RECOGNIZING EXPOSURE, DROWNING, AND "MISSED BEATS": PLATFORM-INTERIOR TO PLATFORM-MARGIN SEQUENCE STRATIGRAPHY OF MIDDLE ORDOVICIAN LIMESTONES, EAST TENNESSEE

D. MARK STEINHAUFF AND KENNETH R. WALKER
Department of Geological Sciences, The University of Tennessee, Knoxville, Tennessee 37996-1410 U.S.A.

ABSTRACT: **Stratigraphic sequences in a Middle Ordovician platform-interior carbonate succession (Steinhauff and Walker, in press) are correlated to the platform margin. Surfaces of subaerial exposure are correlated among seven stratigraphic sections, four from the platform succession and three from platform-margin rocks. Surfaces of subaerial exposure define stratigraphic sequences within a carbonate succession that shows little evidence of cyclicity in the field. Interpretation of carbonate facies geometry is based on outcrop observation, petrographic and geochemical analysis of samples, and consideration of paleobathymetric curves. In the platform succession, most sequences are bounded by exposure surfaces, but in more continuously subtidal areas periods of shallowing and drowning are discerned in bathymetric curves on the basis of multiple lines of evidence. Exposure surfaces are evidenced by subjacent meteoric cements or other features indicating exposure such as truncated marine cements, vuggy porosity with vadose silt and pendant cements, or mud cracks. At some localities, a marked shallowing event correlates to exposure elsewhere. In subtidal sediments, drowning is indicated by the lack of shallow-water physical sedimentary features and water-depth curves based on multiple lines of evidence including the presence of red algae, thin-shelled (eyeless) trilobites, delicate arborescent bryozoa, and deposit-feeding organisms. Evidence for drowning unconformity is in some cases provided by cephalopod-rich, black to blood-red limestone beds rich in iron and manganese oxides, and occasionally by corroded surfaces encrusted with these minerals.**

We have referred to the succession as "apparently noncyclic" because evidence for exposure and shallowing is subtle and is not always observable in the field. Nonetheless, these strata show fourth-order subsequences that can be grouped into third-order sequences by the existence of pronounced and less pronounced exposure surfaces. Pronounced surfaces of exposure are those that overlie fenestral mudstones that contain exposure features, such as crystal silt and calcite cement in vugs lined by reddish crusts, and are truncated by deeper-water lithologies. For example, seven pronounced surfaces of subaerial exposure define six third-order sequences, 10-50 m thick, on the platform near Thorn Hill, Tennessee. Within the lower four third-order subsequences, 19 less pronounced surfaces showing fewer exposure features are present in approximately 400 m of section. These surfaces define fourth-order subsequences that are correlative from place to place in the platform succession. Many, but not all, of these platform fourth-order subsequences can be correlated to the platform margin. Also, some fourth-order subsequences are present only at the platform edge. Fifth-order, "meter-scale" packages, or parasequences, are present within these fourth-order sequences, but are not correlative over wide areas as are the other sequences. Most are probably the result of migration of lateral environments. Geometries unlike those of siliciclastic sequences result where condensed sections or deepening events are followed by exposure in this carbonate succession.

The sequences defined here constitute shallowing-upward packages that are, then, a type of cycle. These are used to construct modified Fischer plots for both the platform-interior and platform-margin stratigraphic successions. Surfaces of subaerial exposure are correlated from the platform to the platform margin by matching pronounced exposure surfaces and deepening events shown in water-depth curves for the platform with pronounced exposure surfaces and deepening or shallowing events at the platform margin. This analysis provides several possible solutions, the most conservative of which suggests that some sequences or cycle "beats" are missing. Beats are missed in three ways: (1) sea level remains near the platform margin, causing deposition to be restricted to that area; (2) tectonic uplift exposes the platform interior but not platform-margin areas until subsidence allows resubmergence; and (3) drowning carries platform margin areas to depths precluding carbonate deposition there, though sediment does accumulate on the platform. In Cases 1 and 2 the missed "beats" would be on the platform, but in Case 3 they would be at the platform margin.

INTRODUCTION

Carbonate platforms provide one of the most accurate gauges for investigating changes in sea level. Sediment type, geometry, and diagenesis all record information about sea-level changes. Because the surface of most platforms is nearly horizontal, even small changes in sea level expose or drown large areas. Previous work of this sort has concentrated on the shallower, peritidal parts of platforms (e.g., Hardie et al. 1986). In an earlier paper (Steinhauff and Walker, in press) we have detailed the complex sequence stratigraphy of the Middle Ordovician platform-interior succession of the Southern Appalachians.

Although evidence may be more subtle, information on ancient changes in sea level is also recorded near the platform margin in more continuously subtidal sediments. In the present paper, we extend the sequence stratigraphic framework that we have previously established on the platform (only summarized here) to the platform margin, and discuss how platform-interior and platform-margin parts of the same large-scale succession record relative changes in sea level. An important aspect of such a record is that evidence for specific changes in sea level may be present in one of the areas but absent in the other. Here we refer to these missing sea-level changes as "missed beats" in the record of relative sea-level cyclicity.

Fischer plots have been used to help explain relative changes in sea level on ancient platforms (e.g., Fischer 1964; Read et al. 1986; Read 1989; Koerschner and Read 1989; Goldhammer et al. 1987, 1990). Although their interpretation is controversial, Fischer plots provide valuable clues for understanding platform deposition (Sadler et al. 1993). Many workers have cited eustatic sea-level change as the primary mechanism yielding shallowing-upward, meter-scale packages termed "cycles" and their systematically arranged larger-scale counterparts (e.g., Read et al. 1986; Read 1989; Koerschner and Read 1989; Goldhammer et al. 1987, 1990). Other workers, however, note that autocyclic causes of change in relative sea level may also play an important role (e.g., Kozar et al. 1990; Hardie et al. 1991; Goldhammer et al. 1993). Fischer (1964) recognized three possible controls of patterns seen on Fischer plots: (1) relative changes in sea level related to "accretion of sediments" and subsidence, (2) tectonic changes, and (3) eustatic changes. Because these different components are not easily resolved, there are limits on how the Fischer plot can be interpreted. The most serious limitation is the implicit assumption that each cycle is of the same duration. This is almost certainly not true (Kozar et al. 1990; Hardie et al. 1991). Indeed, it is likely that some cycles represented by sediment elsewhere are not represented in any given stratigraphic succession. These absent cycles or "beats" may be missed when sedimentation rates are depressed or during periods of subaerial exposure (e.g., Hardie et al. 1986; Goldhammer et al. 1990).

JOURNAL OF SEDIMENTARY RESEARCH, VOL. B65, NO. 2, MAY, 1995, P. 183–207

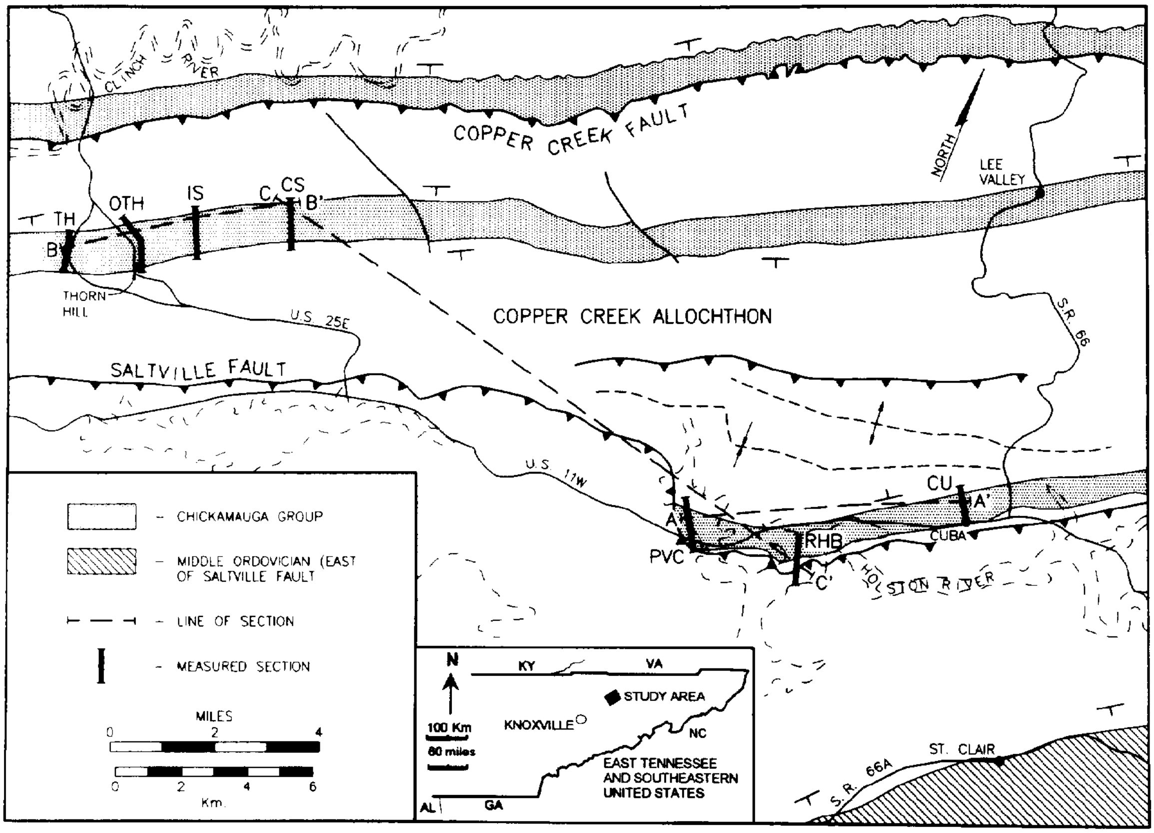

FIG. 1.—Location map for study area within the Copper Creek allochthon, modified from Ruppel (1979). Letters refer to sections considered in this study (solid section symbol). Platform (on-shelf) sections are: Thorn Hill (TH), Old Thorn Hill (OTH), Idol Mine (IS), and Cedar Springs (CS). Platform-margin (shelf-edge or near shelf-edge) sections include: Poor Valley Creek (PVC), Red House Branch (RHB), and Cuba (CU). Inset shows study area in East Tennessee in relation to the southeastern United States.

Specific Objectives

Our study shows how stratigraphic sequences are correlated among seven closely spaced stratigraphic sections, four on the Middle Ordovician platform and three at or near the platform margin. Some surfaces of subaerial exposure can be correlated from platform interior to platform margin; other surfaces cannot be correlated. Thus, it is possible to show how each sequence on the platform correlates or fails to correlate with a platform-margin counterpart. That is, it is possible to show how some subaerial and submarine unconformities or "beats" are missed in both areas. Missed beats are caused by distinctly different processes in the two areas.

There are seven aspects to this study: (1) bathymetric indicators and cycle (third, fourth, fifth order) criteria are defined; (2) the previously established platform-interior sequence stratigraphy is summarized; (3) the methods of establishing the sequence stratigraphy of the platform margin are discussed (inflection points in water-depth curves, relative stratigraphic relationships, evidence for changes in water depth, evidence for drowning and drowning unconformity, and changes in lithologies); (4) correlation criteria are defined; (5) stratigraphic sequences and their correlations are established; (6) stratigraphic sequences are classified into types; and (7) variations in correlations are interpreted to account for missing sequences or "beats."

Study Area

The study area contains four platform-interior localities and three platform-margin localities. A regional environmental and generalized stratigraphic framework, based on these and more than 20 other sections, was developed by Walker (1977, 1980, 1985), Ruppel (1979), and Ruppel and Walker (1982, 1984). The platform-interior localities are along the northwest limb of the Copper Creek allochthon and are fully documented by Steinhauff and Walker (in press). At those localities, more than 540 m of Middle Ordovician strata are exposed, ranging from the upper Knox Group through the Five Oaks, Lincolnshire, Rockdell, Benbolt, Wardell, Witten, and Moccasin Formations. From southwest to northeast these localities are at Thorn Hill (TH), Old Thorn Hill (OTH), Idol Mine (IS), and Cedar Springs (CS). Each section is separated from the next by about 2 km (Figs. 1, 2). The three platform-margin sections are overturned and exposed on the southwest limb of the same allochthon. About 300 m of Middle Ordovician strata are exposed, ranging from the upper Knox Group through the Five Oaks, Lenoir, Holston, and Rockdell Formations. From southwest to northeast, these localities are at Poor Valley Creek (PVC), Red House Branch (RHB), and Cuba (CU) (Fig. 1).

PREVIOUS WORK

Bathymetric Indicators and Cycle Criteria

Paleobathymetry on the platform was established by Steinhauff and Walker (in press) using multiple lines of evidence to determine a range of possible water depths (enlarging upon Elias 1937 and Benedict and Walker 1978). There are four types of bathymetric indicators: (1) chemical, such as blackened grains; (2) physical or sedimentologic, such as mud cracks and ooids, (3) biologic, such as the distribution of algae; and (4) strati-

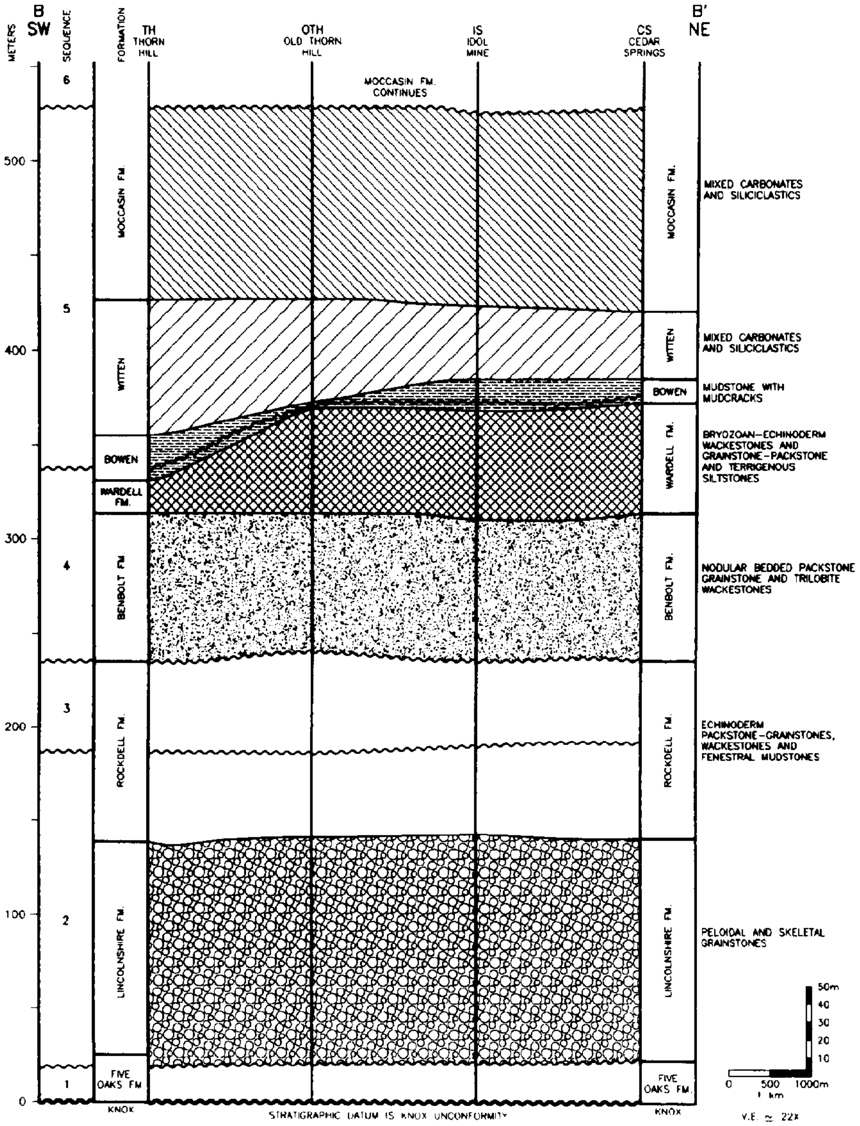

FIG. 2.—Stratigraphic sequences 1-5, Thorn Hill area. This platform-interior succession is restored along depositional strike (after Steinhauff and Walker, in press). From southwest to northeast, sections are at Thorn Hill (TH), Old Thorn Hill (OTH), Idol Mine (IS), and Cedar Springs (CS).

graphic. Each category contains criteria observable at different scales, ranging from petrographic to patterns of regional scope. Not all the indicators are applicable in every situation. Indeed, some indicators (i.e., those for very deep water) were not used in the present study. Rather, emphasis here is on those indicators that are most useful in the study of Middle Ordovician platform carbonates (Fig. 3).

