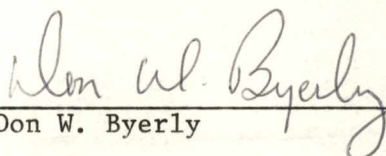
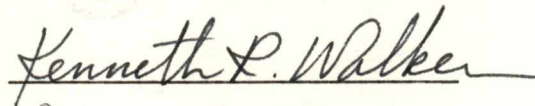
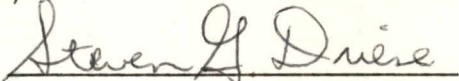


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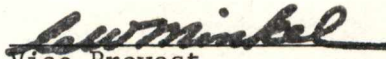
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STRATIGRAPHY AND SEDIMENTOLOGY OF THE MIDDLE ORDOVICIAN
SEVIER SHALE BASIN NEAR AVENS BRIDGE,
WASHINGTON COUNTY, VIRGINIA

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Bryn David Howze

June 1987

This volume is dedicated with love to my mother,
Janette Howze, and the rest of my family,
whose constant support made this thesis possible.

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ABSTRACT

The Middle Ordovician Sevier Shale basin in southwest Virginia near Avens Bridge is described and discussed in terms of its stratigraphy, sedimentology, depositional environments, and petrology. The Middle Ordovician stratigraphy includes (in ascending order): the Lenoir Formation (17 meters thick), the Blockhouse Formation (67 meters thick), the Sevier Formation (approximately 1,000 meters thick), and the Tellico Formation (465 meters thick).

These formations were deposited in an evolving foreland basin that underwent five stages of evolution (Shanmugan, 1978; Shanmugan and Walker, 1978, 1980, 1983): (1) a stable shelf edge, represented by the Lenoir; (2) a downwarping stage; (3) a starved-basin stage represented by slow pelagic fallout of Blockhouse sediments; (4) a turbidite-fill stage, represented by sedimentary rocks of the Sevier and Tellico Formations; and (5) a contour-current stage, that can be seen in shale and siltstone strata in the upper part of the Tellico Formation.

The coarsest terrigenous-clastics in the Sevier basin are represented by the rocks of the Tellico Formation which consist of interbedded shale, siltstone, massive sandstone, pebbly sandstone, conglomerate, and chaotic units. The Tellico Formation was the main focus of this study. The Tellico Formation was studied in detail to determine its sedimentological characteristics and environments of deposition. Lithofacies of the Tellico including: classic turbidites, massive sandstone, pebbly sandstone, clast-supported conglomerate, debris flows,

chaotic units (glide slides and slumps), and contourites in the upper part were separated into three lithofacies associations.

Lithofacies association I includes interbedded hemipelagic shales, classic turbidites, massive sandstones, and chaotic units (debris flows and glide slides) that represents deposition on the mid fan.

Lithofacies association II includes minor amounts of hemipelagic shale and classic turbidites in a sequence dominated by massive sandstones, pebbly sandstones, conglomerates, debris flows, and slumps interpreted to be deposits of an inner-fan channel.

Lithofacies association III seen as thick sequences of hemipelagic shale, thin-bedded classic turbidites, and possible contourites that are thought to represent interchannel deposits on a submarine fan.

The submarine fan is interpreted to have entered the basin from the south, prograding by lateral migration of mid-fan complexes. Lateral migration of mid-fan complexes could explain the lack of well-developed coarsening- and thickening-upward sequences in the lower fan in the study area.

Sandstone compositions in the Tellico Formation consist of quartz, rock fragments, and feldspar in a matrix of clay minerals, sericite, and chlorite. Sandstone beds in the study area may be classified as lithic graywackes (Pettijohn, 1975) and litharenites (sedarenites) (Folk, 1974). Modal analysis of the three coarse packages in the study area revealed no major compositional changes through time.

The Tellico Formation lies within the recycled orogenic provenance field of Dickinson et al. (1983). Source rocks for the terrigenous

clastics of the Tellico Formation include the Shady Dolomite, Chilhowee Group, Knox Group, Lenoir Formation, and Fetzer Formation.

Comparison of compositional suites of the Tellico Formation with the Tourelle Formation reveal major variations in source rocks. The Tourelle contains up to 31% vs. 1.4% (for the Tellico) volcanic rock fragments. Chromite in the Tourelle Formation is thought to have been derived from ophiolites (Hiscott, 1978). No evidence for ophiolites was found in the sediments of the Tellico Formation. Variations in provenance of these Middle Ordovician foreland basins may reflect differences in the tectonic style along the Taconic orogenic belt.

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CHAPTER I

INTRODUCTION

Paleoenvironmental studies on the Middle Ordovician of the Southern Appalachians of east Tennessee and southwest Virginia have revealed a complex mosaic of carbonate and terrigenous clastic facies composed of three parts: (1) a northwestern carbonate shelf bounded on the southeast by a shelf-edge skeletal sand bank/reef; (2) a deep-water foreland basin southeast of the shelf; and (3) a shallow-water, near-shore environment southeast of the basin (Figures 1-1 and 1-2) (Walker, 1977; Read, 1977, 1980; Walker et al., 1980; Walker et al., 1983; Shanmugan and Walker, 1983). Shale, siltstone, massive sandstone, pebbly sandstone, and conglomerate of the Blockhouse, Sevier, and Tellico Formations compose the second part of this regional model. These formations are thickest and contain their coarsest components in a belt extending from Virginia to Georgia (Kellberg and Grant, 1956). This belt comprises the southeasternmost exposed part of the Middle Ordovician Sevier Basin, which was overridden by thrust sheets of the Blue Ridge Province. Outcrops in the present study area are located in this belt and are believed to represent the most proximal parts of the southeasterly derived sediments (Kellberg and Grant, 1956) deposited in the Sevier Basin.

Purpose

This study is mainly concerned with the deep-water, basinal terrigenous clastic sequence, with emphasis on the coarser clastics near the top of the stratigraphic sequence. Great progress has been made

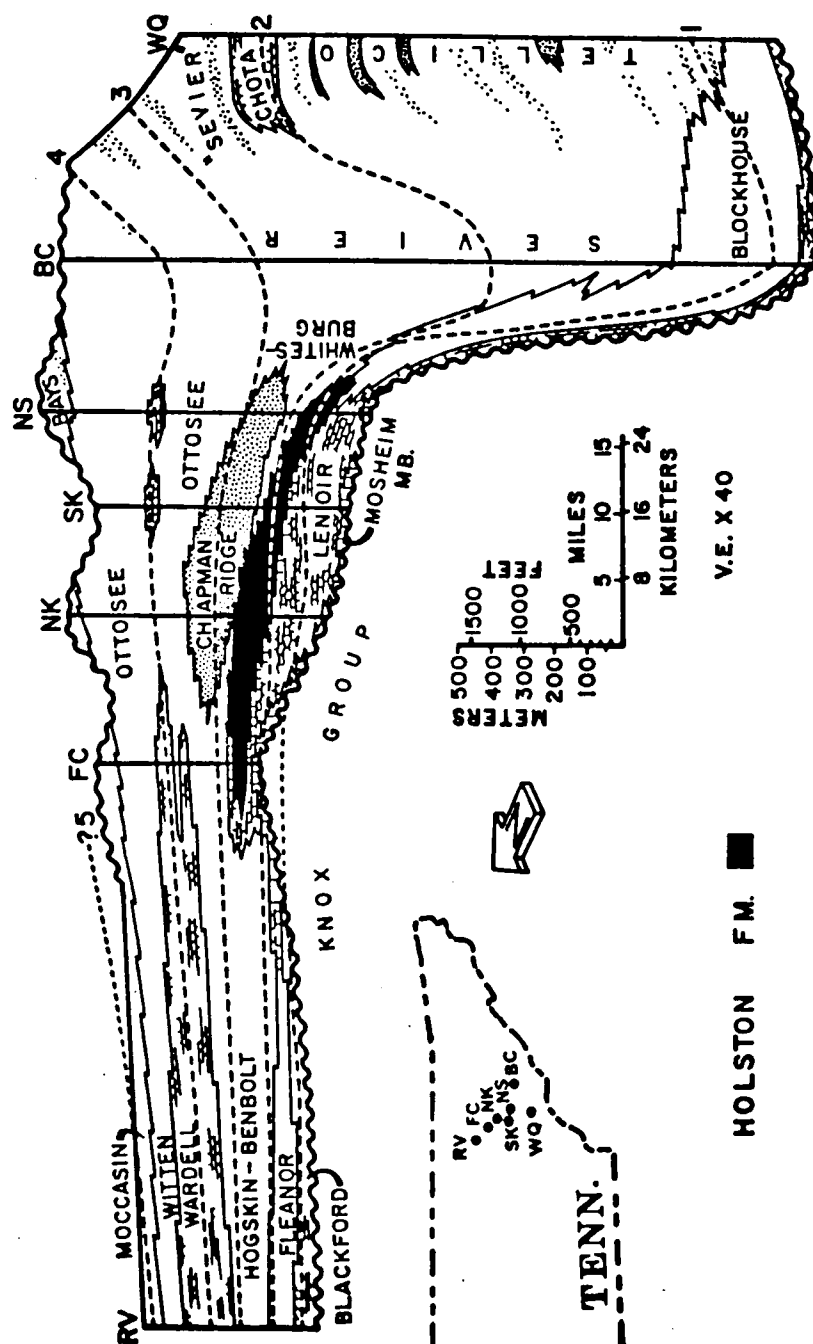


Figure 1-1. Regional facies pattern of the Middle Ordovician in east Tennessee. This palinspastically reconstructed section trends northwest to southeast. Dotted lines represent four time lines. From Walker (1977).

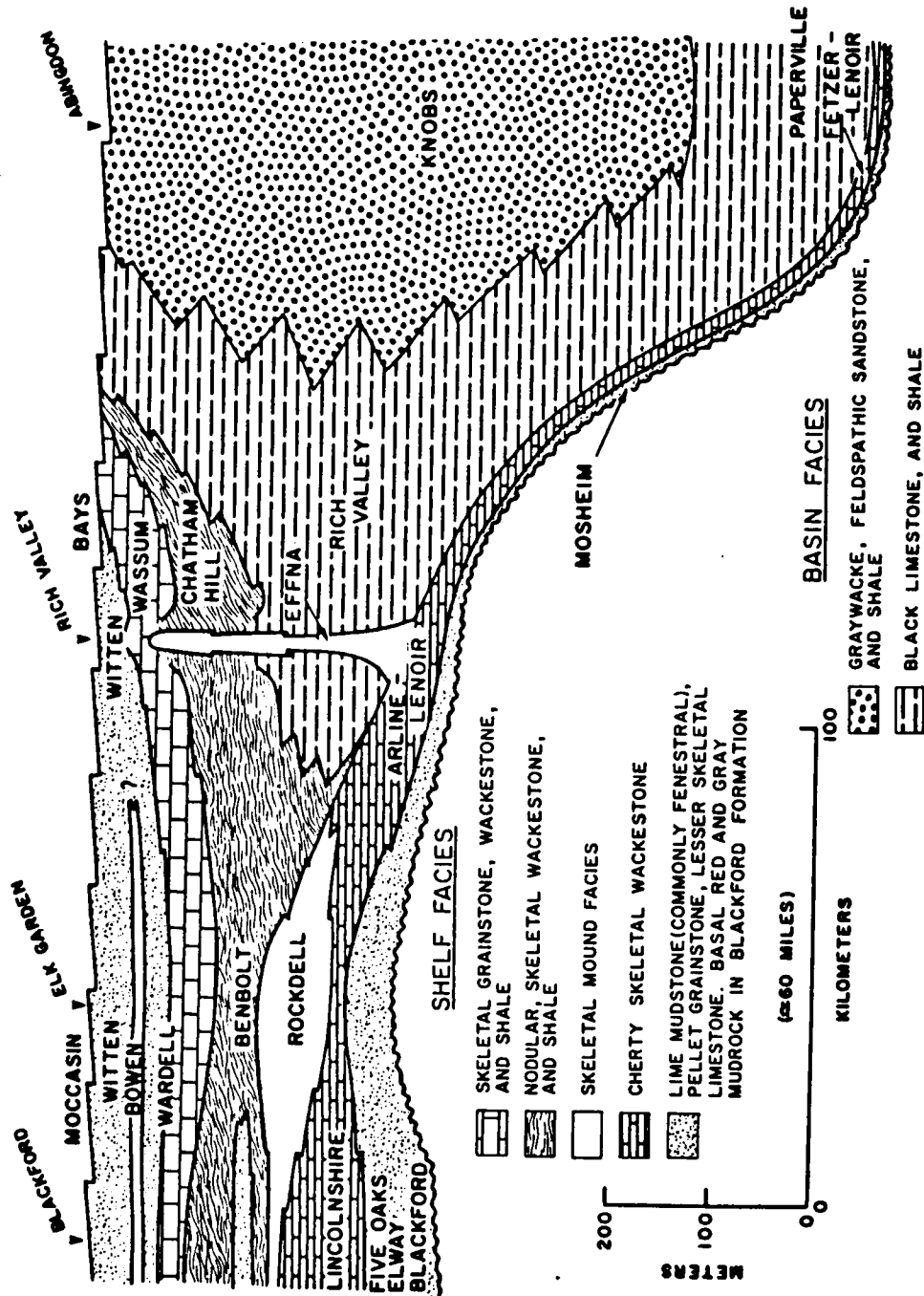


Figure 1-2. Regional facies pattern in southwest Virginia. Cross-section trends northwest to southeast showing lithofacies distributions and the commonly used formation names in Virginia. From Read (1977).

within the past decade in resolving the paleoenvironments of the western shelf and associated transitional slope paleoenvironments of the Sevier Basin. In contrast, fewer detailed investigations (Shanmugam, 1978, 1980; Bowlin, 1979; Bowlin and Keller, 1980; Raymond et al., 1979) of the terrigenous clastics of the basin have been made to test this part of the regional model as put forth by Walker (1977); Read (1977, 1980); Walker et al. (1980); and Shanmugan and Walker (1983). The main purpose of this study is to interpret the depositional environments of this part of the Middle Ordovician sequence. Detailed field measurements including variations in bedding thicknesses, grain size, and sedimentary structures, and examination of thin sections to determine compositional and textural characteristics of the rocks, have been used in this interpretation.

This investigation provides three important contributions to our knowledge of the Sevier Basin: (1) lithologic and environmental characteristics are used to separate the shale and siltstone sequence from the overlying shale, massive sandstone, and conglomerate sequence; (2) a measured stratigraphic section from the base of the Middle Ordovician to the top of its exposure, as can best be determined in this structurally complicated area; and (3) the coarse clastics are analyzed in terms of depositional mechanisms involved and are then placed within the realm of a submarine fan depositional environment.

Location of the Study Area

The study area is located within that portion of the Southern Appalachian Valley and Ridge Province embraced by the northwestern

corner of the Shady Valley (213 SW) Tennessee Valley Authority (TVA) 7.5 minute topographic quadrangle. The outcrops that were studied are located along the shoreline of South Holston Lake and along Virginia State Route 670 in the vicinity of Avens Bridge in Washington County, Virginia (Figure 1-3). Avens Bridge is approximately 9 kilometers southeast of Abingdon, Virginia and 16 kilometers east of Bristol, Virginia. Figure 1-4 and Plate I show the locations of the outcrops studied. The most continuous exposures of the coarser clastics in the stratigraphic sequence are along the shore of an inlet of South Holston Lake, southeast of Avens Bridge. Outcrops of the finer-grained clastics of the basin and the carbonate deposits of the shelf are also located along the shoreline of South Holston Lake.

Geology and Structure in the Study Area

The study area is situated on the northwest limb of the northeast-southwest trending South Holston syncline within the Pulaski thrust sheet. The Pulaski thrust sheet is bounded by the Pulaski fault on the northwest, and on the southeast by the Holston Mountain fault, where Cambrian rocks of the Chilhowee Group truncate the southeast limb of the South Holston syncline. Typical of Valley and Ridge structures, the faults dip to the southeast at low angles and the rocks display northeast-trending strikes. The Middle Ordovician sequence here lies unconformably on the Upper Cambrian and Lower Ordovician Knox Group.

Middle Ordovician rocks in the sections studied strike between 44 and 66 degrees to the northeast and dip southeasterly between 40 and 79

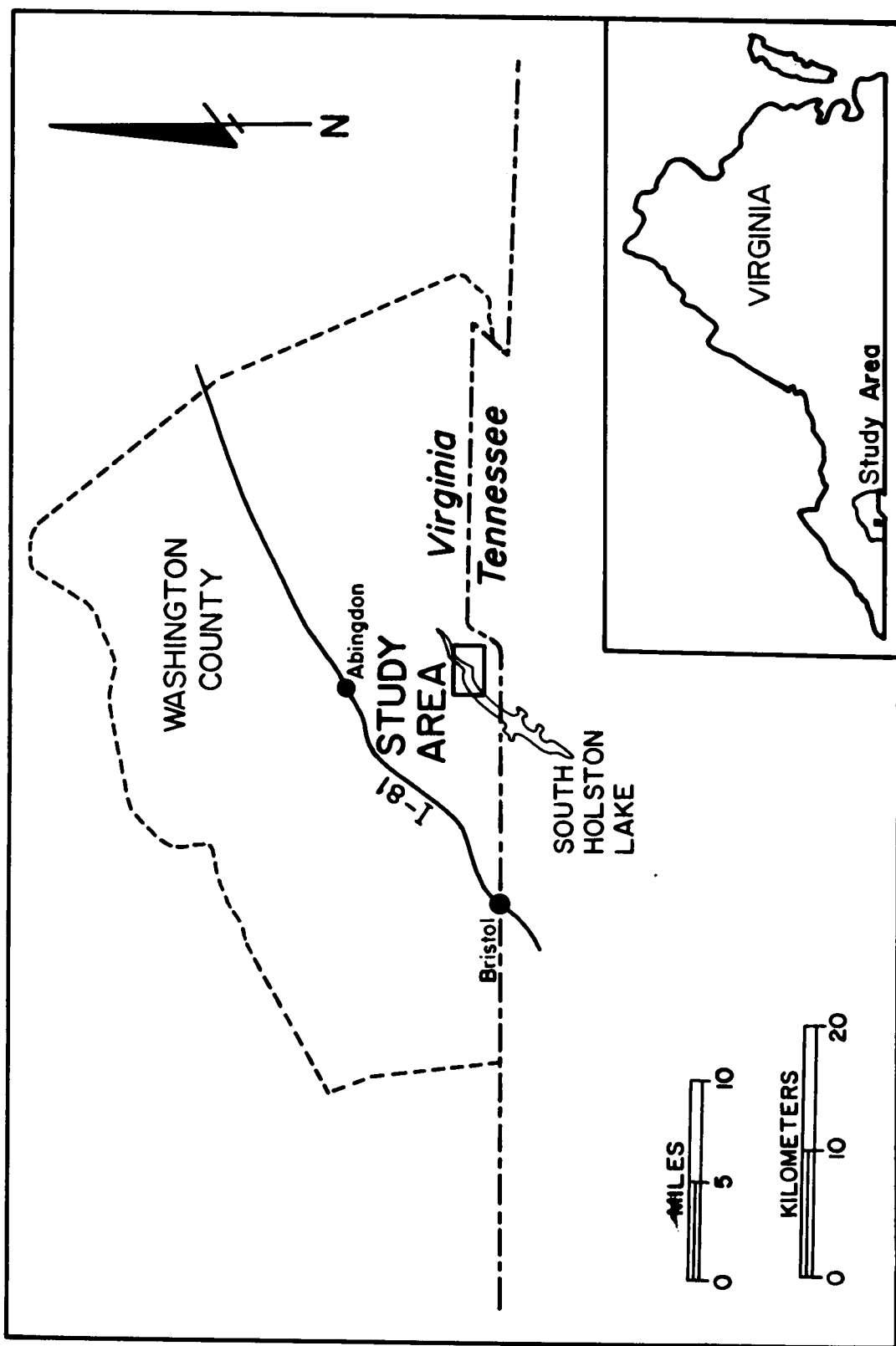


Figure 1-3. Location map of the study area.

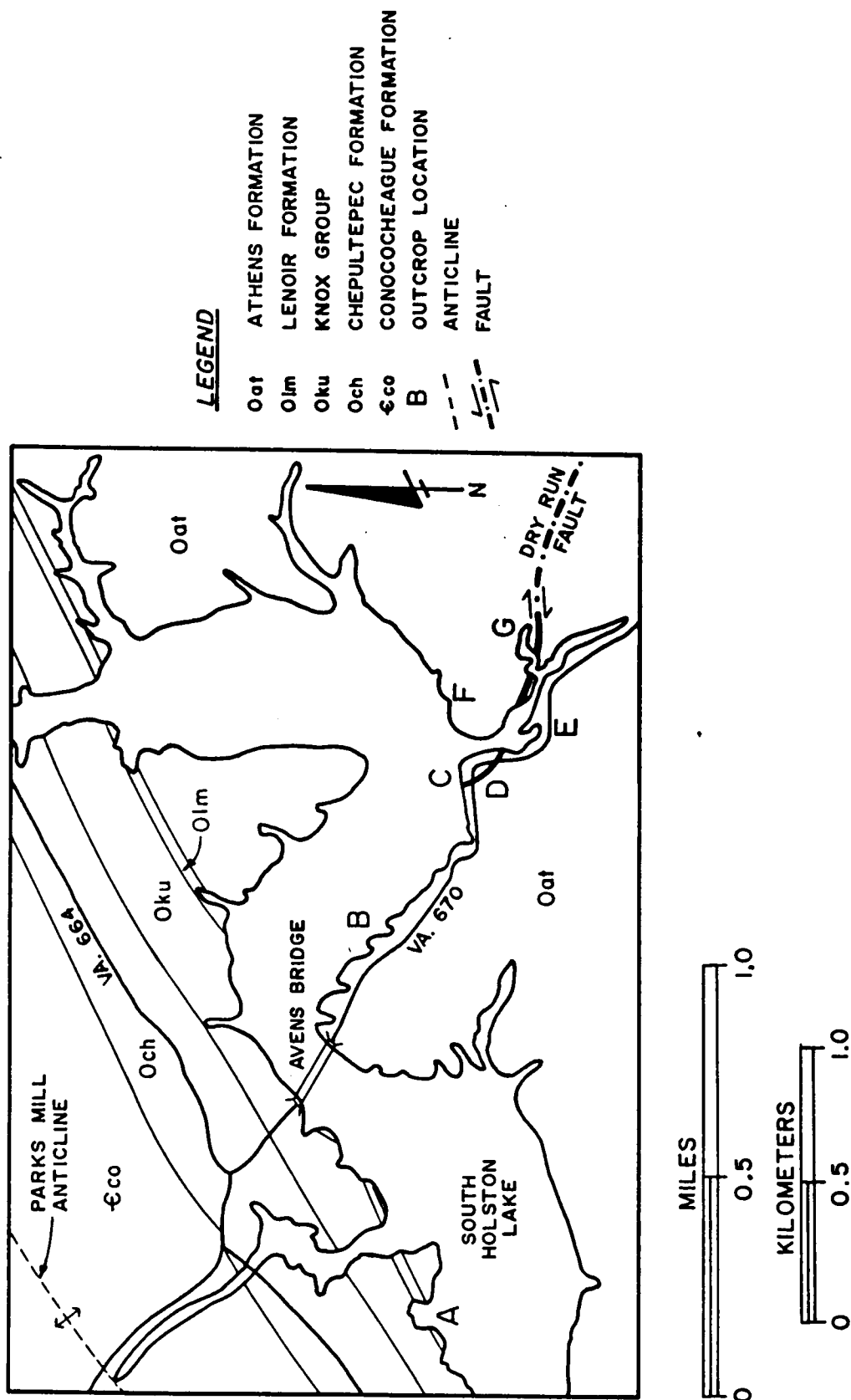


Figure 1-4. Geologic map showing outcrop locations along South Holston Lake and Virginia State Route 670. Modified from Bartlett and Biggs (1980).

degrees. However, locally, the rocks are nearly vertical or overturned, especially on the southeast limb of the South Holston syncline. Because of the greater intensity of deformation of the southeast limb and limited exposures of the coarse clastics, units forming the northwest limb were selected for this study. Furthermore, it is conceivable that the upper half of the Middle Ordovician sequence containing the coarse clastics on the southeast limb has been displaced by a thrust fault, possibly as an extension of the Lodi thrust fault which was mapped by Bartlett and Biggs (1980) in the area just northeast of the study area (Figure 1-4).

Another major structural feature in the study area is the Dry Run transverse fault. This right-lateral fault transects the study area at approximately right angles to the strike of the strata. In order to remove as much as possible the uncertainties of stratigraphic correlation caused by offset along the Dry Run fault, a detailed geologic map was constructed by using a plane table and alidade. In the immediate study area, the offset along the fault decreases from a maximum of 107 meters to a minimum of 46 meters to the northwest as the fault dissipates in that direction. Numerous small faults and folds within the syncline also complicate the task of determining thicknesses of the different units, especially in the shale sequences.

Previous Investigations

The earliest work done in this region was the mapping for the U.S. Geological Survey folio series by Cambell (1899) and Keith (1907). The

Abingdon folio, which includes the study area, was partially mapped by Keith, but this work was not completed nor published. Butts' (1933, 1940) work in Virginia subdivided the Middle Ordovician rocks there and mentions specific occurrences of coarse clastics in the Abingdon area.

More detailed descriptions of the rocks in the study area were provided by Kellberg and Grant (1956) and King and Ferguson (1960). Kellberg and Grant (1956) described the occurrences of coarse conglomerates within Middle Ordovician rocks in the southern Appalachians, including the area of this study at Avens Bridge, and South Holston Dam, approximately 15 kilometers southwest of the study area. King and Ferguson (1960) summarized these descriptions in their much broader study of the stratigraphy and structure of northeast Tennessee. In addition to these studies, dam construction investigations by McGavock and Finfrock (1949) include descriptions of the rocks in the South Holston Reservoir area, especially the Middle Ordovician sequence. McGavock and Finfrock noted variations in the thicknesses of the Middle Ordovician clastics from information derived from exploratory drilling at bridge sites spanning the reservoir and from their mapping around the reservoir.

These early studies did not have the benefit of the modern theoretical models used to presently interpret the depositional processes of subaqueous gravity flows. The fact that these early studies were not process-oriented is seen in their lithologic descriptions which do not include sedimentologically important characteristics such as grading, bed thickness, imbrication, maximum clast size, scouring, sole marks,

and other sedimentologic parameters (Bowlin, 1979). Any inferences concerning depositional environments in these early reports were therefore speculative in nature.

Detailed mapping in the study area by Tyler (1960) contributed to the descriptions of the rocks as well as to the subdivision of the Middle Ordovician clastics into two units--the Paperville and Knobs Formations. Bartlett and Biggs (1980), mapping for the Virginia Division of Mineral Resources, revised the stratigraphy used by Tyler and reinterpreted some of the structure in the area. Tyler had suggested that the Dry Run fault transected the South Holston syncline farther to the southwest than has been interpreted by other investigators, as well as this writer. Detailed mapping during this study generally agrees with the structural interpretations put forth by Bartlett and Biggs (1980) and King and Ferguson (1960).

Unpublished theses by Leible (1975) and Bowlin (1979) described the conglomeratic outcrops at Avens Bridge and South Holston Dam and put forth possible depositional environments. Leible, through apparent failure to recognize inverse grading at the Avens Bridge section, interpreted what this writer and others (Walker and Keller, 1977; Bowlin, 1979; and Raymond et al., 1979) recognized as the Bouma C interval of turbidites, as ripples formed by some type of shallow-water emplacement mechanism. Bowlin (1979), utilizing concepts proposed by Walker and Keller (1977) in their studies at South Holston Dam, interpreted the environment of deposition of the sequence as a submarine fan complex. Subsequent work by Raymond et al. (1979); Bowlin and Keller

(1980); and Read (1980) have added to the submarine fan model put forth by Bowlin.

Methods

Initial phases of this investigation consisted of measuring the stratigraphic section beginning at the unconformity on the Knox Group, and of obtaining thicknesses of the overlying Lenoir, Blockhouse, and Sevier Formations. Intense deformation in the upper half of the Sevier Formation made obtaining an accurate thickness for this part of the section difficult at best. Therefore, a range of thicknesses was determined for the Sevier Formation based on measured sections at the base and thicknesses taken from map distances from the upper part. The coarse clastics in the study area (Tellico Formation) were measured and described in detail. Two stratigraphic sections within 100 meters of each other were measured in the Tellico Formation in order to determine structural and facies relationships.

Structural complications in the Tellico Formation initially hindered correlation of outcrops and made piecing together a stratigraphic section arduous. Therefore, to overcome this problem a detailed geologic map on the scale of 1:800 was made using a plane table and alidade (Plate I). This map made possible the correlation of outcrops on either side of the Dry Run Fault in order that a complete, detailed stratigraphic sequence could be measured with a reasonable degree of confidence. The section was measured and described using a Jacobs staff, a Brunton compass, and a grain-size card. Outcrop locations and measured

sections are given in Appendix A and illustrated in Plate I. Important characteristics such as bed thickness, grain-size, sedimentary structures, clast composition, sole marks, lateral variations, scouring, paleocurrent data, and fossils were recorded.

A total of 164 samples was collected from the study area. From these, samples were slabbed and forty-three 5 x 8 centimeter thin sections were made. The thin sections, along with slabbed samples, were studied and described, with sedimentary structures the main object of this portion of the research. Slab descriptions are presented in Appendix B. Thin sections were described in detail and classified according to Folk (1974) and Pettijohn (1975). Thirteen thin sections representative of the coarse lithologies (massive sandstone and pebbly sandstone) were selected and point counted. Approximately 600 points were counted per slide, with at least 400-500 counts of framework grains per slide for massive sandstone and 200 framework grains per slide for pebbly sandstones. Point count data are presented in Appendix D and are discussed in Chapter V.

CHAPTER II

STRATIGRAPHY OF THE MIDDLE ORDOVICIAN AT AVENS BRIDGE,
WASHINGTON COUNTY, VIRGINIAStratigraphic Nomenclature

The Middle Ordovician section in the study area rests unconformably on the Upper Cambrian and Lower Ordovician Knox Group. The base of the Middle Ordovician is the Lenoir Limestone, which in turn is overlain by the terrigenous clastics. The nomenclature applied to the Middle Ordovician terrigenous clastics in the study area has varied among the workers who have studied these rocks. Table 2-1 provides a summary of the stratigraphic nomenclature applied to these rocks by workers in Tennessee and Virginia. Facies and structural complications pose correlation problems, and hence the dilemma of nomenclature. For example, formational names have been applied to rocks in the area merely on the basis of stratigraphic succession, even though they differ markedly from the rocks described at the type sections of these formations.

Campbell (1899) and Keith (1907) divided the clastic sequence of the area into two units--the Athens Shale (Hayes, 1894) comprised of black graptolitic, carbonaceous shale and blue calcareous shale which is sandy toward the top of the Formation, and the Tellico Sandstone (Keith, 1895) which overlies the Athens and consists of bluish-gray calcareous sandstone and shale. Although the Athens and Tellico of Campbell (1899) and Keith (1907) differ from the rocks of the type sections bearing

these names, most other workers have found their stratigraphic subdivisions sound, but have applied different names to these subdivisions (Table 2-2). For this same stratigraphic interval, Rodgers (1953) utilized the name Sevier Shale for the whole mass of shale where undivided, but also stated that in the stratigraphic sequence southeast of the Pulaski fault around South Holston Reservoir, ". . . a distinction into two mappable units can certainly be made" corresponding to the divisions made by Campbell (1899) and Keith (1907).

A revision of the classification of the Middle Ordovician Tellico-Sevier belt by Neuman (1955) introduced the name Blockhouse Formation for the lower part of the Athens of Keith (1895) and Rodgers (1953). The term Athens Shale has been widely used for black carbonaceous shale containing abundant graptolites (Keith, 1895; Ulrich, 1911; Butts, 1940; Decker, 1952; and others), a description which is distinctly different than that of the type locality of the Athens. Because of this misuse, Neuman (1955) proposed the name Blockhouse Formation for strata comprised mainly of dark gray, finely laminated carbonaceous shale containing graptolites. This body of rocks has been recognized by several workers in the Tellico-Sevier belt and in the Pulaski thrust sheet (Table 2-1). Because the term Blockhouse Formation has priority over the term Paperville Formation of Cooper (1956), which was used for the same sequence of carbonaceous rocks in Virginia, it is used in this report. The Blockhouse Formation of this report occupies the basal portion of the lower shale sequence (Table 2-2). The remainder of the shale sequence also containing sandstone, shale, and conglomerate had previously been included in the Tellico Formation or Knobs Formation of

Tyler (1960), however, this writer believes that the shale and siltstone strata of the shale sequence above the Blockhouse Formation are distinct and environmentally significant enough to warrant distinguishing them from the overlying coarser-grained sedimentary rocks. This part of the sequence lithologically and environmentally corresponds to the Sevier Formation of Shanmugan (1978), and is therefore correlated with the Sevier Formation. Overlying the Sevier Formation is the sequence of sandstone, shale, and conglomerate called either the Tellico Formation by some workers or the Knobs Formation by other workers in Virginia (Table 2-2). Tyler (1960), who first used the term Knobs Formation, stated that it is the approximate equivalent of the Tellico Formation of Neuman (1955). Tellico Formation is used here in preference to Knobs Formation because the former has priority as well as the fact that Tyler never formally introduced the Knobs Formation into the literature. A type section is, however, described in his unpublished thesis just south of Abingdon, Virginia.

The Middle Ordovician section as presented in this report consists in ascending order of the Lenoir, Blockhouse, Sevier, and Tellico Formations (Figure 2-1). The remainder of the stratigraphic section has been removed by erosion or is concealed beneath the Holston Mountain thrust sheet.

