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REFLECTION OF DEEP VS SHALLOW WATER DEPOSITION BY SMALL SCALE SEDIMENTARY FEATURES AND MICROFABRICS OF THE CHATTANOOGA SHALE IN TENNESSEE

Jürgen Schieber
Department of Geology
University of Texas at Arlington
Arlington, TX 76013, U.S.A.

Abstract

The Chattanooga Shale was deposited on a continental platform in central Tennessee, and in a slope/peripheral trough setting in eastern Tennessee. Careful examination of shale samples shows distinct differences between these two settings. A total of 14 shale types has been distinguished on the basis of sedimentary features, lithologic associations and small scale sedimentary sequences. Sedimentary features attributable to fine grained turbidites characterize most of the shales from eastern Tennessee. On the basis of the clay/silt ratio two types of fine grained turbidites can be distinguished. They may represent deposition in an interlobe slope (large clay/silt ratio) and lobe margin environment (small clay/silt ratio). Silt laminae produced by storm induced wave and current reworking characterize the shales of the platform region. Differences in energy levels, probably reflecting seafloor morphology, are indicated by sedimentary features of the various shale types.

Bioturbation in these shales is subtle and has been under-estimated in the past. Burrows of the platform region are more elaborate and complex than those of the trough region. Even units that lack visible signs of bioturbation contain peloids that could be fecal pellets of polychaete worms or similar surface dwellers. This observation indicates that oxygen levels in the bottom waters were not as low as previously assumed and that truly anoxic conditions were rare in the Appalachian Basin.

Résumé

Le schiste argileux Chattanooga fut déposé sur une plate-forme continentale dans le Tennessee central, et dans un contexte de pente/fosse périphérique dans l'est du Tennessee. L'examen soigneux d'échantillons de schistes argileux démontre des différences distinctes entre ces deux contextes. Au total 14 types de schistes argileux ont été distingués en se basant sur les caractéristiques sédimentaires, les associations lithologiques et les séquences sédimentaires à petite échelle. Les caractéristiques sédimentaires attribuables aux turbidites de faible granulométrie distinguent la plupart des schistes argileux de l'est du Tennessee. En se basant sur le rapport argile/silt deux types de turbidites à grain fin peuvent être identifiés. Ils peuvent représenter une sédimentation dans un milieu de pente entre deux lobes (rapport argile/silt élevé) et de marge de lobe (rapport argile/silt bas). Des lames de silt produites par un remaniement causé par les vaques et les courants de tempête caractérisent les schistes argileux de la région de la plate-forme. Des différences dans les niveaux d'énergie, reflétant probablement la morphologie du fond marin, sont indiquées par les caractéristiques sédimentaires des divers types de schistes argileux.

La bioturbation de ces schistes argileux est subtile et a été sous-estimée dans le passé. Les terriers dans la région de la plate-forme sont plus élaborés et complexes que ceux dans la région de la fosse. Même les unités qui manquent de signes visibles de bioturbation renferment des pelletoïdes qui pourraient être des coprolithes des vers polychètes ("polychaete") ou de semblables habitants de la surface. Cette observation indique que les teneurs en oxygène dans les eaux de fond n'étaient pas aussi basses que supposées précédemment et que des conditions vraiment anoxiques étaient rares dans le bassin appalachien.

Introduction

Despite recent publications that attest to a decade of progress in mudrock research (e.g., Schieber, 1989, 1990; O'Brien and Slatt, 1990; Kuehl et al., 1988, 1990; Bennett et al., 1990), our understanding of shales is still quite rudimentary. For a better understanding of shale sedimentology detailed petrographic studies of shale facies are needed. Suitable stratigraphic units are those with abundant shales, a well established stratigraphic framework and a wide range of environments. Prior studies of associated lithologies that allow independent assessment of environmental interpretations of shales are helpful.

These criteria are met by shale units in the Late Devonian Appalachian Basin. In particular, the Chattanooga Shale (Tennessee and Kentucky) and its lateral equivalents probably represent one of the most thoroughly investigated shale sequences (Woodrow et al., 1988; Conant and Swanson, 1961; Broadhead et al., 1982; Lundegard et al., 1985; Ettensohn et al., 1988). Recent investigations of the Chattanooga Shale in Tennessee have clarified some remaining controversial points concerning water depth, paleocurrents, basin topography and energy regime (Schieber, this volume).

For a study of shale fabrics petrographic thin sections were prepared for a large number of samples from central and eastern Tennessee (Fig. 1). A number of distinct fabrics or shale types were recognized, reflecting prevalent depositional processes and conditions.

GEOLOGIC SETTING

The Upper Devonian (Frasnian-Famennian) Chattanooga Shale forms the distal part of a thick clastic wedge that accumulated in a foreland basin. Estimated latitudinal positions of the Chattanooga Sea range from equatorial (e.g., Ettensohn and Barron, 1981) to 30 degrees south latitude (Witzke and Heckel, 1988). Climatic indicators suggest seasonal rainfall, tropical temperatures and predominantly perennial streams (Woodrow et al., 1988). From east to west major environments of deposition include alluvial plain, delta plain, shelf, slope with turbidites and basin floor with black shale accumulation.

Accumulation below the dysaerobic-anaerobic boundary of a stratified water column (Byers, 1977) has been a popular hypothesis for the origin the black shales. However, it conflicts with evidence for shallow water deposition and water circulation over the basin floor on a more or less continuous basis (ripples, magnetic fabric measurements; Schieber, this volume).

In central Tennessee approximately 9 m of Chattanooga Shale are found above a basal unconformity (Fig. 1). Deposition in a shallow water platform setting (Conant and Swanson, 1961; Schieber, this volume) is indicated by hummocky cross stratified siltstone/sandstone interbeds, lag deposits (bone beds) and erosion surfaces. In eastern Tennessee the Chattanooga Shale reaches a thickness of approximately 650 m (Hasson, 1982; Fig. 1), and interfingers eastwards with the Brallier Formation. The latter is characterized by turbidite deposition on a westward dipping clinoform along the eastern margin of the Appalachian Basin (Lundegard et al., 1985). The base of this clinoform may have been at 100-200 m water depth (Potter et al., 1982).

Paleocurrent data and sedimentological constraints (Schieber, this volume) are consistent with the existence of a peripheral trough along the eastern basin margin (e.g., Potter et al., 1982). This trough received most of its sediment from the eastern basin margin (clinoform), but also received a minor contribution from the western platform area. To examine if the shales reflect this scenario, samples from the platform region (central Tennessee) the western slope of the trough (eastern Tennessee), and the eastern slope of the trough (easternmost Tennessee) were examined and compared.

SHALE TYPES

TROUGH SHALES

Shales deposited in the peripheral through of the Appalachian Basin can be grouped into two broad categories, (1) clay-rich (greenish gray in colour), and (2) carbonaceous (medium gray to black colour). A total of 9 shale types can be distinguished. Shale types form massive packages (10 cm or more in thickness), or are interbedded on a centimetre scale.

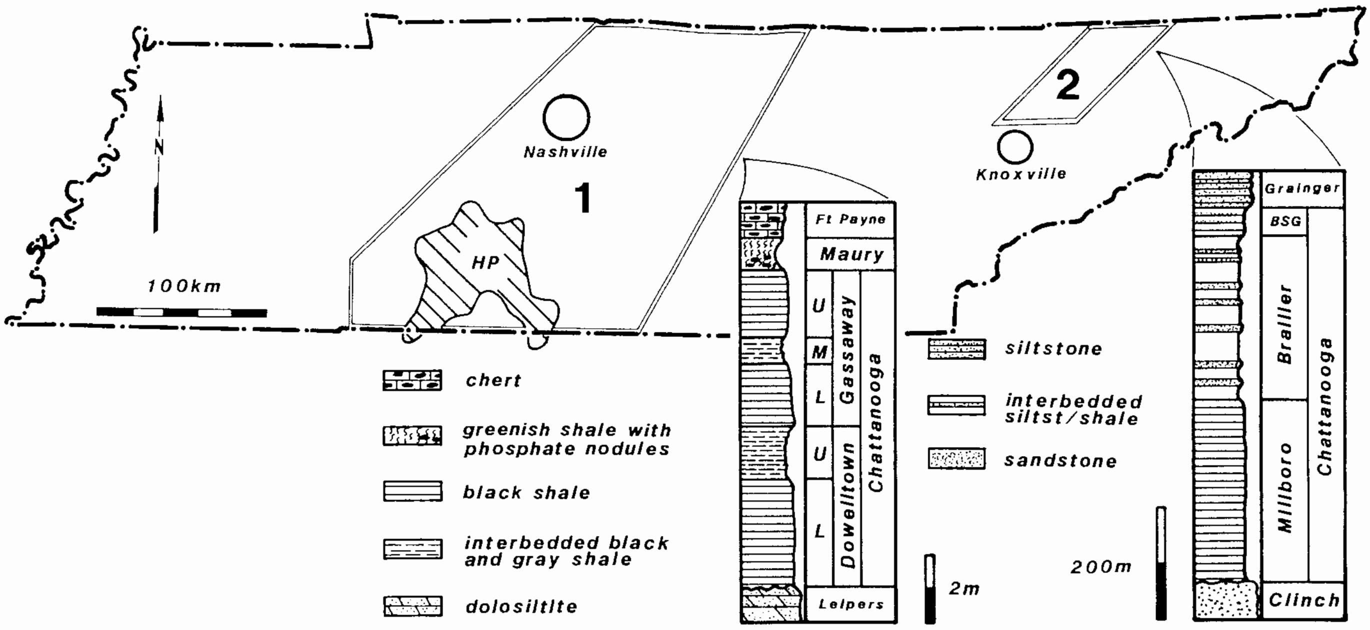


Fig. 1. Outline of Tennessee and location of study areas (marked with double lines). Platform shales were examined in area marked 1, trough shales in area marked 2. Stratigraphic section for area 1 from Conant and Swanson (1961), for area 2 from Hasson (1982). Area marked HP shows location of Hohenwald Platform, an island area during Chattanooga deposition. Note different scales foı the two sections.

