Evidence for high-energy events and shallow-water deposition in the Chattanooga Shale, Devonian, central Tennessee, USA

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Abstract

The Upper Devonian Chattanooga Shale of central Tennessee, a classical black shale, was deposited in an epicontinental setting, west of the Appalachian foredeep. Its finely laminated and highly carbonaceous nature is commonly interpreted to indicate deposition in comparatively deep and stagnant water. Interbeds of bioturbated greenish-gray shale, indicating oxygenated bottom waters, are commonly ascribed to pycnocline fluctuations. However, laminated fine sand and silt and hummocky cross-stratification (HCS) at the base of some of these beds indicates interaction of storm waves with the seabed, and suggests that greenish-gray shale beds are post-storm mud drapes.

Other interesting features are inclined-undulose erosion surfaces that are conformably overlain by shale beds, sets of inclined shale beds that suggest low-angle cross-bedding, and clearly and uniformly developed alignment of clay particles (magnetic fabric studies). These observations show that the seabed was at times subject to prolonged erosion by bottom currents (erosion surfaces), agitation and reworking by storm waves (HCS and greenish-gray shale beds), and sediment transport by long-lived bottom currents (particle alignment). The epicontinental sea setting and the presence of HCS and other storm-produced features suggest a relatively shallow water depth (possibly only a few tens of meters). Together with abundant evidence of variably strong bottom currents and bioturbation of black and gray shale beds this suggests that abundant planktonic organic matter production rather than stagnant bottom waters are the primary cause for black shale formation.

INTRODUCTION-statement of problem

The Chattanooga Shale is part of a thin, epicontinental black shale sequence of Upper Devonian age that was deposited over vast areas of the North American craton (de Witt et al., 1993). The depth at which these shales were deposited has been a subject of debate, and both a shallow (e.g. Conant and Swanson, 1961) and deep water origin (e.g. Potter et al., 1982, Ettensohn, 1985) has been proposed. Various estimation methods (Woodrow and Isley, 1983) lead to depth estimates ranging from 39 to 375 meters. Deposition below the dysaerobic-anaerobic boundary of a stratified water column (Byers, 1977) has been a particularly popular idea, leading to suggestions of 100-200 meters water depth (Potter et al., 1982). A water depth in excess of 900 meters was proposed by Lundegard et al. (1980, 1985).

In central Tennessee, the Chattanooga Shale overlies an unconformity and reaches a thickness of slightly more than 9 m. It has been subdivided into two members (Fig. 1) and is conformably overlain by the Lower Mississippian Maury Formation. Locally, a third member, the Hardin Sandstone, is present at the base of the Chattanooga Shale. The Hardin Member grades into the overlying Dowelltown Member. The upper portion of the Formation consists of the Gassaway Member. The latter contains in many places subspherical to discoidal phosphate nodules (up to 10 cm long) in the uppermost 50 cm.

Conant and Swanson (1961) studied the Chattanooga Shale in central Tennessee and proposed a shallow water origin based on the following observations: 1) the fact that it overlies an unconformity; 2) presence of siltstone/sandstone lenses and scour channels; 3) onlap of black shales towards the Nashville Dome; 4) the area on which the Chattanooga Shale accumulated was of low relief and site of shallow water sedimentation since the Precambrian; 5) the succeeding Mississippian sea, generally considered shallow, was more widespread and presumably deeper than the Chattanooga Sea; 6) the presence of linguloid brachiopods. Conant and Swanson (1961) state with regard to water depth that they "....believe that it was only a few tens of feet, quite likely less than 100 feet" and that "....in some places near the shore, accumulation of mud must have begun when the water was only a few feet deep". However, most of their evidence is circumstantial, and a depth assessment that is more directly based on sedimentary features is desirable. Sedimentary features that strongly suggest a relatively shallow origin for the Chattanooga Shale of central Tennessee were observed during recent field work and are described below.

2. Observations

2.1. Greenish-Gray Shales and Laminated Silt Beds

Certain intervals of the Upper Devonian black shale sequence contain interbedded greenish-gray shales (e.g. Three Lick Bed, Provo et al., 1978) that may be bioturbated or show parallel lamination. In the Chattanooga Shale of central Tennessee only the bioturbated greenish-gray shales occur. These have been related to pycnocline shifts (Broadhead et al., 1982; Jordan, 1985).

