Sedimentology and Ichnology of Paleozoic Estuarine and Shoreface Reservoirs, Morrow Sandstone, Lower Pennsylvanian of Southwest Kansas, USA

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Abstract

Integration of ichnologic, sedimentologic, and stratigraphic studies of cores from Lower Pennsylvanian oil and gas reservoirs (lower Morrow Sandstone, southwest Kansas) allows researchers to distinguish between estuarine- and open-marine deposits. This study represents one of the first published ichnologic analyses of a Paleozoic reservoir and, therefore, provides a unique opportunity to test the applicability of models based on observations from Mesozoic and Cenozoic reservoirs. Fifteen facies grouped in two facies-assemblages (estuarine and open-marine) were recognized from the lower Morrow.

The estuarine facies-assemblage includes both interfluve and valley-fill deposits, encompassing a variety of depositional environments, such as fluvial channels, interfluve paleosols, upper-estuarine channels, estuary bay, restricted tidal flats, tidal channels, and estuary mouth. The presence of a low-diversity, opportunistic, impoverished-marine ichnofauna dominated by infaunal structures, which represents a mixed *Skolithos* and depauperate *Cruziana* ichnofacies, supports a brackish-water setting. Overall distribution of ichnofossils along the estuarine valley was mainly controlled by the salinity gradient, with other parameters, such as oxygenation, substrate and energy, acting at a more local scale. The lower Morrow estuarine system displays the classical tripartite division (seaward marine sand plug, fine-grained central bay, and sandy landward zone) of wave-dominated estuaries, with local evidence of tidal action. The estuarine valley displays a northwest-southeast trend, draining to the open sea towards the southeast. A major lowstand of sea level at the Mississippian-Pennsylvanian boundary is thought to be responsible for incision of the estuarine valley.

The open-marine facies assemblage includes upper-shoreface, middle-shoreface, lower-shoreface, offshore-transition, offshore, and shelf deposits. In contrast to the estuarine assemblage, open-marine ichnofaunas are characterized by highly diverse biogenic structures produced by a benthic fauna developed under conditions of normal salinity. Trace-fossil and facies analyses allow environmental subdivision of the shoreface and offshore packages and suggest deposition in a weakly storm-affected nearshore area. An onshore-offshore replacement of the *Skolithos* ichnofacies by the *Cruziana* ichnofacies is clearly displayed. Identification of incised valley systems in the lower Morrow has implications for hydrocarbon exploration and subsequent production because reservoir quality is largely determined by facies distribution and external geometry. While the open-marine model predicts a layer-cake style of facies distribution as a consequence of strandline-shoreline progradation, recognition of valley-fill sequences points to more compartmentalized reservoirs, due to heterogeneity created at different scales by valley incision and distribution of facies and facies assemblages. The emergent picture is one of a heterogeneous and compartmentalized reservoir, displaying high variability in sedimentary facies and a complex pattern in distribution and connectivity of reservoir sandstones.

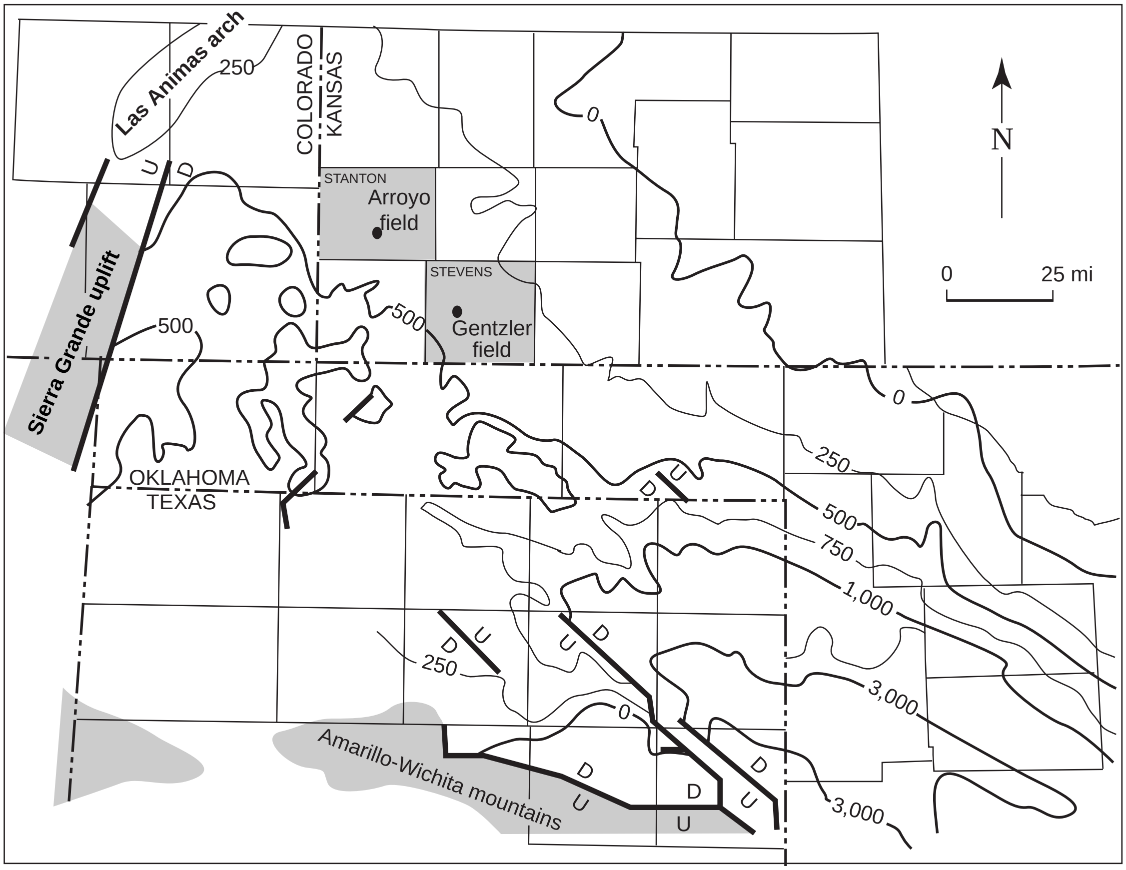

FIGURE 1. Isopach map of the Morrow Sandstone showing location of the Arroyo and Gentzler fields in southwest Kansas. Contour interval = 250 feet (76.2 m).

Introduction

Integration of facies and trace-fossil evidence tests and refines depositional models constructed solely on the basis of physical sedimentology. In recent years, the petroleum industry has increasingly used trace-fossil analysis of cores as an aid in reservoir characterization. In particular, ichnologic data have been instrumental in the recognition of estuarine deposits and their distinction from open-marine facies (e.g., MacEachern and Pemberton, 1994). Previous ichnologic analyses of cores, however, have concentrated on post-Paleozoic reservoirs (e.g., Bockelie, 1991; Pemberton, 1992; Taylor and Gawthorpe, 1993; Howell et al., 1996; Martin and Pollard, 1996; MacEachern and Pemberton, 1997). The present study represents one of the first attempts to apply trace-fossil analysis to cores from Paleozoic reservoirs.

The Lower Pennsylvanian Morrow Sandstone contains oil and gas reservoirs in a wide variety of shallow and marginal-marine depositional environments. Delta-front, shoreface, and estuarine valley-fill reservoir sandstones are encased in offshore and estuarine mudstones (Sonnenberg, 1985; Krystinik and Blakeney, 1990; Sonnenberg et al., 1990; Wheeler et al., 1990). An integrated stratigraphic, sedimentologic, and ichnologic study provides a more accurate characterization of reservoir facies and geometry. This study allows distinction between marine-shoreface and estuarine valley-fill sandstones from four cores of the lower Morrow in southwestern Kansas. Core analysis subsequently was integrated with well-log information. Previous studies have emphasized the presence of estuarine valley-fills in the upper Morrow (Wheeler et al., 1990). Our integrated approach extends the estuarine valley interpretation into the lower Morrow. Within the midcontinent, trace fossils are useful in distinguishing different facies in estuarine incised valleys and marine shorefaces. Detailed study of biogenic structures provides high-resolution information to solve problems in facies, stratigraphic, and reservoir modeling. In some cases, they represent the only evidence available to develop a reasonable picture of depositional conditions and to estimate reservoir heterogeneity. The present study provides a detailed analysis of the sedimentary facies, documents the associated trace fossils, and illustrates how trace fossils are used to refine environmental interpretations of the lower Morrow sandstone reservoirs.

Geologic and Stratigraphic Framework

The Morrow Sandstone (Kearny Formation) in the subsurface of southwest Kansas, southeast Colorado, and northwest Oklahoma (fig. 1) includes rocks that lie

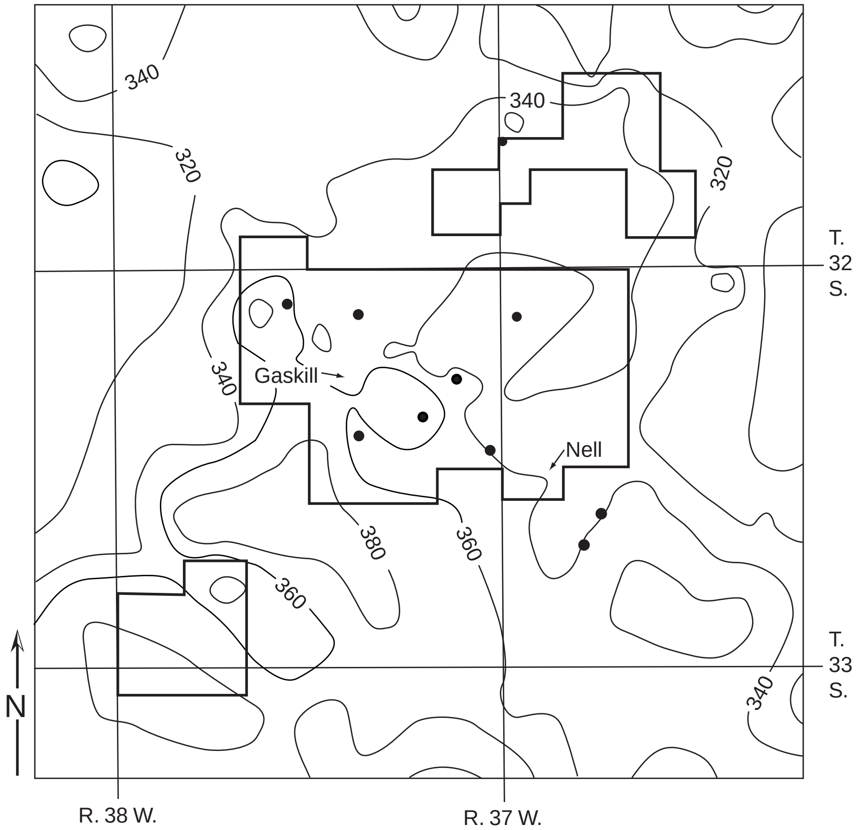

FIGURE 2. Isopach map of the lower Morrow Sandstone in the Gentzler field showing location of Gaskill No. 10-2 and Nell "A" 19-1 wells. Contour interval = 20 feet (6.1 m).

immediately below strata of Atokan age and immediately above Mississippian rocks (Sonnenberg et al., 1990). This formation has been divided into two informal units: lower and upper Morrow (Swanson, 1979). The lower Morrow traditionally has been interpreted mainly as offshore shales and shoreface sandstones, though more recently Breyer (1995) documented an estuarine valley in lower Morrow cores from Oklahoma. The upper Morrow was interpreted as marine shales that encase transgressive valley-fill sequences (Wheeler et al., 1990; Krystinik and Blakeney, 1990). Marginal- and shallow-marine deposits of the Morrow Sandstone accumulated in the Hugoton embayment, which stretched into Kansas and Colorado from the deeper-water Anadarko basin in Oklahoma (Krystinik and Blakeney, 1990; Krystinik and Blakeney-DeJarnett, 1997). This embayment was flanked by a series of tectonic positive areas resulting from orogenic movements due to the collision between the North American and South American-African plates during the Late Mississippian to Early Pennsylvanian (Rascoe and Adler, 1983; Sonnenberg et al., 1990). These topographic highs, including the Front Range, the Cambridge arch-Central Kansas uplift, the Amarillo-Wichita uplift, the Apishapa uplift, and Las Animas arch, were important sedimentary sources for Morrow clastics (Sonnenberg, 1985; Sonnenberg et al., 1990).

The lowest sea levels in the Carboniferous occurred during the Morrowan and strongly affected sedimentation (Ross and Ross, 1988). Wheeler et al. (1990) recognized seven estuarine-valley sequences in the upper Morrow. Incision at the base of each sequence resulted from sea-level drop, with valley infill occurring during the subsequent sea-level rise (Wheeler et al., 1990; Krystinik and Blakeney, 1990; Krystinik and Blakeney-DeJarnett, 1997). During sea-level lowstands, valleys were incised into older shelf-deposits and the basin was drained to the shelf-slope break located in Oklahoma in the Anadarko basin (Sonnenberg, 1985; Sonnenberg et al., 1990). During highstands, valleys were backfilled, and a broad shelf covered the area (Sonnenberg, 1985; Sonnenberg et al., 1990; Wheeler et al., 1990). Incised valleys in the upper Morrow are oriented along a northwest-southeast axis (Sonnenberg et al., 1990; Wheeler et al., 1990).

The Study Area

This study is based on the analysis of cores from the Gentzler and Arroyo oil and gas fields. The Gentzler field is one of a group of Morrow gas reservoirs located in northwest Stevens County, Kansas (fig. 2). Two cores of the lower Morrow in this field were examined as part of this study. The Anadarko Petroleum Corp. Gaskill No. 10-

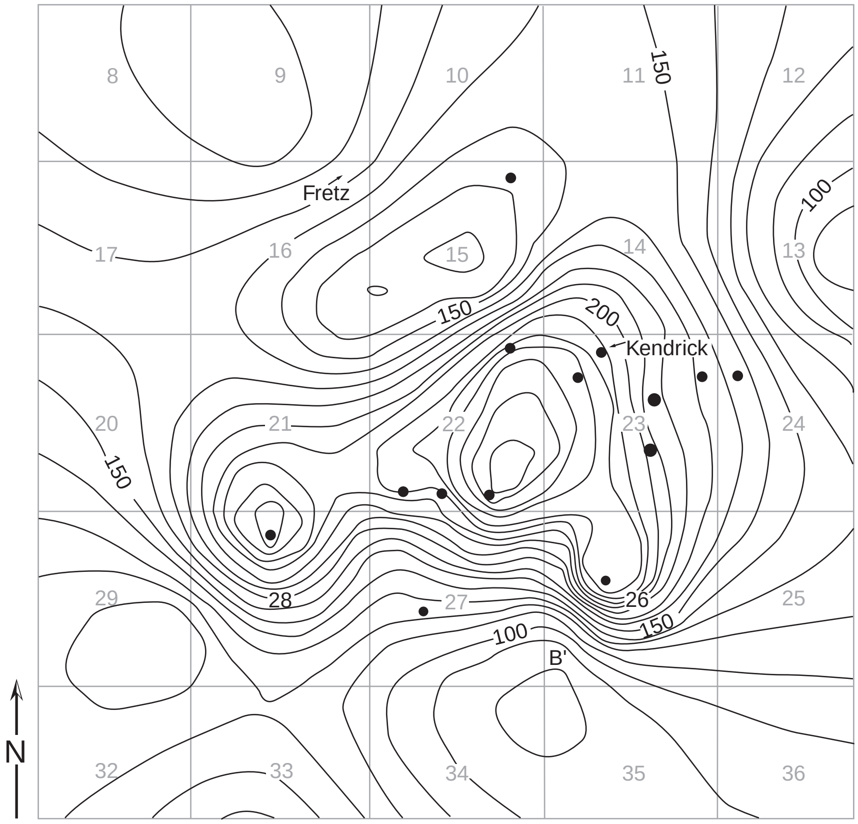

FIGURE 3. Isopach map of the lower Morrow Sandstone in the Arroyo field showing location of Kendrick 23-1 and Fretz 16-1 wells. Contour interval = 10 feet (3 m).

2 (C SE sec. 10, T. 33 S., R. 38 W.) recovered 133 ft (40.5 m) of core (5,952–6,085.5 ft; 1,814. 2–1,854.9 m; datum is ground level) and penetrated 19 ft (5.8 m) below the base of the Pennsylvanian-Mississippian erosional contact. The Anadarko Petroleum Corp. Nell "A" 19-1 (C W/2 NE, sec. 19, T. 33 S., R. 37 W.) recovered 42 ft (12.8 m) of core (6,036–6,078 ft; 1,839.8–1,852.6 m) beginning above the lower Morrow sands and ending above the base of the formation.

