Allostratigraphic and Sedimentologic Applications of Trace Fossils to the Study of Incised Estuarine Valleys: An Example from the Virgilian Tonganoxie Sandstone Member of Eastern Kansas

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Abstract

The Tonganoxie Sandstone Member (Stranger Formation) records part of the infill of an estuarine valley system that was incised during a late Missourian (Late Carboniferous) drop in sea level and subsequently infilled during a transgressive episode later in the Virgilian (Late Carboniferous). At Buildex Quarry, in an eastern valley margin position, this unit is represented by planar-bedded-and-laminated siltstone beds (tidal rhythmites) overlying a coplanar surface of lowstand erosion and subsequent transgression. These tidal rhythmites contain a relatively diverse ichnofauna dominated by arthropod trackways, surface grazing trails, fish traces, and tetrapod tracks, including the ichnogenera *Circulichnis* Vyalov, *Dendroidichnites* Demathieu, Gand, and Toutin-Morin, *Diplichnites* Dawson, *Diplopodichnus* Brady, *Gordia* Emmons, *Helminthoidichnites* Fitch, *Helminthopsis* Heer, *Kouphichnium* Nopcsa, *Mirandaichnium* Aceñolaza, *Stiaria* Smith, *Stiallia* Smith, *Tonganoxichnus* Mángano, Buatois, Maples, and Lanier, *Treptichnus* Miller, and *Undichna* Anderson. The Buildex ichnofauna represents a mixture of the nonmarine *Scoyenia* and *Mermia* ichnofacies and records the activity of a terrestrial and freshwater biota. Ichnologic evidence, coupled with sedimentologic data, suggests that the Buildex succession was deposited on tidal flats in the most proximal zone of the inner estuary, between the landward limit of tidal currents and the salinity limit further towards the sea. This type of trace-fossil assemblage seems to characterize the lower part of transgressive system tracts, immediately overlying the coplanar surface during the late Paleozoic. As transgression proceeded, tide-influenced freshwater facies tended to be replaced by retrogradational brackish-water parasequences, and the mixed *Scoyenia* and *Mermia* ichnofacies was replaced by a *Skolithos*-impoverished *Cruziana* ichnofacies. The coplanar surface (flooding surface and sequence boundary) that marks the base of the Tonganoxie sequence at Buildex lacks the substrate-controlled, marine *Glossifungites* ichnofacies. The coals and paleosols with upright plant remains that typify the coplanar surface at Buildex represent erosional truncation and subsequent omission close to the interfluves and may be regarded as the landward equivalent of the *Glossifungites* ichnofacies. Buildex-type ichnofaunas probably are widespread in Pennsylvanian tidal rhythmites of the U.S. Midcontinent and may be used to identify freshwater inner estuarine facies, to delineate fluvio-estuarine transitions in incised valley systems, and to refine models based exclusively on lithofacies evidence.

The sedimentary facies, depositional dynamics, and sea-level history of estuarine paleovalleys have received increased attention during the last few years (e.g., Dalrymple et al., 1990, 1992, 1994; Allen, 1991; Nichols et al., 1991; Allen and Posamentier, 1993; Zaitlin et al., 1994). The ichnology of estuarine depositional systems is also becoming a focus of intense research (e.g., Bjerstedt, 1987; Wightman et al., 1987; Pattison, 1992; Benyon and Pemberton, 1992; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992; Pemberton, Reinson et al., 1992; Greb and Chesnut, 1994; MacEachern and Pemberton, 1994). Studies of organism-sediment interactions in such environments provide valuable information on the role of salinity as a controlling factor in benthic faunal distributions, allowing the recognition of estuarine deposits and discontinuity surfaces due to estuarine valley incision.

The Tonganoxie Sandstone Member (Stranger Formation, Douglas Group) of eastern Kansas records sedimentation within an estuarine paleovalley that was incised during a late Missourian (Late Carboniferous) drop in sea level and was later infilled during a Virgilian (Late Carboniferous) transgressive episode (Lins, 1950; Lanier et al., 1993; Archer, Lanier et al., 1994; Archer and Feldman, 1995; Feldman et al., 1995). At Buildex Quarry (fig. 1),
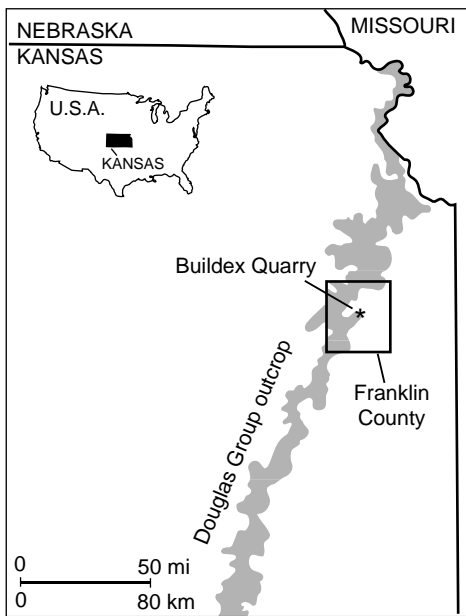
FIGURE 1. Map showing surficial distribution of the Douglas Group and location of Buildex Quarry (adapted from Lanier et al., 1993).

well-exposed deposits of the Tonganoxie Sandstone Member are interpreted as having been formed in a fluvio-estuarine transitional setting (Bandel, 1967; Lanier, 1993; Lanier et al., 1993). These deposits host a rich and very well preserved vertebrate and invertebrate trace-fossil assemblage. The Buildex ichnofauna was first analyzed by Bandel (1967), who described some arthropod traces and suggested deposition in a river valley close to the river's mouth. Subsequently, Buildex trace fossils were mentioned or briefly discussed in a series of sedimentologic papers (Archer, 1993; Lanier et al., 1993; Archer, Feldman et al., 1994; Archer, Lanier et al., 1994; Feldman et al., 1995; Tessier et al., 1995).

This paper deals with the sedimentologic and stratigraphic implications of the Tonganoxie Sandstone ichnofauna at Buildex Quarry (fig. 1). Our conclusions on the paleoenvironmental significance of this ichnofauna are based on the study of 65 rock slabs collected by the authors and 12 samples from Bandel's original collection. The aim of this paper is threefold: (1) to discuss the relevance of the Buildex ichnofauna for facies delineation of estuarine valley systems, in particular at the fluvio-estuarine transition; (2) to analyze the allostratigraphic implications of this ichnofauna; and (3) to emphasize the regional significance of the Buildex trace-fossil assemblage.

Stratigraphy and Location of the Study Area

Strata of the Douglas Group (Missourian-Virgilian) (Late Carboniferous) are exposed in the eastern Kansas outcrop belt (fig. 1). The Douglas Group, which is underlain by the Lansing Group (Missourian) and overlain by the Shawnee Group (Virgilian), comprises the Weston Shale, Stranger Formation, and Lawrence Formation (fig. 2). The Stranger Formation is in turn subdivided into the Ottawa coal and the Tonganoxie Sandstone, Westphalia Limestone, Vinland Shale, Haskell Limestone, and Robbins Shale Members.

This study focuses on a 9-m (30-ft)-thick succession of the Tonganoxie Sandstone Member exposed in the Buildex Quarry, southwest of the town of Ottawa in Franklin County, Kansas (NW sec. 23, T. 17 S., R. 19 E.). At Buildex Quarry, the Stranger Formation overlies the Weston Shale, and consists of the Ottawa coal and the Tonganoxie Sandstone Member. Exposures of the Tonganoxie Sandstone Member are present along the north, west, and south faces of the quarry. The north (fig. 3) and south walls are too steep to allow detailed observations; however, the west wall contains a bench along its expanse allowing full access to this outcrop face.

Trace fossils analyzed in this paper were collected from the lowest 5 m (16.5 ft) of the Tonganoxie Sandstone Member. The specimens described by Bandel (1967), also considered in this study, were recovered from the same locality. With respect to the stratigraphic position of these specimens, Bandel recorded that they "occur in a sequence, 1 m thick, of about 20 thin-bedded siltstone and claystone strata overlying the Ottawa coal" (Bandel, 1967, p. 2).
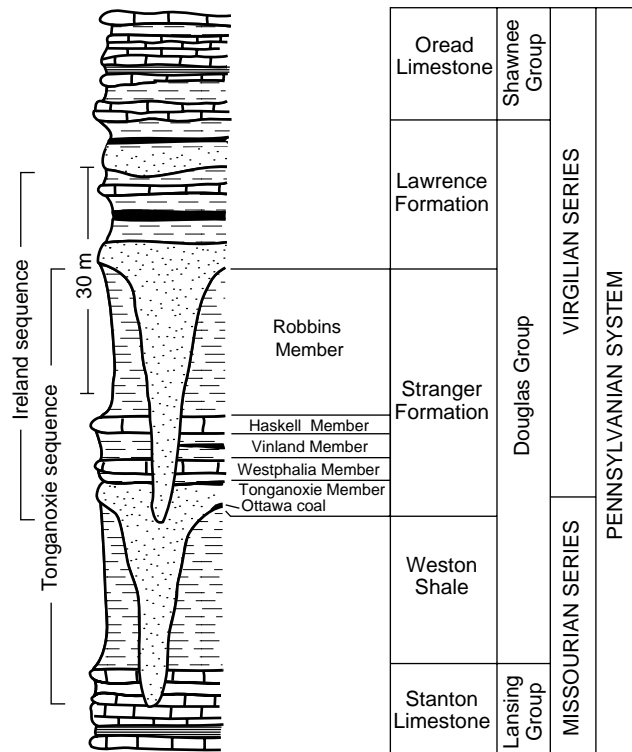

FIGURE 2. Stratigraphy of the Douglas Group (after Archer, Lanier et al., 1994). Two valley-fill sequences (Tonganoxie and Ireland) are illustrated.

FIGURE 3. General view of the north wall at Buildex Quarry. Note the disconformable contact between the laterally continuous Tonganoxie Sandstone Member and the underlying Weston Shale Member. The Ottawa coal occurs between these two units.

Sedimentary Facies of the Buildex Succession

The sedimentary facies of the lowest 5 m (16.5 ft) of the Tonganoxie Sandstone at Buildex Quarry have been analyzed recently by Lanier et al. (1993) (table 1). These authors recognized two facies: planar-bedded-and-laminated facies (PBL) and channel-and-levee facies (CL) (fig. 4). Facies PBL was further subdivided into three vertically-stacked units and facies CL into two units. Descriptions and interpretations of these facies are summarized as follows.

Facies PBL: Planar-bedded-and-laminated

This facies consists of gray siltstone beds that are laterally persistent, normally graded, parallel laminated, and coarse grained. Convolute lamination is present locally. Total thickness of facies PBL is 2.8 m (9.2 ft). Individual laminae and beds range from 0.05 cm to 12.5 cm (0.02–5 in). Strata of PBL facies are stacked, forming symmetric cycles that display a gradual increase and then decrease in bed thickness. The PBL facies is subdivided into three discrete units (A1–A3) based on vertical changes in bed thickness and physical sedimentary structures (fig. 4).

Unit A1 is about 25 cm (10 in) thick and overlies the Ottawa coal. It consists of 0.05–1.38-cm (0.02–0.56-in)-thick, sharp-based, siltstone laminae and beds. Incipient climbing ripples and syndepositional normal microfaults are present locally. Upright plant remains rooted in the Ottawa coal also were detected.

Unit A2 is 2.2 m (7.3 ft) thick, gradationally overlies unit A1, and comprises thicker-bedded, sharp-based, siltstone beds that range in thickness from 1.4 cm to 12.5 cm (0.5–5 in). Climbing ripples are fully developed. A convoluted bedset interval occurs 1.25–1.75 m (4.13–5.78 ft) above the base of unit A2, which is 1.5–2.0 m (5–6.6 ft) above the base of the Tonganoxie Sandstone Member. A vertically repeating pattern of sedimentary structures occurs within most beds. Siltstone strata include, from base to top, a massive or normally-graded division, a parallel-laminated division, a climbing-ripple division, and an upper parallel-laminated division. Bedding-surface structures are diverse and common, including physical sedimentary structures (tool marks, load casts, raindrop impressions, runnel marks) and trace fossils of both invertebrates and vertebrates. Plant leaves commonly are preserved.

