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TECTONIC SIGNIFICANCE OF DISTAL TURBIDITES IN THE MIDDLE ORDOVICIAN BLOCKHOUSE AND LOWER SEVIER FORMATIONS IN EAST TENNESSEE

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ABSTRACT. The lower 900 m of the 2500+ meter-thick Ordovician Blockhouse-Sevier shales of eastern Tennessee are interpreted as of ultradistal turbidite–hemipelagic origin. These sediments are characterized by alternations of thin (2-5 mm) silt layers and clay-rich layers of variable thickness. Silt layers show sharp bases, positive grading, and Bouma sequences T_{cde} and T_{de}, with convolute laminations indicative of distal turbidity-current deposition. Pseudonodule zones are the result of soft-sediment deformation caused by differential liquefaction of lower layers. Microload and microflame structures are common. Clay zones between silt laminae are unlaminated, contain common graptolites and tintinnines, and are of hemipelagic origin. The proportion of hemipelagic layers decreases and that of distal turbidite layers increases upward in the section. Approximately correlative proximal turbidites 30 to 40 km palinspastically to the southeast of this sequence indicate a southeasterly source. Depth of water at time of deposition is inferred to have been greater than 200 m and probably 600 to 800 m. These figures are based on conservative interpretation of stratigraphic relationships with adjacent contemporaneous slope and carbonate-shelf deposits to the northwest as well as absence in these shales of algae, shallow-water fauna, and sedimentary structures indicating deposition above wave base. The depth may well have been greater. Shallow-water (10 m depth) carbonates *conformably* underlie the sequence of shales, separated only by a thin zone of slope facies. The stratigraphy indicates a sudden increase in water depth of 500 m or more. Such a "foundering" of continental crust is doubtless a manifestation in the basin of more profound Taconic tectonic events that took place to the southeast. Perhaps study of the detailed subsidence history of this basin will lead to new insights into Taconic deformation.

INTRODUCTION

The Middle Ordovician sequence of the eastern Valley and Ridge Province in Tennessee (fig. 1) consists of an extremely thick succession of shales, siltstones, and sandstones. In places, this sequence is as much as 3000 m thick. The relationships between this terrigenous clastic sequence and carbonate rocks to the northwest have been discussed in another publication (Walker, 1977). Some aspects of these relationships are shown in figure 2. The shales of this succession have never been studied in detail, and prior to our work their origin was unknown. We will demonstrate here that the lower 900 m of the succession consist largely of ultradistal turbidites, which were deposited in a deeper water basin that formed by very rapid subsidence during the Whiterockian(?) Age of earliest Middle Ordovician.

Since the recognition of the ideal sequence of internal sedimentary structures (A through E divisions) in turbidites by Bouma (1962), several workers have attempted to explain the depositional mechanics involved (Walker, 1965; Walton, 1967; Kuenen, 1967; Allen, 1970; and Middleton and Hampton, 1976). Still, knowledge of the characteristics and origin of the silt and clay deposits of distal turbidites is not complete.

Our interpretation of the environment of deposition of this sequence of Ordovician shales is based on detailed study of minor sedimentary structures in polished slabs, acetate peels, thin sections, and X-radio-

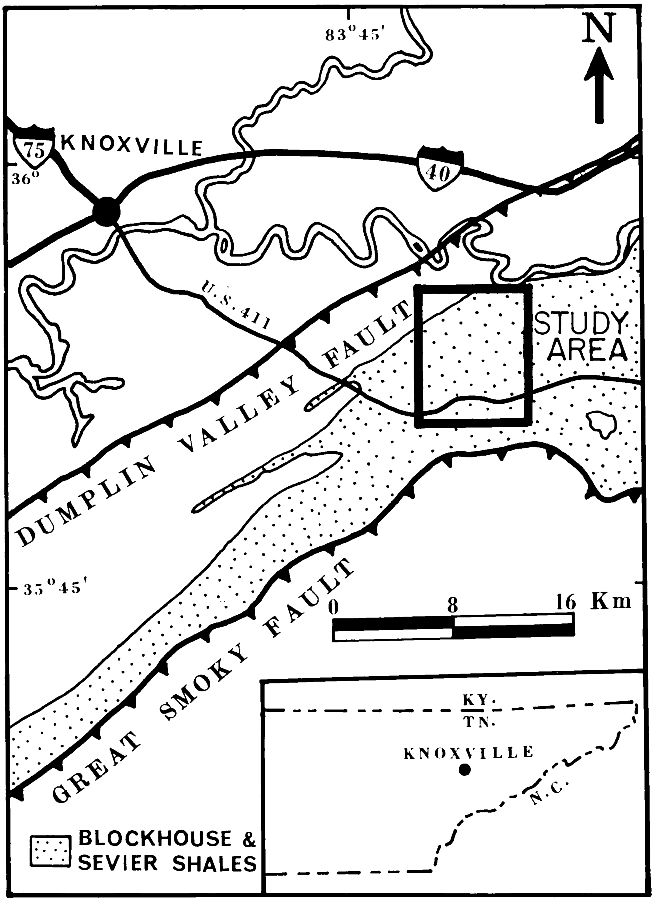


Fig. 1. Location map showing Boyds Creek study area.

graphs. Many of the critical structures are microscopic in scale, and many similar shale sequences may have been previously misinterpreted as pelagic and in some cases even shallow water in origin.

A nearly continuous sequence of the Blockhouse and Sevier Shales is exposed in the Boyds Creek area (fig. 1; section BC in fig. 2). This locality was chosen because the rocks are well exposed and structural complications are minimal. Although the entire Middle Ordovician sequence here is probably more than 2500 m thick, we have concentrated on the basal 900 m. As shown in figure 2, the interval rests unconformably on Lower Ordovician Knox Group dolomites and consists of: (1) a basal limestone unit (Lenoir-Whitesburg formations), which is 47 m thick, (2) a thinly laminated calcareous, graptolitic clay shale (Blockhouse Formation of Neuman, 1955), which is 379 m thick, and (3) a thick sequence of shale, siltstone, and fine sandstone 500+ m thick, which we refer to

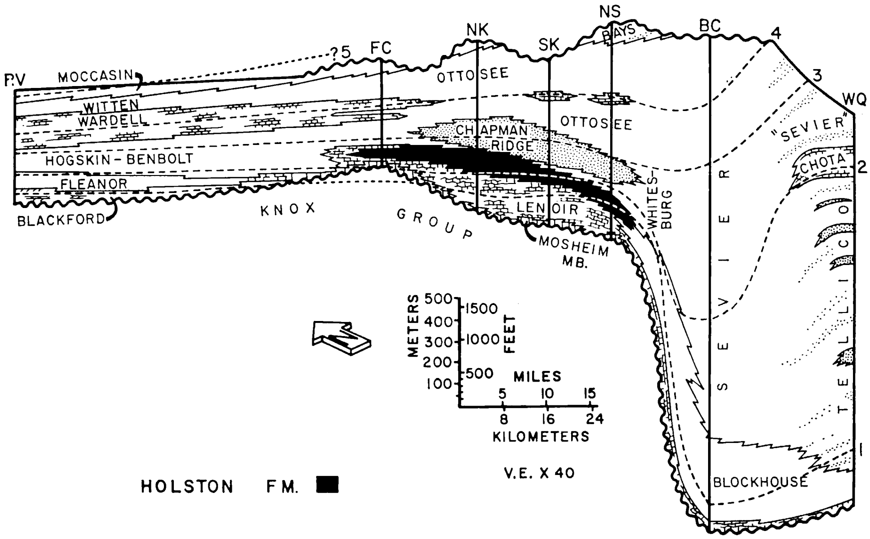


Fig. 2. Regional facies pattern of the Middle Ordovician in east Tennessee. Line of this palinspastically reconstructed section trends northwest (left) to southeast. BC refers to Boyds Creek section. Four time lines are shown as dotted lines. Holston Formation is shown in black for reference. From Walker, 1977.

the Sevier Shale following the usage of Rodgers (1953). We were most concerned with the shale sequence, but some observations were also made on the basal limestone unit. This unit consists in ascending order of several meters of dark gray dismicrite of probable tidal-flat origin, 30 m of lumpy bedded algal-rich, fossiliferous limestone of shallow (10± m) subtidal origin. At the top of this limestone sequence is a transition zone (Whitesburg) about 10 m thick which consists of medium beds of dark gray, pelmatozoan grainstone interbedded with intervals of dark gray, graptolitic clay shales like those of the overlying Blockhouse. The grainstones contain abundant phosphatized grains and are rich in manganese. We interpret this transition zone as a slope deposit. Conformably overlying this transition are the shales that are the concern of the rest of this paper.

