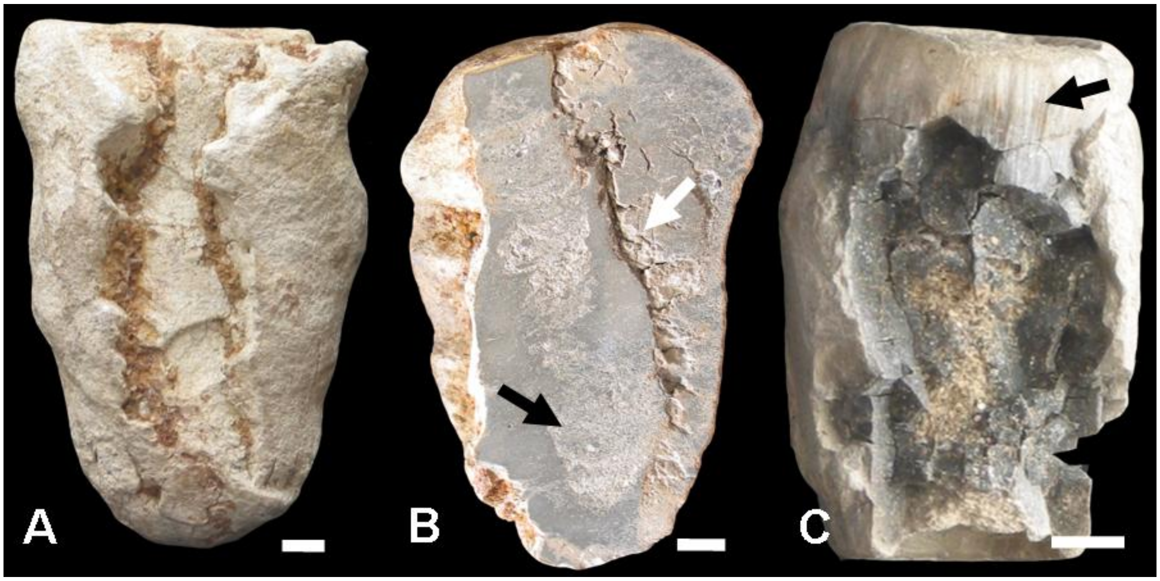

Figure 33 – Photographs of phosphatized vertical burrows. All scale bars are ~5 mm. (A,B) Exterior and interior of concretion. Interior view (B) shows discrete meniscate back-fill (black arrow) and remnants of a shell-lining (white arrow). (C) View of slickensides (black arrow) on concretion.

Taken as a whole, the Ripley trace assemblage represents the *Cruziana* ichnofacies. *Cruziana* ichnofacies assemblages are generally ethologically diverse. They typically are dominated by horizontal endogenic traces produced by deposit feeders (including common *Chondrites* and *Thalassinoides*) but also may include vertical burrows of suspension feeders. Epibenthic traces produced by mobile carnivores and scavengers also may be common, but only in sequences preserving bedding planes beneath event beds (Ekdale et al., 1984). The *Cruziana* ichnofacies is most commonly associated with deposition in low- to medium-energy, shallow marine environments situated between fair-weather and storm wave bases (Frey and Seilacher, 1980; Ekdale et al, 1984). Hence, the Ripley trace assemblage is consistent with the environmental setting inferred from sedimentologic evidence.

Ophiomorpha generally is more typical of the *Skolithos* ichnofacies, which characterizes coarser, relatively unstable sediments in higher-energy settings (e.g., foreshore through shoreface environments) (Pemberton et al., 1992; Ekdale et al., 1984). However, the horizontal to subhorizontal forms of *Ophiomorpha* that dominate the Ripley at Dry Cedar Creek previously have been recognized in facies representing lower-energy offshore environments (Ekdale et al., 1984). Notably, certain forms of *Ophiomorpha*, including the ichnospecies *O. annulata* recognized in the Ripley Formation (e.g., see section 7.3.2 and Fig. 29C,D), have been observed elsewhere in Cretaceous offshore shelf deposits (Howard and Frey, 1984).

The diversity of the Ripley ichnofossil assemblage is relatively low compared to that of other previously described Cretaceous offshore shelf sequences (e.g., Pemberton et al., 1992). This could reflect less than favorable benthic conditions on the Ripley shelf. However, low diversity may be related to limited and selective preservation. The role of diagenetic mineralization in ichnofossil preservation in the Ripley, as well as in other deposits, is discussed below.

8.0 DISCUSSION

8.1 Ripley Concretions and Preserved Trace Fossils

Trace fossil assemblages recognized in unmineralized Ripley sediments and in association with phosphatic concretions are compared in Table 5. Clearly, discrete ichnofossils are more common or evident on or in concretions, and concretion-hosted assemblages are more diverse. This indicates that preferential mineralization enhanced the preservation of trace fossils in the Ripley Formation.

In a recent review of trace fossil taphonomy, Savrda (in press) indicated that trace fossil preservation is influenced by a variety of physical environmental (substrate character, rates and frequencies of deposition), ecologic (e.g., tracemaker behaviors or activities), and diagenetic (e.g., preferential mineralization) factors. These factors control (1) ichnological fidelity, the "extent to which ichnofabrics reflect the complete range of activities of a community or communities of trace-making organisms" and (2) trace fossil visibility, "the extent to which preserved ichnofossils are manifest or accessible to the viewer." In the case of the Ripley Formation, enhanced trace fossil preservation is related mainly to improved trace fossil visibility.

As noted previously, it is difficult to discern well-defined ichnofossils in unmineralized Ripley sediments. These sediments are highly bioturbated and probably were influenced by a variety of organisms performing different behaviors. However, trace fossils are poorly expressed in these unconsolidated muds owing to (1) limited

Table 5 – Comparison of trace fossils observed in unmineralized sediments and concretions in the Ripley Formation at Dry Cedar Creek.

Trace Fossil Types	**Unmineralized Sediments**	**Concretions**
Diopatrichnus	◦	◦
Chondrites	○	◯
Thalassinoides	●	◯
Ophiomorpha	●	◯
Unidentified Traces		
Vertical to subvertical burrows	●	◯
Horizontal to subhorizontal burrows	●	◯
Back-filled burrows	●	◦
“Skid mark” structures	●	◦
Spreiten(?) structures	●	◦

●	◦	○	◯
Not Seen	Rare	Common	Abundant

compositional and textural differences between burrow fills and ambient sediments, (2) lack of three-dimensional views of biogenic structures, and (3) compression of traces resulting from mechanical compaction. Phosphate concretion growth improved trace fossil visibility in several ways. Migration of diagenetic mineralization fronts was apparently influenced by subtle differences in texture and/or composition between host sediments and burrow fills or linings, resulting in at least partial three-dimensional expression of ichnofossils on concretion exteriors. Moreover, because mineralization occurred at shallow depths, ichnofossils preserved on or in concretions were protected from significant compaction.