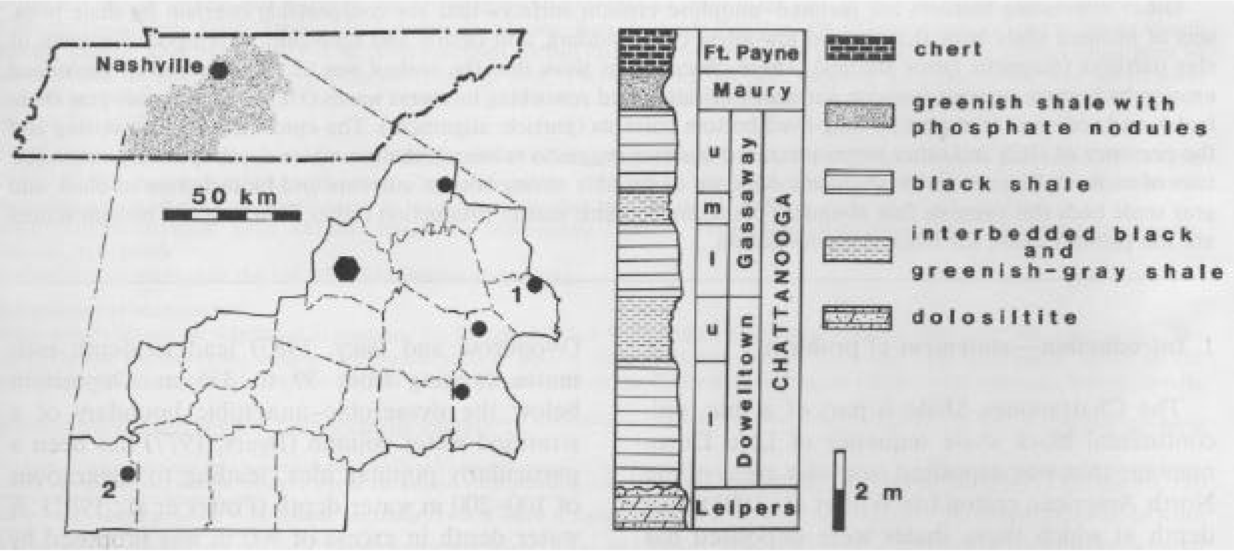


Figure 1: Outline of Tennessee and location of study area (stippled). Enlarged map shows study area and county boundaries. In both maps the location of Nashville is indicated by hexagon. Filled circles indicate locations where internal erosion surfaces (like in Fig. 7) in Chattanooga Shale were observed. Stratigraphic section of locality marked 1 is shown to the right. This locality was sampled in detail for bioturbation traces and also contains an exposure of the "varved bed", a hummocky cross-stratified storm layer. Locality marked 2 also contains hummocky cross-stratified sandstone beds.

In a typical section (Fig. 1), bioturbated greenish-gray shales are interbedded with black shales in the upper unit of the Dowelltown Member (Fig. 2), and in the middle unit of the Gassaway Member (Conant and Swanson, 1961). Alternating black and gray shale beds are between 1 and 10 cm thick. Burrows cause diffuse boundaries between successive beds (Fig. 3), and are in many samples sufficiently dense to completely obscure and obliterate primary sedimentary features in greenish-gray shale beds. However, some greenish-gray shale beds show (in thin section) clearly visible laminae (0.1-0.5 mm thick) in their basal portion, consisting of quartz grains (0.01-0.08 mm), mica flakes, and variable proportions of conodonts. Bundles of closely spaced laminae (Fig. 4) may show (a) upwards decrease of grain size and thickness, as well as sharp bases and gradational tops for individual laminae; and (b) simple alternation of silt and clay laminae. In bioturbated samples, overall size grading (silt to clay) may still be visible.

A local marker bed, the so-called "varved bed" (Conant and Swanson, 1961), occurs at the base of the middle unit of the Gassaway Member. It has an undulose sharp contact (erosive) with underlying black shales, shows regular thickness variations (pinch and swell, wave length 1-1.5 m), and is overlain by greenish-gray shale (Fig. 5). The internal parallel laminae (0.01-0.08 mm grain size, 0.3-1 mm thick) of the "varved bed" drape the basal erosion surface. Internal erosion surfaces dip at a low angle to bedding and are covered by conformable laminae (Fig. 6). The surface of the "varved bed" has an overall hummocky appearance (Fig. 5), and laminae may show systematic thickening into hummocks and thinning into swales. Comparable beds (although thinner) can be observed elsewhere in the Chattanooga Shale. At locality 2 (Fig. 1), closer to the shoreline of the Chattanooga Sea (Conant and Swanson, 1961), fine to medium sand beds with above sedimentary features are common in the Dowelltown Member. These sand beds may also show amalgamation.

2.2. Erosion Surfaces

Undulose to almost flat and horizontal shale-on-shale erosion surfaces were observed at various localities (Fig. 1) within the Dowelltown and Gassaway Member. Black shale beds are typically truncated at angles of less than 10 degrees, but truncation angles of up to 17 degrees occur. Relief on these erosion surfaces amounts to as much one meter. Erosion surfaces are overlain by conformable layers of black shale, which themselves may be truncated by later erosion surfaces (Fig. 7). In the latter case the shale may actually take on a cross-bedded appearance (Fig. 7). Efforts to correlate erosion surfaces between closely spaced outcrops have so far been unsuccessful, possibly suggesting that they are a local phenomenon.

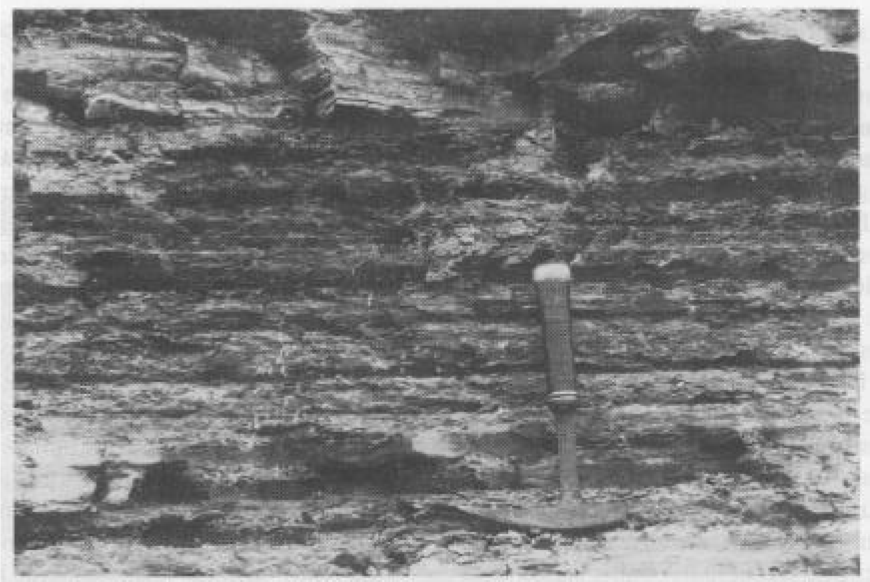


Figure 2: Outcrop photo of upper unit of Dowelltown Member. Light gray layers are greenish-gray shale beds, dark layers are beds of black shale. Hammer is 31.5 cm long.

Figure 3: Photo of hand specimen from upper unit of Dowelltown Member. Shows bed of greenish-gray shale (light gray) between black shale beds. Bioturbation is pervasive and both upper and lower boundaries of greenish-gray shale bed are diffuse. Note black shale filled burrows below the upper black shale bed (arrows). Scale bar is 20 mm long.