Clay-Rich Trough Shale

The four shale types in this category (Fig. 2) are characterized by greenish gray layers or laminae (0.1-100 mm thick) that consist predominantly of clays, with a few percent scattered quartz silt (0.01-0.03 mm) and 5-10 percent detrital micas (muscovite, 0.02-0.06 mm). These layers may contain in addition small fragments of organic matter (up to 0.3 mm, mainly plant fragments) and scattered pyrite in single crystals or small framboids (up to 0.02 mm). The majority of micas are aligned subparallel to bedding, but approximately 10 percent are significantly out of alignment or even oriented perpendicular to bedding. Bioturbation is typically sparse and seems more commonly to affect top portions of individual shale layers. Occasional shale horizons that show elevated degrees of bioturbation tend to contain calcite filled brachiopod shells and calcite cemented silt laminae.

The first shale type, massive clayshale (TC1), consists entirely of even, massive (50-100 mm thick), greenish gray clay beds (Fig. 2). Bedding is only discernible in very good outcrops and in thin sections.

The second type, laminated clayshale (TC2), consists of alternating (a) clay laminae with 10-20 percent quartz silt (0.01-0.06 mm) and 10-20 percent micas (0.02-0.08 mm), and (b) silty laminae that contain approximately 20-40 percent quartz silt and are otherwise of similar composition to the clay laminae (laminae 0.1-2 mm thick). Layers of laminated clayshale (15-40 mm thick) show sharp basal contacts which may be erosive, and may grade upwards into beds of greenish gray clay. Lower portions of TC2 beds may show convolute bedding, slumps and synsedimentary microfaults (Fig. 2). The transition to overlying clay beds may contain discontinuous, lenticular silt laminae. Shales of this type (TC2) are interbedded with clayshales of type TC1, TC3 and TC4.

Graded clayshale (TC3) is the third type of clay-rich trough shale. Its 10-30 mm thick beds are compositionally and texturally the same as TC1 and have sharp basal contacts. At the

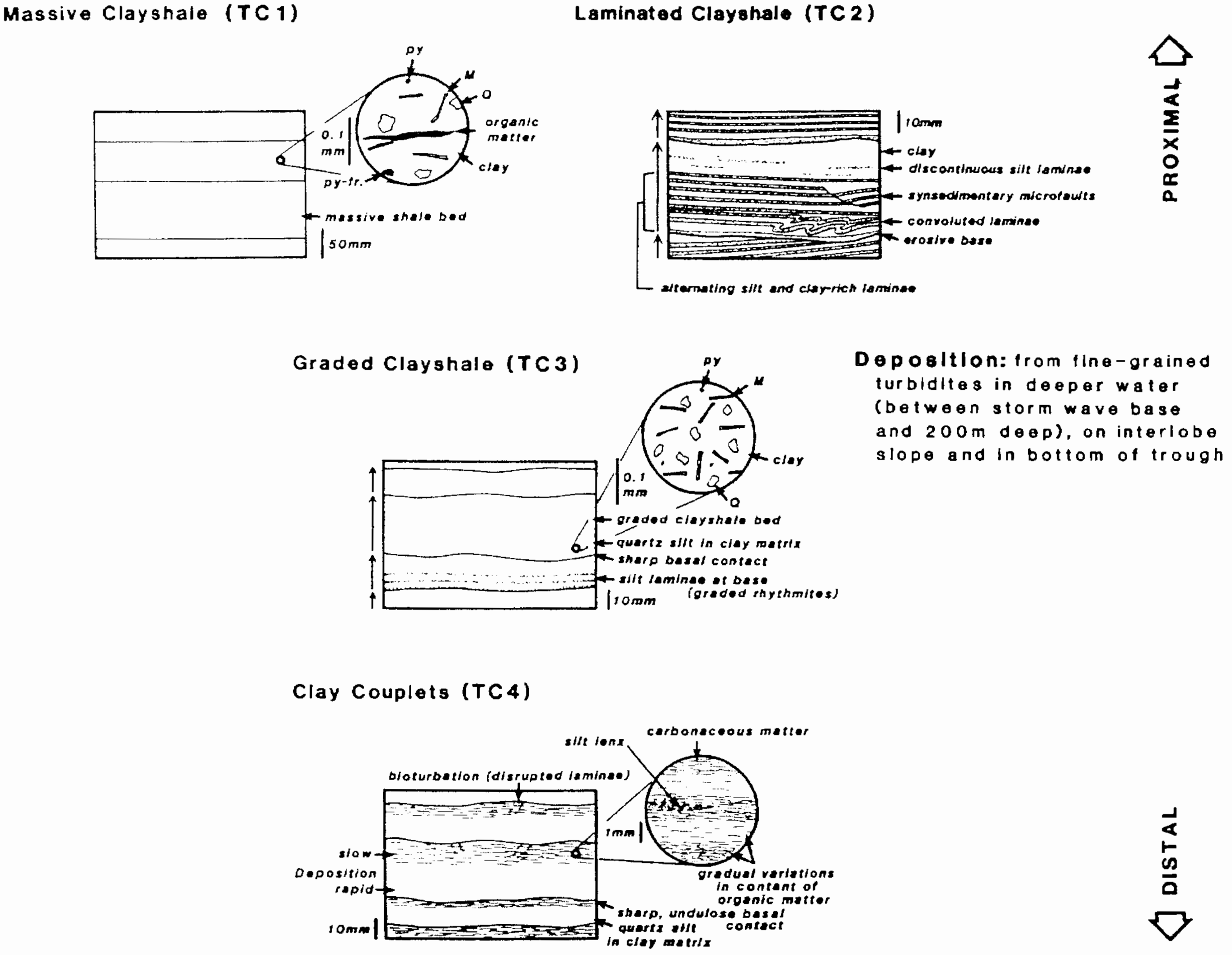


Fig. 2. Overview of sedimentary features observed in clayshales of trough region. TC1 through TC4 are interpreted to be representatives of a continuous spectrum of fine grained turbidites. Proximal/distal arrangement of shale types reflects the author's view of relative proximity to the source of these fine grained turbidites. Carbonaceous top portions of clay couplets (TC4) suggest that TC4 was probably deposited most distal. Note variability of scale bars.

base they contain a larger proportion of scattered quartz silt than in the remainder of the bed, and may show undulose contacts, load casts and graded silt laminae (Fig. 3).

Clay couplets (TC4) are the fourth type. They have sharp basal contacts (Fig. 4) and their lower portion consists of greenish gray clay as seen in TC1 and TC3. Streaks of carbonaceous matter (up to 1 mm long) increase in abundance upwards and give the upper portion a dark, discontinuously laminated appearance. Top portions of couplets may show clay filled burrows (Fig. 2) and thin discontinuous silt lenses (0.1-0.2 mm thick; quartz silt, fish bones). The density of carbonaceous streaks varies, leading to alternating bands (gradational boundaries) with larger versus smaller concentrations of carbonaceous streaks (Fig. 2).

Significance of Sedimentary Features (TC1 through TC4)

Sharp basal contacts and grading, the most notable features of clay-rich trough shales (Fig. 2) suggest deposition by short lived sedimentation events. Laminated clayshales (TC2, Fig. 2) resemble the fine grained turbidites of Stow and Shanmugam (1980). Shale types TC1 through TC4 are probably representatives of a continuum of clayshales deposited by fine grained turbidites.

Fig. 3. Photomicrograph of graded rhythmite at base of graded clayshale bed (TC3). Field of view is 5.5 mm wide.