Aside from diagenetic factors, environmental and ecologic factors also likely played a part in preferential preservation of ichnofossils on or in concretions. Type 3 concretions in the Ripley Formation preferentially nucleated on or within burrows, presumably owing to compositional and textural differences among burrow fills, burrow linings, and enclosing sediments. These differences could be related to environmental processes that resulted in the passive accumulation of contrasting burrow fills or to ecologic processes whereby tracemakers actively segregated sediment (including shells) in linings or fills. In either case, sediments associated with these relatively large ichnofossil-nucleated concretions apparently were more porous and permeable and served as conduits for phosphate-charged fluids. Additionally, these large burrow nuclei may have contained passively or actively introduced organic detritus or mucus secretions that served as microenvironments favorable for phosphate precipitation.

Collateral preservation of trace fossils on exteriors of type 1 and type 2 concretions also may be related to environmental and ecologic factors. Most traces are preserved in negative relief on concretion surfaces. This indicates that the fills and/or linings of these structures were commonly less prone to phosphatization. In these cases, passive or active burrow fills may have been finer-grained or more densely packed than surrounding sediments and, hence, they locally retarded migration of mineralization fronts. In particular, pelleted linings constructed by the *Ophiomorpha* tracemaker appear to have served as relatively impermeable barriers to flow of pore fluids.

Whatever the processes and factors involved, it is clear that phosphatization enhanced the preservation of trace fossils in sediments of the Ripley Formation. The trace fossil assemblage preserved on or in the concretions provides a more complete record of benthic activities and paleoenvironmental conditions than that preserved in unmineralized sediment. In this regard, the concretion-bearing strata can be regarded as a form of conservation lagerstätte.

8.2 Other Examples of Diagenetically Enhanced Ichnofossil Preservation

Review of previous literature reveals numerous other examples of enhanced trace fossil preservation associated with early diagenetic mineralization. In addition to phosphatization, preservation may be related to the precipitation of silica, carbonate (calcite, dolomite, siderite), and/or pyrite.

8.2.1 Phosphate Concretions

Preservation of trace fossils related to phosphate concretion growth has been documented in a variety of Phanerozoic sequences representing deposition in marine shelf and epicontinental sea settings. These include the Eocene London Clay (England), Cretaceous shales of the U.S. Western Interior (Pierre and Carlile shales), and the Devonian Moscow Formation (New York).

Eocene London Clay

Relationships between early diagenetic phosphatization and fossil preservation in the Eocene London Clay of southeast England have been documented by Balson (1980), Hewitt (1980, 1982, 1986), and Allison (1988a). Phosphate concretion growth within these clays not only preserved plant and animal body fossils but also preserved various ichnofossils. The London Clay and Ripley deposits at Dry Cedar Creek are similar in many respects. Both are dominated by marine shelf clays. Moreover, the phosphate preservation modes of body fossils and trace fossils are comparable.

Balson (1980) and Allison (1988a) described concretions that are analogous to Dry Cedar Creek type 1 concretions. Therein, hard body parts of vertebrates (i.e., bones and teeth) and invertebrates (i.e., gastropod, bivalve, and other mollusk shells) served as nucleation sites, forming either steinkerns or mummy concretions. Allison (1988a) noted that burrows, commonly pyritized, are preserved on surfaces of most fossil-bearing London Clay concretions.

The London Clay also contains rounded to irregular phosphatic concretions with no discernable nuclei (Balson, 1980; Hewitt, 1980, 1982, 1986; Allison, 1988a), similar to type 2 Ripley concretions. Burrows are commonly expressed on exteriors of these concretions. According to Allison (1988a), the presence of well-preserved burrows in or on London Clay concretions indicates that mineralization occurred before the onset of significant sediment compaction, as was the case for the Ripley concretions.

As with the type 3 concretions of the Ripley Formation, many London Clay concretions nucleated on or in biogenic structures. Allison (1988a) noted that fecal pellets and burrows were among the most common sites for nucleation, possibly because these structures were originally phosphate rich. Balson (1980) also recognized that pelleted fills in some mineralized burrows were favorable phosphate nucleation sites. According to Hewitt (1980, 1982), segments of large *Thalassinoides* commonly served as nuclei for phosphate concretion growth.

Balson (1980) described phosphatic concretions with polished and pitted exteriors. He interpreted the pits as the termini of clavate borings similar to *Gastrochaenolites*. Borings were emplaced on all surfaces of these concretions after the nodules were exhumed during sea-level fall. Boring organisms penetrated the somewhat softer outer margins of the concretions, but their progress was halted when they encountered the harder, inner core. Reworking of these bored concretions eventually removed the majority of the less competent outer margins, leaving a polished surface with numerous small indentions. These bored Eocene concretions were subsequently incorporated into Miocene sediments.

Cretaceous Shales of the U.S. Western Interior

Bishop and others (Bishop, 1972, 1977, 1981, 1986; Bishop and Williams, 1986) conducted detailed studies of phosphatic concretions from Upper Cretaceous shales (Pierre Shale, Carlile Shale) in South Dakota. These concretions preserve a decapod-dominated body fossil assemblage similar to that of the Ripley Formation. Trace fossils also are recognized in the South Dakota concretions. However, their published descriptions of ichnofossils are vague and incomplete.

Bishop and others (Bishop, 1972, 1977, 1981, 1986; Bishop and Williams, 1986) recognized various vertebrates, decapods, and mollusks preserved by early diagenetic phosphatic concretion growth. Many occur as steinkerns of decapods and mollusks.

Steinkerns described from South Dakota assemblages are reminiscent of those from Dry Cedar Creek in that they preserve various mollusks. However, the South Dakota assemblages also contain common decapod steinkerns, which are only rarely observed in the Ripley at Dry Cedar Creek. Bishop and Williams (1986) recognized small (0.25 – 1 mm diameter), sinuous, branched and unbranched, open and filled burrows on some steinkern exteriors. Based on their descriptions, some of these burrows are similar to the *Chondrites* found on the exteriors of Ripley ammonite steinkerns.

Bishop (1977, 1981, 1986) and Bishop and Williams (1986) also described abundant fossil-bearing mummy concretions that partially or fully enclose hard body parts. The exteriors of these concretions commonly exhibit unbranched, pellet-filled burrows produced by deposit-feeding organisms (Bishop, 1977). Fecal pellets, which also were observed in cemented sediments filling body cavities or within enclosing sediments, may have been a source of dissolved phosphate necessary for concretion growth.