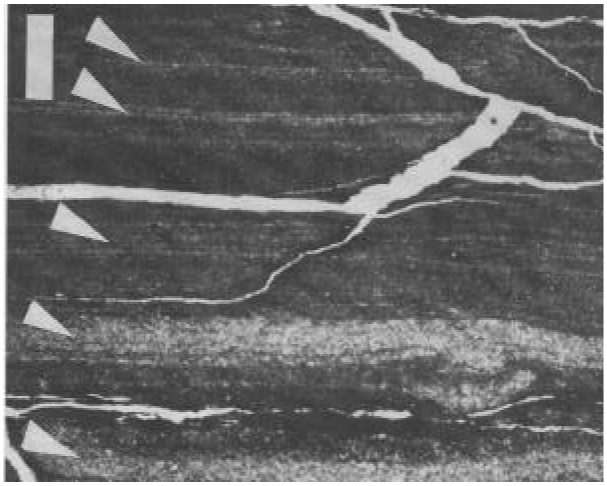


Figure 4: Photomicrograph of graded rhythmite in greenish-gray shale bed (polarized light). Silt laminae are light colored (arrows). The bottom two laminae are coarsest. Scale bar is 1 mm long.

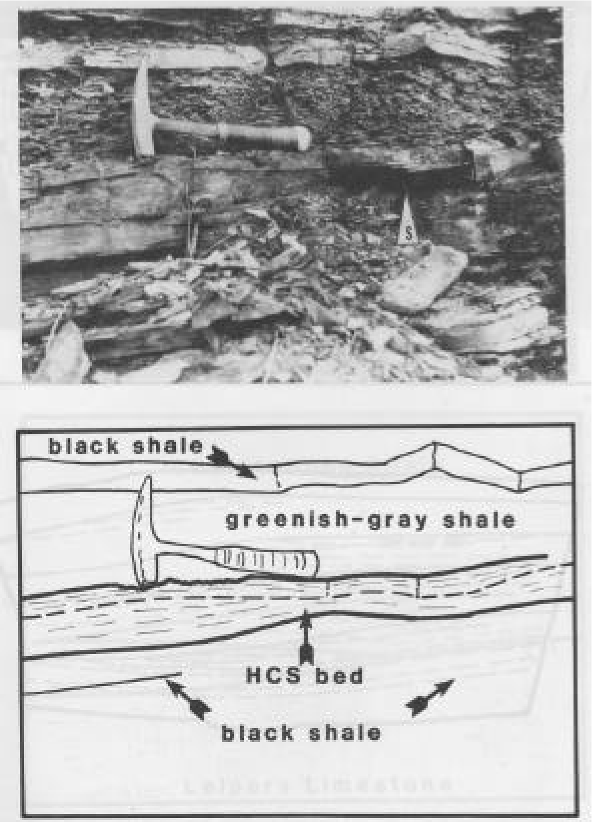


Figure 5: Hummocks in the "varved bed". Hummocky bed is highlighted in line drawing below. One of the internal truncation surfaces is clearly visible (dashed line in line drawing). Hummock is just below the hammer head, swale is located at arrow S. HCS bed is located at the base of the middle unit of the Gassaway Member, is overlain by greenish-gray shale, and overlies black shale of the lower unit of the Gassaway Member. Hammer is 31.5 cm long.

Anisotropy of magnetic susceptibility (AMS) can be used to detect current induced particle alignment in shales (Schieber and Ellwood, 1988, 1993). AMS measurements of samples from the Chattanooga Shale show well developed magnetic lineation due to current alignment of shale particles (Schieber and Ellwood, 1991)

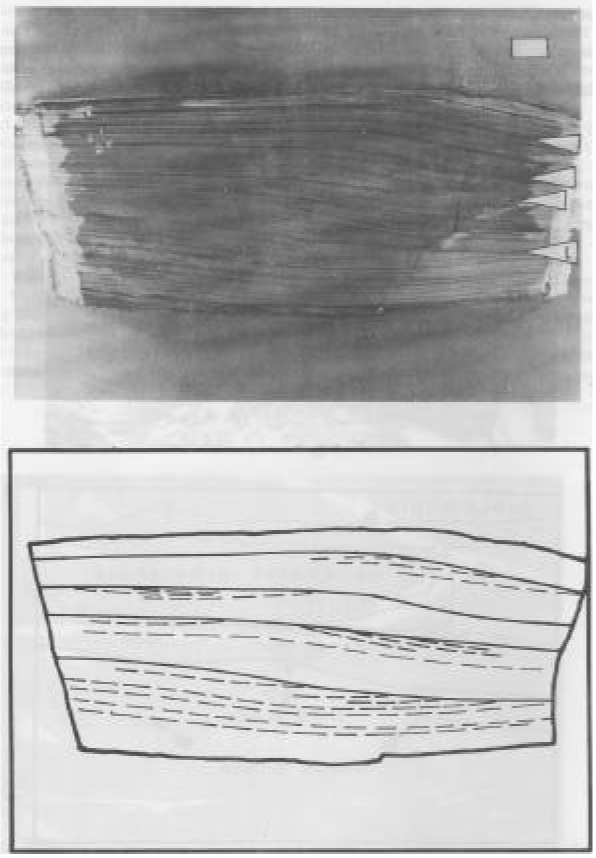


Figure 6: Photo of hand specimen of "varved bed". Shows internal erosion surfaces (arrows) and the draping of parallel laminae over these surfaces. The lowermost erosion surface is the most obvious one (arrow L). Scale bar is 1 cm long. Line drawing below photo shows internal erosion surfaces as solid lines and truncated laminae with thinner dashed lines.

