DISTRIBUTION AND DEPOSITION OF MUDSTONE FACIES IN THE UPPER DEVONIAN SONYEA GROUP OF NEW YORK

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Abstract: Petrographic and small-scale sedimentary features of the mudstone-dominated Upper Devonian Sonyea Group of New York were examined in order to (1) improve our understanding of mudstone facies, (2) examine coeval mudstone facies within a broader depositional context, and (3) promote a simple methodology for the study of mudstones. Six mudstone facies are distinguished, each characterized by several component mudstone types or subfacies. Sedimentary conditions and environments are reconstructed from primary sedimentary structures and bioturbation characteristics. Mudstone facies are characterized by soils and flood deposits in the coastal-plain region, by rapid sediment deposition and frequent reworking in nearshore areas, by storm-dominated offshore transport on a wide, basin-margin platform, by turbidite slope deposits below storm wave base, and by bottom currents and slow settling in the distal, "deep"-basin black mudstones. The latter, although commonly thought of as deposits of a stratified anoxic basin, contain indications of benthic life, such as burrows, disrupted laminae, and clay/silt fecal pellets. These observations are incompatible with a stratified-basin model, and indicate the need to search for alternative models of black shale accumulation.

INTRODUCTION

Mudstones are essential as source and seal of hydrocarbons in sedimentary basins and constitute two thirds of the sedimentary rock record. They contain by far the largest part of earth history, typically in a relatively continuous record. Yet, in spite of recent efforts (e.g., O'Brien and Slatt 1990; Kuehl et al. 1990; Wignall 1989; Zimmerle 1991; Schieber 1990a; Macquaker and Gawthorpe 1993), the sedimentologic study of mudstones lags far behind that of sandstones and carbonates.

Progress has been made, however, to relate lithologic (e.g., O'Brien and Slatt 1990; Macquaker and Gawthorpe 1993), paleontologic (e.g., Savrda and Bottjer 1991; Oschmann 1991), and geochemical (e.g. Brumsack 1991; Brassell 1992) characteristics of mudstones to depositional environments. Application of the electron microscope has made it possible to examine textural (SEM; e.g., O'Brien and Slatt 1990) and petrographic features (BSE, backscattered electron images; e.g., Pye and Krinsley 1986), to treat textural and compositional components quantitatively, and to relate them to depositional variables, such as sediment transport path (Macquaker and Gawthorpe 1993), bioturbation (O'Brien 1987), and flocculation (O'Brien and Slatt 1990). Although this approach has fostered much progress in mudstone research (e.g., Pye and Krinsley 1986; Cuomo and Bartholomew 1991; Macquaker and Gawthorpe 1993), the field of view is typically 1 mm or less. Because sample preparation and examination is time consuming, sedimentary features exceeding that scale either tend to be examined less thoroughly or are altogether neglected.

Yet, numerous sedimentary features at the millimeter and centimeter scale are readily observed on polished slabs and in petrographic thin sections. They can be related to a variety of processes, such as the activity of organisms, soft-sediment deformation, and current and wave action. Surprisingly, although this approach can provide valuable insights into the origin of mudstone successions (Schieber 1994a, 1994b), it has not yet found wide application.

In past studies of Precambrian mudstones (Schieber 1986, 1989, 1990a, 1990b), examination of features at millimeter and centimeter scales has revealed lateral facies variability in mudstones, allowed the distinction of a number of facies types, and yielded useful sedimentologic information. In light of these results, it is probable that similar methods might be applied to Phanerozic mudstones to better understand:

(1) the relative importance of lateral facies migration vs. broadly based changes in environmental parameters (e.g., climate, nutrient supply) with regard to producing vertical facies variations in mudstone successions (Potter et al. 1980; Macquaker and Gawthorpe 1994; Oschmann 1988; Wignall 1989; Pedersen and Calvert 1990; Demaison and Moore 1980; Heckel 1991; Wignall 1994).

(2) the application of sequence stratigraphic concepts to the study of shale units (Bohacs and Schwalbach 1992; Leithold 1994).

In order to make such a contribution, and to show that the examination of millimeter and centimeter scale features can indeed be utilized to

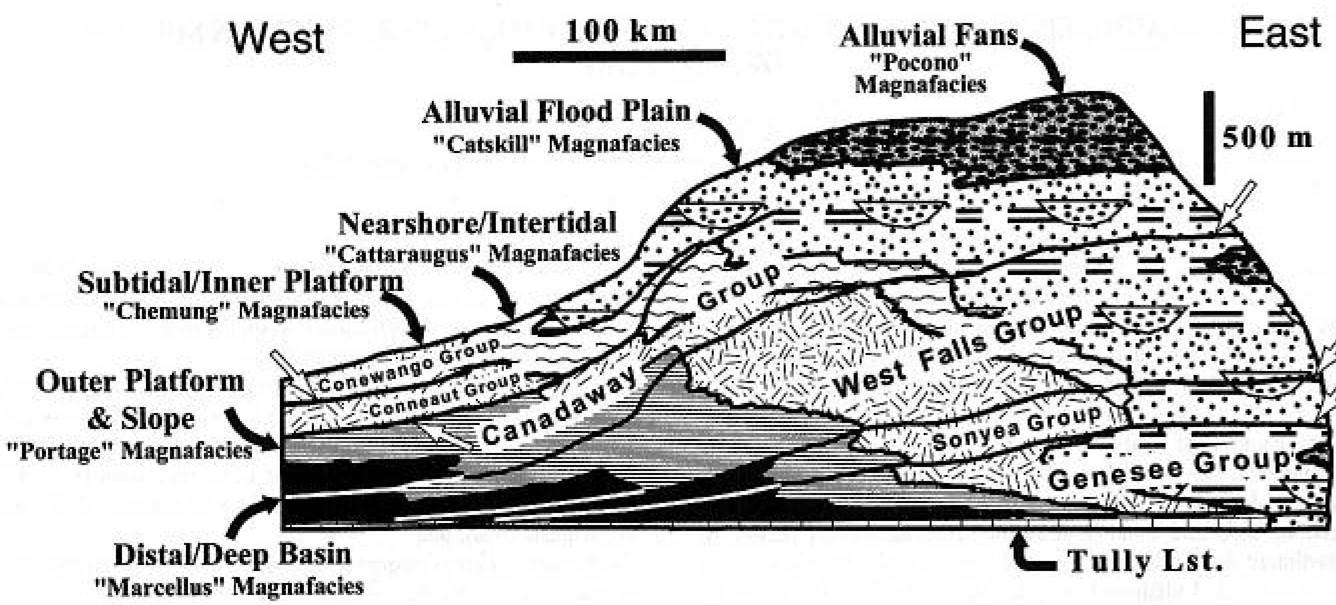

Figure 1: Stratigraphic overview of the Late Devonian Catskill clastic wedge (after Rickard 1981), showing east-west change of facies within given stratigraphic intervals and distribution of Rickard's (1981) magnafacies types (magnafacies used as defined in the AGI Dictionary of Geological Terms 1976). The empty arrows point out the position of key transgressive black shales that define the boundaries of groups and major depositional cycles.

make paleoenvironmental interpretations of Phanerozoic mudstones, I searched the geologic literature for a suitable mudstone succession. The key requirements were that the succession be laterally extensive, that associated lithologies had already been studied, so that the stratigraphy was well constrained, that the fauna had been studied from a paleoecologic perspective, and that there were indications of lateral facies variability. The lower part of the Upper Devonian Sonyea Group was an ideal candidate for this study because the Devonian of New York, a classical region for sedimentary geologists, is a well investigated succession that has seen a wide range of stratigraphic, sedimentologic, and paleontologic studies. Detailed work by Sutton et al. (1970) provided the crucial stratigraphic framework, and also showed the existence of a range of mudstone types that were deposited in diverse but related depositional environments.

GEOLOGIC SETTING

During the Middle to Upper Devonian, debris was shed westward into the Appalachian foreland basin from the eroding Acadian fold-thrust belt. The resulting clastic wedge is also known as the Catskill delta complex. Its upper part was subdivided by Rickard (1981) into six groups (Fig. 1). Of these, the Sonyea Group is thinnest, and through tracing of thin, laterally persistent black shale horizons it can be subdivided into an upper and lower interval (Fig. 2; Sutton et al. 1970). The duration of the lower interval was approximately half that of the middle *asymmetricus* zone (Woodrow et al. 1988). Use of current estimates of the average duration of conodont zones (Johnson et al. 1985), suggests that the lower Sonyea interval was deposited over a time span of a few hundred thousand years. The Sonyea Group is exposed along an east-west-trending outcrop belt approximately 350 km long, extending from Lake Erie in the west to the Catskill Mountains in the east (Fig. 2). The outcrop belt is oriented perpendicular to depositional strike, which facilitates lateral comparison of rocks that were deposited in environments ranging from alluvial plains to deeper-water basinal conditions (Fig. 1).

In the Catskill delta succession the facies stacking patterns are repetitive, and Rickard (1964, 1981) distinguished a series of magnafacies types that are independent of the stratigraphic subdivisions (Fig. 1). Thus, within each group there is an east-to-west change from continental to basinal facies. Likewise, because the original formation names predate Rickard’s (1964) designation of the magnafacies, there is also an east-to-west change in formation names within a given subgroup (see Figure 2 for formations in the lower part of the Sonyea Group). In this study, the bounding black shale horizons within the Sonyea Group (Sutton et al. 1970) were used as the primary stratigraphic guides. The traditional stratigraphic nomenclature (Sutton et al. 1970) is included here to facilitate comparison with earlier studies of the Sonyea Group.

The easternmost unit of the Sonyea Group, the Walton Formation (Fig. 2), was deposited on a nonmarine flood plain as part of a westward-growing delta complex. In this unit Sutton et al. (1970) argued that low-sinuosity streams were interspersed