Bishop (1977, 1981) and Bishop and Williams (1986) also described spherical to irregular concretions that are barren of macrofossil material. These concretions are analogous to Ripley type 2 concretions in that they preserve various traces fossils, including *Ophiomorpha*, on their exteriors.

Bishop and Williams (1986) briefly noted the presence of branched and unbranched, large, elongate phosphatic concretions that resemble some of the type 3 concretions from the Ripley at Dry Cedar Creek. They suggested that these concretions nucleated on or in large burrows produced by crustaceans. Based on body fossil remains found in some burrow fills, the tracemaker may have been a lobster (*Linuparus*). In some cases, these large phosphate concretions were later entombed in siderite.

Devonian Moscow Formation, New York

Baird (1978) described phosphatic pebbles that mark a submarine discontinuity in the Devonian Moscow Formation in western New York State. Phosphatic pebbles in the Moscow Formation are relatively small (2 to 10 mm in diameter), typically black, spherical to irregular concretions. In some cases, phosphate nucleated on or within remains of brachiopods, gastropods, trilobites, arthropods, bivalves, and vertebrates (i.e., fish teeth) to form steinkerns or mummy concretions. In other cases, unidentified burrows served as sites of phosphate nucleation. Phosphatization occurred at shallow substrate depths, and concretions were subsequently reworked to form a lag deposit.

Baird (1978) proposed that phosphate was concentrated in sediments through a combination of bioturbation and slow erosion. In his model, burrowing beneath the erosional surface enhanced chemical exchange across the sediment-water interface and concentrated organic material in the sediments. This, in turn, created alkaline microenvironments favorable for phosphate precipitation. Finer-grained sediments were progressively winnowed away, leaving a lag of phosphate clasts. After sedimentation resumed, pyrite precipitated as thin crusts and within smaller burrows on or within the phosphatic nodules.

8.2.2 Silicification

Enhanced preservation of ichnofossils by preferential silicification is not uncommon, particularly in carbonate-dominated sequences. In some Paleozoic sequences, chert selectively replaced the fills of burrows, particularly *Thalassinoides* (e.g., Watkins and Coorough, 1997). However, relationships between silicification and trace fossil preservation are probably best exemplified by Cretaceous flint nodules within European chalks. Modes of ichnofossil preservation of ichnofossils in flints, documented by Bromley and others (Bromley, 1967; Kennedy, 1975; Bromley and Ekdale, 1983, 1984; Ekdale and Bromley, 1984), are similar to those recognized in the Ripley phosphate concretions.

The Cretaceous flints preferentially nucleated on or in a variety of chalk trace fossils. These include small burrow systems such as *Chondrites* (Bromley, 1967) and enigmatic, vertically extensive (up to 9 m), cylindrical structures referred to as *Bathichnus paramoudrae* (Kennedy, 1975; Bromley and Ekdale, 1983; 1984; Ekdale and Bromley, 1984). However, morphologies of flint nodules generally indicate that *Thalassinoides* served as the most common nuclei for early diagenetic silicification. Bromley and Ekdale (1983,1984) suggested that preferential silicification of *Thalassinoides* was related to (1) elevated concentrations of organic matter in these burrows and (2) higher permeabilities of actively or passively introduced burrow fills. In some cases, silicification extended only to the margins of *Thalassinoides* or segments thereof, resulting in flint nodules that reproduced original burrow morphologies. In other cases, silicification continued beyond burrow walls. This “oversilicification” resulted in a variety of flint-nodule forms (e.g., horned flints, tabular flints, etc.) (Kennedy, 1975; Ekdale and Bromley, 1984).

Oversilicification around large burrows (e.g., *Thalassinoides*) also resulted in collateral preservation of other traces within the surrounding host sediments. Biogenic structures such as *Chondrites* and *Zoophycos* are commonly well expressed in negative or positive relief on the exteriors of oversilicified flint nodules, in much the same way that ichnofossils are preserved on exteriors of Ripley phosphate concretions (particularly type 2 concretions).

8.2.3 Carbonate Concretions

Previous studies also indicate that trace fossil preservation may be enhanced by early diagenetic precipitation of carbonate minerals. These include calcite, dolomite, and, less commonly, siderite.

Calcite

Studies of various marine mudrock sequences indicate that trace fossil preservation may be enhanced by the growth of early diagenetic calcite. In some instances, early concretion growth enhanced preservation by protecting ichnofossils from the effects of compaction. Maples (1986) noted that the interiors of early-formed carbonate concretions in black shales of the Pennsylvanian Dugger Formation, southwestern Indiana, preserve primary laminae, diverse body fossil assemblages, and biogenic structures (*Chondrites*). With the exception of a few distorted body fossils, none of these features are preserved in the unmineralized and highly compacted shales that host the concretions.

Similar preservation of precompaction ichnofabrics dominated by *Chondrites* were recognized by Savrda and Bottjer (1988) in a concretionary limestone bed within laminated black shales of the Jurassic Posidonienshiefer, southern Germany. These authors also noted stenomorphism of larger burrows (e.g., *Thalassinoides*) on the base of the limestone bed, which indicates that some burrow emplacement occurred after earlier carbonate cementation. Savrda and Bottjer (1988) suggested that the emplacement of

Chondrites, which occurred during a brief oxygenation episode, facilitated carbonate concretion growth. Kennedy (1975) earlier noted that burrowing activities of organisms can alter Eh and pH levels within sediments and, by impacting the sediment porosity and organic content, could create microenvironments conducive to the precipitation of carbonate and other early diagenetic minerals.

In other examples, trace fossils are preferentially preserved in positive or negative relief on the exteriors of carbonate concretions. As in the phosphatic and siliceous concretions described above, this is related to differential migration of mineralization fronts through host sediment. Hewitt (1980) noted this type of preservation on the exteriors of carbonate concretions in the Eocene London Clay. He recognized (1) *Thalassinoides* (horizontal, branched burrows with diameters ranging from 15 to 30 mm), (2) *Chondrites* (dendritically branched systems of small [0.4 to 1.0 mm] burrows), (3) *Ophiomorpha* (subhorizontal burrows with an average diameter of 4 mm), and (4) segments of unidentifiable burrows. The *Ophiomorpha* described by Hewitt (1982) is lined with small (0.5 to 0.6 mm) ovoid pellets oriented perpendicular to burrow axes. Both the *Ophiomorpha* and *Thalassinoides* observed on and in London Clay carbonate concretions closely resemble those described in the Ripley phosphate concretions.

