

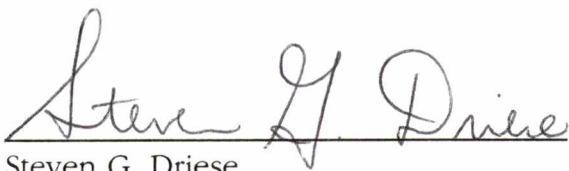
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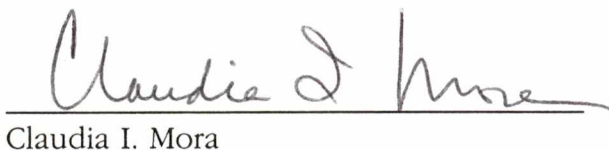


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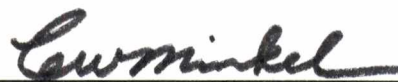


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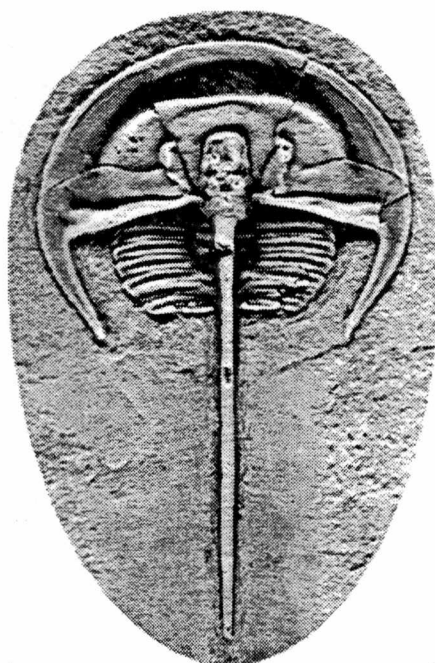
**THE STRATIGRAPHY AND DEPOSITIONAL HISTORY OF
THE MIDDLE CAMBRIAN RUTLEDGE LIMESTONE,
EAST TENNESSEE**

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

Andrew Stefaniak
August 1996

This thesis is dedicated to
my mentor and friend

Dr. Matthew A. Beebe



Norwoodia bellspina Beebe (1991)
(Middle Cambrian, Utah, x5)

His influence has been a major part of my success
and I will always be

"a Beebe wannabe"

ACKNOWLEDGMENTS

It is a rare event when one does something totally by themselves, and like many of the goals that I have reach in my life thus far, I could have not completed this thesis without the help and support of many people. I would like to express my sincere thanks to Dr. Kenneth R. Walker for giving me the opportunity to work on Cambrian carbonates. His constant friendship and support have made this journey beneficial and rewarding, and his love for three-day old coffee and his willingness to discuss the virtues of a certain computer platform have made my days in the "Bank" enjoyable. Most importantly, Dr. Walker has shown me what it takes to be a scientist during a time when I consider it to be very hard time for scientists. I can't thank him enough for that and for all that he has done for me.

Drs. Claudia I. Mora and Steven G. Driese are also thanked for their help along the way with this work. I have gained a lot from each of them, both in the classroom and out, and our friendship, I hope, will last well into the future. The Department of Geological Sciences here at the University and at the College of William and Mary have provided me with the skills and tools that I will need in my future endeavors and I would like to thank all my professors for their time and efforts in showing me the beauties and the realities of geology. I would like to thank, in particular, the secretaries here at the University, Cindy Turner, Denise Stansberry, and Melody Branch for their invaluable help throughout my stay and also Drs. Harry McSween, Theodore Labotka, and Robert D. Hatcher for the use of their computer facilities.

My deepest gratitude is given to the people to whom I consider to have taught me the art of carbonate sedimentology, my fellow "Bankers." Drs. Srinivasan Krishnan and Kenneth Tobin, and soon to be doctorates, Bosiljka Glumac, Gene Rankey, and Stan Dunagan have provided me with a great deal of

knowledge and ideas, have constructively disagreed with me many times, and have argued with me about the silliest of things, but through it all they have shown me that they are some of the best and most careful researchers I know. Their friendships are and will be greatly cherished and I only wish that all graduate students could have the same working conditions and experiences that I have had with this research group.

I would also like to thank Dr. Matt Joeckel, Kevin Howard, Chris Foster, Janee Ansley, and my sedimentology/stratigraphy lab class (Spring 1995) for their help in the various labs that I have worked in and for helping me prepare thin sections of my samples.

A person's character is a measure of the friendships that they share and I have could not have had a better resource to draw upon then the friends I have made during my stay here at Tennessee. Stan Dunagan (and Steph D., too), Daniel Capelle (and Angie C., too), and Angie Harton have been the best to me in "oh, so many ways" and have influenced me greatly in about every aspect of my life. They are my dearest friends and I could have never made it through all the ups and downs without them. The times we spent together will always remain with me as some of my best memories of graduate school. A great deal of joy and admiration, through their visits, hospitality, cookies, and friendship, were gained from Marianne, Gus, and Willie Beebe. I can't express to them enough how much they mean to me. Katy Dodd gave me constant "support" and provided me with an always present resource for a smiling face. Janee Ansley (and Lucy! - the best "black dog in the whole world") is thanked for her always, cheery friendship and for those crucial, stress-relieving walks in the park, especially in the snow and those towards the end of my term. All my students here at Tennessee are thanked for being sometimes the only bright thing in my, otherwise, sometimes mundane, busy schedule. Lastly, thanks goes to those friends not mentioned above and to

those whose friendships I hold closest to my heart, they know who they are and I thank them greatly for giving me the courage to be myself and to have faith in myself in all that I do.

A final word of thanks goes to my parents and my brother. They, more than anyone, are responsible for what I have accomplished and will accomplish in my lifetime. Their always present support and encouragement have provided me with a great deal of opportunities. Their instruction and understanding provided me with a stable base with which I use to make all my decisions. Their love and friendship have made me one of the luckiest kids in the world. I owe everything to them.

ABSTRACT

The Middle to Upper Cambrian strata of east Tennessee consist of the alternating shale and carbonate formations of the Conasauga Group. The Conasauga was deposited during the final stages of evolution of the Laurentian passive margin following the Late Precambrian to Early Cambrian rifting of Rodinia. The shale and carbonate formations record the interplay between a broad, carbonate bank (Honaker/Elbrook Formations) to the present day east and a western deeper-water intrashelf basin (Conasauga Shales). This research investigates the stratigraphy and sedimentology of the first carbonate formation, the Middle Cambrian Rutledge Limestone. Three major goals were addressed: 1) build a stratigraphic framework for the Rutledge, 2) determine the depositional environments of the major lithofacies, and 3) carry out a preliminary study of diagenesis.

Detailed study of 6 stratigraphic sections, 130 thin sections, and associated polished slabs reveal that the Rutledge is from 53 to 65 meters thick. The formation consists of seven distinct lithofacies. The dominant one, burrow-mottled mudstone/wackestone, consists of a carbonate mudstone matrix with an anastomosing network of burrows. Burrow fabric is preserved through the partial to complete dolomitization of the burrow-fill and is characteristic of *Thalassinoides*. The burrow-mottled lithofacies, together with the ribbon-laminated mudstone lithofacies, the skeletal, oncoid wackestone/packstone lithofacies, and the nodular mudstone with shale lithofacies, comprise over ninety-five percent of the Rutledge and attest to its dominantly muddy character. The ooid, peloidal grainstone lithofacies is limited to a thin, correlatable interval in the middle of the Rutledge section. The calcareous/non-calcareous shale lithofacies and the interbedded carbonate mudstone/wackestone/packstone and shale

lithofacies are limited to the lower transitional interval with the underlying Pumpkin Valley Shale and to a shale interval in the lower Rutledge.

Deposition occurred on a gently sloping carbonate ramp. The ramp is interpreted to have been a protected, homoclinal ramp facing the deeper-water intrashelf basin to the west and bordered to the east by shallow-water carbonate deposits. Deposition was characterized by the settling from suspension of shallow-water derived fine-grained carbonate sediment into environments below fair-weather wave base and below mean storm wave base. Subsequent burrowing by infaunal, soft bodied organisms produced the burrow-mottled fabric of the units. The overall homogeneity suggests that the ramp depositional system persisted throughout deposition of the Rutledge. Marked shallowing events, periodic reworking of sediments by storms, and progradation of the shallow-water environments into the basin are interpreted to have occurred during deposition, but these processes were minor in the overall history of the Rutledge in the field area.

Deposition was controlled by three factors: the relative position of sea level, the rate of clastic influx from the craton, and thermal subsidence. Sea level and the resulting water energy gradients controlled the distribution of facies. The rate of clastic influx from the craton, along with changes in the rate of sea level rise and fall, played a major role in the transition between the Rutledge and the underlying Pumpkin Valley and the overlying Rogersville Shales. Continuous, relatively high rates of thermal subsidence controlled the overall depositional *stasis* of the ramp system.

The Rutledge is interpreted as a highstand systems tract that, when combined with the underlying Pumpkin Valley Shale, comprises a third-order depositional sequence and defines the first grand cycle of the Cambrian grand

cycles of the southern Appalachians. Carbonate deposition began as the result of a decrease in the rate of sea level rise during the initial phases of the Sauk II transgression. Increased production of carbonate sediment in shallow-water environments kept-up with increases in accommodation space allowing for the transport of carbonate sediment basinward. Carbonate deposition possibly concluded as the result of sea level fall that temporarily suppressed carbonate production. Subsequent sea level rise resulted in the onlap of terrigenous clastics of the Rogersville Shale.

The Rutledge Limestone did not evolve into a flat-topped carbonate platform as did younger, major carbonate units of the Conasauga because of higher thermal subsidence rates, higher rates of input of terrigenous clastics, and decreased carbonate production area. This suggests that thermal subsidence and the effects of siliciclastics on carbonate deposition decreased throughout deposition of the Conasauga and that deposition of the older carbonate units of the Conasauga were controlled by subsidence and "catch-up" sedimentation whereas younger units were characterized by slower rates of subsidence and "keep-up" or "prograde" sedimentation. The antecedent topography of the Rutledge provided younger carbonate units with a larger sediment source area which resulted in a faster establishment of ramp deposition in the basin and an enhanced progradation potential of the shallow-water environments. Finally, continued aggradation of early Conasauga carbonates and time equivalent shallow-water deposits to sea level, coupled with eustatic sea level rise and subsidence, led to the development of an elevated shelf edge and sediment starved conditions in the area between the bank and the craton. The combined effects of above mention processes gradually led to the deepening of the area between the bank and the craton and the development of the intrashelf basin.

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CHAPTER 1

INTRODUCTION AND PREVIOUS RESEARCH

INTRODUCTION

The Middle to lower Upper Cambrian Series of the Tennessee Appalachians consists of the alternating shale and carbonate formations of the Conasauga Group (Figure 1.1). The formations comprise a portion of the thick Cambro-Ordovician pericratonic succession deposited on the evolving passive margin of Laurentia (Hatcher, 1989; Thomas, 1991). Studies have shown that the large scale alternation of the carbonate and shale formations were the result of the interplay between a broad carbonate bank and a deeper water intrashelf basin (Walker and others, 1990; Srinivasan and Walker, 1993). Changes between the shale and carbonate formations have been mainly attributed to changes in eustatic sea level, but other mechanisms, such as differing rates of subsidence, the amount of clastic influx, and non-thermal subsidence, have been shown to have played a role in the differing styles of deposition (see for example Cowen and James, 1993; Rankey and others, 1994;).

The alternating character of the Conasauga is similar to other Middle to Upper Cambrian passive margin successions (Aitken, 1981; Srinivasan and Walker, 1993; Rankey and others, 1994). These successions are generally referred to as "grand cycles" (Aitken, 1966) and have been studied in detail in the southern Canadian Rocky Mountains (Aitken, 1966, 1978), the western Great Basin of North America (Hinze and Robison, 1975; Palmer and Halley, 1979), the northern Appalachians of Newfoundland (Chow and James, 1987a; Cowen and James, 1993), and the southern Appalachians of Virginia and Tennessee (Markello and Read, 1981, 1982; Koerschner and Read, 1989; Srinivasan and Walker, 1993;

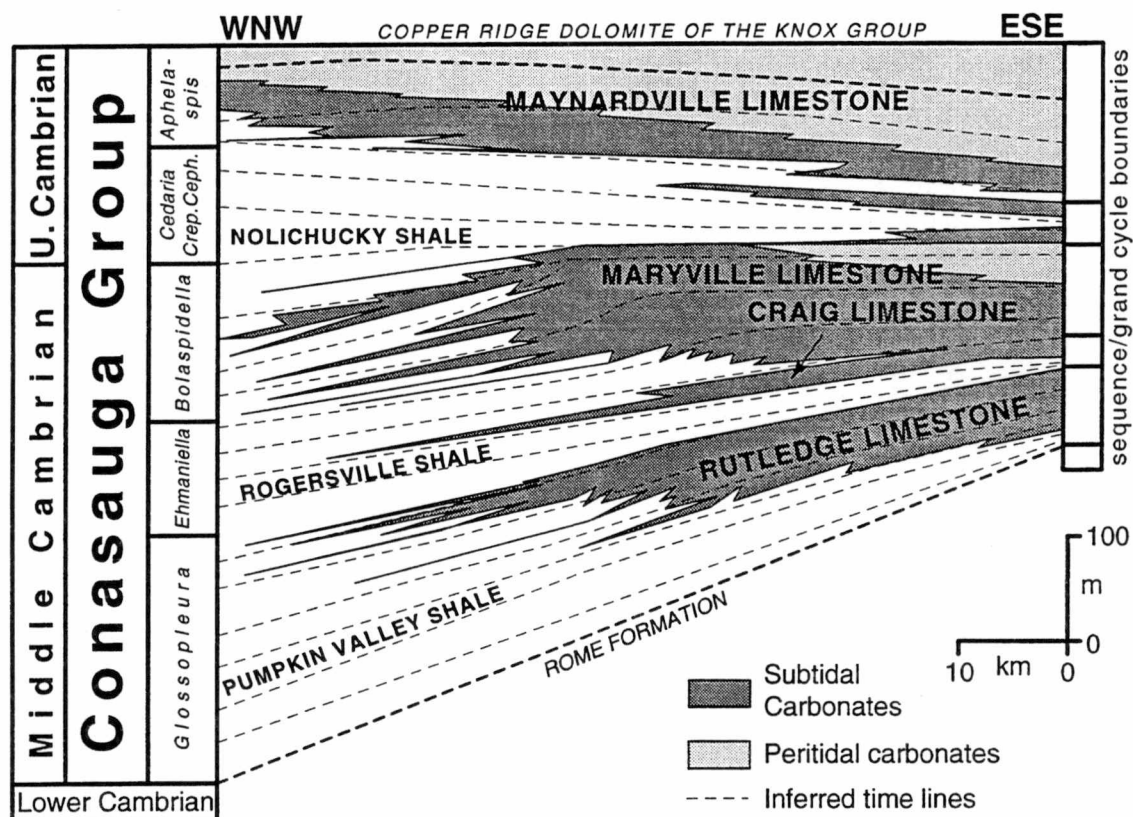


Figure 1.1. Middle to Upper Cambrian Conasauga Group stratigraphic model. The model, originally developed by Walker and others (1990) and modified here from Srinivasan and Walker (1993), shows the stratigraphic units of the Conasauga Group and their stratigraphic relationship along a northwest to southeast cross-sectional line through central eastern Tennessee. The interpreted sequence boundaries/grand cycle boundaries are illustrated on the right of the diagram. Trilobite biostratigraphy based on Rasetti (1965), Palmer (1971), and Derby (1965).

Rankey and others, 1994).

Grand cycles were originally defined as large-scale cycles "300 to 2,000 feet thick, and spanning two or more fossil zones (Aitken, 1966)." Today, grand cycles are considered to consist of a lower shaly half cycle that is diachronously overlain by a carbonate half-cycle (Aitken, 1981). The lower half-cycle is usually interpreted to represent deeper water deposits and typically contains abundant meter-scale shallowing-upward cycles. The carbonate half cycle consists of various kinds of shallow water limestones and dolostones, with meter-scale cyclicity varying from absent to widely apparent. A complete grand cycle may be a few tens of meters to several hundred meters thick (Palmer, 1981). The top of each cycle is often synchronous over wide areas and is marked by the abrupt change back into terrigenous mudstones. This change marks the beginning of the next cycle.

In the southern Appalachians, the Middle to Upper Cambrian grand cycles are 60 meters (early cycles) to 150 meters (late cycles) thick. The shale half-cycles are represented by the Pumpkin Valley Shale, the Lower Shale Member of the Rogersville Shale, the Upper Member of the Rogersville Shale, the Lower Shale Member of the Nolichucky Shale, and the Upper Shale Member of the Nolichucky Shale. They are overlain by carbonate half-cycles represented by the Rutledge Limestone, the Craig Limestone, the Maryville Limestone, the Nolichucky oolites, and the Maynardville Limestone. A complete cycle is considered to be a third order sequence (Walker and others, 1990).

The primary objective of this research was to investigate the stratigraphy, sedimentology, and diagenesis of the Rutledge Limestone, the first carbonate unit of the Conasauga Group. Two major goals were addressed: 1) the development of a stratigraphic framework for the Rutledge Limestone; and 2) the interpretation

of depositional environments of individual units and the explanation of the overall depositional history of the formation. Results were used to make comparisons on the styles of development between the Rutledge and younger carbonate units of the Conasauga.

This report is the first detailed analysis of the Middle Cambrian Rutledge Limestone. The results show that, unlike younger carbonate units of the Conasauga, the Rutledge did not evolve into a flat-topped carbonate platform. Instead, it remained in a carbonate ramp depositional regime through-out its history. The failure of the Rutledge to evolve into a flat-topped platform was due in part to high thermal subsidence rates that prohibited platform development and also to the morphology of the continental shelf during deposition. Younger carbonate units of the Conasauga show evidence for platform development and progradation, thus suggesting that subsidence may have waned through-out Conasauga time. This decrease in subsidence rates is related to the final establishment of the passive margin of Laurentia during Late Cambrian time. Very preliminary diagenetic work done by the author suggests that diagenesis of the Rutledge occurred in the marine and burial realms (See Appendix B). Evidence for exposure and meteoric alteration of the Rutledge was not observed in the study area. Porosity occlusion is interpreted to have begun in the active phreatic marine diagenetic environment with final occlusion occurring during subsequent burial diagenesis.

REGIONAL STRATIGRAPHY

Conasauga Group

The Conasauga was named by Hayes (1891) and Walcott (1891) for strata

exposed along the Conasauga River in Whitfield and Murry Counties, Georgia. In that region, the Conasauga is composed dominantly of shale with abundant lenses and layers of blue-gray limestone, leading Hayes and Walcott to refer to the unit as the Conasauga Shale. Time equivalent strata in east Tennessee were initially described by Safford (1869) and were referred to as the Knox Shale. It was not until the detailed mapping by Campbell (1894, 1899) and Keith (1895) that the identification of separate shale and carbonate formations was made. This work led to the recognition of six shale and limestone formations within the Middle to lower Upper Cambrian System of east Tennessee and southwestern Virginia. The formations were combined to establish the Conasauga Group.

In east Tennessee, the total thickness of the Conasauga ranges from 350 meters to 750 meters. The basal contact is placed between the Lower Cambrian Rome Formation and Middle Cambrian Pumpkin Valley Shale. It is defined in the field as the top of the highest prominent sandstone unit within the Rome Formation (Rodgers, 1953). The upper contact of the Conasauga Group is defined in east Tennessee by the contact between the Upper Cambrian Maynardville Limestone and the Upper Cambrian Copper Ridge Dolostone of the Cambro-Ordovician Knox Group. This boundary is traditionally placed at the 'lowest bed of the dark massive coarse-grained chert-producing dolomite' of the Copper Ridge (Rodgers, 1953). However, more recent studies by Glumac (1995, in prep) suggest that the boundary be placed within a conformable interval (~10-20 meters thick) marked by the presence of coarser siliciclastics within the peritidal sequence of the upper Maynardville and lower Copper Ridge Dolostone. This interval is interpreted to be time-equivalent to the well-documented Dresbachian/Franconian unconformity of the craton (Glumac, in prep; Lochman-Balk, 1971; Palmer, 1981; Osleger and Read, 1993).

Stratigraphic research on the Conasauga Group before the 1950's consisted of very generalized descriptions of stratigraphic sections (see for example Hall and Amick, 1934; Rodgers and Keith, 1948) and of the development of faunal lists for the individual units in the Group (Butts, 1940; Woodward, 1949). With the publication of his geologic map of east Tennessee in 1953, Rodgers set forth a new understanding of the lithologic relationships of the Conasauga and time equivalent formations in east Tennessee and southwestern Virginia. He separated the Middle to Upper Cambrian into three phases; the northwestern, central, and southeastern phases (Figure 1.2).

The northwestern phase consists predominantly of shale with common layers and lenses of limestone. It becomes increasingly shaly to the west, where

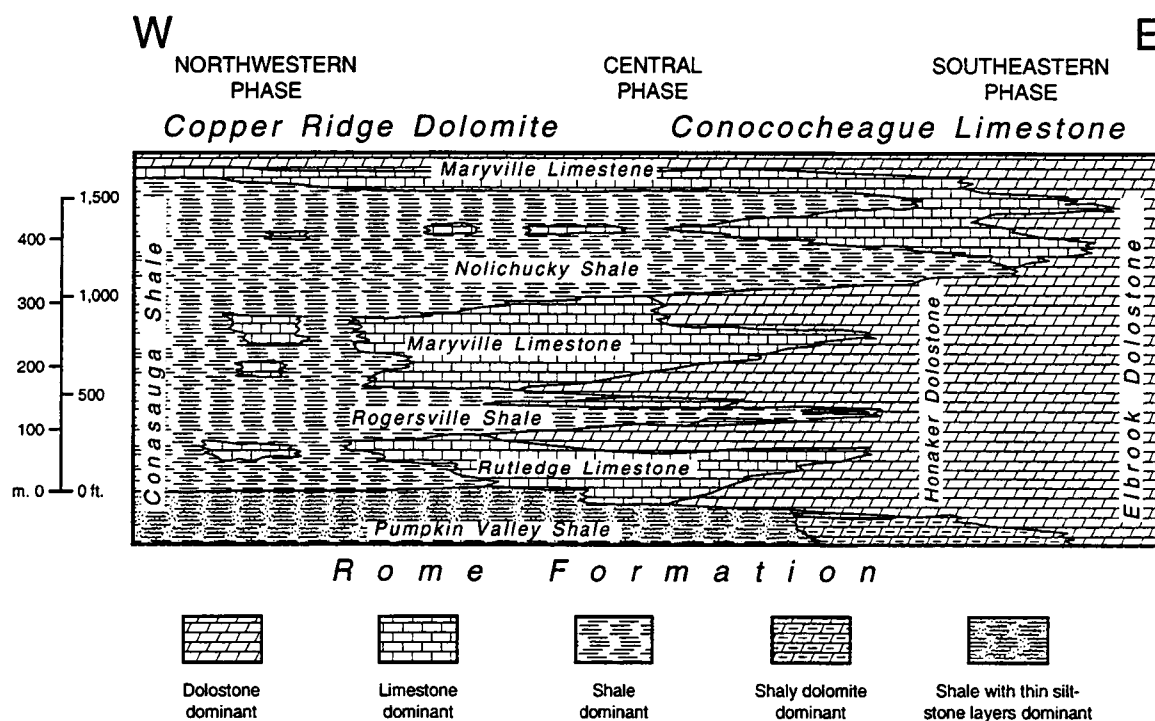


Figure 1.2. Generalized facies relationships of the Conasauga Group in east Tennessee and southwestern Virginia showing the major stratigraphic phases of Rodgers (1953). Redrawn from Rodgers (1953, Figure 3, p. 46). Cross-section is based on an imaginary belt starting at Madisonville, Tennessee and moving diagonally west of Knoxville towards Tazewell and ending at the Pulaski fault. Rodgers used this model to infer a northwesterly cratonic source for the clastic sediments.

the units grade into the Conasauga Shale. To the east, limestone interbeds become more prevalent marking the boundary with the central phase. The central phase is composed of the six alternating shale and carbonate formations herein and is located between Knoxville and Morristown, Tennessee. The southeastern boundary of the central phase is placed where the Rogersville Shale pinches out and the Rutledge and Maryville Limestones merge to form the Honaker Dolostone. In Tennessee, this boundary lies under or just northwest of the Pulaski fault. The southeastern phase is characterized by the mainly dolostone units of the Honaker and Elbrook Dolostones and the Maynardville Limestone.

Since the seminal work of Rodgers (1953), the main focus of research in the Conasauga Group has been to further refine the stratigraphy and to determine the origin and diagenesis of the units. In east Tennessee, this has been done through the detailed study of the upper Conasauga units, namely the Maryville Limestone (Erwin, 1981; Simmons, 1984; Kozar, 1986; Srinivasan, 1993; Rankey, 1993), the Nolichucky Shale (Derby, 1965; Markello, 1981; Weber, 1988; Foreman, 1991), and Maynardville Limestone (Glumac, in progress).

Descriptions Of Conasauga Units Pertinent To This Study

Pumpkin Valley Shale

Rodgers and Kent (1948) originally described the Pumpkin Valley Shale in Lee Valley, Tennessee. In the type area it has a thickness of up to 109 meters. It consists of interbedded olive green to yellowish brown shale, siltstone, sandstone, and limestone. The lower contact with the Rome Formation is placed at the top of the highest sandstone unit of the Rome (Rodgers, 1953). The upper contact with the Rutledge is conformable and is placed at the first appearance of massive

to very-thick bedded limestone (VanArsdall, 1972; this study). Near Thorn Hill, Tennessee, Simmons (1984) measured the total thickness of the Pumpkin Valley as 101 meters. The total thickness of the Pumpkin Valley was not determined in this study due to poor exposure and only the upper 10-25 meters of the unit were measured. It consists of bedded calcareous siltstone and shale, with thin carbonate mudstone layers up to 10 cm thick.

Rutledge Limestone

The Rutledge Limestone was named for the town of Rutledge, Tennessee where it is exposed in stream valleys that flow through town (Campbell, 1894). There has been no type section for the Rutledge put forth, but in the type area, Campbell (1894) described the Rutledge as a medium to thick-bedded, dark bluish gray limestone ribboned with dolostone. West of the type area, workers have described the Rutledge as a massive dark bluish gray, medium to thick-bedded limestone ribboned with dolostone. This bedded limestone is overlain by a fine-grained, dark bluish gray, medium-bedded dolostone near the top of the unit (Rodgers and Kent, 1948; Haney, 1966). The Rutledge is conformably underlain by the Pumpkin Valley Shale and is overlain by the Rogersville Shale. The upper contact is placed at the first occurrence of fissile shale and is generally sharp. To the east of the field area, the Rutledge merges with the Maryville Limestone to form the Honaker Dolostone (Erwin, 1981)

In this study the Rutledge has a stratigraphic thickness between 52 and 65 meters. This thickness is similar to thicknesses given by other workers (Simmons, 1984; Rodgers and Kent, 1948; Hall and Amick, 1934; see Appendix I). It consists dominantly of thick-bedded medium to dark gray burrow-mottled

carbonate mudstone. Intraclastic packstones and grainstone units up to 85 cm thick occur throughout the unit, total to less than 10% of the whole stratigraphic thickness of the Rutledge. In the study area, there is no evidence for a dolostone unit at or near the top of the Rutledge, as found elsewhere by other workers (see Rodgers and Kent, 1948; Haney, 1966).

Rogersville Shale

The Rogersville Shale was named for exposures near the town of Rogersville, Tennessee (Campbell, 1894). It was described by Rodgers and Kent (1948) as consisting of three members: a lower shale member, a middle limestone member, referred to as the Craig Limestone, and a thin upper shale member. It is underlain by the Rutledge Limestone and is conformably overlain by the Maryville Limestone. The shales are fissile, light olive-gray to dark gray in color, and may have a silt sized component to them (VanArsdall, 1974; Rankey 1993). The total thickness for the Lower Member has not been determined in the field, but to the east of the field area Bridge and Hatcher (1973) suggested that it may reach thicknesses of up to 50 meters. The upper shale member, at the type section at Craig Quarry in Rutledge, Tennessee, is 5.2 meters thick. The Craig Limestone has been described to consist predominantly of burrowed, carbonate mudstone with minor wackestones. It has a thickness of 26.2 meters in the type area (Bridge, 1956; Rankey, 1993). Massive dolostone units may be present in the upper part of the unit or the upper part of the Craig may be completely dolomitized (Erwin, 1981). To the west of the type area, the Craig pinches out and the two shale members merge (VanArsdall, 1974), and to the east, the Craig merges with the Maryville Limestone (Erwin, 1981). In the study area, the total thickness for the

Rogersville was not determined due to poor exposure. Where exposed, the lower shale member consists of a dark gray to brown, fissile, non-calcareous shale with thin (< 5 cm) siltstone and sandstone lenses.

TECTONIC AND PALEOGEOGRAPHIC SETTING

Late Proterozoic to Early Cambrian rifting of the supercontinent Rodinia (term after McMenamin and McMenamin, 1990) led to the formation of the continents of Gondwana and Laurentia. This rifting event is preserved within the Upper Proterozoic to Ordovician sedimentary sequences of eastern North America (also referred to in this thesis as eastern Laurentia, but this is not meant to reflect geographic position during deposition). The units trace the evolution of the Laurentian margin from an active rift to a stabilized passive margin. Detailed discussion of the tectonic and stratigraphic synthesis of eastern North America is given by Hatcher and others (1989).

After initial rifting, the margin is interpreted to have been a series of fault-bounded basins along an Atlantic-type rifted continental margin (Hatcher, 1989; Schwab, 1986; Thomas, 1991). Synrift sedimentation on the Precambrian crystalline basement within these basins began with deposition of the basal clastics of the Ocoee Supergroup and the Grandfather Mountain Formation (Thomas, 1991; Neton, 1992). The basal units are fluvial to shallow-marine in origin and are interpreted, based on sedimentologic data and regional thicknesses, to have been deposited in local, steep-sided basins framed by faults (Rankin, 1976; Rast and Kohles, 1986; Thomas, 1991). Post-rift sedimentation is marked by the deposition of the Upper Proterozoic/Lower Cambrian Chillhowee Group (Simpson and Eriksson, 1989; Walker, 1990; Thomas, 1991). The lower units of this Group

may overlie rift-fill units of the Ocoee or rest unconformably upon crystalline basement rocks outside rift basins and towards the craton interior (Thomas, 1991). The Chillhowee is composed of sandstones and shales that represent alluvial fan deposits in the lower formations and marine deposits in the upper formations (Walker, 1990; Thomas, 1991). Together they form the basal unit for the craton-wide transgressive Sauk sequence (Sloss, 1963). Marine transgression is interpreted to have been related to post-rift thermal subsidence and eustatic sea-level rise (Vail and others, 1977; Bond and others, 1984; Thomas, 1991)

The Lower Cambrian, transgressive Shady Dolostone conformably overlies the Chillhowee in the east and unconformably rests upon Proterozoic basement towards the craton (Pfeil and Read, 1980; Thomas, 1991). Easternmost facies of the Shady define a shelf edge and a southeastern slope facing the Iapetus Ocean (Pfeil and Read, 1980). The Shady is conformably overlain by the clastics of the Rome Formation. Consisting dominantly of siltstone, sandstone, and shales that grade eastward into a carbonate facies, the Rome has been interpreted by McReynolds and Driese (1994) to represent a mosaic of shallow marine environments that inherited the rimmed shelf morphology of the underlying Shady Dolostone. Carbonate sedimentation on the shelf edge, as evidenced by the carbonate facies of the Rome, continued throughout Rome deposition.

By Middle Cambrian time, the north-south axis of the Laurentian craton roughly paralleled the equator and the present-day eastern continental margin was located at approximately 15-20° south latitude (Figure 1.3; Zeigler and others, 1981). The margin consisted of a well-established carbonate bank that was bordered seaward by the Iapetus Ocean and cratonward by a deeper-water intrashelf basin (Figure 1.4, Palmer, 1971; Thomas, 1991). Beneath and inboard of the carbonate bank, a series of intracratonic fault systems had developed as the

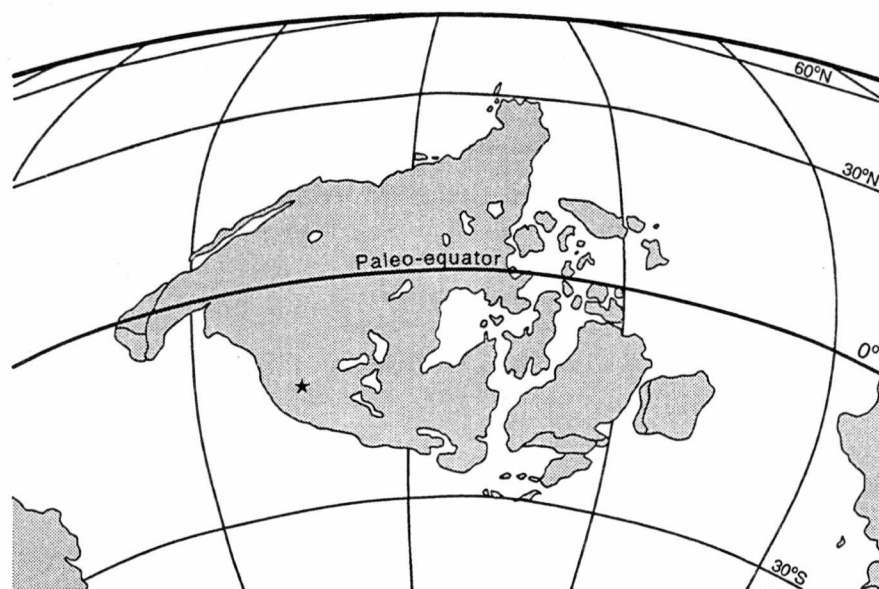


Figure 1.3. Paleogeographic reconstruction of the Laurentian craton during the Middle Cambrian. The study area was located approximately 15° south latitude. Paleogeographic map was generated by Scotese and Denham (1988), redrawn here from Beebe (1990).

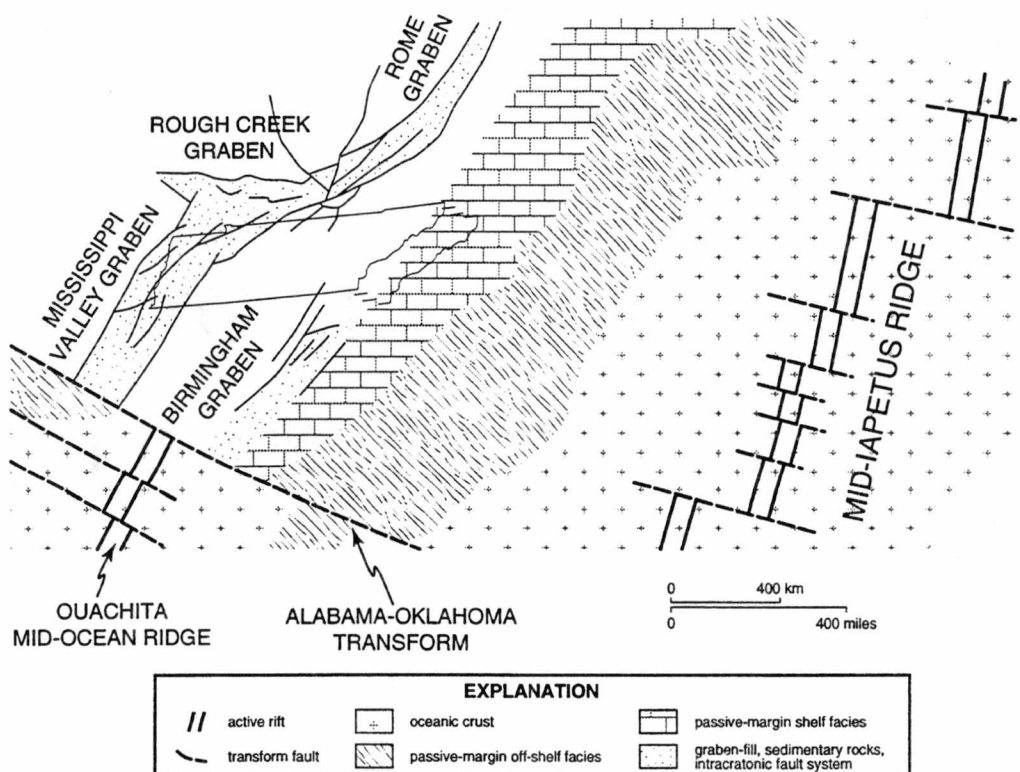


Figure 1.4. Map showing major structural features of the early Paleozoic Laurentian margin. The margin was characterized by a wide carbonate bank flanked on the east side by the Iapetus Ocean and on the west by a deeper-water intrashelf basin. Modified from Thomas (1991).

result of renewed extension. These graben systems are interpreted to have developed by latest Early Cambrian time and probably remained active until the middle Late Cambrian (Thomas, 1991). Remnant tectonism has been shown to have been active on the carbonate bank as well (Rankey and others, 1994). This tectonism is interpreted to have controlled depositional patterns on the platform and to have accentuated the effects of sea level change and subsidence. Rankey and others (1994) postulated that the eastern margin of Laurentia did not completely stabilize until Late Cambrian time (Maynardville Limestone; Glumac, in prep). Thus, the Conasauga Group may represent the transition from an immature passive margin, characterized by remnant tectonism associated with rifting, to a mature passive margin that was dominated exclusively by thermal subsidence.

PREVIOUS INVESTIGATIONS

Conasauga Group

Prior to the work of Rodgers (1953), an easterly source for the shales of Conasauga was inferred (see Howell and others, 1944; Moore, 1949). The publication of Rodgers' (1953) geologic maps and accompanying text revealed the lateral relationships of the carbonate and shale formations in east Tennessee. The maps and figures showed an increase in thickness of the shales to the west and northwest and a gradual pinch out of the shales toward the east. The shales were interpreted to be time equivalent to the carbonate units of the Conasauga and to the Honaker and Elbrook Dolostones. Thus, Rodgers interpreted a northwesterly source for the terrigenous clastics of the Conasauga.

In 1964, Harris further strengthened Rodgers' interpretation by showing that the Conasauga shales of Tennessee pinch out in the subsurface and grade laterally

into the Cambrian clastics of the craton (see also Sloss, 1963). Palmer (1971a) also argued for a westerly clastic source by relating the strata of east Tennessee to those of the Great Basin (Palmer, 1971b). He postulated that, during the Cambrian, the Laurentian margin was paralleled by an inner detrital belt bordered seaward by a carbonate bank, which was in turn bordered by an outer detrital belt. Palmer likened the carbonate bank to the present day Great Bahaman Bank and interpreted the inter-fingering relationship of the shales and carbonates to be the result of the interaction between adjacent sources of clastic and carbonate sediments.

Markello (1979) and Markello and Read (1981, 1982) provided detailed stratigraphic and petrologic information on 21 stratigraphic sections of the Nolichucky Shale exposed in southwestern Virginia. Their results led to the development of a depositional model for the Nolichucky which they used to infer the depositional relationships of the Maryville and Maynardville Limestones of the Conasauga, the Honaker and Elbrook Dolostones, the Conococheague Limestone, and the Copper Ridge Dolostone. The model shows that the Nolichucky was deposited in an array of environments within, and adjacent to, a shallow intrashelf basin located along the Laurentian margin (similar to the interpretation of Palmer, 1971a). The intrashelf basin was bordered to the west by the Laurentian craton and to the east by a carbonate ramp-tidal flat complex (Honaker and Elbrook Dolostones). Depositional environments for the Nolichucky and time-equivalent strata ranged from those below fair-weather wave base within the intrashelf basin to those on the shallow subtidal to supratidal flats of the peritidal platform (Figure 1.5).

The Nolichucky consists of an informal lower shale member, a middle limestone member, and an upper shale member, which was interpreted by

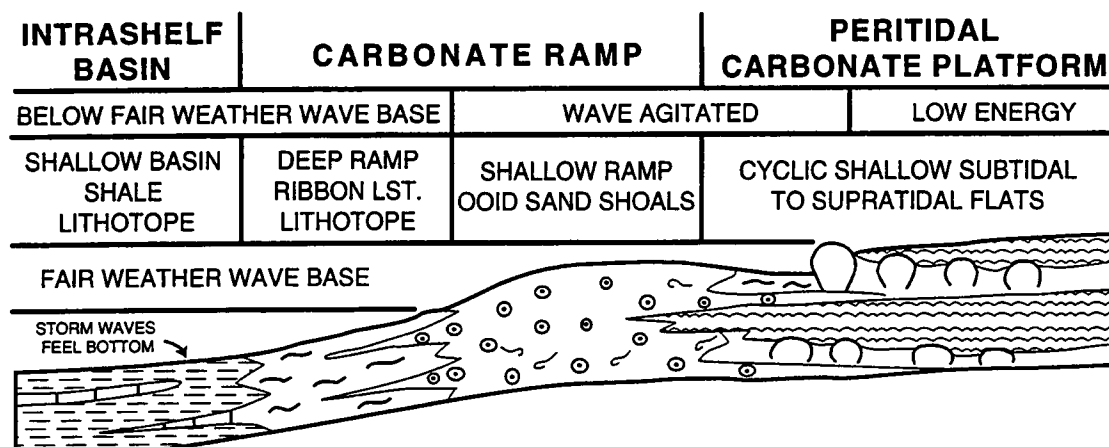


Figure 1.5. Sedimentary facies of the Nolichucky Shale. This schematic diagram shows the progression of facies from intrashelf clastic basin (left) to shallow carbonate shelf (right) as interpreted by Markello and Read (1982, Figure 7, p. 866). Markello and Read (1981, 1982) interpreted the Nolichucky as a gently sloping carbonate ramp.

Markello and Read (1981, 1982) to represent a transgressive-regressive cycle. The transgression, they argue, occurred from southwest to northeast and it was interpreted that the basin remained in open marine conditions due to relatively shallow basin depths that would favor surface to bottom mixing. However, Markello and Read (1981, 1982) did indicate that the basin may have been euxinic to the southwest where depths may have been below storm weather wave base. Later work on the Nolichucky of east Tennessee by Walker and Foreman (1990) and Foreman (1991) showed that the intrashelf basin was deeper (up to 200 meters) than what was proposed by Markello and Read (1981, 1982) and that open-marine conditions (oxygenated) prevailed throughout the duration of deposition of the Nolichucky.

Markello and Read (1982) noted that the development of the carbonate shelf and the adjacent intrashelf basin may have been related to increased production of carbonate on the shelf edge coupled with tectonic subsidence, reduction in clastic influx from the craton, and an overall transgressive event.

They advocated that Milankovitch-style sea level fluctuations were the dominant factors in controlling facies distributions. This interpretation was further advocated by Read (1989), who ruled out other causal factors, such as autocyclic controls or jerky subsidence. This view has come under some debate by later workers who have shown that these other factors may have played a significant role (see for example Cowen and James, 1993; and discussion below).

Erwin (1981) defined the inter-tonguing relationships and the depositional environments of the Maryville Limestone and Honaker Dolostone in southwestern Virginia and northeastern Tennessee. His study expanded the model of Markello and Read (1981, 1982) to include descriptions of the peritidal dolostones and lagoonal pelletal carbonates that would have been located on the peritidal platform as defined by Markello and Read (1981, 1982). Erwin interpreted the Maryville and Honaker as a homoclinal carbonate ramp consisting of shallow water facies (Honaker) that pass downslope into deeper-water facies (Maryville) without any increase in depositional slope (definition after Ahr, 1973). Erwin went further in estimating the width and expanse of the shelf by integrating the work of Markello and Read (1981, 1982) with his own on the Honaker. He stated that the lagoonal portion of the shelf was at least 20 km wide during maximum progradation and that the entire shelf was between 40 and 60 km wide, thus leading Erwin to calculate depositional slopes of less than 2.5 m/km.

Detailed stratigraphic work on the Conasauga of east Tennessee was completed by Walker and others (1990) and by a series of students at the University of Tennessee, Knoxville. Much of the work was on the Maryville Limestone, including that of Simmons (1984), Kozar (1986), Srinivasan (1993) and Rankey (1993). In addition, Weber (1988) and Foreman (1991) studied the Nolichucky Shale and Glumac (in progress) is analyzing the uppermost carbonate

unit of the Conasauga, the Maynardville Limestone. From Srinivasan's work on the Maryville, a depositional model was published illustrating the sequence stratigraphy and the development of the Maryville Limestone (Srinivasan and Walker, 1993, summarized below). This model was also used to generalize the development of all the carbonate units of Conasauga. Rankey and others (1994) expanded that model to include information on the response of the shelf to changing tectonic and eustatic controls. Srinivasan also worked on the burial diagenesis of the Conasauga (Maryville), with special attention paid to fluid flow (Srinivasan and others, 1994).

In contrast to the depositional models of Markello and Read (1981, 1982) and Erwin (1981), the depositional model proposed by Srinivasan and Walker (1993) showed that deposition of the Maryville Limestone resulted in the formation of a more or less flat-topped carbonate platform. The platform was bordered to the west, northwest by an intrashelf basin (represented by the equivalent Conasauga shales) and to the east, southeast by the Iapetus Ocean (Figure 1.6). Their model (Figures 1.7) was based on the detailed stratigraphic and petrographic analysis of five stratigraphic sections representing a basin to platform margin transect.

