SEQUENCE STRATIGRAPHY OF THE SILURIAN CLINCH FORMATION, NORTHEASTERN TENNESSEE AND SOUTHWESTERN VIRGINIA

by

CHRISTOPHER LEE GINN

(Under the Direction of Steven M. Holland)

ABSTRACT

Stratigraphic columns of the Clinch Formation were measured at three locations in northeastern Tennessee and southwestern Virginia. Two additional sections were measured in a portion of the overlying Clinton Formation, which has similar facies. Four additional incomplete exposures of the Clinch were used to supplement regional facies descriptions and relations. The Clinch Formation contains three depositional sequences with two distinct facies associations representing eight individual facies. The first and second sequences contain wave-dominated shelf facies associations with transgressive (TST), highstand (HST), and falling-stage (FSST) systems tracts. The FSST is expressed by surfaces of forced regression, which become more frequent down depositional dip. A major sequence boundary is recognized across the study area, above which a reorganization of the depositional basin occurs. Lying above this sequence boundary, the third sequence is an incised-valley fill with tidally dominated estuarine facies in lowstand and transgressive system tracts, possibly with HST and FSST deposits.

INDEX WORDS: Clinch Formation, Hagan Shale, Poor Valley Ridge Sandstone, Silurian, sequence stratigraphy, wave-dominated shelf, tidal estuary

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DEDICATION

I would like to dedicate this thesis to my wonderful family, Elbert L. Ginn, Jr., Sherri L. Ginn, and Asa Ginn. I would be nowhere without your continued support and love. I am forever in debt.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

This thesis is best read as one chapter. The second chapter includes the discussion of the previous literature, geological background and stratigraphic framework, methods, results, interpretation, discussion, and conclusions. The third chapter concludes the research.

The purpose of this study is to re-evaluate the stratigraphy of the early Silurian Clinch Formation of northeastern Tennessee and southwestern Virginia and provide a sequence stratigraphic framework for it. Stratigraphic columns of the Clinch Formation (Hagan Shale and Poor Valley Ridge Sandstone) were measured at three locations in northeastern Tennessee and southwestern Virginia. Two additional sections were measured in a portion of the overlying Clinton Formation, which has similar facies. Four additional incomplete exposures of the Clinch were used to supplement regional facies descriptions and relations. This paper established two facies associations representing eight individual facies.

Previous research has reported on regional lithostratigraphy and brief facies models for the Clinch Formation and correlative units, however these studies did not examine important surfaces in the sequence stratigraphy paradigm (Cotter 1983; Driese 1991, Driese 1996, and Brett et al. 1998). This study does so, recognizing flooding surfaces, surfaces of forced regression, and sequence boundaries within the Clinch Formation.

CHAPTER 2

SEQUENCE STRATIGRAPHY OF THE SILURIAN CLINCH FORMATION, NORTHEASTERN TENNESSEE AND SOUTHWESTERN VIRGINIA

INTRODUCTION

The Lower Silurian (Llandovery) Clinch Formation of the Valley and Ridge province in eastern Tennessee and southwestern Virginia (Fig. 2.1) includes two members, the Hagan Shale and the Poor Valley Ridge Sandstone. The Clinch Formation is correlated with the Rockwood Formation of Tennessee (Fig. 2.2; Miller 1976). Regional lithostratigraphic nomenclature varies, but for the sake of clarity, this study will use the Virginia nomenclature.

The Clinch Formation was deposited in the Appalachian foreland basin (Fig. 2.3). It represents a clastic wedge associated with the Blountian phase of the Middle Ordovician to Early Silurian Taconic Orogeny (Driese 1991), the first of three accretionary events to have affected the Appalachian orogen in the Paleozoic (Williams and Hatcher 1982).

Previous research on the Clinch Formation established a facies model and regional correlations along strike of the Appalachian Mountains for the Clinch Formation and correlative units (Cotter 1983; Driese 1991, Driese 1996, and Brett et al. 1998). Regional interpretations of the Clinch Formation have focused on lithostratigraphy. These studies did not examine important surfaces in the sequence stratigraphy paradigm such as flooding surfaces, surfaces of forced regression, or sequence boundaries. In addition, the facies descriptions in these studies are brief and only three facies were described for the Clinch Formation: a cross-stratified sandstone facies, a hummocky cross-stratified sandstone, and a thin-bedded sandstone and shale facies (Fig. 2.4; Driese 1991).

The objective of this study is to re-evaluate the stratigraphy of the Clinch Formation. This study presents on interpretation of five measurable sections and four supplemental exposures to create new facies models and a sequence stratigraphic framework for the early Silurian deposits of the Clinch Formation in northeastern Tennessee and southwestern Virginia.

GEOLOGICAL SETTING AND STRATIGRAPHIC FRAMEWORK

Regional studies have suggested the depositional history of the southern Appalachians is characterized by Late Ordovician regression followed by widespread transgression at the beginning of the Silurian (Cotter 1983; Driese 1991, Driese 1996, and Brett et al. 1998). Upper Ordovician red beds of the Juniata Formation are interpreted as tidal flat deposits, and they also display evidence of paleosols (Ghazizadeh 1985). Major transgression began during the early Silurian, with deposition of the thin-bedded sandstone and shale facies of the Clinch Formation (Driese 1991). A retrograding shoreline dominated by erosional shoreface retreat characterized Early Silurian deposition (Driese 1991). As the Taconic thrust load began to introduce sediment to the system at a faster rate than sea level rise, shoreline progradation began (Driese 1991). During this progradation, deposition of the hummocky cross-stratified sandstone and the cross-stratified sandstone facies of the Clinch Formation began (Driese 1991). Overall, the Clinch Formation records initial deepening followed by a shallowing. The Clinton Formation overlies the Clinch and represents initiation of subsequent deepening.

Contacts between facies of the Clinch Formation have been interpreted as gradational, and therefore following Walther's Law (Fig. 2.4; Driese 1991), suggesting that facies, which conformably overlie one another, must have accumulated in adjacent depositional environments. However, the thin-bedded sandstone and shale facies shares a Waltherian contact with both the cross-stratified sandstone facies and the hummocky cross-stratified sandstone (Fig. 2.4). This violates the accepted wave-dominated shelf facies model (Plint 2010) in two ways. First, it suggests that the offshore thin-bedded sandstone and shale facies and the shoreface cross-stratified sandstone facies were deposited adjacent to one another. Second, it suggests that the offshore facies has Waltherian contacts with both transition zone and upper shoreface deposits. Thus, the reported facies relationships of Driese (1991) invite further investigation and interpretation.

METHODS

Stratigraphic columns of the Clinch Formation were measured at three locations in northeastern Tennessee and southwestern Virginia (Fig. 2.1). Three of these sections are complete (Flat Gap, Stickleyville, and Hagan). Four additional incomplete outcrops (House Mountain, Bean's Gap, Little War Gap, and Little Moccasin Gap) were used to supplement regional facies descriptions and relations. Two additional sections were measured in a portion of the overlying Clinton Formation, which has similar facies (Cumberland Gap and Tennessee/Virginia Border). Measurable columns in the Appalachian Mountains are rare, owing to thick vegetation and few railroad and road cuts. Locations were chosen from sites where previous stratigraphic work on the Clinch Formation was conducted (Driese 1991; Driese 1996), and supplemented with newly scouted sites.

Each section was described at 10 cm resolution, and descriptions include sedimentary structures, thickness, grain size, sorting, lithology, color, thickness, bioturbation, ichnofossils, and paleocurrents. The Ingram (1954) scale for bedding thickness was used in this study: very thin (1-3 cm), thin (3-10 cm), medium (10-30 cm), thick (30-100 cm), very thick (100-300 cm), and massive (>300 cm). Important surfaces representing sequence stratigraphic boundaries (e.g., flooding surfaces, surfaces of forced regression, sequence boundaries) were described in detail. Paleocurrents were recorded from azimuths from the maximum foreset dip-directions of high-angle cross-strata, wave-ripple crest orientation, and flute and gutter cast orientations (Fig. 2.5; Driese 1991). Where sedimentary rocks are tectonically tilted, stereographic correction was used to determine orientation prior to deformation (Driese 1991; Collinson and Thompson 1989).

Although the cross-section line has a strong component of depositional dip, based on previous studies (Driese 1991), it also includes a substantial component of depositional strike. To compensate, two additional short columns from the Clinton Formation (Cumberland Gap and Tennessee/Virginia border) and four exposures that were insufficient for measuring section from the Clinch Formation (House Mountain, Bean's Gap, Little War Gap, and Little Moccasin Gap) were used to supplement regional facies descriptions and relations detailed in the three primary sections.

CLINCH FORMATION FACIES ASSOCIATIONS

Facies were identified in the field based on sedimentary structures, lithology, lithologic associations, grain size, and ichnofossils. Two major facies associations were recognized within the Clinch Formation: (A) a wave-dominated shelf association, and (B) a tidal estuarine association (Fig. 2.6 and 2.7).

Facies Association A: Wave-dominated Shelf

Facies Association A contains four facies: offshore (A-1), offshore transition/lower shoreface (A-2), bioturbated shoreface (A-3), and cross-stratified shoreface (A-4). Facies association A is present in the Hagan Shale, the lower part of the Poor Valley Ridge Sandstone, and the overlying Clinton Formation.

Facies A-1: Offshore

Description – Facies A-1 is dominated by gray mudstone with scarce very thin to thin beds of fine-grained sandstone (Fig. 2.8A). Facies A-1 contains gutter casts that range in width from 5 cm to 25 cm (Fig. 2.8B). Paleocurrents from 62 gutter cast orientations (including Facies A-2) indicate an NE-SW sense of flow at depositionally down-dip locations and a more E-W sense of flow in up-dip locations (Fig. 2.5; Driese 1991). Paleocurrents from twenty flute casts (including Facies A-2) indicate SW flow at down-dip locations and E-NE flow at up-dip locations (Fig. 2.5; Driese 1991). Planar lamination and hummocky cross-stratification is present in sandstone beds (Fig. 2.8C). Abundant burrow casts are present on the soles of some sandstone beds (Fig. 2.8D). A ball-and-pillow structure is present at Stickleyville (22 m; numbers in parentheses indicate location in measured sections).

Facies A-1 ranges from 6 m to 23 m thick in measured sections, but is generally incompletely exposed. For example, Stickleyville is the only location where the basal contact with the Juniata Formation is recognized. Thus, the true thickness for Facies A-1 may exceed 23 m. However, from limited exposure, Facies A-1 generally thickens down depositional dip.

At Stickleyville, where the basal contact with the Juniata Formation is visible, Facies A-1 sharply overlies it (1 m). At Flat Gap, Hagan, Cumberland Gap, and Tennessee/Virginia Border, measurable sections all begin with Facies A-1. Facies A-1 is sharply overlain by Facies A-2, offshore transition/lower shoreface deposits, at Flat Gap (7 m), Stickleyville (24 m), and Hagan (20 m, 24 m, and 33 m). At Hagan, Facies A-1 also gradationally (22 m) and sharply (25.5 m) overlies offshore transition/lower shoreface deposits of Facies A-2 and sharply overlies tidal flat deposits of Facies B-2 (57 m).

Interpretation – Facies A-1 is interpreted as having been deposited in an offshore shelf environment that was beyond the influence of most current or wave processes. The dominance of mudstone indicates a generally calm depositional environment. Very thin to thin beds of fine-grained sandstone with sharp erosional bases, planar lamination, and hummocky cross-stratification are typical of episodic storm deposition (Plint 2010). These storm beds were deposited over cohesive muds that were reworked by organisms, resulting in burrow casts (MacEachern et al. 2010). Emplacement of distal storm beds below fair weather wave base tends to increase preservation potential (MacEachern and Pemberton 1992). The presence of a ball-and-pillow structure suggests liquefaction of unconsolidated sediments during an earthquake or rapid deposition of sand on uncompacted muds with excess poor fluid pressures (Boggs 2006). Overlying facies include offshore transition/lower shoreface and bioturbated shoreface deposits, which suggest Facies A-1 is the lowermost facies in a wave-dominated shelf succession (Plint 2010).

The down-dip change in gutter and flute cast orientation is interpreted as reflecting a circulation that becomes less shore-perpendicular and more influenced by a SW geostrophic flow (Driese 1991). Typically, gutter casts in nearshore facies are shore-perpendicular (Leckie and

Krystinik 1989). However, small gutters of thinner bedded, more offshore facies tend to be shore-oblique to shore-parallel and may record geostrophic flows (Aigner 1985; Plint 2010).

Facies A-2: Offshore Transition / Lower Shoreface

Description – Facies A-2 consists of mudstone with common very thin to thin beds of fine-grained sandstone that pass upwards into thin to medium beds of fine-grained sandstone beds separated by thin mudstone intervals (Fig. 2.8E). Gutter casts ranging from 5 cm to 10 cm are present. Paleocurrent data is discussed in Facies A-1. A ball-and-pillow structure (20.5 m) and abundant load casts (20.5 m; Fig. 2.8F) are present at Hagan. Prod marks are also present on a few beds at Stickleyville (25 m to 26 m). Sandstone beds exhibit rare current-ripple lamination, which was observed only at Stickleyville (24.5 m). Phosphate pebbles are present at the base of Facies A-2 in two locations at Hagan (20 m and 33 m).

Total thickness of Facies A-2 ranges from 3 m to 7 m, and regional trends in thickness are not apparent.