Formation Descriptions

Lenoir Formation

In the study area, the Lenoir rests unconformably on the Knox Group. Locally a basal conglomerate unit corresponding to the Douglas

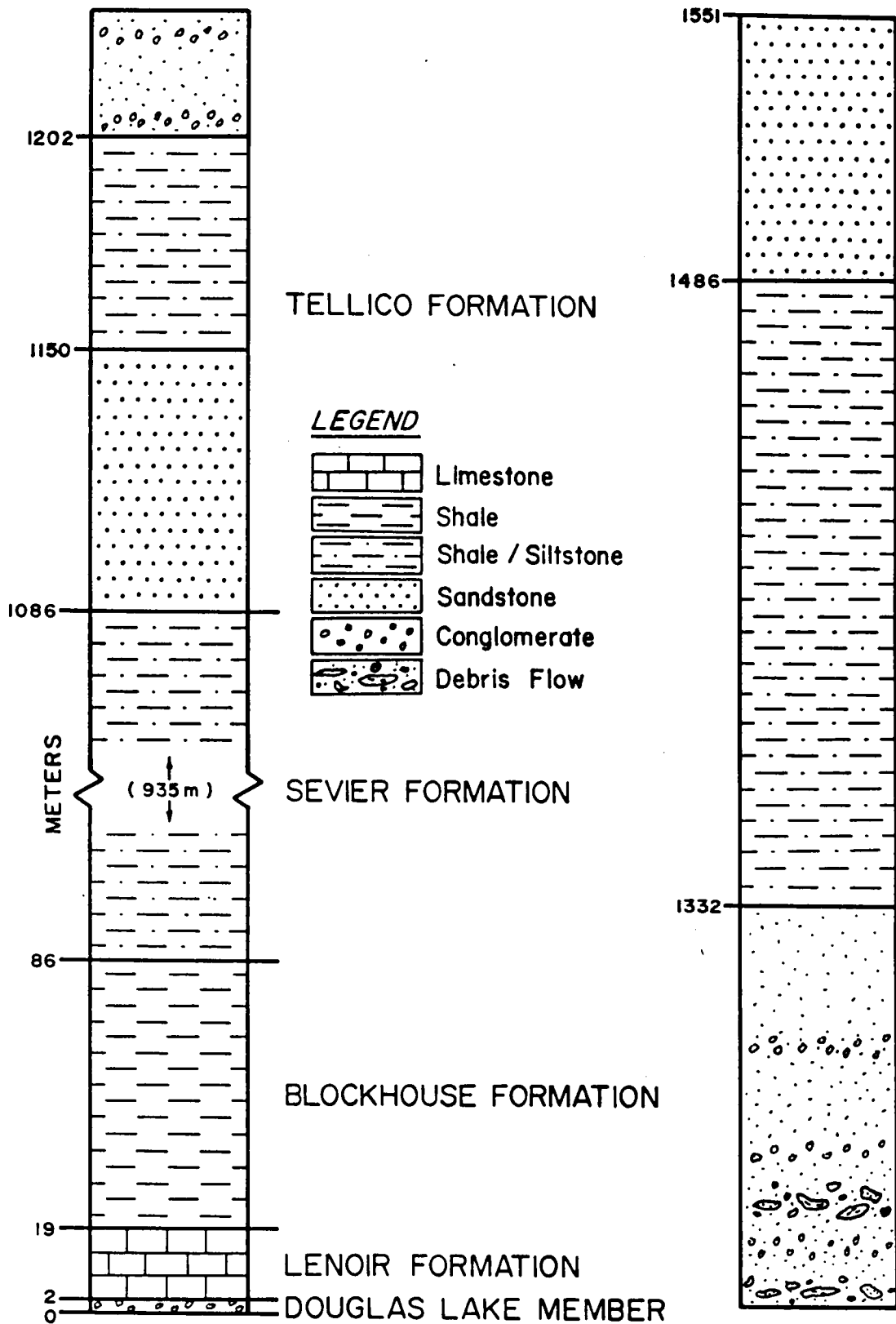


Figure 2-1. Stratigraphic column of the Middle Ordovician Section at Avens Bridge, Virginia.

Lake Member described by Bridge (1955) and Neuman (1955) lies directly on the unconformity. This member is composed of chert, limestone, and dolomite clasts derived from the Knox Group. The unit is discontinuous and varies in thickness depending on the relief along the upper surface of the Knox Group. Bartlett and Biggs (1980) give an average thickness range of 0.3 to 1.5 meters with a maximum thickness of 5.0 meters. In the study area, the Douglas Lake Member has a maximum thickness of approximately 2.0 meters.

The main body of the Lenoir overlies the Douglas Lake Member with a sharp contact and lies below the Blockhouse Formation. The Lenoir is a medium dark-gray, argillaceous limestone that is medium- to thick-bedded. Wavy, silty laminations produce a distinct nodular pattern upon weathering. Lithologies in the Lenoir include fine-grained skeletal wackestone, packstone, and bioturbated mudstone. Fossils in the Lenoir include gastropods, trilobites, brachiopods, echinoderms, abundant Nuia and conodonts. The total thickness of the Lenoir within the study area ranges from 11 to 17 meters, within a distance of 2 kilometers along strike.

Blockhouse Formation

Resting conformably on the Lenoir with a sharp contact is the Blockhouse Formation. Lithologically the unit is a dark gray to black, carbonaceous, thinly laminated shale containing abundant graptolites and rare inarticulate brachiopods. Contained in the upper half of the Blockhouse is a zone of septarian nodules. These impure argillaceous carbonate nodules are distinctly oblate with polygonal shrinkage cracks

on the upper surfaces that are filled with calcite. The largest septarian nodule observed was 89 x 32 centimeters. The upper contact with the Sevier Formation is gradational over approximately 2 to 5 meters. The first appearance of siltstone in the shale sequence marks the contact between the Blockhouse and Sevier Formations. The total thickness of the Blockhouse is 67 meters.

Sevier Formation

The Sevier is mainly a thick body of calcareous shale and siltstone with minor intercalations of very fine- to fine-grained sandstone. The lower part of the Sevier is mainly medium-gray to olive-gray shale and siltstone beds, which are gradational with the dark gray shale of the Blockhouse Formation below. The siltstone strata are thin-bedded and the shale sequences are laminated, silty and clay-rich. Grading, convolute laminae, and cross-bedding occur in some silty layers. Overall, siltstone and silty shale layers become more numerous and thicker up-section, along with minor beds of very-fine to fine-grained sandstone. Sandstone beds average 3-5 centimeters in thickness with a maximum of 11 centimeters in the lower 250 meters of the Sevier. Sequences suggestive of rhythmic sedimentation, similar to those described by Shanmugan (1978, 1980) in Tennessee, can be seen in the upper half of the Sevier. The only thick sandstone unit observed in the Sevier Formation is a bed 2.3 meters thick. The bed consists of fine to medium sand and occurs approximately 190 meters below the Sevier-Tellico contact.

The contact between the Sevier and Tellico Formations selected for the purposes of this report occurs at the first appearance of thick,

massive sandstone beds. This contact does not occur at the same stratigraphic interval on a regional level due to facies relationships and is one reason for the variations in thickness of the Sevier. If, as this study proposes, the terrigenous clastics in the study are best interpreted in terms of a submarine fan model, the abrupt facies changes expected in this depositional setting could account for the variable thicknesses of the Sevier Formation. Besides the actual thickness variations due to deposition, measurements of the Sevier thickness are ordinarily complicated by the fact that these rocks have been tectonically involved. For example, in the study area, intense deformation in the upper part of the Sevier has rendered determination of an exact thickness impossible. A range of thicknesses from 680 meters as a minimum to 1,000 meters as a maximum is therefore given for the rocks of the Sevier in the study area. These thicknesses are based on measured sections at the base and on thicknesses taken from map distances for the upper part, with known structural features accounted for. Graptolites occur in the Sevier, but are not as abundant as in the Blockhouse.

Tellico Formation

The Tellico Formation is a sequence of blue gray to greenish gray shale, massive sandstone, pebbly sandstone, and polymictic conglomerate, overlying the Sevier Formation. Characteristic of the Tellico in the section described in this study is the stacking on top of each other of three different lithofacies associations.

One type of lithofacies association consists of shale, massive sandstone, and chaotic units. This association occurs in thick packets

at the base of the Tellico, where it is approximately 64 meters thick, and at the top of the exposed section in the study area, where it is approximately 65 meters thick.

Separating the upper and lower packets of this association is another association consisting of a thick sequence of shale and siltstone which resembles the shale and siltstone of the Sevier Formation. The thick shale/siltstone sequence is itself divided by a thick (approximately 130 meters thick) sequence of interbedded shale, massive sandstone, pebbly sandstone, polymitic conglomerate, and debris flows. The lower shale sequence is approximately 52 meters thick with the upper shale/siltstone sequence being approximately 154 meters thick (Figure 2-1).

Graded bedding, scouring, amalgamation surfaces, debris flows, slumps, and other characteristics of the Tellico Formation indicate deposition on a submarine fan. Characteristics of the Tellico Formation are described in more detail in Chapters III and IV. The maximum thickness obtained for the Tellico Formation is 465 meters. This figure is the result of measuring two stratigraphic sections that occur within 100 meters laterally of each other.

Previous workers have given various thicknesses for the Middle Ordovician sequence in the area. Campbell (1899) and Keith (1907) indicated a maximum thickness of 550 meters (1,800 feet). Butts (1940) estimated the section to be 1,530 to 3,050 meters (5,000 to 10,000 feet) thick and Kellberg and Grant (1956) suggested a thickness range of 1,530 to 2,440 meters (5,000 to 8,000 feet). Kellberg and Grant also mentioned that the shale sequence is approximately 920 meters (3,000 feet)

thick in the Avens Bridge area. A minimum thickness of 1,525 meters (5,000 feet) was used by King and Ferguson (1960) for the area between the South Fork of the Holston River and Holston Mountain necessary to balance their structural cross sections. Tyler (1960) and Bartlett and Biggs (1980) proposed a maximum of 1,770 meters (5,800 feet) for the Middle Ordovician section in the South Holston syncline. The total maximum thickness for the Middle Ordovician in this study is 1,520 meters (4,990 feet) (Figure 2-1, p. 18). The Middle Ordovician is truncated above by erosion in the study area so that the original thickness is unknown.

Biostratigraphy

Recently, Coffey (1986) studied the top of the Lenoir Formation near Avens Bridge. His collection of conodonts indicated that biostratigraphically this part of the Middle Ordovician belongs to the Pygodus serra Conodont Zone. This correlates with the collection of conodonts gathered during this study. This assemblage includes Belodella nevadensis, Belodina monitorensis, and Eoplacognathus sp.

Graptolites were observed and collected from the Blockhouse, Sevier, and Tellico Formations. Specimens taken from the lower half of the Blockhouse include Pseudoclimacograptus anagulatus, Glyptograptus teretiusculus, Dicellograptus sextans, Cryptograptus marcidus, Didymograptus sp., and Azyograptus sp. At approximately 50 meters above the Blockhouse/Sevier contact, specimens of Glyptograptus teretiusculus and Dicellograptus sextans were recovered from the Sevier. The uppermost, thick shale sequence in the Tellico Formation yielded Dicellograptus

gurleyi, Gryptograptus marcidus, and Glyptograptus teretiusculus.

Finney (1983, personal communication) assigned this assemblage of graptolites to the lower half of the Nemograptus gracilis Graptolite Zone.

CHAPTER III

SEDIMENTOLOGY OF CLASTIC LITHOFACIES

Introduction

As noted in Chapter I, this study deals primarily with the coarse clastic deposits of the Tellico Formation which belong to the resedimented coarse-clastic family of deep-water sandstone facies of Walker and Mutti (1973) and Walker (1978). Five members make up this family and are described by Walker (1978) as: "(1) classic turbidites, (2) massive sandstone, (3) pebbly sandstone, (4) clast-supported conglomerate, and (5) matrix-supported" or chaotic beds (debris flows, pebbly mudstone, slides, and slumps). All five of these members or lithofacies (as they will be termed in this study) have been recognized in the study area.

These lithofacies are the result of transport of coarse detritus from a continental margin into a deep-ocean basin by mass flows. These flows, which move primarily under the influence of gravity, have been named sediment gravity-flows by Middleton and Hampton (1973, 1976). Four different sediment gravity-flow types have been distinguished on the basis of how the grains are supported during flow (Figure 3-1): (1) turbidity currents, in which the sediment is supported by fluid turbulence; (2) grain flows, in which the sediment is supported by dispersive pressure arising from grain-to-grain collisions or near misses; (3) fluidized sediment flows, in which the sediment is supported by upward moving intergranular fluid; and (4) debris flows, in which the large

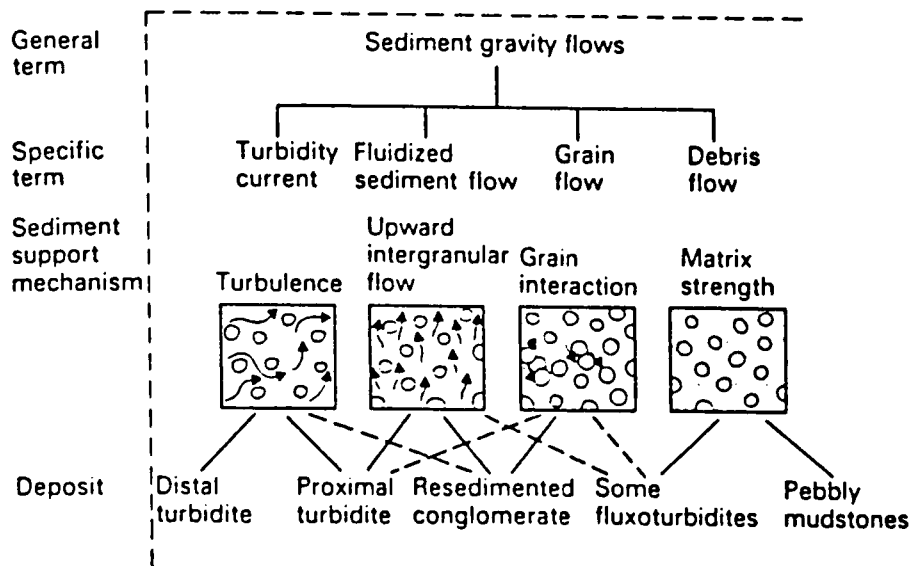


Figure 3-1. Classification of sediment gravity flow types based on the type of grain support. From Middleton and Hampton, 1976.

clasts are supported by a cohesive matrix composed of a mixture of intergranular fluid and fine sediment (Middleton and Hampton, 1973, 1976). Deposits characteristic of each type of flow are illustrated in Figure 3-2 along with possible interrelationships.

In this chapter, each of the five lithofacies will be described and interpreted with respect to transport and depositional flows. First, however, a brief review concerning the deposition of the pelagic shale of the Blockhouse Formation will be discussed.

Pelagic Shale

The pelagic shale strata of the Blockhouse Formation are thinly laminated, dark gray to black clay shale layers containing graptolites. These shale sequences are located at outcrops A and A'.

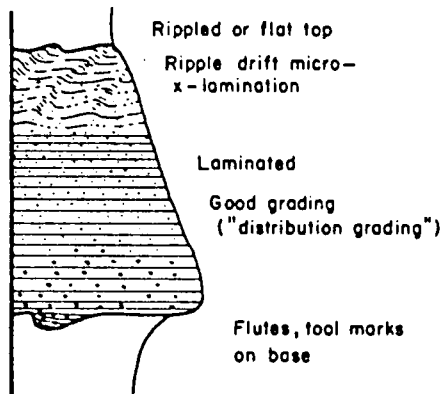
Due to the lack of traction-current features, its pelagic fauna, fine grain size, and thin laminae, these shale layers have been interpreted to be hemipelagic in origin and deposited in a "starved" basin (Shanmugan, 1978; Keller, 1980; Read, 1980).

Classic Turbidites

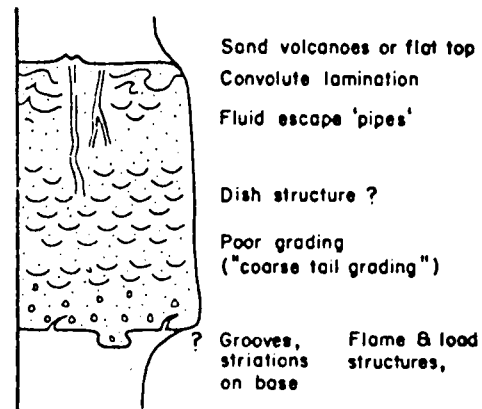
Introduction

Classic turbidites can be distinguished from other resedimented lithofacies by their very parallel bedding, consistent alternations of sandstone and shale along with a characteristic set of internal sedimentary structures, which form the basis of the Bouma (1962) model (Walker, 1978) (Figure 3-3).

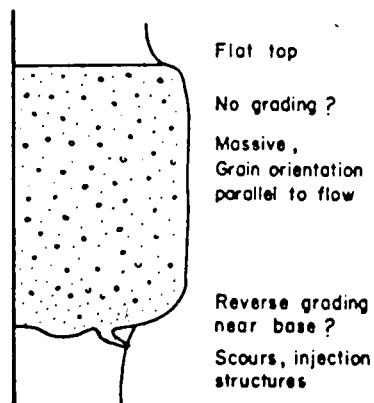
Turbidity Current



Fluidized Flow



Grain Flow



Debris Flow

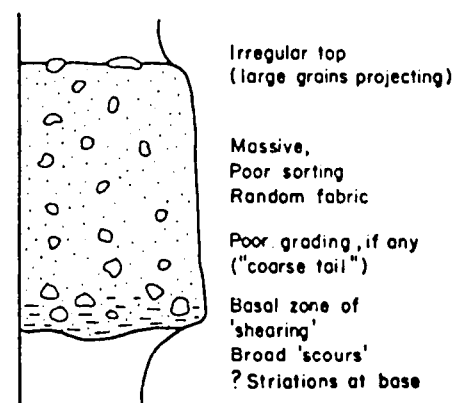


Figure 3-2. Characteristic deposits of four types of sediment gravity flows. From Middleton and Hampton (1973, 1976).

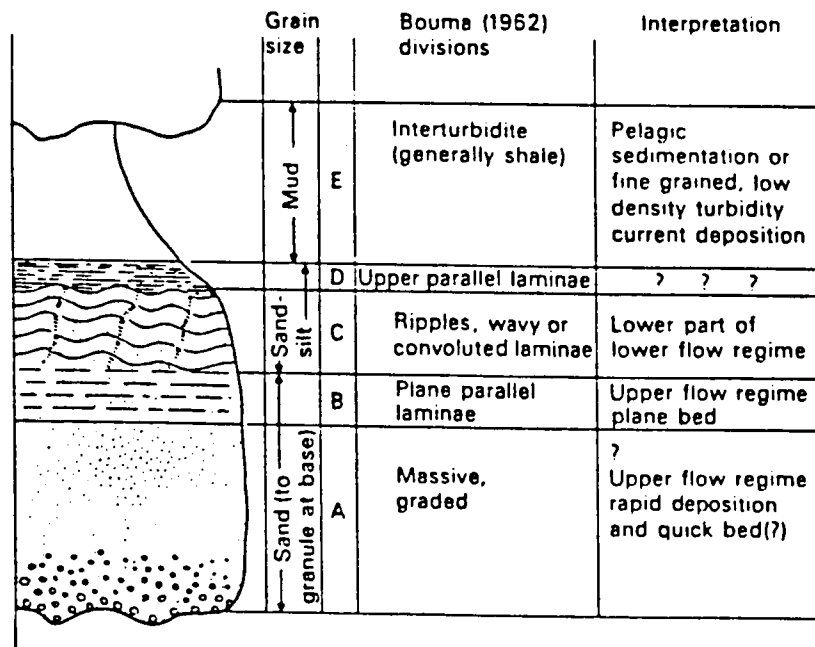


Figure 3-3. Bouma (1962) sequence for sedimentary structures in a turbidite bed. From Middleton and Hampton (1976).

The Bouma sequence is composed of five divisions: (1) A is massive or graded sand to granular, (2) B is parallel laminated sand, (3) C is rippled sand or silt, (4) D consists of faint laminations in silt or clay, and (5) E is pelitic.

Occurrences in the Study Area

Classic turbidites occur at all the outcrops of this study except outcrops A and A'. They occur alone in thick sequences in the lower part of the section and interbedded with the coarser massive sandstone, pebbly sandstone, and conglomerate strata in the upper part of the section.

Textures and Structures

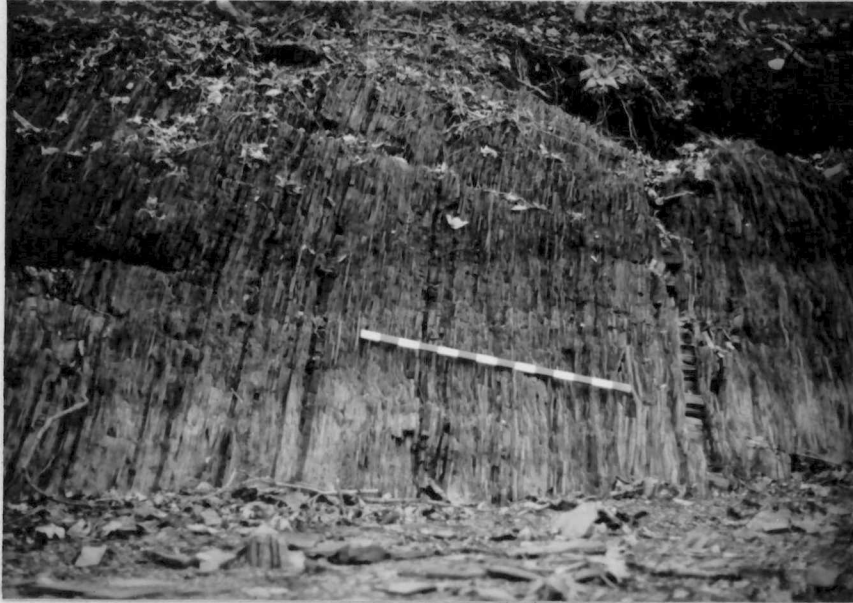
Turbidites in this study resemble the turbidites described by Shanmugan (1978) in his study in the Douglas Lake area.

These turbidites are thin-bedded shale and siltstone layers, with some sandy beds. Grain sizes in the sandstone beds are rarely greater than medium sand. Beds contain normal distribution grading, sharp basal contacts, asymmetrical ripples, climbing ripples, and convolute laminae (Figures 3-4, 3-5, 3-6). Beds are dominantly tabular and have a monotonous appearance.

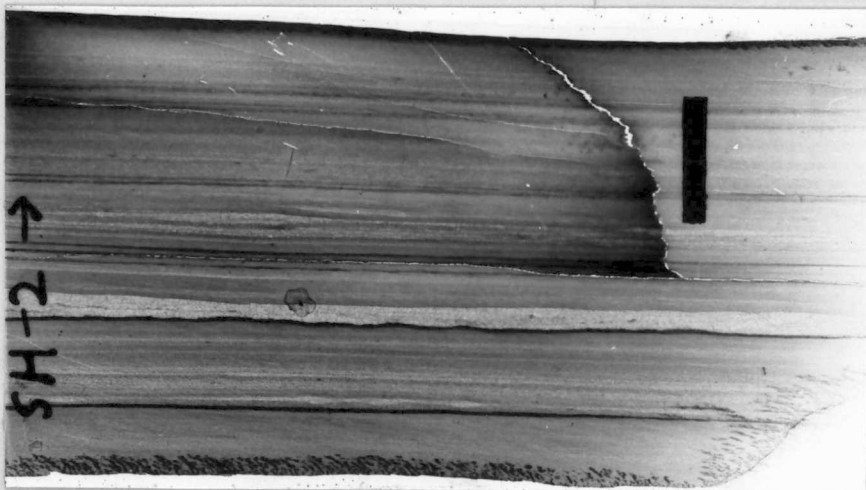
Complete Bouma sequences are rarely seen in the study area with most sequences being a combination of the D division and some other division such as AD or CD.

Figure 3-4. Classic turbidites in the Sevier and Tellico Formations.

- A. Thin-bedded classic turbidites of the Sevier Formation. Jacobs staff is 140 cm.
- B. Thin-section photograph showing thin laminae in classic turbidites from the Tellico Formation. Bar scale is 1 cm.



A



B

Figure 3-4.

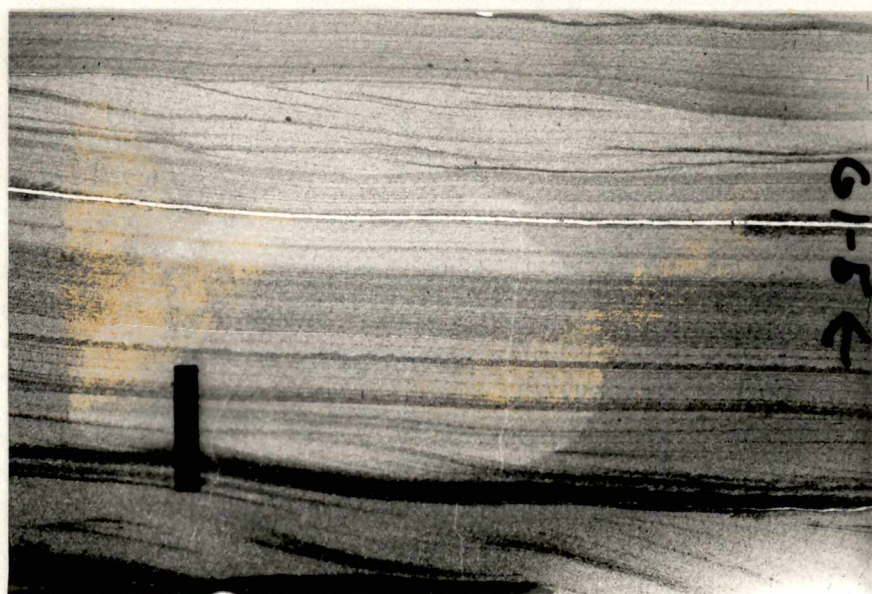
Figure 3-5. Thin-section photographs of classic turbidites in the Tellico Formation.

A. Bouma C, D, and E divisions from outcrop G1. Bar scale is 1 cm.

B. Bouma C, D, and E divisions from outcrop G1. Bar scale is 1 cm.



A



B

Figure 3-5.

Figure 3-6. Sedimentary structures in shale/siltstone strata in the Tellico Formation.

- A. Climbing ripples in shale/siltstone at outcrop G1. Lens cap is 5.5 cm in diameter.
- B. Slabbed siltstone with convolute laminae from outcrop G1. Bar scale is 3 cm.



A



B

Figure 3-6.

Transport and Deposition

An extensive amount of literature has developed concerning classical turbidites (Bouma, 1962; Kuenen, 1951; Middleton, 1967, 1970; Middleton and Hampton, 1973, 1976; Walker, 1965, 1978; Walker and Mutti, 1973). These studies conclude that thin-bedded turbidites are best explained by a low-concentration turbidity current mode of transport and deposition. That interpretation is accepted in the present study.

Massive Sandstone

Introduction

The term massive sandstone implies a texturally homogeneous sandstone. This is not always the case when the term is used to describe thick sandstone beds deposited from sediment gravity-flows (Walker and Mutti, 1973). Massive sandstone sequences derived from sediment gravity-flows are commonly graded, stratified, and have faint laminations and dewatering features, such as dish-and-pillar structures (Lowe, 1975). On the outcrop, massive sandstones are often thick-bedded and may have a "massive" appearance with intervals of little or no textural change. However, most massive sandstones do exhibit some textural changes that can be discerned on close examination.

An outcrop of massive sandstone could be described as AAA . . . using the notation of the Bouma (1962) model. However, a distinction should be made because the Bouma model is a five-part model and should not be applied to beds that typically contain one part and have likely had different modes of transport (Walker, 1984). Massive sandstone sequences most likely are a result of a combination of sediment gravity

flows working at different stages in the flow's history (Middleton and Hampton, 1973, 1976; Lowe, 1976; Walker, 1978), which differ from the dominantly turbulent flow, characteristic of true turbidites. In addition, massive sandstone deposits contain dewatering features, amalgamation surfaces, and more abundant evidence of channeling than does the Bouma A interval.

Occurrences in the Study Area

Massive sandstone is the most common of the coarse lithofacies in the study area and occur at all the outcrops containing coarse clastics (outcrops C1, C2, C3, D1, D2, E2, E3, F1, F5, F7, G2) (Plate I) (Figure 3-7). Massive sandstones also occur as rare isolated beds in the thick shale/siltstone sequences of the section. These isolated occurrences are more abundant in the thick shale/siltstone sequences of the Tellico Formation than the thick shale/siltstone sequence of the underlying Sevier Formation. Only one thick massive sandstone was observed in this underlying interval and it occurs approximately 190 meters below the first coarse clastic sequence.

Textures and Structures

Massive sandstones in this study are generally medium- to thick-bedded with some beds up to 6.1 meters thick (bed C1-16). These very thick beds represent at least 2 to 3 different depositional events; in some instances, later flows must have scoured into the deposits of the earlier flow, often removing any interturbidite shale along with the tops of the earlier deposit. The result is a composite of deposits

Figure 3.7. Massive sandstone beds in the Tellico Formation.

- A. Outcrop F1', thick amalgamated massive sandstone beds. Jacobs staff (center of photograph) is 140 cm.
- B. Outcrop C3, thick amalgamated massive sandstone beds in a thinning upward sequence. Jacobs staff (center of photograph) is 140 cm.



A



B

Figure 3-7.

welded together along an amalgamation surface (Figure 3-8). In several beds, no grain size or other textural changes occur across these surfaces, thus making identification of separate depositional events nearly impossible.

Bedding is tabular to lenticular with some beds pinching out completely within a few meters laterally from their point of maximum thickness. Channel-shaped beds are also present, but are less common. Most beds have a relatively constant thickness at least on the small scale of outcrop exposures. Bed contacts are sharp with the basal contact commonly erosional in nature, as evidenced by scoured surfaces (Figure 3-9), ripped-up intrabasinal shale clasts, and sole marks. Sole marks such as flutes and grooves (Figure 3-10) were not abundantly exposed. This was probably due to the poor exposure of basal surfaces of beds. Another feature seen along basal contacts is the filling of depressions by sediment coarser grained than sediment above or adjacent to these pockets. Kuenen and Menard (1952) provided an explanation for the origin of these deposits: the coarsest grains of a flow would "outdistance finer grains and collect at the front of the flow," with some of these becoming trapped in bottom depressions. As the flow passes by, grain-size decreases with finer-grained sediment being deposited on top and adjacent to the coarser material.

Other features include imbricated grains, ripped-up shale clasts, dewatering pipes or pillars (Figure 3-11), faint laminations (Figure 3-12), and graded bedding. No evidence of cross-stratification was observed in any of the massive sandstone beds of this study or by Bowlin (1979) and Bowlin and Keller (1980).

Figure 3-8. Amalgamation surfaces in massive sandstone beds in the Tellico Formation.

- A. Amalgamation surfaces at outcrop E3. Stratigraphic top is to the right of the photograph.
- B. Amalgamated massive sandstone at outcrop D2. Stratigraphic top is to the left of the photograph.



A



B

Figure 3-8.



Figure 3-9. Scoured base of massive sandstone bed at outcrop D2. Lens cap is 5.5 cm in diameter.

Figure 3-10. Flute casts on basal surfaces of massive sandstone beds in the Tellico Formation.

- A. Flute casts at outcrop E2. Jacobs staff is 140 cm.
- B. Close-up view of flute casts at outcrop E2. Top of rock hammer for scale.



A



B

Figure 3-10.

Figure 3-11. Thin-section photographs of massive sandstone with dewatering pillars.

- A. Dewatering pillars in massive sandstone from outcrop G2. Bar scale is 1 cm.
- B. Dewatering pillars in massive sandstone from outcrop C3. Bar scale is 1 cm.