The Maryville evolved from a gently sloping carbonate ramp to a flat-topped platform as the result of platform progradation into the intrashelf basin. The lower portions of the Maryville, represented by subtidal burrow-mottled and ribbon limestones, record the initial start-up phase (after Kendall and Schlager, 1981; "Aggradational Stacking Pattern" of Srinivasan and Walker, 1993) of deposition characterized by the aggradation of the ramp to near sea level. As carbonate production on the platform kept up with or out-paced sea level rise (decreasing accommodation space), the platform prograded ("Progradational

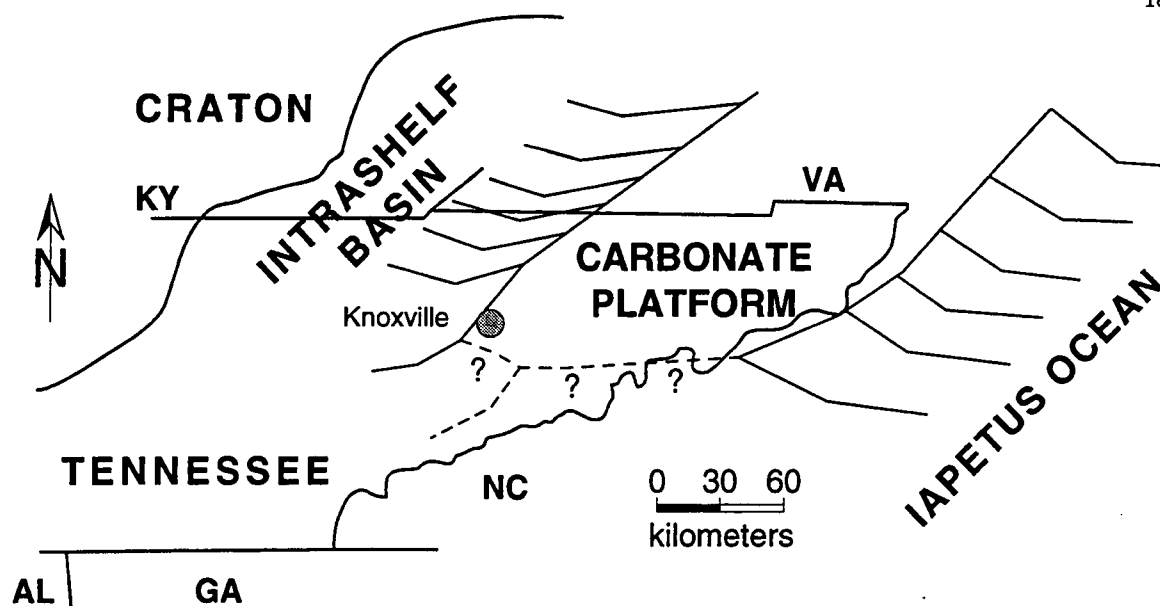


Figure 1.6. Schematic diagram of the paleogeography for the Middle Cambrian Maryville Limestone. Srinivasan and Walker interpreted the Maryville Limestone as a flat-topped carbonate platform bordered to the west, southwest by a deeper-water intrashelf basin. Modified from Srinivasan and Walker (1993, Figure 8, p. 893).

Stacking Pattern”) towards the basin. Overlying these lithologies are shelf-edge deposits (ooid/oncoid grainstones) and reef lithologies composed dominantly of *Renalcis*-sponge-*Girvanella* boundstones, indicating progradation of the platform into the basin (“Rimmed Shelf Progradational Stacking Pattern”). The close of deposition began with exposure of the platform-top due to a relative sea level fall. This exposure shut down carbonate production on the platform and the exposure surface is interpreted as a sequence boundary. A subsequent sea level rise occurred causing the abrupt drowning and onlap of basinal shales (Nolichucky) at platform margin localities and a backstepping of the platform (Retrogradational Stacking Pattern).

Further support of this model was put forth by Rankey (1993). In a field area east of that of Srinivasan (1993), Rankey documented a similar transition from slope to platform for the Maryville. However, in Rankey’s work, the transition

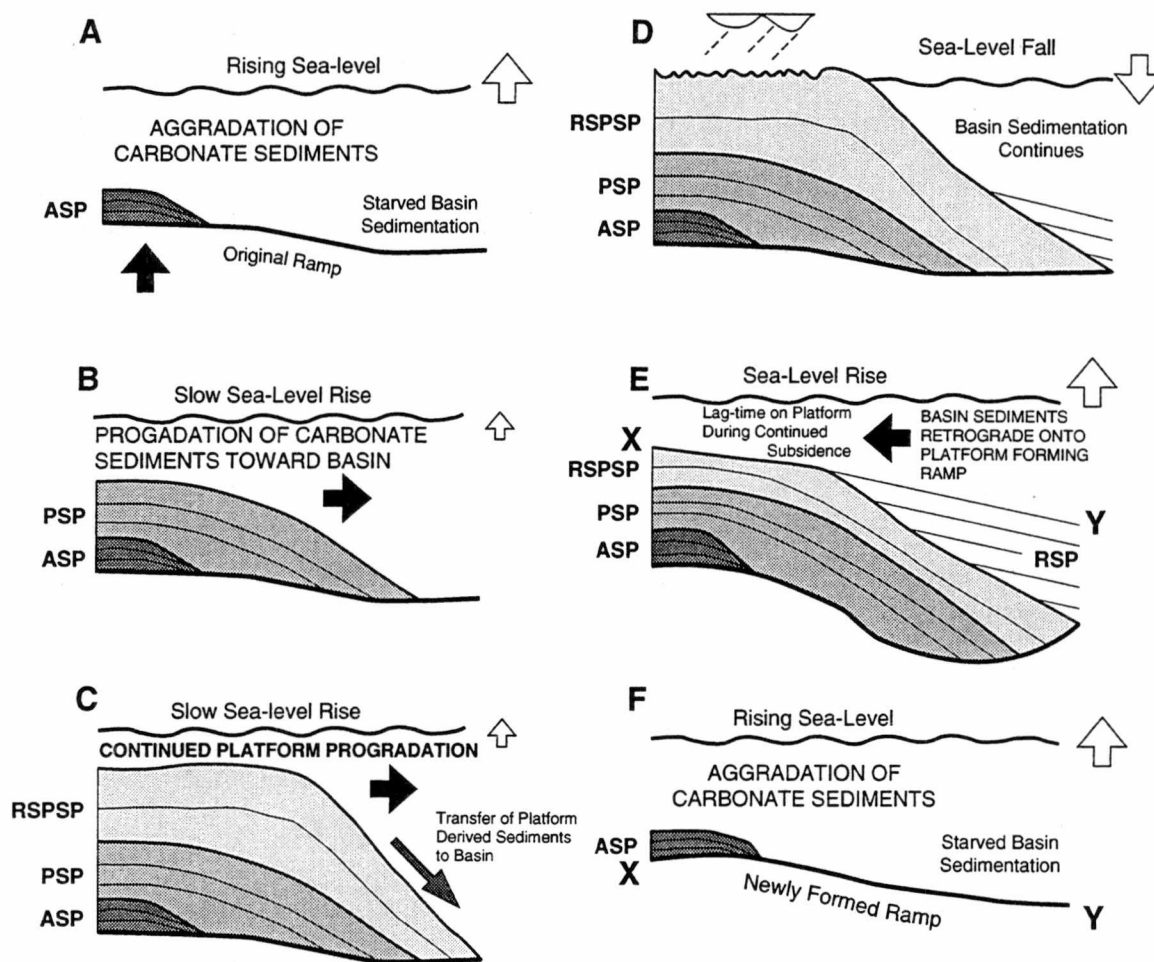


Figure 1.7. Idealized depositional model for the development of Conasauga Group platforms as interpreted by Srinivasan and Walker (1993). A = oldest, F = youngest. Black arrows indicate facies migration direction. See text for discussion. ASP = aggradational stacking pattern where sedimentation "keeps up" with increase in accommodation space. PSP = progradational stacking pattern where carbonate sediment production outpaces increase in accommodation space and the platform progrades basinward. RSPSP = rimmed shelf progradational stacking pattern in which a steepened slope results in mass movement of platform edge sediments down slope. RSP = retrogradational stacking pattern in which basinal facies are deposited onto the old platform. Redrawn from Srinivasan and Walker (1993, Figure 7, p. 892).

from slope to "on-platform" sediments was placed much lower in the section, strengthening the interpretation of platform progradation into the basin (see also Stefaniak and others, 1994; Dunagan and Stefaniak, 1995). The dominant lithologies in Rankey's study area were those associated with peritidal environments of the platform interior (Rankey, 1993). The transition between the Maryville and Nolichucky also differed between the two studies. Instead of being directly overlain by shales of the Nolichucky as in areas to the west, Rankey found the transition between the Maryville and Nolichucky to be characterized by a back-stepping package that recorded shallow-water sediment that accumulated after "the lag time" (shut down of the carbonate production on the platform) recorded so prominently elsewhere by a highly condensed interval. This package was deposited over a prominent exposure surface that was correlated across the basin to the platform margin and it represents the gradual drowning of the platform (Rankey and others, 1994).

Rankey's results also offered a better understanding of the mechanisms that controlled facies distributions and the development of the carbonate platform. He agreed with Srinivasan (1993) that aggradation and progradation of the platform, caused by gradual sea-level rise, thermal subsidence, and varying clastic influx, were the dominant factors controlling the decimeter-scale stacking patterns in the Maryville. However, Rankey (1993) further suggested that non-thermal tectonism played a significant role in the distribution of facies on the platform (see Rankey and others, 1994). Rankey proposed that remnant or episodic tectonism caused by sediment loading and/or regional extension along reactivated normal faults acted with numerous other mechanism (autocyclic, changes in relative sea-level) to control the meter-scale stacking patterns on the platform. In addition, this "jerky" style of tectonism acted to enhance the effects of other processes (such as eustasy

and thermal subsidence) on the development and drowning of the platform. The recognition of these processes showed that tectonism associated with the Late Proterozoic to Early Cambrian rifting of Rodinia may have extended into the early Upper Cambrian. This suggests that the margin of Laurentia was not truly passive at that time. This argument will be further clarified by Glumac (in progress) who will show that deposition of the Maynardville Limestone marks the transition from this immature passive margin phase (lower to middle Conasauga Group) to a truly mature passive margin (upper Maynardville Limestone and Knox Group).

Diagenetic models proposed for the Conasauga Group have been developed through the study of the Maryville Limestone. Srinivasan (1993), Srinivasan and others (1994), Rankey (1993), and Dunagan and others (1994) have shown that the diagenesis of the Maryville platform followed a complex path ranging from marine cementation to meteoric alteration, and finally ending in the burial realm. Marine and meteoric diagenesis played a significant role on the interior portions of the platform (see Rankey and others, 1994; Dunagan and others, 1994), in the development and stabilization of shelf margins (fibrous cements in ooid shoals/boundstones; Foreman and others, 1989; Srinivasan and Walker, 1993) and in the recognition of exposure surfaces (see Srinivasan and others, 1993). However, due to the muddy character of most of the Maryville, the products of these diagenetic pathways are primarily limited to the grainy units.

Srinivasan and others (1994) determined the source of burial diagenetic fluids and traced the pathways of these fluids by analyzing burial dolomite cements in the Maryville. By using data from petrography, trace and rare earth element (REE) chemistry, and isotope geochemistry (carbon, oxygen, and strontium), they argued that burial fluids originated from the adjacent coeval Cambrian shale basin and migrated updip from present day west to east.

Interpretations for non-marine burial diagenetic fluids are based on the perturbations of strontium and oxygen isotopic values from published marine values for the time of sediment deposition. These perturbations suggest a radiogenic source (elevated Sr ratios) for the fluids, and that precipitation occurred at a range of temperatures and probably from an isotopically heavier fluid, as would be expected from shales of the Conasauga intrashelf basin. Iron and manganese trace element chemistry, as well as REE chemistry, of burial dolomite cements from different lithofacies show a decrease in concentration from west to east, suggesting that burial fluid became depleted in those elements in the direction of flow. Timing of the fluid migrations and further constraining the pathway of fluids still remains a major focus for the diagenetic study of the Conasauga Group.

Rutledge Limestone

The present research is the first study of the depositional and diagenetic history of the Rutledge Limestone. Previous investigations have been limited to the description of macro features and lithostratigraphy. VanArsdall (1972) measured stratigraphic sections of the Rutledge in east Tennessee (Hunter Valley and Copper Creek thrust blocks; this study includes a reexamination of one of his sections) and preliminarily concluded that the Rutledge represented a portion of a regressive sequence from deeper marine sedimentation (Pumpkin Valley) to tidal flat sedimentation (Maynardville). Simmons (1984) measured sections of the Rutledge within the field area (this study includes a reexamination of two of his sections). His study mainly focused on the Maryville and not on the Rutledge.

STUDY AREA AND METHODS

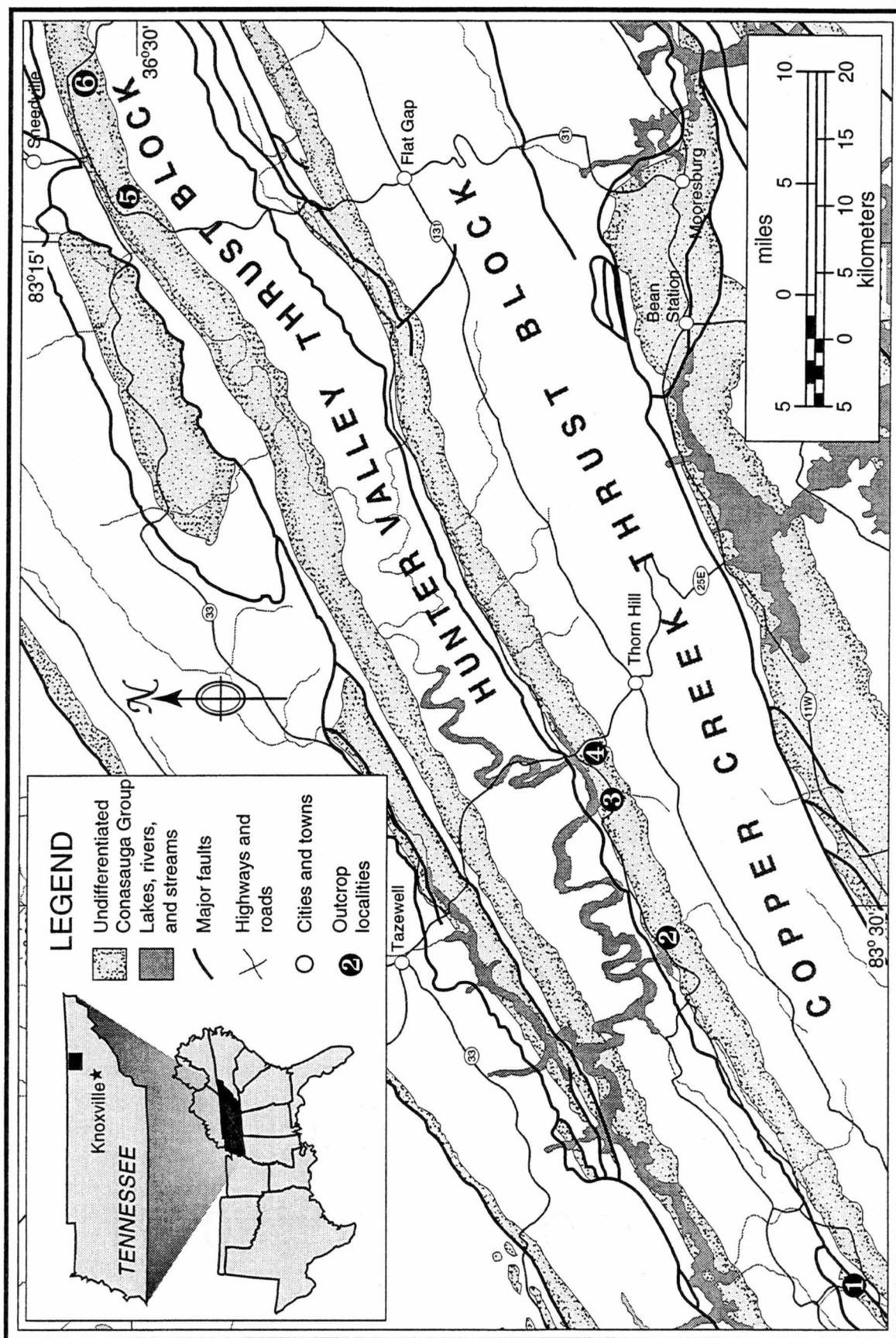
The study area for this research was located in the Valley and Ridge Physiographic Province of the Tennessee Appalachians. Characterized by southeasterly dipping, imbricated thrust sheets, the Province is underlain by strata ranging in age from Lower Cambrian to Mississippian. Ridges in the area trend southwest to northeast and are held up by units from the Rome Formation (Lower Cambrian), Maryville Limestone (Middle Cambrian), Maynardville Limestone (Upper Cambrian), Knox Group (Upper Cambrian to Middle Ordovician), Chickamauga Group (Middle Ordovician), and Clinch Sandstone (Lower Silurian). Valleys are generally underlain by shale and shaly limestone formations of the Conasauga and Chickamauga Groups.

Six stratigraphic sections were studied for this research (Figure 1.8, see also Appendix I). The Sneedville and Highway 31 sections are located on the Hunter Valley Thrust Block. The remaining four sections, Lays Gap, Puncheon Creek, Notchy Creek, and Thorn Hill, are located on the Copper Creek Thrust Block. Using palinspastic reconstructions (Roeder and Witherspoon, 1978) and general stratigraphic models for the area (Walker and others, 1990), the outcrop localities form a rough line that is oblique to depositional strike.

Outcrop localities were chosen on the basis of completeness and degree of exposure. Individual stratigraphic sections were measured in the field on the centimeter scale and detailed lithologic descriptions were taken. Hand samples were collected at noted stratigraphic levels to study representative lithologies and key sedimentologic/stratigraphic features in the laboratory. Special attention to structural elements of the localities was given so that true stratigraphic thicknesses could be confidently measured.

A total of 198 samples were collected from five of the outcrop localities.

Figure 1.8. Location map for this study. Shaded stippled area represents present day outcrop belts of the Middle to Upper Cambrian Conasauga Group in a portion of east Tennessee (based on map by Hardeman and others, 1966). Six stratigraphic sections were selected based on completeness and exposure quality. For detailed locations see Appendix I. Copper Creek Thrust Block Localities - ❶ Lays Gap Section (LG); ❷ Puncheon Creek Section (PC); ❸ Notchy Creek Section (NC); ❹ Thorn Hill Section (TH). Hunter Valley Thrust Block Localities - ❺ Highway 31 Section (HY); ❻ Sneedville Section (SN).



From this collection, a suite of 127 samples were made into thin sections (5x7.5 cm). All thin sections were stained with Alizarin Red S and with a 3:2 mixture of Alizarin Red S and potassium ferricyanide (after Dickson 1965, 1966) to aid in distinguishing between carbonate phases. An additional suite of 25 polished hand samples were made, with some overlap between the two suites. The thin sections were analyzed using standard petrographic techniques to gain information on the fabric and texture of the samples.

CHAPTER 2

STRATIGRAPHIC PACKAGES AND DEPOSITIONAL SYSTEMS OF THE MIDDLE CAMBRIAN RUTLEDGE LIMESTONE

INTRODUCTION

This chapter focuses on the stratigraphy and depositional environments of the Rutledge Limestone. There are three main objectives. First, the overall sedimentary packaging of the Rutledge is outlined and these packages are placed within a stratigraphic framework. Second, the field and petrographic characteristics of the individual sedimentary packages are described. Finally, interpretations of the depositional environments of individual packages are given.

Results will show that the preserved depositional textures of the Rutledge reflect deposition on a gently sloping carbonate ramp that was boarded by a shallow-water carbonate bank and seaward by a deeper-water intrashelf basin. The units of the Rutledge are subtidal in origin and were deposited primarily below fair-weather wave base. The fine-grained nature of the majority of the Rutledge units records the suspension deposition of allochthonous micrite that was derived from shallow-water environments. These deposits were subsequently burrowed by infaunal detritus feeders, ultimately leading to the formation of the burrow-mottled lithofacies that is characteristic of the Rutledge Limestone in the field area. Changes in the degree of burrowing, as evidence by the preserved textures, may indicate that conditions, mainly sediment supply, input of organic material, and oxygenation, fluctuated during deposition of this lithofacies. A thin, but distinctive, grainstone unit near the middle of the Rutledge section marks a short lived shallowing event that appears to have affected the entire shelf. This event represents a shift of shallow-water environments basinward as the result of a

lowering of relative sea level or, possibly, as the result of aggradation of the ramp to shallower water depths. The presence of similar grainstone lithofacies and other allochem rich lithofacies in other parts of the Rutledge section suggests that the migration of shallower-water environments may have occurred throughout deposition the Rutledge. However, the patchy distribution of these lithofacies within the studied sections indicates that this migration was not a shelf-wide event and that the ramp was a dynamic depositional system characterized by a homoclinal progression of shallow water environments to deeper-water environments interrupted by a discontinuous network of ooid shoals and patch reefs that formed at or near the fair-weather wave base interface. The ramp depositional system is interpreted to have existed throughout deposition of the Rutledge and controls on deposition were mainly related to accommodation space and sediment supply, which are interpreted to have been a function of relative changes in sea level. These latter aspects of the Rutledge are examined in the following chapter.

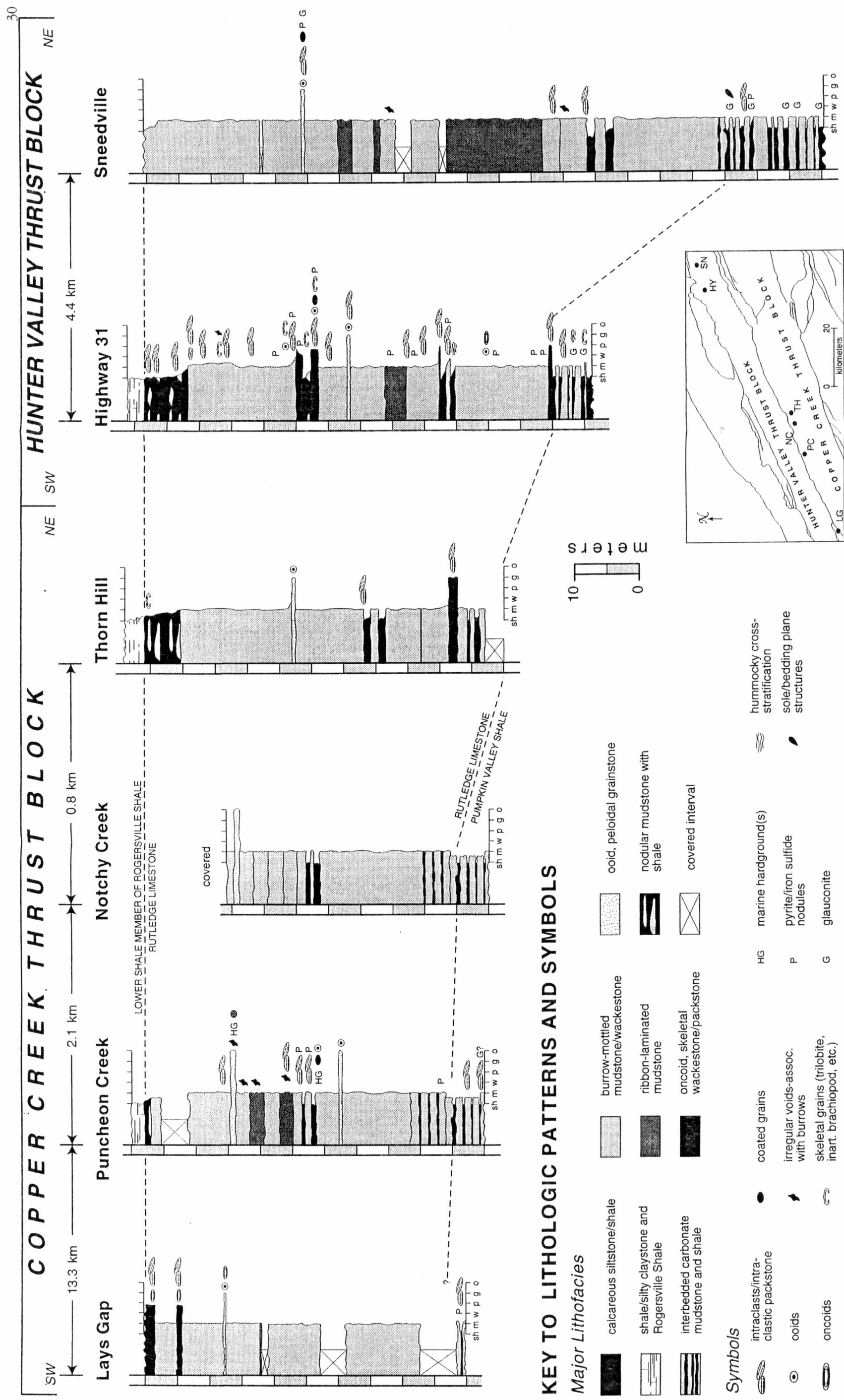
STRATIGRAPHY AND SEDIMENTARY PACKAGES

Field and petrographic study of six stratigraphic sections reveal two distinct sedimentary packages composed of eight different lithofacies (Table 2.1, Figure 2.1). The term *sedimentary package* is used to refer to a group of units deposited in a set of related depositional environments. The different sedimentary packages reflect major changes in depositional regime and generally coincide with the observed differences between the Pumpkin Valley and Rogersville Shales and the Rutledge Limestone. Boundaries between the two sedimentary packages, on the formational scale, are gradational or transitional. Within the Rutledge, package

Table 2.1. Major lithofacies of the Rutledge Limestone in the study area. Two sedimentary packages, basin/slope and ramp, were defined. The recognition of separate lithofacies was based on field and petrographic characteristics. See text for descriptions.

SEDIMENTARY PACKAGE	LITHOTYPE/LITHOFACIES	DEPOSITIONAL SYSTEM
Basin/slope	calcareous siltstone calcareous/non-calcareous shale interbedded mudstone/wackestone/ packstone and shale	Siliciclastic dominated shelf
Ramp	burrow-mottled mudstone/wackstone ribbon-laminated mudstone nodular mudstone with shale ooid, peloidal grainstone oncoid, skeletal packstone	Carbonate ramp

Figure 2.1. (next page) Measured stratigraphic sections of the Upper Pumpkin Valley Shale, Rutledge Limestone, and Lower Shale Member of the Rogersville Shale. Distances between individual sections are shown at the top of figure. Stratigraphic sections are located on two adjacent thrust blocks (see locality map at lower center). Together, the sections represent a transect that is oblique to depositional strike (based on palinspastic reconstruction of Roeder and Witherspoon, 1978). For detailed information in individual sections, see Appendix 1.



boundaries are sharp.

The term *lithofacies* is used for units with the same gross textural and fabric characteristics. Individual lithofacies represent units deposited in similar depositional environments within a particular depositional system. Thus, the term lithofacies has both a descriptive and an interpretive definition. Physical or chemical conditions during deposition of individual lithofacies may have varied but these conditions did not cause an overall change in depositional environment. Boundaries between the lithofacies are either sharp, gradational, erosional or diagenetic (stylolitic).

Stratigraphic thickness for the Rutledge Limestone ranges from 52 to 65 meters. This range is based on nearly complete measured sections of the Rutledge within the Copper Creek (Puncheon Creek Section) and Hunter Valley Thrust Blocks (Highway 31 Section). The majority of each section is composed of one lithofacies: the burrow-mottled mudstone/wackestone. This lithofacies makes up greater than seventy-five percent of the total stratigraphic thickness of the Rutledge (Table 2.2). Other common lithologies included units of the other mud-rich lithofacies, namely the ribbon-laminated mudstone, interbedded carbonate mudstone/wackestone/packstone and shale, and packstone/wackestone. When the individual stratigraphic percentages of the mud-rich lithofacies are combined they comprise over ninety-five percent of the total measured thickness of the Rutledge Limestone.

The remaining units are characterized by three lithofacies. The interbedded calcareous siltstone and shale and the calcareous/non-calcareous shale lithofacies are limited to an interval in the lower portion of the Rutledge. This interval is correlatable in each measured section except at Lays Gap, which is probably due to the structural complexities of that section. The ooid, peloidal grainstone

Table 2.2. Total thickness (in meters) and percentage (parenthesis) of individual lithofacies within stratigraphic sections of the Rutledge Limestone (see Figure 2.1). The data used to construct table was based on complete or near complete measured stratigraphic sections. Notchy Creek Section data was not used because that section is incomplete. Thorn Hill data is from Simmons (1984). The interbedded carbonate mudstone and shale lithofacies (*) is a combination of two lithofacies: interbedded mudstone/wackestone/packstone and shale, and nodular mudstone and shale.

LITHOFACIES	SNEEDVILLE SECTION	HIGHWAY 33 SECTION	LAYS GAP SECTION	PUNCHEON CREEK SECTION	THORN HILL SECTION	TOTAL
Burrow-mottled mudstone/wackestone	80.52 (85.1%)	50.14 (77.5%)	35.7 (72.3%)	39.32 (73%)	44.8 (79.6%)	250.48 (78.6%)
Ribbon-laminated mudstone	3.15 (3.3%)	4.22 (6.5%)	0.24 (0.5%)	4.38 (8.5%)	0	11.99 (3.8%)
Calcareous/non- calcareous shale	1.28 (1.4%)	0.35 (0.5%)	0	0.55 (1.1%)	1.3 (2.3%)	3.48 (1.1%)
Interbedded carbonate mudstone and shale*	1.25 (1.3%)	9.47 (14.6%)	0	3.65 (7%)	6.7 (11.9%)	21.07 (6.7%)
Ooid, Peloidal Grainstone	0.52 (0.5%)	0.49 (0.8%)	0.27 (0.5%)	0.75 (1.4%)	0.5 (0.9%)	2.53 (0.8%)
Oncoid, skeletal packstone	0	0	2.34 (4.7%)	0	0	2.34 (0.74%)
Covered interval	7.95 (8.4%)	0	10.84 (22%)	4.88 (9.4%)	3 (5.3%)	26.67 (8.4%)
Total Thickness (in meters)	94.67	64.67	49.39	53.53	56.3	318.56

lithofacies forms a thin correlatable unit located in the middle of the Rutledge section. This lithofacies is also found in thin beds in the Puncheon Creek and Highway 31 Sections.

The Rutledge does not exhibit the same style of lithologic cyclicity as seen in younger units of the Conasauga in east Tennessee (Rankey and others, 1994; Glumac, in prep) and units of similar stratigraphic position in southwestern Virginia (Koerschner and Read, 1989; and others). This absence is probably due to overall differences in depositional systems between the successions, namely, deeper-water, carbonate ramp for the Rutledge versus shallow-water platform for the Maryville and Virginia units.

DESCRIPTION OF SEDIMENTARY PACKAGES

Basin/Slope

Calcareous siltstone and shale

This lithofacies is found in the upper part of the Pumpkin Valley Shale and in a thin interval in the lower Rutledge. It typically weathers to a light brown, medium brown, or gray green color (Figure 2.2a and b). Beds are up to 30 centimeters thick and are composed of thick laminae, of less than 1 centimeter. The laminae are planar or hummocky cross-stratified and sole markings are common on bedding surfaces. Contacts between the siltstone beds are sharp and planar.

In thin section, silt grains are mostly quartz, glauconite, and Fe-sulfides, with lesser amounts of micaceous minerals (Figure 2.2c). The matrix is composed dominantly of micrite, which has been diagenetically altered to microspar. The quartz and glauconite occur as sub-angular to sub-rounded grains of coarse silt

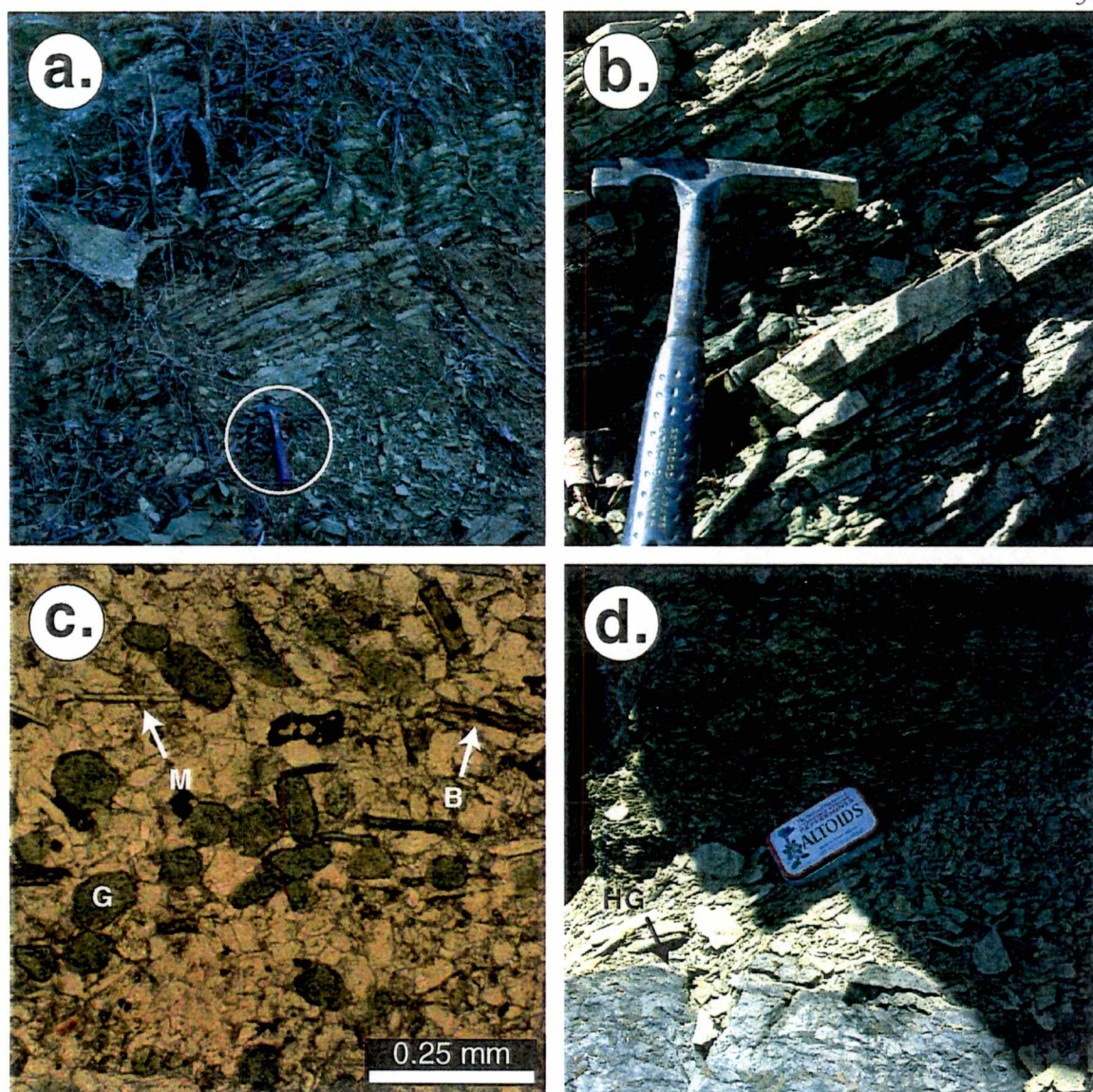


Figure 2.2. Outcrop photos and photomicrographs of representative lithologies from the calcareous siltstone and calcareous/non-calcareous shale lithofacies of the basin/slope sedimentary package. a. Outcrop photo of the interbedded shales and siltstones of the Pumpkin Valley Shale. Sneedville Locality. Hammer (circled, ~ 30 centimeters in length) for scale. b. Close up of interbedded shales and siltstones of the Pumpkin Valley Shale. Puncheon Creek Locality. Hammer (~ 30 cm in length) for scale. c. Photomicrograph (plane light, 100x) of calcareous siltstone showing quartz (clear grains), glauconite (G), mica lathes (black arrow, M) and inarticulate brachiopod fragments (black arrow, B). Sample S1/7.3, Sneedville locality. d. Outcrop photo of the shale interval within the Rutledge. The shale interval is characterized by paper-laminated shales, with or without lenses of carbonate mudstone and siltstone. A marine hardground, developed on the underlying burrow-mottled mudstone, characterizes the lower contact. The upper contact is marked by a intraclastic packstone layer that grades upward into units of the burrow-mottled lithofacies. Curiously strong peppermint tin (long axis = 9.5 centimeters) for scale.

size. Framboidal pyrite, with minor amounts of planar euhedral dolomite, are concentrated along lamina contacts to form the conspicuous bedding of this lithofacies. Micaceous minerals occur as thin laths randomly oriented in individual beds; rare disarticulated, inarticulate brachiopod and trilobite fragments are also present. Siltstones are typically interbedded with thin (<1 centimeter), green claystone layers.

Calcareous/non-calcareous shale

This shale dominated lithofacies is present in all three of the studied formations. Thickness of individual intervals range from less than <0.5 meter in the Pumpkin Valley Shale and Rutledge Limestone to over 12 meters in the Rogersville Shale (Figure 2.2d and e). The units are paper laminated (bedding less than 1 mm) and weather to a greenish brown or gray green color. Thin (<2 centimeters), discontinuous interbeds of calcareous siltstone and carbonate mudstone may or may not be present and, other than bedding and interbeds, sedimentary structures are virtually absent. In the Rutledge, this lithofacies occurs in the shaly interval in the lower portion of the section (Figure 2.2f). It overlies an interbedded carbonate mudstone and shale unit and is overlain by units of the burrow-mottled mudstone lithofacies.

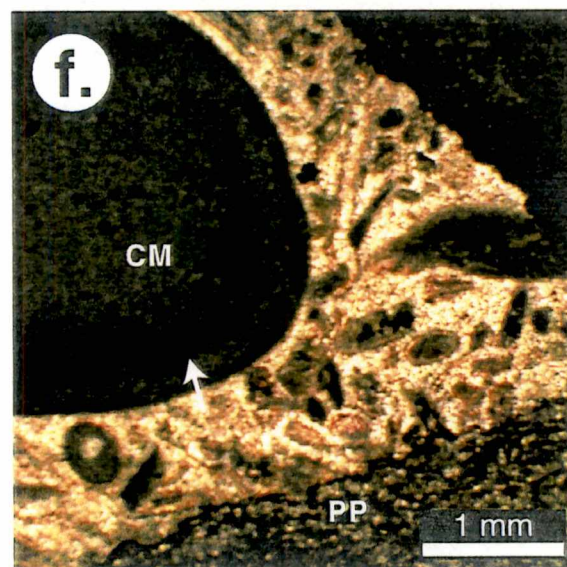
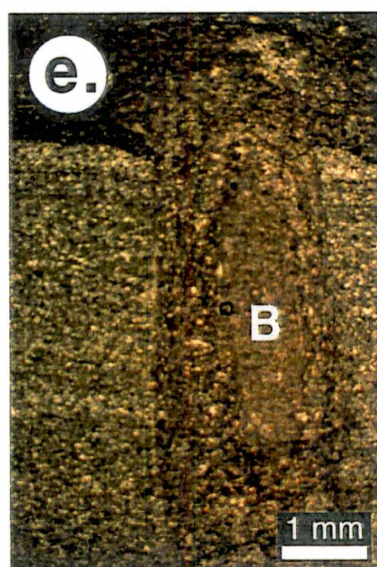
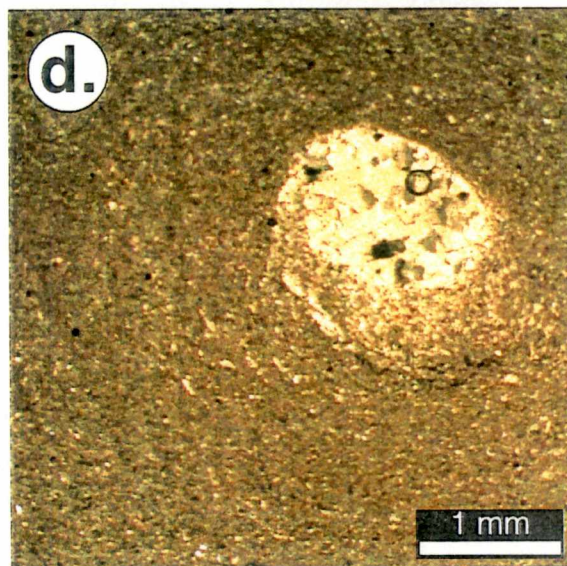
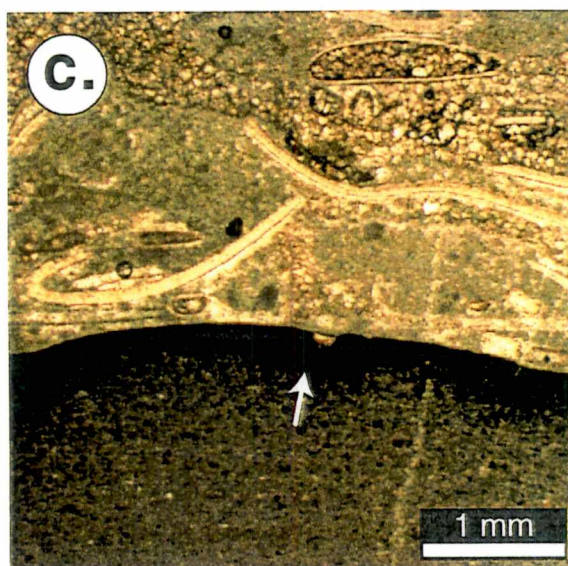
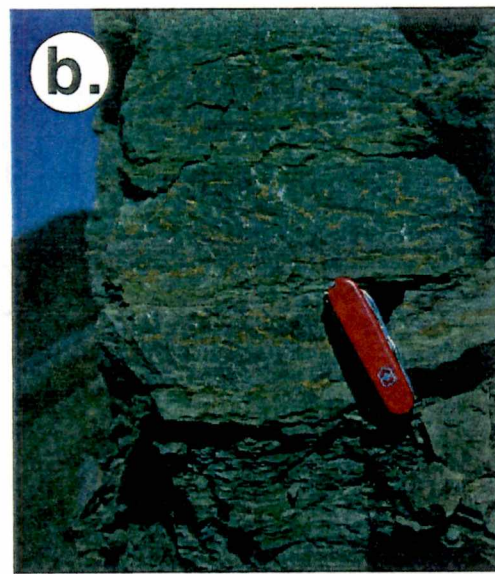
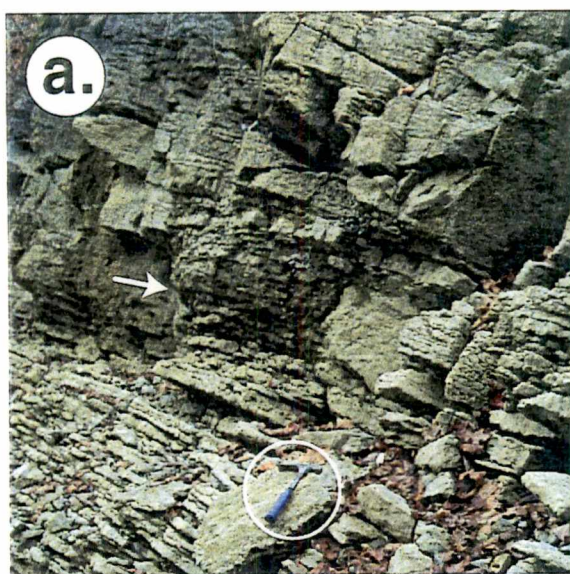
Interbedded carbonate mudstone/wackestone/packstone and shale

This group of lithologies is best represented in the transitional intervals between the Rutledge and the underlying and overlying Pumpkin Valley and Rogersville Shales, respectively. The lithofacies is characterized by a variety of

carbonate lithologies interbedded with shale and silty shale layers (Figure 2.3a and b). The carbonate units are brown or light gray on the weathered surface and vary in thickness from 2 to 50 centimeters. Sedimentary structures in the carbonate lithologies are related to the individual lithologies, but marine hardgrounds, characterized by mineralized and truncation surfaces, occur throughout this facies (Figure 2.3c). Shale intervals, when exposed, are less than 10 centimeters thick and are brown to greenish brown in outcrop. They are similar in appearance and texture to the calcareous siltstone and shale lithofacies described above. Contacts between the shale and carbonate layers are sharp.