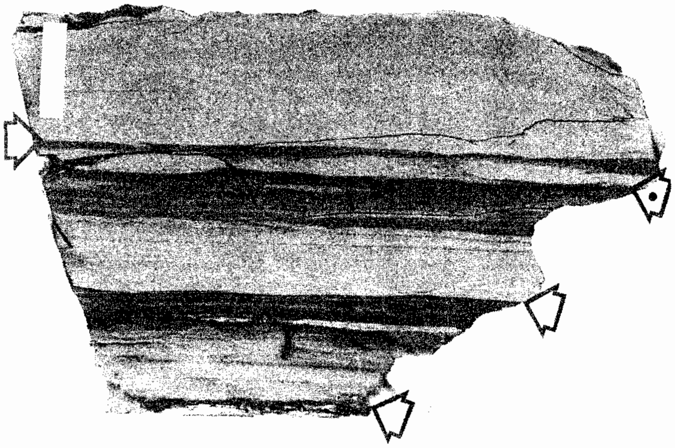


Fig. 4. Photo of hand specimen of shale with clay couplets (TC4). Shows sharp bases of clay couplets (arrows), and dark laminated carbonaceous top portions. The third couplet (black dot in arrow) was possibly disrupted by bioturbation while sediment was still quite soft. Scale bar is 1 cm long.

A turbidite interpretation is consistent with microfabric observations on these shales, such as non-aligned micas and clays (Fig. 2). Comparable fabrics in other fine grained turbidites have been interpreted as indicative of rapid deposition from suspension involving flocculation (O'Brien and Slatt, 1990).

By comparison, the carbonaceous top portion of TC4 couplets probably accumulated much more slowly than the clay dominated lower portion. Subtle and gradual variations of organic matter content suggest continuous background sedimentation with slight variations in the supply of sedimentary components (Schieber, 1989).

Among clay-rich trough shales TC4 is the only shale type where readily identifiable intervals of background sedimentation alternate with fine grained turbidites. The lack of background intervals in TC1 through TC3 may be due to the combined effects of more frequent turbidite deposition and erosion of background deposits. Relative to the source of the fine grained turbidites, TC4 is a probably typical for distal regions. Judging from overall thickness of beds, TC1 and TC2 were probably the most proximal deposits, whereas TC3 probably has an intermediate position.

CARBONACEOUS TROUGH SHALE

The five shale types in this category contain various proportions of carbonaceous shale beds. The latter consist of a matrix of clay, organic matter and scattered pyrite (framboids and single crystals), with variable amounts of quartz silt (0.01-0.08 mm) and mica flakes (0.02-0.12 mm).

The first type, peloidal carbonaceous shale (TCS1), consists of clay-rich bands (0.2-2 mm thick) that alternate with carbonaceous shale layers (1-10 mm thick). Boundaries between clay bands and carbonaceous shale are diffuse (Fig. 5). The most notable feature of TCS1 are elongate clay peloids (0.1-0.5 mm long, up to several percent) in carbonaceous shale layers (Figs. 6 and 7). TCS1 occurs interbedded with clay-rich trough shales (TC1 through TC4).

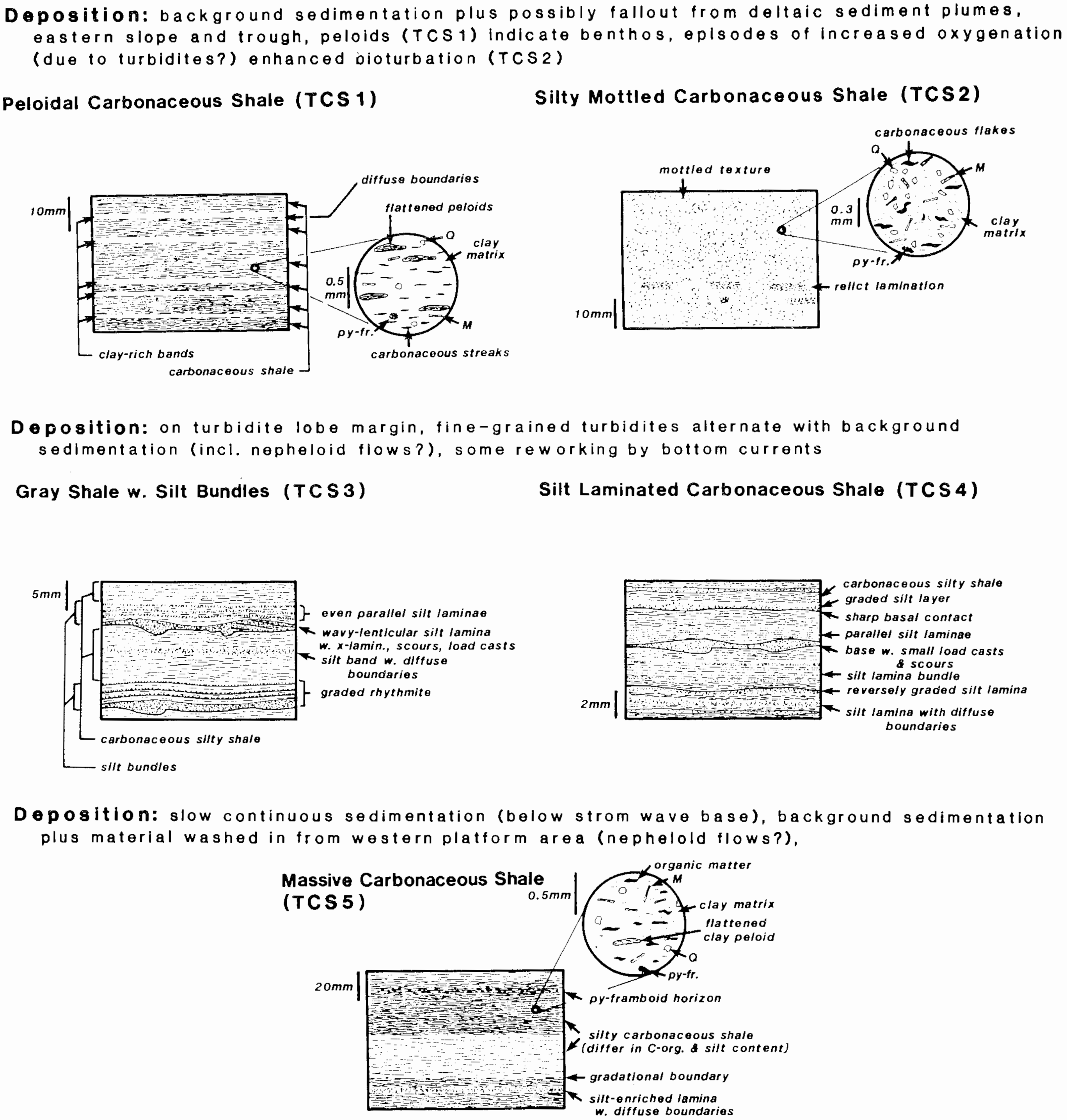


Fig. 5. Overview of sedimentary features observed in carbonaceous shales of the trough region. TCS1 through TCS4 were probably all deposited on the eastern slope and in the bottom of the trough, whereas TCS5 was apparently deposited on the western slope of that trough (see Fig. 6). Note variability of scale bars.

The second type, silty mottled carbonaceous shale (TCS2), typically occurs interbedded with TCS1. It forms 2-5 cm thick beds, but contains more quartz silt (10-20 percent) and mica (5-10 percent) than TCS1. It shows relict lamination as well as homogenized portions and has a mottled texture (Fig. 5).

The next two types, gray shale with silt bundles (TCS3) and silt laminated carbonaceous shale (TCS4), are always closely associated and occur together with turbidite siltstone beds. In addition to the commonly observed constituents, silt laminae contain detrital feldspar, zircon and tourmaline. TCS3 consists of layers of moderately carbonaceous silty shale (3-10 mm thick) that are interbedded with bundles of silt laminae (3-7 mm thick). Basal laminae of silt bundles are in many cases wavy-lenticular (up to 2 mm thick) and may show low angle cross lamination, load casts and small scours (Fig. 5). The overlying silt laminae are thinner (0.05-0.3 mm), parallel, separated by thin clay-rich laminae (0.1-0.2 mm thick), and may show a systematic upwards decrease in thickness. Carbonaceous silty shale layers may contain bands (0.2-0.8 mm thick) of larger silt content that show gradational upper and lower boundaries. TCS4 is a variant of TCS3, the main difference being thinner development of carbonaceous silty shale layers in TCS4 (Fig. 5). TCS4 has abundant silt laminae (0.1-0.6 mm thick) that are interbedded with laminae of silty carbonaceous shale (0.1-1.2 mm thick). Silt laminae occur as (1) thin, even laminae (0.1-0.2 mm thick) that may be arranged in bundles of up to 6 laminae, as (2) thicker (up to 1 mm thick), sharp based, wavy-lenticular layers with small scale load casts at the base, and as (3) even bands (0.2-1 mm thick) with diffuse boundaries to over- and underlying shale laminae (Fig. 5). Thicker, wavy-lenticular silt laminae may be directly overlain by a bundle of thin silt laminae. Normal grading in silt laminae is common, and in rare instances reverse grading was observed (Fig. 5). Carbonaceous laminae contain 10-20 percent quartz silt and compressed *Tasmanites* spores, and may contain internal, thin discontinuous laminae and lenses of silt (0.1-0.2 mm thick).