Unit A3 grades transitionally upwards from unit A2. It is about 50 cm (20 in) thick and comprises thinner-bedded siltstone strata that are 0.1–1.8 cm (0.04–0.72 in) thick. Dominant sedimentary structures include normal grading, parallel lamination, and climbing ripples. Starved ripples also are present locally. Bedding-plane structures, which are varied and abundant, consist of various types of tool marks, raindrop impressions, falling-water marks, surface drainage or seepage rill marks, wrinkle marks, and trace fossils. Plant leaves and logs are common.

Facies CL: Channel-and-levee

Facies PBL grades into facies CL, which is characterized by an increase in siltstone bed thickness. This facies is

TABLE 1. Sedimentary facies of the Buildex succession (based on Lanier, 1993 and Lanier et al., 1993).

Facies	Unit	Description
CL	B2	Planar-stratified siltstones locally truncated by the channelized surface. Normal grading, poorly-developed cross-lamination. Drip marks associated with upright plants. Plant leaves and roots. Total thickness: 1.8 m.
CL	B1	Channelized siltstone body, 1 m thick and 10–12 m wide. Strata thin and pinched out laterally towards the erosive bounding surface and culminate upward into planar-stratified beds and a horizontal upper bounding surface. Climbing ripples, parallel-lamination, clay drapes, linguoid ripples, cross-lamination. Drag marks, wrinkle marks, rill marks, runnel marks, runoff washouts, foam marks, raindrop impressions. Trace fossils. Root structures.
PBL	A3	Sharp-based siltstone beds. Normal grading, parallel-lamination, climbing ripples, starved ripples. Tool marks, falling-water marks, raindrop impressions, surface drainage or seepage rill marks, wrinkle marks. Trace fossils. Plant leaves and logs. Beds 0.1–1.8 cm thick. Total thickness: 50 cm.
PBL	A2	Sharp-based siltstone beds. Climbing ripples fully developed. Convolute lamination. Individual strata typically include, from base to top, a normally graded division, a parallel-laminated division, a climbing ripple division, and an upper parallel-laminated division. Tool marks, load casts, raindrop impressions, runnel marks. Trace fossils. Plant leaves. Beds 1.4–12.5 cm thick. Total thickness: 2.2 m.
PBL	A1	Sharp-based siltstone beds. Incipient climbing ripples and syndepositional normal microfaults. Upright plant remains rooted in the Ottawa coal. Beds 0.05–1.38 cm thick. Total thickness: 25 cm.

1.8 m (5.9 ft) thick and is capped by a thin, pervasively rooted, silty coal. The channel-and-levee facies was subdivided into units B1 and B2 (fig. 4).

Unit B1 represents a channelized body approximately 1 m (3.3 ft) thick and 10–12 m (33–40 ft) wide. The channel fill is composed of a series of strata that thin and pinch out laterally towards the erosive bounding surface. Beds display climbing ripples, parallel laminations, thin clay drapes, linguoid ripples, and cross-laminations. Channel deposits pass upward into planar-stratified beds and a horizontal, upper bounding surface. Bedding-plane structures include various types of trace fossils, drag marks, wrinkle marks, rill marks, runnel marks, runoff washouts, foam marks, and raindrop impressions. Root casts are also present towards the channel margin.

Unit B2 consists of planar-stratified siltstones, which are truncated locally by the channelized surface. Beds typically are normally graded or display poorly developed cross-lamination. Upright plants with well-preserved leaves and roots are very common. Drip marks that are associated with some of these upright plants occur in this unit.

Depositional Environment

According to Lanier et al. (1993), the Buildex succession was deposited on a tidal flat, close to or at the fluvial-estuarine transition of a macrotidal estuarine paleovalley.

Analysis of the systematic variations in bed thickness demonstrates the influence of tidal processes (fig. 5) and indicates that these deposits are tidal rhythmites, with thicker sets of strata representing deposition during spring tides and thinner sets recording deposition during neap tides (Lanier et al., 1993). Lanier et al. (1993) also suggested that evidence of brief periods of subaerial exposure existed in the strata based upon on the presence of certain bedding surface structures (e.g., raindrop impressions, rill marks, runnel marks) and the absence of desiccation cracks or oxidized horizons. Although small desiccation cracks were found in one of Bandel's slabs (KUMIP 25131), they are rare in this section.

Architecture and Sequence Stratigraphy of the Tonganoxie Valley Fill

The Tonganoxie Sandstone Member occurs at the base of a large estuarine paleovalley incised in the underlying Weston Shale and Lansing Group (Lins, 1950; Sanders, 1959; Lanier, 1993; Gibling et al., 1993; Lanier et al., 1993; Archer, Lanier et al., 1994; Archer and Feldman, 1995; Feldman et al., 1995). At Buildex, the basal erosion surface is marked by a rooted coal (Ottawa coal) developed on the Weston Shale, indicating that the paleovalley walls were subaerially exposed (Archer, Lanier et al., 1994). The Tonganoxie paleovalley was oriented NE-SW
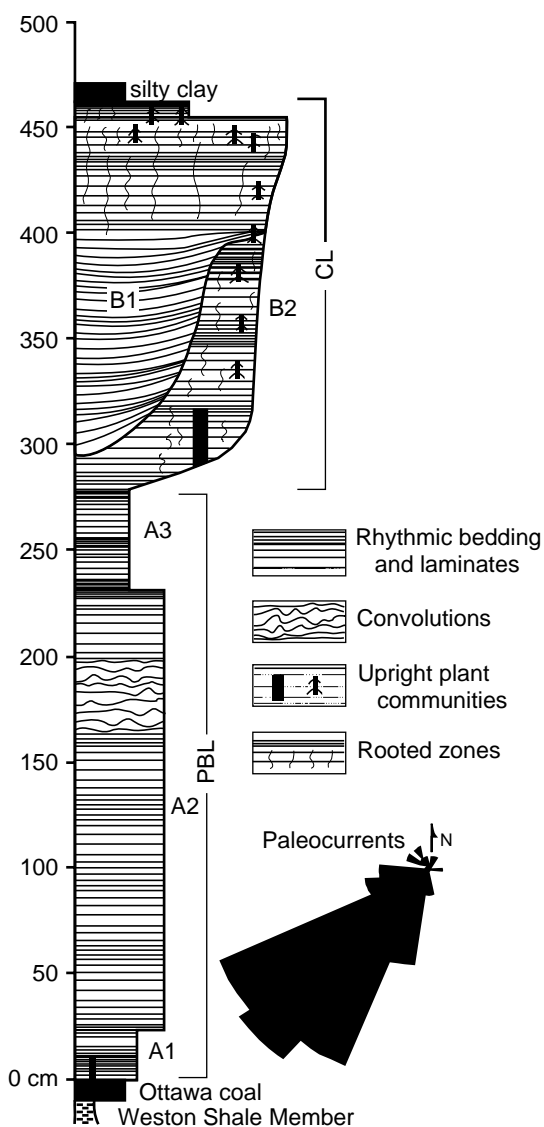
FIGURE 4. Sedimentologic log of the Buildex Quarry section from the west wall and paleocurrent rose diagram (adapted from Lanier et al., 1993). See table 1 for information on sedimentary facies and units.

and was about 41 m (135 ft) deep, 11 km (6.8 mi) wide, and 240 km (149 mi) long (Archer, Lanier et al., 1994). The valley was formed during the latest Missourian sea-level fall and filled during a subsequent transgression in the earliest Virgilian (Gibling et al., 1993; Archer, Lanier et al., 1994; Feldman et al., 1995).

Archer, Lanier et al. (1994), Archer and Feldman (1995), and Feldman et al. (1995) discussed the problems associated with the recognition of system tracts within the Tonganoxie incised valley system (fig. 6). In the present study, the definitions of Dalrymple et al. (1992) were used to determine boundaries between system tracts. However, if the terminology of Van Wagoner et al. (1990) were used, the boundary between the lowstand and transgressive system tracts would be placed further up in the sequence

(at the base of the Westphalia Limestone Member). The basal erosion surface represents a type 1 sequence boundary (Van Wagoner et al., 1990) resulting from sea-level fall and subaerial exposure. The lowstand system tract is recorded by coarse-grained fluvial channel deposits at the base of the Tonganoxie Sandstone Member (type I sandstone of Feldman et al., 1995). Dalrymple et al. (1992) suggested that the boundary between lowstand and transgressive system tracts should be placed at the lowest evidence of marine influence. Accordingly, Archer, Lanier et al. (1994) and Feldman et al. (1995) placed the boundary near the top of the type I sandstone package within the Tonganoxie Sandstone Member, where clay-draped bedforms indicate the onset of estuarine deposition. Upwards in the sequence, however, a widespread transgression is suggested by deposition of the Westphalia Limestone Member. Above this limestone, retrogradational parasequence sets are stacked (Westphalia Limestone, Vinland Shale, and Haskell Limestone Members), culminating with an open-marine, condensed section in the lowermost part of the Robbins Shale Member (Archer, Lanier et al., 1994). Because they judged this condensed section to represent the maximum flooding surface, Archer, Lanier et al. (1994) regarded the remainder of the Robbins Shale Member as the highstand system tract.
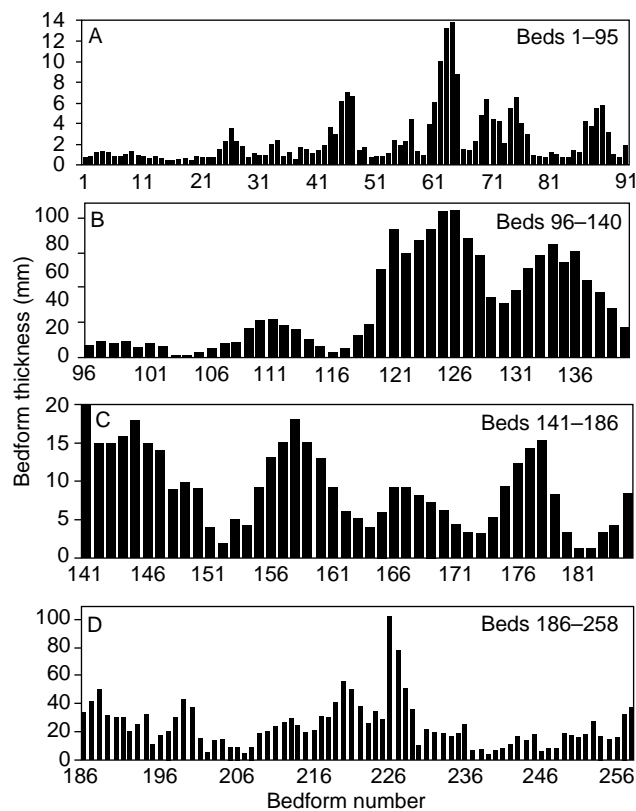

FIGURE 5. Thickness of beds 1 to 258 in the Tonganoxie Sandstone Member at the Buildex Quarry. (A) Unit A1, (B) Unit A2, (C) Unit A3, (D) Facies CL (adapted from Lanier, 1993; Lanier et al., 1993).
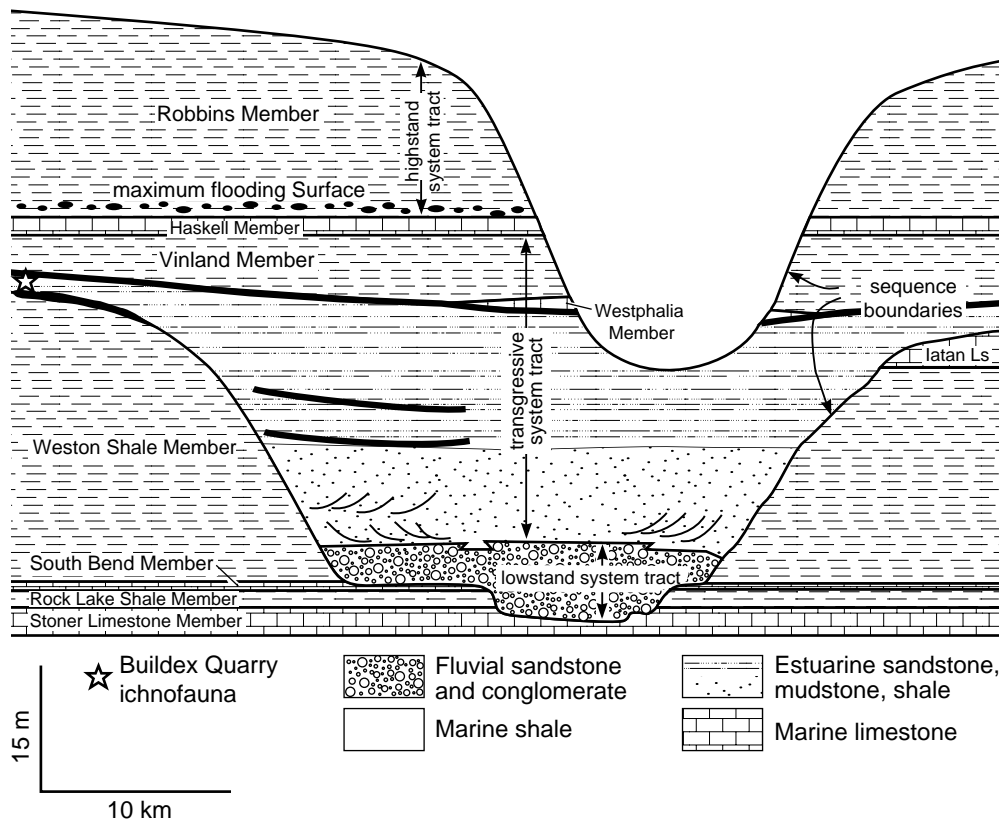
FIGURE 6. Sequence stratigraphic model for the Tonganoxie paleovalley (adapted from Archer, Lanier et al., 1994). Placement of system-tract boundaries based upon the definitions of Dalrymple et al. (1992).

