PALEOFLOW PATTERNS AND MACROSCOPIC SEDIMENTARY FEATURES IN THE LATE DEVONIAN CHATTANOOGA SHALE OF TENNESSEE: DIFFERENCES BETWEEN THE WESTERN AND EASTERN APPALACHIAN BASIN

Jürgen Schieber

Department of Geology, University of Texas at Arlington, Arlington, Texas 76019

ABSTRACT

Previously, paleocurrent data from the Chattanooga Shale and its lateral equivalents suggested deposition on a westward dipping paleoslope (westward paleoflow). However, new paleocurrent data (measurements of anisotropy of magnetic susceptibility, AMS) are not in agreement that view. They indicate eastward flowing paleocurrents in eastern Tennessee, and irregular flow in central Tennessee.

Macroscopic sedimentary features also point to significant differences in sedimentary setting between eastern and central Tennessee. In eastern Tennessee, the Chattanooga Shale intertongues with turbidites of the Brallier Formation, lacks shallow water features, and may have been deposited in depths between 100-200m. In central Tennessee, HCS siltstones and sandstones, shale-on-shale erosion surfaces, lag deposits (bone beds), and ripples, suggest relatively shallow water (tens of metres) and reworking of the sea bed by waves and strong currents.

A shallow water platform in central Tennessee, and deeper water conditions in eastern Tennessee require an eastward dipping sea floor (paleoslope) between these two areas. Further east however, where the Chattanooga Shale interfingers with the Brallier Formation, the paleoslope was inclined in the opposite direction (westward flowing paleocurrents). These two opposing slopes formed an elongate trough along the eastern margin of the Appalachian Basin.

The portions of the Chattanooga Shale whose AMS data suggest eastward paleoflow, occur between the shallow water Chattanooga of platform origin and the area where it interfingers with the Brallier Formation. Thus, the eastward dipping paleoslope suggested by sedimentary features is in good agreement with AMS paleocurrent data.

INTRODUCTION

Research on Upper Devonian black shales in the Appalachian Basin (e.g. the Chattanooga Shale) received substantial impetus from the search for uranium and hydrocarbons, and many studies were carried out along multiple lines of inquiry (stratigraphy, petrology, sedimentology, geochemistry, paleontology etc.). The efforts of the last 30 years led to a well established stratigraphic framework (Woodrow et al., 1988), and a large amount of data exists on geochemistry (e.g. Leventhal, 1987), distribution of lithologies, and sedimentary features (e.g. Conant and Swanson, 1961; Broadhead et al., 1982; Lundegard et al., 1985; Ettensohn et al., 1988). In fact, the published record leaves one with the impression that this is one of the most thoroughly investigated shale sequences, and that major questions concerning its origin have been satisfactorily answered.

However, a variety of issues, such as for example water depth and environment of deposition, remain a subject of debate. Both a shallow (e.g. Conant and Swanson, 1961) and deep-water origin (e.g. Potter et al., 1982, Ettensohn, 1985) has been proposed, and a review of the issue by Woodrow and Isley (1983) showed that various methods led to depth estimates ranging from 39 to 375 metres. The popular idea that these shales may owe their origin to pycnocline development (Byers, 1977), led to suggestions of water depth of at least 100-200 metres (Potter et al., 1982). Lundegard et al. (1985) even arrived at a maximum estimate in excess of 900 metres. Large water depth and stratification of the water column provide for stagnant bottom waters with little or only weak current activity, commonly thought to be the conditions under which finely laminated black shales (such as the Chattanooga Shale) are most likely to accumulate (Potter et al., 1980).

Conant and Swanson (1961) studied the Chattanooga Shale in central Tennessee and found that (1) it rests on a basal unconformity; 2) it contains silt and sandstone lenses and scour channels; 3) it onlaps towards the Nashville Dome; 4) the region had low relief and shallow water sedimentation since the Precambrian; 5) the Mississippian sea was shallow and more extensive than the Devonian one; 6) it contains linguloid brachiopods. Although these observations suggested shallow water deposition to Conant and Swanson (1961), most of the evidence is circumstantial in nature.

This paper was written to report new observations that have a bearing on the origin of the Chattanooga Shale. Aside of paleocurrent measurements via AMS (anisotropy of magnetic susceptibility), other observations that are reported were exclusively made in outcrop. They suggest that contrary to commonly held opinions, large portions of the Chattanooga Shale were deposited in comparatively shallow water, and

that strong currents at times eroded and winnowed the sea floor.

GEOLOGIC SETTING

The Chattanooga Shale and its lateral equivalents form the distal part of a westward thinning clastic wedge that accumulated in a foreland basin to the west of the Acadian Mountains. It is known as Chattanooga Shale primarily in Alabama, Tennessee, and south-central Kentucky, towards the northeast as Ohio Shale, and towards the northwest (Illinois Basin) as New Albany Shale (de Witt, 1981).

Overall sediment transport was towards the west (Lundegard et al., 1985). Going east to west, major environments of deposition include alluvial plain, delta plain, shelf, slope with turbidites, and basin floor with black-shale accumulation (Woodrow et al., 1988). Estimated 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).

