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CARBONATE DEPOSITION AND SEQUENCE STRATIGRAPHY OF THE TERMINAL CAMBRIAN GRAND CYCLE IN THE SOUTHERN APPALACHIANS, U.S.A.

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ABSTRACT: **The cessation of shale and carbonate deposition of the Conasauga Group grand cycles (Middle to Upper Cambrian) and the establishment of the widespread peritidal carbonate deposition of the Knox Group (Upper Cambrian to Lower Ordovician) represent a prominent change in sedimentation along the early Paleozoic passive continental margin in the southern Appalachians. To evaluate the causes for this change, this study focuses on the Maynardville Formation, which is the uppermost carbonate unit of the Conasauga Group. The Maynardville consists of: (1) a lower subtidal facies succession, which is underlain by the Nolichucky Shale and resembles the rest of the Conasauga Group carbonate deposits; and (2) an upper peritidal facies succession, which is conformably overlain by similar peritidal deposits of the Copper Ridge Dolomite (Knox Group). Deposition of shale and subtidal carbonate took place in deep-ramp (Nolichucky) to shallow-ramp, subtidal-shoal, and lagoonal settings (lower Maynardville). The carbonate ramp was westward sloping toward the Conasauga intrashelf shale basin. To the east, the ramp was linked to a broad, semiarid carbonate tidal flat encompassing a variety of peritidal environments (upper Maynardville and Copper Ridge). The Maynardville is a shallowing-upward succession that formed by carbonate platform aggradation and basinward progradation. The transition between the Maynardville and the Copper Ridge Dolomite is within a conformable peritidal carbonate succession that contains common siliciclastic sand-size detritus. This interval is interpreted as a sequence boundary correlative with the craton-wide late Steptoean (Dresbachian–Franconian or Sauk II–Sauk III) unconformity.**

The change from a Conasauga to a Knox depositional style may be related to distinct stages in passive-margin evolution. The end of grand-cycle deposition in the early Late Cambrian is coincident with the cessation of tectonic activity along extensional features (an intracratonic graben and other fault systems), and marks the transition into a mature-passive-margin setting. The mature margin was characterized by decreased rates of thermal subsidence, which, coupled with the infilling of the Conasauga intrashelf basin, favored shallow-water carbonate deposition. The final stabilization of the margin is reflected in the deposition of the thick peritidal carbonate strata of the Knox Group.

INTRODUCTION

This study focuses on a distinct change in the style of Cambro-Ordovician passive-margin sedimentation in the southern Appalachians: the cessation of the alternating shale and carbonate deposition of the Conasauga Group (Middle to Upper Cambrian), and establishment of the shallow-water, peritidal carbonate deposition of the overlying Knox Group (Upper Cambrian to Lower Ordovician; Fig. 1). The Conasauga Group deposits have been described as grand cycles (*sensu* Aitken 1966), composed of a lower shale half-cycle and an upper carbonate half-cycle (Fig. 1). Grand cycles also have been recognized in the Great Basin (Palmer and Halley 1979; Mount and Rowland 1981; Osleger and Montañez 1996), the southern Canadian Rocky Mountains (Aitken 1966, 1978), and the northern Appalachians (Chow and James 1987; James et al. 1989; Cowan and James 1993). The formation of grand cycles is attributed to a complex interplay of eustatic sea-level change (Aitken 1978; Bond et al. 1988), tectonism (Rankey et al. 1994), and the rate of sedimentation and sediment supply (Walker et al. 1990; Srinivasan and Walker 1993; among others).

The end of grand-cycle deposition in the southern Appalachians is marked by the deposition of the Maynardville Formation (uppermost Conasauga Group), which overlies the Upper Shale Member of the Nolichucky Shale (Fig. 1). The Maynardville is conformably overlain by the Copper Ridge Dolomite (Knox Group; Fig. 1). The *Cedaria* zone and *Crepicephalus* zone fauna in the Nolichucky Shale, and the *Aphelaspis* zone fauna in the lower Maynardville Formation, indicate a Dresbachian or late Marjuman to early Steptoean age for these deposits (Fig. 1; Rasetti 1965). The Marjumiid–Pterocephaliid Biomere boundary (Marjuman–Steptoean Stage boundary) is within the upper part of the Nolichucky Shale. The lowermost Knox Group strata in the southern Appalachians were deposited during the early Franconian or late Steptoean (Fig. 1; Glumac and Walker 1998).

The lower part of the Maynardville Formation consists of subtidal carbonate and shale, which are similar to the rest of the Conasauga Group deposits, whereas the peritidal carbonates from the upper part of the Maynardville resemble deposits of the overlying Knox Group. Thus, the Maynardville represents a transitional unit between the Conasauga and the Knox sedimentary successions (Fig. 1). The major objectives of this paper are to: (1) interpret depositional environments for the Maynardville Formation as the carbonate half-cycle of the terminal Cambrian grand cycle; (2) propose sequence stratigraphic interpretations for the Maynardville; (3) compare the Maynardville with the Middle Cambrian carbonate deposits of the Conasauga Group in order to document the changing style of passive-margin sedimentation; and (4) relate the changing depositional regimes and the end of grand-cycle deposition to the distinct stages in the evolution of the early Paleozoic passive margin of the southern Appalachians.

GEOLOGIC SETTING

The rifting and breakup of the supercontinent Rodinia in the Late Proterozoic to Early Cambrian produced passive continental margins that almost completely circumscribed the Laurentian continent (Bond et al. 1984; Karlstrom et al. 1999). The Middle to lower Upper Cambrian sedimentary record of the southern Appalachians reveals the existence of a carbonate platform 150–200 km wide along the passive margin of eastern Laurentia (Fig. 2). This carbonate platform faced the Iapetus Ocean to the east and the Conasauga intrashelf shale basin to the west (Fig. 2). The western margin of the platform was characterized by deposition of alternating shale and carbonate units, or grand cycles, of the Conasauga Group, which are overlain by carbonate deposits of the Knox Group (Fig. 1). These rocks crop out within several imbricated, northeast–southwest-trending thrust blocks in the Valley and Ridge physiographic province of eastern Tennessee. Five stratigraphic sections from three northwesternmost thrust blocks were examined in the course of this study (Figs. 2, 3). Towards the west the grand cycles are replaced by Conasauga Group shale (Fig. 1; Rodgers 1953). Lateral equivalents of the Conasauga and Knox Group in northeastern Tennessee and southwestern Virginia are extensively dolomitized carbonate platform deposits of the Honaker, Elbrook, and Conococheague Formations (Read 1989). The Knox Group represents a predominance of shallow-water (primarily dolostone) deposition that continued into the Early Ordovician. Passive-margin sedimentation terminated in the late Early

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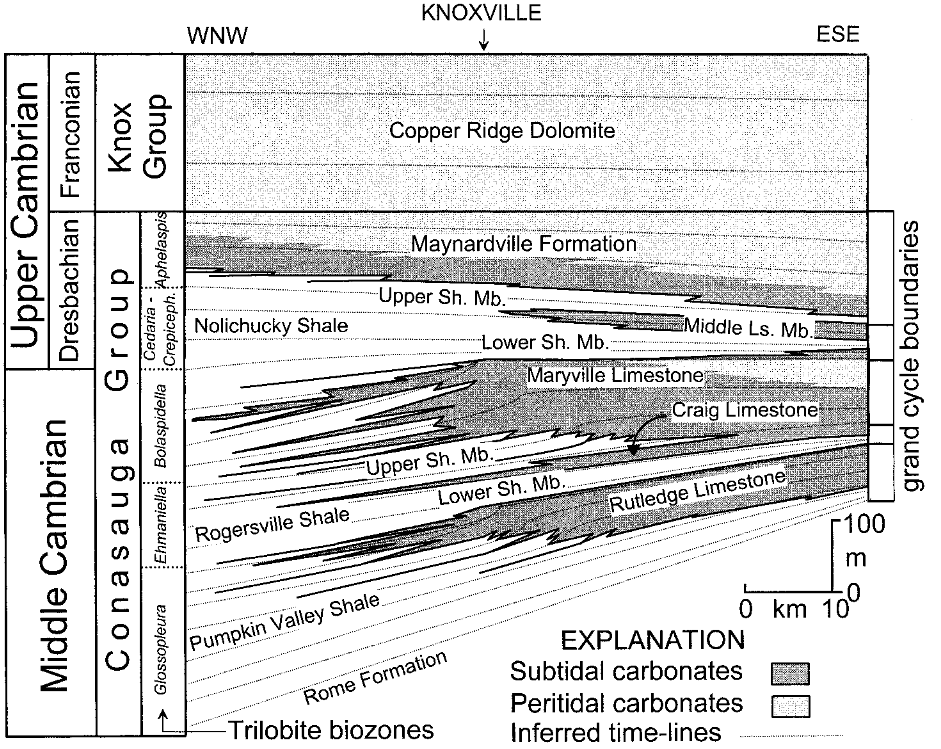

FIG. 1.—Middle to Upper Cambrian stratigraphy of eastern Tennessee Appalachians (modified from Walker et al. 1990). Note the characteristic interfingering relationship between shale and carbonate units, or grand cycles, of the Conasauga Group, the predominance of carbonate deposits in the Late Cambrian (Maynardville Formation and Copper Ridge Dolomite), the distribution of subtidal and peritidal carbonates, and the position of grand-cycle boundaries.

