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4111 S Darlington
Suite 100
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USA

Phone: 918-610-3361
Fax: 918-621-1685
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GRADUAL ESTABLISHMENT OF IAPETAN "PASSIVE" MARGIN SEDIMENTATION: STRATIGRAPHIC CONSEQUENCES OF CAMBRIAN EPISODIC TECTONISM AND EUSTASY, SOUTHERN APPALACHIANS

EUGENE C. RANKEY*, KENNETH R. WALKER, AND KRISHNAN SRINIVASAN
Department of Geological Sciences, 306 G & G Building, University of Tennessee, Knoxville, Tennessee 37996-1410 USA

ABSTRACT: **The Middle to Upper Cambrian Conasauga Group of the southern Appalachians constitutes part of the thick pericratonic Cambro-Ordovician Sauk sequence that represents the interplay between an extensive carbonate platform to the east and a deeper-water intrashelf shale basin to the west. The Conasauga Group consists of a series of interfingering carbonate and shale formations; the shales represent deeper-water deposition (50 m+), and the carbonates show evidence for gradual shoaling (through aggradation and progradation) from deeper water to shallow water. The upper parts of the Craig Limestone Member (Rogersville Shale) and the Maryville Limestone (both Middle Cambrian) contain evidence for subaerial exposure of subtidal sediments followed by platform drowning. Following platform exposure that shut down carbonate production, a large relative sea-level rise (driven by an increase in the rate of subsidence) led to platform reinundation, but was rapid enough to drown the carbonate platform. Flooding was sufficient to allow deeper-water basinal shales to onlap the drowned platform. Changes in the rate of subsidence driven by thermal cooling of the lithosphere, sediment loading, and/or regional extension were probably responsible for "cyclic" sedimentation, even though burial curves suggest gradual, "thermal" subsidence through this time.**

Lithofacies patterns and the regional tectonism reviewed herein suggests that the Iapetan margin was not fully stabilized (subsiding uniformly spatially and temporally, a true passive margin) until the Late Cambrian. Critical stratigraphic studies of other Cambrian (and younger) "passive" margins may reveal comparable "anomalies" related to similar, "jerky" subsidence patterns.

INTRODUCTION

Passive margins form following a period of rifting associated with continental breakup. Once the newly formed active spreading center migrates away from the continental margin and active rifting ceases, the continental margin is assumed to subside uniformly at an exponentially decreasing rate by thermal subsidence (Sleep 1971; McKenzie 1978). First-order subsidence patterns (R1 curves, calculated by plotting sediment thickness, with various corrections, versus time; Bond and Kominz 1984) of many newly formed margins follow an apparently simple, predictable subsidence history. Because subsidence is thus assumed to be known, perturbations from predicted sedimentation patterns have been interpreted to be the result of allogenic mechanisms, particularly eustatic sea-level fluctuations (Vail et al. 1977; Haq et al. 1988; Sarg 1988; Koerschner and Read 1989; Bond et al. 1988; Bond et al. 1989; Osleger and Read 1991, 1993; Read et al. 1991).

In the southern Appalachians, Late Proterozoic–Early Cambrian rifting associated with continental breakup is indicated by thick syn-rift deposits (Ocoee Group, Mount Rogers Group, etc.; Hatcher 1989). The rift sediments are unconformably overlain by alluvial-fan to marine siliciclastics of the Lower Cambrian Chilhowee Group (Simpson and Eriksson 1989, 1990; Hatcher 1989; Thomas 1991). Fichter and Deicchio (1986), Simpson and Eriksson (1989, 1990), Hatcher (1989), Read (1989), Thomas (1991), and others have suggested that the transition from rift to passive margin occurred during the Early Cambrian and the period following was characterized by thermal subsidence and passive-margin sedimentation. We propose that the passive margin fully stabilized only in the Late Cambrian and that nonthermal episodic subsidence was involved in sequence development into the Late Cambrian.

By the Middle Cambrian, an extensive carbonate platform had developed on this margin. In the southern Appalachians, the platform was bounded to the east by the deep, open Iapetus ocean, and to the west by a shallower intrashelf basin (Hasson and Haase 1988; Walker et al. 1990; Srinivasan and Walker 1993). The Middle and Upper Cambrian Conasauga Group of the southern Appalachians (Fig. 1) represents the interplay between the carbonate platform to the east and the shale basin to the west (Walker et al. 1990), carbonate units representing times when the platform prograded over previously basinal (shaly) areas (Fig. 1; Walker et al. 1990; Srinivasan and Walker 1993). This study focuses on two Middle Cambrian carbonate units of the Conasauga, the Craig Limestone Member of the Rogersville Shale, and the Maryville Limestone, exposed in the Dumplin Valley and Copper Creek thrust sheets in east Tennessee.

Many workers have recognized third-order (1–10 My) cyclic alternations of shale-dominated formations and carbonate-dominated formations similar to those of the Conasauga on many Cambrian early passive margins (Canadian Rocky Mountains, Aitken 1966, 1978; Great Basin, Hinze and Robinson 1975, Palmer and Halley 1979, Mount and Rowland 1981; northern Appalachians, Chow and James 1987, Cowan and James 1993; southern Appalachians, Palmer 1971, Koerschner and Read 1989, Srinivasan and Walker 1993). Aitken (1966, 1978, 1981) called these repetitions "grand cycles," which consist of a lower shale half-cycle (with or without carbonate beds) gradationally overlain by a carbonate half-cycle. Grand cycles were originally loosely defined as "300 to 2,000 feet of strata" spanning "two or more fossil zones" (Aitken 1966), although these distinctions are probably overgeneralizations (Aitken 1981). Many grand cycles represent a general shoaling-upward trend from deeper-water shale to shallow-water limestone (but see Chow and James 1987 and Cowan and James 1993). At any one location, grand cycles may not culminate in peritidal deposits because environments from deeper-water to peritidal could be affected by platform exposure and drowning, as shown by the present study. As in the southern Appalachians, carbonate units of many grand cycles represent *cratonward* platform progradation across intrashelf basins (Palmer and Halley 1979; Aitken 1981).

The origin of Cambrian grand cycles, like that of other third-order sequences, has most commonly been attributed to eustatic sea-level fluctuations (Aitken 1981; Read et al. 1986; Bond et al. 1988, 1989; Koerschner and Read 1989; Osleger and Read 1991, 1993). Other controls on grand-cycle development that have been suggested include tectonism (Palmer 1981), changes in sediment supply related to climatic changes (Chow and James 1987; Cowan and James 1993), changes in the rate of sea-level rise (Palmer and Halley 1979; Mount and Rowland 1981; Chow and James 1987), combinations of changes in the rate of subsidence and rate of sedimentation (Hardie 1989; Kozar et al. 1990; Srinivasan and Walker 1993), and a combination of platform exposure, "lag time," and thermal subsidence (Rankey et al. 1992; Srinivasan and Walker 1993). The results of the present study suggest that: (1) sedimentary aggradation and progradation controlled the internal stratigraphic packaging of these third-order sequences; (2) nonthermal, or "jerky," subsidence, possibly

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* Present address: Department of Geology, University of Kansas, 120 Lindley Hall, Lawrence, Kansas 66045-2124 USA.

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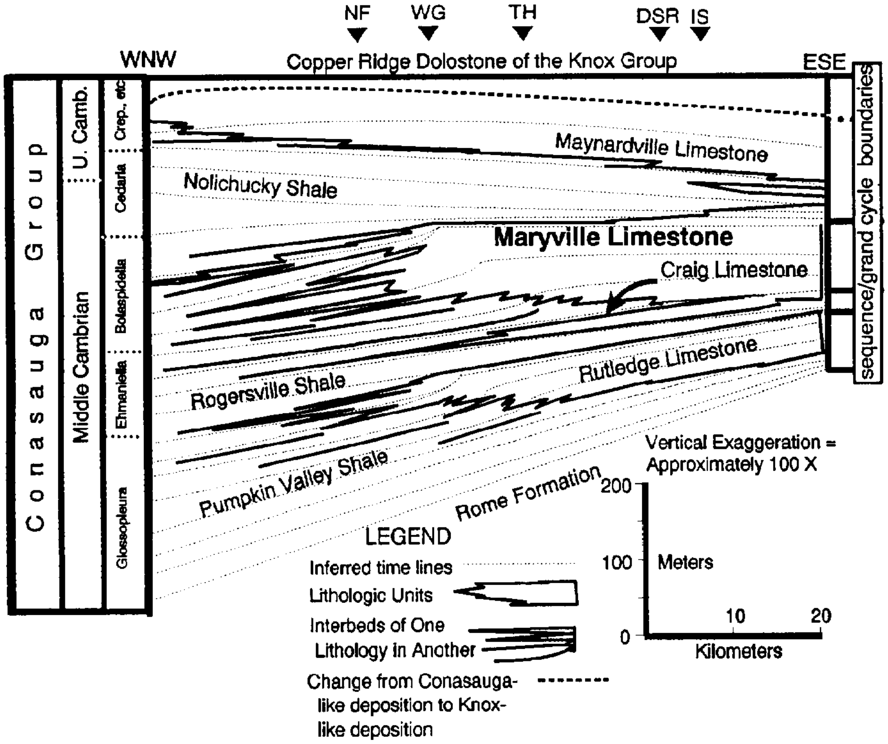


FIG. 1.—Regional stratigraphic model. Note *cratonward* progradation of the carbonate platform (limestone units) over previously basinal areas (shale units). Modified from Walker et al. (1990) and Srinivasan and Walker (1993). Trilobite zones are from Palmer (1971, 1981) and Derby (1965). The abbreviations at the top of the figure represent the following localities: NF = Norris Freeway, WG = Woods Gap, TH = Thorn Hill, DSR = Deep Springs, IS = Interstate.

coupled with eustasy, controlled or enhanced development of the Middle Cambrian sequence boundaries; and (3) this nonthermal subsidence characterized the Iapetan margin until the Late Cambrian. Only then did a true passive margin develop, which subsided uniformly by thermal subsidence alone.

The present study is based on outcrop analysis of 21 localities (Fig. 2; see also Srinivasan and Walker 1993; Srinivasan 1993; Rankey 1993), study of 98 slabs and 250 thin sections, and analysis of 31 samples for oxygen and carbon stable-isotopic ratios. This report expands on the work of Srinivasan and Walker (1993) and includes the Craig Limestone and more platform-interior environments of the Maryville Limestone, documents variable responses to exposure and drowning across the platform, describes the effect of episodic tectonism on platform termination, and comments on the tectonic implications of our findings.

GENERAL STRATIGRAPHY

The Rogersville Shale consists of lower and upper shale members separated by the Craig Limestone Member (Fig. 1; see Rodgers 1953). The shales of the Rogersville are thickest to the west/southwest and pinch out to the east and northeast as the limestones thicken (Rodgers 1953). The lower Rogersville (below the Craig) is up to 85 m thick (Hatcher 1965), and the Craig is up to 25 m thick. Together, these are interpreted to form a previously undocumented grand cycle. The Rogersville is characterized by the trilobite *Ehmaniella* (Middle Cambrian), which is present both below and above the Craig (Resser 1938).