The Buildex Quarry succession is situated at the eastern edge of the Tonganoxie paleovalley (Feldman et al., 1995) and is part of the transgressive system tract. At this locality, the boundary between the Tonganoxie Sandstone Member and the Ottawa coal represents a coplanar surface of lowstand erosion and flooding.

Conceptual Background of Ichnology

Trace fossils are biogenic sedimentary structures that reflect the behavior of their producers. As noted by Pemberton, Frey et al. (1992), trace fossils are both paleontologic and sedimentologic entities, and therefore they bridge the gap between these two fields of study. Trace fossils are used for the analysis of sedimentary successions in two different but sometimes complementary ways: the ichnofacies and ichnofabric approaches (cf., Bromley, 1996). An ichnofacies is a trace-fossil assemblage that recurs through geologic time and is characteristic of a given set of environmental conditions (Seilacher, 1967; Pemberton, Frey et al., 1992). Eleven archetypical ichnofacies have been formally proposed, the *Termitichnus, Scoyenia, Mermia, Psilonichnus, Skolithos, Cruziana, Zoophycos, Nereites, Teredolites, Glossifungites,* and *Trypanites,* the latter subdivided into the *Entobia* and *Gnathichnus* ichnofacies (Seilacher, 1967; Frey and Seilacher, 1980; Bromley et al., 1984; Frey and

Pemberton, 1987; Bromley and Asgaard, 1993; Buatois and Mángano, 1995) (fig. 7). Ichnofabrics, on the other hand, comprise all aspects of the texture and internal structure of a sediment that result from bioturbation (Bromley and Ekdale, 1986). As such, they include both the identifiable and unidentifiable biogenic structures (Bottjer and Droser, 1991). Bedding-plane trace fossils, however, commonly are overlooked in ichnofabric analysis (but see Miller and Smail, 1997).

Ichnology of Incised Estuarine Valleys

A typical vertical succession of ichnofacies is commonly associated with estuarine valley incision and subsequent infill (Pattison, 1992; Ranger and Pemberton, 1992; MacEachern et al., 1992; Pemberton, Reinson et al., 1992; MacEachern and Pemberton, 1994). Open-marine, highstand, progradational parasequence sets that underlie estuarine deposits typically contain a high-diversity *Cruziana* ichnofacies, reflecting the work of an equilibrium community developed under fully marine conditions (MacEachern and Pemberton, 1994). Such open-marine deposits are truncated by a discontinuity surface caused by incision during a sea-level fall and subsequent transgressive erosion (coplanar surface). This discomformity typically hosts the *Glossifungites* ichnofacies, which records colonization in a firmground substrate associated

Woodground	Hardground		Firmground	Softground		
	Trypanites			*Termitichnus*	subaerial	NONMARINE
				Scoyenia	transitional	
				Mermia	subaqueous	
				Psilonichnus	TRANSITIONAL	
Teredolites		*Entobia*	*Glossifungites*	*Skolithos*	high energy	
				Cruziana	medium energy	MARINE
				Zoophycos		
		Gnathichnus		*Nereites*	low energy	

FIGURE 7. Archetypical ichnofacies and their characteristic environments (adapted from Pemberton, Frey et al., 1992).

with erosional exhumation (MacEachern et al., 1992). MacEachern and Pemberton (1994) noted that where basal fluvial lowstand deposits separate the sequence boundary from the initial flooding surface, the *Glossifungites* ichnofacies is absent. Under lowstand conditions, this ichnofacies is only present at the seaward end of the estuarine valley (MacEachern et al., 1992). Valley-fill deposits overlying the coplanar surface accumulate during the subsequent transgression and sea-level highstand and contain an impoverished ichnofauna characterized by a mixture of the *Skolithos* and *Cruziana* ichnofacies (Pemberton and Wightman, 1992; Pemberton, Reinson et al., 1992; MacEachern and Pemberton, 1994). This depauperate ichnofauna records the activity of an opportunistic community developed under stressful conditions in a brackish-water estuarine setting. According to Wightman et al. (1987) and Pemberton and Wightman (1992), brackish, marginal-marine trace-fossil assemblages are characterized by (1) low diversity, (2) forms typically found in marine environments, (3) the dominance of infaunal traces rather than epifaunal trails, (4) simple structures produced by trophic generalists, (5) a mixture of vertical and horizontal traces from the *Skolithos* and *Cruziana* ichnofacies, (6) the abundance of a few forms, and (7) the presence of monospecific suites. Brackish assemblages may be replaced vertically by high-diversity, open-marine assemblages of the *Cruziana* ichnofacies associated with the termination of estuarine deposition by a major flooding event (Pemberton, Reinson et al., 1992). In other cases, the ichnologic record of the valley fill is more complex where the estuarine system varies repeatedly between brackish and fully marine conditions (e.g., MacEachern and Pemberton, 1994). In "compound" valley systems, highly diverse equilibrium and depauperate opportunistic trace-fossil assemblages tend to alternate.

The Buildex Ichnofauna

The assemblage present in the Tonganoxie Sandstone Member at Buildex Quarry consists of arthropod locomotion, resting, and feeding traces; grazing traces; feeding structures; fish traces; tetrapod trackways; and root traces

(table 2). Arthropod trackways include *Dendroidichnites irregulare* (Holub and Kozur) (fig. 8), *Diplichnites gouldi* Gevers in Gevers et al. (fig. 9), *Diplopodichnus biformis* Brady (fig. 10), *Kouphichnium* isp. (fig. 11), *Mirandaichnium famatinense* Aceñolaza (fig. 12), and *Stiaria intermedia* Smith (fig. 13). *Stiallia pilosa* Smith (fig. 14) represents a combined resting and feeding trace. *Tonganoxichnus buildexensis* Mángano et al. (fig. 15) and *Tonganoxichnus ottawensis* Mángano et al. (fig. 16) are the resting and feeding traces of apterygote insects (Monura). Grazing traces are represented by *Gordia indianaensis* (Miller) (fig. 17), *Helminthoidichnites tenuis* Fitch (fig. 18), and *Helminthopsis hieroglyphica* Wetzel and Bromley (fig. 19). Feeding structures include *Circulichnis montanus* Vyalov (fig. 20), *Treptichnus bifurcus* Miller (fig. 21), *Treptichnus pollardi* Buatois and Mángano (fig. 22), and irregular networks (fig. 23). Vertebrate traces are represented by the fish trails *Undichna britannica* Higgs (fig. 24) and *Undichna simplicitas* Anderson (fig. 25) and by tetrapod trackways (fig. 26). Plant biogenic structures are represented by root traces (fig. 27B). For detailed descriptions of the Buildex trace fossils, see Buatois et al. (1998).

Trace fossils are more abundant in the planar-bedded-and-laminated facies (PBL) than in the channel-and-levee facies (CL). Additionally, within PBL facies, they are particularly common in unit A2, where they tend to concentrate along certain bedding planes that alternate with others devoid of ichnofossils. However, no remarkable change in trace-fossil types has been detected throughout the Buildex Quarry section. Tidal rhythmites exposed in a roadcut northeast of the quarry along the quarry road occur stratigraphically above the Buildex Quarry succession. A few escape burrows of infaunal animals occur at this small outcrop (fig. 28).

The Buildex ichnofauna is characterized by many surface trails and trackways and few burrows. Observations in outcrops and cores show that trace fossils are essentially restricted to bedding planes (both soles and tops), and original stratification is for the most part undisturbed (figs. 27A,C), the only exception being the root traces in levee deposits (fig. 27B). Accordingly, the Buildex ichnofauna records the activity of a surface or near-

Table 2. Ethologic classification, inferred producer, and relative abundance of Buildex Quarry ichnotaxa. Forms left in open nomenclature are not included. Very rare = 1 specimen; rare = 2 to 10 specimens; common = 11 to 20; abundant = more than 20 specimens.

Ichnotaxa	Ethology	Inferred Producer	Abundance
Circulichnis montanus	Fodinichnia	Annelid	Very rare
Dendroidichnites irregulare	Repichnia	Arthropod	Rare
Diplichnites gouldi A	Repichnia	Myriapod	Abundant
Diplichnites gouldi B	Repichnia	Myriapod	Abundant
Diplopodichnus biformis	Repichnia	Myriapod	Abundant
Gordia indianaensis	Pascichnia	Arthropod-Nematomorph	Abundant
Helminthoidichnites tenuis	Pascichnia	Arthropod-Annelid	Common
Helminthopsis hieroglyphica	Pascichnia	Arthropod-Nematode	Abundant
Kouphichnium isp.	Repichnia	Limulid	Rare
Mirandaichnium famatinense	Repichnia	Myriapod	Very rare
Stiallia pilosa	Fodinichnia / Repichnia	Apterygote insect?	Common
Stiaria intermedia	Repichnia	Apterygote insect	Rare
Tonganoxichnus buildexensis	Cubichnia	Monuran insect	Abundant
Tonganoxichnus ottawensis	Fodinichnia	Monuran insect	Rare
Treptichnus bifurcus	Fodinichnia	Arthropod-Annelid	Common
Treptichnus pollardi	Fodinichnia	Arthropod-Annelid	Rare
Undichna britannica	Repichnia	Fish	Common
Undichna simplicitas	Repichnia	Fish	Rare
Irregular networks	Fodinichnia	Arthropod-Annelid	Abundant

FIGURE 8. *Dendroidichnites irregulare,* ×2.

FIGURE 9. *Diplichnites gouldi,* ×1.