When sea level drops well below the platform margin and sediments are exposed for long periods, evidence for exposure is generally easy to recognize (e.g., Esteban and Klappa 1983). However, if sea level remains at or near the platform margin and sediments experience only a short period of exposure, evidence for exposure becomes subtle. Inflection points in water-depth curves indicate stratigraphic intervals that also contain subtle indicators of subaerial exposure. Such indicators help deduce changes in water depth after initial deposition. Evidence for exposure includes: calcite-filled vugs lined by reddish crusts and/or filled with crystal silt; fibrous calcite cement with marine isotopic ($^{87}Sr/^{86}Sr$ and ^{18}O) values truncated by later marine cement or by bladed and equant calcite with meteoric isotopic values; pendant cements; horizontal fenestrae; and mud cracks (Figs. 3, 4). Geochemical data and diagenetic fabrics for both the platform-interior and platform-margin successions are documented by Steinhauff (1993), and suggest that crystal silt is of vadose origin (Dunham 1969). Pronounced surfaces of exposure are those where fenestral mudstones that contain multiple exposure features such as crystal silt and/or calcite-filled vugs lined by reddish crusts are truncated by deeper-water lithologies. Pronounced surfaces of exposure define six third-order sequences, 10–50 m thick, on the platform around Thorn Hill, Tennessee (Table 1). Within these third-order sequences, less pronounced surfaces showing fewer exposure features define fourth-order sequences, 2–20 m thick (Table 1). Water-depth curves indicate multiple shoaling events or possible exposure surfaces within many fourth-order subsequences. These form fifth-order sequences comparable in scale to the parasequences of other authors (Read et al. 1986; Osleger 1991; Van Wagoner et al. 1990).

Platform-Interior Lithologies

Lithologies on the platform are fully documented by Steinhauff and Walker (in press), but we summarize briefly here. Seventeen limestone facies, lettered A through S, are recognized within Sequences 1 through 4

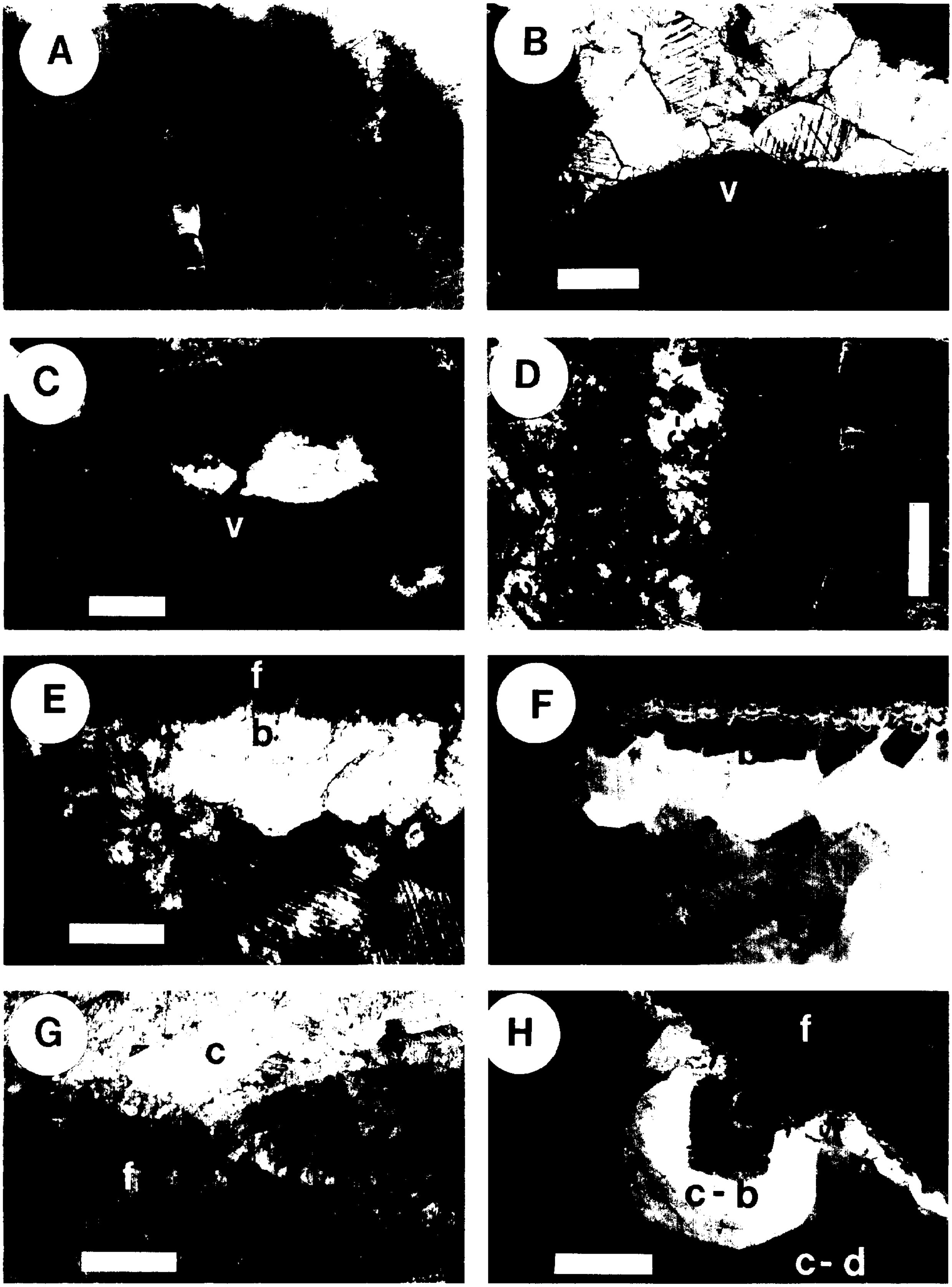
A
B
V
C
V
D
E
f
b
F
b
G
c
f
H
f
c - b
c - d

TABLE 1.—*Stratigraphic cyclicity and associated terminology*

Orders of Stratigraphic Cyclicity	Terminology Used in this Paper	Synonyms or Other Related Phenomena	Associated Exposure Surfaces	Approximate Thickness in Meters	Approximate Duration
First order	None	"The older of the two first-order [global] cycles" (Vail et al. 1977).	Not applicable	1000s of meters	>300 million years
Second order	None	Tippecanoe Sequence (Sloss 1963); Ordovician-Silurian (O-S) second order-cycle (Vail et al. 1977); Paleozoic Sequence II, Middle Ordovician to Lower Devonian (Walker 1985; Byerly et al. 1986).	Knox unconformity	1383 m (Paleozoic Sequence II, East Tenn.)	10–80 million years for the 14 Phanerozoic second-order cycles (Vail et al. 1977). According to Vail et al., the Ordovician-Silurian (O-S) second-order-cycle spans about 80 million years.
Third order	Sequence	Third-order [global] cycles of relative change of sea level (e.g., Vail et al. 1977).	Pronounced	20 to 170 m	2.5 to about 3 million years
Fourth order	Subsequence	Fourth-order cycles of relative change of sea level or "high-frequency" sea-level fluctuations (e.g., Kendall and Schlager 1981; Read 1989); parasequence sets (Van Wagoner et al. 1988, 1990); megacycles (Goldhammer et al. 1990).	Less pronounced	2.5 to less than 60 m	Hundreds of thousands of years
Fifth order	Parasequence (text tells how parasequences in this paper are different)	Other related phenomena: (meter-scale) cycle (e.g., Wilson1975; Read et al. 1986; Read 1991); Parasequence (Van Wagoner et al. 1990); punctuated aggradational cycles (Goodwin and Anderson 1985).	Shoaling and possible exposure	0.5 to less than 2.5 m	Thousands of years

(Figs. 2–6, Table 2). Numbers are also assigned to these facies (Fig. 7). These numbers generally correspond to the standard microfacies numbers of Wilson (1975) and Flügel (1982). Platform-interior rocks include mud-rich lithologies, peloidal grainstones and associated mud-rich lithologies, echinoderm grainstones, a variety of coated-grain grainstones, and other less common lithologies (Fig. 5). More detailed descriptions and interpretations, including environment of deposition, are given in Table 2, but the general characteristics are given below. Later, we will contrast these platform lithologies with platform-margin rock types.

Fossil Content.—Echinoderms and bryozoans are the most common and abundant fossils and are generally present as fragments (Fig. 6). Two faunal associations are generally recognized: an arthropod-mollusk association (i.e., thick-shelled trilobites or ostracods, or both, with gastropods) and a brachiopod-bryozoan association (Fig. 6).

Water Depths.—Most deposition on the platform probably took place in water only a few meters deep (Steinhauff and Walker, in press). Maximum water depths on the platform never exceeded 20 m during deposition of the Five Oaks, Lincolnshire, and Rockdell Formations. During deposition of the middle to upper Benbolt Formation and the lower Wardell Formation, maximum water depths may have been slightly deeper. Many stratigraphic intervals, particularly those with abundant oncoids and other coated grains, were probably deposited in very shallow water (less than one or two meters) and may have been occasionally exposed. Stratigraphic intervals containing abundant subaerial exposure criteria (pronounced surfaces) probably experienced exposure for some considerable but unknown length of time, and intervals containing fewer exposure criteria (less pronounced surfaces) were probably exposed for a shorter time.

The Platform-Interior Succession

In the Middle Ordovician platform succession, more than 400 m thick, in a 6 km transect near Thorn Hill, Tennessee, subaerial exposure surfaces define stratigraphic sequences. Carbonate platform cycles described by Wilson (1975) often have lower open-marine beds with the upper part of the cycle dominated by peritidal mudstones that have a sharp contact at the top of the cycle. Such peritidal mudstones are commonly dolomitized. Thus, such cycles can be recognized easily in the field (e.g., Hardie and Shinn 1986; Read et al. 1986; Osleger 1991; Van Wagoner et al. 1988). In contrast, the sequences studied here are often entirely subtidal, and generally cannot be recognized by field criteria alone. However, they are shallowing-upward packages similar to cycles and can be recognized by methods outlined below.

We have recognized seven pronounced surfaces of subaerial exposure to define six third-order sequences on the platform at Thorn Hill, Tennessee. Within the lower four third-order sequences there are 19 less pronounced surfaces, with a total of 23 surfaces recognized in approximately 400 m of section. These less pronounced surfaces define fourth-order subsequences that appear to be correlative across the platform. These third- and fourth-order sequences contain "fifth-order" or "meter-scale" packages comparable in scale to the parasequences of other authors (Van Wagoner et al. 1988, 1990). Parasequences are not correlative across the platform, and many of these are probably the result of lateral migration of environments. Pronounced surfaces of exposure (Table 1, Fig. 2) are indicated on the platform where fenestral mudstones are erosionally truncated and overlain by cross-bedded grainstones and packstones. Truncated

←

FIG. 3.—Indicators of subaerial exposure. Scale bars at bottom of field represent 1 mm. **A)** Typical exposure of mud-rich beds, platform-interior Thorn Hill section, about 220 m above Knox unconformity. **B)** Geopetal vadose silt (v) along bottom of cavity filled with blocky clear calcite. Host rock is bioclastic wackestone and packstone (Facies B) and whole-fossil wackestone (Facies A), 213.5 m above Knox, Thorn Hill section; plane-polarized light (PPL). **C)** Additional vadose silt (v) followed by blocky clear calcite, 213.5 m above Knox, Thorn Hill section; PPL. **D)** Fibrous calcite (f) grew along bottom of cavity followed by bladed calcite (not shown). Vadose silt (v) and ferroan coarse to blocky white calcite (cb) occupy intermediate pore-filling positions followed by a final ferroan coarse blocky white calcite (c), 20.6 m above Knox, Poor Valley Creek section; PPL. **E)** Cavity filled with fibrous calcite (f) followed by blocky clear calcite (b), and coarse to blocky clear calcite (c), 24.6 m above Knox, Poor Valley Creek section, PPL. **F)** Same cavity under cathodoluminescence (CL) shows that some blocky cements have pendant shapes. **G)** More typical cavity, same stratigraphic interval as E and F; fibrous calcite (f) is truncated by ferroan coarse pink sparry calcite (c), Poor Valley Creek section; PPL. **H)** Pendant cement under CL, nonluminescent fibrous calcite (f) is followed by brightly luminescent, coarse, blocky calcite (cb); and dully luminescent ferroan coarse sparry calcite (cd); 41.5 m above Knox, Red House Branch section. Fibrous calcite is interpreted to be marine on the basis of marine isotopic (^{87}Sr/^{86}Sr and ^{18}O) values; bladed and equant calcite have probable meteoric isotopic values; and sparry calcite is interpreted to be of burial origin on the basis of depleted ^{18}O values and elevated trace-element content. Diagenesis and geochemistry is discussed by Steinhauff (1993), Steinhauff and Walker (1993), and Steinhauff et al. (1993).

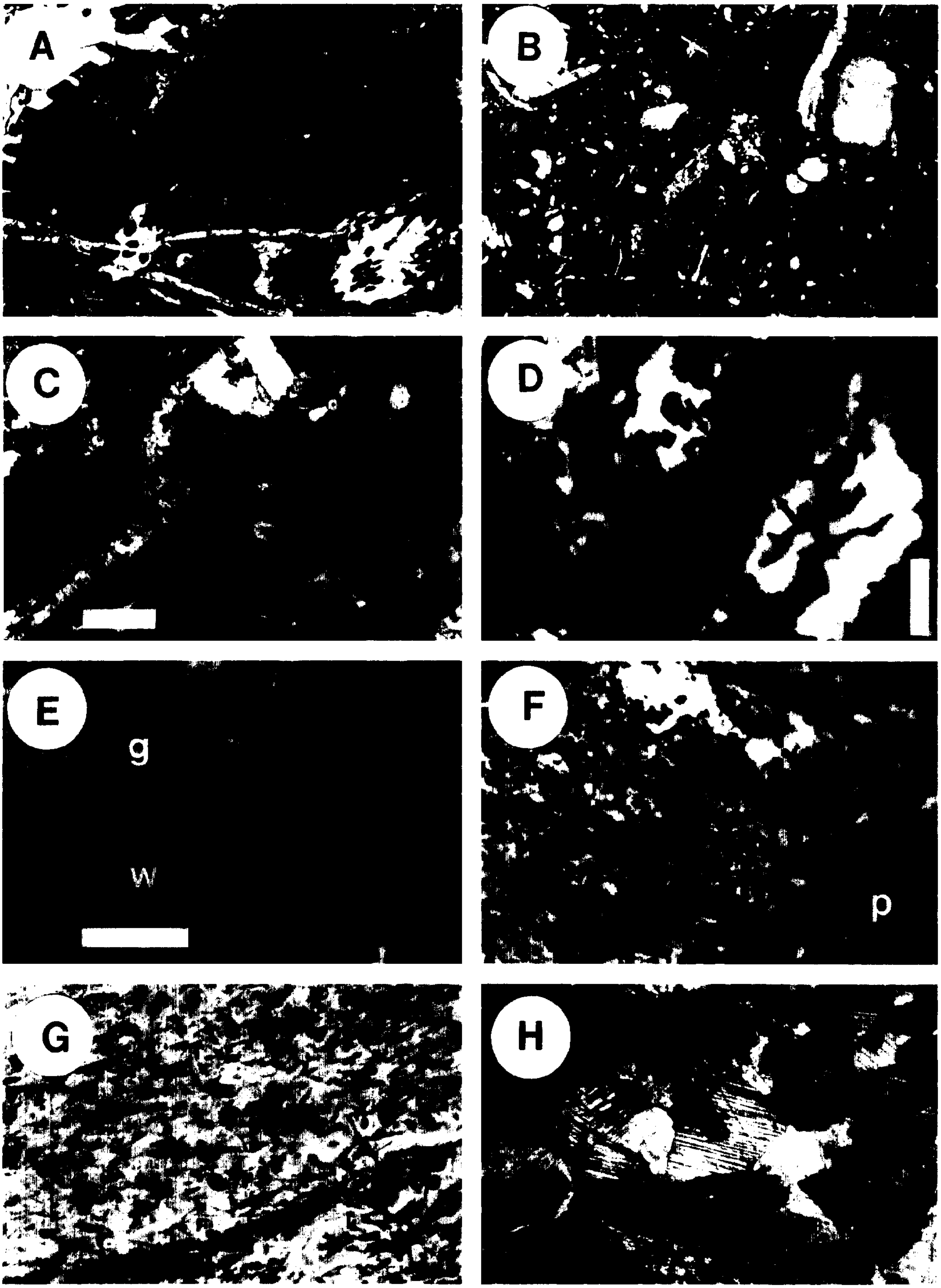
A
B
C
D
E
g
w
F
p
G
H

TABLE 2.—*Facies interpretation*[1,2]

