DEVELOPING A SEQUENCE STRATIGRAPHIC FRAMEWORK FOR THE LATE DEVONIAN CHATTANOOGA SHALE OF THE SOUTHEASTERN U.S.A.: RELEVANCE FOR THE BAKKEN SHALE

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ABSTRACT

The Late Devonian Chattanooga Shale of Tennessee and Kentucky is in most areas a thin black shale fewer than 10 m thick. It is a distal equivalent to the almost 3000 m thick Catskill strata, and encompasses most of the Frasnian and Fammenian succession.

Although originally thought of as a continuously, though slowly, deposited deep water shale unit, the Chattanooga Shale shows internal erosion surfaces at various scales as well as storm deposits. These features suggest comparatively shallow water deposition (tens of metres water depth), and a stratigraphic record with numerous hiatuses of various duration. A number of erosion surfaces are laterally extensive and can be traced through the entire outcrop area (over distances of as much as 300 km). Erosion surfaces of this type are considered sequence boundaries *sensu* Vail, and tracing them has made it possible to subdivide the Chattanooga Shale into as many as 14 sequences.

These sequence boundaries are very subtle. The following features are indicative of their presence in a given outcrop: 1) sandy, silty, or pyritic lag deposits up to several centimetres thick; 2) sharp-based shale beds; 3) low-angle truncation of shale beds; 4) scoured surfaces; and 5) soft-sediment deformation in underlying shales. Tracing erosion surfaces from outcrop to outcrop is based on a combination of: 1) petrographic matching of lag deposits; 2) the petrography and microfabrics of individual shale packages; 3) conodont data; and 4) gamma-ray surveys.

Collection of additional conodont data and extension of this stratigraphic framework to adjacent areas may eventually lead to a comprehensive stratigraphic framework for the entire Late Devonian black shale complex of the eastern United States. Comparison between distal and proximal successions may allow differentiation of truly eustatic events from those due to tectonism and sedimentation.

The lower Bakken is of Late Devonian age and is probably equivalent to the upper half of the Gassaway Member of the Chattanooga succession. Cursory examination of drill core has shown lag deposits and evidence of erosional gaps. These features could be physical evidence of sequence boundaries that are traceable through careful examination of cores in conjunction with geophysical logs.

INTRODUCTION

The Chattanooga Shale is part of a thin, epicontinental black shale succession of Late Devonian age that was deposited over vast areas of the North American craton (de Witt *et al.*, 1993) at the distal end of a westward thinning clastic wedge. In central Tennessee the Chattanooga Shale overlies an unconformity, and in most areas its thickness does not exceed 10 m (Fig. 1). It has been subdivided into three members (Conant and Swanson, 1961). The lowermost member, the Hardin Sandstone, occurs only in southwestern Tennessee. Thought of as the deposit of a deep stagnant basin (*e.g.* Potter *et al.*, 1982; Ettensohn, 1985), recent investigations show that the Chattanooga Shale accumulated in relatively shallow water, prone to influence by storm waves and episodic erosive events (Schieber, 1994a, 1994b, 1998). Erosive events of variable strength and/or duration are indicated by truncation surfaces, beneath which from a few centimetres to more than a metre of section is missing. Hummocky cross-stratified sand/silt beds and mud tempestites indicate that the seabed was close to or within reach of storm waves (Schieber, 1994a). Widespread but subtle bioturbation features suggest that bottom waters were not as anoxic as is commonly believed (Schieber, 1994a).

"Pure" shales pose a challenge to the stratigrapher, because they are not easily differentiated. The recognition that mudstone properties vary systematically at several significant scales, and that these variations are controlled by depositional environment and stratal stacking (Bohacs, 1998), provides opportunities for advances in analyzing the stratigraphy of mudstones. Stacking of mudstone sequences that are separated by erosion surfaces and their correlative conformities can be found in a wide range of depositional settings (Bohacs, 1998; Schutter, 1998), and suggests that sequence stratigraphic approaches can be successfully applied to a wide range of mudstone successions.

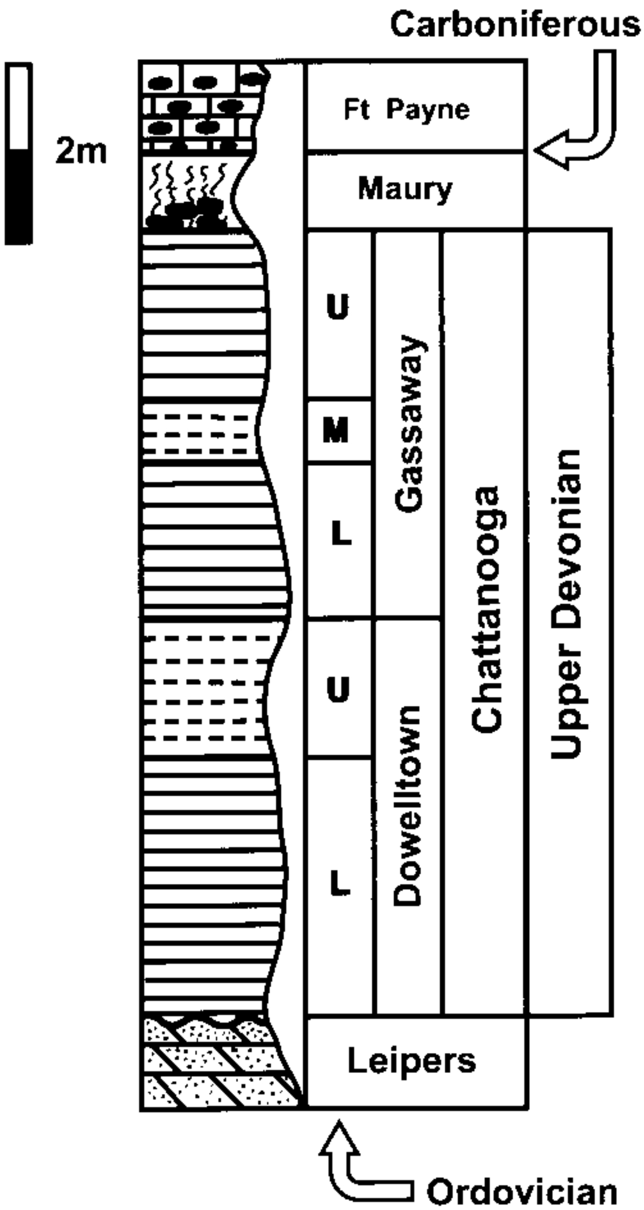

Figure 1: Stratigraphic overview for the type Chattanooga Shale east of the Nashville Dome. The Chattanooga Shale is about 9 m thick in that area. It unconformably overlies the Ordovician Leipers Formation and is in turn overlain by the Tournaisian Maury Formation. The subdivision into Dowelltown and Gassaway members is by Conant and Swanson (1961). Their informal subdivision of these members into lower, middle, and upper portions (left column) is only applicable to the area between sections 1 through 8 (Fig. 2; location map), and is based on the occurrence of softer weathering grey to dark grey shale interbeds (dashed lines) that separate black shale (solid lines).