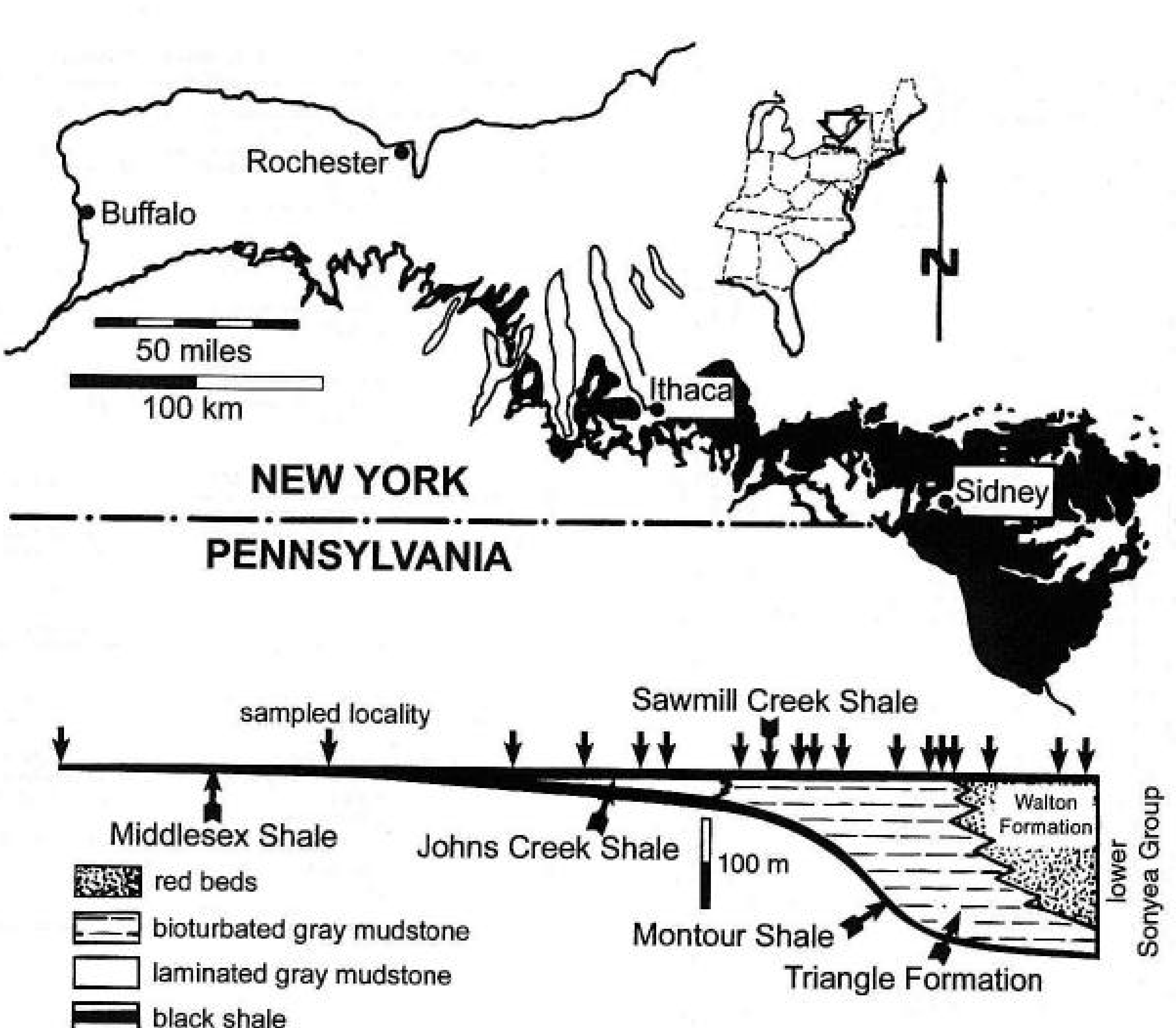

Figure 2: Location of study area and stratigraphic overview. In the inset map of the eastern US, the study traverse is marked by a line of black dots and pointed out by an open arrow. Enlarged map portion shows the Sonyea Group outcrop belt of upstate New York (in black) in relationship to major cities (after Sutton et al. 1970). Stratigraphic relationships of formations that make up the lower part of the Sonyea Group are shown in the restored cross section below. The short arrows above the cross section indicate the positions of sampled localities. The Walton Formation is representative of the Catskill magnafacies, the Triangle Formation represents the Chemung magnafacies, the Johns Creek Shale represents the Portage magnafacies, and the Middlesex Shale represents the Marcellus magnafacies (see Fig. 1). Thickness data are from Sutton (1963), Sutton et al. (1970), and Colton and de Witt (1958). The thickness of black shale horizons is not to scale.

with vegetated plains and lakes. The presence of calcareous concretions in the soil deposits suggests that the climate was warm and seasonally wet at this time (Gordon and Bridge 1987). The Triangle Formation, located to the west of the Walton

Formation (Fig. 2), is composed of gray fossiliferous (benthic marine fauna) mudstones and sandstones. The Triangle Formation is interpreted to have been deposited on a marine shelf (Sutton et al. 1970; Bowen et al. 1974; Sutton and McGhee; 1985). The Johns Creek Shale, located west of the Triangle Formation (Fig. 2), comprises laminated, sparsely fossiliferous gray mudstones with siltstone interbeds. The sedimentary structures within the siltstone beds suggest that deposition occurred from turbidity currents in a slope setting (Walker and Sutton 1967; Sutton et al. 1970). The Middlesex Shale, the westernmost unit of the Sonyea Group (Fig. 2), consists of dark gray and black laminated mudstones (Colton and de Witt 1958). This unit has long been interpreted to have been deposited on the anoxic floor of a stratified basin because of the apparent absence of bioturbation and benthic fossils (Byers 1977).

SAMPLING AND METHODS

The lower Sonyea Group was sampled along the outcrop belt (Fig. 2), from localities described by Gordon and Bridge (1987; Walton Formation), Sutton (1963), Sutton et al. (1970; Triangle Formation); and Colton and de Witt (1958; Johns Creek and Middlesex Shale). Samples were collected

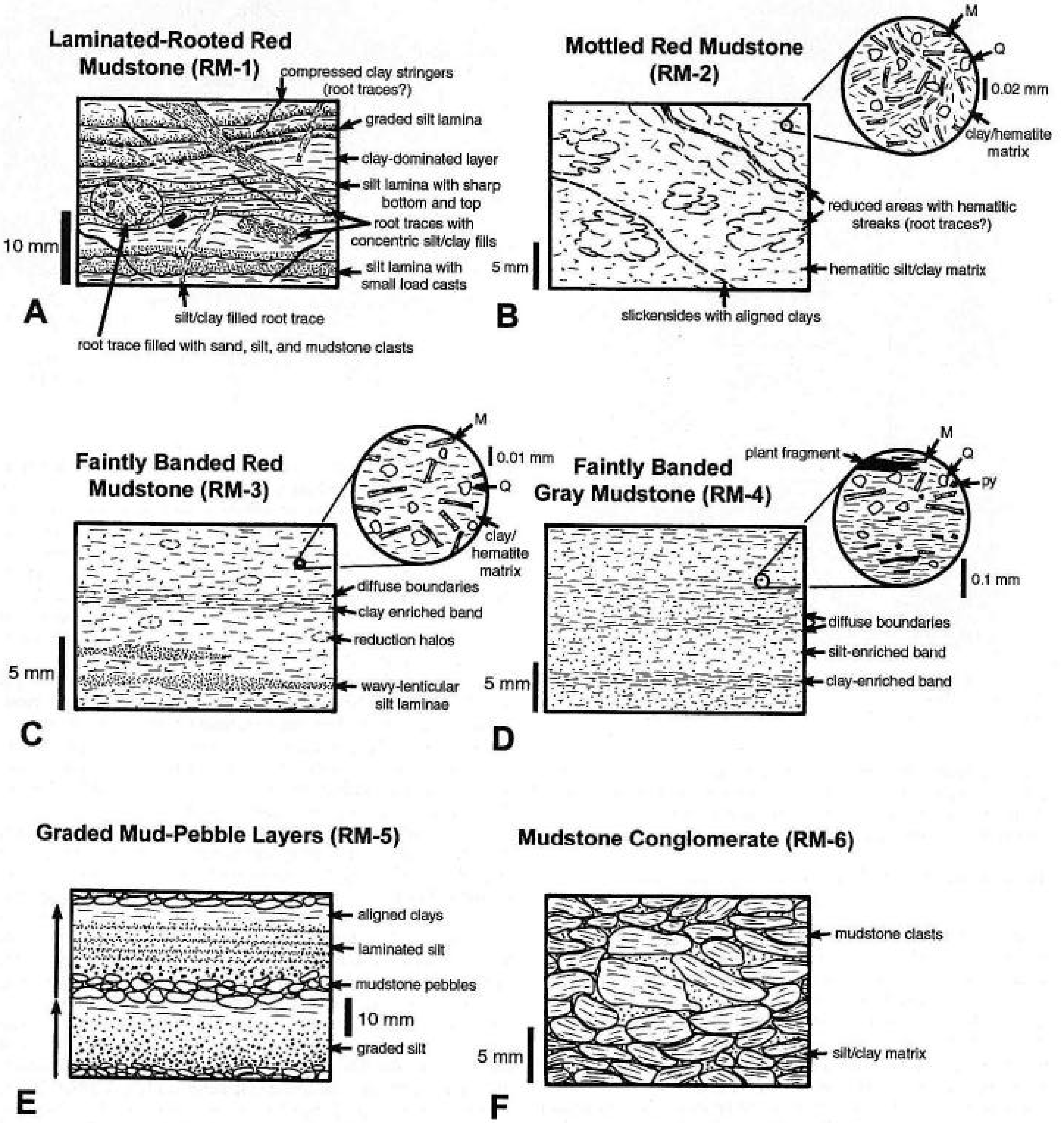

Figure 3: Line drawings that summarize features observed in the six mudstone facies of the red-gray mudstone facies association (RM). Note that the length of scale bars is variable. M = mica; Q = quartz; py = pyrite.

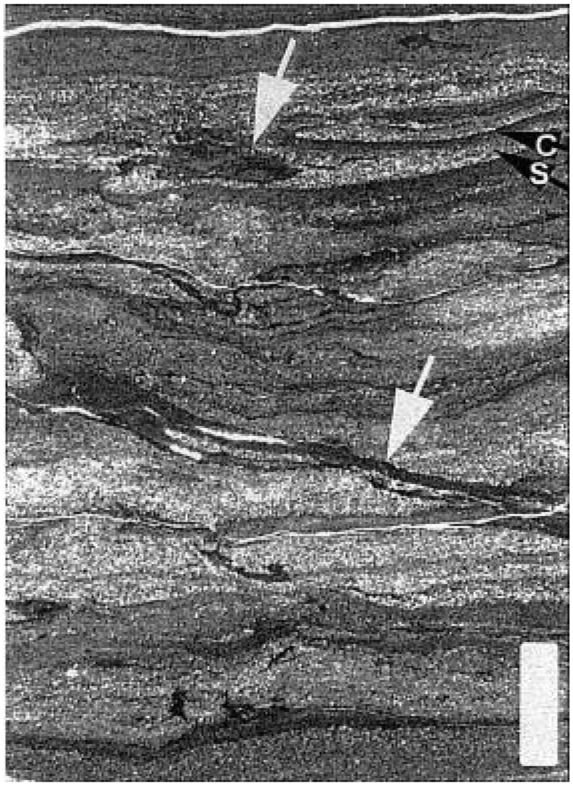

Figure 4: Photomicrograph of laminated-rooted red mudstone (RM-1), showing alternating silt (black arrow S) and clay laminae (black arrow C) and root traces (white arrows). Compare with Figure 3A. Scale bar is 2 mm long.

from either creek beds or road and railroad cuts to minimize the effects of weathering. Where necessary, trenches 30-60 cm deep were dug to obtain reasonably fresh material (degree of weathering evaluated on the basis of the state of preservation of the pyrite grains).

In the studied units the mudstone beds were found to vary in thickness from a few centimeters to a few decimeters, and sampling intervals ranged from 1-2 m in the east (proximal facies) to about 20 cm in the west (most distal facies). "Continuous" samples (touching or overlapping samples) were collected in good outcrops over intervals of up to 0.5 m thickness, in order to determine contact relationships and the degree (at the centimeter and decimeter scale) at which various mudstone types are interbedded.

In order to prevent disintegration of the rock, samples were stabilized with epoxy resin prior to slabbing and thin-section preparation. Two hundred polished slabs and 150 thin sections were examined by binocular and petrographic microscope. Abundances of components in thin sections were estimated with comparison charts (Flügel 1978). Petrographic observations are summarized in Table 1. Color designations were determined from unweathered

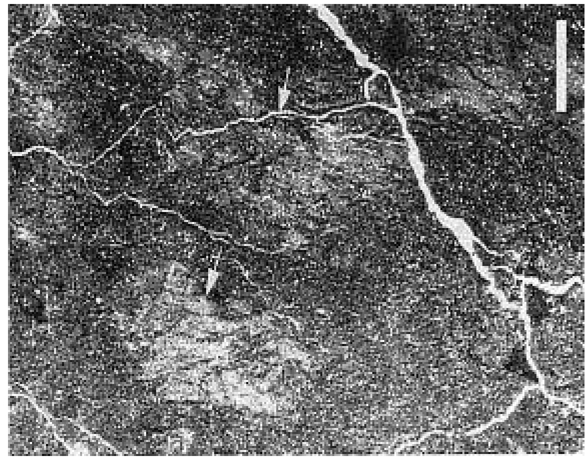

Figure 5: Photomicrograph of mottled red mudstone (RM-2), shows mottled texture. Bleached, light-colored cloudy areas (arrows) are probably developed along small root traces. Compare with Figure 3B. Scale bar is 2 mm long.

material, and do not reflect the effects of outcrop weathering.