The fifth type, massive carbonaceous shale (TCS5), consists of 5-50 mm thick layers of silty carbonaceous shale. It also contains flattened *Tasmanites* spores. Adjacent layers typically have gradational boundaries, marked by shifts in silt and organic matter content (Fig. 5). In places relatively sharp boundaries have been observed. In some thin sections silt-enriched (up to 30%) laminae (1-3 mm thick) with gradational upper and lower contacts occur (Fig. 5). In some samples stratiform selective pyritization has produced pyrite enriched laminae. This shale type also contains small flattened peloids of clay and silt (0.2-0.3mm long).

Significance of Sedimentary Features (TCS1 through TCS5)

A variety of features observed in TCS3 and TCS4, such as graded rhythmites, low angle cross lamination in silt laminae and graded silt laminae with sharp erosive bases (Fig. 5) suggest short lived sedimentation events and are compatible with the fine grained turbidite model of Stow and Shanmugam (1980). However, not all silt laminae in TCS3 and TCS4 are necessarily of turbidite origin.

Thin, wavy-lenticular silt laminae with sharp upper and lower boundaries suggest current transport of silt over the seabed (Fig. 5, TCS4). Rare reversely graded silt laminae may either represent current reworking of silt laminae that had originally diffuse boundaries (Fig. 5, TCS4), or possibly the transport of silt over a very soft to soupy mud surface. However, because features indicative of soft sediment deformation (convolute lamination, loading, slumping) are absent, the latter possibility is unlikely.

Carbonaceous silty shale beds of TCS3 and TCS4 are characterized by large organic matter content, as well as by repeated gradual variations in sedimentary components. These features suggest slow but continuous background sedimentation. In the same beds thin, even silt laminae with diffuse upper and lower boundaries occur (Fig. 5). They lack any features indicative of fine grained turbidites, and may instead indicate gradually shifting silt supply, possibly from nepheloid or turbid-layer flows (Moore, 1969).

Peloidal carbonaceous shales (TCS1, Figs. 6 and 7) probably record background deposition of clays and organic matter. Minor organic matter content of thin clay-rich bands suggests that these were deposited more rapidly, possibly as fallout from clay plumes of distant rivers, or from storm-suspended shelf muds that moved downslope, analogous to nepheloid flows. The significance of peloids will be discussed in the section on bioturbation.

Whereas all of the above shale types are primarily found on the eastern slope and in the bottom portions of the peripheral trough of the Appalachian Basin (Fig. 8), the massive carbonaceous shales (TCS5) dominate the western slope of the trough and may well pass laterally into massive to banded carbonaceous shales (PCS3 and PCS4) of the platform region (Fig. 8).

Fig. 6. Photomicrograph of peloidal shale (TCS1), crossed polarizers. Light coloured (±no organic matter), elongate to elliptical spots are clay peloids. Field of view is 2.2 mm high.

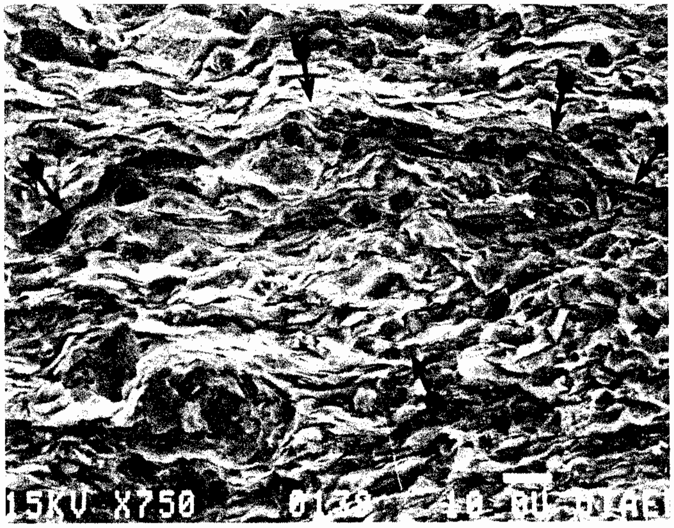


Fig. 7. SEM photo of peloid in peloidal shale bed (TCS1). Clays have been compressed along the margins of peloid (arrows).

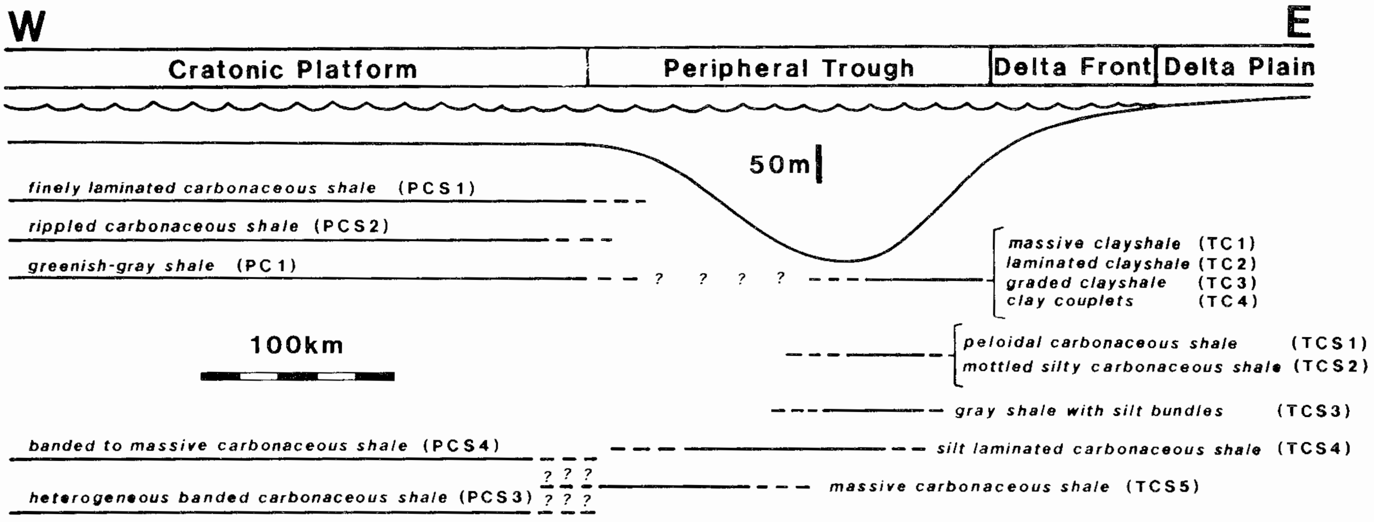


Fig. 8. Overview that shows how the author envisions distribution and lateral association of shale types within a basinal context. Question marks between greenish gray shale of platform and clayshales of trough indicate possible lateral connection between these shales (at times when the trough fills up and sediment can escape to the west). Question marks between banded shales of platform and massive carbonaceous shales of trough indicates that these shale types are probably laterally linked across the western trough margin. Scales are approximate.

Diffuse boundaries between bands of carbonaceous shale (Fig. 5) suggest more or less continuous accumulation and absence of sediment reworking by currents or waves. Thin horizons enriched in pyrite framboids (Fig. 5) are suggestive of time intervals with strongly reduced sediment accumulation rates (sediment starvation). The significance of peloids will be discussed in the section on bioturbation.

PLATFORM SHALES

These shales were deposited in a cratonic platform setting in relatively shallow water (Schieber, this volume) and can be grouped into two broad categories, clay-rich and carbonaceous. However, carbonaceous shale types strongly dominate the section. Individual shale types form massive packages (10 cm or more in thickness), or are interbedded on a centimetre scale.

Flattened *Tasmanites* spores are common and may contain small amounts of pyrite (usually as framboids) in the centre. A small number of them have a rounded to elliptical appearance and are filled with diagenetic chert (Fig. 9).

Clay-rich platform shale

Greenish gray shale (PC1) occurs mainly interbedded (beds 1-10 cm thick) with black shales of the upper unit of the Dowelltown Member and the middle unit of the Gassaway Member. Bioturbation typically causes diffuse boundaries with over- and underlying black shale beds and often obliterates primary sedimentary features (Figs. 9, 10, 11). However, in a small number of samples lamination is still clearly visible. Internal laminae are thin (0.1-0.5 mm) and consist of quartz grains (0.01-0.08 mm), mica flakes and variable proportions of conodonts. Where well preserved these laminae show a sharp base, grade into overlying clay laminae and form sets of closely spaced laminae (Fig. 9). These bundles of graded laminae have coarser and thicker laminae at the base and grade upwards into finer and thinner laminae (Fig. 9). In addition, in several samples of greenish gray shale, internal size grading (silt to clay) is still visible although bioturbation has obliterated internal laminae. Other greenish gray shale beds consist in their basal portions of alternating silt and clay laminae (Fig. 9).