Sedimentologic study of the Chattanooga Shale also reveals that previous stratigraphic correlations between the western and eastern portion of the Nashville Dome are in error. Tracing of major erosion surfaces within the Chattanooga Shale shows them to be continuous over large distances. These erosion surfaces are therefore viewed as sequence boundaries and have been utilized to redefine the internal stratigraphy of the Chattanooga Shale.

EROSION SURFACES IN THE CHATTANOOGA SHALE

Erosional features in the Chattanooga Shale range from mm-deep scours at the base of silt beds to broad trough-like features that may cut as deep as 0.6 m in a given outcrop. Over larger distances it can be demonstrated that as much as 1.5 m of shale has been removed beneath some erosion surfaces. As long as underlying beds are truncated at an angle, these erosion surfaces are comparatively easy to recognize (Schieber, 1994a, b; 1998), but once they are conformable to underlying beds they are not immediately detected. In order to improve recognition in the latter scenario, associated sedimentary features were evaluated (Table 1).

All erosional features in the Chattanooga Shale may be associated with lag deposits (Table 1) that can be ranked by likely depth of erosion. Sand lags and bone beds indicate erosion on the order of $X*10^2$ cm; pyritic lags $X*10^1$ cm; silt lags and conodont lags $X*10^0$ cm; and *Lingula* lags $X*10^{-1}$ cm (Schieber, 1998). Lag deposits are the most easily recognizable indicators of erosion surfaces. Major erosion

Table 1. Sedimentary features associated with erosion surfaces.

Feature	Ease of Recognition	Significance
Silt lags	in outcrop, careful examination reveals thicker beds (>5 mm); in hand specimen and on cut surfaces, beds of 1-2 mm thickness readily seen.	with major erosion surfaces when several cm thick
Sand lags	in outcrop, careful examination typically reveals coarser beds, 5-20 mm thick; in hand specimen and on cut surfaces, beds of 1-2 mm thickness readily seen.	typically with major erosion surfaces
Bone beds	typically a variant of sandy silty lags, with comparable ease of recognition; larger bone fragments readily recognizable with hand lens on fresh surfaces.	typically with major erosion surfaces
Pyritic lags	in outcrop, thicker pyritic lags, 10 or more mm thick, may be recognized via rusty stains or crusts of secondary white and yellow hydrous ferric sulphates; in hand specimen, layers as thin as 1 mm are readily seen on fresh surfaces.	typically with major erosion surfaces
Conodont lags	may form a variant of sandy/silty lags, with comparable ease of recognition; mostly as layers of concentrated conodont material, 1-3 mm thick, that are best observed in hand specimen (bedding plane examination with hand lens).	mostly with minor erosion surfaces
Lingula lags	in outcrop and hand specimen, easily recognized only when shale is split along bedding planes; in thin section, shell cross-sections easily identified, but may be missed when shells are sparse on surface.	mostly with minor erosion surfaces
Low angle truncations	typically not recognizable in outcrop; best recognized on cut/polished surfaces and in oversize thin sections.	with major and minor erosion surfaces
Soft sediment deformation	deformation on the scale of tens of cm (*e.g.* with associated ball and pillow structures) can be recognized in outcrop; small scale deformation (mm to cm) best recognized on cut surfaces and in thin section.	with major and minor erosion surfaces
Sharp based shale beds	recognition easiest on cut and polished surfaces and in thin section; difficult and tentative in outcrop.	typically with major erosion surfaces

surfaces may be associated with sand lags, bone beds, pyritic lags (reworked concretionary pyrite, pyritized burrow tubes, pyritized fossils, *etc.*), and thick silt lags (Table 1). In absence of a lag deposit, other sedimentary features, such as low-angle truncations of laminae, soft-sediment deformation and sharp-based shale beds may be indicative (Table 1).

Sharp-based shale beds are black shale beds with a sharp and even erosional base that conformably overlie other black shale beds. They tend to be slightly more weathering resistant owing to a higher organic matter content, and are finely laminated and nonbioturbated. Although there may only be subtle compositional differences between the black shales below and above the erosion surface, these beds tend to stand out in outcrop. The erosion surface needs to be verified through thin section examination.

Deeply cutting (erosion in excess of 50 cm) erosion surfaces in the Chattanooga succession can be traced from outcrop to outcrop over distances in excess of 50 km. They show incision, random paleocurrent indicators and storm wave reworking of lag deposits (HCS). Considering the degree of consolidation of some of the shales, the current

Table 2. Outcrop to outcrop correlation of suspected sequence boundaries.

	Definition of Sequence Boundaries
Depth of erosion	In at least one outcrop, the visible depth of erosion should equal or exceed 50 cm.
Lateral extent	The erosion surface should be traceable over a distance of 50 km or more.
	Tracking Sequences, Sequence Boundaries and their Lateral Equivalents
Lag petrography	Composition of lags can be unique. With knowledge of the overall stratigraphy they can be connected between adjacent outcrops.
Sharp-based shale beds	Resistant, finely laminated black shale beds that conformably overlie erosion surfaces. These beds mark shale-on-shale erosion surfaces in absence of lags, but can be conspicuous due to higher weathering resistance.
Resistant black shale ledges	Petrographically very similar to sharp-based shale beds, but no visible erosion surfaces. Deposit on deeper water flooding surface?
Gamma-ray spectroscopy	Measuring K, U, Th, and total gamma-ray radiation at 10 cm intervals. Erosion surfaces show up as shifts in gamma-ray curves, which helps to identify erosion surfaces where lags were not found or where exposure is not optimal.
Lithology	Successive shale bodies typically have compositional and textural characteristics that distinguish them from lithologies above and below. In most cases there is comparatively little lateral variability for units between two erosion surfaces.
Fossil content	Lateral comparison of conodont faunas. Traces of *Protosalvinia/Foerstia*, a fossil seaweed of short stratigraphic range.