Dolomite

Preferential dolomitization of burrows is common in Paleozoic carbonates. As an example, Morrow (1978) described selectively dolomitized ichnofabrics in Ordovician carbonates from the Canadian Arctic Archipelago. The lime mudstones they describe are highly mottled, reflecting partial dolomitization. Dolomite is generally restricted to burrow fills and does not intrude into the host calcitic muds and wackestones. Morrow

(1978) suggests dolomite precipitation was initiated during salinity changes induced by freshwater influx in a lagoonal environment. Higher porosities and permeabilities of burrow fills facilitated the diffusion of magnesium from overlying seawater and led to selective precipitation of dolomite.

Trace fossil preservation related to dolomitization is also recognized in some modern substrates. Brown and Farrow (1978) described dolomite concretions that were dredged from Holocene sediments of Loch Sunart, Scotland. These concretions grew within muds immediately adjacent to open, horizontal to vertical, branched, possibly mud-lined crustacean burrow systems. In this case, dolomite precipitation was attributed to the development of highly alkaline microenvironments along burrow margins, probably in response to bacterial sulfate reduction. Notably, the early-formed dolomite nodules were subsequently exhumed and colonized by encrusting and endolithic organisms. Borings occur on most concretion surfaces, indicating that they were periodically overturned by bottom currents.

Siderite

Archer and Hattin (1984) described trace fossil preservation associated with early diagenetic siderite concretions in Upper Cretaceous shales of the U.S. Western Interior basin. A variety of trace fossils, including *Chondrites*, *Planolites*, and unnamed narrow, horizontal to vertical, pyritized burrows, were recognized on siderite concretion exteriors and interiors. In contrast, discrete ichnofossils and evidence for bioturbation are rare in the relative clay-rich sediments (offshore noncalcareous shales) that host the concretions. The apparent absence of discrete burrows in host sediments was attributed to textural homogeneity and relatively high initial pore-fluid contents, which resulted in significant compaction. Because siderite precipitated early, before compaction, trace fossils were preferentially preserved in the concretions (Archer and Hattin, 1984).

Baird et al. (1986) also described examples of trace fossil preservation in early diagenetic siderite concretions in the Carboniferous Francis Creek Shale, in the Mazon Creek area of Illinois. In addition to abundant body fossils and plant material, nuclei of siderite nodules include rare horizontal to oblique traces, some containing the body fossil remains of the presumed tracemaker. These authors interpret these burrows as escape structures, or fugichnia. Baird et al. (1986) attribute the precipitation of siderite in the Mazon Creek deposits to rapid burial, organic decay, abundant terrigenous iron supply, and low concentrations of sulfate.

8.2.4 Pyrite

Pyritization of trace fossils is relatively common. Numerous authors have briefly noted preferential pyrite mineralization of ichnofossils. Examples include growth of pyrite nodules around burrows (e.g., Bromley, 1967), complete to partial pyritization of burrow fills (Kennedy, 1975; Baird, 1978; Ekdale and Bromley, 1984; Dix and Mullins, 1987; Hewitt, 1986), and precipitation of thin “films” or coatings on or near burrow walls (Kennedy, 1975; Byers and Stasko, 1978). Where genetic mechanisms are discussed, the aforementioned authors attribute pyrite mineralization to anaerobic decay of organic material concentrated within or along walls of burrows. The role of mucous linings in the pyritization of burrows was the focus of studies by Thomsen and Vorren (1984) and Schieber (2002, 2003).

Thomsen and Vorren (1984) described a variety of pyritized burrows from Pleistocene glaciomarine deposits of Norway. Some burrows are preserved as narrow

(0.5 to 3.5 mm), straight to slightly curved, externally ornamented, hollow pyrite tubes. These are interpreted to reflect preferential pyrite replacement of mucous linings secreted by the trace makers. Other structures include relatively narrow (0.5 to 1.2 mm), branched and unbranched burrows in which sediment fills have been completely pyritized. In the latter structures, pyrite may have formed from microbial degradation of foreign organic matter in burrow fills, as well as mucous linings.

Schieber (2002, 2003) described the role of pyritization in preserving trace fossils that otherwise would not be recognized in the stratigraphic record. In sandstones of the Ordovician Winnipeg Formation in Saskatchewan, Canada, Scheiber (2002) noted small (3 to 15 mm diameter), vertical to subvertical, irregular to elongate pyrite concretions within which sand grains display loose packing. He interpreted these concretions to have nucleated within mucous slime trails excreted by organisms as they burrowed through relatively fluid sediments without producing discrete burrows. In Devonian black shales, Scheiber (2003) documented narrow (<2.0 mm), vertical to horizontal, straight to irregularly curved or branched, pyritized burrow systems, some of which resemble *Nereites* and *Spirophycos*. Pyritization occurred in anaerobic microenvironments formed by mucous linings and trails emplaced in highly fluid muds. Early diagenetic mineralization protected the burrows from the effects of intense compaction. Subsequent compaction of surrounding unmineralized muds resulted in pseudolaminated fabrics wherein evidence for bioturbation is lacking.

8.3 Describing Relations Between Mineralization and Trace Fossils

Results of the current study and observations made by previous workers on a variety of deposits indicate that trace fossil preservation is commonly impacted by concretion growth. Hence, it would be useful to have a broadly applicable set of terms for describing the relationships between diagenetic mineralization and trace fossil preservation. A proposed classification scheme is presented in Figure 34 and discussed below. This scheme includes terms that refer to the (1) relative timing of concretion growth and trace fossil production, (2) type of mineralization, (3) spatial relationships between concretion nuclei and preserved trace fossils, and (4) modes of trace fossil expression relative to concretion interiors and exteriors.

Trace fossils preserved on or in concretions may be produced before, during, or after mineralization takes place. Such ichnofossils can be referred to as (1) pre-mineralization, (2) syn-mineralization, and (3) post-mineralization structures (Fig. 34A-C). Most of the structures preserved in association with Ripley phosphates and other previously described concretions are pre-mineralization structures; i.e., biogenic structures were produced in sediments prior to concretion growth (Fig. 34A). Although rare, some ichnofossils, including the “skid mark” structures observed on some type 1 Ripley concretions, represent syn-mineralization structures. Their morphologies indicate that the tracemaker’s path was influenced by at least incipient mineralization and that mineralization and lithification continued after trace emplacement (Fig. 34B). Post-mineralization structures are those that were produced on or in concretions after lithification. These features include borings and other bioerosion features, rather than softground burrows (Fig. 34C). Bioerosion features were not observed in Ripley concretions, probably because lithified phosphate nodules were not exposed at the seafloor. However, borings in concretions observed by others (e.g., Brown and Farrow, 1978; Balson, 1980) qualify as post-mineralization traces.