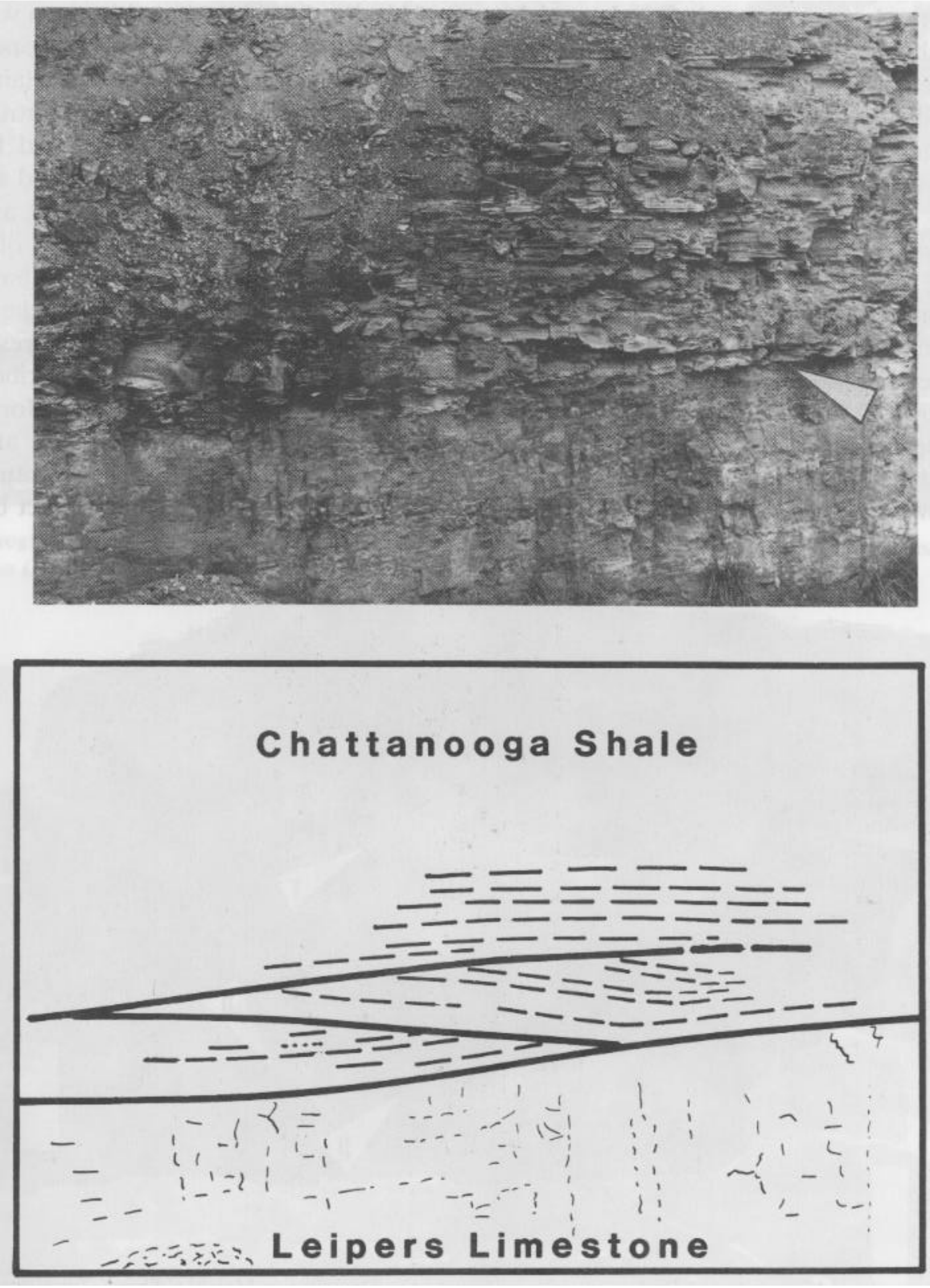


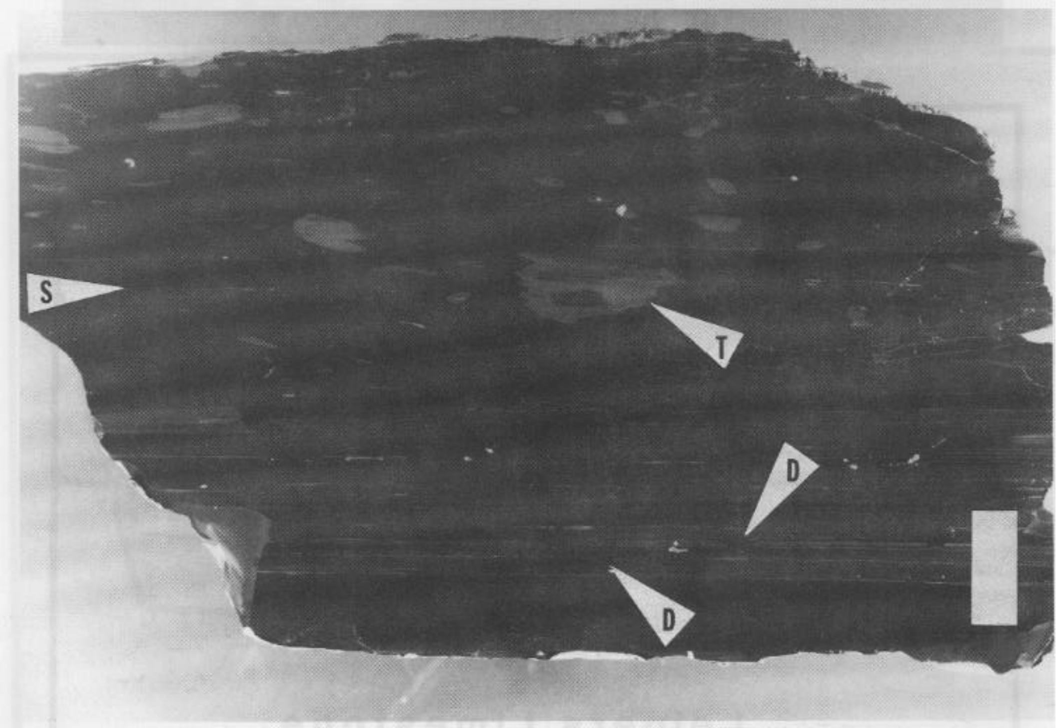
Figure 7: Truncation surfaces and "pseudo cross-bedding" in the basal Chattanooga Shale (Dowelltown Member). Chattanooga Shale unconformably overlies massive dolosiltstones of the Leipers Limestone (Ordovician), basal contact indicated with arrow. Line drawing below photo shows truncation surfaces and basal unconformity with heavy, solid lines, and orientation of shale beds with dashed lines. Photo shows approximately 3 m of Chattanooga Shale.