Facies A-2 sharply overlies offshore Facies A-1 at Flat Gap (7 m), Stickleyville (24 m), and Hagan (20 m, 24 m, and 33 m). It is sharply overlain by bioturbated shoreface deposits of Facies A-3 at both Stickleyville (26 m) and Hagan (34.5 m). In addition, it is both sharply (25.5 m) and gradationally (22 m) overlain by offshore facies A-1 at Hagan. At Flat Gap, Facies A-2 sharply overlies (15 m) and is sharply overlain (11 m and 17.5 m) by cross-stratified shoreface deposits of Facies A-4.

Interpretation – Facies A-2 is interpreted to record deposition in the offshore transition to lower shoreface in the region lying between storm and fairweather wave base. Thin to medium beds of sandstones have erosional bases, planar lamination and hummocky cross-stratification, and are capped by deposits of mud, typical of storm beds (Plint 2010). Storm beds become more proximal up section through Facies A-2 (Aigner 1985). The lack of hummocky cross-stratification suggests a relatively low-energy margin (Clifton 2006). The upward increase in number and thickness of sandstone storm beds up section suggests upward shallowing. Similar to Facies A-1, the presence of a ball-and-pillow structure and load casts suggests rapid deposition of sand on uncompacted muds with excess poor fluid pressures or liquefaction of unconsolidated sediments during an earthquake (Boggs 2006). The significance of phosphate pebbles at the base of Facies A-2 will be discussed below, in Sequence Stratigraphic Framework.

Facies A-3: Bioturbated Shoreface

Description – Facies A-3 is characterized by tan very thick beds of medium to coarse sandstone that coarsens upwards and is pervasively bioturbated. This facies is seen distinctly at Hagan and Stickleyville and exhibits biofabric ranging from ii3-ii6, with ii4-5 being the most common (Droser and Bottjer 1986). No individual traces were identified. Bioturbation is often expressed as gray, tan, and orange mottling, such as at Stickleyville (26 m to 27 m; Fig. 2.9A). At Hagan, Facies A-3 occurs in one bed (34.5 m). At Stickleyville, it occurs in two distinct beds (26 m and 28 m). Phosphate pebbles are present at the base of the overlying bed (28 m).

Thickness of this facies ranges from 2 m to 3 m. This facies is thinnest at Hagan, the most distal location, and it increases towards the depositionally updip Stickleyville.

At both Stickleyville (26 m) and Hagan (34.5 m), Facies A-3 sharply overlies the subjacent offshore transition/lower shoreface Facies A-2. At Hagan, the upper bedding surface of Facies A-3 is characterized by a hematite-cemented sandstone conglomerate (36.5 m; Fig.

2.9B). Above this upper bedding surface lies tidal flat deposits of Facies B-2. Mudstone with sand-filled burrows of Facies B-4 sharply overlie Facies A-3 at Stickleyville (29.3 m).

Interpretation – Facies A-3 is interpreted as having been deposited in the upper shoreface, a region above fairweather wave base in an area affected by shoaling and breaking waves (Plint 2010). The intense and pervasive bioturbation in the sandstones of Facies A-3, and general lack of sedimentary structures, suggest considerable time between storms or limited storm influence (Baniak et al. 2014).

Facies A-4: Cross-stratified Shoreface

Description – Facies A-4 is dominated by large-scale (> 5 cm; Ashley 1990), primarily trough cross-stratified thick to very thick beds of medium to coarse gray-green to dark tan sandstone (Fig. 2.9C). No biogenic sedimentary structures were identified in Facies A-4.

This facies is present only at Flat Gap, the most depositionally updip outcrop, where this facies ranges from 4.5 m to 5 m thick. Of the two intervals recognized, the uppermost is the thickest (starting at 17.5 m).

Facies A-4 sharply overlies offshore transition/lower shoreface deposits of Facies A-2 (11 m and 17.5 m) and is sharply overlain by Facies A-2 (15 m) and tidal compound dunes of Facies B-3 (23 m). The limited and overgrown exposure at Flat Gap prevents more detailed description of this facies.

Interpretation – Similar to Facies A-3, Facies A-4 lacks mud and is interpreted as having been deposited in the upper shoreface, a region above fairweather wave base in an area affected by shoaling and breaking waves (Plint 2010). Large-scale trough cross-stratification is the only clear sedimentary structure observed, and it tends to commonly be preserved in upper shoreface deposits (Plint 2010). It is unclear if bioturbation or the extremely weathered nature of the rock contributes to the lack of observed sedimentary structures. Important to the interpretation as upper shoreface deposits is the relationship to the down-section offshore transition/lower shoreface deposits of Facies A-2 at Flat Gap.

Summary of Facies Association A

Previously, Facies Association A was interpreted as only two facies, thin-bedded sandstone and shale and cross-stratified sandstone (Fig. 2.4; Driese 1991). These two facies were inferred to represent deposition from distal shelf settings to the upper shoreface. The data from this study suggests that original interpretation of facies and depositional environments were simplified. Facies Association A expands the original interpretation and provides a detailed wave-dominated shelf facies model for the Hagan Shale, the lower part of the Poor Valley Ridge Sandstone, and the overlying Clinton Formation. Facies Association A contains four facies: offshore (Facies A-1), offshore transition/lower shoreface (Facies A-2), bioturbated shoreface (Facies A-3), and cross-stratified shoreface (Facies A-4). Paleocurrent data from gutter and flute casts (Fig. 2.5) suggest a NE-SW oriented paleoshoreline with primarily unidirectional paleoflow parallel to shore to the SW.

Facies Association B: Tidal Estuary

Facies association B contains four facies: tidal channel (B-1), tidal flat (B-2), tidal compound dunes (B-3), and mudstones with vertical sand-filled burrows (B-4). Facies Association B is present in the upper part of the Poor Valley Ridge Sandstone.

Facies B-1: Tidal Channel

Description – Facies B-1 is characterized by thick to very thick fine to medium-grained fining-upward beds of sandstone interbedded with thin beds of mudstone (Fig. 2.9D). Large-scale trough cross-stratification with clay drapes, 3D current ripples, and mud rip-up casts are common. A ball-and-pillow structure ~30 cm in width is present in the uppermost tidal channel (51.5 m; Fig. 2.9E).

Facies B-1 is recognized only at Hagan and thickness ranges from 2 m to 4 m thick. This facies increases up-section, with the uppermost occurrence being the thickest.

Facies B-1 both sharply overlies (39 m and 48 m) and is sharply overlain (40.5 m and 52 m) by tidal flat deposits of Facies B-2. Each interval of Facies B-1 fines upward to the contact with Facies B-2.

Interpretation – Facies B-1 represents estuarine tidal channel deposits within an incised-valley fill. Large-scale trough cross stratification has common clay drapes suggesting tidal influence (Dalrymple 2010). Fining-upward beds of sandstone interbedded with thin beds of mudstone are typical of tidal channel deposits (Dalrymple 2010). Furthermore, mud rip-up clasts are common in tidal channel and tidal flat successions (Dalrymple 2010). The ball-and-pillow structure suggests liquefaction of unconsolidated sediments during an earthquake or rapid deposition of sand on uncompacted muds with excess poor fluid pressures (Boggs 2006). Each tidal channel begins at a flooding surface and sharply transitions into the tidal flat deposits of Facies B-2.

Facies B-2: Tidal Flat

Description – Facies B-2 is characterized by beds of very thin mudstone with very thin to thin fine-grained sandstone beds that demonstrate an overall fining-upward trend. 3D current-ripples (Fig. 2.9F) and large-scale trough cross-stratification with clay drapes is common. Mud rip-up clasts are common throughout (Fig. 2.10A). Small-scale 2D vortex-ripples are present (Fig. 2.10B). Paleocurrent data from 20 wave-ripple crests indicate a NW-SE sense of flow (Fig. 2.5; Driese 1991).

This facies is found only at Hagan, where it ranges from 2 m to 7.5 m in thickness. Thickness of Facies B-2 varies within the section at Hagan. The thinnest occurrence is the lowermost (36.5 m) and the thickest occurrence is in the middle interval (40.5 m). The first of these three deposits at Hagan demonstrates a different pattern than the overlying two. The first deposit of 2 m has sand beds that thicken upsection to the base of the overlying channel fill. Conversely, the two overlying occurrences show an upward decrease in sand beds and display an overall decrease in grain size.

Facies B-2 sharply overlies bioturbated shoreface deposits of Facies A-3 (36.5 m) and tidal channel deposits of Facies B-1 (40.5 m and 52 m). This facies is sharply overlain by both tidal channel deposits of Facies B-1 (39 m and 48 m) and offshore deposits of Facies A-1 (57 m).

Interpretation – Facies B-2 is interpreted as having been deposited in a tidal flat environment. The fining-up nature of these tidal flat deposits indicates an upward shallowing (Dalrymple 2010). 3D current-ripples, large-scale trough cross stratification, and mud rip-up clasts are all typical features in tidal flat deposits (Dalrymple 2010).

The presence of 2D vortex-ripples in Facies B-2 suggests this is an open-coast tidal flat (Yang et al. 2005). Open-coast tidal flat sedimentation is typically wave-influenced despite the existence of a large tidal range (Yang et al. 2005). The thickness of tidal channel/tidal flat successions measured in section is approximately 10 m, suggesting a macrotidal setting. Twenty paleocurrent orientations on wave-ripple crests from Facies B-2 suggest a NW-SE sense of flow, or a NE-SW oriented paleoshoreline. In addition, 100 paleocurrent wave-ripple orientations from other localities in the Clinch indicate a similar NW-SE flow direction (Driese 1991).

Facies B-3: Tidal Compound Dunes

Description – Massive beds of medium to coarse-grained sandstone with compound cross-stratified dunes characterize Facies B-3. These compound dunes are characterized by complex bounding surfaces that intersect master bedding planes at low angles and help define foresets of very large-scale sets of cross-strata (Driese 1991; Driese 1996). Second- and even third-order surfaces separating smaller scale sets of cross-strata are present within the major foresets. Bi-directional foresets are common (Fig. 2.10C). Tracing of beds on photomosaics demonstrate the complexity of these deposits (Fig. 2.11 and 2.12). Sigmoidal cross bedding is present at Bean’s Gap (Fig. 2.10D). *Arthrophycus* traces are present on the soles of beds at Little War Gap (Fig. 2.10E), Stickleyville, and Bean’s Gap. 214 azimuths were obtained from the maximum foreset dip direction of high-angle cross-strata (Driese 1991). Paleocurrent trends are primarily unimodal and show a W-NW transport direction (Fig. 2.5; Driese 1991). A SE trend is present, albeit minor (Driese 1991).

This facies is present at Flat Gap, Stickleyville, House Mountain, Bean's Gap, Little War Gap, and Little Moccasin Gap, all depositionally updip localities. The thickness of this facies at measurable localities ranges from 11 m at Stickleyville to 16 m at Flat Gap. The thicknesses must be considered minimum thicknesses as a result of being at the end of measurable outcrops at each location.

At Stickleyville, Facies B-3 sharply overlies mudstones with sand-filled burrows of Facies B-1 (29.5 m). At Flat Gap Facies B-3 sharply overlies cross-stratified shoreface deposits of Facies A-4 (23 m). At its upper contact Facies B-3 is sharply overlain by offshore Facies A-1 of the Clinton Formation (Driese 1991; Driese 1996), but this contact is not exposed at Flat Gap or Stickleyville.

Interpretation – Facies B-3 was originally interpreted as "sand waves" being maintained by a storm-influenced wave-dominated shoreface environment (Driese 1991). Facies B-3 is here interpreted as tidal compound dunes having been deposited in a tide-dominated estuary. Tidal compounds are characterized by internal discontinuities created by the troughs of smaller and faster moving superimposed dunes as they migrate down the lee face of the more slowly migrating large dune (Dalrymple 2010). Tracing of bedding in photomosaics displays these characteristics (Fig. 2.11 and 2.12). Deposits of compound dunes in Facies B-3 coarsen upward, because the current speed is higher near the crest, and the trough and bottom-set region can be the site of mud deposition (Dalrymple 2010; Olariu 2012). In addition, bi-directional cross-stratification and sigmoidal cross-bedding are characteristics of tidal deposits (Dalrymple 2010).

The most seaward facies in tide-dominated estuaries consists of elongate sand bars and compound dunes deposits are commonly found on these elongate sand bars (Dalrymple 2010). Possible modern analogues to this depositional environment are found in the Bay of Fundy (Dalrymple 1984) and the Ager Basin, Spain (Olariu 2012).

Azimuths from the maximum foreset dip-directions of high-angle cross-strata show a unimodal primary transport direction to a W-NW direction. This is interpreted to be transport offshore, trending down a paleoslope dipping west (Yeakel 1962, Meckel 1970, Whisonant 1977, and Driese 1991).

Facies B-4: Mudstones with Vertical Sand-filled Burrows

Description – Facies B-4 is characterized by 70% very thin very fine sandstone beds and 30% very thin shale beds. Beds of mudstone contain abundant vertical burrows of *Skolithos* filled with sand (Fig. 2.10F).

This facies is present only at Stickleyville, where it is 0.8 m thick. It sharply overlies (29.3 m) bioturbated shoreface deposits of Facies A-3 and is sharply overlain (30.5 m) by tidal compound dunes of Facies B-3.

Interpretation – *Skolithos* ichnofacies is indicative of high levels of current or wave energy and is typical in clean, well-sorted, loose, or shifting substrates (MacEachern et al. 2010). This ichnofacies occurs in many environments, including the foreshore and shoreface of beaches, bars, and spits, estuarine channels, tidal inlets, and tidal channels (MacEachern et al. 2010; Baniak 2014). Additional evidence is often needed to correctly identify depositional environment, such as cross-bedding type and occurrence of other ichnofossils. Facies B-4 lacks other identifiable ichnofossils. Facies B-4 contains a substantial mud component, which the underlying bioturbated shoreface deposits of Facies A-3 do not. This suggests that Facies B-4 is associated with the overlying tidal estuarine deposits of Facies Association B. This leads to the determination that Facies B-4 represents deposition in a tidal estuarine channel. Limited exposure of Facies B-4 renders the interpretation uncertain, as does the wide array of environments in which the *Skolithos* ichnofacies exists.