In central Tennessee the Chattanooga Shale is of Late Devonian (Frasnian-Famennian) age, and is a nearly flat-lying Formation that reaches a thickness of slightly above 9m (Fig. 1). It has been subdivided into the Hardin (base), Dowelltown, and Gassaway (top) members (Fig. 1), and is conformably overlain by the Lower Mississippian Maury Formation (Conant and Swanson, 1961). The Hardin Sandstone Member is only locally present at the base of the Chattanooga Shale, and grades into the overlying Dowelltown Member. Uniform thickness and low rates of lateral thickness change suggest that, aside of a few exceptions, the Chattanooga Shale was deposited on a very smooth and even peneplain. The most notable of these exceptions is known as the Hohenwald Platform (Fig. 1), an island in the Chattanooga Sea SW of Nashville (Conant and Swanson, 1961).

In eastern Tennessee the Chattanooga Shale reaches a thickness of approximately 650 m (Hasson, 1982), and is subdivided into the basal Millboro Member, the middle Brallier Member, and the upper Big Stone Gap Member (Fig. 1). The Chattanooga Shale unconformably overlies the Lower Devonian Wildcat Valley Sandstone, and is conformably overlain by the Mississippian Grainger Formation.

OBSERVATIONS

Macroscopic Sedimentary Features, Western Portion of Basin

Hummocky cross-stratification (HCS), soft sediment deformation, erosion surfaces, bone beds, and ripples can readily be observed in outcrop and provide information about water depth and energy conditions. In addition, a wealth of small scale sedimentary features can be observed in sawed slabs and thin sections (Schieber, this volume).

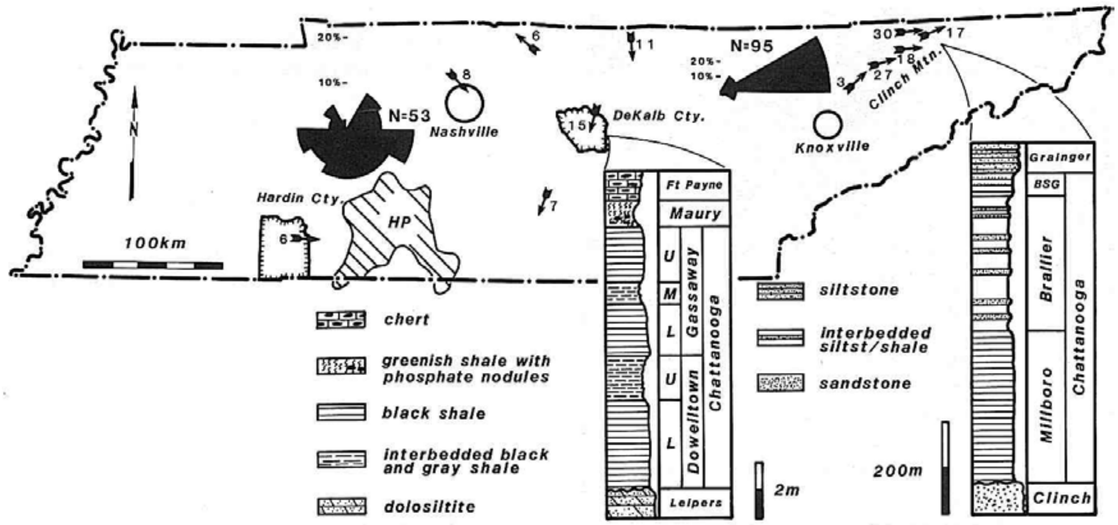
HCS Beds

Conant and Swanson (1961) described a local marker bed ("varved bed") from outcrops in DeKalb County (Fig. 1), Tennessee. It is thin (1-10cm) and fine grained (silt to fine sand), has an erosional lower contact, and is overlain by greenish-gray shale (Fig. 2). Thickness variations are regular (pinch and swell) and the surface of the bed appears hummocky. Internal laminae conform to the basal erosion surface as well as to gently undulose internal erosion surfaces, and may show systematic thickening into hummocks and thinning into swales.

These characteristics fit the definition for hummocky cross-stratification as proposed by Harms et al. (1975). Thinner, but otherwise comparable beds of laminated silt and sand were observed elsewhere in the Chattanooga Shale where it contains interbeds of greenish-gray shale. 200 km to the SW in Hardin County (Fig. 1), Tennessee, HCS beds (medium sand) are common in the Dowelltown Member, and amalgamation of HCS beds has been observed as well.

Soft Sediment Deformation

Ball-and-pillow structures were observed in association with a HCS sandstone bed (10-20 cm thick) in the Dowelltown Member. This bed has in places completely



dissintegrated, forming isolated balls (10-20cm diameter; Fig. 3) in a shale matrix.

"Pockets" of chaotic bedded shale occur in the same outcrop. Shale beds in these "pockets" (several metres wide, up to 1 m thick) show convolution accompanied by disruption of beds. A matrix of homogenized black shale surrounds randomly oriented bed fragments. There are no sharp boundaries between pockets and surrounding, even bedded shales.

Large scale deformation of shale beds occurs below major submarine erosion surfaces (Fig. 4). It is probably best described as convolute bedding.

Erosion Surfaces

Erosion surfaces in the Chattanooga Shale are undulose to almost flat and horizontal, truncate underlying beds of black shale typically at angles of less than 10 degrees, and show surface relief amounting to as much as one metre. They are overlain by conformable layers of black shale, which themselves may be truncated by later erosion surfaces (Fig. 5).

been unsuccessful, possibly suggesting that they are phenomena of only local extent.

An exception may be the erosion of Dowelltown shales at the Dowelltown/Gassaway contact in areas NE of Nashville (Fig. 6). This contact is knife sharp all over central Tennessee (Conant and Swanson, 1961), suggesting that pre-Gassaway erosion was widespread even though it is not always as obvious as in Fig. 6.