FIGURE 10. *Diplopodichnus biformis,* ×2.
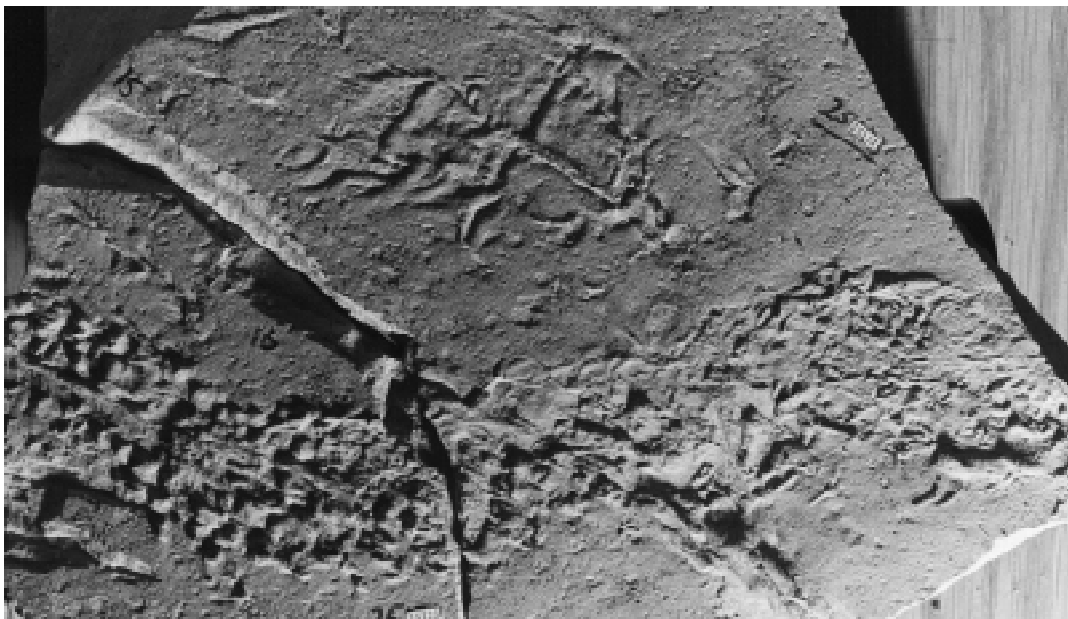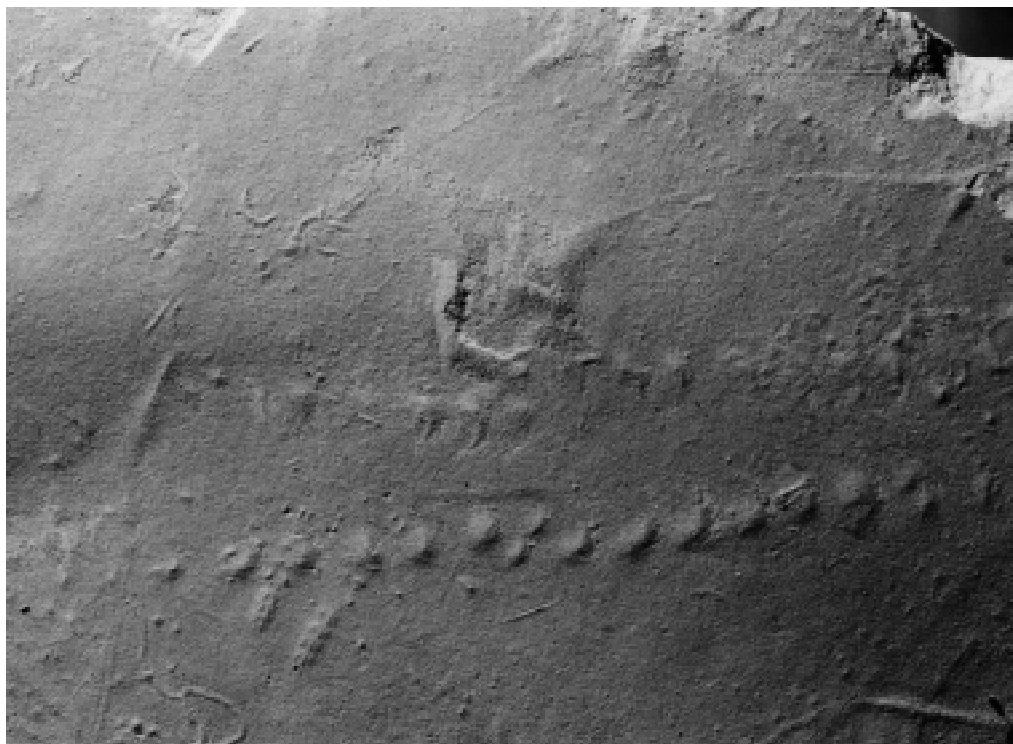
FIGURE 11. *Kouphichnium* isp., ×0.5.

FIGURE 12. *Mirandaichnium famatinense,* ×1.5. Note the presence of several specimens of *Tonganoxichnus buildexensis* (lower center).
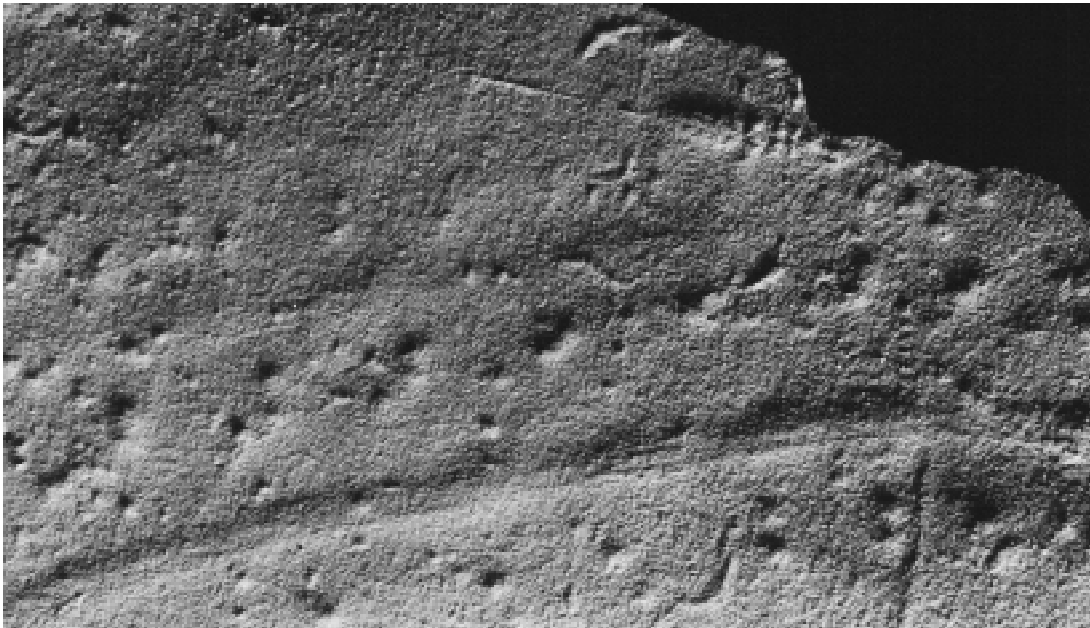
FIGURE 13. *Stiaria intermedia* and *Tonganoxichnus buildexensis* (upper right), ×2.3.

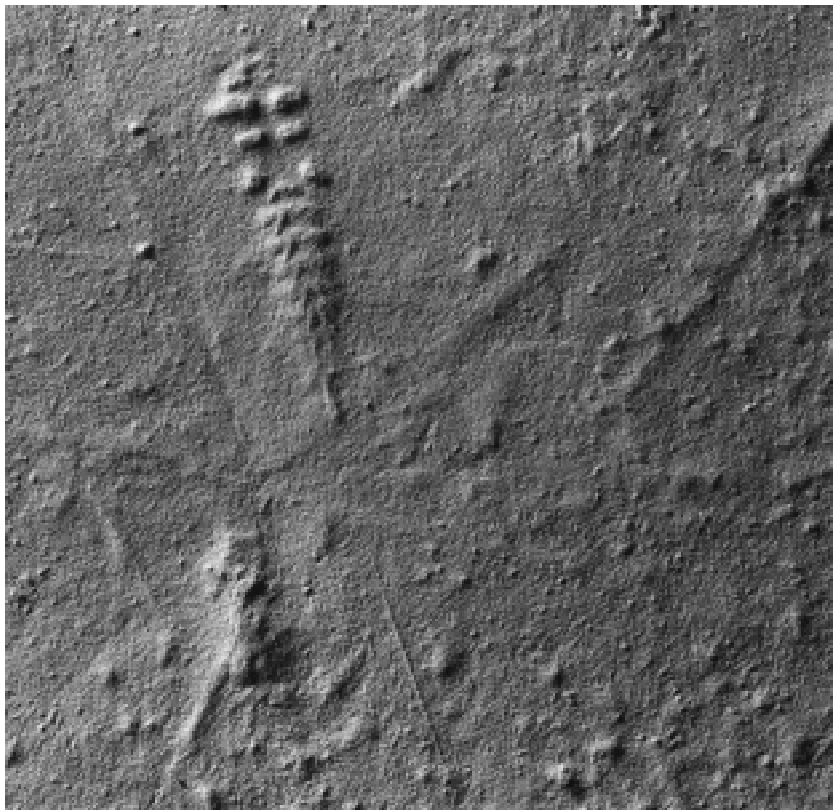FIGURE 14. *Stiallia pilosa* (center) and *Tonganoxichnus buildexensis* (lower right), ×1.5.

FIGURE 15. *Tonganoxichnus buildexensis,* ×2.8.
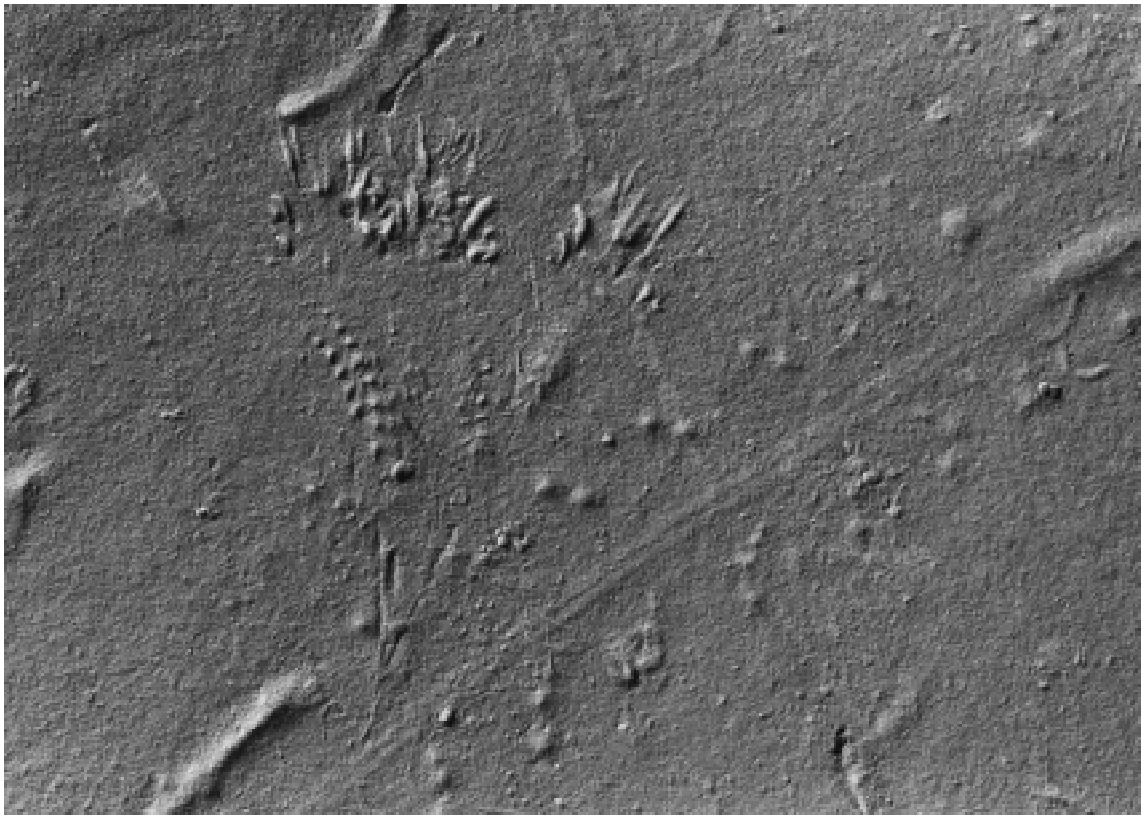
FIGURE 16. *Tonganoxichnus ottawensis* and *Stiaria intermedia* (lower left to upper right). ×3.
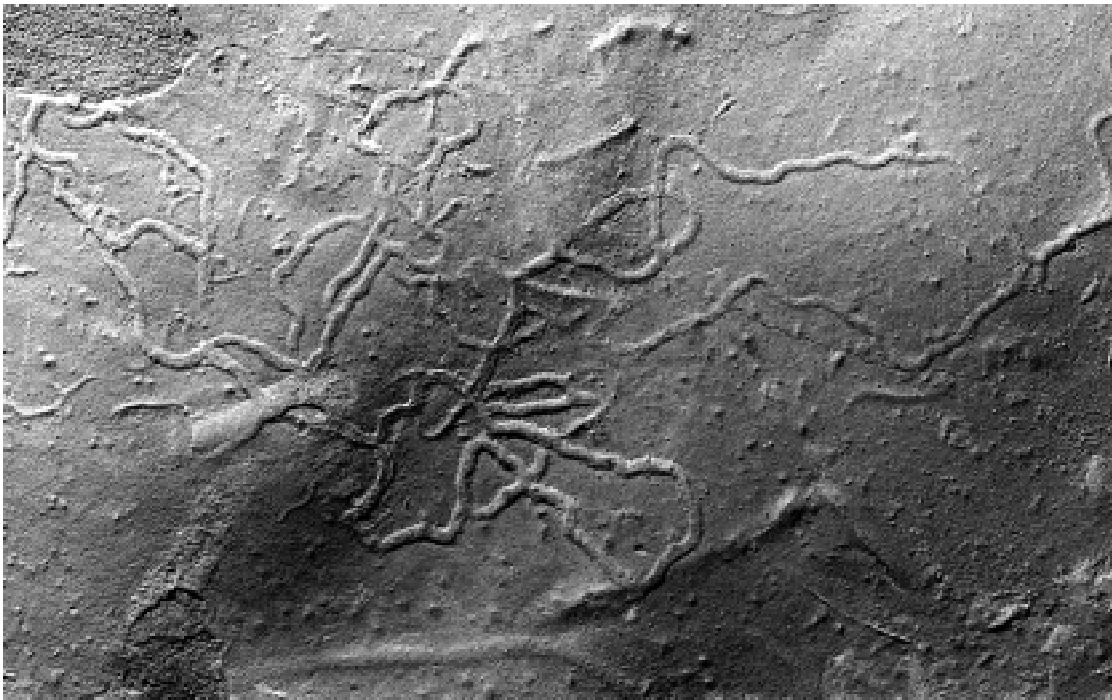
FIGURE 17. *Gordia indianaensis,* ×1.3.

