Sedimentology, Geochemistry, and Paleobiology of a Pennsylvanian Marginal Marine Depositional Environment, Mansfield Formation, Indiana

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SEDIMENTOLOGY, GEOCHEMISTRY, AND PALEOBIOLOGY OF A PENNSYLVANIAN MARGINAL MARINE DEPOSITIONAL ENVIRONMENT, MANSFIELD FORMATION, INDIANA

by Glenn A. Simonelli, Claudia C. Johnson, Erika R. Elswick, Erle G. Kauffman, Cortland F. Eble, and Stephen T. Hasiotis

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ABSTRACT

Outcrops of the Pennsylvanian Mansfield Formation in Martin County, Indiana, were examined to integrate sedimentological, geochemical, and paleobiological data for refinement of local paleoenvironment and age designation. The stratigraphically older HR-150 outcrop contains in the lower section a combination of wavy-, flaser-, and ripple-bedded silty and very fine grained sandstone, overlain first by dark gray, friable, clayey siltstone, then by laminated, wavy- and planar-bedded siltstones with clay drapes. Geochemical analysis shows that all total sulfur values are <0.2 weight percent, with most values well below 0.04 by mass. Total organic carbon ranges from <0.1 to 0.4 by mass except for a thin layer of organic-rich, friable siltstone with coal inclusions where TOC is slightly under 13 wt percent by mass. Total organic carbon/total sulfur ratios vary from 1:1 in the lower to 76:1 in the upper section. Feeding trace fossils occur in the lower section of the outcrop, and vertical burrows are common at the top. The stratigraphically younger H-435 outcrop contains friable siltstone overlain by a coal seam near the base, with beds of wavy and laminated sandstones with ripples, roots, and clay drapes composing the rest of the section. Total sulfur is 0.6 to 0.7 wt percent in the coal seam and near or below 0.1 wt percent in the rest of the outcrop. Total organic carbon varies from 51.4 to 66.8 wt percent in the coal seam and is below 0.15 wt percent above the seam. Total organic carbon/total sulfur ratios vary from 122.4:1 to 1.7:1. Trace fossils indicative of feeding behavior are common, although insect repichnia or pascichnia and tetrapod tracks also occur. Palynological analyses of samples extracted from the coal seam limit the upper age of the stratigraphically younger H-435 outcrop to the early Atokan. Sedimentology, geochemistry, and paleobiology point to a fluviodeltaic paleoenvironment with negligible marine influence for both outcrops.

INTRODUCTION

The Mansfield Formation has a long history of investigation in southwestern Indiana, most notably for exploration of economic resources and the geologic history associated with its numerous lithologies. In the nineteenth century, the abundant sandstone of the Mansfield Formation was valued as an important building stone (Owen, 1862). The Hindostan Whetstone Beds from the Mansfield in Orange County, Indiana, provided sharpening stones that achieved nationwide sales and distribution (Kindle, 1896). During the twentieth century, some of the thick coal beds were exploited for energy use throughout the eastern United States (Hopkins, 1896; Logan, 1922; Franklin, 1939; Gray, 1962).

Outcrops of the Mansfield Formation in Indiana form a 8- to 40-km-wide band that stretches from the south-central boundary of the state to the north-northwest near the Illinois border (fig. 1A). The formation consists of a series of mudstones, shales, siltstones, sandstones, and coal seams deposited from 320 to 300 million years ago near the shorelines of an inland ocean (Mangano and others, 2001; Kvale and others, 2004). Mansfield lithologies reflect a broad range of depositional environments over its geographic area, as shallow marine, fluvial, intertidal, or subaerial processes are interpreted from outcrops of the formation. Paleogeographic maps indicate a tropical, near-equatorial depositional setting (Scotese and others, 1979).

The terms "lower Mansfield Formation" and "upper Mansfield Formation" have been used to differentiate trough and wedge cross-bedded sandstones in the lower section from the wavy, thinly bedded sandstones and mudstones of the upper section of the formation (Gray and others, 1960). Major rock types of the lower Mansfield Formation include dark carbonaceous shale and cross-bedded sandstone with quartz- and chert-pebble conglomerates (Hasenmueller and Hutchison, 1986). The upper Mansfield Formation is further divided into two units near Shoals, Indiana, and three units in southwestern Indiana—a lower sandstone unit and an upper unit of shale and mudstone separated by the Pinnick Coal Member near Shoals, and the Cannelton Lithofacies (siltstone and mudstone), the Shoal Lithofacies (cross-stratified sandstone), and the Bloomfield Lithofacies (gray shale) in southwestern Indiana (Hasenmueller and Hutchison, 1986). Nine major facies types have been identified in the formation: coarse-grained sandstone; coarse- to medium-grained sandstone; fine-grained sandstone; medium- to fine-grained sandstone; interbedded shale and sandy siltstone; micaceous gray shale; iron-stained conglomerate; quartz-pebble conglomerate; and planar cross-stratified conglomerate (Ridgeway, 1986).

The Mansfield Formation is included as part of the Raccoon Creek Group (Hasenmueller and Hutchison, 1986). The formation rests unconformably on the Late Mississippian Kinkaid Limestone at its southern extreme and the Upper Devonian New Albany Shale at the northern reaches of the group; rocks below the unconformity increase in age from south to north (Gray, 1962). The Brazil Formation bounds the Mansfield Formation at the top. In areas where it is present, the Lower Block Coal marks the lower boundary of the Brazil Formation and identifies the point of contact between the two formations. South of Bloomfield, Indiana, the Lower Block Coal is absent, and determining the boundary between the two formations can be difficult.

The Mansfield Formation was originally placed in the Morrowan Series (Shaver and Smith, 1974), with the Mansfield-Brazil Formation division as the basis of Morrowan-Atokan division. More recent studies, however, include the upper part of the Mansfield Formation as part of the Atokan series (Kvale and others, 2004, citing Peppers, 1996) and date it to the Westphalian and Namurian stages—the approximate European equivalents of the Morrowan and Atokan Series—based on palynological analysis.

In this study, two outcrops of the Pennsylvanian Mansfield Formation located at the Naval Surface Warfare Center (NSWC), Crane Division, in Martin and Greene Counties of southern Indiana are examined (fig. 1B). Outcrops studied are plotted on the U.S. Geological Survey 7.5-minute topographic series, Odon quadrangle (2013), and their specific Universal Transverse Mercator (UTM) locations were determined from this map (fig. 1B). Geologic maps of surface elevations and underlying strata show very little stratigraphic dip between the two locations (Kvale, 1992). Differences in surface elevation between the outcrops correspond to, at most, a 2-m difference in elevation of the underlying strata, with a difference of less than 1 m likely; thus, H-435 is approximately 40 m stratigraphically higher and, therefore, younger than HR-150.