DESCRIPTION AND INTERPRETATION OF MUDSTONES

Introduction

In this study six mudstone facies associations were recognized. Each of these consists of several interbedded mudstone facies. Stratigraphic intervals composed of a single mudstone facies range in thickness from 1 cm to more than a meter. The essential features of each facies association are summarized in Figs. 3, 6, 8, 10, 14, and 18.

The current correlations cannot be refined further through biostratigraphy, because the lower Sonyea interval represents only about half a conodont zone (Woodrow et al. 1988). Some Triangle Formation exposures, however, show subtle vertical variations that could be described as cyclic, and tracing these might improve stratigraphic resolution (Van Tassell 1994). The distribution of outcrops, however, is not sufficient to unequivocally determine if these "cycles" can be correlated across all or part of the study area. Thus, the work of Sutton (1963) and Sutton et al. (1970) was used to place the individual samples and outcrops in stratigraphic context. In order to minimize stratigraphic uncertainty here, sampling efforts were concentrated on outcrops that were located closely above the basal black shale of the interval (Fig. 2)

Although the lower Sonyea Group is only partially exposed, sampling was possible throughout

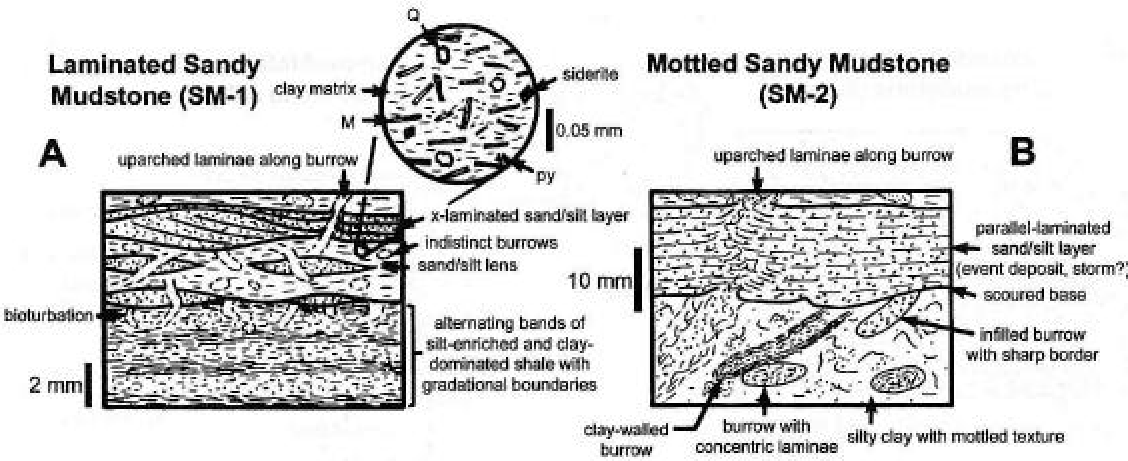

Figure 6: Line drawings that summarize features observed in the two mudstone facies of the sandy mudstone facies associations (SM). Note that the length of scale bars is variable. M = mica; Q = quartz; py = pyrite.

the whole interval by collecting material from adjacent outcrops. Aside from areas where there are major magnafacies changes (e.g., the change from the Triangle Formation to the Johns Creek Shale, Fig. 2), the mudstone facies associations present did not change between adjacent exposures. This suggests that the mudstone facies associations are not sensitive to stratigraphic position within a formation. Consequently, although samples cannot be directly compared within a narrowly defined "time slice", mudstone facies associations that occur along the outcrop belt can be considered lateral equivalents of each other, and can be interpreted in terms of coexisting facies and Walther's Law. Basic preliminary interpretations for each facies association are summarized in Table 2.

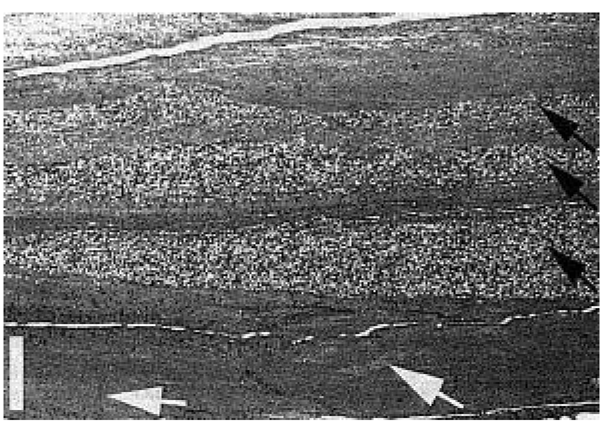

Figure 7: Photomicrograph of laminated sandy mudstone (SM-1), showing wavy-lenticular silt laminae (black arrows) alternating with clay layers. Note bioturbation in clay layers (white arrows). Compare with Figure 6A. Scale bar is 2 mm long.

Facies Association RM: Red-Gray Mudstones of the Walton Formation

The mudstones in facies association RM (RM-1 through RM-6) occur in fine-grained intervals of the Walton Formation and separate fluvial sandstone bodies (4-15 m thick). Sandstone beds (0.1-0.5 m thick) within these mudstone intervals show planar lamination, trough cross-stratification, climbing ripples, symmetrical ripples, and flute and groove casts. The interbedded sandstones may form single beds, may be part of erosionally based upward-fining bedsets with sheetlike, lenticular, or wedge-shaped geometry, or may be part of coarsening- and thickening-upwards sequences (Gordon and Bridge 1987). There are no correlations between specific sandstone types and any particular mudstone type. Sedimentary and textural features of the six mudstone facies in this facies association are summarized in Figure 3.Individual units constituting RM-1 and RM-2 range in thickness from a few decimeters to more than a meter, may vertically grade into one and other, and may contain interbeds of RM-3 (thickness on the order of some decimeters). The observed sedimentary features in these mudstones include raindrop imprints, mudcracks (RM-1, RM-3), root traces (RM-1, RM-2), pseudoanticlines, and calcareous concretions (RM-2; Gordon and Bridge 1987). In RM-2, intersecting irregular planes that are lined with clays and slickensides define irregular aggregates (10-30 mm across).

RM-4 texturally resembles RM-3, but it is of gray color and contains compressed carbonized plant fragments. RM-4 forms horizons that range from a few decimeters to more than a meter in thickness, and it lacks raindrop imprints, mudcracks, and silty laminae. RM-5 and RM-6 are characterized by mudstone clasts and are interbedded with RM-4 in mud-filled channels (interval thickness from a few centimeters to 20 cm) Interpretation.---Root traces in

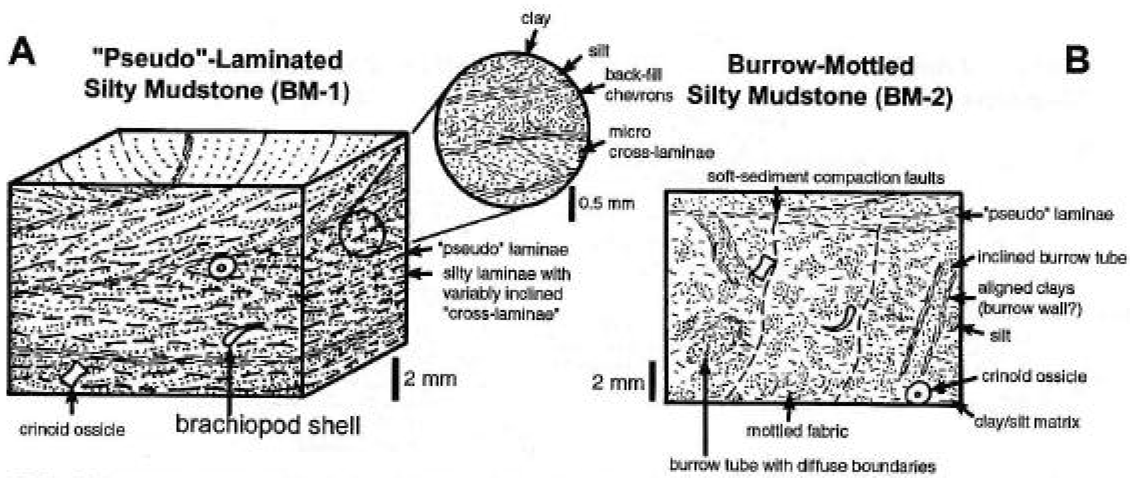

Figure 8: Line drawings that summarize features observed in the two mudstone facies of the burrowed mudstone facies association (BM). Note that the length of scale bars is variable.

RM-1 and RM-2 (Figs. 3A, 3B, 4, 5) indicate that soil-forming processes were operating during deposition of facies RM. This is confirmed by the presence of slickensides and irregular aggregates in RM-2, which are interpreted to be fossil cutans and soil peds (see Retallack 1988). Slickensides and pseudoanticlines also suggest a vertisol origin for RM-2 (Retallack 1988; Mack et al. 1993), and imply a seasonally wet and dry climate (e.g., Buol et al. 1980). Reduced areas with hematitic/clayey streaks in RM-2 (Figs. 3B, 5) resemble drab-haloed root traces. These could represent either the chemical microenvironment of the rhizosphere, or gleying associated with anaerobic decay of root material soon after burial of the paleosol below the water table (Retallack 1988). The presence of well preserved primary sedimentary features in RM-1, despite the presence of disrupting roots (Figs. 3A, 4), suggests that RM-1 represents a very weakly developed paleosol (Retallack 1988). RM-3 and RM-4 share a massive appearance, homogeneous texture, and a low degree of clay and mica alignment (Fig. 3C, D). These features could for example have been produced by intense bioturbation (Potter et al. 1980; O'Brien and Slatt 1990), were it not for the fact that primary features, such as silty laminae and silt-enriched vs. clay-enriched bands, are undisturbed (Fig. 3C, D). Thus, it is more likely that deposition occurred through rapid settling from suspension, probably as a consequence of clay flocculating from concentrated suspensions (Potter et al. 1980; O'Brien and Slatt 1990; Parthenaides 1990). The presence of lenticular silty laminae in RM-3 (Fig. 3C) indicates erosion and bedload transport, but the overall rarity of this feature suggest that flow velocities rarely exceeded the threshold of motion for silt in the case of RM-3, and never reached it in the case of RM-4. Diffuse transitions between silt-enriched vs. clay-enriched bands (Fig. 3D) suggest uninterrupted deposition for successive bands. Thus, individual beds of RM-3 or RM-4 probably accumulated from slow-moving suspensions as the product of distinct depositional events. Mudcracks and raindrop imprints imply that flooding and depositional events alternated with periods of subaerial exposure in the case of RM-3.
The absence of these features in RM-4, as well as the gray color of this shale type, suggests deposition in a subaqueous setting for RM-4.

