SEDIMENTARY FEATURES INDICATING EROSION, CONDENSATION, AND HIATUSES IN THE CHATTANOOGA SHALE OF CENTRAL TENNESSEE: RELEVANCE FOR SEDIMENTARY AND STRATIGRAPHIC EVOLUTION

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ABSTRACT

Recent investigations show that the finely laminated and highly carbonaceous Upper Devonian Chattanooga Shale of central Tennessee accumulated in relatively shallow water, prone to influence by storm waves and episodic erosive events. Recurring erosive events of variable strength and/or duration are indicated by truncation surfaces beneath which from a few centimeters to more than a meter of section is missing. That the seabed was close to or within reach of storm waves through large portions of Chattanooga history is suggested by hummocky cross-stratified sand and silt beds, and mud tempestites.

In many places truncation surfaces cut underlying beds at a very shallow angle, or even become conformable to under- and overlying beds. In hand specimen or thin section, these essentially "invisible" erosion surfaces may be associated with one or more of the following features: (1) sharp-based shale beds, (2) basal sand lags (some mm to cm thick), (3) bone beds, (4) abundant reworked pyrite, (5) conodont or *Lingula* lags, (6) soft sediment deformation of shale laminae below erosion surface, and (7) localized low-angle truncation of shale laminae.

On erosion surfaces, the concentration of reworked pyrite (framboids, fecal pellets, fills of *Tasmanites* cysts, pyritic ooids) can in places lead to pyrite enrichment by a factor of 20-30 relative to "normal" black shale, and may give rise to sharp-based beds of pyritic shale. Diffuse-based pyritic shale beds, lacking an association with erosional features, but otherwise texturally identical, have also been observed. In these beds, the very strong enrichment of diagenetic (pyrite) and biogenic (conodonts) components suggests minimal terrigenous sedimentation, probably an indication of condensation and/or hiatuses. Pyritic shale beds as thick as 10 cm have been found, possibly representing as much as 2-3 m of eroded and reworked (sharp-based) or condensed section (diffuse-based). This makes them potentially significant stratigraphic elements (marker horizons).

Erosion or condensation on the cm scale might be due to local conditions, and seems to define macroscopic bedding in outcrops of the Chattanooga Shale. Meter-scale erosion and thick pyritic beds on the other hand define substantial discontinuities that may well be the result of more regional phenomena, such as a basin-wide lowering of sea-level. In order to see whether these latter features are expressions of sequence boundaries in slowly accumulating black shale sequences, work is underway to test whether they correlate with transgressive-regressive cycles found in the Upper Devonian of the Catskill Delta.

INTRODUCTION

The origin of black shales is an enduring issue of great geological significance that stimulated numerous investigations by stratigraphers, sedimentologists, paleontologists, and geochemists. In North America, the Late Devonian black shales are one of the most prominent and economically significant stratigraphic intervals, studied intensively because they are important hydrocarbon source beds (Conant and Swanson, 1961; Comer and Hinch, 1987; Charpentier et al., 1993; Roen and Kepferle, 1993). Although we understand now how large-scale and/or long-term tectonic, paleogeographic, paleoclimatic, and sedimentary processes may have interacted to control their deposition (Conant and Swanson, 1961; Kepferle and Roen, 1981; Kepferle, 1993; Hasenmueller and Woodard, 1981; Hasenmueller et al., 1983; Ettensohn, 1992; Ettensohn et al., 1988; Schieber, 1994a, 1994b), there are still many unanswered questions.

Recent debate on black shale formation has centered on two major controls: increased primary production, or widespread anoxia due to water column stratification (Demaison, 1991; Demaison and Moore, 1980; Byers, 1977; Parrish, 1982; Pedersen and Calvert, 1990; Pedersen et al., 1992; Calvert, 1987; Calvert and Pedersen, 1992; Calvert et al., 1992; Ingall et al., 1993; Chow et al., 1995; Calvert et al., 1996). Although a stratified anoxic basin model has been the preferred explanation for black shale formation in the Devonian inland sea of North America for a number of years (Potter et al., 1982; Ettensohn et al., 1988), recent sedimentologic investigations suggest otherwise. Large scale submarine erosion surfaces, storm deposits, and widespread, albeit subtle, bioturbation in the Chattanooga Shale of central Tennessee suggest deposition of this black shale sequence in a comparatively shallow platform setting, possibly under an aerated water column (Schieber, 1994a, 1994b).

In order to better understand the possible origins of these erosion surfaces, I conducted a very detailed investigation of several outcrops in central Tennessee (Fig. 1). Results indicate that erosion features are much more common in these black shales than originally appreciated, and that the sedimentary manifestations of erosion and non-deposition can be rather subtle. My primary objective in this contribution is: (1) documentation of sedimentary features related to erosion at various magnitudes, (2) insights into the origin and history of erosion surfaces, and (3) a discussion of the significance of these observations with a focus on questions yet to be answered.

GEOLOGIC SETTING

The Chattanooga Shale belongs to an extensive Late Devonian black shale complex that accumulated in a large inland sea (Fig. 1A) between the Acadian Mountains and the Transcontinental Arch (Kepferle and Roen, 1981), as the distal part of a westward thinning clastic wedge (Fig. 1C). Over the past 30 years much information about stratigraphy and the distribution of lithologies and sedimentary features has accumulated (Conant and Swanson, 1961; Roen and Kepferle, 1993; Ettensohn et al., 1988; Potter et al., 1982; Woodrow et al., 1988; Lundegard et al., 1985). The Chattanooga Shale and its lateral equivalents (Fig. 1C) overlie an unconformity, and over most of the study area (Fig. 1A) it is less than 10 m thick. In Tennessee it is subdivided into the lower Dowelltown and the upper Gassaway member (Fig. 1B).

These finely laminated and highly carbonaceous shales were long considered the result of deposition in a deep, stratified, and anoxic basin (e.g. Kepferle, 1993; Ettensohn et al., 1988; Potter et al., 1982). In contrast, my recent investigations support accumulation in relatively shallow water, where deposition was influenced by storm waves and episodic erosive events. The latter resulted in truncation surfaces from beneath which a few centimeters to more than a meter of section can be missing, whereas the former is evident through hummocky cross-stratified sand and silt beds and mud tempestites (Schieber, 1994a, 1994b).

METHODS

Five of the largest and best exposed Chattanooga outcrops in central Tennessee were selected for a detailed study of erosion surfaces in the Late Devonian black shale sequence (Fig. 1A). For each outcrop a photo mosaic was assembled, and all visible sedimentary features (bedding, erosion surfaces, contacts, etc.) were transferred to a mylar overlay. During detailed outcrop examination, all additional features (e.g. ripples, silt/sand layers, soft sediment deformation, etc.) were added to the mylar overlay, and key surfaces were marked and indexed. Continuous slot samples were taken over those intervals that contained erosion surfaces. Slot samples were cut perpendicular to bedding with a portable concrete saw (Fig. 2). Samples were stabilized with fiber glass matting and epoxy resin prior to removal. Slot samples were marked on the overlay and also keyed into highly detailed stratigraphic sections (1:10 scale) that were measured at the same time. After return to UTA, ground slabs were produced from slot samples (Fig. 3), and thin sections prepared from critical intervals with hard-to-see features. Slab and thin section observations were logged in great detail (1:2 scale), and observed features were correlated with outcrop features and measured sections.

OBERVATIONS

I will begin this section with a description of the geometry of erosion surfaces, followed by descriptions of associated sedimentary features. The latter are primarily a variety of lag deposits, but also truncations and soft sediment deformation. The section will be concluded with descriptions of deposits suggestive of minimal sedimentation, such as stratiform pyrite and silica enrichment.

Erosion surfaces in the Chattanooga Shale of central Tennessee are either undulose-concave, or essentially flat and conformable. Undulose-concave surfaces that are traced laterally will in many instances change to a conformable habit over a distance of some meters or tens of meters. Erosion may be as shallow as a millimeter or less and only be observable in thin section (Fig. 4), but can equally well cut as deep as 0.6 meters in single outcrops (Fig. 5). Correlation of marker beds between outcrops suggests that over a distance of kilometers to tens of kilometers, as much as 1.5 meter of shale may have been removed below some erosion surfaces. Although this translates into an angular difference of less than 0.01 degrees between successive shale packages, such erosion is nonetheless highly significant if one takes into account the thin development of the Chattanooga Shale in the study area (less than 10 m), and the large time interval that it records (approximately 10-15 million years).

Potentially, spatial heterogeneities in sediment accumulation could account for thickness variation between marker horizons. The fact, however, that the sediments in the study area (Fig. 1A) were deposited 200km or more from the eastern shoreline of the basin, and that there was an intervening trough that acted as a sediment trap (Fig. 1C), makes this a remote possibility. Furthermore, shale packages that have been traced over distances of kilometers to tens of kilometers are conformable at the base and show truncation at the top. This suggests that thickness variation is indeed due to erosion and not to spatial heterogeneities in sediment accumulation.

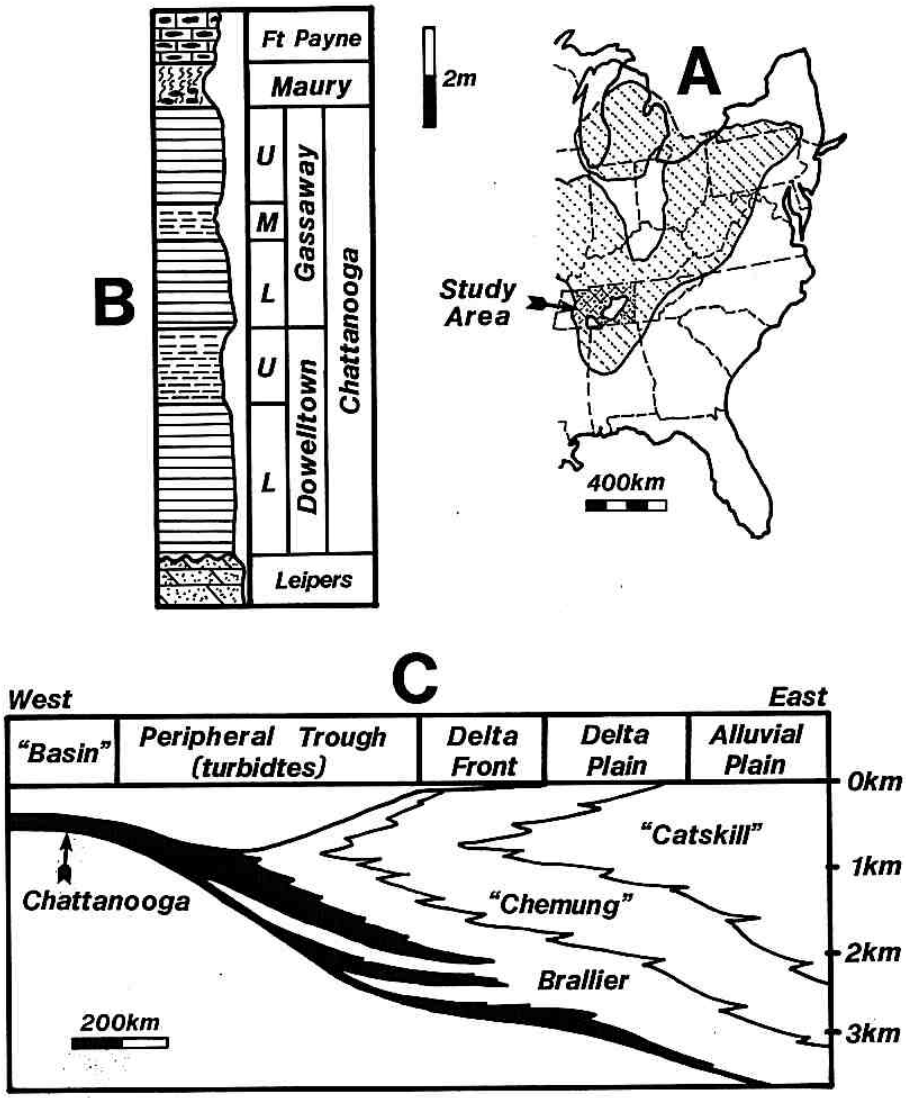

Figure 1: Location map and stratigraphic background. **(A)** shows outline of eastern USA with state boundaries (dashed lines) and distribution of Late Devonian black shales and associated sediments (area hatched with diagonal dotted lines). White spots in the latter area represent primarily post-Devonian erosion. Study area marked by cross-hatched dotted lines. **(B)** shows a stratigraphic summary of the Chattanooga Shale in the study area, and under- and over-lying formations. Rock signatures for Chattanooga Shale: (1) horizontal continuous lines = predominantly black shale; (2) horizontal broken lines = interbedded black and gray shale. **(C)** shows a schematic cross section of the Catskill delta clastic wege, and the lateral relationships between offshore black shales (Chattanooga) and basin marginal sediments. Catskill and Chemung are established facies descriptors that describe alluvial and sea marginal sediments respectively, and the Brallier Formation is taken to represent the slope turbidites.