METHODS OF STUDY

The shaly sequence is megascopically monotonous and devoid of distinct marker beds. Hence, outcrops were examined bed by bed only for bed thickness and grain-size variations. Maximum grain size of quartz within each bed from bottom to top was determined using an Edscorp comparator magnifier. Stratified random samples were collected representing the measured interval (Krumbein and Graybill, 1965). In many instances friable rocks had to be impregnated in the field before sampling. Others required impregnation in the laboratory. The position of samples is shown on figure 4.

When the monotonous-looking shale is studied under the microscope or using X-radiographs, a great wealth of environmentally sensitive sedimentary features are evident. Hence, several types of sample material were used to study these micro-sedimentary features (table 1). Using these materials, details of small-scale sedimentary features were recorded. Maximum grain size of quartz grains was measured in thin sections to corroborate field measurements. A total of nearly 9000 individual beds were examined in the laboratory.

PALEOBATHYMETRY

A paleobathymetric analysis of the Ordovician rocks in the Southern Appalachians is given by Benedict and Walker (this issue, p. 579-607). The major problem we faced with the shaly rocks of the Boyds Creek area was the absence of good paleobathymetric indicators such as algae. However, we have established an estimate of depth of deposition of the Boyds Creek section based on biological, physical, and stratigraphic criteria.

The depth of water during deposition of the Lenoir Formation, which lies at the base of this section (fig. 2), was not more than 10 m, judging by the presence of oncolites, *Girvanella,* other algae, sponges, and abundant shallow-water brachiopods (Walker, 1974). The Whitesburg Formation which overlies Lenoir rocks and underlies the calcareous, dark-gray, graptolitic shaly sequence has been interpreted as a slope deposit (Walker, 1977). It contains an abundance of microscopic octracodes and unabraded echinoderm plates. A near lack of evidence of algal activity contrasts sharply with the abundant algae of the Lenoir. Occasionally, we found abraded, transported specimens of the shallow-water alga *Nuia.* The presence of phosphatic grains and the high manganese content of grainstones in the Whitesburg also suggest a shelf-basin boundary environment. Finally, intercalation of graptolitic clay shales typical of more basinal conditions (see below) also indicates slope conditions. Based on these data and on the stratigraphic relationship with the adjoining shallow shelf to the northwest and deep basinal rocks to the southeast (fig. 2), we postulate a depth of water of 150 to 200 m during deposition of the Whitesburg.

We have used various lines of paleobathymetric evidence in the Blockhouse and Sevier Formations. First, the presence of graptolites and

TABLE 1

Methods used in the study of micro-sedimentary structures in the shales of the Blockhouse and Sevier formations

Methods of approach	Number of samples studied
1. Polished slabs	250
2. Thin sections (50-75 mm)	200
3. Acetate peels	50
4. Enlarged negative prints of selected thin sections and peels	100
5. X-radiographs of selected samples	30

tintinnines is suggestive of an open marine environment. The protozoan tintinnines, rare in the Ordovician (Horowitz and Potter, 1971), are usually associated with deep-water marine facies of ancient sediments (Loeblich and Tappan, 1968). Second, a total absence of algae and evidence of algal activity and the absence of shallow-water fauna are suggestive of deep-water conditions. Third, absence of wave-ripple marks, rill marks, desiccation features, and scarcity of current bedding (only small-scale current laminations are present) indicate deposition below wave base. Fourth, the negligible amount of coarse grains and the uniformity and lateral continuity of most of the beds suggest a quiet, level-bottom environment distant from the shore. Finally, the lateral stratigraphic relationship of the Sevier Shale with adjacent shelf-edge reef-tract/skeletal sand-bank sediments (Holston Formation, see Walker, 1974 and 1977) and associated shelf sediments to the northwest places the Blockhouse and the lower Sevier paleogeographically in a basinal position.

Such observations suggest that these shaly rocks were deposited well below wave base at a depth exceeding 200 m. Paleobathymetric information derived independently from the environmental facies pattern for the Middle Ordovician rocks in eastern Tennessee by Walker (1977) suggests a water depth of more than 200 m for the Blockhouse and lower Sevier Shale. This depth is near the shelf-slope boundary in modern oceans, but the Blockhouse and lower Sevier lack the characteristics of shelf sediments (Kukal, 1971) and are also separated stratigraphically from the shelf sediments to the northwest by the slope sediments of the Whitesburg Formation.

If we take the approximate palinspastic distance from the Boyds Creek stratigraphic section to the nearest correlative shelf edge deposits (about 10-15 km) and a reasonable slope gradient of 2° to 3° for the intervening Whitesburg environment, the maximum water depth at Boyds Creek would have been about 600 to 800 m. Considering the total thickness of sediment deposited in this basin (in excess of 2000-2500 m) a greater depth is a definite possibility. Without further evidence, then, we are only able to suggest a rather broad range of possible depth of 200+ to 800 m for the depositional environment of the Blockhouse-Sevier sequence. The higher values are more likely.

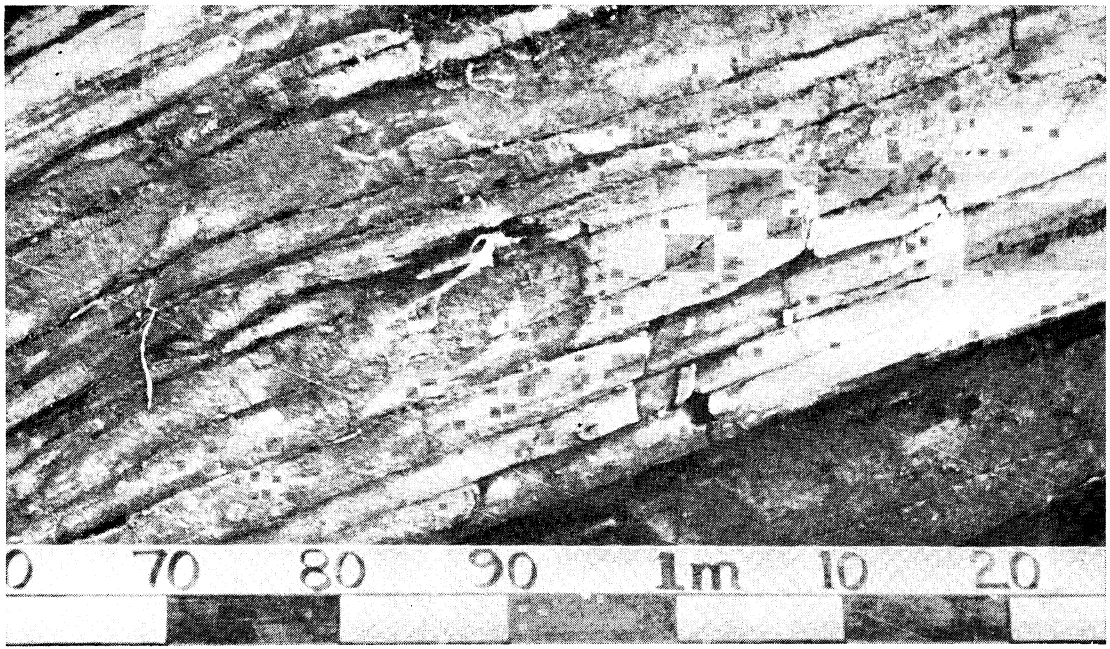
SEDIMENTARY STRUCTURES

The sedimentary structures of the Blockhouse and the lower Sevier formations are quite varied (Shanmugam and Walker, 1977). Some can be readily seen on outcrop, but many are visible only on specially prepared sample material, and some only in magnified thin sections or by other methods. The most important structures are illustrated in plates 1, 2, 3, and 4; the captions give pertinent details. In the following part of this paper, we discuss the hydrodynamic origin and significance of individual types and sequences of sedimentary structures.