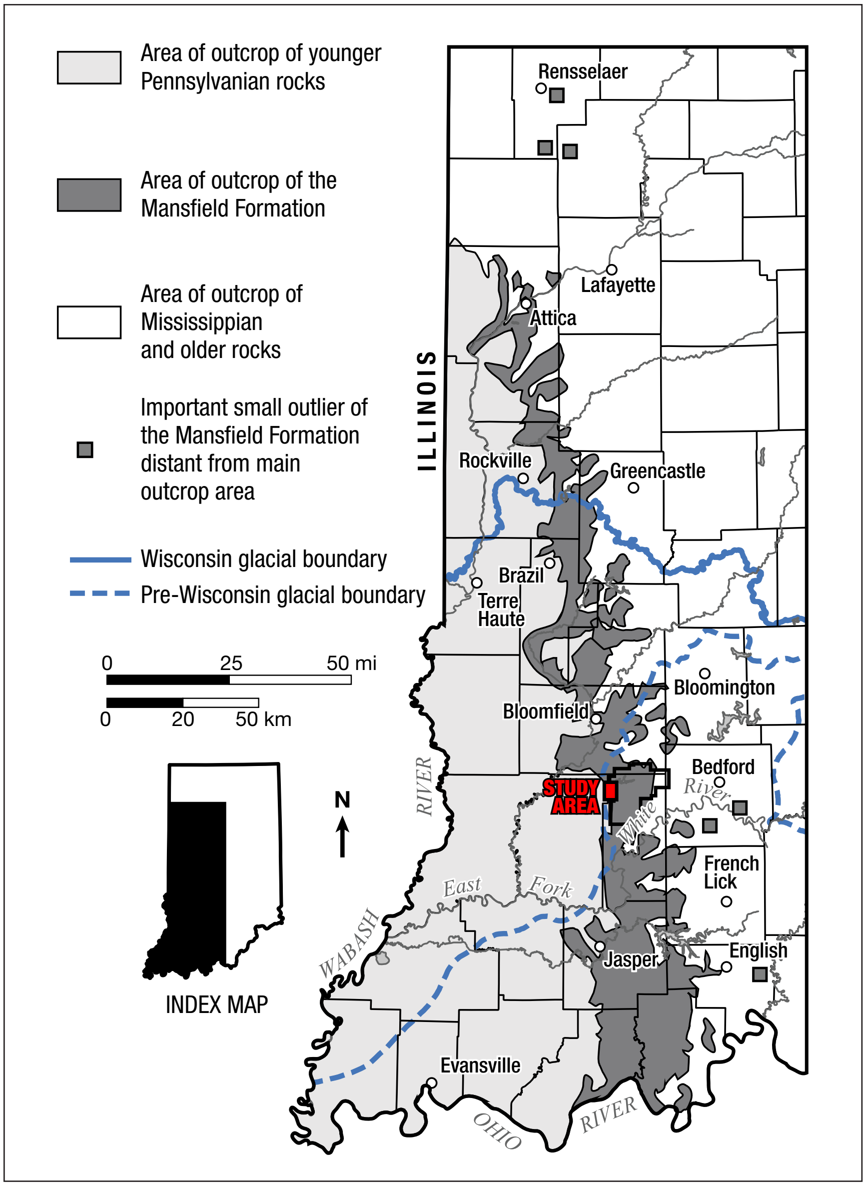

Figure 1A. Map showing the geographic extent of the Mansfield Formation in Indiana. Map is modified from Gray (1962) to show location of study area at the Naval Surface Warfare Center (NSWC), Crane Division.

The purpose of this study is to use sedimentology, stratigraphy, geochemistry, and paleobiology to describe and interpret the paleoenvironmental history of these local outcrops, and to determine the age of deposition using new palynological data.

METHODS

Outcrops of the Mansfield Formation located at NSWC, Crane Division, were examined and photographed. Individual units were measured from the base of the outcrop and developed into stratigraphic profiles. Rock samples were collected at ~10 cm intervals and examined under a binocular microscope for grain size, shape, and sorting.

Samples for geochemical analysis of carbon, organic carbon, and total sulfur were collected at 20 cm or less intervals from the stratigraphically older HR-150 outcrop and 10 cm or less intervals from the younger H-435 outcrop to assess the salinity of the paleodepositional setting. All exposed surfaces were removed before collection, and samples were

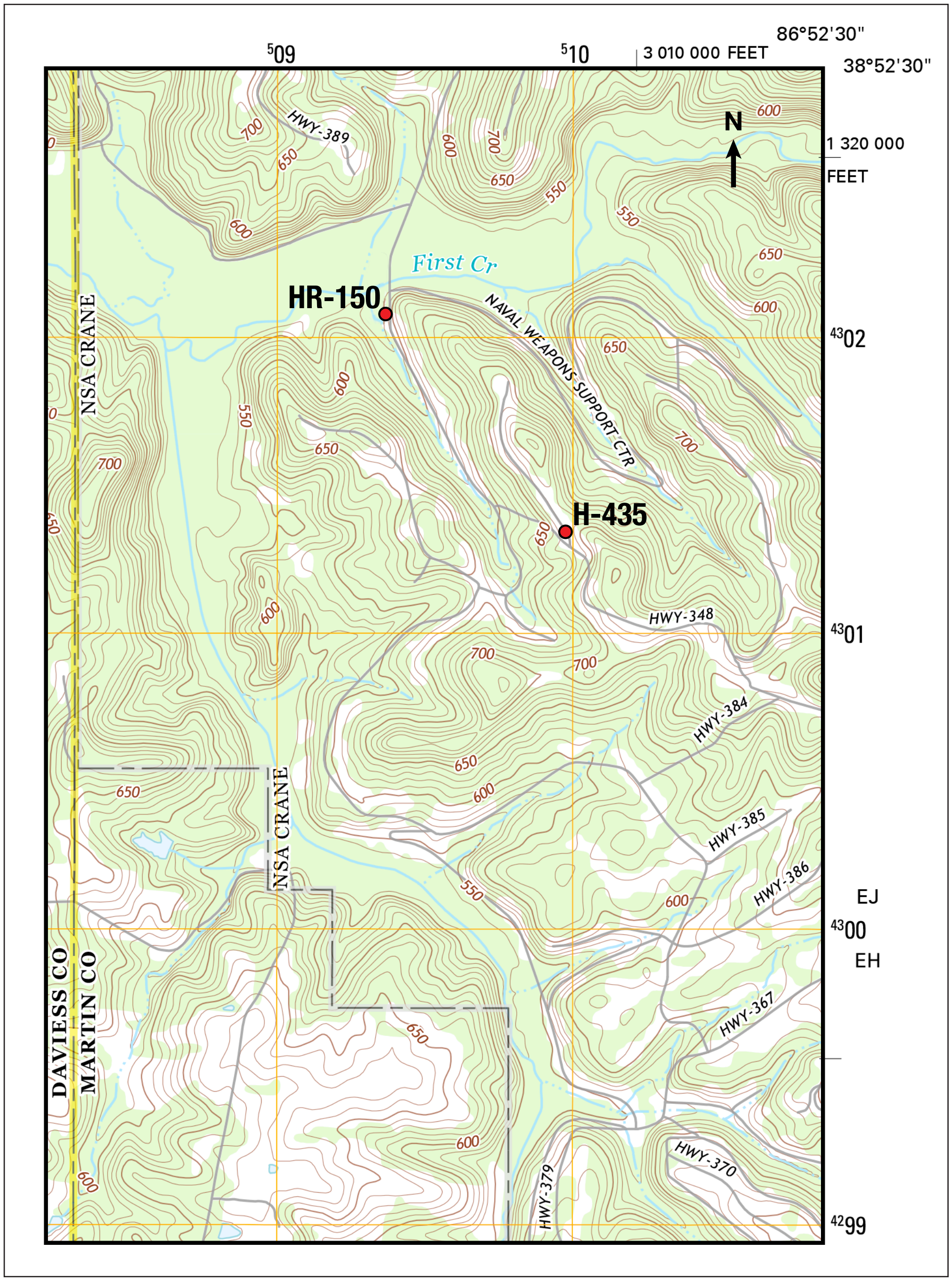

Figure 1B. U.S. Geological Survey 7.5-minute topographic map of Odon quadrangle, Martin County, Indiana (scale 1:24,000, 10-ft contour interval) (USGS, 2013) showing location of stratigraphic sections identified. The outcrop identified as HR-150 is named for a gravel road formed when railroad tracks were abandoned and removed. The outcrop is located at the intersection of H-383 and HR-150 and faces HR-150. The UTM coordinates are NAD 83, zone 16S, $^{5}09^{000m}$E, $^{43}01^{930m}$N and the approximate elevation is 165 m (540 ft) above sea level. The outcrop identified as H-435, named for the road it faces, runs parallel to railroad tracks. The UTM location is NAD 83, zone 16S, $^{5}09^{990m}$E, $^{43}01^{190m}$N). The elevation is ~207 m (680 ft) above sea level. HR-150 is ~1 km NNW of Outcrop H-435.

transported and stored in annealed aluminum foil to avoid carbon contamination prior to grinding and analysis. Total organic carbon (TOC) data were taken from powdered samples immersed in 1N HCL at 60°C for 12 to 14 hours, then filtered and recovered on baked glass-fiber filters. Total carbon (TC) and total sulfur (TS) data were taken from nonacidified ground samples. The samples were analyzed in an Eltra CS2000 resistance furnace set to 1,450°C. The Eltra CS2000 was calibrated using standards USGS SDO-1 (10 percent C, 5.6 percent S) (Kane and others, 1990) and Alpha Resource AR4019 (0.1 percent C, 0.1 percent S) and the calibration was checked after every eight to ten sample runs. Samples were analyzed in random order to prevent potential influence from instrument drift.