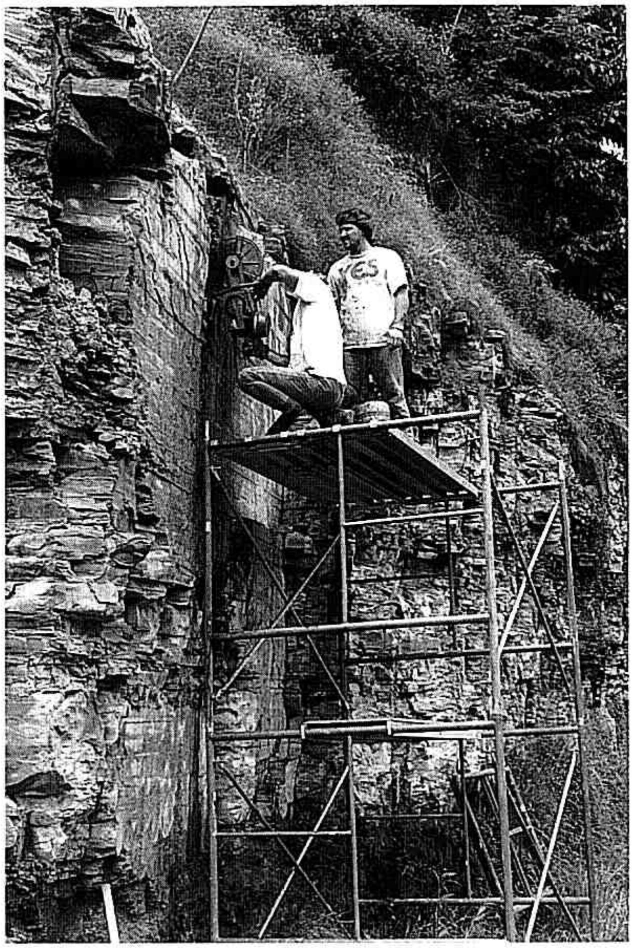

Figure 2: Cutting slot samples with a portable concrete saw. Flat surfaces, such as fracture planes, are ideal but may require working from ladders and/or scaffolding.

Despite their significance, recognition of major erosion surfaces is not an easy task. Although the comparatively distinct examples shown in Figs. 5 and 6 are from well known and often visited exposures, they escaped notice for three decades. Indeed, if one stands directly in front of the rock face, above erosion surfaces (Fig. 5 and 6) are barely perceptible. They do, however, become obvious once one steps back from the outcrop for about 10 meters. Possibly because we are conditioned to search for small scale features in shales, investigators failed to carefully examine these outcrops from a distance. Although at the moment I can conclusively demonstrate large lateral extent for only two erosion surfaces of the type illustrated in Figs. 5 and 6, work is underway to trace several more erosion surfaces of this type across the study area.

Recognition of erosion surfaces is comparably easy for those that are undulose-concave and for those that show a noticeable angular difference between beds below and above. Where underlying beds are cut at a very shallow angle, or where erosion surfaces conform to underlying beds, identification is very difficult. Outcrops and samples were examined for sedimentary features that are associated with undulose-concave erosion surfaces, in order to identify features that might indicate erosion surfaces in places where there is no discernible discordance associated with them. Table 1 shows a listing of sedimentary features associated with recognized major surfaces,

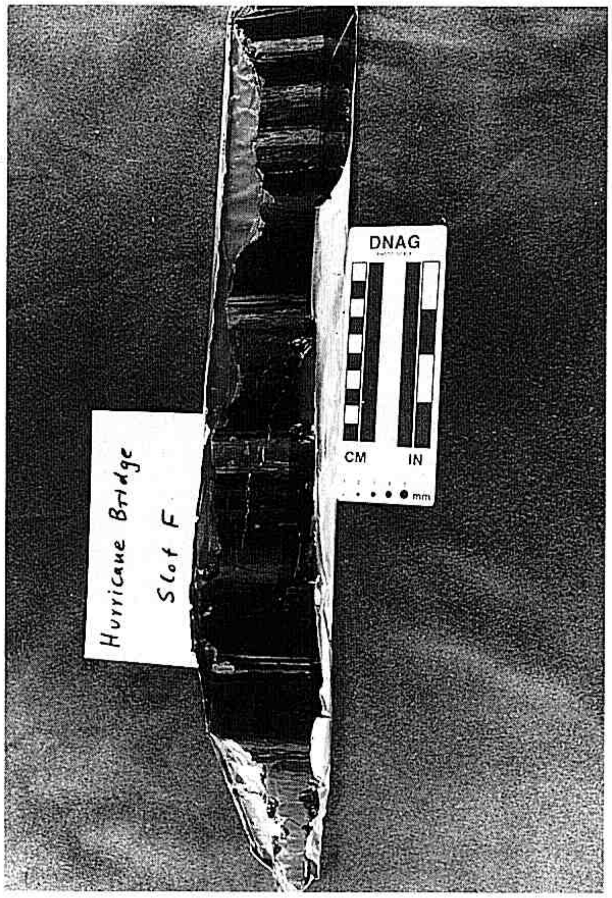

Figure 3: Picture of the final product, a slot sample after it has been cut and ground flat. Shows alternating black and gray shale intervals, laminated and rippled silt/sand layers (storm beds), and mottling due to bioturbation.

as well as information on their ease of recognition. In the following paragraphs, these features are described in detail.

Lag deposits, the residual accumulations of coarser particles produced by winnowing of finer material, are among the more readily recognizable sedimentary features found associated with erosion surfaces. Grain types observed in these lags include quartz sand and silt, reworked pyritic material, phosphatic debris (fish bones, conodonts, *Lingula*), and glauconite. Most lags contain these grain types in varying amounts, and several lag types are distinguished, including sand and silt lags, bone beds, and pyritic lags. Conodont lags and *Lingula* lags have also been observed in the Chattanooga Shale, but so far not in association with major erosion surfaces of the type shown in Figs. 5 and 6.

Silt lags typically vary in thickness from 1 to 20 mm, and one exceptional example reaches in places a thickness of as much as 100 mm. They consist primarily of quartz silt (angular to subangular, 0.01-0.06 mm), a few percent mica flakes (0.01-0.06 mm, muscovite, ±biotite), and trace amounts of glauconite, tourmaline, and zircon. Pyrite occurs in highly variable amounts, as scattered crystals (0.005-0.03 mm in diameter), framboids, and as patches of contiguous-concretionary cement. At the base of these lags conodonts may contribute up to several percent of the detrital grains. Small basal scours (up to 5 mm deep), tiny load casts (up to 1 mm deep), horizontal to gently undulose laminae, wavy-lenticular bedding, and cross-lamination, are common sedimentary features (Fig. 7). Silt lags may also contain plant fragments of a few mm's to cm's length, which when abundant may exhibit preferred Sand lags are typically lenticular-discontinuous and vary in thickness from a few mm to 20 mm. In one locality, however, a lag with a thickness of up to 60 mm is continuous through an outcrop 100 m wide. Their most abundant component is subrounded to rounded quartz sand (up to 0.7 mm). A small percentage of quartz grains shows embayments and lobate/pointed projections, pyrite inclusions, cherty, chalcedonic, and colloform textures. Phosphatic components are next in abundance. In their majority these are rounded, sand sized (0.1-1 mm), phosphatic granules with relict textures suggestive of fish bones and peloidal mud. Additional phosphatic components are conodonts and *Lingula* shells. Well-rounded glauconite grains (0.1-0.2 mm) are conspicuous, but constitute less than one percent of the sand grains. They may show internal shrinkage cracks and deformation between quartz grains due to compaction. Such glauconite grains have also been observed as trace constituents in thin sections of Chattanooga black shale. orientation on bedding planes.

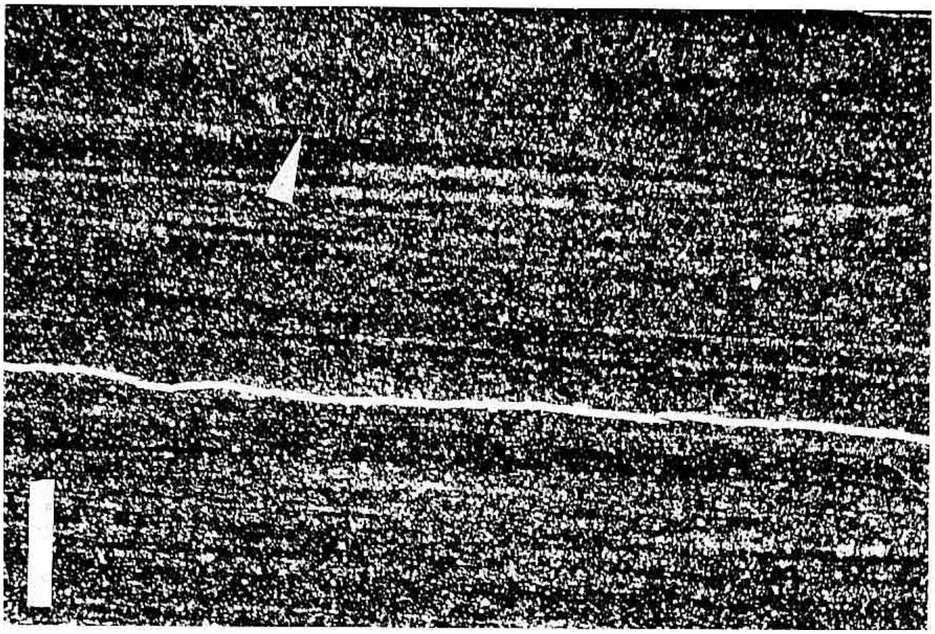

Figure 4: Transmitted light photomicrograph of shallow erosion in laminated black shale that cuts out an underlying lamina of darker shale (3/18/93-3X). Arrow points out erosion surface Light laminae are silt enriched. Scale bar represents 1mm.

Trace constituents in sand lags are small grains of zircon, tourmaline, and feldspar (0.07-0.3 mm). In some localities scattered shale rip-up clasts (up to 30 mm) were found in sand lag deposits. Pyrite occurs as euhedral crystals and clusters of crystals (0.01-0.15 mm in diameter) in pore spaces, as spheroidal and rounded-elongate aggregates with polyframboidal internal texture (up to 0.6 mm in size), and also forms oblate concretions (up to 60 mm long). Localized basal scours (up to 25 mm deep), parallel to undulose laminae, and ripple cross-laminae are the most commonly observed sedimentary features. In a number of cases there is very little appreciable differential compaction around sand- or silt-filled basal scours (Fig. 8). Basal scours may also cut into pyrite concretions of underlying shale units (Fig. 8).

Bone beds in the Chattanooga Shale were first mentioned by Conkin et al. (1980). They consist primarily of a sand matrix with scattered fishbone debris (10% or more). Fishbone debris (up to 25mm in size) is irregular-shaped to rounded-abraded (Fig. 9). The sand matrix is of the same general composition as the sand lags.