PLATE 1

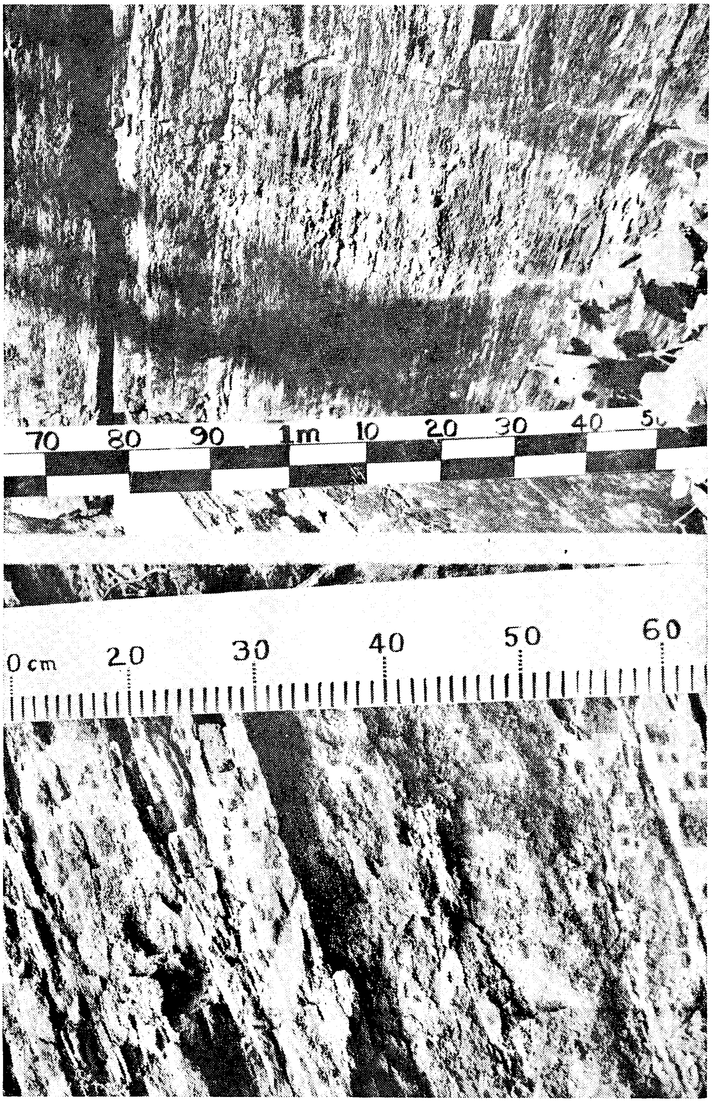
Field photographs showing bedding characteristics.

A. Laterally continuous bedding with uniform bed thickness.



A.

C.



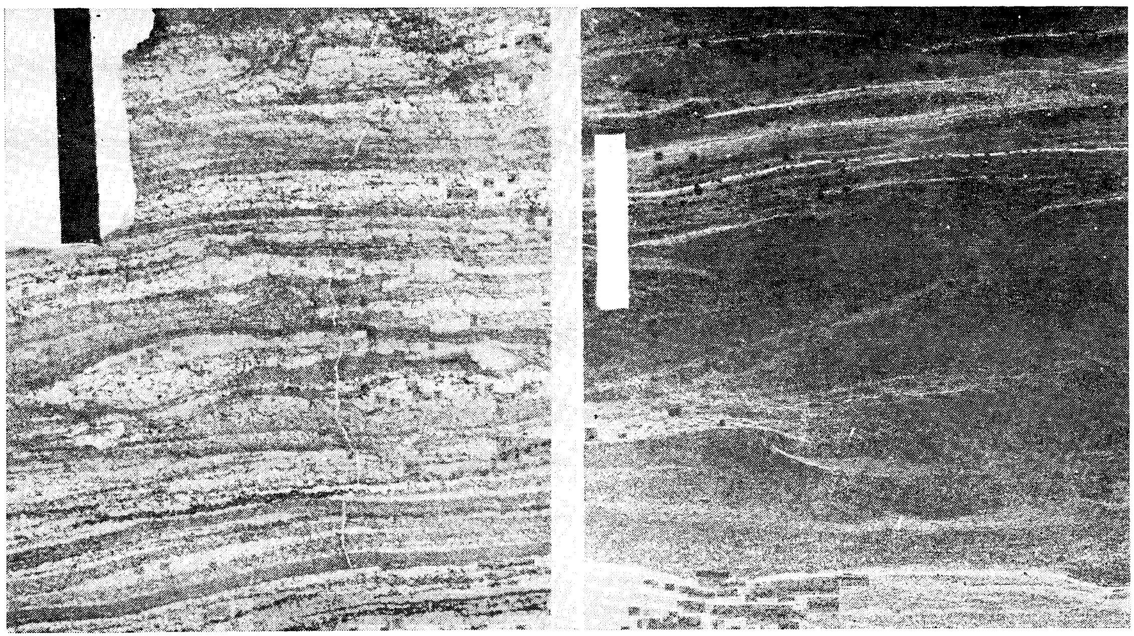
B.

B. Alteration of siltstone and claystone beds. Often, these siltstone beds show grading.
C. Beds showing internal laminations.

PLATE 2

A. Photograph of a thin section showing parallel (lower part) and irregular (upper part) laminations. Bar scale is 1 cm.

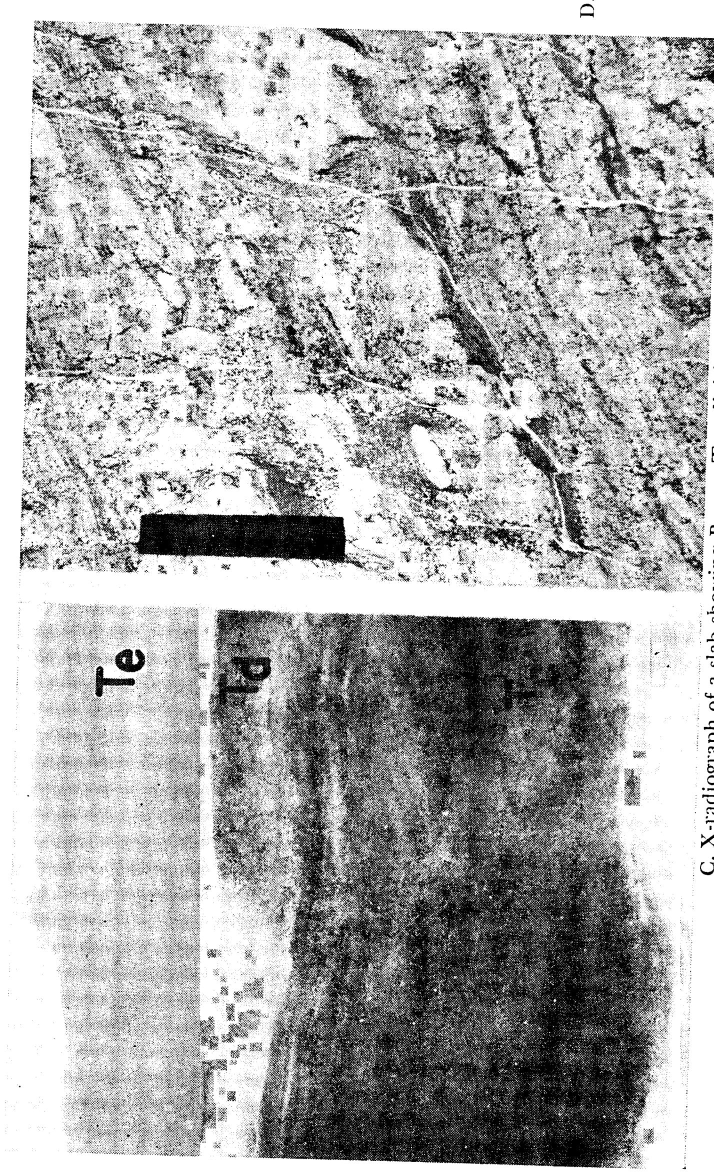
B. Negative print of a peel showing cross laminations. Probable current direction is from right to left. Bar scale is 1 cm.