Specimens of trace fossils and associated rocks collected for paleoecological interpretation are housed with location data in the Indiana University Paleontology Collections in the Department of Geological Sciences, Indiana University (IU), in Bloomington, Indiana. Coal samples were collected from H-435 and processed at the Kentucky Geological Survey for palynological analysis to determine the age of the coal.

RESULTS

Stratigraphy

The stratigraphically older outcrop, HR-150 (fig. 2) is similar to the Bloomfield Lithofacies described by Gray (1962) in that cross-stratified sandstones are the predominant lithology. The outcrop extends ~5.5 m vertically and 30 m laterally, and can be divided into two sections: a lower wavy-, flaser-, and ripple-bedded silty and very fine grained sandstone section <4 m thick (units 1–13), and an upper section of ~1 m of laminated, wavy- and planar-bedded siltstone (units 15–18). Dark gray, organic-rich, friable clayey siltstone with coal inclusions separates the sections (unit 14).

The basal unit of the H-150 outcrop extends below the surface. Grains in the lower section of the outcrop tend to be subangular silt to very fine-grained, moderately sorted sand with occasional wavy layers of poorly sorted material. Layers of thin, discontinuous wavy beds bounded by clay drapes alternate with large cross-bedded units, and the upper boundary of the drapes are often marked by iron staining. Many clay drapes contain flecks of mica grains. Individual beds in the large, cross-bedded units tend to be thinner and lack clay drapes. In the upper section of the HR-150 outcrop, grains become more rounded, and sorting varies from moderate to poor. Bedding planes are wavy in the lower part of this section, but become less wavy, almost planar, near the top of the outcrop. The top of the outcrop is covered with ~1 m of modern soil.

The stratigraphically younger outcrop, H-435, (fig. 3) is ~3.5 m thick and spans 10 m laterally. The outcrop contains friable siltstone overlain by a coal seam near the base, and beds of wavy and laminated sandstones with ripples, roots, and clay drapes compose the rest of the section. Because laminated and thinly bedded siltstones and sandstones predominate, the outcrop appears to represent a hybrid of the Bloomfield and Shoals Lithofacies as described by Gray (1962).

The base of the H-435 outcrop contains friable siltstone (unit 1) that extends below the surface. Root and other plant traces mark the top of this siltstone unit. Beds of laminated siltstone with clay drapes overlie the coal seam (units 3–6). Grains tend to be well sorted and rounded. Layers immediately above the coal (units 3–4) are wavy but become planar with clay drapes along with current ripples and occasional sediment-starved ripples further up-section (units 5–6).

Plant material appears in repeating intervals toward the middle and upper sections of the outcrop (units 8–12). Beds become thin, wavy, and scoured (units 9, 10). Iron concretions (1–2 mm) are common. Grain size and angularity increase, whereas sorting decreases, becoming moderate to poor, and there is evidence of plant roots. Further up in the section, beds become planar again, and laminae of varying thickness appear in repeating cycles (unit 11). Lamina average ~1 mm thick, but in several units individual laminae are obscured by short vertical burrows. The two uppermost units (units 11, 12) contain planar laminae between intervals of vertical burrows. Asymmetrical ripples occur near the top of the outcrop (unit 12).

Geochemistry

In general, in the older HR-150 outcrop carbon and sulfur values are very low. TOC/TS ratios, TS and TOC percentages, and the percent carbonate of TC (fig. 2), in many cases, are near the detection limit

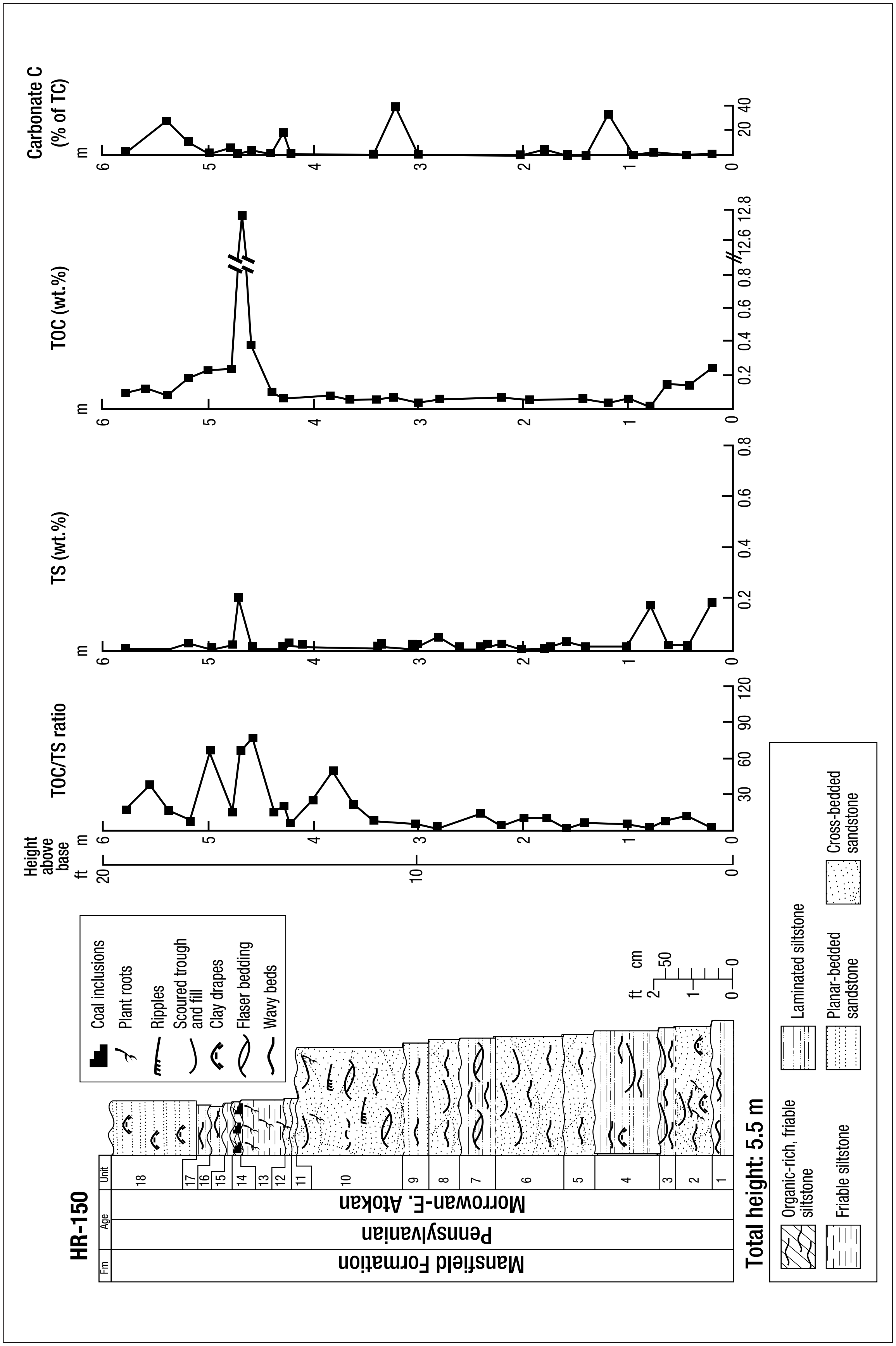

Figure 2. Chart showing the stratigraphy of HR-150, total organic carbon (TOC)/total sulfur (TS) ratios, TS and TOC percentages, and percent carbonate C (TC) of HR-150.