Ordovician with prolonged subaerial exposure that produced the Knox or Beekmantown (post-Sauk) unconformity. This event marks the transition into a convergent-margin setting (Benedict and Walker 1978; Shanmugam and Walker 1980; Mussman and Read 1986; Read 1989).

LITHOFACIES DESCRIPTION

Table 1 contains a summary of characteristics of the lithofacies present in measured stratigraphic successions (Fig. 3). The Maynardville Formation conformably overlies the Nolichucky Shale (Figs. 1, 3); the contact is at the base of the lowest thick limestone unit (Fig. 4A). The shale-rich deposits of the Conasauga Group are poorly exposed. The uppermost part of the Nolichucky Shale consists of calcareous and silty shale interbedded with carbonate layers. The latter are similar to deposits from the lower part of the overlying Maynardville.

The Maynardville Formation consists of a lower subtidal and an upper peritidal facies succession (Figs. 1, 3). The subtidal deposits are dominated by ribbon rocks, which contain centimeter-scale layers and lenses of limestone alternating with argillaceous dolostone, siltstone, or shale (Fig. 4B; Table 1). Limestone layers are composed of normally graded

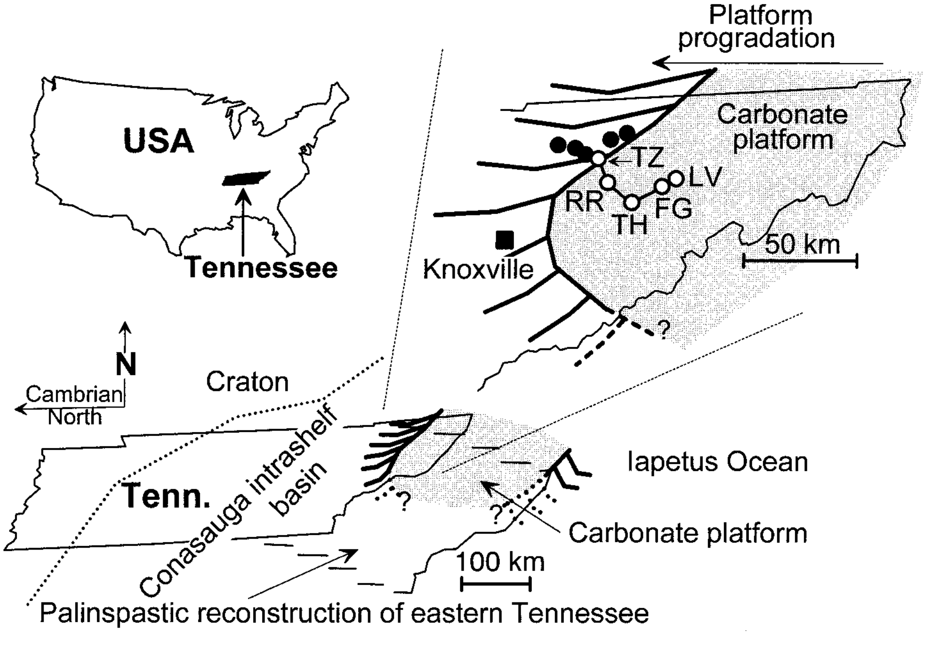

FIG. 2.—Schematic paleogeographic reconstruction of Tennessee during the Middle to early Late Cambrian (palinspastic reconstruction after Roeder and Witherspoon 1978). A carbonate platform (shaded area) faced the Iapetus Ocean to the east (present-day orientation), and was separated from the exposed craton to the west by the Conasauga intrashelf shale basin. The area along the western carbonate platform margin is enlarged, showing present-day (solid circles) and palinspastically reconstructed (open circles) locations of the outcrops studied. Outcrop key: TZ, Tazewell; RR, River Ridge; TH, Thorn Hill; FG, Flat Gap; LV, Lee Valley.

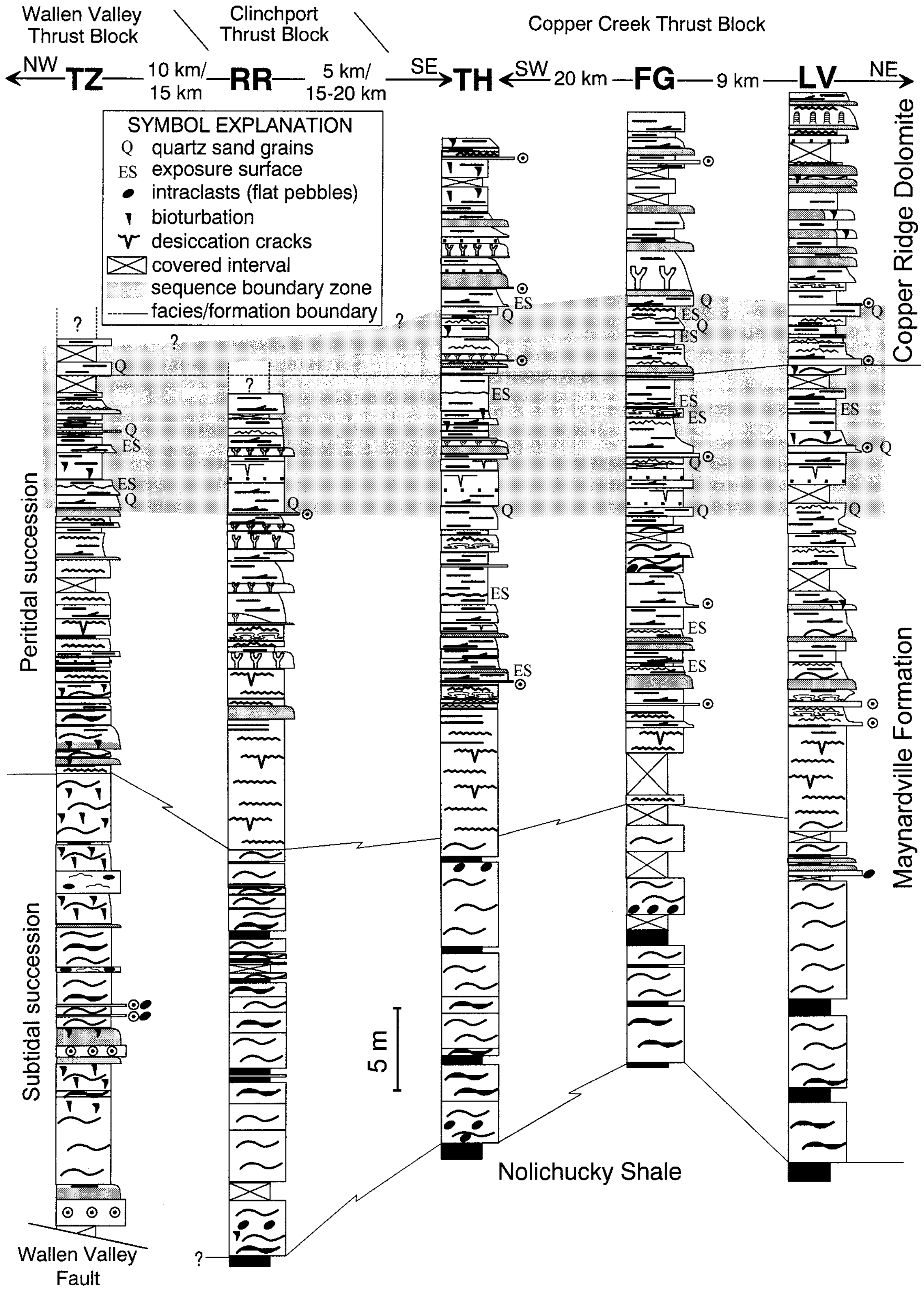

FIG. 3.—Stratigraphic columns of the Maynardville Formation and the lower Copper Ridge Dolomite. See Table 1 for the explanation of the symbols. The columns are hung on a horizon defined by the occurrence of sand-size siliciclastic detritus, and interpreted as a sequence boundary zone (shaded; see text for additional explanation). Key to distance between outcrops: present day/reconstructed distance. Outcrop key: TZ, Tazewell; RR, River Ridge; TH, Thorn Hill; FG, Flat Gap; LV, Lee Valley.