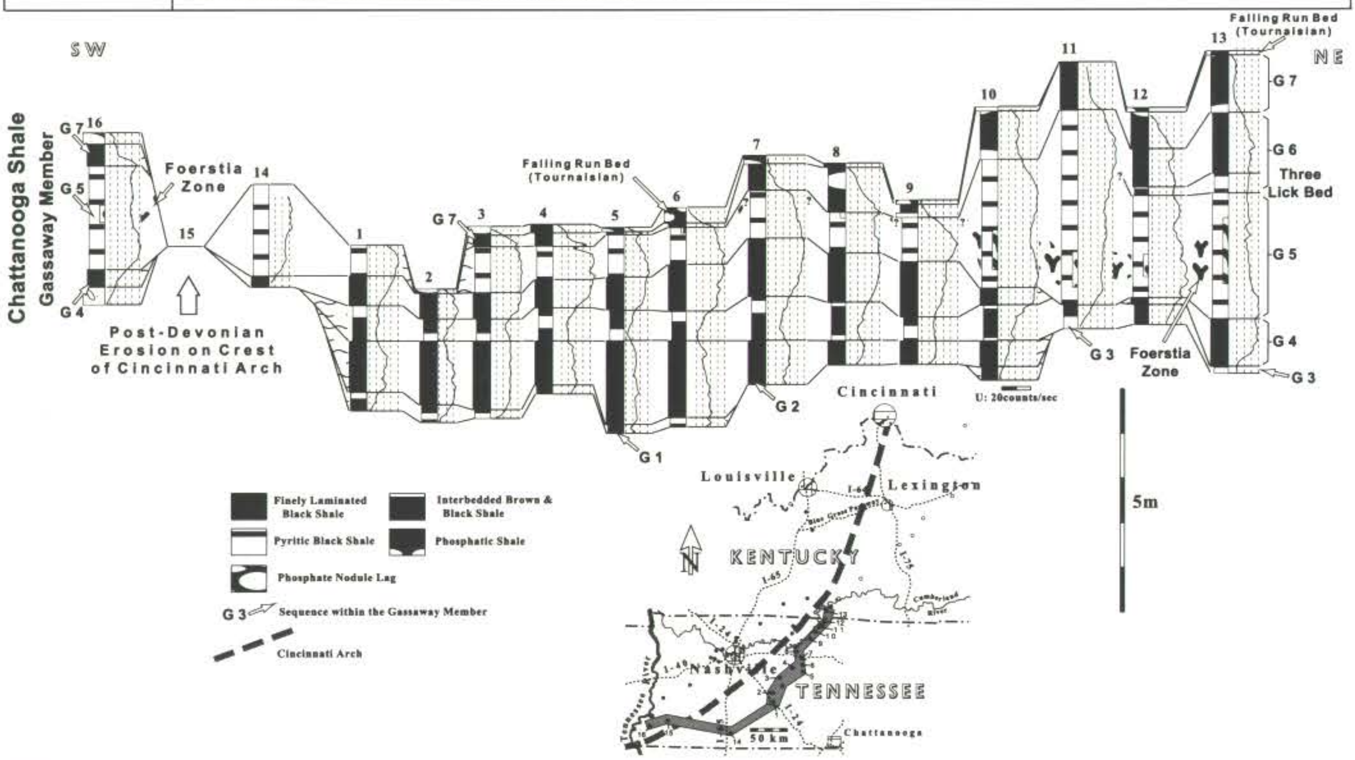

Figure 2. Correlation of sequences in the Gassaway Member for 13 sections along the Southern and Eastern Highland Rim of central Tennessee (the grey shaded area in the location map). The crest of the Cincinnati Arch is marked with a broad dashed line. The Gassaway Member is subdivided into 7 sequences (G1 through G7) that are marked with arrows or brackets. Measured stratigraphic sections are marked with black dots and circles. Numbers above sections correspond to numbers along section line (location map). The *Foerstia* Zone is characterized by fossil seaweed known under the names *Foerstia* and/or *Protosalvinia* (Ettensohn *et al.*, 1989). The Falling Run Bed is found at the base of the Maury Formation in many places and consists of phosphate nodules reworked from the underlying Chattanooga Shale. The legend illustrates rock types and symbols. Gamma-ray logs are for U.

velocities necessary to erode them would have been in excess of 150 cm/s (Schieber, 1998). These observations indicate comparatively strong wave action during the formation of major erosion surfaces, and suggest formation as a result of sea level lowering and intensified wave reworking. Considering their large lateral extent, it is very likely that these erosion surfaces are indeed sequence boundaries in the sense of Vail *et al.* (1991).

A multifaceted approach was used to correlate suspected sequence boundaries between outcrops (Table 2). Sequence boundaries in the Chattanooga Shale seem to be largely of subaqueous/shallow marine origin, although some very thick lag deposits that occur near the crest of the Cincinnati Arch may have been subaerially exposed. Judging from their relative position to the Cincinnati Arch, thick sandy lag deposits (tens of centimetres thick) were deposited in shallowest water, thin lags (centimetres thick) and simple erosion surfaces formed farther offshore, and nonbioturbated black shale bodies without indications of basal erosion formed in comparatively deep water.

How the outlined approach yields a workable internal stratigraphy of shale units that otherwise would be difficult to subdivide is illustrated in Figure 2 and summarized in Table 3. The figure shows the internal stratigraphy of the Gassaway Member, the upper portion of the Chattanooga Shale. Sections 16, 15, 14, and 1 (Fig. 2) show, for example, the influence of the Cincinnati Arch as a positive element in that Gassaway sequences G1 through G3 pinch out between sections 1 and 14. No Gassaway is preserved at section 15 because of post-Devonian removal of these sediments. Sections 1 through 6 are comparatively distal to the arch, and thus the lower sequences (G1 through G3) are present, albeit of variable thickness (Fig. 2). Closer to the arch from section 6 to 9, lower sequences pinch out or thin (Fig. 2), and even closer towards section 13, sequence G3 almost disappears.