The absence of significant postdepositional deformation in many mudstone clasts of RM-5 and RM-6 (Fig. 3E, F) suggests that many had been hardened prior to transport. It is possible that reworking of dried out mudcrusts (e.g., RM-3) provided these "hard" clasts, whereas the deformed clasts may have been produced by rip-up of

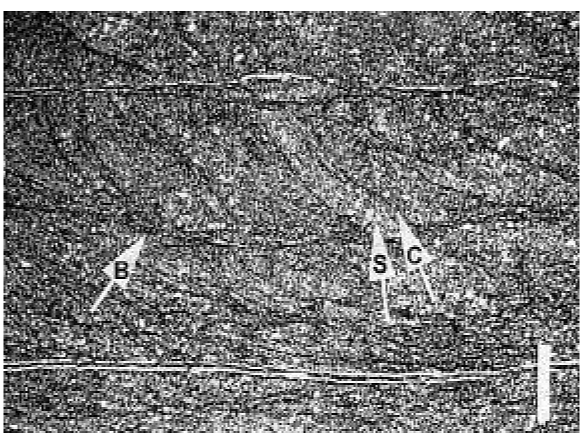

Figure 9: Photomicrograph of micro-laminated silty mudstone (BM-1), showing alternating micro-cross-laminae of silt (arrow S) and clay (arrow C) within macroscopically visible laminae (arrow I points out macroscopic lamina boundaries). These micro-cross-laminae are probably compacted *Zoophycos* back-fill menisci. Compare with Figure 7A. Scale bar is 1 mm long.

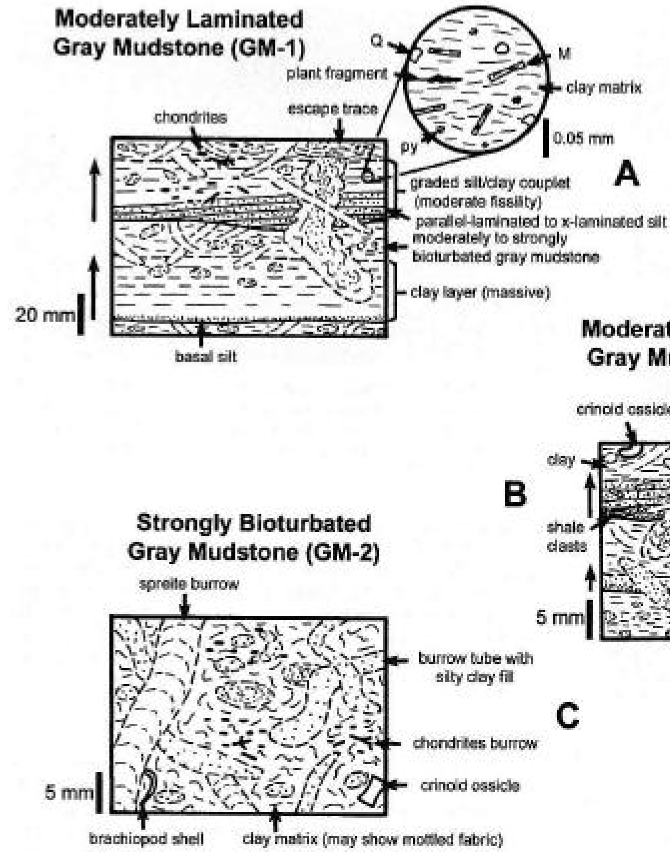

Figure 10: Line drawings that summarize features observed in the three mudstone facies of the graded mudstone facies association (GM). Note that the length of scale bars is variable. M = mica; Q = quartz; py = pyrite.

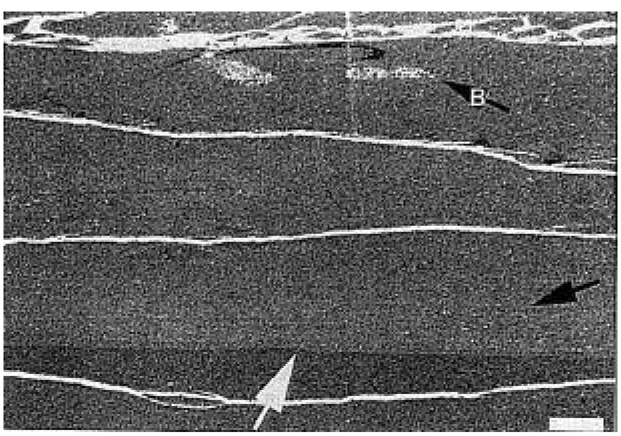

Figure 11: Photomicrograph of graded silt/mud couplet in moderately laminated gray mudstone (GM-1). Arrow points to base of silt/mud couplet. The couplet shows faint horizontal laminae in the lower part (black arrow), and bioturbation in the upper part (black arrow marked B; lighter colored, oval burrows). Compare with Figure 10A. Scale bar is 2 mm long.

unconsolidated sediment by traction currents (e.g., RM-4). Because mudstone clasts get abraded rapidly during transport (Smith 1972), these clasts were probably only transported over short distances. Graded beds in RM-5 (Fig. 3E) suggest size segregation via settling through water and imply subaqueous deposition from waning currents. Gordon and Bridge (1987) also concluded from observation of the interbedded sandstones in these fine-grained intervals that deposition took place from waning overbank flow, and that thicker, fining-

and coarsening-upward sequences reflect crevasse- splay abandonment or progradation, respectively. They also argued that the recognition of wave ripples indicated the presence of ponded water.

Facies Association SM: Sandy Mudstones of the Easternmost Triangle Formation

The easternmost part of the Triangle Formation (Fig. 2) consists of two mudstone facies (SM-1, SM-2; Fig. 6A, B), which are interbedded on a decimeter scale. They contain a relatively large component of sand-size grains (Table 1). Sandstone intervals (fine to

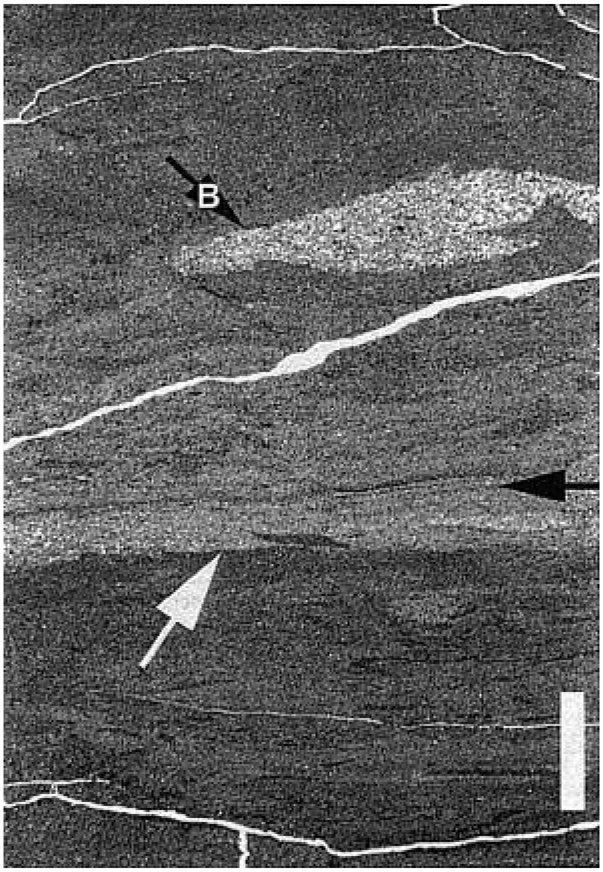

Figure 12: Photomicrograph of moderately bioturbated gray mudstone (GM-2), showing graded silt layer (light) with sharp base (white arrow) and internal parallel laminae (black arrow). Note that there is more bioturbation in clay layers below and above, and that the top of the silt layer is more bioturbated as well. Compressed, light-colored burrow in upper half of photo (black arrow marked B) is filled with fine sand, probably derived from interbedded storm sands. Graded silt layers like the one pictured here also occur in GM-1. Compare with Figure 10B. Scale bar is 2 mm long.

medium sand, 3-15 cm thick, spacing 0.5-2 m) within these units exhibit even to wavy bedding and may show basal erosion, horizontal to gently undulose parallel laminae, and normal grading. The basal parts of these sandstone beds may contain fossil debris and mudstone rip-up clasts (up to 20 mm across).

Laminated sandy mudstone (SM-1; Fig. 6A) consists of two interbedded elements: (1) lenticular-wavy interbedded sand and clay (upper half of Fig. 6A, Fig. 7), and (2) banded clay layers (lower half of Fig. 6A). Although typically of the thickness shown in Figure 6A, sand layers may be as thick as 30 mm, and show cross-lamination and parallel lamination, opposing foreset dips in the same layer, draping laminae, and cross-stratal offshoots (Reineck and Singh 1980, p. 34, 103). The banded clay layers (lower half of Figure 6A) are more poorly sorted than the clay layers that are interbedded with sand layers (upper half of Figure 6A), and show only minor bioturbation at their top (Fig. 6A).

The mottled sandy mudstone (SM-2) consists of silty clay with interbeds of parallel-laminated fine sand (10-20 mm thick). Silty clay

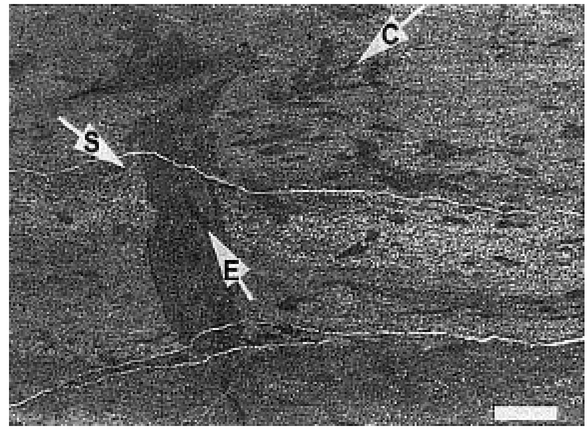

Figure 13: Photomicrograph of *Chondrites* (arrow C) in laminated silt layer of GM-2. On left side of photo silt layer is cut by a vertical escape trace. Note silt laminae next to escape trace that have been dragged upwards (arrow S). *Chondrites* is abundant and also cuts across escape trace (darker spots, arrow E). Compare with Figure 9B. Scale bar is 2 mm long.

intervals have a mottled texture and contain subhorizontal, sand-filled burrow tubes (Fig. 6B). Burrow tubes may exhibit thick, concentrically laminate linings, or relatively thick walls that contrast with the surrounding sediment by being composed mainly of clay (Fig. 6B). Well defined, sand-filled burrows are found below sandstone interbeds and cut across other burrow types .Interpretation.---Lenticular and wavy bedding in SM-1 (Figs. 6A, 7) imply alternating current flow and slackwater conditions (Reineck and Singh 1980). Features such as opposing foresets, draping laminae, and cross-stratal offshoots are interpreted as an indication of wave action (Boersma 1970; De Raaf et al. 1977).

In the banded clay layers (SM-1), the lack of bioturbation implies rapid deposition, and gradational boundaries between silty and clay-rich bands implies that the sediment was deposited rapidly from suspension (Schieber 1989). The banded clay layers within the lenticular and wavy-bedded intervals (upper half of Figure 6A) could be relict deposits that escaped complete reworking, perhaps because they were either too thick, or there was not enough time for complete reworking.