TABLE 1.—*Lithofacies of the subtidal and peritidal successions. Symbols correspond to those in Figure 3.*

Subtidal Lithofacies	**Symbols and Descriptions**			**Environments**
Thrombolite	▨		microbial bioherms; *Renalcis-Epiphyton-Girvanella* boundstones; commonly originate on intraclastic deposits (flat-pebble conglomerate); burrowed.	Shallow subtidal patch reefs
Oolite	⊙ ⊙ ⊙ ⊙ ⊙		ooid- and intraclastic-ooid grainstone; cross-bedding present; rare echinoderm, trilobite, and brachiopod fragments; micritized ooids and peloids present.	Agitated shallow subtidal shoals
Fossiliferous-peloidal packstone/ grainstone	○〰○		common echinoderm and trilobite fragments, intraclasts, pellets, and some ooids; horizontally and cross-laminated; intraclasts composed of mudstone, peloidal packstone, and fossiliferous wackestone; some burrows present.	Moderately agitated shallow subtidal
Ribbon rock			alternating cm-scale limestone and fine-grained siliciclastic layers; wavy-laminated and nodular; argillaceous layers contain pressure dissolution and compaction features; flat-pebble conglomerate layers, and hardgrounds with pyrite crusts and coated grains present.	Protected to agitated subtidal:
	〰	**with shale**	carbonate alternating with siltstone and shale; carbonate layers are commonly fining upward: skeletal grainstone to peloidal-fossil wackestone/packstone to horizontally laminated and burrowed mudstone; trilobite, brachiopod, and echinoderm fragments.	Storm-dominated shallow ramp
	〰	**without shale**	carbonate alternating with argillaceous dolostone and calcareous siltstone; carbonate layers composed mainly of burrow-mottled mudstone and peloidal packstone.	Protected lagoon
Shale	■		silty shale and calcareous siltstone; in places contain thin limestone layers compositionally similar to limestone from the ribbon rock.	Shallow to deep ramp
Peritidal Lithofacies	**Symbols and Descriptions**			**Environments**
Couplets			alternating couplets or mechanical laminites of basal coarse-grained deposit grading upward into laminated and in places burrowed fine-grained deposits; extensively dolomitized; common stylolites.	Storm-, wave-, and tide-dominated semiarid tidal flat:
	☰	**Coarse-grained**	intraclastic packstone/grainstone (+/- ooids, quartz sand and silt), grading upward into peloidal packstone and mudstone; couplet bases sharp, scoured.	Agitated shallow subtidal to intertidal
	☰	**Medium-grained**	horizontally and cross-laminated peloidal packstone/grainstone (+/- small intraclasts, ooids, and quartz silt), grading upward into mudstone with some desiccation cracks; couplet bases wavy (scoured) to planar.	
	☰	**Fine-grained**	laminated and massive dolomicrite with thin laminae or lenses of peloidal packstone at the base (starved ripple); desiccation cracks, evaporite molds, and microbial laminae present in the upper part of some couplets.	Less agitated upper intertidal to supratidal
Dolomitized mudstone	☐		massive dolomicrite; some horizontal (microbial?) lamination, mottling (burrows?), desiccation cracks, and subaerial exposure surfaces present; evaporite molds common.	
Calcareous siltstone	⁘		thinly bedded; horizontally and cross-laminated; desiccation cracks common; microbial laminae, fenestrae, and peloids present; interbedded with calcareous and silty shale.	Moderately agitated intertidal
Oolite	⊙		ooid grainstone; single layers of variable thickness or composite bodies of several layers; ooid packstones at bases of coarse-grained couplets.	Small localized high energy ooid shoals
Microbial deposits	▨	**Thrombolite**	bioherms with clotted fabric; irregular to digitate and branching patches of dense micrite; some *Renalcis*(?) grains present; common burrows.	Agitated shallow subtidal
	Y Y Y	**Digitate stromatolite**	bioherms composed of branching columns of low relief; crudely laminated micritic pelleted fabric; burrows present.	
	∩ ∩ ∩	**Columnar stromatolite**	laminated, non-linked, vertically stacked columns of cylindrical or clubbed shape; desiccation cracks and fenestrae present.	Agitated to protected intertidal
	⌒⌒	**Domal stromatolite**	hemispheroids composed of wavy laminated micrite; small desiccation cracks and fenestrae present.	
	〰	**Microbial laminites**	flat, planar, crinkly laminae; common desiccation cracks; large prism cracks; lenses with pellets, peloids, ooids, and quartz silt grains; common fenestrae; evaporite molds and some burrows present.	Restricted upper intertidal and supratidal

skeletal packstone/grainstone (Fig. 4C), burrow-mottled mudstone, and peloidal packstone (Table 1). Argillaceous layers of the ribbon rocks have common compaction and pressure-dissolution features (Glumac 1997). Thrombolitic bioherms, flat-pebble conglomerate (coarse-grained intraclastic packstone/grainstone), and shale layers (up to 1.2 m thick) are interbedded with the ribbon rocks (Fig. 3; Table 1). Carbonate clasts from flat-pebble conglomerate layers are well rounded and commonly have pyrite coatings (Fig. 4D). At the most basinward outcrop (Tazewell), the subtidal succession also contains ooid grainstone, intraclastic–ooid grainstone, fossiliferous–peloidal packstone/grainstone, and more common thrombolitic bioherms (Fig. 3; Table 1). No apparent cyclicity was observed in the subtidal lithofacies succession (Fig. 3).

The vertical transition from the subtidal to the peritidal depositional succession is in most outcrops represented by a gradual change from ribbon rocks into microbial laminites or stratiform stromatolites (Figs. 3, 5A–B). At the Tazewell outcrop, the subtidal to peritidal transition is marked by the first occurrence of microbial laminites overlain by thrombolites and ribbon rocks (Fig. 3). Overlying this interval at Tazewell, and the microbial laminites at other localities, is a variety of peritidal lithofacies, most of which are substantially dolomitized (Fig. 3; Table 1). Fining-upward centimeter-scale couplets or mechanical laminites are the predominant peritidal lithofacies (Fig. 5C; Table 1). Coarse-grained couplets contain intraclasts along sharp, scoured bases (Table 1). Peloid-rich, medium-grained couplets display wavy and lenticular bedding, and current and wave ripple cross-stratification (Fig. 5C). Upper parts of couplets are composed of horizontally laminated or massive dolomicrite (Table 1). Couplets are interbedded with dolomitized mudstone and a variety of microbial carbonate deposits including thrombolites, digitate stromatolites (Fig. 5D), columnar and dom-