We also see that erosion has cut down to variable depths into sequences G3 and G4, and its effect is most severe in localities close to the Cincinnati Arch. In sequence G5, the position of the *Foerstia* Zone or its absence also attests to a significant erosional episode prior to deposition of the next sequence (Fig. 2). Unit G6, a combination of the Three Lick Bed and overlying black shales, is missing in southern sections, and so was either completely eroded or not deposited. The Three Lick Bed is a widespread marker in the Late Devonian black shale succession of the United States (Provo *et al.*, 1978; de Witt *et al.*, 1993). Sequence G7, a black shale with diagenetic phosphatic nodules and apparently distributed along the section line, was eroded in part or in places completely removed (sections 1, 14, 15) in post-Devonian time. In places, these phosphate nodules have been reworked into a lag of Tournaisian age, the so called Falling Run Bed (Hasenmueller, 1993).

SEQUENCES IN THE CHATTANOOGA SHALE

Conant and Swanson (1961) report that the lowermost unit, the Hardin Sandstone, grades upwards into the Dowelltown Member and is its lateral equivalent, and that locally there are erosional contacts between the Dowelltown and Gassaway members and between the Gassaway Member and the overlying Maury Formation. They were, however, of the opinion that overall there was not much of an erosional gap between the Dowelltown, Gassaway and Maury, and that in many areas deposition was more or less continuous across those contacts. Later work in northern outcrop areas indicates that at least the contact between the Gassaway Member and the Maury Formation is marked by a substantial disconformity (Ettensohn *et al.*, 1989).

The sections that were measured along the line shown in Figure 2 not only contain the Gassaway Member, but also other Devonian strata that were described as Dowelltown and Hardin by Conant and Swanson (1961). These strata have been subdivided into sequences (Table 3) following the same approach as illustrated above for the Gassaway Member (Fig. 2). When the sequences are correlated from outcrop to outcrop, a restored cross-section like that in Figure 3 results. It is readily apparent that the Gassaway Member overlies older strata with a substantial unconformity, and that parts of the Gassaway have been removed by post-Devonian erosion. Variable thickness and internal pinch-out of individual shale beds are reflective of erosional surfaces within the major bodies (Table 3).

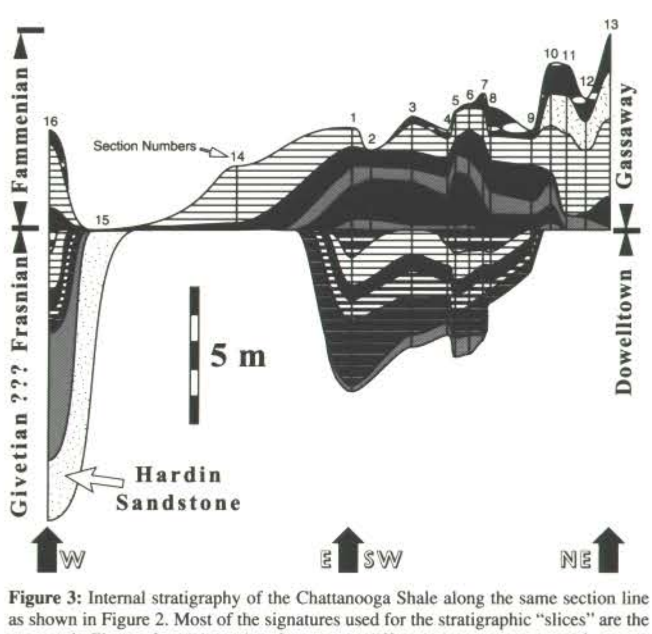

Figure 3: Internal stratigraphy of the Chattanooga Shale along the same section line as shown in Figure 2. Most of the signatures used for the stratigraphic "slices" are the same as in Figures 2 and 4, but in a few cases a different signature was used for better contrast. The datum is the Dowelltown/Gassaway contact (approximately the Frasnian/Fammenian boundary). Section numbers correspond to section numbers in Figure 2.

Broadly speaking, the Chattanooga Shale as described by Conant and Swanson (1961) can be subdivided into three lithologic bodies that are separated by regional erosion surfaces (Table 3). The lowermost includes the Hardin Sandstone (Conant and Swanson, 1961) and some overlying black shales with interbedded sandstones, and has been correlated with the Blocher Formation as defined in central Kentucky (Ettensohn *et al.*, 1989). The middle body is essentially the Dowelltown Member (Conant and Swanson, 1961), and the uppermost body is the Gassaway Member (Conant and Swanson, 1961). Within each up to seven sequences are recognized. Conant and Swanson (1961) considered strata of the lowermost body (Table 3) to be lateral equivalents of the Dowelltown Member body but the two bodies are in fact separated by a substantial erosional gap.

Under the assumption that the erosion surfaces are sequence boundaries, and given that sequence boundaries probably form over relatively short time periods (Mitchum *et al.*, 1977), the sequences of Figure 3 can be organized into an approximation of a chronostratigraphic chart, so that the vertical dimension is representative of time, not just rock thickness (Fig. 4). Individual sequences are shown as horizontal slices bounded by erosion surfaces. For each slice, the shape of the lower boundary reflects whether or not deposition occurred on a fairly flat surface, or whether it was moving up onto positive elements (such as the Cincinnati Arch), and the shape of the upper boundary reflects the amount of erosion at the top of the sequence. The shape of individual slices will probably undergo some modification once more conodont data are incorporated into the current data set, but the overall arrangement of sequences is well established through lateral tracing of their boundaries.

BLOCHER EQUIVALENTS

Blocher equivalent rocks lie mainly along the western side of the Cincinnati Arch. Correlation with the Blocher Formation in Kentucky (Ettensohn *et al.*, 1989) has been made by comparison of lithologic and sedimentary features (Table 3). The Blocher Formation was originally defined from the basal part of the New Albany Shale in Indiana *(e.g.*

Table 3. Sequences in the Chattanooga Shale.