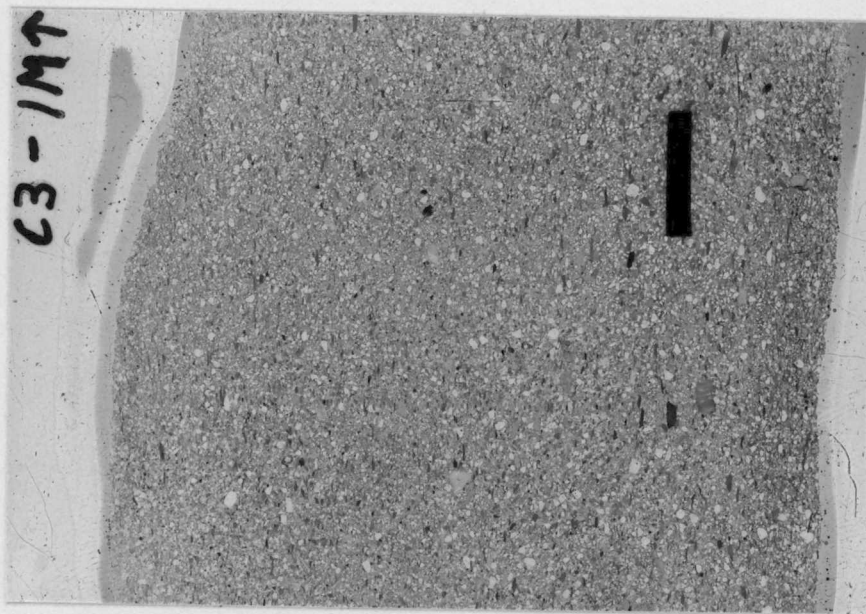
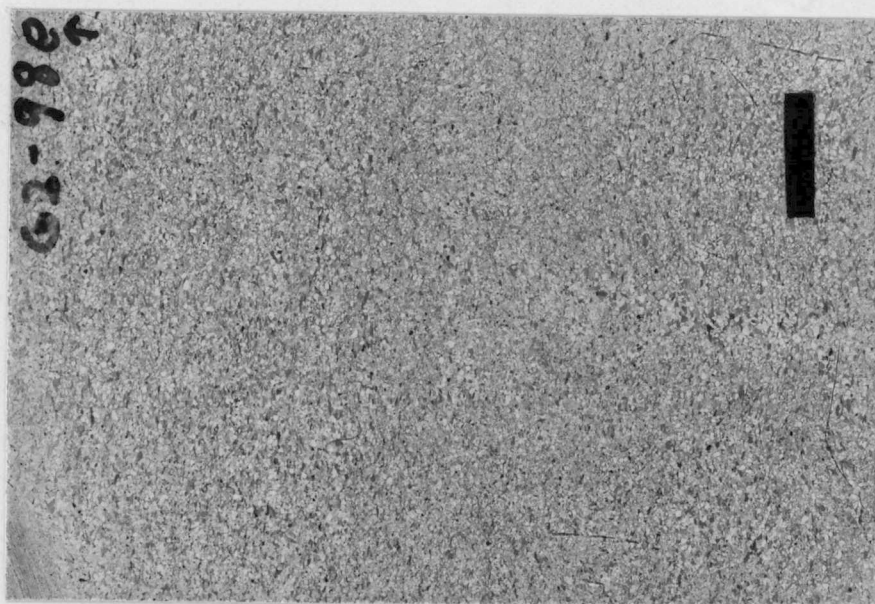
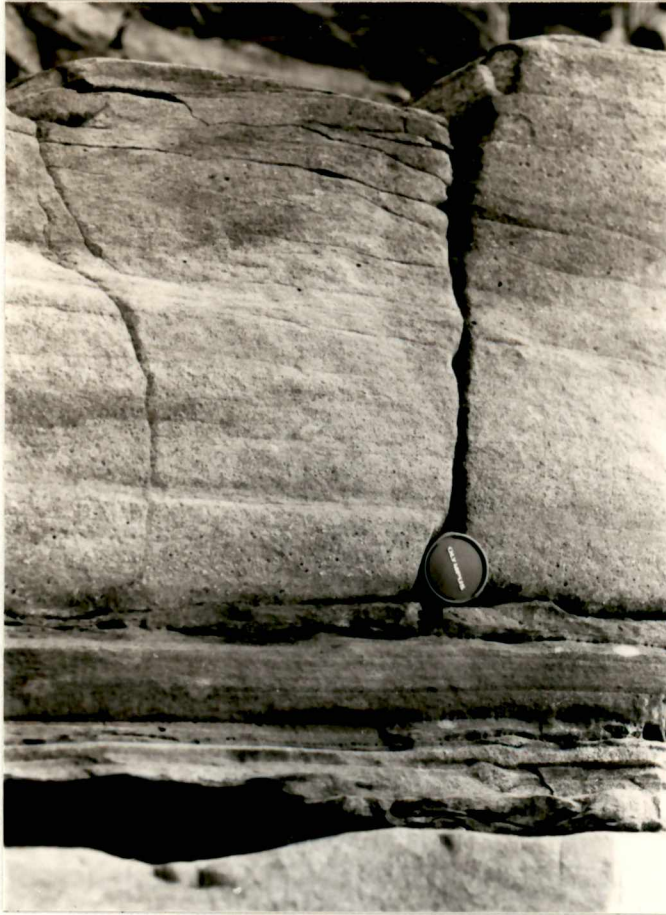
**B****A**

Figure 3-11.

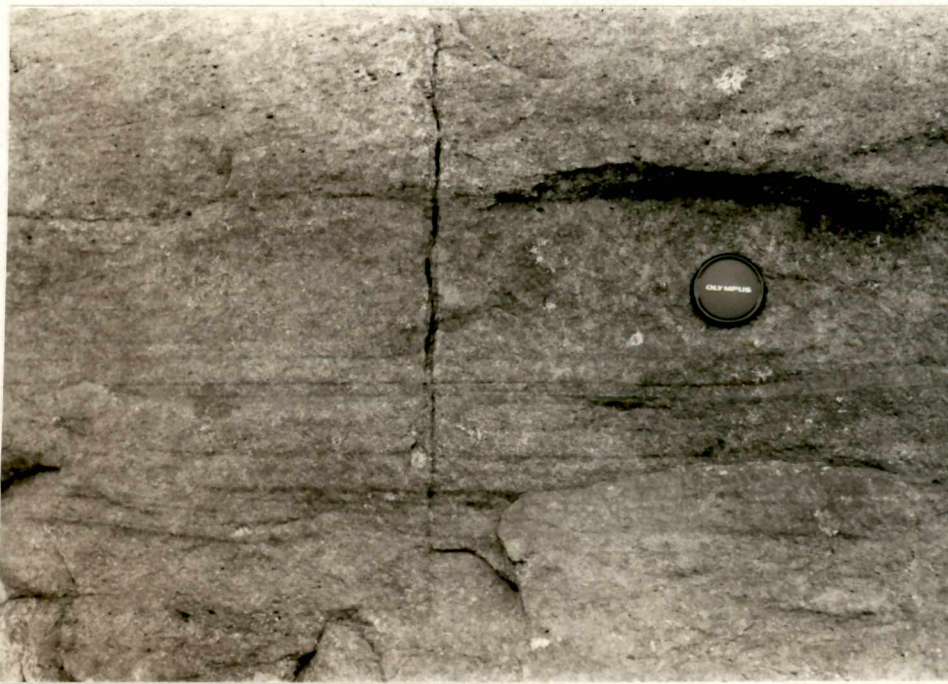
Figure 3-12. Faint laminations in massive sandstone in the Tellico Formation.

A. Laminae in massive sandstone. Lens cap is 5.5 cm in diameter.

B. Faint laminations in massive sandstone at outcrop D2. Lens cap is 5.5 cm in diameter.



A



B

Figure 3-12.

Although dewatering pillars were observed in the middle to upper parts of beds, no dish structures characteristic of massive sandstone deposits (Walker and Mutti, 1973; Lowe, 1975; Middleton and Hampton, 1976; Walker, 1978, 1984) were found. Hiscott (1980), in his work on the Lower Ordovician Tourelle Formation of Quebec, also noted the presence of dewatering pillars without associated dish structures.

Faint laminations, when present, occur in the upper parts of beds and are not laterally continuous. These laminations are not readily apparent and may be more abundant than is noted in this report. MacDonald (1986) in his work on the massive sandstone deposits of the Lower Cretaceous Cumberland Bay Formation also noted crude, poorly developed parallel laminations in some beds, but gave no explanation for their formation.

Several types of graded bedding occur in the massive sandstone sequences of this study: (1) normal distribution; (2) normal coarse-fraction, including both coarse-frequency and coarse-tail grading; and (3) inverse grading. Grading, irrespective of type, is rarely continuous throughout a bed, except for the thinner beds. Commonly the middle portions of beds have a homogeneous texture with little evidence of grading of any kind.

The following discussion on graded bedding is taken from the work of several authors (Kuenen, 1953; Middleton, 1967, 1970; Stauffer, 1967; Allen, 1970; Middleton and Hampton, 1976; Cas, 1979). The reader is referred to these reports for a more detailed discussion of the different types of graded bedding and their inferred origins.

Normal distribution grading is where the whole grain-size distribution moves to finer sizes as one progresses upward in a bed (Middleton and Hampton, 1976). Well-developed distribution grading in this study is most commonly seen in the uppermost few centimeters of massive sandstone beds, where grain sizes may rapidly grade from fine sand to silt or clay within the upper 5 to 10 centimeters (Figure 3-13).

Coarse-fraction grading can be divided into two types: coarse-frequency grading, in which the coarser grains do not decrease in size, but instead, decrease in abundance upward, and coarse-tail grading, in which the coarsest grains decrease in size upward. As Bowlin (1979) noted at South Holston Dam, these two types of coarse-fraction grading typically tend to occur together or are not dominant enough to be distinguished from one another. Thus he combined them under the category of coarse-fraction grading, as this study does. Coarse-fraction grading occurs at the base of beds and will commonly pass gradually into a texturally homogenous middle interval.

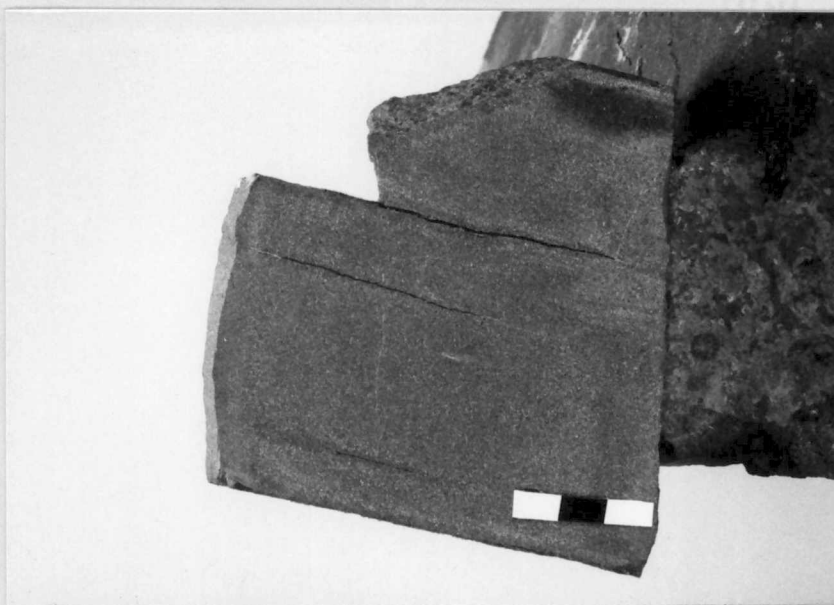
Inverse grading is not a common type of grading in these beds, but where it does occur it is a significant feature indicative of the mechanics of the depositing flow. Inverse grading is the vertical increase upwards in grain size of a bed. It occurs at the base and within 5 to 10 centimeters of the base of the bed (Figure 3-14) and is followed by normal grading, typically coarse-fraction grading. This characteristic of massive sandstone deposits has also been observed by Macdonald (1986) in the Cumberland Bay Formation on the island of South Georgia. Of all the massive sandstone beds examined in this study,

Figure 3-13. Top of massive sandstone bed (G2-93B).

- A. Slabbed sample (G2-93B), showing rapid distribution grading at the top of the slab along with dewatering pillars. Stratigraphic top is towards the top of the photograph. Bar scale is 3 cm.
- B. Thin-section photograph of G2-93B showing in detail rapid distribution grading and dewatering pillars. Bar scale is 1 cm.



B



A

Figure 3-13.

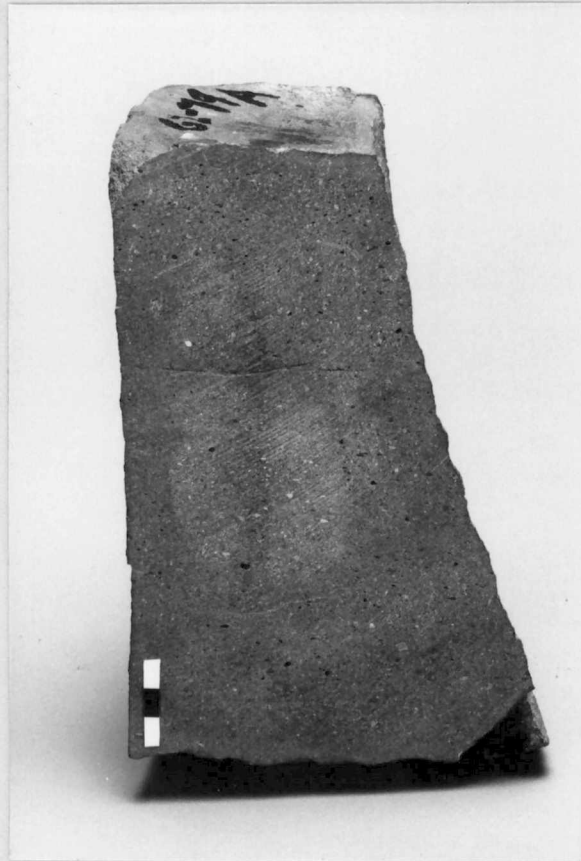


Figure 3-14. Slab of massive sandstone with poorly developed inverse grading at the base of the slab. Stratigraphic top is towards the top of the photograph. Bar scale is 3 cm.

(approximately 450) not one contained inverse grading throughout the bed or in a thick interval.

Although not a common feature, some stratified or multiple sets of graded layers were observed.

Transport and Deposition

Much debate has been generated over the years on the different kinds of flows involved with the transport and deposition of massive sandstone beds (Bagnold, 1954,1956; Stauffer,1967; Chipping, 1972; Middleton and Hampton, 1973,1976; Link, 1975; Lowe, 1976,1982; Walker, 1978, 1984; Nardin et al., 1979; Hein, 1982). Bagnold (1954,1956) proposed a grain-flow type of grain-support mechanism in which grain-to-grain collisions in a cohesionless sediment produced a "dispersive pressure" that supported the grains in the flow. Features characteristic of grain flow deposits include inverse grading, imbrication (Rees, 1968), diffuse laminae, and sharp upper contacts (Middleton and Hampton, 1976).

Deposition of grain flow deposits is one of the least understood aspects of the four sediment-gravity flows. The early experimental work of Bagnold (1954, 1956) was later added to by Stauffer (1967) working in the Lower Tertiary of the Santa Ynez Mountains. Middleton and Hampton (1976) developed their concepts for grain flow based on these early studies. A later study (Link, 1975) on the sequence studied by Stauffer (1967) proposed that the sequence was deposited from high-concentration turbidity currents rather than grain flows. Work by Lowe (1976) demonstrated that a minimum slope of 18° is required to sustain movement of

sediment by true grain flow as well as producing a deposit less than 5 cm thick. Lowe (1976) also noted that thicker grain flow deposits may form on much lower slopes when transport of sediment involves other sediment-gravity flows as well as grain flow. Lowe called these type of flows density-modified grain flows.

Evidence for fluidized flow exists in these beds. Fluidized flow is where upward flow of escaping pore fluid is the active grain-support mechanism. It is illustrated in this study by dewatering pillars caused by rapid escape of pore fluids, and by massive portions near the middle of beds.

Massive intervals are thought to originate from rapidly deposited high-concentration flows, in which beds were sheared and churned by waves (Helmholtz waves) moving along the surface between the previously deposited bed and the sediment still moving immediately above the bed. (Middleton, 1967; Middleton and Hampton, 1976). This has the effect, along with dewatering, of destroying any laminations or other structures, thus producing a texturally homogenous interval.

Transport and deposition by turbidity currents, at least in parts of beds is indicated by coarse-tail grading and normal-distribution grading (Cas, 1979). Middleton and Hampton (1976) stated that coarse-tail grading forms only from high-concentration flows. They stated that "grading is probably caused in part by decay of initial turbulence, in part by decreasing competency in the tail of the turbidity current, and in part by the concentration of coarse grains in the head of the current" (Middleton and Hampton, 1976). Normal distribution grading has

been shown in experimental flows to be the result of deposition layer-by-layer from low-concentration turbidity currents (Middleton and Hampton, 1976).

Evident from the preceding discussion is the fact that no one type of sediment gravity-flow is responsible for the transport and deposition of massive sandstone sequences. Instead, a combination of sediment gravity flows interacting together at various stages of the flow's evolution is most likely. Flows depositing massive sandstone were most likely high-density turbidity currents with episodes during which grain flow and fluidized flow were important grain-support mechanisms (Lowe, 1982).

Pebbly Sandstone

Introduction

Pebbly sandstone deposits are distinguished from massive sandstone mainly on the basis of grain size. Grains range from granular to pebble-size, may be imbricated, graded, stratified, and commonly clast-supported. Beds typically have scoured bases, are highly lenticular, and are discontinuous. Walker (1978) reported that the most common sedimentary structures are stratification and cross-stratification. Although some beds encountered in the present study do exhibit evidence of stratification, no examples of cross-stratification were observed. Walker also reported the presence of sole marks and dish-and-pillar structures in pebbly sandstones. Only one sole mark was observed in this study, and there was no evidence of dish and pillar structures.

For the present, no "Bouma-like" model has been developed to categorize the internal structures of pebbly sandstone beds.

Occurrences in the Study Area

Pebbly sandstone deposits occur in this study only in the coarse sequences containing turbidites, massive sandstone, conglomerate, and debris flows (outcrops F5, D1, D2). These outcrops occur in the middle of the section, which contains coarse clastics. The significance of this aspect will be examined in Chapter IV.

Textures and Structures

Pebbly sandstone deposits in this study are granular to pebble size, highly lenticular, and generally exhibited a scoured base. Beds range from 7 centimeters to 163 centimeters in thickness with the average thickness approximately 41 centimeters. Bases and tops of beds are sharp. Imbrication of grains is present (Figure 3-15) as is grading, (commonly normal distribution). However, grading in these pebbly sandstone deposits is not as abundant as Bowlin (1979) noted in his study area. Most beds of this type are clast-supported and exhibit little evidence of marked grading (Figure 3-16). Stratification of beds is also present, although not common.

Transport and Deposition

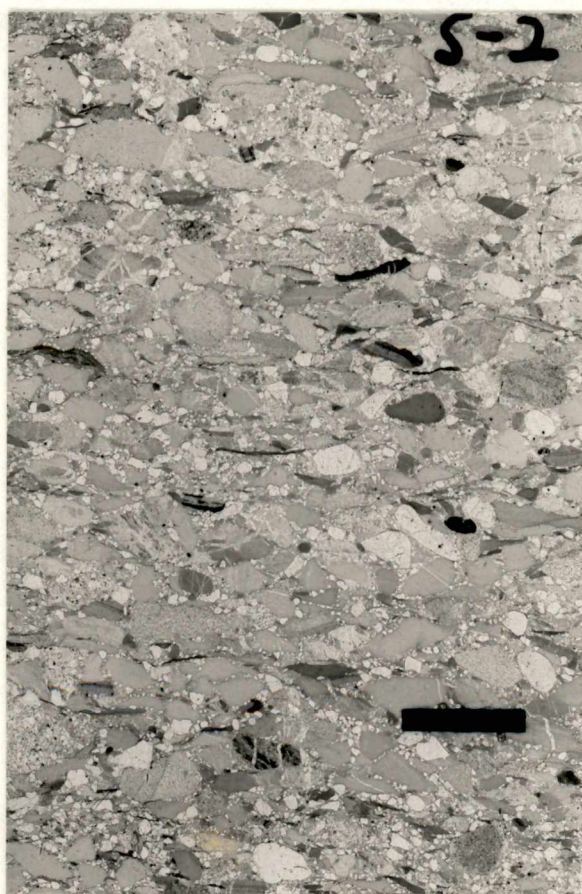
The transport and depositional mechanisms for pebbly sandstone deposits in this study are probably similar to those for massive sandstone. These would include an early phase of suspension by fluid turbulence (turbidity current) during sediment transport, with later



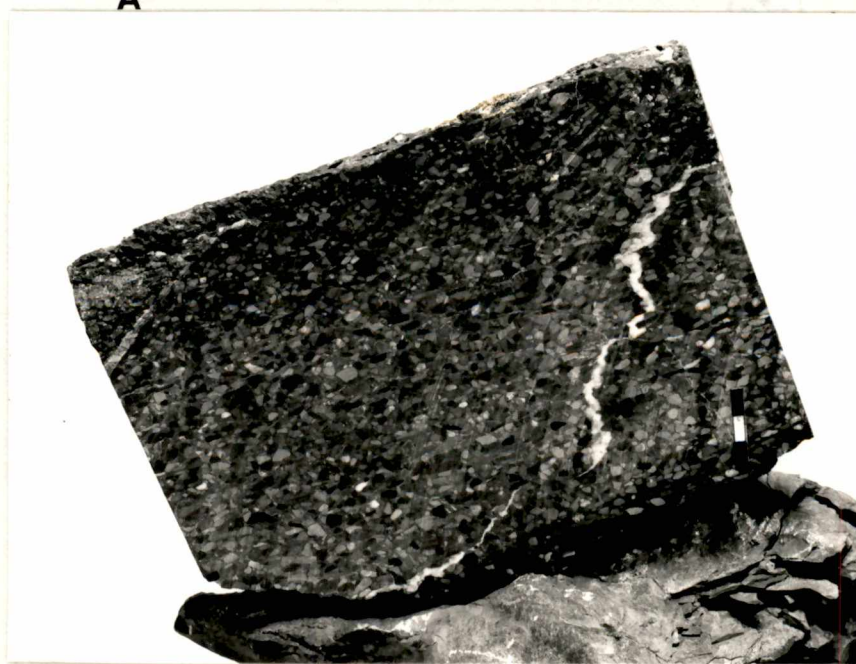
Figure 3-15. Pebbly sandstone at outcrop D1 with imbricated clasts. Lens cap is 5.5 cm in diameter.

Figure 3-16. Pebbly sandstone in the Tellico Formation from outcrop D1.

- A. Thin-section photograph of pebbly sandstone with clasts aligned parallel to bedding. Stratigraphic top is towards the top of the photograph. Bar scale is 1 cm.
- B. Slab of pebbly sandstone with pebbles aligned parallel to bedding. Stratigraphic top is to the top of the photograph. Bar scale is 3 cm.



A



B

Figure 3-16.

modifications during deposition (i.e., grain flow) (Walker, 1978). The importance of fluid turbulence is also evident from erosive bases, generally clay-free matrix, and rather good sorting (Bowlin, 1979). Imbrication of grains would be due to dispersive pressure.

In conclusion, pebbly sandstone beds were transported and deposited from a combination of sediment gravity-flows working at different stages during the flow's travel into the basin, with high-concentration turbidity currents having the major role and grain flow (dispersive pressure) having a secondary role.

Clast-Supported Conglomerates

Introduction

Although they are not as abundant as classical turbidites, conglomerate beds represent the coarsest deposits of deep water environments. They also represent the coarsest deposits in the study area. Walker (1975) proposed four models for resedimented conglomerate deposits: (1) graded-stratified, (2) graded-bed, (3) inverse-to-normally graded, and (4) disorganized bed. As a result of these models there is now some agreement on the important parameters, that should be noted in the field such as types of grading, stratification, and imbrication.

Occurrences in the Study Area

Clast-supported conglomerate beds occur at two outcrops (D1 and F5) in this study. These outcrops occur in the middle of the section containing coarse clastics. The conglomerate beds occur throughout outcrops D1 and F5.

Textures and Structures

Clast-supported conglomerate beds (Figures 3-17, 3-18) in this study range from 6 centimeters to 193 centimeters in thickness. Bedding is quite lenticular. Scoured bases are common. Most of the 20 conglomerate beds are disorganized or exhibit normal grading. The largest clast was contained within the thickest conglomerate bed (193 cm) and measured 17 x 6 centimeters. Stratification of these conglomerate beds was not observed. Imbrication of clasts, although present, was rare.

Transport and Deposition

The primary transport and depositional mechanisms for clast-supported conglomerate beds was fluid turbulence as the sediment was transported into the basin. Late-stage modifications during deposition (grain flow) resulted in imbrication (Walker, 1978).

Matrix-Supported Beds

Introduction

Matrix-supported beds are typically poorly sorted, with pebbles, cobbles, and boulders supported by a fine-grained matrix (debris flows) and may contain evidence of internal deformation (slumps and slides). The matrix-supported beds of this study can be attributed to subaqueous slumps, slides, and debris flows.

Slumps

One large slump (3.55 meters thick) involving several different beds was observed in this study. The slump occurs at outcrop F5 (Figure 3-19). Movement along a concave-upward shear plane has had a

Figure 3-17. Clast-supported conglomerates in the Tellico Formation.

- A. Photograph looking down on bed surface showing clast-supported conglomerate with clasts aligned parallel to bedding. Stratigraphic top is to the left. Large clasts are carbonate rock fragments. Lens cap is 5.5 cm in diameter.
- B. Bed-perpendicular view of clast-supported conglomerate. Stratigraphic top is towards top of the page. Large clasts are dominantly carbonate rock fragments. Lens cap is 5.5 cm in diameter.



A



B

Figure 3-17.



Figure 3-18. Graded clast-supported conglomerate. Stratigraphic top is to the top of the photograph. Bar scale is 3 cm.



Figure 3-19. Slump at outcrop F5. Contorted beds can be seen to the right of the photograph. Rock hammer, lower center of photograph for scale. Stratigraphic top is to the right of the photograph.

churning effect on the beds involved. The slump apparently blocked or plugged a small channel within what is interpreted to be an inner-fan channel. Immediately above the slump is a massive sandstone that also has a churned-up appearance. This sandstone is overlain by 4.2 meters of shale/siltstone that is interpreted by the writer as representative of an interchannel deposit that blanketed an abandoned channel.

Slides

Deposits of slides are to be found in all outcrops that contain coarse clastics (Figures 3-20, 3-21). These slides are of the translational (glide) type (Cook et al., 1982) in which movement has occurred along shear planes that are seen as gently undulatory surfaces parallel to bedding. The slides in the study area exhibit various degrees of internal deformation. Slides in this study exhibit plastic behavior in which unconsolidated sediment was deformed and folded. Tabular clasts in these slides may have formed by the breakup of horizontal beds. Cook (1979) described the breakup of such clasts as he traced a translational slide laterally from a slide with well preserved bedding to overfolds with tabular clasts to a deposit of graded clasts all within 5 meters. This type of lateral transition has also been observed in the Tellico except for the formation of graded clasts. In the study area these slides are typically confined to interbedded shale and siltstone sequences often immediately below a massive sandstone bed. It is possible that rapid deposition of the sandstone resulted in shearing of the sediment below thus initiating a slide. Similar type features

Figure 3-20. Translational (glide) slide deposits in the Tellico Formation.

- A. Translational slide at outcrop D2 showing tabular clasts. Stratigraphic top is to the left. Lens cap is 5.5 cm in diameter.
- B. Translational slide at outcrop D2 showing tabular clasts. Stratigraphic top is to the left. Lens cap is 5.5 cm in diameter.



B



A

Figure 3-20.



Figure 3-21. Slab of translational slide with folded shale stringers in a sandy matrix. Bar scale is 3 cm.

have recently been described in Italy (Alvarez et al., 1985) and in Newfoundland (Coniglio, 1986).

Debris Flows

Debris flows in this study have a sandy matrix that supports clasts as large as boulder-size. The largest clast (an interbedded shale/siltstone lithology) measured was 1.80 meters x 0.32 meters in a 5.1 meter-thick debris flow at outcrop F5 (Figures 3-22, 3-23). Other debris flows are located at outcrops F1', D1, D2, and C2. Large clasts are usually parallel to bedding and rarely touch. These deposits are the result of transport by the debris flow mechanism.

Figure 3-22. Debris flow deposits in the Tellico Formation.

- A. Debris flow (5.1 meters thick) at outcrop F5 containing boulder size shale and sandstone clasts. Stratigraphic top is to the right. Jacobs staff is 140 cm.
- B. Debris flow at outcrop D2 showing matrix-supported clasts. Stratigraphic top is to the left.



A



B

Figure 3-22.



Figure 3-23. Slab of debris flow deposit with randomly oriented, matrix-supported clasts. Stratigraphic top is towards the top of the page. Bar scale is 3 cm.

CHAPTER IV

ENVIRONMENTAL INTERPRETATIONS OF LITHOFACIES
ASSOCIATIONSIntroduction

A regional facies pattern of Middle Ordovician sequences in the southern Appalachians was first proposed by Walker and Alberstadt (1973) (Figure 1-1, p. 2). Walker (1977, 1980) and Shanmugan and Walker (1983) working in east Tennessee, along with Read (1977, 1980, 1982) in southwest Virginia have proposed a facies pattern composed of three parts: (1) a northwestern carbonate shelf, bounded on the southeast by a shelf-edge skeletal sand-bank/reef; (2) a deep-water foreland basin southeast of the shelf; and (3) a shallow-water nearshore environment southeast of the basin. The foreland basin was bordered by developing tectonic highlands (Kay, 1951; Rodgers, 1971). The basin developed following foundering of the previously passive Cambrian-Ordovician carbonate shelf which was uplifted, deformed, and eroded during the Early Ordovician (Rodgers, 1971). Five stages of basin evolution (Shanmugan, 1978; Shanmugan and Walker, 1978, 1980, 1983) have been proposed for the Sevier basin in East Tennessee: (1) a stable shelf-edge represented by the Lenoir; (2) a downwarping stage represented by the Whitesburg Formation; (3) a starved-basin stage represented by slow pelagic fallout of the Blockhouse Formation; (4) a turbidite-fill stage represented by sedimentary rocks of the Sevier and Tellico Formations; and (5) a

contour-current stage, that can be seen in shale and siltstone strata of the Sevier and Tellico Formations. Evolution of this sequence through the Middle Ordovician led to the filling of the basin, with southeasterly derived terrigenous clastics of the Blockhouse, Sevier, and Tellico Formations.

Great progress has been made within the past decade in resolving the paleoenvironments of the western shelf and associated transitional slope paleoenvironments of the Sevier Basin. In contrast, fewer detailed investigations of the terrigenous clastics of the basin have been made to test this part of the regional model. Previous studies in basinal sequences (Walker and Keller, 1977; Bowlin, 1979; Raymond et al., 1979; Keller, 1977, 1980; Bowlin and Keller, 1980; Read, 1980; Shanmugan, 1978; and Shanmugan and Walker, 1983) have proposed that turbidites filled the basin from westward-prograding submarine fan systems. The lithofacies associations observed in this study support this model and are used to interpret subenvironments in these deposits. First, however, a brief review of submarine fan models and related turbidite systems is in order.

Submarine Fan Models and Related Turbidite Systems

The following discussion is primarily based upon the work of several authors (Mutti and Ricci Lucchi, 1972; Walker, 1978; Normark, 1970, 1978; Howell and Normark, 1982; Bouma et al., 1985; Stow et al., 1985; Nelson, 1983; and Shanmugan and Moiola, 1985) to which the reader is referred for more complete details.

A large number of modern fans have been studied over the last few years and a growing number of ancient turbidite sequences have been interpreted as being deposited on submarine fans. Examples from both modern and ancient turbidite sequences have been used to develop a variety of models that characterize morphology and facies distribution. Although it is evident that several different types of fans exist, it is also true that turbidite sequences may also be deposited in other environments such as slope aprons, submarine canyons, and trenches (Stow et al., 1985).

Several problems have arisen when comparing models for modern and ancient turbidite sequences. These include nomenclature and conceptual problems that are due, to a large degree, to the lack of a common data set. The lack of a common data set can be traced to differences in the scale of observation and methods of data collection (Normark et al., 1983). Data sets from studies of ancient turbidite sequences provide details on bedding characteristics, grain-size variations, sedimentary structures, trace fossils, paleocurrents, and vertical and lateral distribution of facies. Stratigraphic sections may vary from a few meters to hundreds of meters, with lateral exposures limited to the outcrop or a series of outcrops (Figure 4-1) (Bouma et al., 1985). Covered intervals, erosion, compaction, and tectonic complications can prevent or hamper detailed correlation of sequences and as a result, any reconstruction of a basin's vertical morphology (Bouma et al., 1985).

Data from studies on modern fans include basin configuration, gradients, lateral facies, and surface morphology. Using side-scan sonar,

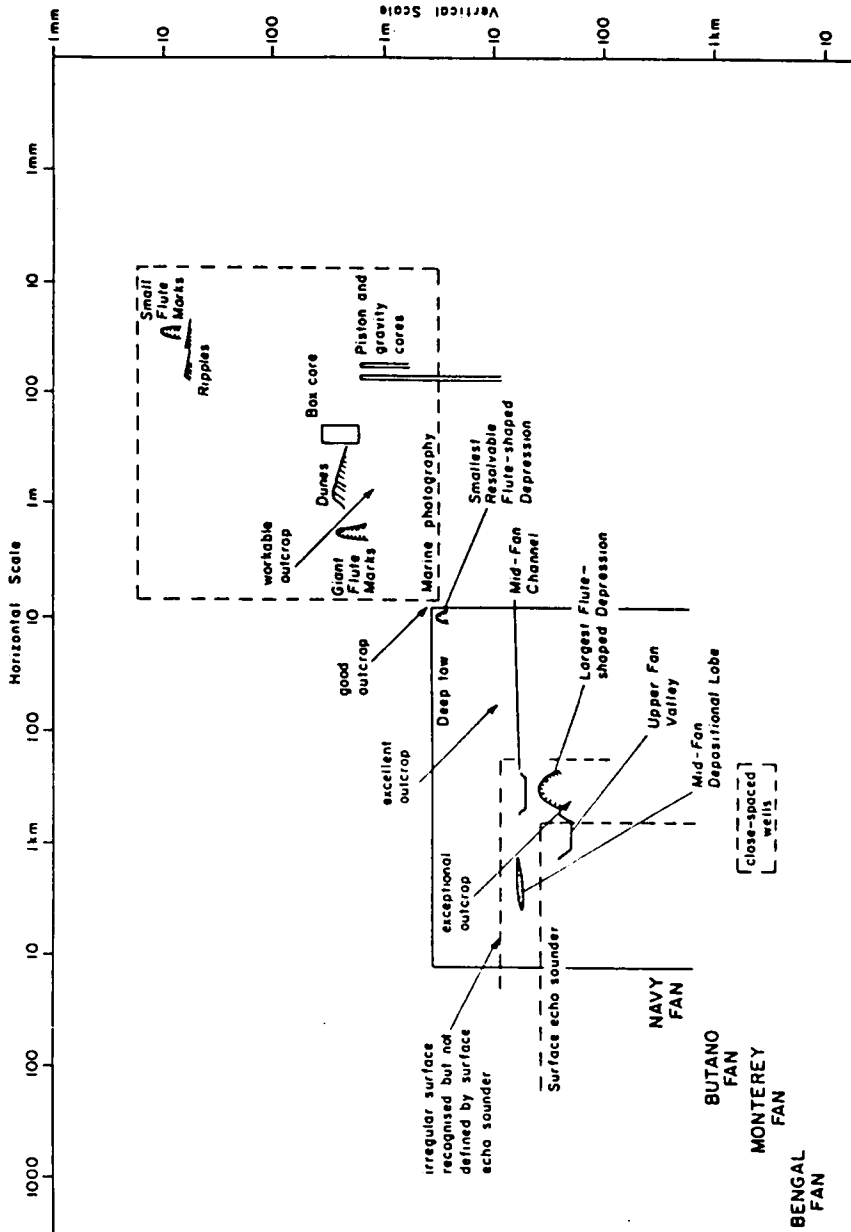


Figure 4-1. Horizontal and vertical scale comparison for submarine fan data sets from modern fans and studies on outcrops of ancient turbidite sequences. From Bouma et al. (1985).

echo-sounding, and high resolution seismic reflection techniques, acoustic facies for some fans can be correlated across the basin on the order of several kilometers (Figure 4-1) (Bouma et al., 1985). One of the main problems when comparing modern fans with ancient turbidite systems can be seen in Figure 4-1. When water depths are greater than a few thousand meters acoustical techniques cannot delineate small-scale morphological features. As a result, the smaller size of many of the features described in ancient fan sequences are beyond the resolution of most of the instruments used in modern studies. More detail may be provided by side-scan sonar towed at great depths, but due to slow towing speeds and the limited areas covered, their use has been restricted (Bouma et al., 1985).