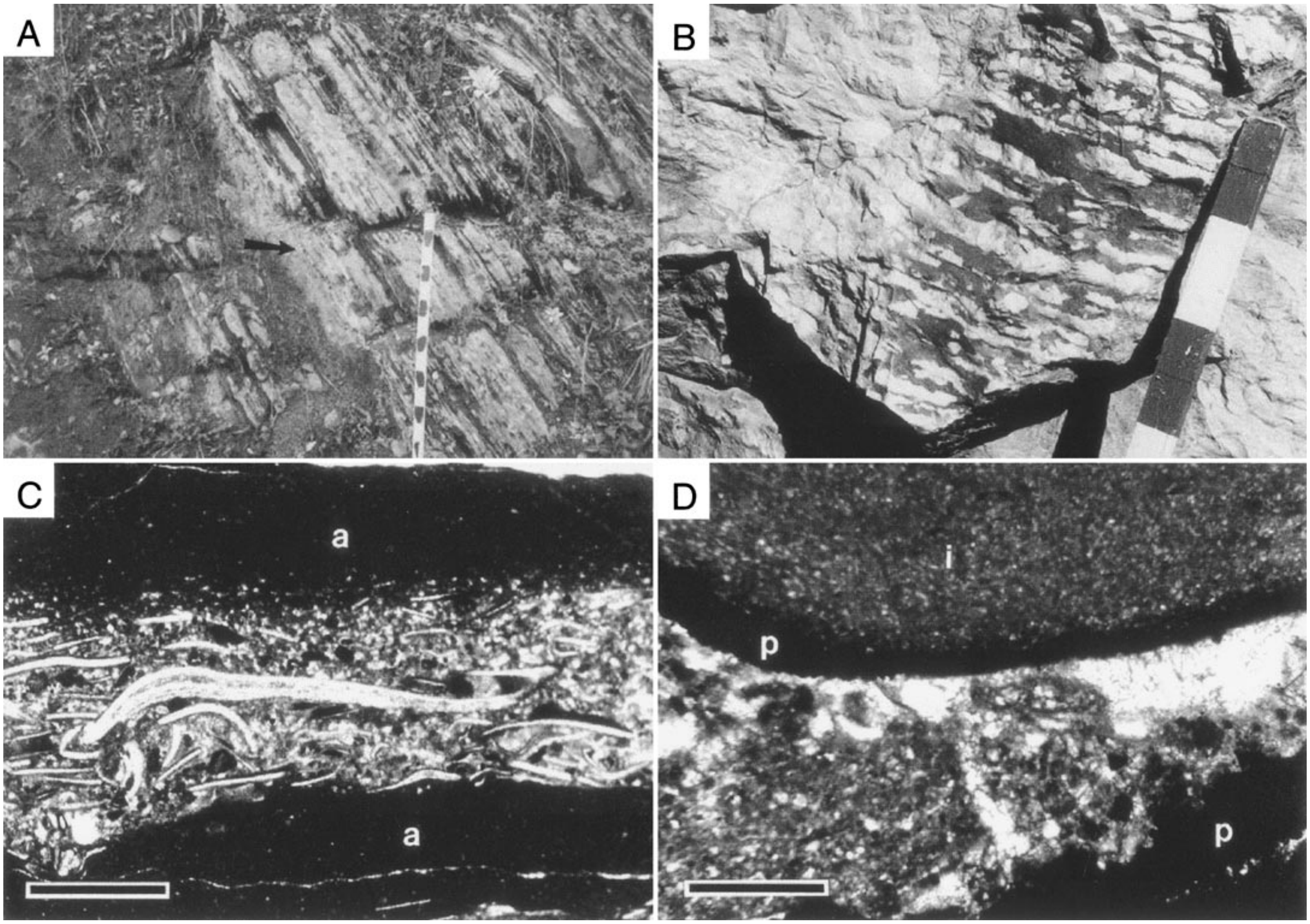

FIG. 4.—Subtidal deposits. **A)** Base of the Maynardville Formation (arrow) is at the base of first thick limestone unit overlying the Nolichucky Shale. Intervals on Jacob's staff = 10 cm. **B)** Ribbon rocks from the subtidal succession of the Maynardville. Light-colored limestone layers are interbedded with darker argillaceous layers. Intervals on Jacob's staff = 10 cm. **C)** Plain-light photomicrograph showing a skeletal packstone layer interbedded with argillaceous layers (a) of the ribbon rocks. Note the gradational upper contact and the sharp base of the skeletal layer. Scale bar = 1 mm. **D)** Photomicrograph of a flat-pebble conglomerate composed of centimeter-scale micritic intraclasts (i) interbedded with ribbon rocks. Note common pyrite (p) as coatings on intraclasts and in the matrix. Scale bar = 1 mm.

al stromatolites, and microbial laminites (Fig. 3; Table 1). The vertical succession of the peritidal lithofacies is complex (Fig. 3). Meter-scale shallowing-upward cycles with oolitic or thrombolitic bases, overlain by stromatolites and/or couplets and capped by dolomitized mudstones and microbial laminites, are present in the succession (Fig. 3). Some of these cycles are also capped with subaerial exposure surfaces with up to 30 cm of erosional relief (Figs. 3, 5E).

The Maynardville is conformably overlain by the peritidal carbonate deposits of the Copper Ridge Dolomite (Knox Group). The most common criteria for the placement of this boundary in outcrop include the first appearance of abundant chert (Rodgers 1953; Bridge 1956), thick-bedded, coarsely crystalline dolostone (Bridge 1956; Milici 1973), or thin quartz sandstone layers (Finlayson et al. 1965; Oder and Milici 1965; see also Hasson and Haase 1988). A combination of these criteria was used in this study (Fig. 3). The Maynardville–Copper Ridge boundary is contained within a conformable interval 10–15 m thick, characterized by the occurrence of quartz and feldspar sand grains (Figs. 3, 5F).

ENVIRONMENTS OF DEPOSITION

Nolichucky Shale

The Nolichucky Shale was not examined in detail. A brief summary of the interpretations by other workers is included here to document the changing style of sedimentation during the Late Cambrian in the southern Appalachians. The most basinward lithofacies of the Nolichucky Shale in central eastern Tennessee represent deposition in slope and basinal environments reaching 250–300 m water depth (Foreman et al. 1991). The Nolichucky Shale from the Copper Creek thrust sheet in eastern Tennessee (see Fig. 3) was deposited in a moderate-depth (30–50 m) to shallow-water (5–30 m) intrashelf basin setting (Weber 1988). The gradual transition from the Nolichucky Shale to the Maynardville Formation represents a shift from fine siliciclastic to carbonate-dominated sedimentation (Fig. 1). This transition reflects the shallowing or the infilling of the Conasauga intrashelf basin and the cratonward (westward) progradation of the carbonate platform (Figs. 1, 2; Markello and Read 1982).

Subtidal Facies Succession of the Maynardville Formation

The Upper Cambrian ribbon rocks are most commonly interpreted as shallow subtidal deposits (Demicco 1983; Osleger and Read 1991; Chow and James 1992). The shaly ribbon rocks with layers of flat-pebble conglomerate from the lower part of the Maynardville Formation were deposited on a storm-dominated shallow subtidal ramp (Fig. 6). High-energy storm waves were capable of breaking the semilithified carbonate layers into clasts, which were then deposited nearby, forming flat-pebble con-