The upper Rogersville, here interpreted to be the lower shale of the upper-Rogersville–Maryville grand cycle, is up to 20 m thick. The Maryville Limestone is up to 210 m thick and overlies the upper Rogersville shale. The Maryville platform (discussed below) represents a more complete evolution than the Craig platform, as suggested by its greater thickness and lateral extent (Hasson and Haase 1988) and more complete shoaling trend. Like the Craig, however, the Maryville is marked by a prominent exposure surface coincident with a sequence boundary above which there is a significant change in sedimentation patterns. This exposure surface is at the *top* of the Maryville in shelf-margin areas and *within* the Maryville in more platformward areas. The top of the Maryville ranges between the *Bolaspidella* zone (to the west/northwest) and the overlying *Cedaria* zone (to the east/northeast) (Resser 1938; Derby 1965; Rasetti 1965; Erwin 1981).

Overlying the Maryville is the Nolichucky Shale, which, like the other shale units, was deposited in deeper water (Walker et al. 1990; Srinivasan and Walker 1993). The Maryville-Nolichucky contact has been previously recognized as the top of a grand cycle (Aitken 1981; Palmer 1981) and a sequence boundary (Srinivasan and Walker 1993). As we show in this study, however, the grand-cycle top and sequence boundary are not always the same stratigraphic horizon.

INTERNAL STACKING PATTERNS OF SOUTHERN APPALACHIAN GRAND CYCLES

The term *stratigraphic package* refers to a group of genetically related rock types, all "linked" because they represent subenvironments of a similar setting (i.e., slope or peritidal) and is essentially synonymous with "lithofacies association". The Craig and Maryville consist of several stratigraphic packages (Fig. 3), each of which consists of several rock types. We briefly review Craig and Maryville stacking patterns here, because they help illustrate controls on sequence development and termination. Table 1 summarizes pertinent lithologic information.

BASIN/SLOPE PACKAGE

The lower and upper Rogersville Shale underlie the basin/slope package of the Craig and Maryville. The black, clay shales of the Rogersville contain paper-thin laminae, glauconite, and framboidal pyrite, but few fossils and no evidence of bioturbation or wave activity. The basin/slope packages of the Craig and Maryville consist of polymictic, multigenerational intraclast packstone (Fig. 4A), nodular mudstone, thinly laminated calcareous siltstone, and oncoid/ooid/trilobite packstone. Shale interbeds (identical

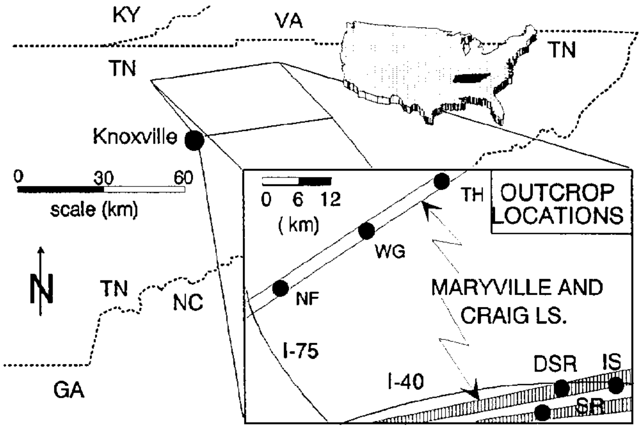


FIG. 2.—Generalized sketch of Craig and Maryville outcrops and primary measured sections in the study area. Section key: DSR = Deep Springs Road, IS = Interstate 40 section, SR = Sockless Road, BR = Botherton Road, SQ = Sevierville Recycling Center (*Dumplin Valley fault zone*). WG = Woods Gap, NF = Norris Freeway, TH = Thorn Hill, GR = Graveston (*Copper Creek fault*).

to the Rogersville shales) thin up section and are absent above this package. Hardgrounds, fine quartz silt, glauconite, partial Bouma sequences, framboidal pyrite, and phosphate- and manganese-coated grains are common, and fossils are rare to absent (when present, they are commonly coated with phosphate and manganese). In intraclastic beds, polymictic clast associations, rafted and projecting clasts, and random to subparallel clast orientation are all present (Srinivasan and Walker 1993). No thrombolites, microbial laminites, or encrusting *Girvanella* are present in carbonates interbedded with the shales (cf. Aitken 1978; Markello and Read 1981, 1982).

In more basinward (west) sections, the Craig and Maryville may consist of this package alone (up to 70 m thick) (see also Kozar 1986, Srinivasan 1993). In more platformward sections, the basin/slope package and the underlying and/or interbedded shales are thinner and siliciclastics are much less common. On the basis of these observations, the Rogersville shales and the basin/slope package are interpreted to represent slow, deeper-water deposition below storm wave base in water depths of 40–50 m. Bond et al. (1989) and Osleger and Read (1991) suggested similar (and greater) water depths for identical deposits in the Upper Cambrian of the Appalachians and Cordillera.

MID-RAMP AND AGGRADING-RAMP PACKAGES

The mid-ramp and aggrading-ramp packages gradationally to abruptly overlie the basin/slope package. Together they are up to 50 m thick and consist of burrow-mottled mudstone-wackestone (Figs. 3, 4B) and thin packstone-grainstone layers or lenses. Packstone-grainstone layers consist of ooids, peloids, fossils, and composite grains, and commonly have a scalloped base and gradational to sharp upper contact. Packstone-grainstone layers are thin (mid-ramp package, all less than 0.15 m thick, most less than 0.05 m thick; aggrading-ramp package, 0.01–1.2 m thick) and commonly discontinuous across a lateral distance of less than 300 m (Rankey and Walker 1993). Many grainy layers contain no sedimentary structures and are internally homogeneous; fining-upward layers, hardgrounds, and cross-lamination are present but rare. No evidence for shoaling-upward cycles, peritidal deposition, or subaerial exposure is present (with the exception of the sequence boundary at the top of the Craig, discussed in the section on development of sequence boundaries in the intrashelf basin below). Likewise, no regular thickening, thinning, or "bundling" of beds, other than a general upward increase in thickness of grainy units, is present (Rankey and Walker 1993). In the most platformward study area (DSR; Fig. 3), the Craig is capped by the aggrading-ramp package and a surface of subaerial exposure. The Craig platform thus did not complete the shoaling trend (to peritidal deposits) as the Maryville platform did. Instead, it appears that the platform was "aborted" prior to full development.

The sediments of the mid-ramp and aggrading-ramp packages represent the beginning of *in situ* carbonate production and platform aggradation. The upward increase in abundance and thickness of grainy layers reflects a general shoaling-upward trend into a zone of more frequent reworking by major storms. The mid-ramp and aggrading-ramp packages correspond to the aggradational stacking pattern of Srinivasan and Walker (1993) and the start-up and catch-up phases of Kendall and Schlager (1981), Sarg (1988), and Kendall et al. (1991).

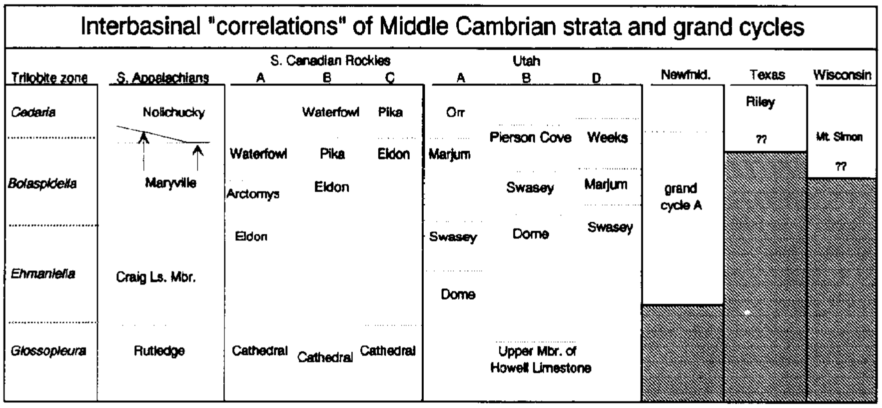
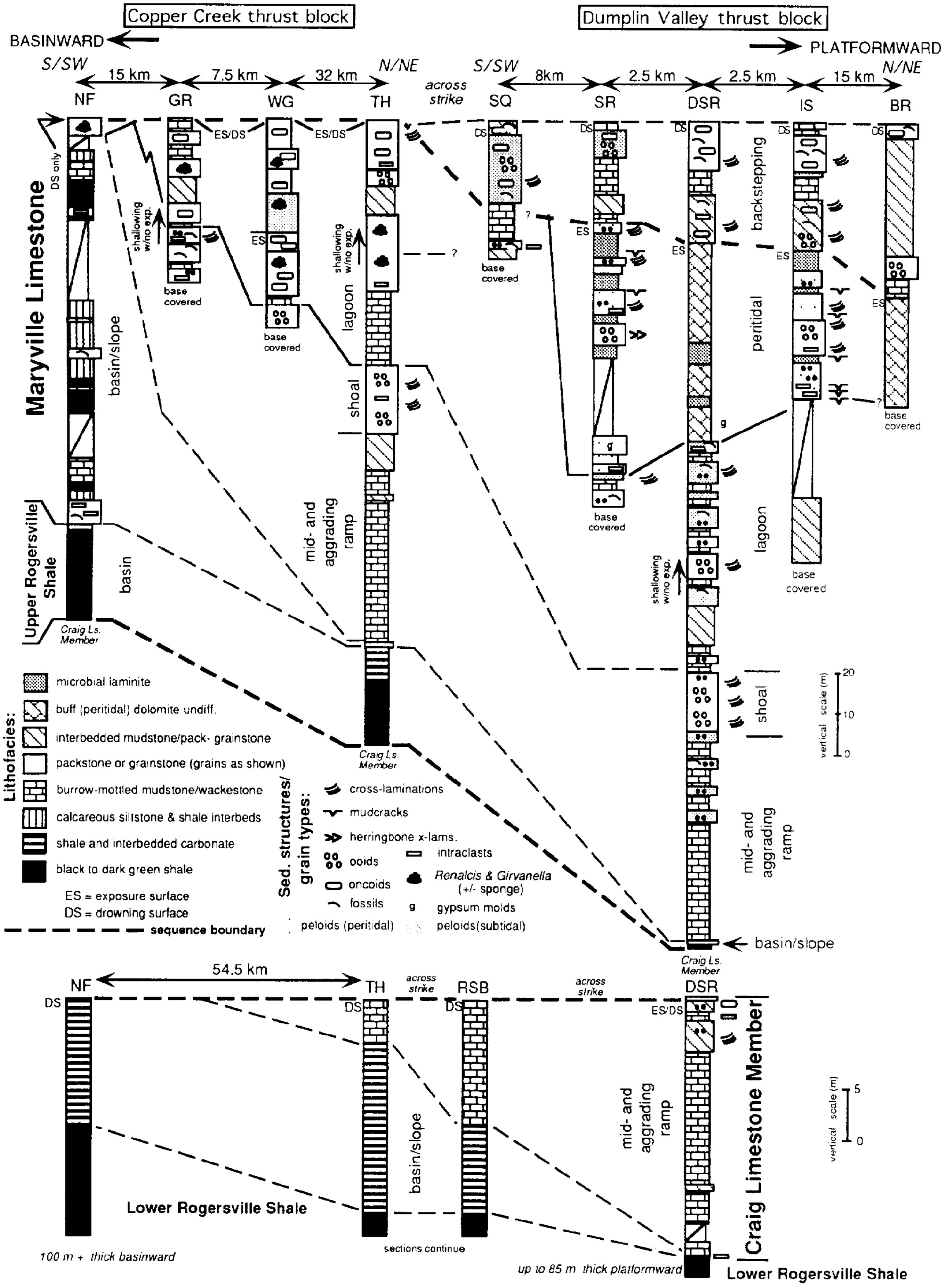