A. B.

D.

C.



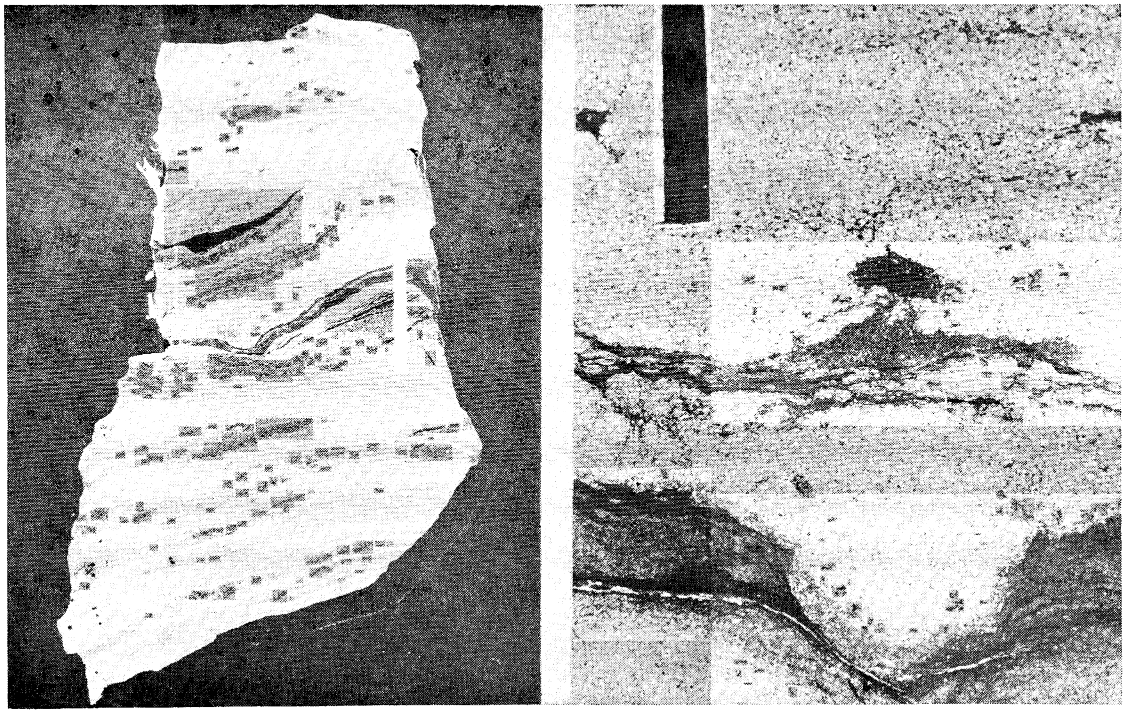
C. X-radiograph of a slab showing Bouma T_{cde} divisions.
D. Photograph of a thin section showing mottling. Bar scale is 1 cm.

PLATE 3

Sedimentary structures indicative of rapid sedimentation. Bar scale is 1 cm.

A. Negative print of a peel showing convolute laminations.

B. Photograph of a thin section showing loading caused by sinking of upper silt layer into the underying clay layer.



A. B.

D.

C.

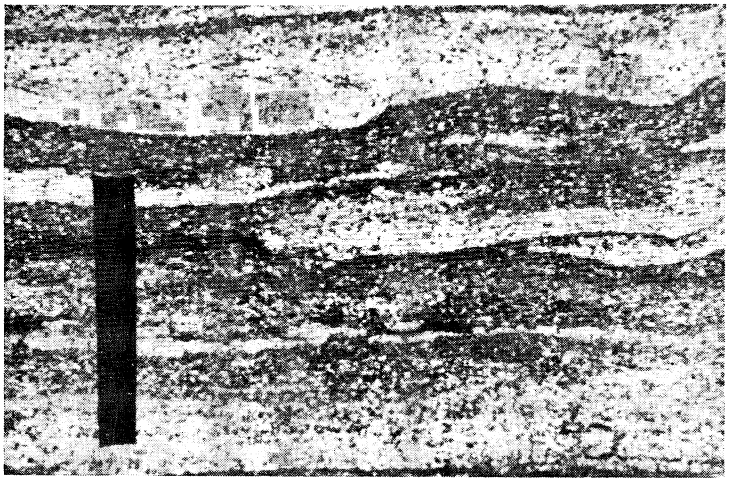
C. Photograph of a thin section showing pseudonodules caused by differential liquefaction.
D. Photograph of a thin section showing animal escape burrows.

PLATE 4

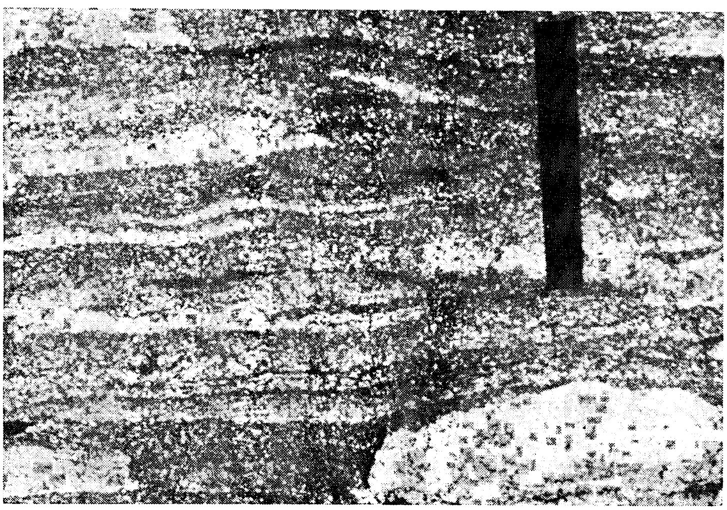
Features indicative of probable deep ocean current deposition. Bar scale is 1 cm.

A.

A. Negative print of a peel showing beds with sharp basal and sharp top contacts.



B.



C.

B. Photograph of a thin section showing lenticular lamination.
C. Photograph of a thin section showing discontinuous lamination.

Individual Types of Structures

Parallel layering is the only observable feature of these rocks in outcrop. Use of a conventional classification to differentiate bedding from lamination (for example, Ingram, 1954) is difficult because of rapid microthickness variation from lamina to lamina and the complex intercalation of different types of layers. Furthermore, the layers are internally laminated because of textural rather than compositional changes.

Megascopic continuous bedding.—The shales exposed in the Boyds Creek section are characteristically uniform in *megascopic* bedding thickness, which ranges from 2 to 5 cm (pl. 1-A). Occasionally bedding thickness reaches 50 cm. Most of the beds are constant in gross lithology (primarily calcareous siltstone with 5 to 35 percent terrigenous quartz and calcisiltites) and uniform in thickness. Individual megascopic beds could be traced up to 50 m along the outcrop, and lateral interruptions and pinch-outs are absent. The contact between beds is exceedingly sharp and planar. Bedding partings are well developed throughout.

Each bed is composed of several internal laminations. These laminations are rarely visible on outcrop but can be seen more easily under the microscope.

Megascopic graded bedding.—Because of the general fine grain size, recognition of graded bedding on outcrop is difficult. Most beds look homogeneous, but microscopic field and laboratory examination reveals grading from very fine sand or coarse silt at the base to clay at the top. Alternation of graded siltstone beds with claystone layers is common in the exposures (pl. 1-B).