Mottled, bioturbated textures in SM-2 (Fig. 6B) suggest slower sediment accumulation and less reworking than in SM-1. In addition, the presence of lined and walled burrows suggests that the burrows were occupied for prolonged periods (Bromley 1990). Where the diffuse mottled background texture is present it is possible that the sediment at deposition was soft-soupy and mixed by endobenthos (Bromley 1990). In contrast, the well defined sand-filled burrows below sand beds were apparently constructed within a firm substrate (Bromley 1990), late in burrowing history, probably after erosion had removed the soft-soupy surface sediment.

Upwards-bent laminae along burrows that cross thin sandstone layers (Fig. 6B) suggest that

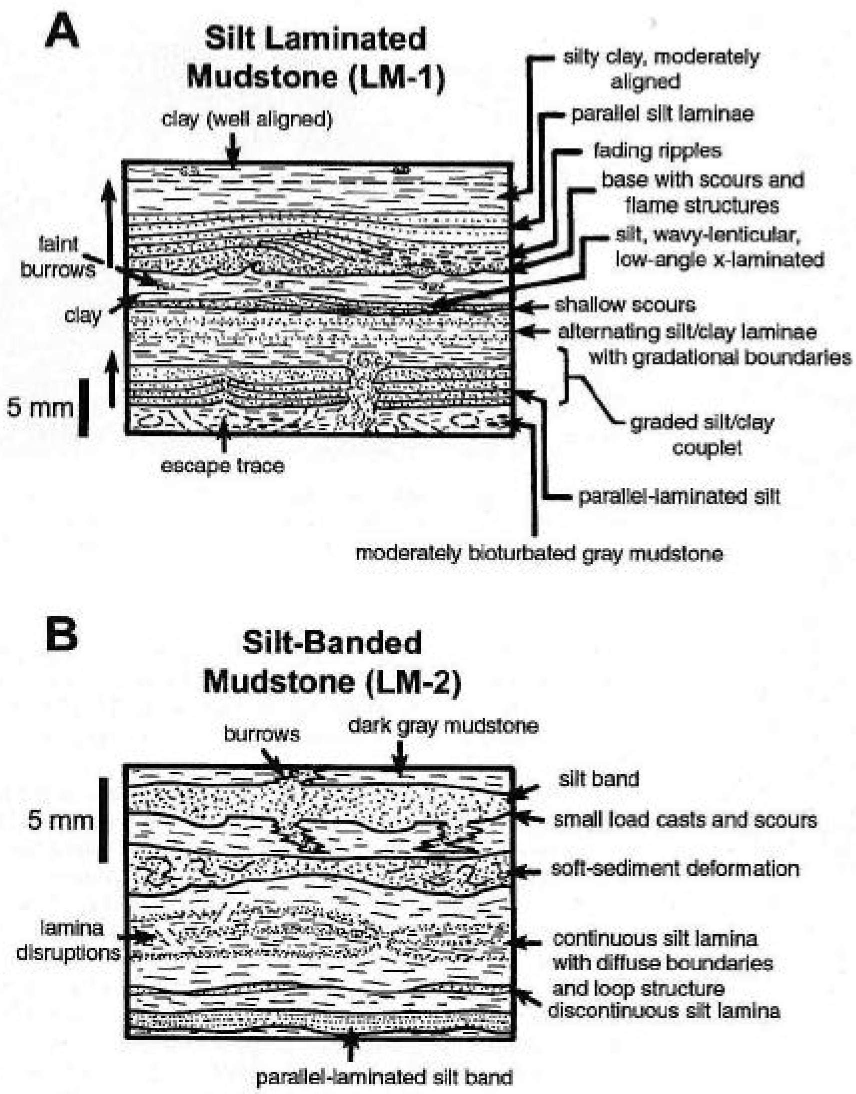

Figure 14: Line drawings that summarize features observed in the two mudstone facies of the laminated mudstone facies association (LM). Note that the length of scale bars is variable.

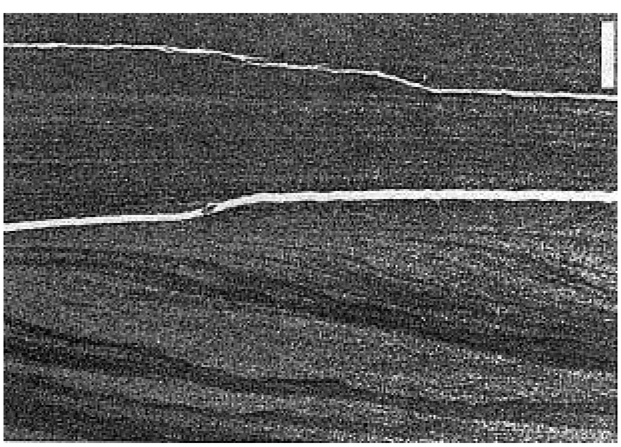

Figure 15: Photomicrograph of silt-laminated mudstone (LM-1). Shows graded silt/clay couplet (fine-grained turbidite) with fading ripples in lower half, and in upper half mud with parallel silt laminae grading to clay. Compare with Figure 14A. Scale bar is 2 mm long.

these burrows are escape traces. Together with basal scouring (Fig. 6B), this suggests these sand layers originated as rapidly deposited high-energy event deposits (Seilacher and Einsele 1991). Thicker sandstone interbeds (3-15 cm thick) in these mudstones show sharp erosional basal contacts and normal graded bedding. These are also interpreted as event deposits (Seilacher and Aigner 1991).

Facies Association BM: Burrowed Mudstones of the Eastern Triangle Formation

The two mudstone facies of this facies association (BM-1, BM-2) dominate the eastern Triangle Formation. They are interbedded on the centimeter to decimeter scale and differ mainly in texture. Mudstone intervals 0.3-2 m thick alternate with fine-grained sandstone beds (5-150 cm thick), and may show mud-filled scours with concave bases (depth up to 1 m). Scour surfaces lack body fossils and burrows, and are overlain by interbedded BM-1 and BM-2.

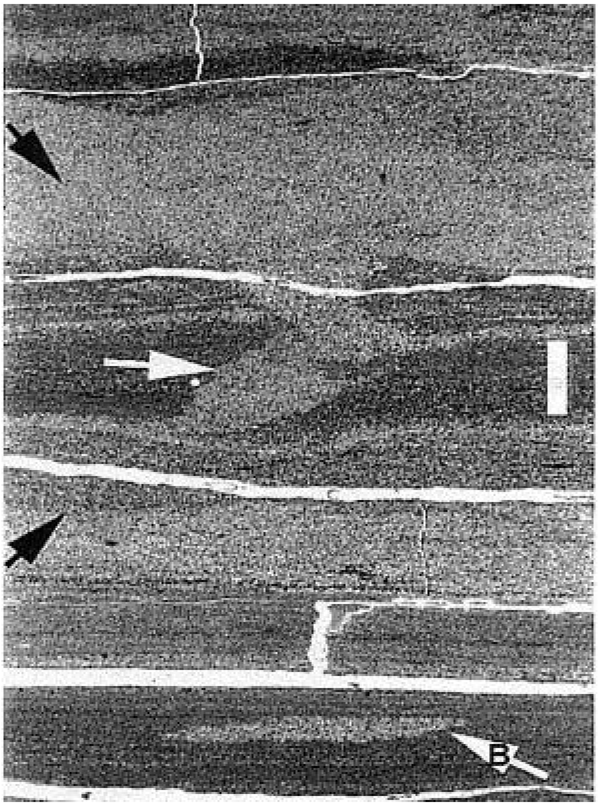

Figure 16: Photomicrograph of silt-banded mudstone (LM-2). Shows silt bands (light gray; black arrows) with lack of internal sedimentary structures and silt-filled burrows that connect silt layers (white arrow; central part of photo). Note diffuse silt laminae, low degree of bioturbation, and compressed burrows (white arrow marked B) in clay layers (dark gray). Compare with Figure 14B. Scale bar is 2 mm long

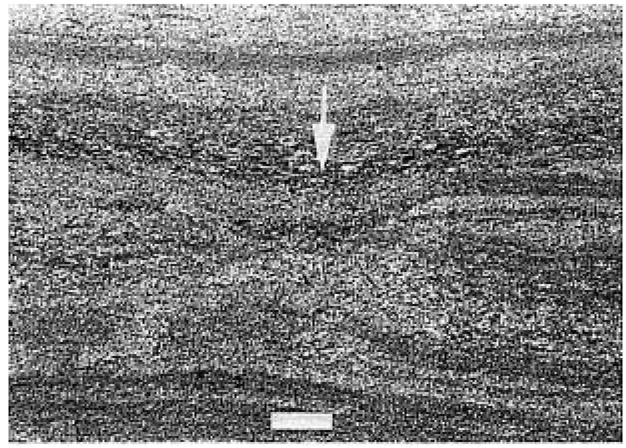

Figure 17: Photomicrograph of loop structure in LM-2. Note convergence of laminae and thinning of lamina bundle towards center of photo (white arrow), suggestive of stretching due to downslope gravitational pull. Compare with Figure 13B. Scale bar is 1 mm long.

Mudstone facies BM-1 dominates exposures of this facies association and is characterized by small-scale, complex, internal lamination (Fig. 8A, 9). In contrast, BM-2 has a mottled fabric that is traversed by various types of burrows and compaction faults (Fig. 8B). Where BM-1 and BM-2 are in contact, compaction faults and burrow tubes of BM-2 terminate against silt and clay laminae of BM-1 (Fig. 8B).

Sandstone beds have erosional bases with grooves, scours, and gutter casts, may show normal grading with fossil debris in the basal part, and parallel horizontal lamination and hummocky cross-stratification. The thinner sandstone beds (5-40 cm) are either planar or sheet-like, whereas thicker intervals show considerable thickness variations and give the appearance of channel fills (up to 1 m deep). The latter may also show amalgamation and ball-and-pillow structures. In one exposure, a thick sandstone bed (0.5-1.5 m thick) with deep basal scours and hummocky cross-stratification showed downlapping low-angle cross-bedding indicating westward sediment transport.

Interpretation.---What upon casual inspection appear to be laminae in BM-1 (Fig. 8A, 9) could be mistaken for wave produced intricately interwoven cross-lamination (Reineck and Singh 1980). The crosscutting relations and lateral alternation of silt and clay within laminae (Fig. 9), however, are incompatible with laminae produced through ripple migration. Instead, the chevron-shaped micro-cross-laminae (Fig. 8A) are interpreted to be back-fill menisci produced by sediment feeders. Comparison with published descriptions of trace fossils (Chamberlain 1978; Thayer et al. 1990), suggests that the laminated fabric of BM-1 represents compacted *Zoophycos* burrows. Thus, we have here a mudstone with a laminated appearance whose laminae are an artifact of bioturbation, rather than a primary depositional fabric.

The mottled texture and clay-lined burrow tubes of BM-2 (Fig. 8B) are suggestive of bioturbation in a soupy-soft substrate. Termination of BM-2 fabric elements against laminae of BM-1 (Fig. 8B) suggests (1) that mottling preceded construction of *Zoophycos* burrows, and (2) that the change from BM-2 to BM-1 represents a succession of burrow types. Because softground conditions and shallow-tier position are indicated for BM-2, and because *Zoophycos* typically reflects deep-tier deposit feeding in a firm substrate (Bromley 1990), this succession is probably best explained through tiering within a single community of trace makers.

Basal scours and fossil debris, gutter casts, grading, and hummocky cross-stratification suggest that sandstone beds in this facies are also storm deposits (Dott and Bourgeois 1982). This issue will be explored in more detail in the final discussion.