The tectonic setting of fan models must also be considered when comparing modern fans and ancient turbidite sequences. Most ancient systems that have been studied are interpreted as having been deposited in active margin settings or during periods of low sea-level (Shanmugam et al., 1985; Shanmugam and Moiola, 1984, 1985). In contrast, the upper surficial deposits of most modern fans have been accumulating during the recent rise in sea-level and should reflect deposition by turbidity currents during the declining or inactive stage of fan development (Shanmugam and Moiola, 1985). Therefore, as Shanmugam and Moiola (1985) stated, the "comparison of surface sediments deposited during the waning stage of modern fan development with the bulk of ancient sequences that represent the prime stage of fan development is questionable." However, modern fans deposited along active margins could, taking into account

variations in controlling factors (i.e., tectonic setting, basin configuration, sediment-type and supply, climate and sea-level stability), be compared to ancient turbidite systems with similar characteristics.

Comparison of modern submarine fans and related systems with ancient turbidite systems should be done with caution. The definition of modern systems and their subenvironments is based primarily upon morphologic characteristics. Ancient turbidite sequences, on the other hand, are described by their sedimentary facies and vertical trends (Bouma et al., 1985). Only with exceptional outcrop exposure can the dimensions of ancient turbidite sequences be delineated on the outcrop scale; thus, the original morphology and areal extent of ancient sequences can only be speculated on (Bouma et al., 1985).

The radial fan model of Walker (1978) is used in this study to illustrate the different subenvironments of fans and their facies associations (Figure 4-2). The use of the radial fan model here is not meant to imply that the deposits of this study were necessarily deposited on a fan with a radial shape. The complex interplay of controlling factors such as tectonics, sediment supply, and basin configuration in the Sevier basin may have prevented the formation of a fan similar to the "idealized" radial fan model presently in vogue (i.e., model of Mutti and Ricci Lucchi, 1972; Normark, 1978; Walker, 1978). Fan shapes and basinal characteristics of the Sevier basin in the area will be considered at the end of this chapter after the subenvironments have been discussed and related to the "idealized" radial fan model.

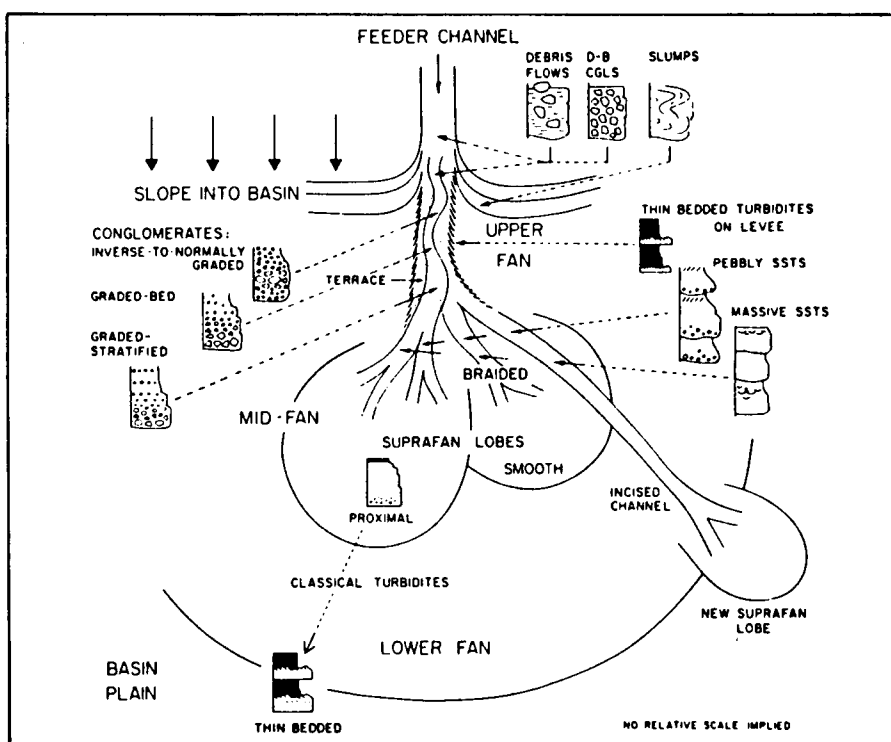


Figure 4-2. Fan model of Walker (1978). From Walker (1984).

The radial fan model can be characterized by four major divisions (Figure 4-2): (1) an inner or upper fan with a single commonly leveed channel; (2) a mid fan, composed of an upper zone of shallow braided channels which feed a lower depositional lobe; (3) a smooth outer or lower fan, that may be indistinguishable from; (4) the basin plain (Walker, 1984). Each of these divisions can be characterized by typical lithofacies associations, which were first developed by Mutti and Ricci Lucchi (1972) and added to by Walker (1978). Table 4-1 describes the lithofacies of Mutti and Ricci Lucchi and Figure 4-3 illustrates their distribution.

The upper fan is characterized by the presence of a prominent, leveed valley that is fed by a feeder channel located up depositional slope. Within the upper fan channel there is typically a smaller, thalweg channel. This channel is commonly flanked by nearly flat terraces (Walker, 1978). Howell and Normark (1982) reported the presence of smaller channels within the upper fan channel of modern submarine fans. These smaller channels are actively cutting the valley floors and are typically several meters deep and tens of meters wide for small fans. On large fans these channels may be tens of meters deep and several hundred meters wide (Howell and Normark, 1982). Lithofacies typical of the upper fan include coarse-grained channel-fill sequences and extensive overbank silt and mud, levee deposits, and hemipelagic sediment (Normark and Howell, 1982). The channel-fill lithofacies may be conglomerate, pebbly sandstone, massive sandstone, classical turbidites,

Table 4-1. Classification of turbidites and other resedimented lithofacies.

Bouma sequence not applicable	Facies A Very thick and very coarse-grained beds of pebbly sandstone, and conglomerate Subfacies A₁: Disorganized conglomerate Subfacies A₂: Organized conglomerate Subfacies A₃: Disorganized pebbly sandstone. Facies B Thick-bedded, medium- to coarse-grained sandstone Subfacies B₁: Massive sandstones with dish structures. Subfacies B₂: Massive sandstones without dish structures.
Beds can reasonably be described using the Bouma sequence	Facies C Thick-bedded classical turbidites characterized by the presence of the basal <u>a</u> division of the Bouma sequences Subfacies C₁: Coarse- to fine-grained sandstone characterized by T_{ace} and T_{ac} partial Bouma sequences Subfacies C₂: Medium- to fine-grained sandstone characterized by the complete Bouma sequence of T_{abce} and T_{abde} partial Bouma sequences Facies D Base-missing partial Bouma sequences Subfacies D₁: T_{bcd}, T_{cde}, and T_{de} partial Bouma sequences; the sandstone-to-shale ratio > 1 Subfacies D₂: T_{bcd}, T_{cde}, and T_{de} partial Bouma sequences; the sandstone-to-shale ratio < 1 Facies E Similar to D, but higher sand/shale ratios and thinner more irregular beds
Bouma sequence not applicable	Facies F Chaotic deposits formed by gravity sliding and slumping Facies G Hemipelagic mudstone and shale

Note: Data are after Mutti and Ricci Lucchi (1972, 1975); Walker and Mutti (1973).
Table modified from Lash (1986).

DISTRIBUTION OF FACIES					
FACIES	ENVIRONMENT				DEPOSITIONAL PROCESSES
	SLOPE	FAN			
		UPPER	MIDDLE	LOWER	
A					DEBRIS FLOWS, LIQUIFIED FLOWS
B					DEBRIS FLOWS, LIQUIFIED FLOWS, TURBIDITY CURRENTS (HIGH ENERGY)
C					TURBIDITY CURRENTS
D					TURBIDITY CURRENTS (LOW ENERGY)
E					LIQUIFIED FLOWS, TURBIDITY CURRENTS,TRACTION CURRENTS (?)
F					SLUMPS, DEBRIS FLOWS
G					PELAGIC & HEMIPELAGIC SEDIMENTATION

Figure 4-3. Distribution of turbidite facies in submarine fan environments. From Shanmugam and Muiola 1985. Original facies nomenclature from Mutti and Ricci Lucchi (1972).

debris flows, and slumps in thinning- and fining-upward sequences (Walker, 1978; Normark, 1978).

The middle fan occurs at the end of the active channel of the upper fan where a convex-upward depositional bulge forms. Normark (1970, 1978) termed this bulge a suprafan that can be divided into upper and lower parts. The upper suprafan typically contains numerous, leveed or unleveed distributary channels (Normark, 1978). These distributary channels are commonly braided, and may coalesce to form extensive coarse-grained deposits (Walker, 1978). The upper, suprafan channels on modern fans are typically sinuous, several hundred meters wide, from one to tens of meters deep, and a few kilometers long (Howell and Normark, 1982). On the other hand, the lower suprafan consists of dominantly unchannelled sand, is smooth, and commonly, but not necessarily, is seen as a coarsening- and thickening-upward sequence (Normark, 1978).

Channels of the upper suprafan in outcrop are commonly manifested as thin, lenticular beds of massive and pebbly sandstone arranged into thinning- and fining-upward channel-fill sequences (Walker, 1978). Classic, fine-grained turbidites, as well as conglomeratic lag deposits, may also be deposited in suprafan channels (Walker, 1978). However, Walker (1978) stated that "the braided suprafan is dominated by massive and pebbly sandstone." The lower part of the suprafan is characterized by more laterally continuous deposits of coarse, classic turbidites (Walker, 1978; Normark, 1978). Thinly bedded, fine-grained turbidites, without any preferred sequential order are interpreted as interchannel deposits on the suprafan.

The middle fan aggrades by lateral switching and stacking of suprafan lobes (Walker, 1978). While one lobe is the site of deposition, an adjacent lobe may be cutoff from its sediment supply and would be covered in a blanket of interchannel shale and siltstone (Figure 4-4) (Walker, 1978; Hiscott, 1980, 1982). Walker (1978) noted that reoccupation of a lobe over a previously abandoned lobe's position would lead to overlying thickening- and thinning-upward sequences, with interchannel blankets separating them.

For many modern and ancient submarine fans, the lower fan and basin plain are indistinguishable. Both the lower fan and basin plain are topographically smooth, low-relief areas consisting of laterally continuous, tabular beds of classic turbidites, which periodically interrupted slow hemipelagic deposition (Walker, 1978). These interbedded shale and sandstone deposits form thick, monotonous sequences typical of many "flysch" sequences of the past. Stow (1985), recognized two types of basin plains: (1) undersupplied basin plains, characteristically found in large, unrestricted basins with low relief and a stable tectonic setting, and (2) oversupplied basins which develop in small, generally restricted, tectonically active settings. Undersupplied basin plains are characterized by fine-grained sediment, while basin fill sequences in oversupplied basins may be characterized by a chaotic distribution of coarse- and fine-grained sediment (Stow, 1985). Stow cited as one of his examples the Oligo-Miocene foredeep basin plains of Italy.

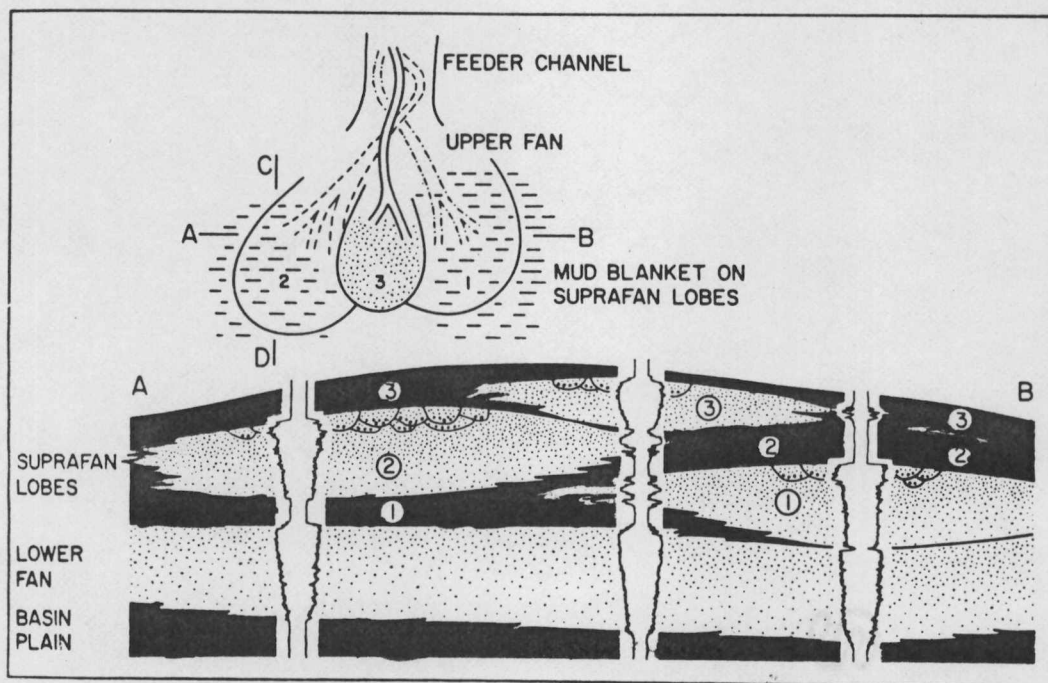


Figure 4-4. Theoretical cross-section through a prograding mid-fan system showing a vertical sequence due to lateral switching of mid-fan lobes. Abandoned lobes are covered by mud blankets. Hypothetical electric logs illustrate coarsening-upward sequences due to prograding lobes. From Walker (1978).

Environmental Interpretation of the Lenoir, Blockhouse,
and Sevier Formations

Lenoir Formation

The Lenoir Formation in the study area is 17 meters thick and consists of thick-to-thin-bedded, dark gray, fine-grained skeletal wackestone, packstone, and bioturbated mudstone. Skeletal debris includes echinoderms, trilobites, brachiopods, ostracods, and abundant Nuia. Read (1977, 1980) has interpreted the Lenoir depositional setting in southwest Virginia as a shallow subtidal ramp facies which is in agreement with the interpretations by Walker (1977, 1980) and Shanmugan (1978) for the Lenoir Formation in east Tennessee. This writer agrees with their interpretations, which can be applied to the Lenoir in this study.

Blockhouse Formation

The Blockhouse Formation is approximately 67 meters thick in the study area. Dark gray to black, thinly laminated, clayey shale containing graptolites is characteristic of the Blockhouse Formation. The Blockhouse has been interpreted as representing deposition under reducing conditions in a deep-water environment, due to the lack of shallow-water fauna, lack of coarse-grained lithologies, and its graptolite assemblage characteristic of an open-marine environment (Shanmugan, 1978; Shanmugan and Walker, 1978, 1983). This interpretation can also be applied to the Blockhouse of this study. Furthermore, the Blockhouse may represent deposition in an undersupplied basin plain.

Sevier Formation

The Sevier Formation has a maximum exposed thickness of approximately 1,000 meters in the study area. Interbedded medium to olive-gray shale and siltstone with minor thin-bedded, fine-grained sandstone comprise this sequence. These rocks represent fine-grained distal turbidites, which filled the basin from the southeast (Shanmugan, 1978, 1980). Shanmugan, working in East Tennessee, attributed his first-order cycles (rhythms) to deposition of thickening-upward turbiditic sequences on the lower fan, which resulted from the westward progradation of a deep-sea fan system. This interpretation is also valid for the fine-grained turbidites of the Sevier Formation in this study. The Sevier Formation can be described as being deposited on an oversupplied basin plain.

Environmental Interpretation of the Tellico Formation

A composite stratigraphic section for the Tellico Formation in the study area was compiled, based on detailed mapping and by measuring two stratigraphic sections within 100 meters laterally of each other. Based on this work, the Tellico Formation is divided into five packages (Figure 4-5). Each package can be characterized by one of three different lithofacies associations: (1) lithofacies I consisting of interbedded hemipelagic shale, classic turbidites, massive sandstone, and chaotic units (debris flows and glide slides); (2) lithofacies II composed of minor amounts of hemipelagic shale and classical turbidites in a sequence dominated by massive sandstone, pebbly sandstone, conglomerate, and chaotic units; and (3) lithofacies association III, a thick

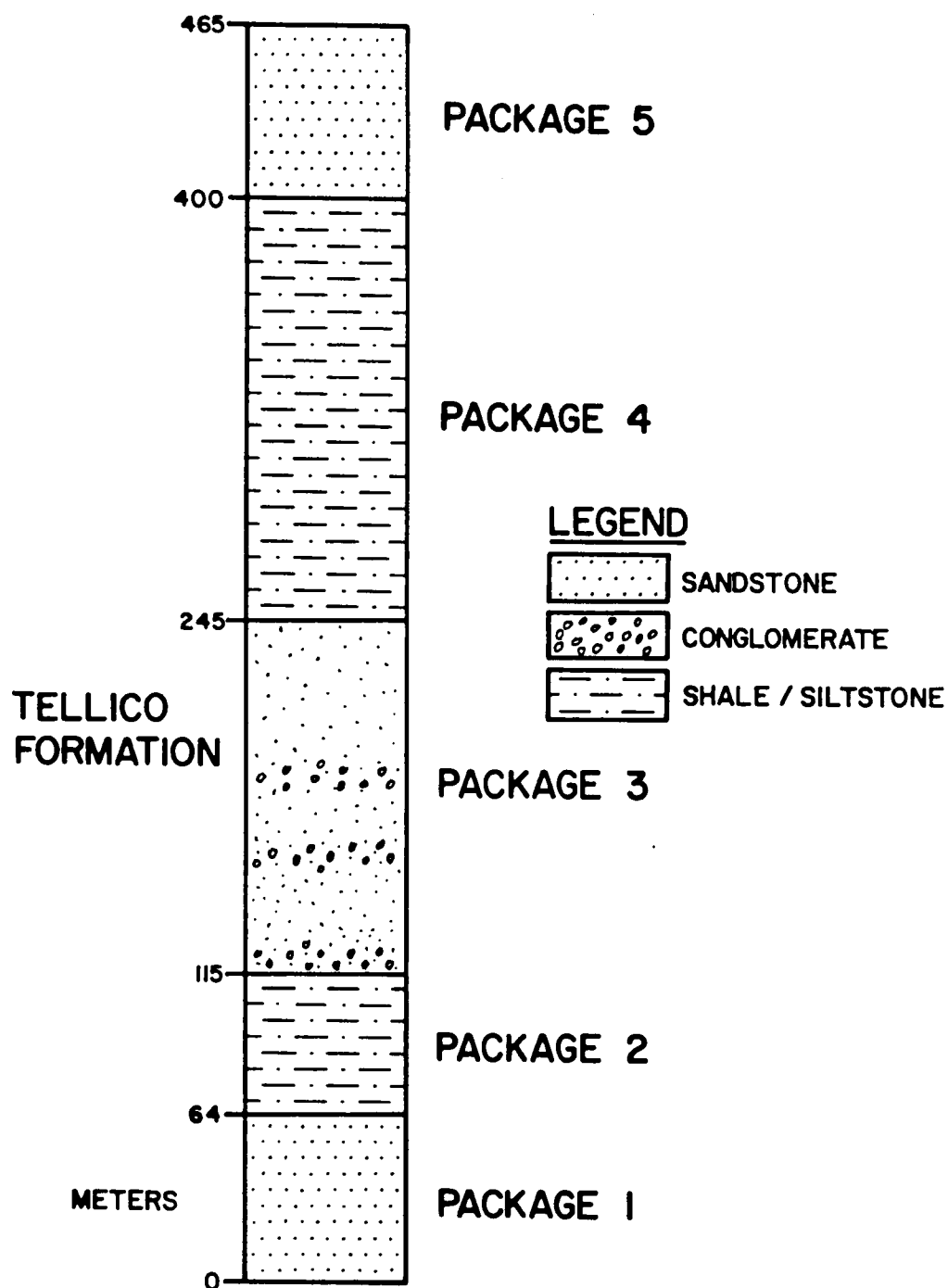


Figure 4-5. Stratigraphy of the Tellico Formation at Avens Bridge, Virginia, illustrating the coarse-grained packages separated by thick shale/siltstone packages. Packages 1 and 5 comprised of lithofacies association I, packages 2 and 4 consist of lithofacies association III, and package 3 is comprised of lithofacies association II.

sequences of hemipelagic shale, thin-bedded classic turbidites, and possible contourites.

Lithofacies association I is represented by the lowermost (package 1) and uppermost packages (package 5). Lithofacies association II (package 3) is inserted between lithofacies association III (packages 2 and 4). The environments of these lithofacies associations will be discussed environmentally using the composited stratigraphic section with examples taken from both measured sections.

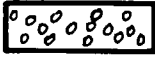
Lithofacies Association I

The lowermost package of lithofacies association I is exposed at outcrops F1', C1, C2, and C3. Outcrop F1' is the most complete section of this package and is therefore used to illustrate it (Figure 4-6). The upper package of association I is exposed at outcrops F7, E2, E3, and G2 with G2 containing the most complete exposure (Figure 4-7).

Lithofacies association I is characterized by the predominance of thick-bedded, tabular to lenticular, massive sandstone beds which are commonly amalgamated along scoured bases. Sandstone/shale ratios range from 8.4:1 at outcrop F7, 6.4:1 at F1', 5.3:1 at C2, to 4:1 at G2, which are comparable to the characteristics of mid-fan facies of Walker and Mutti (1973), Nelson and Nilsen (1974), and the work of several authors on ancient fan systems (Hiscott, 1980; Pickering, 1982; Chan and Dott, 1983; Link et al., 1984; and Lash, 1986). Interbedded hemipelagic shale, classical turbidites, and occasional chaotic units compose approximately 20% of lithofacies association I.

Figure 4-6. Measured section of outcrop F1', lithofacies association I.

LEGEND

	Shale
	Sandstone
	Conglomerate
	Debris Flow
	Slump
	Slide
	Thinning Upward Cycle
	Thickening Upward Cycle

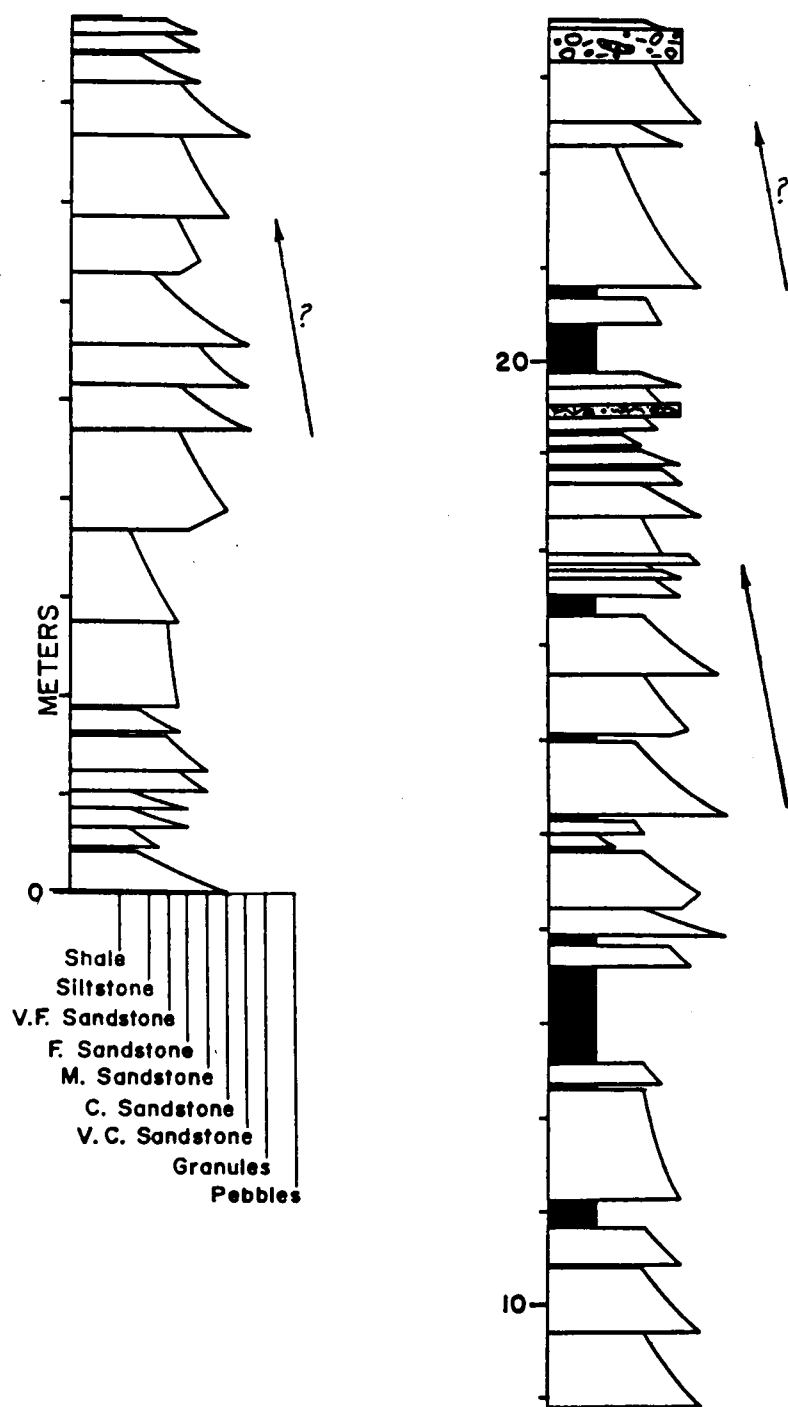


Figure 4-6.

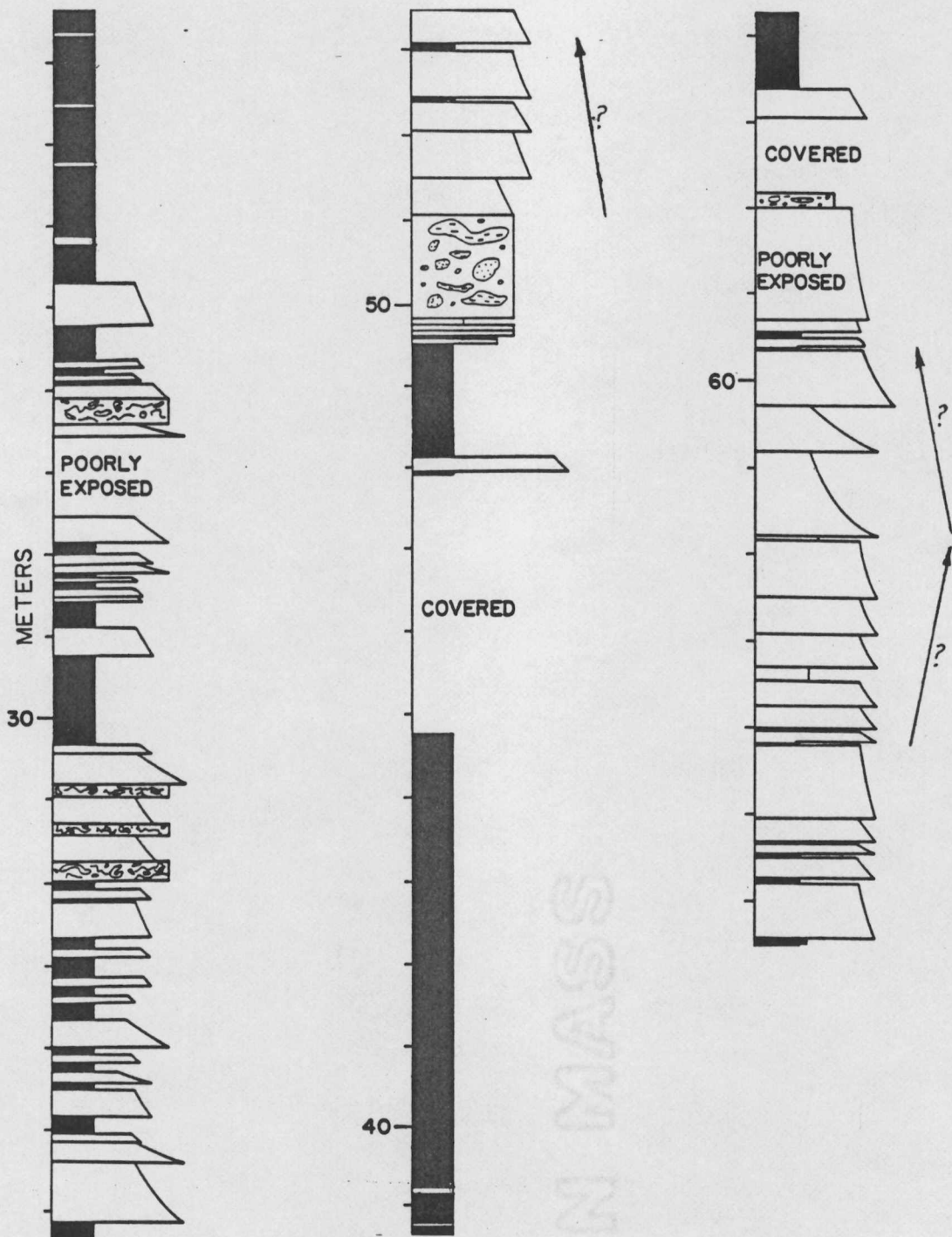
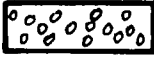
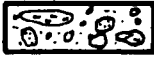


Figure 4-6 (continued).

Figure 4-7. Measured section of outcrop G2, lithofacies association I.

LEGEND

	Shale
	Sandstone
	Conglomerate
	Debris Flow
	Slump
	Slide
	Thinning Upward Cycle
	Thickening Upward Cycle

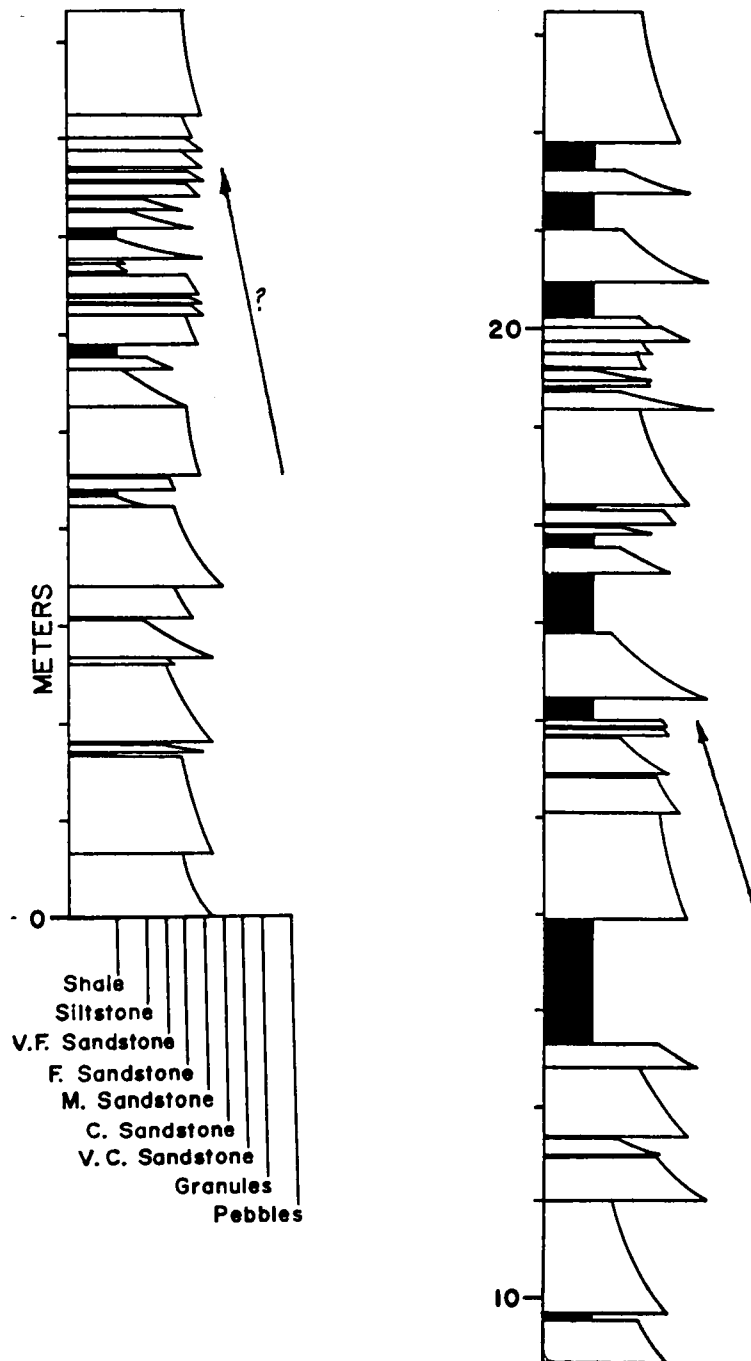


Figure 4-7.