Summary of Facies Association B

Previously, Facies Association B was interpreted as only two facies, hummocky cross-stratified sandstone and cross-stratified sandstone (Fig. 2.4; Driese 1991). Data from this study suggests that original interpretation of facies and depositional environments were simplified. Facies Association B expands the original interpretation by offering a new tidal estuary facies model for the upper part of the Poor Valley Ridge Sandstone and contains four facies: tidal channels (Facies B-1), tidal flats (Facies B-2), tidal compound dunes (Facies B-3), and mudstones with vertical sand-filled burrows (Facies B-4). Paleocurrent data from wave-ripple crests and azimuths from the maximum foreset dip-directions of high-angle cross-strata show a unimodal primary transport direction to a W-NW direction (Direse 1991). This is interpreted to be transport offshore, trending down a westward-dipping paleoslope (Yeakel 1962, Meckel 1970, Whisonant 1977, and Driese 1991).

SEQUENCE STRATIGRAPHIC FRAMEWORK

The Clinch Formation encompasses 3 depositional sequences (Fig. 2.7), where each of the four systems tracts - Lowstand Systems Tract (LST), Transgressive Systems Tract (TST), Highstand Systems Tract (HST), and Falling-Stage Systems Tract (FSST) - is present (Hunt and Tucker 1992; Van Wagoner et al. 1990). However, individual sequences do not include all four systems tracts.

Sequence 1

The basal contact of Sequence 1 is sharp and only recognized at Stickleyville (m 1). A biostratigraphic gap of at least two million years occurs at this surface that separates underlying Ordovician tidal flat deposits of the Juniata Formation from the Hagan Shale member of the Clinch Formation (Driese 1991; Holland and Patzkowsky 1996). This gap, evidence of paleosols (Ghazizadeh 1985), and the non-Waltherian relationship of the overlying offshore deposits of the Hagan Shale indicate that this surface records a hiatus and is a subaerial unconformity. It is interpreted as a combined transgressive surface - sequence boundary (TS/SB).

The lower part of Sequence 1 contains offshore deposits of the Hagan Shale, which represent an abrupt deepening of facies above the tidal flat deposits of the Juniata Formation. At Hagan, the most down-dip location, storm beds in offshore deposits decrease upwards and overall mud content increases upwards, indicating a deepening trend in the lower part of Sequence 1 (0 m to 10.5 m). At Stickleyville, a similar deepening trend is recognized (1 m to 6 m). This is interpreted as retrogradational stacking, and thus suggests TST deposits.

Above the TST deposits, at Hagan and Stickleyville, Sequence 1 demonstrates very subtle increases in storm bed frequency and thickness immediately up-section. This suggests a net upward shallowing and is interpreted as initiation of progradational HST deposits. The maximum flooding surface (MFS) is the surface that designates the transition from TST to HST deposition. This surface is difficult to place precisely at Hagan and Stickleyville, and it can be inferred only by the subtle shift in facies.

The upper part of Sequence 1 is characterized by sharp surfaces, which record abrupt shallowing and an abrupt increase in grain size. These surfaces are well exposed at Hagan, Stickleyville, and Flat Gap. At Hagan, directly above this initial abrupt surface, 1 mm to 1 cm phosphate pebbles are present in a thin bed of coarse sandstone (20 m; Fig. 2.13A). At Stickleyville, one of these abrupt surfaces lies at the base of a single sandstone dune encased by offshore muds above and below (12 m; Fig. 2.13B). The initial abrupt surface at Flat Gap is characterized by a similar thick bed of coarse sandstone encased by offshore muds (3.5 m; Fig. 2.13C). Above these first surfaces, facies relations demonstrate a rapid net upward shallowing from offshore to upper shoreface deposits in all sections measured. This trend of abrupt surfaces with anomalous coarse-grained beds of sandstone above and the rapid net upward shallowing is interpreted as surfaces of forced regression (SFR), and the beginning base-level fall in the FSST. The end of HST deposition is marked by the basal surface of forced regression (BSFR). This surface is recognized at both the Hagan (20 m) and Stickleyville (12 m). However, at Flat Gap, it is not possible to interpret the first surface of forced regression (3.5 m) as the BSFR, owing to limited exposure. The FSST marks a stepped shallowing in all sections measured and is characterized by multiple abrupt surfaces of forced regression.

The top of Sequence 1 is characterized by a hematite-cemented sandstone conglomerate in the bioturbated shoreface facies A-3, and it is overlain by tidal flat deposits of Facies B-1 at Hagan (37 m; Fig. 2.9B; Fig. 2.13D). This surface is characterized at Stickleyville by an abrupt transition from bioturbated shoreface deposits of Facies A-3 to the mudstones with vertical sand-filled burrows of Facies B-4 (Fig. 2.13E). At Flat Gap, the upper surface of Sequence 1 is characterized by an abrupt shift to the deeper water offshore transition zone/lower shoreface Facies A-2. These suggest the upper surface of Sequence 1 is a major sequence boundary that is recognized in all three primary sections. At Hagan and Stickleyville, this sequence boundary separates underlying wave-dominated shelf facies of Sequence 1 from overlying tidal estuary deposits. This exposure surface of Sequence 1 is similar to recently studied examples of incised valley fills (Nordfjord et al. 2005). At Flat Gap, this sequence boundary separates wave-dominated shelf facies of Sequence 1 from another succession of wave-dominated shelf facies.

Sequence 1 is 35 m thick at Hagan, 26 m at Stickleyville, and 15 m at Flat Gap. Because the contact with the Ordovician Juniata Formation is not exposed at Hagan and Flat Gap, the thickness of Sequence 1 at these localities is a minimum thickness.

Sequence 2

Sequence 2 is comprised of wave-dominated shelf facies of offshore Facies A-1, offshore transition/lower shoreface Facies A-2, and cross-stratified shoreface A-4. This sequence is only recognized in section at Flat Gap.

An abrupt switch from cross-stratified shoreface deposits of Facies A-4 to the deeper water offshore transition/lower shoreface Facies A-2 characterizes the basal contact of Sequence 2. This surface is ambiguous and difficult to interpret on the outcrop. The deposits above this surface are similar to the offshore transition/lower shoreface deposits of Sequence 1, and they are interpreted to be analogous TST and HST deposits. Furthermore, cross-stratified beds of sandstone overly Facies A-2 as they do in Sequence 1 and suggests a repeat of facies architecture. Thus, this surface is interpreted as a combined transgressive surface – sequence boundary.

Cross-stratified shoreface deposits of Facies A-4 characterize the upper part of Sequence 2. The most obvious feature of Sequence 2 at Flat Gap is the abrupt upper contact. An abrupt shift in facies from cross-stratified shoreface deposits to tidal compound dunes of Facies B-3 is recognized (23 m; Fig. 2.13F). This sharp contact and drastic shift in facies association is interpreted as a major sequence boundary, similar to what is seen in at the upper contact of Sequence 1 at Hagan and Stickleyville.

The paucity of data from Flat Gap leads to a lack of certainty regarding this interpretation. However, Sequence 2 may also be present at Bean's Gap. Interpretation of a photo of now-covered outcrop supports the existence of Sequence 2 (Fig. 2.14) along the updip Clinch Mountain. Poor Valley Ridge Sandstone beds overlie a surface of truncation here, which could be the boundary between Sequence 1 and 2. Across Hwy 25E, at Bean's Gap the compound dunes of Facies B-4 are exposed (Fig. 2.11). Thus, somewhere from the edge of this photograph and the Bean's Gap outcrop, a sequence boundary between Sequence 2 and 3 exists.

Sequence 3

The upper part of the Poor Valley Ridge Sandstone and the overlying Clinton Formation comprise Sequence 3. This sequence contains tidal channel Facies B-1, tidal flat Facies B-2, tidal compound dune Facies B-3, mudstones with vertical sand-filled burrows Facies B-4 and is recognized at Hagan, Stickleyville, Flat Gap, House Mountain, Bean's Gap, Little War Gap, Little Moccasin Gap, Cumberland Gap, and the Tennessee/Virginia Border Exposure.

The basal surface of Sequence 3 is characterized by sharp contacts at all three primary sections (Fig. 2.13D, E, and F). At Flat Gap, there is an abrupt shift from cross-stratified shoreface deposits of Faces A-4 to tidal compound dunes of Facies B-3 (23 m). At Stickleyville, this surface is characterized by an abrupt shift from bioturbated shoreface deposits of Facies A-3 to mudstones with vertical sand-filled burrows of Facies B-4 (29.5 m). This surface is characterized by a shift from bioturbated shoreface deposits of Facies A-3 to tidal flat deposits of Facies B-2 at Hagan (36 m). This abrupt shift in facies association is recognized across all measurable sections and is interpreted as a major sequence boundary.

The lower part of Sequence 3 is recognized in two major variations. At the updip Flat Gap and Stickleyville, this sequence is dominated by stacked tidal compound dunes of Facies B-3. At both Stickleyville and Flat Gap, the measured columns terminate in this part of Sequence 3. Downdip at Hagan, the lower part of Sequence 3 is recognized as alternating cycles of tidal channels and tidal flats. Two shallowing-up parasequences are present (PS-1 and PS-2) characterized by flooding surfaces (38 m and 48 m). The stacking trends of these parasequences are difficult to determine with certainty. PS-2 displays a marginal increase in sand content up-section. The lower part of Sequence 3 is interpreted to be LST deposits filling in the incised valley at the major sequence boundary between Sequence 1 and Sequence 3 at Hagan and Stickleyville and the major sequence boundary between Sequence 2 and Sequence 3 at Flat Gap.

The upper part of Sequence 3 is recognized at Hagan, Cumberland Gap, and the Tennessee/Virginia Border exposures. At Hagan, the top of PS-2 is capped by a surface that displays an abrupt decrease in grain size (57.5 m). Above this surface, there is an abrupt change from tidal flat deposits of Facies B-2 to true offshore deposits of A-1. This evidence suggests this is a major flooding surface and is interpreted as the transgressive surface (TS) that separates the LST and TST. Measurable section ends soon after this abrupt shift to offshore deposits. However, at the Cumberland Gap Tunnel location, offshore Facies A-1 is present in a ~15 m exposure. The stratigraphic position of this outcrop suggests it is an exposure of the Clinton

Formation. Two prominent 0.5 m sand bodies with sharp-based contact underlying shale beds suggest surfaces of forced regression (10.5 m and 12.5 m). Basins often display depositional motifs and these sand bodies could represent the initiation of a subsequent base-level fall, as seen in Sequence 1. More data is needed to confirm this idea.

DISCUSSION

Relationship to Previous Stratigraphic Research on the Clinch Formation

Although facies in the Clinch Formation have been previously described and interpreted (Miller 1976, Driese 1991, and Driese 1996), this study expands the breadth of facies within the Clinch, consolidates previous nomenclature of Miller (1976), and proposes the first sequence stratigraphic framework for the Clinch. The most recent interpretations (Driese 1991) suggested that the Clinch contains only a thin-bedded sandstone and shale, a hummocky cross-stratified sandstone, and a cross-stratified sandstone facies. The proposed two facies associations of this study, the wave-dominated shelf of Facies Association A and the tidal estuarine Facies Association B, clarifies the depositional history of the Clinch Formation.

Furthermore, Driese's (1991) hummocky cross-stratified sandstone, which previously denoted the Rockwood Formation (Miller 1976), was not seen at any of the study areas (Driese 1991). This study suggests the nomenclature for the Rockwood Formation be abandoned for the Clinch Formation in northeastern Tennessee and southwestern Virginia.

The proposed sequence stratigraphic interpretation explains many stratigraphic features not addressed or even identified in previous studies of the Clinch. The ubiquitous and unrealistic Waltherian relationships in these previous studies are entirely replaced by regionally extensive surfaces, such as sequence boundaries and surfaces of forced regression, that explain the non-

Waltherian relationships observed within the Clinch Formation (Fig. 2.15). Moreover, the presented sequence stratigraphic framework suggests lithostratigraphic models in past research (Cotter 1983; Driese 1991, Driese 1996, and Brett et al. 1998) that attempt to correlate Early Silurian siliciclastic rocks of the Appalachian foreland basin need to be reappraised. Specifically, previous studies correlated sand bodies within the Clinch along strike of the Appalachian foreland basin with certainty. This study suggests there are important chronostratigraphically significant surfaces *within* the Clinch. Many of the sand bodies characterized as the Clinch Formation and its correlatives may represent more time than originally thought.

Falling-Stage Systems Tract Deposition

Evidence throughout the Clinch Formation supports the existence of a nearly complete record of base-level fall deposition in the form of a Falling-Stage Systems Tract. Anomalous sand bodies in all three primary locations and one supplemental location record a sharp surface across which there is abrupt shallowing and grain size increase. The sequence boundary at the basal surface of Sequence 3 marks a major reorganization from the predominately wave-dominated shelf lower Poor Valley Ridge Sandstone to the tidally dominated upper Poor Valley Ridge Sandstone.

Complications with Data and Interpretation

It is important to note there are three complications with the presented sequence stratigraphic framework that are difficult to resolve given the rarity of exposures, particularly of complete sections through the Clinch.