Bioturbation

Examination of sawn slabs and thin sections of unweathered material showed bioturbation to be more widespread in the Chattanooga Shale than commonly known. At locality 1 (Fig. 1), 41 evenly spaced samples were taken across the entire thickness of the Chattanooga Shale (Fig. 1). Of these, 23 showed various signs of bioturbation. Within stratigraphic subdivisions, proportions of bioturbated samples are as follows: lower Dowelltown = 75%, upper Dowelltown = 83%, lower Gassaway = 14%, middle Gassaway = 65%, upper Gassaway = 0%. Thirty kilometers southwest of locality 1, a bioturbated horizon with abundant Lingula shells was found in the upper Gassaway.

Criteria proposed by Chamberlain (1978) and Bromley (1990) were used to identify trace fossil types on surfaces cut vertical and horizontal to bedding (Figs. 8 and 9). Identified types include Planolites, Teichichnus, Chondrites, and possibly a zoned variety of Asterosoma. Sets of parallel ribs (2-3 cm wide) were found at the base of a sandstone bed (1-3 cm thick) from the base of the Chattanooga Shale. Similar features, interpreted as arthropod traces, were described from the Chattanooga Shale of Kentucky (Jordan, 1985).

Figure 8: Photo of sample of bioturbated shale from the lower unit of the Dowelltown Member. Shows Teichichnus burrow in the center (arrow T). Darker spot in center of Teichichnus burrow due to crosscutting burrow filled with darker material. This is one of the few samples that shows a sharp contact between a dark gray shale bed and an overlying black shale bed (arrow S). Silt laminae in the black shale bed at the bottom of the sample show disruption by bioturbation (arrows D) but no obvious burrow traces. Scale bar is 20 mm long.



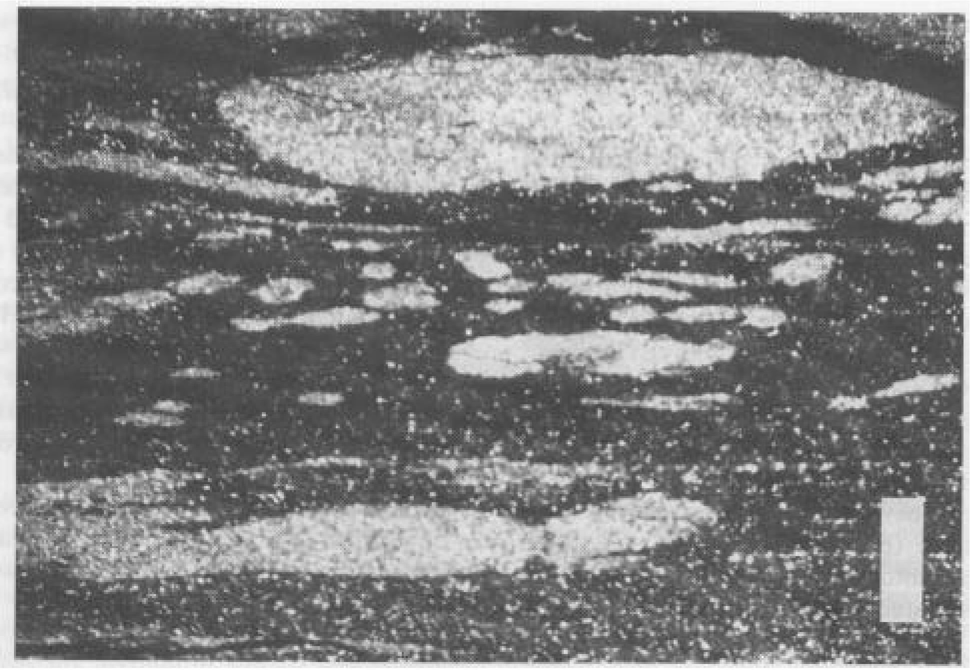


Figure 9: Photomicrograph of bioturbated black shale (Dowelltown Member). Large burrows have been identified as Planolites, small burrows belong to Chondrites. Scale bar is 1 mm long.

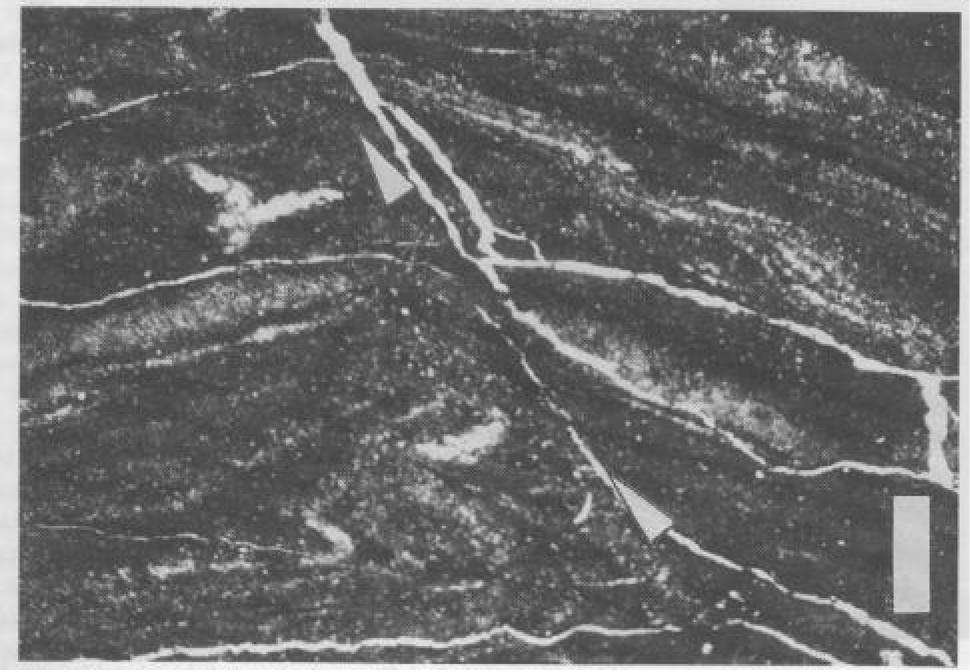


Figure 10: Photomicrograph of escape trace through graded rhythmite at base of greenish-gray shale bed (polarized light). Laminae are disrupted and uparched along the trace (outlined by arrows). Scale bar is 1 mm long.