Significance of Sedimentary Features (PC1)

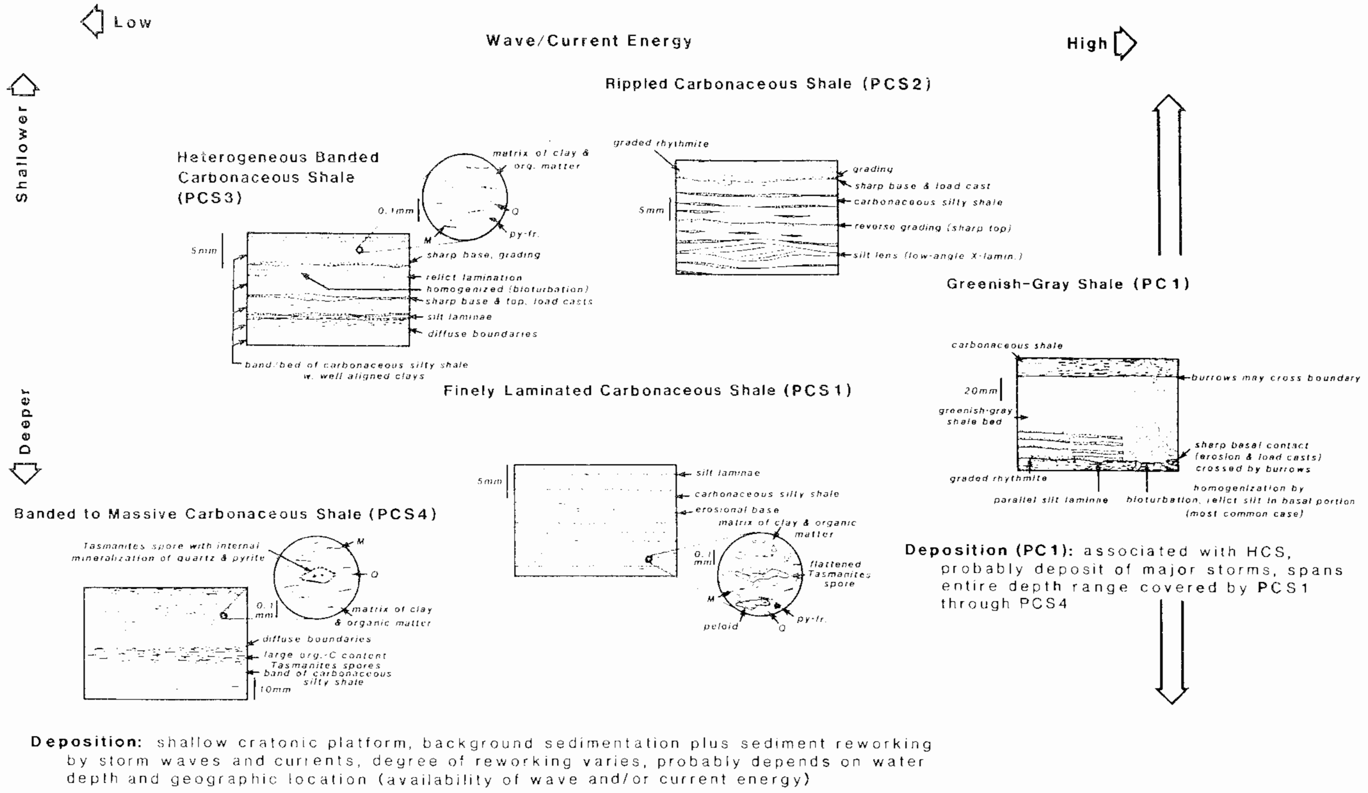
Grading in greenish gray shale beds (PC1) suggests that they are probably the product of short lived sedimentation events. Bundles of graded silt laminae closely resemble graded rhythmites (Reineck and Singh, 1980). The latter are sedimentary features thought to form during deceleration of a moving suspension (Reineck and Singh, 1980).

Carbonaceous Platform Shale

Shale types in this category consist of various proportions of carbonaceous silty shale and silt and are differentiated on the basis of sedimentary features. Silt layers consist mainly of quartz silt (0.03-0.08 mm), with variable amounts of mica flakes and biogenic debris (primarily conodonts). Carbonaceous silty shale layers contain 10-30 percent silt grains of the same types and proportions as found in the associated silt layers.

Finely laminated carbonaceous shale (PCS1) is characterized by alternating even laminae of silt (0.04-0.08 mm thick) and carbonaceous silty shale (0.4-4 mm thick). The latter contain scattered *Tasmanites* spores and clay/silt peloids (Figs. 12, 13). Silt laminae are typically continuous across a given thin section and vary little in thickness (Fig. 9). In places silt laminae have a clearly defined erosional base cutting out 1 or 2 of the underlying laminae (Fig. 9).

Rippled carbonaceous shale (PCS2) is a textural variant of PCS1 in which a subordinate proportion of silt laminae has a wavy or pinch and swell appearance (Fig. 14). Thickened



Deposition (PC1): associated with HCS, probably deposit of major storms, spans entire depth range covered by PCS1 through PCS4

Deposition: shallow cratonic platform, background sedimentation plus sediment reworking by storm waves and currents, degree of reworking varies, probably depends on water depth and geographic location (availability of wave and/or current energy)

Fig. 9. Overview of sedimentary features in platform shales. It is envisioned that two factors, (1) the amount of energy input from waves and currents, and (2) the water depth are the main determinants of the resulting shale fabric at any given location. PC1 beds are probably due to major storms and can occur over the whole depth range. Note variability of scale bars.

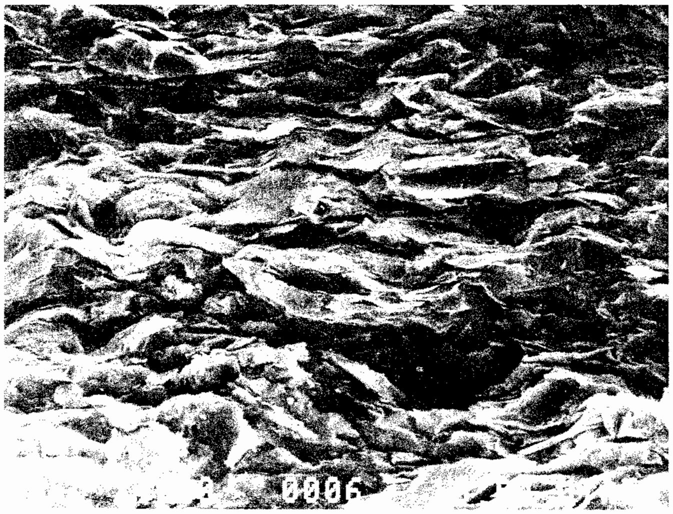


Fig. 10. SEM photo of clay microfabric within unbioturbated greenish gray shale (PC1). Clays show good alignment parallel to bedding. Compare to Fig. 11.

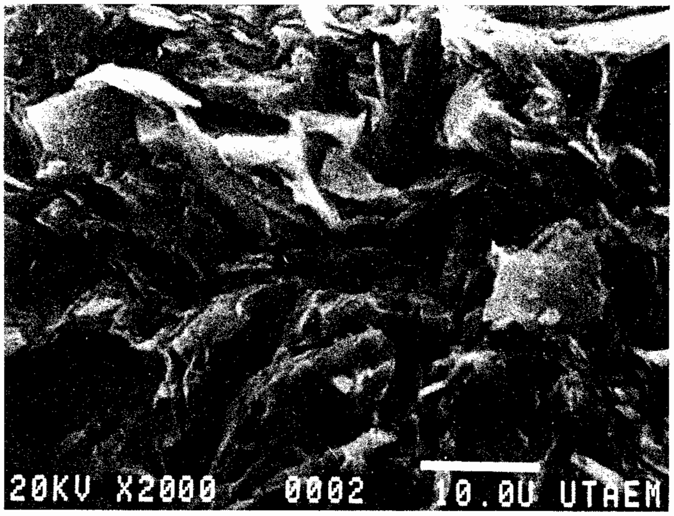


Fig. 11. SEM photo of clay microfabric of bioturbated greenish gray shale (PC1). Note the randomized clay fabric and compare to unbioturbated fabric in Fig. 10.

portions of silt laminae may develop into low angle cross laminated silt lenses (up to 5 mm thick, 5 cm long). Silt lenses typically show sharp bases and tops, and may show small scours and load casts at the base (Fig. 9). Rare reverse graded laminae with a diffuse base and sharp top are also present. In a few samples wavy-lenticular graded silt layers (1-2 mm thick) pass upwards into thin (0.04-0.08 mm) parallel silt laminae (separated by laminae of carbonaceous silty shale) and then are overlain by carbonaceous silty shale (Fig. 15).