Pyritic lags are dominated by sand-sized pyritic grains. Because typically a certain type of pyrite grain strongly dominates in a given place, several subcategories can be distinguished.

Peloidal pyrite lags (up to 30 mm thick) consist of a large proportion of pyritic pellets (60-80 percent; 0.1-0.4 mm long). Pellets generally show an oval outline and may exhibit deformation due to compaction (Fig. 10). Internally, pellets are characterized by a matrix of minute pyrite crystals (0.002-0.006 mm), which may surround small, spherical, pyrite framboids (0.025-0.08 mm). Phosphatic particles are abundant and conspicuous, including conodonts (as much as 10 percent), fragments of small fish bones and *Lingula* shells, and small phosphatic pellets (0.05-0.2 mm). *Tasmanites* cysts, either flattened or with an infill of pyrite and/or quartz, are a common minor constituent (a few percent). Quartz grains (10-20 percent) are scattered randomly amongst above constituents. They are predominantly of silt size, but there is a small population of rounded sand-sized grains.

Spheroidal pyrite lags (up to 30 mm thick) stand out because of conspicuous pyritic spheres (up to 10 percent; 0.1-0.3 mm diameter). Polishing and etching reveals that, although they now consist of solid pyrite throughout, they have an internal polyframboidal texture (Fig. 11). There are also crescent-shaped pyrite grains that appear to be broken or incomplete pyrite spheres. Pyritic grains may constitute 50-70 percent of the rock. Although the pyrite spheres are very distinct, most pyrite grains are pellets as described in the preceding paragraph, as well as single and clustered framboids. Short pieces (up to 5 mm) of single or branching pyritic tubes (0.3-0.5 mm wide) also occur, probably remains of pyritized burrows. Conodont elements (up to 2 mm long) are next in abundance (10-20 percent) after pyritic particles (Fig. 12). Other phosphatic particles include fishbones (up to 6 mm long), small phosphatic pellets (0.1-0.5 mm), and *Lingula* shells. *Tasmanites* cysts, either flattened or with an infill of pyrite and/or quartz, are a common minor constituent (a few percent). Quartz grains (10-20 percent) are scattered randomly amongst above constituents. Of the total quartz content, 30-50 percent is composed of sand size grains (up to 0.6 mm). The latter may show embayments and lobate/pointed projections, pyrite inclusions, cherty and chalcedonic textures. A final, but noteworthy, component are streaks of coal (up to 3 mm thick and 60 mm long), that can be locally abundant in the base of this type of lag.

TABLE 1: SEDIMENTARY FEATURES ASSOCIATED WITH EROSION SURFACES

Feature	Ease of Recognition
Silt Lags	in outcrop, careful examination reveals thicker silt beds (>5mm) in hand specimen and on cut surfaces, beds of 1-2 mm thickness readily seen
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
Bone Beds	typically a variant of sand silt lags, with comparable ease of recognition larger bone fragments readily recognizable with hand lens on fresh 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 sulfates in handspecimen, layers as thin as 1 mm are readily seen on fresh surfaces
Conodont Lags	may form a variant of sand/silt lags, with comparable ease of recognition mostly forms almost pure layers of conodont material, 1-3 mm thick, that are best observed in handspecimen (bedding plane examination with hand lens)
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 Lingula shells are sparse on surface
Low-Angle Truncations	typically not recognizable in outcrop best recognized on cut/polished surfaces and in oversize thin sections
Soft Sediment Deformation	deformation on the scale of tens of cm's (e.g. with associated ball and pillow structures) can be recognized in outcrop small scale deformation (mm's to cm's) best recognized on cut surfaces and in thin section
Sharp-Based Shale Beds	recognition easiest on cut and polished surfaces and in thin section very difficult and tentative in outcrop

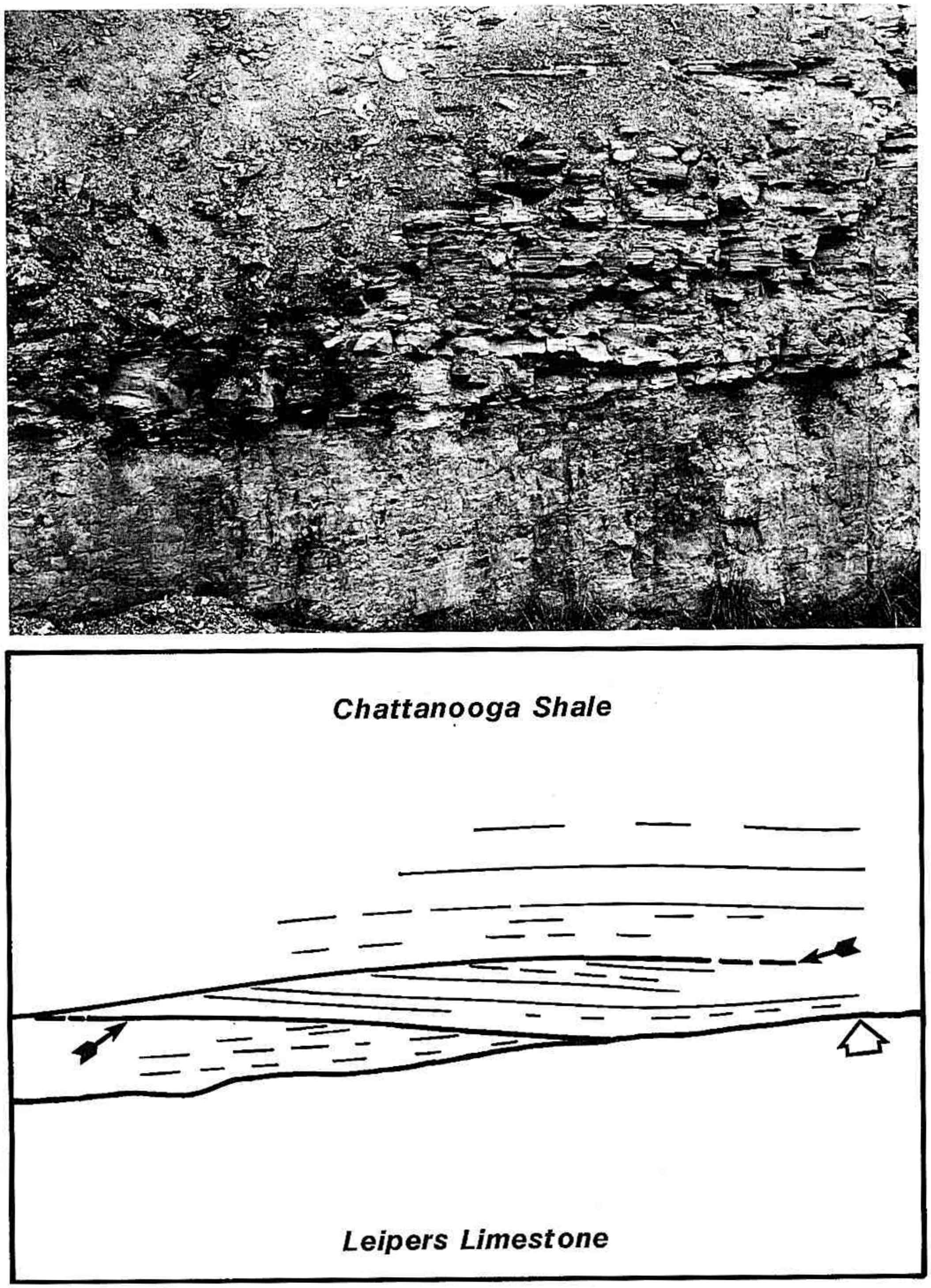

Figure 5: Photo of major erosion surfaces in the Dowelltown member of the Chattanooga Shale (Fig. 1B). Ink tracing highlights bedding planes (thin, partially dashed lines) and erosion surfaces (heavy lines, black arrows). These erosion surfaces are covered with a thin lensoidal lag of sand and bone fragments. Basal unconformity of the Chattanooga Shale (Chattanooga overlies the Middle Ordovician Leipers Limestone) is marked by large open arrow. Photo shows approximately 3 m of Chattanooga Shale.

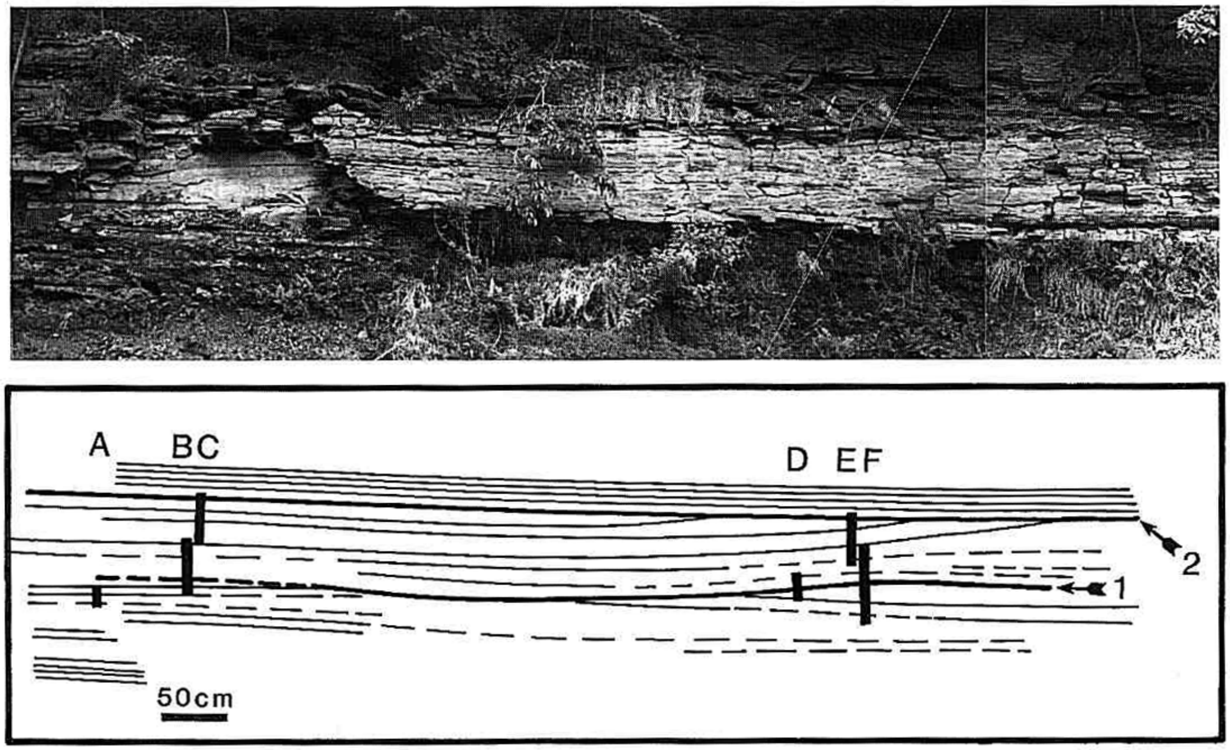

Figure 6: Photo of major erosion surfaces in the Gassaway member of the Chattanooga Shale (Fig. 1B). Ink tracing highlights bedding planes (thin, partially dashed lines) and erosion surfaces (heavy lines, black arrows 1 and 2). Vertical black bars marked A through F mark locations of slot samples (see Figs. 16 and 19 for details). In the middle of the picture, erosion surface 1 and 2 bracket approximately 1 m of black shale. Erosion surface 2 is capped by the so called "varved bed" of Conant and Swanson (1961).