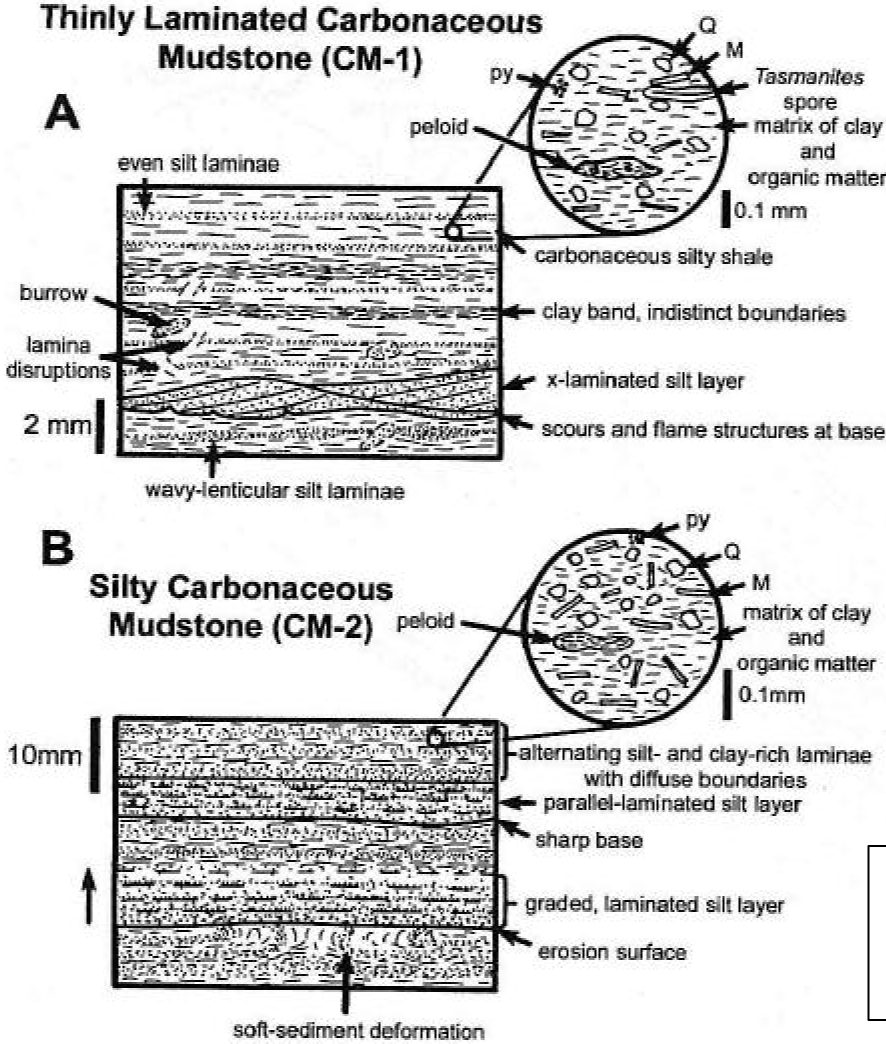

Figure 18: Line drawings that summarize features observed in the two mudstone types of the carbonaceous mudstone facies (CM). Note that the length of scale bars is variable. M = mica; Q = quartz; py = pyrite.

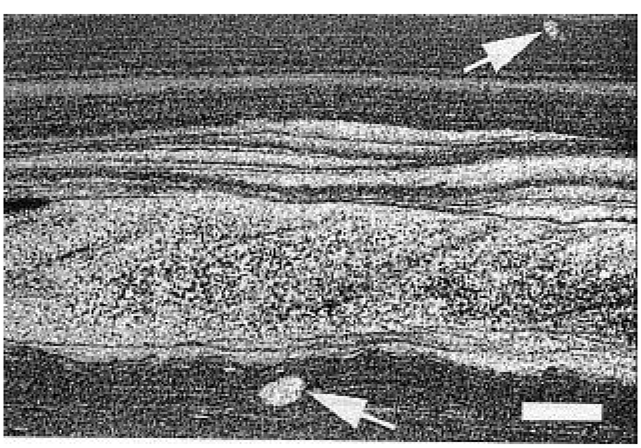

Figure 19: Photomicrograph of thinly laminated carbonaceous mudstone (CM-1), showing in the central part of the photo a cross-laminated, sharp-topped silt layer, possibly a product of reworking by bottom currents. Note the fine silt laminae and silt-filled burrows (arrows) in overlying and underlying carbonaceous mudstone. Compare with Figure 17A. Scale bar is 2 mm long.

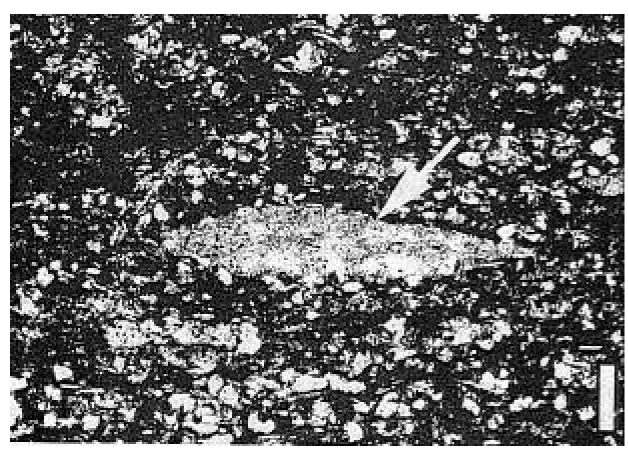

Figure 20: Photomicrograph of silt/clay peloid (white arrow; light gray particle, central part of photo) in CM-1. These are interpreted as fecal pellets of benthic organisms, and suggest the former presence of soft-bodied benthos. Scale bar is 0.1 mm long.

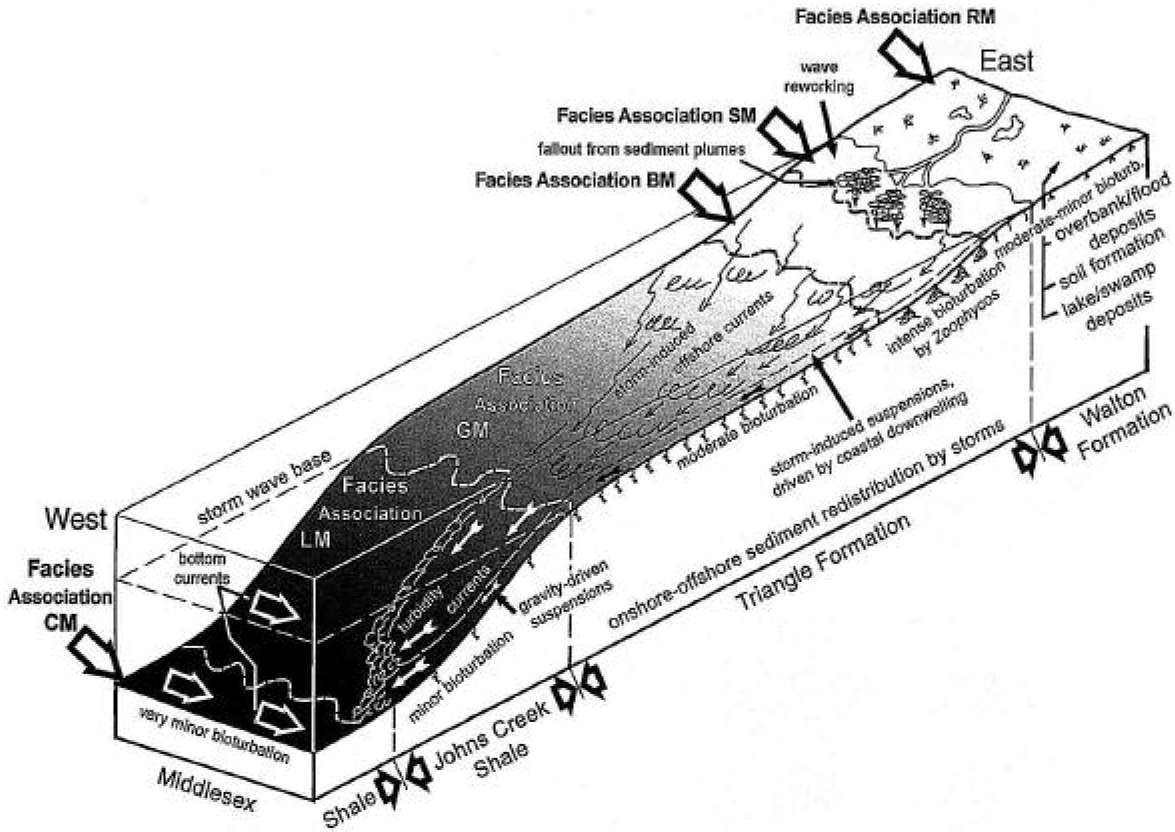

Figure 21: Summary depositional model for the lower Sonyea interval, showing distribution of the six shale facies associations with respect to laterally equivalent stratigraphic units. Boundaries of subaqueous facies associations are marked with double-dotted dashed lines.

Facies Association GM: Graded Mudstones of the Western and Central Triangle Formation

The fossiliferous mudstones of this facies association (GM-1, GM-2, GM-3) are interbedded at the centimeter to decimeter scale and make up the western and central Triangle Formation (Fig. 2). Packages of mudstone, 5-50 cm thick, alternate with very fine- to fine-grained sandstone beds (5-20 cm thick).

Moderately laminated gray mudstone (GM-1) consists of interbedded layers of bioturbated clays, graded silt/mud couplets, and massive clay layers (Figs. 10A, 11). Erosional features and normal grading are common. A variety of burrows are present, including narrow subhorizontal tubes (2-7 mm wide), vertical burrows with diffuse margins, and *Chondrites* (Fig. 11). *Chondrites* cuts across the other burrow types. Moderately bioturbated gray mudstone (GM-2) is similar to GM-1 and consists of alternating graded silt layers and bioturbated clay layers (Figs. 10B, 12, 13). Bioturbation, however, is more severe in GM-2. Whereas in GM-1 primary layering is the most conspicuous feature (Figs. 10A, 11), in GM-2 bioturbation is the most noticeable characteristic (Figs. 10B, 12, 13). In GM-3 bioturbation is so extensive that all primary sedimentary features have been obliterated (Fig. 10C). In addition to burrows observed in GM-1 and GM-2 (Fig. 10A, B), it may also show subvertical to oblique spreite burrows (tubular, up to 7 mm wide) and mottled fabric in its silt/clay matrix. In terms of overall abundance, GM-1 is least abundant and GM-2 is most abundant. Within facies association GM, the overall abundance of *Chondrites* increases westwards.

Interbedded sandstones show variable thickness, have sharp scoured bases, contain basal lenses and layers of fossil debris, and show hummocky cross-stratification. They generally persist across the outcrop, but they may also pinch out and form trains of sandstone lenses (2-5 cm thick).

Interpretation.---Vertical burrows that show upturned laminae where they cross silt layers (Figs. 10A, 13) suggest upwards movement through the sediment and can be interpreted as escape traces. Together with basal scours, grading, and bioturbated tops, this indicates that silt/mud couplets, graded silt layers, and massive clay layers in GM-1 and GM-2 are event deposits (Seilacher and Aigner 1991). Initial strong currents (basal scour) were followed by waning flow (grading). Whether these events were storms, as suggested by HCS in sandstone beds (Dott and Bourgeois 1982), will be explored in the final discussion.