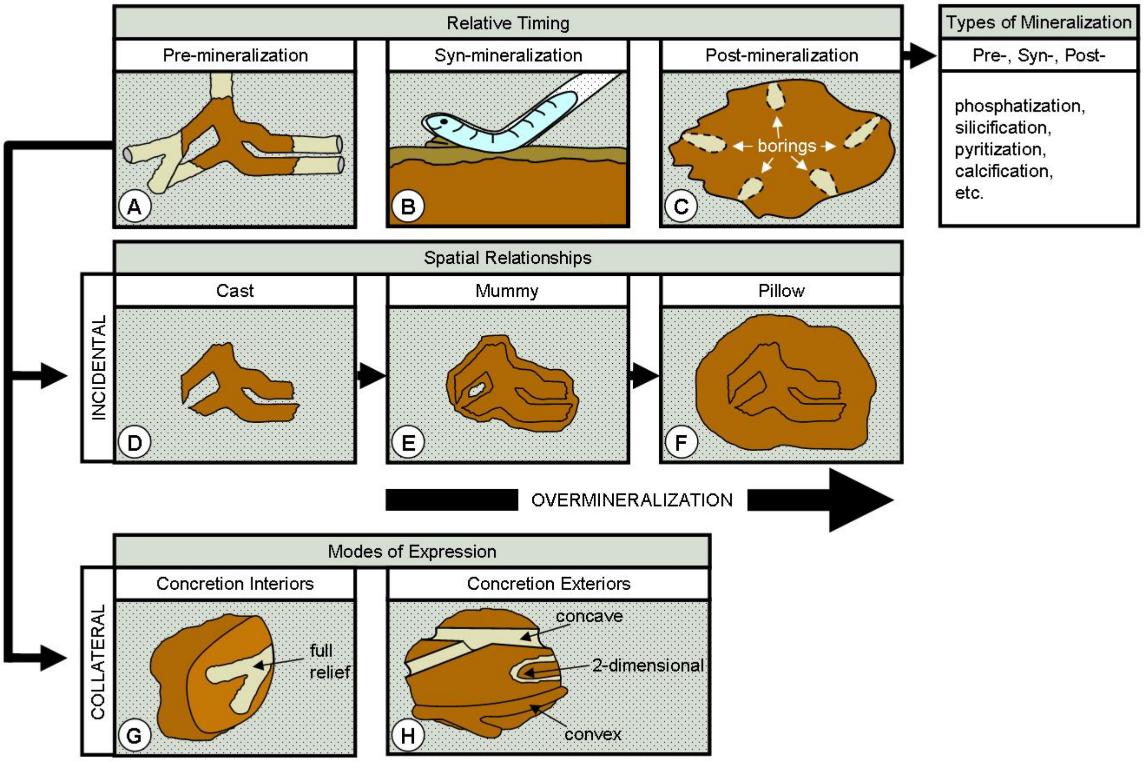

Figure 34 – Suggested terminology for describing relationships between concretions and trace fossil preservation.

As noted above, preservation of trace fossils may be influenced by the precipitation of a variety of minerals, including phosphate, silica, pyrite, and carbonates. Hence, terms that are more specific than "mineralization" can be applied. As examples, ichnofossils influenced by early diagenetic phosphate, silica, pyrite, or calcite mineralization can be referred to as pre-, syn-, or post- phosphatization, silicification, pyritization, and calcification structures, respectively.

Terminology to describe the spatial relationships between concretion nuclei and preserved trace fossils is also necessary. As described above, some ichnofossils serve as the nucleus for concretion growth, while others are passively preserved because they happened to be emplaced in sediments in close proximity to nucleation sites. These two situations can be referred to as incidental (Fig. 34D-F) and collateral mineralization (Fig. 34G,H), respectively. Examples of incidental mineralization include type 3 concretions of the Ripley Formation, as well as the various mineralized *Thalassinoides* burrows described in earlier works (Bromley, 1967; Kennedy, 1975; Bromley and Ekdale, 1983, 1984; Ekdale and Bromley, 1984; and others). Preservation of trace fossils by collateral mineralization is illustrated in most type 1 and type 2 concretions of the Ripley Formation, and in many of the other deposits described above.

In the case of incidental mineralization, it is important to note the degree to which mineralization extends beyond the ichnofossil nucleus into the surrounding sediments. When mineralization preferentially preserves a trace without extending past its margins, the resulting mass can be referred to as a cast concretion (Fig. 34D). Mineralization may extend past trace fossil margins to incorporate host sediments, but the shape of the resulting mass preserves the original shape of the trace fossil nucleus. Borrowing from terminology employed by Mundlos (1975) for body fossil nuclei, resulting concretions can be referred to as mummy concretions (Fig. 34E). Mummy concretions can be described as thin- or thick-skinned, depending on thickness of mineralized sediment rinds around the ichnofossil nucleus. Progressive migration of mineralization fronts may eventually obscure the original shape of the ichnofossil nuclei. Again borrowing from Mundlos (1975), resulting masses can be referred to as pillow concretions (Fig. 34F).

Collaterally preserved trace fossils may be completely entombed within a concretionary mass and, hence, they are observed only when the concretion is cut or broken. This can be referred to as full-relief preservation (Fig. 34G). Collaterally preserved ichnofossils also are commonly preserved on exteriors of concretions. These structures may or may not be expressed in relief, depending on the extent of differential migration of mineralization fronts through ichnofossils and surrounding sediments. Where trace fossils were more and less susceptible to mineralization, they are preserved in convex and concave relief, respectively (Fig. 34H). In the case of no differential mineralization, expression of trace fossils is two-dimensional.

9.0 SUMMARY AND CONCLUSIONS

Phosphate concretions are locally common in the Upper Cretaceous (Late Campanian to Maastrichtian) Ripley Formation in central Alabama. Common *in situ* concretions in outcrops and abundant allochthonous concretions on modern stream bars along Dry Cedar Creek provided the opportunity to evaluate the origins of the concretions and to investigate the role of phosphate mineralization in trace fossil preservation. The main observations and conclusions derived from the study of Ripley phosphate concretions and associated sediments are summarized below.

(1) The relative abundance of concretions varies significantly along the studied segment of Dry Cedar Creek. Mapping of the distribution and abundance of both *in situ* and allochthonous concretions indicates that virtually all phosphatic material examined in this study derived from a relatively thin (< 6 m) interval of Ripley strata exposed along creek bluffs *within* the study area.