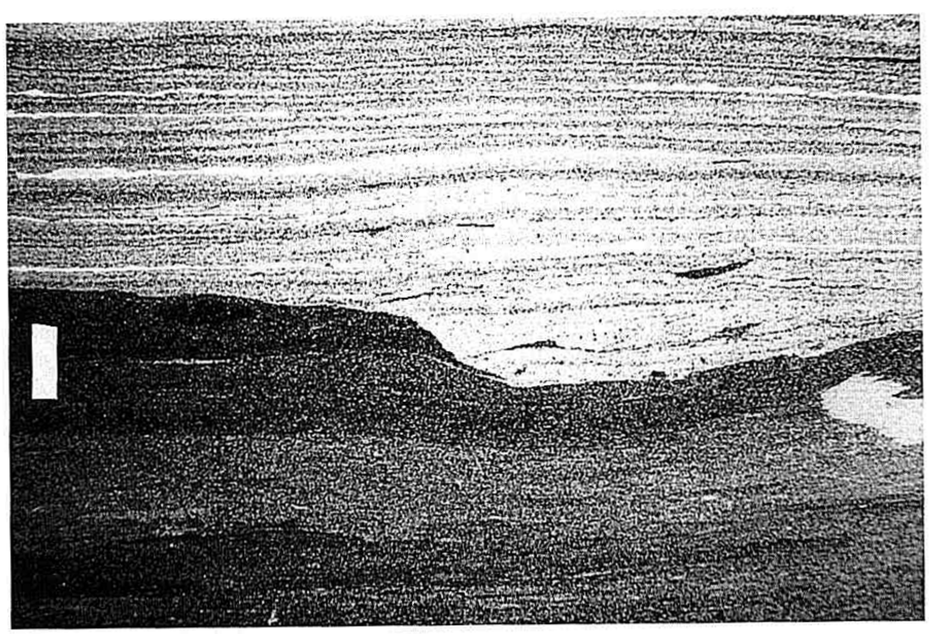

Figure 7: Transmitted light photomicrograph of silt lag (8/2/94-1). Lag is horizontally laminated and fills in an erosional scour at its base. Dark streaks within the light colored lag deposit are small shale rip-ups. Scale bar represents 2mm.

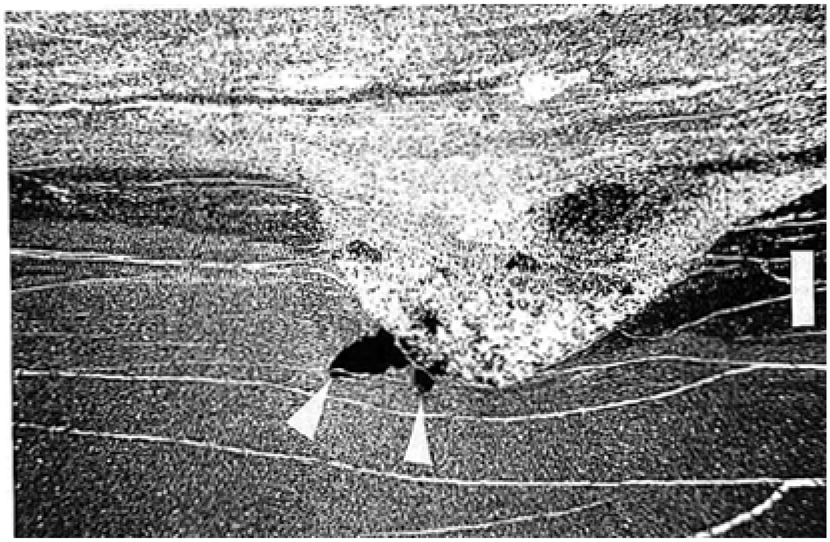

Figure 8: Transmitted light photomicrograph of scour at the base of a sand lag deposit (8/6/95-1B). Note that the underlying shale does not show much much differential compaction around the sand-fill of the scour. The scour also appears to truncate small pyrite nodules that formed within the shale (arrows). These features suggest that the shale that was being eroded was of firm consistency and had already undergone substantial compaction. Scale bar represents 2mm.

Pyrite ooid beds are a type of pyritic lag (up to 100 mm thick) that is characterized by very well rounded, concentrically laminated pyrite grains (Fig. 13). Pyrite ooids range in size from 0.2 to 1.2 mm, and are predominantly of oblate shape. When visible in thin section, cores of these ooids consist of reworked pyrite grains (e.g. framboid clusters, pyritic pellets, fragments of preexisting pyrite ooids), phosphatic debris (conodonts, bone fragments), and in a few instances -of quartz grains. Pyritic cortexes may alternate with transparent layers that appear to consist of clays and possibly phosphatic material. Some larger ooids contain clusters of smaller ooids in the core. In pyrite ooids that incorporate non-pyritic cortexes, compaction has caused deformation and crushed pyrite cortexes. The overall pyrite content in these beds is approximately 50-80 percent, but a substantial portion of this (10-25 percent) appears to be diagenetic overgrowth on pyrite grains. The abundance of pyrite ooids varies from 20-50 percent, additional pyritic particles are pyritic pellets, polyframboid clusters, and pyrite spheroids. Non-pyritic particles include conodonts, fragments of fish bones and *Lingula* shells, phosphatic pellets (0.1-0.3 mm), phosphatic ooids (0.1-0.7 mm), quartz sand (0.1-0.8 mm), and deformed shale rip-up clasts (up to 30 mm long). Quartz grains may show embayments and lobate/pointed projections, pyrite inclusions, and cherty and chalcedonic textures. Fine-grained components, such as quartz silt and clay, are masked due to the overall opaque nature of this lag type, and thus are very difficult to observe and quantify.

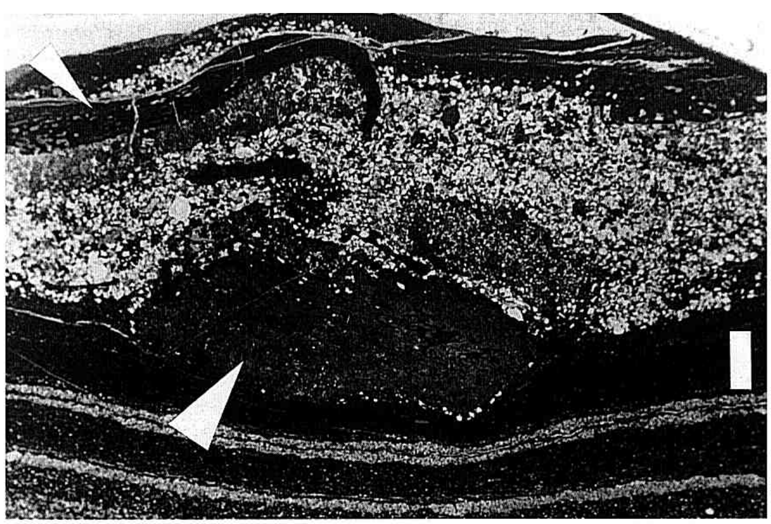

Figure 9: Transmitted light photomicrograph of Bone Bed (8/10/94-1) overlying laminated black shale. Large bone fragments (arrows) still shows porous bone structure. Sand matrix is a mixture of mainly quartz grains (bright white) and sand-size phosphatic grains (gray). Scale bar represents 1mm.

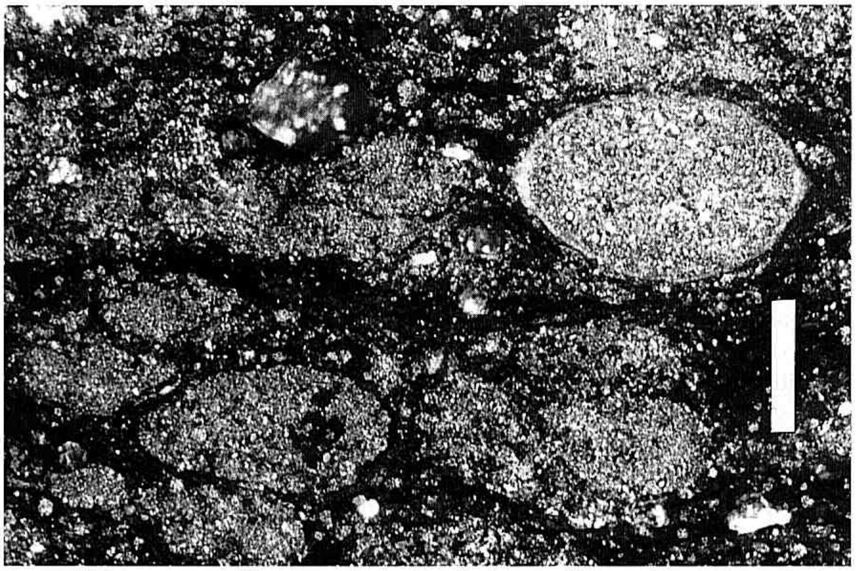

Figure 10: Photomicrograph of peloidal pyrite lag (94CM-I-C), reflected light, crossed polarizers. Shows pyritic peloids as light colored oval grains in a darker matrix of clay, silt, organic matter, and scattered pyrite grains. Scale bar represents 0.1mm.

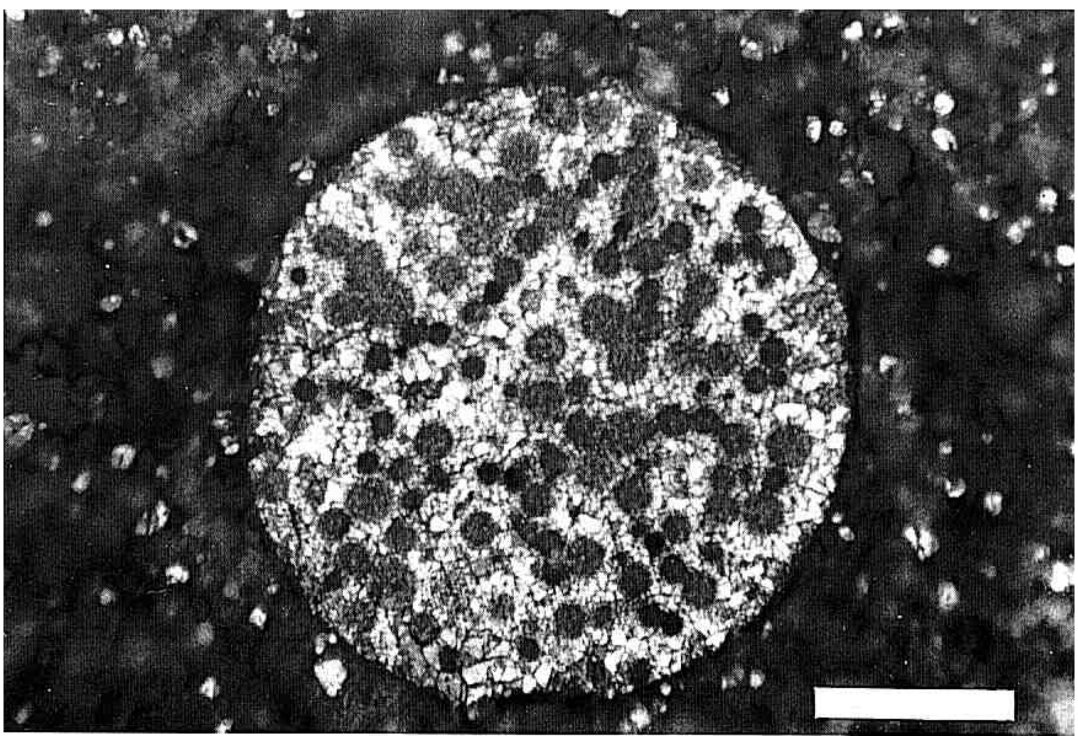

Figure 11: Photomicrograph of pyritic sphere (7/28/95-1A), reflected light. The darker circles within the pyrite sphere are places where HNO_3 dissolved the fine crystalline pyrite of pyrite framboids. The bright reflective areas between framboids are coarser crystalline pyrite that was deposited as cement between the initial pyrite framboids. Scale bar represents 0.05mm.

Figure 12: Transmitted light photomicrograph of spheroidal pyrite lag that shows the abundance of conodont debris (7/28/95-1B). Conodonts are white to gray in color, in a dark matrix of organic matter, silt, clay, and pyrite. Scale bar represents 1mm.