Lithology/Microfacies[3]	Rock Name after Dunham (1962)	Probable Water-depth Range	Energy of Environment	Environment of Deposition
A/8	Wackestone	> 0 to 15 m	Low	Subtidal open platform or shelf lagoon below normal wave base
B/9	Bioclastic wackestone/packstone	0–12 m	Low	Shallow shelf or lagoon with open circulation at or just below normal wave base
C/10g	Grainstone/cortoid grainstone	0.5–30 m	Very high to high	Very shallow, intertidal shelf or lagoon, shoals or tidal bars
D/11	Grainstone/cortoid grainstone	0.5–4 m	Moderate	Very shallow, intertidal, shelf or lagoon, shoals or tidal bars in zone of winnowing
E/12g	Echinoderm grainstone	0.5–30 m, generally less than 15 m deep	High to moderate	Shelf to shelf-edge subtidal environment above or near normal wave base
F/12p	Echinoderm/bryozoan packstone	0.5–15 m, generally less than about 12 m	Moderate to low	Shelf to shelf-edge subtidal environment below or near normal wave base
G/13	Oncoid grainstone	< 0.5 to < 2 m	High to moderate	Very shallow intertidal, shelf or lagoon, shoals or tidal bars in zone of winnowing
H/14	Grainstone, conglomeratic lag	< 0.5 to 6 m	Generally high	Represents slow accumulation of coarse material in zone of winnowing, subtidal, agitated environment
I/16	Peloidal grainstone	< 0.5 to < 15 m	Moderate to low	Very shallow, intratidal to subtidal, shelf or lagoon with moderate water circulation
J/17	Grainstone/peloidal grainstone	> 0 to 8 m	Moderate to low	Shallow, intertidal, shelf or lagoon with restricted circulation
K/18	Dasycladacean grainstone	< 0.5 to 12 m	High to moderate	Concentration of algal grains in tidal bars and channels
L/19	Wackestone/mudstone	exposed to < 2 m deep	Low	Tidal flat, supratidal to intratidal
L/191	Laminated wackestone/mudstone	Very deep; 30 to > 1000 m	Very low	Deep open shelf or lagoon with restricted circulation
L/19F	Fenestral wackestone/mudstone	exposed to < 2 m	Low	Tidal flat, supratidal to intratidal
M/21	Spongiostrome mudstone	0–2 m	Very low	Tidal flat, intertidal ponds
N/22	Wackestone/packstone-oncoid Wackestone/packstone	< 0.5 to 8 m	Moderate to low	Shallow shelf or lagoon (along margins of tidal ponds?) with restricted circulation
O/24	Lithoclastic grainstone/packstone	0–10 m	Generally low with brief periods of high energy	Represents filled channels and potholes developed on tidal flat. Clasts derived from lime mud on levees and algal mats.
P Not numbered	Dolostone/dolomitic limestone	Very shallow; exposed to < 0.5 m	Low	Exposed tidal flat
Q Not numbered	Siltstone/carbonate siltstone	0.5–30 m	Low	Deep lagoon receiving influx of siliciclastic material
R Not numbered	Shale/shaly carbonate	0 to > 150 m	Very low	Deep lagoon receiving influx of siliciclastic material
S Not numbered	Bentonite	Bedded bentonites best preserved in low-energy, shallow-water environments, 0.5 to less than 15 m deep.	Generally low; some bentonites may have been reworked.	Ash fall preserved within shallow, low energy, subtidal and peritidal environments

[1] Based either on previous work (Ruppel and Walker 1982, 1984; Jernigan 1987) or on comparative work by Steinhauff (1993) using materials and interpretations from similar environments near Knoxville provided by Moore (1978), Benedict and Walker (1978), Breland (1980), and Johnson (1988).

[2] Facies descriptions are provided by Steinhauff (1993).

[3] Microfacies numbers generally correspond to standard microfacies of Wilson (1975); however, some microfacies are modified (i.e., 10g, 12g, 12p, 191, 19F) to account for criteria characteristic of Middle Ordovician limestones but not generally observed in younger rocks.

fenestral mudstones contain most, if not all, of the subaerial exposure indicators we have listed. Less pronounced surfaces of exposure are indicated by crystal silt and one or more other indicators of subaerial exposure within underlying rocks.

METHODS: ESTABLISHING A PLATFORM-MARGIN SUCCESSION OF SEQUENCES

Thin sections and slabs provided data from which paleobathymetry could be inferred, allowing construction of water-depth curves. In the entire succession, 1041 thin sections from 784 stratigraphic intervals were used. Additionally, polished slabs from more than 325 of these stratigraphic intervals were prepared to look for features such as burrows, flat algal laminae, and different categories of fenestrae. These features can be difficult to discern in the field and typically are at a scale inappropriate for thin-section observation. Serial sections of slabs ranging from about 50 mm × 100 mm to about 200 mm × 250 mm were prepared for each stratigraphic interval examined. Comparative observations were also made in 162 thin sections provided by Breland (1980) from the Knoxville area (Figs. 5, 6). Each successive, lithologically homogeneous interval, represented by at least one 50 mm × 75 mm thin section, was scored for the presence or absence of Middle Ordovician paleobathymetric indicators such as blackened grains, mud cracks and ooids, different categories of algae, and sedimentary microstuctures. Some features, such as thickness of bedding or megaripples, are best observed in the field. Very conservative

←

FIG. 4.—Lithologies: **A)** Bioclastic wackestone and packstone (Facies B), 42.5 m above Knox, Red House Branch section; plane-polarized light (PPL), scale bar = 1 mm. **B)** Additional bioclastic wackestone and packstone, same stratigraphic interval as A; PPL, scale bar = 1 mm. **C)** Echinoderm and bryozoan packstone (Facies F), 57 m above Knox, Red House Branch section; PPL, scale bar = 1 mm. **D)** Echinoderm and bryozoan packstone (Facies F). Black areas (arrow) between spar-filled cavities are sediment rich in iron-manganese oxides, 20.6 m above Knox, Poor Valley Creek section; polished slab, "up" to left margin of page, scale bar = 2 cm. **E)** Wackestone (w) (Facies A with Facies L, poorly developed) is overlain by echinoderm grainstone (g) (Facies E). Boring (arrow) suggests that wackestone was lithified and possibly exposed before grainstone was deposited; 41.5 m above Knox, Red House Branch section; polished slab, scale bar = 3 cm. **F)** Typical contact between echinoderm grainstone (g) (Facies E) and echinoderm and bryozoan packstone (p) (Facies F), 42 m above Knox, Red House Branch section; polished slab, scale bar = 3 cm. **G)** Echinoderm grainstone (Facies E), 13.8 m above Knox, Poor Valley Creek section; polished slab, scale bar = 3 cm. **H)** Echinoderm grainstone (Facies E) with bryozoan fragments, 50.5 m above Knox, Red House Branch section; PPL, scale bar = 1 mm.

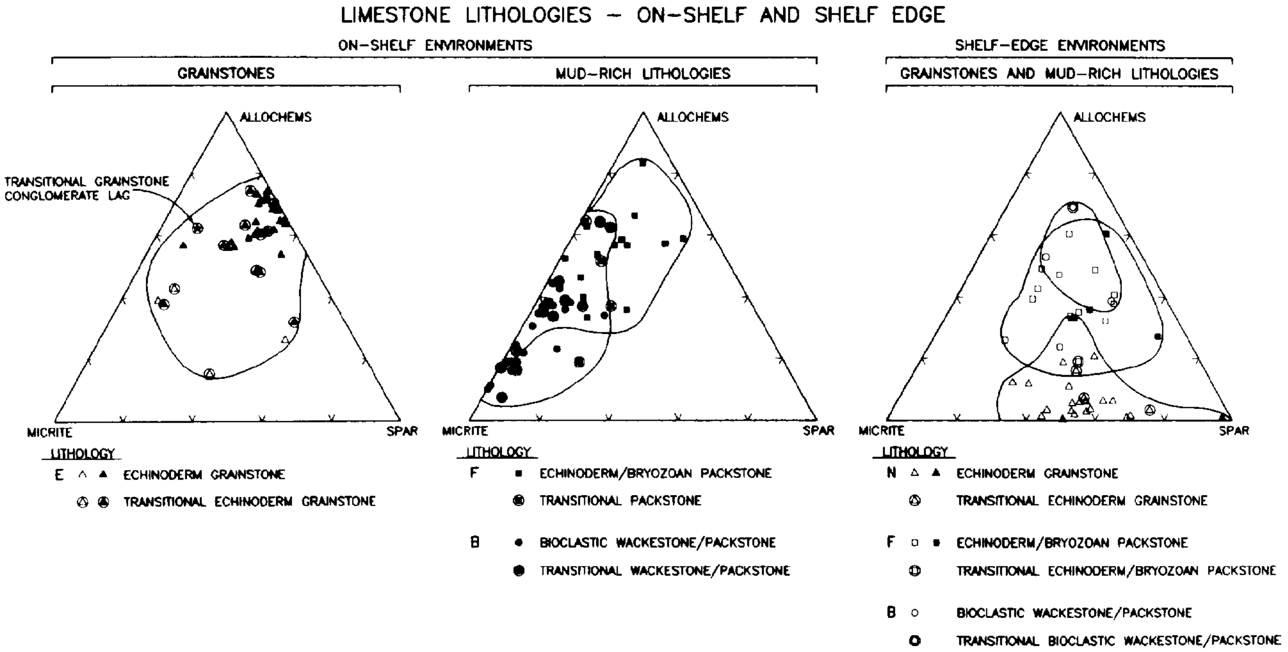

FIG. 5.—Comparison of Middle Ordovician limestone lithologies from platform-interior (on-shelf) environments to similar environments at or near the platform margin (shelf edge) in East Tennessee. Selected point-count data are from Ruppel (1979), Breland (1980), and Jernigan (1987). Open symbols indicate cement-priority point counting (cf. Jernigan 1987), and solid symbols indicate standard grain-priority technique. In standard grain-priority point counting, the interior of a snail would be counted as "snail", though the interior space might be filled with cement. Using "cement priority" the area would be counted as cement. Symbols enclosed by a ring indicate transitional facies, where an estimated 1/2 to 2/3 of the plotted lithology is recognized.

water-depth estimates were used for paleobathymetric criteria. Steinhauff and Walker (in press) provide discussion and references for the more than 70 criteria used in this study to infer water-depth ranges for stratigraphic intervals.

Inflection Points in Paleobathymetric Curves

Indicators of shallow water depths discriminate a narrower range of possible water depths than do those indicating deeper water depths. Thus, a geometric scale was selected to plot a range of possible water depths at the time of deposition (e.g., Figs. 7–12). A midpoint for each range is also plotted. When more than one thin section was observed for a stratigraphic interval, these might represent slightly different lithologies (e.g., skeletal grainstone versus skeletal packstone) and thus yield slightly different water-depth estimates. For these intervals, the combined range is plotted and two "midpoints" are indicated (e.g., Figs. 7, 8).

"First iteration" water-depth curves were used to identify shallow-water intervals that may have been exposed. These curves were compared with detailed lithologic descriptions at a scale of 1 inch (2.54 cm) to 1 meter. Stratigraphic intervals having inflection points indicating possible exposure or shoaling were reexamined, either in outcrop or in thin section, for the presence of indicators of subaerial exposure. The "first iteration" water-depth curves were then replotted to reflect the subaerial exposure of some stratigraphic intervals (dashed lines on water-depth curves, e.g., Figs. 7, 8).

Relative Stratigraphic Relationships

Biostratigraphic, lithostratigraphic, and sequence stratigraphic correlation along strike on the platform is simple compared with correlation from the platform interior to the platform margin because measured sections on the platform are separated from each other by only about 2 km. For example, some individual beds can be traced for about 400 m. Correlation along strike on the platform is described and illustrated by Steinhauff and Walker (in press). The present paper documents correlation along strike near the margin of the platform (Figs. 9–11) and then from the platform margin to the platform interior. The assumptions or "guiding principles" (e.g., Krumbein and Sloss 1951) that constrain the latter correlations are given in Table 3.

Evidence for Drowning and Drowning Unconformity

Evidence for drowning comes from inflection points on water-depth curves that indicate deepening. Evidence for drowning unconformity, on the other hand, is more circumstantial. A drowning unconformity forms when carbonate-producing environments pass below the euphotic zone and carbonate production is greatly suppressed or halted (Schlager 1981). Cephalopod limestone overlying shallow-water carbonate was cited by Schlager (1981) as evidence for drowning unconformity in many Paleozoic and Mesozoic examples. Additionally, high metal contents are characteristic of deep-sea sediments and provide additional supporting evidence for deep-water deposition and drowning unconformity (Kennett 1982). Because drowning unconformity is dependent on shutting down the "carbonate factory", analogous unconformities are probably not produced on siliciclastic shelves. For example, "maximum flooding" surfaces (the first transgressive surface and the downlap surface) described on siliciclastic shelves (Loutit et al. 1988) should not be considered drowning unconformities even though sedimentation is suppressed or even halted. In contrast, a carbonate platform continues to accrete sediment during maximum flooding if it remains within the euphotic zone. In fact, we provide an example where carbonate strata continued to be vertically accreted during a probable maximum flooding event in our discussion below of Sequence 2.

Platform-Margin Lithologies

A much smaller number of lithologies (9) were deposited near the platform margin than in the platform interior (17). Indeed, just three lithologies account for about 85% of the total thickness and are present through-

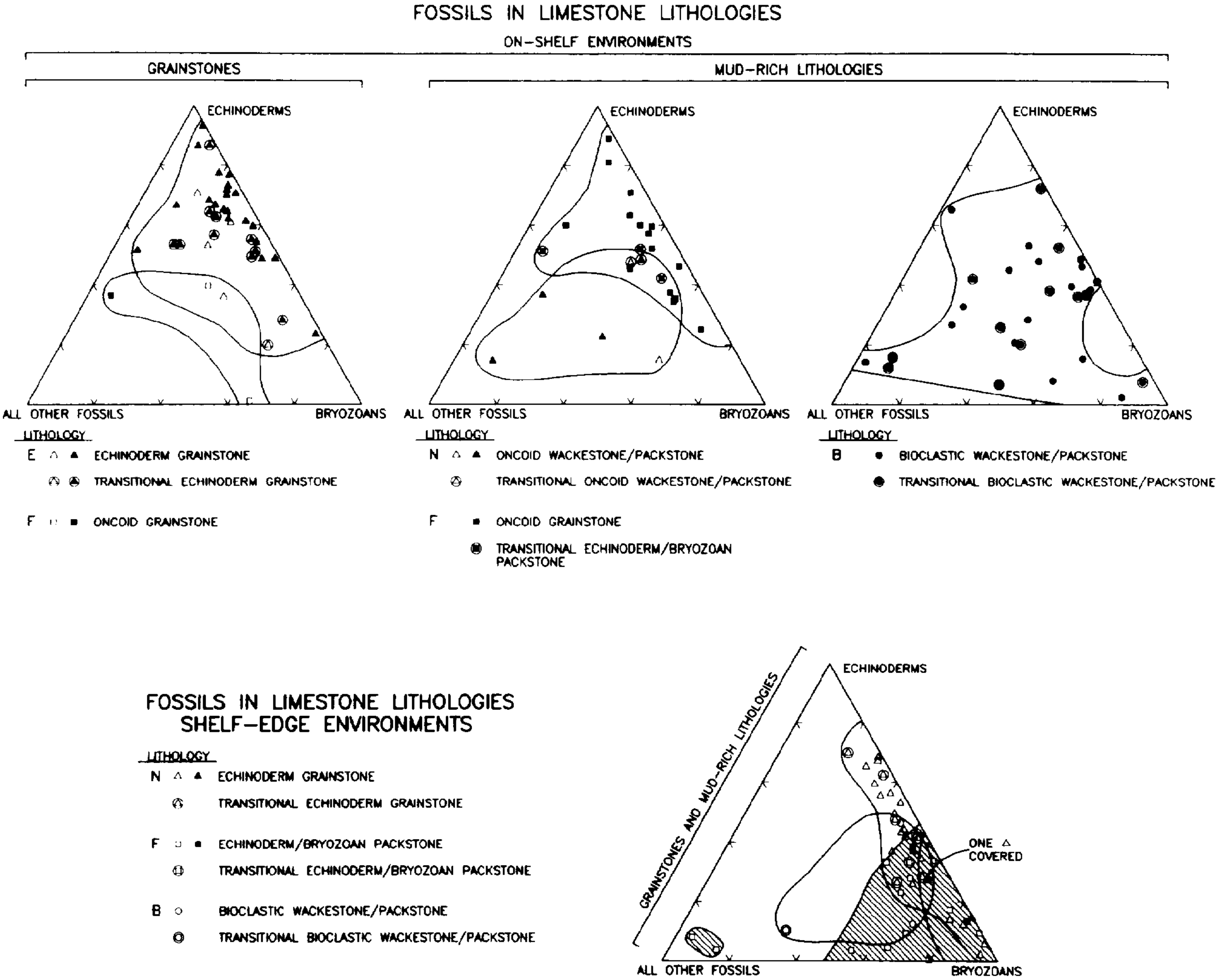

FIG. 6.—Comparison of fossils in Middle Ordovician limestone lithologies from platform-interior (on-shelf) environments to similar environments at or near the platform margin (shelf edge) in East Tennessee. Selected point-count data are from Ruppel (1979), Breland (1980), and Jernigan (1987). See caption of Figure 5 for details.

out the platform-margin succession. In order of relative abundance these are: echinoderm or bryozoan, or both, packstone (Facies F of Table 2), echinoderm grainstone (Facies E), and bioclastic wackestone and packstone (Facies B) (Figs. 4, 5). All three lithologies are laterally and, less so, vertically gradational with each other. Six less common lithologies account for the remaining stratigraphic thickness, and these generally are present only above and below unconformable surfaces (Fig. 9). These less common lithologies generally contain evidence for exposure such as (1) vugs filled with calcite or crystal silt, or both, and lined by reddish crusts, (2) truncated fibrous marine cement overlain by more fibrous cement or by bladed and equant calcite with probable meteoric isotopic values. In some cases pendant cements and horizontal fenestrae are present.