Bone Beds

Conkin and Conkin (1980) reported four bone beds (phosphatic debris, glauconite) from the Chattanooga Shale, one each at base and top of the formation, one within the Dowelltown, and one at the Dowelltown/Gassaway contact. Locally they can be as thick as 30 cm, but typically they are only a few cm thick and lenticular. In many places they are only represented by a thin (a few mm) layer of fine sand or silt.

Ripples

Thin silt lenses (up to 5mm thick, up to 50mm long) are the most common ripple type,

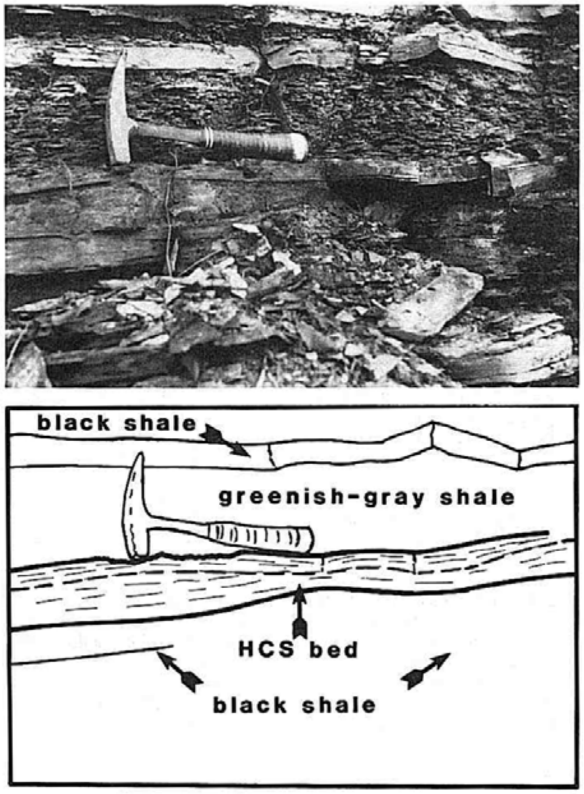


Figure 2: Varved bed (middle unit of Gassaway Member) with hummocky appearance. Hummocky bed highlighted inline drawing below. One of the internal truncationsurfaces is clearly visible(dashed line in line drawing). Hummock is just below the hammer head, swale is located at arrow S. HCS bed is overlain by greenish-gray shale and overlies black shale of the lower unit of the Gassaway Member. Hammer is 31.5 cm long

and occur single or as ripple trains on bedding planes. Silt grains are of the same size as present in the associated shales. Low angle cross-lamination has been observed.

Other ripples consist of a mixture (grain size range 0.1-1.5 mm) of quartz grains, fish bones, glauconite granules, and dolomite, and are up to 10mm thick and up to 80mm long. They are typically found in the basal 30 cm of the Chattanooga Shale, may be cross-laminated, and may occur as single ripples or discontinuous wavy sandstone beds.

Ripples of the same composition, but of somewhat finer grain size, are common in the Hardin/Dowelltown transition in Hardin County, Tennessee. Depending on the sand/mud ratio in the section, flaser bedding, wavy bedding, and lenticular bedding occurs. These ripples show cross-lamination, chevron structures, bundle-wise upbuilding, and intricately interwoven cross-lamination.

Macroscopic Sedimentary Features, Eastern Portion of Basin

In eastern Tennessee, the Chattanooga shale thickens and has a siltstone-rich middle interval that is equivalent to the Brallier Formation farther north (Dennison, 1985). These siltstones were described by Lundegard et

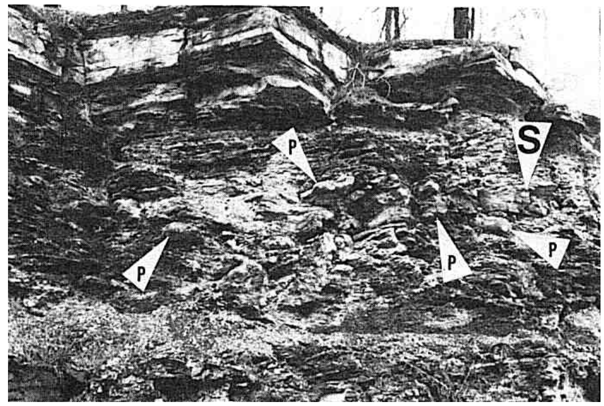


Figure 3: Ball and Pillow structures related to HCS sandstone bed in the Dowelltown Member. The sandstone bed (arrow S) has broken up into pillows in the centre of the photograph (arrows P). Photo shows approximately four metres of exposure.

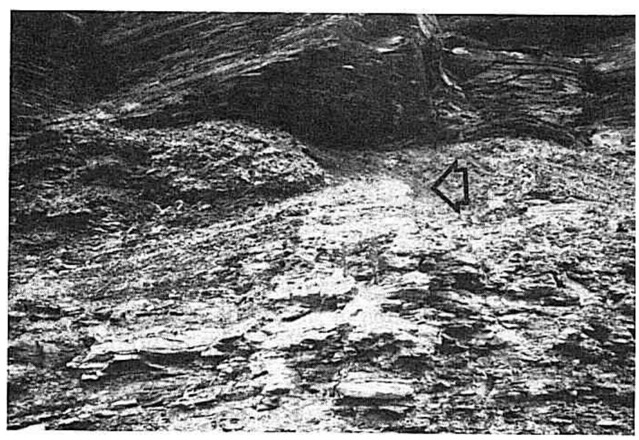


Figure 4: Contorted Bedding below the Dowelltown/Gassaway contact. Shale beds of the Dowelltown have been folded over to the left (arrow). Photo shows approximately two metres of exposure.