The sequence stratigraphic framework presented here is based on only three nearly complete columns and two partial columns, spanning 70 km palinspastically. This spatial restriction on exposures limits the certainty of the sequence stratigraphic interpretation. For example, recent research in the Turonian Ferron Notom deltaic complex of south-central Utah presented a sequence stratigraphic framework for stepped forced regressions similar to this study (Fig. 2.16; Zhu et al. 2012). However, the scale between these FSST deposits is much smaller than recorded in this study. This suggests it is possible the framework presented for the Clinch Formation is missing important surfaces as a result of spatial restriction of exposures. To bolster this sequence stratigraphic framework in the future, drill cores and well logs could be used to aid interpretation.

Second, it is strange there is no record of Lowstand Systems Tract (LST) deposition until after the uppermost sequence boundary. In addition, once LST deposits are present, they are very thick relative to other systems tracts. Furthermore, the thickest LST deposits are in the most depositionally downdip location, Hagan. It is possible that this may be caused by modern erosion of the top of the outcrops at Flat Gap and Stickleyville.

Finally, It is strange that the up-dip Sequence 2 is preserved in the manner that it is. Normally, valley incision would erase up-dip indications of previous sequences instead of preserve them. However, the nature of incised valleys are complicated and do not follow one standard rule (Van Wagoner 1990).

CONCLUSIONS

1) Eight facies are recognized within the Clinch Formation and they are associated with two distinct facies associations. Facies Association A reflects a wave-dominated shelf, and Facies Association B reflects a tidal estuary.

2) There are numerous surfaces of abrupt facies change present within the outcrops of the Clinch Formation in northeastern Tennessee and southwestern Virginia. These include flooding surfaces, surfaces of forced regression, and sequence boundaries. Flooding surfaces are characterized by relatively deeper water facies sharply overlying more shallow water facies. Conversely, an abrupt shallowing and grain size increase characterize surfaces of forced regression. Sequence boundaries are characterized by an abrupt change in facies association, evidence for subaerial erosion, and erosional truncation.

3) Two sequence boundaries are identified in the Clinch Formation. One sequence boundary is seen in all three of the primary locations and is considered to be a major sequence boundary, separating wave-dominated shelf facies from tidal estuarine facies within the Clinch Formation. The second sequence boundary is present only in depositionally updip sections (Flat Gap and Bean's Gap) and is considered to be a combined sequence boundary - transgressive surface within storm-dominated shelf Facies Association A.

4) Anomalous sand bodies recognized at all three primary locations and one supplemental section record a falling-stage system tract (FSST). These sand bodies are characterized by a surface of forced regression at the base of each, recording an abrupt shallowing and a distinct

grain size increase. The number of these surfaces of forced regression increases down depositional dip, as expected.

REFERENCES

Aigner, T., 1985, Storm Depositional Systems, Lecture Notes in Earth Sciences: Springer-Verlag, Berlin. 174 p.

Ashley, G.M., 1990, Classification of large-scale subaqueous bedforms: a new look at an old problem: Journal of Sedimentary Petrology 60, p. 160-172.

Baniak, G.M, Murray, K.G., Beverly, A.B., and Pemberton, S.G., 2014, An example of a highly bioturbated, storm-influenced shoreface deposit: Upper Jurassic Ula Formation, Norwegian North Sea: Sedimentology, v. 61, p. 1-25.

Boggs, S.B, 2006, Principles of Sedimentology and Stratigraphy: Pearson Prentice Hall, New Jersey, 662 p.

Brett, C.E., Baarli, B.G., Chowns, T., Cotter, E., Driese, S., Goodman, W., and Johnson, M., 1998, Early Silurian condensed intervals, ironstones, and sequence stratigraphy in the Appalachian foreland basin: Bulletin - New York State Museum, v. 491, p. 89-143.

Clifton, H.E., 2006, A reexamination of facies models for clastic shorelines: SEPM Special Publication, v. 84, p. 293-337.

Collinson, J.D. and Thompson, D.B., 1989, Sedimentary Structures, 2nd Ed., Unwin Hyman Ltd, London, 207 p.

Cotter, E., 1983, Shelf, paralic, and fluvial environments and eustatic sea-level fluctuations in the origin of the Tuscarora Formation (Lower Silurian) of central Pennsylvania: Journal of Sedimentary Petrology, v. 53, p. 25-49.

Dalrymple, R.W., 1984, Morphology and internal structure of sandwaves in the Bay of Fundy: Sedimentology, v. 31, p. 365-382.

Dalrymple, R.W., 2010. Tidal depositional systems. *in* James, N.P. and Dalrymple, R.W. (Eds.), Facies Models 4. Geological Association of Canada, St. John's, p. 201-231.

Driese, S.G. and Swift, D.J.P., 1991, Model for genesis of shoreface and shelf sandstone sequences, Southern Appalachians; paleoenvironmental reconstruction of an Early Silurian shelf system: Special publications of the IAS, v. 14, p. 309-338.

Driese, S.G., 1996, Depositional history and facies architecture of a Silurian foreland basin, eastern Tennessee: Studies in Geology [Knoxville], v. 26: p. 68-106.

Droser, M.L. and Bottjer, D.J., 1986, A semiquantitative field classification of ichnofabric: Journal of Sedimentary Research, v. 56: p. 558-559.

Ghazizadeh, M., 1985, Depositional environment interpretation of the Juniata Formation at Beans Gap, Clinch Mountain, Tennessee: Studies in Geology [Knoxville] 10: p. 93-99.

Holland, S. M., and Patzkowsky, M.E., 1996, Sequence stratigraphy and long-term paleoceanographic change in the Middle and Upper Ordovician of the eastern United States: *in* Witzke, B.J., Ludvigsen, G.A., and Day, J.E. (Eds.), Paleozoic sequence stratigraphy: views from the North American craton. Geological Society of America Special Paper 306, Boulder, p. 117-130.

Hunt, D., and Tucker, M.E., 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. Sedimentary Geology, v. 81, p. 1-9.

Ingram, R.L., 1954, Terminology for thickness of stratification and parting units in sedimentary rocks: Geological Society of American Bulletin, v. 65: p. 937-938.

Jennette, D.C., and Pryor, W.A., 1993, Cyclic alteration of proximal and distal storm facies; Kope and Fairview formations (Upper Ordovician), Ohio and Kentucky: Journal of Sedimentary Petrology, v. 63, p. 183-203.

Leckie, D.A. and Krystinik, L.F, 1989, Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle-shelf deposits?: Journal of Sedimentary Petrology, v. 59, p. 862-870.

MacEachern, J.A. and Pemberton, S.G., 1992, Ichnological aspects of Cretaceous shoreface successions and shoreface variability in the Western Interior Seaway of North America, *in* Pemberton, S.G. (Ed.), Applications of Ichnology to Petroleum Exploration, SEPM Core Workshop No. 17, Calgary, AB, p. 57-84.

MacEachern, J.A., Pemberton, S.G., Gingras, M.K., and Bann, K.L., Ichnology and Facies Models, *in* James, N.P. and Dalrymple, R.W. (Eds.), Facies Models 4, Geological Association of Canada, St. John's, p. 19-58.

Meckel, L.D., 1970, Paleozoic alluvial deposition in the central Appalachians: a summary, *in* Fisher, G.W., Pettijohn, F.J., Reed, J.C, and Weaver, K.N. (Eds.), Studies of Appalachian Geology, Central and Southern: Wiley-Interscience, New York, p. 49-67.

Miller, R.L., 1976, Silurian nomenclature and correlations in southwest Virginia and northeast Tennessee, U.S. Geological Survey Bulletin, 1405-H, 23 p.

Nordfjord, S., Goff, J.A., Austin, J.A., and Sommerfield, C.K., 2005, Seismic geomorphology of buried channel systems on the New Jersey outer shelf: assessing past environmental conditions, Marine Geology, v. 214, p. 339-364.

Olariu, C., Steel, R.J., Dalrymple, R.W., and Gingras, M.K., 2012, Tidal dunes versus tidal bars: The sedimentological and architectural characteristics of compound dunes in a tidal seaway, the lower Baronia Sandstone (Lower Eocene), Ager Basin, Spain: Sedimentary Geology, v. 279, p. 134-155.

Plint, A.G., 2010, Wave- and Storm-Dominated Shoreline and Shallow-marine Systems, *in* James, N.P. and Dalrymple, R.W. (Eds.), Facies Models 4. Geological Association of Canada, St. John's, p. 167-199.

Roeder, D. and Witherspoon, W.D., 1978, Palinspastic map of east Tennessee: American Journal of Science, v. 278, p. 543-550.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Tulsa, Oklahoma, American Association of Petroleum Geologists Methods in Exploration Series, No. 7, 55 p.

Whisonant, R. C., 1977, Lower Silurian Tuscarora (Clinch) dispersal patterns in western Virginia: Geological Society of American Bulletin, v. 88, p. 215-220.

Williams, H., and Hatcher, R.D., 1982, Suspect terranes and accretionary history of the Appalachian orogen: Geology, v. 10, p. 530-536.

Yang, B.C., Dalrymple, R.W., and Chun, S.S., 2005, Sedimentation on a wave-dominated, open-coast tidal flat, southwester Korea: summer tidal flat – winter shoreface: Sedimentology, v. 52, p. 235-252.

Yeakel, L. S., 1962, Tuscarora, Juniata, and Bald Eagle paleocurrents and paleogeography in the central Appalachians: Geological Society of American Bulletin, v. 73, p. 1515-1550.

Zhu, Y., Bhattacharya, J.P., Li, W., Lapen, T.J., Jicha, B.R., and Singer, B.S, 2012, Milankovitch-scale sequence stratrigraphy and stepped forced regressions of the Turonian Ferron Notom deltaic complex, south-central Utah, U.S.A: Journal of Sedimentary Research, v. 82, p. 723-746.

FIGURE 2.1 - Location map of field sites. Red stars indicate locations of measured sections. White stars indicate supplemental exposures (Image from Google Maps).

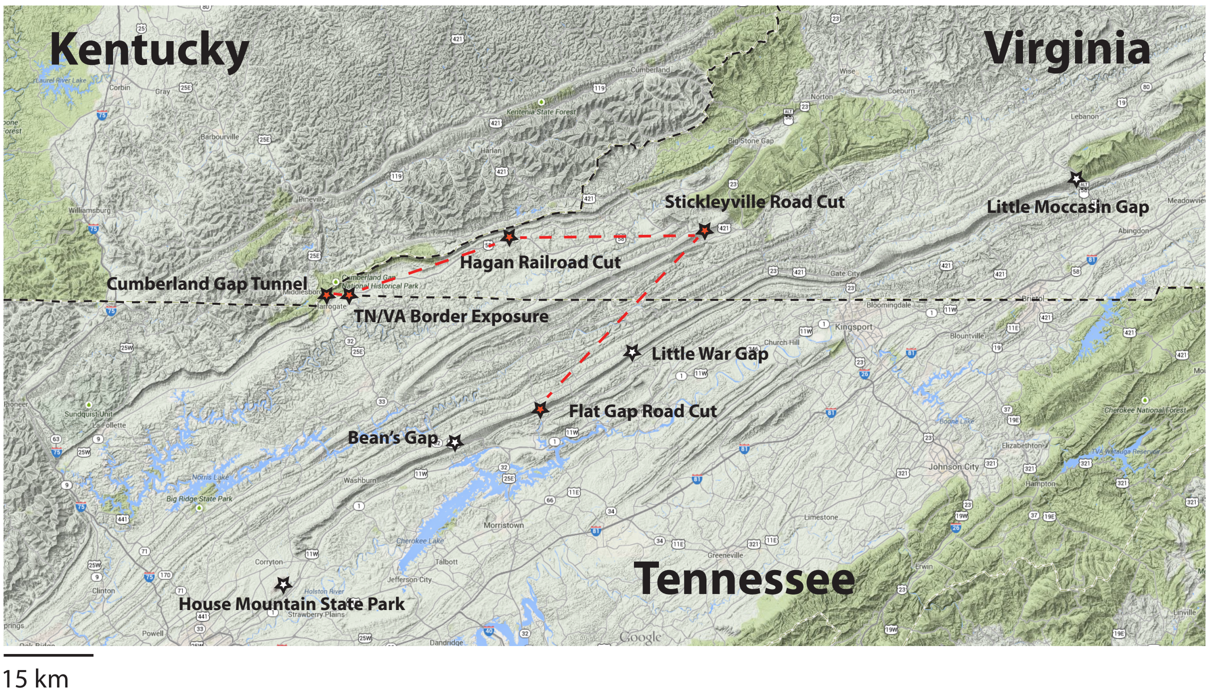

Kentucky
Virginia
Tennessee
Stickleyville Road Cut
Little Moccasin Gap
Hagan Railroad Cut
Cumberland Gap Tunnel
TN/VA Border Exposure
Little War Gap
Flat Gap Road Cut
Bean's Gap
House Mountain State Park
15 km

FIGURE 2.2 - Regional lithostratigraphic nomenclature of the lower Silurian of the Cumberland Gap region (Miller 1976).