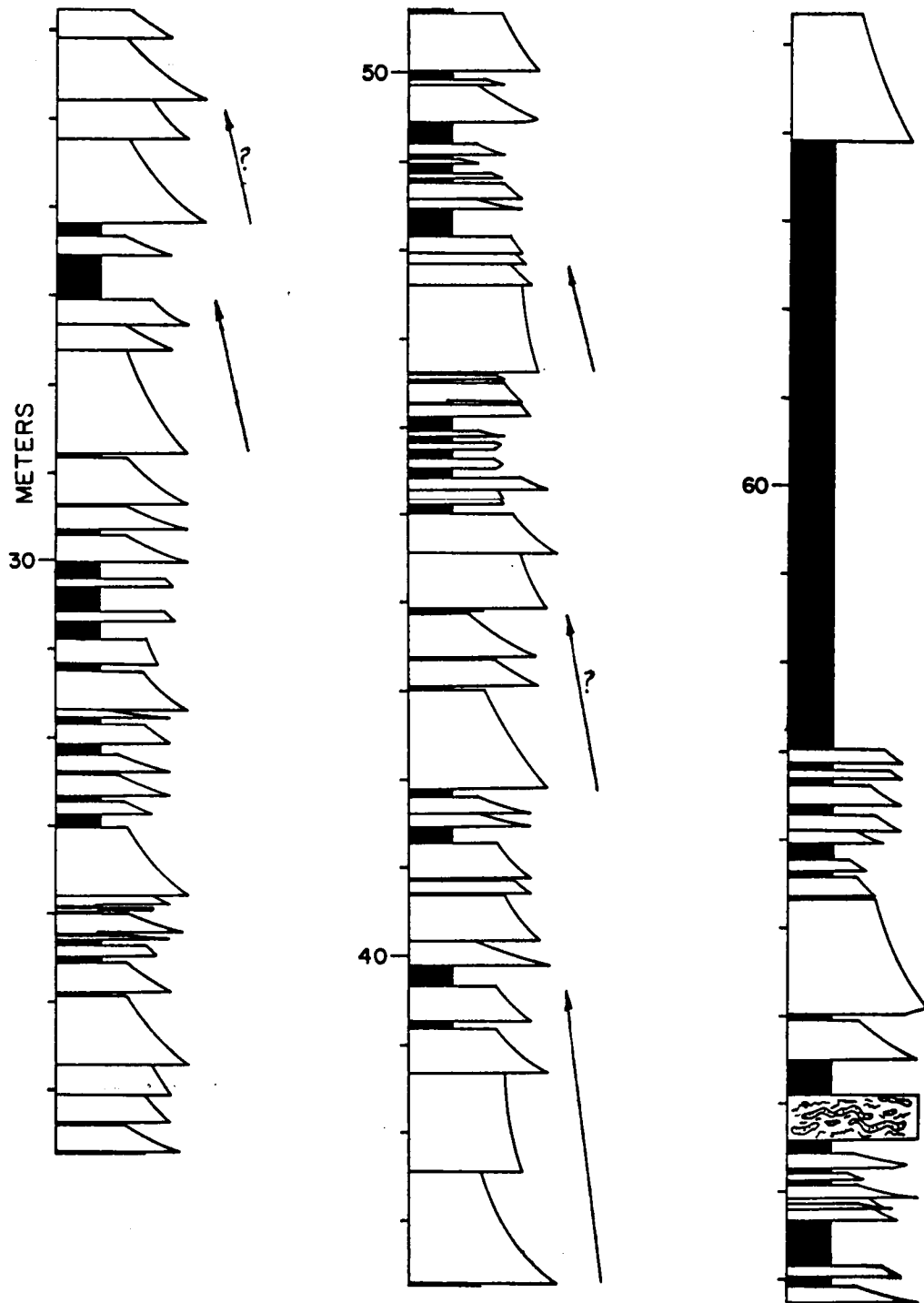


Figure 4-7 (continued).

A test (using Markov analysis) for departure from random behavior in vertical facies transitions provided no evidence of any ordered facies transitions, as might be expected in a depositional environment of braided distributary channels on the mid fan. Results of this analysis are provided in Appendix C.

Massive sandstone deposits that are channel-shaped (up to 107 centimeters thick) are located at outcrops F1', F7, E2 and G2. Scouring of previous deposits occurs at the base of these channel-shaped beds. Other thicker, mid-fan channels may be indicated by channel-fill sequences. These channel-fill sequences may consist of several or only a few beds. Work by several authors (Ricci Lucchi, 1975; Walker, 1978, 1984; Hiscott, 1980, 1981; Chan and Dott, 1983; Pickering, 1982; and Lash, 1983) has shown that these channel-fill sequences may or may not be represented by thinning-upward cycles.

Figures 4-8 and 4-9 illustrate the lack of well-defined cycles for association I. However, several possible thinning-upward sequences can be seen. These possible cycles seem more realistic when they are bounded by thick shale deposits which could possibly represent slow hemipelagic sedimentation over a small channel-fill sequence, with the overlying thick, massive sandstone representing renewed channel activity. Defining thinning- and thickening-upward sequences is often subjective. The problem exists of how many beds need be present before a trend can be defined. Random variations in bed thickness may produce asymmetric cycles or they may be due to external controlling factors (i.e., sediment supply, tectonics, sea-level fluctuations) that could

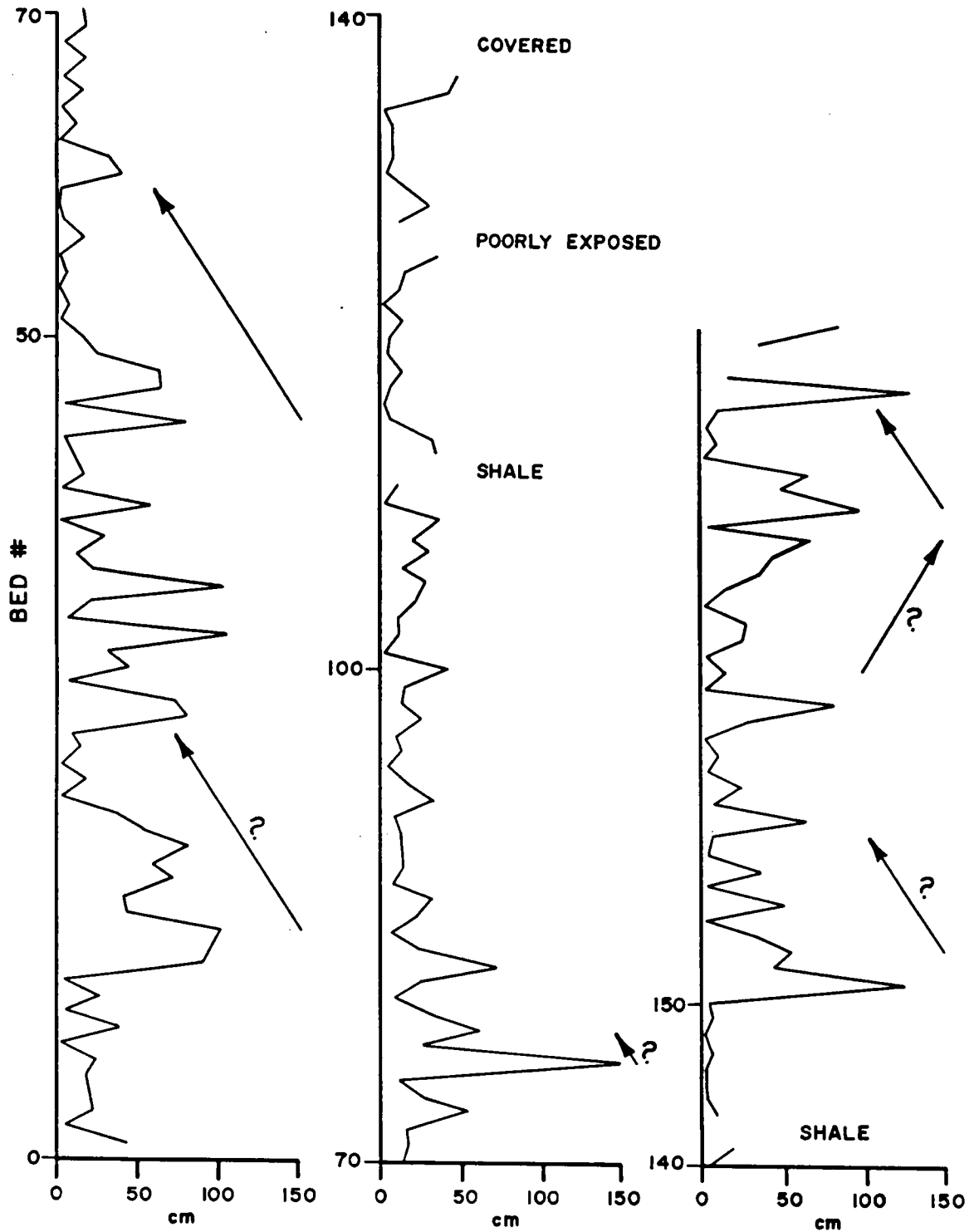


Figure 4-8. Bed # versus bed thickness plot for outcrop F1'. Arrows pointing to the upper left define thinning-upward trends. Arrows pointing to the upper right define thickening-upward trend.

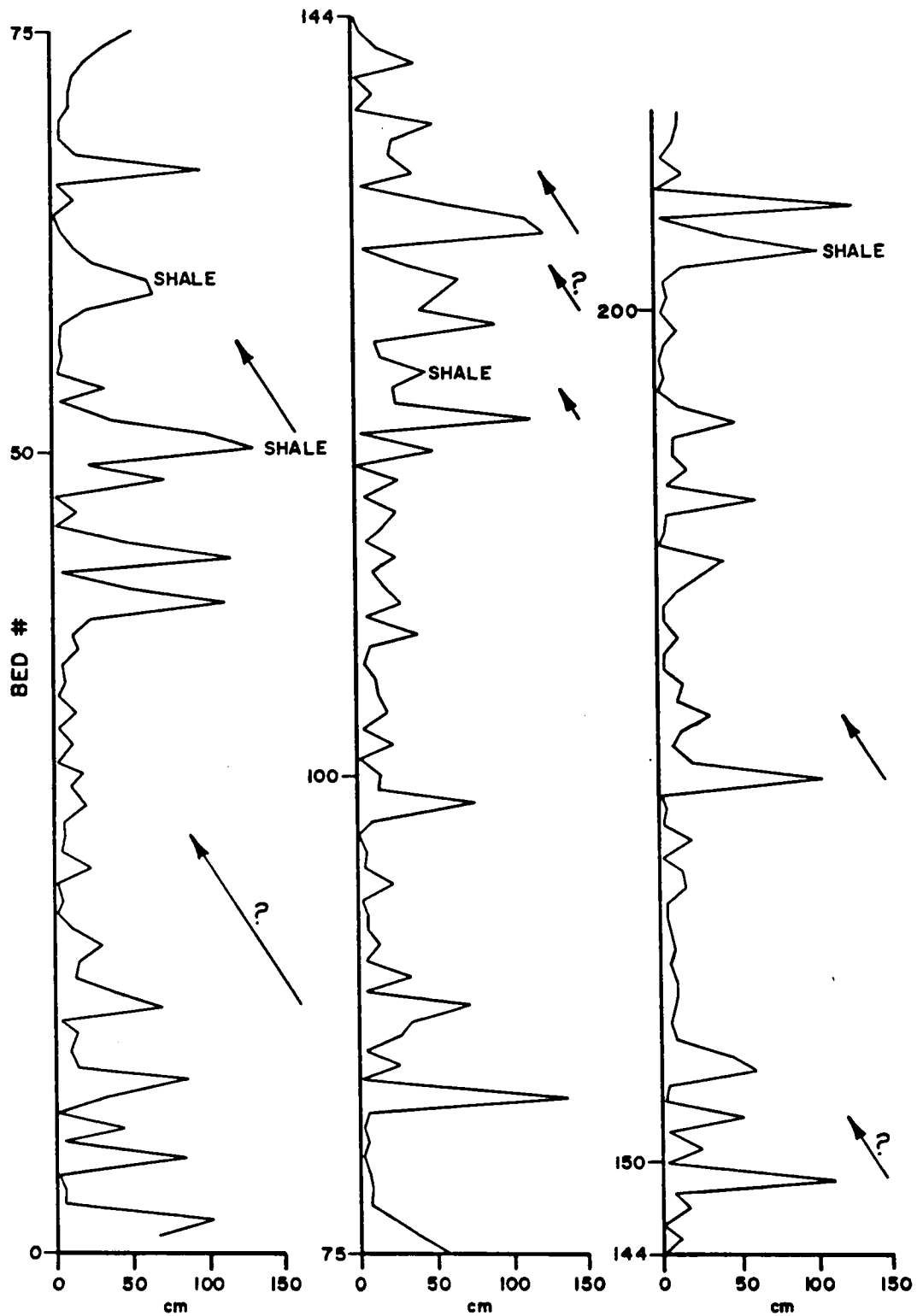


Figure 4-9. Bed # versus bed thickness plot for outcrop G2. Arrows pointing to the upper left define thinning-upward trends.

mask the local environmental controls (Hiscott, 1981; Pickering, 1982). Amalgamation and channeling of beds would also obscure thickness relationships.

Although no well-defined thinning-upward sequences have been established for association I, there does seem to be a trend in outcrop F1'. At the base of outcrop F1' there are several thick- to very thick-bedded, massive sandstone deposits, which are followed by an interbedded sequence of massive sandstone and shale, with the sandstone/shale ratio decreasing upsection until a thick (9.5 meters) shale interval is reached. This sequence may be comparable to channel-fill sequences observed by Hiscott (1980) in the Middle Ordovician Tourelle Formation (Figure 4-10). The thick shale interval would represent interchannel deposits consisting of classic turbidites and hemipelagic shale. The overlying sequence of massive sandstone could represent the introduction of another channelized lobe.

Within the massive sandstone bodies of association I, occur classic turbidites, which are interpreted to represent small levees or overbank deposits. Recently, small levees have been observed in the mid-fan areas of two modern fans, the Navy fan (Normark et al., 1983) and on the Mississippi fan (Bouma and Coleman, 1985). Thin layers of chaotic units also occur in association I. Their presence would seem to indicate an environment with a gradient higher than that of the smooth, outer suprafan.

Lithofacies association I is best explained by deposition on the mid-fan, which may have been occupied by shallow channels (Howell and

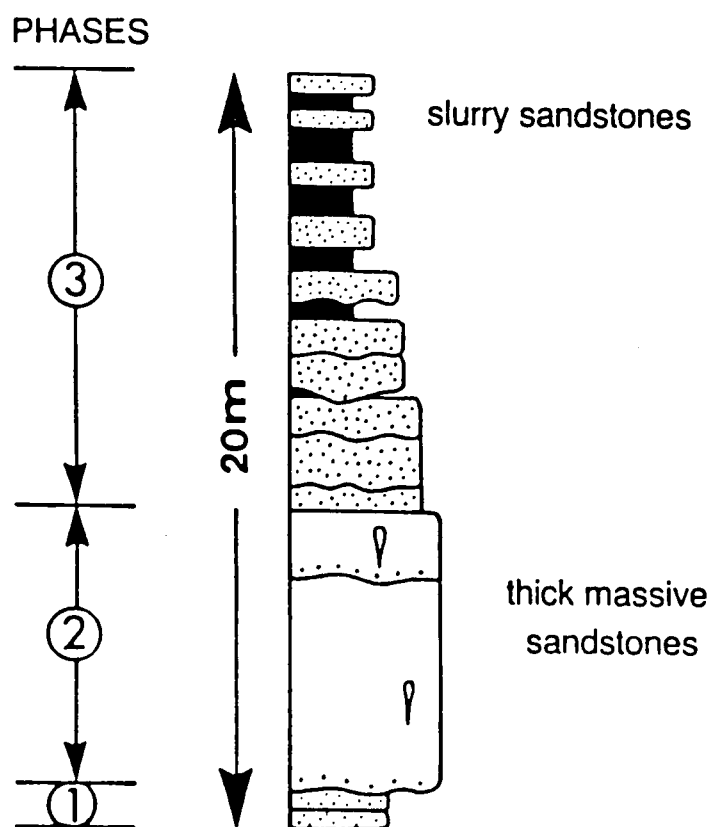


Figure 4-10. Representative thinning-upward sequences in the Lower Ordovician Tourelle Formation. Phase 1, open flow in the channel represented by thin-bedded sandstone; phase 2, plugging by large flow as seen by thick massive sandstones; phase 3, progressive abandonment represented by sandstone beds thinning-upward. From Hiscott (1980).

Normark, 1982; Link et al., 1984; Pickering, 1982, 1985; Chan and Dott, 1983; Lash, 1986). Shallow channels would have permitted overbank and interchannel deposits to intertongue with coarser-grained deposits. Failure along channel flanks would have resulted in chaotic units typically composed of contorted overbank deposits (Nilsen, 1977; Howell and Normark, 1982).

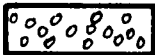
Lithofacies Association II

Lithofacies association II is exposed at outcrops F5, D1, and D2. The Dry Run fault cuts out the upper part of the sequence at F5 and the lower part of the sequence at D1. A composite section was assembled for this interval by correlating outcrops F5 and D1 based on an approximately 5 meter-thick debris-flow and beds of conglomerate common to both outcrops (Figure 4-11).

Lithofacies association II includes thick massive sandstone, pebbly sandstone, conglomerate, and chaotic units, along with minor amounts of shale that increase up-section. Sandstone/shale ratios range from 99:1 at outcrop D1, 55:1 at F5, 11:1 for the lower half of D2, to 3.4:1 for the upper half of D2. These ratios compare favorably to ratios given by several authors for inner-fan channel deposits (Walker and Mutti, 1973; Nelson and Nilsen, 1974; Eriksson, 1982; Chan and Dott, 1983). The range from high ratios at the base of the channel (i.e., D1, F5) to lower ratios in the middle (D2) and top (D1) of the sequence is characteristic of channel-fill sequences in the inner fan, which result from sudden channel abandonment or termination of coarse-grained sediment to the fan (Nilsen, 1977). Inner-fan channels are commonly the site of the

Figure 4-11. Measured composite section of outcrops F-5, D-1, and D-2; lithofacies association II.

LEGEND

	Shale
	Sandstone
	Conglomerate
	Debris Flow
	Slump
	Slide
	Thinning Upward Cycle
	Thickening Upward Cycle

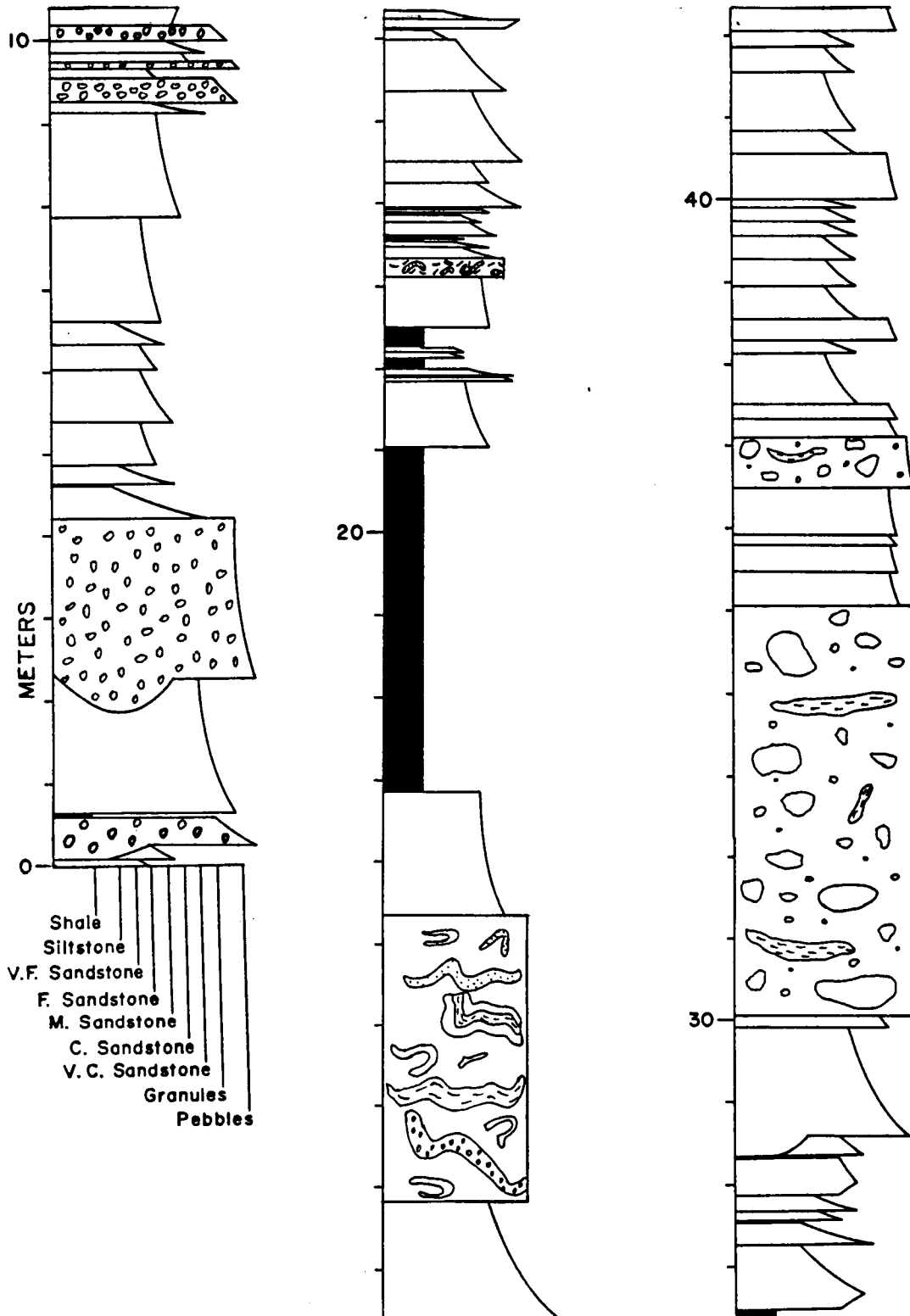


Figure 4-11.

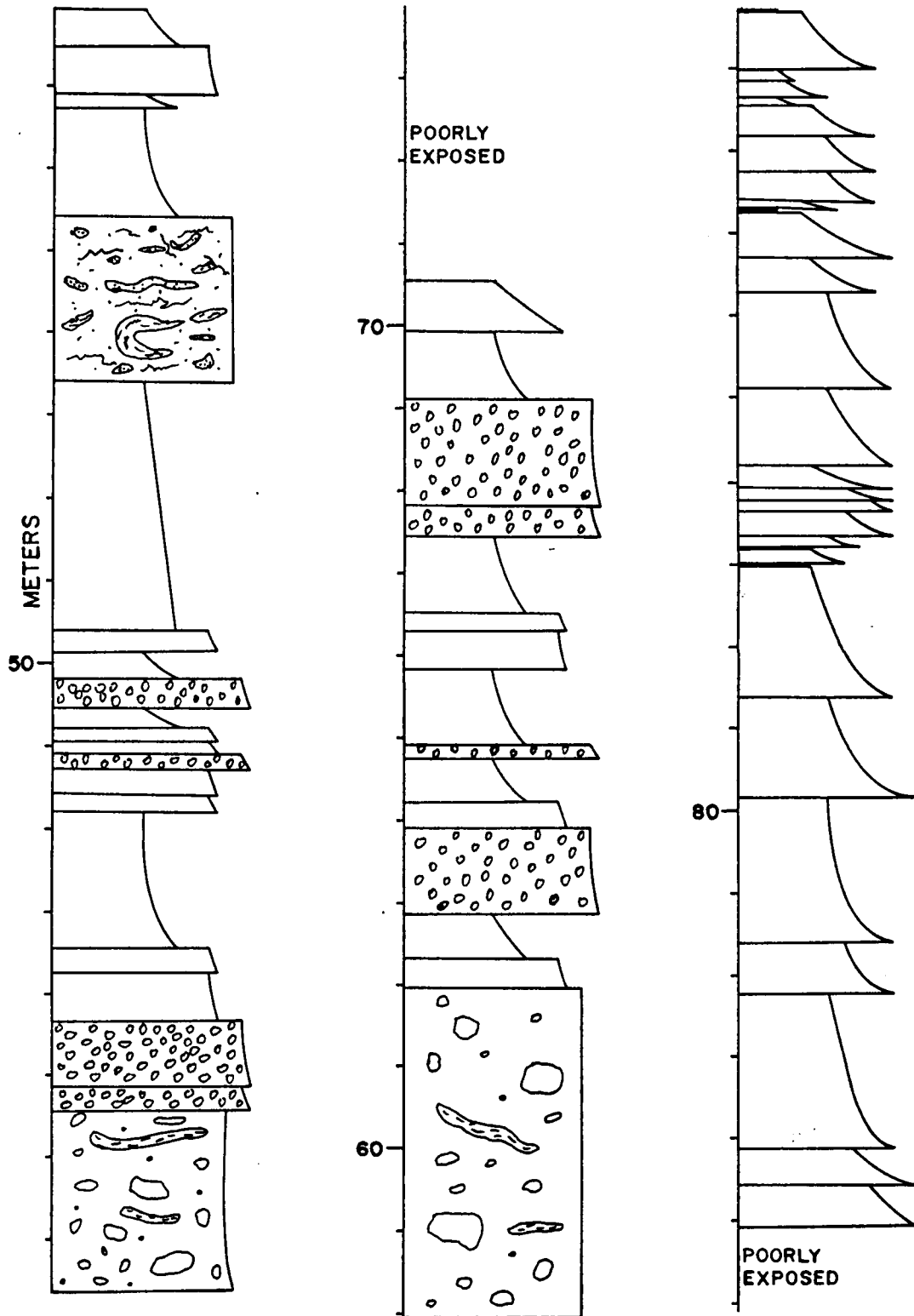


Figure 4-11 (continued).

Figure 4-11 (continued).

coarsest-grained deposits in a fan system. Within the inner-fan channel there may be several smaller channels present. These concepts can be applied to association II in which very marked lenticular bedding and channel-shaped, pebbly sandstone and conglomerate deposits are indicative of channel activity. Several beds were observed to pinch out laterally within a few meters of their maximum thickness, and many beds have scoured tops and bases, which would also indicate channel activity.

In an earlier study, Bowlin (1979) examined part of lithofacies association II at outcrop D1 (roadcut), where the base of the coarse clastic sequence has been removed by the Dry Run fault and the top of the sequence is not exposed along the road. He concluded from his observations that the interval along the roadcut (D1) exhibited "no well-developed sequential patterning" of bed thickness, clast size, nor lithotype succession. Although this is true of outcrop D1, it is not true of the entire reconstructed sequence of association II. The missing lower interval of outcrop D1 can be seen at outcrop F5 across a small inlet from outcrop D1. The missing upper interval is represented by outcrop D2 along South Holston lake immediately below the roadcut where outcrop D1 is exposed. After reconstruction of the section (Figure 4-11), it is the interpretation of this writer that a general trend of fining- and thinning-upward does exist. The fining- and thinning-upward sequence is better developed in the uppermost part of the section where beds of massive sandstone are separated by thick shale intervals, until the occurrence of sandstone completely ceases. The fining-upward trend is also indicated by the marked decrease in the frequency of coarse-grained lithofacies of this association after the first 50 meters

of this sequence. These trends were not detected by Bowlin in his study of only part of the sequence at outcrop D1. His interpretation that association II of this study represents a channel fill on the mid to upper part of the suprafan was in part based on the lack of "development of the sequential features associated with gradual abandonment." Gradual abandonment is indicated at the top of outcrop D2, thus association II is interpreted in this study as representing a channel-fill sequence located on the inner fan Shanmugan (personal communication, 1985) or perhaps as a proximal mid-fan channel.

However, the interpretation of inner-fan channel-fill is favored, if the thickness of the channel-fill along with comparison of the channel-fill sequence to Walker's (1978) model for the stratigraphic sequence produced during fan progradation is considered (Figure 4-12). The channel-fill of association II is approximately 130 meters thick. Such a thick channel-fill would be more characteristic of the inner fan than the mid fan. The lithofacies association of this channel-fill is also more characteristic of the inner fan of Walker's model for progradation where conglomerate, debris flows, and slumps are found together. Outcrop F5 and D1 are the best examples of this association in this study.

Lithofacies Association III

Lithofacies association III is exposed at outcrops F2, F4, F6, E1, and G1. Association III occurs in thick sequences (up to 155 meters)

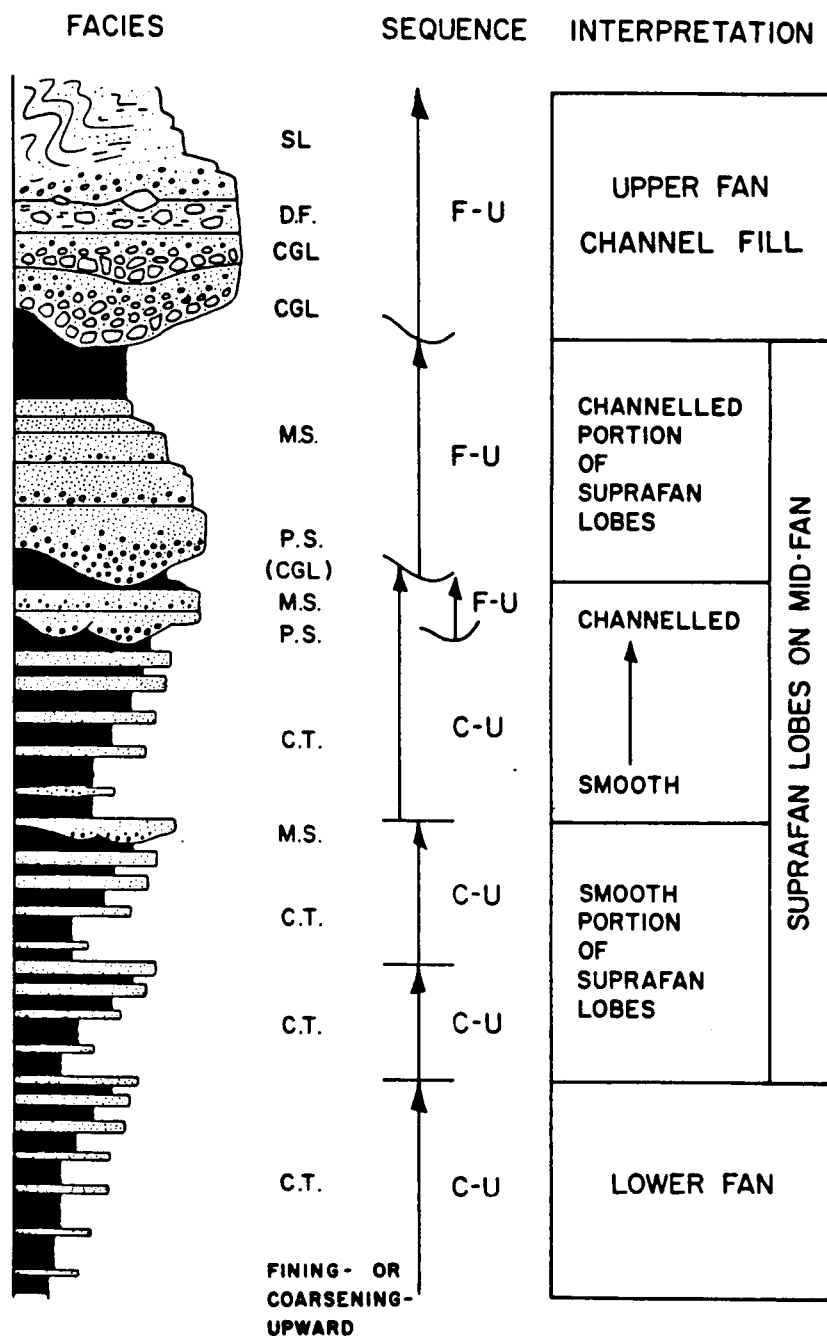


Figure 4-12. Idealized stratigraphic sequence during submarine fan progradation. C-U represents coarsening- and thickening-upward sequence; F-U represents fining- and thinning-upward sequence; C.T., classic turbidites; M.S., massive sandstone; P.S., pebbly sandstone; CGL, conglomerate; D.F., debris flows; SL, slumps. From Walker (1978).

which separate associations I and II. Association III is composed of hemipelagic shale, classic turbidites, and in the uppermost shale sequence, (package 4) possible contourites (Shanmugan, personal communication, 1985). Association III is interpreted in this study to represent deposits on the outer fan fringe, on levees, or as thick interchannel deposits over abandoned mid-fan complexes of association I and the abandoned inner-fan channel of association II (Walker, 1978; Hiscott, 1980; Lash, 1986).

Work on modern fan systems indicate that thick deposits of mud and silt can accumulate in each of these areas. The best explanation for the thick shale/siltstone (association III) sequences of this study is that of interchannel deposits, which filled in depressions between migrating mid-fan complexes as well as covering them after abandonment. The same interpretation would hold true for the abandoned inner-fan channel of association II.