All three pyritic lag types are characterized by sharp basal contacts (may show localized scours), and a gradational upper contact with "normal" black shales. Due to vertical variations in the proportion of components they may show crude internal stratification. All pyritic lags show various degrees of diagenetic overprint. The latter manifests itself primarily as coarser overgrowth pyrite on e.g. ooids and pellets, and as cement in pore spaces. Reliable distinction of pyrite grains and diagenetic overgrowth/cement requires reflected light examination of polished and etched thin sections. Pyritic spheres, framboids, framboid clusters, and pyritic peloids occur in small and variable amounts in the black shales that underlie lag deposits.

Conodont lags are highly variable in composition, and may contain all the various grain types found in sand/silt lags and peloidal pyrite lags. Although they may reach in places several mm thickness, they are typically only tens of mm's thick and characterized by an abundance of conspicuous conodonts on bedding planes (Fig. 14). Because of their minuscule thickness, they are most readily recognized when shale is split along bedding planes. Though conodonts are their identifying feature, other grain types, particularly quartz sand/silt, pyritic grains, and *Tasmanites* cysts, are typically more abundant than conodonts. Thicker conodont lags may show tiny scours and load structures at the base (1 mm or less deep), which may be filled almost entirely with conodonts. Where larger bedding planes are exposed, conodont lags tend to exhibit a patchy distribution.

Lingula lags are conspicuous enrichments of phosphatic *Lingula* shells (2-10 mm long) on bedding planes (Fig. 15). They may be found on the top surface of sand lag deposits, or may form accumulations on shale bedding planes. *Lingula* shells may be as sparse as 0.2 shells per cm^2, or may cover the entire bedding plane. Rarely are these lags more than one *Lingula*-shell thick. When examined carefully, most lags that occur on shale bedding planes consist actually of multiple lag horizons that are spaced a few mm's to cm's apart. On larger bedding planes, preferred long-axis orientation of *Lingula* shells is discernible. Shales directly below such lags may show simple, shallow, and well-defined burrows, obliquely embedded *Lingula* (up to 30 degrees relative to bedding), and also tend to contain *Tasmanites* cysts (a few percent) that are infilled with pyrite and quartz. In some instances, minute silt lenses may be associated with *Lingula* lags, but in the majority of cases where thin sections were examined, the lag horizons are marked solely by *Lingula* shells. Erosive features, such as scours and sharp-based shale beds, are absent. Lags may also contain flattened pieces of fossil wood (up to 10 cm long).

Low-angle truncation of underlying shale beds is another feature associated with erosion surfaces in the Chattanooga Shale. In outcrop, this feature can only be identified where erosion surfaces are undulose-concave (Figs. 5 and 6). Erosion surfaces, however, also have small-scale irregularities that are from 1-10 mm deep and up to tens of cm's wide. These may produce low-angle truncations even in those places where erosion surfaces are essentially flat and conformable. Although too subtle to be recognized in outcrop, truncations of that magnitude are nonetheless discernible on cut and ground surfaces of hand specimens and in thin sections (Fig. 16).

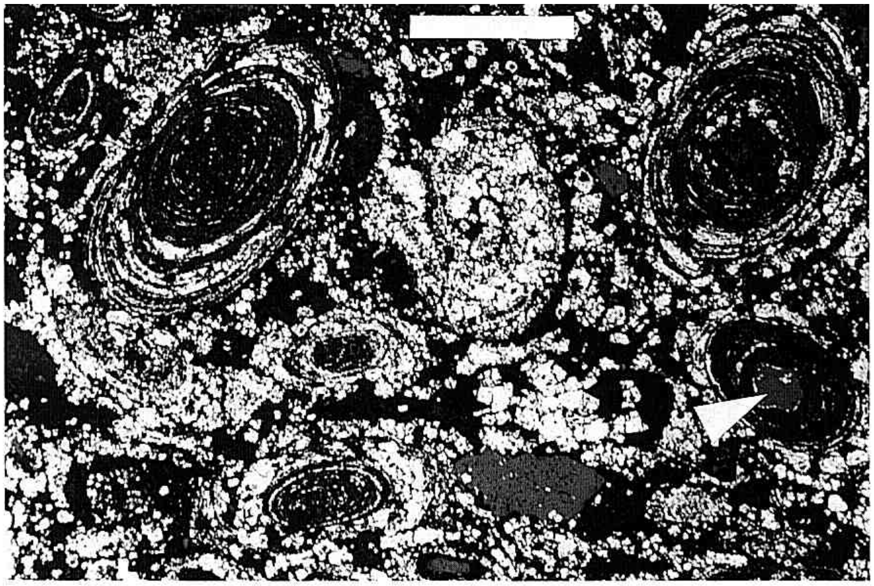

Figure 13: Photomicrograph of pyritic ooid bed (8/3/94-15A), reflected light. Sample has been etched with HNO_3 to reveal concentric pyrite laminae of pyrite ooids. Pyrite reflects brightly and is white to gray in color. Space between pyrite ooids is filled with a matrix of later diagenetic pyrite cement, sand grains (phosphate, quartz), and shale rip-ups. One ooid has a quartz grain in the center (arrow). Scale bar represents 0.5mm.

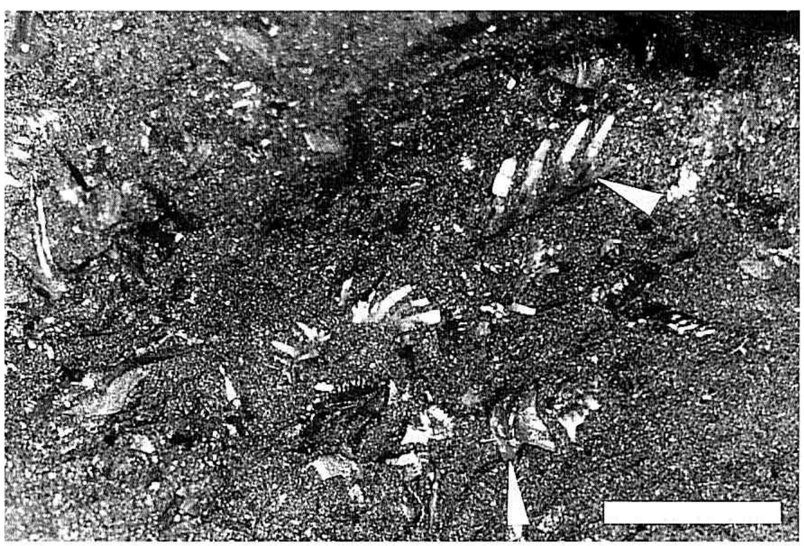

Figure 14: Close-up photo of conodont lag, conodonts (arrows) on bedding plane (8/6/95-6). Scale bar represents 1mm.

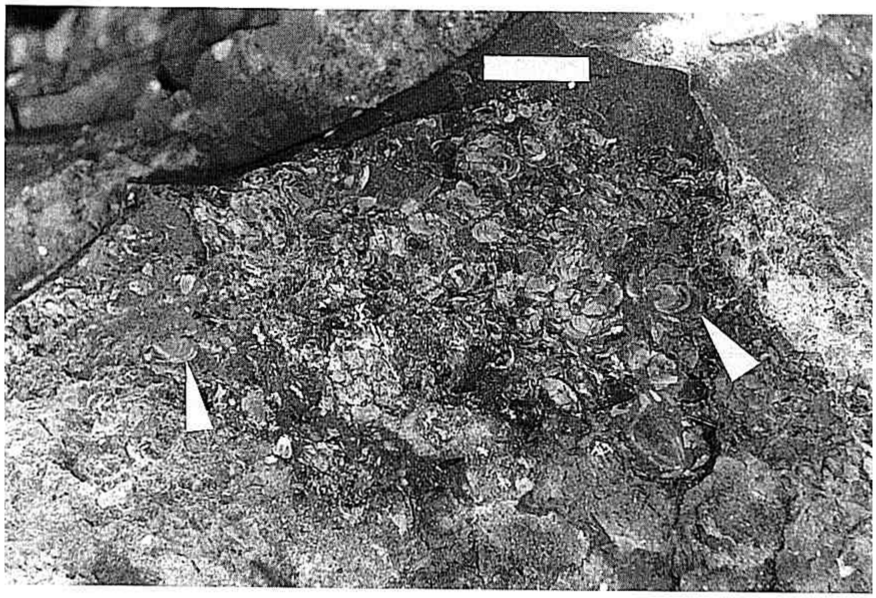

Figure 15: Close-up photo of a Lingula lag (8/15/94-21). Lingula shells (arrows) are scattered over bedding plane. Scale bar represents 10mm.

Soft-sediment deformation is not uncommon below erosion surfaces examined for this study. Typically, the erosion surface is relatively flat and smooth, and shale layers just below the truncation surface show folding and convolute bedding (Figs. 16 and 17). The downward extent of deformation ranges from a few mm to as much as 10 cm. In outcrop, this feature is usually only seen on freshly broken or cut surfaces. It is best observed on cut and ground surfaces of hand specimens. In a few instances, soft-sediment deformation (convolute laminae, small ball and pillow structures) was also observed in shale beds directly above erosion surfaces.

Sharp-based shale beds are the most subtle sedimentary feature associated with erosion surfaces, and are best identified in thin section. Typically in the Chattanooga Shale, successive shale beds of differing composition have gradational boundaries or are separated by silt laminae (Schieber, 1994b). In the case of sharp-based shale beds, however, two successive shale beds that differ in composition have a knife-sharp contact with an abrupt change of composition (content of silt and organic matter), but no intervening lag deposit (Fig. 18). This feature is associated with erosion surfaces of any scale.

The initial research was designed to examine erosion related sedimentary features in the context of visible, large-scale erosion surfaces, such as shown in Figs. 5 and 6. During the examination of slot samples and thin sections I realized, however, that erosive features are not restricted to easily recognizable major erosion surfaces, but that they are also common between such surfaces. To illustrate this point, highly detailed logs of slot samples taken from the outcrop in Fig. 6 are shown in Figs. 16 and 19. As visible in Fig. 19, erosion surface 1 is marked by a sharp-based shale contact (Fig. 18; shale-on-shale erosion surface), rather than any lag deposits. Erosion surface 2, in contrast, is marked by a thick silt lag, the so called "varved bed" of Conant and Swanson (1961). Thin sections were necessary to pin-point erosion surface 1 in the slot samples, and also showed that small-scale erosion surfaces may be spaced as closely as 1 surface per 2 cm (Fig. 16). Comparison of adjacent slot samples (Fig. 19) indicates considerable lateral variability in the shale package delineated by erosion surface 1 and 2.

Stratigraphic sequences that are characterized by the presence of submarine erosion surfaces may also show features that attest to non-deposition or very slow sedimentation (e.g. Vail et al., 1992). In the Chattanooga Shale, the latter conditions are indicated by stratiform pyrite and silica enrichment (see discussion), by high concentrations of *Tasmanites* cysts, and abundant "filled" *Tasmanites* cysts. Table 2 summarizes the ease of recognition of these features.