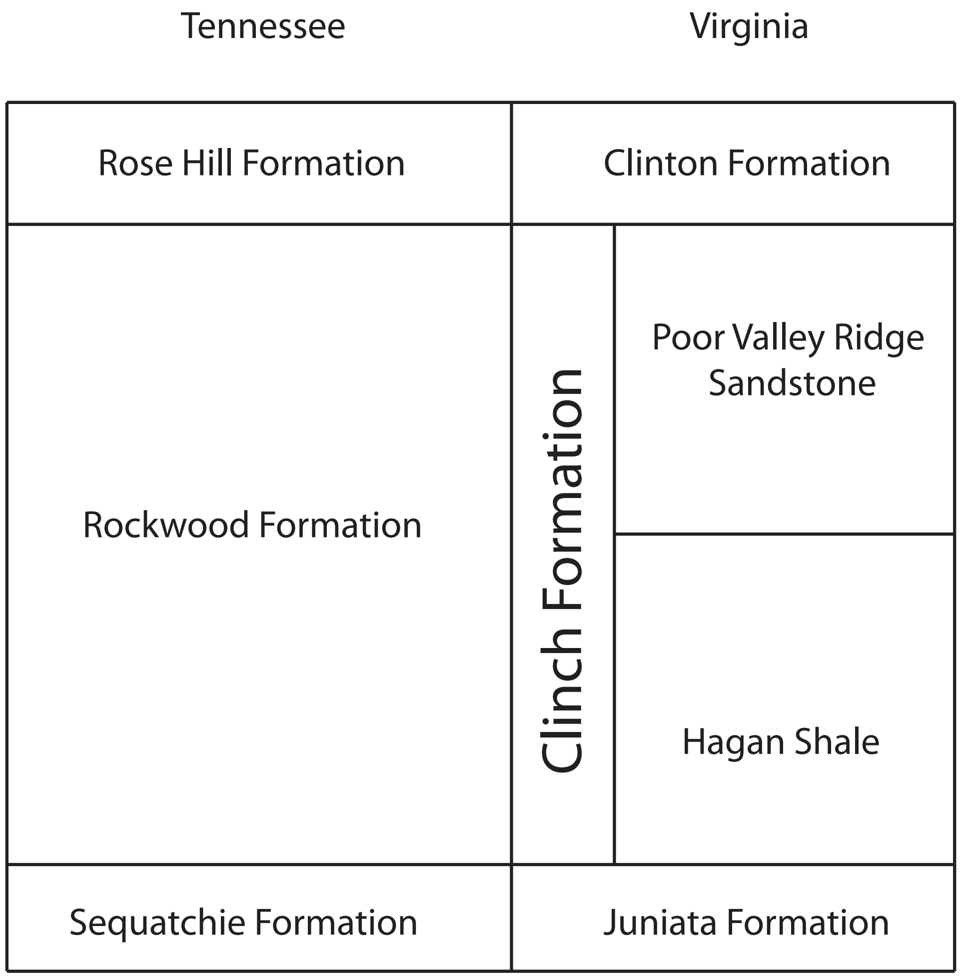

Tennessee
Virginia
Rose Hill Formation
Clinton Formation
Poor Valley Ridge Sandstone
Rockwood Formation
Clinch Formation
Hagan Shale
Sequatchie Formation
Juniata Formation

FIGURE 2.3 - Paleography of study area. Image modified from Ron Blakey Northern Arizona paleogeography website (http://jan.ucc.nau.edu/rcb7/).

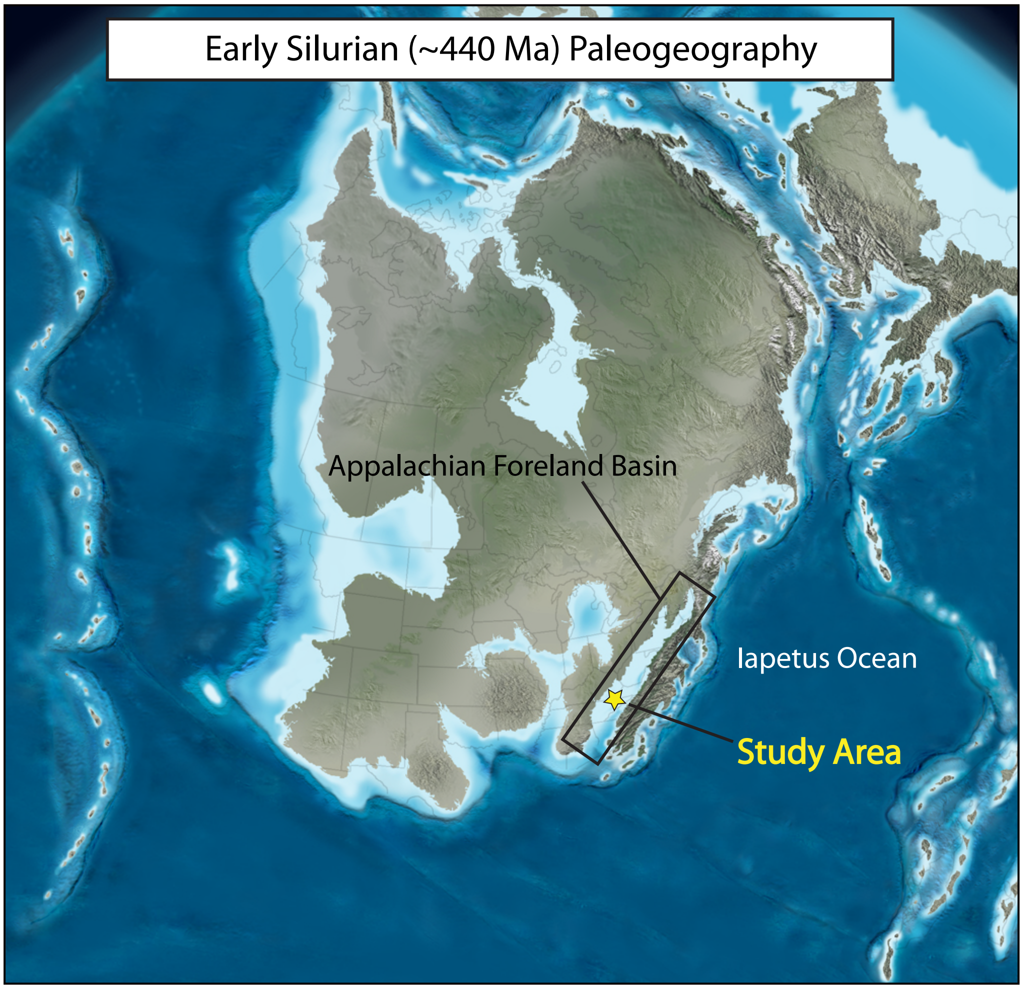

Early Silurian (~440 Ma) Paleogeography
Appalachian Foreland Basin
Iapetus Ocean
Study Area

FIGURE 2.4 - Regional stratigraphic interpretation of Driese (1991). HCS – hummocky cross-stratified sandstone.

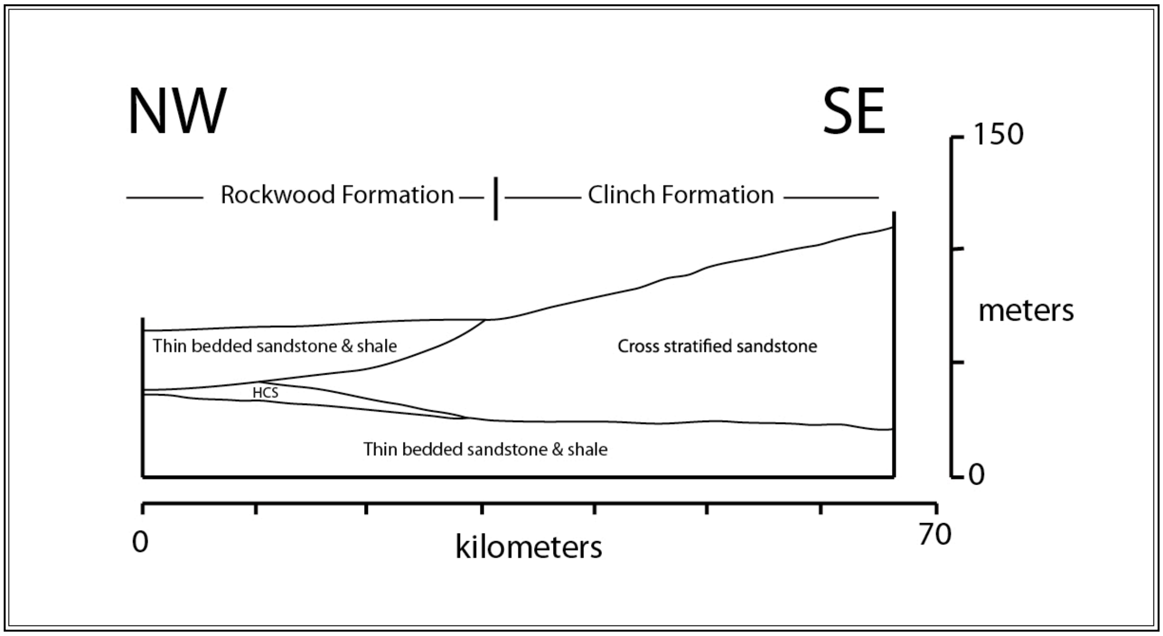

NW
SE
Rockwood Formation
Clinch Formation
150
meters
0
Thin bedded sandstone & shale
Cross stratified sandstone
HCS
Thin bedded sandstone & shale
0
kilometers
70

FIGURE 2.5 - Paleocurrent data plotted on palinspastic map of east Tennessee. Red numbers indicate where data from this study was added. PVR – Poor Valley Ridge; PM – Powell Mountain; and CM – Clinch Mountain (from Driese 1991, and Roeder and Witherspoon 1978).

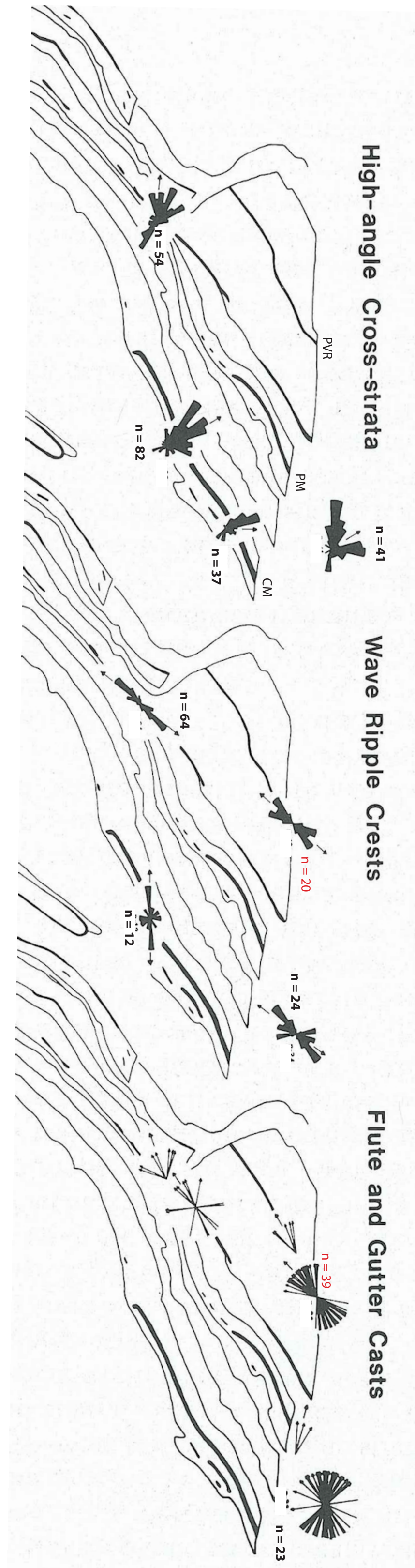

High-angle Cross-strata
Wave Ripple Crests
Flute and Gutter Casts
PVR
PM
CM
n = 54
n = 82
n = 41
n = 37
n = 64
n = 20
n = 12
n = 24
n = 39
n = 23

FIGURE 2.6 - Lithostratigraphic and sequence stratigraphic framework of the Clinch Formation in the Cumberland Gap region.