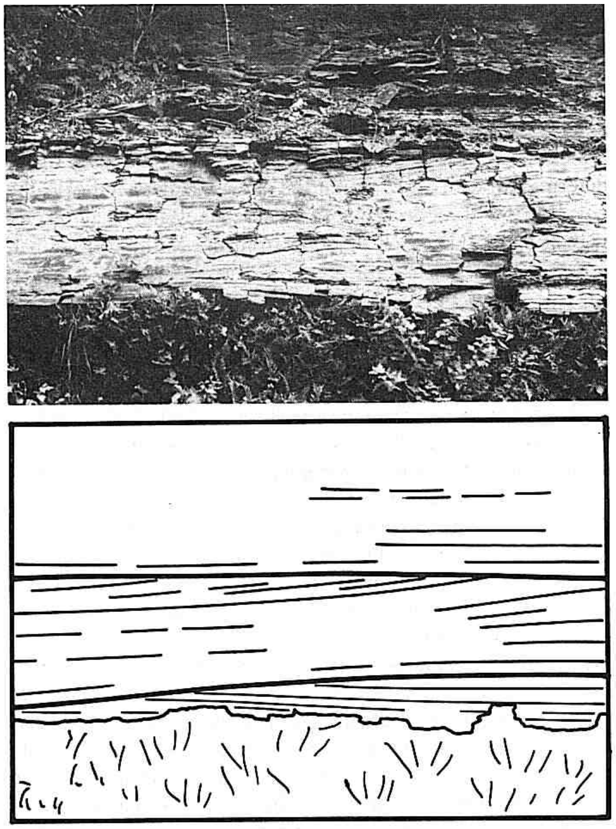


Figure 5: Pseudo-crossbedding in Gassaway Member, produced by repeated erosion alternating with shale deposition. Line drawing highlights erosion surfaces (heavy lines) and bedding planes (thin lines). The "cross-bedded" interval highlighted in the line drawing is approximately one metre thick.

Figure 6: Erosion surface with appearance of angular unconformity at base of Gassaway Member. The tilting of the beds below the contact is, however, not due to tectonic forces, but rather to soft sediment deformation and convolution of beds in the Dowelltown Member (contorted bedding shown in Fig. 6 was observed in the same outcrop). Sequence of events appears to have been: 1) deposition of Dowelltown beds; 2) disturbance and destabilization of beds e.g. by storm waves; 3) a prolonged period of erosion, winnowing, and levelling; and 4) deposition of Gassaway beds. Photo shows approximately two metres of exposure.

al. (1985), and their observations are summarized here.

Siltstones are typically thin bedded (1-30cm) and consist of even, persistent beds with base truncated Bouma sequences (Tbcde, Tcde). Top portions of beds may show ripple cross-lamination; sole marks are common at the base of beds.

A small proportion of siltstone beds occurs as thickly bedded (2-150cm) bundles of sharply defined beds with erosional bases (top-truncated Bouma sequences; Ta, Tab, Tabc). Beds may contain shale clasts and wood fragments, and may show amalgamation.

Thin siltstone beds (1-10cm) that are found in shale-dominated portions of the sequence and in the black shales below and above the Brallier Formation typically show base-truncated Bouma sequences (Tcde, Tde).

New Paleocurrent Data from AMS Measurements

Measurement of anisotropy of magnetic susceptibility (AMS) has been an extensively applied method in fabric studies of sediments and sedimentary rocks (e.g. Hrouda, 1982). AMS is commonly expressed as an ellipsoid, which in general terms reflects the orientation of magnetic elements in the sample. In sediment samples, the AMS ellipsoid reflects the petrofabric orientation (Taira and Lienert, 1979), which results from any process orienting grains in the sediment (current flow, compaction, diagenesis). In sand- and silt-sized terrigenous clastics the long axis of the AMS ellipsoid generally coincides with flowdirection (e.g. Taira and Lienert, 1979), and the ellipsoid is inclined in upcurrent direction.

In the past, extraction of paleocurrent information from shale sequences has been fraught with difficulties. A variety of approaches have been applied, e.g. (1) measurement of flow indicators in interbedded sandstones and carbonates, (2) alignment of fossils and detrital quartz grains, and (3) lateral distribution of detrital components. Drawbacks are that paleoflow indicators from interbedded lithologies may not be representative of