FIG. 3.—Middle Cambrian grand-cycle interbasinal "correlations", showing only units that constitute the tops of cycles. The top of the Craig is within the *Ehmaniella* zone. The top of the Maryville is time-transgressive, within the *Bolaspidella* zone in basinal areas, and within *Cedaria* zone in on-platform areas. The sequence boundary (dashed line) is within the *Bolaspidella* zone, however. Note that a consensus on correlation is not present, yet many workers use correlations to suggest eustatic control on cycle development. Pierson Cove (in Utah) is biostratigraphically equivalent to the lower Marjum in Utah (Robison 1976). Long-term (Sauk) sea-level rise is manifest as transgression in cratonic sections (Texas, Wisconsin) in Late Cambrian. See text for discussion. A = Palmer (1981); B = Bond et al. (1989); C = Aitken (1981); D = Hinze and Robison (1975); Newfoundland data from Chow and James (1987); Texas data from Palmer (1954); Wisconsin data from Ludvigson and Westrop (1985); Southern Appalachian data from Rasseti (1965), Palmer (1981), and interpretation in this report.

TABLE 1.—*Lithologic description of Maryville Package Components*

Lithology	Bedding Thickness	Basal Contacts	Constituent Particles	Sedimentary Structures	Other	Package
Packstone to grainstone	up to 5 m	abrupt to gradational	major: ooids, oncoids, trilobites minor: echinoderms, peloids, intraclasts	cross-lamination imbricated intraclasts hardgrounds		backstepping
Mud-wacke- to packstone	up to 4 m	gradational to abrupt	major: micrite minor: peloids, ooids, quartz silt, glauconite	fine lamination burrows and hardgrounds		
Cryptalgal laminite	up to 4 m, most < 2 m	gradational to abrupt	small peloids, micrite	fine, planar lamination, undulose; fining upwards "anti-gravity" features mudcracks; irregular and laminar fenestrae	many completely dolomitized thin (cm) packstone layers early cementation, as shown by truncated cements and laminite intraclasts	peritidal
Fenestral mudstone/ packstone	up to 2 m	gradational	peloids, small intraclasts, ooids	laminar to irregular fenestrae	fenestrae filled with coarse blocky dolomite to calcite	
Ooid packstone-grainstone	< 2 m	abrupt, irregular, erosional?	major: ooids minor: peloids, small intraclasts (ooids or underlying lithology)	uni- and bidirectional cross-lamination	ooids tangential, tightly packed up to 5 laminae ooid nuclei echinoderms, peloids	
Intraclast packstone	< 1 m	erosional (up to 0.3 m relief)	major: intraclasts minor: peloids, ooids	imbricated intraclasts some layers discontinuous, fine upwards into smaller intraclasts and peloids	intraclasts up to 4 cm long, rounded, made of micrite, ooid peloid packstone, or laminite locally channel morphology	
Peloid packstone	< 3 m	gradational to abrupt	major: peloids minor: intraclasts (near base), ooids	burrowed	dark gray, very fine-grained, often completely dolomitized buff to light gray, fine to coarse grain w/ small intraclasts	
Mudstone	< 1 m	gradational	micrite	none, burrow-homogenized?	commonly completely dolomitized	
Mottled mud-wackestone	up to 4 m	gradational to abrupt	micrite, with minor fossils, peloids, ooids	burrows	contains thin (< 1 cm) fossil and peloid lenses	lagoon
Packstone	up to 1.2 m	gradational to abrupt, irregular	major: peloids, ooids minor: trilobites, echinoderms, small intraclasts near base	cross-lamination	peloids very fine grained often completley dolomitized ooids identicial to those in shelf edge	
Boundstone	up to 25 m	irregular	major: *Renalcis* clusters, *Girvanella* crusts, and fragments. minor: oncoids, sponge spicules trilobites, peloids.	Biohermal geometry, growth cavities floored with geopetal sediment and fibrous cement	Hardground at base of buildup subaerial exposure surfaces within and at the top of buildup.	shoal
Grainstone	up to 10 m	abrupt, irregular	major: ooids minor: echinoderms, trilobites, peloids, ostracods, intraclasts (most commonly oolitic w/ fibrous cement)	cross-laminated	ooids relatively small (up to 2 mm), radial to tangential; nuclei composed of echinoderms, peloids, trilobites early fibrous cement	
Mudstone to wackestone	< 0.5 m	abrupt to gradational	micrite with rare ooids, echinoderms	occasionally burrowed		
Mottled mud-wackestone	up to 5 m	abrupt to gradational	major: micrite minor: trilobites, composite grains, peloids, ostracods	abundant burrows convex-up fossils		aggrading ramp
Packstone-grainstone	up to 1.9 m	abrupt, irregular	major: ooids, peloids, composite grains, small intraclasts minor: oncoids, trilobites, echinoderms, ostracods	grade upwards to mud-wackestone cross-lamination intraclasts common near base of units; made of micrite, similar to underlying unit	laterally continuous across outcrop, but often discontinuous across 0.3 km; may thicken and thin across outcrop	
Mottled mud-wackestone	up to 21 m	gradational	major: micrite minor: trilobites, composite grains, peloids	abundant burrows, convex-up fossils	hardgrounds in lower 7 m	mid-ramp
Packstone-grainstone	< 0.15 m	abrupt, scalloped, up to 2 cm relief	major: peloids, ooids, small intraclasts (commonly identical to underlying lith.) minor: echinoderms, trilobites, oncoids, ostracods	fining-upwards cross-lamination	laterally discontinuous, often form lenses allochems commonly found in burrows in underlying mudstones	
Packstone	< 0.5 m	abrupt, irregular	major: intraclasts, trilobite fragments, oncoids minor: peloids, ooids, glauconite	hardgrounds, imbrication	allochems commonly have mineralized rim fibrous cement	basin/slope
Nodular mudstone	< 0.5 m	abrupt, irregular	micrite, rare trilobites, glauconite	hardgrounds and truncation surfaces		
Black shale	few meters	sharp	black lime mud with terrigenous clay and quartz silt	thinly laminated		


Copper Creek thrust block
Dumplin Valley thrust block
BASINWARD
PLATFORMWARD
S/SW
15 km
7.5 km
32 km
N/NE
across strike
S/SW
8km
2.5 km
2.5 km
15 km
N/NE
NF
GR
WG
TH
SQ
SR
DSR
IS
BR
Maryville Limestone
DS only
ES/DS
ES/DS
shallowing w/no exp.
ES
DS
ES
base covered
base covered
lagoon
shallowing w/no exp.
?
base covered
basin/slope
shoal
mid- and aggrading ramp
backstepping
peritidal
g
base covered
base covered
lagoon
shallowing w/no exp.
base covered
Upper Rogersville Shale
basin
Craig Ls. Member
Craig Ls. Member
shoal
mid- and aggrading ramp
vertical scale (m)
20
10
0
Lithofacies:
microbial laminite
buff (peritidal) dolomite undiff.
interbedded mudstone/pack- grainstone
packstone or grainstone (grains as shown)
burrow-mottled mudstone/wackestone
calcareous siltstone & shale interbeds
shale and interbedded carbonate
black to dark green shale
ES = exposure surface
DS = drowning surface
sequence boundary
Sed. structures/ grain types:
cross-laminations
mudcracks
herringbone x-lams.
ooids
intraclasts
oncoids
Renalcis & Girvanella (+/- sponge)
fossils
gypsum molds
peloids (peritidal)
peloids(subtidal)
basin/slope
Craig Ls. Member
NF
54.5 km
TH
across strike
RSB
across strike
DSR
DS
DS
DS
ES/DS
basin/slope
mid- and aggrading ramp
Craig Limestone Member
vertical scale (m)
5
0
Lower Rogersville Shale
100 m + thick basinward
sections continue
up to 85 m thick platformward
Lower Rogersville Shale

SHOAL PACKAGE

The shoal package is up to 25 m thick (Fig. 3) and is composed of thick-bedded ooid grainstone and *Renalcis-Girvanella*-sponge boundstone. Srinivasan and Walker (1993) and Simmons (1984) recognized two subenvironments in Maryville ooid shoals: (1) an interval characterized by ooid grainstone, cross-lamination, and marine cements, representing the active oolite zone; and (2) an interval characterized by more common micrite, small intraclasts, and less common (although still dominant) ooids and cross-lamination. Ooid grainstones are thick-bedded, and the proportion of ooids increases up section. Cross-bed sets are up to 1 m thick but quite variable. Thin mudstone lenses/layers are rare, and no peritidal facies or minor exposure surfaces are present.

Renalcis-Girvanella-sponge boundstones (Fig. 4D) are present above mid-ramp and aggrading-ramp packages of the Maryville in basinward locations (e.g., TH, WG; see Figure 2). These deposits contain growth cavities with internal sediment and common fibrous marine cement and have a mound-like shape (Srinivasan and Walker 1993). In these locations, the top of the Maryville Limestone (a coincident subaerial-exposure and drowning surface, discussed below) is interpreted to be a sequence boundary. One exception is in the most basinward study location (NF), where the boundstones overlie slope deposits and contain no evidence for subaerial exposure, but were drowned like the mounds on the shelf.

The thick, cross-bedded oolitic deposits appear to be similar to those documented in Holocene ooid shoals by Hine (1977) and Harris (1979), and in the Cambrian by Markello and Read (1981, 1982) and Erwin (1981). The thick ooid grainstones in the shoal package represent migrating ooid shoals, and the boundstones represent shelf-edge bioherms. These sediments correspond to the progradational stacking pattern of Srinivasan and Walker (1993) and the keep-up phase of Kendall and Schlager (1981). The downslope bioherm with no evidence for subaerial exposure (NF) formed during the relative fall in sea level that exposed most of the shallow platform (Srinivasan and Walker 1993).