Carbonate lithologies in this lithofacies include carbonate mudstones, intraclastic, skeletal packstones, and skeletal, peloidal packstones. A number of these lithologies may be present in one carbonate layer and individual or composite lithologies do not occur in any particular order in the vertical section. Instead, the layers occur in a random distribution throughout the lithofacies. Carbonate mudstones may or may not be burrowed, and typically contain a percentage (<15%) of sub-angular to sub-rounded fine, quartz silt (Figure 2.3d and e). Burrowed lithologies are characteristic of the burrow-mottled mudstone/wackestone lithofacies. Bedding is absent in burrowed mudstones, but is present in mudstone lithologies. When present, bedding is not thicker than 2.5 centimeters. Packstones of this lithofacies are composed of intraclasts and/or skeletal allochems in a matrix of either micrite or microspar, with varying percentages of peloids, skeletal allochems, and quartz silt. The intraclastic lithologies may either be mono- or polymict. The monomict packstones are made up of carbonate mudstone intraclasts and are limited to the upper transition zone with the Rogersville Shale. Polymict intraclastic units are composed of elongated sub-elliptical clasts of carbonate mudstone, skeletal peloidal packstone, quartz silt/

Figure 2.3. Outcrop photos and photomicrographs of representative lithologies from interbedded carbonate mudstone/wackestone/packstone and shale lithofacies of the basin/slope sedimentary package. **a.** Outcrop photo of the transition interval between Pumpkin Valley Shale and Rutledge Limestone at Cracker Creek, Puncheon Creek locality. Hammer (circled, ~30 centimeters) for scale. Black arrow marks the contact between the interbedded calcareous siltstones and shales of the Pumpkin Valley and massive burrow-mottled mudstones of the Rutledge. **b.** Outcrop photo of the contact between the Pumpkin Valley Shale and the Rutledge Limestone at the Highway 31 locality. The contact is marked by the presence of an intraclastic packstone (at same horizon as pocket knife) overlain by units of the burrow-mottled lithofacies. Swiss army knife for scale (long axis of knife = 9 centimeters) **c.** Photomicrograph (plane light) of mineralized hardground (white arrow) developed on a carbonate mudstone. Mudstone layer is overlain by a skeletal packstone, characterized by abundant trilobite fragments and peloids. Upper transition interval, Sample Hy 32/69, Highway 31 locality. **d.** Photomicrograph (cross-polarized light) of circular burrow in the silty mudstone. The burrow is partly geopetally filled with sediment. Note the orientation of mica grains (elongated, white) around the burrow, indicating the possible modification of the sediment during burrowing. Pumpkin Valley Shale, Sample S3/13.9, Sneedville locality. **e.** Photomicrograph (plane light) of escape burrow (B) in bedded, silty, carbonate mudstone overlain by siltstone layer (top of photograph). Lower transition interval, Sample S1/7.3, Sneedville locality. **f.** Photomicrograph (plane light) of an intraclastic packstone in the lower transition interval. This polymict packstone contains lithoclasts of carbonate mudstone (CM) and peloidal packstone (PP). The matrix is dominantly a skeletal grainstone characterized by trilobite fragments and smaller lithoclasts. Note the black staining (arrow) on rim of carbonate mudstone clast. Lower transition interval at Sneedville Locality.



peloidal packstone, and intraclastic packstone (Figure 2.4f). Skeletal, peloidal packstone occurs in individual layers in the composite lithologies or as thin units in both the upper and lower transition zones of the Rutledge. These lithologies are typically dominated by trilobite fragments and have a lesser abundance of peloids, quartz silt, hyolithid, and echinoderm fragments.

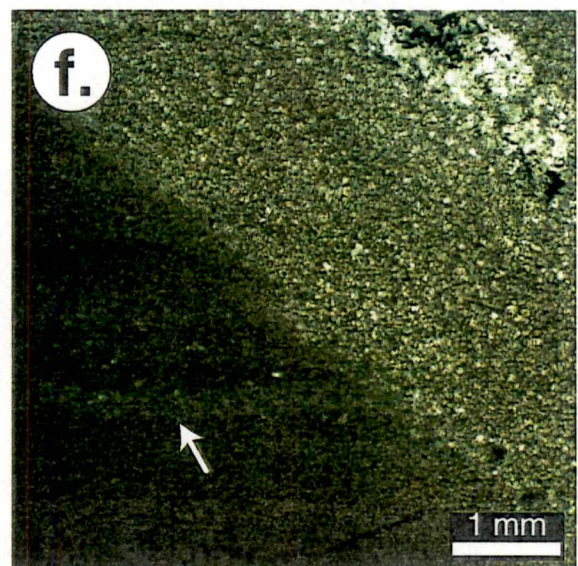
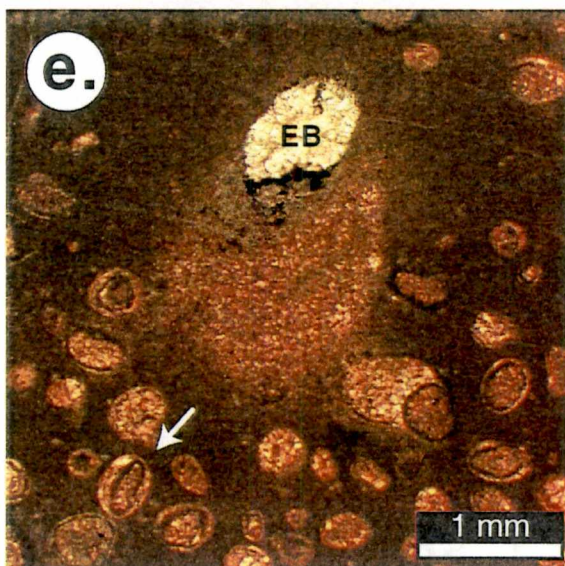
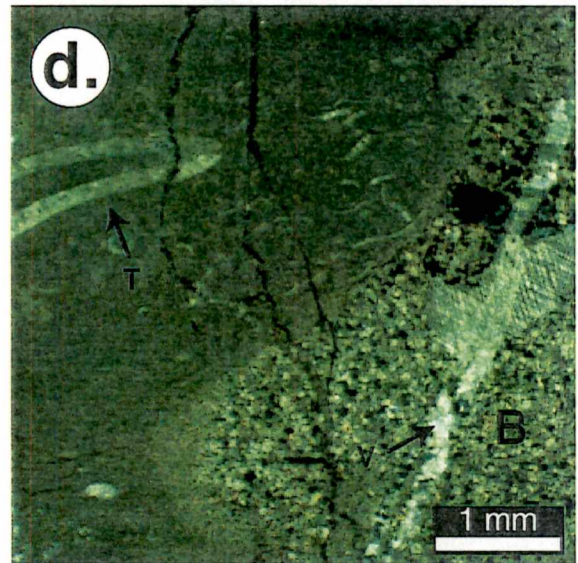
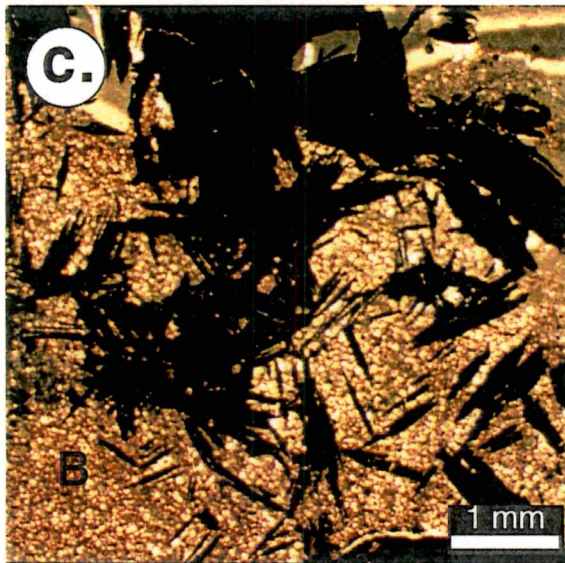
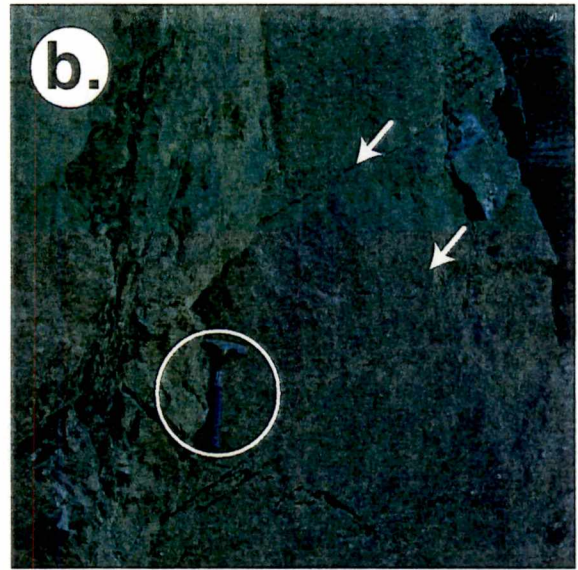
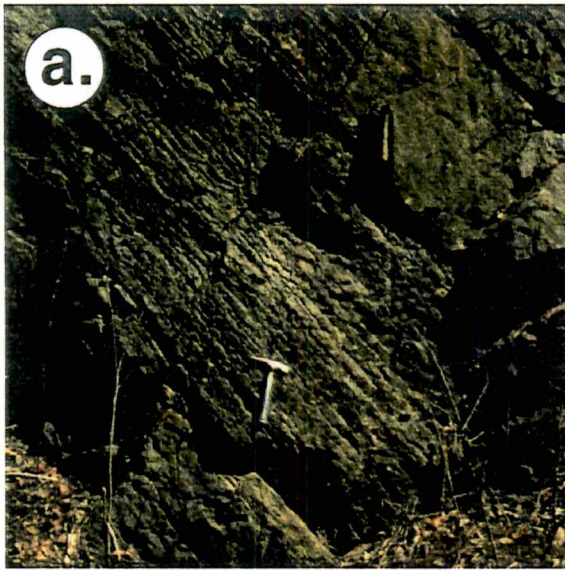
Ramp

Burrow-mottled Mudstone/Wackestone

The burrow-mottled mudstone/wackestone lithofacies is the dominant lithofacies of the Rutledge. It is composed of carbonate mudstone and lesser wackestone that is mottled by an anastomosing network of dolomitized burrows. In the field, this lithofacies weathers to a medium gray or light brown color and, depending on the degree of weathering and the style of burrowing, the units have either an irregular weathering profile, with pseudo bedding structures, or appear as massively bedded units (Figure 2.4a and b). In either case, the burrow mottled fabric is the result of the differential weathering of the burrows and surrounding micrite, and it is this selective dolomitization of the burrows that characterizes the majority of the units of the Rutledge. Thin (< 2 centimeters) interbeds of argillaceous material and dolomite may or may not be present within the lithofacies, depending on the degree of bioturbation. Besides the burrow-mottling, clay lamina, and the massive-bedded character, macroscopic sedimentary structures are rare to absent. Pyrite nodules up to 2 centimeters in diameter are common in the burrow-mottled units of the lower and upper Rutledge (Figure 2.4c).

Intraclastic packstone units of less than 0.75 meter in thickness commonly

Figure 2.4 Outcrop photos and photomicrographs of the major features of the burrow-mottled mudstone/wackestone lithofacies. **a.** Outcrop of irregular weathering pattern, showing pseudo-bedding structures, of the burrow-mottled mudstone facies at Puncheon Creek. Sedimentary bedding is dipping toward the lower right-hand corner of photo. Hammer (~ 30 centimeters in length, lower center of photo) for scale. **b.** Outcrop photo of massive beds of the burrow-mottled lithofacies. Black arrows define the upper and lower contact of the prominent grainstone unit within the Rutledge. Sneedville Section. Hammer (circled, ~ 30 cm in length) for scale. **c.** Thin section photomicrograph (plane light) of pyrite nodule in a burrow-mottled (B) wackestone. Pyrite nodules cross-cut depositional textures, suggesting a late diagenetic origin. Rutledge Limestone, Sample S26/108.1, Sneedville Locality. **d.** Photomicrograph (Crossed polarized light) of sub-vertical burrow cross-cutting skeletal (mainly trilobite fragments (T)) wackestone layer. Burrow (B) is filled with planar-E dolomite and coarse equant calcite cement. Burrow is cross-cut by late diagenetic vein (V). Rutledge Limestone, Sample LG7/9.08, Lays Gap Locality. **e.** Photomicrograph (plane light) of allochthonous ooids (arrow, concentrated in a 2 cm layer, photo is taken at the top of this layer) in burrow-mottled lithofacies. Ooids are partially to fully replaced and/or micritized. Burrow is filled with a geopetal fine planar-E dolomite, framboidal pyrite, and clear, equant calcite cement. Rutledge Limestone, Sample S12/64.3, Sneedville Locality. **f.** Photomicrograph (crossed polarized light) of sub-vertical burrow cross-cutting primary sedimentary laminations (arrow) in burrow-mottled lithofacies. Burrow is filled with planar-E dolomite, argillaceous material, and equant calcite cement. Rutledge Limestone, Sample S60.1, Sneedville locality.



occur in the burrow-mottled units. They are found at the lower contacts between shale intervals and overlying burrow-mottled units (see Figure 2.2d), but also occur at different stratigraphic horizons within the lithofacies. However, their occurrence is limited to the base of individual units. The beds have erosive bases and gradational upper contacts with the overlying burrowed units. The units are similar to the polymict intraclastic units of the interbedded mudstone and shale lithofacies. They are poorly sorted and have chaotic bedding. Clasts are imbricated, with some clasts lying at a high angle to sedimentary bedding ("edgewise conglomerates" of Sepkoski, 1982). The matrix between the clasts consists of abundant skeletal fragments, smaller intraclasts, minor amounts of micrite, and abundant marine cements.

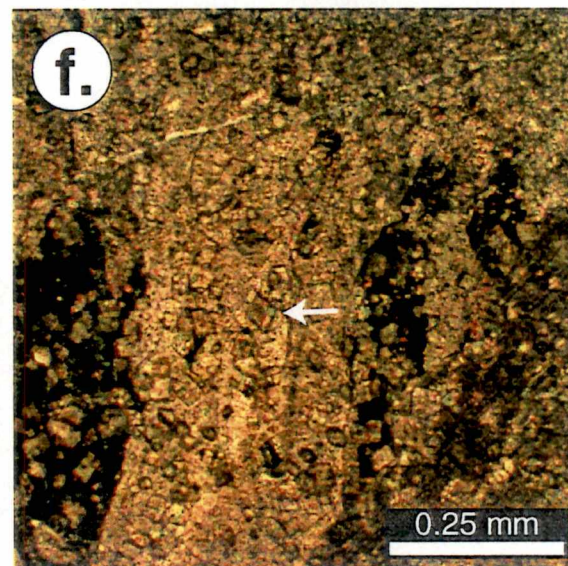
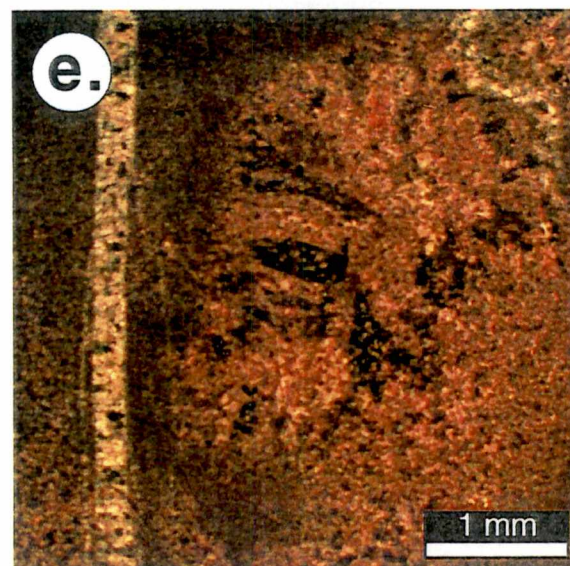
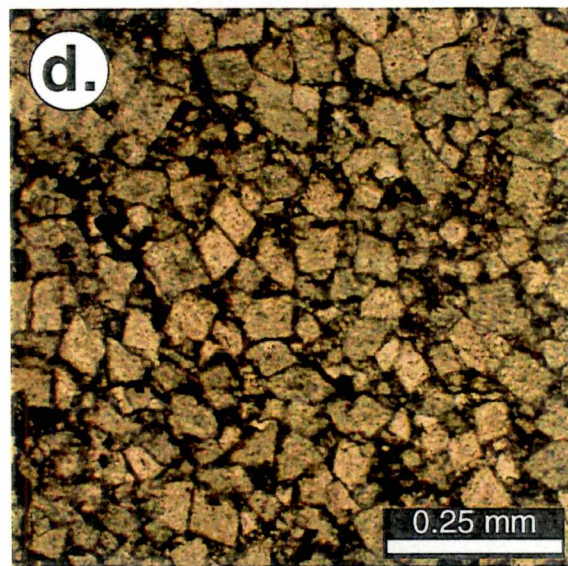
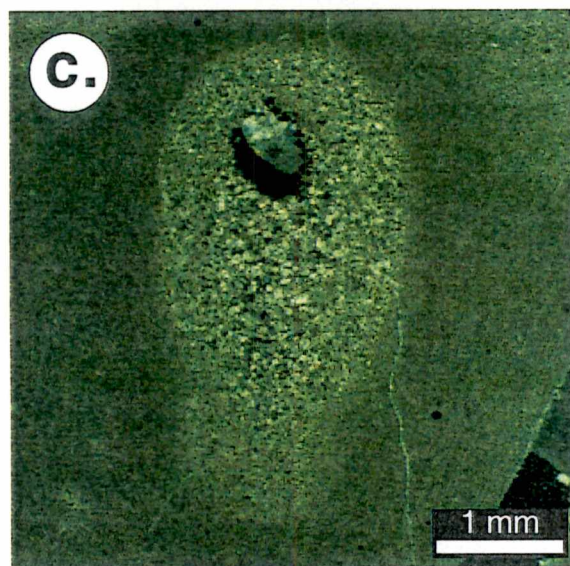
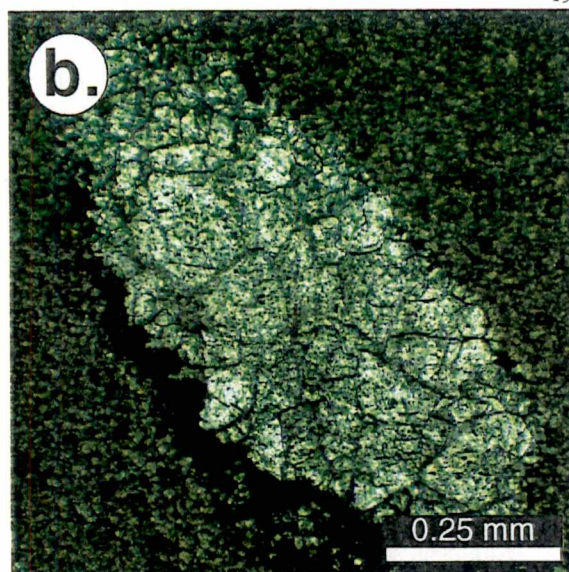
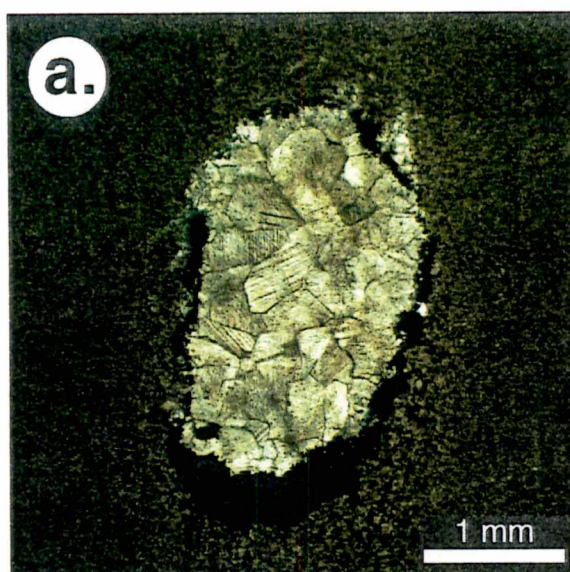
In thin section, the matrix is dominated by homogenous micrite and dolomicrite. Thin, wackestone intervals are present through-out the section, with skeletal fragments (mainly trilobite), ooids, intraclasts, and quartz silt comprising the dominant sedimentary grains. These grains may be concentrated in layers or they may occur randomly oriented within the matrix (Figure 2.4d and e). Laminations (< 1 cm), either skeletal lags or primary laminations, were observed in the section but are rare in the total lithofacies (Figure 2.4f). Burrows are preserved through the dolomitization of the sediment or through the precipitation of marine and/or shallow burial cements in the voids left by organisms after burrowing organisms. These differing styles of burrow preservation, their stratigraphic distribution, and examples of each are described and illustrated in Table 2.3 and Figure 2.5.

The macroscopic burrowed fabrics preserved in this lithofacies are similar in morphology to those described from Cambrian and Ordovician strata of the Great Basin (Droser and Bottjer 1986; Droser, 1987; and Droser and Bottjer 1988,

BURROW FILL	DESCRIPTION	STRATIGRAPHIC OCCURRENCE	REP. PHOTOS
Equant calcite cement	Isolated rounded to sub-rounded burrows occluded by clear, equant calcite. Crystal size may reach up to 0.25 mm in size. Geopetal and burrow lining pyrite (framboidal) and dark organic(?) material or clays may also be present. Burrow boundaries may be sharp and/or have a halo of micro-dolomite.	Ubiquitous in all lithofacies but most common in ribbon-laminated lithofacies.	Figure 2.5a and b; Figure 2.6b.
Planar-E dolomite and argillaceous material	Dense mosaic of planar-euhedral dolomite and opaque, argillaceous material. Dolomite rhombs have a max. size of 0.2 mm and are generally ferroan. Interstices between rhombs is filled with argillaceous material and/or calcite cement. Framboidal pyrite may or may not be present along burrow walls. Pyrite and equant calcite cement often occur as a central burrow fill. Burrow walls may be sharp, gradational, or stylolitic.	Most common burrow fill in all units of the burrow-mottled lithofacies. May represent a diagenetic stabilization product of fibrous calcite and microdolomite fill (see below).	Figure 2.4d,e, and f; Figure 2.5c and d; Figure 2.6j.
Fibrous calcite and micro-dolomite	Fibrous calcite with abundant microdolomite $\pm$ equant calcite fills burrow. Fibrous calcite emanates from burrow wall, with crystal size up to 1 mm in length. Micro-dolomite is ubiquitous in all fibrous calcite cements. Burrows may have final occluding phase of equant calcite. Burrow walls may be sharp, gradational, or stylolitic.	Rare burrow fill in the burrow-mottled lithofacies. Occurrence is random throughout section.	Figure 2.5d and e

Table 2.3. Dominant burrow fill material found in the burrow-mottled lithofacies of the Rutledge Limestone. Data presented is based on petrography of selected samples. Representative photomicrographs of different burrow fills are shown in Figures 2.4, 2.5, and 2.6.

Figure 2.5. Photomicrographs of dominant burrow-filling diagenetic phases of the burrow-mottled lithofacies. **a.** Photomicrograph (plane light) of large, circular, horizontal burrow filled with equant calcite cement. Framboidal pyrite lines the burrow and forms a geopetal "sediment" on the bottom of the burrow chamber. Notice gradational contact of the lower part of burrow with the host sediment. This style of contact suggests that diagenesis may have accentuated the size and shape of individual burrows by recrystallization of the surrounding micrite. Rutledge Limestone, Sample S60.1, Sneedville locality. **b.** Photomicrograph (plane light) of sub-horizontal burrow (?) similar to burrow shown in (a). This burrow is more typical of equant cement filled burrows. Again, notice the framboidal pyrite and the altered halo around the burrow. Thin section was etched in dilute hydrochloric acid, allowing the detection of the bimineralic (calcite and dolomite) matrix material. Rutledge Limestone, Sample S13/38.63, Sneedville locality. **c.** Photomicrograph (crossed polarized light) of planar-E dolomite and argillaceous material filling burrow in burrow-mottled lithofacies. This style of burrow-fill is the most common in the Rutledge units. The burrow is characterized by dense mosaic of dolomite rhombs and argillaceous material with a central void filled with geopetal pyrite (framboidal?) and equant calcite cement. The walls of the burrow are gradational and diffuse, suggesting that the host sediment may have been altered during formation of the subsequent burrow-fill. Rutledge Limestone, Sample LG7/9.08, Lays Gap locality. **d.** Photomicrograph (plane light) of planar-E dolomite and argillaceous material from burrow in photo (c). Notice the euhedral character of the dolomite and the dark, argillaceous material filling the space between dolomite crystals. Rutledge Limestone, Sample LG7/9.08, Lays Gap locality. **f.** Photomicrograph (crossed-polarized light) of fibrous calcite cement filling burrow in burrow-mottled lithofacies. The "pebbly" extinction pattern of the burrow fill is due to the presence of micro-dolomite within the burrow. Vertical vein occluded by equant calcite is present on the left third of photo. Rutledge Limestone, Sample S5/21.4, Sneedville locality. **e.** Photomicrograph (crossed polarized light, 100x) of fibrous calcite emanating from burrow wall (micrite) at the top of photo. Notice the euhedral, micro-dolomite (arrow) inclusion rich nature of the fibrous calcite. This phase may have been a precursor to the planar-E dolomite burrow-fill phase. Rutledge Limestone, Sample S5/21.4, Sneedville locality.



1989). The dominant ichnofabric in the Rutledge and in time equivalents of the Great Basin belong to the genus *Thalassinoides* (Ekdale and others, 1984).

Thalassinoides is characterized by either a two dimensional maze network (type A) or a boxwork network (type B). Type B is similar in morphology to the burrowed textures of the Rutledge. It is commonly associated with the disruption of the primary sedimentary fabrics, making it difficult to determine the exact depth and extent of bioturbation. The preserved burrow textures of the Rutledge conform to indices 2-5 of the classification of Droser and Bottijer (1986, 1988). These textures, their stratigraphic distribution, and interpreted conditions of formation are summarized and illustrated in Table 2.4 and Figure 2.6.

Ribbon-Laminated Mudstone

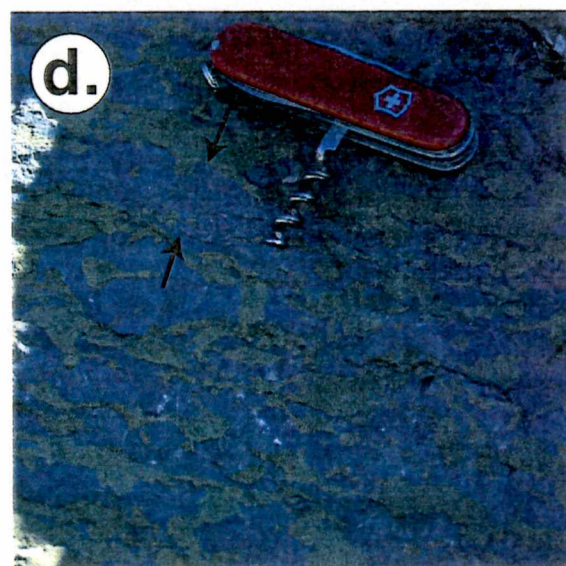
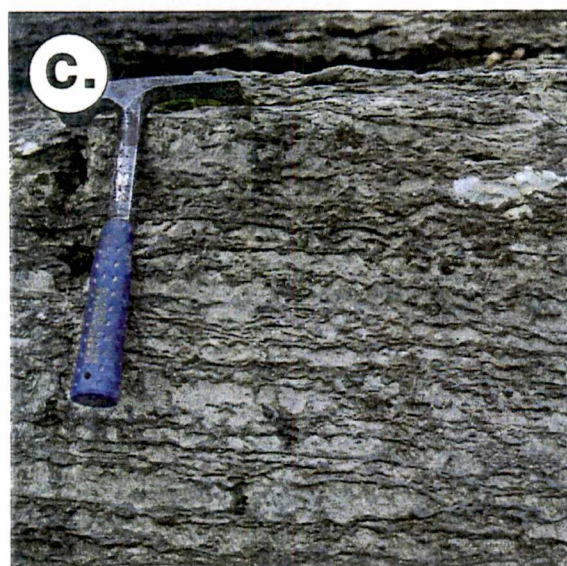
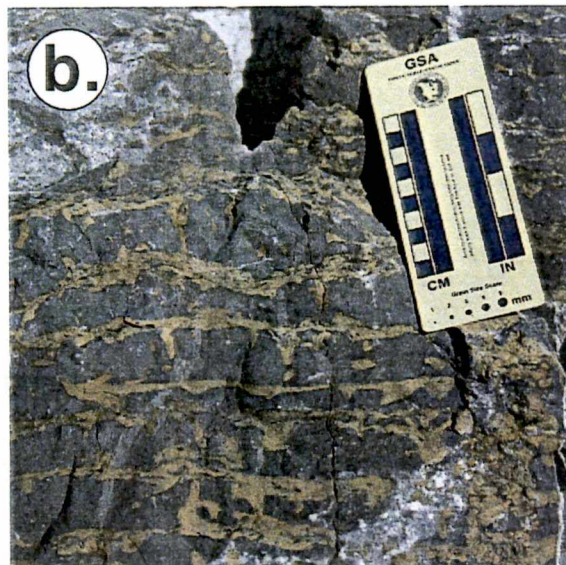
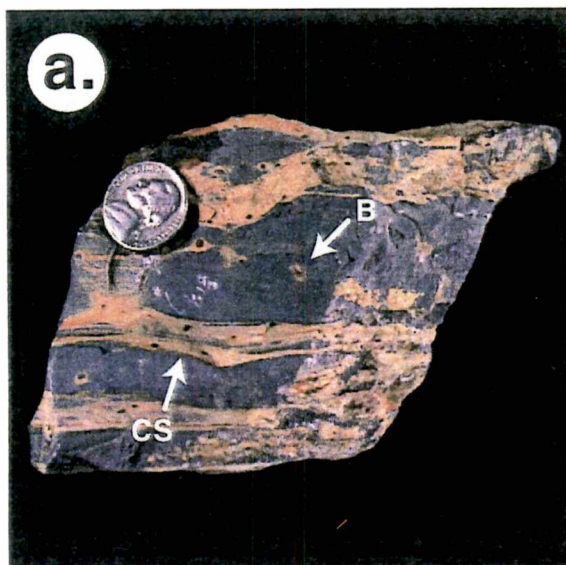
This lithofacies consists of interbedded micrite and dolomicrite layers and layers argillaceous dolostone (Figure 2.6a and b). The micrite layers are featureless with the exception of small (less than 0.5 centimeters) spar-filled sub-horizontal burrows (Figure 2.6a). Skeletal and non-skeletal allochems were not observed. The argillaceous layers consist of euhedral dolomite crystals in a matrix of opaque clay and pyrite. The dolomite rhombs are similar in morphology to that of the dolomite in the burrows of the burrow-mottled lithofacies. Abundant, small pyrite nodules are present throughout this lithofacies (Figure 2.6a). The boundaries between the micrite and argillaceous layers are wavy yielding the characteristic ribbon-laminated appearance to this lithofacies.

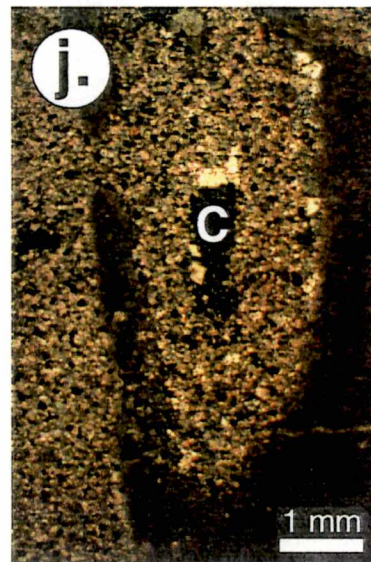
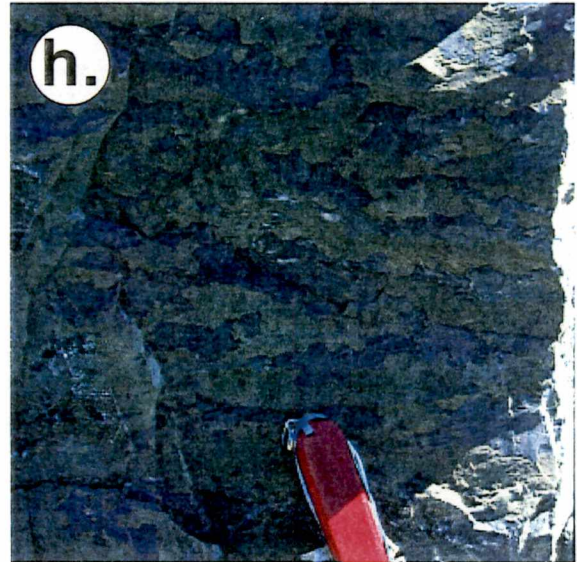
Ribbon-laminated mudstones occur in the lower half of all sections. Correlation from one section to another is problematic due to the similar weathering patterns of this lithofacies and the burrow-mottled lithofacies.

ICHO FABRIC INDEX	DESCRIPTION	STRATIGRAPHIC OCCURRENCE	DEPOSITIONAL CONDITIONS	REP. PHOTOS
2	Discrete, isolated trace fossils; up to 10% of original bedding disturbed.	Exemplified by the ribbon-laminated lithofacies. Present in lower part of all measured sections and in the upper transitional interval (nodular carbonate lithofacies). Limited to beds up to 3 meters thick.	Slowed sedimentation, reduced oxygenation.	Figure 2.6 a and b
3	Approximately 10 to 40% of original bedding disturbed. Burrows generally isolated, but locally overlap.	Most common ichnofabric in the Rutledge section. Present in all sections at all stratigraphic horizons.	Normal depositional conditions, characterized by constant sedimentation in a well-oxygenated environment.	Figure 2.6 c, d, and e
4	Last vestiges of bedding discernable; approximately 40% to 60% disturbed. Burrows overlap and are not well defined.	Common in all sections. Occurs with ichnofabric index 3. Differentiation between the indices is difficult due to weathering.	Normal depositional conditions, characterized by constant sedimentation in a well-oxygenated environment.	Figure 2.6 f and g
5	Bedding is completely disturbed, but burrows are still discrete in places and the fabric is not mixed.	Limited to beds of less than 1 meter. Observed only in middle portion of the Highway 31 Section (limited occurrence may be due exposure quality). Beds are distinctive in outcrop.	Normal depositional conditions, characterized by constant sedimentation in a well-oxygenated environment.	Figure 2.6 h and i
no diagrams exist	vertical burrows of up to 5 centimeters. Burrows are discrete and commonly cut across sedimentary bedding.	occur in thin (<10 centimeters) beds below grainstone beds in upper part of the Rutledge section.	High sedimentation rate, well-oxygenated environment.	Figure 2.6j

Table 2.4. Summary Table of burrow fabrics of the burrow-mottled mudstone/wackestone lithofacies of the Rutledge Limestone. Ichnofabric indices and descriptions are from Droser (1987). Individual ichnofabric diagrams represent a 50 centimeters by 35 centimeters area. No plate exists for the vertical burrow index. Stratigraphic occurrences of individual indices are based on qualitative data collected from the Highway 31 Section and from selected portions of the Puncheon Creek and Notchy Creek Sections. Interpretation of the origin of the fabric is based on the assumption that burrowing was a function of water depth and sediment supply. The last column gives reference to photographs of individual textures (see Figure 2.6a through j).

Figure 2.6. (next two pages) Representative outcrop photographs and photomicrographs of the dominant burrow-mottled fabrics of the burrow-mottled and ribbon-laminated lithofacies of the Rutledge Limestone. **a.** Hand sample photograph of ribbon laminated lithofacies (ichnofabric index 2). This lithofacies is characterized by alternating mudstone and argillaceous dolomite layers. The contacts are generally undulose giving rise to the ribbon character of this lithofacies. The mudstone layers are characterized by horizontal spar filled burrows (arrow B) and small pyrite nodules. The argillaceous layers (arrow CS) weather to a light brown in outcrop and small pyrite nodules are also present. Nickel (2 centimeters in diameter) for scale. Rutledge Limestone, Sample Hy19/no measure, Highway 31 locality. **b.** Outcrop photograph of an example of ichnofabric index 2 from Highway 31 locality. Compare to indices in Table 2.4. **c.** Outcrop photograph of ichnofabric index 3 from Notchy Creek locality. Hammer (~ 30 centimeters in length) for scale. **d.** Close-up outcrop photo of an example of ichnofabric 3 from Highway 31 locality. Arrows define the upper and lower contacts of intraclastic layer within the unit. Swiss army knife (long axis = 9 centimeters) for scale. **e.** Outcrop photo of bedding plane exposure (unit has an index of 3) of the burrow-mottled lithofacies. The bedding plane exposure of the burrows is characteristic of the ichnofabric *Thalassinoides*. Curiously strong peppermint tin (long axis = 9.5 centimeters) for scale. Notchy Creek locality. **f.** Outcrop photo of bedding-plane exposure (unit has an index of 3) showing similar fabric characteristics as (e) but not as well developed. Hammer (~30 centimeters) for scale. Notchy Creek locality. **g.** Outcrop photo of surface demonstrating ichnofabric index 4. Camera lens cover (6.5 centimeters) for scale. Highway 31 locality. **h.** Outcrop photo of an example of ichnofabric index 4. Swiss army knife (short axis = 2 centimeters) for scale. Highway 31 locality. **i.** Outcrop photo of ichnofabric index 5. Hammer (~30 centimeters) for scale. Highway 31 locality. **j.** Photomicrograph (cross-polarized light) of vertical burrow in burrow-mottled lithofacies directly below skeletal, intraclastic packstone unit. The burrow is filled with mosaic of planar-E dolomite, coarse, equant calcite (C), and micro-crystalline calcite.





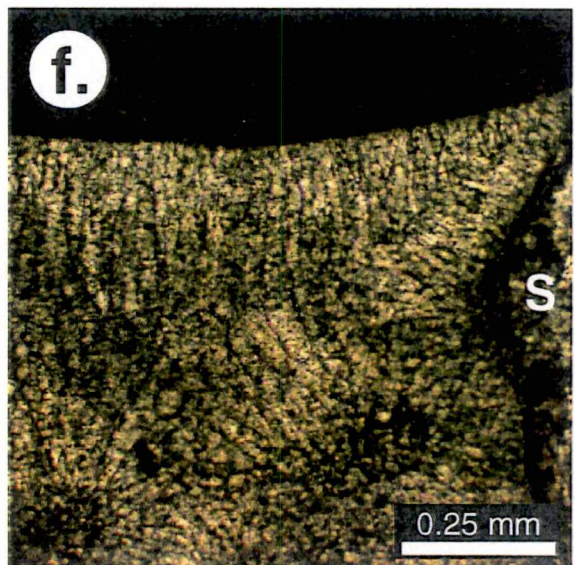
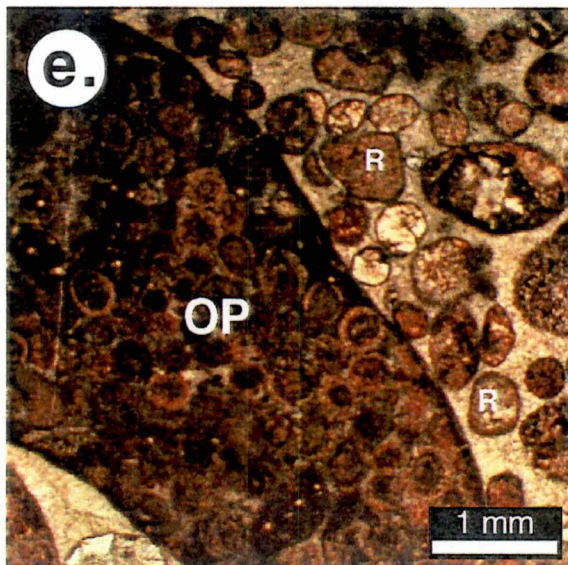
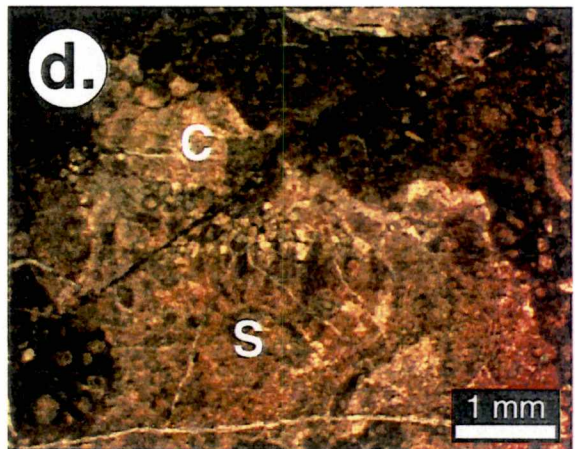
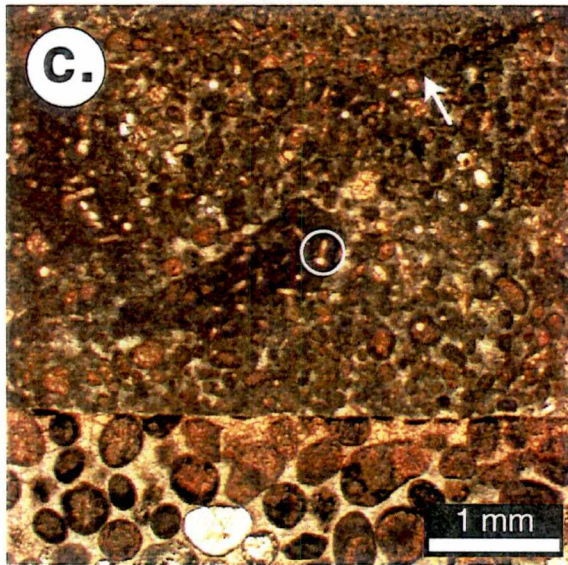
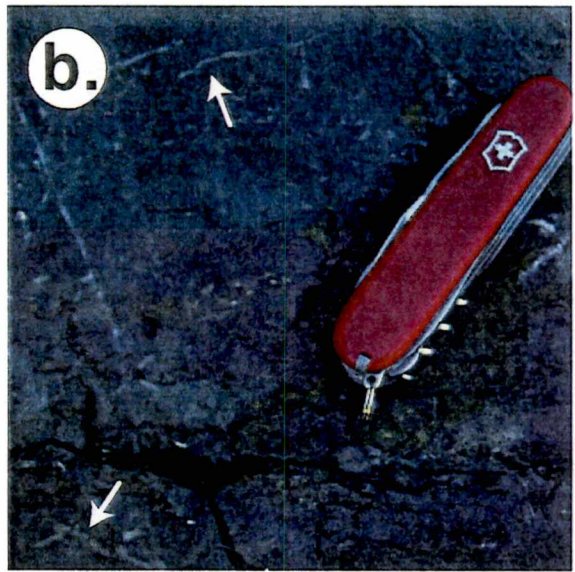
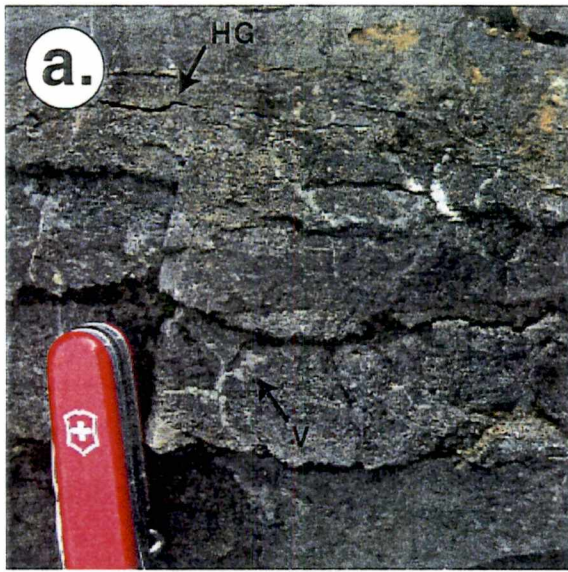
However, the presence and stratigraphic abundance of this lithofacies in the different sections may have been related to the origin and areal extent of this environment during deposition. The basal and upper contacts of the ribbon facies with the burrow-mottled facies are gradational over a 5 to 10 centimeter interval.

Peloidal/Ooid Grainstone

The similar stratigraphic position and distinct textural characteristics of this lithofacies make it an excellent marker bed for the Rutledge in the study area. The unit is medium to light gray on the weathered surface and ranges from 40 centimeters to 60 centimeters thick. In the field this unit is recognized by the reduction in mottling and its grainy texture (Figure 2.7a). It is underlain and overlain by units of the burrow-mottled lithofacies. The lower contact is stylolitic but grains specific to the grainstone facies occur within the upper 10 centimeters of the underlying unit. The upper contact is undulose (up to 5 centimeters of relief) to planar and is characteristically sharp in the field. No grains from the underlying grainstones are present in the overlying lithologies. The lithofacies is a complex mix of lithologies ranging from ooid, peloidal grainstones to peloidal packstones and wackestones. Primary sedimentary structures were not observed in the field. However, early diagenetic features, such as marine hardgrounds, truncation surfaces, glauconite, and cement filled voids (2 to 3 centimeters in size) were readily observable in the field and in thin section (Figure 2.7a, b, and c).

The lithofacies shows a progression of lithologies from ooid/peloidal packstones to ooid grainstones in the lower half of the unit and interbedded carbonate mudstones with peloidal packstones and ooid/cyanobacterial grainstones in the upper half of the unit. The lower peloidal packstones consist

Figure 2.7. Outcrop photos and photomicrographs of lithologies from ooid, peloidal grainstone lithofacies. **a.** Outcrop photo of interbedded carbonate mudstone and ooid grainstones at Lays Gap Locality. Swiss Army Knife (short axis = 2 cm) for scale. Note abundant marine hardgrounds (black arrow, HG), irregular voids (black arrow, V), and absence of burrow-mottled texture. Tiny voids result from the weathering of glauconite and pyrite. **b.** Outcrop photo of peloidal packstone at Puncheon Creek locality. Swiss Army Knife (long axis = 9 cm) for scale. Note irregular voids (black arrows). **c.** Photomicrograph (plane light) of ooid grainstone sharply overlain by peloidal packstone. Marine truncation surface marks contact (lower third of photo). Surfaces of early cementation (black arrow) and authigenic quartz crystals (circled) are present. Sample S20/84.41, Sneedville locality. **d.** Photomicrograph (plane light) of irregular void filled with geopetal sediment (S) from surrounding peloidal packstone and cement (C). Sample PC 9/10, Puncheon Creek locality. **e.** Photomicrograph (plane light) of ooid grainstone layer with large ooid packstone intraclast (OP) and replaced ooids or cyanobacterial (?) fragments (R). Note mineralized rim (black) on ooid packstone clast. Sample S20/84.41. **f.** Photomicrograph (plane light) of marine fibrous cements emanating from an intraclast (top of photo) and replaced skeletal (?) grain (S). Sample PC3/25.52, Puncheon Creek locality.



of rounded to sub-rounded peloids up to 0.3 mm in size (Figure 2.7d). Many of the peloids show no internal structures but some have outer concentric layers resembling ooid lamellae. Also occurring in this lithology are abundant circular and irregular voids filled with internal sediment from the surrounding lithology and/or crystal silt. Pore filling equant cements occlude the remaining porosity in these voids. Overlying this lithology is an ooid grainstone consisting of radially concentric ooids, commonly micritized and/or replaced by dolomite and ferroan calcite cements, and rounded intraclasts consisting of ooids in a micrite matrix (Figure 2.7e). Fibrous and equant calcite cements make up the dominant pore filling cements in this lithology (Figure 2.7f).