Peloidal and associated mud-rich lithologies are restricted to the Five Oaks, Lenoir, and lowermost Holston Formations in the platform-margin succession (Fig. 9). Also, wackestone and mudstone (Facies L) is well developed only within the Five Oaks Formation and is gradational with peloidal grainstone (Facies I). Bioclastic wackestone (Facies B) accounts for about 10% of the total stratigraphic thickness at the platform margin.

Fossil Content.—Stromatoporoid and bryozoan boundstones are abundant only near the platform margin (Figs. 9, 10). Cephalopod-rich packstones are present along drowning surfaces between Sequences 1C and 2C and between Sequences 2A and 2C at Poor Valley Creek and Red House Branch, respectively (Figs. 9–11).

Water Depths.—Using the same criteria as those used in the platform interior for paleobathymetric analysis (Steinhauff and Walker, in press) we established water depths for the platform-margin succession. Maximum water depths in the latter area were on the order of 60 m (Figs. 9–12). Minimum water depths for deposition near the platform margin were probably a meter or two, but since exposure surfaces do exist in that part of the succession, clearly water depth was sometimes zero. During times of exposure it is, of course, impossible to determine how far sea level dropped below the depositional surface. Nonetheless, the profundity of the exposure surface produced is an indication of a combination of magnitude of sea-level drop and duration of exposure.

CORRELATION CRITERIA

Chronostratigraphic Criteria

Biostratigraphic investigations by Bergström (Bergström 1971, 1973, 1977; Bergström and Carnes 1976) and Anita Harris (personal communication, 1990) and lithologic correlations by Ruppel (1979) and Ruppel and Walker (1982, 1984) provide the framework for the more detailed sequence stratigraphic correlations presented here. Bentonite beds provide additional chronostratigraphic control (Time Line 5 of Walker 1980 and Ruppel and Walker 1982) for correlation.

Most previous attempts at correlation within the total succession have been most successful within the platform-interior part. Correlation from the platform interior to the margin is more difficult. Although the two areas are within the same fault block, in restored position interior localities are separated from margin localities by about 20 km. For example, conodont biostratigraphy is used to help correlate Sequences 1A through 2D and their constituent lithologies between the two areas. However, starting about 50 m above the base of the succession (the Knox unconformity) only the *Prionidous gerdae* Subzone of the *Amorphognathus tvaerensis* Zone is recognized in both the platform interior and platform margin parts of the succession. Thus, many unconformable surfaces of subaerial exposure or drowning, or both, can be correlated from the platform interior to the platform margin only on the basis of relative stratigraphic position, presence of deepening events, and lithologic patterns.

Exposure Surfaces

Surfaces of subaerial exposure are used to correlate stratigraphic sequences between the two areas. Some exposure surfaces are more pronounced than others (on the basis of the number of exposure features along each surface). Thus, the relative degree of exposure (pronounced or less pronounced) has been used to help guide correlations. Exposure surfaces also help constrain correlation of deepening events (Table 3). The recognition of exposure surfaces is described above.

Deepening Events

A number of water-deepening events occurred within this Middle Ordovician succession. These events are relatively easy to correlate along strike on the platform because water-depth indicators are most sensitive to depth changes in shallow water. These deepening events may be a result of eustatic rises of sea level or to periods of slow deposition coupled with continued subsidence. On the other hand, correlation of deepening events along strike at the platform margin and from those areas to the platform interior is more difficult (Figs. 12–14). For example, in deep-water depositional facies, such as those in Sequences 2A and 2B at Poor Valley Creek, water-depth changes are difficult to resolve and no indication of a maximum depth can be inferred.

TYPES OF STRATIGRAPHIC SEQUENCES

Third-Order Sequences and Timing

As previously mentioned, starting with and including the Knox unconformity, seven pronounced surfaces of subaerial exposure are recognized in the 600-meter-thick Middle Ordovician platform succession near Thorn Hill. These seven pronounced surfaces define six stratigraphic sequences, numbered 1 through 6 (Fig. 2). The sixth surface is in the Moccasin Formation and has been documented by Ruppel and Walker (1982, 1984) and Simonson (1985). The uppermost (seventh) surface, followed by a pronounced deepening, is at the top of the Moccasin and separates that formation from the overlying Martinsburg Formation (Simonson 1985; Walker 1992). The lower five surfaces are considered in this study (about the lower 400 m of the Middle Ordovician).

Middle Ordovician deposition took place over a period of approximately 20–25 million years. This is based on the biostratigraphic work of Bergström and Carnes (1975) and absolute ages assigned to series boundaries as summarized by Bond et al. (1988). The interval considered here represents about three quarters of the entire Middle Ordovician, and therefore probably had a duration of 15–17 million years. Thus, the estimated time for deposition of each sequence is 2.5 million years to a little more than 3 million years. These sequences, then, appear to be of duration similar to those commonly referred to as the products of "third-order" sea-level cycles (e.g., Vail et al. 1977; Van Wagoner et al. 1988, 1990).

Fourth-Order Subsequences

Sequences bounded by pronounced exposure surfaces are subdivided by less pronounced exposure surfaces. These less pronounced exposure surfaces are correlated parallel (Figs. 8–13) and perpendicular (Fig. 14) to depositional strike. Starting above the Knox unconformity, 19 less pronounced exposure surfaces are recognized in the lower 400 m (in Sequences 1–4) of the platform succession near Thorn Hill (Figs 13, 14). When these 19 less pronounced surfaces are combined with the five pronounced surfaces, a total of 23 surfaces are recognized in approximately 400 m. This leads to 22 subsequences recognized within the previously defined and numbered third-order sequences. These subsequences bounded by less pronounced surfaces are designated alphabetically within the numbered third-order sequence in which they are found (e.g., 2A, 2B, 2C, etc.; Figs. 8–14). These subsequences appear to be of thickness similar to intervals referred to as the products of "fourth-order" sea-level cycles or "high-frequency" sea-level fluctuations (e.g., Kendall and Schlager 1981; Read 1989) and parasequence sets (Van Wagoner et al. 1988, 1990), and are of similar duration (hundreds of thousands of years).

Parasequences: "Fifth-Order" or "Meter-Scale" Packages

Multiple shoaling events, many with possible exposure surfaces, are indicated within many fourth-order subsequences. These are comparable in scale to the parasequences of Van Wagoner et al. (1990), upward-shoaling cycles of Wilson (1975), and punctuated aggradational cycles of Goodwin and Anderson (1985). Evidence for shoaling comes from the paleobathymetrically significant features and from lithologic changes. This evidence is often apparent only in thin section or polished slabs, such as subtle transitions from a mud-rich lithology lacking oncoids to one containing only a few percent oncoids. The packages are similar to the cycles of other authors (e.g., Wilson 1975; Read et al. 1986; Osleger 1991) in that they often have lower-open-marine beds, but they differ in that many packages are dominated by packstones and grainstones and are sometimes capped by thin lensoidal micritic lithologies that often lack a sharp contact at the upper surface.

The parasequences described here differ from sequences and subsequences in three ways. (1) Steinhauff and Walker (in press) have shown that inflection points on the water-depth curve and subtle lithologic changes are not correlative across the entire 6 km platform-interior transect. (2) In the following paragraphs it will be shown that most fourth-order subsequences are recognized at platform-interior and platform-margin localities, yet parasequences cannot be similarly correlated. (3) There are a variable number of parasequences at each locality. This suggests that most meter-scale parasequences are probably a result of migration of local environments. Indeed, some parasequences that extend over only a small distance are capped by mud-rich sediments containing features suggesting supratidal and intertidal deposition (on islands?). The facies characteristics of these parasequences, then, are similar to those described by Ginsburg (1971), who interpreted the parasequences he observed in modern sediments to be of autocyclic origin.

DISCUSSION OF STRATIGRAPHIC SEQUENCES AND CORRELATIONS

Third-Order Sequence 1

Description.—This third-order sequence includes the lower Five Oaks Formation on the platform and the Five Oaks and lower Lenoir Formations at the platform margin. Third-order Sequence 1 comprises fourth-

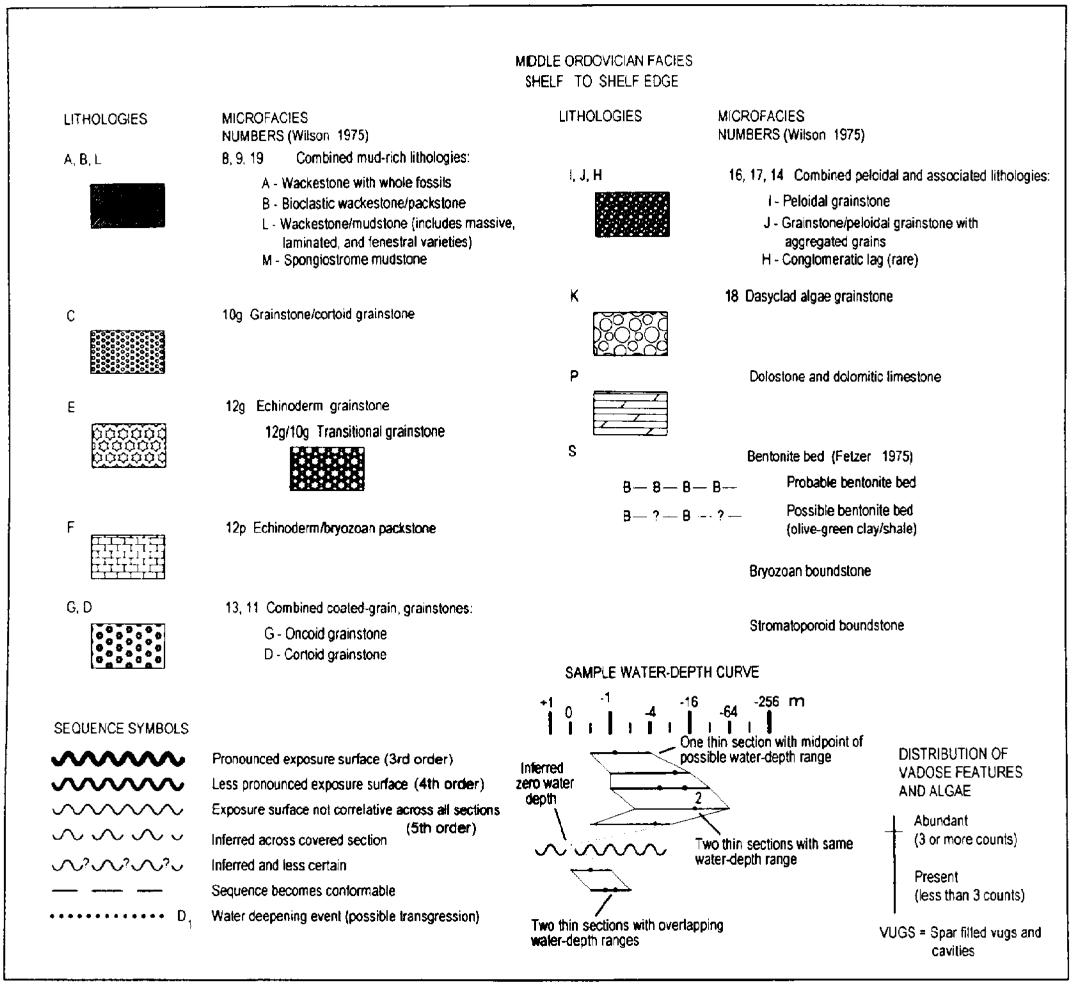

FIG. 7.—Key to facies for stratigraphic sequence diagrams and columnar sections of Figures 6, 7, 10, 11, and 12.

order Subsequences 1A, 1B, and 1C. All three fourth-order subsequences are represented in the platform interior, whereas only Subsequences 1B and 1C are present at the margin (Figs. 12–14). This is true in our study area even though, in general, conodonts indicate that Middle Ordovician deposition started earlier in southeastern fault blocks than in northwestern blocks in the Southern Appalachians (Bergström 1971, 1973, 1977; Bergström and Carnes 1976). Their data suggests, then, that there should be pre-Sequence 1 rocks above the Knox unconformity southeast of our study area.

Platform-Interior Stratigraphy.—Fenestral mudstones and very thin peloidal grainstones of the Five Oaks Formation are present above the Knox unconformity. At least two exposure surfaces can be traced along the platform in the Five Oaks Formation. These surfaces define Subsequences 1A, 1B, 1C, and 2B (Fig. 8).

Platform-Margin Stratigraphy.—The Five Oaks Formation is overlain by the Lenoir Formation (Fig. 9). The Lenoir grades laterally into the Five Oaks to the west (Fig. 14). The Lenoir at Red House Branch is a fine-grained limestone with a diverse fauna including large gastropods, cephalopods, trilobites, sponges, and algae. Oncoids are present in several horizons in the Lenoir Formation, suggesting quite shallow water during deposition.

Analysis.—This lowermost Middle Ordovician sequence has been studied by Roberson (1994). Roberson concluded that two exposure surfaces in Sequence 1 are regionally diachronous and are the result of facies migration. He suggested that the Five Oaks Formation in Sequence 1 represents infilling of the Knox surface with tidal-flat deposits during initial Middle Ordovician transgression. He interpreted the exposure surfaces in the Five Oaks to represent migration of beach ridges through a tidal-flat complex (Roberson 1987; Roberson and Foreman 1989; Roberson and Walker 1990; Roberson 1994). Roberson proposed that Sequence 1 sediments filled accommodation space made available by a combination of a migrating foreland basin and a peripheral bulge. As the pair moved toward the craton, transgression and shallow-water sedimentation occurred in the forward basin, followed by regression and subaerial exposure as the trailing bulge shifted northwest indicated at the surface between Subsequences 1A and 1B (Figs. 8, 14, 15A) on the platform and the surface between Subsequences 1B and 1C at the margin (Figs. 9, 14, 15A).