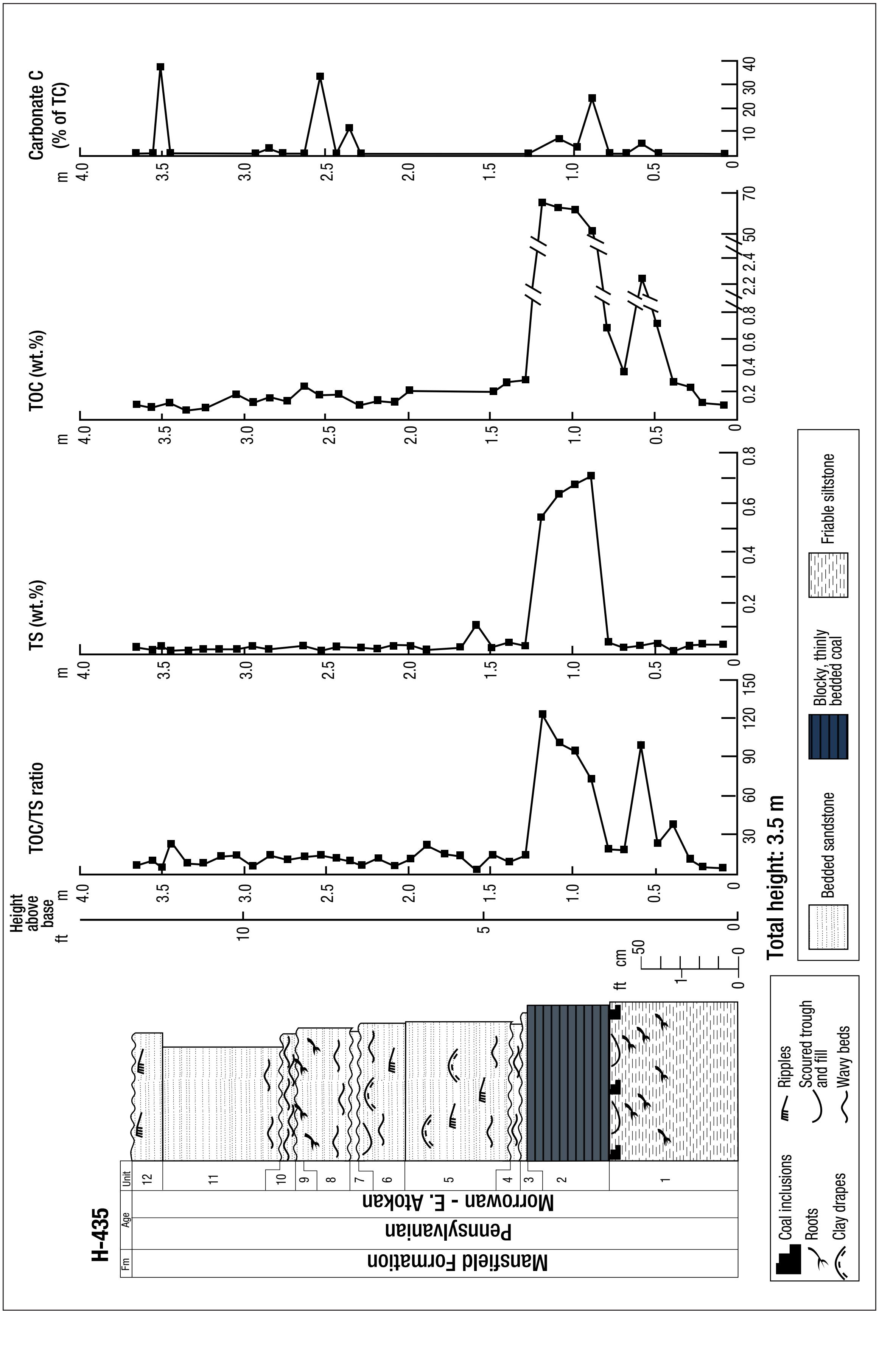

Figure 3. Chart showing the stratigraphy of H-435, total organic carbon (TOC)/ total sulfur (TS) ratios, TS and TOC percentages, and percent carbonate C (TC) of H-435.

of the equipment. Mean TOC ranges from <0.1 to 0.4 wt percent by mass except for a thin layer of organic-rich, friable siltstone with coal inclusions in the upper section (unit 14), where TC and TOC are slightly under 13 wt percent. All sulfur values are <0.2 wt percent, with most values well below 0.04 wt percent by mass. Slightly higher sulfur values are found near the base and near the friable siltstone layers, but the mean TS value for the entire outcrop is 0.03 wt percent.

Total organic carbon/total sulfur ratios vary from 76:1 in the upper section down to 1:1 in the lower half of the outcrop. The widest variations appear in the upper siltstone and sandstone units. In the lower sandstone units the ratio fluctuates from ~12.5:1 to 1:1, with a mean ratio of 5.5:1. Organic carbon levels closely approximate TC. All carbonate carbon values are less than the range of values reported for the low standard; there are no carbonate rocks in the outcrop.

Both TOC and TS levels are very low in the younger H-435 outcrop (fig. 3). Of 38 samples collected, 33 showed TOC levels well below 1.0 wt percent, with most samples at or below 0.2 wt percent. Rhizocretions near the top of the basal siltstone (unit 1) elevate TOC to 2.24 percent by mass. In the coal seam TOC varies from 51.4 to 66.8 wt percent. Mean TOC value above the coal seam is 0.15 wt percent.

As with the older outcrop, most of the carbon in the samples is of organic origin. Carbonate values are consistently below or near the detection limit. A sample collected from the upper units showed a TC loss slightly beyond the range of reported sample values, so it is likely that this sample experienced a small amount of carbon loss; adjacent samples did not show any loss under acid treatment.

With the exception of the coal seam near the base, most TS levels are at or below 0.04 wt percent, also near the detection limit. Although above background level, TS in the coal seam is still very low, between 0.6 and 0.7 wt percent, indicating a low sulfur coal. Above the coal seam, mean TS value is 0.02 wt percent, and 0.11 wt percent is the highest level in one sample collected from a unit noted for the presence of many trace fossils.

Total organic carbon/total sulfur ratios vary widely, from 122.4:1 to 1.7:1. Thirty-four of 38 samples have TOC/TS ratios above 4:1, and 21 samples have ratios above 10:1. Above the coal seam, TOC/TS ratios vary from 23:1 to 1.7:1, and 9.5:1 is the mean.

Ichnology

For the area under investigation, trace fossil data are limited, but tentative assessments are made for the morphology and distribution of trace fossils within the two outcrops (fig. 4).

Feeding traces are the predominant ichnological feature of the stratigraphically older HR-150 outcrop. Common near the base, these trace fossils diminish in number and remain sparse until the top of the outcrop (unit 18), where vertical burrows appear. The basal siltstone unit of the HR-150 outcrop contains numerous annulated burrows tentatively identified as *Scalarituba* isp. (fig. 5A). Burrows are concave epirelief in bedding surfaces, ~6 mm wide and as much as 36 cm long, with backfill of ~3 mm that makes up the burrow fill. Burrows are horizontal to oblique relative to bedding surfaces. Approximately 70 cm above the basal unit, *Scalarituba* reappears. *Asterosoma* isp. (fig. 5B) burrows vary from 1.5 to 2.5 cm and are horizontal to oblique relative to the bedding surface. Rhizoliths of various sizes with preserved root fragments are common (fig. 5C). These represent the body parts of a plant within its trace (Kraus and Hasiotis, 2006). Numerous very small (<0.5 mm diameter) horizontal straight and meandering trails in convex hyporelief on surfaces appear slightly up-section (fig. 5D). The morphology is somewhat similar to *Treptichnus*, but the pattern observed is more discontinuous in these examples. These trails are generally <8 mm long, but occasional straight trails extend up to 3 cm. The diameters tend to be consistent across the entire length but taper to points at the ends of the trails. Grain size and shape inside the burrows do not appear noticeably different from those grain characteristics outside the burrows. As noted, trace fossils that are common at the base decrease in frequency up-section. A few similar meandering burrows reappear near the middle and again at the top of this outcrop, along with vertical burrows, but they are uncommon and widely spaced. Individual meandering burrows of *Planolites* (fig. 5E) vary in diameter from 2 to 3 mm over their length.