Heterogeneous banded carbonaceous shale (PCS3) consists of silty intervals (up to 4 mm thick) that alternate with moderately carbonaceous laminae (0.1-4 mm thick) that have well aligned clay minerals. Although black in hand specimen, these shales have a light brown to amber appearance in thin section

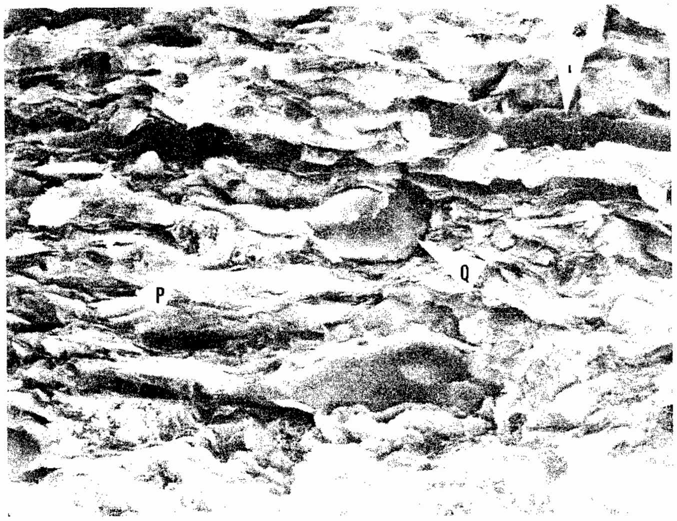


Fig. 12. SEM photo of microfabric of carbonaceous silty shale lamina in finely laminated carbonaceous shale (PCS1) of platform setting. Note preferred alignment of clay parallel to bedding. Fabric undulosity primarily due to compaction around *Tasmanites* spores (arrow T), pyrite framboids (arrow P) and quartz grains (arrow Q).

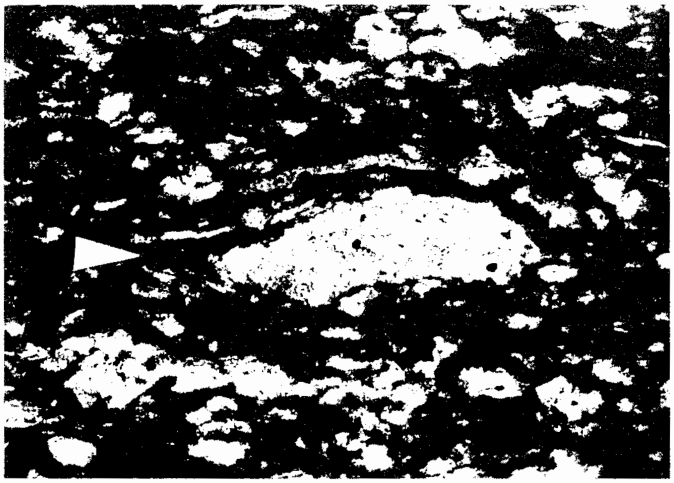


Fig. 13. Photomicrograph of clay/silt peloid (light coloured elliptical object in centre of photo) in carbonaceous silty shale lamina of finely laminated carbonaceous shale (PCS1) of platform setting. Silt grains within clay matrix of peloid are faintly visible. Orientation of platy particles (*Tasmanites* spores and micas) shows that carbonaceous shale was compacted around the peloid (arrow). Thus the peloid was of a higher compaction state than the shale it was deposited with, a relationship to be expected from fecal pellets. Field of view is 0.22 mm high.

because of generally smaller organic content than PCS1, PCS2 and PCS4 (dark brown). Carbonaceous laminae (well aligned clay minerals) alternate with silty intervals, or may be over- and underlain by laminae that contrast only slightly in the content of silt and organic matter (Fig. 9). Scattered clay/silt peloids as well as lamina disruption (silt laminae terminate laterally against homogenized silty carbonaceous shale; Fig. 9) have been observed.

Banded to massive carbonaceous shale (PCS4) consists of parallel bands or laminae (1-15 mm thick) of carbonaceous

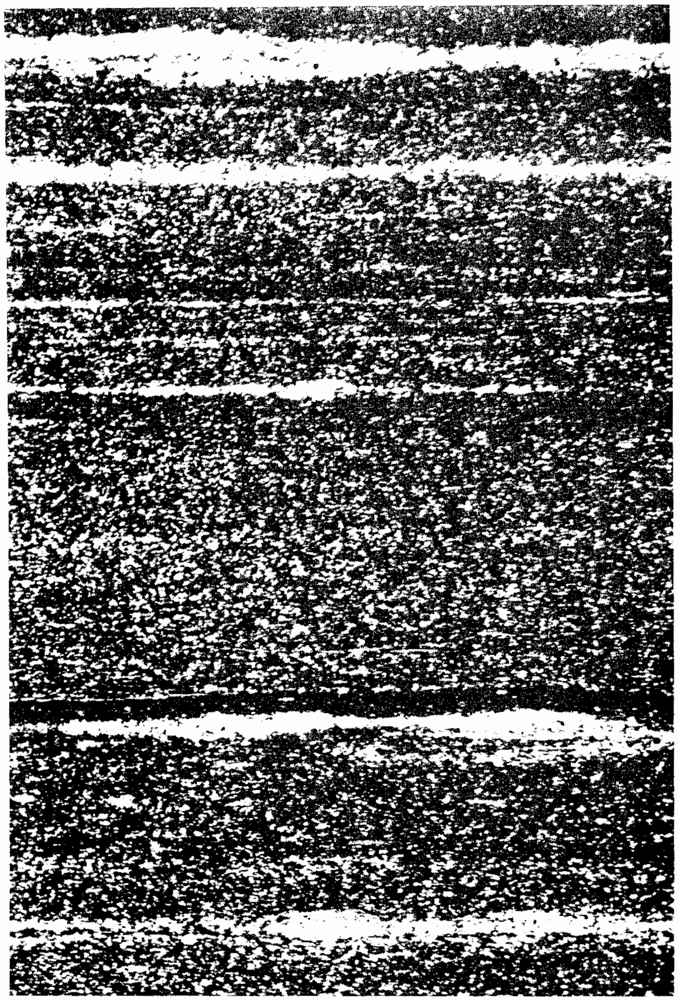


Fig. 14. Photomicrograph of rippled carbonaceous shale (PCS2). Shows wavy-lenticular silt laminae (light colour) alternating with carbonaceous silty shale laminae (dark). Field of view is 5.5 mm wide.

Fig. 15. Photomicrograph of graded rhythmite in rippled carbonaceous shale (PCS2). Note how silt laminae above basal lenticular lamina fade out upwards. Base of rhythmite shows small load casts and possibly scour. Gray elliptical features within carbonaceous silty shale beds are *Tasmanites* spores (arrow). Field of view is 2.2 mm high.

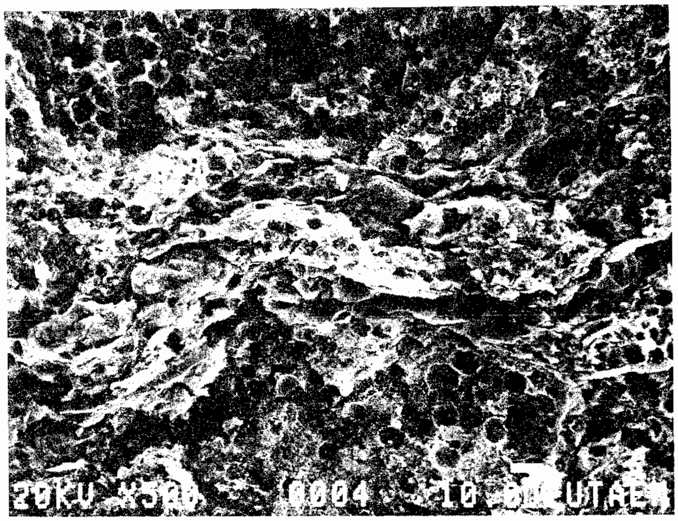


Fig. 16. SEM photo of thin pyritic horizon (1-2 mm thick) in banded to massive carbonaceous shale (PCS4). Photo shows that horizon consists of densely packed pyrite framboids (molds because of pyrite weathering) with only small amounts of clay and silt. This suggests that pyrite accumulated when mud still had high initial porosity. Stratiform nature of framboid layer suggests that it marks an interval of very slow deposition or absence of sedimentation (upward diffusion of iron, downward diffusion of sulfate, stationary zone of pyrite formation). Could this be an analog to hardgrounds in carbonates?

silty shale. The latter has a homogeneous "salt and pepper" texture and contains scattered silt/clay peloids. Differences between adjacent bands or laminae are due to compositional variations (e.g., quartz silt, organic matter) and gradational boundaries are the norm (Fig. 9). Silt laminae are rare or absent. Bands that are strongly enriched in organic matter contain large numbers of *Tasmanites* spores. In places thin (1-2 mm thick) horizons with abundant framboids (Fig. 16) have been observed. The latter also occur in other carbonaceous shales of platform setting.