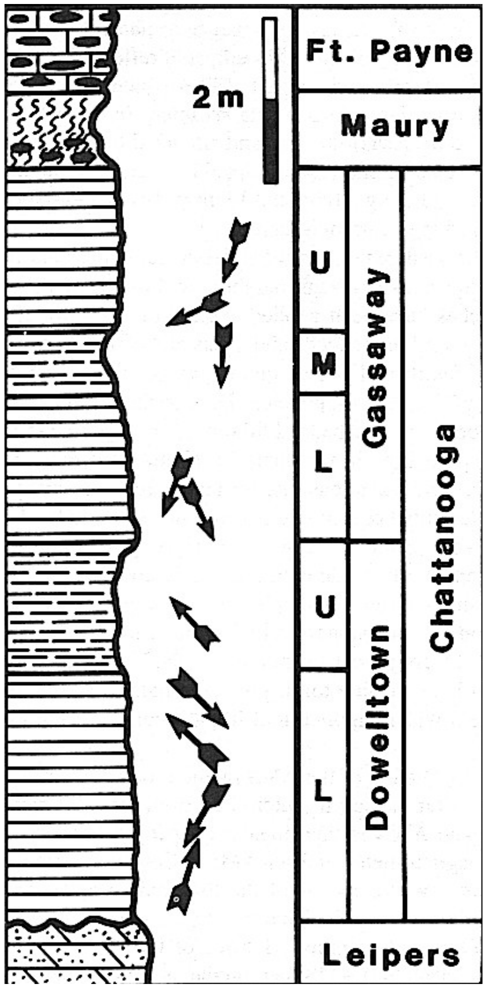


Figure 7: Stratigraphic variability of AMS paleocurrent data in the Hurricane Bridge section of the Chattanooga Shale, DeKalb County (Kepferle and Roen, 1981). Arrows indicate paleoflow direction relative to north. Center of arrow approximately at sample elevation above base. Lithologic symbols are the same as in Figure 1. Only the more consistent data for the Gassaway member are shown in Fig. 1.

paleoflow in the shale itself, and that other methods either require fortuitous circumstances (e.g. oriented fossils) or are very time consuming because of extensive field work (detailed mapping) or laboratory work (microscopy).

Recent work by Schieber and Ellwood (1988, 1993) has shown that the same principles that are applied to deduce flow directions of sandstones and siltstones, can also be applied to shales. In contrast to other methods, the AMS paleoflow method is applicable to all kinds of shales, and will probably become a widely applied tool in paleocurrent studies of shale basins.

For application of the AMS method, oriented cores (24mm diameter) are drilled in outcrop or from oriented hand specimens. The AMS is then measured using a low-field torsion fiber magnetometer and an AMS ellipsoid is calculated for each core. Vector means of the long axis orientations of the ellipsoids are then calculated for each outcrop.

In a study of magnetic fabrics of the Chattanooga Shale, approximately 200 AMS measurements were made on oriented samples from Tennessee. These samples were collected along and in the vicinity of Clinch Mountain (northeast of Knoxville, Fig. 1), and in outcrops in central Tennessee. This study is still continuing, and at present the data coverage for central Tennessee is less dense as one would desire. However, preliminary data from central Tennessee are reported here because they contrast so strongly with those from eastern Tennessee.

The samples from Clinch Mountain were collected from the basal Millboro Member. AMS data are fairly consistent and suggest sediment transport in a easterly to northeasterly direction (Fig. 1). In contrast, samples from central Tennessee (only data from Gassaway Member are presented in Fig. 1) are much more variable. Although more data are still needed to define clear paleocurrent patterns in central Tennessee, the present data suggest a random or possibly rotary flow pattern (Fig. 1), and contrast strongly with the unidirectional pattern observed in eastern Tennessee.

In order to examine changes of paleoflow directions with time, a comparatively large number of samples was collected over the entire thickness of the Chattanooga Shale in one stratigraphic section in central Tennessee (Fig. 7). The data suggest very irregular flow directions for the Dowelltown Member, and fairly consistent paleoflow directions for the Gassaway Member. For that reason only Gassaway data are shown for the central Tennessee portion of Fig. 1.

DISCUSSION AND INTERPRETATION

AMS Paleocurrent Data

These new data contrast with earlier paleoflow studies of the Appalachian Basin, where it was concluded that paleoflow was uniformly to the west (Potter et al., 1982; Lundegard et al., 1985). However, the latter assumption was solely based on data from the eastern portion of the basin (flute-cast measurements in Brallier Formation), where down-slope gravity-driven flow (westward) and storm-induced coastal downwelling were dominant (Potter et al., 1982; Lundegard et al., 1985).

AMS data from Clinch Mountain (Tennessee) overlap geographically with data by Lundegard et al. (1985), but suggest flow in an easterly rather than a westerly direction. There are two possible reasons for this discrepancy. (1) Inclinations of AMS ellipsoids from the Chattanooga Shale are not indicative of flow direction (AMS measurements only allow determination of flow azimuth). (2) The AMS data indicate the correct flow direction, but the discrepancy may have to do with the fact that AMS data are from the Millboro Member, whereas flute-cast data are from the overlying Brallier Member (Fig. 1). Possibility (1) seems unlikely from prior applications of the AMS method to shales (Schieber and Ellwood, 1988, 1993), and possibility (2) is discussed in the following paragraphs.

Paleoflow in a sedimentary basin is strongly influenced by basin configuration (location of depocenters, distribution of shallow and deep water environments etc.), and flow patterns can be altered due to changes in basin tectonics, sediment supply, and sea level. In a recent review of the sedimentary dynamics of the Appalachian basin, Ettensohn et al. (1988) discuss the possible interrelationships between sedimentation patterns, tectonism, and sea-level changes at length, and envision two basic basin configurations (Fig. 8). A smooth, westward dipping paleoslope, merging gradually into the basin floor to the west (Fig. 8A), would be established during times of abundant sediment input and rapid regression (sedimentation exceeds subsidence). In contrast, during times of small sediment supply and rapid transgression (subsidence exceeds sedimentation), a peripheral trough is supposed to have formed that acted as a sediment trap and prevented coarser sediments from reaching the western portion of the basin (Fig. 8B). According to Ettensohn et al. (1988), these two configurations are associated with deposition of "regressive" (more clastic components, less organic matter) as opposed to "transgressive" (organic-rich) black shales respectively.