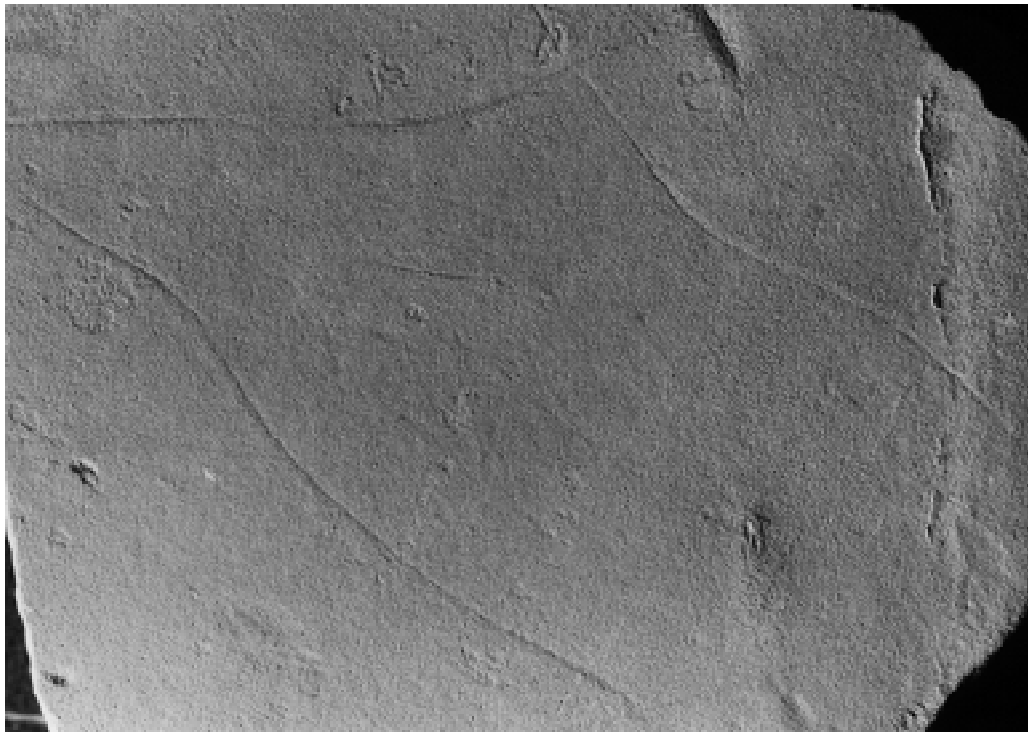FIGURE 18. *Helminthoidichnites tenuis,* ×1.

FIGURE 19. *Helminthopsis hieroglyphica,* ×1.3. Note the presence of poorly preserved specimens of *Tonganoxichnus buildexensis* and *Undichna britannica* (left).

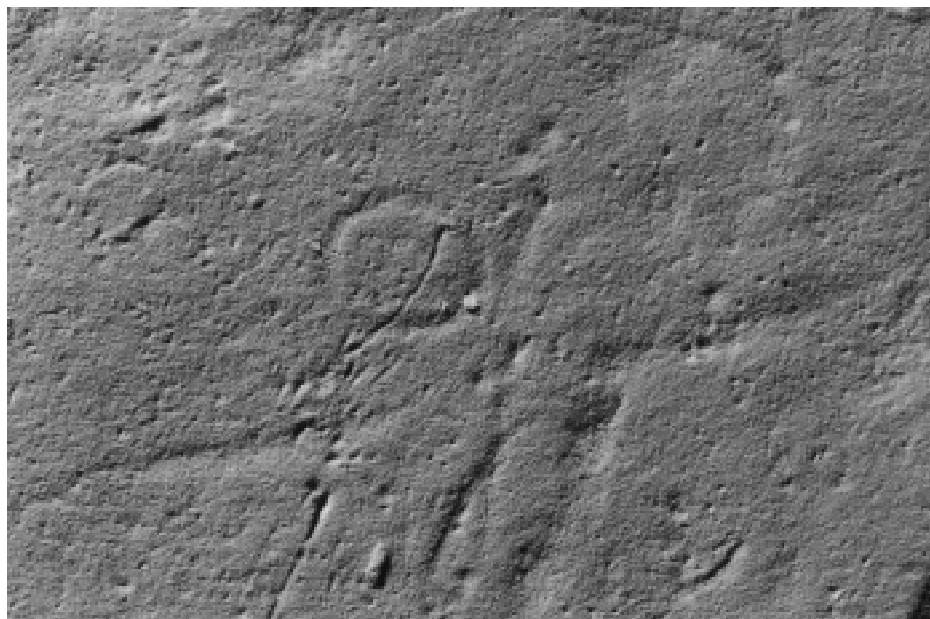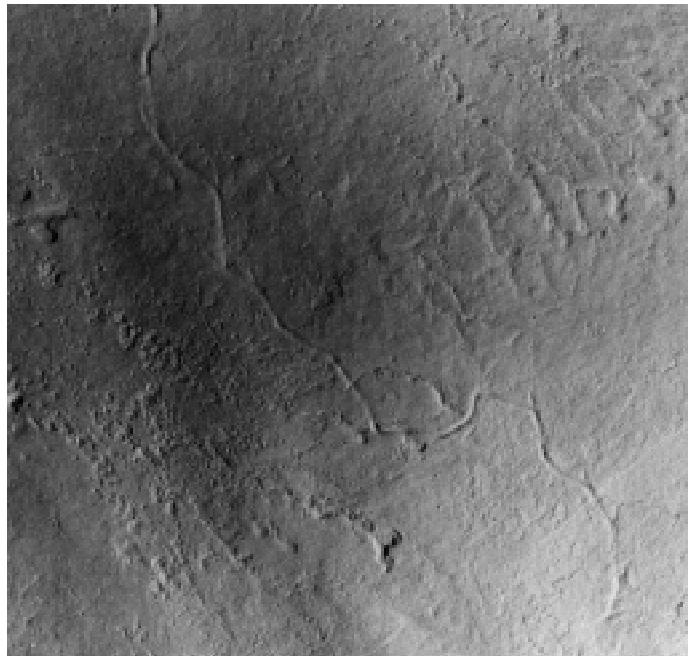FIGURE 20. *Circulichnis montanus,* ×2.

FIGURE 21. *Treptichnus bifurcus* (center), ×0.3. Note runnel marks on upper right.
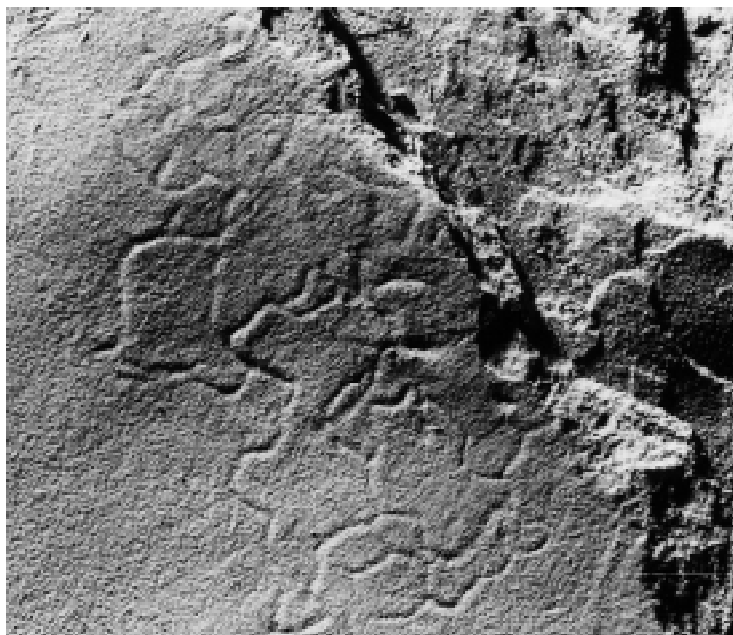

FIGURE 22. *Treptichnus pollardi,* ×1.5.

FIGURE 23. Irregular networks, ×1.3.
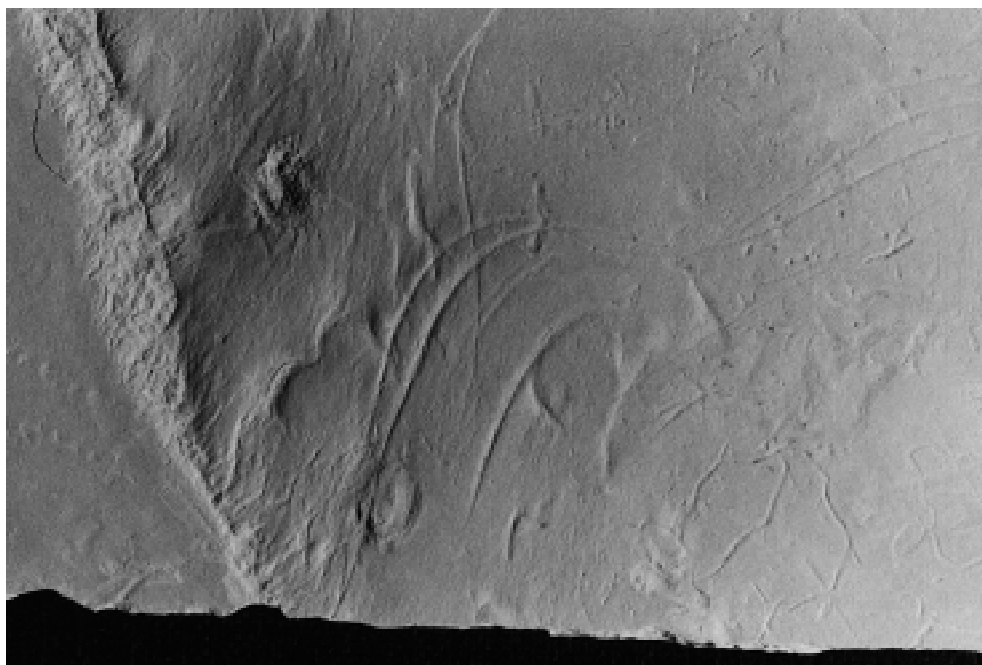

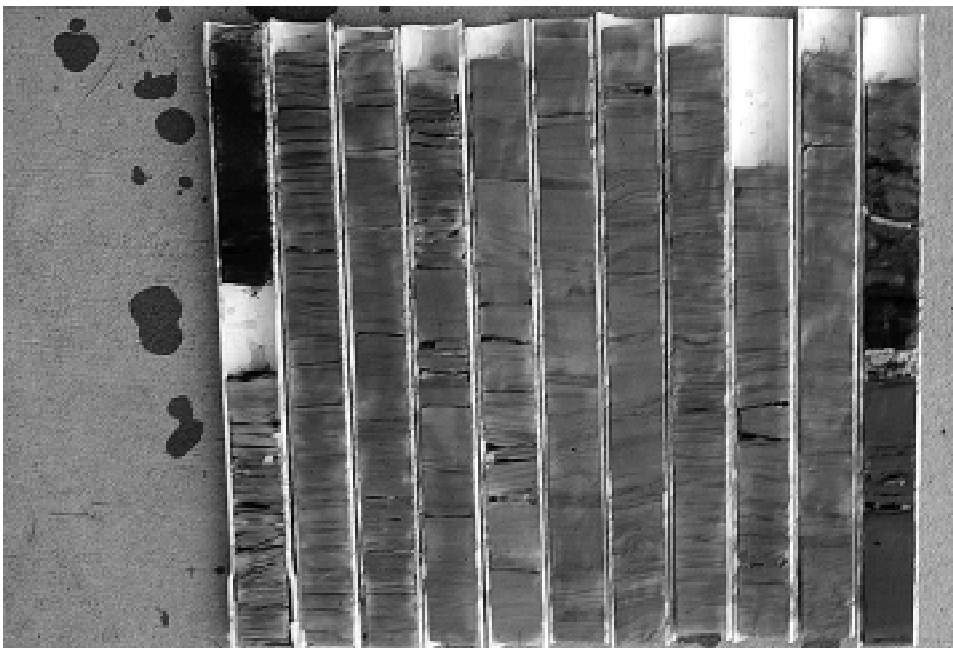FIGURE 24. *Undichna britannica,* ×0.7. Note *Treptichnus bifurcus* (upper left).