Depositional Model

The observed lithofacies associations of this study are thought to represent subenvironments on a submarine fan. This submarine fan prograded into an elongated basin that was being filled from the southeast. The shape of the fan represented by the deposits in this study is highly speculative. Although the writer has been able to trace some conglomeratic sequences for over a kilometer, this hardly begins to define the shape of a fan that can be 10's of kilometers in radius. Sparse paleo-current data from this study (Figure 4-13) indicate a general west to

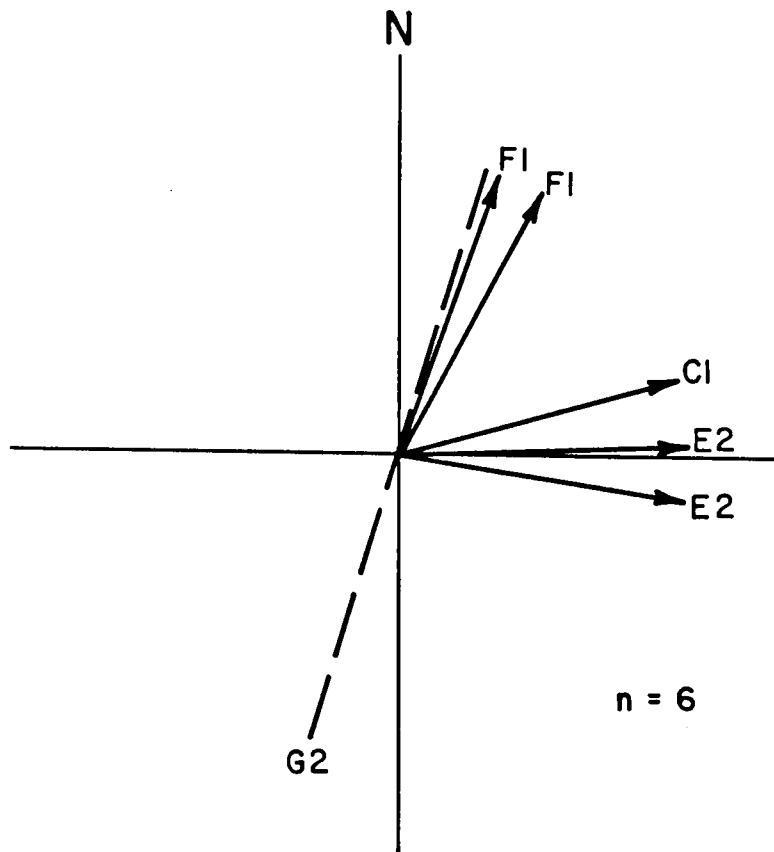


Figure 4-13. Paleocurrent diagram for flute casts (solid arrows) from five massive sandstones and one shale bed containing current aligned graptolites (dashed line) with outcrop locations indicated.

east trend, along with a southwest to northeast trend. Although the data set is small, the general trends indicated by the paleocurrents compare favorably with the regional model developed by Walker and his co-workers in east Tennessee (Walker, 1977, 1980; Walker et al., 1980; Walker et al., 1983; Shanmugan, 1978; Shanmugan and Walker, 1978, 1980, 1983; Benedict and Walker, 1978), as seen in paleobathymetric and sediment dispersal maps of Walker et al. (1983). In their Figure 7, Walker et al. (1983) illustrate a general west to east trend for the Sevier basin in the general area of this study, which would explain the west to east and southwest to northeast paleocurrent trends observed in this study, as well as the southeast to northwest trend seen by Bowlin (1979) at South Holston Dam. The deposits at South Holston Dam, which are located approximately 15 km to the southwest of this study area, are situated where the basin had a southwest to northeast trend. The southeast to northwest paleocurrent trend observed by Bowlin (1979) could represent progradation of the submarine fan into the basin from the southeast. The submarine-fan deposits at Avens Bridge would reflect a general west to east trend in the basin as the fan prograded into the basin from the south. An elongated fan parallel to the basin axis could have produced such a pattern (Chan and Dott, 1983; Lash, 1986). Alternatively, laterally migrating suprafan lobes of a radial fan could have produced such a paleocurrent pattern. In his discussion of narrow, trough basins, similar to the Sevier basin, Walker (1978, 1984) suggested that submarine fans of the radial type may enter these basins from several point sources and form at the base of the marginal slope.

Walker (1978, 1984) also noted that these fans are typically destroyed by subsequent tectonic activity. Within these troughs, any consistent proximal to distal changes are masked by sediment input up and down the trough (Walker, 1978, 1984). Walker concluded his discussion by stating, "at the present, there is no facies model that acts as a good predictor in this type of basin." Stow et al. (1985) have suggested that these complex systems may be better termed "basin-fill systems."

It is, however, the belief of this writer that the Tellico Formation in the study area represents deposition on one of the marginal fans that was entering the basin from the south. The vertical sequence of lithofacies in the Tellico Formation can be compared to that of the Lower Ordovician Tourelle Formation. Hiscott (1980) interpreted the Tourelle Formation as having been deposited on a series of laterally migrating submarine fans that entered a foreland basin from the southeast during the early stages of the Taconic orogeny. The Tourelle is characterized by a segregation of massive sandstone into thick amalgamated packets that are separated by thick shale sequences (Hiscott, 1980). This is also the case for the Tellico Formation of this study (Figure 4-14). These sandstone packets represent deposition on the mid fan of a prograding lobe complex (Hiscott, 1980). During lobe abandonment, these packets would be covered by a mud blanket (Hiscott, 1980). Re-occupation, at a later time, would result in another sand packet being deposited (Hiscott, 1980). This sequence of events can also be used to explain the separation of coarse packages in the Tellico Formation by thick shale/siltstone sequences.

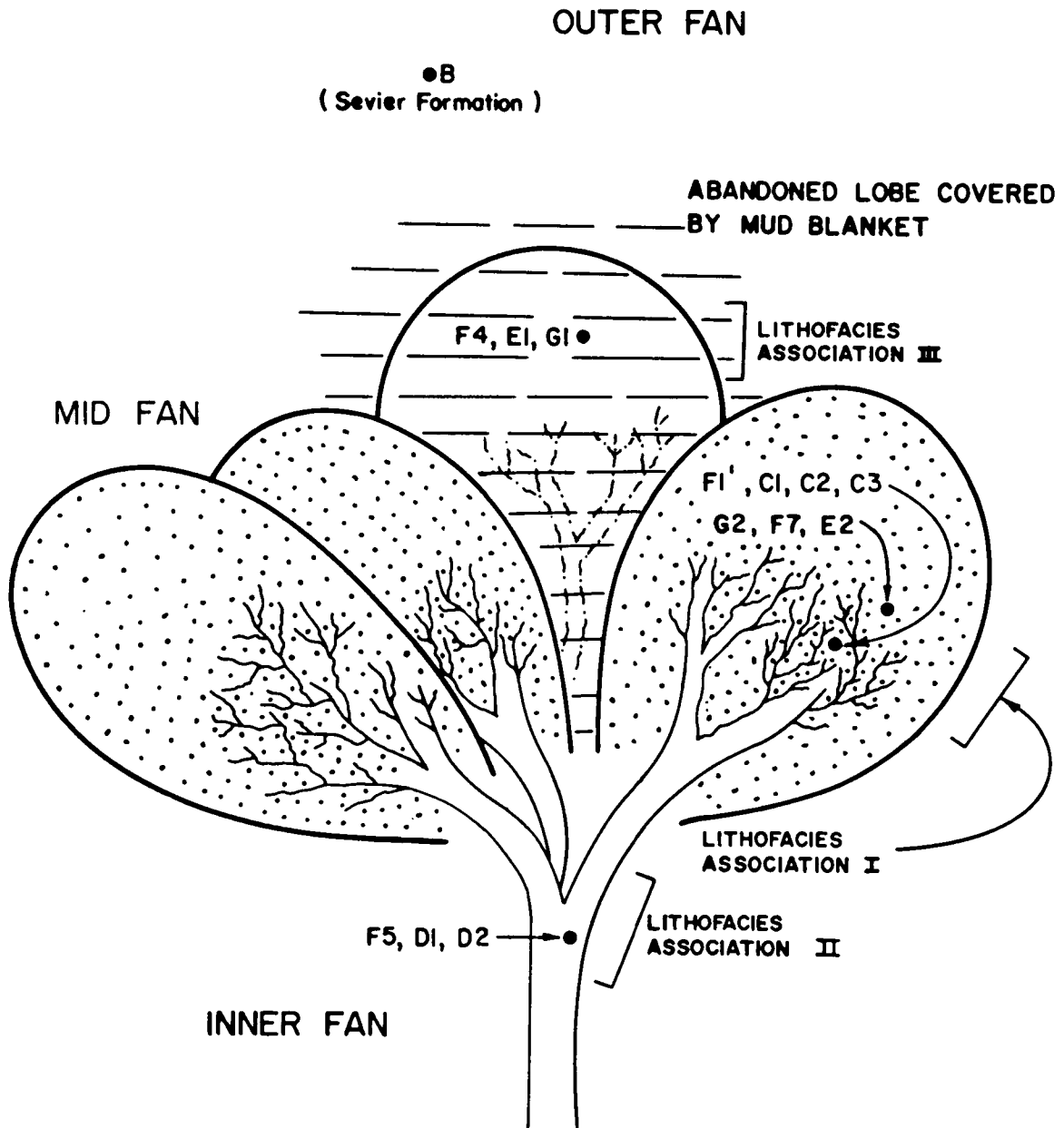


Figure 4-14. Depositional model for the Middle Ordovician clastic sequence at Avens Bridge, Virginia. Outcrops are shown in their proposed depositional sites. Model is based on depositional model for the Tourelle Formation (Hiscott, 1980) modified for the Tellico Formation.

CHAPTER V

PETROLOGY

Introduction

The main focus of this study involved measuring and describing, in detail, the coarse-grained terrigenous clastics of the Tellico Formation and the interpretation of the depositional mechanisms involved. Forty-three 5 x 8 cm thin sections were studied and described with sedimentary structures being the main object of this portion of the research. Twenty-seven thin-sections of massive sandstone and three of pebbly sandstone were studied. Thirteen thin-sections representative of the coarse-grained lithologies (10 massive sandstone beds and three pebbly sandstone beds) were selected and point counted (Appendix D). Approximately 600 points were counted per slide with at least 400-500 counts of framework grains per slide for massive sandstone lithologies. The number of point counts per slide in this study is comparable to the number of points counted in studies of similar type deposits (200 framework grains by Hiscott, 1978 and 400 framework grains by Lash, 1986). Due to the large grain size (pebbles) of the pebbly sandstone deposits, a smaller number of framework grains (200 per slide) were counted for these three samples.

Clast compositions vary with grain size (Dott, 1964; Dickinson, 1970; Ingersoll et al., 1984; Suttner and Basu, 1985; Decker and Helmond, 1985). Kellberg and Grant (1956) and Leible (1975) have

reported the variation in composition between rocks of different grain sizes in the study area. As grain size increases from sand to cobbles and larger, the proportion of rock fragments (dominantly limestone fragments) increases (Table 5-1). In contrast, sandstone layers have a higher percentage of quartz than the conglomerate beds, but still have a large number of rock fragments.

One of the aspects of this study was to determine whether major compositional variations existed in the coarse clastic sequence. The coarsest lithology common to all three coarse packages of the Tellico Formation is massive sandstone. Two thin-sections from the lower coarse package (outcrop C3), four thin-sections from the middle package (outcrop D1), and four thin sections from the upper package (outcrop G2) were selected as representative samples and point-counted. Samples selected for this analysis were medium- to coarse-grained sandstones. The upper limit for matrix that was used was 0.03 mm, as suggested by Dott (1964) and Dickinson (1970) for the study of graywackes. Average compositions from each package are compared in Table 5-2. No major compositional variations were indicated by this analysis or by the study of the other massive sandstone thin sections. Due to the lack of significant compositional variations and the intense leaching of the lake outcrops, which only permitted the sampling of a small number of fresh samples, no additional samples were thin-sectioned. It is believed by the writer that the point-counted sandstone samples are representative of the composition of the Tellico sandstone sequence.

Table 5-1. Variation in clast composition with different grain size intervals in the Tellico Formation.

Component	Average of 10 medium to coarse-grained sandstones (0.3-1.0 mm)	Average of 3 pebbly sandstones (1.0-10.0 mm)	Average of 15 conglomerates with clast size greater than 2.5 cm*
Quartz	42.4	14.5	2.6
Feldspar	4.1	0.2	-
Shale rock fragments	9.8	7.6	-
Sandstone and siltstone rock fragments	2.3	12.7	14.5
Limestone rock fragments	5.4	30.5	80.9
Metamorphic rock fragments	0.6	0.5	-
Volcanic rock fragments	0.5	1.4	-
Unidentified rock fragments (pseudomatrix)	11.9	15.9	-
Chert	1.7	3.6	1.9
Matrix	13.6	9.2	-
Calcite cement	6.2	3.5	-
Others	1.5	1.5	0.1

*Data for conglomerates from Kellberg and Grant (1956) based on 1924 pebbles counted.

Table 5-2. Comparison of composition averages for the three coarse packages of the Tellico Formation represented by outcrops C3 (lower package), D1 (middle package), and G2 (upper package).

Component	C3	D1	G2
Quartz (mono- and polycrystalline)	38.6	44.8	41.9
Feldspar (orthoclase, microcline, plagioclase)	3.5	4.8	3.8
Shale rock fragments	11.6	9.4	9.4
Limestone rock fragments	5.3	5.1	5.8
Sandstone and siltstone rock fragments	2.0	2.6	2.1
Chert	1.4	1.7	1.9
Metamorphic rock fragments	0.4	0.8	0.5
Volcanic rock fragments	0.3	0.5	0.7
Unidentified rock fragments (pseudomatrix)	17.3	9.5	11.6
Matrix	13.8	11.3	15.8
Calcite cement	4.1	8.5	4.9
Chlorite cement	0.4	0.1	0.4
Muscovite	0.1	0.3	0.2
Biotite	0.3	0.3	0.3
Heavy minerals (zircon and rutile)	0.3	0.4	0.3
Opakes	0.6	0.4	0.3

Petrology of the Tellico Formation

Sandstone samples of the Tellico Formation contain poorly sorted, angular to some subrounded framework grains with a large matrix component (up to 18%). In addition to primary matrix, a significant proportion of the samples contain squashed rock fragments (pseudomatrix of Dickinson, 1970) and diagenetically altered rock fragments and other framework grains (epimatrix of Dickinson, 1970). Framework grains are mainly quartz and rock fragments with shale fragments, limestone fragments, and sandstone/siltstone fragments composing the majority of the rock fragments (Figure 5-1). The sandstone samples were classified as lithic graywacke (Pettijohn, 1975) and litharenite (sedarenite) (Folk, 1974). Components of the sandstone samples are described more fully below.

Quartz

Quartz grains in this study were divided into four categories proposed by Basu et al. (1975): (1) monocrystalline quartz with slight undulose extinction, less than 5°; (2) monocrystalline quartz with strong undulose extinction, greater than 5°; (3) polycrystalline quartz with less than 3 crystals per grain; and (4) polycrystalline quartz with more than 3 crystals per grain.

Monocrystalline quartz is by far the most abundant quartz type in this study, ranging from 34% to 47% of the total rock composition as compared to 1% to 8% for polycrystalline quartz. Monocrystalline quartz with undulose extinction greater than 5° is the dominant quartz type

Figure 5-1. Photomicrographs of massive sandstone in the Tellico Formation.

- A. Sample S-4. Poorly sorted massive sandstone. Framework grains consist of quartz, shale rock fragments, carbonate rock fragments, sandstone/siltstone rock fragments, plagioclase, and chert in a matrix of squashed rock fragments (pseudomatrix) and diagenetically altered rock fragments (epimatrix). Crossed polars. Field of view in the long dimension is 1.5 mm.
- B. Sample S-10. Poorly sorted massive sandstone. Framework grains consist of quartz, shale rock fragments, carbonate rock fragments, plagioclase, volcanic rock fragments in a matrix of squashed rock fragments (pseudomatrix) and diagenetically altered rock fragments (epimatrix). Patchy calcite cement is also present. Crossed polars. Field of view in the long dimension is 1.5 mm.

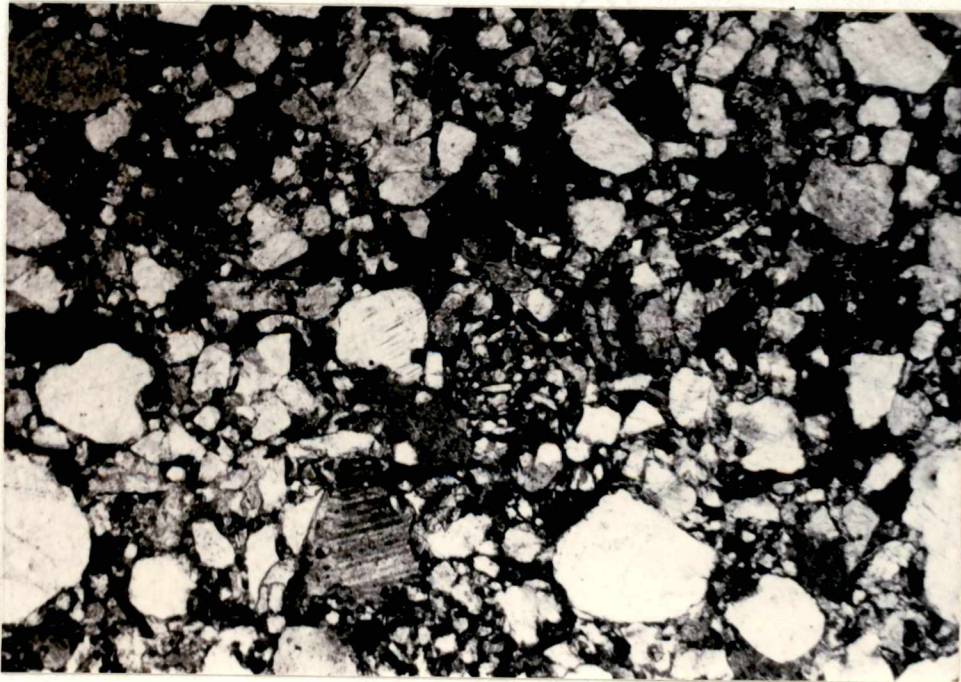
**A****B**

Figure 5-1.

(27% to 41% of the total rock composition). These grains are angular, contain vacuoles, and were in some cases observed to have reworked quartz overgrowths. Leible (1975) reported that monocrystalline quartz in this area was most likely derived from reworked sandstone strata of the Lower Cambrian Chilhowee Group, namely the Unicoi and Erwin Formations. This interpretation is accepted in this study.

The majority of polycrystalline quartz in this study contains more than 3 crystals per grain and using the classification of Basu et al. (1975), is classified as low-rank metamorphic quartz. These grains are subangular to rounded and, commonly are coarser than the surrounding framework grains. These grains, as well as polycrystalline quartz with less than 3 crystals per grain, may have also been derived from reworked sandstone strata of the Lower Cambrian Chilhowee Group (Leible, 1975).

Feldspar

Feldspar grains make up approximately 4% of the total sandstone composition in this study. They include orthoclase (0.8%), microcline (0.3%), plagioclase (2.9%), and one sample with a trace of perthite grains. Orthoclase and microcline may be more abundant than was observed in the point counting, because both have been heavily altered to sericite and calcite with microcline being the more intensely altered of the two. Orthoclase and microcline are most likely to have been derived from reworked sandstone sequences of the Chilhowee Group as well as the plagioclase (Leible, 1975). Plagioclase grains are angular to subangular and have also been altered to calcite, but not to the same

degree as the potassium feldspars. Some plagioclase grains appear to be fresher than others and as Leible (1975) noted may reflect a source other than reworked Chilhowee sandstones, possibly the Mt. Rogers Formation or Precambrian basement. Plagioclase compositions as reported by Leible (1975) range up to An_{32} .

Rock Fragments

Other than quartz, rock fragments are the most abundant of the framework grains in the Tellico Formation. They comprise approximately 32% of massive sandstone samples and up to 52% of pebbly sandstone samples (Table 5-1). The majority of rock fragments are sedimentary fragments that include shale, limestone, siltstone, and sandstone fragments. Minor amounts of volcanic (0.5%) and metamorphic (0.6%) rock fragments are also present. As mentioned earlier, limestone rock fragments are more abundant in pebbly sandstone and conglomerate samples than in massive sandstone samples. This relationship also applies to siltstone and sandstone rock fragments and can be explained by the fact that these clasts have been disaggregated, mainly into single quartz grains, in the massive sandstone samples. Therefore, they are not recognized as lithic fragments from which they were derived.

Shale or argillaceous rock fragments are more abundant than limestone fragments in the sandstone samples of this study (9.8% vs. 5.4%). In contrast, limestone fragments are more dominant than shale fragments in the coarse lithologies of the Tellico Formation (Table 5-1). Shale as well as siltstone lithic fragments, typically appear as abraded,

elongated clasts that tend to parallel bedding. Most of the shale and siltstone fragments were probably derived from within the basin (from the Sevier and Tellico Formations). This conclusion is supported by the comparison of thin sections from shale/siltstone sequences in the study area with shale and siltstone clasts of the coarse-grained lithologies. The remaining shale and siltstone fragments were most likely derived from the Rome or Nolichucky Formations (Kellberg and Grant, 1956).

Limestone fragments include micrite, pelmicrite, intramicrite, and minor amounts of skeletal debris which include algae and mollusc fragments. Three pebbly sandstone samples from the study area were stained for calcite to determine the carbonate composition of the limestone clasts. The clasts are composed of calcite and not dolomite. The absence of dolomite clasts may be due to the Knox Group (a possible source) being dominated by limestone in this region (Kellberg, personal communication, 1983). Limestone clasts in the study area are light gray and subround to round in shape. Micrite clasts are by far the dominant limestone clast in both sandstone and conglomerate lithologies in the study area. Micrite clasts containing skeletal fragments (including algae) were probably derived from the Lenoir Formation (Kellberg and Grant, 1956; Leible, 1975). Micrite clasts containing quartz grains were most likely derived from the Conococheague Limestone (Kellberg and Grant, 1956). The remainder of the carbonate rock fragments were probably eroded from the Knox Group, Lenoir Formation, Fetzer Formation, or Honaker Formation (Kellberg and Grant, 1956; Leible, 1975).

Sandstone rock fragments comprise 1.4% of the massive sandstone samples and 9.9% of the pebbly sandstone samples. One variety of sandstone fragment dominates this category (1.2% vs. 0.2% in massive sandstone and 7.9% vs. 2.0% in pebbly sandstone) and can be characterized as a well-indurated, dark green, quartz-rich sandstone (as seen on the outcrop). In thin section, these clasts consist of subangular quartz grains with greater than 5° undulose extinction along with some plagioclase, mica flakes, chlorite, and opaque grains. Kellberg and Grant (1956) suggested the Unicoi Formation as a possible source for clasts of this type (the interpretation also used in this study). Breakdown of these clasts could account for a large proportion of quartz grains with greater than 5° undulosity, plagioclase grains, and chlorite in the sandstone strata of the Tellico Formation. Other sandstone clasts in this study are brown and light gray in color, with the Erwin Formation as a possible source (Kellberg and Grant, 1956). Some of the sandstone fragments may also represent reworked intrabasinal sandstone (i.e., Tellico Formation).

Metamorphic and volcanic rock fragments comprise approximately 1% of sandstone layers in this study. Metamorphic fragments consisted of reworked slate and phyllite fragments. Volcanic rock fragments have been heavily altered and have a dull brown, hazy appearance in thin section with numerous inclusions and opaques. The actual percentage of volcanic rock fragments may be slightly higher than that given, because their heavily altered state made their recognition difficult.

Chert grains comprise 1.7% of massive sandstone compositions and 3.6% of pebbly sandstone compositions. Black chert grains in the study

area were considered by Kellberg and Grant (1956) as characteristic of the Lenoir, and red and green chert typical of the Shady Dolomite.

Pseudomatrix or unidentified rock fragments (URF) make up approximately 12% of massive sandstone compositions. This category is so large, due to the fabric of the rocks in which large framework grains bend and squash rock fragments. These squashed clasts break up into smaller grains which in turn may be so heavily altered that precise identification of the original rock fragment type is unattainable. These unidentified squashed rock fragments are typically clay to fine sand-sized grains. To have included them with the true matrix content of the rocks would have distorted that category.

The matrix content of sandstone beds averages 13.6% and ranges from 7.2% to 17.7%. As mentioned above, the upper limit of matrix used in this study was 0.03 mm. Matrix includes clay minerals, sericite, biotite, chlorite, and detrital grains less than 0.03 mm.

Cements in the sandstones include patchy calcite cement (6.2%) and chlorite cement (0.3%).

Interpretation of Petrology

Within the last few years, studies by Dickinson and his colleagues (Dickinson and Suczek, 1979; Dickinson et al., 1983) have attempted to relate terrigenous sandstone compositions from several different basin types to provenance regimes. These provenance regimes, along with their associated basins, can be characterized by their plate-tectonic setting and as a result, sandstone compositions (based on framework grains) can

be used to derive the tectonic setting of different basin types and their provenance regimes (Dickinson and Suczek, 1979; Dickinson et al., 1983).

Detrital framework modes of the sandstones of the Tellico Formation lie within the recycled orogenic field of Dickinson et al. (1983) (Figure 5-2) with the exception of one sample. This is due to the fact that samples S-2, S-8, and S-9 are pebbly sandstone, which differ in modal compositions from the massive sandstone due to grain-size differences. The pebbly sandstone samples discussed above are lithic-rich; especially abundant are carbonate fragments, which Dickinson and Suczek (1979) advised against using in ternary compositional plots due to the limitations of their data set. However, Mack (1984) demonstrated the value of including carbonate clasts in compositional plots, a fact that was acknowledged by Dickinson et al. (1983) while noting the limitations of such ternary diagrams.

The recycled orogenic field can be further subdivided into three fields namely: a transitional recycled provenance that falls in between a quartzose recycled provenance and a lithic recycled provenance. Figure 5-3 illustrates the distribution of the Tellico Formation on a $QmFL_+$ plot containing these three fields. The massive sandstone samples lie within the transitional and quartzose recycled fields, whereas the pebbly sandstone samples once again reflect their lithic-rich character by plotting in the lithic recycled field.

Dickinson et al. (1983) used sandstone compositional suites to determine provenance types as they related to paleotectonic maps

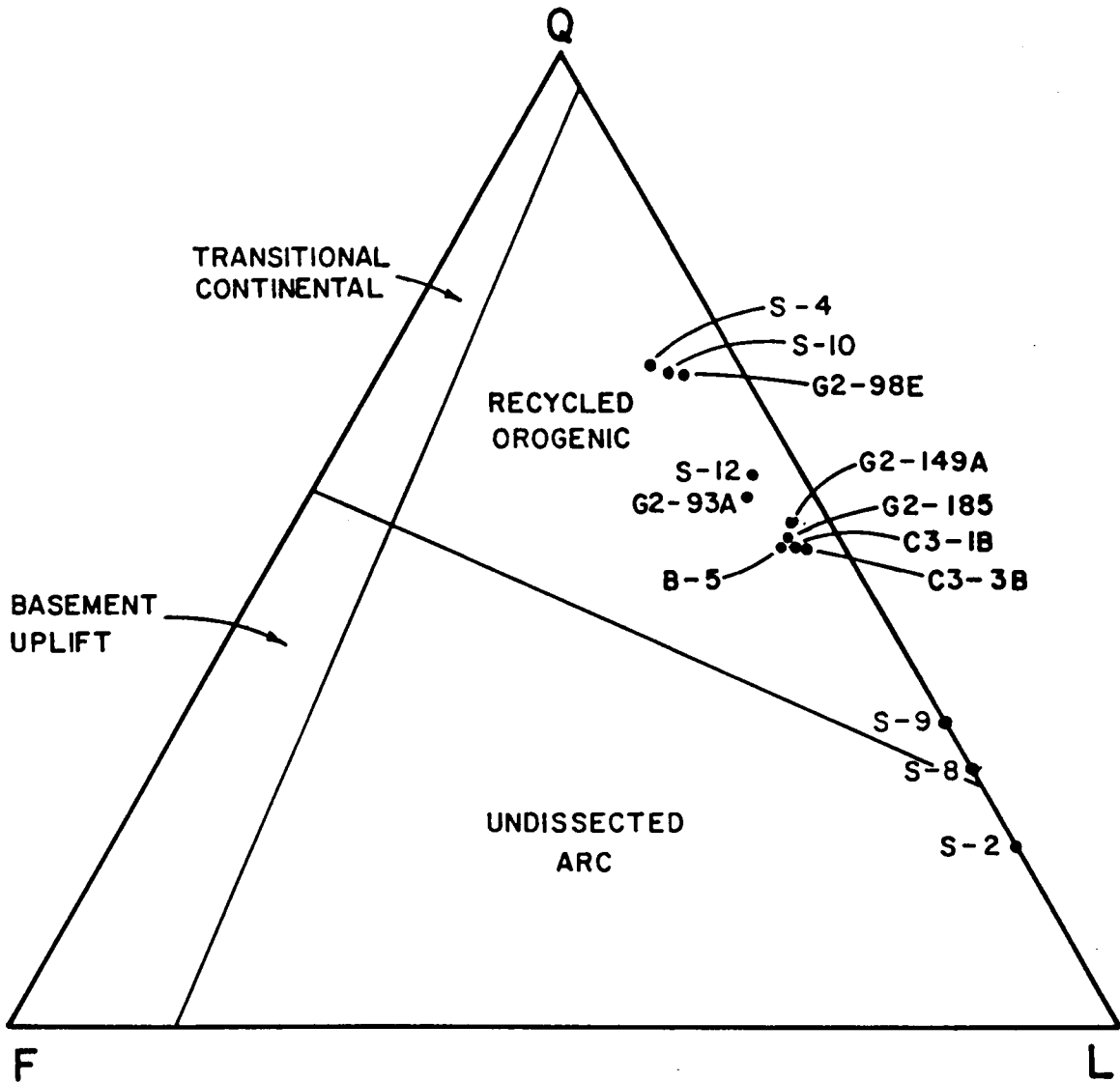


Figure 5-2. Tellico Formation sandstone data superimposed on a QFL triangular plot. Fields and QFL plot from Dickinson et al. (1983). Q, total quartzose grains, mono- and polyerstelline quartz plus chert. F, total feldspar. L, all unstable lithic fragments.

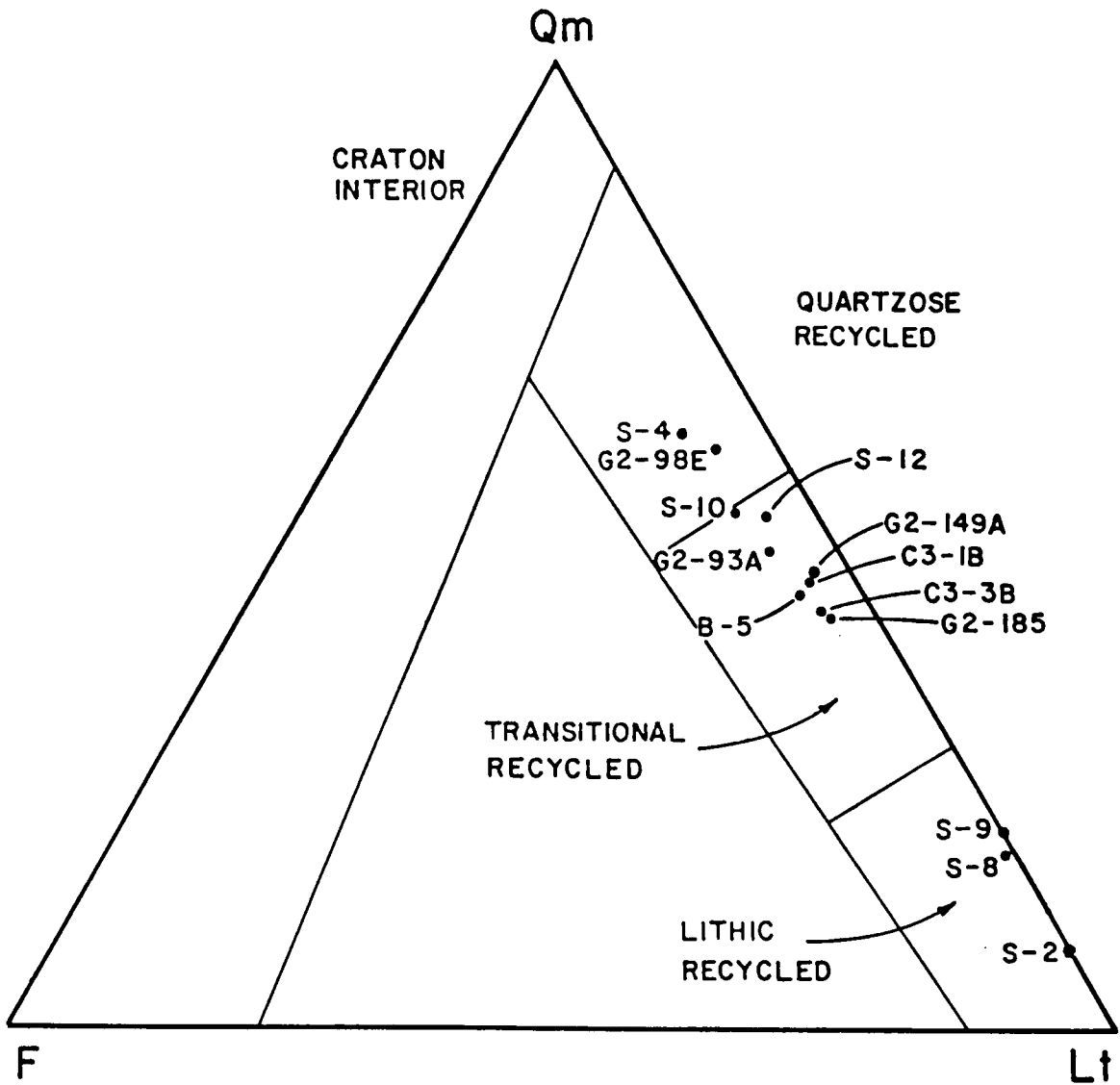


Figure 5-3. Tellico Formation sandstone data superimposed on a Qm FLt triangular plot. Fields and Qm FLt plot from Dickinson et al. (1983). Qm, monocrystalline quartz grains. F, total feldspar. Lt, total polycrystalline lithic fragments.

determined for major tectonic events in the Appalachians. Their interpretation for the Middle Ordovician to the Middle Devonian has the Appalachian continental margin undergoing deformation as a result of an arc/continent collision during the Taconic orogeny. Sandstone suites from the Taconic foreland basin (similar to the Tellico Formation) have been interpreted by Dickinson et al. (1983) as representing sediments derived from a recycled orogenic provenance. The source rocks for these sediments may have been uplifted miogeoclinal rocks (Dickinson et al., 1983). In this study, the miogeoclinal rocks are represented by rock fragments of the Chilhowee and Knox Groups from which much of the Tellico Formation was derived. The Tellico Formation is therefore interpreted as representing deposition in a foreland basin during the Taconic orogeny with sediments derived from a recycled orogenic provenance (i.e., Chilhowee and Knox Groups) southeast of the basin.