LAGOON PACKAGE

The lagoon package is up to 50 m thick and consists of burrow-mottled mudstone-wackestone, very fine-grained peloid packstone, and ooid-peloid-fossil-oncoid packstone-grainstone (Fig. 3, Table 1). No evidence for development of tidal-flat caps or minor subaerial exposure is present in this package. Mudstone-wackestone beds are up to 4 m thick, while packstone-grainstone layers may be up to 5.6 m thick (although most are much less). The fine-grained peloidal packstone units are commonly homogeneous with rare burrows. The grainstone units are sometimes cross-laminated with cross-bed sets less than 0.4 m thick. These deposits are distinguished from shoal-package ooid deposits in that they are thinner and contain more mud and thinner cross-bed sets. Mudstone and packstone-grainstone layers are interbedded, but no cyclicity (such as that observed by Osleger and Read 1991) is present.

Mottled mudstone-wackestone and fine-grained peloid packstone represent deposition in environments similar to those documented in the modern Bahamas by Purdy (1963) for "mud" and "pellet-mud" facies. Ooid-peloid-fossil packstone probably represents sporadic bankward storm or tidal deposits or washovers, similar to those in the lagoonal facies of the modern Bahamas (Purdy 1963) and in the Plio-Pleistocene of the Bahamas (Beach and Ginsburg 1980). Some of the thicker, cross-laminated oolitic deposits may represent relative falls in sea level or shoals, although no evidence for minor subaerial exposure is present. Thus, the sediments of the lagoonal package suggest deposition in protected subtidal settings bankward of the shelf-edge shoals.

PERITIDAL PACKAGE

The peritidal package is 0–58 m thick in the Dumplin Valley strike belt (Figs. 2, 3) and is absent to the west/northwest. It consists of microbial laminite, fenestral mudstone-packstone, ooid packstone-grainstone, intraclast packstone, peloid packstone, mudstone, and several thin, dolomitized intervals where no primary depositional features remain (Table 1). Mud cracks, fenestrae, and intraclasts are common; channel-like bedding, gypsum molds (Fig. 4E), club-shaped cyanobacterial heads (SH), and decimeter-scale herringbone cross-lamination are present but relatively rare. Ooid packstone-grainstone units usually have an intraclastic lag at the base and may contain small-scale cross-lamination. These rock types are arranged in shoaling-upward cycles that are not correlative across 3 km (Rankey and Walker 1993).

Regionally, this package is discontinuous along and across strike (Rankey and Walker 1993). It ranges from over 30 m thick to absent within less than 1 km, and thus contrasts with time-equivalent peritidal deposits (Honaker and Elbrook Dolomites just north of the study area), which prograded rapidly across much of the 200-km-wide platform in periods of 20 ka according to Koerschner and Read (1989). Correspondingly, modern tidal-flat progradation rates are measured in kilometers per thousand years. The peritidal deposits of the Maryville, 30 m + thick, probably represent several hundreds of thousands of years, yet the tidal flat prograded less than 2 km. We suggest that this pattern may be due to some kind of tectonic retardation of progradation (e.g., minor tilting) that maintained deeper water (1–10 m?) in areas less than 1000 m away from areas with peritidal deposition. The area where these rapid facies transitions are present was also the location of a Middle Ordovician platform edge, indicating possible reactivation at that time.

These Maryville peritidal sediments indicate deposition on an arid tidal flat in environments similar to those in the modern Persian Gulf. The uppermost strata of the peritidal package in the Dumplin Valley area (Fig. 2) contain evidence for prolonged exposure (discussed below) and are correlative to the subaerial exposure surface at the top of the Maryville on subtidal lagoonal and shelf-edge deposits in more basinward sections (Srinivasan and Walker 1993). In those sections, deeper-water shales of the Nolichucky directly overlie the exposure surface, and the top of the Maryville is within the *Bolaspidella* zone (Rasetti 1965; Erwin 1981).

BACKSTEPPING PLATFORM/SHELF PACKAGE

In the Maryville, this package is up to 28 m thick in the Dumplin Valley area (Figs. 2, 3) but thins to absent to the west/northwest and thickens to the east-northeast. It is characterized by packstone-grainstone with ooids, oncoids, fossils, and (less commonly) intraclasts, quartz-silty peloid packstone, and burrow-mottled mudstone-wackestone (Table 1). Hardgrounds, glauconite, pyrite, and truncation surfaces (with up to 30 cm relief; Fig. 4F) become more common up-section, and no evidence for subaerial exposure is present. The quartz-silty peloid packstone (up to 0.6 m thick)

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FIG. 4.—Stratigraphic sections of middle Conasauga Group grand cycles. Locations and abbreviations are as shown in Figure 2 and its caption. Lithologies and facies patterns are somewhat lumped due to scale. Upper and lower cross sections have different vertical scales. All sections are hung on the lithologic tops of the carbonate units (i.e., the grand-cycle tops). Note that these grand-cycle tops may not correspond to the sequence boundaries. Where the "backstepping platform shelf" package is present at the top of the Maryville, the limestone-shale contact is demonstrably younger than where it is not. Light dashed lines represent gross lithologic correlations; time equivalence is not inferred. Modified and expanded from Srinivasan and Walker (1993). Sections are described in detail by Srinivasan (1993), Rankey (1993), and Simmons (1984).

in this package is similar to that in the basin/slope package and often contains millimeter-scale laminae, centimeter-scale grading, and framboidal pyrite. Ooid packstone-grainstone (most beds < 0.5 m thick) commonly contains oolitic intraclasts, peloids, echinoderms, and trilobites, is poorly sorted, and may have decimeter-scale (hummocky?) cross-lamination. *Girvanella* oncoids are rare to dominant in grainy sediment types and sometimes have a thin mineralized rim. Mudstone-wackestone is commonly, although not always, burrow mottled and may contain abundant glauconite. Where this package is present, the top of the Maryville is in the *Cedaria* zone.

A bed of peloid-oncoid packstone-grainstone 0.2 m thick is also present at the top of the Craig (above the subaerial exposure surface), and contains features identical to those described above for the Maryville, except that grains coated with phosphate and manganese are much more common. Immediately above these sediments are the shales of the upper Rogersville, which represent significant deepening (see above).

This package represents the "back-step" stage of Kendall et al. (1991), during deposition of which the platform retreats to an inner-shelf position in response to relative sea-level rise. The biostratigraphically younger age of the top of the Maryville to the east/northeast (Derby 1965) is probably the result of the distribution of this package. Above this package (Maryville) are the deeper-water basinal shales of the Nolichucky Shale, which represent complete drowning of the platform. As discussed above, where this package is present, the sequence boundary is *within* the Maryville carbonates.

Craig and Maryville stacking patterns are summarized in the block diagrams of Figure 5. The most important controls on internal stratigraphic packaging were probably sedimentary aggradation and progradation (Srinivasan and Walker 1993) with *cratonward* progradation, toward the intrashelf basin, an area with a greater rate of subsidence.

CORRELATION OF GRAND CYCLES

In attempts to evaluate controls on the development of grand cycles, many workers have speculated on their transcontinental correlation. There is considerable disagreement concerning the relations between units on different continental margins and between different areas on the same margin (Fig. 6). The lower Rogersville-Craig cycle does not have a biostratigraphically equivalent cycle top elsewhere in North America. The shales of the lower and upper Rogersville contain *Ehmaniella.* The top of the Craig, which must then be within the *Ehmaniella* zone, cannot be equivalent to cycle top 8 (tops of the Swasey and Eldon formations) or 8′ (top of the Arctomys Formation) of Palmer (1981), which are at or above the top of the *Ehmaniella* zone. It is possibly equivalent to cycle top 7 (top of the Dome Formation) of Palmer (1981), which he recognized only in the House Range of Utah. The base of the *Ehmaniella* zone is 25 m above the base of the Dome (Robison 1976), however, so the Dome is probably correlative with the upper Rutledge Limestone and the lower part of the lower Rogersville (Figs. 1, 6; see also Palmer 1981).

The Maryville Limestone does not lack possible correlatives; instead, it has been correlated with many *different* units by different geologists (Fig. 6). Aitken (1981), for example, correlated the Maryville with the Eldon in the Canadian Rockies on the basis of grossly similar ages. Bond et al. (1988) used formation-scale stratigraphy and geophysical modeling to correlate the Maryville with the Eldon. Bond et al. (1989), using similar methods, correlated the Maryville top with the Pika top. Palmer (1981) presented biostratigraphic data that suggested that the Maryville top is closest to the top of the Waterfowl. In spite of these disagreements, some geologists use these "correlations" to suggest eustatic control and relatively "isochronous" platform response (Aitken 1981; Bond et al. 1988, 1989), yet the data do not conclusively support such contentions, for several reasons. First, there are enough grand cycles to accommodate many different correlations (Fig. 6), none of which may be correct. Because two margins have the same *number* of cycles does not necessitate a purely eustatic driving mechanism; rather it may indicate similar controlling periodicities (eustatic plus tectonic). Second, Cambrian biostratigraphic resolution is not sufficiently precise to prove (or disprove) conclusively that two cycle tops near the top or near the base of a trilobite zone were created by the same eustatic event. Third, the cycle top might not actually be the sequence boundary, as documented herein. Correlating grand-cycle tops is not necessarily the same as documenting synchronous development of sequences and their boundaries, and proving a eustatic control. Finally, many authors ignore the possible effects of variable rates of sedimentation and subsidence, simply citing "shallow-water" deposition and a "passive-margin" setting.

Palmer (1981) noted several anomalous Cambrian cycle tops similar to the Craig reported here. The changes upward from the Naomi Peak Limestone, the Arctomys Formation, the lower part of the Cathedral Limestone, and the Dome Limestone to overlying shale units do not appear to have biostratigraphically equivalent tops elsewhere. Some of these "anomalies" may represent local nonthermal subsidence like that we suggest below for the "anomalous" Craig.

DEVELOPMENT OF SEQUENCE BOUNDARIES IN THE CONASAUGA BASIN

Field, petrographic, and geochemical evidence from the upper parts of both the Craig and the Maryville indicates that platform exposure was followed by a rapid relative sea-level rise. Because strata overlying these surfaces reflect significant changes in sedimentary processes and patterns, the surfaces represent sequence boundaries (Srinivasan and Walker 1993). In more platform-interior locations, the sequence boundary is within the carbonates, but in basinward areas, it is at the carbonate-shale contact.