(2) The concretion-bearing interval consists of calcareous, carbonaceous mud and sandy mud. High degree of bioturbation and abundant benthic invertebrate body fossils indicate that deposition occurred in a moderately well-oxygenated, quiet-water shelf setting. However, the presence of admixed sand and vestiges of primary sedimentary structures indicates that the depositional site was at least periodically subjected to storm generated currents. Unusually high organic carbon contents likely reflect relatively high productivity in the overlying water column.

(3) Many Ripley phosphate concretions preferentially nucleated in or around various invertebrate (e.g., crabs, ammonites, and other mollusks) and vertebrate (e.g., fish, reptile, and unidentified bone fragments) body fossils, and their shapes closely conform to that of their respective fossil nuclei (type 1 concretions). Other concretions exhibit irregular morphologies and contain no obvious nuclei (type 2 concretions). Less commonly, concretions nucleated on or in the fills of relatively large burrows (type 3 concretions).

(4) The preservation state (e.g., articulated and undistorted) of most body fossils entombed within concretions indicates that mineralization occurred during early stages of diagenesis, prior to significant biological or mechanical degradation and sediment compaction. Petrographic observations of sediment textures and geochemical data also indicate that phosphatization occurred very early at shallow substrate depths. The biodegradation of organic matter effectively lowered pH levels and also served as a primary source for phosphate. Precipitation of phosphate occurred at or near the oxic/anoxic boundary in the sediment, perhaps during periods of reduced sedimentation rate and /or episodes of hypoxia.

(5) Discrete trace fossils are rarely observed in unmineralized Ripley sediments. However, trace fossils are preferentially preserved on or within nearly all concretions. Trace fossils, which are most commonly expressed in negative relief on concretions exteriors, are dominated by structures produced by deposit feeders (*Chondrites*, *Thalassinoides*, and unidentified backfilled and spreite structures) but also include structures attributed to suspension feeders (*Diopatrichnus* and *Ophiomorpha*). This

assemblage, which represents an impoverished *Cruziana* ichnofacies, is consistent with a shelf depositional environment between fair-weather and storm wave bases.

(6) Distinct trace fossils are very poorly expressed in unmineralized sediments owing to limited textural and compositional contrast, lack of three-dimensional expression, and compactional deformation. Trace fossils are more common on or in concretions, and concretion-hosted ichnofossil assemblages are more diverse. Early diagenetic phosphatization enhanced trace fossil visibility by limiting compaction and by providing at least partial three-dimensional views of ichnofossils. Trace fossils served as concretion nuclei or in other ways influenced the flow of diagenetic fluids. Differential mineralization of trace fossils reflects passively or actively generated contrasts in sediment permeability and/or microenvironments favorable for phosphatization. Because Ripley concretions provide ichnologic information that otherwise would not be available, they represent a form of conservation-lagerstätte.

(7) Based on observations made in the current investigation and in previous studies, a set of terms is proposed for describing the relationships between diagenetic mineralization and trace fossil preservation. These terms refer to relative timing of concretion growth and trace fossil production, type of mineralization, spatial relationships between concretion nuclei and preserved trace fossils, and modes of trace fossil expression relative to concretion interiors and exteriors.

10.0 REFERENCES

Abston, S.A., Savrda, C.E., and Lewis, R.D., 1990, A decapod-dominated fossil-lagerstätte, Upper Cretaceous Ripley Formation, Alabama: Preliminary investigations: Geological Society of America, Abstracts with Program, v. 22, no. 4, p. 1.

Abston, S.A., and Savrda, C.E., 1990, Decapod horizons in the Ripley Formation (Upper Cretaceous) of central Alabama: Mass mortality and phosphatic concretion growth induced by hypoxia: Geological Society of America, Abstracts with Program, v. 22, no. 7, p. 236.

Allison, P.A., 1988a, Konservat-Lagerstätten: Cause and classification: Paleobiology, v. 14, p. 139-154.

——, 1988b, Taphonomy of the Eocene London Clay biota: Palaeontology, v. 31, p. 1079-1100.

——, 1988c, The role of anoxia in the decay and mineralization of proteinaceous macro-fossils: Paleobiology, v. 14, p. 139-154.

Archer, A.W., and Hattin, D.E., 1984, Trace fossils in Upper Cretaceous argillaceous marine facies of the U.S. Western Interior: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 45, p. 165-187.

Baird, G.C., 1978, Pebbly phosphorites in shale: A key to recognition of a widespread submarine discontinuity in the Middle Devonian of New York: Journal of Sedimentary Petrology, v. 48, p. 545-555.

Baird, G.C., Sroka, S.D., Shabica, C.W., and Kuecher, G.J., 1986, Taphonomy of Middle Pennsylvanian Mazon Creek area fossil localities, northeast Illinois: Significance of exceptional fossil preservation in syngenetic concretions: Palaios, v. 1, p. 271-285.

Balson, P.S., 1980, The origin and evolution of Tertiary phosphorites from eastern England: Journal of the Geological Society of London, v. 137, p. 723-729.

Baturin, G.N., 1970, Recent authigenic phosphorite formation on the south west African shelf: Report - Natural Environment Research Council, Institute of Geological Sciences, v. 70/13, p. 87-97.

Benmore, R.A., Coleman, M.L., and McArthur, J.M., 1983, Origin of sedimentary francolite from its sulphur and carbon isotope composition: Nature (London), v. 302, no.5908, p. 516-518.

Bishop, G.A., 1972, Moults of *Dakoticancer overanus*, an Upper Cretaceous crab from the Pierre Shale of South Dakota: Paleontology, v. 15, p. 631-636.

——, 1977, Pierre feces: A scatological study of the *Dakticancer* assemblage, Pierre Shale (Upper Cretaceous) of South Dakota: Journal of Sedimentary Petrology, v. 47, 129-136.

——, 1981, Occurrence and fossilization of the *Dakticancer* assemblage, Upper Cretaceous Pierre Shale, South Dakota, *in* J. Gray, A.J. Boucot, and W.B.N. Berry, *eds*., Communities of the Past: Hutchinson Ross Publishing Company, Stroudsburg, PA, p. 383-413.

——, 1986, Taphonomy of the North American Decapods: Journal of Crustacean Bilogy, v. 6, no. 3, p. 326-355.

Bishop, G.A., and Williams, A.B., 1986, The fossil lobster *Linuparus Canadensis*, Carlile Shale (Cretaceous), Black Hills: National Geographic Research, v. 2, p. 372-387.

Brett, C.E., and Baird, G.C., 1986, Comparative taphonomy; a key to paleoenvironmental interpretation based on fossil preservation: Palaios, v. 1, no. 3, p. 207-227.

Briggs, D.E.G., 2003, The role of decay and mineralization in the preservation of soft-bodied fossils: Annual Review of Earth and Planetary Sciences, v. 31, p. 275-301.