In the stratigraphically younger H-435 outcrop, stigmaria and other plant materials are common in the basal unit just below the coal seam. Scour structures are present at the contact between the

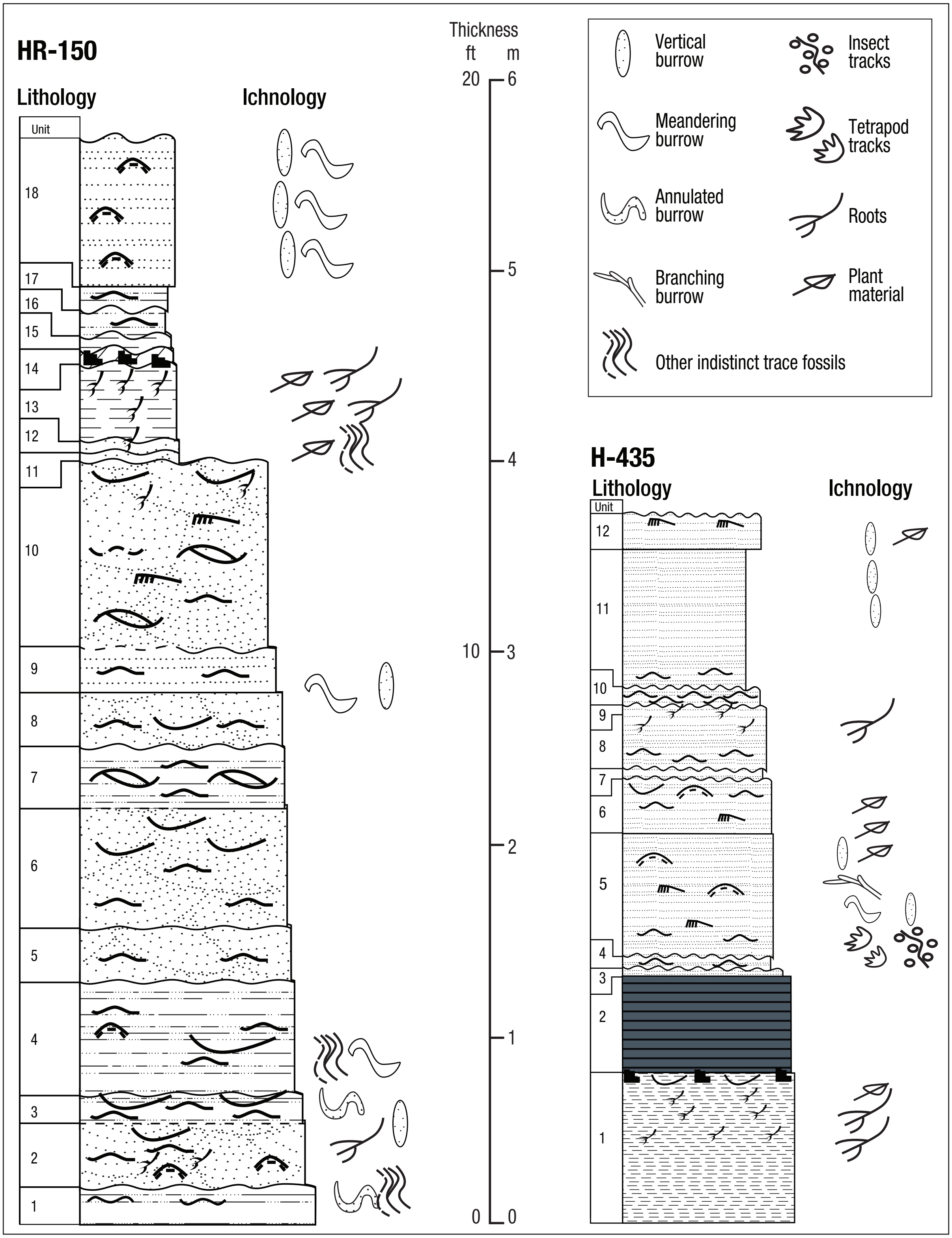

Figure 4. Chart showing the ichnology of HR-150 and H-435. Refer to Figures 3 and 4 for legends of lithologies and sedimentary structures.

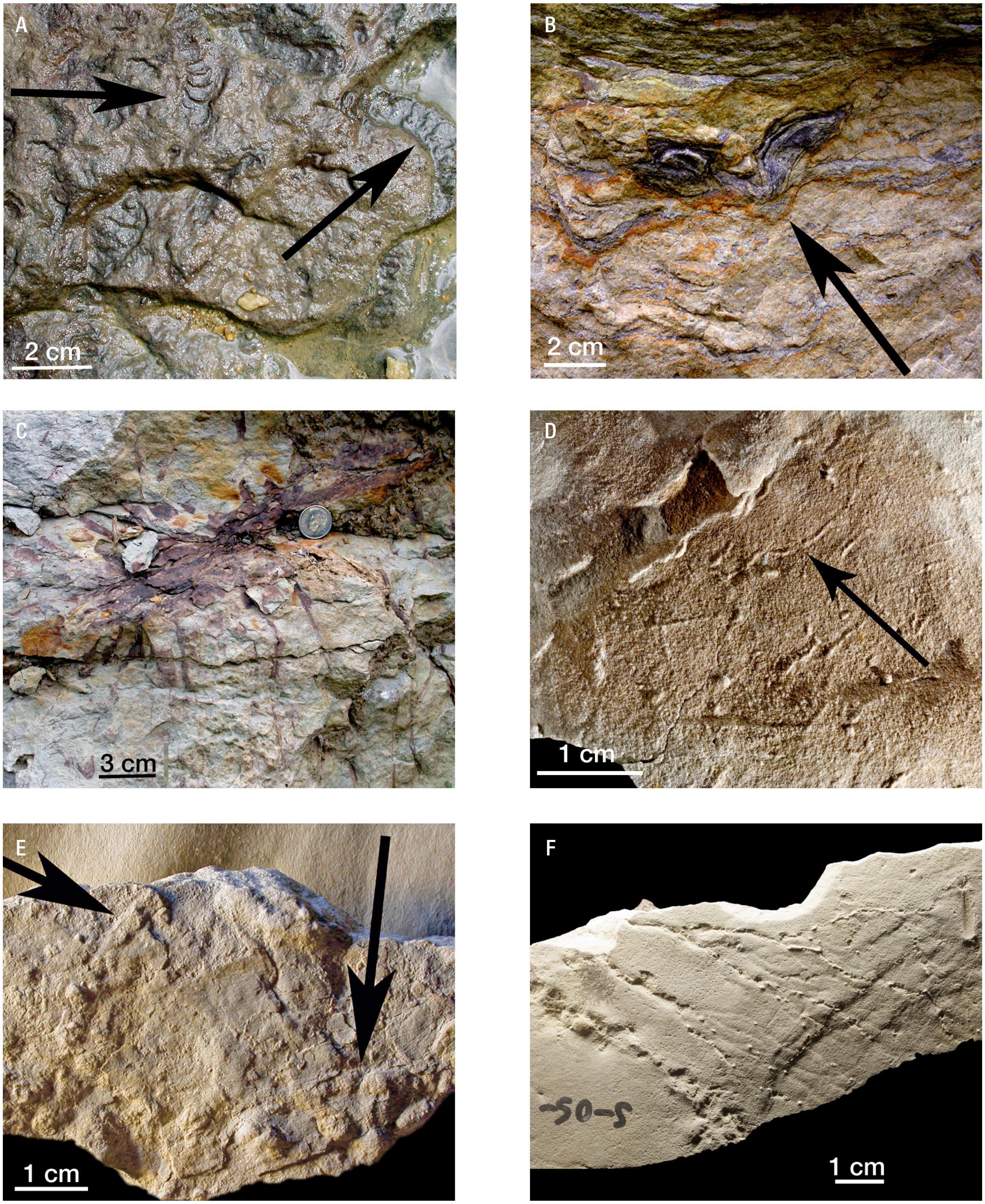

Figure 5. Photographs of trace fossils from HR-150 (A–E) and H-435 (F). A) Arrows point to *Scalarituba* isp. at the base of Unit 1 of HR-150. B) Field photo of *Asterosoma* (at arrow), common in Units 1-4 of H-150. C) Field photo of an association of plant root fossils within their trace fossils, rhizoliths, in Unit 2 of HR-150. D) Example of small horizontal trail (at arrow) assignable to *Treptichnus* isp. in reversed relief in Unit 4 of H-150. E) *Planolites* isp. (at arrows) from Unit 7 of HR-150. F) Close view of *Treptichnus* isp. from Unit 5 of H-435.