The upper portions of this lithofacies consist of interbedded ooid grainstones (less than 2 centimeters thick) and wackestones/peloidal packstones (2 to 5 centimeters thick). In the Copper Creek sections, the ooid grainstone layers are recognized by an abundance of replaced ooids, whereas in the Hunter Valley sections, the ooid grainstone layers show less replacement textures (Figure 2.8a). In all sections, the ooid grainstone layers are characterized by ooids, intraclasts from the underlying lithology, and by grains with a clotted to saccate texture resembling the cyanobacterium, *Renalcis* (Figure 2.8b; see also Srinivasan and Walker, 1993; Pratt, 1984). *Renalcis* grains are partially to wholly replaced by glauconite and framboidal pyrite (Figure 2.8c and d) or by ferroan calcite and dolomite cement. The wackestone/peloidal packstone layers have a matrix of either micrite or packed peloids (Figure 2.9a). Allochems include grains from the underlying and overlying ooid lithologies, including *Renalcis* and trilobite fragments. The mud-rich layers also contain locally abundant small authigenic euhedral quartz crystals (up to 500 μm in size) and irregularly shaped voids filled with radial axial fibrous calcite cements and equant calcite cements. The quartz

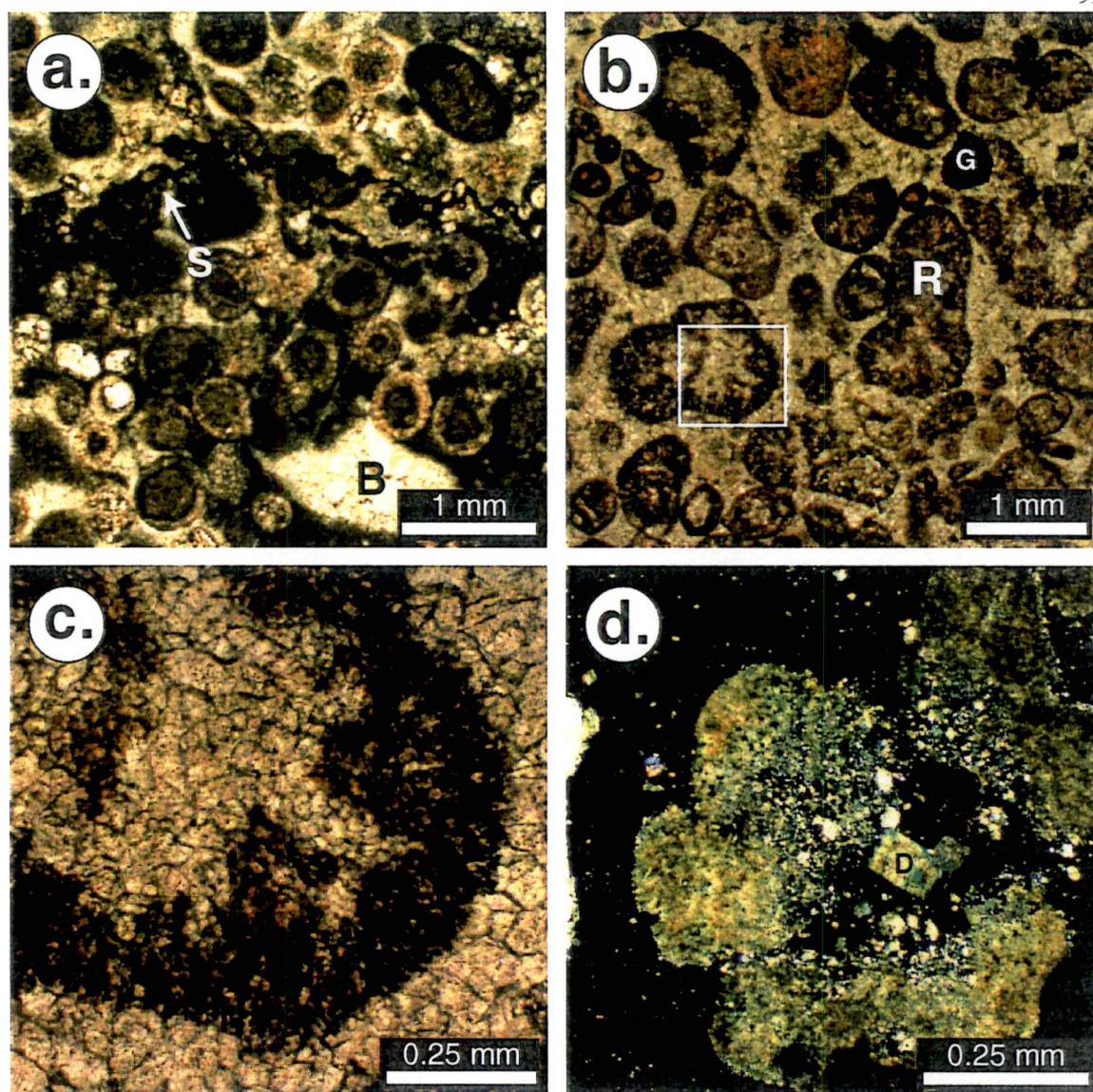


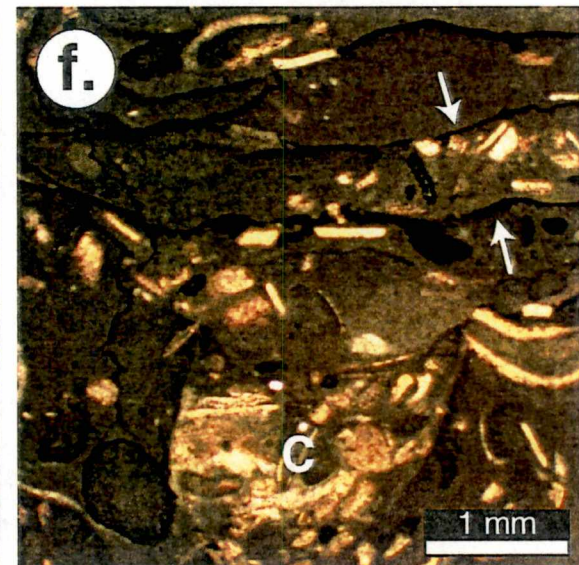
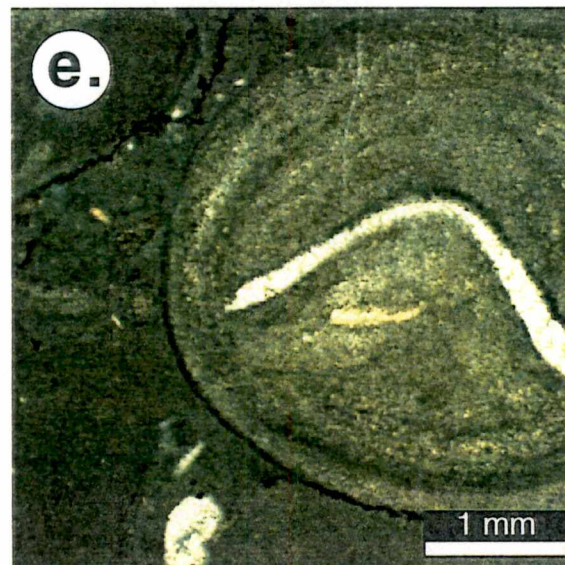
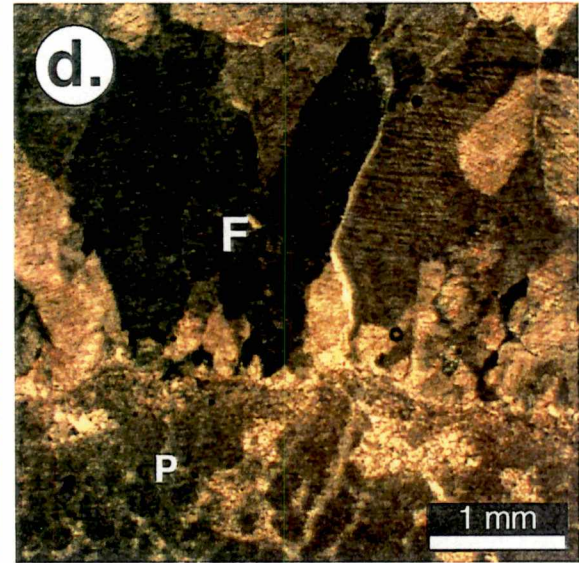
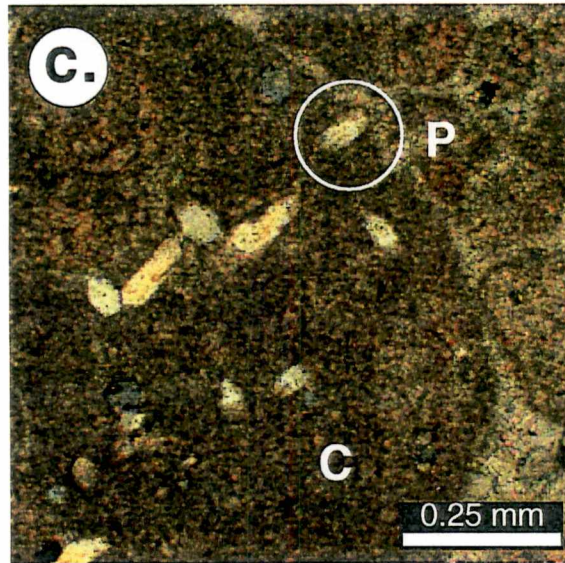
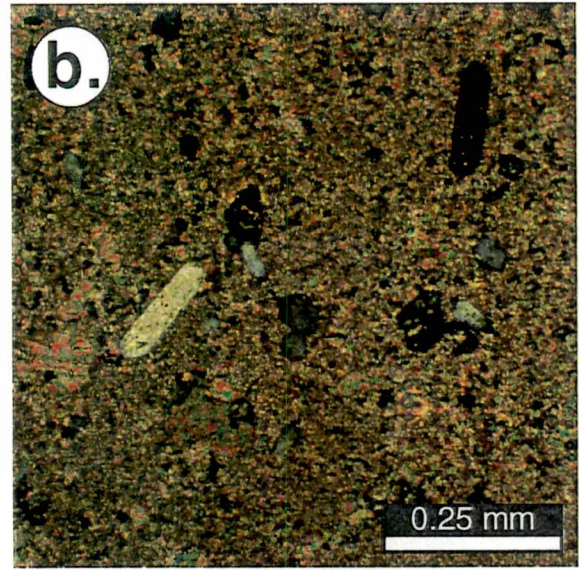
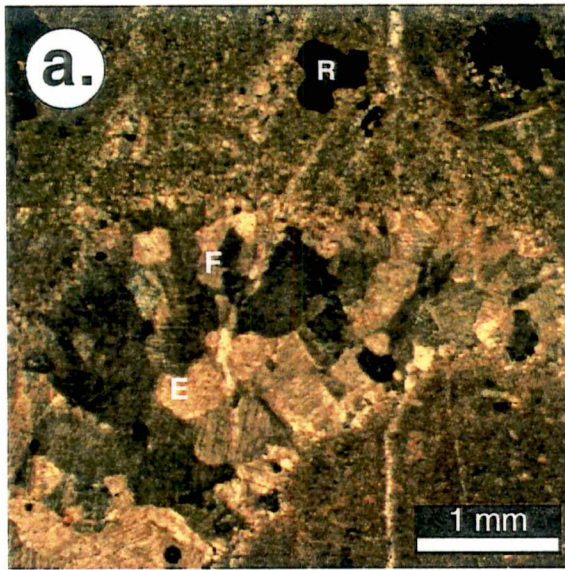
Figure 2.8. Photomicrographs of sedimentary features from ooid, peloidal grainstone lithofacies. a. Photomicrograph (plane light, 20x) of ooid grainstone. This sample is from the Highway 31 locality (Hunter Valley thrust block). In the Hunter Valley thrust block sections ooid grainstones are generally characterized by better preserved ooids with visible cortices. Horizontal cement-filled burrow (B) is located in the lower part of the photo. S = stylolite. Sample HY21/39.02, Highway 31 Locality. b. Photomicrograph (plane light, 20x) of *Renalcis* grainstone layer. *Renalcis* (R) have a saccate morphology and are generally replaced by pyrite and/or glauconite (see c and d). Pratt (1984) defined this morphology of *Renalcis* as being rare in the rock record. Sample S20/84.41, Sneedville locality. c. Enlargement of marked area (square) of photomicrograph shown in b. Note the pyrite and glauconite replacement of the *Renalcis* wall structure. Sample S20.84.41, Sneedville locality. d. Grain mount (cross-polarized light, 100x) of replaced *Renalcis*. The wall structure of the *Renalcis* is completely replaced by glauconite. Dolomite (D) rhombs are also present. Sample LG9A2, Lays Gap locality.

crystals are present in the micrite layers of the lithofacies (Figure 2.9b) and in intraclasts within the ooid layers (Figure 2.9c). The mud-rich layers are also characterized by irregular geopetal voids up to 3 centimeters in width that are filled with internal sediment, an initial fibrous cement phase, and a pore-occluding equant calcite cement (Figure 2.9a and d).

Oncoid/Skeletal Packstone

This lithofacies occurs at the top of the Rutledge in the Lays Gap Section and within the upper portion of the Highway 31 section. The individual units are between 0.5 and 0.8 meters thick and are gray to gray brown on the weathered surface. The oncoïd bearing lithologies are massive and show little evidence of sedimentary bedding or other sedimentary structures, whereas skeletal lithologies have abundant marine hardgrounds. Contacts are sharp and evidence for erosion or subaerial exposure was not observed in the field. The lithology is a complex mix of allochems, consisting dominantly of oncoïds, skeletal fragments, and intraclasts, and quartz silt. The oncoïds, up to 2 centimeters in size, are poorly preserved with faint internal laminae (Figure 2.9e). Many of the oncoïds have blackened (mineralized) rims and some show replacement textures of coarse euhedral dolomite. Skeletal allochems consist dominantly of trilobite and echinoderm fragments, with pelecypod, hyolithids, and inarticulate brachiopod fragments present, but are less common in the lithofacies (Figure 2.9f). Carbonate mudstone intraclasts are ubiquitous throughout the lithofacies. Many have blackened rims similar to those present in some of the oncoïds.

Figure 2.9. Photomicrographs of sedimentary features from ooid, peloidal grainstone and oncoid/skeletal packstone lithofacies. **a.** Photomicrograph (cross polarized light) of irregular “stromatactid-like” void in mudstone layer. Void is occluded by fibrous calcite and pore central clear, equant calcite. Replaced Renalcis (R), along with ooids, occur floating in the matrix of the mudstone layers of this facies. Rutledge Limestone, Sample LG 9A1/TOP, Lays Gap locality. **b.** Photomicrograph (cross-polarized light) of euhedral authigenic quartz crystals in mudstone ($\pm$ microspar) matrix. Rutledge Limestone, Sample S20/84.41, Sneedville locality. **c.** Photomicrograph (cross-polarized light) of authigenic quartz, peloidal packstone intraclast (C) in peloidal (P) grainstone layer. Note the presence of authigenic quartz crystals (circled) projecting into the matrix from clast. This observation and the absence of quartz crystals within cement matrix suggests that quartz formation was early and that a source of silica for the quartz may have been metastable phases of biologic silica. Rutledge Limestone, Sample S20/84.41, Sneedville locality. **d.** Photomicrograph (crossed-polarized light) of the lower wall of an irregular “stromatactid-like” void. Note peloidal sediment at bottom of the void (bottom of photo) and the fibrous calcite cements. Rutledge Limestone, Sample LG 9A1/TOP, Lays Gap locality. **e.** Photomicrograph (plane light) of oncoid from oncoid, skeletal packstone lithofacies. Trilobite fragment serves as the nucleus of the oncoid. Quartz silt and intraclasts are present in the matrix around the oncoid. Notice the partial replacement of the oncoid by dolomicrospar. Rutledge Limestone, Lays Gap locality. **f.** Photomicrograph (plane light) of multiple hardgrounds (arrows) in skeletal packstone. Scour cavity (C) is present in the lower part of the photo. Rutledge Limestone, Sample HY 23/42.09a, Highway 31 locality.

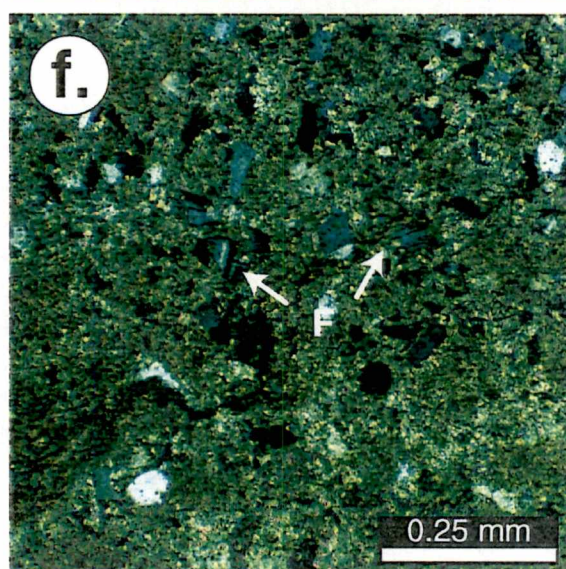
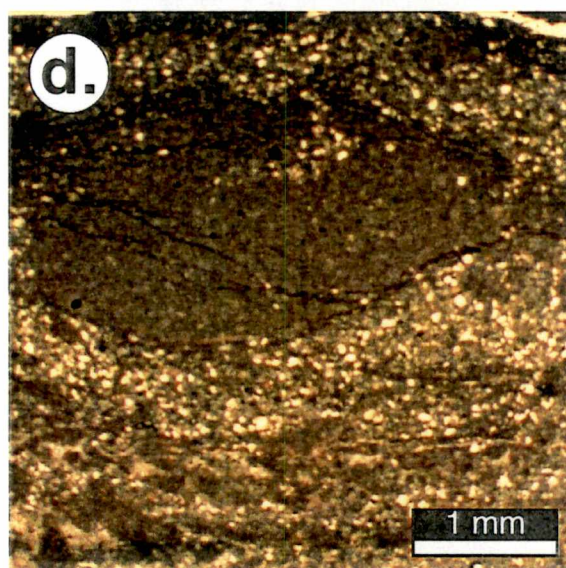
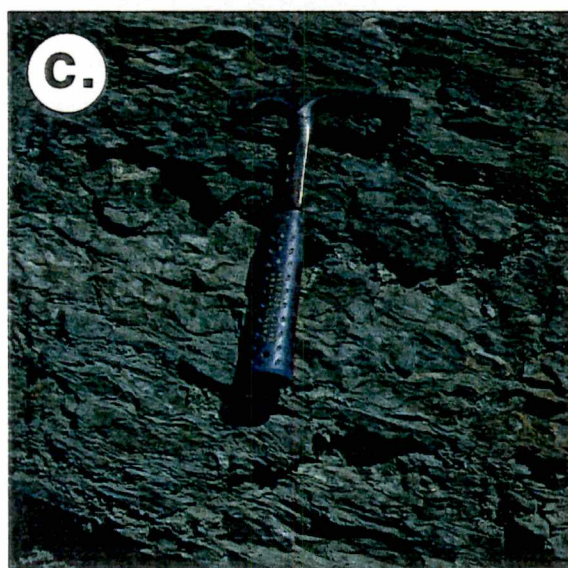
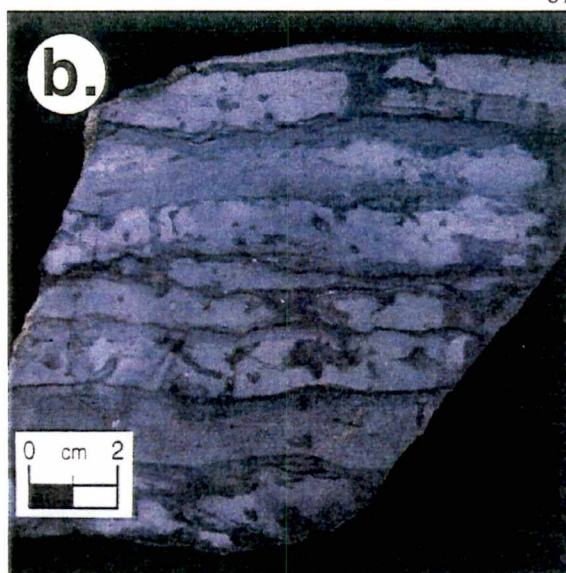
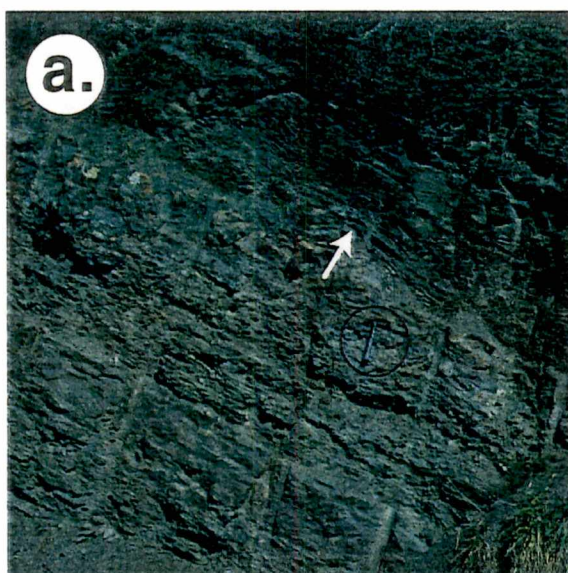


Nodular Carbonate Mudstone with Shale

Gray to light brown nodular mudstones interbedded with shale occur with carbonate mudstones and intraclastic packstones in this lithofacies. The lithofacies occurs at the top of the Rutledge and marks the beginning of an ~7 meter thick transition zone between the Rutledge and the overlying Rogersville Shale (Figure 2.10a). The lower part of the lithofacies has the same general character as the rest of the Rutledge Limestone. Shale beds become increasingly more abundant and thicker upwards through the lithofacies and units near the top of the Rutledge are characterized by calcareous shale interbedded with nodular mudstones and intraclastic packstones. The lower part of the lithofacies is made up of burrow-mottled to ribbon-laminated mudstone beds (up to 0.25 meters thick) interbedded with thin, argillaceous shales (Figure 2.10b). The mudstones commonly contain intraclastic, skeletal layers, of irregular thickness that pinch out laterally over distances of 2 to 3 meters. Pyrite nodules up to 4 cm in size become more prevalent upward through the lower part of this lithofacies.

The upper part of this lithofacies consists of interbedded calcareous shale, nodular mudstone, and intraclastic packstone. The shale is dark gray to dark brown in color and is composed of a mixture of carbonate mud and fine, quartz silt (Figure 2.10c). It is fissile and hummocky cross-stratified in places. Nodular mudstones consist of mudstone layers or "boudins" in a matrix of calcareous shale and/or argillaceous micrite (Figure 2.10d and e). The mudstones contain some skeletal fragments, abundant, fine to medium quartz silt, and fine, sub-angular, silt sized potassium feldspars grains. Intraclastic packstones layers, up to 8 cm in thickness, punctuate the upper lithofacies (Figure 2.10f). They have scoured or erosional bases and commonly have normal grading upward into overlying mudstone layers.

Figure 2.10. Outcrop photos and photomicrographs of representative lithologies from the nodular carbonate lithofacies and upper portions of the Rutledge Limestone. **a.** Outcrop photograph of the contact between the Rutledge Limestone and Rogersville Shale. The contact (black arrow) is sharp in the field, but is characterized by a transitional interval (5-10 meters thick). Hammer (circled, ~30 centimeters) for scale. Highway 31 locality. **b.** Hand sample photograph of typical interbedded carbonate mudstone (light areas) and argillaceous layers (dark layers). The mudstone layers are characterized by both sub-horizontal burrows (filled with equant calcite) and *Thalassinoides* burrows. The argillaceous layers are generally featureless, but may show some wavy bedding structures. Upper transition interval, Rutledge Limestone, Sample Hy30/72., Highway 31 locality. **c.** Outcrop photograph of the nodular carbonate lithofacies of the upper transitional interval. Hammer (~30 centimeters) for scale. Rutledge Limestone, Highway 31 locality. **d.** Photomicrograph (plane light) of carbonate "boudin" (relatively quartz free area in the center of the photograph, surrounded by a matrix of quartz silt and micrite. The "boudins" are interpreted to have formed by the result of differential compaction of semi-lithified sediment. The dark lines in the "boudin" are microstylolites. Upper transition interval, Rutledge Limestone, Sample Hy33/73.78, Highway 31 locality. **e.** Photomicrograph (plane light) of large carbonate "boudin," bounded by argillaceous layers. Note the possible preserved soft bodied organism (white arrows) within the center of the "boudin". Upper transitional interval, Rutledge Limestone, Sample PC14/9.45, Puncheon Creek locality. **f.** Photomicrograph (crossed-polarized light) of terrigenous silt grains in micrite matrix. Rounded to sub-rounded quartz grains comprise the dominant population of terrigenous grain types. Lesser amounts of potassium feldspar (microcline, F) occur. Upper transitional interval, Rutledge Limestone, Sample Hy33/73.78, Highway 31 locality.



INTERPRETATION OF DEPOSITIONAL SYSTEMS

Siliciclastic Dominated Shelf

Units in this depositional system are represented by the upper Pumpkin Valley Shale and the lower Rogersville Shale. This system represents periods of time when craton-derived, terrigenous clastics dominated outer shelf environments. Sedimentation of quartz silt, mica, and clays occurred below fair-weather wave base and probably below mean storm-wave base. This is based on the general absence of sedimentary structures (i.e., wave or current ripples) indicative of shallow-water environments and the fine-grained nature of the units. However, coarser siltstone beds and their associated planar laminations and hummocky cross-stratification may indicate times of lowered wave-based.

Sedimentation rates are interpreted to have been low, as supported by the presence of glauconite, and by the presence of marine hardgrounds in the carbonate units of these lithofacies. The greenish color of the Pumpkin Valley Shale is generally attributed to the high percentage of glauconite found within these lithologies (Hasse, 1982). Glauconite, although ubiquitous in many marine environments, is thought to be precipitated in reducing, marine environments and/or in marine environments characterized by slow sedimentation rates (Amorosi, 1995; Odin and Fullagar, 1988; McRae, 1972). Hardgrounds in the carbonate lithofacies have blackened, mineralized crusts and represent periods of slow sedimentation rates and/or no sedimentation in stagnant and reducing waters (Wilson and Palmer, 1992).

A complete paleoenvironmental framework for the shale and siltstone units of the Pumpkin Valley and Rogersville is lacking in the literature and it is not realistically possible to derive such a framework from the data presented in this thesis. The underlying Rome Formation was interpreted by McReynolds and

Driese (1994) as a mosaic of shallow-water clastic environments deposited in and just below the tidal range. Based on similar shallow-water sedimentary structures in the lower portions of the Pumpkin Valley Shale in an area around Oak Ridge, Tennessee, earlier work by Hasse (1982) led to an interpretation of a similar range of environments for the lower Pumpkin Valley. Hasse (1982) noted that the sedimentary structures in the upper units of the Pumpkin Valley did not have the same character and he inferred a subtidal depositional environment for these upper units. Work on the Rogersville is lacking, but in general the units of the Rogersville consist of dark-colored, paper-laminated shales with interbeds of siltstone present in the lower portions.

Thus, the shales and siltstones of the Upper Pumpkin Valley Shale, Rutledge Limestone, and Lower Rogersville Shale are interpreted here to have been deposited in subtidal environments below fair-weather wave base, and in most cases below storm wave base. Water depths were not likely as deep as proposed for the Nolichucky Shale (200 meters; Foreman and others, 1991) and depths greater than 50 to 100 meters are tentatively suggested for these clastic units.

The transition zones between the Pumpkin Valley Shale and the Rutledge Limestone, and between the Rutledge and Rogersville Shale, are marked by interbedded carbonate and shale lithofacies. The interbedding of the carbonate and shale units records the interplay between the two sediment sources during periods of time when carbonate production in shallow waters became significant enough to influence deposition within the basin or, in the latter case, when carbonate production decreased as the result of clastic poisoning and increased water depths. In the lower transition zone (~5 meters thick), the shales of the Pumpkin Valley give way to the carbonate mudstones of the Rutledge. Normal deposition in the interval was characterized by the sedimentation of fine-grained,

terrigenous clastic sediment in environments similar to those of the shale and siltstone units proposed above. Pulses of allochthonous carbonate sediment from shallow-water environments are represented by the carbonate beds, which consist of a variety of unsorted allochems in either a micrite or sparite matrix, and which typically have erosive lower contacts and gradational upper contacts. These beds are common in the lower portion of the transitional interval, and are interpreted as storm-induced gravity flows. Increases in the burrowed-mottled mudstones and decreases in the amount of shale interbeds through the interval mark establishment of carbonate sedimentation in the basin. The first appearance of massive beds of burrow-mottled mudstone of the Rutledge is coincident with the upper limit of the lower transition interval.

The upper transitional interval (5 to 10 meters thick) defines the contact between the Rutledge Limestone and Rogersville Shale. It is similar to the lower transition interval, but the stacking patterns are opposite. In this interval, carbonate mudstones of the Rutledge are gradually replaced by the shales and siltstones of the lower Rogersville. The abundance of burrow-mottled lithologies in the lower portion of the interval suggests the dominant sedimentary environments were those associated with the burrow-mottled lithofacies (see below). Decreases in burrowing activity, evidenced by the occurrence of beds of the ribbon-laminated mudstones (see below), and increases in the amount of shale interbeds characterize the middle portion of the interval. Skeletal and intraclastic packstone layers punctuate the middle interval and record the influence of storm reworking. The upper portion of the interval is characterized by nodular carbonates consisting of interbedded shales and discontinuous lenses of carbonate mudstones and wackestones. The carbonate beds represent the most distal portions of storm layers that were deposited in deeper-water shale-dominated

environments. The carbonate mud layers became semi-lithified at or near the sediment-water interface and were then penecontemporaneously deformed, as a result of sediment loading (Figure 2.11). The first appearance of interbedded dark-colored, paper-laminated shales and thin siltstones mark the upper contact of this interval and the contact between the Rutledge Limestone and Rogersville Shale.

The transition intervals record the gradual changes in sedimentation patterns in the basin from a clastic dominated regime to a carbonate dominated regime and then back again to clastic dominated. Changes between these regimes were the result of changes in rates of sea-level rise, changes in the rate of carbonate production, and in the rate of clastic influx from the craton. The units of these zones were deposited in quiet-water environments below fair-weather wave base and near or below storm wave base. Oxygenation of the environments in these zones is interpreted to have increased in the lower zone and decreased in the upper zone, as evidenced by the increase and decrease of preserved burrows in the carbonate mudstones, respectively. The interbedded character of these zones is similar to what Wilson (1969) described as "deeper water" lime mudstones that were interpreted to have been deposited in depths of 90 to 607 meters. Water depths for the transitional zones or the Rutledge probably ranged from those proposed for the intrashelf basin (50 to 100 meters, see above) to those proposed for the deepest depositional limit of the burrow-mottled mudstone/wackestone lithofacies (<50 meters, see below).

Carbonate Ramp

The carbonate ramp depositional system is defined through the carbonate

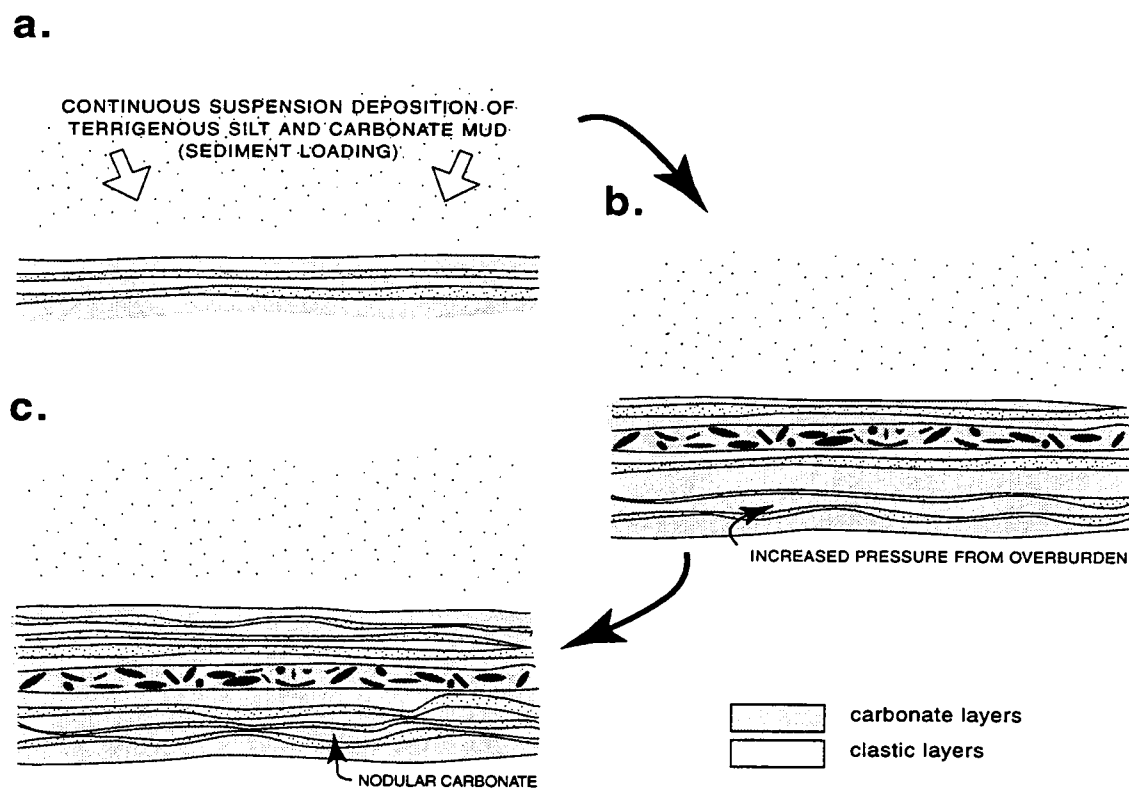


Figure 2.11. Schematic model for the formation of the nodular carbonate lithofacies of the Rutledge Limestone. Normal depositional conditions were characterized by the suspension deposition of the terrigenous clay and silt (craton-derived) and carbonate mud (ramp-derived). Purer carbonate layers are interpreted to represent the most distal portions of storm or event beds. **a.** Normal deposition progressed, creating an overburden pressure on the underlying carbonate and silty carbonate layers. **b.** Increased pressure on the partially lithified carbonate layers and the thixotropic, unlithified clastic layers resulted in the deformation of bedding. **c.** Continued deformation of bedding by sediment loading (overburden pressure) caused pinching and swelling of the carbonate layers and produced the nodular carbonate fabric.

units of the Rutledge Limestone. The absence of shallow water indicators, both physical and biological, and the fine-grained, non-skeletal character of the majority of the units indicate that deposition resulted from suspension deposition of shallow-water derived, fine-grained sediment into environments below fair-weather wave base. The overall homogeneity of the units of the Rutledge suggests that this depositional system was dominant throughout the depositional history of the Rutledge. The ooid, peloidal grainstone unit was deposited as the result of a basinward shift of high energy, shallow subtidal environments during a relative sea level lowstand. Similarly, the presence of oncoid, skeletal packstone units in the upper portion of the Rutledge may indicate still further shallowing events or, quite possibly, the presence of these units within the Rutledge section may indicate a migration (or progradation) of these environments into the field area. Subtle fabric changes in the burrow-mottled mudstones suggest that smaller scale shallowing events may have been more common.

Mud-rich lithofacies

The dominant lithologies of the Rutledge are those belonging to the burrow-mottled lithofacies. Dominated by fine-grained micrite, with lesser amounts of skeletal and non-skeletal allochems and layers of skeletal, intraclastic packstones, the units contain no evidence of shallow-water algae or cyanobacteria that would suggest *in situ* micrite production. Primary sedimentary structures are virtually absent in all units of this lithofacies due to the disruption of depositional textures by infaunal burrowers. When present, however, primary laminations are sub-horizontal and less than 1 centimeter thick. Allochems occur as either randomly oriented, individual grains in the micrite matrix or they are concentrated

into discrete layers. Based on the above criteria, the burrow-mottled lithofacies is interpreted to represent deposition in environments below fair-weather wave base and below mean storm wave base. The micrite is interpreted to be allochthonous sediment derived from shallow-water environments. The micrite was transported from shallow-water environments by the action of waves and deposited from suspension into deeper-water environments. The presence of intraclastic and skeletal layers within the lithofacies suggests that these environments were periodically affected by the action of storms or other events. An event stratigraphic interpretation for these units, as opposed to an origin related to the burrowing, is favored due to the chaotic bedding exhibited by these units, the polymict character of the clasts and the general stratigraphic occurrence of these beds at the base of individual units. Intraclastic packstones of similar character (flat-pebble conglomerates) are a common constituent of Cambrian subtidal sedimentary sequences and have been interpreted to result from the transport of shallow-water derived allochems through either storm-related or debris-flow events into deeper-water environments (see Sepkoski 1982; and Kozar and others, 1986).

Burrowed fabrics are ubiquitous throughout the burrow-mottled lithofacies and subtle changes in the ichnofabric (determination of ichnofabric indices of Droser and Bottijer, 1986) may have resulted from changes in physical and chemical conditions during deposition. The differing styles of ichnofabric are interpreted to be the result of four factors: (1) the depth of water in which the sediment was deposited, (2) the extent of oxygenation of the depositional environment, (3) relative sedimentation rates (coupled with the influx of detrital organic material), and (4) the extent of the effects of early and late diagenesis. As will be argued in Chapter 3, the dominant controls on the distribution of facies

of the Rutledge were directly related to the position of relative sea-level and overall sedimentation rates. If these controls were indeed dominant, then the extent of bioturbation may have been related to these same factors. With this in mind, a progression of burrow fabrics may be extracted from the stratigraphic section. Deeper-water conditions, characterized by slowed sedimentation rates and reduced oxygenation, may have resulted in a low intensity of burrowing activity and thus, a low ichnofabric index. Increases in oxygenation and the amount of sediment input, as a result of a decrease in water depth, would favor an increase in burrow activity and concomitant higher ichnofabric index. Finally, when sedimentation rates reach a maximum and water depth reaches a minimum for the burrow-mottled facies, burrowing activity would result in the formation of a network of vertical burrows.

The majority of the units of the burrow-mottled lithofacies are characterized by the ichnofossil *Thalassinoides*. The burrowing organisms churned up and disrupted sedimentary textures up to 5 cm below the sediment/water interface. The degree of bioturbation varied during deposition, as evidenced by the recognition of different burrow fabrics (indices of Droser and Bottjer, 1986) and differing styles of burrow preservation within the vertical section. During deeper-water conditions, slowed sedimentation rates and reduced oxygenation limited burrowing activities (index 2), and burrow preservation is characterized by cement-filled sub-horizontal burrows. The ribbon-laminated mudstone lithofacies, with its absence of burrowed fabric, is considered to be this variant of the range of burrow fabrics preserved within the Rutledge. Increases in sedimentation rates and levels of oxygenation, interpreted as normal depositional conditions, led to the formation of the higher ichnofabric indices. Although only limited stratigraphic data were collected, the changes between indices 3 through 5 may be

due to an increase in sediment supply and oxygenation resulting from a decrease in water depth.

Determinations of paleobathymetric conditions for depositional environments of the mud-rich facies of the Rutledge are problematic due to a lack of criteria for determining water depths (see discussion by Benedict and Walker, 1978). Studies of the Middle Cambrian of the Great Basin of western North America (Kepper, 1976) and studies of the Nolichucky Formation in Virginia (Markello and Read, 1981, 1982) have assigned similar lithofacies to deep sublittoral or deep ramp environments. Srinivasan and Walker (1993) assigned burrow-mottled units of the Maryville Limestone to either upper slope or possibly on-shelf environments and gave a water depth range of 10 to 20 meters. Based on stratigraphic relationships, the burrow-mottled and ribbon-laminated lithofacies of the Rutledge are interpreted to have been deposited in water-depths ranging from 10 to 20 meters (as suggested by Srinivasan and Walker, 1993 and by stratigraphic relationships with the grainstone lithofacies, see below) to as much as 50 to 60 meters. This latter depth is based on the stratigraphic position of burrow-mottled units directly overlying shale and siltstones of the Pumpkin Valley. Additionally, changes in burrow-mottled fabric may further suggest ranges in water depths and varying depths of oxygenation of marine waters. This is based on the assumption that burrow-mottled fabrics are a factor of water depth and sedimentation rates.

Grainstone and packstone lithofacies

Grainstone facies are restricted to thin units in the middle portion of the Rutledge. The units are composed dominantly of ooid, cyanobacteria grainstones interbedded with carbonate mudstones/wackestones and peloidal packstones.

Primary sedimentary structures are absent, and these units are more aptly characterized by their early diagenetic features, such as marine hardgrounds, irregular voids filled with marine cement and sediment, and glauconite. Based on the absence of primary sedimentary structures, the thickness of these units (< 0.5 meter), and their interbedded nature, a combined allochthonous and autochthonous origin is proposed. Modern ooid shoals (Ball, 1967; Harris, 1979; Wright and Tucker, 1990) and ancient examples from the Cambrian of Newfoundland (Chow and James, 1987b) and Tennessee (Srinivasan and Walker, 1993) consist of cross-stratified grainstones of greater thickness (>2 meters), with a dominant population of ooids and lesser amounts of skeletal allochems and intraclasts. *Renalcis*, along with *Epiphyton*, are common constituents of Lower Paleozoic platform margin build-ups (McIlreath, 1977; James, 1981; Srinivasan and Walker, 1993) and patch reefs (Ahr, 1971; Pratt and James, 1982). The ooid, cyanobacteria grainstones of the Rutledge are interpreted to be allochthonous in origin, with sedimentary grains being derived from active ooid shoals and patch reefs located in shallower water (Figure 2.12). The grainstone layers may have been deposited as pulses of sediment that were brought down slope. Based on cement morphology, the intergranular fibrous and equant calcite cements found within the grainstone facies are interpreted to have formed in the active marine phreatic diagenetic environment (James and Choquette, 1983; Harris and others, 1985). The presence of marine cements accompanied by glauconite within these units suggests that these environments may have been sediment-starved, and, quite possibly, deeper-water environments near or just below fair-weather wave base.

Peloidal packstones and carbonate mudstones/wackestones are interpreted as autochthonous microbial and siliceous sponge mounds that developed in

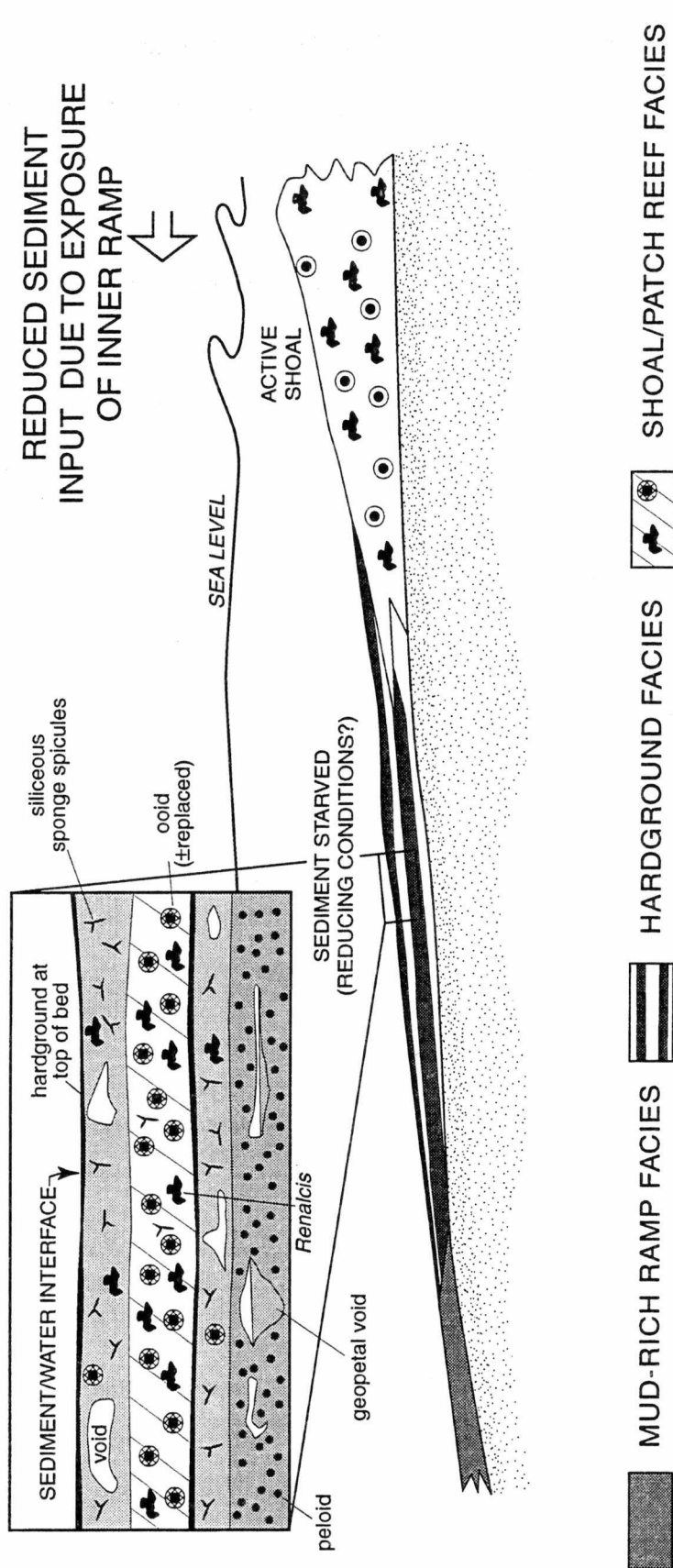


Figure 2.12. Schematic model for the deposition of the ooid/peloidal grainstone lithofacies of the Rutledge Limestone. During sea level low-stand, the areal extent of the carbonate "factory" was small due to exposure and thus sediment production was significantly reduced. Active shoals and patch reefs developed along the ramp at or above the fair-weather wave base (FWWB) interface. Basinward of the shoals and patch reefs a sediment-starved (reduced allochthonous sediment transport) environment existed. This environment (inset) was characterized by sponge mounds (stromatolite-like) developed upon allochthonous grainstone layers of ooids and *Renalcis* fragments (now replaced by glauconite). The sponge mounds were characterized by siliceous sponges (metastable, now replaced by authigenic quartz), irregular voids, and grains from surrounding facies. Coarse-grained sediment was derived from up-slope facies, whereas finer-grained sediment was trapped and bound by sponges and cyanobacteria that existed in the environments.

deeper-water, sediment-starved environments adjacent to, but downslope from, active ooid shoals and patch reefs. The formation of peloids within marine sediments is associated with either algal or cyanobacterial processes, fecal processes, mechanical abrasion of sediment, the replacement of a sediment precursor, or precipitation from marine waters (see discussion by MacIntyre, 1985). Coniglio and James (1985) discussed the role of calcifying algae (mainly the cyanobacteria, *Girvanella* and *Epiphyton*) as major sediment contributors in Lower Paleozoic Rocks. These authors suggested that many of the peloids and intraclasts in Lower Paleozoic rocks may owe their origin to the sediment binding action of these organisms. In the Rutledge, the presence of peloids in association with voids filled with marine sediment and marine cements suggest that these beds may have been partially lithified in the sedimentary environment. Although no microstructures were observed, the peloids are interpreted to have a microbial origin (Coniglio and James, 1985). The peloids were bound together by either cyanobacterial, microbial, or bacterial filaments forming a partially lithified sediment. Dissolution by carbonate-undersaturated marine (?) waters, and by syndimentary excavation as the result of sediment collapse, produced the distinctive voids of these layers. The irregular voids were subsequently filled with the surrounding sediment and by marine cement.