Significance of Sedimentary Features (PCS1 through PCS4)

In PCS1 through PCS3 sharp basal and top contacts of most laminae, basal scours and erosion, low angle cross lamination and lenticular-wavy laminae (Figs. 14 and 15) all suggest silt deposition under increased bottom shear stress in conjunction with sea bed erosion and traction transport over a firm substrate. In contrast, scattered reversely graded and sharp topped silt laminae (Fig. 9) suggest that at times silt migrated over soft or soupy substrates, where mixing with underlying muds could occur.

Heterogeneous banded carbonaceous shales (PCS3) show approximately the same energy levels as rippled carbonaceous shales (PCS2). However, in PCS3 diffuse boundaries between adjacent bands of carbonaceous silty shale (Fig. 9) suggest intervals of uninterrupted deposition that alternated with episodes of reworking. Proportions of silt laminae versus carbonaceous shale bands suggest that reworking was generally less common than in PCS2. In PCS4 the absence of silt laminae and diffuse boundaries between adjacent bands of carbonaceous shale suggest slow accumulation without marked interruption and reworking.

Discussion of Sedimentary Features in Shales

Trough Shales

Sedimentary features suggest that most of TC1, TC2 and TC3, as well as considerable proportions of TC4, TCS3 and TCS4 were deposited by fine grained turbidites. Spatial association of these shales with turbidites of the Brallier Formation (Lundegard et al., 1985) supports this interpretation. A much larger clay content differentiates TC1 through TC4 from TCS3 and TCS4, suggesting that the two groups of shales had slightly different origins (or sites of origin). The descriptions and sedimentation model of Lundegard et al. (1985) suggests a possible reason for the presence of two types of fine grained turbidites. TCS3 and TCS4 (more silty) were likely deposits of the lobe margin. TC1 through TC4 (clay-rich type) can be viewed as deposits of the interlobe slope and might have originated from fluvial sediment plumes during floods and from re-suspension of shelf mud during storms. In addition, they could have accumulated in the bottom of the trough through ponding of fine grained turbidite tails.

Paleocurrent data for these fine grained turbidites indicate that they were brought into the basin by westward flowing currents (Lundegard et al., 1985). In contrast, paleocurrent data for massive carbonaceous trough shales (TCS5) indicate eastward flowing currents for that shale type (Schieber, this volume) and deposition on the western slope of a peripheral trough (Fig. 8). Beds of TCS5 might have been deposited in part as very dilute density currents that fed on material suspended on the western platform by wave action, similar to generation of nepheloid or turbid-layer flows on modern shelves (Moore, 1969). Occasional suspension of larger proportions of silt, for example during storms, may explain the rare silt enriched laminae with diffuse boundaries (Fig. 5).

Platform Shales

Graded rhythmites as observed in the greenish gray shales (PC1) are a common feature of modern shelf muds (Reineck and Singh, 1980) and have been interpreted as the deposits of storm-wave driven suspension clouds (Aigner and Reineck, 1982). In this context grading in basal silty portions of greenish gray shale beds is probably best attributed to settling from storm induced suspensions as well, whereas the upper, clay-dominated portion is possibly a post-storm mud drape (Gadow and Reineck, 1969). Additional parallels between PC1 beds and storm deposits of modern shelf seas are that both may contain alternating silt and clay laminae and shale beds without a basal silt layer. The latter are known as mud tempestites in North Sea shelf muds (Aigner and Reineck, 1982).

The close resemblance between sedimentary features (Fig. 9) of greenish gray shale beds (PC1) and muddy storm deposits from the North Sea (Aigner and Reineck, 1982) strongly suggests that PC1 beds are storm deposits. This conclusion is supported by macroscopic sedimentary features (HCS beds, erosion surfaces, bone beds) that indicate that the Chattanooga Shale of central Tennessee was deposited in the comparatively shallow water of an epicratonic platform (Schieber, this volume).

North Sea graded rhythmites occur at a depth of less than 30 m (Aigner and Reineck, 1982). This is within the same depth range as estimated for Chattanooga HCS beds (Schieber, this volume) and suggests that platform shales accumulated at a water depth of a few tens of metres.

Sedimentary features of silt laminae in carbonaceous platform shales (PCS1, PCS2, PCS3) suggest silt deposition in conjunction with erosion and bedload transport. In general the fine even silt laminae of PCS1 seem to reflect less energy than silt laminae of PCS2 and PCS3, which are more commonly wavy-lenticular. The latter observation also suggests more prominent bottom currents for PCS2 and PCS3, whereas the even silt laminae of PCS1 might be more reflective of a setting dominated by wave winnowing of silt.

Interlamination of silt and carbonaceous shale suggests episodic reworking and winnowing. Judging from the presence of other storm produced features, episodic storm reworking was probably a main factor in the production of silt laminae.

With regard to details of the silt laminae observed in PCS1, PCS2 and PCS3, one might speculate that the type of silt laminae is partly a reflection of the energy imparted to a gently undulating seafloor (Fig. 9). Perhaps wavy-lenticular laminae (PCS2, PCS3) formed at shallower depth than fine and even laminae of PCS1, and the occasionally observed reversely graded and sharp topped laminae formed in protected/depressed areas where soupy mud accumulated.

Sedimentary features of PCS4 suggest continuous slow background sedimentation and a general absence of wave reworking. This, and its close similarity to TCS5 suggest that it was deposited in deeper water than the other carbonaceous platform shales (Fig. 9).

Uncompressed and internally silicified spores in platform shales (Fig. 9) probably reflect the fact that rates of sediment accumulation were much larger for trough shales than for platform shales. Thus the rate of compaction should have been much larger for trough shales, compressing spores before internal silica cement could accumulate.

The composition of silt laminae also reflects large differences in accumulation rates between platform and trough. Conodonts and other phosphatic particles are common constituents in silt laminae of the platform region, whereas they are virtually absent in those of the trough region because of the much larger dilution of organic particles by terrigenous clastics.

The preceding discussion of carbonaceous platform shales suggests that these shale types (PCS1 through PCS4) reflect subtle differences in sedimentation conditions. Thus the generally observed interbedding of these shale types on the on centimetre to decimetre scale poses an interesting question as to its origin. Possible explanations for changes from one shale type to another could, for example, be changing sea floor topography due to tectonic movements or differential compaction, or, equally well, changes in sea level. Addressing that problem will require a very detailed fabric study of thin shale horizons over a large area.

BIOTURBATION

OCCURRENCE

Bioturbation in shales is typically under-appreciated because it is difficult to see in outcrop. Even minor amounts of weathering completely obscure bioturbation features. They are therefore best recognized and observed on sawn slabs of fresh material and in thin sections. All shale types examined in this study show bioturbation to various degrees.

Except for TCS2 bioturbation is minor or absent in trough shales. In platform shales it is ubiquitous in PC1 and also occurs in all the black shale types (PCS1 through PCS4). More than 50 percent of samples from central Tennessee had visible signs of bioturbation (burrows, mottling, lamina disruptions). Also, platform shales contain well organized burrow structures (e.g., *Teichichnus*, *Planolites*, *Asterosoma*), whereas trough shales have primarily simple tube-like burrows.

In platform shales bioturbation has previously been thought to be associated only with greenish gray shale beds (Kepferle and Roen, 1981; Jordan, 1985). However, samples examined for this study show that bioturbation is more pervasive and not necessarily associated with greenish gray shale beds (75% bioturbated samples in lower Dowelltown, 83% in upper Dowelltown, 14% in lower Gassaway, 65% in middle Gassaway, 0% in upper Gassaway).

SIGNIFICANCE

On a basic level bioturbation can furnish information about oxic versus anoxic conditions in the water column. Absence of bioturbation may indicate anoxic conditions in overlying waters (Byers, 1977; Savrda and Bottjer, 1986). Thus the bottom waters of the Chattanooga sea may have been anoxic for a considerable time interval during deposition of the upper Gassaway Member (Fig. 1).

However, the abundant clay and silt/clay peloids observed in carbonaceous trough and platform shales (Figs. 7, 8, 13) may have a considerable bearing on the identification of anoxia. These peloids are of the same size range as reported for surface dwelling polychaete worms and could indicate the presence of benthic organisms (Cuomo and Rhoads, 1987; Cuomo and Bartholomew, 1991) in the absence of body fossils and identifiable bioturbation. Alternatively, these peloids may represent small shale rip-ups. However, the narrow size range, their scattered occurrence in carbonaceous shale and the absence of current sorting of peloids into "peloid sand" is incompatible with a rip-up origin.