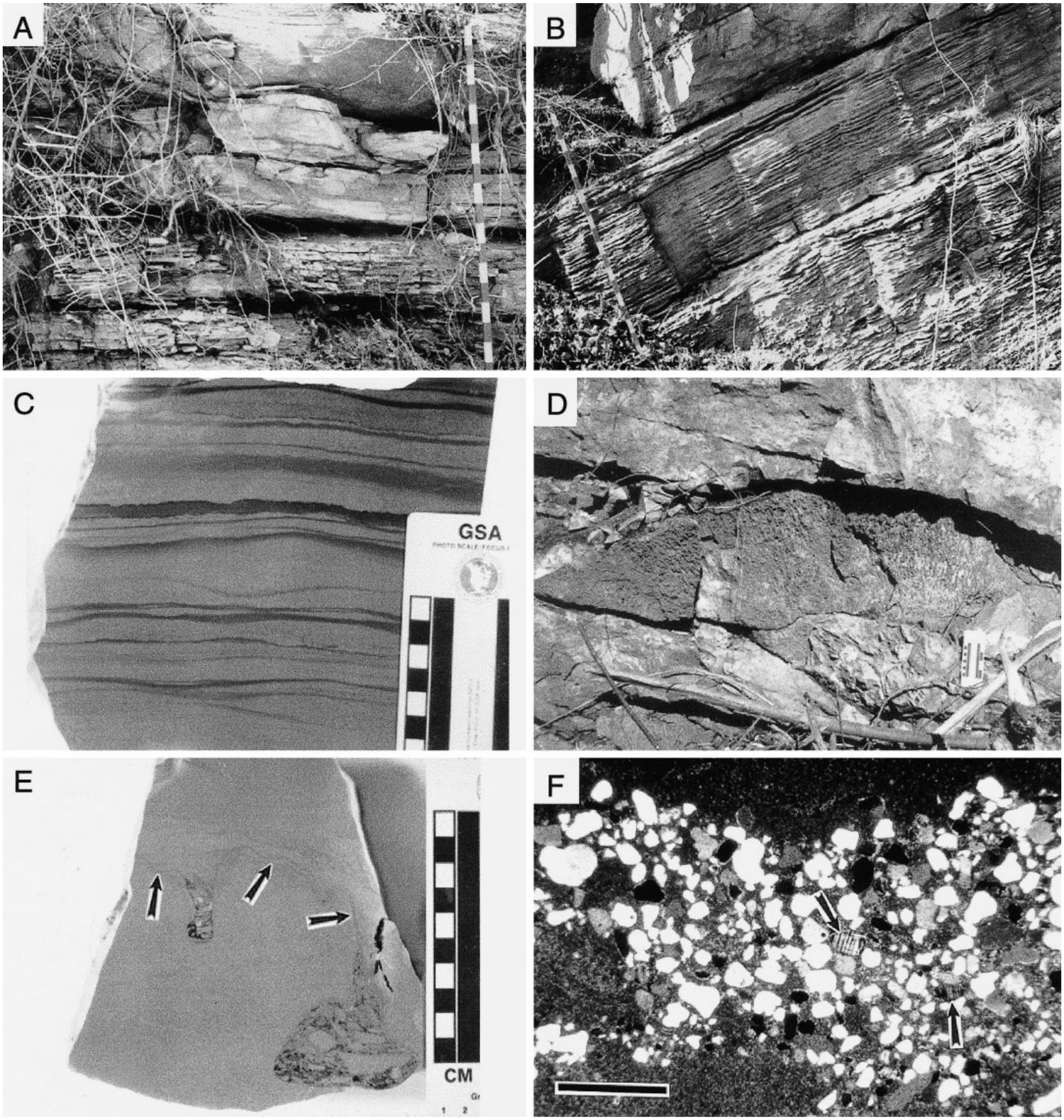

FIG. 5.—Peritidal deposits. **A)** Gradual transition between ribbon rocks (base) and microbial laminites (top) marks a transition from the subtidal into the peritidal facies succession of the Maynardville Formation. Intervals on Jacob's staff = 10 cm. **B)** Characteristic crinkly, wavy lamination and prominent desiccation cracks within microbial laminites. Intervals on Jacob's staff = 10 cm. **C)** Polished slab illustrating characteristic wavy and lenticular bedding, scoured bases, and current and wave ripple cross-lamination of couplets or mechanical laminites. Intervals on scale bar = 1 cm. **D)** A digitate stromatolite bioherm (middle) interbedded with couplets and dolomitized mudstone (top and bottom). Photo scale is 16.5 cm long. **E)** Polished slab of dolomicrite illustrating a subaerial exposure surface (arrows) with two erosional depressions filled with intraclasts. Thin microbial coating is seen as a dark outline along the erosional surface. Intervals on scale bar = 1 cm. **F)** Cross-polarized-light photomicrograph showing quartz and feldspar (arrows) grains in dolomicritic matrix from a conformable interval at the Maynardville–Copper Ridge transition interpreted as a sequence boundary zone (see Fig. 3). Scale bar = 1 mm.

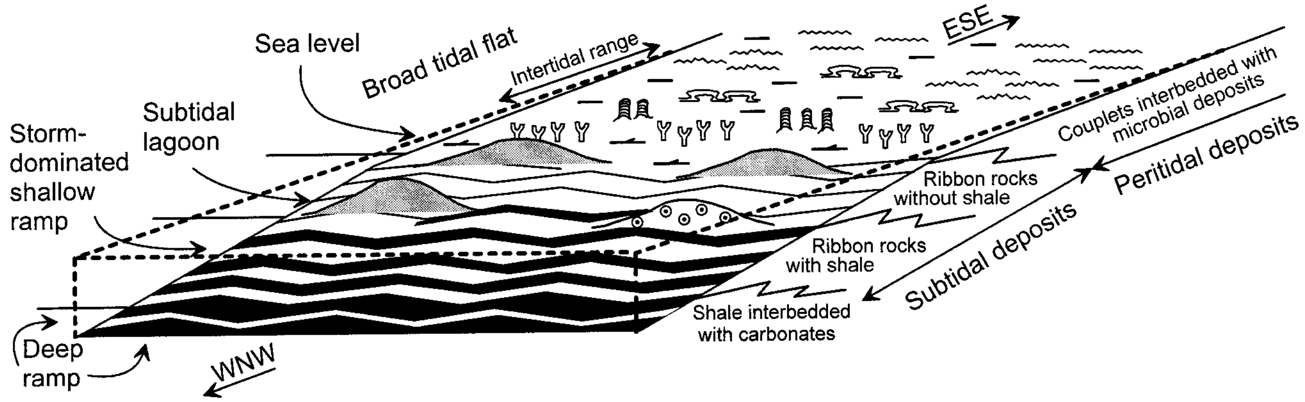

FIG. 6.—Schematic illustration of depositional environments for the deposits present within the succession examined (not to scale). See Table 1 for additional explanation of the symbols.

glomerates (Sepkoski 1982; Demicco 1985; Whisonant 1987). The prolonged residence of clasts on the sea floor under low-energy conditions and slow deposition or nondeposition between storms is suggested by pyrite coatings (Fig. 4D), a common feature of submarine hardgrounds (Chow and James 1992). Normally graded carbonate layers interbedded with thin shale were deposited by storm waves and currents, as suggested by their scoured bases and skeletal lag deposits (Kreisa 1981; Markello and Read 1981). Deposition of the laminated mudstone in the upper parts of normally graded limestone layers, and the overlying shaly layers of the ribbon rocks, took place between major storms. Primary sedimentary layering of the ribbon rocks has been modified during burial by compaction of soft argillaceous layers around more firmly lithified carbonate layers (Bathurst 1987) and by pressure dissolution along nonsutured dissolution seams, microstylolites, or clay seams (Wanless 1979; Simpson 1985; Choquette and James 1987; Railsback 1993).

The ribbon rocks composed of bioturbated lime mudstone and peloidal packstone interbedded with calcareous siltstone and argillaceous dolostone represent deposition in less agitated, shallow subtidal lagoonal environments (Fig. 6). This interpretation is supported by the paucity of skeletal allochems and the abundance of micritic and peloidal sediment (Table 1). In addition, the association with thrombolites reflects deposition in a shallow subtidal setting where the thrombolites were forming broad, low-relief patch reefs (Figs. 3, 6; Demicco et al. 1982; Glumac and Walker 1997). Microbial buildups, along with oolites and fossiliferous–peloidal grainstone deposits, are most common at the most basinward Tazewell outcrop (Figs. 2, 3). These deposits formed on low-relief subtidal shoals (Fig. 6). These shoals never developed into a prominent, continuous platform margin, judging from the fact that the characteristic platform margin deposits are not abundant (Fig. 3). However, the shoals likely played an important role in the periodic establishment of subtidal, restricted, lagoonal-type sedimentation in more eastward localities (Fig. 6). Thus, the subtidal succession of the Maynardville was deposited on a shallow ramp, and in locally developed shoals and lagoonal settings (Fig. 6).

Peritidal Facies Succession of the Maynardville Formation

The vertical transition from ribbon rocks into microbially laminated deposits (Fig. 5A) represents a change from entirely subtidal to predominantly peritidal carbonate deposition in response to progressive carbonate-platform aggradation and shallowing. The establishment of a wide, restricted tidal flat covered by extensive microbial mats with deposition that was able to keep up with changing accommodation is suggested by laterally extensive, thick, uniform microbial laminites in the lower part of the peritidal succession (Figs. 3, 5B).