The wackestones and peloidal packstones of the upper portions of the grainstone lithofacies are interpreted to be siliceous sponge mud-mounds that the resemble stromatactis limestones of younger-aged carbonate successions (see Bourque and Boulvain, 1993; and rare example cited by Roberson and Foreman, 1989). The genesis of these enigmatic, stromatactid lithologies has been assigned to either the action of bacteria or cyanobacteria (Pratt, 1982; and Bathurst, 1980) or to sponges (Bourque and Boulvain, 1993). In general, stromatactid limestones are

defined by "masses of sparry calcite embedded in a lithified carbonate mud" (Bathurst, 1980). The calcite cements in the majority of the stromatactis are radial fibrous calcite, with a final occluding phase of equant calcite present in some voids (Roberson and Foreman, 1989; and Bathurst, 1980). In the Rutledge, although the fabric is not typical of traditionally defined stromatactis, the wackestones and peloidal packstones are interpreted to have formed as a result of the partial lithification of sediment by siliceous sponges. The occurrence of authigenic quartz in intraclasts within these lithologies suggests that this quartz formed in a very early diagenetic environment. Although no spicules were described from this lithofacies, the authigenic quartz within these lithologies may have formed as a result of dissolution and stabilization of metastable opaline spicules in marine waters. The formation of these mounds would then result in a layer of partially lithified sediment. Unlithified portions were removed by syndimentary excavation and dissolution resulting from marine waters circulating through the sediment. The voids were then subsequently occluded by radial fibrous and equant calcite cements similar in morphology to those associated with traditionally defined stromatactis (Roberson and Foreman, 1989; Bathurst, 1980).

Stromatactis and other mud-mounds of similar origin are interpreted to have formed in environments ranging from deep-water (Bourque and Boulvain, 1993) to, in a single example, tidal flat (Roberson and Foreman, 1989). In the Rutledge, the mud mounds are interpreted to have formed in environments near fair-weather wave base. The grainstone lithofacies is characterized by an absence of burrow-mottled mudstones. This, coupled with the presence of marine hardgrounds at the top of individual mud-mound layers and an overall preponderance of glauconite and framboidal pyrite, suggests that these environments may have been sediment-starved and that reducing conditions may have existed during deposition.

The oncoid, skeletal packstone lithofacies at the top of the Rutledge at Lays Gap is interpreted to be allochthonous sediment deposited during a possible lowering of relative sea-level. Oncoids in modern depositional environments have been described forming in shallow, subtidal environments (<1m water depths for Gebelein, 1976; shallow subtidal settings for Logan and others, 1964; Ginsburg, 1960). Deeper-water oncoids, peripheral to active shoals, have also been described (Hine, 1977). In the Maryville Limestone and Nolichucky Shale, oncoid grainstone and packstone lithologies, which also contain varying percentages of quartz silt and skeletal fragments, were interpreted to have been deposited as carbonate sand and mud in deeper subtidal environments, with the oncoids being transported from shallow subtidal environments (Srinivasan, 1993; Kozar, 1986; Markello and Read, 1981, 1982). The similar character of this lithofacies to those described in the Maryville and Nolichucky argues for a similar origin. The presence of non-abraded oncoids suggests a minimal degree of transport and the occurrence of mineralized rims on many of the oncoids and intraclasts suggests that these grains may have been inactive in the environment of deposition for long periods of time. This lithofacies is thus interpreted to have been deposited in water depths below fair-weather wave base. Allochems and quartz silt were transported into the environment as the result of periodic reworking of shallower-water deposits by storms.

DISCUSSION

Stratigraphic packaging and preserved depositional textures of individual lithofacies of the Rutledge Limestone suggest that deposition of the Rutledge occurred primarily upon a gently sloping carbonate ramp. The ramp, based on

regional stratigraphy and previous investigations (see summary by Read, 1988), faced a deeper-water intrashelf basin to the present day west and southwest (Conasauga Shales) and was bordered to the east and northeast by a carbonate bank with a high-relief seaward eastern margin characterized by shelf margin build-ups (see Pfeil and Read, 1980; Read and Pfeil, 1983; Demicco, 1985; Barnaby and Read, 1990). The Rutledge records the interplay between the intrashelf basin and the shallow-water carbonate environments. The shallow-water environments are preserved in the time-equivalent portions of the lower Honaker and Elbrook Dolostones of northeastern Tennessee and southwestern Virginia. Shallow-water limestones are not exposed in the field area and, as it has been shown, the Rutledge is composed wholly of subtidal rocks that were deposited downslope from these environments in environments below fair-weather wave base.

The carbonate ramp depositional system was initially proposed by Ahr (1973). Through his work on the Holocene and the Jurassic, Ahr (1973) defined the carbonate ramp model, as opposed to the traditional view of a carbonate shelf or carbonate platform, as a "sloping topographic surface on which carbonate facies are deposited while subject to open ocean conditions from the surf zone to depth of hundreds of feet." Ahr's (1973) definition stated that a carbonate ramp will have gentle slope ($<1^\circ$) and the following characteristics: (1) concentric facies belts which follow bathymetric contours, (2) grainstones updip passing to pelagic mudstones downdip, (3) rather monotonous wedge-shaped deposits thickening seaward, except where local topography modifies the depositional trend, and (4) absence of continuous reef trends; rather, patch reefs may be present locally. Read (1982, 1985) expanded the concept of the carbonate ramp by classifying ramps as either homoclinal or distally steepened. Homoclinal ramps are gentle

ramps that pass from shallow-water carbonate sands into hemipelagic shales without a major change in slope. Distally steepened ramps are defined as ramps that have a break in slope at the seaward edge of the shelf. In addition, Read (1982, 1985) related the different depositional regimes, namely ramp versus platform, to the maturity of passive continental margins and to the degree of equilibrium of the depositional basin with subsidence, tectonic influences, and sea-level.

Recent work by Burchette and Wright (1992) summarized the concepts and models of carbonate ramp depositional systems and provided a framework for their classification. A summary of their classification scheme, with application to the present work, is given in Figure 2.13. Underlying Burchette and Wright's classification are two assumptions: (1) many ramps are storm dominated shelves and (2) the hydrodynamic and morphological character of carbonate ramp, although variable from one depositional setting to the next, resembles that of a siliciclastic "shelf." With these assumptions and the recognition of the differing processes controlling deposition on clastic versus carbonate shelves, they argued that the subdivision of carbonate ramp systems should logically follow the classification scheme of siliciclastic shelves. They noted that the "yardsticks" or the critical depth indicators within each system, are the fair-weather and storm wave bases. The recognition of these interfaces within a particular ramp succession allows for the subdivision of individual systems and for the comparison of different ramp systems.

In the field area, the Rutledge is dominated by the burrow-mottled lithofacies (>75%) and, together with other mud-rich lithofacies, the entire Rutledge (>95%) is dominated by mud-rich units. The absence of shallow-water indicators, physical or chemical, coupled with the paucity of skeletal allochems

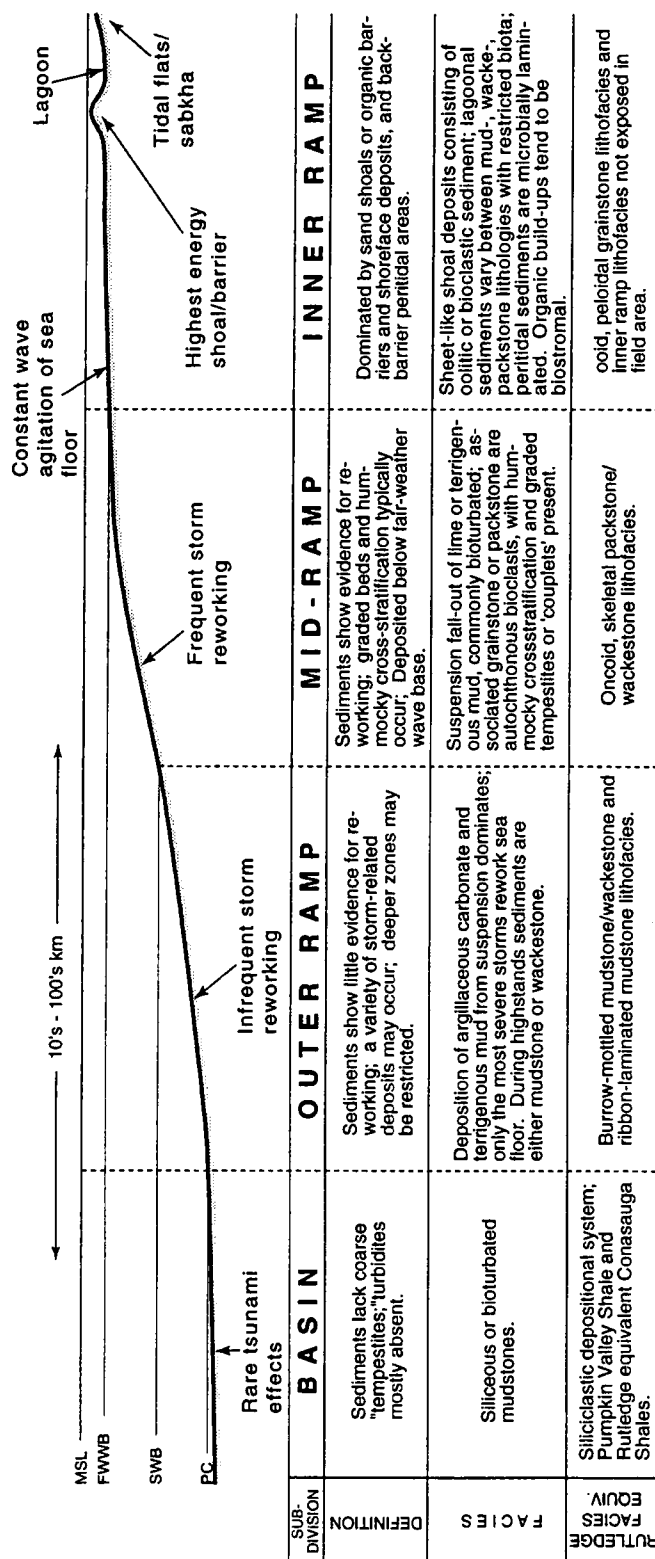


Figure 2.13. Carbonate ramp depositional system model after Burchette and Wright (1992). The figure includes Burchette and Wright's definitions and general lithofacies found in each subdivision of the ramp. Rutledge lithofacies equivalents to those proposed by Burchette and Wright are shown at the bottom of the figure.

suggest that the units of the Rutledge were deposited below fair-weather wave base in environments below the photic zone, or possibly in restricted environments. However, homogenization of the lithofacies by infaunal burrowers suggests that depositional conditions may have remained oxygenated. Reefs and shoal bodies were not observed within the Rutledge section and the absence of these shallow-water facies indicates that during deposition, a continuous margin was either not developed, or that water depth was below optimum depths for such bodies to form.

Taken together, the above characteristics of the Rutledge indicate that deposition occurred within the mid-ramp to outer ramp zone of a carbonate ramp depositional system. The homogeneity of the lithofacies indicates that the ramp regime persisted throughout the depositional time of the Rutledge. A ramp model, as opposed to the carbonate platform model proposed for younger units of the Conasauga (Srinivasan and Walker, 1993), is favored due to the lack of shallow-water build-ups and shoals and due to the absence of allochthonous shallow-water derived slump blocks and turbidites. In modern and ancient carbonate platform successions, platforms are commonly rimmed by either organic reefs or by active ooid shoals (Ginsburg and James, 1979; Harris, 1979; James, 1981; Read and Pfeil, 1983; Srinivasan and Walker, 1993). These shallow-water facies are deposited in the active surf zone and act as barriers and baffles to the inner platform environments, which are characterized by quiet-water lagoons (Ginsburg and James, 1979). The intrinsic depositional properties of platform-margin deposits, such as high depositional and aggradation rates, facilitate the development of steeper depositional slopes (several degrees to $\sim 60^\circ$) which favor the transport of reef talus and allochthonous blocks into deeper water as the result of storms, slope failure, and collapse (Kendall and Schlager, 1981; Schlager and

Camber, 1986; Schlager, 1992). These allochthonous blocks form talus aprons downslope from the platform margins (McIlreath, 1977; Mullins and others, 1984).

The geometry of the ramp is interpreted to have resembled that of a homoclinal ramp (after Read, 1982). There is no evidence for talus slopes or slump blocks, either in the field area or in areas southwest and northwest of the field area, that would support the interpretation of a distally steepened ramp (Fox, 1943; Harris, 1964). Therefore, gentle depositional slopes ($<1^\circ$) are suggested based on previous depositional models and examples (Ahr, 1973; Markello and Read, 1981, 1982). The presence of debris-flow deposits suggests that reworking by major storms or by other events occurred throughout deposition. The units of the Rutledge are interpreted to have been deposited, *sensu stricto*, in mid-ramp and, possibly, outer-ramp environments (below storm wave base; after Burchette and Wright, 1992). However, these environments may have actually been located in distal parts of the inner ramp, or even possibly within the inner ramp itself. This may be true because the classification scheme proposed by Burchette and Wright (1992) might not be applicable to ramps facing intrashelf basins due to the limited wave fetch and wave height of such basins, thus preventing significant storm reworking. Burchette and Wright (1992) noted this condition and suggested that ramps of this nature be regarded as protected ramps. Taking this into account, and considering proposed water depths (~100 meters) for the intrashelf basin during deposition, the Rutledge may be best considered as a protected ramp. The presence of debris-flow and storm layers within the lithofacies succession, however, suggest that the environments of deposition may have been subjected to storm reworking.

Deposition on the ramp was dominated by micrite. Mud-producing environments were located updip in the shallower-water portions of the ramp.

The origin and rates of production of the micrite are difficult to assess because shallow-water lithologies are absent in the field area and due to the lack of well preserved mud-producing organisms within the examined strata. Burchette and Wright (1992) stated that although many ancient ramps are characterized by muddy lithologies, the origin of this micrite remains elusive and detailed studies of the origin of this fine-grained sediment need to be conducted. They noted that the volume of sediment deposited within the mid-ramp zone far exceeds the volume of sediment produced within inner-ramp environments. This suggests that the majority of the mud in many ancient ramps may have been produced in offshore environments and then transported by either longshore currents or by storms to adjacent mid-ramp environments, or transported downdip to outer ramp environments.

Deposition of the units of the Rutledge occurred as the result of suspension deposition of allochthonous micrite derived from the inner ramp or mid-ramp zones. The deposition of this sediment occurred during a period of relative sea level high-stand. Increased accommodation space in inner-ramp environments would favor a greater production of micrite and, in addition, the increased accommodation space favored the transport of the fine-grained sediment to outer-ramp environments. This style of sediment production and transport, so-called "high-stand shedding," is a common feature of many modern carbonate platforms (Schlager and others, 1994; Boss and others, 1995). Rates of sedimentation in Rutledge ramp environments decreased with increasing distance from the inner ramp, the sediment source. Thus, mid-ramp and proximal outer-ramp environments would have experienced higher sedimentation than outer portions of the ramp. This fact parallels the similarity of a carbonate ramp with a siliciclastic shelf (Burchette and Wright, 1994). Recognition of the continued

sedimentation on the ramp, with little sediment bypass, combined with the early partial lithification of ramp sediments, would favor the modification and evolution of the ramp from homoclinal ramp to distally steepened ramp, and possibly to rimmed platform, over time (Read, 1985). This idea and its application to the carbonate units of the Conasauga are examined in Chapter 3.

Finally, the grainstone and packstone lithofacies of the Rutledge, although relatively thin and characterized by their patchy distribution, are important evidence for understanding the depositional history of the Rutledge. They represent the shift of shallow-water inner-ramp environments into the field area as a result of a decrease in accommodation space through either a lowering of relative sea level or, possibly, by the aggradation of the ramp to shallower depths. The deposition of the ooid, peloidal grainstone lithofacies represents a regression event and reflects the migration of ooid shoals and associated patch reefs and mud mounds into previously outer-ramp areas. These environments were deposited during a relative sea level low-stand, when either little sediment was being produced in shallower portions of the ramp, as the result of subaerial exposure, or when possible wave fetch prohibited the deposition of fine-grained sediment. The ooid, peloidal grainstone lithofacies may be analogous to the hardground facies which occur directly adjacent to shallow water shoals on the leeward side of the western margin of the Bahamian platform (Mullins and others, 1984). With a subsequent rise in sea-level, ramp deposition was re-established. However, the low-stand event may have had profound effects, such as modifying ramp morphology by development an inner-ramp area characterized by a lesser degree of depositional slope. Deposition of the oncoid, skeletal lithofacies represents a later decrease in accommodation space. The absence of ooids and *Renalcis* within this lithofacies suggests that the shoals and patch reefs were not established in this

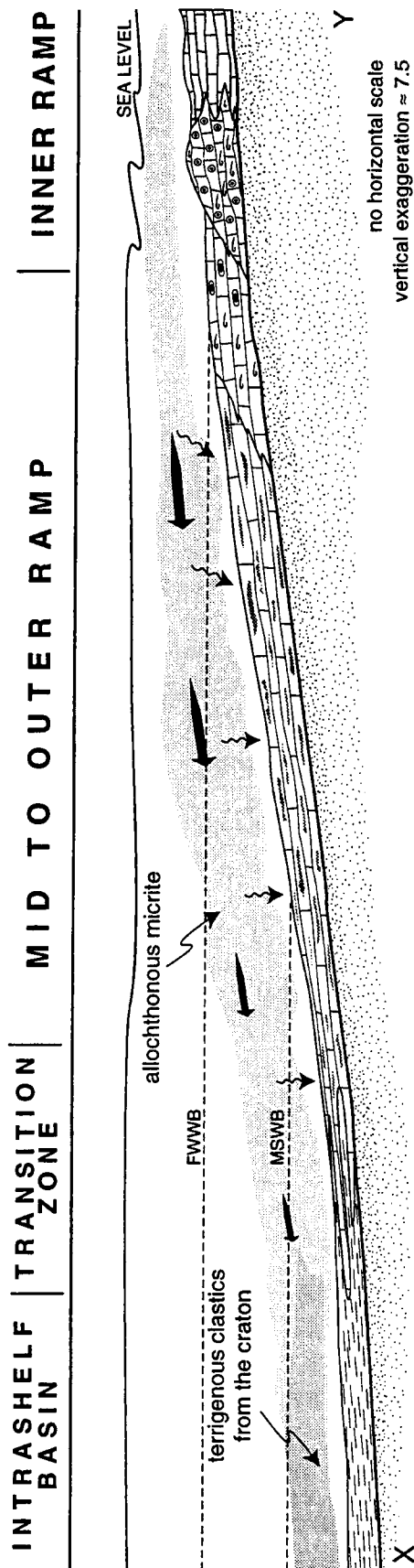
area of deposition. This may reflect that this lithofacies was deposited in depths greater than those required for deposition of such lithofacies (<10 m, Benedict and Walker, 1978) or, more than likely, that the shoals and build-ups were not a continuous feature along depositional strike of the ramp.

SUMMARY

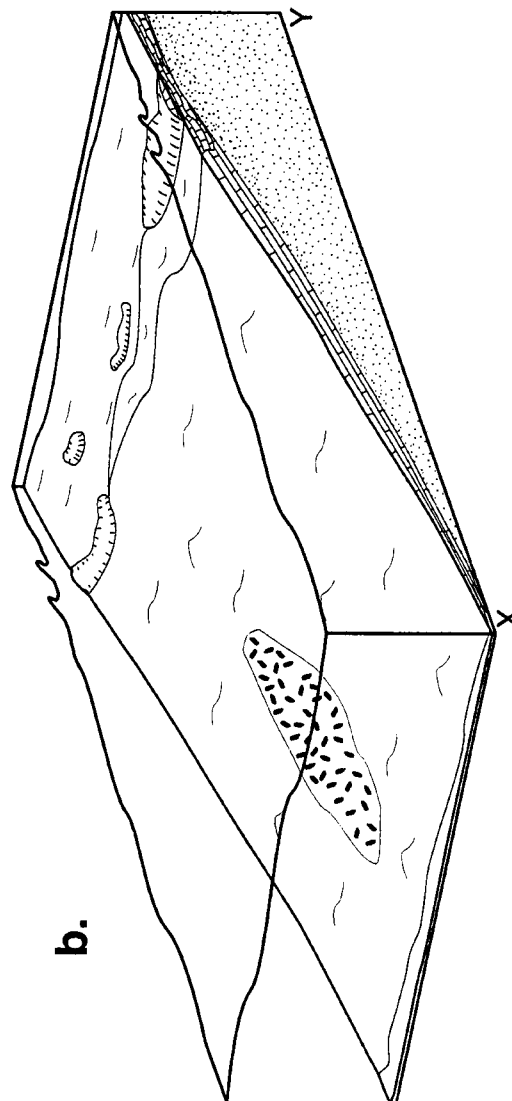
The fine-grained nature, lack of sedimentary structures indicative of shallow-water deposits, and the overall homogeneity of the units of the Rutledge Limestone together suggest that deposition of the Rutledge occurred mainly through suspension deposition of shallow-water derived, allochthonous micrite into deeper-water environments (below fair-weather wave base and below mean storm wave base). Regional depositional trends (based on previous studies, such as Read, 1989; Srinivasan and Walker, 1993) and observed stacking patterns indicate that deposition was primarily on a gently sloping, carbonate ramp that was bordered to the north (present day west, southwest) by a clastic intrashelf basin and to the south (present day east, north east) by a broad, shallow-water carbonate bank. The ramp is interpreted to have had a gently sloping depositional gradient and is further interpreted as a homoclinal protected ramp (after Read, 1982; and Burchette and Wright, 1992). The ramp depositional regime was characterized by shallow-water mudstones and grainstones (inner-ramp, preserved west of the field area?) that gave way to deeper-water mudstones (outer ramp, this study) without a major break in depositional slope (Figure 2.14a). The interbedding relationships between the carbonate facies of the Rutledge and the clastic facies of the Pumpkin Valley and Rogersville Shales define a transitional boundary between the clastic and carbonate regimes. Based on the patchy

Figure 2.14. Carbonate ramp facies model for the Rutledge Limestone. FWWB = fair-weather wave base. MSWB = mean storm wave base. **a.** Schematic cross-section showing lateral relationships of different lithofacies within the depositional systems. Sediment deposited upon the ramp is interpreted to be allochthonous and derived from inner and mid-ramp environments. Vertical exaggeration was calculated by determining the depositional dip of the ramp as drawn in the figure ($\sim 7.5^\circ$) and then dividing it by interpreted depositional dip of the ramp during deposition ($\sim 1^\circ$). No horizontal scale is intended. **b.** Block diagram of the ramp showing the lateral relationships of the different lithofacies and environments. The observed stacking patterns suggest that a discontinuous network of ooid shoals and patch reefs existed in the inner ramp.

a.



b.



distribution of the ooid, peloidal grainstone and oncoid, skeletal packstone/wackestone lithofacies within the upper portions of the Rutledge section, a discontinuous network of ooid shoals and cyanobacterial patch reefs (?) is interpreted to have existed along depositional strike; these environments mark the boundary between the outer ramp, characterized by the burrow-mottled and ribbon-laminated lithofacies, and the middle ramp (Figure 2.14b). Deposition of these shallower-water facies is interpreted to have occurred at or near the fair-weather wave base interface, suggesting a decrease in water depth (allowing for the migration of these facies) or a general build-up (aggradation) of the ramp to shallow-water depths.

Based on regional stacking patterns and the homogeneity of the lithofacies, the Rutledge appears to have remained in a period of depositional stasis throughout its history. The presence of the correlatable grainstone facies in the middle portion of the Rutledge section suggests that the depositional history of the Rutledge was punctuated by periods of lowered sea level, resulting in a shift of shallow-water facies basinward. This shift of facies is interpreted to have resulted from a drop of relative sea level, and the presence of this facies at a similar stratigraphic position in every section suggests that this drop was a basin-wide event, marking this facies (in essence a single unit) as a chronostratigraphic unit. Recognition of changes in the style of ichnofabric within the burrow-mottled lithofacies may similarly add to the determination of sea level history, and in turn how changes in sea level may have affected the depositional history of the Rutledge. The depositional history, the mechanisms controlling deposition, and the role of Rutledge deposition in the overall history of the Laurentian margin is discussed in the following chapter.

CHAPTER 3

DEPOSITIONAL MODEL AND EVOLUTION OF THE LAURENTIAN SHELF DURING EARLY CONASAUGA TIME

INTRODUCTION

Carbonate depositional systems are governed by a series of extrinsic and intrinsic controls that can be broadly assigned to those related to water-depth, or accommodation space, and to those that regulate the production rates of carbonate sediment. Of the properties inherent to carbonate systems, the fact that the majority of carbonate sediment is of biologic origin uniquely sets carbonate systems apart from siliciclastic systems. The reliance of the overall depositional system on the "health" of this biologic "carbonate factory" limits carbonate sedimentation to warm, shallow-waters, conducive to the activity of photosynthetic organisms. Modern, shallow-water carbonate deposits are restricted to tropical waters in a zone bounded by the 30° north and south latitudes (Schlager, 1992).

The carbonate system is also self-governing, with respect to growth and development, during periods when extrinsic factors yield favorable conditions for carbonate production. The carbonate depositional system, as a result of the continued ability to build to sea level, is able to grow laterally, or prograde, into adjacent sedimentary basins. Progradation is a function of high, sustained carbonate production rates during periods of time characterized by slowed rates of increase in accommodation space. It begins with the transport of fine-grained sediment from shallow-water environments into deeper-water slope environments surrounding the platform. Continued sedimentation of this allochthonous platform sediment upon the adjacent slopes results in the aggradation of the slope environments to fair-weather wave base, thus allowing the migration of high-

energy, high-sediment producing, shallow-water reefs and shoals basinward. The off-platform sediment flux reaches its optimum output during sea level highstands and, in the vernacular of sequence stratigraphy, this process is known as highstand shedding (*sensu stricto* Schlager and others, 1994). Highstand shedding has been identified as the main factor in the Cenozoic progradation of the leeward side of the Great Bahama Bank (Eberli and Ginsburg, 1989). This process has also been identified as a contributing factor in the development of many ancient carbonate successions (for example, the Permian of west Texas, Dolan, 1989; the Devonian of northwestern Australia, Kennard and others, 1992; the Cambrian of the southern Appalachians, Srinivasan and Walker, 1993).

Our understanding of carbonate depositional systems, including the concept of highstand shedding and its applications to sequence stratigraphy, was developed primarily through the study of carbonate platform sequences (see reviews by Schlager, 1992, Handford and Loucks, 1994). The principles essential to the understanding of platform aggradation, progradation, and sequence development are related to the flat-topped morphology of most carbonate platforms and also to the sensitivity of the shallow subtidal carbonate regime to changes in relative sea level. These concepts have not been applied as frequently to carbonate ramp systems (see, however, Tucker and others, 1993; and Handford, 1995). Models for the development of ramp sequences are just now being examined (Burchette and Wright, 1992; Handford and Loucks, 1994; Handford, 1995).

The primary reason for our lack of understanding of ramp systems is the absence of a true modern analog (the best example probably being the southern Persian Gulf; Purser, 1973) and, because ramp sequences develop into rimmed platforms over time (Read, 1982, 1985), the lack of ramp sequences preserved in

the geologic record. This chapter examines the depositional history and development of the Rutledge ramp within the previously established stratigraphic framework. The intent is to develop a model illustrating the depositional dynamics of the Rutledge and then, using this model as a template, to compare the development of the Rutledge with that of younger carbonate units of the Conasauga in an attempt to relate the deposition of the Rutledge to the overall history of the Laurentian margin during early Conasauga time. Although some of the terms used in this chapter agree with those proposed by traditional sequence stratigraphic workers (see review by Van Wagoner and others, 1988), the ideas expressed herein are the same as those developed by earlier workers (such as Krumbein and Sloss, 1963). In addition, the terms in this chapter are used purely in a descriptive manner and are not intended to necessarily agree with the eustatic genetic explanations usually invoked by sequence stratigraphers.

As it will be shown, the major controlling factors on deposition of the Rutledge were thermal subsidence, changes in relative sea-level, and the varying input rates of clastic and carbonate sediment into the system. These factors acted in concert to control deposition and the development of the ramp. Changes in relative sea-level and the varying rates of clastic and carbonate sediment influx appear to have controlled facies distributions and were the dominant factor in the transitions between the depositional regimes. Thermal subsidence is interpreted to have been a major factor in the continued ramp morphology of the Rutledge throughout its depositional history.

By firmly establishing carbonate sedimentation in the basin and by developing an existing ramp morphology on the shelf edge, deposition of the Rutledge and the time equivalent units of the Honaker and Elbrook Formations played a key role in the evolution and development of younger carbonate units of

the Conasauga. The Rutledge provided an antecedent topography that greatly increased the growth potential of younger carbonate successions of the Conasauga. In addition, the development of the Rutledge and the time-equivalent units of the Honaker and Elbrook Formations, coupled with eustatic sea level rise and thermal subsidence, had a major role in the development of the Cambrian intrashelf basin. These later points will be explained at the end of this chapter.

DEPOSITIONAL CONTROLS

The shallow-water character of carbonate platforms makes them an excellent laboratory for the study of the mechanisms that control the deposition and the development of carbonate successions. Small changes in relative sea level, autocyclic processes, tectonic conditions of the underlying shelf and sedimentary basin, and changes in sedimentation rates and/or oceanic chemistry all have a profound affect on sedimentary processes. The resulting effects of these processes are often preserved in the meter-scale shallowing-upward cycles that are characteristic of many platform-interior deposits. It is because of the sensitivity of carbonate platforms to these changes, that a great deal of research has been devoted to the understanding of the depositional controls of modern and ancient carbonate platforms. As a result, a great deal of literature discussing the roles of eustasy (as defined by the traditional concepts of sequence stratigraphy, see Sarg, 1988), environmental change (see recent discussions by Schlager, 1993, 1992), and tectonics (for example Rankey and others, 1994) has appeared in attempts to describe the resulting stacking patterns of carbonate successions. However, in light of this work, most researchers (see for example Schlager, 1993; Handford and Loucks, 1994) now agree that platform growth and development are a result

of the combination of all the factors mentioned above, and as Schlager (1992) pointed out, a complete understanding of the dominant processes governing platform growth can only be obtained through a detailed sedimentologic understanding of the platform deposits and their regional stacking patterns.

Carbonate ramp systems differ from carbonate platform systems in that the shelf is not characterized by a major break in depositional slope. Rather, the ramp is defined by a gentle, depositional slope passing from shallow-water carbonate deposits into deeper-water deposits, with or without the presence of build-ups or shoals. In ramp systems, facies patterns form a concentric pattern around a topographic high (or shallow, inner ramp) and the distribution of these facies is a function of water depth and energy gradients (Burchette and Wright, 1992). The interpreted mid- to outer-ramp origin for the majority of Rutledge units indicates that deposition was controlled by (1) the amount and type of sediment being introduced into the environment of deposition, and (2) the position of the sediment-producing environment relative to that of the environments of deposition. In the Rutledge, the dominant control on deposition was mainly the relative position of sea-level (water depth) and to a lesser degree (although important in the lower and upper transition intervals) the type of sediment being introduced into the system. Relative changes in sea level did occur during deposition and such changes were most likely responsible for the deposition of the prominent grainstone unit within the middle of the Rutledge section. In addition, changes in sea level may have played a supporting role in the patchy distribution of facies within the upper Rutledge, the differences in the fabrics of the burrow-mottled lithofacies, and the demise of the Rutledge ramp.

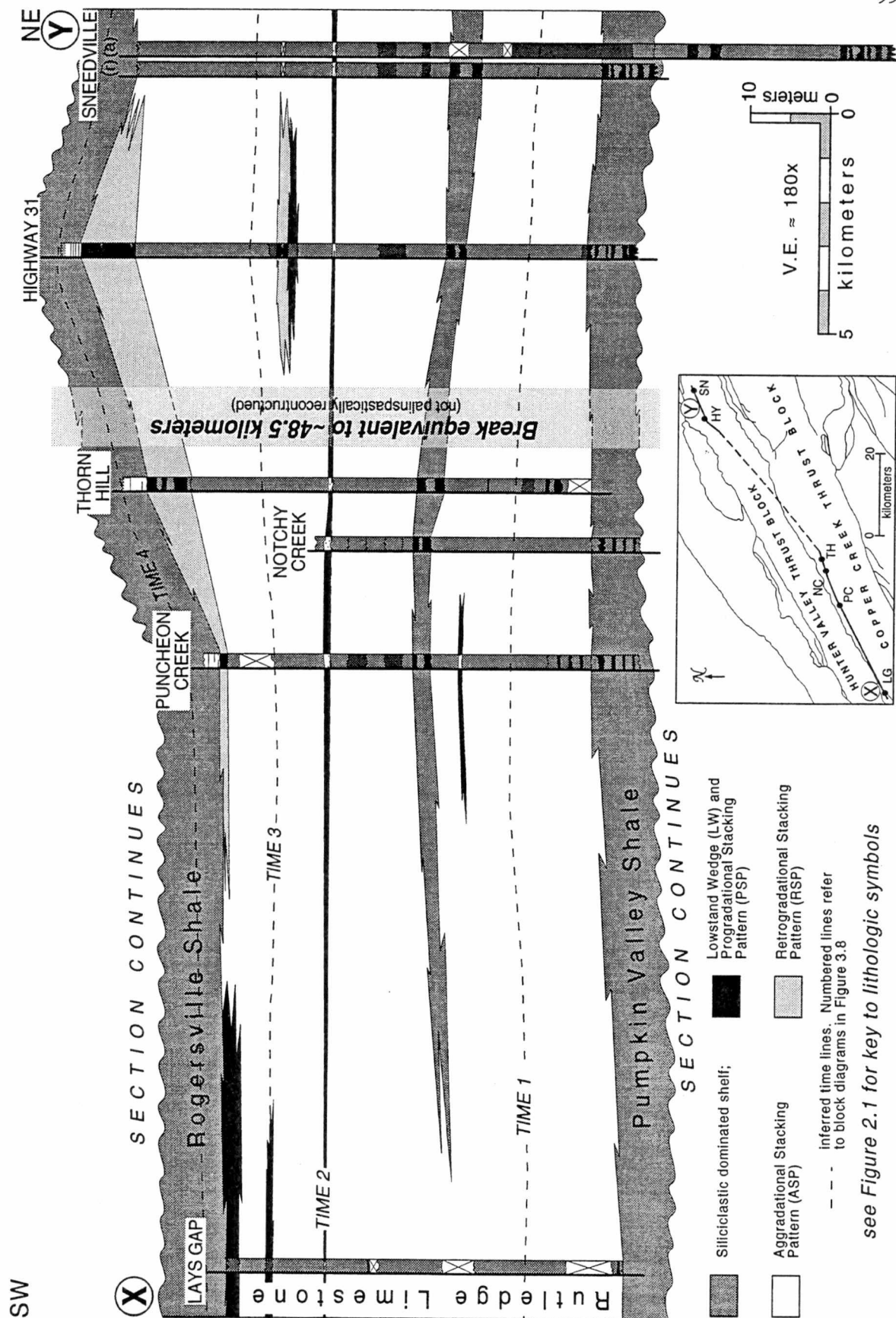
Other controls, such as tectonically induced, jerky subsidence (as observed in the Maryville by Rankey and others, 1994), biological productivity, and

autocyclic processes were not discernible in the field. This may be due, in part, to the minor role of these processes in deposition or, more likely, to the position of the field area with respect to the depositional environments and facies that better record such signals (for example, shallow subtidal to peritidal). Long-term, thermal subsidence models (Bond and others, 1984; Walker and others, 1992; Srinivasan and Walker, 1993) suggest that an increased rate of subsidence existed during Early to early Middle Cambrian time and it is postulated that this rate of subsidence decreased with decreasing age (Figure 3.1). Thus, long-term thermal subsidence may have played a key role in the overall homogeneity and gross depositional stasis of the Rutledge system. The shallow-water environments of the Rutledge mainly played "catch-up" (rate of accommodation increase > growth potential, term after Kendall and Schlager, 1981) and "keep-up" (rate of accommodation increase $\approx$ growth potential) with sea level, rather than "prograde" (growth potential > rate of accommodation increase) as observed in younger units of the Conasauga (see Srinivasan and Walker, 1993; Rankey and others, 1994; Glumac, in prep.).

DEPOSITIONAL SEQUENCES

Based on regional stacking patterns and facies distributions, the Rutledge Limestone can be divided into four depositional subsequences (Figure 3.2, Table 3.1). The Aggradational Stacking Pattern (ASP, after Srinivasan and Walker, 1993) is the dominant subsequence of the Rutledge and comprises nearly all of the units of the Rutledge Section. The Lowstand Wedge (LW) and Retrogradational Stacking Pattern (RSP, after Srinivasan and Walker, 1993) are limited in their occurrence within the total vertical section of the Rutledge but the separate intervals can be

Figure 3.2. Southwest to northeast cross-section along a line roughly parallel to depositional strike. Individual sections are hung on the prominent grainstone unit in the middle of the Rutledge section. Detailed descriptions of stratigraphic sections are shown in Figure 2.1 and given in Appendix I. The Sneedville Section (SN) was restored (r) to interpreted correct thickness. The actual section (a) is believed to have been faulted, giving an overestimated stratigraphic thickness (see Appendix I). Key to patterns on cross-section incorporates traditionally used sequence stratigraphic terms (after Van Wagoner and others, 1988), see text for disclaimer and discussion. Clastic lowstand and transgressive systems tracts are incomplete due to the incompleteness of the Pumpkin Valley Shale and Rogersville Shale sections. Time lines are inferred and are used to delineate certain time intervals in the development of the Rutledge ramp.



see Figure 2.1 for key to lithologic symbols

Table 3.1. Summary table for the major depositional variables and depositional sequences of the Rutledge Limestone. This table serves as reference for the symbols used in the figures included in this chapter. Depositional sequences are described in text relative to individual sections, except for the clastic-dominated shelf, which is outlined in the first part of the discussion.

DEPOSITIONAL VARIABLES	DEPOSITIONAL SEQUENCES
G_p growth potential - maximum rate of growth the carbonate ramp can sustain.	
G_r growth rate - rate at which the carbonate factory of the ramp produces sediment. A function of water depth, biologic productivity (<i>G</i>), and sediment composition.	AGGRADATIONAL STACKING PATTERN (ASP) $G_r \approx A_r$ decreasing L_r sea level increasing size of inner ramp (increasing G_p) carbonate bank "keeps-up" with increasing accommodation space
A_r rate of change in accommodation space - the sum of the rates of subsidence by crustal cooling, sediment loading, sediment compaction, structural deformation, eustasy, etc. (definition after Schlager, 1992).	
S_r rate of sediment supply	
D_r depositional rate - rate of deposition of allocthonous sediment in mid- to outer portions of the ramp. Directly proportional to G_r and S_r	LOWSTAND WEDGE (LW) $A_r < 0, G_r \geq 0$ sea level fall sea level possible exposure of inner ramp (decreased G_p) shallow-water facies shifted basinward
L_r rate of change in relative sea level.	
SUB_r Rate of change in thermal subsidence - qualitative measure based on burial curves of Cambrian passive margin sequences and Middle Cambrian to Middle Ordovician Stratigraphic data from east Tennessee (see Figure 3.1)	
C amount of input of terrigenous clastics into the system.	PROGRADATIONAL STACKING PATTERN (PSP) $G_r > A_r$ shallow-water facies prograde basinward sea level increasing size of inner ramp (increasing G_p) carbonate bank "outpaces" increasing accommodation space
CLASTIC DOMINATED SHELF	RETROGRADATIONAL STACKING PATTERN (RSP) $G_r < A_r$ carbonate bank returns to "catch-up" sedimentation increasing sea level sea level sig. C from craton decreasing size of inner ramp (decreasing G_p) termination of carbonate sedimentation and onlap of basinal states carbonate bank plays catch-up with increasing accommodation space (low G_p)

confidently correlated across the basin. The Progradational Stacking Pattern (PSP, after Srinivasan and Walker, 1993) is present in only the Lays Gap and Highway 31 sections, and is limited to only a few, thin intervals within these sections. These intervals cannot be correlated from section to section.

Aggradational Stacking Pattern

The burrow-mottled and ribbon-laminated lithofacies of the Rutledge represent the allochthonous transport of shallow-water micrite into deeper-water ramp environments. The units are interpreted to be equivalent to the initial start-up phase of carbonate platform sedimentation (Kendall and Schlager, 1981; Srinivasan and Walker, 1993). Deposition on the ramp resulted from continued highstand conditions in the ramp interior that allowed for the constant transport of fine-grained sediment toward the adjacent basin. Sediment was transported in suspension, and rates of deposition are interpreted to have been slightly below or equivalent to the rate of increase in accommodation space ($D_r \leq dA$). Depositional rates are further interpreted to have decreased with increasing distance from the ramp interior, as supported by thinning of the Rutledge southwestward (away from source area), and by the allochthonous characteristics of the units of the Rutledge (thus resembling siliciclastic shelves). Lateral variations in sediment thickness in the lower part of the Rutledge indicate that deposition rates parallel to depositional strike were more or less equal. However, by late Rutledge time, sedimentation in the northwestern part of the field area may have been greater due to the proximity of this area to shallower portions of the ramp (shallow-water carbonates of Honaker/Elbrook Formations of Virginia, Read, 1988).

Lowstand Wedge

The distinct textural characteristics and stratigraphic occurrence of the ooid, peloidal grainstone lithofacies suggest that this lithofacies was deposited during a relative sea level lowstand. The drop in sea level is interpreted to have been basinwide and a relatively synchronous event, because of the similar stratigraphic position of the lithofacies in all measured section. Progradation, as a mechanism for development of this lithofacies, is not supported by the observed sharp contact between the underlying, outer ramp, burrow-mottled mudstones and the inner to proximal, mid-ramp grainstone lithofacies. Based on stratigraphic thickness, the magnitude and duration of sea level fall are interpreted to have been minor and the lowstand a minor perturbation in the overall highstand conditions that characterized deposition of the Rutledge. Deposition on the ramp during the lowstand was characterized by a shift of shallow-water facies basinward. Rates of deposition are interpreted to have been low because inner-ramp environments were probably subaerially exposed (reduction in G_p), with a resulting reduction in the source area (decreased G_p) for outer-ramp sediments. Upon sea level rise, ramp sedimentation was reestablished with little or no lag time, and normal depositional conditions (ASP) on the shelf continued.

Progradational Stacking Pattern

The irregular distribution of the oncoid, skeletal packstone lithofacies in the stratigraphic sections and the interpreted depositional environments of this lithofacies suggest that these lithologies were deposited as progradational lobes of mid-ramp environments into outer portions of the ramp. The limited stratigraphic occurrence and thin units of this facies in the overall section indicate that

progradation may have been a factor during deposition, but it was not dominant. Progradational patterns in the Hunter Valley sections are interpreted to be the result of increased aggradation rates (from higher S_r and D_r) of outer ramp environments. Increased sedimentation, possibly due to the closer proximity of these localities to shallower portions of the ramp, led to a decrease in water depths (decreasing A_r) and a progradation of shallower water mid-ramp environments toward the basin.