SEQUENCE	MEMBERS
	Gassaway Member
G7	Dense, bluish weathering black shale with incorporated phosphate nodules. In places erosional lags with scours and conodont concentrations at base.
G6	Finely laminated black shale. The base includes the Three Lick Bed. The Three Lick Bed is a marker (deWitt *et al.*, 1993) that consists of three bioturbated grey-brown shale beds that alternate with black shale. Total thickness is approximately 20-40 cm in northern Tennessee and south-central Kentucky.
G5	Finely laminated pyritic black shale. Many layers with pyrite-enrichment. These include hiatal deposits with abundant pyritized fecal pellets (Schieber, 1998), disseminated pyrite in shale matrix and pyrite-cemented silt layers and lenses. This interval also includes the *Protosalvinia/Foerstia* Zone (deWitt *et al.*, 1993).
G4	Finely laminated black shale, erosional base on G3.
G3	Alternating beds of bioturbated grey-brown shales and black shale. Bed thickness varies from 1 to 15 cm. Black shale beds are bioturbated from the top down. This unit is equivalent to the middle portion of the Gassaway Member as defined by Conant and Swanson (1961). Base of unit is marked by the "varved bed" of Conant and Swanson (1961).
G2	Finely laminated black shale, erosional base.
G1	Finely laminated black shale with thin interbeds (5-20mm) of bioturbated brown shale. Sharp basal contact with Dowelltown Member representative of regional erosional surface.
	Dowelltown Member
D5	Interbedded brown, black, and grey shale. Brown and black shale dominant variable degrees of bioturbation. Regional erosion causes unit to be absent in places. Base of unit marked by a pair of hard black shale beds (essentially nonbioturbated in most places).
D4	Interbedded grey, brown, and black shale. Grey shale approximately 50%. At base of unit minor erosional features and a resistant black shale (horizontal silty laminae, largely no bioturbation).
D3	Interbedded black, brown, and grey shale. Bioturbated black shale dominates interval (>50%). At base of unit a resistant black shale (horizontal silty laminae, no bioturbation).
D2	Interbedded brown and black shale. Brown shale homogenized by bioturbation; black shale shows a variety of burrow tubes. In places scoured surface with lag deposit at base.
D1	Thickly bedded black shale with thin interbeds of bioturbated brown shale. Erosion surface with sand lag/bone bed at base.
	Blocher Equivalents
B2	Interbedded carbonaceous shale and sandstone. Proportion of shale increases upwards. HCS beds, wave and current ripples, conspicuous bioturbation in shale and sandstone. Scattered dolomite grains in shale matrix and as cement in sandstone. Dolomite content increases towards Kentucky. Top of unit shows in places angular truncation beneath essentially flat erosion surface. Additional truncation surfaces recognized, but tracing difficult.
B1	Hardin Sandstone and lateral equivalents (Conant and Swanson, 1961). Mostly a fine-grained, thick and even-bedded sandstone that shows remnant horizontal lamination. Top appears truncated and overlain by bed of heavily bioturbated sandstone.

Lineback, 1970) and its distribution in Kentucky has been described by Ettensohn *et al.* (1989). Its age is still in dispute. Ettensohn *et al.* (1989), based on conodont collections from Kentucky outcrops, are of the opinion that the Blocher is as old as lower to middle Givetian, that it extends into the lower Frasnian, and that its upper portions have been removed by erosion. In contrast, a study of conodonts from the Blocher in Indiana (Illinois Basin) indicates the Blocher to be of lower to middle Frasnian age (Sandberg *et al.*, 1994). Lineback's (1970) study also suggests a Middle Devonian (Givetian) to lower Upper Devonian (Frasnian) age based on comparison with the European conodont zonation. Part of the problem may be that the Blocher Formation is diachronous over larger distances (it onlaps the Cincinnati Arch and is eroded at the top), and thus the data may bracket the entire time of Blocher deposition. The question deserves further investigation. Preliminary examination of samples from Blocher sections in Tennessee and southern Kentucky indicates the presence of Givetian conodonts (J. Barrick and J. Over, pers. comm.).

On the basis of disseminated dolomite in the basal Chattanooga sequence on the eastern side of the Cincinnati Arch and capping of the sequence by a well developed erosion surface, the basal black shale in sections 1 through 6 has been assigned to sequence B2 (Table 3, Fig. 4). If additional conodont data should show that this shale does not overlap with strata assigned to B2 on the western side of the Cincinnati Arch (Fig. 4), it may have to be reassigned to

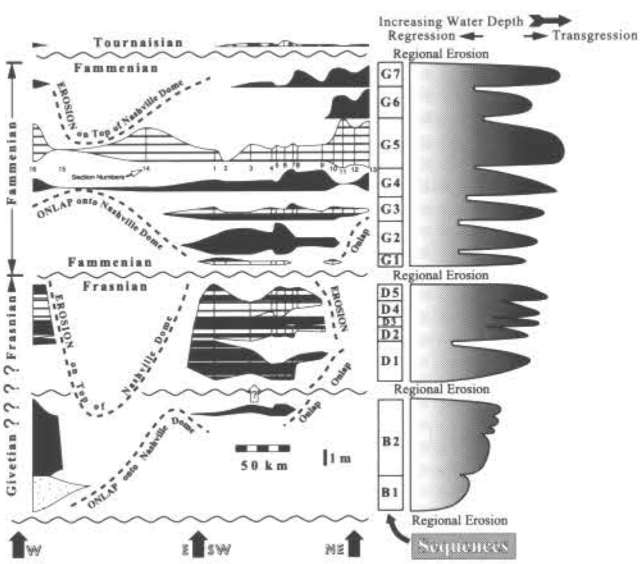

Figure 4. Chronostratigraphic presentation of Chattanooga sequences. The succession forms three members that are separated by regional erosion surfaces. Geometric presentation of sequences takes into account observed amounts of erosion on top, and perceived onlap on the Cincinnati Arch/Nashville Dome. The apparent gaps between sequences D2, D3, and D4 northeast of section 3 are an artifact of the current presentation. The vertical dimension of slices is the actual sequence thickness, and the sequences thin due to smaller rates of deposition closer to the arch. Sea-level curve at right based on synthesis of currently available data. The question marks between Givetian and Frasnian indicate uncertainty about the exact age of the lowermost member (Table 3). Section numbers correspond to section numbers in Figure 2.

the Dowelltown (Table 3), in effect increasing its number of sequences from 5 to 6.