Briggs, D.E.G., and Wilby, P.R., 1996, The role of the calcium carbonate – calcium phosphate switch in the mineralization of soft-bodied fossils: Journal of the Geological Society of London, v. 153, p. 665-668.

Bromley, R.G., 1967, Some observations on burrows of Thalassinidean crustacea in chalk hardgrounds: Quarterly Journal of the Geological Society of London, v. 123, p. 157-182.

Bromley, R.G., and Ekdale, A.A., 1983, Flint and fabric in the European chalk: in Sieveking, G., and Hart, M.B., *eds*., The Scientific Study of Flint and Chert: Cambridge University Press, Cambridge, p. 71-82.

Bromley, R.G., and Ekdale, A.A., 1984, Trace fossil preservation in flint in the European chalk: Journal of Paleontology, v. 58, p. 298-311.

Brown, B.J., and Farrow, G.E., 1978, Recent dolomitic concretions of crustacean burrow origin from Loch Sunart, west coast of Scotland: Journal of Sedimentary Petrology, v. 48, p. 825-834.

Byers, C.W., and Stasko, L.E., 1978, Trace fossils and sedimentologic interpretations—McGregor Member of Plattesville Formation (Ordovician) of Wisconsin; Journal of sedimentary Petrology, v. 48, p. 1303-1310

Coleman, M.L., 1985, Geochemistry of diagenetic non-silicate minerals; Kinetic considerations, *in* Eglington, G., Curtis, C.D., McKenzie, D.P., and Murchinson, D.G., *eds.*, Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences, v. 315, p. 39-56.

Copeland, C.W., 1972, Upper Cretaceous series in central Alabama: Guidebook - Geological Society of America, Southeastern Section, v. 72, p. 1.

de Gibert, J.M., 1996, *Diopatrichnus odlingi* n. isp. (annelid tube) and associated ichnofabrics in the White Limestone (M. Jurassic) of Oxfordshire: Sedimentologic and palaeoecological significance: Proceedings of the Geologists' Association, v. 107, p. 189-198.

de Gibert, J.M., Fregenal-Martinez, M.A., Buatois, L.A., and Mángano, M.G., 2000, Trace fossils and their paleoecological significance in Lower Cretaceous lacustrine conservation deposits, El Montsec, Spain: Paleogeography, Paleoclimatology, Paleoecology, v. 156, p. 89-101.

Dix, G.R., and Mullins, H.T., 1987, Shallow, subsurface growth and burial alteration of Middle Devonian calcite concretions: Journal of Sedimentary Petrology, v. 57, p. 140-152.

Ehrenberg, K., 1944, Ergänzende Bemerkungen zu den seinerzeit aus dem Miozän von Burgschleinitz beschriebenen Gangkernen und Bauten dekapoder Krebse: Paläontologische Zeitschrift, v. 23, p. 354-359.

Ekdale, A.A., and Bromley, R.G., 1984, Comparative ichnology of shelf-sea and deep-sea chalk: Journal of Paleontology, v. 58, p. 322-332.

Ekdale, A.A., Bromley, R.G., and Pemberton, S.G., 1984, Ichnology: The use of trace fossils in sedimentology and stratigraphy, Society of Economic Paleontologists and Mineralogists Short Course 15, 371 p.

Folk, R.L., 1954, The distinction between grain size and mineral composition in sedimentary rock nomenclature: Journal of Geology, v.62, p.344-359.

Frey, R.W., and Bromley, R.G., 1985, Ichnology of American chalks, The Selma Group (Upper Cretaceous), western Alabama: Canadian Journal of Earth Sciences, v. 22, no. 6, p. 801- 828.

Frey, R.W., and Seilacher, A., 1980, Uniformity in marine invertebrate ichnology: Lethaia, v. 13, p. 183-207.

Frey, R.W., Howard, J.D., and Pryor, W.A., 1978, *Ophiomorpha*: its morphologic, taxonomic, and environmental significance: Paleogeography, Paleoclimatology, Paleoecology, v. 23, p. 199-229.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, *in* C. K. Wilgus, B. S. Hastings, C. A. Ross, H. Posamentier, J. Van Wagoner, and C. G. St. C. Kendall, *eds.*, Sea-level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 71-108.

Hewitt, R.A., 1980, Microstructural contrasts between some sedimentary francolites: Journal of the Geological Society of London, v. 137, p. 661-667.

——, 1982, Studies of London clay concretions, with special reference to Leigh-on-Sea in Essex: Tertiary Research, v. 3, p. 161-170.

——, 1986, Bioturbation in the upper London Clay Formation of Southend-on-Sea (Essex, England): Tertiary Research, v. 8, p. 7-15.

Howard, J.D., and Frey, R.W.., 1984, Characteristic trace fossils in nearshore to offshore sequences, Upper Cretaceous of east-central Utah: Canadian Journal of Earth Sciences, v. 21, p. 200-219.

Jones, D.E., *eds*., 1967a, Geology of the Coastal Plain of Alabama. 80th Annual Meeting, Geological Society of America, New Orleans, LA, Field Trip Guidebook, 113 p.

——, 1967b, The Selma Group in west Alabama, *In* Jones, D.E., *eds*., Geology of the Coastal Plain of Alabama, Annual Meeting, Geological Society of America, New Orleans, LA, Field Trip Guidebook, p. 26-32.

Kennedy, W.J., 1975, Burrows and surface traces from the Lower Chalk of southern England: Bulletin of the British Museum (Natural History), Geology, v. 15, p. 127-167.

Kern, J.P., 1978, Paleoenvironment of new trace fossils from the Eocene Mission Valley Formation, California: Journal of Paleontology, v. 52, p. 186-194

King, D.T., Jr., 1993a, Eustatic and tectonic effects within sequence stratigraphy of the outcropping paralic-marine section, Upper Cretaceous, Alabama: Transactions, Gulf Coast Association of Geological Societies, v. 43, p. 157-164.

——, 1993b, Depositional sequence analysis and the characteristics of some confined clastic aquifers, Upper Cretaceous, Alabama: Transactions, Gulf Coast Association of Geological Societies, v. 43, p.165-172.

——, 1994, Upper Cretaceous depositional sequences in the Alabama Gulf Coastal Plain: their characteristics, origin, and constituent clastic aquifers: Journal of Sedimentary Research, v. 64, p. 258-265.

King, D.T., Jr., and Skotnicki, M.C., 1990, Upper Cretaceous stratigraphy and relative sea-level changes, Gulf coastal plain, Alabama: Program and Abstracts, Annual Research Conference, Gulf Coast Section, Society of Economic Paleontologists and Mineralogists. v. 11, p. 417.