A comparison of the Tellico Formation with another sequence deposited in the Taconic foreland basin can be made. A comparison between the Tellico Formation and the Lower Ordovician Tourelle Formation (Hiscott, 1978, 1980) of Quebec (Table 5-3) shows several similarities along with some differences. In both the Tellico and the Tourelle Formations, quartz and feldspar grains are interpreted as being derived from reworked quartz-rich sandstones. These quartz-rich sandstones (Chilhowee Group in Tennessee) were originally derived from Grenville basement rocks. Both formations contain carbonate rock fragments which were derived from carbonate banks. However, some differences do occur in the compositions of the Tellico and Tourelle Formations. The

Table 5-3. Comparison of average compositions of medium to coarse sandstones of the Tellico Formation (10 samples) and the Tourelle Formation (19 samples).

Component	Tellico Formation	Tourelle Formation*
Quartz	42.4	45.6
Feldspar	4.1	8.2
Rock fragments	32.2	13.4
Matrix	13.6	16.6
Calcite cement	6.2	15.3
Others	1.5	0.9

*Data from Hiscott (1978).

Tourelle has a larger number (31% vs. 1.4%) of volcanic rock fragments (in granule size grains) than does the Tellico Formation. This may be due to the heavily altered nature of volcanic rock fragments in the Tellico which prevented the true original component of volcanic rock fragments from being determined. Evidence of volcanic activity in the Middle Ordovician of east Tennessee and southwest Virginia can be seen in tuff deposits in the Blockhouse Formation. A 2 meter thick tuff near the base of the Blockhouse has been described by Shanmugan (1978) at Douglas Lake in east Tennessee while a thin bed of tuff in the Blockhouse along U.S. Highway 58 was observed by Bartlett and Biggs (1980) in southwest Virginia. Chromite grains in the Tourelle have been interpreted by Hiscott (1978) as being derived from ophiolites. No evidence of ophiolites as a source rock was detected in this study in the Tellico Formation. In conclusion, similarities between the compositional suits of the Tellico and Tourelle Formations reflect their both being deposited in Taconic foreland basins, while differences in composition may indicate differences in the types of some source rocks (i.e., ophiolites) for the two formations.

CHAPTER VI

CONCLUSIONS

1. The Middle Ordovician stratigraphic succession was studied at Avens Bridge, Washington County, Virginia. This succession consists of (in ascending order): the Lenoir Formation (17 meters thick), the Blockhouse Formation (67 meters thick), the Sevier Formation (approximately 1,000 meters thick), and the Tellico Formation (465 meters thick, with the top of the formation not exposed).

2. These formations were deposited in an evolving foreland basin that underwent five stages of evolution (Shanmugan, 1978; Shanmugan and Walker, 1978, 1980, 1983): (1) a stable shelf edge, represented by the Lenoir; (2) a downwarping stage; (3) a starved-basin stage represented by slow pelagic fallout of Blockhouse sediments; (4) a turbidite-fill stage, represented by sedimentary rocks of the Sevier and Tellico Formations; and (5) a contour-current stage, that can be seen in shale and siltstone strata in the upper part of the exposed Tellico Formation in the study area.

3. The Tellico Formation was studied in detail to determine its sedimentological characteristics and environments of deposition. Lithofacies of the Tellico including: classic turbidites, massive sandstone, pebbly sandstone, clast-supported conglomerate, debris flows, chaotic units (glide slides and slumps), and contourites in the upper part were separated into three lithofacies associations.

4. Lithofacies association I includes interbedded hemipelagic shale, classic turbidites, massive sandstone, and chaotic units

(debris flows and glide slides) that represents deposition on the mid fan.

5. Lithofacies association II includes minor amounts of hemipelagic shale and classic turbidites in a sequence dominated by massive sandstone, pebbly sandstone, conglomerate, debris flows, and slumps interpreted to be deposits of an inner-fan channel.

6. Lithofacies association III consists of thick sequences of hemipelagic shale, thin-bedded classic turbidites, and possible contourites that are thought to represent interchannel deposits on a submarine fan.

7. Paleocurrent trends (west to east and southwest to northeast) support the regional model developed by Walker and his co-workers (Walker, 1977, 1980; Walker et al., 1980; Walker et al., 1983; Shanmugan, 1978; Shanmugan and Walker, 1978, 1980, 1983; Benedict and Walker, 1978) for the Sevier basin in the study area as is illustrated by paleobathymetric and sediment dispersal maps of Walker et al. (1983).

8. The submarine fan is interpreted to have entered the basin from the south, prograding by lateral migration of mid-fan complexes similar to those of the Lower Ordovician Tourelle Formation in Quebec. Lateral migration of mid fan complexes could explain the lack of well-developed coarsening- and thickening-upward sequences in the lower fan in the study area.

9. Sandstone compositions in the Tellico Formation consist of quartz, rock fragments, and feldspar in a matrix of clay minerals, sericite, and chlorite. Sandstone beds in the study area may be

classified as lithic graywacke (Pettijohn, 1975) and litharenite (sedarenite) (Folk, 1974).

10. Modal analysis of the three coarse packages at the base, middle, and top of the Tellico Formation in the study area revealed no major compositional changes through time.

11. The Tellico Formation lies within the recycled orogenic provenance field of Dickinson et al. (1983). Source rocks for the terrigenous clastics of the Tellico Formation include the Shady Dolomite, Chilhowee Group, Knox Group, Lenoir Formation, and Fetzer Formation.

12. Comparison of compositional suites of the Tellico Formation with the Tourelle Formation in Quebec reveal both similarities and variations in source rocks. Both the Tellico and Tourelle Formations had quartz-rich sandstones and carbonate banks as source rocks. The Tourelle contains up to 31% vs. 1.4% (for the Tellico) volcanic rock fragments. Chromite in the Tourelle Formation is thought to have been derived from ophiolites (Hiscott, 1978). No evidence for ophiolites was found in the sediments of the Tellico Formation. Variations in provenance of these Middle Ordovician foreland basins may reflect differences in the tectonic style along the Taconic orogenic belt.

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APPENDIXES

APPENDIX A

MEASURED SECTIONS

EXPLANATORY NOTE

The following tables contain measured sections from the coarse-grained deposits of the Tellico Formation which were measured and described on the centimeter scale. These deposits were described using the following classification.

- Sh - Interturbidite or hemipelagic shale
- CT - Thin-bedded classic turbidites (shale/siltstone)
- MS - Massive sandstone
- PS - Pebbly sandstone
- Cg - Clast-supported conglomerate
- DF - Debris flow
- SL - Slump
- GS - Glide (translational) slide

Maximum unit thicknesses were used to compile the measured sections, thus in some instances cumulative thicknesses may slightly exceed the true stratigraphic thickness.

Outcrops F1', F5, D1, D2, and G2 were used to compile the composite stratigraphic column of this study and are therefore given first. Outcrops C1, C2, C3, E2, E3, and F7 were also measured and described and are presented at the end of Appendix A. Outcrop C is located approximately 0.8 km southeast of Avens Bridge along Virginia State Route 670. Outcrop D is also along Virginia S.R. 670 approximately 0.9 km southeast of Avens Bridge. Measurements and descriptions of outcrop D1 are based in part on measured thicknesses of Bowlin (1979) that were field checked by the author and remeasured and

redescribed to fit this study's classification of lithofacies. Outcrop F is 1 km southeast of Avens Bridge along South Holston Lake. Outcrop E is approximately 1.1 km southeast of Avens Bridge along South Holston Lake. Outcrop G2 is approximately 1.2 km southeast of Avens Bridge and is exposed along a jeep trail. Outcrop locations are illustrated in Plate I.

Table A-1. Measured section, outcrop F1'.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	41	0.41	MS
2	5	0.46	Sh
3	20	0.66	MS
4	18	0.84	MS
5	16	1.00	MS
6	21	1.21	MS
7	1	1.22	Sh
8	37	1.59	MS
9	0.8-3	1.62	Sh
10	25	1.87	MS
11	2	1.89	Sh
12	88	2.77	MS
13	94	3.71	MS
14	102	4.73	MS
15	43	5.16	MS
16	41	5.57	MS
17	72	6.29	MS
18	58	6.87	MS
19	81	7.68	MS
20	52	8.20	MS
21	36	8.56	MS
22	3	8.59	Sh
23	18	8.77	MS
24	1	8.78	Sh
25	15	8.93	MS
26	8	9.01	Sh
27	79	9.80	MS
28	72	10.52	MS
29	3	10.55	Sh
30	43	10.98	MS
31	32	11.30	MS
32	107	12.37	MS
33	8	12.45	Sh
34	20	12.65	MS
35	101	13.66	CT
36	21	13.87	MS
37	12	13.99	Sh
38	28	14.27	MS
39	1	14.28	Sh
40	58	14.86	MS
41	4	14.90	Sh
42	14	15.04	CT
43	12	15.16	CT

Table A-1 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
44	5	15.21	CT
45	79	16.00	MS
46	6	16.06	Sh
47	63	16.69	MS
48	62	17.31	MS
49	24	17.55	CT
50	15	17.70	MS
51	0.3	17.703	Sh
52	8	17.773	MS
53	1	17.793	Sh
54	4	17.833	MS
55	2	17.853	Sh
56	13	17.983	MS
57	0.8	17.991	Sh
58	1.3	18.004	CT
59	0.6	18.01	Sh
60	41	18.42	MS
61	33	18.75	MS
62	0.6	18.756	Sh
63	12	18.886	MS
64	4	18.916	Sh
65	14	19.056	MS
66	5	19.106	Sh
67	15	19.256	MS
68	4	19.266	CT
69	16	19.456	MS
70	13	19.586	GS
71	18	19.766	MS
72	14	19.906	MS
73	53	20.436	CT
74	28	20.716	MS
75	11	20.826	Sh
76	148	22.306	MS
77	24	22.546	MS
78	62	23.166	MS
79	33	23.496	DF
80	9	23.586	MS
81	27	23.856	CT
82	73	24.586	MS
83	23	24.816	MS
84	8	24.896	CT
85	21	25.106	CT
86	32	25.426	MS

Table A-1 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
87	8	25.506	Sh
88	13	25.636	MS
89	12	25.756	Sh
90	12	25.876	MS
91	10	25.976	Sh
92	33	26.306	MS
93	19	26.496	Sh
94	6	26.556	MS
95	11	26.666	Sh
96	10	26.766	MS
97	25	27.016	Sh
98	11	27.126	MS
99	14	27.266	Sh
100	42	27.686	MS
101	3	27.716	Sh
102	11	27.826	MS
103	10	27.926	CT
104	23	28.156	GS
105	28	28.436	MS
106	14	28.576	GS
107	31	28.886	MS
108	18	29.066	GS
109	37	29.436	MS
110	0.5	29.441	Sh
111	10	29.541	MS
112	106	30.601	CT
113	35	20.951	MS
114	32	31.271	Sh
115	7	31.341	MS
116	1	31.351	Sh
117	7	31.421	MS
118	12	31.541	Sh
119	4	31.581	MS
120	7	31.651	Sh
121	12	31.771	MS
122	1.2	31.783	Sh
123	11	31.893	MS
124	14	32.033	Sh
125	34	32.373	MS
126	100	33.373	covered
127	12	33.493	MS
128	30	33.793	GS
129	18	33.973	MS

Table A-1 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
130	4	34.013	Sh
131	9	34.103	MS
132	7	34.173	Sh
133	8	34.253	MS
134	2	34.273	Sh
135	42	34.693	CT
136	49	35.183	MS
137	393	39.113	CT/Sh
138	550	44.613	CT/Sh
139	316	47.773	covered
140	3	47.803	Sh
141	18	47.983	MS
142	138	49.363	CT
143	8	49.443	MS
144	0.7	49.450	Sh
145	2	49.470	CT
146	0.6	49.476	Sh
147	6	49.536	CT
148	0.8	49.544	Sh
149	6	49.604	CT
150	4	49.644	CT
151	123	50.874	DF
152	41	51.284	MS
153	54	41.824	MS
154	31	52.134	MS
155	3	52.164	Sh
156	52	52.684	MS
157	7	52.754	CT
158	36	53.114	MS
159	3	53.144	Sh
160	6	53.204	CT
161	64	53.844	MS
162	8	53.924	Sh
163	22	54.144	MS
164	4	54.184	Sh
165	10	54.284	MS
166	2	54.304	Sh
167	28	54.584	MS
168	83	55.414	MS
169	1	55.424	Sh
170	14	55.564	MS
171	2	55.584	Sh
172	26	55.844	MS

Table A-1 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
173	28	56.124	MS
174	1	56.134	Sh
175	14	56.274	CT
176	37	56.644	MS
177	43	57.074	MS
178	66	57.734	MS
179	4	57.774	CT
180	99	58.764	MS
181	52	59.284	MS
182	66	59.944	MS
183	1	59.954	Sh
184	10	60.054	MS
185	3	60.084	Sh
186	10	60.184	MS
187	130	61.484	MS
188	17	61.654	DF
189	86	62.514	covered
190	34	62.854	MS
191	88	63.734	CT
covered interval			

Table A-2. Measured section, outcrop F5.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	5	0.05	MS
2	18	0.23	MS
3	36	0.59	Cg
4	4	0.63	Sh
5	163	2.26	PS
6	193	4.19	Cg
7	41	4.60	MS
8	1.5	4.615	Sh
9	25	4.865	MS
10	52	5.385	MS
11	64	6.025	MS
12	30	6.325	MS
13	27	6.595	MS
14	128	7.875	MS
15	126	9.135	MS
16	10	9.235	MS
17	31	9.545	Cg
18	11	9.655	MS
19	6	9.715	Cg
20	15	9.865	MS
21	12	9.985	MS
22	1	9.995	Sh
23	15	10.145	PS
24	24	10.385	MS
25	0.5	10.39	Sh
26	92	11.31	MS
27	50	11.81	MS
28	355	15.36	SL
29	95	16.31	MS
30	54	16.85	MS
31	420	21.05	CT/Sh
32	79	21.84	MS
33	5	21.89	MS
34	1	21.90	Sh
35	10	22.00	MS
36	12	22.12	Sh
37	6.5	22.185	MS
38	1.5	22.20	CT
39	6.5	22.265	Sh
40	23	22.495	CT
41	62	23.115	MS
42	23	23.345	GS

Table A-2 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
43	11	23.455	MS
44	5	23.505	MS
45	5	23.555	Sh
46	2	23.575	CT
47	2	23.595	Sh
48	16	23.755	MS
49	7	23.825	MS
50	3	23.855	Sh
51	6	23.915	MS
52	1	23.925	Sh
53	31	24.235	MS
54	26	24.495	MS
55	86	25.355	MS
56	63	25.985	MS
57	10	26.085	CT
58	1.5	26.10	Sh
59	12	26.22	MS
60	12	26.34	MS
61	13	26.47	Sh
62	78	27.25	MS
63	27	27.52	MS
64	2	27.54	Sh
65	13	27.67	MS
66	18	27.85	MS
67	1	27.86	Sh
68	46	28.32	MS
69	2	28.34	Sh
70	23	28.57	MS
71	133	29.90	PS
72	13	30.03	PS
73	510	35.13	DF
74	157	36.70	MS
75	37	37.07	PS
76	112	38.19	MS
77	29	38.48	PS
78	12	38.60	Sh
79	27	38.87	MS
80	2	38.89	Sh
81	87	39.76	MS
82	30	40.06	MS
83	7	40.13	Sh
84	82	40.95	MS
85	28	41.23	MS

Table A-2 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
86	208	43.31	MS
87	12	43.43	PS
88	4	43.47	Sh
89	41	43.88	MS
90	1	43.89	Sh
91	7	43.96	CT
92	234	46.30	PS
93	29	46.59	Cg
94	48	47.07	MS
95	38	47.45	Cg
96	27	47.72	MS
97	13	47.85	PS
98	34	48.19	MS
99	44	48.63	Cg
100	42	49.05	MS
101	88	49.93	MS
102	87	50.80	Cg
103	48	51.28	MS
104	29	51.57	PS
105	17	51.74	MS
106	16	51.90	Cg
107	89	52.79	MS
108	7	52.86	PS
109	47	53.33	MS
110	83	54.16	MS
111	28	54.44	MS
112	160	56.04	MS
113	132	57.36	MS
114	73	58.09	MS
115	80	58.89	MS
116	90	59.79	MS
117	50	60.29	MS
118	70	60.99	MS
119	270	63.69	MS
120	675	70.44	MS
121	1240	82.84	covered
122	670	89.54	MS
123	1120	100.74	MS
covered interval			

Table A-3. Measured section, outcrop D1.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	42	0.42	Cg
2	34	0.76	PS
3	82	1.58	Cg
4	513	6.71	DF
5	42	7.13	PS/MS
6	30	7.43	PS/MS
7	9	7.52	PS
8	52	8.04	PS/MS
9	63	8.67	DF
10	21	8.88	PS/MS
11	18	9.06	PS
12	61	9.67	MS
13	11	9.78	MS
14	24	10.02	PS
15	2	10.04	Sh
16	38	10.42	MS
17	35	10.77	MS
18	26	11.03	MS
19	19	11.22	MS
20	11	11.33	MS
21	9	11.42	MS
22	51	11.93	PS/MS
23	24	12.17	MS
24	67	12.84	MS
25	36	13.20	MS
26	22	13.42	MS
27	34	13.76	PS
28	208	15.84	DF
29	31	16.15	Cg
30	81	16.96	Cg
31	60	17.56	PS
32	28	17.84	PS
33	162	19.46	MS
34	3	19.49	Sh
35	21	19.70	PS
36	28	19.98	PS
37	18	20.16	Cg
38	15	20.31	PS
39	15	20.46	PS
40	24	20.70	MS
41	35	21.05	Cg
42	30	21.35	MS
43	23	21.58	PS

Table A-3 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
44	132	23.17	MS
45	97	24.14	MS
46	71	24.85	MS
47	200	26.85	GS
48	135	28.20	MS
49	2	28.22	Sh
50	7	28.29	MS
51	13	28.42	CT
52	51	28.93	MS
53	42	29.35	CT
54	8	29.43	MS
55	400	33.43	DF
56	30	33.73	PS
57	56	34.29	MS
58	115	35.44	Cg
59	31	35.75	PS
60	53	36.28	MS
61	17	36.45	CG
62	84	37.29	MS
63	45	37.74	PS
64	24	37.98	PS
65	94	38.92	MS
66	41	39.33	Cg
67	152	40.85	Cg
68	86	41.71	MS
69	52	42.23	MS
covered interval			

Table A-4. Measured section, outcrop D2.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	48	0.48	MS
2	45	0.93	MS
3	191	2.84	MS
4	62	3.46	MS
5	176	5.22	MS
6	123	6.45	MS
7	162	8.07	MS
8	3	8.10	Sh
9	15	8.25	MS
10	3	8.28	Sh
11	13	8.41	MS
12	32	8.73	MS
13	12	8.85	MS
14	14	8.99	MS
15	26	9.25	MS
16	93	10.18	MS
17	118	11.36	MS
18	40	11.76	MS
19	56	12.32	MS
20	4	12.36	Sh
21	7	12.43	MS
22	38	12.81	MS
23	42	13.23	MS
24	39	13.62	MS
25	10	13.72	CT
26	23	13.95	MS
27	12	14.07	CT
28	70	14.77	MS
29	5	14.82	Sh
30	15	14.97	MS
31	5	15.02	Sh
32	42	15.44	MS
33	54	15.98	DF
34	62	16.60	MS
35	148	18.08	MS
36	8	18.16	MS/PS
37	126	19.42	DF
38	114	20.56	MS
39	1.5	20.575	CT
40	5	20.625	CT
41	11	20.735	MS
42	3	20.765	Sh
43	42	21.185	MS

Table A-4 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
44	3.5	21.22	CT
45	13	21.35	CT
46	27	21.62	MS
47	0.3	21.623	Sh
48	24	21.863	MS
49	9	21.953	MS
50	82	25.773	MS
51	28	23.053	MS
52	9	23.143	CT
53	80	23.943	MS
54	28	24.223	GS
55	39	24.613	MS
56	2	24.633	CT
57	10	24.733	CT
58	6	24.793	CT
59	18	24.973	MS
60	5	25.023	CT
61	4.5	25.068	CT
62	26	25.328	CT
63	42	25.748	MS
64	63	26.378	MS
65	2	26.398	Sh
66	117	27.568	CT/Sh
67	72	28.288	GS
68	86	29.148	MS
69	41	29.558	GS
70	89	30.448	MS
71	36	30.808	MS
72	65	31.458	MS
73	55	32.008	MS
74	77	32.778	MS
75	25	33.028	CT
76	70	33.728	MS
77	31	34.038	MS
78	33	34.368	MS
79	33	34.698	CT
80	15	34.848	MS
81	3	34.878	Sh
82	120	36.078	MS
83	92	36.998	MS
84	101	38.008	MS
85	153	39.538	MS
86	48	40.018	CT/Sh

Table A-4 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
87	250	42.518	MS/Sh
88	190	44.418	MS
89	121	45.628	MS
90	14	45.768	GS
91	61	46.378	MS
92	68	47.058	CT/Sh
93	54	47.598	MS
94	108	48.678	CT/Sh
95	9	48.768	MS
96	313	51.898	CT/Sh
97	38	52.278	MS
98	63	52.908	CT/Sh
99	19	53.098	MS
100	64	53.738	CT/Sh
101	13	53.868	MS
102	54	54.408	CT/Sh
103	19	54.598	MS
104	35	54.948	CT/Sh
105	7	55.018	MS
106	11	55.128	CT/Sh
107	8	55.208	MS
108	30	55.508	CT/Sh
109	48	55.988	MS
110	79	56.778	CT/Sh
111	37	57.148	MS
112	117	58.318	CT/Sh
113	13	58.448	MS
114	72	59.168	CT/Sh
115	22	59.388	MS
116	2740	86.788	CT/Sh
			Outcrop E1

Table A-5. Measured section, outcrop G2.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	65	0.65	MS
2	100	1.65	MS
3	6	1.71	Sh
4	6	1.77	MS
5	1	1.78	Sh
6	82	2.60	MS
7	6	2.66	MS
8	39	3.05	MS
9	1	3.06	Sh
10	33	3.39	MS
11	82	4.21	MS
12	13	4.34	CT
13	8	4.42	Sh
14	11	4.53	MS
15	3	4.56	Sh
16	68	5.24	MS
17	37	5.61	CT
18	12	5.73	CT
19	13	5.86	Sh
20	29	6.15	MS
21	10	6.25	MS
22	1	6.26	Sh
23	6	6.32	MS
24	1.5	6.335	Sh
25	21	6.545	MS
26	4	6.585	Sh
27	7	6.655	CT
28	5	6.705	CT
29	20	6.905	CT
30	11	7.015	CT
31	18	7.195	MS
32	2	7.215	Sh
33	11	7.325	MS
34	1	7.335	Sh
35	13	7.465	MS
35'	2	7.485	Sh
35''	8	7.565	MS
36	4	7.605	Sh
37	16	7.765	MS
38	12	7.885	MS
39	23	8.115	MS
40	111	9.225	MS
41	46	9.685	MS

Table A-5 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
42	7	9.755	Sh
43	114	10.895	MS
44	47	11.365	MS
45	1	11.375	Sh
46	16	11.535	MS
47	1	11.545	Sh
48	74	12.285	MS
49	23	12.515	MS
50	133	13.845	CT/Sh
51	108	14.925	MS
52	38	15.305	MS
53	6	15.365	CT
54	35	15.715	MS
55	3	15.745	Sh
56	8	15.825	MS
57	3	15.855	Sh
58	6	15.915	MS
59	23	16.145	Sh
60	68	16.825	MS
61	62	17.445	CT
62	26	17.705	MS
63	14	17.845	CT
64	8	17.925	MS
65	1	17.935	Sh
66	15	18.085	MS
67	5	18.135	Sh
68	98	19.115	MS
69	16	19.275	MS
70	7	19.345	Sh
71	7	19.415	CT
72	11	19.525	CT
73	53	20.055	MS
73'	11	20.165	MS
73''	13	20.295	MS
73'''	22	20.515	MS
74	37	20.885	CT
75	55	21.435	MS
76	38	21.815	CT
77	22	22.035	MS
78	28	22.315	CT/Sh
79	138	23.695	MS
80	2	23.715	Sh
81	27	23.985	MS

Table A-5 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
82	3	24.015	Sh
83	29	24.305	MS
84	34	24.645	MS
85	75	25.395	MS
86	4	25.435	Sh
87	34	25.775	MS
88	3	25.805	Sh
89	13	25.935	MS
90	7	26.005	CT
91	7	26.075	MS
92	1	26.086	Sh
93	24	26.325	MS
94	2	26.345	Sh
95	3	26.375	MS
96	1	26.385	Sh
97	10	26.485	MS
98	78	27.265	MS
99	15	27.415	Sh
100	15	27.565	MS
101	6	27.625	Sh
102	22	27.845	MS
103	3	27.875	Sh
104	20	28.075	MS
105	13	28.205	Sh
106	21	28.415	MS
107	7	28.485	Sh
108	9	28.575	MS
109	42	28.995	MS
110	7	29.065	Sh
111	29	29.355	MS
112	20	29.555	Sh
113	11	29.665	MS
114	27	29.935	Sh
115	9	30.025	MS
116	19	30.215	Sh
117	26	30.475	MS
118	6	30.535	Sh
119	29	30.825	MS
120	1	30.835	Sh
121	54	31.375	MS
122	3	31.405	Sh
123	173	33.135	MS
124	49	33.625	CT

Table A-5 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
125	18	33.805	MS
126	14	33.955	Sh
127	96	34.915	MS
128	44	35.355	MS
129	69	36.045	MS
130	34	36.385	MS
131	2	36.405	Sh
132	128	37.685	MS
133	112	38.805	MS
134	56	39.365	MS
135	7	39.435	CT
136	39	39.825	MS
137	23	40.055	CT
138	26	40.315	MS
139	52	40.835	MS
140	1	40.845	Sh
141	13	40.975	MS
142	1	40.985	Sh
143	41	41.395	MS
144	21.5	41.615	CT
145	15	41.765	MS
146	1	41.775	Sh
147	19	41.965	MS
148	9	42.055	Sh
149	111	43.165	MS
150	4	43.205	Sh
151	27	43.475	MS
152	2	43.495	Sh
153	53	44.025	MS
154	2	44.045	Sh
155	5	44.095	MS
156	62	44.715	MS
157	46	45.175	MS
158	11	45.285	CT
159	8	45.365	MS
160	10	45.465	MS
161	13	45.595	MS
162	11	45.705	CT
163	9	45.795	MS
164	10	45.895	CT
165	8	45.975	MS
166	6	46.035	CT
167	5	46.085	MS

Table A-5 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
168	17	46.255	CT
169	14	46.395	MS
170	1	46.405	Sh
171	23	46.635	MS
172	4	46.675	Sh
173a	6	46.735	MS
173b	1.5	46.75	Sh
173c	107	47.82	MS
174a	24	48.06	MS
174b	10	48.16	MS
174c	15	48.31	MS
175	33	48.64	CT
176	11	48.75	MS
177	17	48.92	MS
178	4.5	48.965	Sh
179	5	49.015	MS
180	12.5	49.14	CT
181	3	49.17	CT
182	5	49.22	CT
183	13	49.35	MS
184	26	49.61	CT
185	43	50.04	MS
186	0.6	50.046	Sh
187	4.4	50.09	MS
188	7	50.16	Sh
189	65	50.81	MS
190	9	50.90	CT
191	18	51.08	MS
192	11	51.19	CT
193	11	51.30	MS
194	52	51.82	CT
195	13	51.95	MS
196	2	51.97	Sh
197	5	52.02	MS
198a	1	52.03	Sh
198b	6	52.09	MS
199	15	52.24	MS
200	5	52.29	Sh
201	8	52.37	MS
202	6	52.43	Sh
203	17	52.60	MS
204a	14	52.74	CT/Sh
204b	53	53.27	GS

Table A-5 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
204c	41	53.68	CT/Sh
205	45	54.13	MS
206	5.5	54.185	Sh
207	130	55.485	MS
208	3	55.515	Sh
209	20	55.715	MS
210	5.5	55.77	Sh
211	12	55.89	MS
212	17	56.06	CT/Sh
213	14	56.20	MS
214	106	57.26	MS
215	685	64.11	CT/Sh
215	145	65.56	MS
covered interval			

Table A-6. Measured section, outcrop C1.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	78	0.78	MS
2	8	0.86	Sh
3	15	1.01	MS
4	1	1.02	Sh
5	11	1.13	MS
6	2	1.15	Sh
7	61	1.76	MS
8	18	1.94	MS
9	11	2.05	CT
10	350	5.55	MS
11	37	5.92	MS
12	6	5.98	Sh
13	8	6.06	MS
14	6	6.12	Sh
15	13	6.25	MS
16	610	12.35	MS
			Fault

Table A-7. Measured section, outcrop C2.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	57	0.57	MS
2	19	0.76	MS
3	83	1.59	MS
4	91	2.50	MS
5	124	3.74	MS
6	34	4.08	MS
7	109	5.17	MS
8	76	5.93	CT
9	38	6.31	MS
10	6	6.37	Sh
11	38	6.75	MS
12	32	7.07	MS
13	11	7.18	Sh
14	27	7.45	MS
15	1	7.46	Sh
16	18	7.64	MS
17	10	7.74	Sh
18	18	7.92	MS
19	42	8.34	CT
20	69	9.03	MS
21	80	9.83	CT
22	246	12.29	MS
23	4	12.33	Sh
24	13	12.46	MS
25	7	12.53	Sh
26	164	14.17	MS
26'	0.6	14.176	Sh
26''	6	14.236	MS
27	13	14.366	Sh
28	84	15.206	MS
29	16	15.366	CT
30	13	15.496	MS
31	3	15.526	Sh
32	23	15.756	MS
33	1	15.766	Sh
34	8	15.846	MS
35	12	15.966	Sh
36	28	16.246	MS
37	7	16.316	Sh
38	39	16.706	MS
39	4	16.746	Sh
40	15	16.896	MS
41	2	16.916	Sh

Table A-7 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
42	7	16.986	MS
43	2	17.006	Sh
44	176	18.766	MS
45	16	18.926	Sh
46	13	19.056	MS
47	14	19.196	Sh
48	60	19.796	MS
49	89	20.686	MS
50	3	20.716	Sh
51	21	20.926	MS
52	3	20.956	Sh
53	84	21.796	MS
54	80	22.596	MS
55	12	22.716	Sh
56	20	22.916	MS
57	5	22.966	Sh
58	32	23.286	MS
59	37	23.656	CT
60	15	23.806	MS
61	29	24.096	Sh
62	4	24.136	MS
63	1	24.146	Sh
64	8	24.226	MS
65	2	24.246	Sh
66	11	24.356	MS
67	13	24.486	Sh
68	6	24.546	MS
69	5	24.596	Sh
70	204	26.636	MS
71	83	27.466	DF/GS
72	30	27.766	MS
73	2	27.786	Sh
74	7	27.856	MS
75	23	28.086	Sh
76	68	28.766	MS
77	20	28.966	GS
78	12	29.086	MS
	320	32.286	CT
			?fault?
			shale

Table A-8. Measured section, outcrop C3.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	35	0.35	MS
2	48	0.83	MS
3	38	1.21	MS
4	49	1.70	MS
5	76	2.46	MS
6	41	2.87	MS
7	53	3.40	MS
8	158	4.98	MS
9	1100	15.98	MS
covered interval			

Table A-9. Measured section, outcrop F7.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	24	0.24	MS
2	1.7	0.257	Sh
3	9	0.347	MS
4	8	0.427	Sh
5	15	0.577	MS
6	9	0.667	GS
7	7	0.737	CT
8	2	0.757	Sh
9	7	0.827	MS
10	31	1.137	CT
11	21	1.347	MS
12	31	1.657	MS
13	91	2.567	MS
14	4	2.607	Sh
15	28	2.887	MS
16	25	3.137	MS
17	5.5	3.192	Sh
18	11	3.302	MS
19	7	3.372	Sh
20	7	3.442	CT
21	7	3.512	Sh
22	88	4.392	MS
23	27	4.662	MS
24	54	5.202	MS
25	6	5.262	Sh
26	43	5.692	MS
27	23	5.922	CT
28	5	5.972	Sh
29	43	6.402	MS
30	27	6.672	MS
31	16	6.832	MS
32	29	7.122	MS
33	21	7.332	MS
34	28	7.612	MS
35	10	7.712	Sh
36	10	7.812	MS
37	2	7.832	Sh
38	68	8.512	MS
39	19	8.702	MS
40	2	8.722	Sh
41	15	8.872	MS
42	1	8.882	Sh
43	36	9.242	MS

Table A-9 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
44	17	9.412	Sh
45	6	9.472	CT
46	1	9.482	Sh
47	9	9.572	CT
48	6	9.632	Sh
49	45	10.082	MS
50	22	10.302	CT
51	23	10.532	MS
52	2	10.552	Sh
53	16	10.712	MS
54	26	10.972	CT
55	24	11.212	MS
56	1	11.222	Sh
57	30	11.522	MS
58	2	11.542	Sh
59	61	12.152	SL
60	5	12.202	Sh
61	16	12.362	MS
62	72	13.082	MS
63	4	13.122	Sh
64	9	13.212	MS
65	531	18.522	CT/Sh
66	47	18.992	MS
67	115	20.142	MS
68	90	21.042	MS
69	48	21.522	MS
70	3	21.552	Sh
71	26	21.812	MS
72	5	21.862	Sh
73	53	22.392	MS
74	22	22.612	MS
75	14	22.752	MS
76	2	22.722	Sh
77	18	22.952	MS
78	16	23.112	MS
79	220	25.312	MS
80	5	25.362	Sh
81	19	25.552	MS
82	63	26.182	MS
83	13	26.312	Sh
84	11	26.422	MS
85	2.5	26.447	Sh
86	11	26.557	MS

Table A-9 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
87	8.5	26.642	Sh
88	182	28.462	MS
89	10	28.562	Sh
90	7	28.632	CT
91	7	28.702	Sh
92	16	28.862	CT
93	13	28.992	Sh
94	12	29.112	CT
95	1	29.122	Sh
96	85	29.972	MS
97	2	29.992	Sh
98	203	32.022	MS
99	1.5	32.037	Sh
100	31	32.347	MS
101	2	32.367	Sh
102	8	32.447	MS
103	9	32.537	Sh
104	9	32.627	MS
105	11	32.737	Sh
106	36	33.097	MS
107	11	33.207	Sh
108	38	33.587	MS
109	1	33.597	Sh
110	10	33.697	MS
111	1	33.707	Sh
112	40	34.107	MS
113	21	34.317	Sh
114	32	34.637	MS
115	7	34.707	Sh
116	110	35.807	MS

Table A-10. Measured section, outcrop E2.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	19	0.19	MS
2	1	0.20	Sh
3	13	0.33	MS
4	1.5	0.345	Sh
5	17	0.515	GS
6	14	0.655	MS
7	11	0.765	GS
8	10	0.865	MS
9	34	1.205	GS
10	135	2.555	MS
11	4	2.595	Sh
12	43	3.025	MS
13	5	3.075	Sh
14	12	3.195	MS
15	8	3.275	Sh
16	9	3.365	MS
17	8	3.445	Sh
18	82	4.265	MS
19	44	4.705	MS
20	46	5.165	MS
21	42	5.585	MS
22	27	5.855	MS
23	75	6.605	MS
24	8	6.685	MS
25	5	6.735	MS
26	4	6.775	MS
27	94	7.715	MS
28	8	7.795	Sh
29	8	7.875	MS
30	2	7.895	Sh
31	58	8.475	MS
32	26	8.735	MS
33	29	9.025	MS
34	17	9.195	CT
35	5	9.245	MS
36	2.5	9.27	CT
37	8	9.35	MS
38	5	9.40	CT
39	40	9.80	MS
40	21	10.01	CT
41	27	10.28	MS
42	23	10.51	MS
43	12	10.63	CT

Table A-10 (continued)

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
44	14	10.71	MS
45	2	10.79	Sh
46	9	10.88	MS
47	10	10.98	MS
48	58	11.56	MS
49	21	11.77	MS
50	34	12.11	MS
51	53	12.64	MS
52	8	12.72	CT
53	95	13.67	MS
54	3	13.70	CT
55	128	14.98	MS
56	17	15.15	CT
57	20	15.35	MS
58	4	15.39	Sh
59	40	15.79	MS
60	103	16.82	covered
61	42	17.24	MS
62	80	18.04	MS
covered interval			

Table A-11. Measured section, outcrop E3.