Laminations.—As mentioned above, most beds display internal laminations (pl. 1-C) caused by textural changes, although compositional changes do play a minor role. The laminations are best observed in thin sections and polished slabs. Where observed in field exposures, laminations 2 to 5 mm thick are traceable for several meters. Two kinds of laminations are present: those that have parallel borders (pl. 2-A, lower part), and those that are irregular (pl. 2-A, upper part). The irregular laminations are probably caused by soft-sediment deformation of parallel laminations, although some bioturbation may also be involved.

Graded silt laminations.—Graded silt laminations are common and range in thickness from 2 to 6 mm. They are characterized by sharp bases and gradational top contacts, a criterion often used to identify turbidite layers.

The different types of grading recognized in the Sevier Shale have been reported by other workers in sandy turbidites (Ksiazkiewicz, 1952; Kuenen, 1953). In many cases, the whole size distribution shifts to finer sizes progressively from a median of 0.088mm (3.5 phi) at the bottom to a median of 0.015mm (6 phi) at the top of the lamina. Middleton (1967) identified this type of distribution grading in his experimental studies and noted that it is caused by deposition of laminae from dilute experimental turbidity currents. This type of grading is analogous to the "ideal type" of Kuenen (1953) and the "continuous with good separation" type of Ksiazkiewicz (1952). Discontinuous grading in which the upper finest grain sizes are missing is rare in the Sevier; it could be attributed to an absence of finest grains in the current or to the erosion of finest grains by a subsequent flow.

Sequences of Sedimentary Structures

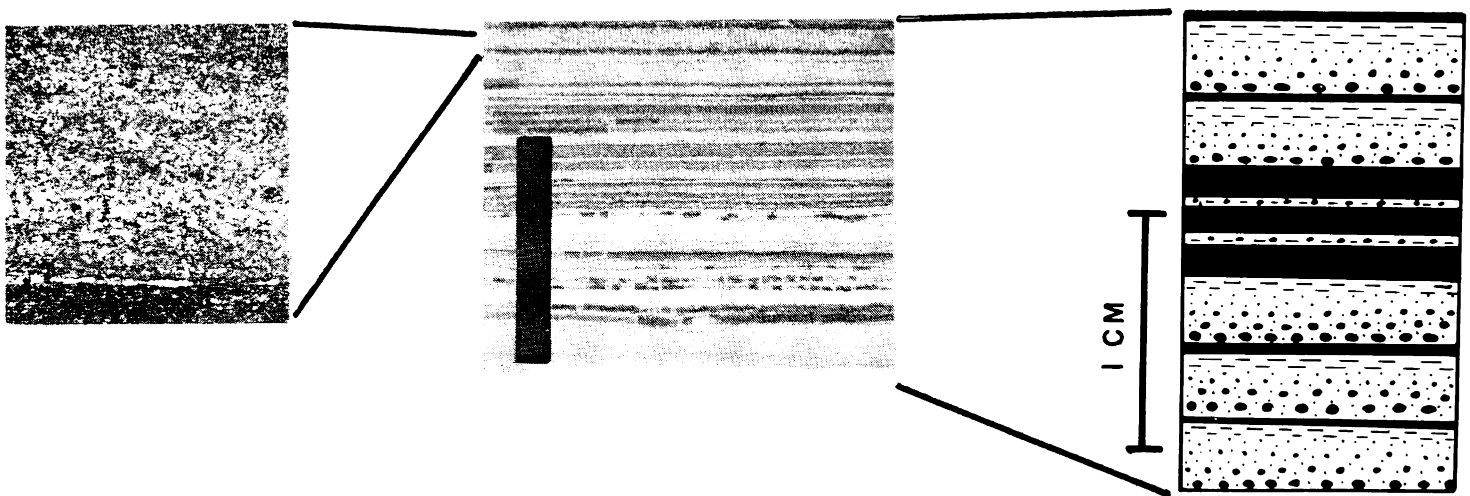
Type 1 sequence.—Multiple graded silt laminations with intervening clay layers are quite common in the Blockhouse and in the lower Sevier (pl. 5). The graded silt laminations are laterally continuous and persistent in thickness (less than 1 cm). Such an alternation of graded silt laminations and clay layers (varying thickness) resembles that of a flysch sequence on a microscopic scale and has been reported from the modern deep sea (DSDP leg 18, Piper, 1973; leg 28, Piper and Brisco, 1975).

Modern oceanographic research has expanded our knowledge of various marine transport and depositional processes. Most of these marine processes have been discussed for modern continental margins by Bouma and Hollister (1973), Kelling and Stanley (1976), Middleton and Hampton (1976), and Pierce (1976). Shaly sequences of deep-water origin are probably enriched with graded silt laminations more commonly than reported in the literature, because modern deep-sea research has emphasized coarse-grained sediments (for example, sandy turbidites). As a result, we know very little about modern fine-grained sediments (for example, mud turbidites). Furthermore, there are no well understood criteria in ancient sediments to distinguish the various deep-sea depositional processes that emplace these sediments. Most important, poor data on the silt/clay-sized regions in the Hjulstrom diagram (Sundborg, 1956) make it very difficult to understand fine-grained sediments in terms of erosion and deposition. Recent experimental work on silt turbidites by Banerjee (1977) has helped to fill this gap in our knowledge, but much remains to be done. Because of our lack of knowledge of depositional processes associated with silt and clay sized particles, any interpretation of sedimentary structures observed in fine-grained sediments can be only tentative. This type of deposit has for too long been avoided by sedimentologists and stratigraphers.

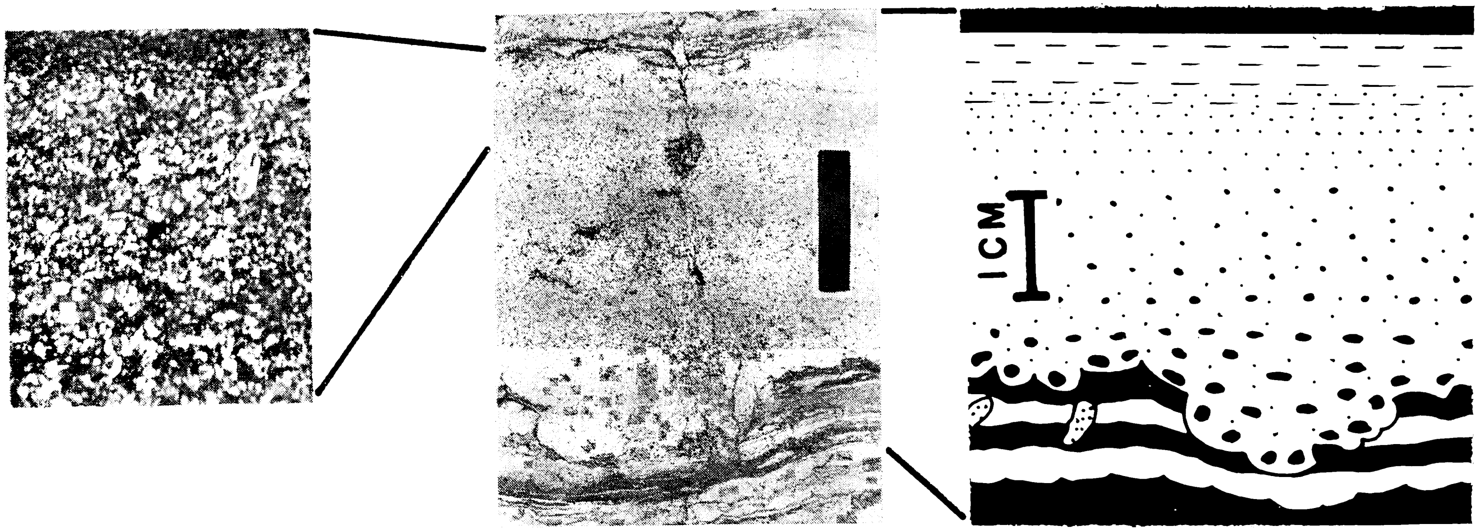
According to Piper (1972), alternate graded silt and mud laminations result from alternating granular and cohesive bed conditions in turbidity currents flowing at a velocity of 15 to 30 cm/sec. His suggestion may not be suitable to explain the graded silt laminations and clay layers of the Sevier Shale. Quartz grains are relatively rare in the silt laminations and are loosely packed; hence granular bed conditions would have been rare. Behavior of calcite grains under these conditions is not yet documented experimentally.