The Arroyo field in Stanton County, Kansas, was discovered in 1990 (fig. 3). Cores were examined across the lower Morrow interval from the Huber Kendrick 23-1 (C NW NE NW, sec. 23, T. 29 S., R. 41 W.) and the Huber Fretz 16-1 (C NE NE NE, sec. 16, T. 29 S., R. 41 W.). The Kendrick 23-1 recovered 85 ft (26 m) of core from 5,375–5,460 ft (1,638.3–1,664.2 m), beginning above the Pennsylvanian-Mississippian contact and ending below the top of the lower Morrow. The Fretz 16-1 recovered core from 5,399–5,452 ft (1,645.6–1,661.8 m) across the Pennsylvanian-Mississippian erosional contact but did not recover Morrow reservoir-quality sand.

Facies Descriptions and Interpretations

Fifteen facies, grouped in two facies-assemblages (fluvio-estuarine and open marine), were identified (table 1). The sedimentology and ichnologic content of each of these facies is discussed below, along with its implications in terms of depositional conditions and sedimentary environments. Facies descriptions include thin-section information. Samples from Gaskill were processed for conodonts and a list of taxa was available for this study (H. R. Lane, unpublished report, 1983). Information on the degree of bioturbation is based on the scheme by Taylor and Goldring (1993). Terminology for skeletal accumulations is based on Kidwell et al. (1986).

Fluvio-estuarine Facies Assemblage

Facies A: Fine-grained Sandstones

Description. This facies consists of light-gray to yellowish gray, fine-grained, calcite-cemented, glauconitic and quartzose sandstones (fig. 4). Sandstones are typically massive, with poorly defined, high-angle, planar crossbedding only preserved locally. Some foresets are delineated by small, flattened coal intraclasts. Stylolites and rare, very thin siltstone drapes occur towards the top of the interval. Pyrite replacements are very common (fig. 5). Facies A is present only at Kendrick, forming a single interval at the base of the core (5,459.7–5,444.5 ft; 1,664.1–1,659.5 m).

Ichnology. Scarce and very small (2–3 mm; 0.08–0.12 in) *Palaeophycus* isp. were recorded.

TABLE 1. Facies scheme of the lower Morrow in the Arroyo and Gentzler fields.

Facies	**Depositional Process**	**Sedimentary Environment**
A: Fine-grained sandstones	Tractive currents	Fluvial channels
B: Rooted siltstones	Pedogenic processes	Paleosol
C: Very coarse grained to fine-grained sandstones with clay drapes	Migration of subaqueous, unidirectional flow dunes and slack-water sediment fallout	Upper-estuarine, bay-head delta channels
D: Parallel-laminated black shales with fading ripples	Sediment fallout and low-energy tidal currents	Central-estuarine bay
E: Flaser- and wavy-bedded sandstones and siltstones	Tidal currents	Restricted-tidal flat
F: Inclined, deformed sandstones and siltstones	Tidal currents, sediment downslope movement and lateral accretion	Tidal channel
G: Laminated calcareous mudstones	Sediment fallout	Lower estuary
H: Poorly to moderately fossiliferous, planar-crossbedded sandstones and pebble conglomerates	Migration of subaqueous, unidirectional flow dunes	Estuarine mouth
I: Highly fossiliferous, planar-crossbedded, very coarse- to medium-grained sandstones and pebble conglomerates	Migration of subaqueous, unidirectional flow dunes	Upper shoreface
J: Rarely to moderately burrowed, planar-crossbedded, medium- to fine-grained sandstones	Migration of subaqueous, unidirectional flow dunes	Proximal middle shoreface
K: Moderately to thoroughly burrowed, rippled, fine-grained sandstones	Migration of subaqueous, unidirectional flow ripples and sediment fallout	Distal middle shoreface
L: Thoroughly burrowed, fine-grained to very fine grained silty sandstones with starved ripples	Migration of subaqueous, unidirectional flow ripples and sediment fallout	Lower shoreface
M: Thoroughly burrowed, very fine grained silty sandstones and siltstones with interbedded, normally graded sandstones	Storm action and sediment fallout	Offshore transition
N: Thoroughly burrowed siltstones	Sediment fallout	Offshore
O: Parallel laminated black shales	Sediment fallout	Shelf

Interpretation. Facies A is interpreted as having been deposited in fluvial channels. Local presence of planar crossbedding indicates migration of unidirectional, subaqueous dunes. A freshwater setting is supported by the paucity of bioturbation. *Palaeophycus* is a facies-crossing form, and no definite marine indicators are present in this interval. Fluvial facies recorded in the upper Morrow by Wheeler et al. (1990) are typically coarser grained.

Facies B: Rooted Siltstones

Description. Facies B consists of dark-gray siltstones with textures and structures indicative of pedogenic processes, such as prismatic peds and very fine grained cutans with striated and smeared surfaces (fig. 6). Root marks and plant debris are present. Scarce fragments of abraded, marine bivalve shells were also detected. Facies

FIGURE 4. Facies A. Massive, fine-grained sandstones (Kendrick).

FIGURE 5. Facies A. Pyrite replacement (Kendrick).

B is only present at Fretz, forming a single interval at the base of the core (5,429–5,449 ft; 1,654.8–1,660.9 m). The upper part of the unit (5,431–5,429 ft; 1,665.4-1,654.8 m) consists of laminated shales.

Ichnology. No animal traces were detected.

Interpretation. This facies is interpreted as a paleosol, which most likely developed in interfluve areas. The local presence of bivalve shells indicates pedogenic modification of marine sediments. The striated and smeared surfaces of the cutans are regarded as slickensides, and the cutans, therefore, are considered to be stress cutans. Although stress cutans may also form simply by the crushing of peds against one another during compaction (Retallack, 1990), the swelling and shrinking of clays during repeated wetting and drying episodes is consistent with the envisaged depositional environment of the associated facies. This facies is comparable to upper Morrow facies 10 of Wheeler et al. (1990).

Facies C: Very Coarse Grained to Fine-grained Sandstones with Clay Drapes

Description. This facies consists of light-greenish- to yellowish-gray, very coarse grained to fine-grained, calcite- and dolomite-cemented, glauconitic and quartzose sandstones with low-angle, planar cross-stratification and ripple cross-lamination (fig. 7). Mud drapes, horizontal mud laminae, flattened mud lenses, and contorted mud laminae are present (fig. 8). Wavy bedding is dominant, but flaser bedding (single and flaser-wavy) is relatively common. Reactivation surfaces are locally present. Stylolites and variably oriented fractures are common. Facies C includes single intervals towards the bases of the Gaskill (6,065.4–6,051.11 ft; 1,848.7–1,844.4 m) and Kendrick cores (5,431.8–5,444.5 ft; 1,655.6–1,659.5 m). At Gaskill, a scour filled with pebble conglomerates occurs at the base of the unit, coincident with the Mississippian-Pennsylvanian (fig. 9). The whole unit displays a fining-upward trend and consists of stacked, erosionally bounded, fining-upward intervals. A package at the top of the unit in the Gaskill core (6,051.11–6,056.2 ft; 1,844.4–1,845.9 m) is a massive to normally graded, medium-grained sandstone with few mud drapes (fig. 10). In the Kendrick core, facies C overlies fine-grained sandstones of facies A. Cross-lamination dipping in opposite directions has been detected at this locality. Pyrite replacements are also very common in the Kendrick core. Bioclasts are very scarce to absent. A low-diversity assemblage of conodonts is present throughout the whole unit, except in the basal interval, which is devoid of microfossils. The conodont assemblage includes *Neognathodus, Idiognathoides,* and *Adetognathus.*

Ichnology. Facies C is characterized by its extremely low degree of bioturbation (typically 0–1 to very rarely 2 at the top of the package in Kendrick) and its low diversity of trace fossils. *Palaeophycus* isp. (fig. 11) is the dominant

FIGURE 6. Facies B. Dark gray siltstone package (Fretz).

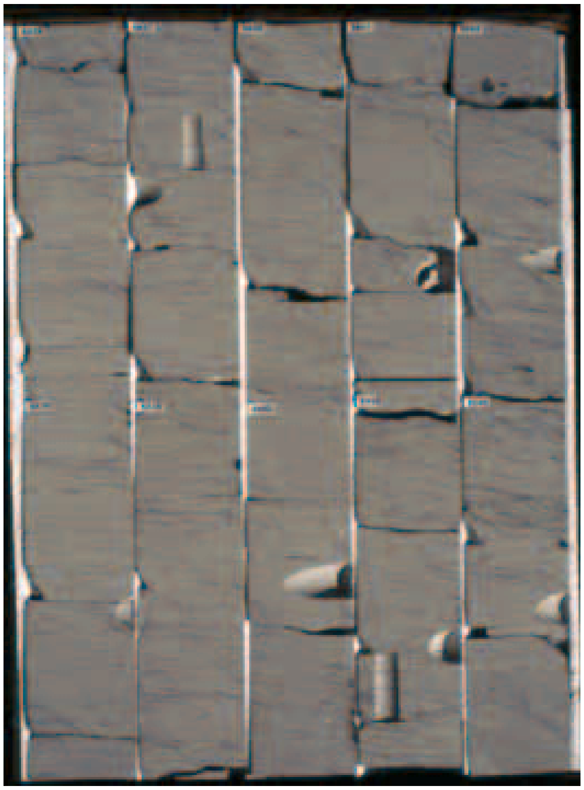

FIGURE 7. Facies C. General view of sandstone package (Kendrick).

form, but occurs in low abundance. *Skolithos* isp. (fig. 12) and robust specimens of *Arenicolites* isp. (fig. 13) are rarely present. *Monocraterion* isp. (fig. 14) occurs towards the top of the unit at Kendrick. The assemblage includes very simple dwelling structures produced by opportunistic suspension-feeders. Ichnodiversity and degree of bioturbation increase slightly towards the top of the package, particularly at Kendrick. This ichnofauna is suggestive of the *Skolithos* ichnofacies.

Interpretation. Facies C is interpreted as having been deposited in upper estuary channels within a bay-head delta. Presence of low-angle cross-stratification indicates migration of subaqueous dunes. A channel-fill interpretation is supported by the presence of erosional basal contacts, fining-upward trends, and upward decrease in bedform size. Dominance of vertical dwelling structures of suspension-feeders also indicates strong currents that keep organic particles in suspension. Presence of mud drapes indicates sediment fallout during slack-water intervals and suggests tidal influence. Tidal action is also indicated by the sporadic presence of cross-lamination dipping in opposite directions and reactivation surfaces. The low diversity of trace fossils and the presence of simple forms produced by opportunistic animals suggest a brackish-water setting (Pemberton and Wightman, 1992). Similar assemblages dominated by dwelling structures of suspension-feeders have been commonly recorded from high-energy zones of estuarine systems, typically estuarine channels (e.g., Bjerstedt, 1987; Benyon and Pemberton, 1992; Pemberton, Reinson et al., 1992). Ichnocoenoses from facies C are clearly different from ichnofaunas recorded from tidally influenced, but freshwater settings (Buatois et al., 1997). A restricted environment is also supported by the conodont fauna (specifically by its low diversity) and by the presence of the genus *Adetognathus*, dominant form of the *Adetognathus* biofacies, which indicates shallow marginal-marine environments (Merrill, 1973; Heckel and Baesemann, 1975; Boardman et al., 1995; Merrill and von Bitter, 1976). The whole interval probably records brackish-water conditions. The increase in degree of bioturbation and trace-fossil diversity is consistent with a transgressive infill of the estuarine channels. The structureless to normally graded sandstone package at the top of this unit at Gaskill is similar to the structureless sandstone facies described by Walker (1995) from estuarine deposits of the Cardium Formation. Walker interpreted that facies as having been formed by underflow currents. Sedimentologic characteristics and stratigraphic relationships suggest a similar origin for the upper interval of facies C. Overall, facies C resembles facies 6 (crossbedded sandstone with shale drapes) described primarily from the upper Morrow by Wheeler et al. (1990).

Facies D: Parallel-Laminated Black Shales with Fading Ripples

Description. Facies D comprises dark-gray to black, monotonous, parallel-laminated, carbonate-cemented

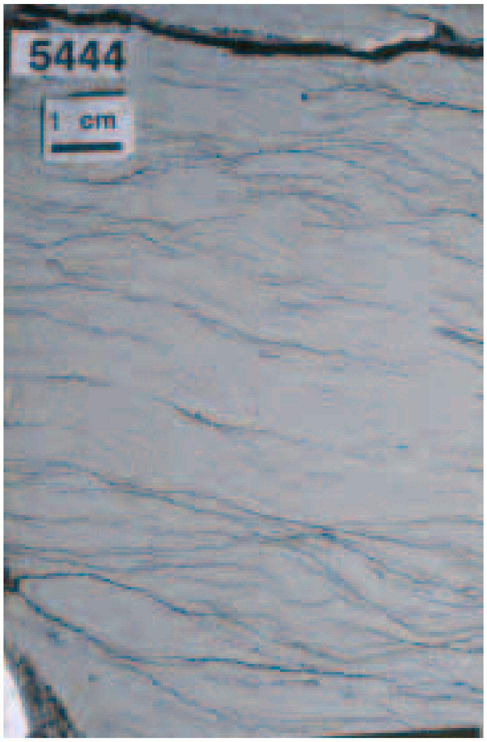

FIGURE 8. Facies C. Mud drapes (Kendrick).

FIGURE 10. Facies C. Massive to normally graded medium-grained sandstone (Gaskill).

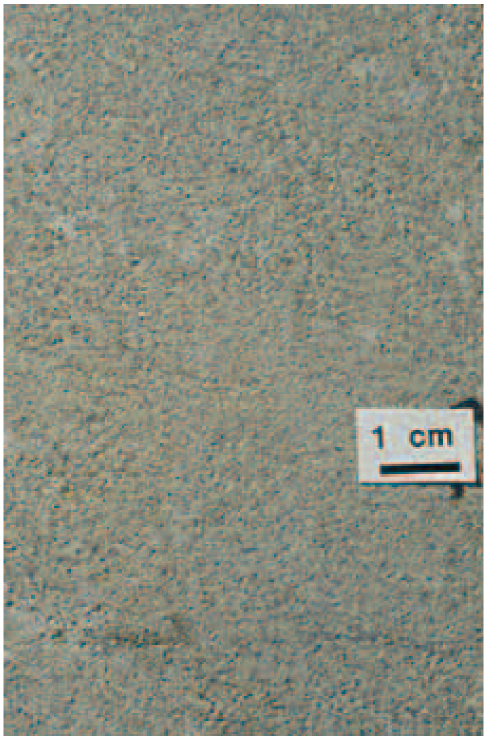

FIGURE 9. Facies C. Fining-upward sandstone package (Gaskill).

FIGURE 11. Facies C. *Palaeophycus* isp. (Kendrick).

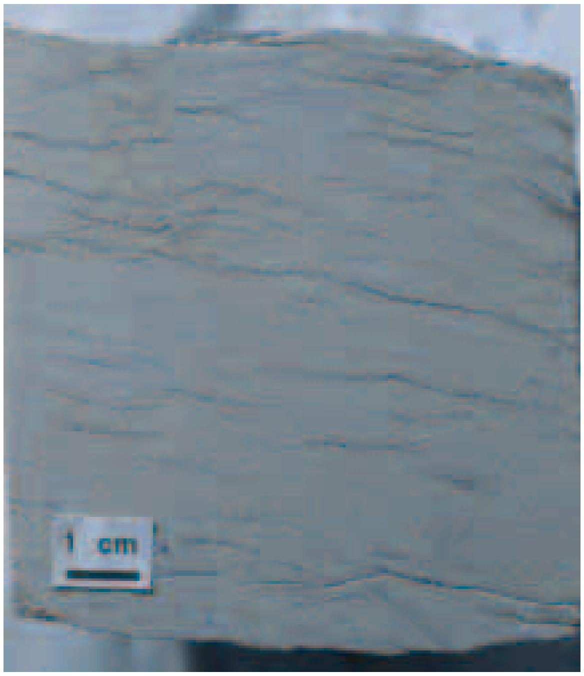

FIGURE 12. Facies C. *Skolithos* isp. (Kendrick).

FIGURE 13. Facies C. Robust specimen of *Arenicolites* isp. (Gaskill).

FIGURE 14. Facies C. *Monocraterion* isp. (Kendrick).