FIGURE 25. *Undichna simplicitas,* ×1

FIGURE 26. Tetrapod trackways, ×0.5.
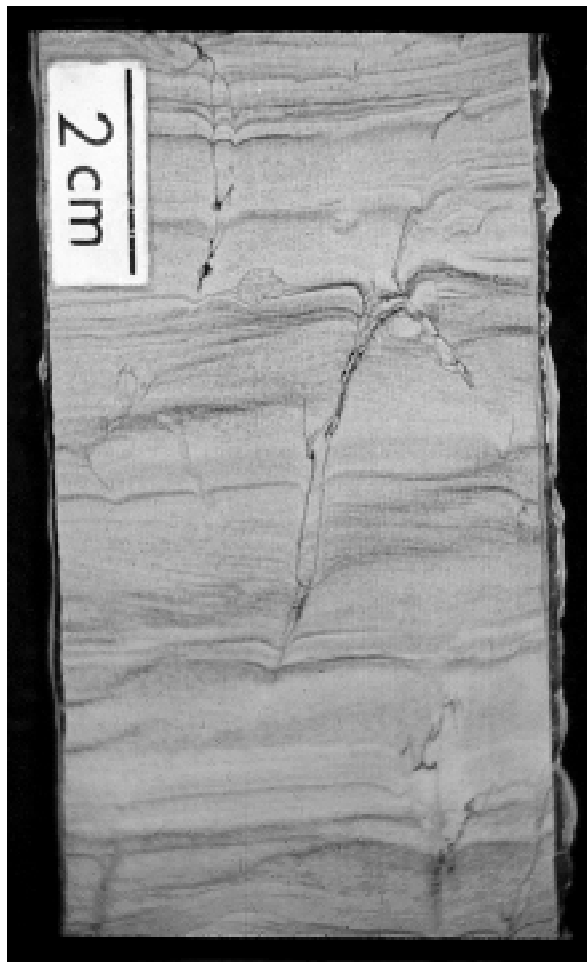
A

B

F<small>IGURE</small> 27. Buildex Quarry core. (A) General view; base on the lower right. (B) Root traces in the levee deposits.
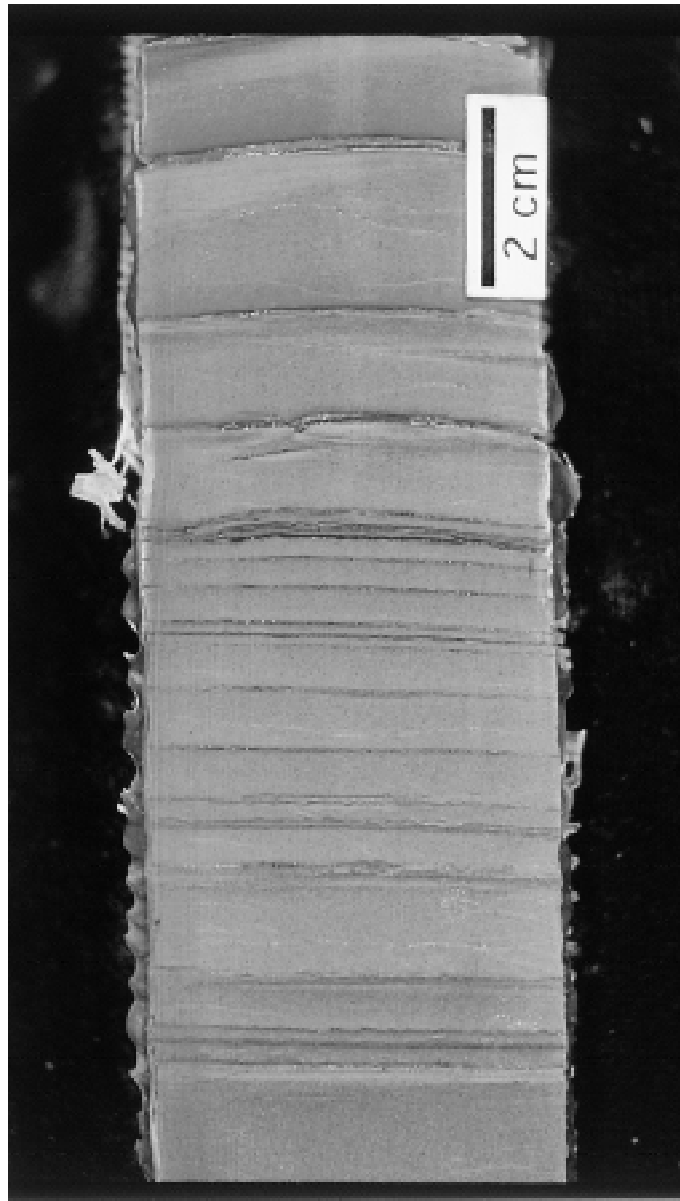
C

FIGURE 27 *(continued).* (C) Detailed view showing absence of infaunal structures and preservation of primary fabric.

surface benthic fauna. Absence of infaunal organisms allowed preservation of delicate biogenic structures, as well as primary stratification. In terms of the index proposed by Miller and Smail (1997), the density of bedding-plane trace fossils is 2 to very rarely 3. Crosscutting between different individuals is relatively common, but surfaces lack a high degree of overlap among specimens.

Sedimentologic Implications of the Buildex Ichnofauna

Because the Tonganoxie Sandstone Member at the Buildex Quarry represents the infilling of an estuarine paleovalley, it is interesting to compare its trace-fossil assemblages with those previously characterized as typical

of brackish-water, marginal-marine depositional systems. Notably, as indicated by Buatois et al. (1997), the Buildex ichnofauna lacks most, if not all, of the features that characterize brackish-water assemblages. The Buildex assemblage is typified by (1) relatively high ichnodiversity, (2) forms typically present in freshwater environments, (3) a dominance of surface trails and absence of burrows, (4) temporary structures produced by mobile deposit-feeding faunas, (5) a mixture of traces belonging to the *Scoyenia* and *Mermia* ichnofacies, (6) a moderate density of individual ichnotaxa, and (7) an absence of monospecific suites.

This apparent anomaly is best explained if we consider the Buildex ichnofauna as produced by a terrestrial and freshwater fauna (Buatois et al., 1997). The relatively high diversity of ichnofossils probably records a secondary
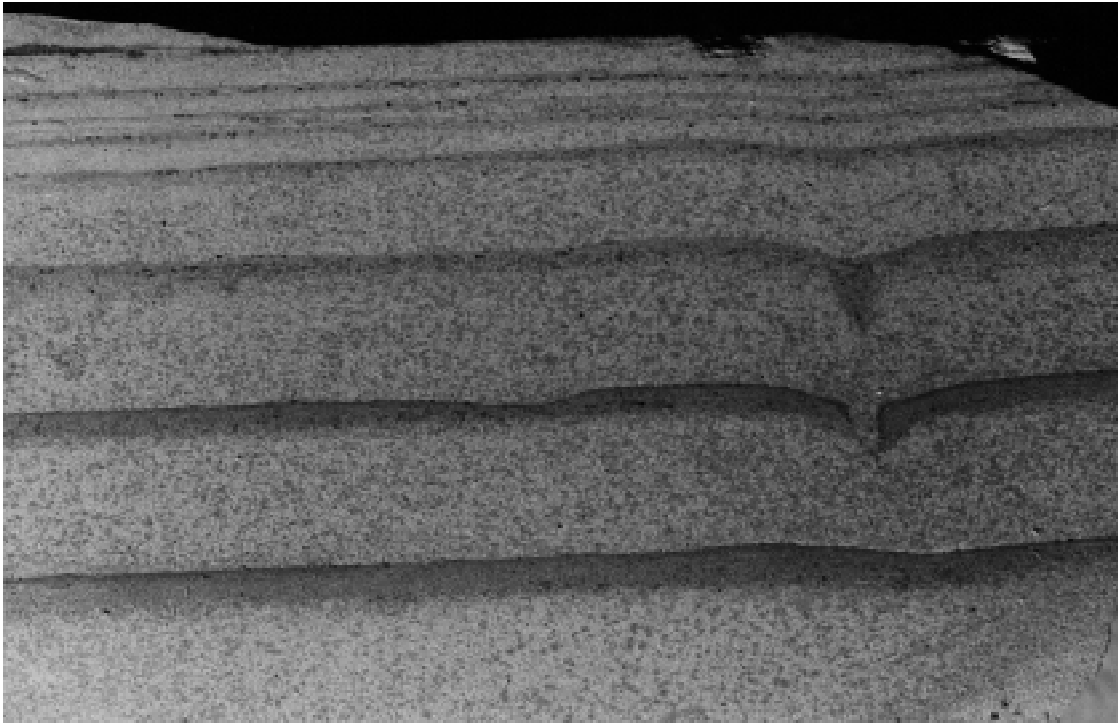
FIGURE 28. Escape structure in tidal rhythmites in a roadcut northeast of the quarry along the quarry road, ×1.2.

peak of diversity of organisms from freshwater environments that contrasts with the minimum diversity of brackish-water ecosystems (Remane and Schlieper, 1971; Ekdale, 1988; Hudson, 1990; Pickerill and Brenchley, 1991). The taxonomic composition of the arthropod-dominated Buildex ichnofauna is also suggestive of terrestrial and freshwater faunas. The assemblage actually represents a mixture of the nonmarine *Scoyenia* and *Mermia* ichnofacies, rather than the characteristically marine *Cruziana* and *Skolithos* ichnofacies. No ichnotaxa unequivocally indicative of marine settings are present. In contrast, some of the forms recorded from Buildex are typical of nonmarine environments (e.g., *Undichna, Stiaria, Stiallia, Dendroidichnites, Mirandaichnium*). In addition to taxonomic composition, the overall aspect of the ichnofauna suggests the activity of nonmarine organisms. Features other than ichnodiversity and taxonomic composition that suggest a terrestrial-freshwater origin include dominance of surface or shallow subsurface trace fossils, absence of infaunal burrows, and a mixture of arthropod trackways and nonspecialized grazing traces.

The presence of a mixed freshwater-terrestrial ichnofauna in these deposits seems to conflict with evidence of tidal activity. However, in estuarine systems, tidal influence commonly extends further landward than the saltwater intrusion (Dalrymple et al., 1992). For example, Allen (1991) noted that in the Gironde Estuary, the maximum limit of tidal currents is located approximately 50 km (31 mi) landward of the saltwater intrusion; therefore, the channels of the upper estuary are rarely

affected by brackish water. A similar situation was documented from the Cobequid Bay-Salmon River estuary (Bay of Fundy), suggested as a modern analogue of the Tonganoxie paleovalley by Lanier et al. (1993) and Archer, Lanier et al. (1994), where the most proximal region of the inner estuary experiences essentially freshwater conditions (Dalrymple et al., 1991).