two units. Beds above the coal contain *Treptichnus* isp. (fig. 5F), branching trails with concave epirelief, 3 mm in diameter and 20 cm in total length (fig. 6A), zig-zag trails attributable to *Haplotichnus* that are concave in epirelief, and ~1.5 mm in diameter (fig. 6B), unattributed meandering burrows with convex epirelief 1 mm in diameter and ~4 cm long, meandering tracks and trails interpreted as insect repichnia or pascichnia (Buatois and others, 1997a; 1998), and tetrapod tracks (Colbert and Schaeffer, 1947; Peabody, 1959). Insect tracks, generally 0.5 mm or smaller, form trails up to 7 cm long. The tetrapod tracks (figs. 7A and 7B), assumed amphibian, are 3.5 cm wide at their widest point from inside toe tip to outside toe tip and 2.5 cm long from base of print to tip of longest digit. The pes contain five digits and the manus four. Plant material (fig. 7C) is common in repeating intervals in these units. Large, well-preserved molds of *Lepidodendron* bark are found near the top of the outcrop (fig. 7D), and layers of *Skolithos* isp. (fig. 8A), separated by many laminae, are abundant in the upper siltstone units. *Skolithos* are vertical to nearly vertical and are densely packed; 20 burrows within 1 cm are not unusual. *Skolithos* in clusters are generally of equal length. The average burrow length is ~35 mm, but length ranges from <1 cm to 7 cm. Burrow width ranges from 1 to 5 mm, and widths of 1.5 to 2 mm are the most common. Most burrows are of uniform width along their length, but burrows that broaden near the top are also common (fig. 8B). Many burrows are flanged, but most are not. Unflanged burrows may be a reflection of the quality of preservation rather than original morphology. Burrows appear unlined, with the material inside the burrow similar to that on the outside. Most burrows form concave epirelief impressions on the surface and convex hyporelief on the soles of the specimens (fig. 8C).

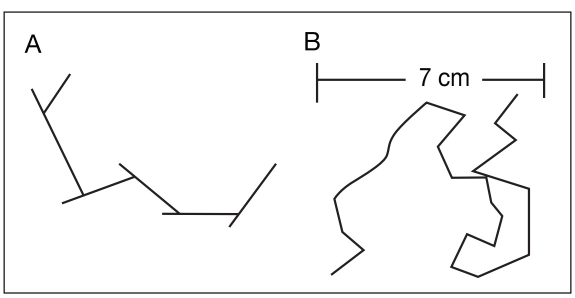

Figure 6. Line drawings of insect trails. A) *Treptichnus*. B) Zig-zag trail, attributable to *Haplotichnus*.

Palynology

Of the 250 palynomorphs extracted from the coal seam in H-435, lycopod tree spores are the dominant palynomorph, and there are significant amounts of tree fern, calamite spores, and cordiate pollen (Table 1). The most abundant lycopod spore identified is that of *Lycospora granulata* (37.6 percent of all identified spores), followed by *L. pusilla*, *L. orbicula*, and *L. micropapillata*. *Punctatisporites minutus* and *Punctatosporites minutus* are the major tree ferns represented. *Laevigatosporites minor* is the most numerous species of calamite and *Florinites mediapudens* the most common cordaite.

Table 1. Palynology of coal samples from H-435

Taxon	Percentage
Lycospora pellucida	1.2
L. pusilla	9.2
L. granulata	37.6
L. orbicula	5.2
L. micropapillata	4.4
Granasporites medius	1.2
Total lycopod tree spores	**58.8**
Cirratriradites saturni	0.4
Endosporites globiformis	0.8
Total small lycopod spores	**1.2**
Punctatisporites minutus	16.0
Punctatosporites minutus	0.8
P. rotundus	7.6
Laevigatosporites minimus	0.4
Total tree fern spores	**24.8**
Granulatisporites adnatoides	0.4
Lophotriletes microsaetosus	0.4
Total small fern spores	**0.8**
Calamospora pedata	0.8
C. microrugosa	0.4
Laevigatosporites minor	6.0
Total calamite spores	**7.2**
Florinites florini	1.2
F. mediapudens	5.6
Total cordaite pollen	**6.8**
Tantillus triquetrus	0.4
Total unknown forms	**0.4**

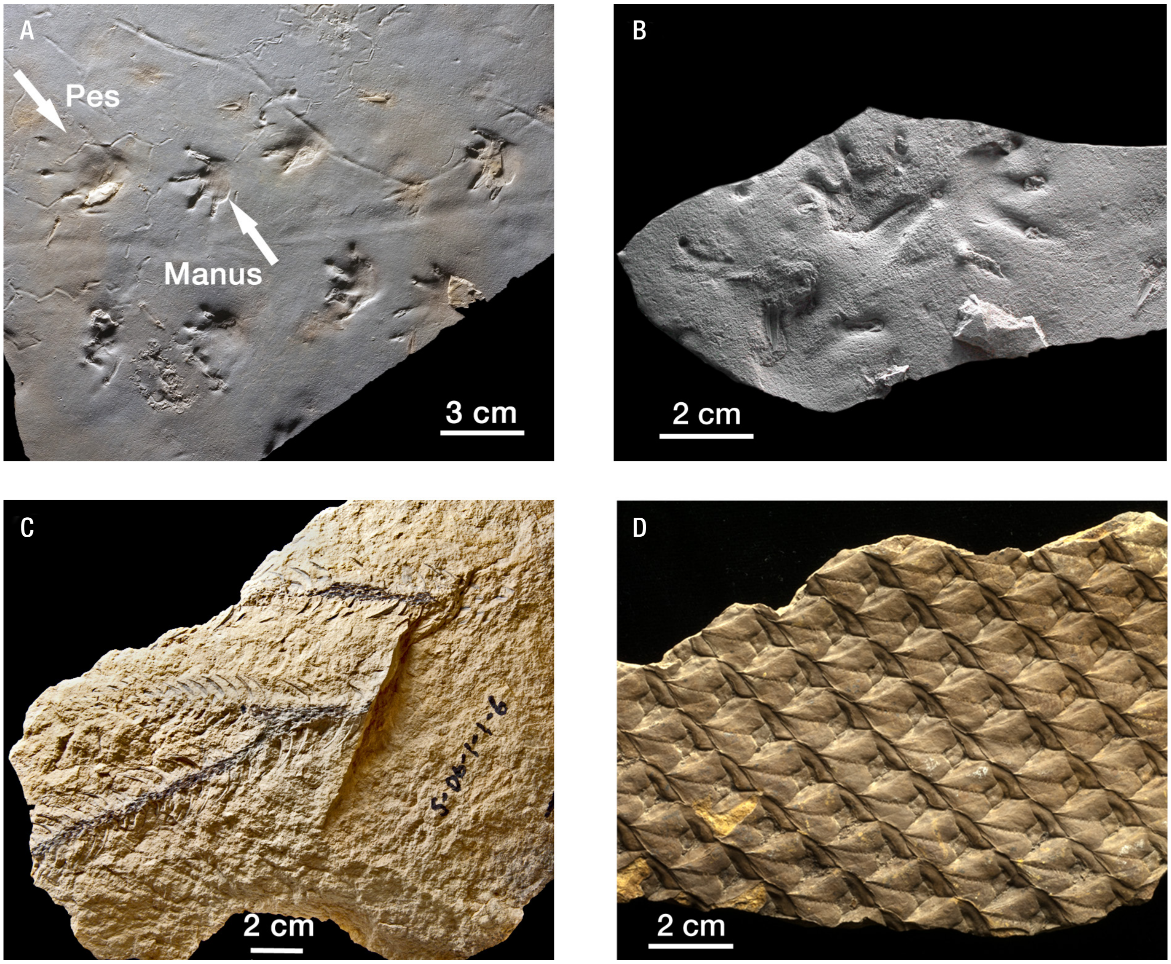

Figure 7. Photographs of trace fossils found at H-435. A and B) Tetrapod tracks. Treptichnus is also visible on the bedding plane in A. C) Plant material from Unit 6 of H-435; specimen #19003. D) Lepidodendron mold from Unit 12 of H-435, with preservation of fine bark details; specimen #19004.