Because the Millboro Shale (sampled for AMS in eastern Tennessee) was probably a "transgressive" black shale during deposition of which a peripheral trough may indeed have existed (Ettensohn et al., 1988), AMS data may actually be correct and indicate deposition of these shales on the western slope of such a trough (Fig. 8B). The Brallier Member in contrast marks a regressive phase in basin history, and the observed westward sediment transport (flute-marks) probably indicates filling of the peripheral trough and establishment of a smooth westward dipping paleoslope (Fig. 8A).

Working from fossil orientations, Jones and Dennison (1970) published westward paleoflow in the Chattanooga Shale of Clinch Mountain from the same outcrops that provided samples for AMS data presented here. Although their results are in conflict with AMS data, if one examines their work carefully one finds that fossil alignment only provided flow azimuth. Paleoflow direction was actually inferred from Upper Devonian isopachs that were supposed to reflect paleoslope. As Fig. 8B shows, the latter assumption is incorrect during presence of a peripheral trough.

The considerable paleoflow variability that is indicated by AMS data from central Tennessee (Fig. 1) is typical for shelf seas (Pettijohn et al., 1987; Selley, 1988). The suggestion of a rotary pattern in central Tennessee could indicate the presence of wind-driven circulation cells in the Chattanooga Sea. The generally eastward dipping paleoslope that is indicated for this area by gradual westward overstepping of the Nashville Dome during the Upper Devonian (Conant and Swanson, 1961) must have been too small to noticeably influence sediment transport across the seafloor.

In vertical section, the change from very irregular paleoflow directions in the Dowelltown Member to fairly consistent flow directions in the Gassaway Member (Fig. 7), probably reflects gradual sea level rise. During initial flooding of the Middle Devonian/Upper Devonian unconformity, surface relief probably caused compartmentalization into numerous sub-basins (Kepferle and Roen, 1981). As water levels rose, communication between sub-basins probably improved and also caused ongoing reorganization of circulation patterns. By Gassaway time, deepening of the Chattanooga Sea had progressed sufficiently to leave only small islands still exposed (Conant and Swanson, 1961). At that point in time, the relief of the underlying unconformity should have had minimal influence on water circulation in the Chattanooga Sea, allowing establishment of stable circulation over larger portions of the basin.

AMS data suggest that conditions of black shale accumulation in the Appalachian Basin differed between east and west. In the eastern portion, gravity driven processes on the