Krajewski, K.P., 1984, Early diagenetic phosphate cements in the Albian condensed glauconitic limestone of the Tatra Mountains, Western Carpathians: Sedimentology, v. 31, p. 443-470.

LaMoreaux, P.E., and Toulmin, L.D., Jr., 1960, Geology and ground-water resources of Wilcox County, Alabama: Alabama Geological Survey County Rept. 4, p. 280.

Maples, C.G.., 1986, Enhanced paleoecological and paleoenviromental interpretations result from analysis of early diagenetic concretions in Pennsylvanian shales: Palaios, v. 1, p. 512-516.

Mancini, E.A., Puckett, T.M., and Tew, B.H., 1996, Integrated biostrtigraphic and sequence stratigraphic framework for Upper Cretaceous strata of the eastern Gulf Coastal Plain: Cretaceous Research, v. 17, p. 645-669.

Mancini, E.A., Puckett, T.M., Tew, B.H., and Smith, C.C., 1995, Upper Cretaceous sequence stratigraphy of the Mississippi-Alabama area: Transactions, Gulf Coast Association of Geological Societies, v. 45, p. 377-384.

Mancini, E.A., Puckett, T.M., Parcell, W.C., Crow, C.J., and Smith, C.C., 1998, Sequence stratigraphy and biostratigraphy of Upper Cretaceous strata of the Alabama Coastal Plain, Mancini, E. A., and Puckett, T. M., *eds*., 35th Annual Field Trip Guidebook, p. 1-10.

Mangano, M.G., and Buatois, L.A., 1995, A conceptual framework of trace fossil-lagerstätten: Extended Abstract, II International Symposium on Lithographic Limestones, p. 103-105.

Monroe, W.H., 1941, Notes on deposits of Selma and Ripley age in Alabama: Alabama Geological Survey, Bulletin 48, p. 150.

Morrow, D.W., 1978, Dolomitization of Lower Paleozoic burrow-fillings: Journal of Sedimentary Petrology, v. 48, p. 295-306.

Mundlos, R., 1975, Öekologie, Biostratinomie und Diagenese brachyurer Krebse aus den Alt-Tertiär von Helmstedt (Niedersachsen, BRD): Neues Jahrbuch für Geologie und paläontologie, Abhandlungen, v. 148, 252-271.

Pemberton, S.G., Van Wagoner, J.C., and Wach, G.D., 1992, Ichnofacies of a wave-dominated shoreline, *in* Pemberton, S.G., *eds*., Applications of Ichnology to Petroleum Exploration, Society of Economic Paleontologists and Mineralogists, Core Workshop 17, p. 339-382.

Russell, E.E., and Keady, D.M., 1983, Notes on Upper Cretaceous lithostratigraphy of the eastern Mississippi embaynment, *in* Russell, E.E., Keady, D.M., Mancini, E.A., and Smith, C.C., *eds*., Upper Cretaceous lithostrstratigraphy and biostratigraphy in northwest Mississippi, southwest Tennessee, and northwest Alabama, shelf chalks and coastal clastics: Spring Field Trip Guidebook 1983, p. 72.

Savrda, C.E., in press, Taphonomy of trace fossils: *in* Miller, W., *eds*., Trace Fossils: Concepts, Problems, Prospects, Elsevier.

Savrda, C.E., and Bottjer, D.J., 1988, Limestone concretion growth documented by trace-fossil relations: Geology, v. 16, p. 908-911.

Savrda, C.E., and King, D.T., Jr., 1993, Log-ground and *Teredolites* lagerstätte in a transgressive sequence, Upper Cretaceous (Lower Campanian) Mooreville Chalk, central Alabama: Ichnos, v. 3, p. 69-77.

Savrda, C.E., and Ozalas, K., 1993, Preservation of mixed-layer ichnofabrics in oxygenation-event beds: Palaios, v. 8, p. 609-613.

Savrda, C.E., Ozalas, K., Demko, T.H., Huchison, R.A., and Scheiwe, T.D., 1993, Log-grounds and the ichnofossil *Teredolites* in transgressive deposits of the Clayton Formation (Lower Paleocene), western Alabama: Palaios, v. 8, p. 311-324.

Schein, J.O., 2004, The Teleost Fish *Enchodus* and the Paleoceanography of Upper Cretaceous Rock Units in Alabama, Unpublished M.S. Thesis, Auburn University, 206 p.

Schieber, J., 2002, The role of an organic slime matrix in the formation of pyritized burrow trails and pyrite concretions: Palaios, v. 17, p. 104-109.

——, 2003, Simple gifts and buried treasures – Implications of finding bioturbation and erosion surfaces in black shales: Sedimentary Record, v. 1, no. 2, p. 4-8.

Seilacher, A., 1970, Begriff and Bedeutung der Fossil-Lagerstätten, Neues Jahrbuch für Geologie und Paläeontologie, v. 1, p.34-39.

Seilacher, A., Reif, W.E., and Westphal, F., 1985, Sedimentological, ecological and temporal patterns of fossil Lagerstätten: Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences, v. 311, no. 1148, p. 47-48.

Skotnicki, M.C., and King, D.T., Jr., 1989a, Stratigraphic revision and facies analysis of the Upper Cretaceous Cusseta Sand, coastal plain of Alabama: Southeastern Geology, v. 29, p. 235-253.

——, 1989b, Depositional facies and eustatic effects in the Upper Cretaceous (Maastrichtian) Ripley Formation, central and eastern Alabama: Transactions, Gulf Coast Association of Geological Societies, v. 39, p. 275-284.

Smith, C.C., 1989, Regional Upper Cretaceous stratigraphy: Upper Cretaceous and Tertiary lithostratigraphy and biostratigraphy of west-central Alabama. Alabama Geological Society, Annual Field Trip Guidebook, v. 26, p. 8-13.

Thomsen, E., and Vorren, T.O., 1984, Pyritization of tubes and burrows from Late Pleistocene continental shelf sediments off Norway: Sedimentology. v. 31, p. 481-492.

Watkins, R., and Coorough, P.J., 1997, Silurian *Thalassinoides* in an offshore carbonate community, Wisconsin, USA: Paleogeography, Paleoclimatology, Paleoecology, v. 129, p. 109-117.

Wheatcroft, R., 1986, Maestrichtian trace fossils from selected localties in the Chatahoochee River Valley: Stratigraphy and sedimentology of continental, nearshore, and marine Cretaceous sediments of the eastern Gulf coastal plain: Georgia Geological Society, Guidebook, v. 6, no. 3, p. 57-71.