FIGURE 15. Facies D. Parallel-laminated shales with thin, very fine grained sandstone lenses forming connected starved ripples (Gaskill).

shales interlaminated with thin, very fine grained sandstone lenses that form isolated or connected starved ripples (fig. 15). This facies includes two packages at both the Gaskill and Kendrick cores. At Gaskill, the intervals are from 6,035.3 ft to 6,051.11 ft (1,839.6–1,844.4 m) and 6,033.5 ft to 6,034.9 ft (1,839.0–1,839.4 m), and at Kendrick, they are from 5,426.3 ft to 5,430 ft (1,653.9–1,655.1 m) and 5,419.1 ft to 5,420 ft (1,651.7–1,652.0 m) cores. The packages interfinger with the interbedded sandstones and conglomerates of facies H (figs. 16–17). In Gaskill, sandstone lenses are more abundant towards the base of the lower package and at the top of the upper package. Conodonts are abundant but not diverse, including the genera *Idiognathoides*, *Neognathodus*, and *Adetognathus.*

Ichnology. As in the case of facies C, trace-fossil diversity is low. No biogenic structures were detected at Gaskill. The ichnoassemblage at Kendrick includes *Planolites montanus* (fig. 18), *Diplocraterion* isp. (fig. 19), *Teichichnus rectus* (fig. 19), *Cruziana problematica*, and

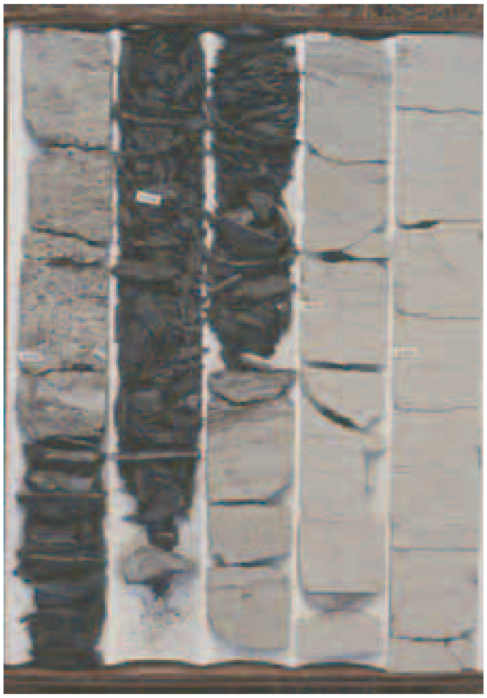

FIGURE 16. Shale packages (facies D) interfingering with interbedded sandstones and conglomerates (facies H) (Kendrick).

FIGURE 17. Shale packages (facies D) interfingering with interbedded sandstones and conglomerates (facies H) (Kendrick).

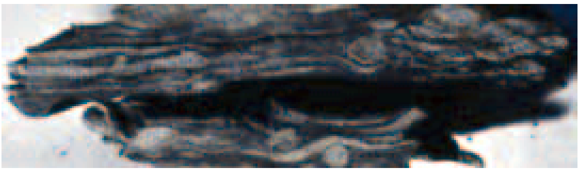

FIGURE 18. Facies D. *Planolites montanus* (Kendrick).

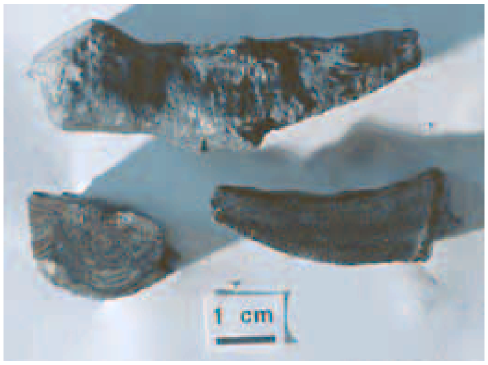

FIGURE 19. Facies D. *Diplocraterion* isp. and *Teichichnus rectus* (Kendrick).

Palaeophycus isp. The degree of bioturbation is highly variable, ranging from 0 to 3. The ichnofauna comprises a mixture of feeding structures of deposit-feeders and dwelling structures of suspension-feeders. The assemblage is an example of a depauperate *Cruziana* ichnofacies.

Interpretation. This facies is interpreted as having been deposited in the central basin of the estuarine system. Dominance of parallel-laminated mudstones indicates the fallout of fine-grained material in a low-energy environment. The fading ripples may record sand deposition due to tidal currents. Absence of root traces and pedogenic slickensides suggests subaqueous conditions. At Kendrick, the presence of an impoverished trace fossil assemblage indicates harsh conditions, most likely a stressful brackish-water environment. In contrast to the assemblage in facies C, this ichnofauna includes feeding structures of deposit-feeders, suggesting a protected, low-energy environment with abundant organic matter in the sediment. Similar ichnofaunas have been reported from restricted bay settings (e.g., Benyon and Pemberton, 1992; Pemberton, Reinson et al., 1992; Pattison, 1992). A restricted estuarine setting is also supported by the presence of the marginal-marine *Adetognathus* biofacies (Merrill, 1973; Merrill and von Bitter, 1976; Boardman et al., 1995). Central-bay mudstones typically accumulate close to or at the turbidity maximum and have been widely recognized in estuarine valleys (e.g., Reinson et al., 1988; Pattison, 1992; Lanier, 1993; Wood, 1994). The turbidity maximum zone represents an area of high mud accumulation linked to high flocculation rates and results from the vertical circulation patterns established in the estuary (Kranck, 1981). Muddying- to sandying-upward vertical trends similar to those identified in this study have been recognized in other estuary-funnel sequences by Pattison (1992), who suggested that they probably reflect fluctuations in sea-level changes or changes in sedimentation rate. In the present case, this vertical succession most likely reflects sand from fluvial sources (at the base of the package), followed by suspension fallout in the deepest areas of the bay (middle mud-dominated portion), and sand brought in via washovers from the estuary mouth (upper part of package).

Facies E: Flaser- and Wavy-bedded Sandstones and Siltstones

Description. Facies E consists of light-yellowish gray, very fine grained, calcite- and dolomite-cemented, glauconitic and quartzose sandstones and siltstones. Heterolithic bedding is dominant, consisting of flaser bedding (typically bifurcated-wavy or, more rarely, wavy), and wavy bedding. Physical sedimentary structures include ripple cross-lamination, mud drapes, low- and high-angle, planar cross-lamination, and reactivation surfaces (figs. 20–21). Cross-lamination dipping in opposite directions is present (fig. 22). Locally interbedded, fine-grained sandstones display planar cross-lamination, with coarser grains tending to concentrate along foresets. Stylolites filled with clays, organic matter, and mica are common. Mudstone intraclasts are rare. Facies E consists of a single package at the Gaskill core (6,031.6–6,025.7 ft; 1,838.4–1,836.6 m), where it is associated with sandstones of facies H. Bioclasts are very scarce to absent. Large carbonized wood logs are abundant.

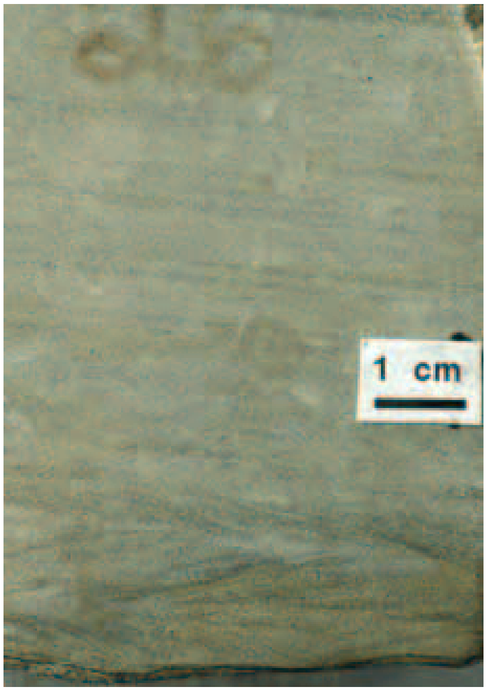

FIGURE 22. Facies E. Sandstone with ripple cross-stratification and cross-lamination dipping in opposite directions (Gaskill).

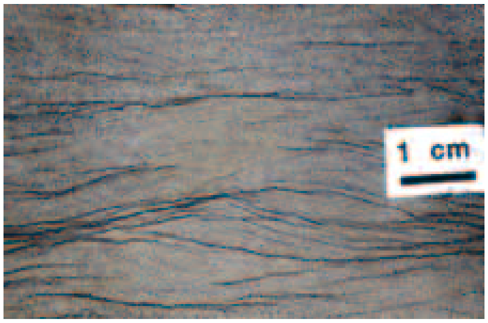

FIGURE 20. Facies E. Sandstone with ripple cross-lamination, mud drapes, and reactivation surfaces (Gaskill).

FIGURE 21. Facies E. Sandstone with ripple cross-lamination, mud drapes, and reactivation surfaces (Gaskill).

Ichnology. No trace fossils have been recorded.

Interpretation. This facies is interpreted as having been deposited in a restricted tidal-flat environment, most likely representing the lower-intertidal sand flat developed in a lower- to middle-estuarine setting. Presence of reactivation surfaces and cross-lamination dipping in opposite directions suggests tidal influence and flow reversals. Bedload transport during tidal flow and suspension settlement during slack-water periods are indicated by alternating flaser and wavy bedding (Reineck and Wunderlich, 1968; Klein, 1971). Local presence of planar cross-lamination is suggestive of sandwave or dune migration during periods of high-energy currents (Dalrymple, 1992). Open-marine, tidal-flat deposits commonly exhibit abundant and diverse biogenic structures (e.g., Mángano et al., 1996a,b). The paucity of body and trace fossils in facies E supports the interpretation of a tidal flat developed in a restricted embayment, rather than in a coastline directly connected with the open sea. The vertical association with facies H also suggests deposition in a transitional middle- to outer-estuarine environment (see discussion of facies H below). Facies E is similar to facies 4 (interlaminated to bioturbated sandstone and shale) described by Wheeler et al. (1990) from the upper Morrow Sandstone.

Facies F: Inclined, Deformed Sandstones and Siltstones

Description. This facies consists of light-gray, very fine grained to fine-grained sandstones interbedded with dark-gray to black siltstones. Wavy bedding, flaser bedding (single, bifurcated, and flaser-wavy types) are dominant, and lenticular bedding (with connected or single, thick lenses) is very common. The diagnostic features of this facies are diverse soft-sediment deformation structures (slumps, ball-and-pillow, pseudonodules, fluid-escape structures, convolute lamination, load casts, and syndepositional fractures) (figs. 23–24). Facies F includes a package at the base of Nell core (6,100–6104.2 ft; 1,859.3–1,860.6 m) and at the top of Fretz core (5,399–5,425 ft; 1,645.6–1,653.5 m). At Nell, inclined-heterolithic stratification is a distinctive structure, with abundant, climbing-ripple cross-lamination, planar cross-stratification, and mud drapes. The whole package at Fretz comprises a rotational slide. The basal part of the unit (5,425–5,420 ft; 1,653.5–1,652.0 m) is highly deformed, slumped and convoluted, with no stratification preserved. The upper part (5,420–5,399 ft; 1,652.0–1,645.6 m) is characterized by inclined strata displaying recurrent variations in lamina thickness and forming symmetric cycles (figs. 25–28).

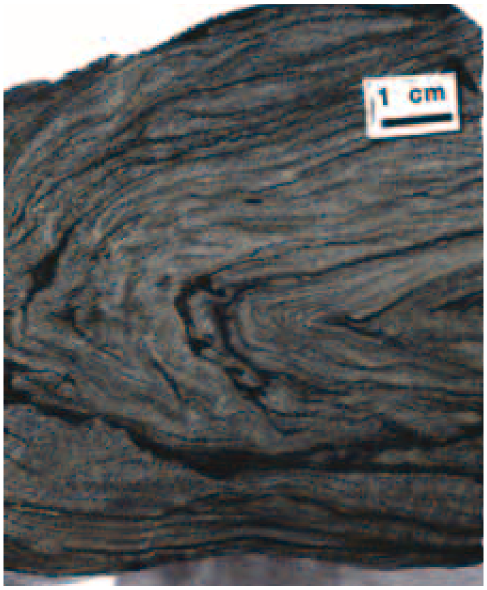

FIGURE 23. Facies F. Slumped sandstone and mudstone (Nell).

FIGURE 24. Facies F. Ball and pillow structures (Nell).

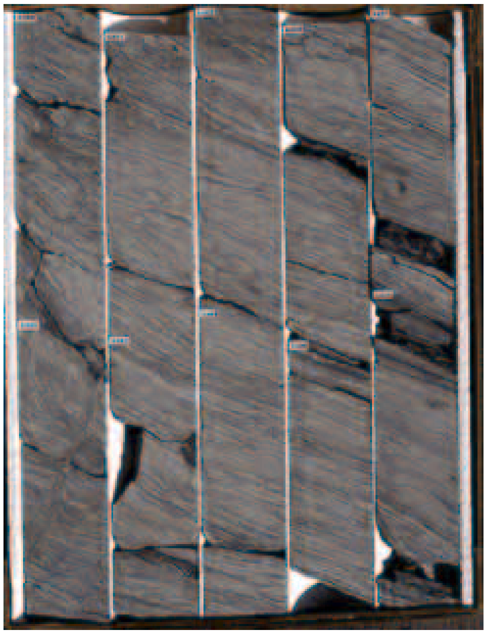

FIGURE 25. Facies F. General view of inclined strata showing recurrent variations in lamina thickness and forming symmetric cycles (Fretz).

Ichnology. No discrete trace fossils have been recorded. At Fretz, some indistinct mottled textures (possibly *Planolites* or *Palaeophycus*) are locally present.

Interpretation. Facies F is interpreted as having been deposited in tidal channels. The inclined-heterolithic stratification present at Nell is interpreted as having been produced by point-bar accretion, a dominant structure in upper-intertidal channels (e.g., Reineck, 1958; Bridges and Leeder, 1976; de Mowbray, 1983; Thomas et al., 1987). The abundance of soft-sediment deformation structures at this core suggests downslope movement of sediment across bar slopes. The presence of flaser and wavy bedding records alternation of bedload transport during tidal flow and suspension settlement during slack-water periods (Reineck and Wunderlich, 1968; Klein, 1971). Planar cross-stratification probably indicates sandwave or dune migration across the channel floor. The package at the Fretz core is thought to record cut-bank rotational slides in an intertidal channel (cf. Bridges and Leeder, 1976). The presence of symmetric cycles is indicative of tidal action and these deposits may be considered as tidal rhythmites, with thicker sets of strata representing deposition during spring and thinner sets during neap tides (e.g., Kvale and Archer, 1989; Archer, 1991; Archer et al., 1991; Lanier et al., 1993; Kvale and Barnhill, 1994). The scarcity of trace fossils is problematic because intense to moderate bioturbation has been recorded in modern (Bridges and

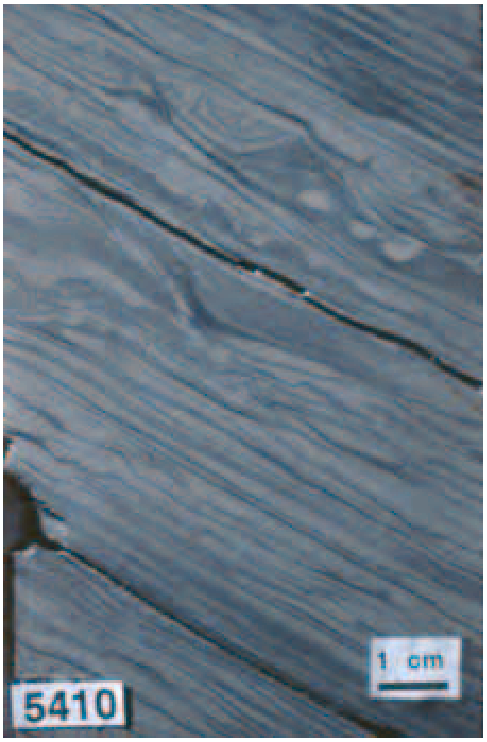

FIGURE 26. Facies F. Inclined strata with pseudonodules and ball and pillow structures (Fretz).

Leeder, 1976) and ancient tidal point bars (Ranger and Pemberton, 1992). This scarcity probably is due to intense syndepositional deformation. Intertidal channels recorded by facies F were probably formed in a middle-estuarine setting. This facies corresponds to facies 9 (ripple-laminated sandstone) of Wheeler et al. (1990).

Facies G: Laminated Calcareous Mudstones

Description. This facies includes light-gray, parallel-laminated, calcareous mudstones (fig. 29). Facies G occurs only at Fretz, forming a single package at the middle interval of the core (5,425–5,429 ft; 1,645.6–1,654.8 m). A 4-cm (1.6-in)-thick lag of small pebbles, granules, and fragmented shells separates this facies from the underlying paleosol siltstones of facies B (fig. 30).

Ichnology. No trace fossils have been recorded.

Interpretation. Facies G is interpreted as having been deposited in a restricted, low-energy, subtidal middle- to lower-estuarine setting. The basal, coarse-grained deposit represents a transgressive lag that indicates inundation of the paleosols developed at the interfluves.