The variety of peritidal lithofacies in the upper Maynardville represent deposition in a wide spectrum of settings ranging from supratidal to shallow subtidal (Figs. 3, 6; Table 1). A great lateral extent and a complex vertical succession of peritidal lithofacies (Figs. 1, 3) reflect an intricate pattern of facies migration on a flat-topped, broad, fully aggraded carbonate tidal flat (Fig. 6). Evaporite molds and desiccation cracks, common in some of the lithofacies (Fig. 5B; Table 1), indicate increased salinity and occasional subaerial exposure of the peritidal deposits. The lack of abundant evaporite deposits suggests a semiarid climate. Intermittent periods of subaerial exposure produced erosional surfaces indicative of surface paleokarst formation (Fig. 5E; Choquette and James 1988; Chow and James 1992).

The coarse- to medium-grained couplets represent deposition in tide-, wave-, and storm-dominated, shallow subtidal and intertidal settings (Figs. 5C, 6; Table 1). The medium-grained couplets resemble peloidal silt and carbonate mud deposited by storm and tidal currents in modern intertidal settings in the Bahamas (Hardie and Ginsburg 1977). Scoured bases of coarse-grained couplets and their intraclastic lag deposits are indicative of storm activity (Table 1). Storms may have also been responsible for the reworking of ooids from small, locally developed, high-energy shoals (Fig. 6). The ooids were redeposited and incorporated at the bases of some of the couplets or scattered in the muddy matrix of other lithofacies (Table 1). The effect of waves and tidal currents is reflected in the rounding of micritic clasts and in the cross-stratification in coarse- and medium-grained couplets (Fig. 5C; Table 1). Similar types of cross-stratification, desiccation features, and microbial laminae are present in the calcareous siltstone, suggesting deposition in a moderately agitated intertidal setting (Table 1). The fine-grained couplets and dolomitized mudstone were deposited on the upper intertidal to supratidal muddy flats of the Maynardville platform (Fig. 6). This interpretation is substantiated by common desiccation features, evaporite molds, absence of skeletal fauna, and the association with laminated microbial deposits (Fig. 3; Table 1).

Thrombolites and digitate stromatolites are among the rare peritidal lithofacies that have not been completely dolomitized. The susceptibility of these deposits to dolomitization may have been reduced by early diagenetic microbial calcification in a shallow subtidal to lower intertidal environment (Glumac and Walker 1997). This environmental setting is supported by the presence of thrombolites in the subtidal depositional succession, and by their association with coarse- and medium-grained peritidal couplets. The succession from thrombolites, digitate stromatolites, columnar stromatolites, domal stromatolites, to microbial laminites or stratiform stromatolites represents decreasing water turbulence from subtidal to supratidal environments (Fig. 6; Logan et al. 1964; Aitken 1967; Chafetz 1973; Glumac and Walker 1997). Microbial laminites, domal stromatolites, and columnar stromatolites formed mainly by sediment trapping in supratidal to lower intertidal environments (Fig. 6; Glumac and Walker 1997). This interpretation is supported by common desiccation features and fenestrae (Table 1).

The Maynardville grades conformably upward into the peritidal deposits of the Copper Ridge Dolomite (Knox Group). The occurrence of quartz sand in the part of the carbonate platform succession that contains the Maynardville–Copper Ridge transition (Figs. 3, 5F) is interpreted as an eastward migration of siliciclastic source areas in response to sea-level lowering and subaerial exposure of the craton. These conditions were established during the well-documented, craton-wide late Steptoean (Dresbachian–Franconian or Sauk II–Sauk III) unconformity (Lochman-Balk 1971; Palmer 1971, 1981; Osleger and Read 1993). The increased rate of siliciclastic sedimentation during this sea-level fall may have contributed to the infilling of the Conasauga intrashelf basin, which set the stage for westward carbonate-platform progradation during the subsequent (Franconian) sea-level rise (Figs. 1, 2; Markello and Read 1982). The Copper Ridge Dolomite marks the predominance of peritidal carbonate deposition in the study area (Fig. 1).

SEQUENCE STRATIGRAPHY

Cambrian grand cycles are commonly interpreted as third-order depositional sequences (*sensu* Vail et al. 1977), composed of a lower shale half-cycle and an upper carbonate half-cycle. Sequence boundaries have been recognized at abrupt carbonate-to-shale contacts on top of several Middle Cambrian grand cycles of the Conasauga Group (Fig. 1; Kozar et al. 1990; Srinivasan and Walker 1993; Rankey et al. 1994). Sequence-bounding disconformities have also been recognized within individual grand-cycle successions elsewhere (Mount et al. 1991; Cowan and James 1993; Osleger and Montañez 1996), suggesting that grand cycles are not always equivalent to depositional sequences. The following sections focus on the interpretation of the sequence stratigraphy for the carbonate half-cycle of the Upper Cambrian grand cycle that consists of the upper Nolichucky Shale and the Maynardville Formation (Fig. 1). Comparisons with sequence stratigraphic interpretations for other Conasauga Group grand cycles are included to demonstrate the change in the nature of sequence-bounding surfaces in the Cambrian strata from the southern Appalachians.

Nolichucky–Maynardville Transition

The termination of Middle Cambrian Maryville carbonate platform deposition by subaerial exposure and/or drowning, followed by an abrupt onlap of basinal shales (the Lower Shale Member of the Nolichucky), produced a sequence boundary on top of the upper Rogersville Shale–Maryville Limestone grand cycle (Fig. 1; Srinivasan and Walker 1993). Likewise, the onlap of the Upper Shale Member of the Nolichucky onto the Middle Limestone Member is interpreted as a sequence boundary (Fig. 1; Kozar et al. 1990). Thus, the Upper Shale Member of the Nolichucky represents a retrogradational parasequence set of a transgressive systems tract (e.g., Van Wagoner et al. 1988) that formed by the migration of relatively deep-water siliciclastic environments towards the carbonate platform as a consequence of an increased rate of relative sea-level rise (Srinivasan and Walker 1993). The deposition of the upper Nolichucky corresponds to the period of maximum flooding of the carbonate platform during the early Late Cambrian (Bond et al. 1988; Osleger and Read 1993). The transition between the Nolichucky Shale and the Maynardville Formation is gradational, and it represents a change from retrogradational to aggradational-to-progradational stacking patterns as a result of a decrease in the rate of relative sea-level rise. Thus, this transition also marks a change from transgressive to highstand systems tracts.

Maynardville Lithofacies Succession

Following the drowning of carbonate platforms and shale onlap in response to a rapid relative sea-level rise, carbonate deposition was reestablished through start-up, catch-up, and keep-up phases (Kendall and Schlager 1981). Deposition of the mixed shale and carbonate deposits of the upper Nolichucky Shale and the lower part of the subtidal succession of the Maynardville is equivalent to the start-up of carbonate platform deposition. The rate of relative sea-level rise was still exceeding the rate of carbonate sediment accumulation, as suggested by the relatively high shale/carbonate ratio and the common hardgrounds in this part of the stratigraphic succession (Figs. 3, 4A, D). The rest of the subtidal succession of the Maynardville is characteristic of a catch-up phase during which the carbonate accumulation rate exceeded the rate of sea-level rise and the platform aggraded to sea level. The increasing rate of carbonate production is reflected in the decreased shale/carbonate ratio in the upper part of the subtidal succession (Fig. 3). Progressive aggradation and shallowing of the carbonate platform resulted in the vertical transition from the subtidal into the peritidal depositional regime (Figs. 3, 5A). The peritidal succession is characteristic of a keep-up phase of carbonate-platform deposition, with the rate of sediment accumulation matching or exceeding the rate of relative sea-level rise. This is supported by the thick succession of very shallow-water deposits and by carbonate-platform progradation in a cratonward direction (Figs. 1–3). Thus, the shallowing-upward lithofacies succession of the Maynardville represents an aggradational to progradational stacking pattern. Such patterns are typical of highstand systems tracts deposited during decreasing rates of relative sea-level rise, a sea-level stillstand, and an initial relative sea-level fall (e.g., Van Wagoner et al. 1988).