More subtly, disrupted laminae and fabric disruption (Fig. 8) also indicate bioturbation. The former occur in absence of distinct burrow traces and are a common phenomenon, whereas the latter is visible in thin sections (polarized light). In one sample an apparent escape trace was found (Fig. 10).

Abundant bioturbation is typically associated with greenish-gray shale interbeds in the upper Dowelltown and the middle Gassaway. In the lower Dowelltown, bioturbation is also associated with interbeds of dark gray shale. Bioturbation extends from these interbeds into underlying black shale (diffuse lower boundary). Typically, the contact with overlying black shales is also diffuse (Fig. 3). Only a few samples show sharp upper contacts (Fig. 8). Burrows tend to be filled with lighter colored material (Figs. 3, 8, and 9), except where they extend downwards from black into gray shale (Fig. 3). Thick black shale beds may contain bioturbated horizons that are unrelated to associated gray shales (Fig. 11).

3. Interpretation and discussion

3.1. Greenish-Gray Shales and Laminated Silt Beds

Sedimentary characteristics of the "varved bed" closely resemble those of hummocky cross-stratification (Harms et al., 1975), and size range and shape of its quartz grains are the same as in underlying black shales. The general consensus is that hummocky cross-stratification (HCS) forms when storm waves interact with the seabed and cause winnowing and/or sediment transport (Duke et al., 1991). Thus, sedimentary features suggest that the "varved bed" and comparable deposits in the Chattanooga Shale originated through storm-winnowing of carbonaceous muds. Amalgamated sandy HCS beds at locality 2 (Fig. 1) suggest deposition in shallower water (Dott and Bourgeois, 1982).

HCS probably forms close to the stability boundary for sheet flow and rippled bed (Dott and Bourgeois, 1982). Thus, for a given grain size, the minimum orbital velocity of generating storm waves can be determined via the threshold velocity for sheet flow. For the "varved bed" (locality 1; Fig. 1) about 50 cm/sec is required, whereas HCS beds at locality 2 (Fig. 1) require about 100 cm/sec.

Clifton and Dingler (1984) presented a method to determine appropriate wave height/water depth combinations for a given orbital velocity. Also, using oceanographic tables (e.g. Shore Protection Manual, and Bialek, 1966) one can find likely wave heights for storm wind regimes once the approximate wave fetch of a basin is known. Woodrow (1985) for example, using tables by Bialek (1966), estimated likely storm wave heights of 4-5 m for the Appalachian Basin.

With above values for orbital velocities and wave heights, the method of Clifton and Dingler (1984) yields a water depth of about 40 m for the "varved bed" (locality 1, Fig. 1), and of 20 m for the HCS beds at locality 2 (Fig. 1). Tables from the Shore Protection Manual furnish a wider range of input data (wave height and wave period), resulting in water depth estimates between 20-50 m for the "varved bed" and between 15-40 m for the HCS beds of locality 2.

Bundles of graded silt laminae as seen in greenish-gray shale beds (Fig. 4) closely resemble graded rhythmites that occur in turbidites and shelf muds (Reineck and Singh, 1980). However, association with HCS beds precludes a turbidite origin. In shelf muds, graded rhythmites have been interpreted as the deposits of storm-wave driven suspension clouds (Reineck and Singh, 1971). In these suspension clouds the maximum grain size of suspended material depends on the amount of wave-generated turbulence, and thus areas of maximum turbulence (suspension clouds) will contain coarser suspensions than less agitated intervening areas. Towards the end of a storm, as the turbulent water flows offshore and wave action declines, a combination of settling and lateral movement of suspension clouds results in deposition of graded laminae (Reineck and Singh, 1972). Modern equivalents of storm produced graded rhythmites have been reported from the North Sea (Gadow and Reineck, 1969) and the Mediterranean (Reineck and Singh, 1971). In this context, grading in the basal portions of greenish-gray shale beds is probably also best explained with settling from storm-induced suspensions. Alternating silt and clay laminae as observed in the Chattanooga Shale have also been described by Aigner and Reineck (1982) from storm deposits of the North Sea. The greenish-gray shale deposited on top of basal silts probably settled out as post-storm mud drapes (Gadow and Reineck, 1969). Aigner and Reineck (1982) also report "mud tempestites" from very distal storm deposits of the North Sea. In the Chattanooga Shale, greenish-gray shale beds without a basal silt layer might by comparison be ancient analogs of "mud tempestites".

North Sea graded rhythmites occur in water depths not exceeding 30 m (Aigner and Reineck, 1982). This is within the same depth range as estimated for the HCS beds above. Thus, a water depth estimate on the order of some tens of meters seems quite reasonable for the Chattanooga Shale of central Tennessee.

3.2. Erosion Surfaces

Lack of soft sediment deformation below above described erosion surfaces (Fig. 7), as well as the smoothness of the truncation surfaces themselves, suggest that the eroded shales were of firm consistency. This in turn suggests that the eroding currents had to be of considerable velocity, probably in excess of 1 m/s (Sundborg, 1956). In offshore areas of epicontinental seas, only strong tidal currents or exceptionally strong storms can be expected to give rise to currents of that magnitude (Johnson and Baldwin, 1986). However, although nearshore tidal deposits occur (Woodrow, 1985; Slingerland and Loule, 1988), the tidal range in the Appalachian Basin is generally thought to have been too small to have influenced offshore sedimentation. On the other hand, the effect of storms on shallow offshore areas of the eastern basin margin is well documented (Woodrow, 1985; Halperin and Bridge, 1988). Likewise, observations reported in this paper indicate storm wave impact on the Chattanooga seabed in central Tennessee.