DOWELLTOWN

Strata assigned to the Dowelltown Member occur primarily east of the crest of the Cincinnati Arch (Fig. 2, location map) and are essentially Frasnian (Hass, 1956). West of the arch, comparable rocks are found only in the southwestern corner of the study area (locality 16, Fig. 2, location map). There the Dowelltown exhibits a lower black shale and an upper interbedded black, grey and brown shale, as observed east of the arch. The main difference is that the black shales in the lower portion contain sandstone interbeds. The Dowelltown at locality 16 is in erosional contact with the underlying sequence B2. Angular truncation of B2 strata can be observed in outcrop. Conodont studies by Hass (1956) show that the Dowelltown at locality 16 correlated lithologically and temporally with the Dowelltown east of the arch.

Conant and Swanson (1961) did not recognize the Blocher equivalents along the west side of the Cincinnati Arch and instead included them in the Dowelltown. This caused their maps and fence diagrams to show Dowelltown strata in many areas where they in fact do not exist. Nonetheless, the fact that *bona fide* Dowelltown strata occur on both sides of the Cincinnati Arch (Fig. 4) indicates a wider distribution at one time across the arch in many areas. Prior to Gassaway deposition, however, large portions of the western flank of the arch were substantially eroded and in all but one area (locality 16) the western Dowelltown was completely removed. Clearly, a regional hiatus separates Dowelltown and Gassaway strata.

Although erosional features have been observed in many areas (Schieber, 1998), the upper portion of the Dowelltown Member has yielded little evidence of significant erosion of the type observed in the Gassaway Member (Fig. 2). Instead, shale beds as thin as 2-3 cm (Fig. 5) show remarkable lateral continuity. In a few places erosional cutouts of up to 10 cm depth can be documented but appear to be local. Such irregularities cannot be correlated over long distances.

Lateral continuity has been studied in detail for sequence D4 at locality 6 (Fig. 6). Although there is significant lateral change in thickness from 10 cm to a few metres in many beds, they are nonetheless continuous (Fig. 6). Variations in the degree of bioturbation seem to be the main cause for lateral thickness variability (Lobza, 1998) and, locally, completely obliterates thin black shale beds. Thin silt lags in D4 (Fig. 6) mark minor erosion in the order of a few centimetres and do not cause lateral disruptions of the underlying succession. The lateral continuity exhibited by beds in sequences D2, D3, and D4 over a distance of about 70 km (Fig. 5) suggests that conclusions from the detailed study at locality 6 (Fig. 6) can be applied to this interval as a whole.

As presented, the boundaries between sequences D2, D3, D4 and D5 are thought to be marked by the base of nonbioturbated, indurated, massive black shale (Table 3, Fig. 5). Although the latter could equally well be interpreted as "classic" mid-sequence condensed sections (Bohacs, 1998), there are several reasons to suggest that they are basal in the depositional sequences. For example, by petrographic and sedimentologic comparisons, these black shales are similar in appearance to the weather-resistant, finely laminated black shales (the sharp-based shale beds) that overlie with deep erosion and lag deposits *bona fide* sequence boundaries elsewhere in the Chattanooga Shale. In places one can also find subtle evidence for erosional truncation of shales underlying massive black shale that initiates sequences D3 and D4. That carbonaceous shales are also found atop basal disconformities in other stratigraphic successions (*e.g.* Leithold, 1993) further indicates that these black shale beds can be interpreted as basal to sequence.

Standard sequence stratigraphic models were developed for rapidly subsiding continental margins with high sedimentation rates (Hallam, 1992). For the study of cratonic sedimentation with extensive stretches of shallow seas, no noticeable shelf-slope break and low sedimentation rates, the underlying principles of sequence stratigraphy are still valid, but the model needs to be modified to reflect the different conditions. Whereas in proximal sections carbonaceous shales are typically best developed about the mid-sequence downlap surface, in distal settings the organic-rich "tails" of parasequences tend to condense into a continuous carbonaceous shale at the base of the sequence (Bohacs, 1998).

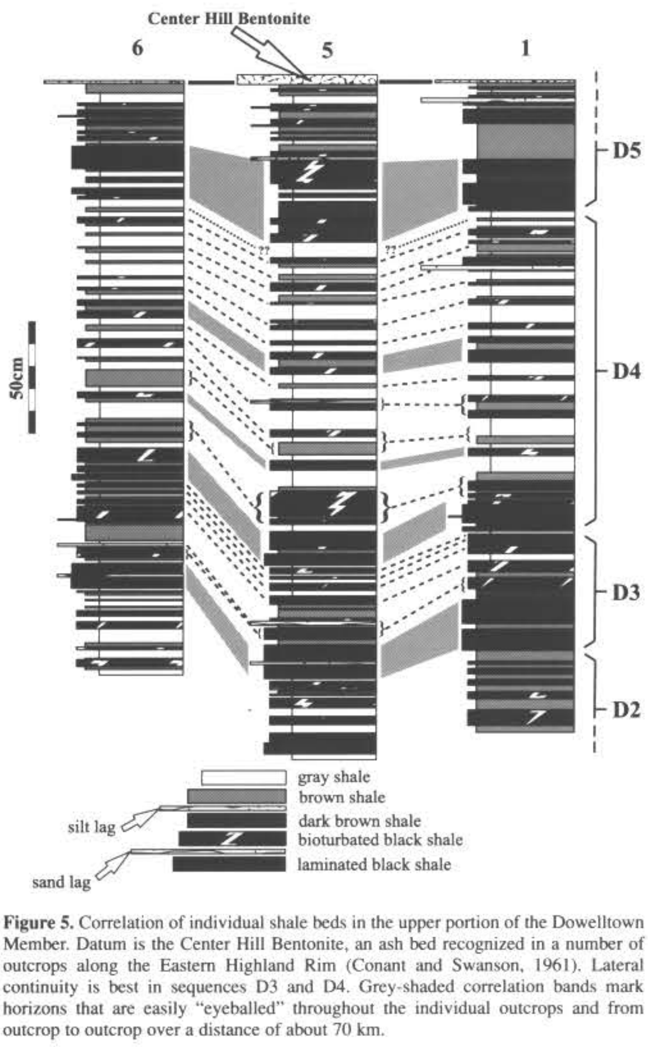

Figure 5. Correlation of individual shale beds in the upper portion of the Dowelltown Member. Datum is the Center Hill Bentonite, an ash bed recognized in a number of outcrops along the Eastern Highland Rim (Conant and Swanson, 1961). Lateral continuity is best in sequences D3 and D4. Grey-shaded correlation bands mark horizons that are easily "eyeballed" throughout the individual outcrops and from outcrop to outcrop over a distance of about 70 km.