THE SEQUENCE BOUNDING SURFACE AT THE TOP OF THE LOWER ROGERSVILLE-CRAIG CYCLE

The uppermost Craig Limestone at platform-interior localities contains evidence of subaerial exposure of subtidal sediments. The uppermost Craig has vuggy pores up to 3 cm in diameter and small-scale autoclastic brecciation, all present only within 0.2 m of the bounding surface. The dissolution voids (Fig. 7A, B) are filled with clear to slightly turbid equant calcite spar, some of which is truncated erosionally (Fig. 7B), indicating an early-diagenetic origin. Fabric-selective dissolution attacked ooids and oncoids up to 5 m below the top of the Craig (Fig. 7A). These equant calcites (including truncated cements) have $\delta^{18}O$ values of $-10.3‰$ to $-12.3‰$ PDB (mean $-11.3‰$; $n = 12$) and $\delta^{13}C$ values of $-0.2‰$ to $-0.9‰$ PDB (mean $-0.4‰$) (Fig. 8). These oxygen values are 5–7‰ lower than values for Cambrian marine carbonates given by Lohmann and Walker (1989). In contrast, there is very little depletion in $\delta^{13}C$ values of these cements relative to Cambrian marine values. This low depletion compared to younger meteoric cements can be attributed to the absence of light organic carbon associated with land plants (Srinivasan and Walker 1993). $^{87}Sr/^{86}Sr$ ratios from these cements are 0.7095, comparable to strontium ratios of approximately 0.7092 for Cambrian marine carbonates (Burke et al. 1982), but significantly different from burial phases in this sequence, which have ratios of 0.7111 to 0.7139 (Srinivasan and Walker in press).

The combination of erosional truncation, depleted $\delta^{18}O$ values, and Cambrian-rock-buffered strontium values suggest that these cements are the result of very early meteoric diagenesis caused by subaerial exposure. The sediments above this surface represent a drowning event culminating in deposition of the deeper-water upper Rogersville Shale.

THE SEQUENCE-BOUNDING SURFACE AT THE TOP OF THE UPPER ROGERSVILLE-MARYVILLE CYCLE

As at the top of the Craig, the uppermost Maryville shows evidence of exposure/drowning. Subaerial exposure of the Maryville platform is man-

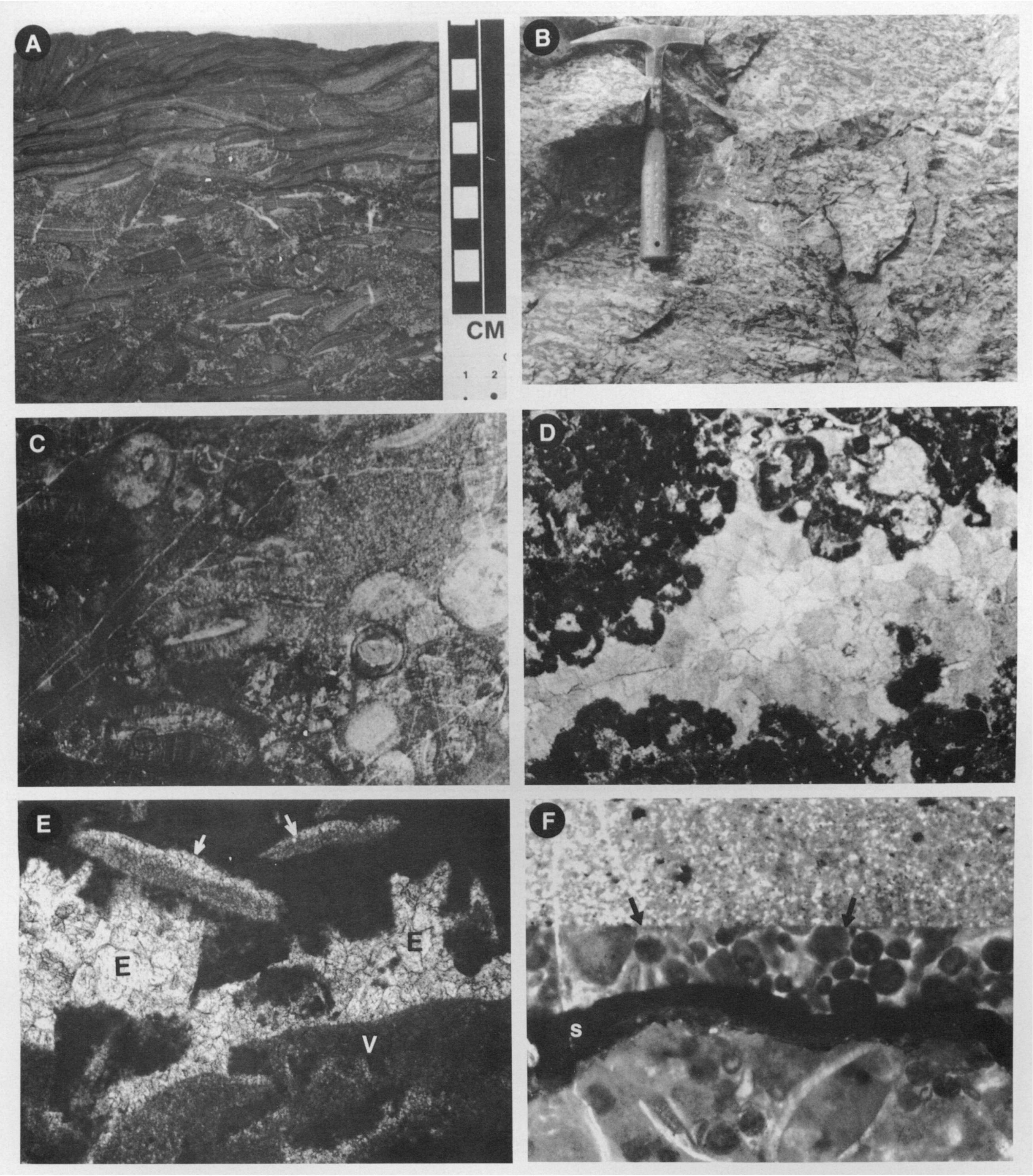

FIG. 5.—Photographs of representative lithologies from stratigraphic packages. In **C–F** (photomicrographs), field of view is approximately 4.5 mm across. **A)** Slope Package. Slab of intraclast packstone. Note imbricated intraclasts, some with shelter porosity. From NF section. **B)** Mid-Ramp Package. Field photo of burrow mottled mudstone/wackestone. Hammer for scale. From DSR section. **C)** Aggrading Ramp Package. Ooid/echinoderm wackestone/packstone. From TH section. **D)** Shoal Package; *Renalcis* boundstone, from shelf-edge bioherm. From WG section. **E)** Peritidal Package. Evaporite molds (E), now filled with clear, equant nonferroan calcite and vadose silt (V). Matrix of very fine-grained peloid packstone. Evaporites are recognized only in the lowermost parts of the peritidal package at the DSR and SR sections. From SR section. **F)** Backstepping Platform Package. Sharp surface (arrows) truncates ooid-peloid grainstone. Surface is overlain by quartz-silty peloid packstone. Stylolite (labeled "s") is also present. From IS section.

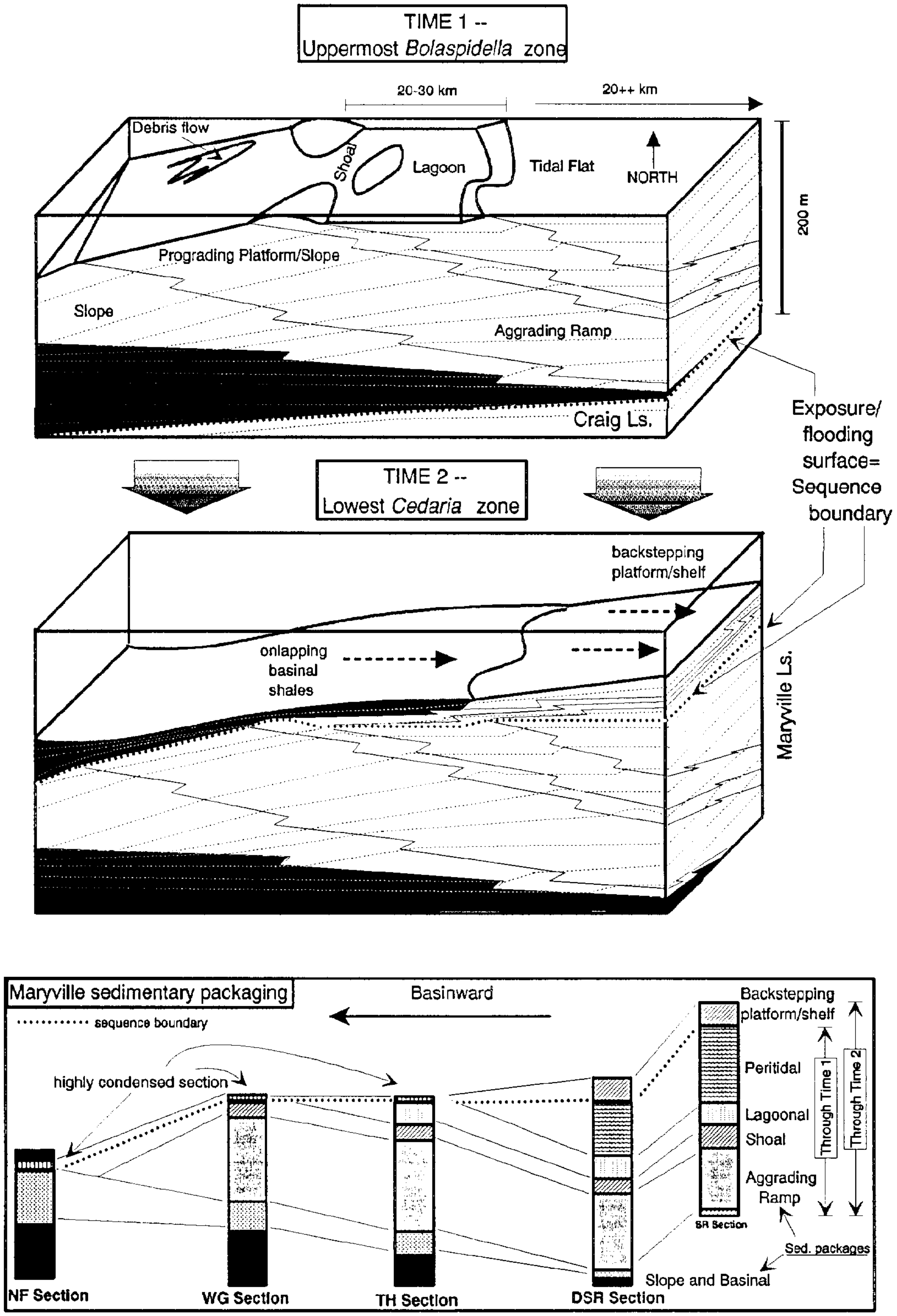

FIG. 6.—Schematic interpretive diagram of Middle Cambrian sedimentation patterns as discerned from the measured sections of Figure 4. Craig stacking patterns are similar to those of the Maryville, except that only slope, aggrading-ramp, and some mid-ramp deposits are present because of "premature" platform termination (see text for discussion). Note that progradation is *cratonward,* toward the intrashelf basin. Effect of differential subsidence on sediment thicknesses is not shown. Top: from the basin/slope through peritidal packages, the Maryville represents platform growth through aggradation and progradation. The shoaling-upward trend is present across the shelf but culminates in peritidal deposits only in the most on-platform sections exposed in Tennessee. Bottom: above the sequence boundary/exposure surface (which is in the *Bolaspidella* zone), sedimentation patterns reflect a deepening-upward trend. Drowning appears "instantaneous" in platform-edge locations (deeper-water shales immediately above the exposure surface developed in shallow-water carbonates) but "gradational" in on-platform locations (exposure surface overlain by backstepping platform/shelf package, which is in turn overlain by shales).