Peloids are found in all black shale types examined for this study, including those of the upper Gassaway. This suggests that truly anoxic conditions were probably rare in the Appalachian Basin, despite the common occurrence of laminated and seemingly unbioturbated black shales. Thus presence of black shales may simply reflect organic matter production greatly in excess of faunal consumption, rather than anoxic preservation of that matter. Attempts to delineate paleopycnoclines in the Appalachian Basin (e.g., Byers, 1977; Ettensohn et al., 1988) may require careful reexamination.

Elaborate burrow systems in platform shales probably reflect shallower water, increased oxygen supply and small rates of sediment accumulation. In the case of the trough shales rapid sedimentation probably forced burrowers to abandon their structures frequently, and also led to substrates that were so soft that stable burrow structures (sharp boundaries between burrow and substrate) could not easily be maintained.

CONCLUSION

The Chattanooga Shale of central and eastern Tennessee shows significant differences in shale facies between the two areas, confirming differences in depositional setting (platform versus peripheral trough) deduced from macroscopic sedimentary features and paleocurrent data (Schieber, this volume). Although subtle, sedimentary features in these shales give clues to sedimentary processes such as turbidity currents, turbid-layer flows, storms, pelagic background sedimentation, wave reworking, bottom currents and bioturbation. Fourteen different shale types were recognized, and study of their sedimentary features leads to interpretations comparable to those reached from macroscopic sedimentary features. This result demonstrates the potential usefulness of shales for basin analysis.

Large differences in sediment accumulation rates and water depth between platform and trough region are reflected by bioturbation features. Clay/silt peloids in carbonaceous shales are possibly fecal pellets of benthic organisms and suggest that even the finely laminated carbonaceous shales were not deposited under anoxic conditions.

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REFERENCES

Aigner, T., and Reineck, H.-E. 1982. Proximality trends in modern storm sands from the Helgoland Bight (North Sea) and their implications for basin analysis. Senckenbergiana marit., v. 14, p. 183-215.

Bennett, R.H., O'Brien, N.R., and Hulbert, M.H. 1990. Determinants of clay and shale microfabric signatures: Processes and mechanisms. *In*: Microstructure of Fine-Grained Sediments. R.H. Bennett, N.R. O'Brien and M.H. Hulbert, M.H. (eds.), New York, Springer Verlag, p. 5-32.

Broadhead, R.F., Kepferle, R.C. and Potter, P.E. 1982. Stratigraphic and sedimentologic controls of gas in shale - example from Upper Devonian of northern Ohio. Amer. Assoc. Petrol. Geol. Bull., v. 66, p. 10-27.

Byers, C.W. 1977. Biofacies patterns in euxinic basins: a general model. Soc. Econ. Paleontol. Mineral. Spec. Publ. 25, p. 5-17.

Conant, L.C., and Swanson, V.E. 1961. Chattanooga Shale and related rocks of central Tennessee and nearby areas. U.S. Geol. Surv. Prof. Pap. 357, 91 pp.

Cuomo, M.C., and Rhoads, D.C. 1987. Biogenic sedimentary fabrics associated with pioneering polychaete assemblages: Modern and ancient. J. sediment. Petrol., v. 57, p. 537-543.

Cuomo, M.C., and Bartholomew, P.R. 1991. Pelletal black shale fabrics: their origin and significance. *In*: Modern and Ancient Continental Shelf Anoxia. R.V. Tyson and T.H. Pearson (eds.). Geol. Soc. London Spec. Publ. No. 58, p. 221-232.

Ettensohn, F.R. and Barron, L.S. 1981. Depositional model for the Devonian-Mississippian black shales of North America: a paleoclimatic-paleogeographic approach. *In*: G.S.A. Cincinnati '81 field trip guide books, volume II: economic geology, structure. T.G. Roberts (ed.). American Geological Institute, p. 344-361.

Ettensohn, F.R., Miller, M.L., Dillman, S.B., Elam, T.D., Geller, K.L., Swager, D.R., Markowitz, G., Woock, R.D. and Barron, L.S. 1988. Characterization and implications of the Devonian-Mississippian black shale sequence, eastern and central Kentucky, U.S.A.: Pycnoclines, transgression, regression, and tectonism. *In*: Devonian of the World, vol. 2. N.J. McMillan, A.F. Embry and D.J. Glass (eds.). Can. Soc. Petrol. Geol., Calgary, p. 323-345.

Gadow, S., and Reineck, H.-E 1969. Ablandiger Sandtransport bei Sturmfluten. Senckenbergiana marit., v. 1, p. 63-78.

Hasson, K.O. 1982. Stratigraphy of the Chattanooga Shale, northeastern Tennessee. Southeastern Geology, v. 23, p. 171-185.

Jordan, D.W. 1985. Trace fossils and depositional environments of Upper Devonian black shales, east-central Kentucky, U.S.A. *In*: Biogenic Structures: Their use in interpreting Depositional Environments. H.A. Curran (ed.). Soc. Econ. Paleontol. Mineral. Spec. Publ. 35, p. 279-298.

Kepferle, R.C., and Roen, J.B. 1981. Chattanooga and Ohio Shales of the southern Appalachian Basin. *In*: G.S.A. Cincinnati '81 field trip guide books, volume II: economic geology, structure. T.G. Roberts (ed.). American Geological Institute, p. 259-323.

Kuehl, S.A., Nittrouer, C.A., and DeMaster, D.J. 1988. Microfabric study of fine-grained sediments: Observations from the Amazon subaqueous delta. J. sediment. Petrol., v. 58, p. 12-23.

Kuehl, S.A., Hariu, T.M., Sanford, M.W., Nittrouer, C.A., and DeMaster, D.J. 1990. Millimeter scale sedimentary structure of fine-grained sediments: Examples from continental margin environments. *In*: Microstructure of Fine-Grained Sediments. B.H. Bennett, N.R. O'Brien and M.H. Hulbert (eds.). New York, Springer Verlag, p. 33-45.

Lundegard, P.D., Samuels, N.D. and Pryor, W.A. 1985. Upper Devonian turbidite sequence, central and southern Appalachian basin: Contrasts with submarine fan deposits. *In*: The Catskill Delta. D.L. Woodrow and W.D. Sevon (eds.). Geological Society of America Special Paper 201, p. 107-121.

Moore, D.G. 1969. Reflection profiling studies of the California continental borderland: Structure and Quaternary turbidite basins. Geol. Soc. Amer. Special Paper 107, 142 p.

O'Brien, N.R., and Slatt, R.M. 1990. Argillaceous Rock Atlas. New York, Springer Verlag, 141 p.

Potter, P.E., Maynard, J.B. and Pryor, W.A. 1980. Sedimentology of Shale. Springer Verlag, New York, 303 p.

Potter, P.E., Maynard, J.B. and Pryor, W.A. 1982. Appalachian gas bearing Devonian shales: Statements and discussions. Oil and Gas Journal, v., 80, p. 290-318.

Reineck, H.-E. and Singh, I.B. 1971. Der Golf von Gaeta (Thyrrhenisches Meer). III. Die Gefüge von Vorstrand- und Schelfsedimenten. Senckenbergiana marit., v. 3, p. 185-201.

Reineck, H.-E. and Singh, I.B. 1980. Depositional Sedimentary Environments. Springer Verlag, Berlin, 549 p.

Savrda, C.E., and Bottjer, D.J. 1986. Trace-fossil model for reconstruction of paleo-oxygenation in bottom waters. Geology, v. 14, p. 3-6.

Schieber, J. 1989. Facies and origin of shales from the Mid-Proterozoic Newland Formation, Belt basin, Montana, U.S.A. Sedimentology, v. 36, p. 203-219.

Schieber, J. 1990. Significance of styles of epicontinental shale sedimentation in the Belt basin, Mid-Proterozoic of Montana, U.S.A. Sediment. Geol., v. 69, p. 297-312.

Schieber, J. 1994. Paleoflow patterns and macroscopic sedimentary features in the Late Devonian Chattanooga Shale of Tennessee: Differences between the Appalachian basin and the American craton. This volume.

Stow, D.A.V., and Shanmugam, G. 1980. Sequence of structures in fine-grained turbidites: Comparison of recent deep-sea and ancient flysch sediments. Sediment. Geol., v. 25, p. 23-42.

Witzke, B.J., and Heckel, P.H. 1988. Paleoclimatic indicators and inferred Devonian paleolatitudes of Euramerica. *In*: Devonian of the World, v. 1. N.J. McMillan, A.F. Embry and D.J. Glass (eds.), p. 49-63.

Woodrow, D.L., Dennison, J.M., Ettensohn, F.R., Sevon, W.T., and Kirchgasser, W.T. 1988. Middle and Upper Devonian stratigraphy and paleogeography of the central and southern Appalachians and eastern Midcontinent, U.S.A. *In*: Devonian of the World, v. 1. N.J. McMillan, A.F. Embry and D.J. Glass (eds.), p. 277-301.