DISCUSSION

A general age of the outcrops under investigation can be assigned based on the palynomorphs obtained from the coal seam in the H-435 outcrop. Phillips and Peppers (1984) determined that the predominance of *Lycospora granulata* is characteristic of the Morrowan and early Atokan stages of the Early Pennsylvanian, and *L. granulata* is succeeded in predominance by *L. micropapillata* by the middle Atokan. Because *L. granulata* is the dominant species in the studied samples of the H-435 coal seam, and *L. micropapillata* makes up only 4.4 percent of the palynomorphs, the upper age of the H-435 outcrop containing the coal seam is constrained to the early Atokan. The HR-150 outcrop lies stratigraphically below the H-435 outcrop by ~40 m, and thus extends into the Morrowan.

Total sulfur concentrations can be used as a proxy for salinity and thus for determining the depositional environments of the outcrops examined. Although low carbon values undermine confidence in using TOC/TS ratios as the sole indicator of salinity (Berner and Raiswell, 1984), a consideration of TS data as a proxy for salinity in combination with TOC/TS ratios help to strengthen interpretations for the Mansfield outcrops. Sulfate concentration in water tends to vary with variations in salinity; average dissolved sulfate concentrations in marine water are ~28.2 per mil compared to <1 per mil for freshwater. Mastalerz and others (1997, 1999) interpreted rocks from the Mansfield Formation having <0.08 wt percent TS

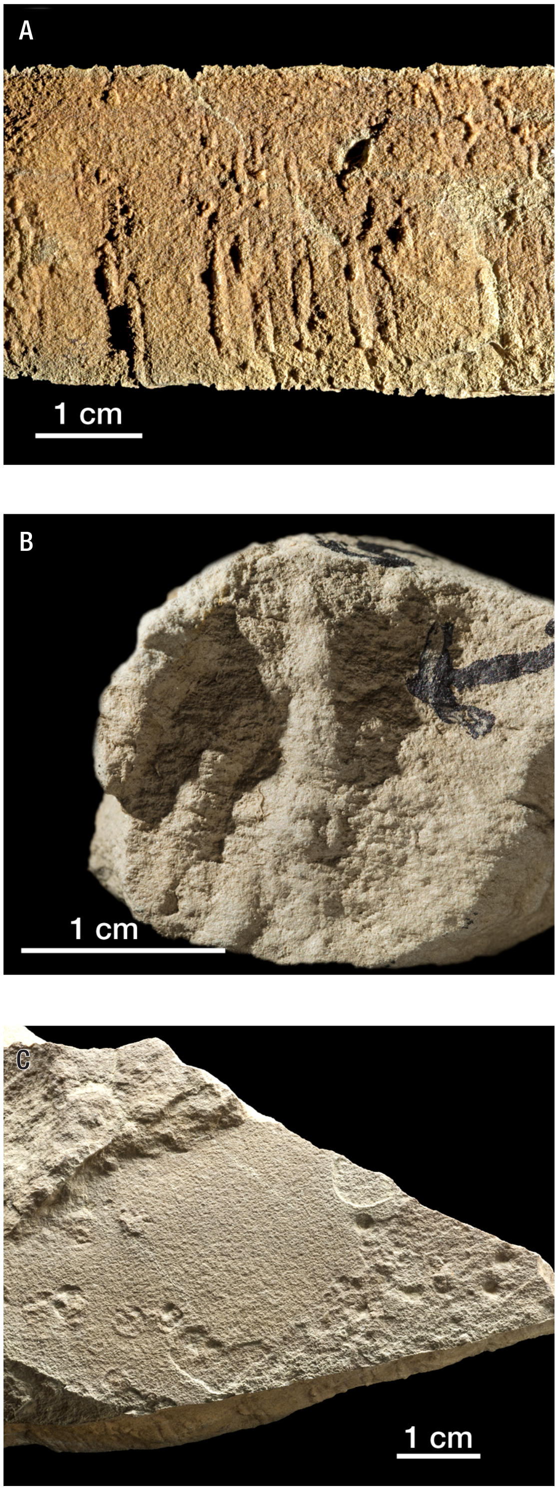

Figure 8. Photographs of burrows from H-435. A) *Skolithos* from near the top of the outcrop; specimen #19005. B) An example of flanged burrows from Unit 12, assigned to *Skolithos*; slight curve of these burrows is unusual; specimen #19006. C) Top view of the same *Skolithos* sample as Figure 8A showing concave epirelief where burrows intersect the bedding plane.

as freshwater and those above 0.08 wt percent TS as deposited in brackish to marine environments. Mastalerz and others (1997, 1999) interpreted coals not covered by thick layers of fine-grained sediments bearing <1.0 wt percent TS—described as low sulfur—as having been inundated by freshwater; coals >2.0 wt percent TS reflect subsequent marine influence. In contrast, Algeo and Maynard (2004) and Algeo and others (2004) found that TS values for shales are generally between 1 and 3 wt percent, with the exception of shales formed in dysoxic water, which contain between 0.4 and 2.0 wt percent TS. The consistently low TS values of the samples analyzed in this study (coal <1 wt percent; all other samples 0.2 wt percent or less) indicate that marine input, and therefore salinity, was generally low to negligible during most of the depositional history of both outcrops.

Archer and Maples (1984) defined ichnofossil assemblages for the Mansfield Formation and assigned the assemblages to different depositional environments. However, trace fossils identified in this study were found in lithofacies different from those associated with the assemblages noted by Archer and Maples (1984). A lack of positive taxonomic identification of the trace fossils collected at Crane NSWC limits but does not preclude inferences about depositional environments; however, all inferences must be regarded as tentative.

The older HR-150 outcrop

The silty sandstone units that make up the lower section of the HR-150 outcrop are indicative of a low-energy, shallow-water environment. Clay drapes, common in the lower units of the outcrop, form by the settling of suspended loads during slack currents (Visser, 1980; Terwindt, 1981). This is typical of varying paleocurrent strength that likely indicates variations in fluvial input resulting from rainfall or tidal influences (Kvale and Barnhill, 1994). This section is similar to Facies I of the Kanawha Formation of West Virginia (Martino, 1989), and the fine-grained sandstone facies of the Morrow Sandstone (Buatois and others, 1999), both interpreted as fluviodeltaic channels. The section appears to be a hybrid of the rooted mudstone, siltstone, and sandstone facies and the wavy-bedded and flaser-bedded sandstone facies described by Barnhill (1992; see also Barnhill and Hansley, 1993, and Kvale and Barnhill, 1994), interpreted as a shallow, intertidal, or supratidal environment.

Scalarituba is indicative of a tidal-flat environment (Conkin and Conkin, 1968; Mangano and others, 2000). These burrows represent the feeding behavior of a sediment-ingesting worm or worm-like organism (Häntzschel, 1975). *Asterosoma* is both a domicile and feeding burrow (Chamberlain, 1971), and has been reported in areas of shallow, low-energy environments of varying salinity (Greb and Chestnut, 1994), such as a tidally influenced estuary. The TOC/TS ratios and low TS values (fig. 2) of the lower section are indicative of freshwater conditions, with possible brief marine water incursions in Units 1 and 3, as indicated by the elevation of TS and the *Scalarituba* trace fossils. The low carbonate levels, which are generally near detection limits, support the interpretation and suggest a strong fluvial influence.