The anomalous presence of the oncoid, skeletal packstone lithofacies at the top of the Lays Gap section is problematic. Its presence at the top of the section, as compared to the transition interval (Retrogradational Stacking Pattern, see below) of other localities, could bear on the gross morphology of the ramp and the overall transition from the Rutledge to the overlying Rogersville Shale. The lithofacies may have been deposited as the result of progradation because of increased sedimentation, like that of the Hunter Valley localities. However, deposition may have also been triggered by a relative sea level fall and a shift of shallower ramp environments basinward. This lithofacies at Lays Gap then, would be better considered part of a lowstand-wedge stacking pattern. Either interpretation, assuming that the bank formed a more or less parallel (concentric) facies pattern around the inner ramp (as proposed from ramp models such as Ahr, 1973, and Burchette and Wright, 1992), is not sufficiently supported by the closely spaced outcrop data of the Copper Creek localities (no shallowing is observed at Thorn Hill or Puncheon Creek). However, if the bank consisted of several topographic highs (or several separated inner ramp areas), the observed stacking patterns may have resulted from transport from these more local sources. A relative fall in sea level is advocated for the deposition of this lithofacies at Lays Gap. Such a scenario would provide a mechanism for the shut-down of carbonate

production in the inner ramp, which is supported by regional data (see Read, 1988). A subsequent rise in sea level would have produced conditions for formation of the upper transitional interval.

Retrogradational Stacking Pattern

The lower shale interval and the upper transitional interval of the Rutledge represent periods of time when carbonate sedimentation in shallow-water ramp areas was reduced, allowing for the gradual onlap of terrigenous clastics of the basin onto previous ramp deposits. A reduction of carbonate sediment production rates (decreased G_r) in the shallow-water portions of the ramp, resulting from either a sea level fall (shut down of carbonate production), increased rates of sea level rise, or clastic influx into the basin, or a combination of the three, led to a decrease in the amount of carbonate sediment supplied (low, $S_r \approx$ sediment starved conditions) to outer portions of the ramp. In the absence of this sediment supply and with continued increases in accommodation rates, the onlap of basinal shale occurred. In the lower shale interval, this event is characterized by the formation of a hardground surface (drowning unconformity of Schlager, 1989) that is immediately overlain by units of the non-calcareous shale lithofacies. Rejuvenation of carbonate sedimentation in shallower-water environments resulted in the re-establishment of carbonate sedimentation on the inner ramp and outer ramp.

The upper transitional interval (nodular carbonate mudstone and shale lithofacies) was deposited when the ratio between the carbonate growth rate in the shallow portions of the ramp and the rate of increase in accommodation space decreased below one ($G_r/A_r < 1$). The initial decrease in carbonate growth rates

was probably due to a sea level fall that exposed the shallow-water portions of the ramp, thus shutting down carbonate productivity. The rate of the subsequent sea level rise outpaced the growth potential (G_p) of the carbonate ramp systems and a backstepping of the shallow water ramp occurred (a return to the "catch-up" phase of sedimentation). The continued increase in accommodation space (G_r/A_r , becoming closer to zero), possibly coupled with an increased amount of clastic influx from the craton, led to the gradual onlap of terrigenous clastics and the "give up" (phrase after Kendall and Schlager, 1981) of carbonate sedimentation in the basin.

DISCUSSION

Prior to deposition of the Rutledge, the Laurentian margin had a rimmed shelf morphology (McReynolds and Driese, 1994). During deposition of the Lower Cambrian Rome Formation, the shelf-edge was characterized by a thin, eastward-facing carbonate belt ($\pm$ build-ups) bordered cratonward by a mosaic of shallow-water, clastic environments. Regional sea level curves (such as the qualitative curve by Read, 1988) suggest that the Rome was deposited during a regressive sea level cycle culminating in the formation of the Sauk I/Sauk II boundary (after Sloss, 1963). As a result of sea level fall, high input rates of clastics into the basin probably stifled carbonate production (creating turbid water ~ clastic poisoning) and limited carbonate sedimentation to topographic highs and the shelf edge. The beginning of the Sauk II sequence (Rome/Pumpkin Valley contact?) led to the gradual retreat of the shoreline cratonward and with it, a gradual reduction in the amount of terrigenous material introduced into the basin. This reduction probably led to the gradual establishment of carbonate sedimentation along the shelf edge

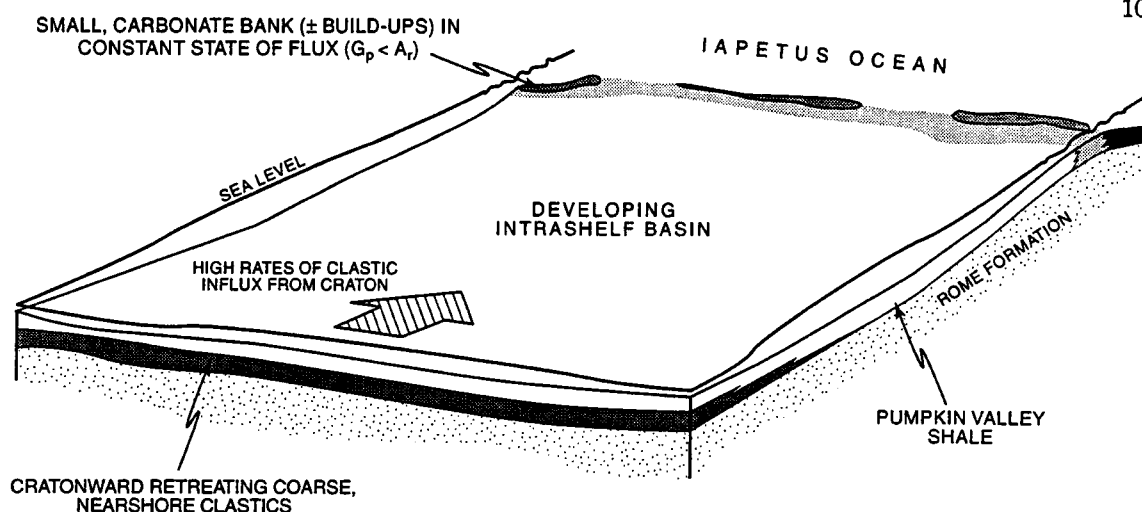


Figure 3.3. Schematic diagram (looking present day southeastward) of the middle to outer portions of the Laurentian shelf during Pumpkin Valley time: The shelf was characterized by a thin carbonate bank (Lower Honaker/Elbrook Formations) bordered cratonward by craton-derived clastics (Pumpkin Valley Shale). Carbonate sedimentation, as the result of clastic poisoning and increased rates of sea level rise, was directed primarily to "catching up" with accommodation space and had little effect on the adjacent intrashelf basin.

(Figure 3.3). However, because the growth potential (G_p) of the carbonate factory, due to its small aerial extent and the waning effects of clastic sedimentation (clastic poisoning), was less than the rate of increase in accommodation space (dA), the majority of carbonate sedimentation was primarily directed to "catching up" with increased accommodation space, and the effect of carbonate sedimentation on the adjacent sedimentary basins was minimal.

A decrease in the rate of sea level rise, resulting in increased growth rates (G_p) and a lesser degree of stress upon the carbonate system, led to an increase in the aerial extent of the shallow-water carbonate bank (increasing G_p). The sediment-producing, shallow-water environments, shifted from the "catch-up" phase of carbonate sedimentation to the "keep-up" phase, in which sediment production (G_p) was equal to or just above the rate of increased accommodation space (dA). The shallow-water environments, as a result of increased sediment

production and continual wave and storm currents, began to shed fine-grained, carbonate sediment and storm deposits northwestward into the adjacent intrashelf basin. The interbedded clastic and carbonate units of the lower transition zone reflect the response in the basin to this newly developed sedimentation pattern. Continued and increased rates of transport of this sediment into the basin, coupled with a further establishment (increasing G_p) of the shallow water bank, led to the establishment of ramp sedimentation.

Deposition of the Rutledge resulted from continued highstand conditions that flooded shallow-water portions of the bank and promoted the high-stand shedding of fine-grained sediment into the adjacent intrashelf basin. Continued sedimentation of the allochthonous sediment on the slopes flanking the shallow water bank led to formation of the aggradational stacking pattern sequence that characterizes the majority of the units of the Rutledge. Aggradation is believed to have been the dominant process controlling the vertical stacking patterns. Based on the interpreted, allochthonous character of the burrow-mottled and ribbon-laminated lithofacies, the rates of aggradation, and hence sedimentation rates, were mainly a function of the rate of sediment supply to the outer ramp from inner and mid-ramp environments, and the distance of the depositional environment from the carbonate source area. Taking this into account, then, the Rutledge ramp, in essence, has the same depositional characteristics of a siliciclastic shelf, in that deposition was dependent primarily upon an extraneous source and the dominant control on deposition was the relative position of sea level.

Changes in relative sea level and sediment progradation affected the ramp during deposition, but their effects were apparently minor as evidenced by the overall, small percentage of shallower-water lithofacies in the Rutledge section.

However, the apparent minor role of these processes may be a function of the location of the field area (deeper-water facies) with respect to the shallow-water portions of the ramp and because of this, the effects of sea level fluctuation and progradation on deposition may have been greater in the Rutledge elsewhere. In addition, there was no observable, meter-scale, lithologic cyclicity in the vertical section, but again this may be a consequence of the location of the field area. Larger-scale cyclicity is apparent in individual sections but correlation between sections was difficult and because of this, such correlations were not attempted. Interestingly, changes in burrow-mottled fabrics, although not tested by this thesis, may record changes in relative sea level or in marine water chemistry. This hypothesis might be tested on the tenet that increases in oxygenation and increases in the input of organic material into the depositional environment, as the result of decreased water depths and higher sedimentation rates, may have resulted in increased burrowing activity and thus higher indices of burrow-mottled fabric (using Droser and Bottjer's classification scheme, 1986). Such increases in burrow-mottling would then be recorded as "burrow-mottling cycles" that, if outcrop data were sufficiently detailed, could be used for correlation.

On the regional scale, the close of deposition of the Rutledge is marked by the nodular carbonate mudstone with shale lithofacies. This lithofacies records the gradual drowning of the ramp. The rate of carbonate sedimentation is interpreted to have decreased (decreasing G_r) as the result a relative sea level fall that stifled sediment production in shallower water portions of the ramp. The drop in sea level was not significant enough to expose outer portions of the ramp, but may have resulted in the shift of shallower-water facies basinward (oncoïd, skeletal lithofacies of Lays Gap locality). Sea level fall also resulted in the migration of the cratonic shoreline basinward which, in turn, may have increased the amount of

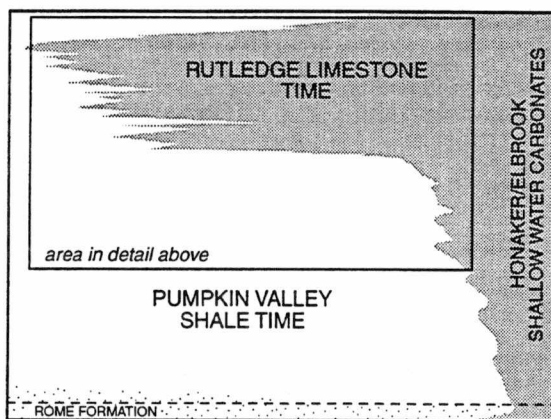
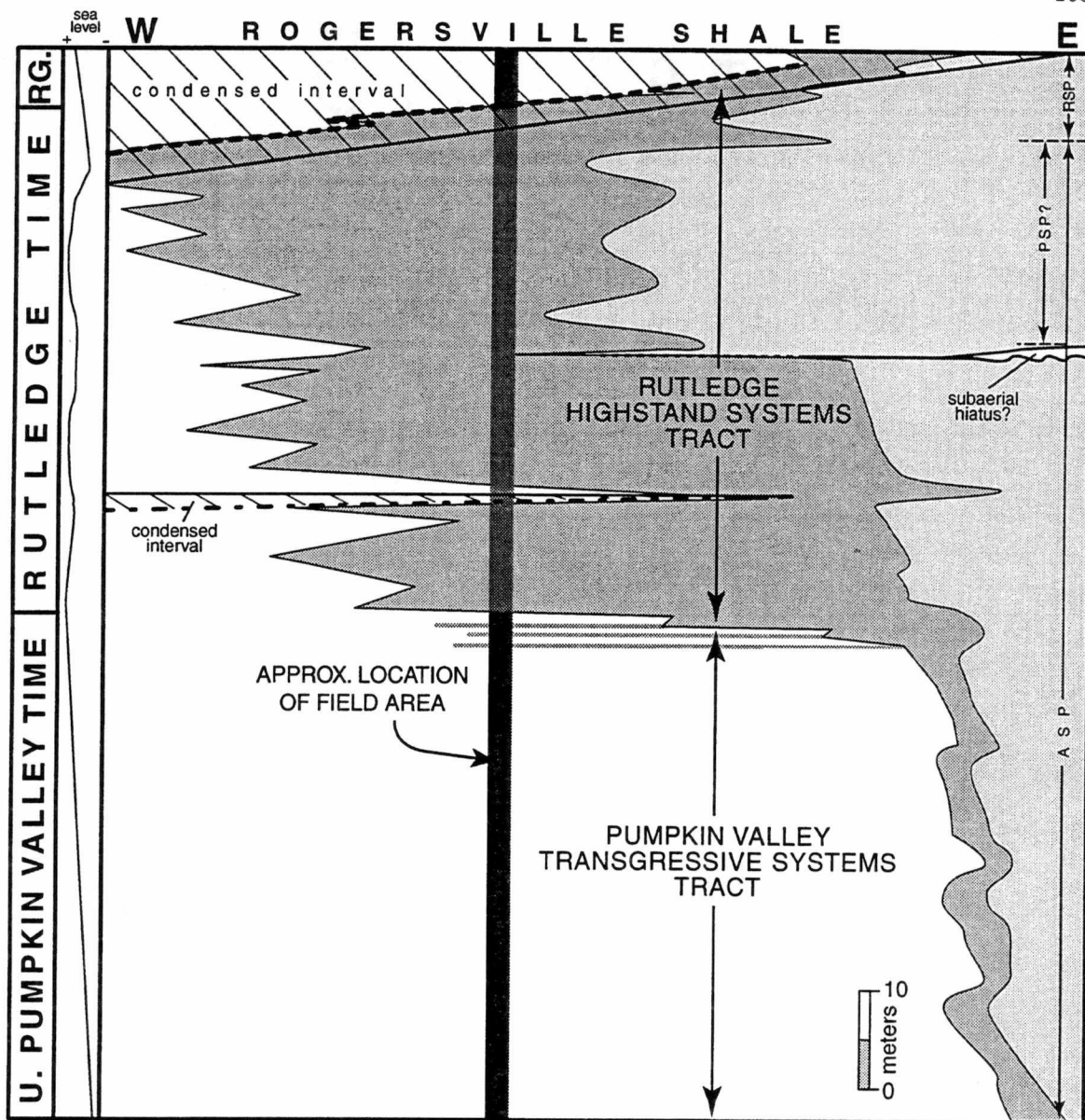
terrigenous silt and clay being transported into the basin. During the subsequent sea-level rise, carbonate sedimentation was re-established and some shedding of fine-grained carbonate material into the basin occurred. However, the rate of sea level rise outpaced the growth rate of the carbonate factory of the mid- and inner ramp ($dA \gg G_r$) leading to a backstepping of the ramp and the onlap of basinal clastics (beginning of Rogersville time). Carbonate sedimentation on the shelf edge did not completely cease (give-up phase of Kendall and Schlager, 1981), as evidenced by the pinching out of the Rogersville shale southeastward into the shallow-water carbonates of the Honaker and Elbrook Formations. Instead, carbonate sedimentation is interpreted to have regressed back into a "catch-up" mode ($dA > G_r$) with the role of carbonate sedimentation in the basin becoming severely reduced.

Sequence Stratigraphy

The Rutledge Limestone is interpreted as a highstand systems tract using the sequence stratigraphic terms originally defined by Mitchum (1977) and Van Wagoner and others (1988). Together with the Pumpkin Valley Shale, it forms a third-order sequence that is equivalent to the first grand cycle of the Middle to Upper Cambrian grand cycles (Figure 3.4). The Pumpkin Valley Shale is interpreted to be a transgressive systems tract that was deposited during the initial sea level rise after the development of the Sauk I/Sauk II boundary. The transition between the Pumpkin Valley and Rutledge is thought to be diachronous and formed as a function of the gradual establishment of carbonate sedimentation in the basin.

The grainstone unit in the middle of the section represents a time when

Figure 3.4. Schematic cross-section showing the sequence stratigraphy and chronostratigraphy of the Pumpkin Valley Shale and Rutledge Limestone along a west to east cross-sectional line. The diagram is interpretive and is an attempt to relate the deposition of the Rutledge to the relative position of sea level and to the increasing growth potential of the inner ramp over time. During Pumpkin Valley time and during most of Rutledge time, sedimentation patterns were dominated by the vertical aggradation of shelf edge carbonates and the carbonate ramp. By late Rutledge time, triggered by a sea level fall or by a possible increase in the rate of sea level rise ($L_r \geq 0$), inner ramp environments may have begun to prograde into the intrashelf basin. Progradation was minor, but resulted in a significant increase in the areal extent of the inner ramp and an increase in the growth potential of the system. Close of deposition and the onlap of basinal clastics occurred as the result of sea level rise and a switch back to "catch-up" sedimentation by the inner ramp. Sequence/grand cycle boundary at the top of the Rutledge indicates the correlative conformity of this surface and the possible diachronous character of this boundary.



-  inner ramp shallow-water carbonates
-  mid- to outer ramp deeper-water subtidal carbonates
-  basinal shales and siltstones
-  sequence/grand cycle boundary
-  drowning surface

there was a lowering of sea level that shifted shallower water facies basinward. By definition then, this unit may be considered as a lowstand wedge (Van Wagoner and others, 1988). However, this unit is relatively thin and this distinction may be invalid. But on the other hand, such a unit may be the only record of such an event. This assumption is based on the detailed study of the stratigraphy of the Rutledge in the field area and previous work on carbonate ramp systems (see discussion by Burchette and Wright, 1992; Tucker and others, 1993). If the sediment source is reduced in size and production rates are diminished, as the result of sea level fall, then sedimentation rates on the outer portions of the ramp would be low, thus creating sediment starved conditions that possibly could extend some distances from the strandline.

The upper contact of the Rutledge with the Rogersville shale has been previously interpreted to be a third-order sequence boundary (Walker and others, 1990; Srinivasan and Walker, 1993). In the field, this contact is not characterized by an exposure surface, nor is there any evidence for a major drowning unconformity. The absence of these defining surfaces (using the strict definitions of Van Wagoner and others, 1988; and Schlager, 1988) does not, however, preclude the defining of this contact as a third-order sequence boundary. Rather, the gradual transition interval between the carbonates of the Rutledge and the shales of the Rogersville may be considered to be the "correlative conformity" of a sequence boundary (as defined by Mitchum, 1977). Therefore the Rutledge/Rogersville contact is here recognized as a third order sequence boundary, although the contact is characterized by a gradual transition. This gradational interval is probably diachronous on the regional scale, but records the partial drowning of the ramp interior. In addition, the contact is defined as a grand cycle boundary, because it records the transition from mostly carbonate sedimentation to

mostly shale sedimentation, thus reflecting a major change in sedimentation patterns in the basin (Aitken, 1981).

Comparisons of the Rutledge with Younger Carbonate Units of the Conasauga

Previous work by Srinivasan and Walker (1993) has shown that deposition of the younger, Maryville Limestone culminated in the development of a flat-topped carbonate platform from an initial carbonate ramp. Citing aggradation and progradation as the main contributors to stacking patterns, Srinivasan and Walker (1993) proposed a model (summarized in Figure 1.7) for the development of the Maryville Limestone. The model was also used as a template for interpreting the development of the carbonate successions of the Conasauga Group. Regional stacking patterns of the Rutledge Limestone indicate that the Rutledge did not culminate in the development of a flat-topped carbonate platform and thus did not follow the predicted path of development proposed by Srinivasan and Walker (1993). Instead, the Rutledge is interpreted to have stayed in the initial stages of platform development and remained within a ramp depositional regime throughout its depositional history. The Rutledge is then placed within the aggradational stacking pattern sequence (Time 1) of Srinivasan and Walker (1993) with the units representing the initial start-up phase (after Kendall and Schlager, 1981) of carbonate platform development.

The inability of the Rutledge to develop into a flat-topped platform is interpreted to be the result of three factors: greater rates of thermal subsidence, greater rates of clastic input from the craton, and the smaller, areal extent of the inner platform (carbonate factory). Subsidence models proposed by Bond and

others (1984), Bond and others (1988), and Walker and others (1992) suggest that during the early Middle Cambrian thermal subsidence rates were higher and that these rates decreased with decreasing age (see Figure 3.1). The higher subsidence rates are interpreted to have been related to a greater degree of cooling (thermal contraction) of the heated lithosphere as a result of the gradual establishment of Laurentian passive margin following the Late Precambrian to Early Cambrian rifting of Rodinia. The result of this cooling on sedimentation, coupled with the effects of long-term sea level rise, was evidence by the continued "catch-up" and "keep-up" phases of carbonate sedimentation of the Rutledge. The greater rates of subsidence provided a continuous increase in "accommodation space," thereby limiting the carbonate factory from outpacing the rise in sea level. This resulted in the aggradation stacking patterns of the Rutledge.

Thermal cooling and long-term sea level rise was also a major factor in determining the type of sediment transported into the basin from the craton and the rate at which this sediment was introduced. During the Early Cambrian, carbonate sedimentation was limited to a few topographic highs and along the outermost shelf edge, where clastic influx was lowest. With the rise in sea level, plus increasing flexural bending of the cratonic edge (sediment loading), the distance between the shoreline and the outer carbonate bank increased (Bond and others, 1988). The retreating shoreline, over time, resulted in a decreasing rate of clastic influx into the basin. During early Conasauga time the rate of clastic influx is interpreted to have been greater than during later Conasauga time because the cratonic shoreline was closer to the carbonate bank. The closer proximity of the shoreline resulted in significant rates of clastic transport into the basin, causing increased turbidity and reduced carbonate production. Reduced production of carbonate sediments may have also limited the development of the Rutledge. By

Maryville time, however, long-term sea level rise and the further retreat of the shoreline cratonward may have been significant enough to reduce the contaminating effects of clastic sediments on carbonate production, thus allowing for greater production rates and increased platform development.

A final factor limiting the development of the Rutledge with respect to later Conasauga carbonate units may have been the overall size of the carbonate bank and the shallow-water carbonate factory. Although it is impossible to assess this hypothesis from the data presented in this thesis and, due to the extent of deformation of the southern Appalachians, a regional test may prove to be equally difficult, a case could be made that the areal extent of shallow-water bank increased with decreasing age. This increase was a direct consequence of the antecedent topography inherited from the preceding carbonate succession (see below). The expanse of the preceding shallow-water bank provided a higher growth potential for the newly developing shallow water bank. The increased source area led to greater aggradational rates on the adjacent slopes and faster progradational rates of the shallow, subtidal platform into the intrashelf basin.

The Importance of Early Ramp Development in the Overall Evolution of the Conasauga Carbonate Platforms

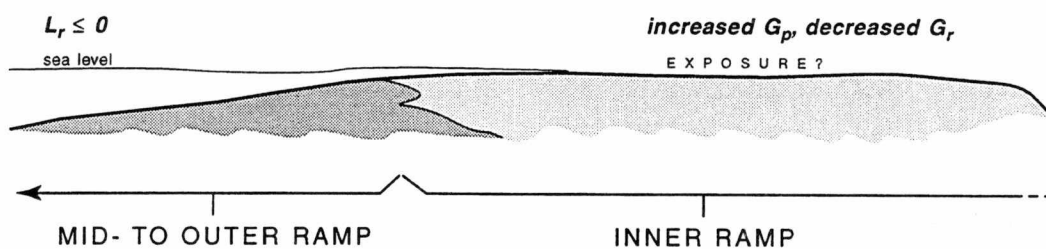
Deposition of the Rutledge marked the first time carbonate sedimentation on the carbonate bank bordering the Laurentian craton was significant enough to influence sedimentation in the adjacent intrashelf basin. Governed by the intrinsic and extrinsic controls discussed above, the Rutledge was characterized by the aggradational accumulation of allochthonous sediment in a carbonate ramp depositional regime. By the end of Rutledge time, the ramp consisted of an inner

ramp area of increased size flanked by a well developed outer ramp that extended well into the intrashelf basin (see Figures 1.1 and 3.4). The increased surface area was a result of the progradation of the inner ramp basinward during the waning phases of the sea level highstand, thereby providing a greater growth potential of the system (Figure 3.5a). However, with the subsequent sea level fall and influx of clastic sediment from the craton, the growth potential of the system was never realized.

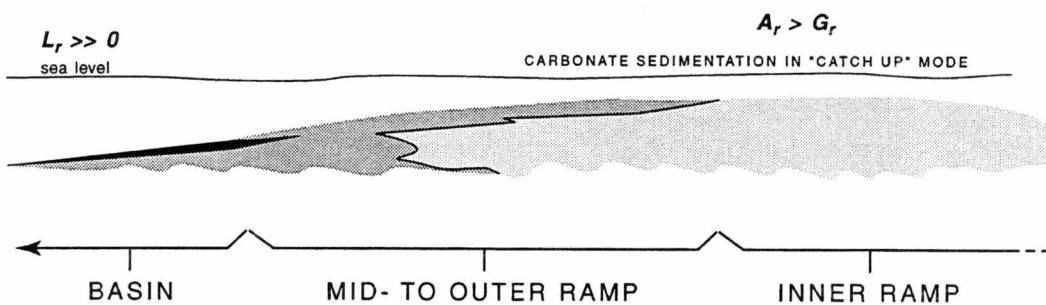
Drowning of the ramp led to a decrease in the influence of carbonate sedimentation in the basin and the base lap of clastic sediments onto the pre-existing carbonate ramp. The ramp evidently did not become completely drowned (gradual pinch-out of the Rogersville into the Honaker Formation) and carbonate sedimentation in the bank interior is interpreted to have switched back to a "catch-up" mode of sedimentation (Figure 3.5b). During the next transgressive phase (upper portions of the Lower Shale Member of the Rogersville Shale), carbonate sedimentation occupied a significant portion of the original topography of the inner ramp of the Rutledge. This increased inner ramp area became critical to the development of the Craig Limestone Member of the Rogersville Shale, by providing a larger productive area for the subtidal carbonate factory and a resulting higher growth potential for the entire system. When the rate of sea level rise decreased and high-stand conditions prevailed, ramp sedimentation (Craig Limestone) was initiated and, because of the increased growth potential of the system, progradation of the ramp basinward occurred at a faster rate (Figure 3.5c). This progradation is supported by a relatively thin section of the Craig Limestone at the Thorn Hill locality (~ 5 meters) which is capped by lithofacies interpreted to have been deposited in the mid- to inner ramp environments (Jennifer Beall, unpublished data). In turn, the Craig Limestone

Figure 3.5. Schematic model illustrating the role of antecedent topography on the development of carbonate successions of the Conasauga. The diagram is a cross-sectional view of the outer portions of the Laurentian shelf and shows the Honaker/Elbrook Formations (right side of diagrams) and the easternmost portions of the carbonate/shale formations of the Conasauga (left of diagrams). **a.** End of Rutledge time. As a result of progradation during late depositional time, the inner ramp (Rutledge/Honaker) is interpreted to have an increased areal extent (compare with Figure 3.4). The increased surface area provided a greater growth potential (increased source area) for the shallow, subtidal carbonate factory and the outer ramp. Deposition was terminated before the full capacity of the inner ramp was realized. **b.** Middle Rogersville time (?). Sea level rise shifted carbonate sedimentation back into "catch-up" mode and carbonate deposition in the basin was terminated. On the shelf edge, sedimentation continued and occupied a significant portion of the inner shelf of the preceding ramp (Rutledge/Honaker). **c.** Early Craig time. Decreased rates of sea level rise resulted in increased growth rates of carbonate sedimentation on the shelf edge. The higher rates of sediment production, coupled with increased area (growth potential) of the inner ramp resulted in a faster rate of ramp development in the basin.

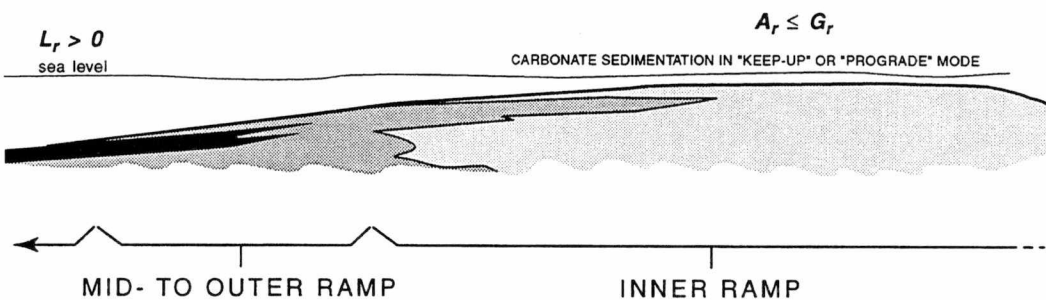
a.



b.



c.



may have occupied the same role, in providing an antecedent topography for the development of the Maryville carbonate platform.

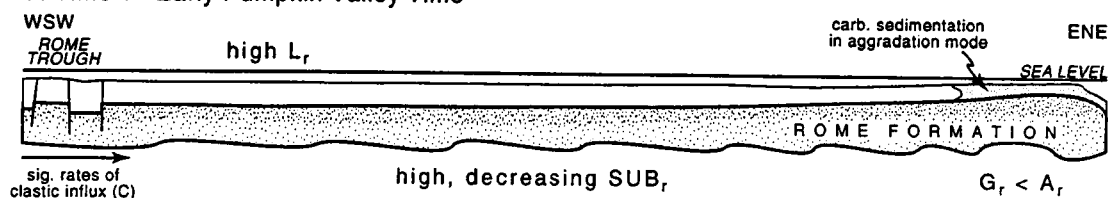
The Role of Carbonate Platform Growth and Sea Level Rise in the Evolution of a Cambrian Intrashelf Basin

Early Cambrian sedimentation patterns are preserved in the clastic tidal flat and subtidal deposits of the Rome Formation (McReynolds and Driese, 1994). The units are interpreted to have been deposited in a mosaic of shallow-water depositional environments that inherited the shelf topography of the underlying lower Cambrian Shady Dolomite. Sea level rise at the beginning of the Sauk II depositional sequence changed sedimentation patterns in the basin to those associated with the deposition of the Conasauga Group and time equivalent formations. Deposition of the Conasauga marked the evolution of the Laurentian passive margin as well as the evolution of the carbonate bank and intrashelf basin. By late, Middle Cambrian to early, Late Cambrian time, water-depths of the intrashelf basin may have reached or exceeded 200 meters (Foreman and others, 1991). It is proposed here (initial ideas were proposed by Walker and others, 1983; Stefaniak and others, 1995a) that carbonate bank sedimentation and gradual eustatic sea level rise, combined with subsidence and decreasing rates of siliciclastic input from the craton, led to sediment starvation in the region between the carbonate bank and to the gradual development of the intrashelf basin.

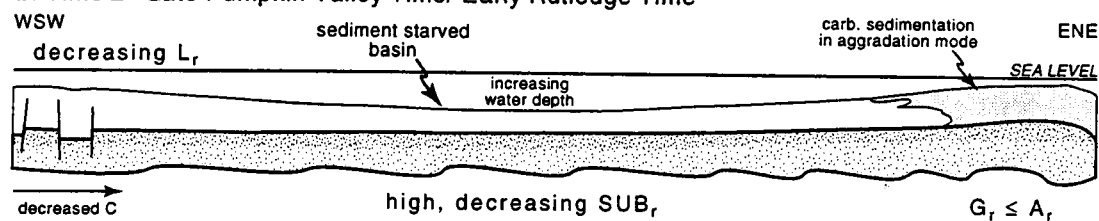
During early Pumpkin Valley time, depositional conditions are interpreted to have been similar to those proposed for the Rome Formation (Figure 3.6a, Hasse, 1982). With increasing relative sea level, carbonate sedimentation became firmly established on the shelf edge as a result of the decreased effects of clastic

Figure 3.6. Schematic model for the role of carbonate deposition and rising sea level on the development of the Cambrian intrashelf basin. Diagrams are drawn along a cross-section perpendicular to depositional strike. Each diagram shows the carbonate bank and the adjacent clastic environments. Placement of the Rome trough is purely diagrammatic. Cratonic shoreline is not shown. **a.** During deposition of the lower Pumpkin Valley shale, the shelf was characterized by shallow subtidal clastic environments similar to those proposed for the Lower Cambrian Rome Formation by McReynolds and Driese (1994). The clastic environments were bordered seaward by a carbonate bank that was in constant flux as the result of clastic poisoning. **b.** Increasing sea level throughout deposition of the Pumpkin Valley led to a retreat of the shoreline cratonward. Increased carbonate production on the shelf edge, coupled with the increase of sea level and its affects, led to sediment-starved conditions in the area between the strandline and carbonate bank. As the result of continued subsidence, sea level rise, and low sedimentation rates, water depths increased in this area. **c.** By Rutledge time, the intrashelf basin may have become quite evolved as the result of the continued establishment of an elevated seaward margin (carbonate aggradation) and continued sea level rise. **d.** The proposed sea level fall at the end of deposition of the Rutledge may have led to an increase in the amount of clastics introduced into the basin, however, with the subsequent sea level rise (**e**), the rate of clastic influx was not significant to fill the basin and with the resumption of carbonate aggradation on the shelf edge deepening of the basin continued.

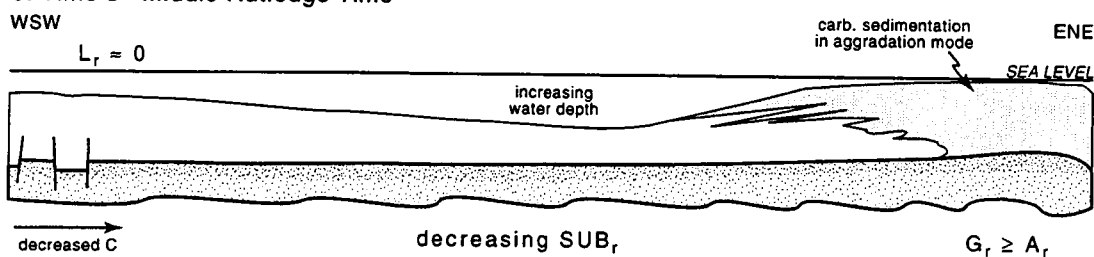
a. Time 1 - Early Pumpkin Valley Time



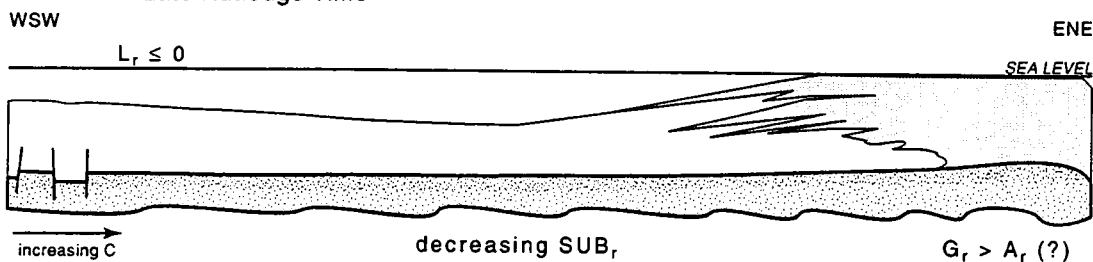
b. Time 2 - Late Pumpkin Valley Time/ Early Rutledge Time



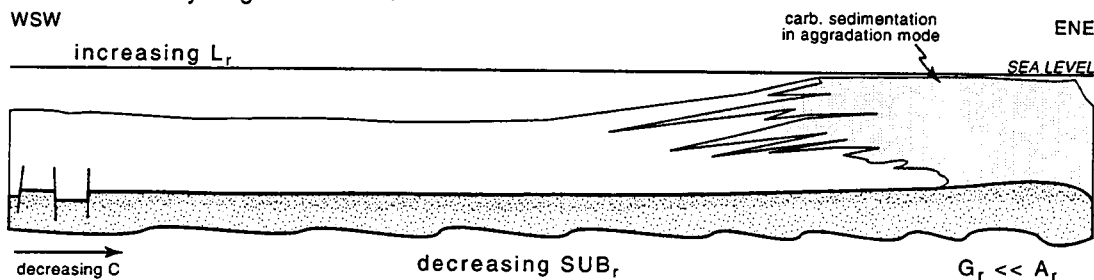
c. Time 3 - Middle Rutledge Time



d. Time 4 - Late Rutledge Time



e. Time 5 - early Rogersville Time



poisoning on the carbonate factory that were associated with a decrease in the rate of siliciclastic sediment from the craton and the possible development of an intracratonic graben system (Thomas, 1991) inboard from the carbonate bank. During early Conasauga time, carbonate sedimentation on the shelf edge was able to keep pace (aggradation) with increasing accommodation space, but had little effect on the adjacent intrashelf basin. As a result of the decreased sediment input from the craton and carbonate bank, sediment-starved conditions developed in the area between the bank and craton (Figure 3.6b).

Continued sedimentation on the carbonate bank and the gradual retreat of the cratonic shoreline led to the gradual deepening of area between the bank and the craton and the development of the intrashelf basin (Figure 3.6c). The differential sedimentation patterns across the shelf were accentuated by the effects of continued thermal subsidence of the shelf due to the thermal contraction of the newly created Laurentian crust. Over time, the differential sedimentation rates and subsidence acted in concert, thereby increasing the depth of the intrashelf basin (Figure 3.6c and d). Initial (early Conasauga - Pumpkin Valley through Rogersville), deepening of the basin may have occurred at a greater rate due to the increased rates of subsidence that characterized early Conasauga time (Figure 3.1, Bond and others, 1988; Walker and others, 1990). This rate, like thermal subsidence, may have decreased during deposition of the Conasauga, suggesting that evolution of the intrashelf basin may have rapid.

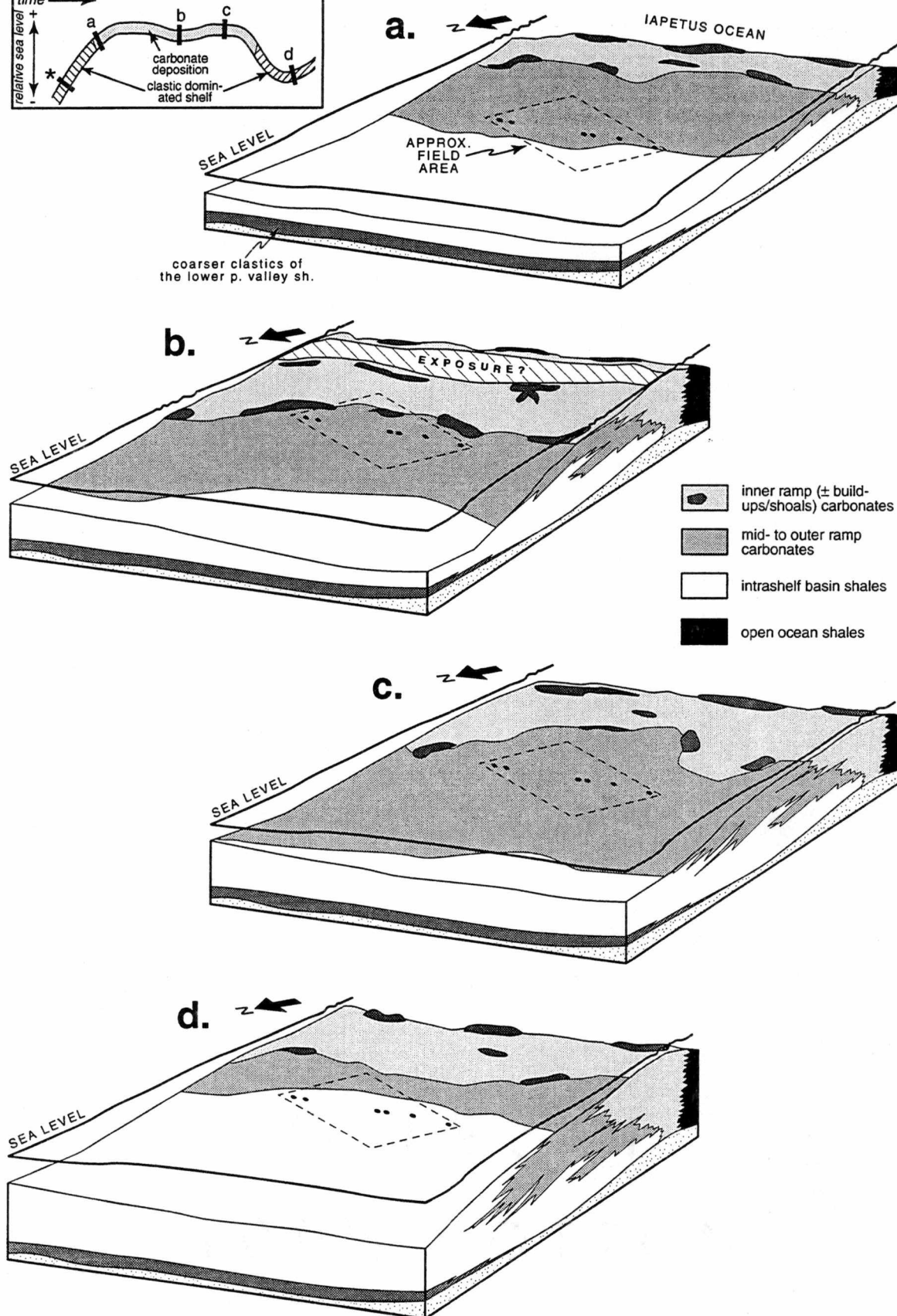
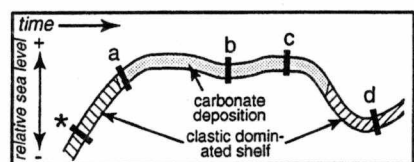
SUMMARY

Deposition of the Rutledge Limestone was primarily controlled by the relative position of sea level and the amount and type of sediment being brought

into the depositional environment (Figure 3.7). The limestone units were deposited during a relative sea level highstand that was part of the larger, craton-wide, transgressive Sauk II sequence (of Sloss, 1963). Deposition was initiated as the rate of increase in sea level declined, thus allowing the subtidal carbonate factory on the shelf edge to switch from "catch-up" mode to "keep-up" mode. This change in sedimentation on the shelf edge, coupled with a decreased rate of clastic influx from the craton, allowed for the shedding of fine grained carbonate sediment into the basin. This highstand shedding ultimately led to the development of the carbonate ramp depositional system.

Sedimentation on the ramp is interpreted to have kept pace with increasing accommodation space, resulting in the aggradational stacking pattern that characterizes the majority of the units of the Rutledge. Changes in relative sea level and in the rate of carbonate production of the shallow-water ramp are interpreted to have had a minor, but critical, role in the development of the ramp and the observed stacking patterns. The roughly synchronous unit in the middle of the section was deposited during a relative sea level lowstand. This event and the possible progradation of the inner ramp during late Rutledge time led to an increased growth potential of the ramp system as a whole. However, a postulated minor drop in relative sea level at the end of deposition shut down the production the ramp system. Subsequent sea level rise resulted in the baselap of basinal clastics and a reduction in the role of carbonate sedimentation in the basin. The demise of ramp sedimentation is interpreted to be the result of a slow down in carbonate production in inner portions of the ramp. This decrease in production led to a reduction in the amount of carbonate sediment transported into the basin. Carbonate sedimentation was, however, reestablished in the ramp interior and is interpreted to have switched back from "keep-up" mode to "catch-up" mode.

Figure 3.7. Summary Block Diagrams of the development of the Rutledge Limestone. (*inset*: relative sea level curve for the upper Pumpkin Valley, Rutledge Limestone, and lower Rogersville. Lettered black bars mark the position of sea level during depositional times of individual block diagrams. The bar marked with an asterisk refers to the depositional time shown in Figure 3.2) **a.** Carbonate sedimentation was initiated during a relative sea level highstand as a result of a switch of carbonate sedimentation from "catch up" ($G_r < A_r$) to "keep-up" ($G_r \geq A_r$) and the highstand shedding of fine-grained carbonate sediment in to the adjacent intrashelf basin. Aggradation of the ramp occurred throughout early Rutledge time. **b.** During a relative sea level lowstand, shallow water shoals and build-ups were shifted basinward, resulting in the deposition of the prominent grainstone in the Rutledge section. Inner ramp environments may or may not have been exposed by the drop in sea level. This event is interpreted to have been a minor perturbation in the overall highstand conditions. **c.** Return to highstand conditions resulted in the possible progradation of the inner ramp basinward and, based on observed stacking patterns, the possible creation of multiple topographic highs in the shallow-water portions of the ramp. Sedimentation during the upper Rutledge was, in the field area, still characterized by aggradation, but progradation may have played a significant role in the development of the entire depositional system. **d.** After shut down of carbonate sedimentation by possible exposure, sea level rise switched carbonate sedimentation back to "catch-up" mode and basinal clastics gradually overlapped the carbonate ramp, thus ending deposition of the Rutledge.