Facies H: Poorly to Moderately Fossiliferous, Planar-crossbedded Sandstones and Pebble Conglomerates

Description. Facies H comprises light-gray, massive, normally graded, parallel-laminated, or low-angle planar-crossbedded, coarse- to medium-grained, calcite-cemented, glauconitic and quartzose sandstones and pebble conglomerates with interbedded fine-grained and very fine grained sandstones and carbonaceous mudstone partings. Ripple cross-lamination (fig. 31), stylolites, mud drapes, mud lenses, and flaser bedding (wavy type) are abundant in the finer-grained interbeds. Mudstone intraclasts are also common. This facies forms three packages at the middle part of the Gaskill core—from 6,035.3 ft to 6,034.9 ft (1,839.6–1,839.4 m), 6,033.5 ft to 6,031.6 ft (1,839.0–1,838.4 m), and 6,014.8 ft to 6,025.7 ft (1,833.3–1,836.6 m)—and two packages at Kendrick—from 5,420 ft to 5,426.3 ft (1,652.0–1,653.9 m) and 5,419.1 ft to 5,415 ft (1,651.7–1,650.5 m). It typically interfingers with the shale deposits of facies D (figs. 16–17) and, in the Gaskill core, with the heterolithic deposits of facies E. It is overlain by bioturbated sandstones of facies L at Gaskill and by fossiliferous, crossbedded sandstones of facies I at Kendrick. At Gaskill, this facies is composed of sandstones, whereas conglomerates are dominant at Kendrick. Pebbles are subangular to subrounded and may be up to 2 cm (0.7 in) but are commonly 0.3–0.8 cm (0.1–0.3 in). The

FIGURE 27. Facies F. Inclined strata showing recurrent variations in lamina thickness and convolute lamination (Fretz).

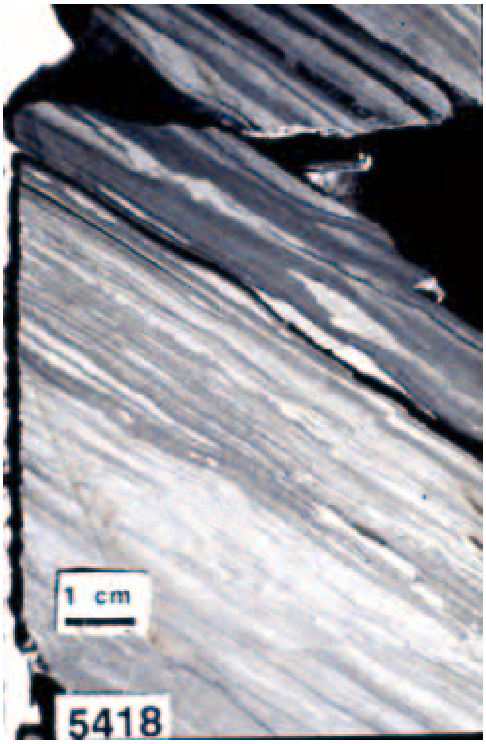

FIGURE 28. Facies F. Inclined strata with wavy and lenticular bedding (Fretz).

matrix consists of fine- to coarse-grained quartzose sand. Bioclast content in this facies is highly variable, commonly ranging from absent to moderate. Crinoid fragments are locally common, and articulate brachiopod shells, rugose corals, and fenestrate bryozoans are also present. Overall, the fossil content increases upwards, with bioclasts becoming more common in the upper packages (fig. 32). A moderately diverse conodont fauna—including the genera *Adetognathus*, *Cavusgnathus*, *Neognathodus*, and *Idiognathoides*—is present at Gaskill.

Ichnology. Trace fossils are extremely rare at Gaskill. Discrete, very simple feeding traces of *Planolites* isp. occur in carbonaceous mudstone partings at the top of the interbedded fine-grained and very fine grained sandstones. Degree of bioturbation ranges from 0 to very rarely 1. At Kendrick, trace fossils are mainly restricted to the uppermost part of the lower package, where the silty matrix of the conglomerate is intensely bioturbated (up to degree 4) (fig. 33). The association includes *Palaeophycus* isp., *Asterosoma* isp., *Diplocraterion* isp., and *Skolithos* isp. (fig. 34), as well as undistinguishable mottled textures. A large, lined burrow probably produced by crustaceans occurs towards the base of this package. Small *Planolites montanus* occur at mudstone partings. The assemblage present in facies H probably represents a mixed, depauperate *Cruziana-Skolithos* ichnofacies.

Interpretation. Facies H is interpreted as having been deposited in the estuary mouth, comprising the sand plug. Such sand plugs are typical elements of wave-dominated estuaries (e.g., Dalrymple et al., 1992; Pattison, 1992; Zaitlin et al., 1994). The stratigraphic position of this facies, interfingering at the base with the central-bay mudstones (facies D) and lying immediately below open-marine, lower-shoreface sandstones (facies L) or upper-shoreface sandstones (facies I), supports deposition at the seaward end of the estuary. A brackish environment is also suggested by the low-diversity conodont fauna and by the occurrence of the genus *Adetognathus,* dominant form of the marginal-marine *Adetognathus* biofacies (Merrill, 1973; Merrill and von Bitter, 1976; Boardman et al., 1995). Facies H includes different subenvironments within the estuary mouth: the coarser-grained facies probably records washovers and flood tidal deltas, and the finer-grained facies represents deposition in more quiet, protected settings. Packages commonly display evidence of increasing marine influence upwards (e.g., more

FIGURE 29. Facies G. General view of parallel-laminated, calcareous mudstone package (Fretz).

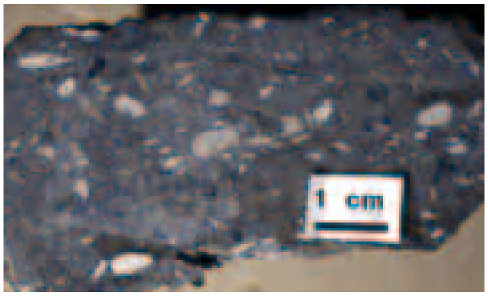

FIGURE 30. Transgressive lag of gravel and fragmented shells separating facies G from the underlying paleosol siltstones of facies B (Fretz).

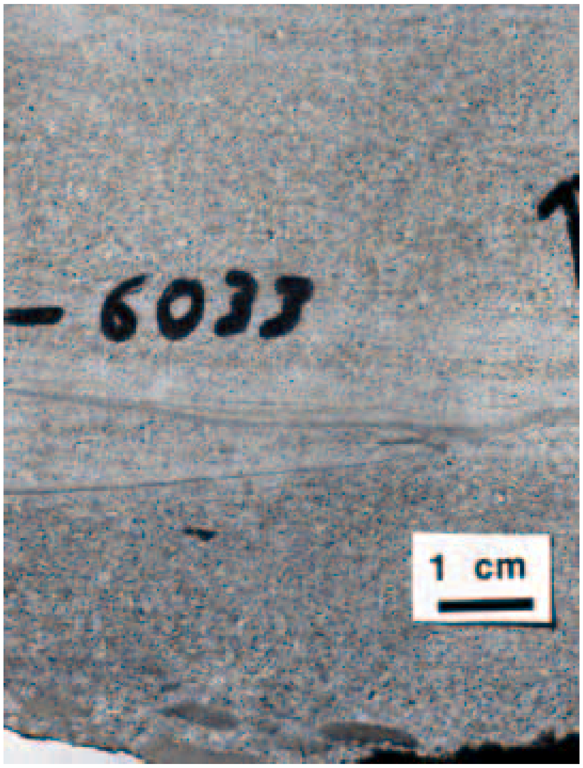

FIGURE 31. Facies H. Ripple cross-laminated sandstone (Gaskill).

bioclasts) and most likely record retrogradation of the barrier complex that separated the estuary from the open-marine environment. The presence of crinoidal, brachiopod, coral, and bryozoan skeletal debris in the sandstones indicates a seaward source of detritus. The absence of bioturbation in the coarser-grained barrier facies at Gaskill probably is due to high energy and sedimentation rate, rather than brackish-water conditions. Monospecific suites of poorly specialized traces of opportunistic animals in the finer-grained deposits at Gaskill are common features of estuarine systems (e.g., Wightman et al., 1987; Keith et al., 1988; Ranger and Pemberton, 1988, 1992; Pattison, 1992; Pemberton and Wightman, 1992; Benyon and Pemberton, 1992; Pemberton, Reinson et al., 1992; MacEachern and Pemberton, 1994). *Planolites* seems to reflect opportunistic colonization after rapid deposition of washover sands derived from the barrier. Brackish conditions also probably precluded the establishment of a more diverse ichnofauna. Washover-fan and flood tidal-delta deposits typically display very few traces (e.g., Pemberton, Van Wagoner et al., 1992). The presence of intensely bioturbated sediments at the top of the lower package in Kendrick probably also records colonization by the infauna after deposition of coarse-grained detritus derived from the barrier. Although Pemberton, Reinson et al. (1992) proposed that the presence of *Asterosoma* is suggestive of periods of normal to quasi-normal salinity conditions, other authors (e.g., MacEachern and Pemberton, 1994; Howell et al., 1996) recorded *Asterosoma* in restricted, brackish-water settings. This facies is probably partially equivalent to facies 5 (crossbedded fossiliferous sandstone) and 6 (crossbedded sandstone with shale drapes) of Wheeler et al. (1990).

FIGURE 32. Facies H. Sandstone containing abundant bioclasts (Kendrick).

Open-marine Facies Assemblage

Facies I: Highly Fossiliferous, Planar-crossbedded, Very Coarse Grained to Medium-grained Sandstones and Pebble Conglomerates

Description. Facies I consists of light-greenish-gray, planar-crossbedded to rarely massive, conglomeratic, very coarse grained to medium-grained, calcite- and dolomite-

FIGURE 33. Facies H. Intensely bioturbated silty matrix of the conglomerate (Kendrick).

cemented quartzose sandstones and pebble conglomerates (fig. 35). Granules and pebbles are dispersed in the sandstones (fig. 36), concentrated at the base of beds (fig. 37) or forming discrete fining-upward beds. Foresets are normally or inversely graded. Fine-grained sandstone interbeds are common, and, in rare cases, display low-angle cross-stratification, probably hummocky cross-stratification. Clay lenses and lamina, as well as stylolitized clay drapes may occur locally. Bed boundaries are either diffuse or erosional. In the latter case, scours filled with pebbles are typical. Bed amalgamation is common. Facies I is the most abundant facies in both fields. At Nell, it occurs as discrete packages throughout the core, typically at the top of coarsening-upward parasequences. At Kendrick and Gaskill, it makes up the upper part of the succession. In the Gaskill core, the whole facies-I unit fines upward, with thicker and more abundant shale lenses towards the top, which are finally replaced by a thick shale unit (facies O). Crinoid plates, bryozoan fragments, solitary and colonial corals, and articulate brachiopod shells are very abundant (fig. 38), forming lenses or paving the erosive bases of fining-upward beds. In some cases, they form polytypic skeletal accumulations, which are bioclast-supported in the lower part of the bed and matrix-supported in the upper one. In these concentrations, brachiopod shells are concordant, but crinoids, corals, and bryozoans do not display any preferential orientation. These fossil concentrations exhibit a simple internal structure of fining-upward type. Brachiopod shells are concentrated towards the base of the bed, while crinoids, corals, and bryozoans, although more abundant at the base, may be present as out-size fragments in the finer-grained upper parts.

Ichnology. The coarse-grained deposits in facies I are essentially unbioturbated. However, *Palaeophycus* isp. and *Ophiomorpha irregulaire* (fig. 39) may occur locally. Degree of bioturbation is low, ranging from 0 to 1. The association consists of dwelling structures of suspension-feeders and represents an example of the *Skolithos* ichnofacies.

Interpretation. This facies is interpreted as upper-shoreface deposits formed seaward and laterally to the estuary mouth. In some cases, distinction of this facies from the coarse-grained, estuarine-mouth barrier is difficult, as both tend to interfinger towards the open marine-estuary transition. Large-scale foresets are most likely part of trough cross-stratification and therefore indicate migration of subaqueous dunes. The high-angle

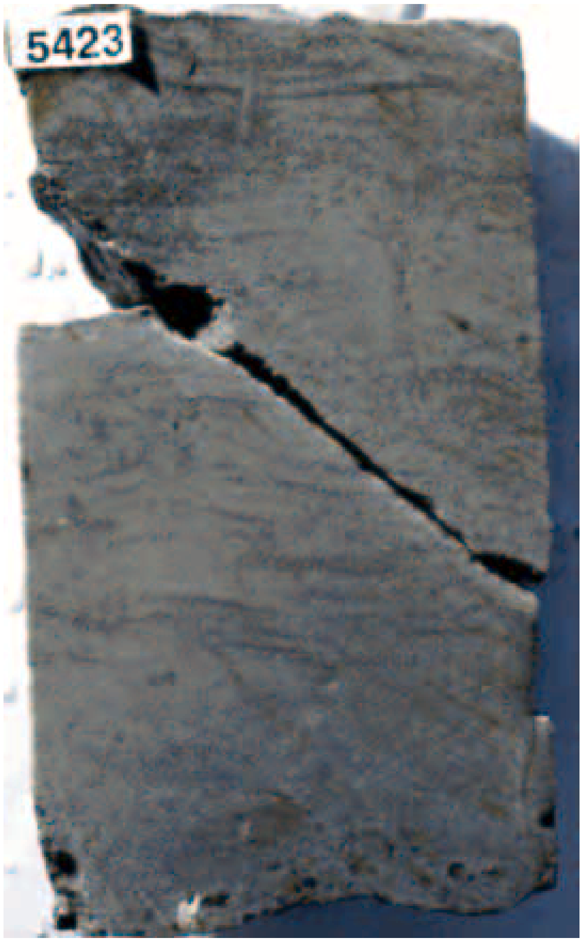

FIGURE 34. Facies H. Small *Skolithos* isp. (Kendrick).

FIGURE 35. Facies I. Planar crossbedded, very coarse grained sandstones (Nell).

foresets allow distinction of upper-shoreface deposits from foreshore facies, which are characterized by very low-angle crossbeds. The presence of trough crossbeds and the scarcity of biogenic structures is currently considered as indicative of the upper shoreface (e.g., Pemberton, Van Wagoner et al., 1992; Raychaudhuri and Pemberton, 1992). The local existence of hummocky cross-stratification suggests wave activity during storms. Furthermore, overall features of the skeletal accumulations indicate a sedimentologic origin due to storm action (cf., Kidwell et al., 1986). Similar fossil concentrations have been described from shoreface environments (e.g., Aigner, 1985). The scarce trace fossils are also a feature of the upper-shoreface deposits described by Pemberton, MacEachern et al. (1992), which include occasional *Palaeophycus, Ophiomorpha,* and escape burrows. The ichnofauna indicates a shifty sandy environment of extremely high energy, with strong physical reworking by currents and waves that keep organic particles in suspension. Facies I of this study is equivalent, at least in part, to facies 5 (crossbedded, fossiliferous sandstone) of Wheeler et al. (1990).

FIGURE 36. Facies I. Granules and pebbles dispersed in the sandstone (Nell).

Facies J: Rarely to Moderately Burrowed, Planar-crossbedded, Medium- to Fine-grained Sandstones

Description. Facies J consists of light-greenish-gray, planar-crossbedded, medium- to fine-grained, quartzose, calcite-cemented sandstones (fig. 40). Ripple cross-lamination occurs locally. Clay lenses and laminae and stylolitized clay drapes are very common (fig. 41). This facies forms several discrete packages at the Nell core, which typically overlie facies K and underlies facies I. Crinoid fragments are locally present.

Ichnology. This facies displays a higher diversity and degree of bioturbation than facies I. However, physical sedimentary structures clearly dominate over biogenic structures. Facies J typically displays a low to, very rarely, moderate degree of bioturbation (commonly 1 to rarely 2).

FIGURE 37. Facies I. Granules and pebbles concentrated at the base of sandstone bed (Kendrick).

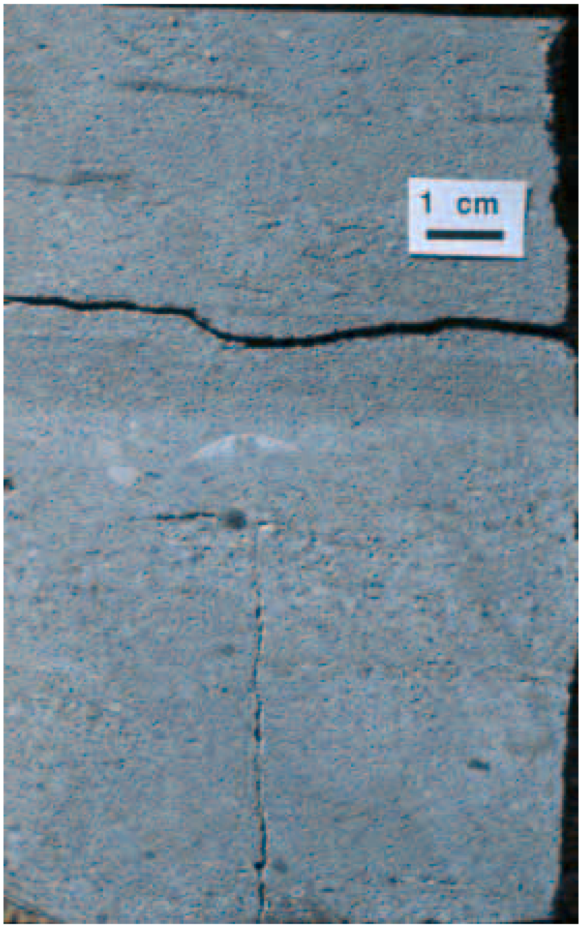

FIGURE 38. Facies I. Abundant bioclasts in planar, crossbedded, very coarse grained sandstones (Gaskill).