The influence of salinity on the composition of invertebrate faunas and intensity of bioturbation also was noted in these studies (Allen, 1991; Dalrymple et al., 1991). In these modern environments, no marine or brackish faunas were detected in the inner estuary, where tidal flats were essentially unbioturbated. On the other hand, infaunal brackish-water organisms, which occur in the middle estuary, thoroughly churned sediments.

Ichnologic evidence from the Buildex Quarry is consistent with deposition on tidal flats in the most proximal zone of the inner estuary (inner end of segment 2 in the terminology of Dalrymple et al., 1994 and Zaitlin et al., 1994) under essentially freshwater conditions. More specifically, this zone is situated between the maximum landward limit of tidal currents and the salinity limit further towards the sea (fig. 29). The freshwater organisms inhabiting this area do not have the adaptations necessary to survive in a brackish environment; therefore, they are restricted to the innermost zone of the paleovalley (cf., Wolff, 1983). Observations on the Buildex ichnofauna show that although lithofacies distribution within the paleovalley is, for the most part, salinity-independent, the distribution of organisms is not. Accordingly, ichnologic
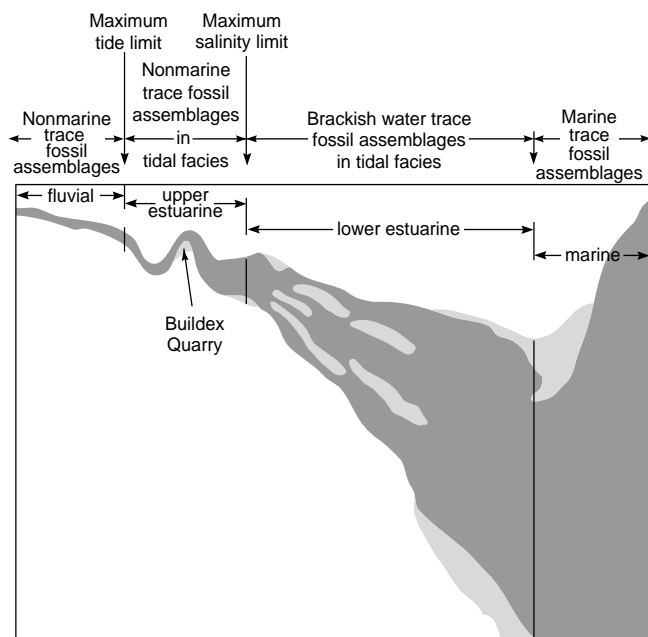
FIGURE 29. Plan view of the Tonganoxie estuarine paleovalley, showing location of the Buildex ichnofauna and relationship with salinity and tidal limits (facies model adapted from Archer, Feldman et al., 1994). Lighter shading represents sandy sediments; darker shading represents silt and mud.

studies of estuarine systems can provide the high-resolution results necessary to delineate fluvio-estuarine transitions and may help to refine facies models constructed only on the basis of physical sedimentary structures.

Implications for Modern Analogues

The Tonganoxie paleovalley has been compared with modern estuarine systems, such as the Bay of Mont-Saint-Michel and the Bay of Fundy (Lanier et al., 1993; Archer, Lanier et al., 1994; Tessier et al., 1995). Documentation of the trace fossils at Buildex may provide additional information, constraining the search for modern analogues of the Tonganoxie paleovalley. No detailed information on biogenic structures is available from the Bay of Fundy. However, Dalrymple et al. (1991) recorded bioturbation in the brackish portions of the estuary and recognized typical structures of a mixed *Cruziana-Skolithos* ichnofacies, such as U-shaped burrows of the amphipod *Corophium volutator* and the polychaete *Nereis virens,* and dwelling and escape traces of the bivalve *Macoma balthica.* Additionally, they recognized a headward decrease in the degree of bioturbation, with tidal rhythmites of the freshwater portion of the inner estuary unaffected by burrowing infauna, as in the case of Buildex rhythmites.

An excellent account of the biogenic structures from the Bay of Mont-Saint-Michel was presented by Bajard (1966). As noted by Lanier et al. (1993) and Tessier et al. (1995), some of the surface or near-surface traces illus-

trated by Bajard are comparable to those from Buildex, including meandering trails of the isopod *Eurydice pulchra* (Bajard, 1966, fig. 23), unidentified sinusoidal trails that were probably produced by nematod or ceratopoginid larvae (Bajard, 1966, fig. 30), and zigzagging, near-surface burrow systems of tabanid larvae (Bajard, 1966, fig. 36). However, these traces occur in close association with biogenic structures produced by a marine fauna, such as U-shaped burrows of the polychaete *Arenicola marina* and the amphipod *Corophium volutator,* crab trackways, dwelling structures of the bivalves *Cardium edule* and *Tellina balthica,* different types of traces produced by the polychaete *Nereis diversicolor,* burrows of the polychaete *Polydora ciliata,* and dwelling burrows of the cnidarian *Sagartia troglodytes* (Bajard, 1966). A diverse and abundant marine fauna has also been recorded in the bay (Larsonneur, 1989, 1994). The widespread distribution of this marine fauna and its associated biogenic structures in the Bay of Mont-Saint-Michel is consistent with the salinity of the estuary that, according to Larsonneur (1994), oscillates between 33‰ and 35‰, being even higher in summer. The surface and near-surface traces are most likely related with tidal-flat emergence during low tide.

Despite the similarities between the Tonganoxie paleovalley and modern analogues, neoichnological information should not be extrapolated uncritically to the analysis of the trace-fossil record. In the particular case of biogenic structures, the fossilization barrier is a taphonomic filter considerably more complex than that separating living animals from body fossils (Bromley, 1996). Although surface traces are present in the Bay of Mont-Saint-Michel, their preservation potential is extremely low. Burrowing activities of the associated marine infauna will probably lead to obliteration of the surface traces. Therefore, the fossil expression of such cases is typically a burrow-dominated assemblage. Accordingly, although the Tonganoxie paleovalley may be comparable to the Bay of Mont-Saint-Michel in terms of physical sedimentary structures and bedding types (see Tessier et al., 1995), the presence of burrows of a marine benthic infauna in the latter is a substantial difference. Interestingly, differences between both cases are easily explained as reflecting brackish to fully marine conditions in the Bay of Mont-Saint-Michel and the existence of an inner freshwater zone in the Tonganoxie paleovalley.

A series of papers on the biogenic and physical structures of estuaries in the Georgia coast also provide valuable information (e.g., Dorjes and Howard, 1975; Howard and Frey, 1975; Howard et al., 1975). Dorjes and Howard (1975) recognized five animal communities in the Ogeeche Estuary, which were essentially controlled by the salinity gradient. The inner freshwater zone of the estuary hosts few infaunal organisms; therefore, the degree of biogenic disturbance was minimal. The dominant biogenic structure was represented by thin, long burrows of the polychaete *Scolecolepides viridis,* a gregarius suspension feeder (Howard and Frey, 1975). Amphipods (*Lepidactylus*

dytiscus) and insect larvae were also observed (Dorjes and Howard, 1975). While insect larvae are important tracemakers in the Buildex assemblage, amphipod and polychaete traces have not been recorded. However, their absence in freshwater Pennsylvanian tidal flats is consistent with the evolutionary and environmental history of these groups, which only later were adapted to freshwater ecosystems (Chamberlain, 1975). This demonstrates again the importance of considering variables other than physical processes, including evolutionary adaptations of the different groups of invertebrates to the freshwater realm through time, in the search for modern analogues.

Allostratigraphic Significance

As discussed above, trace fossil assemblages from valley-fill deposits at Buildex Quarry contrast with the low-diversity ichnofaunas consisting of elements of the *Cruziana* and *Skolithos* ichnofacies typically recorded in estuarine systems (Ranger and Pemberton, 1992; Pemberton, Reinson et al., 1992; MacEachern and Pemberton, 1994). Our studies suggest that such depauperate ichnofaunas are restricted to the brackish, middle to outer portions of the estuarine valley, whereas arthropod-dominated, diverse assemblages occur in the freshwater, inner zone (fig. 29). Buildex-type ichnofaunas not only indicate a certain depositional zone within the incised valley, but also a particular stage of the valley filling history.

Estuarine valleys are typically incised during a sea-level fall (fig. 30). They may begin to fill during a lowstand (fig. 31), but sediments accumulate during the subsequent sea-level rise (Zaitlin et al., 1994). If lowstand, coarse-grained sediments are deposited and preserved, they are replaced vertically by finer-grained facies of the transgressive system tract (fig. 32). Commonly, during a lowstand, the valley acts as a bypass zone (fig. 30), or lowstand deposits are eroded and reworked during the
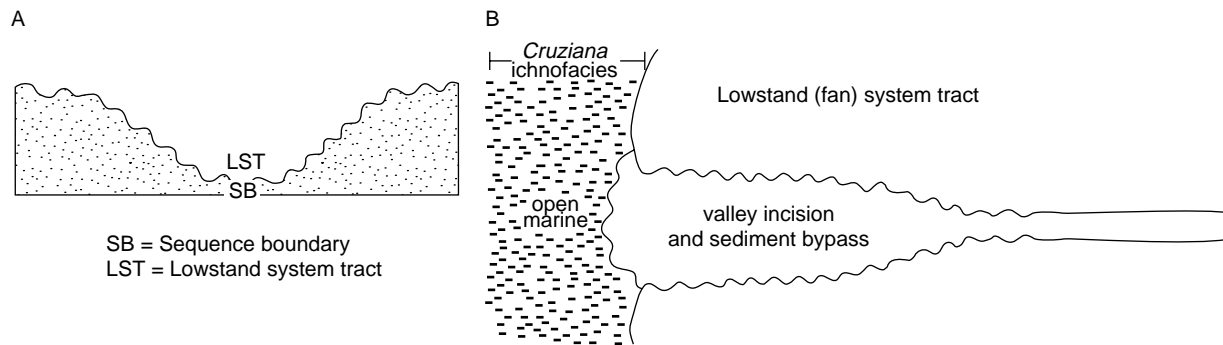

FIGURE 30. Ichnofacies model of a lowstand (fan) system tract in an incised estuarine valley system. (A) Cross section; (B) plan view (adapted from Zaitlin et al., 1994). Boundaries of system tracts are based on definitions by Dalrymple et al. (1992). The lowstand (fan) system tract is characterized by valley incision and sediment bypass. Trace fossils (*Cruziana* ichnofacies) are present only in open-marine sediments.

FIGURE 31. Ichnofacies model of a lowstand (wedge) system tract in an incised estuarine valley system. (A) Cross section; (B) plan view (adapted from Zaitlin et al., 1994). Boundaries of system tracts are based on definitions by Dalrymple et al. (1992). The lowstand (wedge) system tract is dominated by fluvial deposition in the incised valley. Trace fossils are restricted to open-marine settings (*Cruziana* ichnofacies) and high-energy mouth bars of the lowstand delta (*Skolithos* ichnofacies).