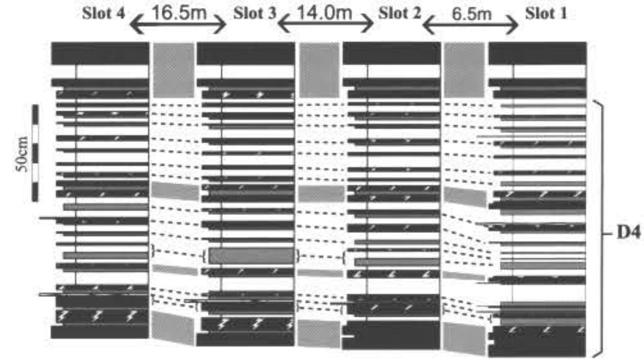

Figure 6. Correlation of shale beds in sequence D4 within a single outcrop (locality 6). Legend and symbols as in Figure 5. Lateral thickness variability of shale beds is apparent, as is the fact that beds can be traced across the outcrop despite this variability which is to a large degree due to bioturbation (Lobza, 1998). Although there are locally thin silt lags, all beds are essentially continuous.

The rhythmic sedimentation displayed by black/grey couplets within Dowelltown sequences D2 through D5 poses another interesting question. Does this reflect climatic variations (Milankovitch cycles) or is it an expression of distal parasequences? Jaminski *et al.* (1998) have presented a model where decimetre-scale variations in the Ohio Shale are explained through climatic variations, and Schieber (1995) provided estimates of cycle frequencies in the Chattanooga Shale that were within the Milankovitch band. Alternatively, the alternation of black and grey shales could be seen as stacked distal parasequences, where each black shale bed represents a flooding event and each grey shale bed is the distal expression of a progradational wedge. Creaney and Passey (1993) have described distal marine shales that are composed of stacked sedimentary units with high TOC values near the base. They also point out that time lines converge, but do not terminate, in distal organic parts of a sequence, similar to what is observed in sequences D2 through D5. Resolution of this question awaits further work.

GASSAWAY

Strata of the Gassaway Member have the widest distribution. They occur on both sides of the Cincinnati Arch and are continuous across it (Fig. 7). Hass (1956) found Fammenian conodonts in the Gassaway, an identification that has been confirmed by Ettensohn *et al.* (1989). The internal stratigraphy of the Gassaway Member in relationship to the Cincinnati Arch has already been discussed above (Fig. 2). Because the stratigraphic break that marks the Dowelltown/Gassaway boundary apparently includes the Frasnian/Fammenian boundary (Hass, 1956), the onset of Gassaway deposition is likely due a major transgressive event at the beginning of the Fammenian (Johnson *et al.*, 1985).

Figure 7 shows that sequences G1 through G4 recognized east of the arch (Fig. 2) are not present in the west except in a few areas where a thin G4 is found at the base. This implies that during the Fammenian, the western flank of the arch was inundated much later then the eastern flank. Sequence G6 pinches out over the crest of the arch (Fig. 7, section 11), and lag deposit and scouring at the base of G7 suggest erosive removal. The additional widespread and deep erosion under sequence G5 (Fig. 4) implies a hiatus between G5 and G7. This conclusion is also expressed by Hass (1956) and Klapper (pers. comm, 1997) on the basis of conodont distribution.

Overall, Gassaway black shales contain more organic matter than black shales of the underlying Dowelltown Member. From a black shale perspective, these are the "best" and toughest weathering of the Chattanooga black shales. Yet, within the Gassaway there seem to be more significant hiatuses than in the less carbonaceous Dowelltown Member (Figs. 2, 4, 7). In the latter, sequences D2 through D5 show lateral continuity of beds over large distances (Fig. 5). Conventionally, one would think that the much more organic-rich Gassaway shales were deposited under more restricted, supposedly deeper water conditions than the less carbonaceous and conspicuously bioturbated (Lobza, 1998) Dowelltown sequences (Fig. 5) and therefore that the Dowelltown should have more discontinuities and erosional hiatuses. This relationship is a good indication that oxygen levels and water depth were probably not the main controls on the accumulation of Late Devonian black shales in central Tennessee (Schieber, 1994a).

CHATTANOOGA SHALE DISCUSSION

The Chattanooga Shale contains numerous erosion surfaces that represent variable scales of erosion. The more significant of these can be traced over large distances and are considered sequence boundaries that reflect temporary lowering of sea level. Recognizing and tracing these surfaces have allowed a 14-fold stratigraphic subdivision of the Chattanooga Shale. These sequences onlap the Cincinnati Arch/Nashville Dome as well as reveal erosional loss of section on the crest of the arch. The regional erosion surfaces separate the succession into three members (Fig. 4).

Ongoing conodont studies by Jeff Over, SUNY Geneseo, will probably allow these sequences to be correlated with the stratigraphic successions in the Illinois, Michigan, and Appalachian basins. This should lead to a coherent stratigraphic framework and allow detailed examination of Late Devonian uplift and subsidence in the eastern black shale region. Comparing proximal sections (New York) with those of distal (Kentucky/Tennessee) and very distal areas (Iowa) should allow differentiation between sequences that owe their origin to tectonism and/or sedimentation controls and those that are of truly eustatic origin. The considerable