The assemblage includes *Asterosoma* isp. (fig. 42), *Ophiomorpha irregulaire* (fig. 40), *Skolithos* isp. (figs. 43–44), *Cylindrichnus concentricus* (fig. 41), *Palaeophycus* isp. (fig. 43), *Teichichnus* isp., *Rosselia* isp. (figs. 41, 45), *Conichnus* isp., *Bergaueria* isp. (fig. 46), *Diplocraterion* isp., thick-walled burrows (fig. 47), and escape structures. Although overall ichnodiversity is moderate, individual beds commonly exhibit only one or two ichnotaxa. Thick-walled burrows tend to occur in loose bundles of four to five individuals. Trace-fossil assemblages in facies J are characterized by the dominance of vertical burrows, most commonly dwelling structures of suspension-feeders (e.g., *Skolithos, Ophiomorpha*) and carnivores (e.g., *Conichnus, Bergaueria*). However, some dwelling structures of deposit-feeders, such as *Asterosoma, Rosselia,* and *Cylindrichnus,* are very common. Spreite feeding burrows of deposit-feeders are represented only by extremely rare occurrences of *Teichichnus.* Facies J is dominated by elements of the *Skolithos* ichnofacies, but members of the *Cruziana* ichnofacies are also present.

Interpretation. Facies J is interpreted as a middle-shoreface deposit. Planar-crossbedding and cross-lamination indicate tractive processes, essentially migration of subaqueous sand dunes and unidirectional ripples. Dominance of physical structures over biogenic ones gives evidence of rapid sedimentation in a high-energy setting. Presence of abundant vertical burrows of suspension-feeders indicates the high energy of waves and currents that kept organic particles in suspension in a mobile, sandy substrate. Rapid sedimentation is also indicated by the escape structures. The presence of dwelling traces of deposit-feeders, however, suggests local accumulation of organic detritus in the sediment, which has been used in the construction of the concentrically laminated burrows (cf. Nara, 1995). Facies J represents the finer-grained components of facies 5 (crossbedded, fossiliferous sandstone) of Wheeler et al. (1990).

Facies K: Moderately to Thoroughly Burrowed, Rippled, Fine-grained Sandstones

Description. Facies K comprises light-greenish-gray, locally ripple-cross-laminated, fine- to (very rarely) medium-grained, quartzose, glauconite-cemented sandstones (figs. 48–49). Glauconite pellets and phosphatic coating of grains are relatively common. Bioturbation

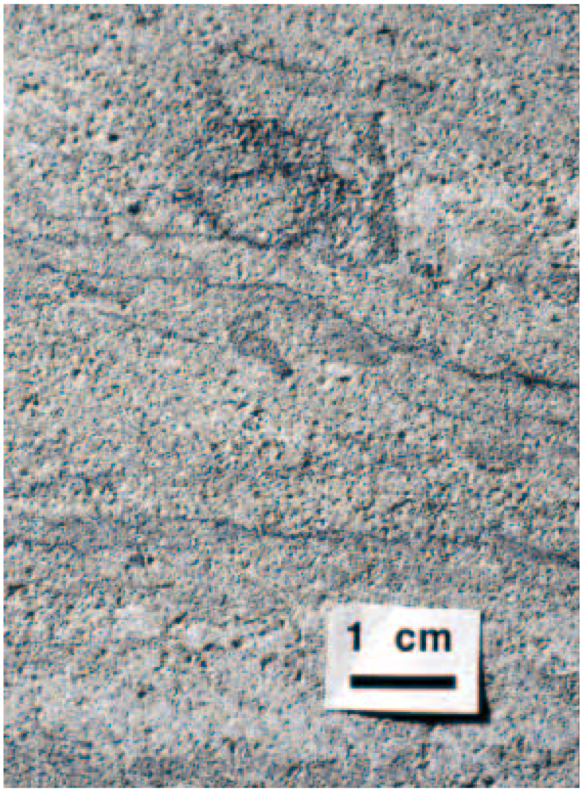

FIGURE 39. Facies I. *Ophiomorpha irregulaire* (Kendrick).

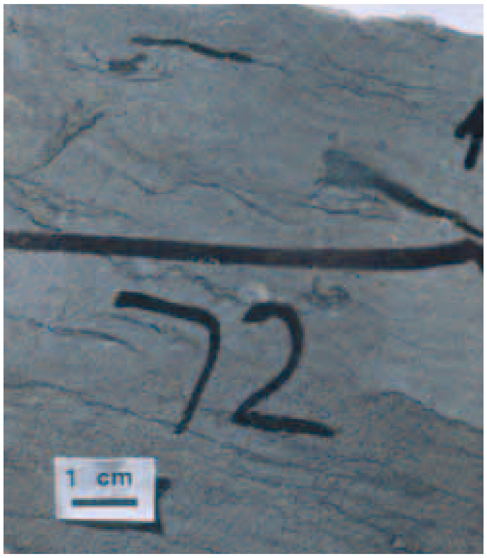

FIGURE 41. Facies J. *Cylindrichnus concentricus* and *Rosselia* isp. (Nell).

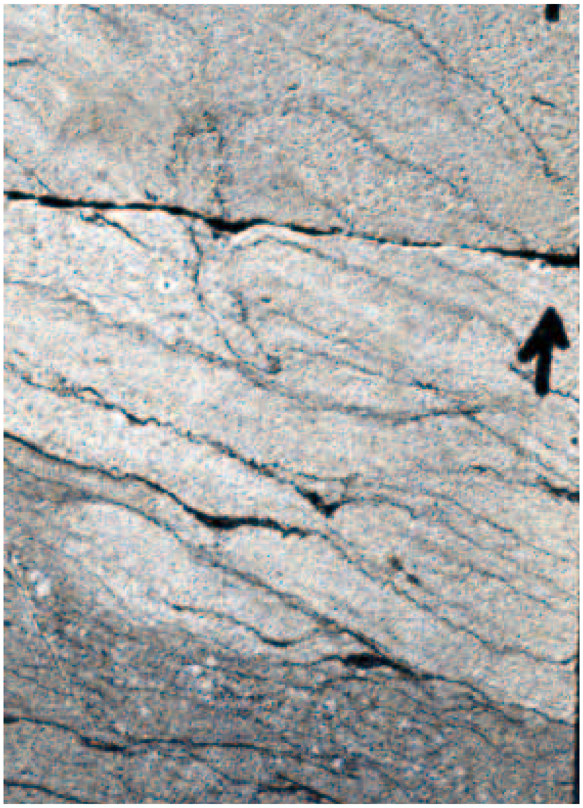

FIGURE 40. Facies J. Planar crossbedded, medium- to fine-grained sandstone with vertical *Ophiomorpha irregulaire* (Nell).

FIGURE 42. Facies J. *Asterosoma* isp. (Nell).

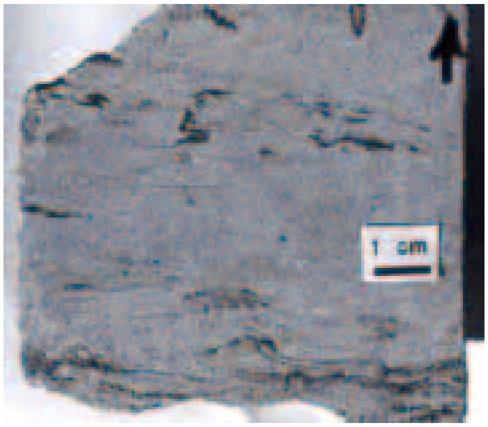

FIGURE 43. Facies J. Small specimen of *Skolithos* isp. and *Palaeophycus* (Nell).

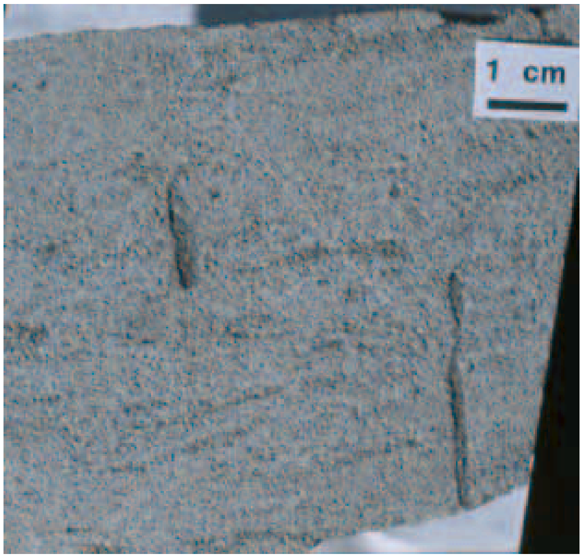

FIGURE 44. Facies J. *Skolithos* isp. (Nell).

obscures most physical structures, but remnants of both symmetric and asymmetric ripples occur rarely. Clay lenses, lamina, and drapes are abundant, commonly giving the sandstone a wispy appearance. This facies is poorly developed and occurs as several discrete intervals only at the Nell core. Facies K is invariably overlain by facies J. Towards the middle part of the Nell core, it overlies facies I, representing the lower building block of the base-missing, coarsening-upward parasequences. At the top of the succession, facies K tends to overlie finer-grained deposits of facies L. Crinoid and inarticulate brachiopod fragments are scarce.

Ichnology. While ichnodiversity in this facies is similar to that in facies J, the degree of bioturbation is remarkably higher, typically between 2 and 5. The ichnofauna includes *Ophiomorpha irregulaire, Arenicolites* isp., *Palaeophycus* isp., *Rhizocorallium* isp., *Planolites montanus, Rosselia* isp., thick-walled burrows, and nonspecific burrow mottling. In contrast to facies J, feeding structures of deposit-feeders are more important components of the ichnocoenoses, and beds tend to host multispecific assemblages. The trace-fossil assemblage combines elements of both the *Skolithos* and *Cruziana* ichnofacies. Overall, the high degree of bioturbation obliterates the

FIGURE 45. Facies J. *Rosselia* isp. and transported Rosselia (Nell).

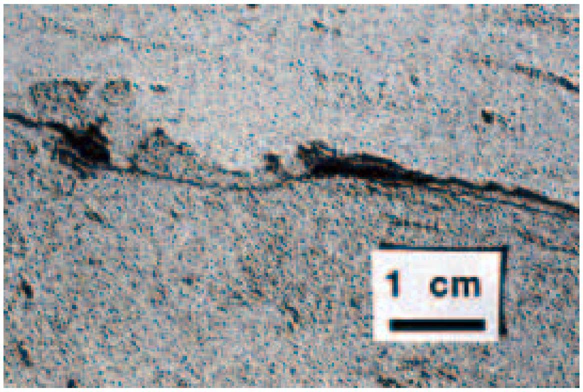

FIGURE 46. Facies J. *Bergaueria* isp. (Nell).

FIGURE 47. Facies J. Thick-walled burrows (Nell).

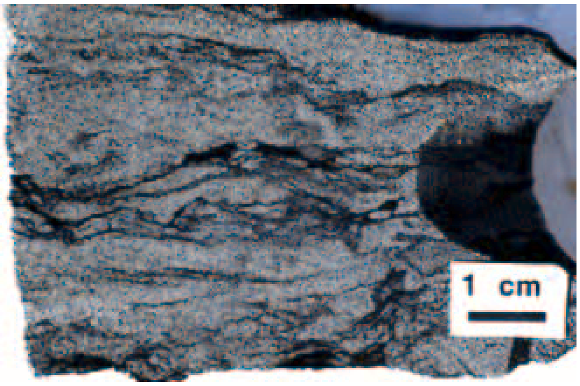

FIGURE 48. Facies K. Ripple cross-laminated and bioturbated sandstones (Nell).

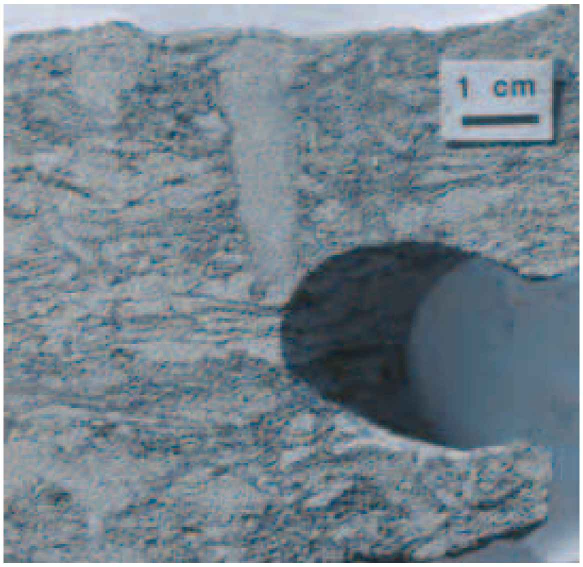

FIGURE 49. Facies K. Bioturbated sandstones. A vertical burrow is overprinting the background ichnofauna (Nell).

original primary fabric and physical sedimentary structures (figs. 48–49). The wispy appearance of this facies is probably due to biogenic activity. In some cases, the wispy streaks can be identified as wall linings of *Ophiomorpha* (see also Raychaudhuri and Pemberton, 1992).

Interpretation. Facies K is interpreted as a proximal lower-shoreface deposit. Rare preservation of remnants of current and wave ripples suggests the activity of oscillatory and translatory currents over the substrate. However, the intense bioturbation, particularly due to the activity of deposit-feeders, which obliterates the primary fabric gives evidence of a low-energy, nutrient-rich environment. Similar facies and ichnofaunas have been described from Cretaceous lower- to middle-shoreface cores by Raychaudhuri and Pemberton (1992). This facies is a partial equivalent of facies 4 (interlaminated to bioturbated sandstone and shale) of Wheeler et al. (1990).

Facies L: Thoroughly Burrowed, Fine-grained to Very Fine Grained Silty Sandstones with Starved Ripples

Description. This facies consists of dark-greenish-gray, fine-grained to very fine grained, dolomite- and quartz-cemented, glauconitic and quartzose silty sandstones. Phosphatic particles are relatively common. Primary structures are obscured for the most part by bioturbation (fig. 50), but starved ripples are locally detected (fig. 51). Ripples are symmetrical to quasisymmetrical, with irregular and undulating lower boundaries. Cross-laminae are strongly tangential towards the lower boundary, commonly sweeping up and ascending on to the adjacent bedform forming offshoots. Mud drapes are abundant and relatively thick. At Nell, this facies occurs in two intervals—from 6,048.3 ft to 6,046.7 ft (1,843.5–1,843.0 m) and 6,057.7 ft to 6,055.6 ft (1,846.4–1,845.7 m) towards the upper part of the succession. The lower interval is present between two thin packages of facies M. The upper interval is overlain by facies K and underlain by facies J, forming the base of coarsening-upward parasequences. At Gaskill, facies L comprises a single interval (6,015.8–6,013.9 ft; 1,833.6–1,833.0 m). This interval is separated

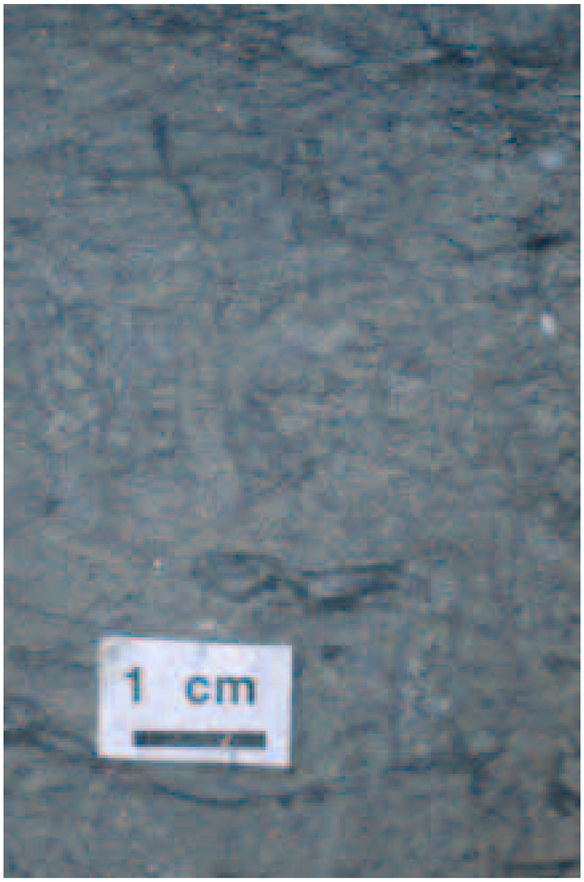

FIGURE 50. Facies L. *Rhizocorallium* isp. and *Diplocraterion* isp. overprinted to the background ichnofauna. Primary fabric totally obliterated by bioturbation (Gaskill).