Correlation.—Subsequence 1A was deposited on the Knox surface in a foreland basin on the platform while a peripheral bulge occupied the platform-margin area. Thus, Sequence 1A was not deposited in the latter area. As the migrating bulge passed northwestward, Sequence 1B was deposited as tidal-flat sediment at the margin and as very shallow-water sediment on the platform (deepening event D_0, Figs. 12–16). Slightly deeper, shallow-water sedimentation continued on the platform and at the

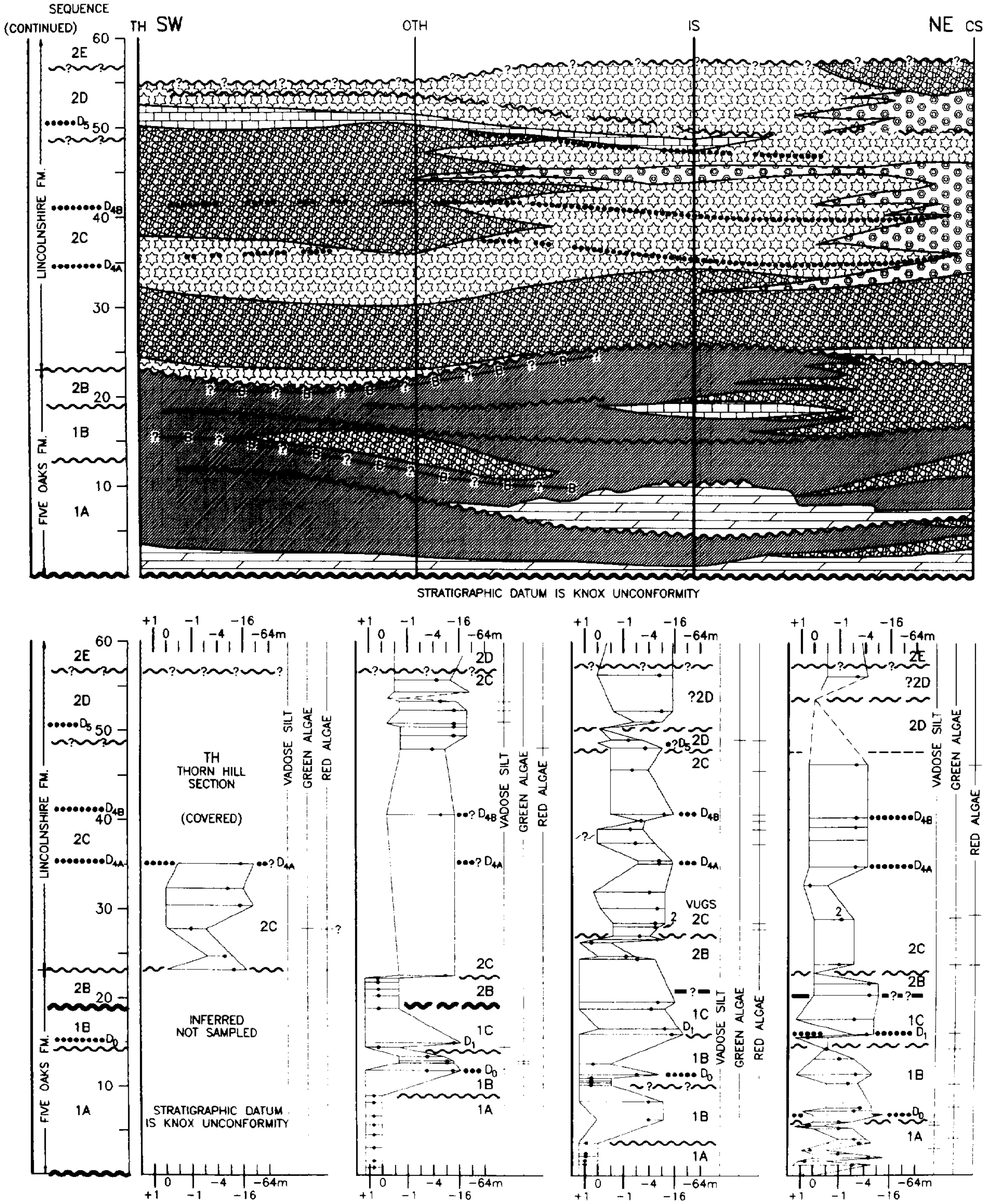

FIG. 8.—Stratigraphic Subsequences 1A, 1B, 1C, 2B, 2C, and 2D on the platform in the Thorn Hill area from Steinhauff and Walker (in press). Bottom panel shows water-depth curves for stratigraphic sections (from southwest to northeast) at Thorn Hill (TH), Old Thorn Hill (OTH), Idol Mine (IS), and Cedar Springs CS). Top panel shows corresponding restored cross section. See Figure 5 for key to facies.

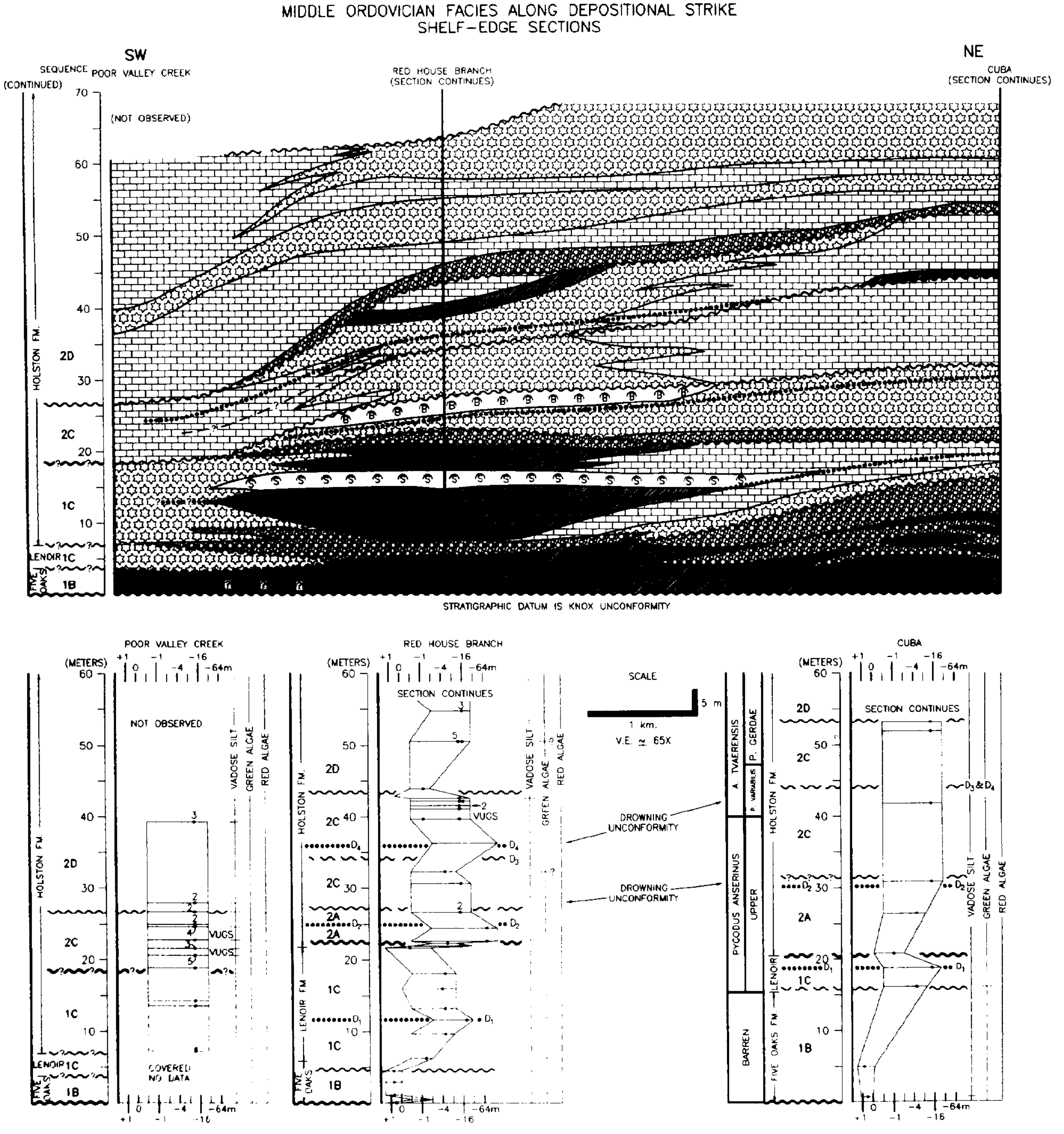

FIG. 9.—Stratigraphic Subsequences 1B, 1C, 2B, 2C, and 2D near the platform margin (shelf edge) in the Red House Branch area. Bottom panel shows water-depth curves for stratigraphic sections (from southwest to northeast) at Poor Valley Creek (PVC), Red House Branch (RHB), and Cuba (CU). Top panel shows corresponding restored cross section. See Figure 5 for key to facies.

margin during deposition of Sequence 1C as indicated by deepening event D_1. Surfaces of subaerial exposure between Subsequence 2B and 1C (Fig. 12; compare Figure 8 with Figure 9) on the platform and between Subsequence 2A and 1C at the margin were probably produced after the trailing edge of Roberson's migrating peripheral bulge had passed into the platform interior (Figs. 13, 14, 15A).

Summary.—Third-order stratigraphic boundaries in Sequence 1 are correlative from the platform interior to the platform margin, yet fourth-order cycles within the third-order sequence show differential preservation and accumulation due to migration of a foreland bulge.

Third-Order Sequence 2

Description.—This sequence includes the uppermost Five Oaks, Lincolnshire, and lower Rockdell Formations on the platform and the upper Lenoir and all of the Holston Formations at the margin. Third-order

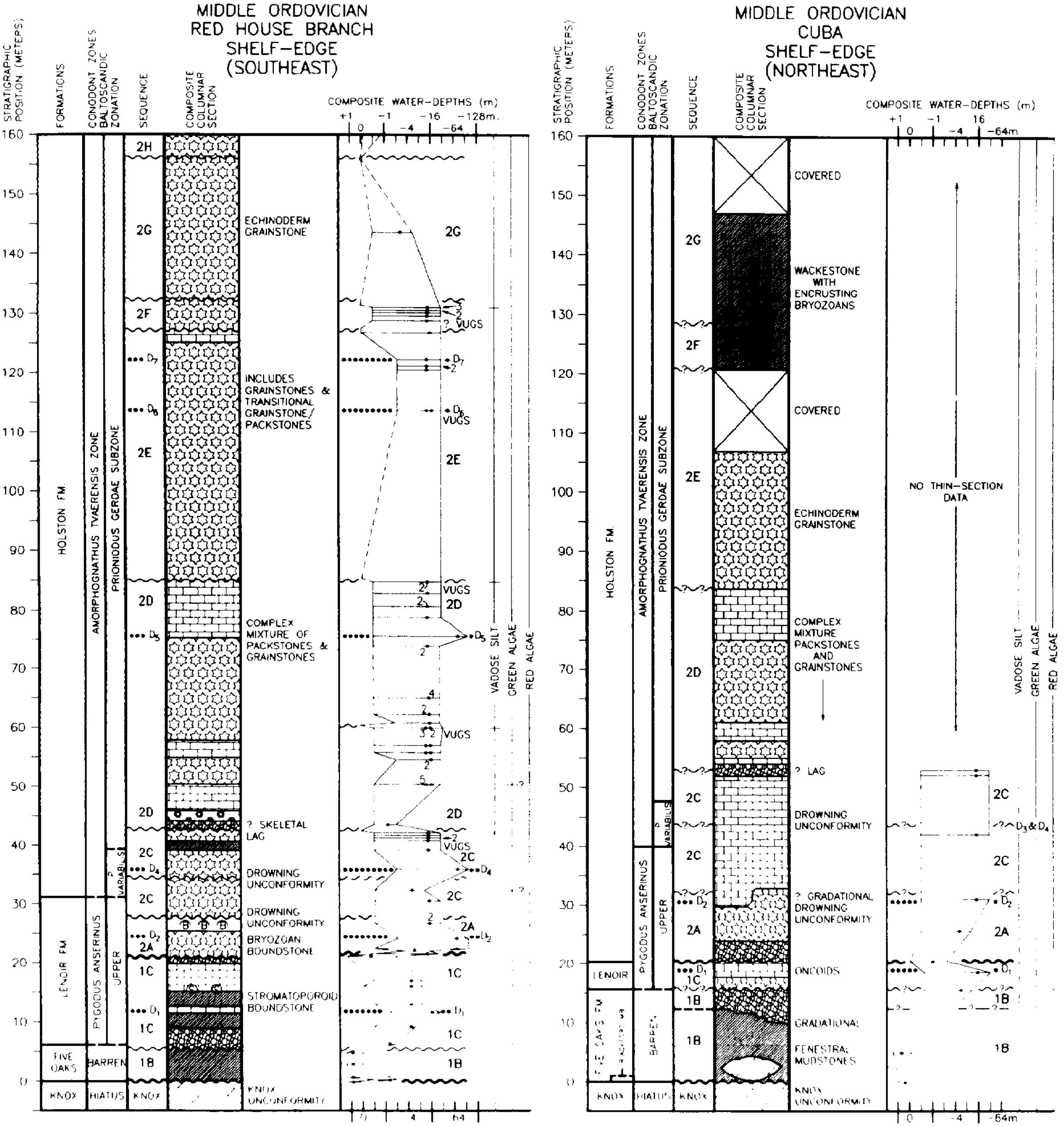

FIG. 10.—Lithostratigraphic and biostratigraphic comparison of sections near the platform margin (shelf edge). Red House Branch (left) is compared to the reference section at Cuba (right). Conodont zonation at Cuba (cf. Carnes 1975; Bergström and Carnes 1976) is projected along depositional strike, into the sequence stratigraphic framework at Red House Branch, approximately 6 km to the southwest.

Sequence 2 contains 11 fourth-order subsequences, labeled 2A through 2K. Two subsequences (2B and 2I) were deposited only on the platform and two (2A and 2F) only at the platform margin (Figs. 12–15A).

Platform-Interior Stratigraphy.—Subsequence 2B, comprising the uppermost Five Oaks Formation, overlies Sequence 1 and consists mainly of mudstones that pinch out toward the platform margin. The Subsequence 2C platform succession comprises the lower Lincolnshire Formation, consisting of peloidal grainstone and echinoderm grainstone beds. The top of Subsequence 2C is capped by lenses of mud-rich lithologies, the most common of which is an echinoderm and bryozoan packstone. Subsequence 2D overlies this shallow-water, mud-rich cap with a thin succession (< 10 m thick) of grainstone beds containing deeper-water indicators and faunas. The overlying Subsequence 2E continues with echinoderm grainstones at its base, followed by grainstones containing progressively shallower-water indicators (i.e., oncoids, peloids, and dasycladacean algae) and is capped by shallow-water wackestones that contain calcite-filled cavities floored with crystal silt at the Old Thorn Hill section. Subsequence 2F is absent on the platform. Therefore, packstones of lower Subsequence 2G directly overlie the Subsequence 2E wackestones (Fig. 12A). Upper Subsequence 2G consists mainly of peloidal grainstones containing coated

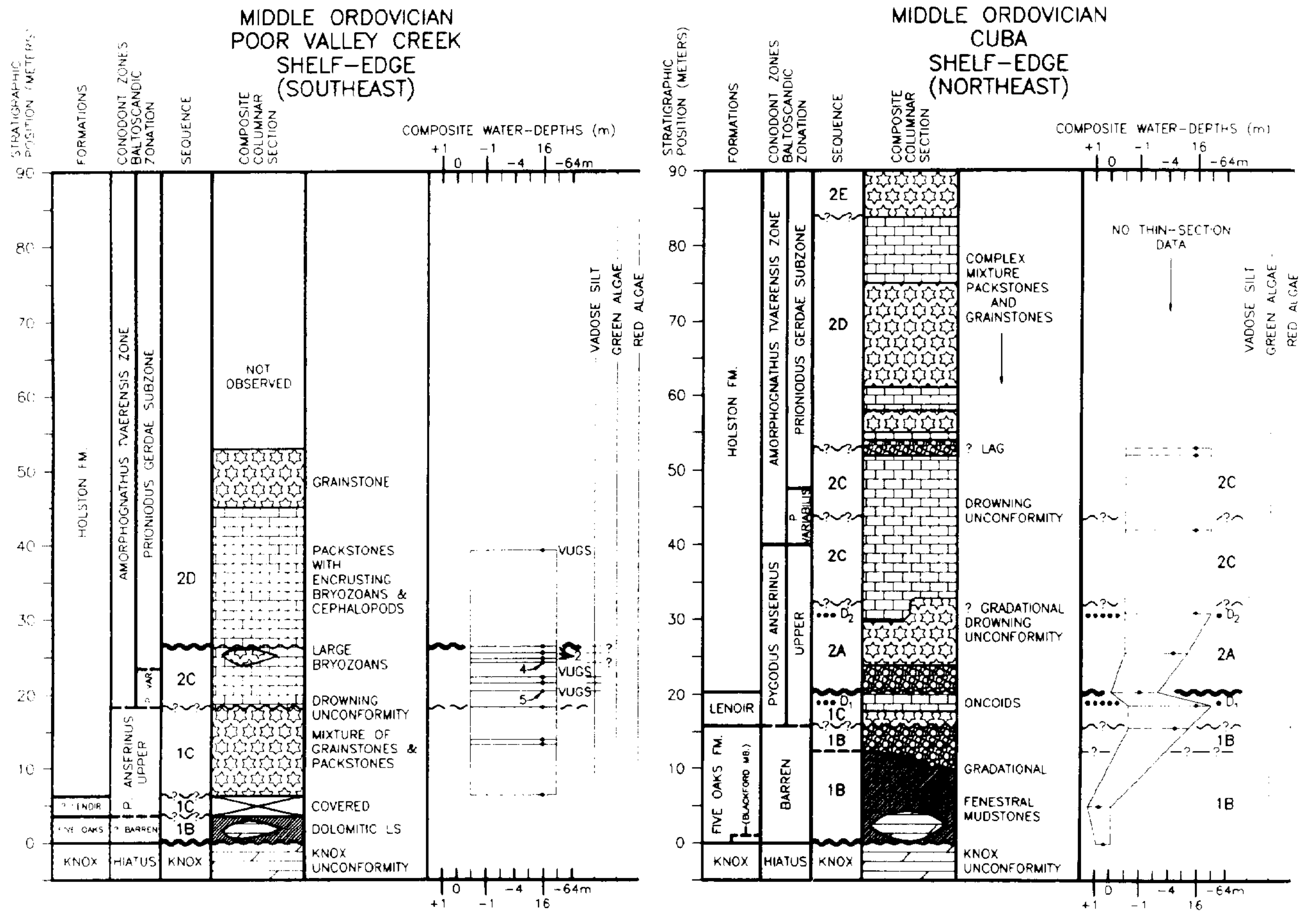

FIG. 11.—Lithostratigraphic and biostratigraphic comparison of sections near the platform margin (shelf edge). Poor Valley Creek (left) is compared to the reference section at Cuba (right). Conodont zonation at Cuba (cf. Carnes 1975, Bergström and Carnes 1976) is projected along depositional strike, into the sequence stratigraphic framework at Poor Valley Creek, approximately 9 km to the southwest.

grains. The upper surface of Subsequence 2G coincides with the contact between the Lincolnshire and Rockdell Formations.