Unit	Unit Thickness (cm)	Cumulative Thickness (m)	Lithofacies
1	168	1.68	CT
2	8	1.76	MS
3	1	1.77	Sh
4	10	1.87	MS
5	28	2.15	CT
6	18	2.33	MS
7	9	2.42	MS
8	23	2.65	MS
9	48	3.13	MS
10	32	3.45	MS
11	12	3.57	CT
12	69	4.26	MS
13	3	4.29	CT
14	92	5.21	MS
15	36	5.57	CT
16	10	5.67	MS
17	98	6.65	CT
18	6	6.71	MS
19	270	9.41	CT
20	34	9.75	MS
21	560	15.35	CT
22	153	16.88	CT
23	260	19.48	MS
24	165	21.13	CT
25	700	28.13	MS
			syncline axis

APPENDIX B

SLAB DESCRIPTIONS

EXPLANATORY NOTE

The slab descriptions in the following section have been described in ascending order from oldest to youngest. Outcrop C3 occurs at the base of the Tellico Formation, D1 in the middle, and G2 at the top of formation. Samples of massive sandstone beds were taken from each outcrop and slabbed and described. Outcrop G2 provided the most complete and least weathered exposure, resulting in it being the most heavily sampled of the three outcrops. Slabbed samples taken from all three outcrops were described using a binocular microscope and a grain size card to determine grain sizes, types of grading, sedimentary structures, and overall grain fabric of the slabs. Slab descriptions were then compared to field note descriptions of the same units to determine if field observations adequately described the rocks in this study. All features observed in the slab descriptions were also observed in the field except for the presence of dewatering pipes (pillars). Grain-size terminology used in this study is that of Wentworth (1922).

Grain Size:

Boulders	>256 mm
Cobbles	64-256 mm
Pebbles	4-64 mm
Granules	2-4 mm
Sand	
Very course	1-2 mm
Coarse	1/2-1 mm
Medium	1/4-1/2 mm
Fine	1/8-1/4 mm
Very fine	1/16-1/8 mm
Silt	1/256-1/16 mm
Clay	<1/256 mm

Outcrop C3 Slab Descriptions

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
C3-1B	35	0-9	Coarse sand in medium to fine sand matrix, dewatering pipes, massive appearance.
C3-1M	35	15-21	Medium to coarse sand with widely distributed very-coarse sand, dewatering pipes, massive appearance.
C3-1T	35	21-35	Coarse to medium sand at base of slab, coarse fraction grading to medium to fine sand with rapid distribution grading in last 0.8 cm to fine to very-fine sand. Dewatering pipes.
C3-2B-M	48	0-14	Coarse to medium sand, massive appearance.
C3-2	48	14-23	Coarse to medium sand, coarse sand fines upward. Possible dewatering pipe, massive appearance.
C3-2	48	23-41	Medium to fine sand at first, followed by coarse to very coarse sand with some granules that exhibit coarse-tail grading. Dewatering pipes. Possible amalgamation surface near base of slab.
C3-2	48	41-48	Very coarse sand to granules in a medium sand matrix, fines upward to medium to fine sand at top. Possible dewatering pipes.
C3-3B	38	0-7	Slight inverse grading at base, medium sand coarsens up to very-coarse sand with granules. Dewatering pipes, massive appearance.
C3-3	38	7-16	Medium to coarse sand with minor very-coarse sand, dewatering pipes, massive appearance.
C3-3	38	16-26	Medium to coarse sand, dewatering pipes, massive appearance.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
C3-3	38	26-38	Medium to coarse sand, coarse fraction grading to medium to fine sand at top. Dewatering pipes.

Outcrop D1 Slab Descriptions

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
D1-3	85	0-9	Polymictic conglomerate, clasts have long axis aligned parallel to bedding, maximum clast size 3.4, 2.9, 3.3, 3.0, 2.5 cm. Lot of carbonate clasts, green sandstone, black chert, white quartz.
D1-3	85	66-85	Coarse to very-coarse sandstone.
D1-4	500	0-500	Debris flow. Large clasts of carbonate, green sandstone, black chert, red chert, intraformational shale and sandstone clasts in a medium to fine sand matrix. Clast size range from granules to boulder size. Clast are matrix supported with elongated clasts tending to parallel bedding (long axis), other clasts are randomly oriented.
D1-5	42	0-9.5	Pebbles up to 0.5 cm at base that rapidly fine upward to medium to coarse sand. Dewatering pipes present.
D1-6	30	0-6	Pebbles up to 1.1, 1.0, 0.8, 0.7 cm with average clast size 0.5 cm, clasts consist of carbonate, red and black chert, green sandstone, and tan sandstone.
D1-10	20	0-12	Medium to fine sand with some granules. Dewatering pipes.
D1-11	16	0-14	Granular at base, lose coarsest clasts approximately 2 cm from top. Possible dewatering pipes.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
D1-13	13	2-13	Medium to coarse sand with some very-coarse sand, massive appearance.
D1-15T	40	28-40	Medium to coarse sand with some very-coarse sand, coarse-frequency grading to medium to coarse sand. Dewatering pipes.
D1-21	55	0-8	Medium to coarse sand with some very-coarse sand and granules.
D2-32	165	150-159.5	Medium to fine sand, possible dewatering pipes.

Outcrop G2 Slab Descriptions

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-1A	65	0-7.5	First 1-2 cm medium to fine sand that coarsens upward to medium sand with some coarse sand (poorly developed inverse grading), preferred orientation of grains parallel to bedding, moderately sorted.
G2-1B	65	25-33.5	Medium to fine sand with some coarse sands, faint discontinuous laminae, some clasts oriented parallel to bedding, moderately sorted.
G2-6A	82	0-8.5	Medium to fine sand with minor to rare coarse sand, ripped-up shale clasts at base, poorly developed coarse fraction grading, grains at base (1-2 cm) have preferred orientation parallel to bedding.
G2-6B	82	15-29	Medium to fine sand with rare coarse sand, no grading, slight preferred orientation of grains parallel to bedding.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-6C	82	77.5-82	Basal 2 cm is fine to very-fine sand. Medium to fine sand with rare coarse sand overlying first 2 cm at a sharp contact. laminated or stratified (1.6 cm) then rapidly fines upward, losing all coarse fraction, last 0.4 cm is very-fine to fine sand.
G2-8A	39	0-11	Medium to coarse sand with some very-coarse sand, possible inverse grading at basal 2 cm, 2-11 cm exhibits both coarse-frequency and coarse-tail grading with coarse-tail more dominant after 7 cm.
G2-8B	39	24-39	Medium to fine sand at base, normal frequency grading to very-fine sand to silt for last 5 cm, moderately sorted, no laminae, massive appearance except for grading.
G2-11A	82	0-10	Approximately 1 cm thick layer of coarse sand with some very coarse sand, poorly developed inverse grading. 3 cm of fine to medium sand that intrudes as a dewatering pillar into very coarse sand above. Sharp contact between fine to medium sand and very coarse sand. Very coarse sand grains have been rotated along margins of dewatering pillars.
G2-11B	82	40-45	Fine to medium sand, no grading, massive appearance.
G2-11C	82	76-82	Basal 3 cm is very-fine sand to silt (massive), followed by coarse sand with some very-coarse sand along an irregular contact (scouring?), slight inverse grading with coarsest grains more frequent near top in layers. Grades rapidly upward to very-fine sand to silt for last 0.3 cm.
G2-31	18	0-4.5	Fine to medium sand with rare coarse sand at base, fines upward, laminated or stratified (possible multiple grading) at top.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-31A	18	6.5-18	Stratified (possible multiple grading), medium to fine sand fines up to fine to very-fine sand and silt at top.
G2-60A	68	0-12	Very-coarse sand to granular base (1 cm thick), coarse-tail grading, very-coarse to coarse sand (very concentrated) that fines up to medium to coarse sand with preferred orientation of grains parallel to bedding.
G2-60B	68	36-46	Medium to fine sand, no grading, massive appearance.
G2-60C	68	49.5-55	Medium to fine sand, 4 stratified layers (possibly graded).
G2-60D	68	55-68	Medium to fine sand at base, fines upward to fine to very-fine sand.
G2-75A	55	0-23	Very coarse sand with some granules at base, coarse-tail grading after 2-3 cm with very-coarse sand widely scattered in coarse to medium sand, preferred orientation of grains parallel to bedding.
G2-75B	55	23-33	Medium sand with some coarse sand, massive, possible dewatering pillar.
G2-75C	55	46-55	Medium to fine sand with some coarse sand at base, fines up (normal distribution grading) to very-fine sand to silt at top with shale at very top. Dewatering pillars composed of medium sand intruding fine sand near top.
G2-79A	138	0-20	Inverse grading at base, first 2 cm is fine to medium sand with rare very-coarse sand that coarsens upward to coarse to very-coarse sand with some granules, coarsest grains widely scattered. Followed by coarse-tail grading with very coarse sand to granules becoming less frequent and fining upward to coarse sand with minor very-coarse sand at top.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-79B	138	30-46	Medium to fine sand with coarse and some widely scattered very-coarse sand. Possible dewatering pillars filled with fine sand. Massive appearance.
G2-79C	138	46-58.5	Medium to fine sand with coarse to very coarse sand widely scattered. Faint dewatering pillars. Massive appearance.
G2-79D	138	58.5-70.5	Medium to coarse sand at base. Normal distribution grading to fine to very-fine sand up to 4.5 cm from top of sample. Last 4.5 cm is stratified or faint laminae of alternating fine to very-fine sand and medium to fine sand. Dewatering pillars present.
G2-79E	138	118-131	Medium to fine sand, massive appearance, poorly developed coarse frequency grading.
G2-79F	138	130.5-136	Basal 0.8 cm is fine to very-fine sand that coarsens up to medium sand with some coarse sand. Normal distribution grading to fine to very-fine sand at top.
G2-79G	138	136-138	Very-fine sand to silt with some fine sand and a 2 cm long shale clast.
G2-89	13	0-13	Coarse to medium sand at base, fines upward (coarse-tail grading) to medium to fine sand for first half of bed. Normal distribution grading at top to very-fine sand to silt. Dewatering pillars filled with medium sand.
G2-93A	24	0-18.5	Medium to coarse sand at base with widely distributed coarse sand, frequency of coarse sand decreases upward, medium to fine sand at top of slab. Dewatering pillars present.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-93B	24	14.5-24	Medium to fine sand at base, fines up (normal distribution grading) to fine to very-fine sand approximately 1 cm from top. Last 1 cm is very-fine sand to silt. Dewatering pillars with rotated grains due to escaping fluids. Ripped-up shale clasts near top.
G2-98A	78	0-11	Basal 4.5 cm is G2-97, medium to fine sand with some coarse sand that scours into G2-96, sole marks present (flutes?). Top half of slab is G2-98 scouring into G2-97, amalgamation surface, ripped-up shale clasts up to 4 cm long in high concentration of coarse to very-coarse sand, coarse fraction grading.
G2-98C	78	18-33.5	Medium to coarse sand near base fining up to medium to fine sand near top. Several dewatering pillars that disrupt faint laminations.
G2-98D	78	33.5-46	Medium to fine sand with faint laminations disrupted by dewatering pillars with grains rotated at angles to overall fabric of slab (parallel to bedding).
G2-98E	78	50.5-59	Medium to fine sand with large dewatering pipe.
G2-98F	78	67-78	Fine to very-fine sand at base with faint laminations disrupted by dewatering pipes, fines up (normal distribution grading) to very-fine sand at top.
G2-100A	15	0-7.5	Multiple graded sets with dewatering pipes disrupting bedding.
G2-100B	15	9-15	Laminated (multiple graded sets) with small dewatering pipes.
G2-109	42	0-13	Inverse grading at base, first 0.6 cm is medium to coarse sand that coarsens upward to very coarse sand that fines up to medium to fine sand. Dewatering pipes disrupt graded layers.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-109A	42	31-42	Fine to medium sand in several stratified (graded) intervals. Dewatering pipes disrupt graded sets. Coarse layer of medium to fine sand near top fines upward to fine to very-fine sand at top.
G2-113	11	0-11	Multiple graded sets, some dewatering pipes present. Graded sets go from medium to coarse sand to fine to very-fine sand and are 1-2 cm thick. Coarsest sets are in middle to upper part of slab.
G2-121A	54	0-5.5	Possible inverse grading at base. Fine sand at base coarsens upward to coarse to very-coarse sand.
G2-121B	54	5.5-13	Medium to fine sand with some coarse sand at base, fines upward (coarse fraction grading) to fine to medium sand. Dewatering pipes present.
G2-121C	54	46-54	Medium to fine sand at base, rapid normal distribution grading at last 2 cm to very-fine sand to silt.
G2-123A	173	0-8.5	Medium to coarse sand at base with some very-coarse sand. Coarse fraction grading to medium to fine sand at top of slab. Dewatering pipes present.
G2-123B	173	107-118	Medium to fine sand with rare coarse sand, last 1-2 cm exhibits rapid normal distribution grading to very-fine sand to silt. Dewatering pipes present.
G2-123C	173	158-171	High concentration of coarse to very-coarse sand for first 9 cm. Top 4 cm consists of several graded sets of medium to fine sand fining upwards to very-fine to fine sand at top. Possible dewatering pipes.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-125A	18	0-6.5	Sole marks (flutes), ripped-up shale clasts up to 1.5 cm long, inverse grading at base, fine to medium sand coarsens up to medium to coarse sand within 0.5 cm, normal distribution grading to medium to fine sand, dewatering pipes disrupt grain fabric.
G2-125B	18	12.5-18	Laminated, medium to fine sand at base, normal distribution grading to silt at top, lot of ripped-up shale clasts in last 2.5 cm (up to 1 cm long). Dewatering pipes disrupt laminations.
G2-149A	111	0-11	Coarse to very-coarse sand in a matrix of medium to fine sand. Massive appearance. Dewatering pipes present.
G2-149B	111	20-31.5	Medium to fine sand with widely distributed coarse, very-coarse sand and minor granules. Dewatering pillars.
G2-149C	111	91-99	Medium to fine sand with some coarse sand, massive, dewatering pillars.
G2-149D	111	103.5-111	Medium to fine sand at base with shale clast 1 cm long, dewatering pillars, gradual coarse-fraction grading to fine sand, last 1.5 cm is rapid normal distribution grading to very fine sand to silt with some medium to fine sand.
G2-160 & 161	14	0-14	Coarse to medium sand, coarse fraction grading to medium to fine sand at top. Possible dewatering pipes.
G2-163	9	0-9	Fine to very-fine sand, amalgamation surface at 3.5 cm with coarse to medium sand along with very-coarse sand and granules filling in scoured troughs, followed by medium to fine laminated sand that rapidly fines up to silt at top. Dewatering pipes present.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-165	8	0-8	Fine to very-fine sand at base, laminated, appears to fine up. Approximately 2 cm from top medium sand with some coarse sand that fines upward. Graded sets disrupted by dewatering pipes.
G2-179	5	0-5	Fine to very-fine sand in layered sets that may be graded, dewatering pipes.
G2-185	43	0-13	Inverse grading at base, first 2 cm is medium to fine sand that coarsens upward to coarse sand and some very-coarse sand that increases in frequency upward. Lose coarsest sand after a few cm's. Dewatering pipes present.
G2-185A	43	35-43	Medium to fine sand at base, fines upward to fine sand to silt at top with clay drop on top. Dewatering pipes fan out after bursting through some coarse intervals.
G2-195	13	0-13	Medium to fine sand at base, laminated except for upper third of slab, fines upward to very-fine sand to silt at top. Dewatering pipes present.
G2-207A	130	0-26	Inverse grading at base, fine to medium sand coarsens up to medium to coarse sand with some very-coarse sand, followed by coarse fraction grading. Dewatering pipes present.
G2-207B	130	26-40	Medium to coarse sand, several ripped-up shale clasts up to 3 cm long. Dewatering pipes present. Massive appearance.
G2-207C	130	40-55	Medium to coarse sand, several ripped-up shale clasts, dewatering pipes, massive appearance.
G2-207D	130	95-110.5	Coarse sand at base, normal distribution grading to fine to very-fine sand at top.

<u>Sample Number</u>	<u>Unit Thickness (cm)</u>	<u>Sample Interval (cm)</u>	<u>Description</u>
G2-207E	130	115.5-130	Laminated base (graded sets) with coarse fraction being medium to fine sand, fines up to fine to very-fine sand at top.
G2-209	20	0-12	Coarse to medium sand with ripped-up shale clasts at base. Rapid distribution grading to fine to very-fine sand for rest of slab. Massive appearance.

APPENDIX C

MARKOV ANALYSIS RESULTS

EXPLANATORY NOTE

The stepwise selection procedure along with log-linear models developed by Carr (1982) were used to test the Tellico Formation for ordered transitions. The limiting factor was $\alpha = 0.20$ (80% confidence level). When the α value was exceeded, then stepping was terminated. The BMDP2F computer program (Brown, 1979) was used for this analysis. No ordered transitions were found to occur in the Tellico Formation. Frequency of vertical transitions are provided in tally matrix tables. Results of computer analysis are provided in summary tables.

Table C-1. Tally matrix, outcrop F1'.

	Shale/ siltstone	Massive sandstone	Chaotic unit	Row totals	
Shale/siltstone	2	45	1	48	
Massive sandstone	46	18	5	69	
Chaotic unit	1	6	0	7	
Column totals	49	69	6	124	Total number of transitions

Table C-2. Summary table, outcrop F1'.

Step no.	Cell coord.	Observed frequency	Expected frequency	Chi square	Probability
1	2,2	18.5	482.66	3.29	0.1933

Table C-3. Tally matrix, outcrop G2.

	Shale/ siltstone	Massive sandstone	Chaotic unit	Row totals	
Shale/siltstone	3	92	1	96	
Massive sandstone	93	41	0	134	
Chaotic unit	1	0	0	1	
Column totals	97	133	1	231	Total number of transitions

Table C-4. Summary table, outcrop G2.

Step no.	Cell coord.	Observed frequency	Expected frequency	Chi square	Probability
1	1,1	3.5	210.03	0.07	0.9657

Table C-5. Tally matrix, outcrops F1' + G2.

	Shale/ siltstone	Massive sandstone	Chaotic unit	Row totals	
Shale/siltstone	5	137	2	144	
Massive sandstone	139	59	5	203	
Chaotic unit	2	6	0	8	
Column totals	146	202	7	355	Total number of transitions

Table C-6. Summary table, outcrops F1' + G2.

Step no.	Cell coord.	Observed frequency	Expected frequency	Chi square	Probability
1	5,5	5.5	277.59	11.85	0.0027
2	3,2	6.5	1.12	5.27	0.0217

Table C-7. Tally matrix, outcrops C1 + C2 + F1'.

	Shale/ siltstone	Massive sandstone	Chaotic unit	Row totals	
Shale/siltstone	2	84	1	87	
Massive sandstone	86	39	7	132	
Chaotic unit	1	8	0	9	
Column totals	89	131	8	228	Total number of transitions

Table C-8. Summary table, outcrops C1 + C2 + F1'.

Step no.	Cell coord.	Observed frequency	Expected frequency	Chi square	Probability
1	2,2	39.5	1573.94	5.47	0.0650
2	1,3	1.5	0.31	3.33	0.0680

Table C-9. Tally matrix, outcrops G2 + F7 + E2 + E3.

	Shale/ siltstone	Massive sandstone	Chaotic unit	Row totals	
Shale/siltstone	3	162	0	168	
Massive sandstone	165	85	3	253	
Chaotic unit	1	4	0	5	
Column totals	169	251	6	426	Total number of transitions

Table C-10. Summary table, outcrops G2 + F7 + E2 + E3.

Step no.	Cell coord.	Observed frequency	Expected frequency	Chi square	Probability
1	1,1	3.5	296.17	4.96	0.0839
2	3,1	1.5	8.60	0.72	0.3955

Table C-11. Tally matrix, outcrops C1 + C2 + F1' + G2 + F7 + E2 + E3.

	Shale/ siltstone	Massive sandstone	Chaotic unit	Row totals	
Shale/siltstone	5	246	4	255	
Massive sandstone	271	124	10	405	
Chaotic unit	3	10	0	13	
Column totals	279	380	14	673	Total number of transitions

Table C-12. Summary table, outcrops C1 + C2 + F1' + G2 + F7 + E2 + E3.

Step no.	Cell coord.	Observed frequency	Expected frequency	Chi square	Probability
1	1,1	5.5	473.79	19.32	0.0001
2	3,2	10.5	1.67	8.42	0.0037

Table C-13. Tally matrix, outcrops F5 + D1 + D2.

	Shale/ siltstone	Massive sandstone	Chaotic unit	Conglomerate	Pebbly sandstone	Row totals
Shale/siltstone	4	49	1	0	3	57
Massive sandstone	52	81	9	11	14	167
Chaotic unit	0	10	0	1	3	14
Conglomerate	1	11	1	2	4	19
Pebbly sandstone	2	15	3	4	9	33
Column totals	59	166	14	18	33	290

Table C-14. Summary table, outcrops F5 + D1 + D2.

Step no.	Cell coord.	Observed frequency	Expected frequency	Chi square	Probability
1	2,1	52.5	8.45	22.98	0.0607
2	1,2	49.5	14.16	12.69	0.4723

APPENDIX D

POINT COUNT DATA

Table D-1. Point count data for sandstones of the Tellico Formation near Avens Bridge, Virginia.

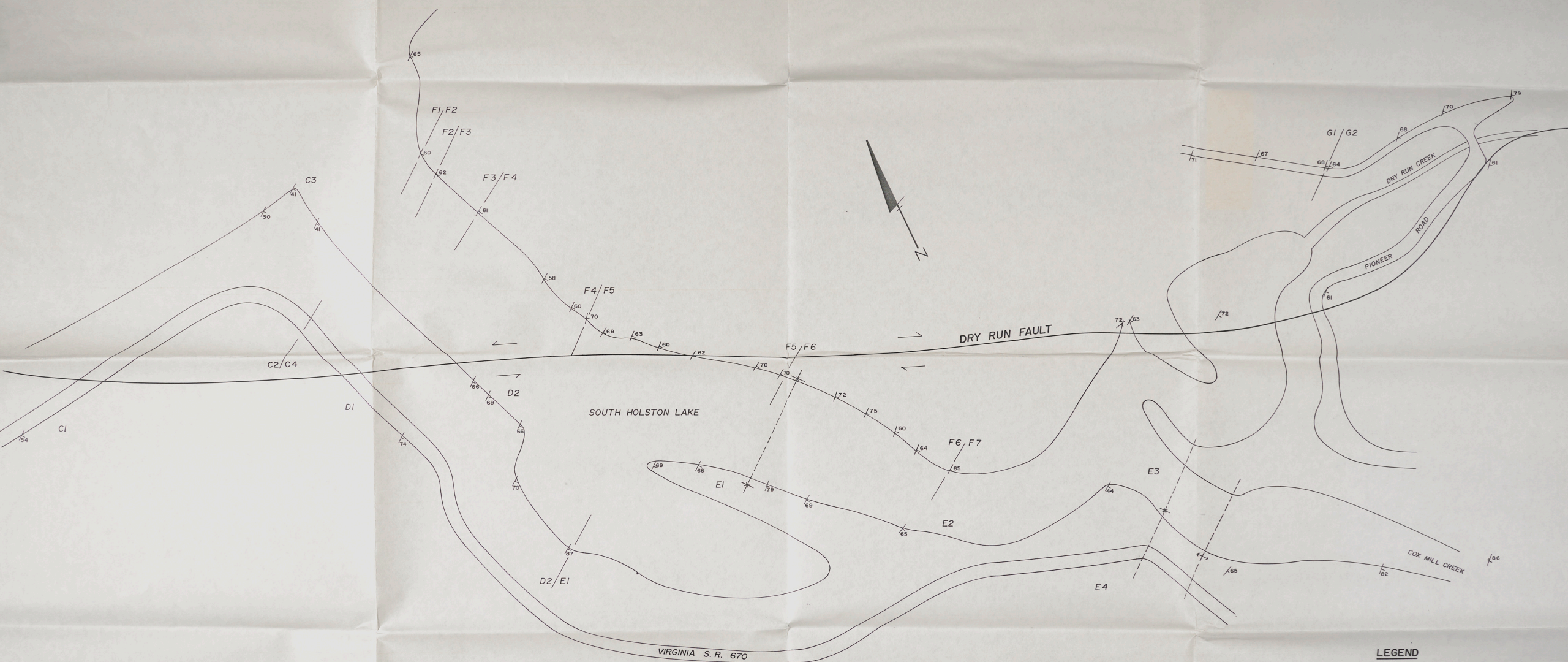
Sample Number	C3-1B	C3-3B	B-5	S-4	S-10	S-12	G2-93A	92-98E	G2-149A	G2-185	S-2	S-8	S-9
Monocrystalline quartz	9.7	6.8	5.9	5.1	6.2	5.1	5.2	6.1	5.1	6.8	1.3	2.0	3.2
< 5° undulosity													
Monocrystalline quartz	26.8	28.7	29.9	41.2	38.3	32.1	34.0	41.3	31.4	26.8	4.7	9.8	13.1
> 5° undulosity													
Polycrystalline quartz	0.2	0.6	0.7	0.6	2.5	1.0	0.6	0.7	0.4	0.4	0.8	0.5	0
< 3 crystals													
Polycrystalline quartz	1.1	3.2	1.8	2.7	5.4	0.6	2.0	2.8	1.9	2.0	3.4	1.5	3.2
> 3 crystals													
Quartz total	37.8	39.3	38.3	49.6	52.4	38.8	41.8	50.9	38.8	36.0	10.2	13.8	19.5
Orthoclase	0.9	0.9	0.2	1.8	0.7	0.6	0.3	1.4	0.4	0.9	0	0	0.5
Microcline	0	0.6	0.2	0.3	0.2	0.4	0.9	0	0.2	0.2	0	0	0
Plagioclase	2.3	2.3	3.8	3.9	4.9	2.1	3.2	3.1	1.9	2.3	0	0.5	0
Perthite	0	0	0	0	0	0	0.2	0	0	0	0	0	0
Feldspar total	3.2	3.8	4.2	6.0	5.8	3.1	4.6	4.5	2.5	3.4	0	0.5	0
Micrite clasts	4.3	5.4	8.9	2.4	2.9	4.9	5.2	3.8	5.4	6.7	26.6	18.2	24.0
Pelmicrite clasts	0	0.4	0.7	0.3	0	0.2	0.2	0	0.2	0.5	3.8	7.4	4.5
Intramictic clasts	0.2	0	0	0	0	0	0	0	0	0	0	1.0	0.5
Detrital vein calcite	0.2	0	0	0.6	0	0.2	0	0	0.2	1.0	1.7	2.0	0.9
Argillaceous clasts	11.7	11.4	7.0	11.3	6.7	12.5	13.4	7.0	10.3	7.0	10.2	6.4	6.3
Sandstone clasts	1.4	1.5	0.7	1.2	1.3	1.7	2.0	0	1.7	2.2	8.5	5.4	10.0
(Unicoi Fm?)													
Sandstone clasts	0	0	0	0	0	0	0	0	0.2	0.2	3.0	1.5	1.4
(other)													
Siltstone	0.5	0.6	1.2	1.2	2.2	0.8	0.4	0.5	0.4	1.3	3.0	3.0	2.3
Chert	1.4	1.3	0.9	1.8	3.1	0.9	1.3	1.9	1.7	2.9	3.4	3.4	4.1
Metamorphic Rock	0.2	0.6	0.7	1.2	0.9	0.2	0.4	0.2	0.2	1.1	0	0.5	0.9
Fragment													
Volcanic Rock Fragment	0.2	0.4	0.5	0.6	0.7	0	0.7	0.7	0.9	0.5	1.7	1.5	0.9
Lithic fragment	20.1	21.6	20.6	20.6	17.8	21.4	23.6	14.1	21.2	23.4	62.7	50.3	55.8
total (including chert)													
Pseudomatrix	17.4	17.1	15.8	8.9	6.7	6.4	8.6	8.9	14.6	14.1	15.1	21.3	11.4
Matrix	14.7	12.9	14.1	7.5	7.2	16.5	13.9	17.1	17.7	14.6	8.2	10.1	9.4
Calcite Cement	4.1	4.1	6.2	5.4	9.7	12.9	5.4	3.8	3.8	6.7	3.8	3.9	2.7
Chlorite Cement	0.6	0.3	0.4	-	-	-	0.7	-	0.2	0.8	-	-	-
Muscovite	0.2	0	0.2	0.6	0	0.2	0.4	0	0.2	0.2	-	-	-
Biotite	0.7	0.4	0.5	0	0.2	0.4	0.2	0.2	0.4	0.2	-	-	-
Heavy Minerals	0.4	0.2	0.2	0.3	0	0.2	0.4	0.5	0.2	0.2	-	-	-
(Zircon and Rutile)													
Opauques	0.7	0.4	0	0.6	0	0.6	0.4	0	0.6	0.2	-	-	-

VITA

Bryn David Howze was born in Johnson City, Tennessee, on November 27, 1956. He attended elementary schools in Memphis and Piney Flats, Tennessee. While living in Piney Flats, Bryn graduated from Sullivan East High School in June of 1975. In September of that same year he entered the University of Tennessee, Knoxville. He graduated with a major in geology in August of 1979.

Bryn returned to the University of Tennessee in September of 1979 as a graduate student in geology and served as a graduate teaching assistant from September 1979 to June 1980. From June 1980 to June 1981, he was a graduate research assistant. He worked as a geologist in the coal consulting industry in Knoxville from May 1983 to September 1985. Bryn returned to the University of Tennessee in September 1985 to complete his degree. He received his degree in June 1987.

At this writing, Bryn is employed as a geologist at MCI Consulting Engineers, Inc. in Knoxville, Tennessee.



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- C2 OUTCROP LOCATION
- F1/F2 OUTCROP CONTACT