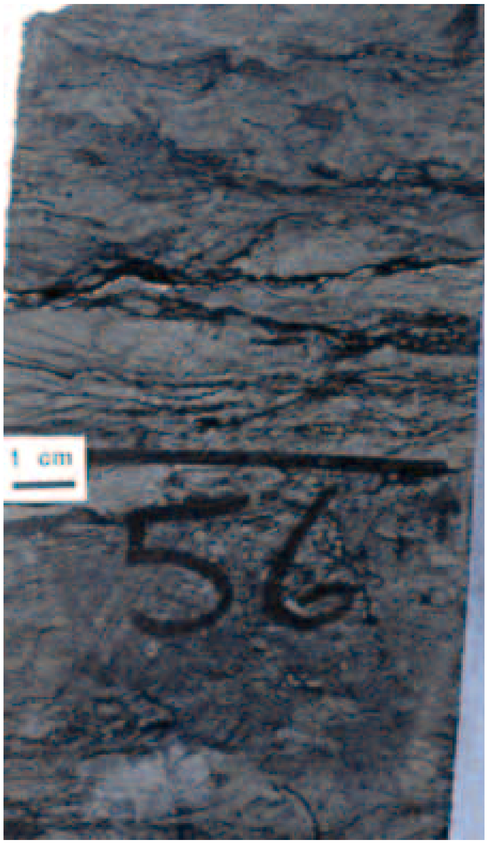

FIGURE 51. Facies L. Starved wave ripples. U-shaped *Arenicolites* burrows reworked by *Chondrites* (Nell).

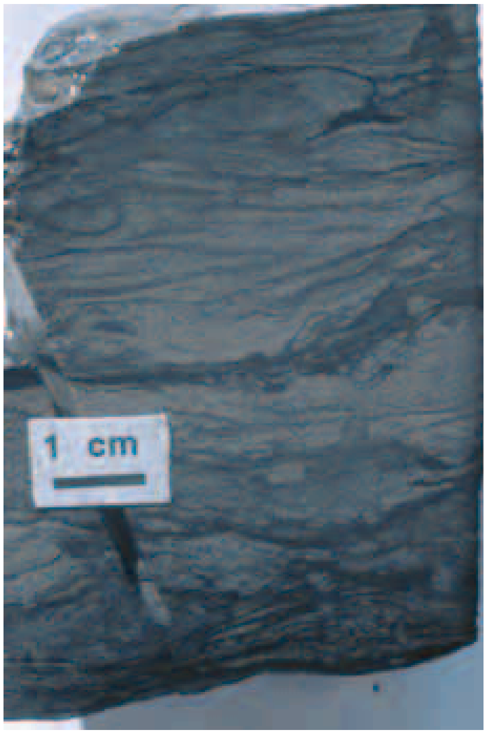

FIGURE 52. Facies L. *Chondrites* isp. and *Diplocraterion* isp. (Nell).

from the underlying facies H by a transgressive lag and is overlain by facies M. The conodont fauna at Gaskill is relatively abundant and diverse and includes the genera *Neognathodus, Idiognathoides, Adetognathus,* and *Idiognathodus.* Crinoid fragments are common in both cores.

Ichnology. This facies displays more intense bioturbation than facies K, ranging from 3 to 5. The assemblage includes *Planolites montanus*, *Chondrites* isp. (figs. 51–52), *Rhizocorallium* isp. (fig. 50)*, Diplocraterion* isp. (figs. *50, 52*), *Teichichnus* isp.*, Zoophycos* isp., *Cylindrichnus concentricus, Asterosoma* isp., *Palaeophycus* isp., *Ophiomorpha irregulaire, Skolithos* isp., and *Arenicolites* isp. (fig. 51). Although some dwelling traces of suspension-feeders are present, the assemblage is dominated by feeding structures of deposit feeders. The association is an example of the *Cruziana* ichnofacies. The high density of trace fossils obliterates all evidence of primary bedding and physical sedimentary structures in most beds. Individual beds typically host several ichnotaxa. As a result of high bioturbation, individual forms are sometimes difficult to recognize. At Gaskill, a mottled indistinctive *Palaeophycus* and

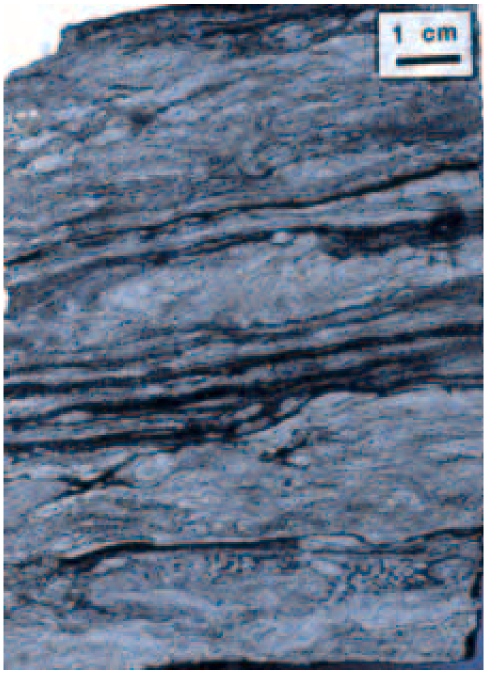

FIGURE 53. Facies M. Silty sandstone and siltstone with *Planolites montanus* and *Chondrites* isp. (Nell).

Planolites background ichnofabric is overprinted by discrete vertical U-shaped, medium-tiered *Diplocraterion,* which in turn are crosscut by very well defined specimens of deeper-tiered *Rhizocorallium.* At Nell, the tiering structure seems to be slightly different. *Rhizocorallium* is not very distinctive and *Chondrites* commonly occurs forming small clusters of up to 20 individuals in mudstone pockets or reworking other burrows, such as U-shaped *Arenicolites,* suggesting emplacement in a deep tier.

Interpretation. Facies L is interpreted as a distal lower-shoreface deposit. The occasional presence of starved wave ripples indicates sporadic distal storm events. However, most evidence of physical sedimentation has been obliterated by bioturbation. Homogenization of event deposits by burrowing activity is a very common phenomenon in shoreface environments (e.g., Dott, 1988; Pemberton, MacEachern et al., 1992; Pemberton and MacEachern, 1997). Nevertheless, the nature of the ripples and the intensity of bioturbation suggest that sand was deposited in relatively thin beds. The conodont fauna is suggestive of nearshore settings (cf. Boardman et al., 1995). Trace-fossil assemblages from this facies resemble other lower-shoreface, fairweather ichnofaunas described from the Cretaceous of Canada (e.g., MacEachern et al., 1992; MacEachern and Pemberton, 1992). This facies is partially equivalent to facies 4 (interlaminated to bioturbated sandstone and shale) of Wheeler et al. (1990).

Facies M: Thoroughly Burrowed, Very Fine Grained Silty Sandstones and Siltstones with Interbedded, Normally Graded Sandstones

Description. Facies M comprises dark-greenish-gray, very fine grained, quartzose and glauconitic, dolomite-cemented silty sandstones and siltstones (fig. 53). Matrix consists of silt, organic matter, and clay. Interbedded mudstone laminae are rich in organic matter and silt grains and are commonly stylolitized. Pyrite is locally present. Facies M includes interbedded, erosive-based, normally graded, coarse- to medium-grained sandstones that are capped by very fine grained silty sandstones with symmetric to quasisymmetric ripples. Lower boundaries of ripples are irregular and undulating. Internal structure consists of strongly tangential cross-laminae that may form offshoots, and swollen lenslike sets. Although dispersed throughout the normally graded division, bioclasts are more abundant towards the base, forming a lag of crinoid and gastropod fragments. Basal surfaces may display relatively deep and steep scours. Fading symmetric to quasisymmetric ripples also occur isolated within fine-grained packages. This facies is not very well represented in the studied cores. It forms two thin intervals at Nell—from 6,057.7 ft to 6,058.2 ft (1,846.4–1,846.5 m) and 6,054.1 ft to 6,055.6 ft (1,845.3–1,845.7 m)—and another one at Gaskill (6,013.6–6,013.9 ft; 1,832.9–1,833.0 m). Facies M is typically associated with facies L and O, being part of both coarsening- and fining-upward successions. At Gaskill, the top of the facies M interval is sharply attenuated by an erosional surface overlain by facies I.

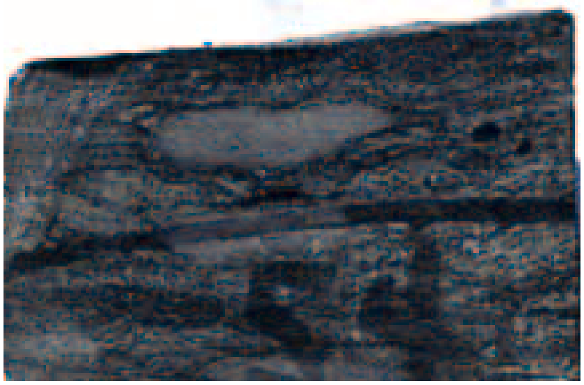

FIGURE 54. Facies N. Intensely bioturbated siltstone with highly compressed *Thalassinoides* cross-cutting a background ichnofabric of *Phycosiphon* and *Chondrites* (Nell).

Ichnology. The degree of bioturbation in facies M is highly variable. Interbedded coarse-grained beds are essentially unbioturbated, but finer-grained tops may exhibit low to moderate bioturbation (2 to 3). Conversely, the degree of bioturbation in very fine grained silty sandstones and siltstones is high (5). Trace-fossil assemblages include *Planolites montanus* (fig. 53), *Chondrites* isp. (fig. 53), *Teichichnus* isp., and *Palaeophycus* isp. *Palaeophycus* tends to occur in the finer-grained sandy tops, while the other forms are more abundant in the siltstone and silty sandstone intervals. The association is dominated by feeding traces of deposit-feeders and represents an example of the *Cruziana* ichnofacies.

Interpretation. This facies is interpreted as having been deposited in the transition zone between the offshore and the shoreface. Sedimentologic and ichnologic analyses reveal the interplay of storm-event deposition and background fairweather sedimentation. The erosional and depositional history of this facies can be summarized in four stages: (1) the initial erosive phase of the storm event recorded by the basal scoured surface, (2) the phase of main storm deposition represented by the coarse-grained, normally graded division, (3) the phase of waning storm deposition recorded by the wave rippled, finer-grained sandstone formed under lower-energy oscillatory conditions, and (4) the post-storm, fair-weather deposition phase characterized by the presence of interbedded, very fine grained silty sandstones and siltstones, which may record the latest stage of sediment fallout after the storm or background sedimentation (see also Pemberton, Van Wagoner et al., 1992; Pemberton and MacEachern, 1997). Biogenic activity was restricted to the third and fourth phases. *Palaeophycus* represents opportunistic colonization immediately after waning storm deposition, while feeding structures of deposit-feeders were emplaced after the storm and record the activity of the resident fairweather assemblage. Bioturbation by this later suite obliterated the upper contact, leading to the formation of diffuse gradational tops. This facies is a partial equivalent of facies 4 (interlaminated to bioturbated sandstone and shale) of Wheeler et al. (1990).

Facies N: Thoroughly Burrowed Siltstones

Description. Facies N consists of dark-gray, intensely bioturbated siltstones (figs. 54–55). Physical sedimentary structures have not been preserved and the only evidence of the primary fabric is the presence of a relic, irregularly parallel lamination. This facies only occurs at Nell, forming a single interval (6,053–6,054.1 ft; 1,844.9–1,845.3 m), which overlies facies M and is sharply attenuated at the top by an erosional surface that separates facies N from the overlying facies J.

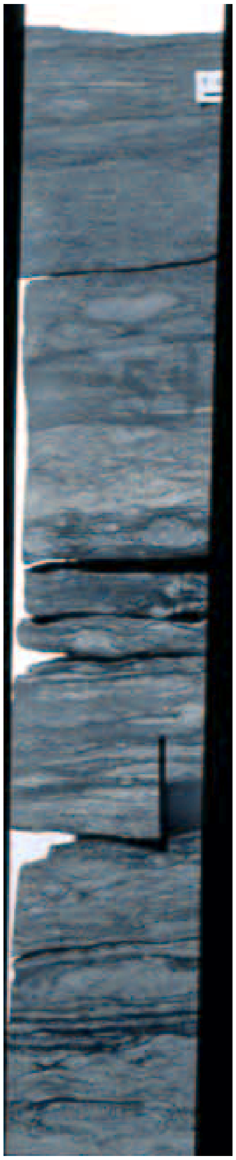

FIGURE 55. Facies N (upper) and facies M (lower). General view of intensely bioturbated siltstone package (Nell).

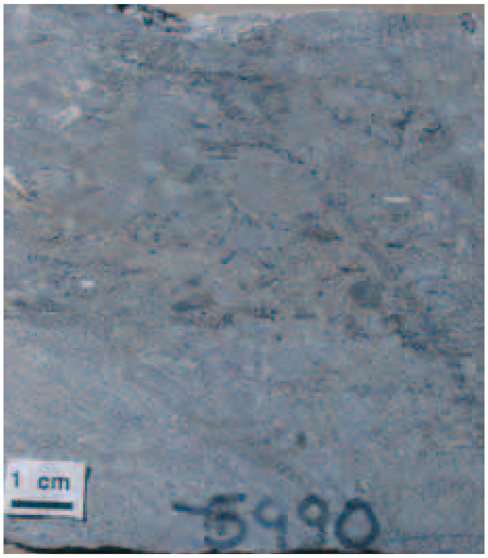

FIGURE 56. Facies O. Transgressive conglomeratic, very coarse- to medium-grained carbonate sandstones (Gaskill).

Ichnology. Degree of bioturbation is extremely high, ranging from 5 to 6. Tiny *Phycosiphon incertum* and *Chondrites* isp. represent the background ichnofabric. This assemblage is overprinted by relatively large and slightly compressed *Thalassinoides* isp. (fig. 54). The assemblage records the activity of a stable deposit-feeder community and may be regarded as an example of a depauperate *Cruziana* ichnofacies.

Interpretation. This facies is interpreted as representing offshore deposits. Deposition was dominated by sediment fallout of silt particles. Intense bioturbation resulted in complete to nearly complete obliteration of the original fabric. The dominance of feeding structures of deposit-feeders indicates a low-energy, nutrient-rich environment. Martin and Pollard (1996) have documented similar low-diversity *Phycosiphon* and *Chondrites* ichnofabrics from offshore deposits of the Fulmar Formation. The low diversity and small size of the burrows are suggestive of stressful environmental conditions, with low-oxygen content being the most likely candidate (cf. Savrda and Bottjer, 1986; Savrda, 1992). The facies-N ichnoassemblage seems to be represented by forms more or less typical of relatively deep tiers. In oxygen-depleted settings, uppermost tiers are replaced by deeper tiers (Bromley and Ekdale, 1984). However, Bromley (1996) urged caution in invoking a low-oxygen content when deeper-tier forms are responsible for total bioturbation. Extensive burrowing activity may have actually lead to the destruction of the shallower traces. This facies is a partial equivalent of facies 4 (interlaminated to bioturbated sandstone and shale) of Wheeler et al. (1990).

Facies O: Parallel-laminated Black Shales

Description. This facies comprises black, parallel-laminated, commonly calcareous shales. It was observed only in the Gentzler field, where it occurs in both Nell and Gaskill wells. In Gaskill, it forms a very thick package at the top of the succession (6,000.6–5,952 ft; 1,828.9–1,814.2 m), overlying the coarse-grained sandstones of facies I. Towards the base of the interval, normally graded, conglomeratic, very coarse grained to medium-grained, carbonate-cemented sandstones are interbedded with the fine-grained deposits (fig. 56). Bioclast content is very high, consisting of crinoid and coral fragments. In some beds, bioclasts and pebbles tend to concentrate at the base, forming lags. In other cases, they are dispersed throughout the bed floating in the matrix. The conodont fauna is relatively diverse and abundant and includes the genera *Idiognathodus, Neognathodus, Adetognathus, Rhachistognathus, Declinognathodus,* and *Idiognathoides.* In Nell, facies O forms a single interval (6,058.2–6,063 ft; 1,846.5–1,848.0 m) in the upper half of the succession. This package is underlain by coarse-grained sandstones of facies I and overlain by facies M.

Ichnology. No trace fossils have been recorded.

Interpretation. This facies is interpreted as having been deposited in a shelf environment. Sediment fallout of fine-grained particles was the dominant depositional process. Interbedded coarse-grained beds may record transgressive ravinement. Preservation of thin laminations, absence of bioturbation, and dark colors are suggestive of anoxic bottom-water conditions. The conodont fauna represents the *Idiognathodus-Streptognathodus* biofacies, most likely the *Idiognathodus* subfacies of Boardman et al. (1995). According to these authors, this subfacies characterizes deposition in oxygen-depleted, open-marine areas. Facies O is an equivalent of facies 1 (dark-gray, thinly laminated shale) of Wheeler et al. (1990).