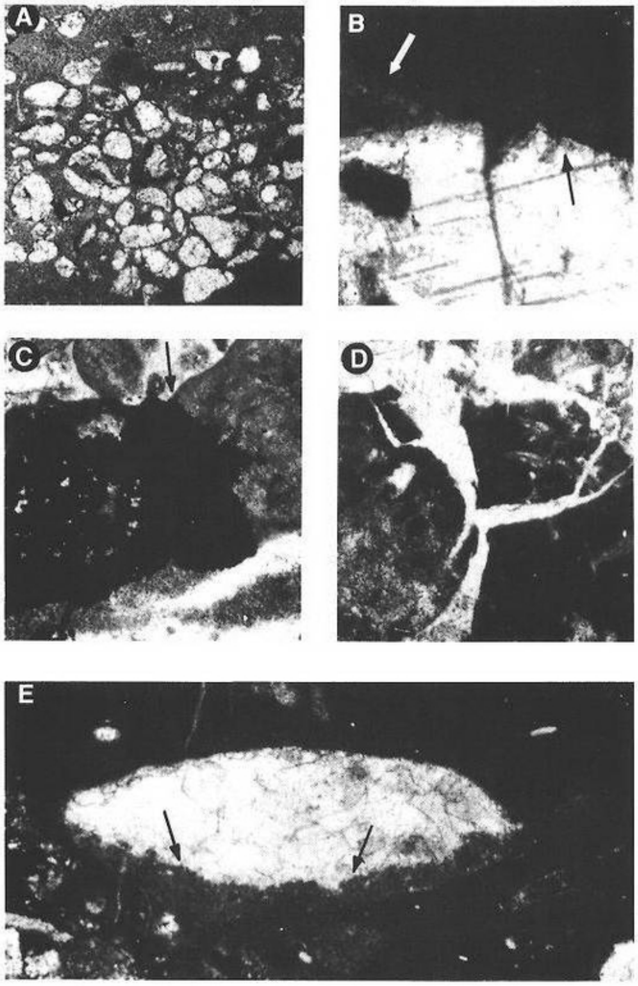

FIG. 7.—Photomicrographs of petrographic features of meteoric diagenesis. Field of view is 2.6 mm across base for **A–D**, 5.3 mm for **E**. **A)** Fabric-selective dissolution voids filled with meteoric equant calcite from 0.2 m below exposure surface; Craig. **B)** Truncated meteoric blocky calcite cement; truncation surface is marked by arrow; Craig. **C)** Truncated (arrow) framboidal pyrite (black) from 1 cm above exposure surface; Craig. **D)** Small-scale internal brecciation and meteoric equant calcite in *Renalcis* boundstone; Maryville (Srinivasan and Walker 1993). **E)** Fabric-selective dissolution, vadose silt (arrow), and meteoric drusy equant clear calcite; Maryville (Srinivasan and Walker 1993).

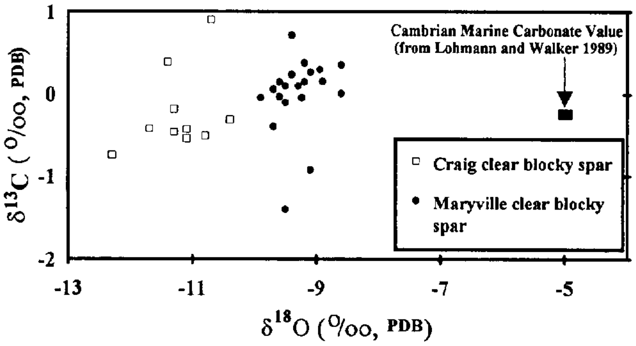

FIG. 8.—Carbon and oxygen isotope cross plot of microsampled equant to (less commonly) drusy clear to slightly turbid calcite from just below the exposure surfaces. Note overall low $\delta^{18}O$ values relative to Cambrian marine carbonate value (−5.5‰; Lohmann and Walker 1989). These cements are erosionally truncated and contain Cambrian strontium ratios, indicating early-diagenetic origin. The differences in $\delta^{18}O$ values between the Maryville and Craig *may* be the result of Cambrian climate shifts (humid Craig vs. arid Maryville). Saller and Moore (1991) have documented climatic control on similar (and even greater) $\delta^{18}O$ shifts in Pleistocene meteoric cements.

ifest by fabric-selective and non-fabric-selective dissolution, vadose silt, and small-scale brecciation (Fig. 7D, E) developed only immediately below the exposure surface. Oncoids, ooids, *Renalcis*, peloids, intraclasts, and trilobites were dissolved by meteoric fluids. The exposure surface in some places shows a dark-reddish impregnation with underlying, non-fabric-selective, dissolution voids (up to 5 mm by 1 cm), circumgranular cracks, alveolar septal (?) structure, and autoclastic brecciation. Blocky (to less commonly drusy) calcite that occludes porosity in dissolution voids has depleted oxygen-isotope ratios of −8.7‰ to −9.9‰ PDB (mean −9.2‰; $n = 19$) and carbon-isotope ratios of −1.2‰ to +0.8‰ PDB (mean +0.1‰) (Fig. 8). The oxygen values are substantially lower than Cambrian marine carbonate (delineated by Lohmann and Walker 1989), but carbon values are again only slightly below marine values. As in Craig meteoric calcite, these cements have $^{87}Sr/^{86}Sr$ ratios of 0.7095, very similar to the Cambrian marine value. These features are all the result of dissolution and subsequent precipitation of calcite during subaerial exposure. The exposure surface is directly overlain by the onlapping basinal shales of the Nolichucky Formation in basinal sections or by the backstepping platform/shelf package and overlying Nolichucky in platformward sections. Both facies reflect significant deepening above the exposure surface. The deep-water character of the Nolichucky has been discussed by Srinivasan and Walker (1993).

EXPOSURE, EUSTASY, TECTONICS, AND SEQUENCE BOUNDARIES

Both of the platforms discussed here "died" as a result of subaerial exposure, perhaps caused by a eustatic sea-level fall. Here we examine the factors that led to the relative sea-level rise after the demise of the Craig and Maryville platforms. Drowning a carbonate ramp or platform requires a change in environmental regime such as: (1) an environmental crisis that "shuts down" carbonate production, such as rapid temperature or salinity variations; (2) a rapid short-term sea-level rise of several tens of meters; (3) clastic "poisoning" of carbonate environments coupled with continued subsidence; (4) a pulse of tectonic subsidence; or (5) a combination of two or more of these processes (Elrich et al. 1990; Read et al. 1991; Schlager 1981, 1991, 1992). Several of these possible causes of drowning can be eliminated in the case of the two platforms studied here. The thin bed of carbonates above the lower Rogersville-Craig sequence boundary and the backstepping platform package of the Maryville indicate that carbonate-producing environments were still present in more on-platform areas as drowning occurred. Thus, environmental crises were not a cause of platform drowning and development of sequence boundaries. The fact that mostly allochthonous (Craig) and *in situ* to allochthonous (Maryville) deeper-water carbonate deposits are present between subaerial exposure surfaces and overlying shales also indicates that siliciclastics did not terminate carbonate platform growth.

Since environmental crises and/or siliciclastic carbonate suppression (Walker et al. 1983) were not the driving mechanisms for platform drowning, eustasy and/or tectonics must have controlled development of sequence boundaries. We suggest that the relative sea-level fluctuations involved in the limestone-shale transition must have been on the order of 40–50 m (from completely subtidal deposition → exposure → basinal deposition). Because the relative sea-level fall exposed subtidal sediments, it may have been eustatic.

The biostratigraphic record discussed previously cannot be used to conclusively prove or disprove a eustatic driving mechanism for the rapid relative sea-level rise that followed to the demise of either platform. While we do not propose that a eustatic cause for cyclicity necessitates a simultaneous craton-wide response, if eustasy on the order of 40–50 m had been responsible for all inferred sea-level fluctuations, a similar response (limestone-shale transition, or even deepening upward) should be evident elsewhere. That such a change is not present (or has not been documented?) during the interval in which the Craig was drowned suggests that a sea-level rise did not occur in the Cordillera, and that the Craig sea-level rise was local in scale, instead of continental or global.

Palmer (1981) and James et al. (1989) noted that the Maryville cycle top does not have a biostratigraphic equivalent in the Cordillera. The genetic top of the Maryville (the exposure surface and coincident sequence boundary) is within the *Bolaspidella* zone, and hence might be biostratigraphically equivalent to cycle top 9 (top of the Marjum, Waterfowl, and other formations) of Palmer (1981), which is near the top of the *Bolaspidella* zone. If this were true, the surface might reflect a continent-wide (eustatic?) sea-level rise. As previously discussed, however, correlation of these cycle tops may or may not be valid. Further sequence-stratigraphic study of Cordilleran grand cycles is necessary to check this possible correlation.

Several observations suggest that nonthermal ("jerky") tectonism instead of a purely eustatic driving mechanism may have influenced platform termination and grand-cycle (sequence) development in the Southern Appalachian intrashelf basin. First, all of the Conasauga carbonate units represent *cratonward* progradation (Fig. 1; see also Rodgers 1953; Walker et al. 1990; Srinivasan and Walker 1993), opposite to that expected for a passive margin. Progradation was toward and across a persistent depocenter (discussed below) that remained in deeper water through the Middle and into the Late Cambrian (Walker et al. 1990; Srinivasan and Walker 1993); Second, isopach maps (Hasson and Haase 1988) indicate that up to 900 m (not decompacted) of Conasauga sediment were deposited in eastern Tennessee. This represents more than four times the thickness deposited on the adjacent Virginia arch (Read 1989), indicating syndepositional differential subsidence. Furthermore, most of the sediments in Virginia are carbonates, whereas highly compactable shales dominate in part of the Tennessee depocenter. If this difference is taken into account, the actual subsidence difference would be even greater than fourfold. Modeling suggests that isostatic response to such sediment loading provides a feedback mechanism through enhancement of accommodation space (Walker et al. 1983; Reynolds et al. 1991). The effects of these processes are clearly resolvable at larger scales (hundreds of meters), but must have proceeded during sedimentation. The time scale for creation and enhancement of accommodation space has not been resolved, but as Kendall et al. (1992) have suggested, this response might not be linear, but might be sporadic or manifest as changing rates of subsidence, as we suggest here. Such accommodation enhancement would be most evident in condensed sections, such as those associated with early platform reflooding after subaerial exposure (such as those described here), but may also be reflected in the rapid facies changes described previously. The third observation supporting localized tectonic subsidence is that the Middle Cambrian was a time of regional extension in the southeastern United States. This extension is reflected in the Rome Trough–Rough Creek Graben (north of our study area; Webb 1980; Collinson et al. 1988), the Birmingham fault system (south of our study area; Thomas 1991), and the Mississippi Valley Graben (west of our study area; Nelson and Zhang 1991). Tensional stresses associated with the waning stages of continental breakup were probably transmitted across the southeastern part of the continent, including the Conasauga intrashelf basin, and may have reactivated preexisting structures. Differential subsidence in the Conasauga depocenter ended in the Late Cambrian (Read 1989), approximately when all these craton-interior features associated with continental breakup ceased activity. This suggests that full stabilization (end of active extension and/or decrease in the rate of thermal cooling and increased crustal rigidity) of the continental margin occurred during this time. Fourth, extensional tectonics is also suggested by the patterns of peritidal deposition and retarded progradation in the Maryville, reflecting the possible influence of (minor) block faulting on sedimentation. These patterns probably reflect tectonic activity during Maryville deposition in the Conasauga basin. Finally, Middle Cambrian seismites are present in southwest Virginia just north of the study area (Pope and Read 1992), indicating that local tectonic activity was occurring at that time.