Grading in these silt laminations was probably caused by simple settling of particles from the tail end of low-concentration turbidity currents in an area farthest from the source region, the intervening clay

PLATE 5



A. Type 1 sequence: center, photograph of a thin section showing multiple graded silt laminations, bar scale is 1 cm; left, a photomicrograph showing positive grading in the top most 1 mm thick lamina; right, a sketch of center photograph to show grading in individual lamina, grain sizes are slightly exaggerated.



B. Type 2 sequence: center, photograph of a thin section of bed showing sharp erosional base and gradational laminated top, bar scale is 1 cm; left, a photomicrograph (height, 5 mm) showing positive grading within the bed; right, a sketch showing above mentioned features, grain sizes are slightly exaggerated.

layers probably representing pelagic settling. Deposition by turbidity currents would also explain the lateral continuity of the laminations. The graded silt laminations may represent Bouma graded division (T_a), but this division is poorly understood, even in sandy turbidites, and in every case is believed to be a product of high flow regime, unlike our silt laminations. Since flow regime depends not only on current velocity but also on the size distribution of material being carried and on bed condition, it is possible however that the current velocities required for graded silt deposition may be much lower than those required for graded sand deposition (see Banerjee, 1977).

Another possible mechanism for depositing these graded laminae is ocean-bottom currents, which are capable of producing grading under waning energy conditions. This mechanism is unsatisfactory as an explanation of Blockhouse-Sevier graded laminae, however, because: (1) modern bottom currents are generally reworking agents and would thus not explain the initial delivery of coarser particles, and (2) bottom currents are local phenomena (Davies, 1972) and would not be expected to produce laminae of great lateral continuity such as those of the Blockhouse-Sevier.

Finally ,the grading in these layers could conceivably have been produced by pelagic settling of regularly varying grain sizes. Such a mechanism would not, however, explain the periodic delivery to the overlying water mass of grains an order of magnitude larger than the finest particles normally present.

Type 2 sequence.—This sequence (pl. 5) shows a sharp base with scouring, indications of minor slumping, loading, and flame structures. Normal grading is present from very fine sand or fine silt at base to clay at top. The graded division is capped by a laminated silty clay layer and a topmost unlaminated clay layer. Such a sequence of sedimentary structures is often attributed to turbidity currents. The head region of a turbidity current tends to erode the sediment layer on which the turbidity current is flowing (Middleton and Hampton, 1976), whereas the body region of the same turbidity current would deposit graded sediment on the eroded depressions. The top laminated, partly graded, silty clay layer could be a product of the tail of the same turbidity current. The topmost unlaminated and ungraded clay layer probably represents pelagic settling. We base this conclusion on the criteria for identification of hemipelagic mud deposition presented by Rupke and Stanley (1974).

Type 3 sequence.—This sequence (fig. 3A) is characterized by a lower cross-laminated zone with minor flames, a middle pseudonodule zone, and an upper parallel-laminated zone.

The lower cross-laminated zone is composed of silt-size quartz. The sinuous configuration of the cross laminae and the low angle of dip resemble small-scale antidunes. Determination of current direction using the small-scale sedimentary structures in the Sevier is difficult, and hence we could not prove the presence of laminae inclined in an up-current direction to support the existence of antidunes. Banerjee (1977) has shown that sinusoidal ripple lamination quite similar to the structures described here can form in silt turbidites under experimental conditions of slow deceleration at low flow velocity. Although, in the Sevier lithology, such conditions would have had to exist early rather than late in turbidite deposition, such a mechanism can not be entirely ruled out. The sinuous cross-laminae of the lower zone of the type 3 structure sequence could also be due to sediment loading.

The middle zone of the type 3 sequence is composed of small-scale pseudonodules (fig. 3A). Skipper and Middleton (1975) have reported similar zones in the distal turbidites of the Cloridorme Formation, which Enos (1969a, b) demonstrated to be of turbidite origin. Pseudonodules are a loading phenomenon caused by sinking of a silt layer into the underlying liquefied mud. Continued sinking with no additional supply of silt results in the "isolated load casts" of Bouma (1962, p. 64). Experimental studies by Middlton (1967) support this origin of pseudonodules in turbidity-current deposits.

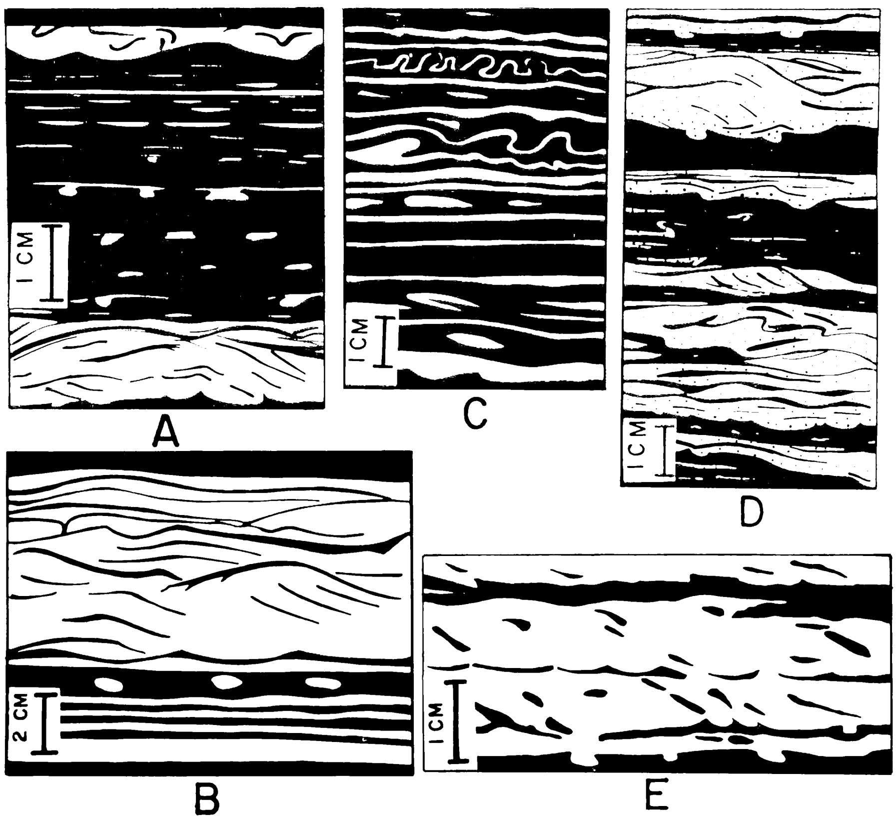


Fig. 3. Sketches of different types of sequences of sedimentary structures. See text for full discussion of each type of sequence. A. Type 3 sequence; B. Type 4 sequence; C. Type 5 sequence; D. Type 6 sequence; E. Type 7 sequence.

The upper zone of the type 3 sequence is characterized by parallel laminations, probably formed by suspension settling from low-concentration turbidity currents. The very top of this zone is often a nonlaminated, quartz-free, clayey layer, which is probably of pelagic origin. Horizontal burrows are observed on the upper surface of this clay layer, indicating a slow rate of deposition.