Discussion

Recognition of Estuarine Deposits

The diagnostic features of brackish, estuarine ichnofaunas have been summarized by Wightman et al. (1987) and Pemberton and Wightman (1992). These authors suggested that brackish assemblages are characterized by (1) low ichnodiversity, (2) forms common in marine environments, (3) a combination of vertical and horizontal traces from the *Skolithos* and *Cruziana* ichnofacies, (4) dominance of infaunal traces rather than epifaunal trails, (5) simple structures produced by opportunistic animals, (6) an abundance of certain ichnotaxa, and (7) presence of monospecific suites. Hakes (1976, 1985) also noted that brackish-water trace fossils are small. Models of brackish-water ichnofaunas were essentially based on studies in the Canadian zone of the Mesozoic Western Interior Seaway (e.g., Wightman et al., 1987; Pemberton and Wightman, 1992) and the modern Georgia coast (e.g., Howard and Frey, 1975; Howard et al., 1975); their application to the analysis of Paleozoic estuaries deserves further discussion.

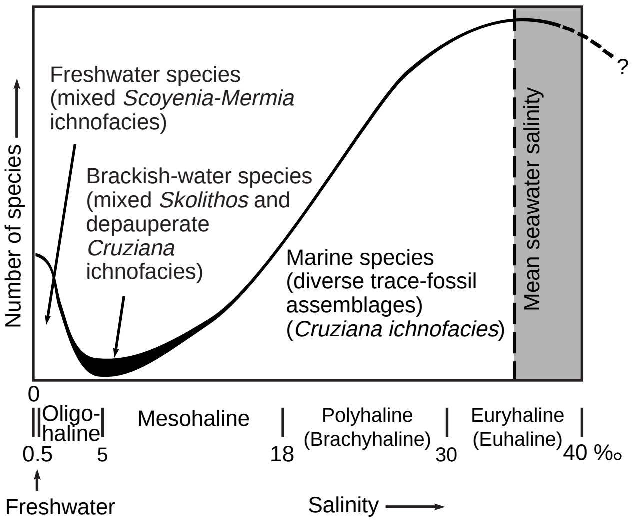

FIGURE 57. Relationships among species diversity, ichofaunas, and salinity along a salinity gradient (after Buatois et al., 1997).

Estuarine ichnofaunas from the lower Morrow resemble brackish-water trace-fossil assemblages documented from post-Paleozoic marginal-marine successions. Morrow estuarine ichnofaunas are characterized by low trace-fossil diversity (nine ichnospecies), reflecting the stressful and harsh conditions of the brackish-water ecosystem. Very few animals have the physiological adaptations necessary to survive under the strong fluctuations in salinity, temperature, and turbidity that characterize marginal-marine environments; consequently, brackish-water biotas are less diverse than marine and freshwater faunas (Croghan, 1983; Barnes, 1984; McLusky, 1989; Hudson, 1990; Pickerill and Brenchley, 1991). Although trace-fossil diversity differs from animal-species diversity (see Bromley, 1996, p. 213–215, for a discussion), the former may provide some basic information on trends in species richness in marginal-marine environments (fig. 57). Marginal-marine, brackish-water ichnofaunas are less diverse than open-marine assemblages (Miller, 1984; Ekdale, 1988; Wightman et al., 1987; Pemberton and Wightman, 1992). The diversity of freshwater animals tends to decline rapidly as salinity increases, but diversity of marine organisms decreases more gradually with the dilution of normal marine salinity (Pemberton and Wightman, 1992; Benyon and Pemberton, 1992) (fig. 57). Therefore, brackish-water trace-fossil assemblages record the activity of depauperate marine biotas, rather than a mixture of freshwater and marine faunas, and are represented by a mixed, impoverished *Skolithos* and *Cruziana* ichnofacies (Wightman et al., 1987; Pemberton and

Wightman, 1992; Benyon and Pemberton, 1992; Ranger and Pemberton, 1992). Morrow estuarine assemblages consist of marine ichnotaxa (e.g., *Teichichnus, Asterosoma*), as well as facies-crossing forms (e.g., *Planolites, Palaeophycus*), but typical freshwater components are absent. In terms of Seilacherian ichnofacies, valley assemblages from the lower Morrow contain representatives of both the *Skolithos* (e.g., *Skolithos, Monocraterion, Arenicolites, Diplocraterion*) and *Cruziana* ichnofacies (e.g., *Cruziana, Asterosoma, Teichichnus*). Buatois et al. (1997) noted that marginal-marine, brackish-water ichnofaunas are essentially different from those present in the freshwater portions of estuaries, which are dominated by surface trails and trackways. Brackish-water trace-fossil assemblages are dominated by structures of infaunal organisms because the deep-infaunal habitat is a refuge from the rapid and extreme salinity fluctuations at the sediment surface (Sanders et al., 1965; Rhoads, 1975). Estuarine ichnofaunas of the Arroyo and Gentzler fields consist of both shallow-tiered (e.g., *Palaeophycus*) and relatively deep-tiered (e.g., *Arenicolites*) structures of infaunal organisms. Additionally, Morrow brackish-water ichnofaunas also are characterized by the presence of very simple forms (e.g., *Planolites, Palaeophycus*) produced by nonspecialized opportunistic organisms displaying R-selected strategies that enable adaptation to stressful environments (Pemberton and Wightman, 1992; Benyon and Pemberton, 1992). Monospecific suites are present in the lower Morrow valley-fill deposits, particularly in upper- to middle-estuarine settings. Monospecific ichnocoenosis of *Palaeophycus* are common in upper-estuary channel sandstones, and *Planolites* tends to occur in monospecific suites in central bay, fine-grained sediments. Small size has been detected in several ichnotaxa from the Morrow estuarine deposits. For example, tiny *Palaeophycus* and *Skolithos* are relatively common in upper-estuary channel facies.

Estuarine assemblages from the lower Morrow compare favorably with other brackish-water ichnofaunas recorded from Carboniferous units of the United States. Low-diversity associations, commonly monospecific, of opportunistic infaunal animals in Carboniferous marginal-marine sequences have been documented by Hakes (1976, 1985), Archer and Maples (1984), Miller and Knox (1985), Devera (1989), Martino (1989), Rindsberg (1990, 1994), Archer (1993), and Mángano and Buatois (1997). Martin (1993) and Miller and Woodrow (1991) also noted similar characteristics in Ordovician and Devonian estuarine ichnofaunas, respectively.

Pennsylvanian, brackish-water ichnofaunas differ from Mesozoic ones in various ways. The Pennsylvanian ichnofaunas are less diverse and are characterized by lower degree of bioturbation, scarcity of crustacean burrows, absence of the *Glossifungites* ichnofacies in firmground surfaces within the estuary, and absence of specific architectural adaptations to escape extreme salinity fluctuations (e.g., *Gyrolithes*). These differences are most likely related to evolutionary innovations in Mesozoic estuarine ecosystems, essentially the adaptation of crustaceans to brackish-water, soft to firm biotopes.

Estuarine systems were not recognized in the lower Morrow in Kansas prior to this study. Sedimentologic and ichnologic signatures indicate the presence of an estuarine paleovalley oriented along a northwest-southeast axis and draining to the open sea. Trangressively filled, estuarine successions have been recorded in the lower intervals of Kendrick and Gaskill wells towards the northwest, while open-marine shoreface parasequences are dominant in Nell well, in the southeast part of the study area. Lateral to Kendrick, at Fretz well, interfluve deposits occur. Integration of ichnologic data with sedimentologic, stratigraphic, and paleogeographic information was crucial in the recognition of valley-fill sandstones in the lower Morrow and in their distinction from open-marine shoreface deposits. The discovery of a low-diversity trace-fossil assemblage that records the activity of a depauparate marine fauna was essential in the recognition of estuarine valley facies. This trace-fossil assemblage contrasts with the more diverse and abundant ichnocoenoses of the open-marine shoreface facies.

The lower Morrow estuarine system is similar to the wave-dominated estuary characterized by Dalrymple et al. (1992). The valley system recorded in the Arroyo and Getzler fields displays a clearly defined, tripartite division into (1) a high-energy, marine-sand plug formed at the seaward end of the valley (estuary mouth), (2) a low-energy, fine-grained middle zone (central bay), and (3) a high-energy inner zone dominated by the discharge of fluvial tributaries (bay-head delta). Tidal influence, however, is suggested by the presence of reactivation surfaces, mud drapes, and cross-lamination dipping in opposite directions in bay-head delta sandstones (facies C) and tidal-flat heterolithic deposits (facies E), as well as the existence of tidal rhythmites (facies F) in intertidal channels.

The base of the estuarine valley was recognized in the Gaskill well at the bottom of facies C interval (6,065.4 ft; 1,848.7 m) and is coincident with the Mississippian-Pennsylvanian boundary (320 +/- 10 my). A major sea-level fall that took place during this time (Ross and Ross, 1988) is thought to be responsible for valley incision. The estuarine valley was subsequently filled during sea-level transgression. The replacement of low-diversity, brackish-water trace-fossil assemblages by the open-marine *Cruziana* ichnofacies supports this interpretation. A second sequence boundary was identified at the base of a forced-regression shoreface package in the Gentzler field, where the firmground *Glossifungites* ichnofacies has been detected (figs. 58–61).

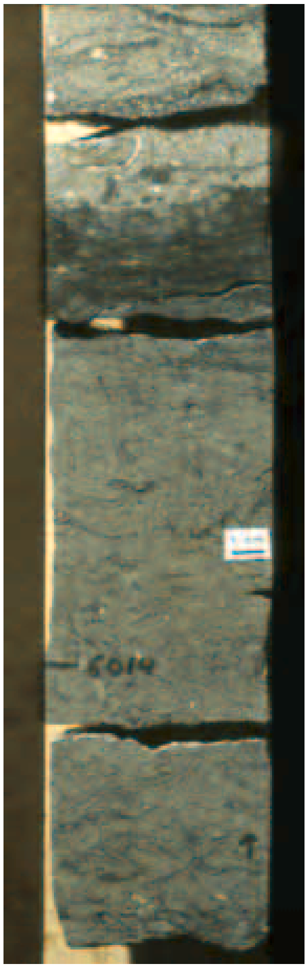

FIGURE 58. Forced-regression surface separating upper-shoreface deposits (facies I) from the underlying lower-shoreface (facies L) to offshore-transition deposits (facies M) (Gaskill).

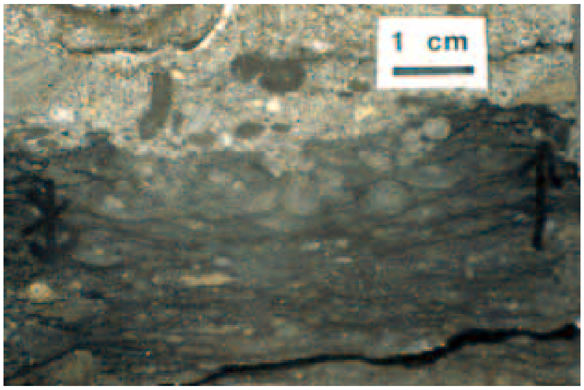

FIGURE 59. Close-up view showing burrows of the firmground *Glossifungites* ichnofacies subtending from the erosional discontinuity (Gaskill).

FIGURE 60. Forced-regression surface separating proximal middle-shoreface deposits (facies J) from the underlying offshore deposits (facies N (Nell).

FIGURE 61. Close-up view showing burrows of the firmground *Glossifungites* ichnofacies subtending from the erosional discontinuity (Nell).

Environmental Zonation of Valley-fill and Open-marine Deposits

Trace-fossil analysis allows delineation of different clastic facies within the estuarine valley (figs. 62–63). The most proximal deposit within the valley consists of sandstones (facies A) deposited for the most part in fluvial channels. This facies is well represented towards the base of Kendrick well, located in the northwest part of the study area. Trace fossils are restricted to tiny *Palaeophycus* isp., and no ichnotaxa indicative of marine influence have been found. Fluvial facies are overlain by sandstones with clay drapes (facies C), which are interpreted as having been deposited within the upper-estuarine channels of a bay-head delta complex. These deposits are more areally extensive, being also recorded in the Gentzler oil field, at Gaskill. Clay drapes indicate tidal influence. The ichnofauna consists of dwelling traces of suspension-feeders, such as *Skolithos* isp., *Arenicolites* isp., *Monocraterion* isp., and *Palaeophycus* isp., representing a typical example of the *Skolithos* ichnofacies. Ichnologic evidence supports marine influence during deposition. Sandstone packages deposited within estuarine channels are replaced upwards by parallel-laminated shales (facies D) that locally exhibit isolated sand lenses and ripple laminae. These deposits are well represented in Kendrick and Gaskill. In contrast to the channelized-sandstone facies, fine-grained deposits host an ichnofauna dominated by traces of deposit-feeders, including *Teichichnus, Planolites,* and *Cruziana.* This assemblage is also suggestive of marine influence, but its low diversity indicates restricted, brackish-water conditions. It represents an impoverished occurrence of the *Cruziana* ichnofacies. Sedimentologic, ichnologic, and stratigraphic information indicates deposition in the central bay of the estuary valley. Fine-grained deposits interfinger with coarse-grained clastics, with shell material (facies H) interpreted as having been deposited in the estuary mouth. This sand-plug facies is present in Kendrick and Gaskill. The trace-fossil association in this facies includes *Palaeophycus* isp., *Asterosoma* isp., *Diplocraterion* isp., *Planolites* isp., and *Skolithos* isp. The assemblage represents a mix between the *Skolithos* and *Cruziana* ichnofacies. Although ichnodiversity is still low, the overall nature of the ichnofauna and the presence of certain ichnotaxa indicate less stressful conditions.

General distribution of ichnofossils along the estuarine valley was controlled by the salinity gradient. Trace-fossil analysis suggests a transition from freshwater to brackish-water to near-normal salinity conditions at the seaward end of the estuary valley. However, other parameters, such as oxygenation, substrate and energy, were important at a more local scale, and can be invoked to explain changes in ethology and trophic types from assemblages in high-energy, oxygenated sandy channels to ichnofaunas in low-energy, less-oxygenated, muddy bays.

Open-marine, Morrow trace-fossil assemblages are more diverse and represent the activity of a K-selected, climax fauna developed under stable conditions in a normal marine environment. Monospecific suites are rare and restricted to the upper shoreface or, more rarely, to the middle shoreface. Integration of sedimentologic and ichnologic information allows delineation of a zonation within shallow, open-marine facies (figs. 62 and 64). Ichnologic models of shoreface sandstones are well established for Mesozoic and Cenozoic strata and have been applied to the study of wave-dominated, shallow-marine successions in the subsurface (e.g., Bockelie, 1991; MacEachern and Pemberton, 1992; Pemberton, Van Wagoner et al., 1992; Martin and Pollard, 1996; Howell et al., 1996). However, the ichnology of comparable facies in Paleozoic cores remains poorly understood.

Although shoreface sequences are best developed in the southeast part of the study area in the Nell well, thick intervals, mostly of upper-shoreface facies, also occur towards the top of Gaskill and Kendrick wells, indicating the replacement of restricted valley-fill clastics by regionally extensive, open-marine sandstones. Morrow upper-shoreface facies (facies I) consists of planar crossbedded sandstones and typically lacks trace fossils. In a few places, *Palaeophycus* isp. and *Ophiomorpha irregulaire* are present. The common situation, however, is that high-energy, shifting sandy substrates, and high rates of sedimentation and erosion associated with the migration of sand dunes across the upper shoreface, prevented the preservation of biogenic structures. Middle-shoreface facies (facies J) contains abundant dwelling structures of suspension-feeders (*Ophiomorpha irregulaire, Skolithos* isp., *Palaeophycus* isp., *Diplocraterion* isp.) and carnivores (*Conichnus* isp and *Bergaueria* isp.). Escape structures and domiciles of deposit-feeders (*Cylindrichnus concentricus, Rosselia* isp.) are also common, while feeding traces of deposit-feeders (*Teichichnus* isp.) are very rare. Trace fossils in the proximal lower-shoreface deposits (facies K) are similar to those of the middle shoreface. However, the degree of bioturbation in the proximal lower shoreface is higher and feeding traces of deposit-feeders (*Planolites montanus, Rhizocorallium* isp.) are more common. The Morrow distal lower shoreface (facies L) contains an ichnofauna dominated by feeding traces of deposit-feeders (*Planolites montanus, Chondrites* isp., *Rhizocorallium* isp., *Teichichnus* isp., *Zoophycos* isp.). Domiciles of deposit-feeders (*Cylindrichnus concentricus, Asterosoma* isp.) are also abundant, while dwelling burrows of suspension-feeders (*Palaeophycus* isp., *Ophiomorpha irregulaire, Skolithos* isp., *Arenicolites* isp.) are subordinated. The offshore-transition facies (facies M) is dominated by feeding traces of deposit-feeders (*Chondrites* isp., *Planolites montanus*). Vertical domiciles of suspension-feeders are absent, the only dwelling structure of suspension-feeders being the horizontal *Palaeophycus* associated with storm deposits.