The presence of spreite burrows (GM-3) and *Chondrites* suggest feeding and dwelling structures of some permanence (Bromley 1990), and imply small rates of sediment accumulation. Bioturbated clay layers (GM-1, GM-2) probably indicate slow, low-energy sediment accumulation between more energetic depositional events, and strongly bioturbated, thicker mudstone beds (GM-3) are probably due to prolonged intervals of slow, low-energy sedimentation.

Well defined burrow tubes and absence of lined and walled burrows suggests initially a comparatively firm substrate for facies association GM (Bromley 1990). The mottled "background" fabric of GM-3 (Fig. 10C), however, is taken to indicate an initially soft surface sediment that after some burial and compaction was reworked by more deeply burrowing trace makers (Bromley 1990),

and/or removed by erosion associated with event deposits.Facies Association LM: Laminated Mudstones of the Johns Creek Shale

This facies association characterizes the Johns Creek Shale, a stratigraphic unit located to the

west of the Triangle Formation (Fig. 2). Its two mudstone facies (LM-1, LM-2) are essentially unfossiliferous, and are significantly less bioturbated than facies association GM (Fig. 14). Mudstone intervals (some centimeters to meters thick) alternate with wavy beds of siltstone (2-15 cm thick). The latter show basal flute and tool marks, and parallel laminae, followed by ripple cross-lamination and draping parallel laminae. Thinner beds lack basal parallel laminae. The orientation of the flute marks and cross-laminae indicates westward-flowing currents at the time of deposition.

Silt-laminated mudstone (LM-1) is characterized by graded silt/mud couplets that are interbedded with clay layers and thin silt layers (Fig. 14A). The graded silt/clay couplets show a vertical sequence (Fig. 14A) of parallel laminae, climbing or fading ripples (Fig. 15), draping silt laminae (continuous to discontinuous), and finally silty clay. Bioturbation is moderate to almost absent. *Chondrites* and vertical burrows along which silt laminae are dragged upwards are most conspicuous. Silt-banded mudstone (LM-2, Figs. 14B, 16) contrasts with LM-1 in that silt layers always have sharp upper boundaries (no grading). They show loop structures (Fig. 17; Cole and Picard 1975), soft-sediment deformation suggestive of lateral flow, and contain flattened, light-colored silt/clay peloids (0.2-0.3 mm long).

Interpretation.---The presence of grading and a vertical succession ranging from ripples to draping parallel laminae (Fig. 14A) and the presence of silt/clay couplets indicates deposition from waning currents. Ripples in the lower parts of these couplets suggest that traction transport and migration of low-relief bedforms occurred. Soft-sediment deformation suggestive of lateral flow and loop structures (Fig. 17; boudinaging of laminae) indicates flowage and stretching of sediment layers, possibly by gravitational forces on a slope. Sharp-topped, wavy lenticular silt laminae (Fig. 14B) suggest bedload transport. Possible causes for the relative decrease of bioturbation in facies association LM will be addressed in the broader discussion of Sonyea deposition.

Facies Association CM: Carbonaceous Mudstones of the Middlesex Shale

The Middlesex Shale, the western equivalent of the Johns Creek Shale (Fig. 2), consists of a succession of carbonaceous mudstones. In this unit thinly laminated carbonaceous mudstones (CM-1; Fig. 18A) are dominant. Here the silt laminae are either thin and even, or somewhat thicker and lenticular (Figs. 18A, 19). Lamina disruptions are the most common sign of bioturbation, whereas well defined silt-filled burrows (Fig. 19) occur only in association with wavy-lenticular silt laminae. Silty carbonaceous mudstones (CM-2) differ from CM-1 in two ways: (1) they have an overall larger silt content (Table 1), and (2) they contain laminated/graded silt layers (Fig. 18B). Light-colored, flattened silt/clay peloids (0.2-0.5 mm long) are common in both mudstone facies CM-1 and CM-2 (Fig. 20).

Interpretation.---Grading and parallel laminae in silt layers of CM-2 suggest deposition from waning flow (see above discussion of LM-1). In CM-1, wavy-lenticular, sharp-topped, and cross-laminated silt layers in CM-1 (Figs. 18A, 19) indicate bedload transport. Basal erosional features (Fig. 18A) indicate that the depositing currents were at times swift enough to erode a muddy substrate.

Lamina disruptions and burrows (Fig. 18A) both indicate the presence of burrowing benthic organisms. The fact that lamina disruptions are not associated with discernible burrows suggests that initially the sediment was quite soft or soupy and that animals plowed or "swam" through the substrate. In contrast, the sharply defined walls of silt-filled burrows (Fig. 19) suggest emplacement in a firm substrate. The association of the latter burrow type with wavy-lenticular silt layers that show basal scouring (Fig. 18A) suggests that erosion removed the soft substrate surface.

DISCUSSION

The mudstones of facies association RM (Fig. 3, 21) suggest overall subaerial or terrestrial deposition (Table 2) in a variety of sub-environments. Gordon and Bridge (1987), in a study of sandstone bodies from this facies association, also concluded that the interbedded mudstones were most likely deposited in interchannel areas of an alluvial plain (e.g., Gordon and Bridge 1987). The various mudstone facies probably were deposited in a variety of sub-environments within this overall setting (Collinson 1986), such as abandoned channels, lakes (RM-4, RM-5, RM-6), low-lying, frequently flooded areas (RM-1, RM-3), and elevated, less frequently flooded areas (RM-2).

Thin sand and silt layers in the mudstones of the Triangle Formation, Johns Creek Shale, and Middlesex Shale share sedimentary features (e.g., basal erosion, escape traces, grading; Figs. 6, 10, 14, 18) that suggest that they are event deposits (Table 2; Seilacher and Einsele 1991). Because they are present in rocks that are lateral equivalents along an onshore-offshore transect, their origin is discussed in context.

The sedimentary features in thin sand layers of facies association SM (Fig. 5) suggest that these layers were deposited by depositional events where initially the currents were strong enough to erode the muddy substrate, and that this was followed by a decrease in flow velocity and deposition of laminated sand. Likewise, silt/mud couplets of facies association GM (Fig. 9) indicate initial erosion, followed by waning flow and sediment deposition. Sedimentary features and overall appearance of these event deposits closely resemble those observed in modern storm-dominated shelf muds, for example those of the North Sea (Gadow and Reineck 1969; Reineck 1974; Aigner and Reineck 1982). Comparison between the recent North Sea shelf muds and the thin sand layers in facies association SM suggests that the latter are proximal storm beds, whereas the graded silt/clay couplets of facies association GM are very similar to distal storm deposits (Gadow and Reineck 1969; Aigner and Reineck 1982). In the North Sea the most distal storm layers are "mud tempestites" (Aigner and Reineck 1982), and their equivalent in the Triangle Formation are probably the massive clay layers in GM-1 (Fig. 10A).

Hummocky cross-stratification, basal scours, grading, and basal fossil debris are observed in thicker sandstone beds of the Triangle Formation (facies associations SM, BM, and GM). These structures are commonly considered good indicators of storm deposits (e.g., Dott and Bourgeois 1982). This view is also supported by the fact that fossil assemblages in sandstones are the same as in intercalated mudstones (Bowen et al. 1974). The shells and rip-ups at the bases of sandstone beds probably formed by winnowing of underlying muds during the storm peak, whereas the overlying sands probably reflect waning of the storm (e.g., Kreisa and Bambach 1982).

The channel-like features that were observed at the bases of sandstone beds have the appearance of gutter casts (Reineck and Singh 1980), and might be attributable to erosion by either rip currents (Nummedal 1991) or concentrated "jet-like" flows (Aigner and Reineck 1982) that resulted from "offshore flowing gradient currents" (Allen 1982). This interpretation is supported by westward (offshore) paleoflow in the Triangle Formation (Sutton et al. 1970), and HCS beds with westward-inclined low-angle cross-beds (facies BM). The latter resemble combined-flow storm beds as described by Nøttvedt and Kreisa (1987). Mud-filled scours in facies association BM are comparable in shape and depth to channel-like features at the beds of sandstone beds, and it is assumed that they have the same origin.

In general, storm deposits become thinner, finer, and less abundant in an offshore direction (Allen 1982; Dott and Bourgeois 1982; Aigner and Reineck 1982). In the Triangle Formation, thick, apparently proximal storm sands, are interbedded with thin sand and silt beds of distal appearance. Aigner and Reineck (1982) attributed comparable interbedding of “proximal” and “distal” storm layers in the North Sea to variable strength of storms. There, strong storms deposit more extensive thick beds, and weaker storms produce the thin storm layers within intervening muddy intervals.

The spacing and proportion of thicker sandstone beds (strong storms) in facies associations SM, BM, and GM, in conjunction with westward paleoflow and westward thinning of the Triangle Formation (Fig. 2), suggest that storms most likely transported sediment across all three facies belts. Yet in facies association BM, located between facies associations SM and GM, we only find the thicker storm sands, but none of the thin storm deposits described from facies associations SM and GM. In our given context, this paradox is explained by the intense bioturbation in facies association BM (see below).

In thin silt layers of the Johns Creek and Middlesex Shale (facies associations LM and CM; Figs. 14, 18), deposition from waning flow is indicated by grading and vertical succession from ripples to draping parallel laminae. Initially this might suggest a storm origin, as proposed for silt layers in facies association GM to the east. The vertical sequence of sedimentary features, however, also closely matches what has been reported from fine-grained turbidites (Stow and Piper 1984; Stow and Shanmugam 1980). One feature in particular, fading ripples (Figs. 15, 14A) in facies association LM, has so far been reported only from fine-grained turbidites (Stow and Piper 1984).

A turbidite interpretation for these thin silt layers is corroborated by observations made on thicker siltstone beds in facies association LM. The vertical succession of sedimentary features in these beds (basal flute casts, parallel laminae, ripples, draping laminae), indicated deposition from waning flow and corresponds to base-truncated Bouma sequences. Comparable siltstone beds were studied by Walker and Sutton (1967) in the upper portions of the Sonyea Group (not covered by this study), and were likewise interpreted as turbidites. Thus, interbedded turbidite siltstone beds as well as subtle differences from graded silt layers of facies association GM (Triangle Formation), suggest that the thin graded silt layers in facies association LM (Johns Creek Shale) and CM (Middlesex Shale) were most likely deposited as fine-grained turbidites. Uniform westward orientation of flute marks and cross-laminae shows that the Triangle Formation was the source for these turbidites.

The lateral change from storm deposits to turbidite deposits in the lower Sonyea Group implies that the Triangle Formation (facies association GM) was deposited above storm wave base, and that the Johns Creek and Middlesex Shale (facies associations LM and CM) were deposited below storm wave base (Walker 1979). Although no change in slope is necessary in the model proposed by Walker (1979), features attributable to downslope gravitational forces (Figs. 14B, 17; Table 2) nonetheless suggest a steeper depositional slope for the Johns Creek Shale.

Deposition to the west of the slope deposits of the Johns Creek Shale (facies association LM), together with its carbonaceous character, westward sediment transport, and westward thinning (Fig. 2), make the Middlesex Shale the most distal and deepest water deposit within the lower Sonyea Group. This view agrees with studies by Byers (1977), Sutton et al. (1970), and Bowen et al. (1974), and is the generally accepted interpretation for black shale facies in the Appalachian Basin (Woodrow 1985).

Not all silt layers in facies associations LM and CM, however, can be attributed to turbidite deposition. As pointed out above, silt laminae with sharp upper contacts (Figs. 14B, 18A, 19) suggest traction transport. In the context of turbidites and deeper-water deposition they probably indicate reworking of the seabed by bottom currents (Shanmugam et al. 1993).