Stratiform pyrite enrichment is taken to mean shale intervals with a pyrite content that is significantly above average. Whereas the average sample of Chattanooga Shale may contain 2-3 percent of finely dispersed pyrite in single grain or framboidal form (e.g. Ettensohn et al., 1988), enriched intervals may contain as much as 20 percent pyrite (determined through microscopic examination of polished thin sections) in a matrix of silt, clay, and organic matter. The thickness of enriched intervals ranges from a few mm to several tens of cm's. The contacts with the over and underlying shale beds are gradual (Fig. 20). On cut and ground

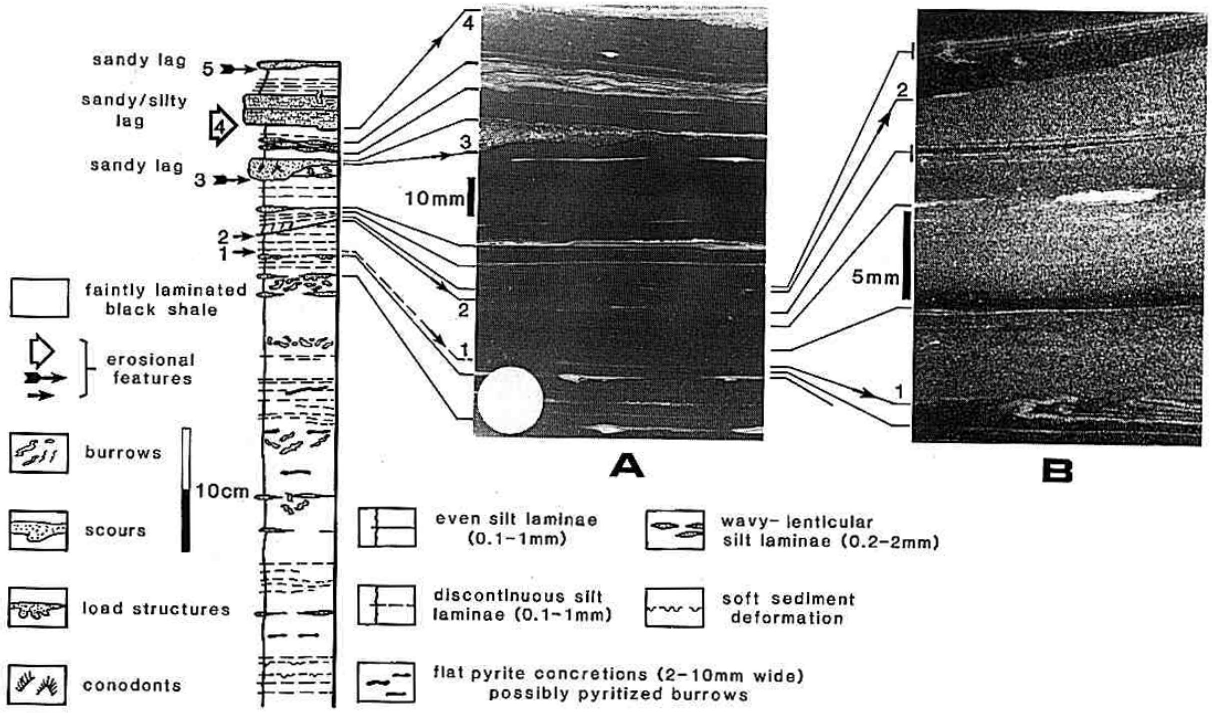

Figure 16: A detailed log of slot sample C from outcrop shown in Fig. 6. The top third of the slot sample shows 5 discernible erosion surfaces (numbered 1 through 5). The open arrow with the number 4 indicates the position of erosion surface 2 from Fig. 6. The other surfaces are not (or rarely) discernible in outcrop. Photo A is a closeup of a corresponding portion of the slot sample (7/29/94-7), to illustrate the subtle nature of lesser erosion surfaces (marked 1, 2, 3). Photomicrograph B (7/29/94-7A) is from a thin section that covers the lower 40 percent of photo A. It shows that surfaces 1 and 2, barely discernible in photo A, are indeed shale-on-shale erosion surfaces with angular truncation at the base. Note also soft sediment deformation below surface 1. Lines drawn between slot sample log and photos A and B correlate corresponding horizons and surfaces (note change of scale from left to right).

surfaces of hand specimens and in slot samples, these horizons are easily recognized by the yellowish color impartet by the high pyrite content. In central Tennessee and southern Kentucky, the *Foerstia* Zone, a stratigraphic marker that has been traced over large portions of the Late Devonian black shale sequence (de Witt et al., 1993), appears to coincide with stratiform pyrite enrichment.

Stratiform silica enrichment is marked by chert layers and nodules (5-50 mm thick). Nodules tend to be flattened and lens-shaped. They pass laterally into non-silicified shale, and surrounding shales show differential compaction. Continuous chert layers tend to be slightly wavy, and may show soft-sediment deformation. Chert layers and nodules are of a black to dark brown color, and show fractures perpendicular to bedding. Internally, they tend to contain numerous siliceous spheroids (0.1-0.3 mm), which may fill *Tasmanites* cysts, or may show recrystallized radiolarian remains (Fig. 21). Chert layers are very rare and thin in Tennessee, but can be quite common in the Chattanooga Shale of northeastern Alabama and northwestern Georgia.

Typically, *Tasmanites* cysts in the Chattanooga Shale are completely flattened due to compaction and form thin streaks within the shale matrix. In “normal” Chattanooga black shale they constitute at best 1-2 percent of the rock volume. There are shale beds (5-100 mm thick), however, where *Tasmanites* cysts make up between 10-20 percent of the rock volume (Fig. 22). Such intervals are best recognized through examination of thin sections.

In places, *Tasmanites* cysts contain a complete or partial fill of early diagenetic minerals, such as quartz and pyrite, and were thus able to withstand compaction (Schieber, 1996). “Filled” cysts, however, are not randomly distributed in the Chattanooga Shale. There are horizons (10-50 mm thick, gradual contacts to shales above and below) where they are very abundant and may compose as much as 20 percent of the total shale volume (Fig. 23), whereas in most of the sequence they are quite rare (much less

Figure 17: Close-up photo of soft-sediment deformation below an erosion surface (8/9/94-23). Erosion surface pointed out by arrows and overlain by parallel laminated silt lag. Silt laminae in underlying shale are clearly contorted and in addition, seem to be truncated at an angle. Coin is 19 mm in diameter.

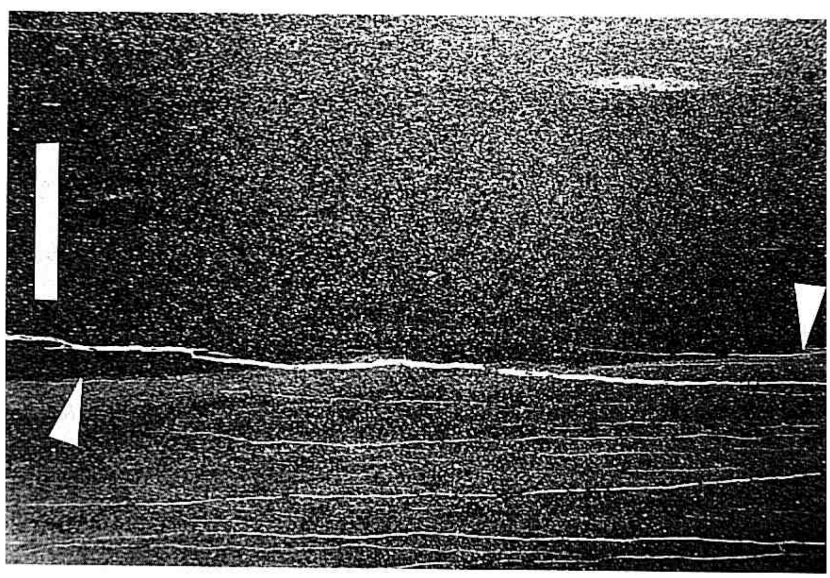

Figure 18: Transmitted light photomicrograph of sharp-based shale bed (94N-H-B) from major erosion surface, the same erosion surface marked as surface 1 in Fig. 6. The thin section was cut from slot sample D (Fig. 6). The shale-on -shale erosion surface (surface 1 of Fig. 6) is marked by arrow. Erosion surface cuts into lighter colored carbonaceous shales below (white lines are epoxy-filled cracks), and is overlain by darker, more carbonaceous shales (faintly laminated). Scale bar represents 5mm.

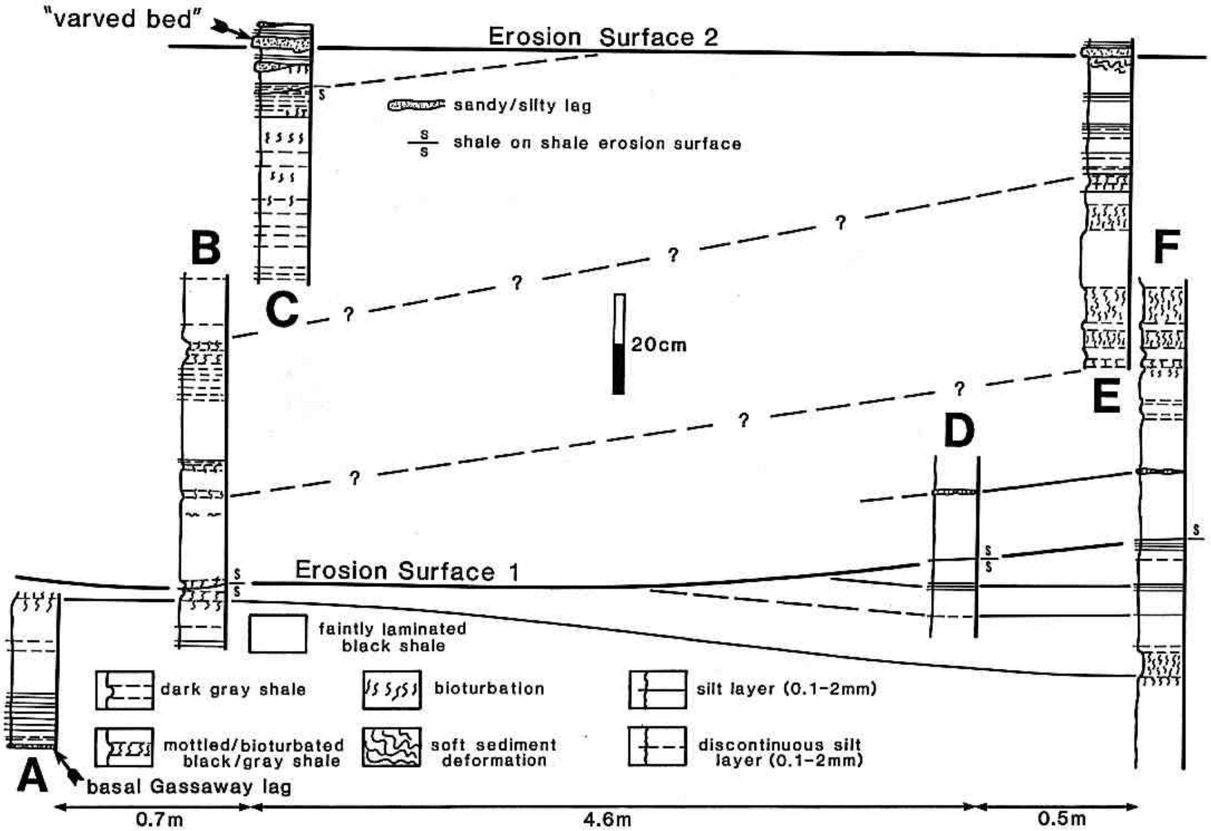

Figure 19: Detailed logs from slot samples marked A through F in Fig. 6. Note that vertical and horizontal scales differ. Tracing of certain layers shows that both erosion surfaces display an angular truncation of underlying shale beds. Also, note a shale interval between erosion surface 1 and 2 that has abundant bioturbated/mottled layers (tentatively correlated with dashed lines). Bioturbated intervals are thicker to the right, where surface 1 seems to arch up and probably formed a positive feature on the sea-floor. This suggests that conditions for benthic life were better on topographic highs (due to O_2 gradient or degree of wave mixing?). Comparing the log for slot C in this figure with that of the more detailed log shown in Fig. 16, should serve to indicate that so much information can be obtained from slot samples that displaying all this infomation effectively can become a problem.

than 1 percent). Horizons of this kind can only be recognized through examination of thin sections. In places, a considerable proportion of pyrite filled cysts are perfectly spherical.