FIGURE 32. Ichnofacies model of a transgressive system tract in an incised estuarine valley system. (A) Cross section of estuary funnel; (B) cross section of upper estuary channels; (C) plan view (adapted from Zaitlin et al., 1994). Boundaries of system tracts are based on definitions by Dalrymple et al. (1992). In the trangressive system tract the estuary funnel and upper estuary channels are separated. At an early stage, freshwater conditions coexist with tidal influence in the upper estuary channels, where a mixed *Scoyenia-Mermia* ichnofacies is present. A mixed *Cruziana-Skolithos* ichnofacies typifies the brackish-water estuary funnel. As transgression proceeds, brackish-water conditions reach the upper estuary channels and the mixed *Cruziana-Skolithos* ichnofacies migrates landward. Normal salinity waters in the estuary funnel may progressively allow the establishment of a more marine *Cruziana* ichnofacies.
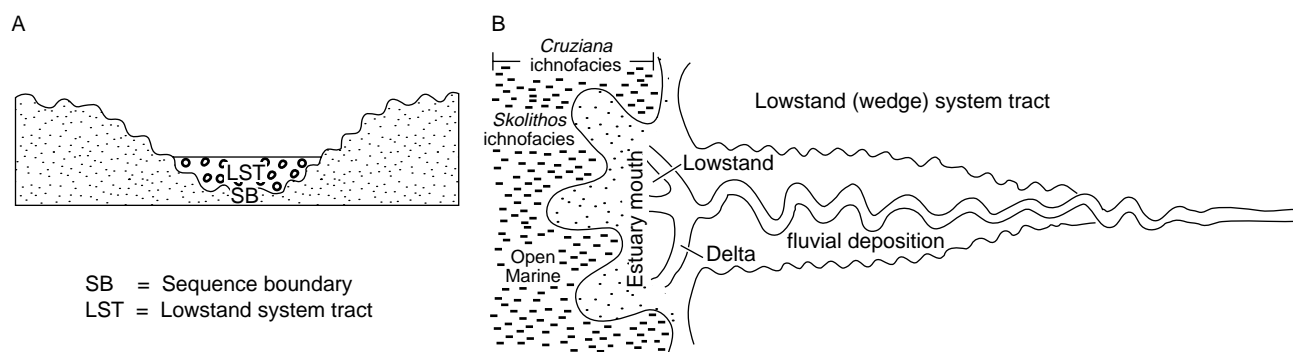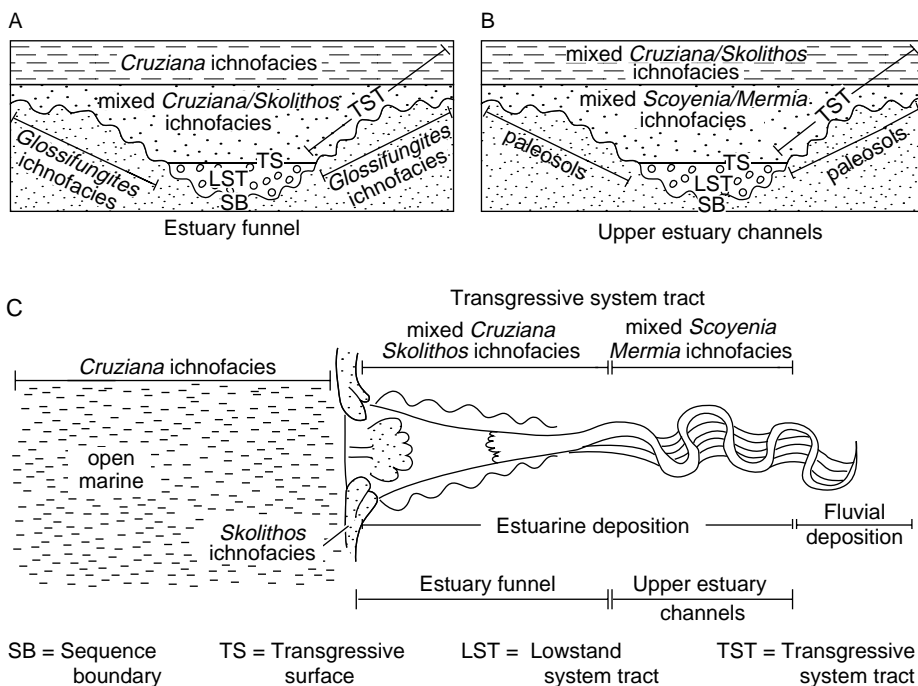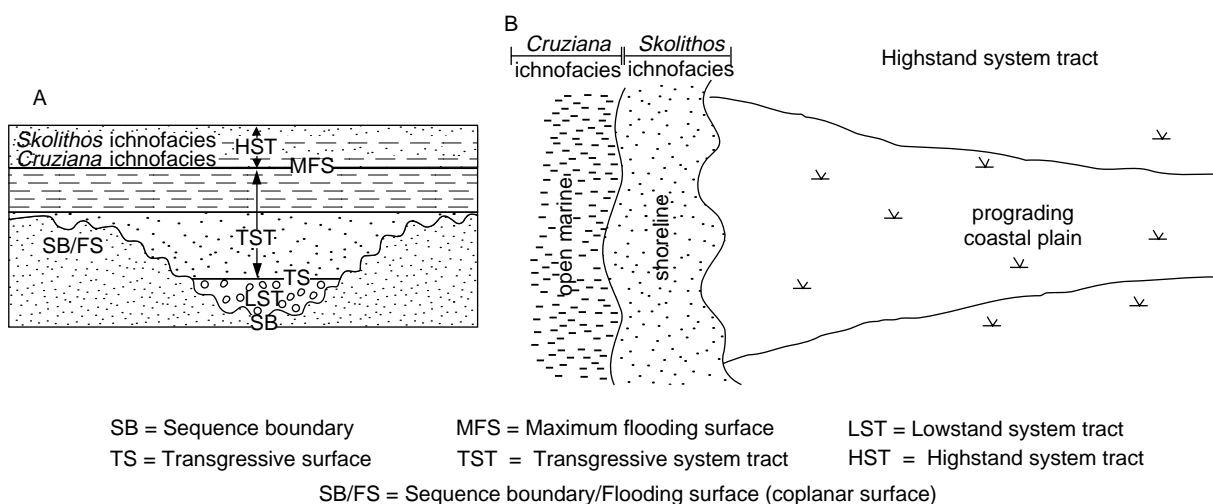

FIGURE 33. Ichnofacies model of a highstand system tract in an incised estuarine valley system. (A) Cross section; (B) plan view (adapted from Zaitlin et al., 1994). Boundaries of system tracts are based on definitions by Dalrymple et al. (1992). The highstand system tract is characterized by progradation of the coastal plain. Fully marine trace-fossil assemblages are dominant. Progressive increase in energy associated with coastal plain progradation may lead to the vertical replacement of the *Cruziana* ichnofacies by the *Skolithos* ichnofacies.

subsequent transgression (MacEachern and Pemberton, 1994). In such cases, transgressive deposits directly overlie the sequence boundary, resulting in the formation of coplanar surfaces. Finally, during highstand, progradation of the coastal plain occurs (fig. 33).

Buildex-type ichnofaunas characterize not only deposition in the upper part of the inner estuary (segment 2 of Zaitlin et al., 1994), but also the basal trangressive deposits immediately overlying the coplanar surface. In this specific setting and at this particular stage of estuarine valley evolution, freshwater conditions coexist with tidal influence. As transgression proceeds, backstepping brackish-water deposits accumulate. The ichnologic signature of such a change in depositional conditions is reflected in the upward replacement of a mixed *Scoyenia* and *Mermia* ichnofacies (Buildex-type ichnofaunas) by a mixed *Skolithos* and impoverished *Cruziana* ichnofacies (fig. 32). The presence of burrows in the strata overlying the Buildex Quarry section is suggestive of brackish-water conditions and a transgressive infill of the estuary. The mixed *Skolithos* and depauperate *Cruziana* ichnofacies is, for example, clearly displayed in cores described by Wightman et al. (1987) and Pemberton and Wightman (1992) as structures of infaunal burrowers, such as *Gyrolithes, Thalassinoides, Teichichnus*, and *Chondrites.* Because the mixed *Scoyenia* and *Mermia* ichnofacies is dominated by surface or shallow subsurface traces, the core expression of such an assemblage is parallel-laminated deposits with minimal or no bioturbation (fig. 27A,C).

MacEachern and Pemberton (1994) noted that the *Glossifungites*-demarcated surfaces are restricted to the limits of marine influence within the valley system. Tracemakers of the *Glossifungites* ichnofacies are unable to colonize freshwater portions of the estuary. The coplanar surface (flooding surface and sequence boundary) at the base of the Tonganoxie sequence at Buildex Quarry lacks the *Glossifungites* ichnofacies. In contrast, this surface is characterized by coals and paleosols with upright plant remains (Lanier, 1993; Lanier et al., 1993) and represents a surface of erosional truncation and nondeposition close to the valley interfluves. This rooted horizon may be regarded as the landward equivalent of the *Glossifungites* ichnofacies (fig. 32).

Regional Implications and Applications

The ichnofauna discussed in this study is not unique to the Buildex Quarry section. Comparable ichnofaunas have been recorded from several localities within the Pennsylvanian Midcontinent basins. One of the best-reported examples of a Buildex-type ichnofauna occurs in the Pennsylvanian Whetstone Beds of Indiana (Archer and Maples, 1984). The Whetstone ichnofauna is dominated by surface trails and trackways and includes several ichnotaxa recorded from Buildex, such as *Treptichnus, Undichna,*

and *Haplotichnus.* Archer and Maples (1984) originally interpreted this association as having developed in a floodplain to lacustrine setting. The subsequent discovery that this facies was deposited under tidal influence (Archer et al., 1988) led Archer (1993) to reinterpret the ichnofauna as having been produced in a transitional fluvioestuarine environment. Overall features and taxonomic composition of this assemblage suggest the work of a freshwater and terrestrial biota. Therefore, ichnologic and sedimentologic evidence indicate deposition in the innermost, freshwater zone of an estuarine system.

Another ichnofauna comparable to that from the Tonganoxie Sandstone Member at Buildex Quarry consists of two assemblages, the *Cincosaurus* and *Haplotichnus* assemblages from the Westphalian Pottsville Formation of Alabama (Rindsberg, 1990). The *Cincosaurus* assemblage consists of locomotion traces of fishes, xiphosurids, and amphibians. Surface grazing trails and trackways make up the *Haplotichnus* assemblage. *Undichna, Haplotichnus,* and *Treptichnus* also are present in the Pottsville ichnofauna. These deposits were interpreted as having accumulated in brackish water, alluvial-swamp, and tidal-flat settings (Demko in Rindsberg, 1990). The nonmarine nature of the ichnofauna and the absence of definitive marine indicators suggest a terrestrial to freshwater biota.

Kvale and Barnhill (1994) recorded an ichnofauna consisting of *Treptichnus, Haplotichnus,* small arthropod trackways, and possible fish-fin drag marks in tidal rhythmites from Lower Pennsylvanian strata of the Illinois Basin. These authors suggested that these strata were deposited on estuarine tidal flats under brackish to freshwater conditions. Both the trace fossils and sedimentary facies are similar to those in the Buildex strata documented in this paper.

The examples briefly discussed here yield clear evidence that a distinctive and recurrent trace-fossil assemblage (Buildex-type ichnofaunas) is widespread in Pennsylvanian tidal rhythmites of the Midcontinent. Identification of such ichnofaunas may be useful in the recognition of freshwater inner estuarine facies and may help to delineate fluvioestuarine transitions in incised valley systems.

Conclusions

The Buildex ichnofauna was produced by a terrestrial and freshwater biota and represents a mixture of the nonmarine *Scoyenia* and *Mermia* ichnofacies. The presence of such an assemblage in tidal rhythmites indicates deposition on tidal flats in the most proximal zone of the inner estuary. This zone is situated between the landward limit of tidal currents and the salinity limit further towards the sea.

Although lithofacies distribution within estuarine valleys is mostly salinity-independent, the distribution of organisms is not. Accordingly, ichnologic analysis of estu-

arine systems can provide the high-resolution data necessary to delineate fluvio-estuarine transitions and may help to refine facies models based only on physical evidence.

In terms of sequence stratigraphy, Buildex-type ichnofaunas characterize the lower part of the transgressive system tract, immediately overlying a coplanar surface. As transgression proceeds, tide-influenced freshwater facies are replaced by backstepping brackish-water deposits, and the mixed *Scoyenia* and *Mermia* ichnofacies may be replaced by a *Skolithos* and impoverished *Cruziana* ichnofacies. The coplanar surface (flooding surface and sequence boundary) at the base of the Tonganoxie sequence at Buildex Quarry lacks the *Glossifungites* ichnofacies, which is restricted to the limits of marine influence within the valley system. The coals and paleosols with upright plant remains that typify the surface represent erosional truncation and nondeposition close to the valley interfluves and may be regarded as the landward equivalent of the *Glossifungites* ichnofacies.

Comparisons with other trace fossil assemblages from marginal marine environments suggest that Buildex-type ichnofaunas are widespread in Pennsylvanian tidal rhythmites of the United States Midcontinent. Recognition of such ichnofaunas may be useful in the identification of freshwater inner estuarine facies and help to delineate fluvioestuarine transitions in incised valley systems.

Acknowledgments

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