The underlying Pumpkin Valley Shale and the Rutledge together comprise a third-order depositional sequence (Vail and others, 1977) and the first grand cycle (Aitken, 1966, 1978) of the Middle to Upper Cambrian grand cycles of the southern Appalachians. The Pumpkin Valley is interpreted to be a transgressive systems tract, with the Rutledge being deposited during the subsequent highstand (highstand systems tract). The gradational contact between the Pumpkin Valley and the Rutledge is interpreted to be diachronous and represents the gradual establishment of carbonate sedimentation in the basin. The upper contact, although sharp, shows no evidence for subaerial exposure, major drowning unconformity, or major break in sedimentation. Rather, it is characterized by a retrogradational stacking pattern deposited during gradual shift from carbonate-dominated sedimentation to shale-dominated sedimentation. The Rutledge/Rogersville contact is defined as a sequence boundary, but more aptly, as the correlative conformity of the traditional sequence boundary defined by Mitchum (1977). It is thought to be diachronous on the regional scale.

The development of the Rutledge did not culminate in the development of flat-topped carbonate platform as seen in younger carbonate units of the Conasauga (Srinivasan and Walker, 1993). Instead it remained in a period of gross depositional stasis. The abandonment of the predicted path of carbonate platform development (Srinivasan and Walker, 1993) was due to the increased rates of thermal subsidence, the waning effects of clastic poisoning, and the possible small growth potential of the carbonate system during Rutledge time. Thermal subsidence and the effects of siliciclastics on carbonate deposition are interpreted to have decreased throughout deposition of the Conasauga, suggesting that deposition of the older carbonate units of the Conasauga were controlled by subsidence and "catch-up" sedimentation whereas younger units were

characterized by slower rates of subsidence and “keep-up” or “prograde” sedimentation (as proposed by Stefaniak and others, 1995b).

The growth potential of the carbonate factory is interpreted to have increased during Conasauga time resulting in an increasing areal extent of the subtidal carbonate factory and a more developed inner ramp topography. The increased growth potential and antecedent topography developed by the Rutledge ramp is interpreted to have facilitated the establishment of carbonate ramp sedimentation and increased the rates of ramp progradation of younger units of the Conasauga. These two factors may have played a major role in the development of younger carbonate units of the Conasauga. Finally, the aggradational character of the shelf-edge carbonates and the Rutledge played a key role in the development of the intrashelf basin over time. The combined effects of differential sedimentation patterns and eustatic sea level rise resulted in sediment-starved conditions in the area between the cratonic strandline and the carbonate bank. Continued aggradation of the carbonate bank with increasing sea level led to the development of a seaward margin of the intrashelf basin, that, over time, led to increased water depths in the intrashelf basin.

CHAPTER 4

SUMMARY AND CONCLUSIONS

1. The Rutledge Limestone ranges in thickness from 53 to 64 meters and is composed of seven distinct lithofacies. The calcareous/non-calcareous shale lithofacies (percentage of thickness of lithofacies in total Rutledge section = 1.1%), the interbedded carbonate mudstone/wackestone/packstone and shale lithofacies (1.5%), and the nodular mudstone with shale lithofacies (5.2%) are characteristic of the lower and upper transition intervals of the Rutledge. The clastic-rich calcareous/non-calcareous shale and interbedded carbonate mudstone/wackestone/packstone and shale lithofacies also occur in a shale interval in the lower portion of the Rutledge section. The burrow-mottled mudstone/wackestone lithofacies (78.6%) and the genetically related ribbon-laminated mudstone lithofacies (3.8%) are the most common lithofacies of the Rutledge. The ooid, peloidal grainstone lithofacies (0.8%) and oncoid, skeletal packstone lithofacies (0.74%) form distinctive units in middle and upper portions of the Rutledge section.
2. Depositional textures and regional stacking patterns reveal that the units of the Rutledge were deposited in a carbonate ramp depositional regime. The ramp, herein defined as a protected homoclinal ramp, faced a deeper-water intrashelf basin (Conasauga Shales) to the present day west, southwest and was bordered to the present day east, northeast by shallow-water carbonate deposits (Lower Honaker/Elbrook Formations). Depositional slopes of the ramp are interpreted to have been low ($<1^\circ$), with no major breaks in depositional slope.

3. Sedimentation on the ramp was dominated by the suspension deposition of shallow-water derived, fine-grained carbonate mud in depositional environments below fair-weather wave base and below mean storm wave base. Subsequent burrowing of the allochthonous sediment by infaunal detritus feeders (*Thalassinoides* ichnofabric) produced the characteristic burrow-mottled lithofacies that makes up much of the Rutledge section. Ramp deposition was dynamic, as evidenced by the presence of differing styles (indices) of burrow-mottled fabric in the vertical section, and by the presence of storm generated packstone and grainstone layers in the predominantly mudstone/wackestone lithofacies. The changing burrow-mottled fabric may represent changes in the relative position of sea level, changing oxygenation conditions of basin waters, or changes in the rate of organic sediment input.
4. Evidence of marked shallowing events is limited to a correlatable grainstone unit in the middle of the section and to uncorrelatable units in the upper portion of the section. The ooid, peloidal grainstone lithofacies, present in the middle of the section, is interpreted as a hardground facies deposited during a relative lowstand. The oncoid, skeletal packstone lithofacies was deposited as progradational lobes of shallower-water ramp environments into the outer ramp. These events, based on their stratigraphic occurrence in the field area, were apparently minor perturbations in the overall depositional conditions of the Rutledge. However, these events on a more regional scale are interpreted to have played a greater role in the evolution of the system by increasing the size of the shallow-water ramp and by building a topography that would later influence deposition of subsequent carbonate units of the Conasauga.

5. Deposition in outer-ramp environments was controlled by three factors: the relative position of sea level, the rate of clastic influx from the craton, and thermal subsidence. Other mechanisms, such as autocyclic processes and non-thermal tectonism, were not resolvable from the stratigraphic section. The relative position of sea level and water-energy gradients controlled the distribution of facies. The rate of clastic influx from the craton, along with changes in the rate of sea level rise and fall, played major roles in the changes between the major depositional regimes. Continuous, relatively high rates of thermal subsidence are interpreted to have controlled the overall depositional *stasis* of the ramp system (see below).
6. Deposition was initiated as the result of a decrease in the rate in sea level rise. This decrease shifted carbonate deposition in the inner ramp from "catch-up" to "keep-up" sedimentation. Throughout deposition, carbonate production in inner-ramp and sedimentation in the outer-ramp are interpreted to have kept up with increases in accommodation space. The "keep-up" character of the outer-ramp led to the overall aggradational stacking pattern exhibited by the Rutledge. The end of deposition resulted from a possible lowering of sea level that slowed down carbonate production in the shallower-water environments. Subsequent sea level rise shifted carbonate sedimentation back into a "catch-up" mode, thereby allowing for the onlap of basinal shales of the Rogersville.
7. The Rutledge is interpreted as a highstand systems tract that, when combined with the underlying Pumpkin Valley Shale (transgressive systems tract), comprises a third-order depositional sequence that defines the first grand cycle of the Cambrian grand cycles of the southern Appalachians. The lower contact

of the Rutledge is a diachronous surface resulting from the gradual initiation of carbonate sedimentation in the basin. The prominent grainstone unit in the middle of the section is interpreted as an approximately synchronous unit and is considered to be a lowstand wedge. The upper contact of the Rutledge with the Rogersville shale is marked by an approximately seven meter thick transition interval. The upper contact of the Rutledge is defined as the correlative conformity of the traditionally defined sequence boundary and is thought to be diachronous on the regional scale.

8. The Rutledge, unlike the younger Maryville Limestone, did not culminate in the formation of flat-topped carbonate platform. Instead, it remained in a ramp depositional regime throughout deposition. The inability of the Rutledge to develop into a platform was the result of higher thermal subsidence rates, higher rates of input of terrigenous clastics, and decreased carbonate production area. Thermal subsidence and the effects of siliciclastics on carbonate deposition decreased throughout deposition of the Conasauga, suggesting that deposition of the older carbonate units of the Conasauga was controlled by subsidence and "catch-up" sedimentation, whereas younger units were characterized by slower rates of subsidence and "keep-up" or "prograde" sedimentation.
9. Deposition of the Rutledge resulted in an increase in the areal extent of the inner ramp and, thus, an increase in the growth potential of the carbonate system. The antecedent topography of the Rutledge provided younger carbonate units with a larger sediment source area, which resulted in faster establishment of ramp deposition in the basin and enhanced progradation

potential of the shallow-water environments.

10. The Rutledge is an aggradational carbonate sequence and it is proposed that carbonate sedimentation on the Laurentian shelf was a major factor in the development of the Cambrian intrashelf basin. Sea level rise during the early Sauk II transgression created sediment-starved conditions in the area between the carbonate bank and the cratonward retreating shoreline. Continued aggradation of the carbonate bank throughout Conasauga time resulted in the build-up of an elevated shelf edge. This elevated shelf edge, coupled with the eustatic sea level rise and subsidence, gradually led to the deepening of the area between the bank and craton and the development of the intrashelf basin.

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APPENDICES

APPENDIX A

DESCRIPTION OF MEASURED SECTIONS

Five measured stratigraphic sections were used to make the interpretations presented in this thesis (Figure A.1). Five of the sections were measured on the centimeter scale during the course of two field summers. The Thorn Hill and Notchy Creek sections were measured by Simmons (1984) and a detailed description of those sections can be found in Simmons' thesis.

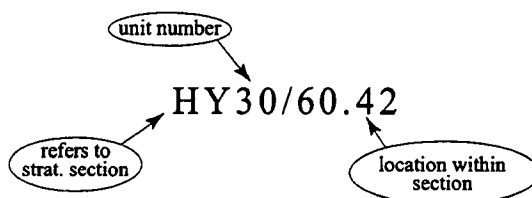
The following is the description of the five measured sections. Accompanying each section is a map showing the location of the section and a detailed stratigraphic section (similar to what has been presented in the main body of this thesis). Locality maps for the individual sections are based on topographic maps published by the USGS.

Stratigraphic sections, except for the Lays Gap Section, were described in ascending order from the base of the measure section. Descriptions are based primarily on field data, but have been augmented by thin section and hand sample data when necessary. Rock names are from Dunham (1965). Unit descriptions have the following format:

Unit number	Unit thickness	Cumulative thickness	lithologic classification, color, grain size/type, texture, skeletal allochems, sedimentary structures, diagenetic and weathering features, bed relationships, samples.
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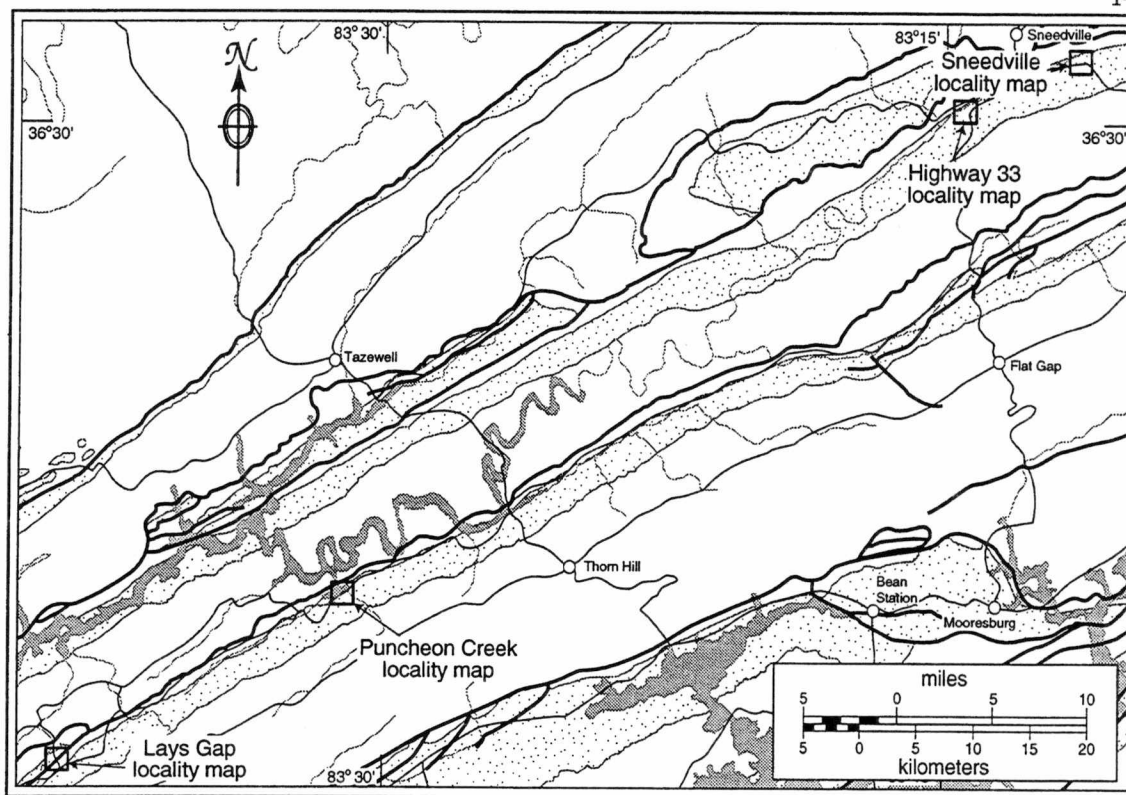
Note: Unit contacts were sometimes not marked by bedding planes, but rather by features readily noted in the field. This is due to the massive character of some of the units. I have noted these contacts in the descriptions.

Sample numbers have the following format:



Abbreviations for stratigraphic sections are LG = Lays Gap Section, PC = Puncheon Creek Section, NC = Notchy Creek Section, HY = Highway 33 Section, and SN = Sneedville Section. Sample numbers that are **bold** and *italicized* have accompanying thin sections. Thin sections and hand samples are stored at the Carbonate Research Laboratory of the University of Tennessee, Knoxville, Geology and Geography Building, Knoxville, TN 37996-1410.

Figure A1. Locality map and key to symbols used in Appendix A. Locality map (top) shows areas of detail for individual locality maps. See Figure 1.8, page 25, for more information on regional geology. Symbol key (bottom) is used to show symbols and lithologic patterns used in the locality maps and measured sections of Appendix A.



KEY TO SYMBOLS USED IN APPENDIX A

LOCALITY MAP AND TOPOGRAPHIC MAPS

	outcrop belts of Conasauga Group (undifferentiated)		lakes, streams, and rivers (locality map)		major faults		major roads (locality map)
	topographic highs		lakes, streams, and rivers (topo. maps)		major roads (topo. maps)		minor roads (topo. maps)
	outcrop locality						

LITHOLOGIC PATTERNS

	shale/ silty claystone		nod. mudstone with shale		burrow mottled carbonate mudstone
	calcareous siltstone/shale		carbonate mudstone		ribbon-laminated mudstone
	interbedded carbonate mudstone and shale		wackestone/ packstone		ooid, peloidal grainstone
			covered interval		

LITHOLOGIC SYMBOLS

	intraclasts, intraclastic packstone		hummocky cross- stratification		irregular voids-assoc. with burrows
	oncoids		coated grains		hardground(s)
	skeletal grains (trilobite, inart. brachiopod)		pyrite/iron sulfide nodules		sole/bedding plane structures
	ooids		glauconite		

LAYS GAP SECTION

Location: Roadcut exposure on the northeast side of Lays Gap Road as it crosses the Log Mountain water gap. Top of measured section is 0.25 mile from the intersection of Lays Gap Road and Tater Valley Road in Grainger County, Tennessee (Figures A1 and A2).

Outcrop: This section is structurally complex and is adjacent to the Copper Creek thrust fault. The total section consists of incomplete exposures of the Lower Cambrian Rome Formation, Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, and possibly the Craig or Maryville Limestone. A splay off the Copper Creek fault emplaces the Rome Formation on top of the exposed Craig or Maryville at the southern end of the outcrop.

The Rutledge, at this locality, has a measured thickness of 47.44 meters including 10.84 meters of covered interval. Exposure quality is poor to good and the section has many small

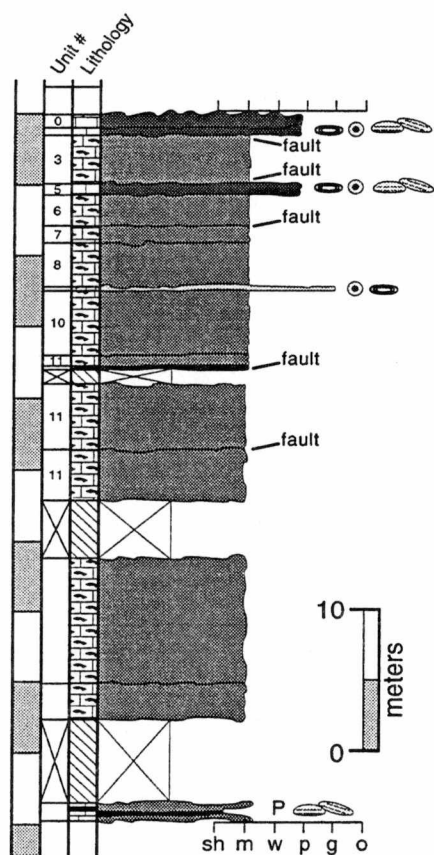
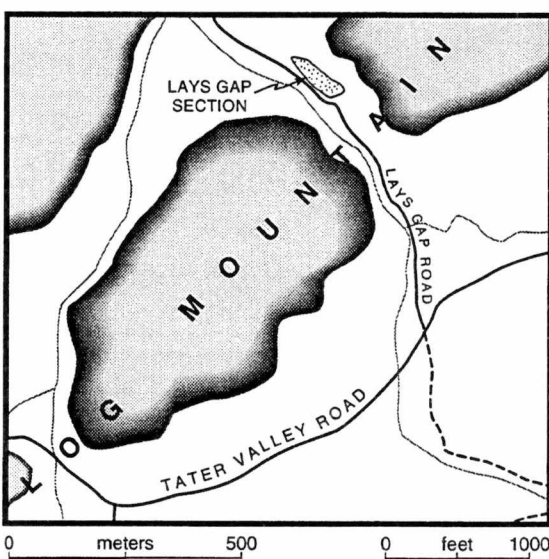


Figure A.2. Measured lithologic section (above) and detailed locality map (right) for Lays Gap locality.



scale faults and folds. The bottom of the Rutledge section is poorly and incompletely exposed. Exposure of the top of the section is good. The Pumpkin Valley Shale is poorly exposed under trees and bushes and a measured thicknesses was not obtained. The Rogersville is basically covered but sapprolite can be seen at the top of the measured section under exposed tree roots.

Notes: This section is quite complex but detailed measurement has resulted in a reasonable approximation of the units exposed and their thicknesses. I am confident with the top part of the section because of its exposure quality. The lower part of the section (grouped together as unit 11) was extremely difficult to measure and if discrepancies exist then they are more than likely found there. The measurement below is in descending order from the top of measured section to bottom of the section. I felt it easier to measure the section from top down because of the exposure quality of the top section versus the bottom section. The samples show the placement of the sample from the top of the measured section. The lowermost 2 units are numbered out of order because I tried first to measure this section bottom up and it didn't work. The samples numbers for these two units have an 'S' behind them and have placements from the base of the measured section. Faults that cross-cut the section are reported.

unit #	thick- ness (m)	cum. thick- ness(m)	description
Rogersville Shale, not exposed			
Rutledge Limestone			
Unit 0	0.92	0.92	Oncoid, skeletal packstone. Medium gray to light brown on the weathered surface/dark to medium gray on the fresh surface. Circular to ellipsoidal oncoids (up to 2 cm in size) are the dominant allochem seen in the field. Other allochems noted were intraclasts, trilobite fragments, echinoderm fragments, hyolithid fragments and rare pelecypod (?) fragments. Sub-rounded quartz silt also present (less than 5%). Sedimentary structures were absent in the field. Many of the oncoids and intraclasts have a black, Fe/Mn oxide coating. Thin, less than 3 millimeters, bed perpendicular, tectonic veins were observed. Sample: LG0/0.05 .
Unit 2	0.62	1.54	Oncoid, skeletal packstone to carbonate mudstone. Medium gray on the weathered surface/medium gray on the fresh surface. Unit is similar to Unit 0, but interbeds of ribbon-lami-

unit #	thick- ness (m)	cum. thick- ness(m)	description
			nated carbonate mudstone are present. Intraclasts and oncoids are no larger than 0.5 cm. Other allochems noted are trilobite and echinoderm fragments. Upper contact is sharp. Samples: (thicknesses reflect those when Unit 1 existed, samples used to give general rock textures and characteristics) LG2/0.03, LG2/0.05, LG2/0.052, and LG2/0.5.
			Fault
Unit 3	3.36	4.90	Carbonate mudstone. Medium to blue gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric dominant, ribbon-laminated fabric less dominant but present. Burrows are dolomitized and form an anastomosing network. Allochems are rare to absent. No sedimentary structures except for burrowing noted. Rare cement filled vugs and pyrite nodules (both less than < 1 centimeter in diameter) occur in the matrix. Stylolites present throughout unit. Thin tectonic veins occur throughout unit. Upper contact is a fault. Samples: LG3/1.84 , LG3/2.24 , and LG3/4.86 .
Unit 4			Designated as fault
Unit 5	0.80	5.70	Oncoid, skeletal packstone. Light gray on the weathered surface/dark gray on the fresh surface. Unit has discontinuous interbeds of different lithologies (mudstone?) formed in what appears to be troughs or depressions. Dominant allochems include: oncoids, trilobite fragments, intraclasts, and echinoderm fragments. Pelecypod (?) fragments also present. Many of the intraclasts have black, Fe/Mn coatings. No sedimentary structures noted. No veins or stylolites observed. Upper contact is a fault. Samples: LG5/5.7 , LG5/5.60 , LG5/ON1 , LG5/ON2 , and LG5/BOT .
Unit 6	2.18	7.88	Carbonate mudstone. Medium to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric similar to what has been described above. Mudstone is basically featureless with allochems virtually absent.

unit #	thick- ness (m)	cum. thick- ness(m)	description
			Burrows are dolomitized. Stylolites and veins are common. Upper contact is sharp. Samples: LG6/7.88
Fault			
Unit 7	1.2	9.08	Carbonate mudstone. Medium to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric. Unit has the same texture as unit 6. No allochems noted. Stylolites and veins are common. Upper contact is faulted. Samples: LG/9.08 .
Unit 8	3.08	12.16	Carbonate mudstone. Medium to dark gray on the weathered surface/dark gray on the fresh surface. Burrow mottled fabric. Unit has the same fabric and texture as units 6 and 7. Burrow fabric may be different but due to weathering this was unresolvable. Upper contact placed at a major parting surface between Units 7 and 8. May not be lithologic contact. Samples: LG8/10.00 and LG8/11.15 .
Unit 9	0.27	12.43	Ooid, peloidal grainstone. Medium gray on the weathered surface/dark gray on the fresh surface. Unit has been divided into two sub-units: 9A and 9B. 9A. Characterized by tiny (<1 mm) circular voids. Sub-unit has mudstone interbeds and what appears to be intraclasts in a dominant grainstone matrix. Dominant allochems appear to be ooids. Quartz silt and fine sand grains were also observed. Abundant pyrite and glauconite grains resembling peloids present. Irregular shaped voids up to 2.5 centimeters in length present in mudstone layers. Upper contact is wavy (dunes?). 9B. Massive peloidal grainstone. Irregular shape voids up to 1 centimeter in length noted. Samples: LG9A1 TOP, LG9A1 BOT, LG9A2, LG9B-1, LG9B2, LG9BC .
Unit 10	4.0	16.43	Carbonate mudstone. Medium gray to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Unit is similar to other burrow-mottled mudstone units. Burrow fabric appears more like ribbon-laminated mudstone

unit #	thick- ness (m)	cum. thick- ness(m)	description
			in places. Upper contact is sharp. Samples: LG10-1, LG10-2A , and LG10-2B . All samples taken within upper 10 centimeters of unit.
Unit 11	1.49	17.92	Carbonate mudstone. Medium gray to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Burrows are sub-parallel and anastomosing. Mudstone is featureless with no allochems noted. Samples: LG11/17.95 , LG11/22.00, and LG11/29.01 .
Fault			
	0.99	18.91	Covered interval.
11 cont.	2.98	21.89	Burrow-mottled carbonate mudstone.
Fault			
11 cont.	3.07	24.96	Burrow-mottled carbonate mudstone.
	4.05	29.01	Covered interval.
11 cont.	8.88	37.89	Burrow-mottled carbonate mudstone.
11 cont.	2.51	40.40	Burrow-mottled carbonate mudstone.
	5.8	46.20	Covered interval.
Unit 3S	0.95	47.15	Carbonate mudstone. Brown to light gray on the weathered surface/medium gray on the fresh surface. Burrow-mottled to ribbon-laminated fabric. Very poorly exposed. Sample: LG3/0.90.
Unit 2S	0.16	47.31	Interbedded calcareous siltstone and carbonate mudstone. Light brown to white on the weathered surface/dark gray on the fresh surface. Very poorly exposed. Samples: LG2/1.0S and LG2S/0.00 .
Unit 1S	0.13	47.44	Carbonate mudstone. Yellow brown to almost white on the weathered surface/dark gray to brown on the fresh. Burrow-mottled fabric. No allochems observed. Pyrite nodules (up to 1 cm) are abundant. Bottom of unit is characterized by an intraclastic packstone. Sample: LG/BOT S .

Base of measure section, Pumpkin Valley Shale not exposed.

Puncheon Creek Section

Location: Composite section consisting of stream and road-cut exposures along the north and south side of Bullen Valley Road. Outcrops are 5.4 miles south of the intersection of Bullen Valley Road with Tennessee State Highway 25E (Figures A1 and A3) in Grainger County, Tennessee. Base of measured section is exposed (Section a.) where Puncheon Creek joins the Clinch River.

Outcrop: This locality offers excellent to good exposures of the Lower Cambrian Rome Formation, Pumpkin Valley Shale (at Cracker Creek, see Simmons 1984), Rutledge Limestone, Rogersville Shale (Puncheon Creek Road) and Craig/Maryville Limestone (Puncheon Creek Road). Weathering is extensive and masks many of the depositional features. The Rutledge has a measured thickness of 53.53 meters at this locality including 4.8 meters of covered interval. The measured section is composite section of three separate outcrops (see map below). The lower outcrop (a., Figure A3) is a stream exposure where

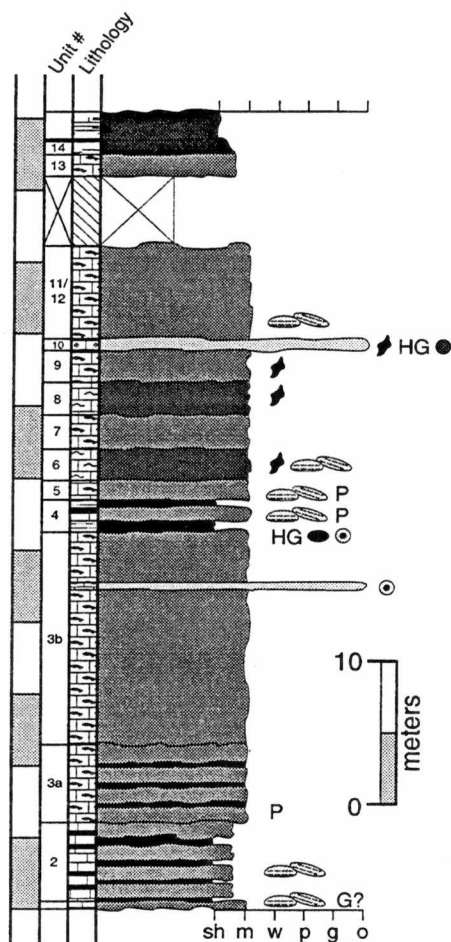
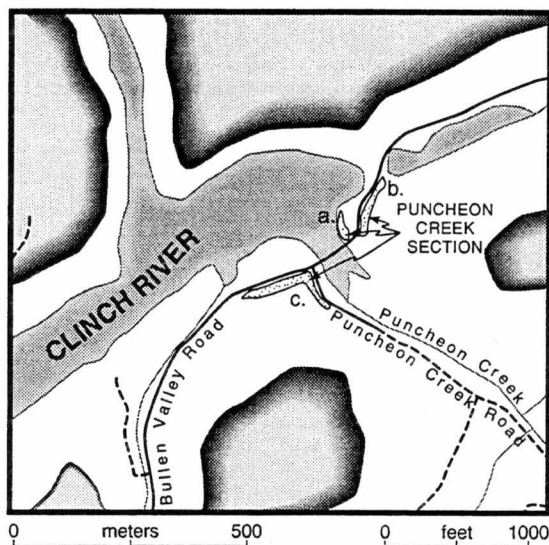


Figure A.3. Measured lithologic section (above) and detailed locality map (right) for the Puncheon Creek locality.



Puncheon Creek enters the Clinch River. The Pumpkin Valley/Rutledge contact and units up to the lower shale interval are exposed at this section. The middle outcrop (b.) is a road cut exposure along south side of Bullen Valley Road. Units from the shale interval to unit 11 are exposed at this section. The upper outcrop (c.) is a road cut exposure along south side of Bullen Valley Road and east side of Puncheon Creek Road. Units from unit 10 to top of measured section are exposed at this section. The lower shale interval and unit 10 were used to correlate between individual sections.

Notes: This locality was originally mentioned by Simmons (1984) but he only measured the Pumpkin Valley Shale. The outcrop is a nice exposure and is second only to the Highway 31 section to its completeness and degree of exposure. Units 11 and 12 were combined due to the similar characteristics of the units. The top of the section is poorly exposed.

unit #	thick- ness (m)	cum. thick- ness(m)	description
<i>Outcrop a.</i>			
Pumpkin Valley Shale			
Unit 1	0.40	0.40	Carbonate mudstone. Grayish orange to grayish pink on the weathered surface/dark gray on the fresh surface. Intraclastic packstone at base grading upward into mudstone. Mudstone has a ribbon-laminated to burrow-mottled fabric with dolomitized burrows and argillaceous layers. Intraclastic packstone consists of elongated oblate clasts (up to 4 centimeters in length) that are imbricated. Argillaceous layers in mudstone are pretty much continuous. Pyrite nodules and glauconite are present throughout unit. Upper contact is sharp and planar. Samples: PC1/0.1 and PC1/0.25 .
Unit 2	5.05	5.45	Interbedded carbonate mudstone/packstone and calcareous shale/siltstone. Grayish orange to yellowish brown on the weathered surface. Shale layers are weathered away. Carbonate mudstone layers have burrow-mottled fabric with dolomitized burrows and are typically 2 to 25 centimeters thick. Intraclastic packstones, similar to unit 1, were observed. Upper part of section becomes increasingly shaly. Upper contact is mark by the first appearance of massive bedded carbonate mudstone. Samples:

unit #	thick- ness (m)	cum. thick- ness(m)	description
Rutledge Limestone			
Unit 3	25.52	30.97	PC2/3.04. Carbonate mudstone. Yellowish brown to gray on the weathered surface/dark gray on the fresh surface. Two sub-units were differentiated based on weathering profiles. Sub-unit 3a (10.86 meters). Interbedded carbonate mudstone with what appears to be thin (<1 cm) argillaceous layers. Carbonate layers have burrow-mottled fabric with dolomitized burrows. Allochems are absent on the macroscale. Carbonate layers may reach thicknesses of up to 1 meter and appear to be thinly laminated (<1 cm) on the weathered surface. Carbonate layers become less mottled up through section. Pyrite nodules are present throughout sub-unit and may reach up to 2 centimeters in size. Sub-unit 3b (14.66 meters). Carbonate mudstone with burrow-mottled fabric. Weathering profile is similar to ribbon-laminated mudstone lithologies. At 22.02 meters an ooid grainstone layer exists. This layer consists of dominantly ooids and some intraclasts with black, Fe/Mn oxide rims. Layer may show cross-bedding (may be due to weathering). Contacts of the layer are sharp and planar. Mudstone is featureless and no allochems were observed. Upper contact marked by a well-developed marine hardground. The hardground has intraclasts of the underlying lithology in a clay matrix. Samples: PC3/9.5, PC3/14.75, PC3/19.12, PC3/22.02, PC3/25.52, PC3/29.92 (should be labeled to 22.02).
Unit 4	2.22	33.19	Interbedded calcareous siltstone and carbonate mudstone/packstone. Brownish yellow to dark gray on the weathered surface/dark gray (carbonates) on the fresh surface. Separated into 3 sub-units. Sub-unit 4a (0.77 meters). Laminated calcareous siltstone. Fine silt-sized grains of indeterminable mineralogy (some mica flakes observed). Carbonate mudstone lenses and

unit #	thick- ness (m)	cum. thick- ness(m)	description
			interbeds become common at the top of sub-unit. Upper contact is gradational. Sub-unit 4b (0.9 meters). Interbedded carbonate mudstone with nodular carbonate mudstone with shale. Carbonate mudstone beds have burrow-mottled fabric. No allochems noted. Upper contact is sharp. Sub-unit 4c (0.55 meters). Paper laminated calcareous siltstone. Bedding is on the sub-millimeter scale and no other sedimentary structures observed. Upper contact is wavy and marked by intraclastic packstone of Unit 5. No samples taken.
Unit 5	1.33	34.52	Carbonate mudstone. Medium gray on the weathered surface/dark gray on the fresh surface. Intraclastic layer (<10 centimeters) grades upward into a carbonate mudstone. Burrow-mottled fabric. Mottling becomes more extensive towards top of unit. Pyrite nodules are present throughout unit. Stylolites observed. Sample: PC5/34.52.
Unit 6	2.14	36.66	Carbonate mudstone. Light to medium gray on the weathered surface/dark gray on the fresh surface. Ribbon-laminated fabric. Carbonate layers are more or less featureless with no skeletal allochems observed. Small circular cement filled pores (1 to 2 centimeters in diameter) are present in carbonate layers. Shaly layers are on the order of 1 to 2 millimeters thick and form continuous layers across outcrop face. Thin packstone layer (<1 centimeter) occurs near the middle of the unit. Rare pyrite nodules (up to 2 centimeters in diameter) were observed. Upper contact is gradational. Sample: PC6/35.02.
Unit 7	2.33	38.99.	Carbonate mudstone. Light to dark gray on the weathered surface/dark gray on the fresh surface. Burrow mottled fabric with dolomitized burrows. Unit is similar to other burrow-mottled units described above. Burrowing appears to be not as extensive. Lesser abundance of pyrite nodules observed. Unit takes

unit #	thick- ness (m)	cum. thick- ness(m)	description
Unit 8	3.24	42.23	on a more ribbon-laminated appearance up through the section. Upper contact is marked by the first occurrence of continuous argillaceous layers of Unit 8. No samples taken. Carbonate mudstone. Light to medium gray on the weathered surface/dark gray on the fresh surface. Unit is similar to unit six. Upper contact is gradational. No samples taken.
Unit 9	2.20	44.23	Carbonate mudstone. Dark to medium gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows in the lower and upper part of unit, ribbon-laminated fabric in the middle portion of the unit. Mottling is generally not as extensive as other units. Allochems are rare to absent in outcrop. Some of the argillaceous dolomite layers in the ribbon-laminated portion of unit appear to almost have a hummocky-cross stratification. Carbonate layers of the ribbon-laminated portions are characterized by circular (to irregular) pores filled occluded by calcite cements. Burrow-mottled fabric of the upper portion of the unit is more distinct and burrows tend to be larger in size. Macrostylolites present throughout section. Samples PC9/42.5 , PC9/43.55, and PC9/10/44.23 .
Unit 10	0.8	45.03	Ooid, peloidal grainstone. Dark gray on the weathered surface/dark gray on the fresh surface. Lower portion of unit is a peloidal grainstone that appears to be laminated in outcrop. Irregular cement filled pores less than 3 millimeters in width. These voids typically cross-cut what appears to be bedding. Middle of unit is marked by a 12 centimeter unit characterized by abundant hardgrounds and large (3 centimeters in diameter) cement filled voids. Grain type indeterminable but glauconite and pyrite seem to be present. Upper portion of unit is a ooid grainstone. This upper layer has some intraclasts and skeletal grains. Samples: PC10.1, PC10.2 , PC10.3, PC10.4, PC10.5, PC10/42.58 , and PC/~45M .

unit #	thick- ness (m)	cum. thick- ness(m)	description
<i>Outcrop b.</i>			
Unit 11/12		6.45	51.48 Carbonate mudstone. Medium to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Discontinuous, thin intraclastic and skeletal packstone layers observed throughout unit. Unit has much the same character as other burrow-mottled units. Besides packstone layers, skeletal and non-skeletal allochems are virtually absent. No sedimentary structures observed. Samples: PC11/46.0 and PC11/46.53.
<i>Outcrop c.</i>			
	4.8	56.28	Covered interval.
Unit 13	1.52	57.80	Carbonate mudstone. Dark gray on the weathered, wet surface/dark gray on the fresh, wet surface. Due to weathering features, depositional textures were not discernible in the field. In hand sample, mudstone has burrow-mottled fabric with dolomitized burrows. Allochems were not observed in thin section. Sample: PC13/8.1.
Unit 14	0.98	58.78	Nodular carbonate mudstone with shale. Carbonate mudstones beds are up to 30 centimeters and have burrow-mottled fabric similar to other units. Shaly layers are less than 2 centimeters. No samples taken.
Rogersville Shale			
Unit 15	>2.00		Top of measured section. Dark brown, paper-laminated shales with thin (<2 centimeters) lenses and interbeds of siltstone.

HIGHWAY 31 SECTION

Location: Roadcut exposure on south side of State Highway 31. Base of measured section is 1.6 miles (2.6 km) from the junction of State Highways 31 and 66 in Hancock County.

Outcrop: Excellent exposure of units from the upper Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale (including Craig Limestone Member), Maryville Limestone, and Nolichucky Shale. The Rutledge section has a thickness of 64.67 meters with no covered intervals. The units are hardly weathered and depositional textures are readily observable. The upper 6.28 meters of the Pumpkin Valley were described and measured. The lower 15 meters of the lower Shale Member of the Rogersville Shale were described and measured.

Notes: This section is the best exposed section of the present study and as far as I know no one has measured it before. There is a fault in the section (displacement ~10 meters) but unit

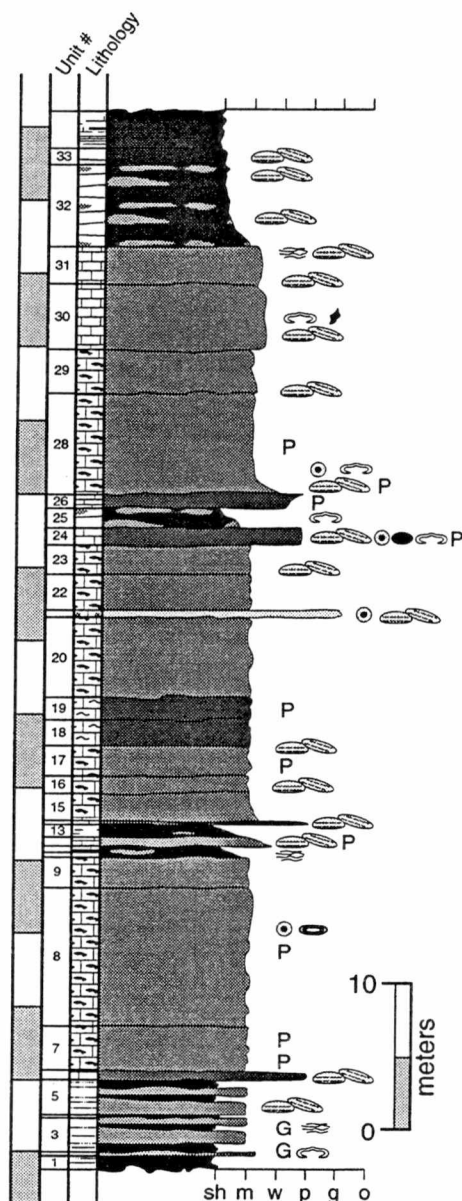
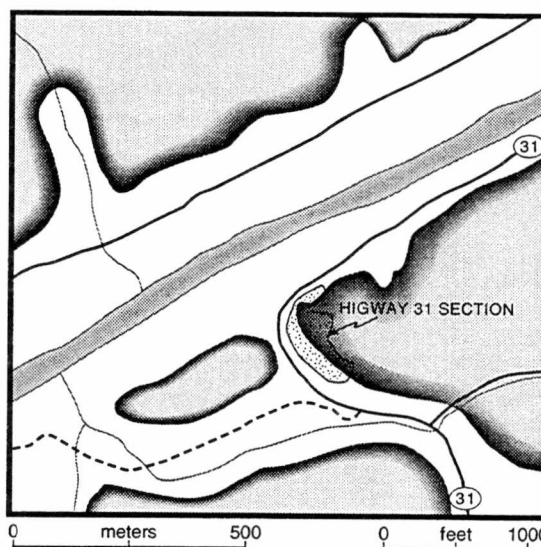


Figure A.4. Measured lithologic section (above) and detailed locality map (right) for the Highway 31 locality.



correlation across the fault negated any possible discrepancies in measured thickness. This section at the present state of weathering and exposure may be the best exposure of the Rutledge in the southern Appalachians.

unit #	thick- ness (m)	cum. thick- ness(m)	description
Pumpkin Valley Shale, base not exposed			
Unit 1	0.93	0.93	Interbedded calcareous siltstone/shale and carbonate mudstone. Calcareous siltstone/shale: brown on the weathered surface/gray on the fresh surface, grain size of siltstone/shale was indeterminable in the field but median grainsize appears to be medium silt to fine sand, siltstone/shale layers are hummocky cross-stratified in plates. Carbonate mudstone: brown to light gray on weathered surface/dark gray on fresh surface, burrow-mottled fabric with dolomitized burrows, no skeletal allochems were observed in the field. Siltstone beds have wavy upper and lower contacts and are on average 3 cm thick. Carbonate mudstone layers are 2-3 cm thick. No samples taken.
Unit 2	0.26	1.19	Carbonate mudstone/wackestone. Light to medium gray on the weathered surface/medium gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Thin, trilobite packstone layers present in the upper part of unit. Samples: Hy2/1.04 , Hy2/1.0.
Unit 3	2.48	3.67	Interbedded carbonate mudstone and calcareous/non-calcareous shale. Shale: dull brown to medium gray on weathered surface. Abundant mica flakes and glauconite grains were observed. Carbonate mudstone: brown on the weather surface/dark gray on fresh, burrow-mottled to ribbon-laminated with dolomitized burrows and argillaceous ribbons. Rare trilobite fragments and irregular cement filled voids were observed. Upper contact is sharp. No samples taken.
Unit 4	0.21	3.88	Intraclastic packstone. Light gray on the weathered surface/medium gray on fresh surface. Unit is graded with abundant elongated clasts at

unit #	thick- ness (m)	cum. thick- ness(m)	description
			the base grading upward into burrow-mottled carbonate mudstone. Skeletal allochems not observed. Multiple marine hardgrounds observed near the top of the unit. Upper contact is wavy and marked by a prominent hardground. No sample taken.
Unit 5	2.40	6.28	Interbedded calcareous shale and carbonate mudstone. Unit is similar in character to unit 3. Shale: brown to medium gray on weathered surface. Carbonate mudstone: light brown to gray on the weathered surface/medium gray on fresh, burrow-mottled to ribbon-laminated texture, thin (less than 0.1 meter) intraclastic packstone stone layers observed. No skeletal allochems observed. Upper contact is sharp. No samples taken.
Rutledge Limestone			
Unit 6	0.32	6.60	Intraclastic packstone. Light gray with brown ribbons on the weathered surface/dark gray on the fresh surface. Elongated intraclasts up to 5 cm in length. Unsorted and appears to be reversely graded in lower portions of the unit and normally graded in upper portions. Upper part of the unit has abundant skeletal fragments (trilobite fragments). Upper contact is sharp, marked by stylolite. Samples: Hy6a/6.81 (sample was mislabeled).
Unit 7	3.04	10.00	Carbonate mudstone. Light gray on weather surface/dark gray on fresh. Burrow-mottled fabric dominant, unit takes on a ribbon-laminated texture in places. Burrows are dolomitized. Mudstone is homogeneous except for a few grainy "layers" associated with stylolites. No allochems noted. Large pyrite nodules (up to 2 cm in size) present throughout mudstone layers. Upper contact sharp. No samples taken.
Unit 8	9.49	19.49	Carbonate mudstone. Light to medium gray on the weathered surface/dark gray on fresh surface. Burrow-mottled fabric with dolomitized burrows. No allochems noted except for a 5 cm

unit #	thick- ness (m)	cum. thick- ness(m)	description
			interval at 17.77 meters. This interval is 5 centimeters in thickness and is wavy and undulose. It is traceable across the outcrop face (~10 meters) and is composed of ooids and oncoids. Pyrite nodules (1-2 cm in size) concentrated in the center of the unit. Tectonic veins are well-developed in the unit. Upper contact is sharp. No samples taken.
Unit 9	2.1	21.59	Carbonate mudstone. Medium gray to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric. Dolomitized burrow fabric is more chaotic than lower unit. No allochems observed. Upper contact is sharp and planer. Samples: Hy9/21.59 .
Unit 10	0.35	21.96	Fissile calcareous to non-calcareous claystone and fine siltstone. Brown on the weathered surface. Very thinly laminated. No other sedimentary structures observed. No samples taken.
Unit 11	0.45	22.41	Interbedded calcareous shale and carbonate mudstone. Shale layers: medium gray to brown on the weathered surface. Grain size indeterminable in the field. Bedding is hummocky cross-stratified in places and in other places bedding is disrupted by what appears to be soft-sediment deformation structures. Carbonate "boudins (or pseudo-nodules)" are present within shale layers. Carbonate mudstone: medium gray on the weathered surface/dark gray on the fresh surface. No allochems observed. Mudstone layers are no more than 3 centimeters thick. Upper contact is sharp and undulose. Samples: Hy11/23.55.
Unit 12	1.29	23.70	Intraclastic packstone. Light to medium gray on the weathered surface/dark gray on the fresh surface. Packstone (Layer = 25 centimeters) grades into Burrow-mottled carbonate mudstone. Intraclasts are elongate to variable in shape and have a maximum size of 5 cm. Some clasts have black, Mn-coated rims. Some intraclasts observed in the overlying mudstone.