In terms of relative abundance, thin silt lag deposits (less than 5 mm thick) are the most common lag deposits. Conodont and *Lingula* lags, however, although far less conspicuous, are probably equally or even more abundant than thin silt lags. Sand lags and bone beds are probably two orders of magnitude less abundant than either silt lags, conodont lags, or *Lingula* lags. Pyritic lags and horizons of stratiform silica and pyrite appear to be similar in abundance to sand lags and bone beds. There is also a stratigraphic preference for certain types of lag deposits. Whereas silt lags, conodont lags, and *Lingula* lags are found throughout the Chattanooga Shale, sand lags and bone beds are typically found in the Dowelltown member, whereas pyritic lags are characteristically found in the Gassaway member. There appears to be no stratigraphic bias with regard to sedimentary features associated with erosion surfaces.

Figure 20: Photomicrograph of lower boundary of a pyrite-enriched horizon (6/24/93-9B), transmitted light. Lower third of photo shows faintly laminated black shale. Upwards, pyritized fecal pellets (arrows) increase in number and density. The boundary between the underlying black shale and the overlying pyrite-enriched zone is gradational. Scale bare represents 0.5 mm.

TABLE 2: SEDIMENTARY FEATURES ASSOCIATED WITH HIATAL SURFACES

Feature	Ease of Recognition
Stratiform Pyrite Enrichment	in outcrop, thicker layers may be recognized via crusts/blooms of secondary white and yellow hydrous ferric sulfates. In slot samples and cut hand specimens they are easily recognized because of yellow pyrite colour
Stratiform Silica Enrichment	continuous or nodular layers of chert form resistant, very hard ledges in outcrop. They are of black colour, and fractured perpendicular to bedding.
Abundant Tasmanites Cysts	horizons only recognizable via thin section examination
Abundant Filled Tasmanites Cysts	horizons only recognizable via thin section examination

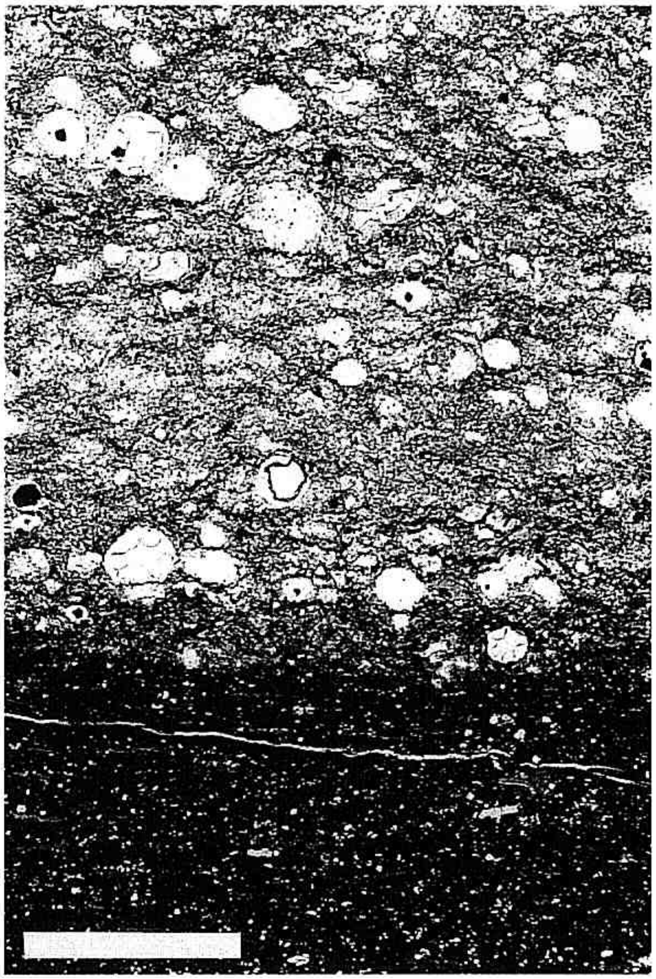

Figure 21: Photomicrograph of chert/shale contact (7/28/95-2A), transmitted light. The dark, lower third of the photo shows black shale, the upper two thirds consist of chert (light color). Note the gradational contact between shale and chert. The large, bright circular spots in the gray-mottled chert matrix are chalcedony-filled *Tasmanites* cysts (Schieber, 1996). Some of the smaller bright spots also contain recrystallized remains of radiolaria. Scale bar represents 1mm.

Figure 22: Transmitted light photomicrograph of black shale with abundant flattened *Tasmanites* cysts (3/17/93-1A). The bright colored *Tasmanites* stand out clearly from the enclosing dark shale matrix. Scale bar represents 0.5mm.

Figure 23: Transmitted light photomicrograph of black shale with abundant silica-filled *Tasmanites* cysts (7/29/92-8A). The silica-filled cysts are the bright spots on the photo, and have been partially compressed and deformed during compaction (for details see Schieber, 1996). Scale bar represents 0.1mm.

DISCUSSION

As pointed out in the introduction, the development of criteria for recognition of erosion surfaces was one of the major objectives of this study. Lag deposits are one of these criteria, because erosion is implicit in the presence of a lag deposit. The extent of erosion associated with a given type of lag deposit does, however, requires further consideration.

Like in many other sedimentary sequences (e.g. Füchtbauer, 1988), scattered glauconite in Chattanooga black shale is probably diagenetic in origin. Such a derivation is also indicated for pyrite framboids and pyritized burrow tubes (e.g. O'Brien and Slatt, 1990; Thomsen and Vorren, 1984). Oval pyritic pellets as shown in Fig. 10 strongly resemble fecal pellets in shape and size. Studies by Cuomo (1984) and Krinsley (pers. comm., 1995) indicate that diagenetic pyritization of fecal pellets is a not uncommon phenomenon. By extension, and taking into account earlier observations of non-pyritic fecal pellets in these rocks (Schieber, 1994b), this suggests that the pyritic peloids in the Chattanooga Shale are also of a fecal pellet origin. Observations reported above and by Schieber (1996) suggest that pyritic spheres, as well as quartz grains with embayments and lobate/pointed projections, pyrite inclusions, cherty, chalcedonic, and colloform textures are diagenetic in origin. Considering the general paucity of such diagenetic grains in "normal" black shales (Schieber, 1996), their concentration into lag deposits thus implies erosion and winnowing of substantial quantities of underlying shales. In first approximation, the thickness of a given lag may even yield a crude estimate of the depth of erosion beneath it. For example, let us assume that the underlying shale contained on average 3 percent pyrite (e.g. Ettensohn et al., 1988), and that all of this pyrite was reworked in form of peloids, spheroids, and framboids to form a peloidal/spheroidal pyritic lag. To form a lag deposit of 10 mm thickness with 80 percent pyritic grains would require erosion and winnowing of 270 mm of underlying shale. Not all of the original pyrite (3 percent), however, is in peloidal, spheroidal, and framboidal form. A portion of it is typically present as micron-size disseminated grains (e.g. Conant and Swanson, 1961). Thus, 270 mm of erosion for a 10 mm pyritic lag is probably a minimum estimate. Because in "normal" black shale, diagenetic quartz and glauconite grain are even rarer than diagenetic pyrite grains, a 10 mm sand lag most likely represents substantially more erosion. Judging from observation of numerous thin sections, bone fragments of the size seen in bone beds are even rarer than diagenetic quartz and glauconite grains, suggesting that bone beds imply a greater depth of erosion than indicated for sand lag deposits. Above assertions are corroborated by the observation that several sand lags and bone beds, like for example the ones found on erosion surfaces in Fig. 5 (on average 10 mm thick), are associated with erosion that cuts out as much as 700 mm of underlying shale.

In contrast, silt in the 0.005-0.050 mm range (mainly quartz) is fairly abundant in the Chattanooga Shale. For that size range, my own estimates and those of Ettensohn et al. (1988, XRD data) suggest an average silt content of around 40 percent (thin section studies, point counts). Thus, to produce a silt lag of 10 mm thickness would only require erosion of approximately 25 mm of underlying shale. The supposition of only shallow erosion for the majority of silt lags is corroborated by the presence of small basal load casts. The latter suggest deposition of these lags on a soft, unconsolidated substrate, and hence shallow erosion. In the case of silt lags on major erosion surfaces, one would expect them to develop to considerable thickness. That expectation is born out by one of the marker horizons in the Chattanooga Shale, the so called "varved bed" (Conant and Swanson, 1961). It is a silt lag (shown in Fig. 7), can be traced over a large area (at least 150km) along the Chattanooga Shale outcrop belt (Conant and Swanson, 1961), and in places it reaches a thickness of as much as 13 cm (Schieber, 1994a). The base of this bed is clearly erosive (Figs. 6 and 7), and its large lateral extent signifies it as an erosion surface of regional significance.

Pyrite beds with oolitic texture are rare sedimentary deposits (Carozzi, 1972), although they are probably more common than generally assumed (F.B. Van Houten, R.M. McKay, and B. Witzke, pers. comm., 1996). Their smooth oval-rounded outline, the fine detail of concentric layers of pyrite (Fig. 13), and the apparent accretion of pyrite cortexes on initial cores (pyrite, phosphatic debris, quartz), are all suggestive of a primary (on the sediment surface), rather than diagenetic (post-depositional) origin. By virtue of the considerable textural parallels between these ooids and carbonate ooids, one might surmise by analogy, that they originated in shallow water with frequent wave agitation. Because of the possibility of primary formation, erosion beneath pyrite ooid beds may be significantly less than beneath other types of pyritic lags. There is, however, a clear need to study these deposits further in order to ascertain their conditions of formation.

Conodonts in the Chattanooga Shale occur in variable quantities, and on average they make up only a small fraction of 1 percent of the rock (Conant and Swanson, 1961). In a standard thin section of Chattanooga Shale one often finds at least a few (1-3), and in some thin sections as many as 10-20 conodonts are found. Samples processed for conodonts yielded between as few as 5 and as many as 200 specimens per 500 grams. These observations suggest that the conodont content of the average Chattanooga Shale is on the order of 0.1 to 0.001 percent. If we assume a conodont content of 0.1 percent, a continuous lag of 2-3 conodonts thickness (0.2 mm thick) would require erosion of as much as 200 mm of shale. Because the typical conodont lag (tens of mm's thick) is patchy-discontinuous and mixed with silt, a smaller depth of erosion, probably on the order of tens of mm's, is more likely associated with the majority of conodont lags in the Chattanooga Shale.

Lingulas on the top surface of sand layers are probably due to the circumstance that the settling velocity of *Lingula* shells will necessarily be much smaller than that of associated sand grains. Thus, when *Lingula* shells are eroded due to wave or current action they will settle last, after all the sand has been deposited on the seafloor. Whether reworking is due to a short-lived event, such as storm wave activity, or whether it is due to prolonged current and wave reworking, should not make a difference. In both instances the *Lingula* shells should end up on top, and the *Lingula* lag can simply be considered a part of the underlying sand deposit. *Lingula* shells on shale bedding planes probably reflect a different set of circumstances. Scarcity of silt lenses and the general absence of indicators of erosion suggest that little erosion occurred. Simple, shallow burrows directly below these lags may actually have been produced by *Lingula*, and their preservation would further indicate that erosion was minor. Overall, available observations suggest that erosion associated with *Lingula* lags on shale bedding planes was negligible, possibly only on the order of mm's. Obliquely embedded *Lingulas* confirm that *Lingulas* did indeed live in these muds, and the association with filled *Tasmanites* cysts indicates conditions of relatively slow sedimentation (Schieber, 1996). One might also ask, in that context, whether the observation that "lags" in many instances actually consist of multiple, closely spaced lags, implies that *Lingula* prospered better under conditions of comparatively slow sedimentation.

Bioturbation features in the Chattanooga Shale suggest the presence of a surface substrate with a slurry-like consistency (Schieber, 1994a). That load structures are absent or not prominent beneath lag deposits suggests that most of the soft surface sediments typically were removed prior to their deposition. In cases where soft-sediment deformation as depicted in Figs. 16B and 17 occurs, plastic behavior of the underlying shales is indicated. Sharp basal surfaces (Fig. 7), as well as sand-filled basal scours that show little differential compaction (Fig. 8), indicate that erosion not uncommonly cut down into fairly consolidated, firm shales.