Thus, the abrupt relative sea-level changes, the "anomalous" Craig, cratonward progradation, Maryville facies patterns, and the pervasive tectonism around the study area suggest that nonthermal subsidence may have controlled or enhanced development and termination of these Middle Cambrian sequences. We propose that a relative (eustatic?) sea-level fall exposed the Craig and Maryville carbonate shelves (*subtidal* and peritidal sediments). Subaerial exposure halted carbonate deposition and led to a sediment-starved shelf once reinundated (the "give-up" phase of Kendall and Schlager 1981). Cambrian tectonism (associated with release of stresses associated with thermal cooling, sediment loading, and/or regional extension), reflected as changing rates of subsidence or "jerky" subsidence, caused or enhanced the drowning of the Craig and Maryville platforms. This tectonism was compounded in the condensed sections and resulted in the stratigraphically abrupt deepening. Such patterns may have been present during deposition of the Craig and Maryville but were probably masked by high accumulation rates.

The Late Cambrian end of regional extension associated with decrease in rate of thermal contraction (Bond et al. 1989) and/or with increasing flexural rigidities (which would tend to distribute accommodation space laterally) probably led to an end of tectonic influence on sequence development in this intrashelf basin. The transition from Conasauga-type sequences (deeper-water shale to shallow-water carbonate; this report; Srinivasan and Walker 1993) to Knox-type sequences (sheet-like peritidal deposits; Read 1989; Osleger and Read 1991, 1993) might thus reflect the full stabilization of the passive margin.

Quantitative subsidence analysis for the Iapetan margin, like that of many other passive margins, has an apparently "predictable" thermal subsidence pattern (Bond et al. 1988, 1989; Read 1989). By assuming that short-term subsidence is linear, deviations from predicted thermal accommodation patterns on these margins have been interpreted to represent eustatic fluctuations (Bond et al. 1988, 1989; Read 1989; Osleger and Read 1991, 1993). As we suggest here, however, although the overall form of subsidence is "thermal" (Bond et al. 1989) short-term subsidence patterns may be nonlinear, possibly related to sporadic brittle response of the crust to accumulated horizontal or vertical stresses associated with sediment loading, regional extension, or thermal contraction (cf. Cloetingh et al. 1989; Stephenson 1989; Reynolds et al. 1991; Kendall et al. 1992). The "details" that may be lost in construction of burial curves might actually be the sequence-driving mechanisms.

CONCLUSIONS

Sequence stratigraphy represents attempts to interpret relationships between rocks in terms of their genesis. By assuming sedimentation and subsidence constant, the driving mechanism of sequence stratigraphy is assumed to be eustatic fluctuations. We suggest, however, that the assumption of constant subsidence may not be valid on some young passive margins (see also Kendall et al. 1992).

Our study of two southern Appalachian Middle Cambrian third-order sequences (grand cycles) suggests that carbonate platform aggradation and progradation were the main controls on internal stratigraphic packaging. Development of sequence boundaries was controlled by platform exposure, "jerky" subsidence, or changing rates of subsidence, and a possible eustatic component in the case of the Maryville. In particular, platform exposure (by eustatic fall?) caused a shutdown of carbonate production that allowed Middle Cambrian episodic subsidence to be "compounded" in a small stratigraphic interval. During the deepening, shales characteristic of the adjacent basin onlapped the drowned platform. Response to relative sea-level rise varied across the platform, from "instantaneous" drowning in more basinward sections to "backstepping" facies in platform-interior sections. Thus, the sequence boundary is at the top of the carbonates in shelf-edge and basinal areas, but within the carbonates in on-platform locations.

Finally, this study suggests that the evolution of the Iapetan passive margin was more complex than previously recognized, and that the margin fully stabilized at some point in the Late Cambrian. Prior to this time, development of "passive" margin third-order sequences was controlled (or enhanced?) by sedimentologic responses to subaerial exposure and nonthermal subsidence. The change from Conasauga-style shale-carbonate sequences to Knox-style sheetlike peritidal sequences may thus reflect the beginning of purely thermal subsidence (the end of variable subsidence rates). The processes and patterns discussed here may serve as analog for other Cambrian (and younger) sequences developed on similar margins.

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REFERENCES

Aitken, J.D., 1966, Middle Cambrian to Middle Ordovician cyclic sedimentation, southern Rocky Mountains of Alberta: Bulletin of Canadian Petroleum Geology, v. 14, p. 405–441.

Aitken, J.D., 1978, Revised models for depositional grand cycles, Cambrian of the southern Rocky Mountains, Canada: Bulletin of Canadian Petroleum Geology, v. 26, p. 515–542.

Aitken, J.D., 1981, Generalizations about grand cycles, *in* Taylor, M.E., ed., Short Papers for the Second International Symposium on the Cambrian System: United States Geological Survey Open-File Report 81-743, p. 156–159.

Beach, D.K., and Ginsburg, R.N., 1980, Facies succession, Pliocene–Pleistocene carbonates, northwestern Great Bahama Bank: American Association of Petroleum Geologists Bulletin, v. 64, p. 1634–1642.

Bond, G.C., and Kominz, M.A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains, Canadian Rocky Mountains: implications for subsidence mechanisms, age of breakup, and crustal thinning: Geological Society of America Bulletin, v. 95, p. 155–173.

Bond, G.C., Kominz, M.A., and Grotzinger, J.P., 1988, Cambro-Ordovician eustasy: evidence from geophysical modeling of subsidence in Cordillera and Appalachian passive margins, *in* Kleinspehn, K.L., and Paola, C., New Perspectives in Basin Analysis: New York, Springer-Verlag, p. 129–160.

Bond, G.C., Kominz, M.A., Steckler, M.S., and Grotzinger, J.P., 1989, Role of thermal subsidence, flexure, and eustasy in the evolution of early Paleozoic passive-margin carbonate platforms, *in* Crevello, P., Wilson, J.L., Sarg, J.F., and Read, J.F., eds., Controls on Carbonate Platform and Basin Development: SEPM Special Publication 44, p. 40–61.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, B.H., and Otto, J.B., 1982, Variation of sea water ^{87}Sr/^{86}Sr throughout Phanerozoic time: Geology, v. 10, p. 516–519.

Chow, N., and James, N.P., 1987, Cambrian grand cycles: a northern Appalachian perspective: Geological Society of America Bulletin, v. 98, p. 418–429.

Cloetingh, S., Tankard, A.J., Welsink, H.J., and Jenkins, W.A.M., 1989, Vail's coastal onlap curves and their correlation with tectonic events, offshore eastern Canada, *in* Tankard, A.J., and Balkwill, H.R., eds., Extensional Tectonics and Stratigraphy of the North Atlantic Margins: American Association of Petroleum Geologists Memoir 46, p. 283–294.

Collinson, C., Sargent, M.L., and Jennings, J.R., 1988, Illinois Basin region, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton, U.S.: Geological Society of America, The Geology of North America, Vol. D-2, p. 383–426.

Cowan, C.A., and James, N.P., 1993, The interactions of sea-level changes, terrigenous sediment influx, and carbonate productivity as controls on Upper Cambrian Grand Cycles of western Newfoundland, Canada: Geological Society of America Bulletin, v. 105, p. 1576–1590.

Derby, J.R., 1965, Paleontology and stratigraphy of the Nolichucky Formation in southwest Virginia and northeast Tennessee [unpublished Ph.D. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute and State University, 468 p.

Elrich, R.N., Barrett, S.F., and Ju, G.B., 1990, Seismic and geologic characteristics of drowning events on carbonate platforms: American Association of Petroleum Geologists Bulletin, v. 74, p. 1523–1537.

Erwin, P.E., Jr., 1981, Stratigraphy, depositional environments, and dolomitization of the Maryville and Upper Honaker formations (Cambrian), Tennessee and Virginia [unpublished M.S. thesis]: Duke University, Durham, North Carolina, 232 p.

Fichter, L.S., and Diecchio, R.J., 1986, Stratigraphic model for timing the opening of the Proto-Atlantic Ocean in northern Virginia: Geology, v. 14, p. 307–309.

Hao, B.U., Hardenbol, J., and Vail, P.R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea-level Changes: An Integrated Approach: SEPM Special Publication 42, p. 71–108.

Hardie, L.A., 1989, Cyclic platform carbonates in the Cambro-Ordovician of the central Appalachians, *in* Walker, K.R., Read, J.F., and Hardie, L.A., eds., Cambro-Ordovician Carbonate Banks and Siliciclastic Basins of the United States Appalachians: International Geological Congress Guidebook T161, p. 51–81.

Harris, P.M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal: Miami Florida, University of Miami, Sedimenta VII, Comparative Sedimentology Laboratory, 163 p.

Hasson, K.O., and Haase, C.S., 1988, Lithofacies and paleogeography of the Conasauga Group (Middle and Upper Cambrian) in the Valley and Ridge province of east Tennessee: Geological Society of America Bulletin, v. 100, p. 234–246.

Hatcher, R.D., Jr., 1965, Structure of the northern portion of the Dumplin Valley Fault Zone in east Tennessee [unpublished Ph.D. thesis]: University of Tennessee, Knoxville, Tennessee, 168 p.

Hatcher, R.D., Jr., 1989, Tectonic synthesis of the U.S. Appalachians, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 511–535.

Hine, A.C., 1977, Lily Bank, Bahamas: history of an active oolite sand shoal: Journal of Sedimentary Petrology, v. 47, p. 1554–1581.

Hinze, L.F., and Robison, R.A., 1975, Middle Cambrian stratigraphy of the House, Wah-Wah, and adjacent ranges in western Utah: Geological Society of America Bulletin, v. 86, p. 881–891.