The overall TOC/TS ratio increases and fluctuates more widely in the upper part of the HR-150 outcrop. This is typical of freshwater systems (Berner and Raiswell, 1984). Burrows in overlying units are often associated with the *Scoyenia* ichnofacies, characterized by low diversity and a preponderance of fodinichnia (Frey and Pemberton, 1984). The ichnofacies is attributed to shallow, subaqueous environments of very low salinity, relatively high energy, and occasional subaerial exposure (Buatois and others, 1997b). Plant roots and other materials often associated with, but distinct from, the *Scoyenia* ichnofacies suggest a temporary reduction of clastic input (Barnhill and Hansley, 1993).

Friable texture and the presence of abundant rhizoliths and other unidentifiable plant material characterize the transition, at upper unit 13 and unit 14, between the two sections of the outcrop. These features may suggest the presence of a paleosol (upper unit 13) and, if so, may represent an interfluve environment similar to those noted by Buatois and others (1999). An increase in TS value and dip in TOC/TS ratio is recorded in a friable black siltstone layer with coal inclusions (unit 14) that overlies the paleosol. It is likely the result of saline poisoning, sudden burial of the vegetation and inundation with marine water, perhaps indicative of a storm. The organic-rich friable black siltstone layer is overlain by the organic-poor siltstones. Iron staining in these units suggests a predominantly saturated environment.

Further up-section, the alternating cycles of thin laminae and abundant, nonpenetrative bioturbation are typical of seasonal periods of alternating light and heavy sediment input or other biological stresses. The return of meandering *Planolites* isp. near the top of the outcrop may point to a return of fluvial or marine tidal activity. *Planolites*, however, is a facies-crossing ichnofossil (Hakes, 1976), thus the strength of conclusions about depositional environments drawn by its presence must be tempered. The wavy beds suggest a brief return of periodic siliciclastic input, which has apparently transformed the region into a shallow, tidally influenced estuarine-like environment (Barnhill, 1992; Barnhill and Hansley, 1993; Kvale and Barnhill, 1994), possibly caused by settling of underlying sediments or increasing sea level. This interpretation of the uppermost units is supported by a lack of pyrite in the samples collected.

Spikes in the percentage of carbonate carbon throughout the outcrop could be interpreted as possible brackish or marine incursions, but the interpretation is not supported by correlative increases in TS values. With overall carbon levels so low, the spikes in the carbonate percentage may not be particularly significant or they could be related to changes in pH of the system.

The stratigraphically higher H-435 outcrop

The friable texture and rhizoliths below the coal seam in the H-435 outcrop are indicative of a paleosol. The preservation of carbonaceous root material indicates a very poorly drained depositional environment (Kraus and Hasiotis, 2006). Scours are present on top of the unit 1 siltstone. In similar settings the paleosol is often interpreted as evidence of a subaerial or shallow, tidally influenced subaqueous environment (see Retallack, 1988). Iron staining and the marshy environment evident from the overlying coal seam suggest a predominantly wet environment.

Total sulfur in the coal seam is very low, between 0.6 to 0.7 wt percent (fig. 3), indicating a low-sulfur coal. It is generally accepted that Pennsylvanian low-sulfur coals represent peat mires inundated by freshwater incursions, yet the sudden increase in TS in this layer above background levels appears to suggest some marine influence. However, Pennsylvanian coal-producing plants did not tolerate prolonged exposure to saltwater (Hakes, 1976), implying fresh- to brackish water conditions in the immediate area (Martino, 1996). Other possible explanations for the elevated TS levels include organic plant sulfur (Hackley and

Anderson, 1986), sulfate-reducing bacteria (Spiker and others, 1994), or detrital influx (Eble and others, 1994). The absence of high sulfur values (namely, >~2.0 percent) suggests that any inundation was by fresh-, or possibly brackish, water. This supports the interpretation of a fresh- to brackish water depositional environment for similar strata (Mastalerz and others, 1997). For this outcrop TOC/TS ratios further support a predominantly fresh- to brackish water interpretation of the depositional environment.

The thinly bedded sandstone overlying the coal would presumably allow the migration of sulfur via contact with more highly saline water. Yet TS levels remain very low. A primarily freshwater depositional environment may thus be inferred for this unit (unit 3) that overlies the coal seam. However, coals are interpreted to indicate periods of prolonged wetness, whereas siliciclastic flux is more typical of seasonal rainfall (for example, Martino, 1996). Kvale and Barnhill (1994) attribute the association of Pennsylvanian coals and laminated siltstone deposits to freshwater, supratidal deposition. Another possible interpretation of unit 3 is, therefore, of a supra- or intertidal flat.

The overall sequence of paleosol changing to coal to wavy-bedded sandstone and ultimately to laminated siltstones suggests a marine transgression that ultimately created a shallow subaqueous environment influenced by paleocurrents, as indicated by the ripples and starved ripples near the middle of the stratigraphic section. These features are all characteristic of shallow inter- and subtidal or sand-mud flats (Barnhill, 1992; Barnhill and Hansley, 1993; Lucas and others, 2004). There is evidence of rooting in the thin, wavy beds in the middle of the outcrop. Rooting in tidal-influenced beds is indicative of a vegetated tidal flat (Kvale and Barnhill, 1994).

Fluctuations in the percentage of carbonate carbon may indicate brief marine incursions, although low carbon values undermine confidence in this interpretation. Moreover, TS values are well below those generally associated with marine environments. Taken together, the low sulfur content of the coal and overlying strata appear to preclude a marine depositional environment.

The outcrop contains *Haplichnus* and *Treptichnus*, trace fossils similar to those identified by Archer and Maples (1984) in the Hindostan Whetstone Beds, suggesting that facies-crossing organisms are present. Unlike the thinly bedded siltstone-sandstone facies of the Kanawha Formation described by Martino (1994), however, the whetstone facies of the Hindostan Whetstone Beds are interpreted as indicating a freshwater depositional environment (Archer and Maples, 1984). Freshwater, tidally influenced systems have been identified in other sections of the Mansfield Formation (Kvale and others, 1989; Kvale and Mastalerz, 1998). Low TS concentrations suggest that this unit may also have been a tidally influenced freshwater environment.

The change from the horizontally oriented tracks and trails near the middle of the outcrop to vertical burrows near the top suggests a shift from deposit- to suspension-feeding fauna. Packets of thin laminae alternating with thick layers of vertical burrows in the upper units are taken as evidence of tidal influences and variations in sediment input (Ekdale and others, 1984, p. 90), typical of tidally influenced sand and mud flats (Kvale and Barnhill, 1994; Martino, 1994; Mangano and others, 2001). Alternating cycles of thin laminae and abundant, nonpenetrative bioturbation have been attributed to variations in energy, with laminated zones reflecting higher energy events and consequent higher siliciclastic input and bioturbated zones indicative of lower current velocities (Beynon and Pemberton, 1992), typical of seasonal periods of light and heavy sediment input or other biological stresses. The ichnology of the two uppermost units is typical of the *Skolithos* ichnofacies, which is characterized by high abundance and low diversity of ichnofossils (Frey and Pemberton, 1984). This ichnofacies is associated with intertidal zones, shifting sand (Ekdale and others, 1984, p. 75), brackish water (Pemberton and Wightman, 1992; Martino, 1994; Buatois and others, 1998), fluctuating salinity and energy (Martino, 1994), and episodic sedimentation (Maples and Suttner, 1990).

CONCLUSIONS

The two studied outcrops of the Mansfield Formation at Crane NSWC reveal evidence of subtly changing environmental conditions during the time of deposition in the Early Pennsylvanian. Most indications from the geochemical analyses of the two outcrops, coupled with interpretations of bedding features and trace fossils, suggest freshwater to brackish water deposition for most, if not all, of the beds under investigation. A fluviodeltaic system with sands and silts as the predominant lithoclasts is suggested as the dominant paleoenvironment for these outcrops. Although the exact position of the two outcrops within the Mansfield Formation remains unclear, it is suggested that the upper age limit of the younger H-435 outcrop is early Atokan. This contribution is based on palynomorph analyses from fossils in the H-435 coal seam. Units of the younger and older outcrops below the H-435 coal seam thus lie between the early Atokan and the Morrowan, although the exact placement in the Morrowan remains to be discerned with further investigations.

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