In terms of Bouma divisions, type 3 sequence is comparable to Bouma T_{cde} with an intervening division of pseudonodules between T_c and T_d (assuming the lower cross-laminated zone is equivalent to a current ripple or convoluted zone). On the other hand, the sequence may well represent Bouma T_{ade}, with the pseudonodule zone between T_a and T_d (assuming the lower cross-laminated zone is composed of small-scale anti-dunes). Both these possibilities are consistent with deposition from a waning turbidity current. After the formation of the lower cross-laminated zone either by down-current traction or by up-current migration of bed forms, "quick" beds caused by rapid deposition and liquefaction formed pseudonodules. Following this event, settling of particles from the tail of the turbidity current produced the upper laminated zone. Finally, the uppermost unlaminated clay represents pelagic settling.

Type 4 sequence.—This type (fig. 3B) has the following sequence in ascending order: a lower zone of parellel lamination, a pseudonodular zone, a zone of probable current-ripple lamination, an upper zone of parallel lamination, and a topmost clay zone.

Two possible interpretations are proposed for the type 4 sequence. First, it might represent deposition by a single turbidity current yielding a Bouma sequence T_{bcde} with a pseudonodular zone between T_b and T_c. Second, the pseudonodular zone might represent the pelagic division separating two turbidite units — a lower T_{de} sequence and an upper T_{cde} sequence, in terms of Bouma divisions — the second turbidity current arrived immediately following deposition of the lower pelagic division and the uncompacted mud was liquefied, permitting the sinking of the initial silt layer deposited from the second turbidity current to form the pseudonodules.

We have suggested two alternatives because there are no well established criteria to distinguish Bouma T_b from T_d, although the T_b division supposedly possesses primary current lineation and grain orientation (McBride and Yeakel, 1963; also see discussion in Walker, 1965).

Type 5 sequence.—This type of sequence (fig. 3C) consists of alternating silt and clay layers. In the lower half of the sequence, there are lenses of silt resembling pseudonoules in the clay layers but with unusual shapes (unlike the subspherical pseudonodules). Some lenses show evidence of deformation and probably represent micro-rotational slump sheets similar to those of Dzulynski and Walton (1965, compare their fig. 129). The deformation of the lenses was syndepositional, for they are immediately overlain by undeformed clay layers. In the upper half of the type 5 sequence, micro-convolutions produced by current drag are present.

This complex sequence of sedimentary structures represents several depositional events.

Type 6 sequence.—This type (fig. 3D) is characterized by a complex sequence of alternating silt turbidites and clay layers. Turbidites show sharp bases and positive grading, and most show convolute laminations and current-ripple laminations. Evidence of scouring, loading, and flame structures occur at the base of turbidite layers. These layers were subjected to syndepositional deformation and postdepositional compaction.

Type 7 sequence.—This type of sequence (fig. 3E) is mainly a repetition of silt and clay layers with oriented "shale clasts" in the silt layers. Some of the "shale clasts" seem to have been formed by soft-sediment deformation. Notice the right end of the top clay layer in figure 3E where part of the clay layer has been detached from the main body and has sunk into the underlying silt layer. Such an event would require a density gradient reversed from the normal situation, with liquefaction of the underlying silt layer rather than the clay layers. The imbrication of some of these "clasts" suggests orientation by depositing currents. Alignment of clasts seen on polished slabs cut parallel to bedding also suggests current orientation. It is, however, difficult to determine accurate paleocurrent directions because of the small size of the "clasts" and the deformation caused by post-depositional compaction.

STRATIGRAPHIC DISTRIBUTION OF SEDIMENTARY STRUCTURES

The stratigraphic distribution and relative abundances of sedimentary structures is shown in figure 4. Vertical variations in bed thickness and grain size are also shown. The following observations and inferences may be made from this summary diagram.

1. The entire sequence coarsens upward in terms of both bed thickness and grain size. An abrupt increase in bed thickness and grain size occurs at 770 m.
2. A positive correlation exists between bed thickness and grain size.
3. A general increase in energy conditions toward the top of the section is indicated by the distribution of bed thickness, grain size, and type and abundance of sedimentary structures.
4. The lower 300 m of the section is characterized by pelagic laminae and only occasional turbidity-current laminae. The rest of the section shows abundant sedimentary structures of turbidity-current origin.
5. Occasional burrow-mottled zones (see pl. 2-D) in the stratigraphic column suggest biogenic reworking and slow deposition.
6. Influence of turbidity currents increases toward the top as shown by the increasing amount of graded laminations and other sequences of sedimentary structures typical of turbidity-current origin.
7. The presence in the upper 600 m of convolute laminations, animal escape burrows, loading features, and flame structures indicates rapid deposition.
8. Liquefaction and loading structures are present through most of the upper 600 m.

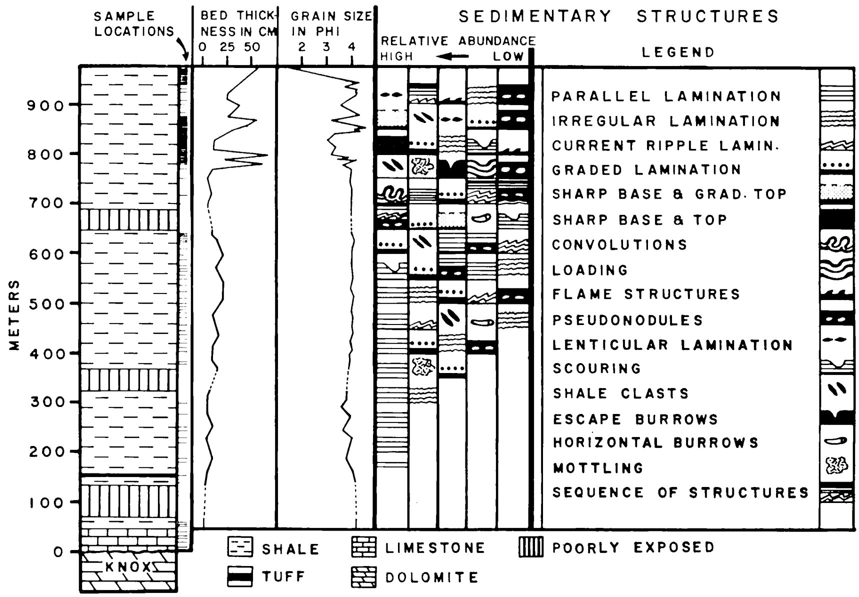


Fig. 4. A summary diagram showing stratigraphic distribution of bed thickness, maximum grain size, and relative abundance of sedimentary structures in the Blockhouse-Sevier shales of the Boyds Creek stratigraphic section.

9. In the uppermost 200 m bottom-current sedimentary features are present.

We infer from these features that the Boyds Creek Section represents a shallowing-upward stratigraphic sequence produced during the filling of a sedimentary basin.

DEPOSITIONAL MECHANISMS

Judging by the various types of sedimentary structures described above, no single mechanism can explain fully the deposition of the Blockhouse-Sevier shales. Hence, we propose the followng multiple theories of origin for these sediments.

Evidence for Turbidity Currents

Properties of turbidity currents and their deposits have been described by several workers both for modern and ancient sediments (for example, Kuenen, 1951 and 1967; Middleton and Hampton, 1976; Nelson and Kulm, 1973; Piper, 1970; Ten Haaf, 1959; Walker, 1965; Walker and Mutti, 1973; Wood and Smith, 1959). An excellent summary on the turbidity-current concept is given by Walker (1973). Although several criteria have been suggested to differentiate turbidites from bottom-current deposits (Bouma and Hollister, 1973; Davies, 1972), the distinction is not always easily made (Piper, 1970; Piper and Brisco, 1975; see also Van der Lingen, 1969).

In spite of the problems surrounding interpretation of turbidite deposits, the following features observed in the Blockhouse-Sevier shales are best explained by turbidity currents.

Moreover, the deep-water marine environment inferred for these units from stratigraphic relationships is a favorable location for turbidity currents.

1. The abundant graded laminations with sharp bases in the Blockhouse-Sevier Shale can be explained by deposition from matured turbidity currents.