In summary, the Lincolnshire Formation consists mainly of peloidal grainstones, commonly containing coated grains. Importantly, thin (less than 2 m thick) beds of mud-rich packstone, wackestone, and fenestral mudstone are present below exposure surfaces separating Subsequences 2C and 2D, 2D and 2E, and 2E and 2G (Fig. 12).

In contrast, the Rockdell Formation is recognized by the first occurrence of pink grainstone beds. The lower Rockdell Formation, containing Subsequences 2H, 2I, 2J, and 2K, consists of peloidal grainstones overlain by mudstone and wackestone beds (less than 0.5 m thick). However, the mud-rich intervals are much thicker than in the Lincolnshire (up to 10 m thick) and are interbedded with amalgamated grainstone beds (less than 5 m thick). Fourth-order Subsequence 2K caps third-order Sequence 2 with very shallow-water limestones, including mudstones containing calcite-filled cavities lined with reddish crusts and often floored with crystal silt.

Platform-Margin Stratigraphy.—Nearly all of Sequence 2 is composed of the Holston Formation at the margin. However, directly overlying Sequence 1 is Subsequence 2A, which is present only here and not in the platform interior. Subsequence 2A comprises the upper Lenoir Formation and consists of grainstones overlain by bryozoan bafflestones. Subsequence 2C overlies Subsequence 2A, because Subsequence 2B is absent at the platform margin. Subsequence 2C comprises the uppermost Lenoir Formation and the lower Holston Formation along the margin and consists mainly of echinoderm grainstone.

Upper Sequence 2, starting with Subsequence 2C, comprises the Holston platform-margin succession, and Subsequence 2D continues the Holston succession with a complex mixture of packstones and grainstones. Subsequences 2E through 2F of the Holston Formation continue with a complex mixture of packstones and grainstones, but bryozoan bafflestones and packstones within mud mounds flanked with lesser amounts of skeletal grainstones are also present (Figs. 9–12). Subsequences 2G, 2H, and 2J consist almost entirely of echinoderm grainstone, a lithology known locally as the "Holston marble". Subsequence 2I is absent along the platform margin. Subsequence 2J is marked by an increase in mud content, and Subsequence 2K caps Sequence 2 with packstones containing calcite-filled cavities floored with crystal silt.

Importantly, mud-rich beds are not as well developed below exposure surfaces at the platform margin as in the interior. However, packstones and wackestones are present below and along the surfaces between Subsequences 1C and 2A and between Subsequences 2C and 2D at Red House Branch, and along the surfaces between Subsequences 2C and 2D at Cuba and Poor Valley Creek (Figs. 9–11). Wackestones and fenestral mudstones are present just below the exposure surface separating Subsequences 1C and 2A at Red House Branch (e.g., Figs. 9, 12).

Analysis.—During deposition of Subsequence 2A, the platform was exposed and sea level was near the margin. Shallow-water sedimentation

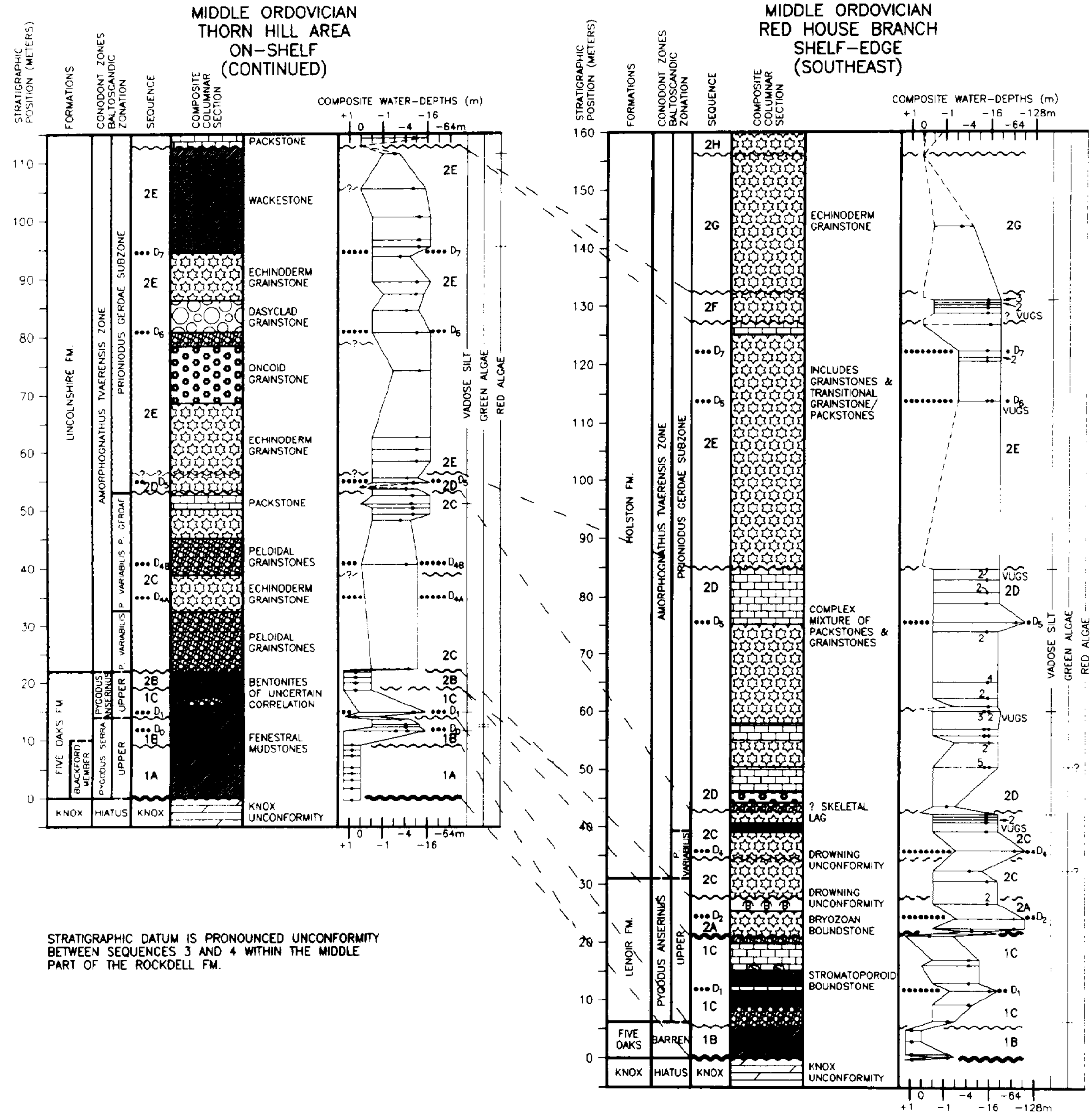

FIG. 12.—Composite columnar sections comparing the Thorn Hill area on the platform (left) to the Red House Branch area near the platform margin or shelf edge (right). Water-depth curves for the platform (on-shelf) are based on individual curves for the Thorn Hill and Old Thorn Hill sections. A more detailed key to lithologies is given in Figure 7. Conodont zonation is based on Cares (1975) and later work by Anita Harris (personal communication). Note that stratigraphic datum is the surface between Sequences 3D and 4A.

occurred at the margin but not in the platform interior. This conclusion was reached after recognizing that the surface between Subsequence 1C and 2A probably lies within the upper third of the Upper *Pygodus anserinus* Zone, by noting the stratigraphic position of major inflections points on the water-depth curve, and by trying to fit all other possible correlations to existing data. Although other correlations are possible, we believe that this correlation offers the simplest explanation. Thus, as relative sea level rose, mudstones of Subsequence 2B were deposited on the platform, but carbonate sedimentation lagged behind at the margin. As relative sea level rose well above the platform margin, Subsequence 2C grainstones accumulated on the platform and grainstones and bryozoan bafflestone were deposited at the margin (cf. Figs. 8, 9).

Our correlation for Subsequence 2D indicates that relative sea level twice dropped below the platform margin: immediately preceding deposition of Subsequence 2D and immediately after deposition of Subsequence 2D. Again, this interpretation offers the simplest solution among other possibilities and helps explain the thicker Subsequence 2D at the platform edge. Subsequence 2D probably represents an interval of time when sea level was at or near the edge of the platform, leading to substantially thicker deposition in that area (about 40 m) than in areas farther

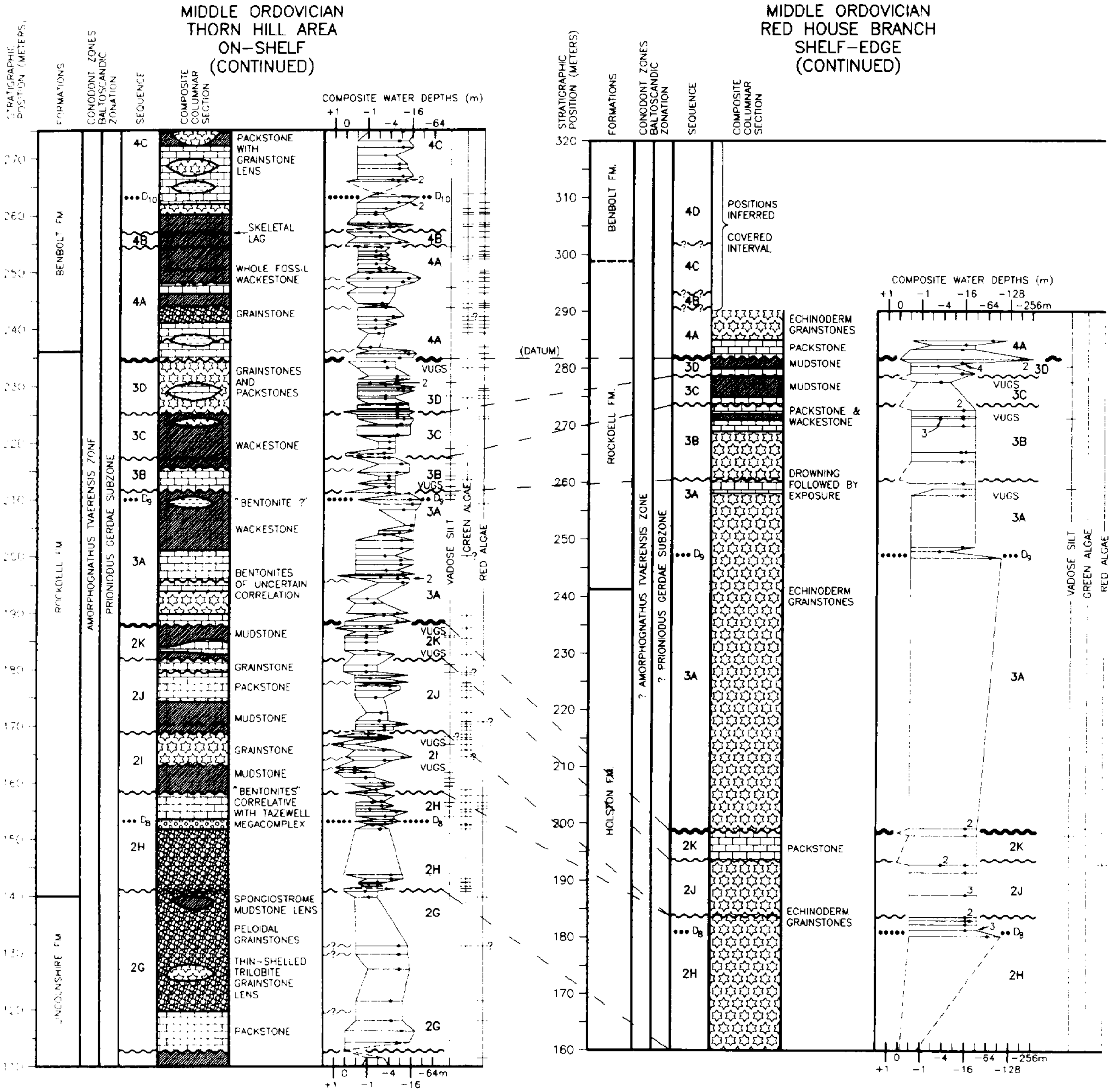

FIG. 12.—Continued.

onto the platform (less than 5 m) (e.g., Fig. 12). Subsequence 2E is of similar thickness in both areas. However, very shallow-water sedimentation characterized by oncoid grainstones and dasycladacean algae grainstones occurred in the platform interior, while slightly deeper-water deposition is indicated by echinoderm grainstones at the margin. Subsequence 2F is present at the margin but not in the platform interior. Subsequence 2F suggests that sea level dropped below the platform edge, and then rose, but covered only the margin area, and then dropped below the platform margin again (Fig. 12).

In the platform interior, a displaced deep-water, thin-shelled trilobite fauna is present in shallow-water deposits of middle Subsequence 2G (Fig. 12). These thin-shelled, eyeless trilobites (e.g., *Lonchodomas* sp.) are generally restricted to deep-water environments (Maitland 1979; Walker et al. 1980). This suggests that the rate of rise of relative sea level during deposition of Subsequence 2F may have slowed and reached highstand, and possibly stillstand, during deposition of middle Subsequence 2G. Importantly, evidence of "maximum flooding" surfaces (the first transgressive surface and the downlap surface) described on siliciclastic shelves by Loutit et al. (1988) cannot be discerned. These surfaces would be expected to be at this position if this were a siliciclastic succession. One might also expect to see evidence of drowning (and suppressed carbonate deposition) along the platform margin at the time of this highstand, but Subsequence 2G was deposited in both areas in approximately equal thicknesses. Apparently the sea-level rise was sufficiently slow so that deposition at the platform margin could be maintained.