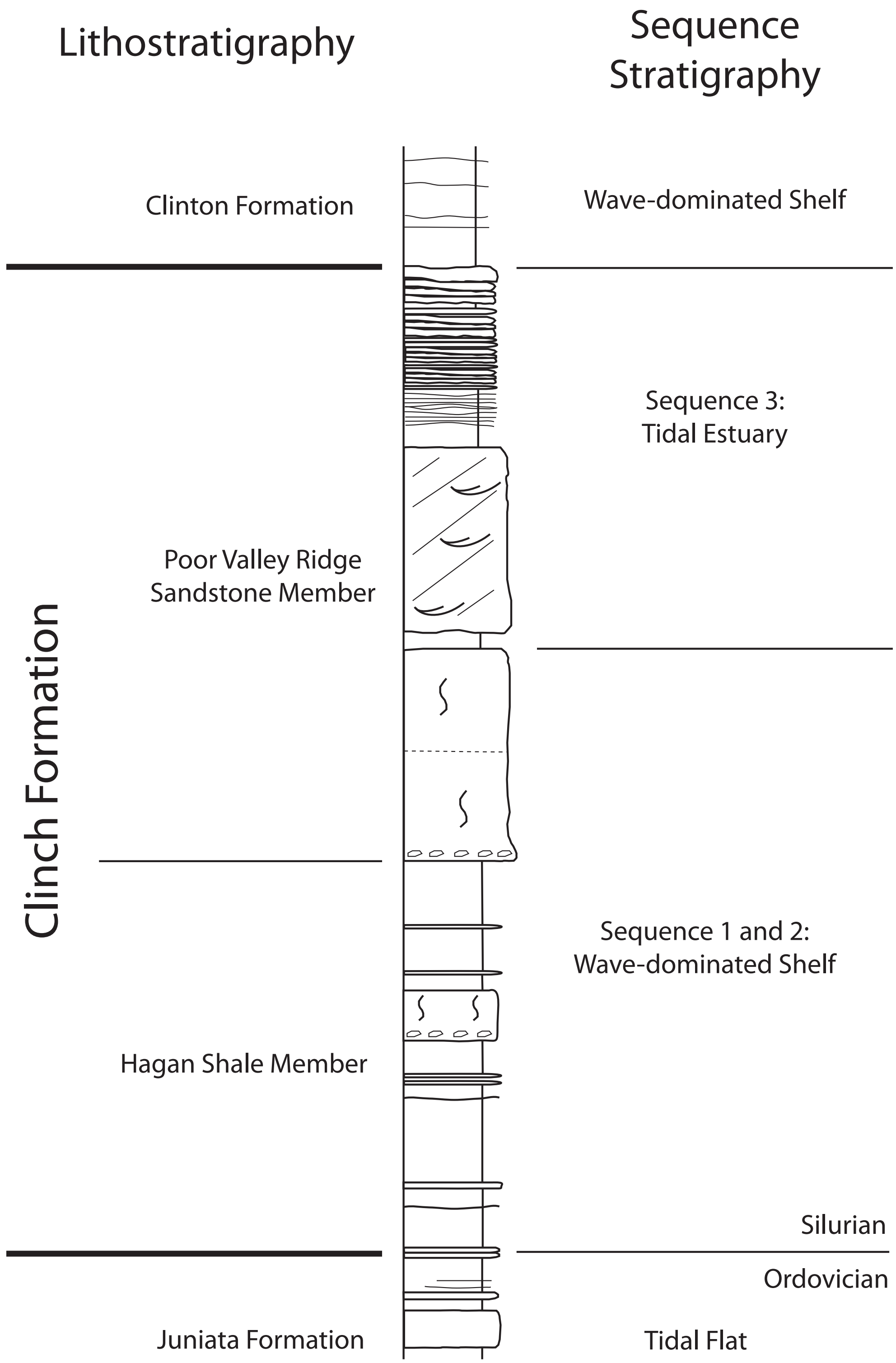
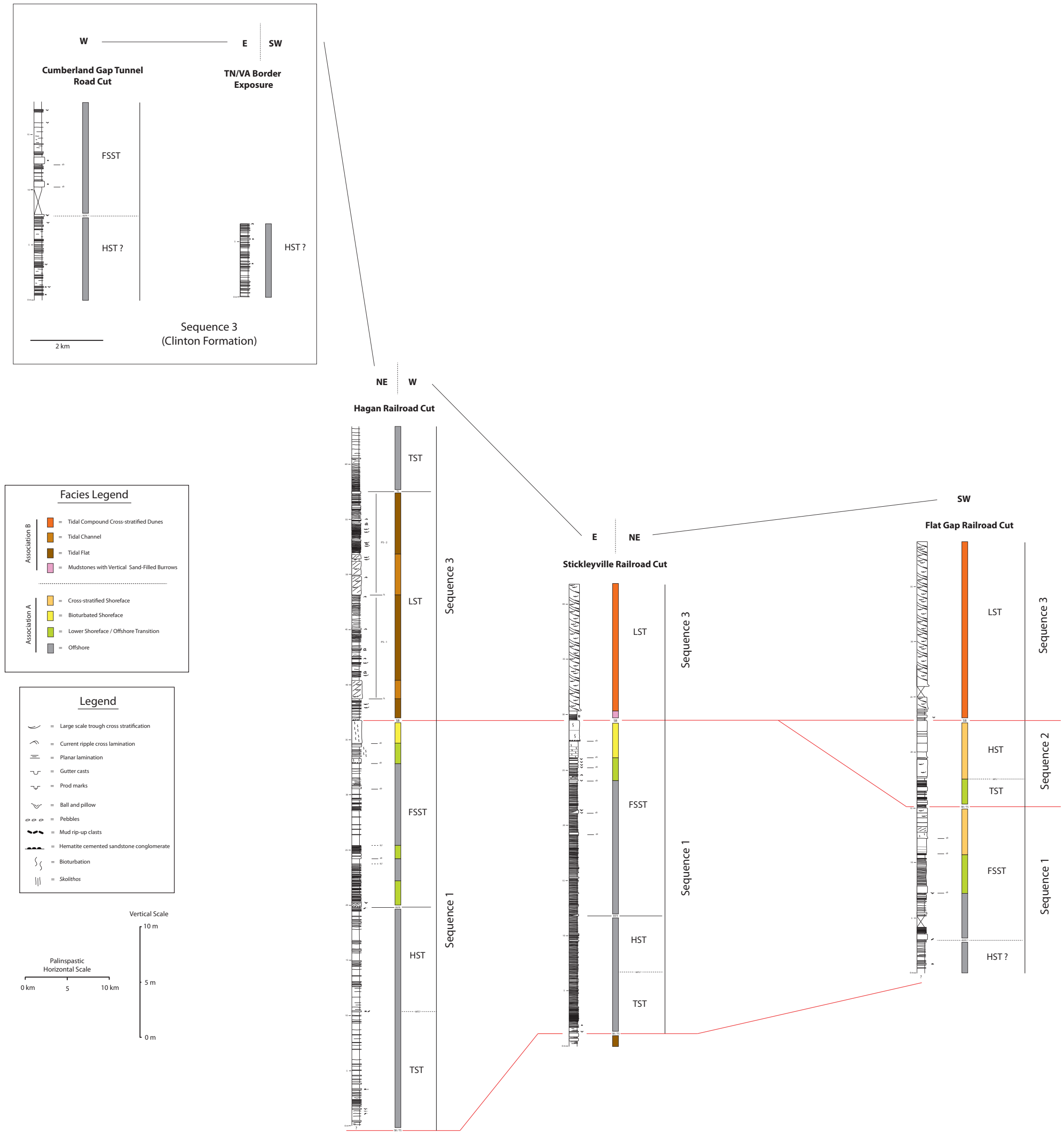

Lithostratigraphy
Sequence Stratigraphy
Clinton Formation
Wave-dominated Shelf
Sequence 3:
Tidal Estuary
Poor Valley Ridge
Sandstone Member
Clinch Formation
Sequence 1 and 2:
Wave-dominated Shelf
Hagan Shale Member
Silurian
Ordovician
Juniata Formation
Tidal Flat

FIGURE 2.7 - Cross-section of measured sections (palinspastic horizontal scale in this study).



W
E
SW
Cumberland Gap Tunnel Road Cut
TN/VA Border Exposure
FSST
HST ?
HST ?
Sequence 3 (Clinton Formation)
2 km
NE
W
Hagan Railroad Cut
TST
LST
FSST
HST
TST
Sequence 3
Sequence 1
E
NE
Stickleyville Railroad Cut
LST
FSST
HST
TST
Sequence 3
Sequence 1
SW
Flat Gap Railroad Cut
LST
HST
TST
FSST
HST ?
Sequence 3
Sequence 2
Sequence 1
Facies Legend
Association B
= Tidal Compound Cross-stratified Dunes
= Tidal Channel
= Tidal Flat
= Mudstones with Vertical Sand-Filled Burrows
Association A
= Cross-stratified Shoreface
= Bioturbated Shoreface
= Lower Shoreface / Offshore Transition
= Offshore
Legend
= Large scale trough cross stratification
= Current ripple cross lamination
= Planar lamination
= Gutter casts
= Prod marks
= Ball and pillow
= Pebbles
= Mud rip-up clasts
= Hematite cemented sandstone conglomerate
= Bioturbation
= Skolithos
Vertical Scale
10 m
5 m
0 m
Palinspastic Horizontal Scale
0 km
5
10 km

FIGURE 2.8 - Outcrop photos of Facies A-1 and A-2. A) Offshore facies A-1, Hagan (1.8 m Jacobs staff); B) Gutter casts facies A-1, Cumberland Gap (1.8 m Jacobs staff, 10 cm increments); C) Hummocky cross-stratification in sandstone bed in facies A-1, Hagan; D) Burrow casts on sole of sandstone bed in facies A-1, Hagan; E) Offshore transition/lower shoreface facies A-2, Hagan (1.8 m Jacobs staff); and F) Load casts on sole of bed in facies A-2, Hagan.

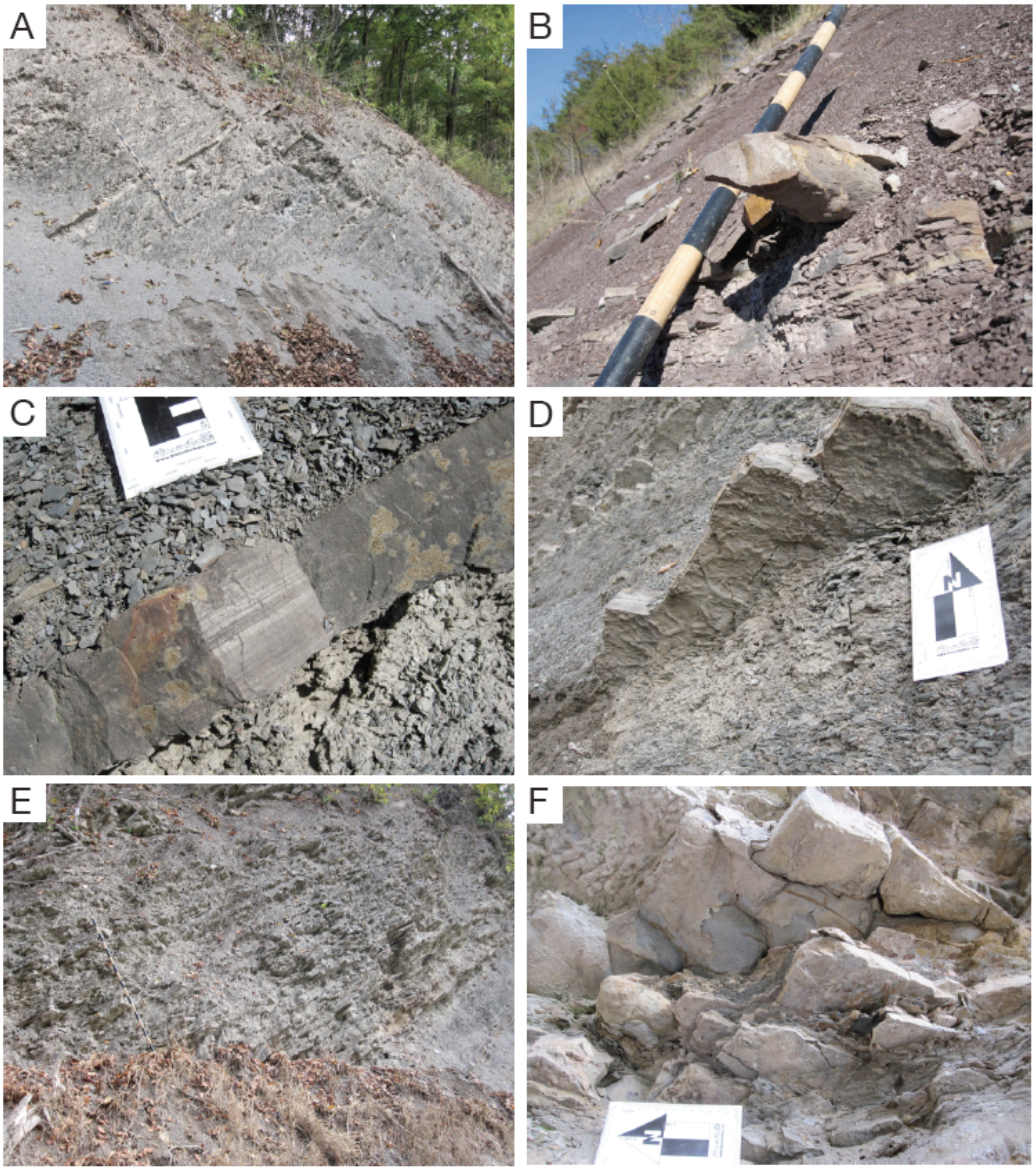

A
B
C
D
E
F

FIGURE 2.9 - Outcrop photos of Facies A-3, A-4, B-1, and B-2. A) Bioturbation expressed by mottling of facies A-3, Stickleyville (1.8 m Jacobs staff, 10 cm increments); B) Upper bedding surface of facies A-3 with hematite-cemented sandstone conglomerate, Hagan; C) Large-scale trough cross-stratification of facies A-4; Flat Gap (1.8 m Jacobs staff, 10 cm increments); D) Tidal channel facies B-1, Hagan (1.8 m Jacobs staff, 10 cm increments); E) Ball-and-pillow structure in facies B-1, Hagan; and F) 3D current-ripples in facies B-2, Hagan (15 cm pencil points in direction of flow).