James, N.P., Stevens, R.K., Barnes, C.R., and Knight, I., 1989, Evolution of a lower Paleozoic continental margin carbonate platform, northern Canadian Appalachians, *in* Crevello, P., Wilson, J.L., Sarg, J.F., and Read, J.F., eds., Controls on Carbonate Platform and Basin Development: SEPM Special Publication 44, p. 122–146.

Kendall, C.G.St.C., and Schlager, W., 1981, Carbonates and relative changes in sea-level: Marine Geology, v. 44, p. 181–212.

Kendall, C.G.St.C., Bowen, B., Alsharhan, A., Cheong, D., and Stoudt, D., 1991, Eustatic controls on carbonate facies in reservoirs, and seals associated with Mesozoic hydrocarbon fields of the Arabian Gulf and the Gulf of Mexico: Marine Geology, v. 102, p. 215–238.

Kendall, C.G.St.C., Moore, P., Whittle, G., and Cannon, R., 1992, A challenge: Is it possible to determine eustasy and does it matter? *in* Dott, R.H., Jr., ed., Eustasy: The Historical Ups and Downs of a Major Geological Concept: Geological Society of America Memoir 180, p. 93–107.

Koerschner, W.F., and Read, J.F., 1989, Field and modeling studies of Cambrian carbonate cycles, Virginia Appalachians: Journal of Sedimentary Petrology, v.59, p. 654–687.

Kozar, M.G., 1986, The stratigraphy, petrology, and depositional environments of the Maryville Limestone (Middle Cambrian) in the vicinity of Powell and Oak Ridge, Tennessee [unpublished M.S. thesis]: University of Tennessee, Knoxville, Tennessee, 242 p.

Kozar, M.G., Weber, L.J., and Walker, K.R., 1990, Field and modeling studies of Cambrian carbonate cycles, Virginia Appalachians—Discussion: Journal of Sedimentary Petrology, v. 60, p. 790–794.

Lohmann, K.C, and Walker, J.G.C., 1989, The δ^{18}O record of Phanerozoic abiotic marine calcite cements: Geophysical Research Letters, v. 16, p. 319–322.

Ludvigson, R., and Westrop, S.R., 1985, Three new Upper Cambrian stages for North America: Geology, v. 13, p. 139–143.

Markello, J.R., and Read, J.F., 1981, Carbonate ramp-to-deeper shale shelf transitions of an Upper Cambrian intrashelf basin, Nolichucky Formation, southwest Virginia Appalachians: Sedimentology, v. 28, p. 573–597.

Markello, J.R., and Read, J.F., 1982, Upper Cambrian intrashelf basin, Nolichucky Formation, southwest Virginia Appalachians: American Association of Petroleum Geologists Bulletin, v. 66, p. 860–878.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32.

Mount, J.F., and Rowland, S.A., 1981, Grand cycle A (Lower Cambrian) of the southern Great Basin: a product of differential rates of relative sea level rise, *in* Taylor, M.E., ed., Short Papers for the Second International Symposium on the Cambrian System: United States Geological Survey Open-File Report 81-743, p. 143–146.

Nelson, K.D., and Zhang, J., 1991, A COCORP deep reflection profile across the buried Reelfoot rift, south-central United States: Tectonophysics, v. 197, p. 271–293.

Osleger, D., and Read, J.F., 1991, Relation of eustasy to stacking patterns of meter-scale carbonate cycles, Late Cambrian, U.S.A.: Journal of Sedimentary Petrology, v. 61, p. 1225–1252.

Osleger, D., and Read, J.F., 1993, Comparative analysis of methods used to define eustatic variations in outcrop: Late Cambrian interbasinal sequence development: American Journal of Science, v. 293, p. 157–216.

Palmer, A.R., 1971, The Cambrian of the Appalachian and eastern New England regions, eastern United States, *in* Holland, C.H., ed., Cambrian of the New World: London, Wiley-Interscience, p. 289–332.

Palmer, A.R., 1981, On the correlatability of Grand Cycle tops, *in* Taylor, M.E., ed., Short

Papers for the Second International Symposium on the Cambrian System: United States Geological Survey Open-File Report 81-743, p. 156–159.

Palmer, A.R., and Halley, R.B., 1979, Physical stratigraphy and trilobite biostratigraphy of the Carrara formation (Lower and Middle Cambrian) in the southern Great Basin: United States Geological Survey Professional Paper 1047, 131 p.

Pope, M.C., and Read, J.F., 1992, Probable Middle Cambrian to Middle-Late Ordovician seismites, a record of extensional to compressional tectonics (abstract): Geological Society of America Abstracts with Programs, v. 24, p. 186.

Purdy, E.G., 1963, Recent calcium carbonate facies of the Great Bahama Bank. 2. Sedimentary facies: Journal of Geology, v. 71, p. 472–497.

Rankey, E.C., 1993, Carbonate platform response to episodic tectonism and eustasy: the Middle Cambrian carbonates of the lower and middle Conasauga Group, east Tennessee [unpublished M.S. thesis]: Knoxville, Tennessee, University of Tennessee, 191 p.

Rankey, E.C., and Walker, K.R., 1993, Milankovitch-induced stratigraphic forcing may not be discernible in the stratigraphic record: "cyclic" facies of the Maryville Limestone (Middle Cambrian), southern Appalachians (abstract): Geological Society of America Abstracts with Programs, v. 25, p. 337.

Rankey, E.C., Srinivasan, K., and Walker, K.R., 1992, Coincident exposure/drowning surfaces within Middle Cambrian Grand Cycles, east Tennessee: a model for abrupt limestone/shale transitions/sequence boundaries (abstract): Geological Society of America Abstracts with Programs, v. 24, p. 318.

Rasetti, F., 1965, Upper Cambrian trilobite faunas of northeastern Tennessee: Smithsonian Miscellaneous Collections 148 (3), 127 p.

Resser, C.E., 1938, Cambrian System (Restricted) of the Southern Appalachians: Geological Society of America Special Paper 15, 140 p.

Read, J.F., 1989, Controls on evolution of Cambrian-Ordovician passive margin, U.S. Appalachians, *in* Crevello, P., Wilson, J.L, Sarg, J.F., and Read, J.F., eds., Controls on Carbonate Platform and Basin Development: SEPM Special Publication 44, p. 147–166.

Read, J.F., Grotzinger, J.P., Bova, J.A., and Koerschner, W.F., 1986, Models for generation of carbonate cycles: Geology, v. 14, p. 107–110.

Read, J.F., Osleger, D., and Elrick, M., 1991, Two-dimensional modeling of carbonate ramp sequences and component cycles, *in* Franseen, E.K., Watney, W.L., Kendall, C.G.St.C., and Ross, W., eds., Sedimentary Modeling: Computer Simulations and Methods for Improved Parameter Definition: Kansas Geological Survey Bulletin 233, p. 473–488.

Reynolds, D.J., Steckler, M.S., and Coakley, B.J., 1991, The role of sediment load in sequence stratigraphy: the influence of flexural isostasy and compaction: Journal of Geophysical Research, v. 96, p. 6931–6949.

Robison, R.A., 1976, Middle Cambrian trilobite biostratigraphy of the Great Basin: Brigham Young University Geology Studies, v. 23, p. 93–109.

Rodgers, J., 1953, Geologic map of east Tennessee with explanatory text: Tennessee Division of Geology Bulletin 58, 168 p.

Sarg, J.F., 1988, Carbonate sequence stratigraphy, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea Level Changes: An Integrated Approach: SEPM Special Publication 43, p. 155–181.

Schlager, W., 1981, The paradox of drowned reefs and carbonate platforms: Geological Society of America Bulletin, v. 92, p. 197–211.

Schlager, W., 1991, Depositional bias and environmental change—important factors in sequence stratigraphy: Sedimentary Geology, v. 70, p. 109–130.

Schlager, W., 1992, Sedimentology and sequence stratigraphy of reefs and carbonate platforms: American Association of Petroleum Geologists, Continuing Education Course Note Series no. 34, 71 p.

Simmons, W.A., 1984, Stratigraphy and depositional environments of the Middle Cambrian Maryville Limestone (Middle Cambrian), near Thorn Hill, Tennessee [unpublished M.S. thesis]: Knoxville, Tennessee, University of Tennessee, 276 p.

Simpson, E.L., and Eriksson, K.A., 1990, Early Cambrian progradational and transgressive sedimentation patterns in Virginia: an example of the early history of a passive margin: Journal of Sedimentary Petrology, v. 60, p. 84–100.

Simpson, E.L., and Eriksson, K.A., 1989, Rift to incipient passive margin sedimentation within the late Proterozoic to early Cambrian Unicoi Formation of southern and central Virginia: Geological Society of America Bulletin, v. 101, p. 42–54.

Sleep, N.H., 1971, Thermal effects of the formation of Atlantic continental margins by continental break up: Royal Astronomical Society Geophysical Journal, v. 24, p. 325–350.

Srinivasan, K., 1993, Depositional history, sequence stratigraphy, and diagenesis of the Maryville Limestone (Middle Cambrian), southern Appalachians [unpublished Ph.D. thesis]: University of Tennessee, Knoxville, Tennessee, 169 p.

Srinivasan, K., and Walker, K.R., 1993, Sequence stratigraphy of an intrashelf basin carbonate ramp to rimmed platform transition: Maryville Limestone (Middle Cambrian), southern Appalachians, Geological Society of America Bulletin, v. 105, p. 883–896.

Srinivasan, K., and Walker, K.R., 1994, Petrographic and geochemical constraints for fluid source and possible pathways during burial diagenesis of Maryville Limestone (Middle Cambrian), southern Appalachians, USA: Sedimentology, in press.

Stephenson, R., 1989, Beyond first-order thermal subsidence models in the formation of sedimentary basins?, *in* Cross, T.A., Quantitative Dynamic Stratigraphy: Englewood Cliffs, New Jersey, Prentice-Hall, p. 89–112.

Thomas, W.A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, p. 415–431.

Vail, P.R., Mitchum, R.M., Todd, R.G., Widmier, J.M., Thompson III, S., Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level, *in* Payton, C.E., ed., Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 49–205.

Walker, K.R., Foreman, J.L., and Srinivasan, K., 1990, The Cambrian Conasauga Group of eastern Tennessee: a preliminary general stratigraphic model with a more detailed test for the Nolichucky Formation: Appalachian Basin Industrial Associates, v. 17, p. 184–189.

Walker, K.R., Shanmugam, G., and Ruppel, S.J., 1983, A model for carbonate to terrigenous clastic sequences: Geological Society of America Bulletin, v. 94, p. 700–712.

Webb, E.J., 1980, Cambrian sedimentation and structural evolution of the Rome trough in Kentucky [unpublished Ph.D. thesis]: University of Cincinnati, Cincinnati, Ohio, 98 p.

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