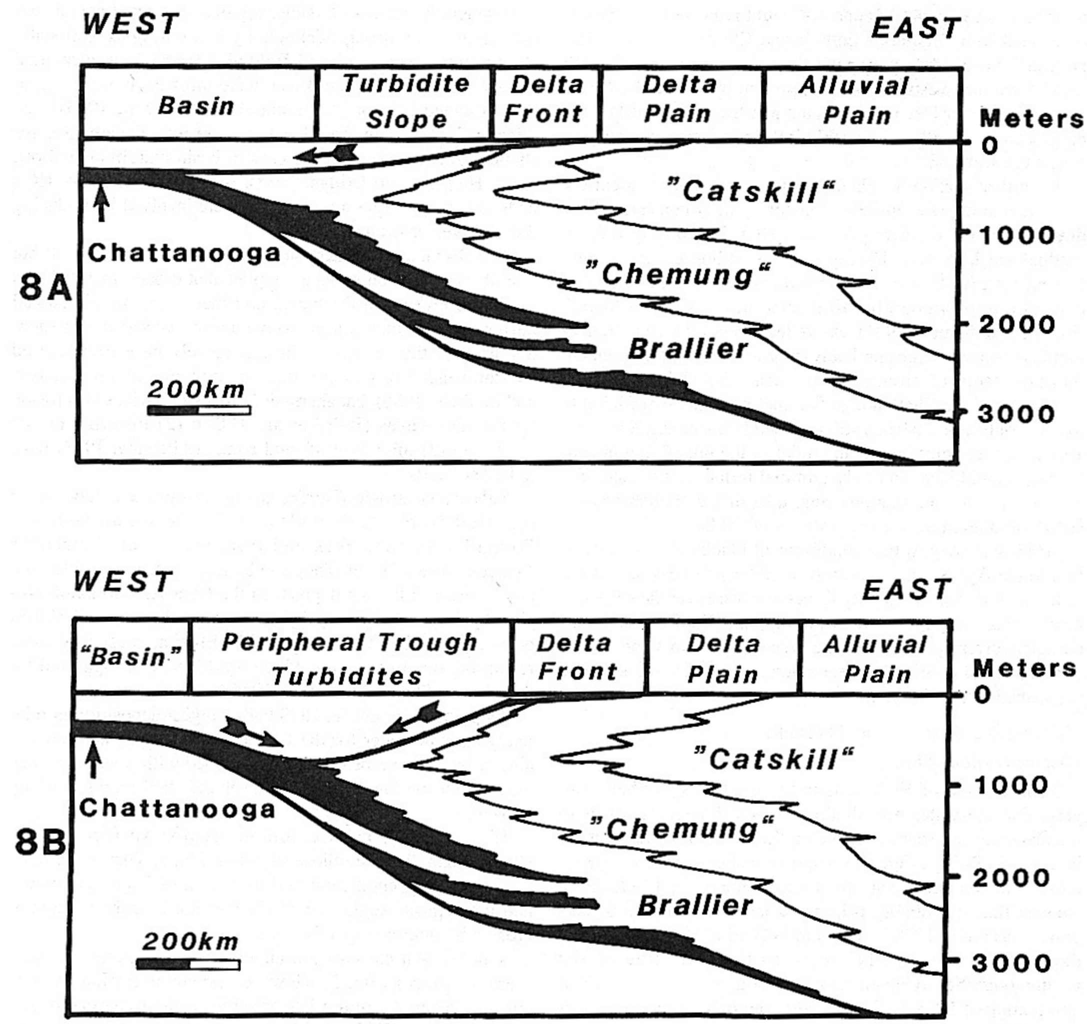


Figure 8: Two scenarios of basin configuration. 8A) during regression, when sediment deposition exceeds subsidence, the peripheral trough gets filled, and an overall westward dipping paleoslope develops. 8B) during transgressions, when sediment supply is small, subsidence exceeds sedimentation and a peripheral trough develops. Metre marks at right serve only as indicators of sediment thickness. Water depth and basin topography are exaggerated.

slopes of a peripheral trough or a westward dipping clinoform dominated paleocurrent patterns. In the western portion, wind driven currents could dominate paleocirculation because the slope of the seabed was insignificant.

Macroscopic Sedimentary Features
Western Portion of Basin

Identification of HCS beds in the Chattanooga Shale suggests that the water was shallow enough for storm waves to interact with the seabed (Duke et al., 1991). For the "varved bed" (DeKalb Cty., Fig. 1)), the compositional similarities between its silt fraction and the silt fraction of underlying black shales suggest that it probably originated from winnowing of carbonaceous muds. HCS beds found in Hardin Cty. (Fig. 1) were deposited considerably closer to the shoreline of the Chattanooga Sea (Conant and Swanson, 1961). Presence of amalgamated

HCS beds indicates deposition in shallower water (Dott and Bourgeois, 1982).

HCS beds also allow water depth estimates following an approach outlined by Clifton and Dingler (1984). Considering that HCS probably forms close to the stability boundary between sheet flow and rippled bed conditions (Dott and Bourgeois, 1982), threshold orbital velocities between 50-100 cm/s are interpreted for Chattanooga HCS beds. Taking into account approximate size of the Appalachian Basin (Conant and Swanson, 1961), and likely heights and periods of storm waves (e.g. Shore Protection Manual; Bialek, 1966), the method of Clifton and Dingler (1984) yields a water depth between 20-50m for the "varved bed", and of 15-40m for the coarser grained HCS beds in Hardin County.

Smoothness of internal erosion surfaces (Fig. 5) suggests a firm substrate and eroding currents that possibly exceeded velocities of 1 m/s (Sundborg, 1956). Currents of that magnitude generally occur in offshore regions of epicontinental seas only in areas of strong tidal activity and during exceptionally strong storms (Johnson and Baldwin, 1986). However, tidal ranges in the Appalachian Basin were most likely too small to have affected offshore sedimentation (Woodrow, 1985). The effects of storms on the other hand are well documented for shallow offshore areas of the eastern basin margin (Woodrow, 1985; Halperin and Bridge, 1988). In view of above HCS beds, this might suggest that storms were involved in producing the observed erosion surfaces.

Absence of lag deposits (such as bone beds) on all but one of these erosion surfaces implies that the eroded material was carried elsewhere in the basin, and that strong unidirectional currents rather than simply wave action caused the erosion. Scouring of the seabed might conceivably have been caused by storm-induced seaward-returning bottom currents (Johnson and Baldwin, 1986), but alternative processes, such as (1) erosion by internal waves (Baird et al., 1988); (2) lowering of sealevel; and (3) migration of mud banks (Allersma, 1971) have to be explored.

Submarine erosion surfaces (discontinuities) have been reported from black shales of the Devonian Genesee Formation in New York, and from the Upper Cretaceous Mancos Shale of Utah. They can be traced for many miles, and are covered with a lag deposit. In the Genesee Formation, erosion by internal waves migrating along the pycnocline has been suggested (Baird et al., 1988). Erosion caused by wave reworking due to lowering of sealevel has been suggested for the Mancos Shale (Swift et al., 1986).

As pointed out above, HCS beds suggest relatively shallow water for the Chattanooga Shale. Therefore, the areally extensive erosion surfaces that are capped with bone beds may indeed indicate lowering of sealevel and shelf mud reworking by waves.

However, the most common erosion surfaces in the Chattanooga Shale are those shown in Fig. 5. They seem to be a more local phenomenon, and their lack of lateral continuity and lag deposits suggests that they do not owe their origin to erosion by internal or surface waves.

Wind-driven currents are another possible cause for these erosion surfaces (Fig. 5). However, potential erosion by such currents generally diminishes with increasing water depth. The overstepping of the Nashville Dome by Upper Devonian sediments (Conant and Swanson, 1961; Ettensohn and Barron, 1981), as well as increasing paleocurrent consistency upward in the section (Fig. 7), indicates a gradual rise of sea level. Yet, despite increasing water depth, these erosion surfaces occur in both the Dowelltown and Gassaway members. This suggests that another cause for their formation has to be sought.

Yet another process that might produce the observed features of these erosion surfaces is mud-bank migration. Mud-banks have been reported from shelf as well as from deep sea environments (Allen, 1982; Allersma, 1971). However, a deep sea (contourite) origin can be excluded from further consideration because a compelling case can be made for shallow water deposition of the Chattanooga Shale in central Tennessee. In mud-banks from the Guyana shelf, annual periods of above average wind and wave action cause intermittent mud transport in a slurry-like flow. This process leads to deposition of inclined mud layers on the downstream side of mud banks (Rine and Ginsburg, 1985), whereas erosion and exposure of consolidated muds occurs in interbank areas. The resulting stratigraphic sequence should resemble outcrops of the Chattanooga Shale where submarine truncation surfaces were observed.