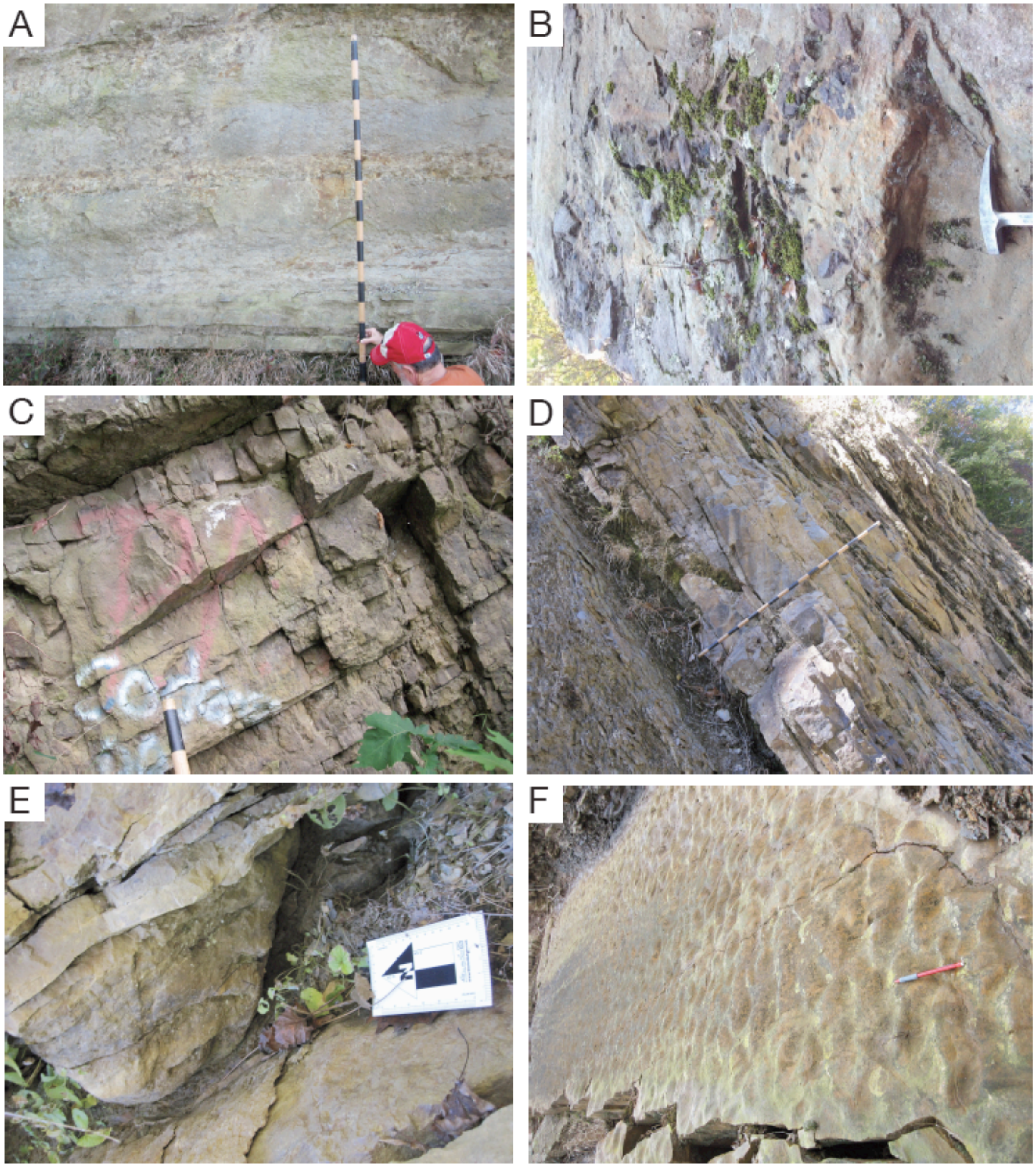

A
B
C
D
E
F

FIGURE 2.10 - Outcrop photos of Facies B-2, B-3, and B-4. A) Mud rip-up clasts in facies B-2, Hagan (V2 11 cm); B) 2D vortex-ripples in facies B-2, Hagan (15 cm pencil); C) Bi-directional cross-stratification in facies B-3, House Mountain; D) Sigmoidal cross-stratification in facies B-3, Beans Gap (1.8 m Jacobs staff, 10 cm increments); E) *Arthrophycus* on sole of bed in facies B-3, Little War Gap; and F) *Skolithos* burrows in facies B-4, Stickleyville.

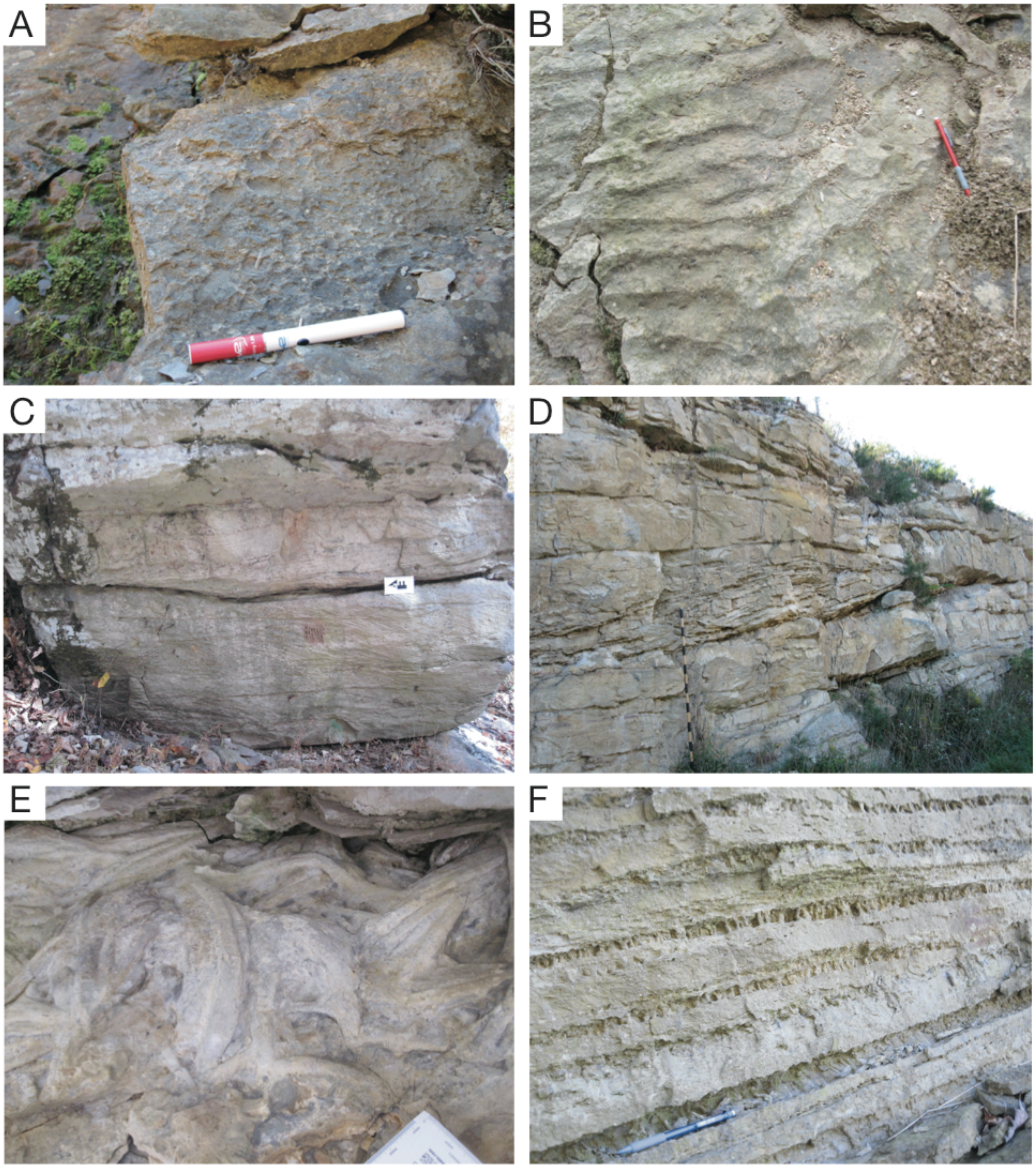
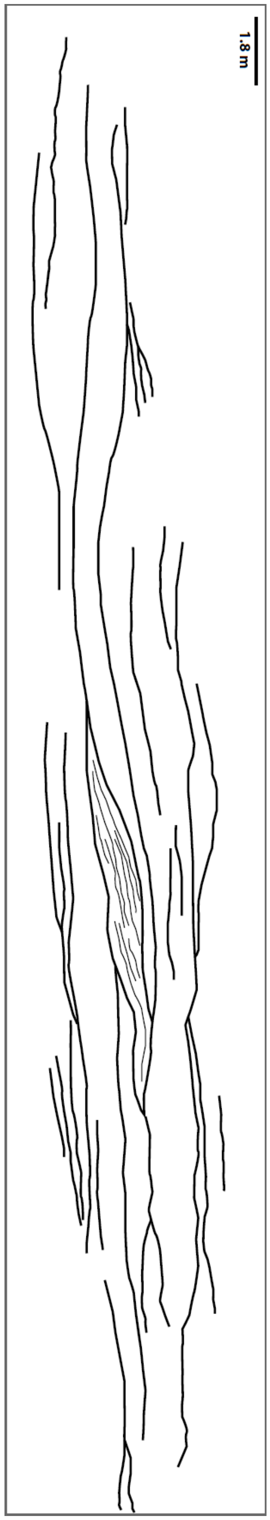

A
B
C
D
E
F

FIGURE 2.11 - Bedding annotations of Facies B-3, Bean's Gap. Along-strike view of tidal compound dunes. Note complex bounding surfaces that intersect master bedding planes. Sigmoidal cross-stratification also present.


1.8 m


1.8 m

FIGURE 2.12 - Bedding annotations of Facies B-3, Stickleyville. Note complex bounding surfaces that intersect master bedding planes at low angles that help define very large sets of cross-strata. Second- and third-order surfaces present. Sequence boundary in red.


2.75 m


2.75 m

FIGURE 2.13 - Outcrop photos of sequence stratigraphic elements. A) 1 mm – 1 cm phosphate pebbles above basal surface of forced regression, Hagan (15 cm pencil); B) Large bedform (outlined) encased in offshore muds, Stickleyville; C) Anomalous sandstone bed above surface of forced regression, Flat Gap; D) Sequence boundary between Sequence 1 and Sequence 3 (in red); Hagan; E) Sequence boundary between Sequence 1 and Sequence 3 (in red), Stickleyville; and F) Sequence boundary between Sequence 2 and Sequence 3 (in red), Flat Gap.

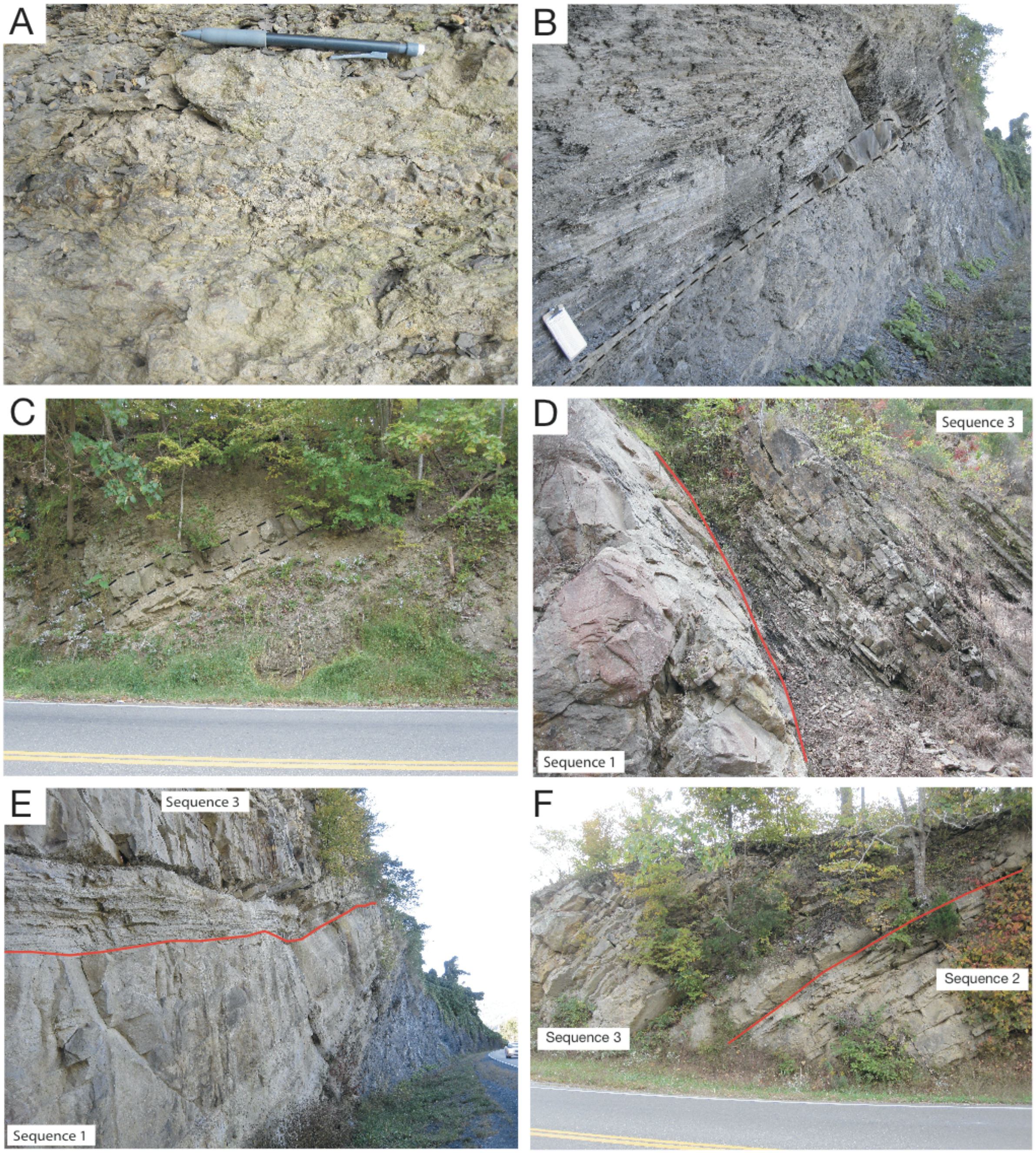

A
B
C
D
Sequence 3
Sequence 1
E
Sequence 3
Sequence 1
F
Sequence 2
Sequence 3

FIGURE 2.14 - Sequence interpretation at Bean's Gap (Photo credit: Steven Holland).