According to Sundborg (1956), erosion of consolidated shales requires current velocities on the order of 100 cm/s. Likewise, transport of bone fragments of the size encountered in bone beds would require current velocities on the order of 100 cm/s (Sundborg, 1956). Flume experiments by Einsele et al. (1974) show that a plastic mud with 70 percent porosity required current velocities of 150 cm/s to produce soft sediment deformation due to current drag on the sediment surface. Soft sediment deformation as seen in Fig. 16B is suggestive of current drag. Furthermore, although the erosional behavior of muds is influenced by a number of variables whose impact is still poorly understood (e.g. fabric, sedimentation rate, composition), it is generally agreed that the erodability of muds is controlled to a large degree by its water content (Potter et al., 1980), with soft-soupy surface muds requiring much less current strength than firm, consolidated ones. Considering all this, and particularly results of the Einsele et al. (1974) study, the fact that in places erosion surfaces were cut into quite consolidated and firm muds (e.g. Fig. 8) strongly suggests current velocities as large as or even in excess of 150 cm/s for the deeply-cut erosion surfaces in the Chattanooga Shale. Minor erosion beneath *Lingula* lags, on the other hand, would most likely have occurred in unconsolidated surface sediment (discussed above). In that case current velocities between 5-10 cm/s would have sufficed (Sundborg, 1956). In view of the aforesaid, it is probably reasonable to assert that erosive features in the Chattanooga Shale were produced by currents flowing at velocities between 5-150 cm/s. Considering the degree of consolidation that the eroded shales suggest in some cases (Fig. 8), current velocities could have been substantially in excess of 150 cm/s. Assuming for a moment an overall crude correlation between approximate depth of erosion and velocity of eroding currents, bone beds and sand lags would have required the largest velocities, followed by pyritic lags, silt lags and conodont lags, and finally *Lingula* lags.

In an earlier paper (Schieber, 1994a), I argued that storms played an important role during deposition of the Chattanooga Shale. Based on approximations of wave fetch, estimates of wave heights from oceanographic tables, orbital velocity estimates from bedforms and grain size data, and methods of water depth estimation described by Clifton and Dingler (1984), I suggested a water depth between 15 and 50 meters for various parts of the Chattanooga Shale. In view of the fact that the coastline of the Late Devonian inland sea was far removed (about 200km) from the study area in central Tennessee and southern Kentucky (e.g. Dennison, 1985), it is my current working hypothesis that wave reworking and associated currents might also have been responsible for deep erosion in the Chattanooga Shale. Assuming the same boundary conditions as in Schieber (1994a), I expanded the calculations to include maximum orbital velocities of 150 and 200 cm/s. Under these conditions, water depth estimates between 10-20 m result.

The preceding water depth estimate applies to major erosion surfaces (Figs. 6 and 7) with substantial removal of underlying shale, because they presumably required the highest current strength. Shallow erosion, on the other hand, mostly associated with the common silt, conodont, and *Lingula* lags, would mostly affect relatively unconsolidated surface sediments and accordingly require comparatively lesser current strength. Erosion beneath *Lingula* lags might have required as little as 5-10 cm/s (see above), and for conodont and silt lags somewhat larger velocities, possibly in the 10-40 cm/s range (Sundborg, 1956, 1967). Current velocities of that order of magnitude can be generated by storm waves at water depths inferred previously from storm deposits in the Chattanooga Shale (15-50 m; Schieber, 1994a). In that context, we may even consider to group bone beds, sand lags, thick silt lags, and pyritic lags together as “high energy” lags, and silt, conodont, and *Lingula* lags as “low energy” lags.

That the comparatively rare and laterally extensive major erosion surfaces (associated with bone beds, sand lags, thick silt lags, pyritic lags) seem to require distinctly greater current velocities than the much more common shallow erosive features (associated with “low energy” lags), may actually point to formation under distinctly different circumstances. One might of course simply assume that the latter were the result of “average” storms, whereas the former were the product of very rare, but exceptionally strong ones. Alternatively, large lateral extent and substantially smaller water depth estimates (see above) for the “high energy” lags can be interpreted to mean intensified wave reworking due to lowering of sea level. Regressive-transgressive (RT) cycles in the Devonian standard sequence of New York State have been interpreted in terms of sea level variations (Johnson et al., 1985), and Ettensohn et al. (1988) interpreted lithologic variations between successive Late Devonian black shale units of central Kentucky as a result of alternating regressions and transgressions. Thus, there is a distinct possibility that “high energy” erosion surfaces in the Chattanooga Shale are sequence boundaries sensu Vail et al. (1992).

In the Appalachian basin, the best record of sea level changes is contained in marginal and shallow marine rocks (Johnson et al., 1985; Dennison, 1985; Van Tassell, 1987; Van Tassell, 1994). As a consequence, when studying sea level changes in the Appalachian basin, one has to untangle the combined effects of eustasy, tectonism, and sediment supply. Because of this, it is quite possible that critical information about the actual causes of sea level changes in the Appalachian basin will in the end come from observations made in distal shales, such as the Chattanooga.

Observations pertaining to “high energy” erosion surfaces pose a number of interesting questions. For example, how can sharp-based shale beds and the absence of lags on some erosion surfaces (Fig. 16) be reconciled with demonstrated deep erosion (Fig. 6) and inevitable production of winnowed grains (quartz. pyrite, fish bones)? Considering that for example in Fig. 6 surface 1 defines a trough-like feature, one would actually expect a thickening of lag deposits in this depression. Instead, surface 1 is a shale-on-shale erosion surface (Fig. 16). At present, a possible explanation is, that in the process of wave-erosion current systems were set up (geostrophic, or coastal downwelling; Swift et al., 1987; Allen, 1982) that were strong enough to remove all the winnowed grains from certain areas. Systematic tracing of erosion surfaces and lags should reveal whether surfaces that have no lag in some areas, do carry a lag in other areas, and whether there are paleogeographically significant distribution patterns.

During winnowing of shale to produce a bone bed, sand lag, or pyritic lag, substantial quantities of silt, clay, and organic matter are removed. Where does all that material end up? Basically, while shale is eroded in shallow areas during sea level drops, the eroded material should collect in adjacent deeper portions of the basin. Can tracing of erosion surfaces verify such a relationship between shallow areas with erosion and deep areas with increased sedimentation? Will the “resedimented” shales show a decreasing silt content away from shallow areas? How, if any, might such “resedimented” shales differ from other black shales in the basin? Potentially, one, albeit subtle, difference could be a lack (or depletion) of sand-sized diagenetic grains.

Considering that the Chattanooga Shale encompasses as much as 18 conodont zones over approximately 10 m thickness (e.g. Woodrow et al., 1988), it is also conceivable that at major erosion surfaces there is a noticeable gap in the conodont record that could be used to correlate these surfaces. Some indications of this have been found by Ettensohn et al. (1989). Conodont data may also help to link erosion surfaces with correlative packages of “resedimented” shale. At present, detailed conodont work on the studied outcrops is underway in cooperation with James Barrick.

In an earlier paper I argued (Schieber, 1996) that stratiform enrichments of pyrite and silica, typically associated with diagenesis of *Tasmanites* cysts, is probably a sign of very slow sedimentation. Mainly because under those conditions there is (a) the best chance for deposited cysts to fill with diagenetic minerals prior to compactional collapse, and (b) the greatest likelihood for high silica concentrations (from radiolaria) in pore waters. How then, do horizons of abundant diagenetic silica (chert nodules, chert bands) or diagenetic pyrite fit into the scheme of things with regard to “high energy” erosion surfaces? Are they laterally related to them and represent (possibly) somewhat deeper areas where wave action was sufficient to prevent settling of most fine grained material, but too weak to effect noticeable erosion? In that case, would they be found between areas of erosion and areas where "resedimented" shales accumulate? Alternatively, are they unrelated to erosion surfaces and simply record conditions of extreme sediment starvation? Finally, could, for example, pyritic lags simply mean very slow deposition and intermittent shallow erosion, rather than erosion and winnowing of a substantial volume of shale? Again, lateral tracing and conodont data may eventually help to answer these questions.

Another interesting problem is posed by the distribution of sand lags and pyritic lags between the Dowelltown and Gassaway members of the Chattanooga Shale. Could this indicate that during Dowelltown deposition the conditions were more favorable for formation of siliceous diagenetic grains, and more favorable for formation of pyritic grains during Gassaway deposition? If so, which paleoceanographic parameters did differ? The degree of oxygenation of the water column (less oxygenation might favor pyritic grains)? The nutrient supply through terrestrial runoff (might affect development of plankton and/or radiolaria)? The overall rate of sedimentation? For example, slow rates of sedimentation should allow formation of larger quantities of siliceous cyst fills, because diagenetic silica deposition is slower than that of pyrite. Ultimately, it should be possible to formulate most of these questions as testable hypotheses, the validity of which can be examined in the broader context of lateral changes of erosion surfaces and lag deposits.

Because erosion surfaces that are clearly marked by a coarse lag in one outcrop, may be perfectly inconspicuous and only marked by a sharp-based shale bed in a nearby exposure, and because lags that seem to be associated with only minor erosion in one outcrop, may be associated with substantial scours elsewhere (Fig. 19), correlating erosion surfaces from outcrop to outcrop presents a formidable challenge. The compositional change, however, that marks sharp-based shale beds might be accompanied by sufficiently large changes in K, U, and Th content, or in ratios of these elements, to be identifiable via spectral gamma ray data. This technique has been employed successfully by Bohacs and Schwalbach (1992) for the correlation of shale packages and erosion surfaces in shales. Total gamma ray counts have been used by Ettensohn et al. (1988) for correlation of outcrops and subsurface data in Kentucky. Application of gamma ray spectrometry to the Chattanooga Shale is in progress.

CONCLUSION

Although this is essentially a report from a study in progress, the observations made to date still allow us to arrive at a number of conclusions. Results can be grouped into three categories, (1) conclusions concerning conditions of Chattanooga Shale deposition, (2) conclusions that have stratigraphic implications, and (3) formulation of questions to guide further investigations.

Conclusions of the first category include:

a) Detailed study of outcrops, slot samples, and thin sections reveals that erosive features are common throughout the Chattanooga Shale, and that there are also intervals that record very slow or halted sedimentation that are marked by stratiform silica or pyrite enrichments.
b) Lag deposits are the most easily recognizable indicator of erosion surfaces and can be ranked by likely depth of erosion. Sand lags and bone beds: $X*10^2$ cm; pyritic lags: $X*10^1$ cm; silt lags and conodont lags: $X*10^0$ cm; *Lingula* lags: $X*10^{-1}$ cm.
c) To a large proportion, the sediment particles found in lag deposits are of diagenetic and biogenic origin.
c) Not all erosion surfaces may be marked by lag deposits. Even major erosion surfaces may be marked by no more than a sharp boundary between shale beds of differing composition.
d) Considerations of sedimentary features, depth of erosion, and firmness of substrate suggest that lags with little erosion (*Lingula* lags) were produced by currents on the order of 5-10 cm/s, silt lags and conodont lags by current velocities in the 10-40 cm/s range, and bone beds, sand lags, and pyritic lags by currents in to 100-200 cm/s range.

Conclusions of the second category include:

a) Prominent erosion surfaces of large lateral extent may be due to sea level drop, and may actually represent sequence boundaries.
b) Intervals with stratiform enrichments of pyrite and silica could be deeper water extensions of prominent erosion surfaces and may aid stratigraphic correlation.

Conclusions of the third category include:

a) In portions of the Chattanooga Shale that were deposited in deeper water, intervals of "resedimented" shale should be found as lateral equivalents of major erosion surfaces.
b) An incomplete or condensed conodont record is likely at major erosion surfaces.
c) Paleoceanographic parameters, such as water column oxygenation, nutrient supply, and sedimentation rates, may have had an influence on which type of diagenetic grains (and lag type) was predominantly produced.

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