The observation that magnetic lineation and aligned shale particles are typical for the Chattanooga Shale of central Tennessee, suggests that current flow over the seabed and water circulation in the Chattanooga Sea was the norm rather than the exception. This conclusion is more compatible with the mud-bank hypothesis than with a scenario that relies on short lived erosive events (e.g. storms). However, the exact cause for the erosion surfaces discussed above needs to be investigated more thoroughly.

Ball and pillow structures generally indicate deposition on soft, water-saturated mud. The fact that they are rare in the Chattanooga Shale suggests that in most cases the mud substrate was sufficiently firm to withstand differential loading by overlying sand/silt beds, or that there was insufficient density contrast between silts and muds.

The observed association of HCS, convolute and chaotic bedding, and major submarine erosion surfaces in the Chattanooga Shale suggests a possible causal connection. Convolute bedding in association with erosion surfaces results for example from current drag in fluvial, tidal, and storm-dominated environments (Reineck and Singh, 1980). Chaotic bedding and complete disruption of sediment fabric occurs for example in collapse depressions on the Mississippi delta (Coleman and Garrison, 1977). They form in shallow-water sediments when impact by storm waves triggers sudden escape of methane gas bubbles and causes fabric collapse. The Chattanooga Shale is highly carbonaceous, and if deposited at the shallow depth suggested by HCS beds, its surface layers should have contained abundant gas bubbles from decay of organic matter (F"rstner et al., 1968). Destabilization by storm wave impact and/or drag by strong currents could then have produced convolute and chaotic bedding.

An alternative cause of sediment destabilization might be seismic shock. However, because of general tectonic quiescence in central Tennessee during the Late Devonian (Conant and Swanson, 1961), and because of localized occurrence and association with erosion surfaces, a seismic origin for the convolute and chaotic beds of the Chattanooga Shale is considered unlikely.

Absence of soft-sediment deformation below most HCS beds suggests that typically the associated storms did not impart sufficient energy to the seabed for sediment destabilization. Favourable conditions might have been brought about by excessively strong storms, lowering of sealevel, strong superimposed bottom currents, and combinations thereof.

Silt ripples in the Chattanooga Shale attest to bottom currents and traction transport of silt. Their presence and preservation also indicates that a firm substrate rather than a soupy organic muck was the norm during most of Chattanooga deposition. Flaser, wavy, and lenticular bedding in the lower Dowelltown Member of Hardin County, Tennessee, have many of the attributes of wave-generated ripples (De Raaf et al., 1977), and suggest deposition above wave base.

Eastern Portion of Basin

On the basis of Bouma sequences, siltstone beds in the Brallier Formation were interpreted as turbidites by Lundegard et al. (1985). Silt beds with base-truncated Bouma sequences were interpreted to reflect small-scale low-velocity turbidity currents, whereas thicker bedded siltstone bundles were interpreted to result from larger, high-flow-intensity turbidity currents, deposited in shallow channels or as lobes of higher energy turbidites. Uniform westward directed paleocurrents suggest multiple point sources (migrating delta distributaries) for turbidites along the eastern basin margin.

Preservation of turbidites in the Brallier Formation implies deposition below storm wave base, but the question of actual depth remains. Lundegard et al., (1985) suggested deposition on slopes with gradients comparable to those of modern lower-fans. Assuming a gradient of 0.06 degrees (Nelson et al., 1970), and a slope of approximately 100km width (Woodrow et al., 1988), one ends up with a depth of about 130m for the base of the clinoform. This suggests that the 100-200m depth estimate of Potter et al. (1982) is probably quite reasonable.

CONCLUSION

For the area between Hardin and DeKalb Counties (approx. 200km; Fig. 1), the Chattanooga Shale of central Tennessee is characterized by sedimentary features (HCS beds, lag deposits, erosion surfaces) that indicate deposition in comparatively shallow water (tens of metres). Paleoslope must have been negligible, and deposition on a shallow cratonic platform is indicated. Random paleocurrent patterns as observed for central Tennessee (Fig. 1) are consistent with that conclusion, because they indicate a lack of slope control on paleoflow (typical for shelf and epeiric seas).

Combining this conclusion with a 100-200m depth estimate for the eastern Appalachian Basin and with paleocurrent measurements from Clinch Mountain, leads to recognition of a peripheral trough that acted as a sediment trap

(Fig. 8B). Periods of abundant sediment supply may have led to a configuration as shown in Fig. 8A. However, further AMS work on the Brallier Member and its black-shale equivalent will be required to determine, if, as predicted, Brallier sedimentation filled this trough completely and established a smooth westward dipping paleoslope.

The suggestion that the laminated black shales of the Appalachian Basin accumulated in the deepest portion of a stratified basin has been a popular hypothesis for a number of years now (e.g. Byers, 1977; Potter et al., 1982; Ettensohn et al., 1988). However, for central Tennessee at least, observations reported in this paper are incompatible with their deposition in quiet stagnant water. Abundant evidence for current activity makes a pycnocline origin for these black shales appear doubtful.

In central Tennessee, prolonged operation of strong currents (on the order of 1 m/s) is suggested by the possibility of mud-bank migration. However, the question whether erosion surfaces and inclined shale beds are due to mud-bank migration will have to be investigated further.

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