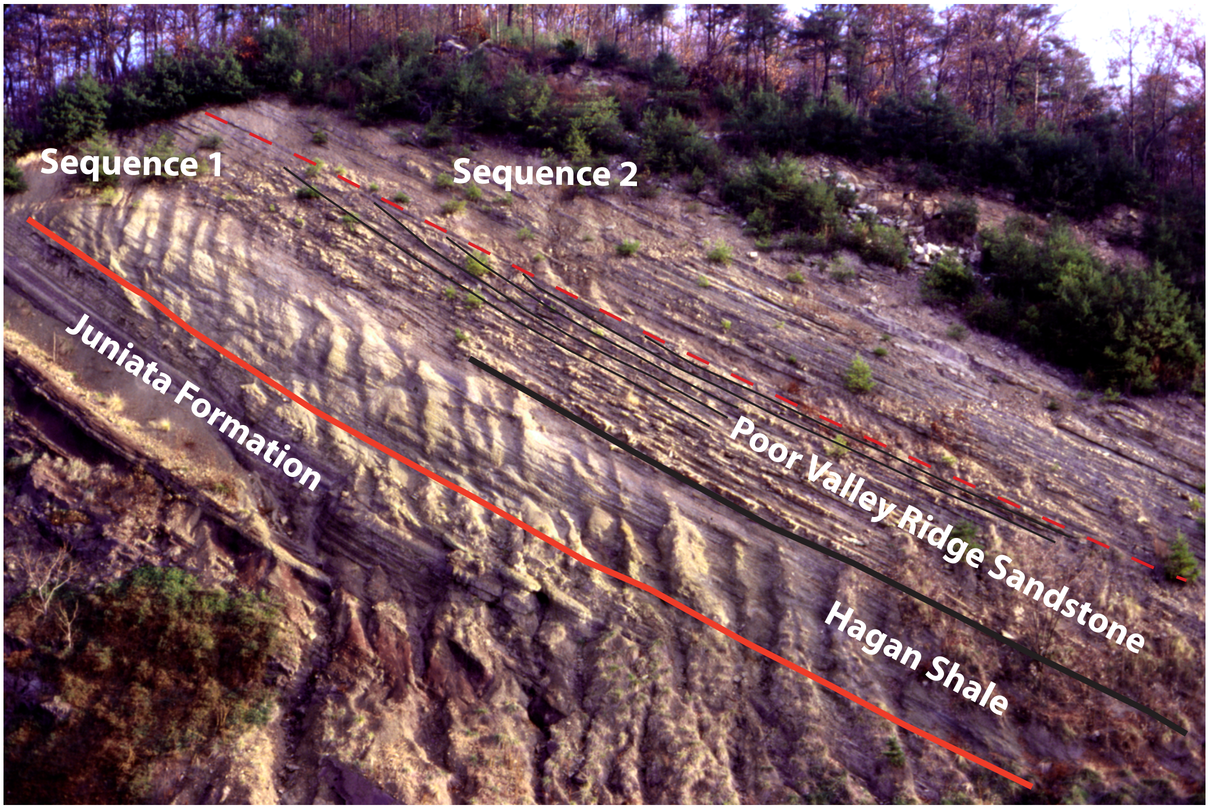

Sequence 1
Sequence 2
Juniata Formation
Poor Valley Ridge Sandstone
Hagan Shale

FIGURE 2.15 – Updated facies model for the Clinch Formation in the Cumberland Gap region.

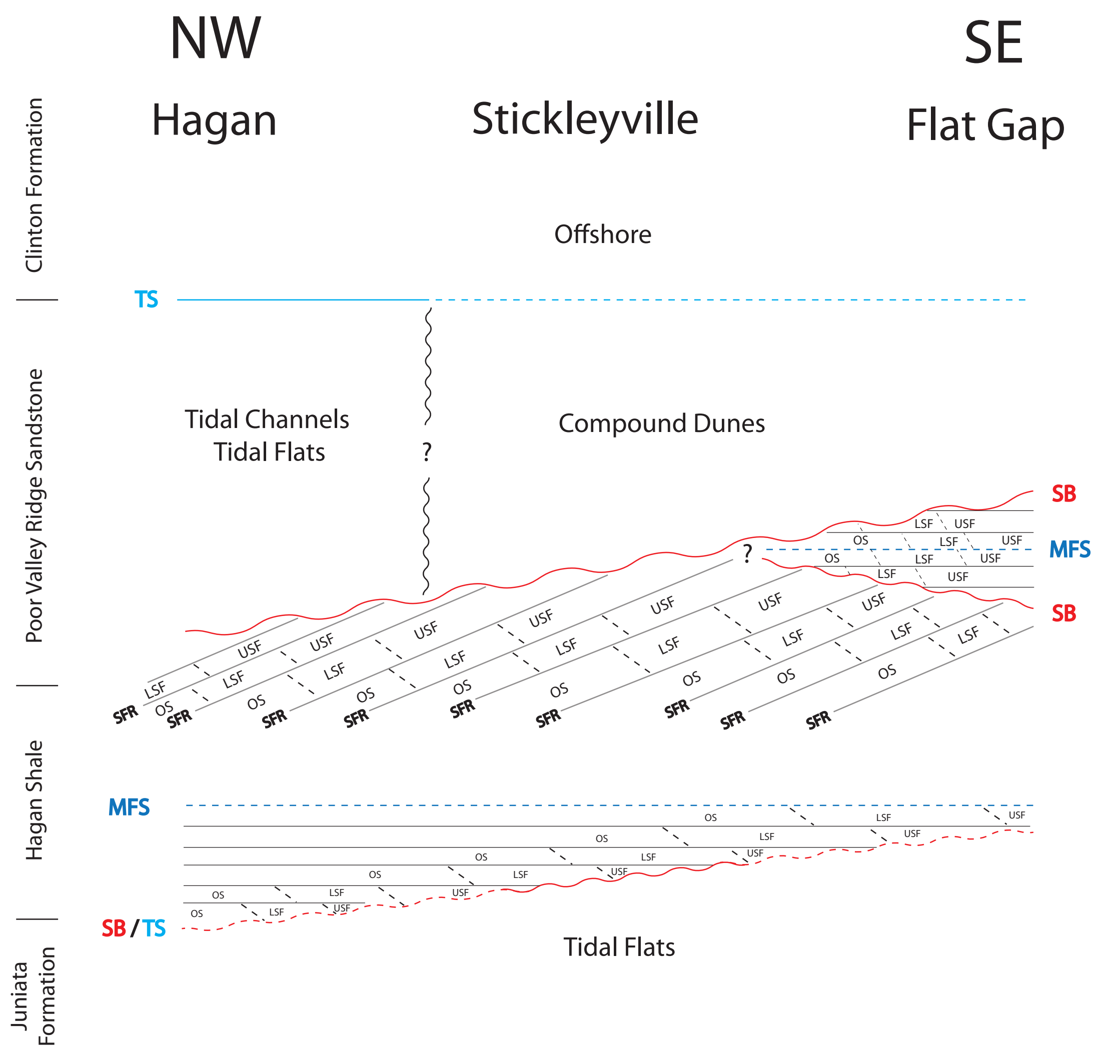

NW
SE
Hagan
Stickleyville
Flat Gap
Clinton Formation
Offshore
TS
Poor Valley Ridge Sandstone
Tidal Channels
Tidal Flats
?
Compound Dunes
SB
MFS
SB
USF
LSF
OS
SFR
Hagan Shale
MFS
SB / TS
Juniata Formation
Tidal Flats

FIGURE 2.16 - Example of sequence stratigraphic framework from the Turonian Ferron Notom deltaic complex of south-central Utah (Zhu et al. 2012). Note the complexity of sequence architecture in a substantially smaller scale than this study. In comparison, the outcrops in this study are 25 to 45 km apart, palinspastically, roughly equal to the total width of this cross-section.

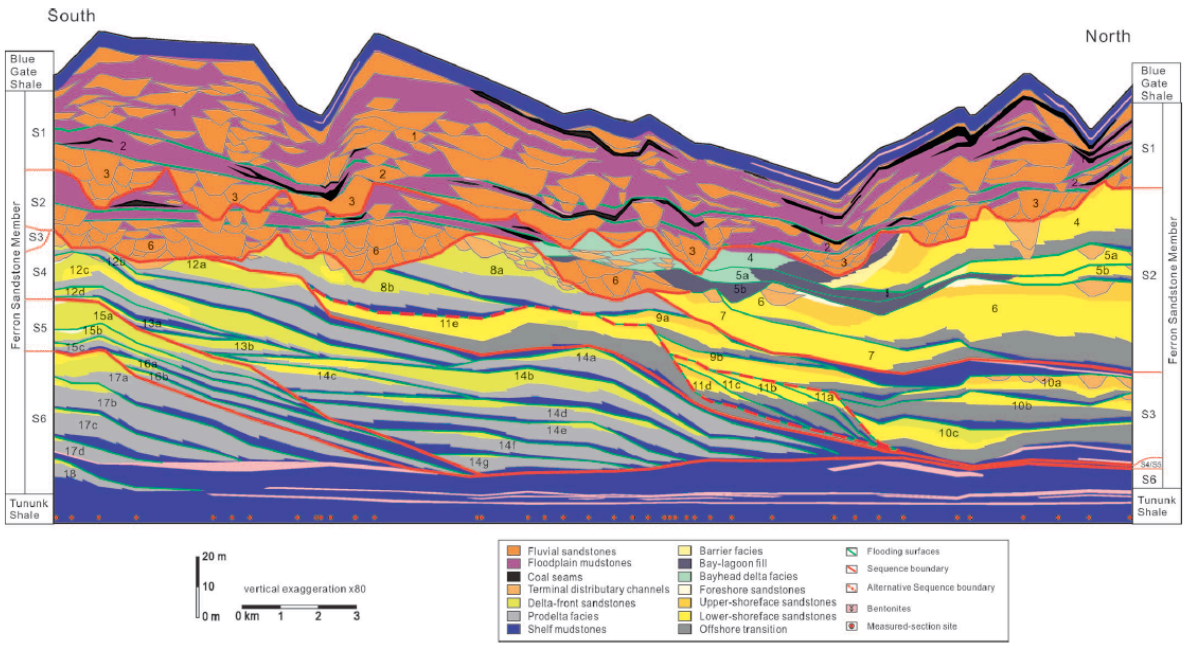


FIG. 15.—Dip stratigraphy of the Ferron Notom Delta. Forty-three parasequences have been identified. They are further grouped into 18 parasequence sets. Five sequence boundaries are recognized, and six depositional sequences (S1-S6) are defined. See detailed correlation panel with measured sections in the JSR data archive, see Acknowledgments section.

CHAPTER 3

CONCLUSIONS

The Silurian Clinch Formation in southeastern Tennessee and southwestern Virginia contains three depositional sequences with two distinct facies associations representing eight individual facies. The first and second sequences contain wave-dominated shelf facies associations. The third contains tidal estuarine facies.

Numerous sequence stratigraphic surfaces are present within the Clinch Formation. These include flooding surfaces, surfaces of forced regression, and sequence boundaries.

Two sequence boundaries are recognized within the Clinch Formation. One is present in all three primary locations and separates underlying wave-dominated shelf facies from overlying tidal estuarine facies below. The second is present within wave-dominated facies and is present only at depositionally updip locations, Flat Gap and Bean's Gap.

Anomalous sand bodies recognized at all three primary locations occur within the falling-stage systems tract. The base of each of these sand bodies is interpreted as a surface of forced regression.

APPENDIX A

FIELD LOCALITIES

I. Primary locations with complete to nearly exposures of the Clinch Formation and Clinton Formation

I) **Hagan railroad cut** – Hagan Shale and Poor Valley Ridge Sandstone exposed in railroad cut northwest of US 58 at Burning Well Dr., Poor Valley Ridge, near base of Cumberland Mountain 0.2 miles west of Hagan, Virginia; 36.70286° N, 83.28967° W

II) **Stickleyville road cut** – Hagan Shale and Poor Valley Ridge Sandstone exposed in road cut along US 58 at summit of Powell Mountain at Scott/Lee County line, 1.7 miles east of Stickleyville, Virginia; 36.71070° N, 82.87560° W

III) **Flat Gap road cut** – Hagan Shale and Poor Valley Ridge Sandstone exposed in road cut along TN 31 at summit of Clinch Mountain, 5.1 miles north of Mooresburg, Tennessee; 36.41073° N, 83.22007° W

IV) **Tennessee/Virginia Border exposure:** Clinton Formation exposed on small hill on eastbound side of US 58, between Tennessee/Virginia state line and Cumberland Gap sign, 0.5 mile east of border; 36.60316° N, 83.64720° W

V) **Cumberland Gap Tunnel** – Clinton Formation exposed on northbound side of US 25E; immediately south of tunnel entrance in Tennessee, on east side of road at the HAZMAT pull off; 0.25 mile north of Harrogate, Tennessee; 36.59341° N, 83.66776°

II. Supplemental Locations with partial exposures of the Clinch Formation

I) **Bean's Gap** - parts of Upper Poor Valley Ridge Sandstone are exposed on both sides of US 25E near the summit of Clinch Mountain, 1.2 miles southeast of Thorn Hill, Tennessee; 36.35014° N, 83.39368° W

II) **Little War Gap** – Poor Valley Ridge Sandstone is exposed on the dip-slope along TN 70 at crest of the Powell Mountain; 10.9 miles north of Rogersville, Tennessee; 36.50564° N, 83.02285° W

III) **Little Moccasin Gap** – Hagan Shale and Poor Valley Ridge Sandstone exposed in road cuts along US 19, 1.2 miles north of Holston, Virginia; 36.78841° N, 82.08781° W

IV) **House Mountain** - Poor Valley Ridge Sandstone exposed in natural bluffs and along hiking trail traversing east side of House Mountain State Natural Area, 0.9 mile west of intersection between Idumea and Hogskin Rd., 19.2 miles northeast of Knoxville, Tennessee; 36.08747° N, 83.81104° W