unit #	thick- ness (m)	cum. thick- ness(m)	description
			Dolomitized burrows decrease in abundance upward in the unit. Allochems, besides intraclasts, were not observed. Stylolites are abundant in the lower part of the carbonate mudstone. Upper contact is sharp and marked by a thin (<3 centimeters), discontinuous intraclastic packstone layer. Samples: Hy 12/23.12 , Hy12/23.70II, Hy12/23.70.
Unit 13	0.88	24.58	Interbedded carbonate mudstone and calcareous shale grading upward into fissile calcareous shale/claystone. Some carbonate mudstone layers have intraclasts (wackestone) and in general, mudstone layers are up to 4 centimeters thick. Upper contact is sharp and planar. Samples: Hy13/24.47, Hy13/23.80.
Unit 14	0.28	24.86	Intraclastic packstone/grainstone. Light gray on the weathered surface/dark gray on the fresh surface. Intraclasts are poorly sorted. In general, intraclasts are elliptical to oblate and range in size from 2 x 2 centimeters and 7 x 13 centimeters. No other allochems noted. Unit pinches and swells with a minimum thickness of 20 centimeters and a maximum thickness of 28 centimeters. Some pyrite nodules noted. Upper contact is undulose and sharp. No samples taken.
Unit 15	1.87	26.58	Carbonate mudstone. Medium to dark gray on weathered surface/dark gray on fresh surface. Burrow-mottled fabric with dolomitized burrows that changes in degree of burrowing upward through unit. Lower part of unit is characterized by sparse dolomitized burrows, middle part of unit is characterized by abundant dolomitized burrows, upper part of unit resembles lower part of unit. No skeletal allochems noted. Lower part of unit also characterized by abundant stylolites. Pyrite nodules, up to 1 centimeter in size are present throughout unit. Upper contact is sharp and marked by grading of burrow-mottled into ribbon-laminated fabric and by the presence of an intraclastic packstone

unit #	thick- ness (m)	cum. thick- ness(m)	description
Unit 16	1.19	27.77	capped by a marine hardground. Samples: Hy15/24.5, Hy15/26.58. Interbedded intraclastic packstone and carbonate mudstone. Carbonate mudstone takes on ribbon-laminated appearance near top of unit. Samples: Hy16/27.77.
Unit 17	2.06	29.83	Carbonate mudstone. Medium gray on weathered surface/dark gray on fresh surface. Burrow-mottled fabric with dolomitized burrows having distinct sharp boundaries around burrows. Burrows have inclusions of mudstone and pyrite within them and also have some cement filled voids in center of burrows. No allochems observed. Abundant stylolites and bed normal veins present. Unit grades into carbonate mudstone with ribbon-laminated fabric near top. Upper contact is marked by a wavy discontinuous intraclastic packstone layer (0 to 7 centimeters thick). Samples: Hy17/27.77, Hy17/29.15 , Hy17/29.75, Hy17/29.83.
Unit 18	1.75	31.58	Interbedded carbonate mudstone and argillaceous dolomite. Medium to light gray on weather surface/dark gray on fresh. Ribbon laminated fabric. Mudstone is featureless and devoid of any allochems. Samples: Hy18.
Unit 19	1.53	33.11	Interbedded carbonate mudstone and argillaceous dolomite. Light gray on the weathered surface/dark gray on fresh surface. Ribbon laminated fabric. Unit is similar to Unit 18 but has Burrow-mottled fabric in places. Abundant pyrite and cement filled horizontal burrows noted. No skeletal or non-skeletal allochems noted. Samples: Hy19.
Unit 20	5.46	38.57	Carbonate mudstone. Medium to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Similar to other burrow-mottled units but mottles have more of a chaotic pattern. No allochems observed. Abundant bed perpendicular veins (<1 centimeter wide) noted. Upper contact appears to be a

unit #	thick- ness (m)	cum. thick- ness(m)	description
Unit 21	0.49	39.06	hardground and contact is planar. Samples: Hy20/33.20, Hy20/38.36, Hy20.38.45. Ooid grainstone. Light to medium gray on the weathered surface/dark gray on the fresh surface. Grainstone has ooids, intraclasts, cyanobacterial grains, and some argillaceous dolomite layers. Grainstone cleaves upward and top part of unit is a pure ooid grainstone. No skeletal allochems noted. Top of unit is marked by abundant little (~1 millimeter) voids resulting from the weathering of glauconite. Upper contact is sharp and wavy (stylolitic?). Samples: HY21/39.02, Hy21/39.4 (misabeled?).
Unit 22	2.45	42.47	Carbonate mudstone. Medium to dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Degree of mottling changes from nearly absent in the lower part of the unit to abundant at the top of unit. Mudstone is basically featureless. Sparse, thin (< 1 cm) grainy layers (grain type not recorded) were observed. The upper contact is marked by a 15 centimeter intraclastic packstone. The contact is sharp. Samples: Hy22/37.10 (misabeled?) and HY22/23 at contact.
Unit 23	2.03	46.50	Carbonate mudstone. Light to medium gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Mottling is extensive in this unit and much of the rock is characterized by the brown weathering, dolomitic burrows. Distinctive intraclastic packstone/grainstone observed. These layers are less than 5 centimeters and pinch and swell along outcrop face. The mudstone is featureless and is devoid of allochems except in layers. The top of the unit is sharp and marked by a very distinctive heavily burrowed layer that appears almost brown due the extensive burrowing. Samples: Hy23/42.6 and Hy23/42.02.
Unit 24	1.16	47.66	Interbedded Intraclastic, skeletal, ooid packstone/grainstone and carbonate mudstone.

unit #	thick- ness (m)	cum. thick- ness(m)	description
			Light to medium gray on the weathered surface/ dark gray on the fresh surface. Major allochems include intraclasts, trilobite fragments, and ooids. Minor allochems include echinoderm and hyolithid fragments. At top of unit, many intraclasts have a black, Fe/Mn oxide coating. Mudstone has a burrow-mottled fabric with dolomitized burrows. Burrow fabric is not as pronounced in this unit as in others and bur- rowing may not be as prevalent. Cement filled voids (~1 centimeter) are present in the bur- rows. Stylolites are present through-out unit. Pyrite nodules are present (up to 1 centimeter in size). Upper contact is sharp and planar and is marked by a marine hardground. Samples: Hy24/47.06 and Hy24/47.66 .
Unit 25	1.35	49.01	Nodular carbonate mudstone with shale. Brownish gray to light gray on the weathered surface. Bottom of the unit is calcareous shale or laminated mudstone that grades up into burrow-mottled mudstone. The mudstone layers appear stretched and form boudinage type structures. Lingulid (?) inarticulate brachio- pods were observed in the shaly layers. No other allochems noted. Stylolites and tectonic veins not observed. Samples: Hy25/47.70.
Unit 26	0.94	49.95	Carbonate mudstone. Light gray in color on the weathered surface/dark gray on the fresh sur- face. Ribbon-laminated fabric. Mudstone layers have abundant inarticulate brachiopod frag- ments and small pyrite nodules (<0.5 centime- ter). Argillaceous layers are wavy. Samples Hy26/33.2 (misabeled?)
Unit 27	0.08	50.03	Intraclastic packstone. Light gray on the weath- ered surface/dark gray on the fresh surface. Micrite intraclasts ranging in size from <0.05 centimeter to >2 centimeters. Matrix appears to be micrite also. Upper contact is sharp and appears to be a hardground. Pyrite nodules (up to 1 centimeter) near top of unit. Samples Hy27/28 at contact.

unit #	thick- ness (m)	cum. thick- ness(m)	description
Unit 28	6.89	56.92	Carbonate mudstone. Dark gray on the weathered surface/dark gray on the fresh surface. Lower 30 centimeters of unit characterized by a grainy texture with abundant ooids, intraclasts and trilobite fragments in a muddy matrix. Large pyrite nodules (up to 2 centimeters) also located at bottom of unit. Grades upward into burrow-mottled carbonate mudstone. Mudstone is basically featureless except for burrow-mottled fabric. Macro-stylolites and bed perpendicular veins present throughout unit. Upper contact is marked by an intraclastic packstone layer. Samples: Hy28/54.86, Hy28/55.14, and Hy28/VEIN .
Unit 29	3.02	59.94	Carbonate mudstone. Dark gray on the weathered surface/dark gray on the fresh surface. Burrow-mottled fabric with dolomitized burrows. Unit similar to other burrow-mottled units. No skeletal or non-skeletal allochems observed. Macro-stylolites and bed normal and bed perpendicular veins observed. Samples: Hy29/59.02, Hy29/59.90, and Hy59.94 .
Unit 30	4.53	64.47	Carbonate mudstone. Light gray to medium gray on the weathered surface with some dark gray areas/dark gray on the fresh surface. Ribbon-laminated to Burrow-mottled fabric with dolomitized burrows and argillaceous ribbons. Ribbon-laminated fabric is dominant and many of the wavy, horizontal argillaceous dolomite layers bifurcate or die out laterally along outcrop face. Mudstone areas are characterized by a variety of structures including burrow-mottles, discontinuous intraclastic, skeletal wackestone/packstone layer (up to 2 cm thick), irregular to circular cement (calcite and dolomite?) filled burrows. Intraclastic layers decrease in abundance upward through the unit. In some argillaceous layers, a shaly fabric was noted. Argillaceous layers become more planar toward top of unit. Small pyrite nodules (0.5 centimeter) are present through-out unit. Samples:

unit #	thick- ness (m)	cum. thick- ness(m)	description
Unit 31	2.52	66.99	HY30/60.25, HY30/60.42, Hy30/60.92, and Hy30/62.5. Carbonate mudstone. Dark gray to medium gray on the weathered surface/dark gray on the fresh surface. Lower part of unit (~45 centimeters) consists of a Burrow-mottled mudstone with dolomitized burrows grading upward into units similar in texture and fabric to unit 30. Intraclastic layers in this unit are more abundant and some reach thickness up to 10 centimeters thick. Argillaceous layers become more laminar towards the top of unit. Some of these layers exhibit hummocky cross-stratification. Upper contact is sharp. Samples: Hy31/65.17 and HY31/66.99.
Unit 32	5.66	72.65	Interbedded carbonate mudstone, intraclastic packstone, and silty argillaceous dolomite. Light brown to light gray on the weathered surface/gray on the fresh surface. Mudstone layers have a nodular appearance and are basically devoid of sedimentary features and allochems. Intraclastic layers are quite common and are characterized by mudstone intraclasts and skeletal fragments. Samples: Hy32/69, HY32/69.75, HY32.72, and HY32/75.65 (misabeled should be HY32/72.65)
Unit 33	1.13	73.78	Interbedded calcareous siltstone/mudstone and nodular bedded carbonate mudstone. Light gray to dark gray on weathered surface/dark gray on fresh surface. Lower part of the unit is characterized by thinly laminated, fissile siltstone/mudstone grading upward into nodular carbonate mudstone. Mudstone is devoid of sedimentary features and allochems. Intraclastic packstone layers are present at top of unit. Clasts are elongate and elliptical and can be up to 3 centimeters in diameters. Upper contact is sharp. Samples: Hy33/73.20 and HY33/78.78.
Rogersville Shale			
Unit 34.	>20 meters		TOP OF MEASURED SECTION. Fissile non-calcareous to calcareous shale with siltstone and fine sandstone lenses and interbeds. Gray to brown on the weather surface.

SNEEDVILLE SECTION

Location: Roadcut exposure along south side of State Highway 66 as it crosses a series of small ridges known as River Knobs (Figures A1 and A6). Base of measured section is 1.6 miles (2.6 km) from the junction of State Highways 31 and 66 in Hancock County, Tennessee.

Outcrop: Exposure is good to excellent but weathering has obscured rock textures. The total thickness measured was 109.1 meters. It has less than 8 meters of covered interval. The Rutledge is 94.67 meters at this locality. The Middle Cambrian Pumpkin Valley Shale is exposed at the base of the section and a total of 15.4 meters of the Pumpkin Valley was measured. The Rogersville Shale is not exposed at this locality and the top unit of the Rutledge is inferred to be the highest exposed carbonate

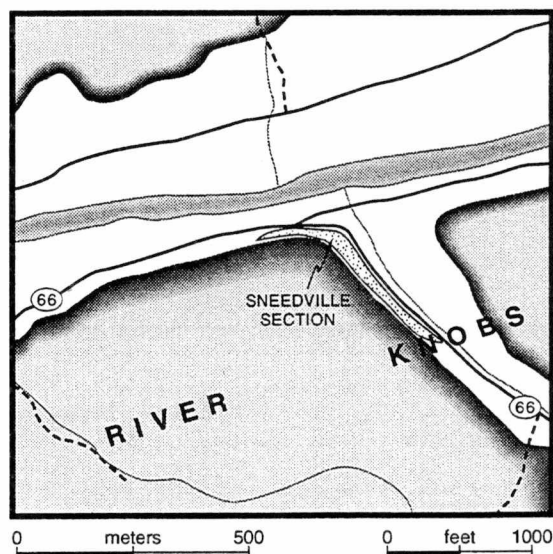
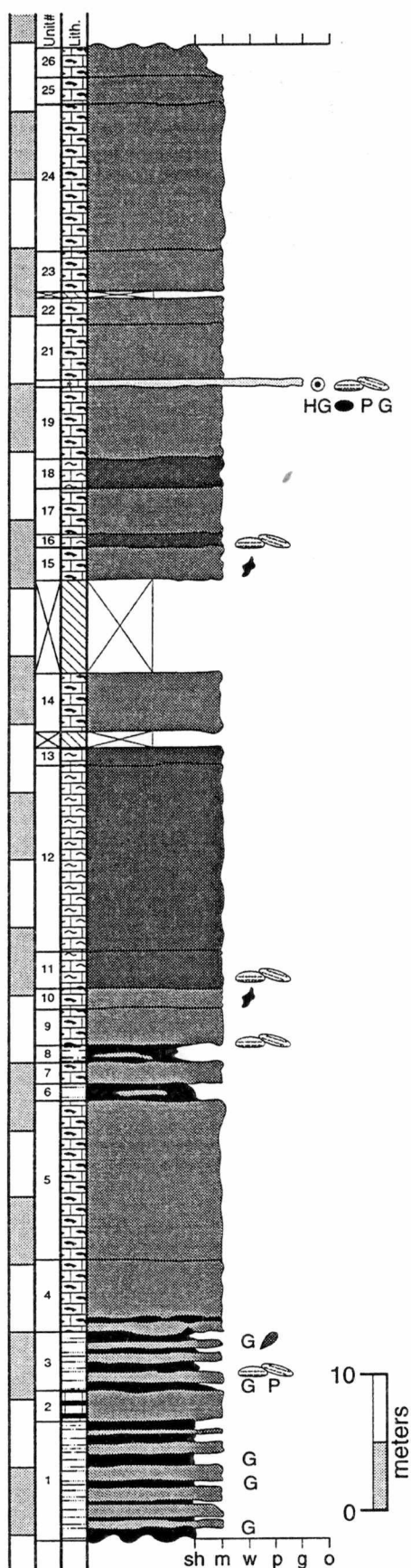


Figure A.5. Measured lithologic section (left) and detailed locality map (above) for the Sneedville locality.

unit.

Notes: This sections was previously measured by VanArsdall (River Knobs Section, 1974). He measured a thickness of the Rutledge of 107 meters. This is within agreement to measurements present here. However, I believe there is a fault between units 12 and 13, causing measured thicknesses to be overestimated from true stratigraphic thickness. The fault is not seen in the field and the paucity of mapping in the area does not allow me to confirm the presence of a fault. However, measured stratigraphic thickness for this section is 30 meters greater than the Highway 33 Section. The Highway 33 section is complete with no covered intervals.

unit #	thick- ness (m)	cum. thick- ness(m)	description
Pumpkin Valley Shale, base not exposed			
Unit 1	8.70 m	8.70 m	Interbedded calcareous siltstone and shale. Brown to green in color on weathered surface. Grain size is medium silt to very coarse silt size. Glauconite is present within calcareous siltstone beds. Planer and faint cross stratification are present within siltstone beds. No sedimentary structures noted in shale interbeds. Rare trilobite and inarticulate brachiopod fragments were seen in thin section. Siltstone beds are 2 to 10 cm thick increasing in thickness to as much as 26 cm. Shale beds are less than 5 cm thick. BASE NOT MEASURED. Upper contact is gradational. Samples: S1/0.0, S1/7.20, S1/7.30, S1/8.53.
Unit 2	2.30 m	11.00 m	Interbedded carbonate mudstone and shale. Light brown to light gray in color on the weathered surface. Carbonate mudstone may be burrowed in places with sub-vertical burrows or take on a ribbon laminated appearance consisting of carbonate layers interbedded with thin (<1cm) dolomitized shale layers. No allochems or sedimentary structures (besides burrows) noted. Upper contact placed at top of burrow-mottled mudstone bed is planer. Samples: S2/8.90, S2/9.90.
Unit 3	4.40 m	15.40 m	Interbedded siltstone/shale and carbonate mudstone. Shale layers weather to a brown or greenish brown color. Carbonate layers weather to a grayish brown color. Grain size

unit #	thick- ness (m)	cum. thick- ness(m)	description
			indeterminable in the field but considered to be less than medium silt size. Glauconite and pyrite are present. Shale layers are fissile and contain abundant soul markings (tool and scour marks). Carbonate layers are intraclastic packstones (flat-pebble conglomerates) or burrowed carbonate mudstones. Top contact planer to undulatory and is marked by a 45-50 centimeter layer of laminated, brown to gray, non-calcareous shale. Samples: S3/11.3, S3/13.9.
Rutledge Limestone			
Unit 4	5.40 m	20.80 m	Burrow-mottled carbonate mudstone. Brown to gray in color. Lower 1.0 meter consists of interbedded carbonate mudstone and thin shale. Interbedded units are laminated and have many intraclastic layers are present. Burrow-mottled mudstone is dominantly mudstone with an anatomizing network of dolomitized burrows. Matrix is rather homogeneous and no skeletal allochems were seen. Bedding is massive. Samples: S4/16.7, S4/20.45.
Unit 5	11.90 m	32.70 m	Burrow-mottled carbonate mudstone. Medium to dark gray on weathered surface. Texture is similar to Unit 4 but burrows are more common or are more distinct on the weathering surface. Primary laminations are present in some areas but these are discontinuous. Upper contact is sharp and planer. Abundant bed normal calcite veins are present. Samples: S5/20.8, S5/21.4, S5/24, S5/31.9.
Unit 6	1.25 m	33.95 m	Interbedded carbonate mudstone and non-calcareous siltstone or shaly dolomite. Light brown on weathered surface. Unit is badly weathered and textural description was difficult. Shaly layers are fissile. Carbonate layers are not burrowed and form discontinuous layers and taking on a nodular appearance. Upper contact is sharp and planer to slightly undulatory. No samples taken.

unit #	thick- ness (m)	cum. thick- ness(m)	description
Unit 7	1.60 m	35.55 m	Burrow-mottled carbonate mudstone. Dark gray to medium gray color on the weathered surface. Similar texture to other burrow-mottled units. Upper contact is sharp and planar. No samples taken.
Unit 8	1.28 m	36.83 m	Interbedded calcareous shale and laminated calcareous siltstone. Gray-green on weathered surface. Grain size indeterminable in the field. No skeletal allochems were observed. Shale beds are burrowed and hummocky cross-stratification was observed in places. White clay stringers were noted. Calcareous siltstones are no more than 2.5 cm thick and occur at irregularly spaced intervals within the unit. Upper contact is sharp. Sample: S8/6.63.
Unit 9	2.68 m	39.51 m	Burrow-mottled carbonate mudstone. Brownish yellow to light gray in color on the weathered surface. Base of unit is marked by an intraclastic packstone layer. Nearly non-burrowed in some places but with typical burrowed texture in others. Unit is massive and no allochems or sedimentary structures were observed. Upper contact is gradational. Samples: S9/36.88, S9/37.43 , S9/38.93 , S9/39.51 .
Unit 10	1.55 m	41.06 m	Carbonate mudstone to burrow-mottled mudstone. Light gray to brownish yellow on weather surface. Textural description was difficult due to weathering of the unit. Appears to be some shale partings in unit. Burrowed texture was noted but it does not seem to be common throughout the unit. Many large tectonic bed normal veins were seen. Unit is massive. Upper contact is sharp and marked by a <3cm shale unit. Samples: S10/39.61 , S10/40.15 .
Unit 11	2.70 m	43.76 m	Ribbon-laminated carbonate mudstone. Light gray to dark gray on weathered surface. Carbonate layers are less than 8 centimeters thick and have wavy contacts with shale layers. They are dominantly mudstones with no allochems. Some layers are intraclastic wackestones consist-

unit #	thick- ness (m)	cum. thick- ness(m)	description
			ing of carbonate mudstone clasts in a matrix of carbonate mudstone. Shale layers are less than 1 cm thick. Small cement filled burrows were noted in thin section. Upper contact is gradational. Samples: S11/41.2 , S11/42.7 , S11/43.76.
Unit 12	13.90 m	57.66 m	Lithology similar to unit 11 and this may be the same unit as Unit 11. There appears to be a fault in this unit. Structural dip changes from 024 SE to 040 SE in the section. A covered interval 1.2 meters lies above this change in dip. Next exposed beds have a structural dip of 026 SE. Samples: S12/43.8, S12/44.86, S12/47.31, S12/52.31 , S12/54.51, S12/57.56.
Unit 13	1.30 m	58.90 m	Lithology similar to units 11 and 13. Sample S13/58.63 .
	1.2	60.1	covered interval.
Unit 14	4.33 m	64.43 m	Burrow-mottled carbonate mudstone. Light gray to brownish gray on weathered surface. Texture similar to other burrow-mottled units. Samples: S14/64.3 and S60.1.
	6.90 m	71.33 m	covered interval
Unit 15	2.43 m	72.26 m	Burrow-mottled carbonate mudstone. Light gray to yellowish brown on weathered surface. Allochems and sedimentary structures are virtually absent in unit. Bottom of unit has a ribbon-laminated character with with carbonate layers 4 to 5 cm thick and argillaceous dolomite layers less than 1 cm thick. Ribbon-laminated grades upward into burrow-mottled texture with a discontinuous anastomosing network of dolomitized burrows. Cement filled burrows are present. Upper contact is gradational. Samples: S15/69.83, S15/71.06, S15/72.26.
Unit 16	0.95 m	73.21 m	Ribbon-laminated carbonate mudstone. Light gray to brown on weather surface. Allochems and sedimentary structures are virtually absent in lower part of unit. Intraclasts and mineralized hardground are present in upper part of unit near top contact. Carbonate layers are 2 to 8.5 cm thick and have wavy contacts with argillaceous dolomite layers. Shaly, argillaceous

unit #	thick- ness (m)	cum. thick- ness(m)	description
Unit 17	3.38 m	76.59 m	layers are up to 2 cm thick. Upper contact is undulatory and gradational. Samples: S16/72.16, S16-S17/73.21. Burrow-mottled carbonate mudstone grading upward into ribbon-laminated mudstone. Light brown to gray on weathered surface. Allochems are absent. Primary, wavy bedding was observed in some of the carbonate layers near the top of unit. Carbonate Layers are 1 to 5 cm thick. Argillaceous layers are less than 1 cm thick. Samples: S17/74.59, S17/76.04.
Unit 18	2.20 m	78.79 m	Ribbon-laminated carbonate mudstone. Brown to gray on weathered surface. Carbonate mudstone layers are up to 8 cm thick and no allochems or sedimentary structures were observed. Argillaceous layers are less than 1 cm thick. Contacts between carbonate and shale layers are planar. Upper contact is undulatory but sharp. Samples: S18/76.6, S18/78.0, S18/78.39.
Unit 19	5.30 m	84.09 m	Burrow-mottled carbonate mudstone. Brown to gray on weathering surface. Mudstone is virtually featureless and unit is quite homogeneous through-out. Unit is massively bedded. Upper contact is wavy and stylolitic. Samples: S19/79.09, S19/81.13, S19/84.09.
Unit 20	0.52 m	84.61 m	Ooid/peloidal grainstone. Light or medium gray to brown on weathering surface. Unit is dominantly composed of ooids and peloids in the lower part of unit and composed of intraclasts and peloids in upper part of unit. Irregular voids are present in the upper part of unit. Marine truncation surfaces and hardgrounds were observed in the field. Upper contact is sharp. Samples: S20/84.41, S20/84.61.
Unit 21	4.12 m	88.72 m	Burrow-mottled carbonate mudstone. brown to gray on weathered surface. Mudstone is homogeneous and no skeletal allochems were noted. Burrowed texture is similar to other burrow-mottled units. Abundant bed normal and bed

unit #	thick- ness (m)	cum. thick- ness(m)	description
			parallel calcite veins present. Small cement filled vugs (burrows) seen in the field. Samples: S21/85.21, S21/87.03, S21/88.72.
Unit 22	1.99 m	90.71 m	Burrow-mottled carbonate mudstone. Light gray to medium gray on the weathered surface. Mottling is similar to other units described in section. Allochems are absent. Stylolites are locally abundant. Samples S22/88.82, S22/90.70.
	0.45 m	94.15 m	Covered interval.
Unit 23	2.99 m	94.15 m	Burrow-mottled carbonate mudstone. Light gray to brown on weathering surface. Lithology is very similar to Unit 22. Massive in character. Stylolites are abundant. Upper contact is not a lithologic contact, but taken where weathering pattern changes. Samples: S23/94.41.
Unit 24	10.78 m	104.93 m	Burrow-mottled carbonate mudstone. Brown to light gray on weathered surface. Massively bedded unit with abundant burrows. Upper part of unit grades into almost ribbon-laminated mudstone lithology. Allochems were not observed in the field. Small cement filled voids (burrows) noted. Calcite veins present. Samples: S24/95.15, S24/98.11, S24/103.15, S24/104.48.
Unit 25	2.00 m	106.93 m	Ribbon-laminated to burrow-mottled carbonate mudstone. Light brown to almost green on weathering surface. Carbonate layers are on average 3 cm thick and thin (less than 0.2 mm). Not many burrows. Allochems are absent. Sample: S25/105.33.
Unit 26	2.17 m	109.1 m	Burrow-mottled carbonate mudstone grading into ribbon-laminated carbonate mudstone. Brown to light gray on weathered surface. Texture similar to Unit 25. Samples: S26/106.95, S26/108.15.
Unit 27	0.40 m	109.5 m	Similar lithology to Unit 26 and probably is the same unit. Sample: S27/109.4.

Top of measure section, Rogersville Shale not exposed.

APPENDIX B

PRELIMINARY DIAGENETIC WORK

This Appendix presents the results of preliminary diagenetic work done on the Rutledge Limestone. Based on textural and fabric characteristics of the lithofacies, two major lithofacies groups were determined: the mud-rich lithofacies group and the grainstone lithofacies group. The mud-rich lithofacies group is composed of the burrow-mottled, ribbon-laminated, and nodular mudstone lithofacies and was characterized by low primary porosity. Diagenetic components of this facies group are primarily related to burrowing and diagenetic cements are represented by planer-euhedral dolomite, equant calcite, and fibrous calcite $\pm$ micro-dolomite. The Grainstone lithofacies group is made up of the ooid, peloidal lithofacies. Diagenetic cements are more prevalent in this lithofacies and occur as intergranular and replacive cements. This facies probably had relatively high primary porosity.

Cathodoluminescence petrography and stable isotope signatures from selected diagenetic phases were gathered and are presented below. The operating conditions and methods are also outlined below. The data presented in this Appendix is preliminary and is intended to only present the results I obtained. I hope that this data will act as guide for future diagenetic study.

CATHODOLUMINESCENCE MICROSCOPY

Observations of polished thin sections (15) by cathodoluminescence microscopy were recorded over a three day period with approximately 8.5 hours of microscope time. The instrument used was a Citl cold cathode luminescence 8200mk3 microscope. Operating conditions were as follows: voltage: 10-12 kV,

beam current: 150-170 mA, chamber pressure 180-200 millitorr.

STABLE ISOTOPIC DATA

Stable carbon and oxygen isotopic data were collected during an one week period at the Science Alliance Stable Isotope Laboratory at the University of Tennessee, Knoxville, Tennessee. Individual samples were drilled from polished thin section billets using a microscope mounted drill. Samples were roasted at 380°C for 1 hour to remove any organic material and then were reacted with 103% phosphoric acid at 25°C (after McCrea, 1950). Calcite samples were reacted for at least 8 hours and dolomite samples were reacted for at least 48 hours. Liberated CO₂ gas from all samples was analyzed on a VG-903 MM gas-source stable isotope ratio mass spectrometer. In house and national standards were also analyzed. Two samples were analyzed before running samples on the mass spectrometer, a standard was analyzed every sixth sample, and two standards were analyzed at the end of the day.

Below are the results of the isotopic study of selected diagenetic phases. The left column refers to in-house labeling scheme of individual samples. This documentation is stored at the Stable Isotope Laboratory at the University of Tennessee. The second column gives the sample name (similar to sample names given in Appendix I) and sample descriptions. The third and fourth columns are the obtained stable isotopic data. For standard data, carbon and oxygen values in parenthesis refer to published values.

Figure A8 shows the isotopic values plotted graphically. Table A1 and Figure A7 give detailed information on the diagenetic phases analyzed.

IN-HOUSE REFERENCE	SAMPLE/ DESCRIPTION	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
STANDARDS			
C2-235-LV3	CHCC	-10.68 (-10.68 $\pm$ 0.06)	-9.32 (-9.28 $\pm$ 0.07)
C2-236-SRV10	CHCC	-10.659 (-10.68 $\pm$ 0.06)	-9.39 (-9.28 $\pm$ 0.07)
C2-235-SRV53	ANU-P3	2.189 (2.19 $\pm$ 0.07)	-0.219 (-0.25 $\pm$ 0.13)
C2-235-SRVMT	ANU-M1	1.27 (1.27 $\pm$ 0.06)	-5.957 (-6.07 $\pm$ 0.12)
C2-235-LRV9	CHCC	-10.71 (-10.68 $\pm$ 0.06)	-9.33 (-9.28 $\pm$ 0.07)
C2-235-LRV9	CHCC	-10.68 (-10.68 $\pm$ 0.06)	-9.34 (-9.28 $\pm$ 0.07)
CALCITE SAMPLES			
C2-236-SRV4	LG9A1-TOP (F) - fibrous calcite cement from mud-mound void	-1.64	-8.35
C2-236-SRV1	LG9A1-TOP II - fibrous calcite cement from mud-mound void	-1.64	-8.18
C2-236-SRV9	PC11/~45M (F) - fibrous calcite cement from mud-mound void	-1.11	-7.47
C2-238-SRV5	LGA1-TOP (E) - pore central equant calcite from mud-mound void	-1.83	-9.74
MICRITES			
C2-238-SRV3	SN24/94.15 - homogeneous micrite next to burrow (sample C2-236-SRV6)	-1.80	-9.06
C2-238SRV50	HY29/59.54 - homogeneous micrite next to burrow (sample C2-236-SRV47)	-2.023	-9.03
FIBROUS CALCITE BURROW FILL			
C2-236-SRV2	HY26/33.2 - Fibrous calcite with micro- dolomite from burrow (dolomite $\approx$ 15-20%)	-2.185	-8.32

Stable Isotope Data Continued

IN-HOUSE REFERENCE	SAMPLE/ DESCRIPTION	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
DOLOMITES			
C2-236-SRV6	SN24/95.15 - planar-e dolomite from burrow (calcite ~<5%)	-0.98	-8.13
C2-235-SRV53	LG10-2B - planar-e dolomite from burrow (calcite ~<5%)	-0.83	-8.029
C2-235-SRV8	SN24/95.15 - planar-e dolomite from burrow (calcite ~<5%). Different burrow from above	-0.92	-8.11
C2-235-SRVWD	HY21/39.02 - planar-e dolomite from burrow (calcite ~<5%)	-0.86	-7.96
C2-235-SRVCD	HY12/23.12 - planar-e dolomite from burrow (calcite ~<5%)	-0.76	-8.14
C2-236-SRV47	HY29/59.95 - planar-e dolomite from vertical burrow (calcite ~<15%)	-1.51	-8.37

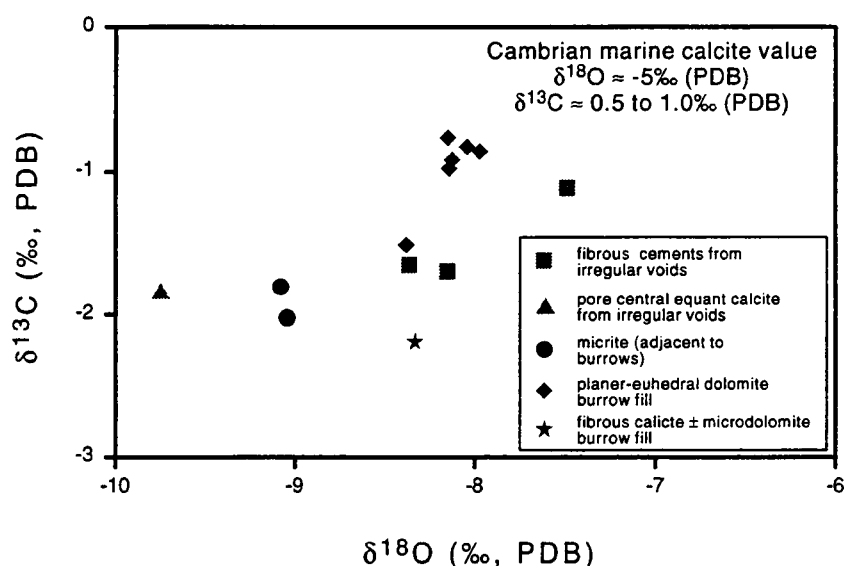
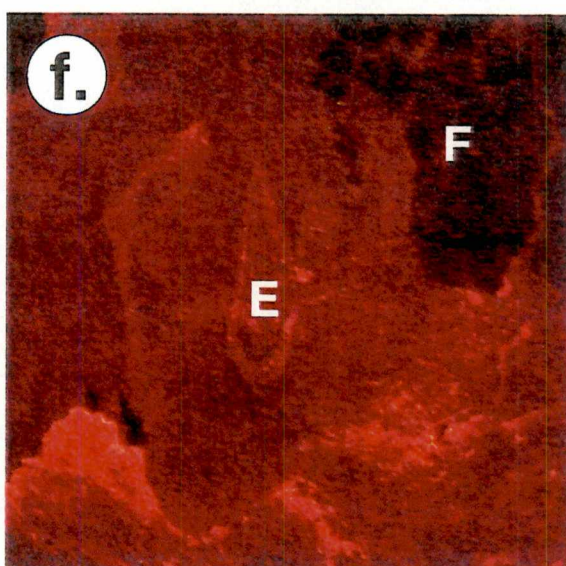
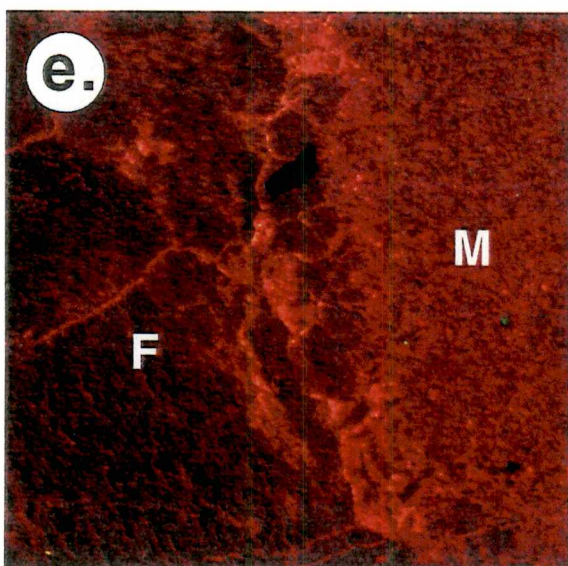
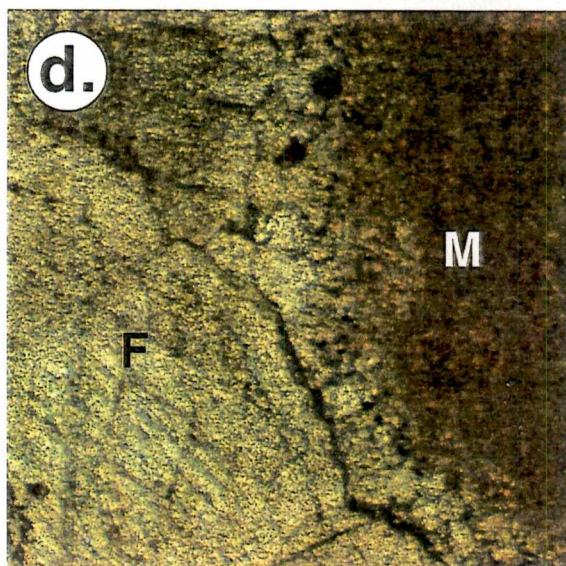
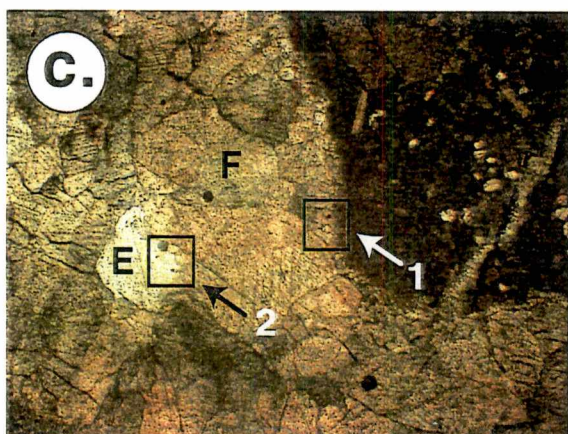
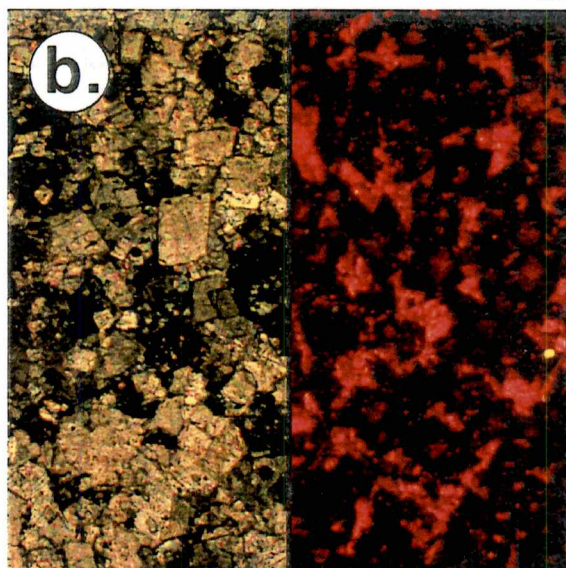
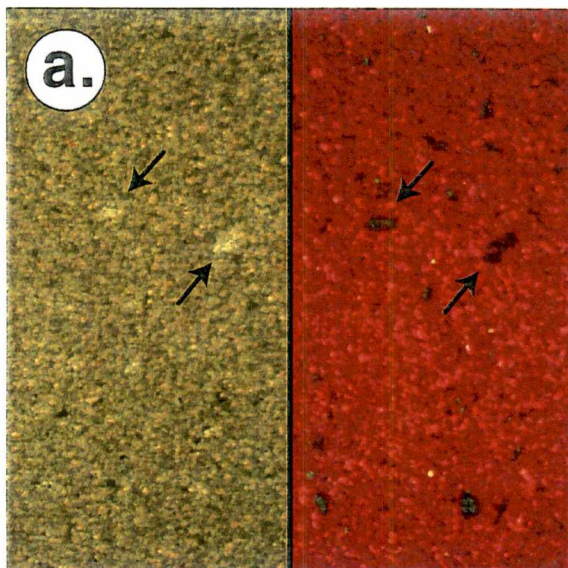


Figure A.6. $\delta^{18}\text{O}$ versus $\delta^{13}\text{C}$ of major diagenetic components of the Rutledge Limestone. The Cambrian marine calcite value is from Lohmann and Walker (1989). Black symbols are analyzed diagenetic phases from mud-rich lithofacies group. Gray symbols are analyzed diagenetic phases from grainstone lithofacies group.

Table A.1. Summary table of the major petrographic characteristics of diagenetic phases sampled for stable isotopic analysis. The individual phases are separated into two groups based on the textural and fabric characteristics of individual units. Figure A7 shows the major phases sampled for stable isotopic work.

DIAGENETIC PHASE	PETROGRAPHIC CHARACTERISTICS	OCCURRENCE
<i>MUD-RICH LITHOFACIES GROUP</i>		
Micrite	Fine-grained cryptocrystalline calcite micrite. Under cathodoluminescence, dull orange in color and it may have a patchy luminescence pattern ranging from dull orange to non-luminescent. Staining reveals a non-ferroan character. Microdolomite may or may not be present.	dominant "diagenetic" product in mud-rich lithofacies.
Burrow-fill dolomite	Euhedral dolomite crystals (planar-e dolomite of Sibley and Gregg, 1987) that range in size from 20 to 50 microns. Crystals show no evidence for zoning and generally occur as a closely packed mosaic with argillaceous (pyrite, clays, and iron oxides?) material filling the interstices. Under cathodoluminescence, planar-e dolomite is non-luminescent (Figure 2.4b) and, in transmitted light, the dolomite appears green in color when stained with potassium ferricyanide (after Dickson, 1965, 1966).	dominant burrow-fill diagenetic phase.
Burrow-fill fibrous calcite $\pm$ dolomite	Turbid, fibrous calcite crystals (up to 1 mm in length) emanating from the burrow wall to the center of the burrow. Individual crystals generally have abundant micro-dolomite inclusions. Cathodoluminescence patterns of these cements are not distinguishable from the surrounding matrix except for the non-luminescent character of the dolomite crystals.	rare burrow-fill diagenetic phase.
<i>GRAINSTONE LITHOFACIES GROUP</i>		
Fibrous calcite cement	Fibrous to bladed, non-ferroan calcite cements. Generally non-luminescent, except for dull luminescent rims around crystal boundaries	First generation cements in irregular voids.
Equant calcite cement	Non-ferroan equant calcite cement. Show dull luminescence under CL.	pore central cement in irregular voids.

Figure A.7. Transmitted and cathodoluminescence photomicrographs of diagenetic phases sample for stable carbon and oxygen analysis. **a.** Paired transmitted (plane light, left) and cathodoluminescent (right) photomicrograph of mud-rich matrix from mud-rich lithofacies group. Field of view ≈ 0.2 mm. The matrix is dominated by homogenous calcite micrite that has a dull orange luminescent pattern (may be patchy in places). Subhedral and anhedral dolomite crystals (black arrow) are found floating in the matrix. Sample S6/33.0, Sneedville locality. **b.** Transmitted (crossed polarized light, left) and cathodoluminescent (right) photomicrographs of planar-e dolomite from burrow-fill dolomite in mud-rich lithofacies group. Field of view ≈ 0.4 mm. Left photograph from vertical burrow shows euhedral dolomite crystals in a matrix of equant calcite cement. Right photomicrograph illustrates the non-luminescent, ferroan character of the planar-e dolomite. Dolomite crystals floating in micrite matrix. Left photomicrograph is from sample S22/90.70, Sneedville locality. Right photomicrograph is from sample LG3/1.84, Lays Gap locality. **c.** Plane light photomicrograph of vuggy porosity occluded by carbonate cements in grainstone lithofacies group. Field of view ≈ 5 mm. The void, interpreted sponge related origin, has an initial generation of fibrous (F) turbid cements followed by a pore central clear, equant calcite (E) phase. Euhedral authigenic quartz is seen in the muddy matrix (right of photograph). Numbered boxes refer to photomicrographs in d through e of this figure. Sample PC11/~45m, Puncheon Creek Locality. **d** and **e.** Paired, close-up (box 1) photomicrographs (d. plane transmitted light, e. cathodoluminescence) of the edge of vuggy porosity showing micrite and initial turbid, fibrous calcite cements. Field of view ≈ 0.95 mm. The fibrous cements have a non-luminescent character except for thin rims of alteration (luminescent) along crystal boundaries. Micrite has a dull orange luminescence. Sample PC11/~45m, Puncheon Creek Locality. **f.** Cathodoluminescence photomicrograph (Box 2) of pore central equant calcite phase. Field of view ≈ 0.95 mm. Equant calcite (E) has a dull orange luminescent patten. Non-luminescent fibrous calcite (F) seen in upper right hand corner of the photograph.



VITA

Andrew Stefaniak was born in Landstul, Germany on November 15, 1969. After sojourns in Germany, the Netherlands, New Mexico, and Texas, his family settled in the coastal plain province of Prince George, Virginia. He attended and graduated in 1988 from Prince George High School. Shortly thereafter, he entered Richard Bland College with the intent on becoming a golf course superintendent. He received an Associate in Science degree with a concentration in biology from Richard Bland College in 1990 and transferred to the College of William and Mary to pursue a degree in environmental science. After an introductory course in Geology, he found a true interest in natural history and over the next three years pursued a Bachelor of Science degree in Geology. Upon graduation from the College of William and Mary in May of 1993, he temporarily put on hold his aspirations of becoming a professional chef, traveled to the beautiful hills and valleys of east Tennessee, and entered graduate school in Geology at the University of Tennessee. With a lot of hard work, good times, and much appreciated help from many people he received his Master of Science degree with a major in Geology in the summer of 1996.

In May of 1996, Andrew Stefaniak accepted a position as a geologist with Exxon Exploration Company in Houston, Texas.