Sedimentologic study of Sonyea mudstones is not restricted to the recognition of storms and turbidites as depositional processes. A variety of other features provide further insights (Table 2). For example, in SM-1 lenticular and wavy bedding suggest an environment with alternating current flow and slackwater conditions (Reineck and Singh 1980), and internal features such as opposing foresets, draping laminae, and cross-stratal offshoots indicate frequent wave reworking (Boersma 1970; De Raaf et al. 1977). Banded clay layers are suggestive of distinct pulses of rapid mud deposition (Schieber 1990b). In contrast, the heavily bioturbated SM-2 records conditions of less frequent reworking, overall slower sedimentation (suggested by heavy bioturbation), and a comparatively soft substrate (lined and walled burrows). The intimate interbedding of SM-1 and SM-2 suggests adjacent environments with differing depositional parameters, a situation common in nearshore marine settings (Elliott 1986). Such an interpretation is substantiated by the presence of proximal storm deposits (see above) and by the severe environmental stress recognized in paleoecological studies (Bowen et al. 1974). In a nearshore context, the rapidly deposited banded clay layers of SM-1 might represent deposition from river plumes during floods.

Neither in this nor in previous studies have classical shoreline deposits (beach, shoreface) been identified in the lower part of the Sonyea Group. Catskill shoreline deposits belong to the Cattaraugus magnafacies (peritidal, cyclic marine and nonmarine sandstones), which is not developed in the lower Sonyea Group (Rickard 1981; see Fig. 1). It is likely that the shoreline was quite muddy during that time interval. Deposits of muddy shorelines in the Catskill succession have previously been described by Walker and Harms (1971) from Pennsylvania.

The fully bioturbated mudstones of facies association BM indicate that the rate of biogenic reworking exceeded that of sedimentation (Bromley 1990), and suggest that between strong storms, sedimentation rates were small enough to allow for full benthic reworking of accumulating muds. The organisms that construct burrows of the *Zoophycos* type probably are specialists that slowly rework the deeper substrate for food and remain in their burrow for life (Bromley 1990). A soft surface substrate in facies association GM is also indicated by the mottled texture of the sediment (Table 2) and paleoecological observations, such as brachiopods that lack functional pedicles and have long spines (Bowen et al. 1974). Ubiquitous *Zoophycos* in facies association BM suggest that, although a soupy-soft surface layer is indicated, overall substrate stability and slow sedimentation was the rule. Much more intense bioturbation in facies association BM (as compared to facies association SM) is consistent with slower deposition in a less energetic and probably deeper setting.

It was pointed out above that facies association BM lacks the thin storm deposits that we find in adjacent facies associations, despite the fact that from a facies-belt perspective they should have been present. The absence of these deposits is probably a matter of preservation. For instance, *Zoophycos* is very abundant in facies association BM, and is a deep-tier ichnofossil with a high preservation potential (Bromley 1990). Its presence in these sediments therefore automatically diminishes the preservation potential of thin storm layers. In combination with slow sediment accumulation, the intense burrowing by *Zoophycos* could conceivably have destroyed any record of minor storms in facies association BM. That this was indeed the case is suggested by paleoecological observations. For instance, shelly benthos in mudstones of facies association BM indicates adaptation to an environment characterized by intermittent erosion and rapid sedimentation events (Bowen et al. 1974). This is consistent with sediment reworking and redistribution by storms.

A marked decrease of bioturbation in facies association GM, despite a decrease in net accumulation rate relative to facies association BM (see above), suggests that other factors besides sedimentation rates influenced bioturbation. The presence of common *Chondrites* facies association GM, but not in facies association BM, suggests that low-oxygen conditions at the seafloor might have been the cause of the decrease in bioturbation (Bromley and Ekdale 1984). Deposition in deeper water could for example have caused reduced oxygen supply to bottom waters. The westward thinning and decrease of storm sands in the Triangle Formation suggests gradual westward deepening (Figs. 2, 21), a view that is consistent with decreasing bottom-water oxygenation as suggested by the westward increase of *Chondrites*. Further support for this interpretation comes from the observation that facies association GM lacks shelly infauna and has a low-diversity epifaunal assemblage with a westward decrease of population density (Bowen et al. 1974).

A drop in bioturbation, relative to facies association GM, in facies association LM (Johns Creek Shale) could indicate (1) more rapid sedimentation, and/or (2) environmental stress, such as oxygen-deficient bottom waters. The obvious westward decrease of sedimentation rates in the lower Sonyea Group (Fig. 2) suggests that possibility (1) is unlikely. In light of the already discussed westward decrease of bottom-water oxygenation in the Triangle Formation (facies association GM), it is probable that further decrease of bioturbation in facies association LM was due to further oxygen depletion. Finding a scarcity of body fossils, Bowen et al. (1974) similarly concluded that mudstones of facies association LM were deposited in a zone of low and fluctuating oxygen contents.

Bioturbation in mudstones of facies association CM (Middlesex Shale) is even more subtle than in facies association LM. Together with abundant organic matter and diagenetic pyrite, this suggests that living conditions on and in the carbonaceous muds of facies association CM were most likely even harsher than farther east in the Sonyea Group (Fig. 2). As the most distal deposit of the Sonyea Group, the carbonaceous mudstones of facies association CM could for example be seen as the product of slow accumulation of pelagic organic debris with minor dilution by distal, fine-grained turbidites. Recent debate on the origin of black shales has centered on two possible controls: (1) increased primary production in surface waters, and (2) widespread anoxia due to water-column stratification (Demaison 1991; Demaison and Moore 1980; Byers 1977; Pedersen and Calvert 1990; Calvert 1987; Calvert and Pedersen 1992; Wetzel 1991; Wignall and Hallam 1991). Evidence for bottom currents (Fig. 18) raises doubts whether there were long-lasting periods of water-column stratification. Although inconspicuous, burrows and lamina disruptions (Figs. 18A, 19) indicate benthic life and suggest that there was at least some oxygen in bottom waters. Above features might also have been produced in the case of intermittent oxygenation, for example by turbidites (Grimm and Föllmi 1994; Potter et al. 1982). The presence of ubiquitous silt/clay peloids (Fig. 20), however, suggest otherwise.

Modern oxygen-deficient organic-rich bottom muds are commonly dominated by deposit-feeding polychaete worms that pelletize surface sediment and produce burrows and burrow tubes (Tyson and Pearson 1991). The latter structures, however, do not survive compaction (Cuomo and Rhoads 1987). Instead, a carbonaceous laminated sediment results in which fecal pellets are the only indication of the former presence of these worms (Cuomo and Rhoads 1987). Cuomo and Bartholomew (1991) suggest that benthic fecal pellets are dominated by silt, clay, and organic matter, whereas zooplankton fecal pellets contain abundant biogenic components. The silt/clay peloids in facies associations LM and CM (Fig. 20) compare closely to benthic fecal pellets described by Cuomo and Rhoads (1987) and Cuomo and Bartholomew (1991). The presence of these peloids is a further indication of benthic life within carbonaceous mudstones of the Sonyea Group.

Thus, although the preferred model for many that worked on Appalachian black shales (e.g., Byers 1977; Potter et al. 1982; Ettensohn 1985; Kepferle 1993), water-column stratification probably has to be ruled out as the primary cause for carbonaceous mudstone accumulation in the distal Sonyea Group. Instead, observations presented in this paper suggest a gradual offshore decrease of bottom-water oxygenation. Bearing in mind that laterally equivalent black shales in other parts of the Appalachian basin accumulated in relatively shallow water with frequent mixing of the water column (Schieber 1994a), increased primary production may indeed be a more likely cause for black shale formation in the Sonyea Group. Alternatively, a model of seasonal oxygen depletion, such as the one suggested by Tyson and Pearson (1991), would also be consistent with features reported in this study.

Conclusions

The coexisting sedimentary environments during deposition of the Sonyea Group are summarized in Figure 21. Although mudstones are the dominant lithology throughout the Sonyea Group, the processes that were involved in mud deposition differ between facies associations. The presence of root traces, slickensides, mudcracks, and raindrop imprints indicates that facies association RM was deposited in a terrestrial environment, specifically as soils and overbank deposits, and in lakes. In contrast, a variety of wave-produced features, rapidly deposited clay layers, and proximal storm deposits suggests that facies association SM was deposited in a nearshore deltaic environment, where wave reworking and sediment fallout from river plumes were important. Westward flowing paleocurrents and the distribution of hummocky cross-stratified sandstone beds, graded silt/mud couplets, and "mud" tempestites in facies associations SM, BM, and GM indicate that storm-induced offshore currents moved sediment westward from facies association SM across facies associations BM and GM. The presence of siltstone beds with Bouma sequences, graded silt/clay couplets with fading ripples, and loop structures in facies association LM suggest that turbidity currents moved sediment across a sloping area into the distal parts of the basin. In addition, indications of traction transport in a portion of the silt beds of facies association LM and CM indicate reworking of the seabed by bottom currents. Bioturbation gradually decreased westward in response to declining bottom-water oxygenation. In facies association BM, intense bioturbation by *Zoophycos* completely obliterated muddy storm deposits and produced a "pseudo" lamination that is an artifact of bioturbation rather than a primary depositional fabric. Benthic life is indicated not only by shelly benthos and bioturbation but also by more subtle features, such as lamina disruptions and silt/clay peloids that are interpreted as fecal pellets of benthic polychaete worms. The latter are ubiquitous in the more carbonaceous facies associations (LM, and especially CM), and suggest that even in presumably anoxic environments, some benthic organisms were able to survive. This suggests that carbonaceous shales in the Sonyea Group probably did not form as a result of water-column stratification and anoxic bottom waters, but rather were the consequence of high productivity in the surface waters.

This study shows that a wealth of information can be extracted from mudstones through careful examination of polished slabs and thin sections, and that along the onshore-offshore transport path a range of coexisting shale facies can be distinguished. Small-scale sedimentary features observed in this study provide information about a variety of sedimentary conditions, including direction and strength of currents, transport and depositional processes, substrate consistency and stability, frequency of reworking, and oxygen supply. Paleoenvironmental reconstructions derived from this combined study of both the mudstones and sandstones provide more information than study of the interbedded sandstones alone. Data derived from the mudstones complement data derived from the sandstones and from paleoecology, and allow us to eliminate the less likely interpretations.

Because of their economic potential, the black shales of the Appalachian Basin have received the most intense scrutiny in numerous prior studies (e.g., Kepferle 1993). Working under the assumption that black shale deposition was well understood and did not require further study, this study was originally initiated to determine the depositional conditions under which the remaining mudstones were deposited. The fact that even the most basinal black shales showed evidence of benthic life was surprising. This prompted reexamination of earlier paradigms and renewed studies of distal black shales in Tennessee and Kentucky (Schieber 1994a, 1994b). Work in progress includes studies of erosion surfaces, sedimentary hiatuses, sequence boundaries, and bioturbation (Schieber 1998a, 1998b; Lobza and Schieber 1999). Results from these ongoing studies will likely mean that a major overhaul of our understanding of black shale formation will result.

The fact that it was possible in this study to provide new information regarding the origin of a sedimentary succession that has previously been studied in considerable detail suggests that the methodology employed has definite potential for beneficial application to shale sequences in general. Because of the simplicity of the approach, it should probably constitute the initial stage of any study in which more narrowly defined problems in mudstone sequences are investigated. Once a larger number of mudstone units have been investigated in the prescribed manner, it may well be possible to recognize repetitive facies patterns for given tectonic and oceanographic settings, and to develop generally applicable sedimentation models with predictable associations of mudstone types.

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