However, erosion was not simply due to wave action on the seafloor, because in that case a storm layer (e.g. HCS bed) should cover the erosion surface. Absence of winnowing products on these erosion surfaces suggests that eroded material was carried to somewhere else in the basin, possibly by a unidirectional current strong enough to erode firm mud,

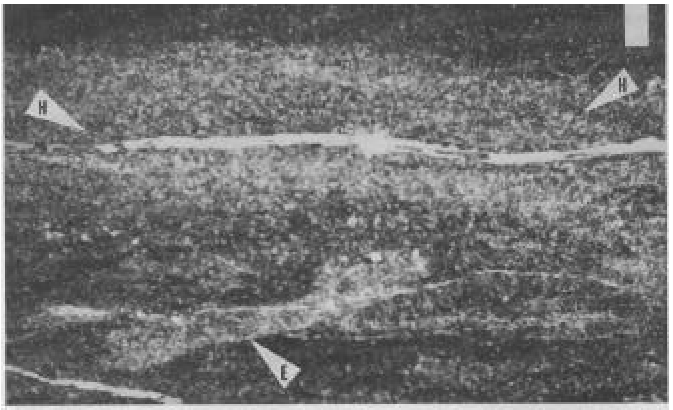


Figure 11: Photomicrograph of burrowed horizon within a black shale bed. Burrow horizon is light colored (arrows H) and has a homogenized to mottled appearance, dark material is black shale. Burrows extend from this horizon into the underlying black shale (arrow E). Scale bar is 1 mm long.

or by a combined-flow current that could transport the eroded material and had an orbital component powerful enough to cause erosion. Currents of this kind can result from coastal water buildup during storms, and have been described as seaward returning bottom currents (Johnson and Baldwin, 1986).

Although such currents conceivably might have scoured the seabed, the truncation surfaces have yet to be linked conclusively to storm-generated return flows, and alternative explanations have to be explored. Possible alternatives are: (1) submarine erosion surfaces produced by internal waves during transgressions (Baird et al., 1988); (2) lowering of sea level; (3) migration of mud waves (Allersma, 1971).

Baird et al. (1988) reported erosion surfaces from black shales of the Devonian Genesee Formation, New York, that can be traced for tens of kilometers and are covered with lenses and layers of reworked material from the underlying shales (particularly pyritized burrow tubes and pyrite nodules, plus fish teeth, bones, and conodonts). It is thought that winnowing occurred where internal waves, migrating along the pycnocline, reached the seafloor (Baird et al., 1988). During transgression, the zone of reworking migrated over the sloping seafloor and produced the observed discontinuities.

However, erosion surfaces in the Chattanooga Shale are unlike the ones described from the Genesee Formation in that they (1) don't seem continuous between outcrops, and (2) lack lag deposits. The absence of lag deposits could have been caused by a lack of suitable particles (e.g. diagenetic pyrite in the Chattanooga typically forms tiny disseminated crystals. only late diagenetic pyrite forms larger grains), or by unidirectional currents that removed all eroded material. The observation that in the Chattanooga Shale silt grains and conodonts are concentrated in HCS beds, but not on the erosion surfaces in question (Fig. 7), suggests that the latter did not form by winnowing and differ in origin from the discontinuities in the Genesee Formation.

Lowering of sea level may lead to increased wave reworking and stronger impact of wind driven currents on bottom sediments. However, although the subtle effects of tectonically and climatically induced regressions and transgressions have been traced from the Appalachian Basin to the craton (Ettensohn et al., 1988), gradual overstepping of the Cincinnati Arch by Late Devonian sediments (Conant and Swanson, 1961; Ettensohn and Barron, 1981) suggests progressive deepening of the Chattanooga Sea. Nonetheless, erosion surfaces occur in the Dowelltown as well as the Gassaway Member. Also, several of these erosion surfaces formed when reconstructions by Ettensohn et al. (1988) suggest transgressions, and their number exceeds the number of potentially available regressions. The sum of these observations suggests that lowering of sea level was not a likely cause for the formation of erosion surfaces.

Allersma (1971) and Rine and Ginsburg (1985) described migration of large mud waves (or mud banks) on the Guyana shelf. They are low relief (approximately 5m high) asymmetrical bedforms with a spacing of tens of kilometers. Intermittent mud movement, related to higher than normal waves and winds, seems to occur in a slurry-like flow, and forms inclined layers (dipping less than 1 degree) on the downstream side of these mud banks. Erosion and exposure of consolidated muds occurs in interbank areas. If the model by Allersma (1971) is correct, inclined layers within mud banks should be truncated by interbank erosion surfaces. Thus, the resulting shale sequence could resemble outcrops where the Chattanooga Shale shows submarine truncation surfaces (Fig. 7).

The observation of apparently current-produced particle alignment in samples from the Chattanooga Shale (magnetic fabrics; Schieber and Ellwood, 1991) suggests that current flow over the seabed was the norm rather than the exception. That inference is more compatible with the mud bank hypothesis than with a scenario that relies on short lived erosive events (e.g. storms).

Whether the truncation surfaces in the Chattanooga Shale were caused by wind driven currents, or if they are due to mud bank migration, is of considerable importance for interpreting the depositional history of the Chattanooga Sea. There is a definite need to study these features in greater detail, because the presently available data do not allow identification of the specific process that formed them. There is a potential here to identify the first fossil example of shelf sea mud banks in the sedimentary record.

3.3. Bioturbation

Although detailed study of trace fossils can delineate environmental gradients and sedimentary environments (Seilacher, 1967), this is not within the scope of the present study and will have to await future investigations. On a more basic level, bioturbation can furnish information about presence or absence of oxygen in the water column and how common (or uncommon) anoxic conditions were during deposition of the sequence in question.

It has been popular to envision formation of bioturbated greenish-gray shale beds as a result of basinward pycnocline retreat in a stratified Chattanooga Sea (Ettensohn et al., 1988; Jordan, 1985; Broadhead et al., 1982), yet storm-produced sedimentary features in these shale beds suggest otherwise. A tempestite scenario for greenish-gray shale beds involves the following steps: (1) black shale reworking by storm waves plus mixing and oxygenation of the water column, (2) deposition of suspended material in the days following storm, (3) benthic colonization of surface, (4) burrowing of soft/soupy substrate results in mottled fabric and poorly defined burrows with diffuse boundaries. Black muds that were covered by these tempestites probably had a firm consistency, because prior storm erosion would have removed the soft/soupy surface muds. Observation of well defined burrows of deposit feeders in black shale underlying greenish-gray shale beds supports that assumption.