The vertical succession of the Maynardville lithofacies is complex (Fig. 3). The subtidal succession does not appear to be cyclic. Parts of the peritidal succession can be divided into meter-scale shallowing-upward cycles. Such cycles are commonly interpreted to be a result of short-term eustatic sea-level oscillations (e.g., Koerschner and Read 1989; Bond et al. 1991; Osleger and Read 1991; Montañez and Osleger 1993; McLean and Mountjoy 1994; Yang et al. 1995). On the other hand, they may reflect the complex pattern of migration of tidal-flat lithofacies independently of periodic extrinsic mechanisms (e.g., Kozar et al. 1990; Hardie et al. 1991; Drummond and Wilkinson 1993; Wilkinson et al. 1996). The meter-scale cycles of the Maynardville Formation cannot be laterally correlated between outcrops with certainty because of the substantial distance between outcrops, poor exposure of parts of the outcrops, and the possibility that the observed cycles may not be laterally extensive (Fig. 3). Additionally, because of the apparent noncyclic nature of parts of the succession, and possible subjectivity in recognizing shallowing-upward trends (see Wilkinson et al. 1996), subdivision of the complete stratigraphic intervals in meter-scale cycles and their lateral correlation were not attempted (Fig. 3).

Maynardville–Copper Ridge Transition

Recognition of the influence of the late Steptoean (Dresbachian–Franconian or Sauk II–Sauk III) sea-level fall on the style of carbonate deposition led to the interpretation of the conformable interval at the Maynardville–Copper Ridge Dolomite transition as a sequence boundary (Kozar et al. 1990; Osleger and Read 1993; Glumac and Walker 1998). This boundary is referred to here as a *sequence boundary zone* correlative to the Dresbachian–Franconian unconformity on the craton (Fig. 3). The sequence boundary separates the Conasauga Group, which was deposited on a carbonate platform laterally linked to an intrashelf shale basin, from the Knox Group, which represents deposition on a broad carbonate shelf that was established following westward progradation of the platform over the infilled intrashelf basin (Figs. 1–3).

THE CHANGING STYLE OF PASSIVE-MARGIN DEPOSITION

Comparison of the depositional and sequence stratigraphic interpretations for the Middle Cambrian Conasauga Group grand cycles with the Maynardville Formation and the overlying Knox Group (Upper Cambrian to Lower Ordovician) provides important information about the changing style of deposition along the early Paleozoic passive margin of the southern

Appalachians. The Middle Cambrian Conasauga grand cycles followed a cyclical pattern of development from ramps during deposition of shale half-cycles, to flat-topped, rimmed platforms resulting in carbonate half-cycles (Srinivasan and Walker 1993; Rankey et al. 1994). Carbonate-platform deposition ended by subaerial exposure and/or drowning, which produced surfaces interpreted as sequence boundaries (Fig. 1). The Maynardville Formation in the study area lacks well-developed shelf-margin buildups and debris-flow deposits comparable to those of the Middle Cambrian Maryville Limestone (Srinivasan and Walker 1993). Thus, the development from ramp to high-relief, rimmed, Middle Cambrian carbonate platforms was replaced in the Late Cambrian by a gently sloping ramp, and locally developed shoals and lagoonal environments that evolved into the broad tidal flat of the Maynardville platform (Fig. 6).

Deposition of the Middle Cambrian Maryville Limestone terminated in a subaerial exposure and drowning unconformity, followed by Nolichucky Shale onlap (Fig. 1; Srinivasan and Walker 1993). In contrast, the transition from the Maynardville Formation into the overlying Copper Ridge Dolomite is within a conformable peritidal carbonate succession (Fig. 3). The deposition of this interval was influenced by the Steptoean (Dresbachian–Franconian) sea-level fall, as evidenced by common siliciclastic sand grains (Figs. 3, 5F). The presence of quartz sand in the coeval carbonate deposits of the Conococheague Formation in southwestern Virginia (Koerschner and Read 1989) suggests a platform-wide influence of this sea-level fall on carbonate deposition. Occurrences of quartz sand in the Steptoean carbonate deposits of the Petit Jardin Formation (Port au Port Group) in western Newfoundland are interpreted to indicate exposure of inboard platform areas and eolian influx of sand (Cowan and James 1993), whereas a quartzose calcarenite sediment apron in the coeval platform margin deposits (the Cow Head Group) represents a period of arrested shallow-water sedimentation, eolian sand bypassing, and margin progradation (James and Stevens 1986). Slope and basin-margin facies in eastern New York and Vermont contain periplatform breccias and resedimented and locally channelized quartz sands (Read 1989, and references cited therein), which may represent lowstand deposits related to the Steptoean sea-level fall. Steptoean deposits of the eastern carbonate platform margin are not exposed in the southern Appalachians, but that area may have been similarly affected by the sea-level fall. To the west of the Maynardville carbonate platform the sea-level fall facilitated the complete infilling of the Conasauga intrashelf basin and carbonate platform progradation toward the craton upon subsequent flooding (Figs. 1, 2). This progradation resulted in the establishment of widespread Upper Cambrian to Lower Ordovician peritidal carbonate deposition of the Knox Group. Similar paleogeographic changes have been documented for the Great Basin area, where a flood of terrigenous sediment (Worm Creek Quartzite), reflecting a sea-level lowering in the late Steptoean, was followed by the infilling of the Eureka–House Range embayment and the establishment of carbonate sedimentation in the entire Great Basin region (Palmer 1971; Brady and Rowell 1976). In addition, Steptoean carbonate rocks from both the Great Basin and the southern Appalachians record a large positive carbon-isotope excursion, with the maximum δ^{13}C values (4 to 5‰ PDB) coinciding with the Dresbachian–Franconian (Sauk II–Sauk III) sea-level fall (Brasier 1993; Saltzman et al. 1998; Glumac and Walker 1998). This indicates that the deposition of this stratigraphic interval is associated with a large perturbation in the global cycling of carbon, which may be related to changing sea level, ocean stratification, climate, sediment accumulation rates, or organic productivity (Glumac and Walker 1998).

PASSIVE-MARGIN EVOLUTION AND GRAND-CYCLE CESSATION

This section proposes a hypothesis on the relationship between passive-margin evolution and the end of grand-cycle deposition in the southern Appalachians. This hypothesis is based on the pattern of sedimentation described in this paper, and on the studies of continental-margin development and tectonic activity along the early Paleozoic Laurentian passive margins by others.

Faulting is common during the post-rift stage of development of basins along divergent plate margins, and is enhanced by sediment and water loading (Watts 1981; Heller et al. 1982; Scrutton 1982; Steckler and Watts 1982; Turcotte 1982; Pitman and Golovchenko 1988; Bott 1992; Frostick and Steel 1993a). These mechanisms generate relatively rapid subsidence superimposed on slower thermal passive-margin subsidence, and can influence the development of depositional sequences (Bally 1982; Watts and Thorne 1984; Cloetingh et al. 1985; Stephenson 1989; Embry 1989; Sloss 1991; Aubry 1991; Frostick and Steel 1993b). The Middle Cambrian was a time of significant tectonic activity along the Mississippi Valley–Rough Creek–Rome Trough intracratonic graben system to the west, the Birmingham fault system to the southwest, and other basement faults to the east of the study area (Fig. 7A; Read 1989; Thomas 1991). Synsedimentary fault movement along the Mississippi Valley–Rough Creek–Rome Trough during the Middle Cambrian produced grabens that were infilled by the Late Cambrian (Fig. 7; Thomas 1991). Early Cambrian initiation of the Birmingham fault system and continued fault movement until the early Late Cambrian are documented from the thickness and distribution of the Conasauga Group deposits (Fig. 7A; Thomas 1986; Ferrill 1989). Deposition of the Middle Cambrian Conasauga Group grand cycles took place during this immature stage of passive-margin development (Fig. 7A). Subsidence generated by episodic tectonic activity along extensional faults may have influenced sequence development by causing abrupt changes from carbonate to shale deposition in response to the drowning of carbonate platforms and the onlap of basinal shale (Figs. 1, 7A; Kozar et al. 1990; Walker et al. 1990; Srinivasan and Walker 1993; Rankey et al. 1994). The change from Conasauga grand-cycle deposition to the thick peritidal carbonate succession of the Knox Group corresponds with the cessation of tectonic activity along extensional fault systems (Fig. 7B). Deposits of the Knox Group extend across the intracratonic graben and basement fault systems without substantial thickness variations, which indicates the end of extension in the area (Thomas 1991). Thus, the end of grand-cycle deposition is coincident with the stabilization of the margin and the transition from immature into a mature passive margin in the Late Cambrian (Fig. 7B). The similarities in the style of deposition along the Cordilleran and Appalachian passive margins suggest that these Laurentian margins, which formed by rifting of Rodinia in the Late Proterozoic to Early Cambrian, experienced similar evolutionary histories.