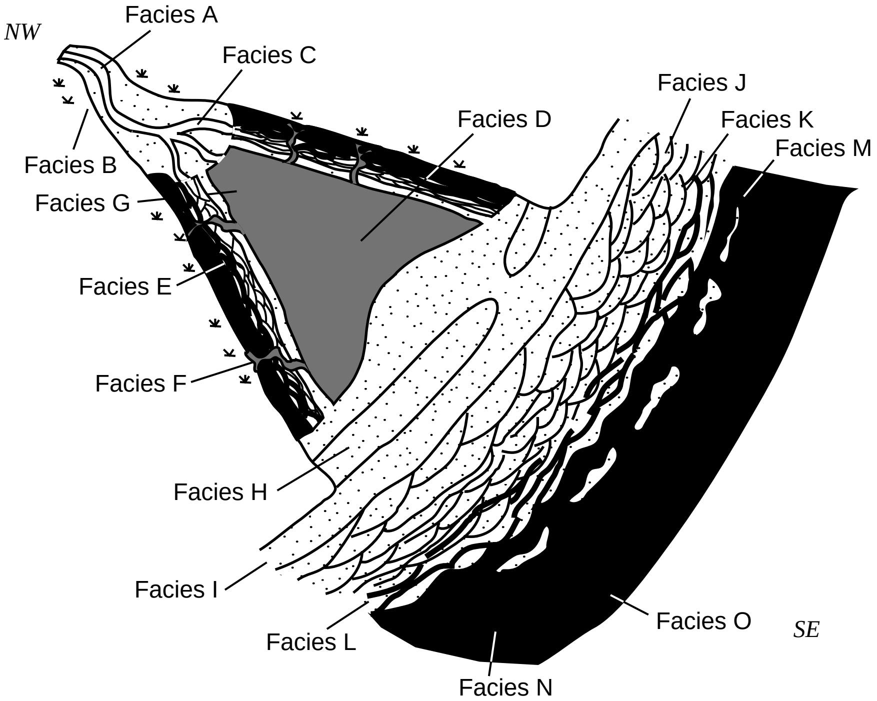

FIGURE 62. Depositional model of the lower Morrow Sandstone in the Arroyo and Gentzler fields.

Finally, offshore deposits (facies N) are totally bioturbated, and the ichnofabric is dominated by patterned, deposit-feeding traces, such as *Chondrites* isp. and *Phycosiphon incertum.*

The ichnologic-sedimentologic model established for open-marine deposits of the Morrow Sandstone is similar to those proposed for Mesozoic shallow-marine sequences of the Western Interior Seaway by MacEachern and Pemberton (1992) and Pemberton, Van Wagoner et al. (1992). MacEachern and Pemberton (1992) characterized three types of shorefaces based on intensity and frequency of storms: intense, moderate, and weak. The lower-Morrow shorefaces exemplify the weakly storm-affected shorefaces of these authors. These shorefaces display well-developed, fair-weather ichnofaunas reflecting the activity of the resident biota. An onshore-offshore replacement of the *Skolithos* ichnofacies (dominated by domiciles of suspension-feeders and predators) by the *Cruziana* ichnofacies (with abundant feeding traces of deposit-feeders) is evident. A transitional zone between both ichnofacies has been detected in the proximal lower-shoreface deposits. The degree of bioturbation increases from the upper shoreface to the offshore deposits. Additionally, while upper- to middle-shoreface facies may display monospecific assemblages, lower-shoreface units typically host multispecific suites.

Similarities between late Paleozoic and Mesozoic, shallow-marine ichnofaunas are remarkable even at the scale of occurrences of individual ichnotaxa. Two differences were noted—namely (1) the presence of small specimens of *Ophiomorpha irregulaire* with poorly developed wall-linings instead of large specimens of *O. nodosa,* with thick, pelletoidal walls, typical of post-Paleozoic, high-energy nearshore settings, and (2) burrows of the *Glossifungites* ichnofacies that are less robust and shallower than those of their post-Paleozoic equivalents.

Moslow and Pemberton (1988) noted that shoreface and delta-front sequences look almost identical on gamma-ray well-log signatures and that distinguishing them requires careful analysis of physical and biogenic sedimentary structures. Deltaic sequences have been described from the Morrow Sandstone in adjacent areas (e.g., Swanson, 1979). As in shoreface sequences, trace-fossil assemblages of delta-front sandstones are characterized by elements of the *Skolithos* ichnofacies proximally and by traces of the *Cruziana* ichnofacies distally. However, delta-front sandstones typically contain low-diversity ichnofaunas due to harsh environmental conditions, such as high turbidity and fluctuating salinity and sedimentation and erosion rates (Moslow and Pemberton, 1988). Additionally, evidence of sediment gravity-flow deposition due to slope instability is common. In the cores analyzed, progradational sandstone units display a high diversity of biogenic structures, even in relatively proximal situations. This high diversity and abundance of trace fossils suggest deposition in open-marine shorefaces, rather than delta fronts. Moreover, facies analysis indicates interplay of waves and currents, but little evidence of sediment gravity-flow processes.

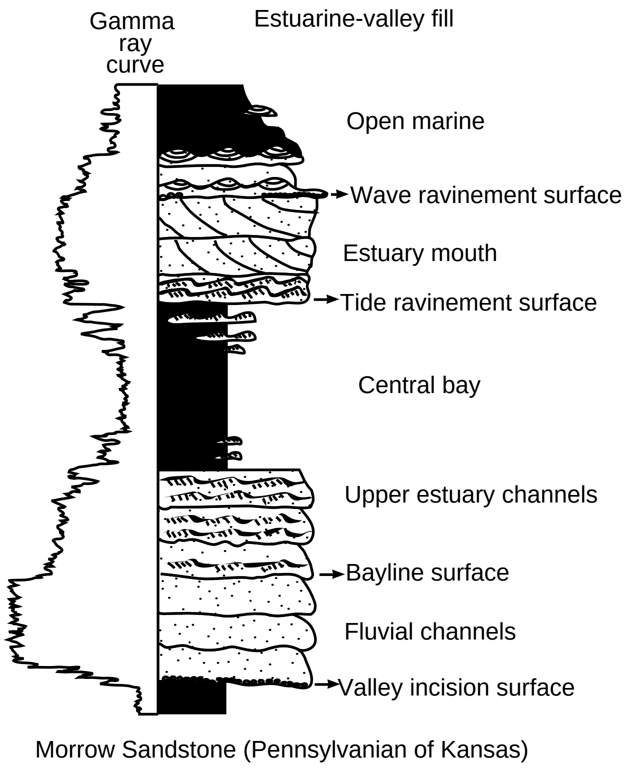

FIGURE 63. Idealized vertical succession of Morrow estuarine-valley deposits.

Implications for Evaluation of Reservoir Heterogeneity

Recognition of valley-fill sandstones in the lower Morrow has profound implications for hydrocarbon exploration and subsequent production because reservoir quality is largely influenced by external geometry and distribution of depositional facies. Our integrated ichnologic, sedimentologic, and stratigraphic approach shows that the lower Morrow Sandstone displays more complex types of heterogeneity than previously envisaged by the open-marine model. In these complex tracts of depositional systems, heterogeneity is created at different scales by facies and facies-assemblage distributions and by spatial partitioning within sandstone bodies. The petrophysical characteristics of the different sedimentary facies were documented in detail by Byrnes et al. (1999).

Three basic styles of heterogeneity have been recognized by Weber and van Geuns (1990): layer cake, jigsaw puzzle, and labyrinth. The open-marine model predicts a layer-cake style of facies distribution as a consequence of strandline-shoreline progradation. On the other hand, recognition of valley-fill sequences points to more compartmentalized reservoirs—either the jigsaw puzzle style (with complex crosscutting relationships of sandstone bodies) or labyrinth style (consisting of isolated reservoir sandstones)—due to heterogeneity created by valley incision and subsequent infill.

Galloway and Hobday (1996) identified five levels of heterogeneity: gigascopic, megascopic, macroscopic, mesoscopic, and microscopic. Gigascopic heterogeneity is shown at the scale of depositional systems, while megascopic heterogeneity deals with the geometry of permeable and impermeable units. The architecture of depositional systems in the lower Morrow of southwest Kansas is more complex than previously believed, and valley, interfluves, and open-marine areas are now recognized. A clear example of controls on reservoir characteristics at the scale of depositional systems is shown in the Arroyo field, where distribution of fluvio-estuarine, valley-fill deposits is roughly coincident with the contours of the reservoir. In interfluve areas, such as those exemplified in the Fretz core, nonproductive paleosol facies are the stratigraphic lateral equivalent of reservoir valley sands.

Macroscopic heterogeneity is expressed at the facies scale. Sedimentologic and ichnologic analyses indicate a high variability in sedimentary facies, which governs fluid behavior, and porosity and permeability heterogeneities. The proposed facies scheme for the Arroyo and Gentzler fields provides a way to analyze heterogeneity at the

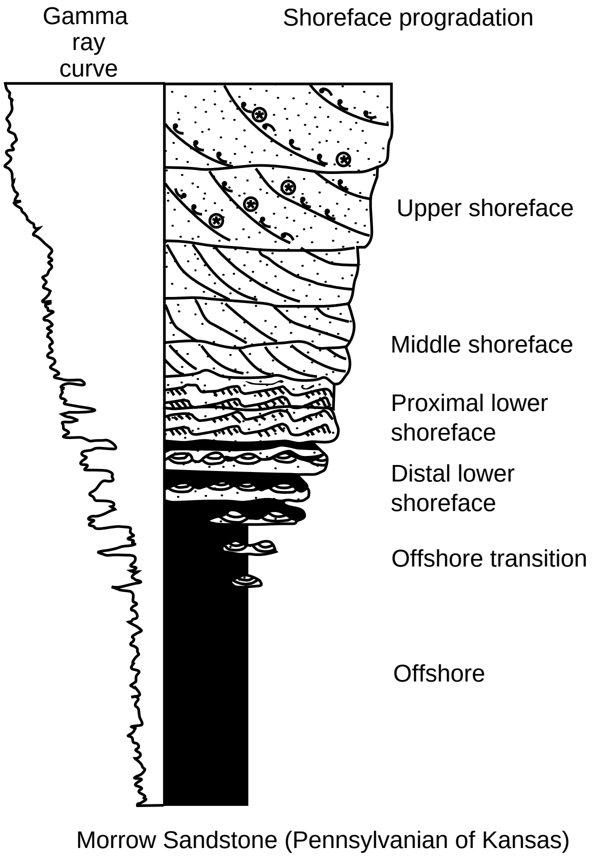

FIGURE 64. Idealized vertical succession of Morrow open-marine deposits.

macroscopic scale (cf. Byrnes et al., 1999). For example, the distinction between fluvial (facies A) and estuarine (facies C) channel sands in Arroyo field is based on the presence of bioturbation and mud drapes (as well as other tidal structures) in the transgressive estuarine sands. Although both channel fills contain good-quality reservoir sands, permeability is higher in the fluvial facies because mud-baffles restrict the flow in the estuarine sands. Shoreface sandstone packages are laterally continuous in Gentzler field. However, facies subdivision of these sandstone bodies in upper-, middle-, and proximal lower-, and distal lower-shoreface facies provides evidence of reservoir heterogeneity. Finer-grained sediments and mud drapes in the proximal and distal lower shoreface commonly create permeability barriers within reservoir shoreface sandstones.

Mesoscopic heterogeneity occurs at the scale of lithofacies and stratification, while microscopic heterogeneity is expressed at the scale of individual grains and pores. In the lower Morrow, mesoscopic and microscopic heterogeneities are reflected by the styles of bedding and lamination, presence of mud drapes, biogenic disruption of primary fabric, and diagenetic overprint. Although the current assumption is that bioturbation reduces porosity and permeability, this is not necessarily the case. Deposit-feeders that backfill their burrows may damage pore connectivity in certain situations, but open structures produced by suspension-feeders and passive carnivores do not reduce porosity and permeability and may even act as conduits for fluid migration (cf. Muñoz, 1994; Gingras et al., 1997). This is shown by high values of porosity and permeability in estuarine-channel facies and upper- to middle-shoreface facies, which contain a suite dominated by traces of suspension-feeders and carnivores.

Compartmentalization also results in a very complex mosaic of flow units. While the open-marine model essentially envisages layer-cake shoreface sandstones, albeit with distinct internal permeability barriers as shown by our facies zonation, the valley-fill model involves a more complex pattern of external geometries of flow units, including ribbons, pods, prisms, belts, lobes, and sheets.

Integration of sedimentologic, petrographic, ichnologic, and stratigraphic data with petrophysic information allows recognition of different reservoir zones. Fluvial sandstones (facies A), encountered at the base of Kendrick, are the highest quality reservoirs. These sandstones contain scarce calcite cement, are mainly unbioturbated, and have very high values of porosity and permeability. A similar reservoir facies has been recognized in the upper Morrow by Al-Shaieb et al. (1994). Although slightly less permeable, bay-head delta sandstones (facies C) also represent very good reservoirs. A suite of dwelling traces of suspension-feeders of the *Skolithos* ichnofacies is present in these deposits, but bioturbation does not seem to have obliterated porosity and permeability. In fact, the presence of burrows probably channelled sediment fluids (e.g. Muñoz, 1994; Gingras et al., 1997). In their discussion of estuarine sands in the upper Morrow, Al-Shaieb et al. (1994) attributed low porosity to clay dispersion by burrowing animals. In the present case, however, the decrease in permeability is most likely related to the presence of mud drapes, which act as local barriers for fluid migration. Secondary porosity was created by dissolution of glauconite grains. Estuary-mouth, coarse-grained sandstones (facies H) also include good-quality reservoirs. These sandstones have porosity values similar to those of fluvio-estuarine channel sandstones, but permeability is remarkably lower. According to Zaitlin and Shultz (1990), estuary-mouth bar sands are typically better reservoir facies than inner-estuary sands. In the present case, however, original permeability may have been reduced by cementation due to calcite precipitation derived from dissolution of skeletal fragments. Central-bay shales (facies D) do not include reservoirs because of their finer grain size, but they may have acted as effective seals for reservoirs in fluvio-estuarine sands (cf. Zaitlin and Shultz, 1990). Associated tidal-flat and channel heterolithic deposits (facies E and F) are also poor reservoirs because of their very fine grained sandstones, intense soft-sediment deformation, and abundant clay drapes.

In the open-marine system, middle- to upper-shoreface sandstones (facies I and J) include reservoirs of high to moderate quality. As in the case of estuarine channel sands, suspension-feeder burrows do not obliterate porosity. However, porosity was reduced due to partial cementation by calcite and dolomite, derived from dissolution of the abundant skeletal fragments present in these facies (cf. Al-Shaieb et al., 1994). Lower-shoreface sandstones (facies K and L) contain relatively poor reservoirs because of their finer grain size and the intense and disruptive bioturbation by deposit-feeding infauna of the *Cruziana* ichnofacies, particularly in the distal lower shoreface. Activity of deposit-feeding animals that backfilled their burrows and dispersed clay sediment throughout the matrix typically obliterates porosity and permeability. Finally, offshore transition, offshore and shelfal deposits (facies M, N, and O) are very fine grained and locally totally bioturbated; therefore, they do not include reservoirs. In summary, the emerging picture is one of a heterogeneous and compartmentalized reservoir, displaying a complex pattern in distribution and connectivity of reservoir sandstones, and impermeable and semi-permeable vertical and lateral seals at different scales.

Conclusions

By integrating data from ichnologic, sedimentologic, and stratigraphic studies of four cores from the lower Morrow Sandstone, we were able to distinguish estuarine from open-marine deposits and thus provide a more precise picture of reservoir sandstones in the Lower Pennsylvanian of southwest Kansas.

The estuarine assemblage includes facies that have been deposited in fluvial channels, interfluves, upper-estuarine channels, estuary bay, restricted tidal flats, tidal channels, and estuary mouth. The lower Morrow estuarine system was northwest-southeast oriented and displays the classical tripartite division of wave-dominated estuaries, with localized evidence of tidal action. Estuarine deposits contain low-diversity trace-fossil assemblages produced by an opportunistic, depauperate marine infauna, indicative of stressful conditions in a brackish-water setting. Distribution of ichnocoenosis within the estuarine system was essentially controlled by the salinity gradient.

The open-marine assemblage includes upper-, middle-, and lower-shoreface sandstones encased in offshore-transition, offshore, and shelf fine-grained facies. These deposits are regionally extensive and were formed under weak storm influence. Open-marine ichnofaunas are characterized by high diversity of trace fossils produced by the resident benthos under normal-salinity conditions. Trace-fossil data are instrumental to propose an environmental subdivision of the shoreface-offshore packages. An onshore-offshore replacement of the *Skolithos* ichnofacies by the *Cruziana* ichnofacies is observed.

Because this study is one of the first ichnologic analyses of a Paleozoic reservoir, it provides original information to test the applicability of models proposed on the basis of observations in Mesozoic and Cenozoic reservoirs. Ichnologic analysis of the Morrow Sandstone suggests that post-Paleozoic trace-fossil models may be applied, albeit with caution, to the study of cores from late Paleozoic reservoirs.

Recognition of valley-fill sandstones in the lower Morrow has implications for hydrocarbon exploration and subsequent production. The emergent picture is one of a heterogeneous and compartmentalized reservoir, displaying high variability in sedimentary facies, and a complex pattern in distribution and connectivity of reservoir sandstones.

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