The surface between Subsequences 2G and 2H marks the approximate

TABLE 3.—*"Guiding principles" and assumptions for correlation from platform to platform margin*

1) The Knox surface is widespread throughout eastern North America and is therefore assumed to be an appropriate stratigraphic datum for local correlation, although it is a time-transgressive surface.
2) During the initial Middle Ordovician transgression, a thicker succession accumulated at the platform margin than on the platform (cf. Ruppel and Walker 1982, 1984; Bergström and Carnes 1976). Thus, correlations made from the platform-interior Lincolnshire and lower Rockdell Formations to the platform-edge Holston Formation should appear to "climb" in time.
3) In general, water depths were shallower in the platform interior and deeper near the edge. So there should be more surfaces of exposure in the platform-interior succession and not all of these surfaces correlate with exposure surfaces in the platform-margin sections. In fact, most of the subsequence boundaries (exposure surfaces) on the platform do not correlate with similar surfaces at the edge.
4) The lower Rockdell Formation was established as a shallow-water facies of the temporally equivalent platform-edge Holston Formation. Later, the upper Rockdell prograded to the platform margin (e.g., Ruppel and Walker 1982). In other words, about ⅔ of the Rockdell was deposited before its temporal equivalent appeared at the platform margin at Red House Branch. This means that exposure surfaces from about the uppermost ⅓ of the Rockdell on the platform correlate with exposure surfaces near the contact of the Holston with the Rockdell at the platform margin. Furthermore, above the contact of the Holston with the Rockdell at Red House Branch, these exposure surfaces no longer appear to "climb" in time from the platform interior to the edge.
5) In the lowermost 200 m of Middle Ordovician rocks, there could have been exceptions to #3 and 4 (above) under the following conditions:
    a) If down-to-basin normal faulting occurred along or near the platform margin.
    b) If sea level remained at or near the platform margin for some period of time and little or no deposition occurred on the platform.
6) Pronounced exposure surfaces in the platform rocks usually correlate with other pronounced exposure surfaces in platform-margin rocks. Less commonly, pronounced surfaces on the platform correlate with less pronounced exposure surfaces at the platform margin. In general, the less pronounced the exposure surface is on the platform, the more likely that the exposure surface correlates to a conformable surface at the shelf-edge.
7) Inflections points recording water-depth increases on the platform should correlate with inflection points recording depth increases at the shelf edge, even though these inflection points transgress time. Inflection points are indicated by minimum or midpoint water depths, or both, and less commonly by maximum water depths as well.
8) Correlation of inflection points of water-depth increases is necessarily constrained between exposure surfaces, i.e., a deepening event cannot be correlated across an exposure surface.

transition from the Lincolnshire Formation into the Rockdell Formation at platform localities. This transition indicates a change from homogeneous, relatively open-shelf conditions, as suggested by generally mud-free peloid grainstones of the Lincolnshire Formation, to a wider spectrum of high-energy tidal environments, as indicated by stacked skeletal grainstone and fenestral mudstone beds of the Rockdell Formation (i.e., Subsequences 2H, 2I, 2J, and 2K).

During deposition of Subsequences 2H through 2K, the platform-margin "reef" tract of the Holston Formation prograded basinward (southeastward; Ruppel 1979). This may have occurred in response to a long-term and gradual fall in relative sea level. Subsidence of the edge may have kept pace with or outpaced relative sea-level fall during deposition of Subsequences 2H through 2J. Intervening surfaces of subaerial exposure, bounding Subsequences 2H through 2J, indicate that relative sea level fell and periodically outpaced subsidence (Figs. 12, 14).

Correlation.—Subsequence 2A is absent on the platform, and Subsequence 2B is absent at the platform margin. Absence of Subsequence 2B at the platform margin probably reflects drowning with unconformity. A second drowning unconformity (labeled deepening event D_3) is indicated at the platform margin within Subsequence 2C and was quickly followed by deepening event D_4 (Fig. 12). Drowning unconformities D_3 and D_4 at the margin are correlated with deepening events D_3 and D_{4A} and D_{4B}, respectively, on the platform. Similarly, deepening events D_5 through D_7 also correlate from the platform to the platform margin (Figs. 12–14). Subsequence 2F, 5 m thick, is present only at the margin, between Subsequences 2E and 2G. Deepening event D_8 lies just below the upper surface of Subsequence 2G. Because Subsequence 2I is present on the platform but not at the margin, this surface probably represents a drowning unconformity at the platform margin and drowning followed by exposure or shoaling on the platform.

Summary.—Third-order stratigraphic boundaries are correlative from the platform interior to the platform margin, but some fourth-order sequences are of unequal thickness or absent in the platform interior or at the platform margin. Changes in relative sea level that affected accommodation space, "producing" either too little in the extreme case of exposure, or too much, in the other extreme case of drowning, led to the sequence geometries described here. Platform environments became vertically stacked to very near sea level on the platform and started to prograde over near-platform-margin environments during a long-term rise of relative sea level.

Third-Order Sequence 3

Description.—This sequence comprises the upper Rockdell Formation on the platform and the upper Holston Formation and approximately the lower three quarters of the Rockdell Formation at the platform margin. Third-order Sequence 3 comprises four fourth-order subsequences, labeled 4A through 4D, all of which are present at platform-interior and platform-margin localities (Figs. 12, 14).

Platform-Interior Stratigraphy.—Subsequence 3A consists of maroon grainstones and packstones of the uppermost Rockdell Formation. Uppermost Subsequence 3A marks establishment of well-developed Rockdell lithologies (Figs. 12, 14). The increase in water depth near the top of Subsequence 3A on the platform (D_9 of Fig. 12B) coincides with a similar increase near or at the top of the Holston Formation at the platform margin (Benedict and Walker 1978; Walker et al. 1980). Subsequences 3B, 3C, and 3D include nodular-bedded packstones and fenestral mudstones of the Rockdell Formation (Fig. 12). Their lateral equivalents at the platform margin are skeletal grainstones of the Rockdell Formation (Fig. 14; Ruppel 1979). Spar-filled vugs with solution features and smaller calcite-filled cavities floored with crystal or vadose silt are abundant in mud-rich Subsequence 3A and 3C lithologies at Thorn Hill and Old Thorn Hill (Figs. 3, 12).

Platform-Margin Stratigraphy.—Subsequence 3A consists of grainstones and grainstones-packstones of the uppermost Holston Formation. Subsequence 3A also includes a transitional unit of fine-grained carbonate mud, marking the transition from the Holston to the Rockdell (Fig. 12). Subsequence 3B consists of about 10 m of echinoderm grainstone overlain by about 5 m of interbedded packstones and wackestones. Subsequences 3C and 3D are both about 5 m thick, with the lower 0.5–1 m consisting of wackestone grading into mudstone.

Analysis.—Important paleoenvironmental changes accompany deposition of Sequence 3. A substantial increase in water depth near the top of Subsequence 3A coincides with culmination of Holston deposition at the platform margin (deepening event D_9; Fig. 12). Immediately upward, at the platform margin, a drop in relative sea level is indicated by the exposure surface separating Subsequences 3A and 3B and by additional exposure features within Subsequence 3B (Figs. 12–14). This may represent a type of drowning unconformity induced by a period of very slow deposition followed by exposure. A relative drop in sea level is also indicated by shallow-water features in the mudstones of Subsequences 3C and 3D.

Correlation.—Deepening event D_9 lies about 10 m below the surface between Subsequences 3A and 3B at the platform margin and less than 1 m below this surface on the platform (Fig. 14). This suggests that deepening occurred earlier along the margin and somewhat later in the platform interior, as would be expected. As deepening progressed, carbonate production was suppressed at the margin, resulting in the unconformity indicated at the surface between Subsequences 3A and 3B. As sea level fell once more, platform environments prograded basinward to the position of Red House Branch. Thus, only a small drop in relative sea level was needed for exposure at the surface between Subsequences 3A and 3B at

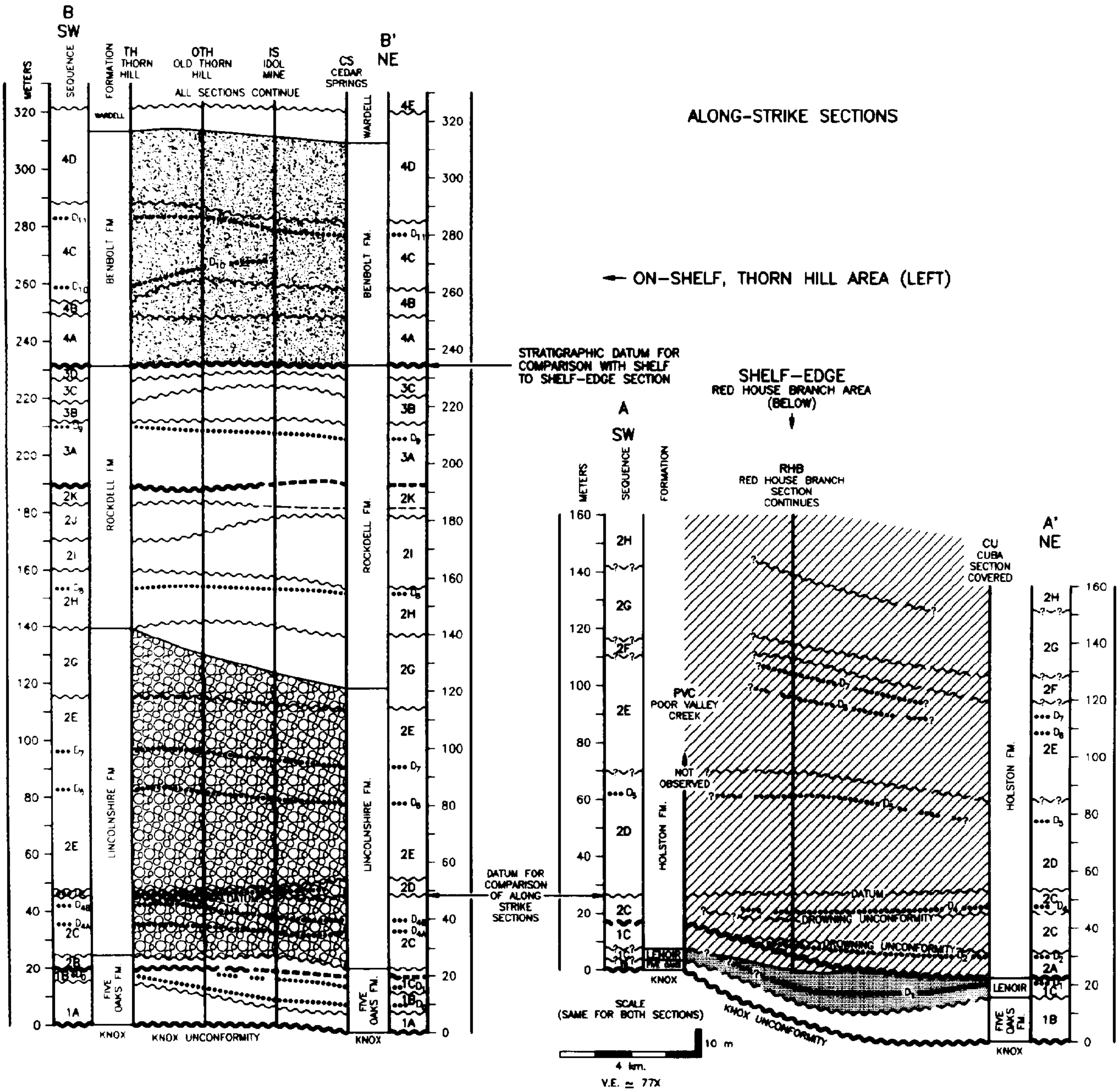

FIG. 13.—Stratigraphic subsequences 1A–4D. Cross sections are restored along depositional strike. The area near the platform margin or shelf edge (left) includes from southeast to northwest, Poor Valley Creek (PVC), Red House Branch (RHB), and Cuba (CU). The platform-interior (on-shelf) area includes, from southwest to northeast, Thorn Hill (TH), Old Thorn Hill (OTH), Idol Mine section (IS), and Cedar Springs (CS). Note that the surface between Subsequences 2C and 2D provides an appropriate stratigraphic datum for comparison of these two along-strike cross sections. The surface between Subsequences 3D and 4A provides a stratigraphic datum for comparison of the platform (left) with the platform-margin cross section of Figure 14.

both platform-interior and platform-margin localities. Similar exposure surfaces are correlative between the two areas at the surfaces between Subsequences 3B and 3C, 3C and 3D, and 3D and 4A (Figs. 12, 14).

Summary.—Third-order Sequence 3 represents culmination of the Holston platform-margin reef tract and is analogous to the "transgressive systems tracts" described by others on siliciclastic shelves (e.g., Van Wagoner et al. 1990). In fact, siliciclastic processes have influenced this transgressive systems tract. For example, minor proportions of silt- and clay-size siliciclastic detritus is mixed with micrite in Sequence 3 on the platform, and increase upward in the sequence. Thus, siliciclastic detritus was transported from the platform interior to areas near the margin (Ruppel and Walker 1982, 1984).

Third-Order Sequence 4

Description.—Third-order Sequence 4 comprises the Benbolt, Wardell, and lowermost Bowen Formations and the upper Rockdell and Benbolt Formations on the platform. Third-order Sequence 4 comprises six fourth-order subsequences labeled 4A through 4F. All six subsequences are pres-

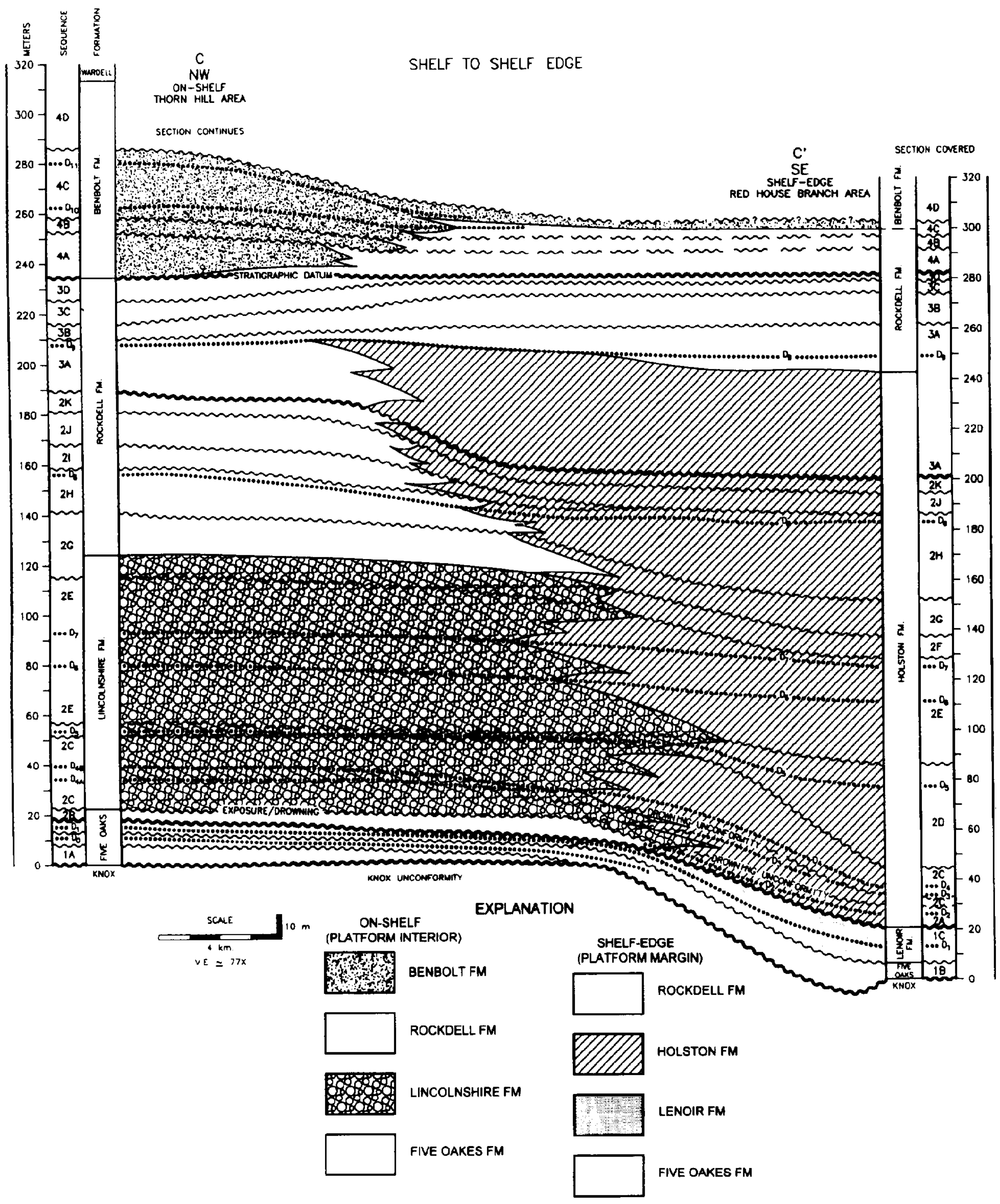

FIG. 14.—Stratigraphic subsequences 1A–4D. Cross section is restored across depositional strike. Stratigraphic position of sequences and subsequences on the platform (on-shelf) in the Thorn Hill area at left is based on the Cedar Springs (CS) section. The section near the platform margin or shelf edge at right is at Red House Branch. Note that the surface between Subsequences 2C and 2D provides a stratigraphic datum for comparison of these two along-strike cross sections. The surface between Sequences 3 and 4 provides a stratigraphic datum for comparison of the platform (left) with the cross section of Figure 13, which represents the platform succession along depositional strike.