The cessation of tectonic activity in the southern Appalachians was accompanied by a decrease in the rate of passive-margin thermal subsidence. Modeling of Laurentian passive-margin subsidence rates indicates the change from high and rapidly decreasing subsidence (95 to 35 m/My) during the Middle Cambrian, to much lower and slowly decreasing subsidence (35 to < 10 m/My) for the Late Cambrian and Early Ordovician (Bond et al. 1989). The decrease in subsidence rate was a consequence of the decline in thermal subsidence caused by an increase in lithospheric rigidity due to crustal cooling and thickening, and was coupled with a long-term sea-level fall (Bond et al. 1988; Bond et al. 1989). The results of numerical modeling by Reynolds et al. (1991) suggest that changing rigidities can influence passive-margin stratigraphy by modifying the distribution of accommodation space generated by flexure or isostatic response of the lithosphere to loading. Passive margins with low flexural rigidities have deposition restricted to a narrow shelf characterized by the vertical distribution of accommodation space produced by sediment loading (Reynolds et al. 1991). These conditions favor the formation of Type 2 sequence boundaries, which form when the rate of sea-level fall is lower than the rate of basin subsidence (Van Wagoner et al. 1988). In contrast, the formation of Type 1 sequence boundaries, which are produced when the rate of sea-level fall exceeds the rate of basin subsidence (Van Wagoner et al. 1988), is favored on margins with high flexural rigidities where accommodation space generated by isostasy is broadly distributed along a much wider shelf (Reyn-

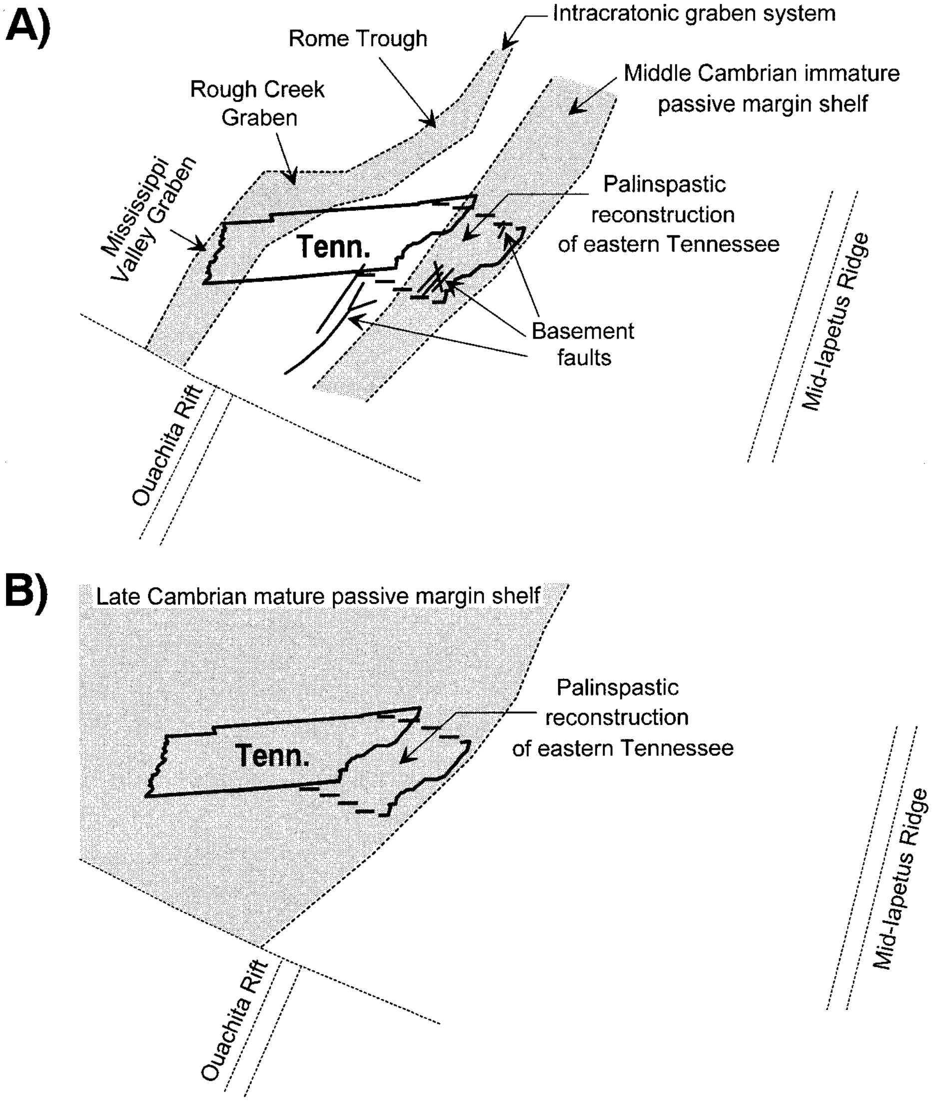

FIG. 7.—Reconstruction of Cambrian passive-margin setting (after Thomas 1991). **A)** Middle Cambrian immature passive margin. Note the position of the active intracratonic graben and basement fault systems. **B)** Late Cambrian mature passive margin. Note the cessation of tectonic activity and lateral expansion of the shelf.

olds et al. 1991). The presence of an intrashelf basin adjacent to a carbonate platform on the narrow Middle Cambrian shelf (Figs. 2, 7A), and Type 2 sequence boundaries within the lower Conasauga Group (Kozar et al. 1990), is consistent with lower flexural rigidities of the Middle Cambrian passive margin as compared to the Late Cambrian and Early Ordovician, when the Maynardville–Copper Ridge carbonate platform expanded laterally towards the craton over the completely infilled intrashelf basin and inactive graben system (Fig. 7B). In addition, the sequence boundary separating the Conasauga from the Knox Group has been interpreted as a Type 1 boundary (Kozar et al. 1990; Osleger and Read 1993). The reduction in rate of early Paleozoic Laurentian passive-margin subsidence, resulting from decay of the thermal anomaly, was augmented by the long-term sea-level fall in the Late Cambrian and Ordovician (Bond et al. 1989). These conditions favored the expansion of shallow-water carbonate platform sedimentation along the margins of Laurentia and can account for the similarities between the Cordilleran and Appalachian stratigraphy. In the southern Appalachians, deposition of the approximately 1000-m-thick, peritidal carbonates of the Knox Group reflects the final establishment of a mature passive margin, with sedimentation controlled by thermal subsidence and eustatic sea-level changes.

CONCLUSIONS

Cambrian grand cycles of the Conasauga Group represent a complex interplay between carbonate platform and intrashelf shale basin sedimentation along the early Paleozoic passive margin of the southern Appalachians. The deposition of the Maynardville Formation (Upper Cambrian) marks the end of grand-cycle deposition and a prominent change in the style of passive-margin sedimentation. The Maynardville was deposited in gently sloping, shallow subtidal ramp and localized shoal and lagoonal environments that were laterally linked to a broad, semiarid tidal flat. The succession of the Maynardville lithofacies reveals upward shallowing from entirely subtidal, mixed carbonate and fine siliciclastic deposits to predominantly peritidal dolostone in response to carbonate-platform aggradation and westward progradation over the infilled intrashelf basin. The establishment of shallow-water carbonate deposition was favored by the decreased rate of thermal subsidence, augmented by the long term sea-level fall, and by stabilization of the passive margin due to cessation of tectonic activity in the Late Cambrian. The final stabilization of the passive margin is reflected in the deposition of the thick, laterally extensive peritidal carbonates of the overlying Upper Cambrian to Lower Ordovician Knox Group. The transition from the Maynardville to the Copper Ridge Dolomite (Knox

Group) is within a conformable interval interpreted as a sequence boundary zone correlative with the craton-wide late Steptoean (Dresbachian–Franconian or Sauk II–Sauk III) unconformity. This boundary separates the sedimentary successions of the Conasauga and the Knox Groups, which were deposited in different tectonosedimentary settings that existed during two distinct stages in the development of the passive margin. Similar transitions in sedimentary successions elsewhere may suggest a similar passive-margin evolutionary history.

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