However, the question remains if burrowers in the Chattanooga Shale populated the seafloor for extended time periods, or if they were simply "doomed pioneers" (Filmy and Grimm, 1990) that died within a few days or weeks after the storm, while stratification of the water column was reestablished. In the Dowelltown Member, widespread bioturbation features appear to indicate that during most of its deposition the water column was not anoxic. Diffuse upper and lower boundaries of gray shale beds (Fig. 3), as well as black shale filled burrows that extend downwards into gray shale beds (Fig. 3), suggest that burrowing organisms were not restricted to the more oxygenated gray interbeds, and that burrowing continued during black shale deposition.

Other observations support that assumption. For example, well delineated burrows (Teichichnus, Planolites etc.) indicate burrowing in a firm substrate. In contrast, black shale beds that lack distinct burrows but show disruption of laminae and fabric, suggest burrowing of a mud with slurry-like consistency. Organisms probably "swam" rather than "tunneled" through the sediment (Bromley, 1990). This suggests that benthic organisms occupied the black muds shortly after deposition and prior to deposition of overlying gray muds (otherwise some of the latter should have been mixed with the underlying black shale). Escape traces (Fig. 10) also indicate black mud colonization prior to deposition of greenish-gray shale beds. The presence of spreite burrows such as Teichichnus probably suggests extended periods of deposit feeding.

The observations discussed in the preceding paragraph, as well as bioturbation horizons within black shale beds that are not associated with interbeds of gray shale (Fig. 11), suggest that anoxic conditions were not a necessary requirement for black shale accumulation. Rather than being brief interludes, oxygenated conditions apparently were quite common at least during deposition of the Dowelltown Member.

Absence of body fossils (except for Lingula on bedding planes) and the common occurrence of trace fossils, disrupted laminae, and disturbed shale fabrics, suggests dysaerobic (Byers, 1977) or restricted (Morris, 1979) conditions for most of the shales deposited in the Dowelltown Member. Black shale deposition may simply reflect abundant deposition of organic matter (planktonic algae etc.) rather than establishment of anoxic conditions in the water column.

Intermittent anoxic conditions above the sediment/water interface are indicated by finely laminated bituminous shale beds that show no sign of bioturbation. These may for example reflect time intervals of peak plankton production (climate related?), when decay of organic matter could have rendered the lower portions of the water column anoxic.

At first sight, the predominance of unbioturbated black shales in the Gassaway Member might be explained with continued deepening of the Chattanooga Sea. Possibly by the time of Gassaway deposition the water was sufficiently deep to prevent complete mixing of the water column by storms. However, if this is to be equated with stratification of the water column and basinwide pycnocline establishment is debatable. Truncation surfaces (Fig. 7) also occur in the Gassaway Member, signaling strong currents flowing across the basin floor. Currents of that strength could easily have mixed and oxygenated the water column. If it can be shown that truncations are related to mud bank migration, it would even imply more or less continuous current flow. That current flow over the basin floor was a common occurrence is also suggested by magnetic fabric data that reflect particle alignment in samples of Chattanooga Shale (Schieber and Ellwood, 1991).

Under such conditions, high rates of plankton production might be the only way to forestall bioturbation of the seabed. In such a scenario, oxygen in the water column would be consumed as organic matter settles to the bottom, possibly rendering the lower portions of the water column anoxic. Nonetheless, bioturbated horizons occur in the lower unit of the Gassaway Member, indicating intermittent dysaerobic conditions. Greenish-gray shale beds and HCS beds in the middle unit of the Gassaway indicate interaction of storm waves with the seabed, and suggest that bioturbation in that unit is linked to aeration of the water column by storms. Storm deposits in the middle Gassaway also suggest somewhat shallower water, possibly due to a temporary drop in sea level. In keeping with this line of reasoning, the upper unit of the Gassaway would then imply renewed sea level rise and return to conditions similar as assumed for its lower unit.

The arguments presented in the preceding two paragraphs suggest that organic productivity rather than sea level rise may have produced the strong dominance of unbioturbated black shales in the Gassaway Member. In a study of the New Albany Shale of Indiana, a lateral equivalent of the Chattanooga Shale, Lineback (1970) suggested that the source of the organic matter in the New Albany Shale was a floating mat of marine plants. Could it be that during deposition of the lower and upper unit of the Gassaway Member such a floatant was so well established that it could not be disrupted even during storms? Obviously, this would have greatly diminished mixing and oxygenation of the water column during storms. Yet, however critical the question of the floatant is for a proper interpretation of the Chattanooga Shale, assessment of its relative importance definitely will require a detailed paleobotanical study.

4. SUMMARY and CONCLUSIONS

HCS beds and related storm deposits suggest that considerable portions of the Chattanooga Shale in central Tennessee were deposited above storm wave base. Instead of hundreds of meters, water depth was probably on the order of tens of meters. Gray shale interbeds may therefore owe their origin to aeration by storm waves, rather than to pycnocline fluctuations.

Erosion surfaces in the Chattanooga Shale may have been caused by storm-induced currents, or may be the product of mud bank migration. The latter scenario implies continuous currents rather than episodic storm currents. In depth investigation of the likely origin of these erosion surfaces will be essential for a proper interpretation of the Chattanooga Shale in central Tennessee.

Bioturbation of black shales suggests that oxygenated albeit dysaerobic conditions prevailed during most of Dowelltown deposition. During Gassaway time bottom waters apparently were predominantly anoxic. However, it remains an open question whether this was caused by increased water depth and pycnocline establishment, or by establishment of a floatant of marine plants and increased organic matter supply. This matter deserves further investigation as well.

Intermittent as well as continuous current flow and reworking is indicated by sedimentary features (storm beds, erosion surfaces, particle alignment) of these shales. Such conditions seem inconsistent with black shale accumulation below the pycnocline of a stratified water body, the favored model for black shale formation in the Appalachian basin.

Subtle differences in lithology and sedimentary features exist between the Chattanooga Shale of central Tennessee, and its lateral equivalents in eastern Tennessee and eastern Kentucky and Ohio. Therefore, conclusions from this study are restricted to central Tennessee, and should not be extended to other areas without critical reexamination. Results from this study reaffirm the original shallow water interpretation of the Chattanooga Shale by Conant and Swanson (1961).

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