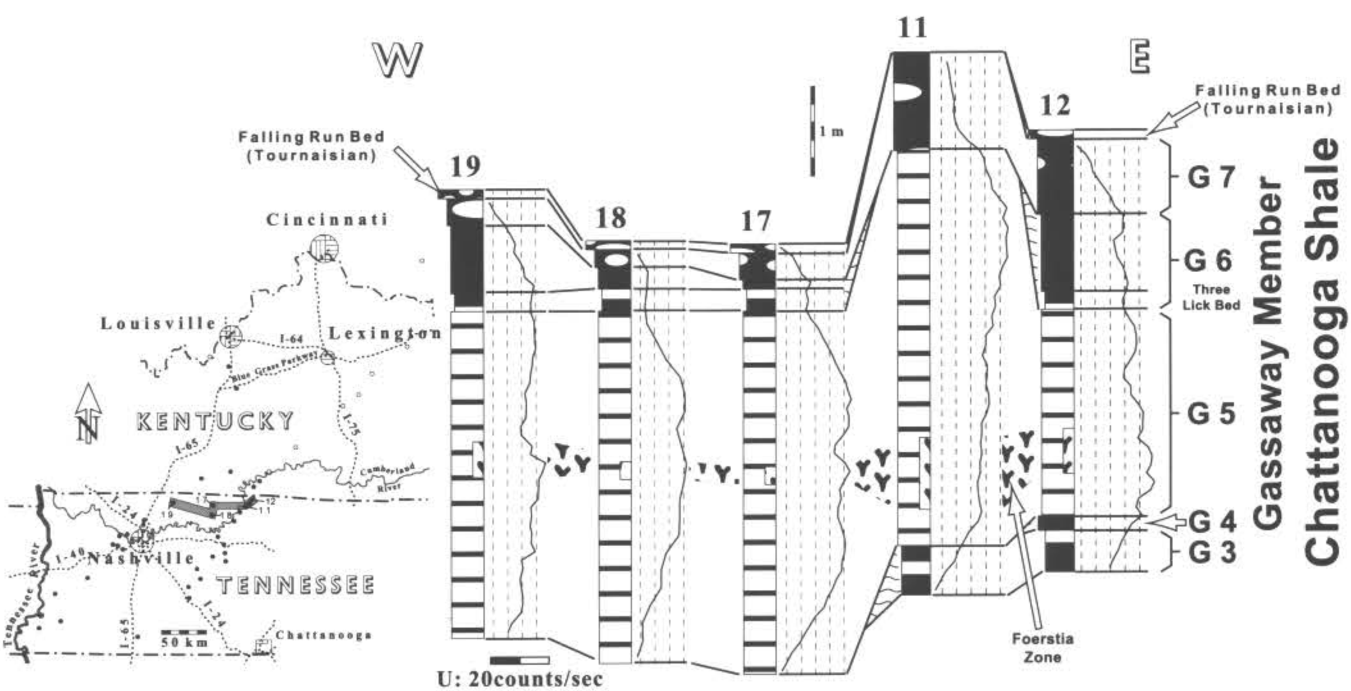

Figure 7. Correlation of Gassaway sequences across the crest of the Cincinnati Arch in north-central Tennessee. See map at left for section line and section numbers. Symbols and rock types as in Figure 2.

dynamics revealed by the sedimentology and internal stratigraphy of the Chattanooga Shale challenge the traditional assumption of a deep stagnant basin, and requires rethinking with regard to the origin of Late Devonian black shales in the United States.

COMPARISON WITH THE BAKKEN SHALE

The Bakken Formation of the Williston Basin straddles the Devonian/Mississippian boundary (Meijer-Drees and Johnston, 1996) and is subdivided into three units. The lower Bakken is essentially a highly carbonaceous, finely laminated black shale, the middle Bakken is characterized by sandstones and siltstones, and the upper Bakken is again a black shale unit.

Meijer-Drees and Johnston (1996) recovered Late Devonian conodonts from the lower Bakken. This basal unit overlies an erosional surface. Its deposition commenced during the lower *expansa* Zone. The contact with the overlying middle Bakken sandstones is erosional as well, and more or less coincides with the Devonian/Mississippian boundary (Meijer-Drees and Johnston, 1996). In Kentucky and Tennessee the *expansa* Zone coincides with shales that contain the *Foerstia/Protosalvinia* Zone (Ettensohn *et al.*, 1989). Thus, the lower Bakken is probably a lateral equivalent of Gassaway sequences G5, G6, and G7. Conodont data suggest that the Sunbury Shale of Ohio is a likely equivalent to the upper Bakken (Meijer-Drees and Johnston, 1996; Ettensohn *et al.*, 1989), which would make the Falling Run Bed and the Maury Formation (Figs. 1, 2) lateral equivalents of the middle Bakken.

The lower Bakken closely resembles upper Gassaway black shales in that it is highly carbonaceous and finely laminated. It differs in that it (1) contains disseminated dolomite and (2) by and large lacks the fine silt laminae that are ubiquitous in black shales of the Gassaway Member (Schieber, 1994b). The latter feature suggests deposition at a greater water depth than assumed for the upper Gassaway (Schieber, 1994b). Smith and Bustin (1996) suggest that the lower Bakken was deposited at considerable water depth (200 m or more). In my own examination of lower Bakken cores, I noted thin lag deposits (coarse sand size) that contained reworked pyrite grains, pieces of pyritized shell material (from *Lingula*?), phosphatic remains (fish bones, conodonts), quartz grains (reworked quartz-filled *Tasmanites* cysts? Schieber, 1996) and clasts of black shale. Lags of this type were also noted by Smith and Bustin (1996) and were interpreted as the product of low intensity bottom currents.

These lags are similar in thickness and composition to lags on sequence boundaries in the Chattanooga Shale (Schieber, 1998). Within the time interval covered by the lower Bakken, three sequences are recognized within the Chattanooga Shale (G5, G6, G7; Fig. 2). Thus, these lags may provide the basis for a sequence stratigraphic differentiation of the lower Bakken and yield surprising new insights upon careful examination. Correlation of thin lags is difficult in the subsurface, but evaluation of various log responses in conjunction with TOC data (an approach used by Creaney and Passey, 1993) may prove effective.

CONCLUSION

Although black shales are traditionally thought of as deep-water deposits containing a more or less continuous record of deposition, recent observations on the Chattanooga Shale suggest otherwise. Long distance tracing of erosion surfaces through detailed outcrop studies and gamma-ray surveys revealed a complex internal stratigraphy that most likely reflects sea-level variations. The lower Bakken was deposited during a time span that saw development of several sequences in coeval portions of the Chattanooga Shale basin. Thus, there is a potential that the uniform appearing lower Bakken is divisible into several depositional sequences.

Sequence stratigraphy in black shales is possible. Its systematic application may lead to a coherent stratigraphic framework for the Late Devonian black shale succession of North America and will likely further our understanding of the mechanisms for widespread black shale deposition.

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