2. The T_{cde}, T_{de}, and questionable T_{ae} Bouma sequences in these shales are indicative of turbidity currents.

3. Alternating graded silt layers and pelagic clay layers best fit into the dynamics of the turbidity-current concept where intermittent turbidity currents and pelagic settling are the norm.

4. The presence of animal escape burrows, convolutions, and load features (pl. 3) suggests rapid deposition, characteristic of turbidity currents.

5. The absence of coarse grains, the predominance of silt and clay sized grains, the abundance of Bouma sequences T_{cde} and T_{de}, and laterally continuous laminae, all suggest deposition by low-density distal turbidity currents.

Evidence for Ocean-Bottom Currents

No standard criteria exist for recognition of ocean-bottom current deposits. However, the following features may suggest the influence of bottom currents during Sevier deposition.

1. Silt layers with sharp base and sharp top (pl. 4) may indicate deposition by ocean-bottom currents. However, erosion of the gradational top of a turbidite bed by the next turbidity current will also yield a sharp upper contact.

2. Some of the beds studied in the Sevier Shale show discontinuous silt lenses (pl. 4). These suggest active ocean-bottom currents because turbidity currents do not form lenticular and discontinuous laminations.

Evidence for suspension settling

Non-graded clay layers probably were formed by pelagic settling. These layers contain tintinnines, which are often associated with deep-water pelagic sediments (Moore, 1954; Loeblich and Tappan, 1968). Horizontal burrows observed on the surface of these clay layers suggest slow deposition.

Nepheloid layers (Jerlov, 1953; Pierce, 1976) and detached turbid layers (Drake, Kolpak, and Fischer, 1972; and Nelson, Pierce, and Colquhoun, 1973), which exist in modern oceans, may have been equally important in Ordovician seas. Sediments from detached turbid layers often settle to become part of nepheloid layers, so we will consider only nepheloid deposits. Distinguishing nepheloid-layer deposits from those of low-density turbidity-currents poses many problems (Stanley and

Unrug, 1972). However, nepheloid-layer deposits are not likely to show the significant grading, current-ripple lamination, and scouring observed in the Sevier shale. Perhaps some of the clay layers we have interpreted as of pelagic origin may owe their origin to nepheloid layers. We believe that, in the Sevier Shale, slightly silty clay layers that show vague grading without any evidence of current activity were probably the product of resuspension by nepheloid layers.

TECTONIC SIGNIFICANCE

The presence of pre-flysch and flysch-like rocks in the Middle Ordovician sequence of the southern Appalachians is documented for the first time here. The base of this sequence is probably of Whiterock Age (Lower Middle Ordovician; see Bergstrom, 1973; Bergstrom and Carnes, 1976), clearly confirming that the Ordovician tectonic event in the Southern Appalachians was earlier (by perhaps 10 m.y.) than the so-called "Taconic disturbance" of the Central and Northern Appalachians (see Rodgers, 1971). Several detailed aspects of this sequence shed light on the relative timing of tectonic events and require further comment.

First, the boundary between the Lenoir-Whitesburg and the overlying Blockhouse marks a sudden and pronounced subsidence. This event could not represent more than a few tens of thousand years, yet it involved a subsidence of several hundred meters. Deposition continued during the subsidence for there is no indication of unconformity between the underlying shallow-water carbonates and the Blockhouse clay shales. Thus, subsidence was at a rate of a meter or more per thousand years. As noted by Roeder and Walker (1975), such a rate is comparable with the highest rates known from modern oceans. Less than 20 palinspastic km to the northwest from Boyds Creek and at the same time, the rate of subsidence was an order of magnitude less (see Benedict and Walker, this issue), and deposition continued on a shallow carbonate shelf. Such a pronounced difference in subsidence rate in adjacent areas might be explained by flexural bending or by down-to-basin normal faulting. The presence of slope facies between the two areas suggests flexural bending, but the rather abrupt lateral increase in thickness of the sequence suggests that down-to-basin faulting may have been involved. If down-to-basin normal faulting formed the basin, a tensional event would be indicated. The evidence is insufficient at the present to choose between these two hypotheses concerning basin formation.

The second aspect requiring comment is the time delay after basin formation before the first arrival of syntectonic sediments. The bulk of the Blockhouse Formation (nearly 300 m thick) represents pelagic, starved-basin deposition. Although the primary source of clay must have been from the southeast (relatively pure carbonate rocks continued to be deposited to the northwest), the source terrane was quite distant. Rate of deposition must have been quite slow, so that this sequence represents a considerable time span. The delay suggests that the tectonic event that formed the basin was distinct from the tectonic event that provided the source for the later turbidite deposition. Sediments derived from the southeast and deposited by turbidity currents appear in the basinal sequence at a point about 250 to 300 m from its base. Coeval proximal turbidites occur in the Tellico Formation 30 to 40 palinspastic km to the east (Indian Creek Embayment of Kellberg and Grant, 1956). Keller (1977) has recently suggested Taconic thrusting in the Blue Ridge, indicating that a compressional event caused the uplift of the source region for the Tellico-Sevier turbidites.

Finally, by the end of Middle Ordovician time the basin was no longer an area of marked subsidence, because basinal stratigraphic sections are topped by a variable thickness of shallow-water terrigenous clastics of the Bays Formation. These sediments contain abundant bidirectional cross-bedding, interference ripple marks, desiccation features, and other indicators of shallow-water deposition. In the southeasternmost stratigraphic sections these sediments are unconformably overlain by Devonian shales, suggesting a period of uplift in the basinal area. Studies of other basinal stratigraphic sections are now underway, and it is apparent that the subsidence and filling of the basin was complex. The broad history of the formation and sedimentary infilling of this Ordovician basin is shown in figure 5.

We realize that we have only outlined the rudiments of the tectonic history of this syntectonic basin and that much additional work needs

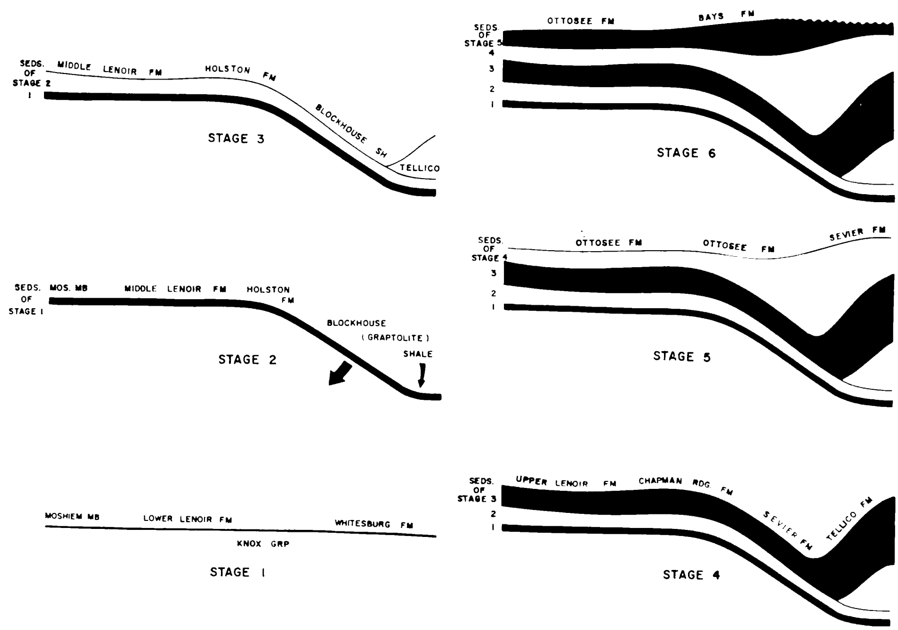


Fig. 5. Tectonic evolutionary stages of the Blockhouse-Sevier basin. This model has been constructed using the flexural bending mode of basin subsidence. A similar model can be constructed using the down-to-basin faulting mode of basin formation (see text).

to be done. It is, however, evident that this kind of basinal analysis will yield constraints that must be taken into full account during tectonic modeling of the development of the Southern Appalachians.

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