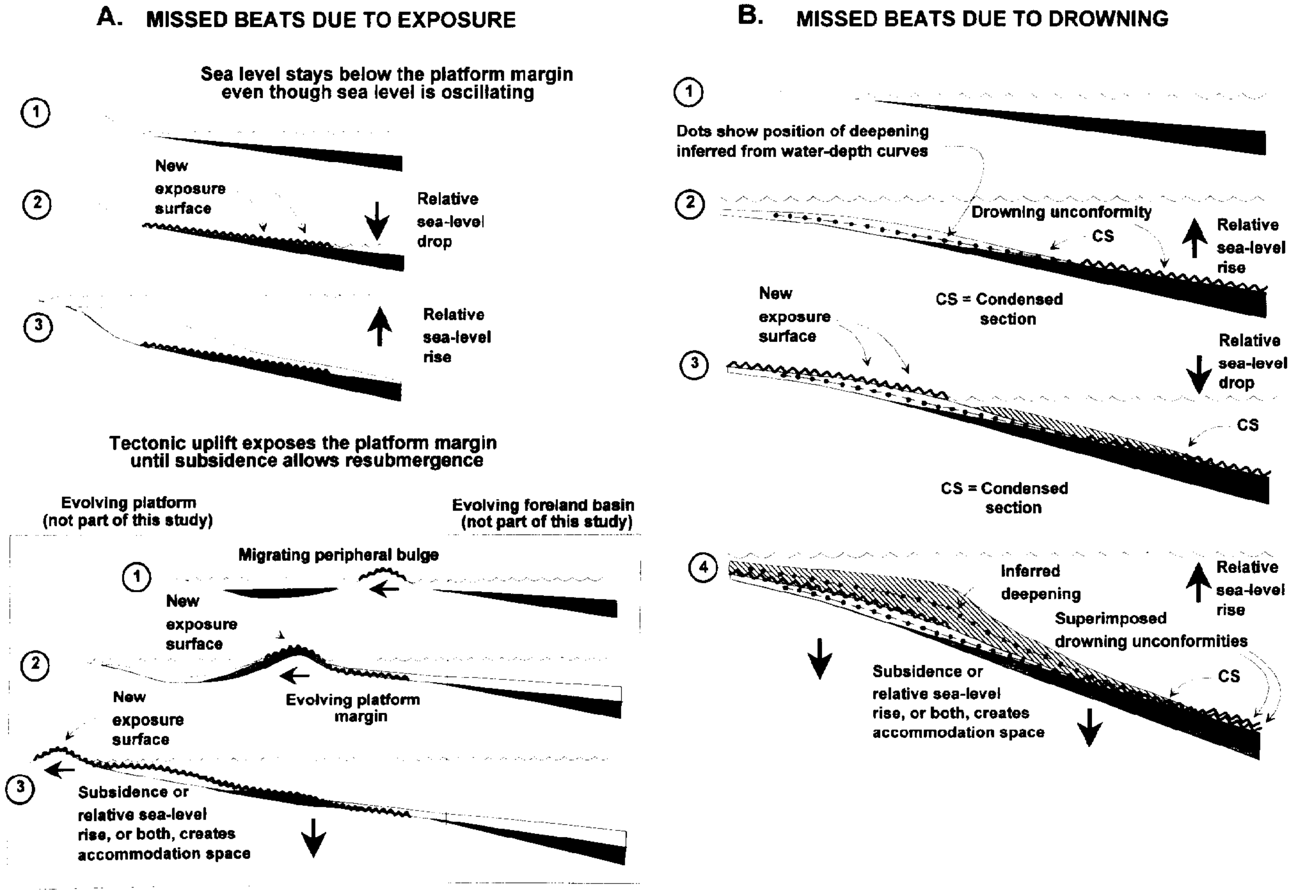

FIG. 15.—Three ways in which beats may be missed. A) Missed beats due to exposure. Top shows that relative sea level stays below the platform margin even though relative sea level is oscillating. Dark ornamentation shows fourth-order subsequence, such as Subsequence 2F, that is present at the platform margin but not on the platform. Light ornamentation shows overlying fourth-order subsequence. Bottom shows tectonic uplift created by migration of peripheral bulge towards the platform interior (craton). Dark ornamentation shows fourth-order Subsequence 1A developed above Knox unconformity. Light ornamentation shows Subsequence 1B of later timing. B) Missed beats due to drowning. Each ornamentation type depicts a separate fourth-order subsequence.

ent at platform-interior localities and probably also near the margin as well, but exposures of the upper parts of the succession are poor at the latter localities.

Platform-Interior and Platform-Margin Stratigraphy.—Work completed at more than 20 other locations (e.g., Ruppel and Walker 1982, 1984) indicates that the stratigraphy and depositional environments are similar at stratigraphic positions occupied by Sequence 4 in both areas. In our study area, most of Sequence 4 is covered at the platform-margin localities. Indeed, only lowermost Subsequence 4A is exposed at Red House Branch.

Subsequences 4A through 4C of the lower Benbolt consist of an array of coated-grain-bearing grainstones and packstones characteristic of very shallow-water deposition (Fig. 13). Shales, siltstones, and skeletal wackestones are particularly abundant in Subsequence 4C. The Wardell Formation includes uppermost Subsequence 4D and Subsequences 4E and 4F, consisting of bryozoan-echinoderm wackestones and grainstones-packstones. Subsequences 4D and 4F are similar in their content of grainstone and packstone-wackestone beds, but 4D contains no mudstone or shale beds, whereas 4F has well developed mudstone and shale beds up to several meters thick (Fig. 13). Beginning with Sequence 3 and particularly in Sequence 4, mud-rich beds both on the platform and at the margin are generally red to maroon because of iron-manganese oxide in the micritic matrix.

Analysis.—Shoaling sand banks of the upper Rockdell gave way to deeper subtidal "lagoonal" deposits of the Benbolt, which spread eastward over the former platform margin (Ruppel 1979). Sequence 4 marks the beginning of a reversal of paleobathymetry (see Ruppel 1979). This reversal continued with deeper-water platform deposits of the Wardell Formation, formed on a gentle westward paleoslope. These deeper-water deposits of the Wardell prograded over lagoonal deposits of the Benbolt. On the platform, this progradation occurred earliest at Cedar Springs and slightly later at Thorn Hill (Fig. 14).

Fine-grained siliciclastic detritus, derived from the east and southeast, is noted in Sequences 3 and 4 and becomes conspicuous starting in the upper Benbolt. It is not clear how this detritus entered lagoonal Benbolt environments, but it may have bypassed Rockdell environments along the margin, which were probably characterized by turbulent water. Alternatively, the detritus may have been transported around Rockdell environments through gaps in platform-margin shoals north or south of the study area.

Correlation and Summary.—Correlation of Sequence 4 along depositional strike on the platform has been discussed by Steinhauff and Walker (in press). Because this sequence is mostly covered at margin localities, correlation of its internal fourth-order sequences between the two areas is not attempted. It is important to note, however, that third-order Sequence 4 marks a major change in style and source of sediment resulting from a reversal in regional paleobathymetry.

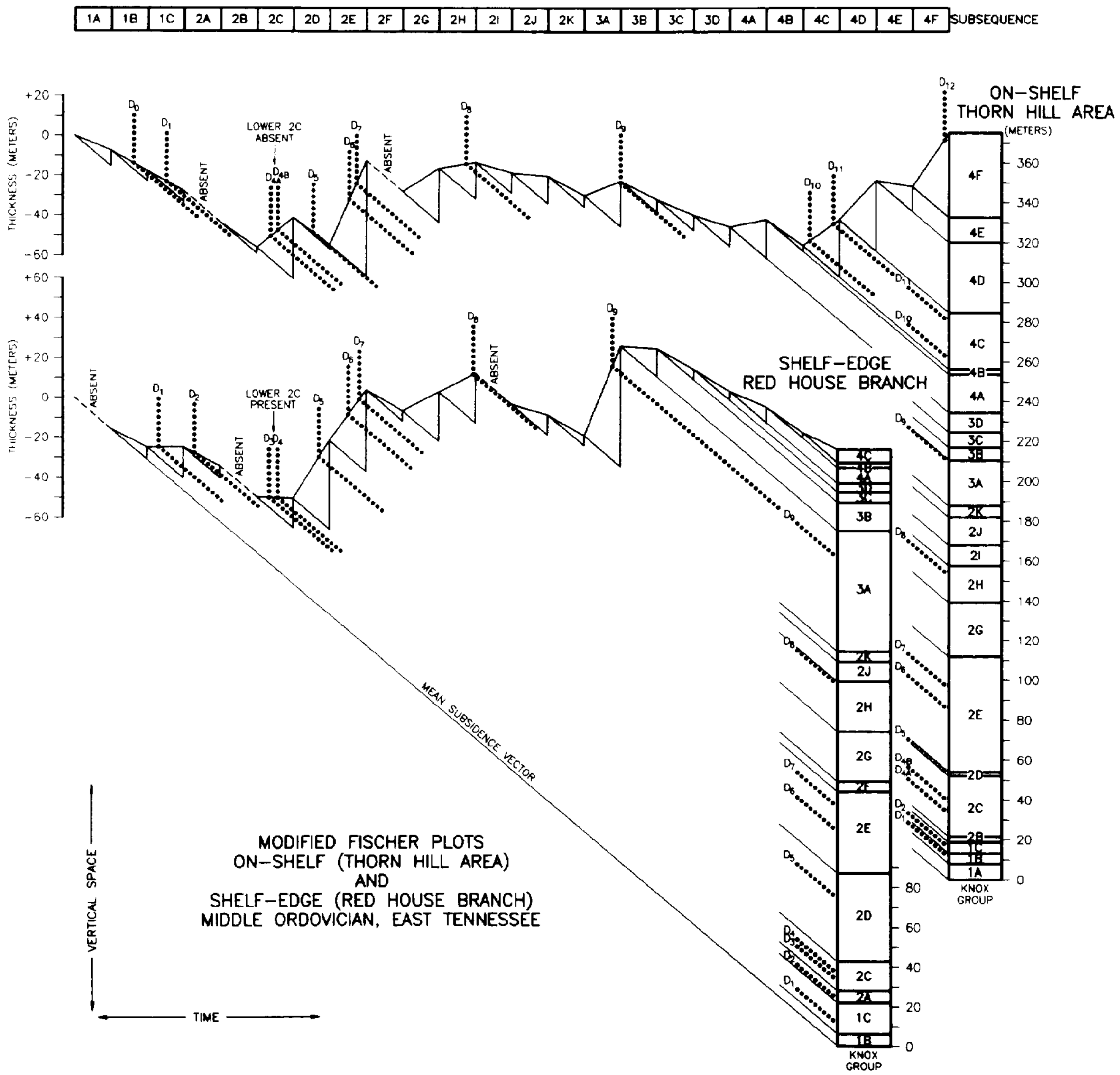

FIG. 16.—Modified Fischer plots comparing fourth-order subsequences from the composite Middle Ordovician platform (on-shelf) section for the Thorn Hill Area to the composite or near-platform-edge section for the Red House Branch area. Dotted lines labeled D_1–D_{12} indicate deepening events and are projected from the vertical stratigraphic columns (right), through the plotted sequences, to the horizontal time axis. A Fischer plot showing the 44 fifth-order parasequences recognized in the platform succession is presented by Steinhauff and Walker (in press). They concluded that fifth-order parasequences cannot be correlated on the platform or from the platform interior to the margin.

Third-Order Sequences 5 and 6

Description.—Fourth-order subsequences within third-order Sequences 5 and 6 are discussed only briefly here because they are unexposed at platform-margin localities in our study area. Sequence 5 comprises the uppermost Bowen, Witten, and Moccasin Formations (Fig. 2). Sequence 6 includes the upper Moccasin to the base of the Martinsburg Formation (not shown). Terrigenous siltstones, calcilutites, calcarenites, and shales are present in various proportions throughout Sequences 5 and 6. The Bowen consists of calcareous siltstone and red calcareous claystone with mud cracks (Wedekind 1986); the Witten is similar to the underlying Wardell. The Moccasin consists of distinctive gray limestone and red- to yellow-weathering calcareous mudstone and shale. Ripple marks and mud cracks are present throughout the Moccasin (Simonson 1985). The uppermost Moccasin comprises Sequence 6, which consists of peritidal deposits. Thinly laminated graptolitic black shales of the lower Martinsburg Formation overlie the surface between Sequences 5 and 6, which represents a significant drowning event (Walker 1992).

Analysis.—The reversal of paleobathymetry that began during deposition of Sequence 4 continued during deposition of Sequences 5 and 6. Eventually, the basin to the east of our study area was completely filled with tidal-flat deposits of the Bays Formation. This tidal-flat deposition prograded westward, transporting terrigenous silt and clay. The result was deposition of the tidal-flat complex of the Moccasin Formation with the bathymetric surface sloping northwestward instead of southeastward as before (Ruppel 1979; Ruppel and Walker 1982, 1984; Simonson 1985). The top of the Moccasin coincides with a pronounced deepening event marked by a flooding surface described by Walker (1992).

Correlation.—Sequences 5 and 6 are covered near the former margin in our study area. However, lithostratigraphic correlation of Sequence 5 and 6 sediments between platform and platform-margin areas based on study of other localities is discussed by Ruppel (1979) and Ruppel and Walker (1982, 1984). As previously noted, we have discussed correlation between platform localities elsewhere (Steinhauff 1993; Steinhauff and Walker, in press). Evidence for the pronounced exposure surface separating Sequences 5 and 6 is documented by Simonson (1985) in his work on the Moccasin Formation at the Thorn Hill section. Simonson noted numerous exposure features, especially fenestral mudstones and mud cracks, where we have indicated this exposure surface (Fig. 2). We have observed similar features at the Idol Mine and Cedar Springs sections.

Finally, we should note here that a seventh third-order sequence overlies those studied here. It consists of the Upper Ordovician Martinsburg and Juniata Formations in this area (Walker 1992), but is not treated in this paper.

DISCUSSION: VARIATIONS IN CORRELATIONS

Exposure

Most of the sequences we have described and illustrated in this paper and elsewhere lack distinct caps containing features diagnostic of tidal-flat accretion. Rather, subtidal grainstones and mud-rich lithologies appear to have usually been exposed without preceding buildup of tidal flats both at platform-interior and platform-margin localities. This is similar to the situation reported by Goldhammer et al. (1987) for Middle Triassic platform carbonates in Northern Italy. However, evidence for exposure in the Middle Ordovician carbonates studied here appears to be much more subtle than the evidence described by Goldhammer et al. (1987) for their cyclic carbonates.

Drowning

Abundant evidence for drowning is preserved in subtidal sediments from both platform-interior and platform-margin localities. Evidence for drowning unconformity, on the other hand, by its very nature is more circumstantial. For example, inflection points on water-depth curves that indicate water deepening are based on numerous criteria presented by Steinhauff and Walker (in press). Deepening events visible on the water-depth curves can usually be correlated from platform-interior to platform-margin localities (Figs. 12, 14). By substituting subsequences for fourth-order cycles we have constructed modified Fischer plots for both areas. These plots provide an alternative way to show correlation of deepening events (Fig. 16, discussed below).

Some lithologic units show clear evidence of drowning. Cephalopod-rich limestone beds overlie deeper-water subtidal limestones along drowning unconformities at the surface between Subsequences 1C and 2A and in Subsequence 2C at Red House Branch and Poor Valley Creek (Fig. 9). Schlager (1981) has cited this lithology as evidence for drowning unconformity in many Paleozoic and Mesozoic examples. Indeed, cephalopod-rich beds are present at several other Middle Ordovician localities in eastern Tennessee (e.g., Steinhauff and Roberson 1989). Black sediment rich in iron and manganese oxides accompanies these cephalopod-rich beds (Fig. 4). High metal contents are characteristic of deep-sea sediments and provide supporting evidence for deep-water deposition and drowning unconformity (Kennett 1982).

Missed Beats

"Missed beats" are missing cycles of sedimentation expected to have been deposited under a Milankovitch glacio-eustatic driving force. Three types of missed beats are recognized. In the Triassic platform carbonates of Italy (Fig. 15A), Hardie et al. (1986) described two possibilities for "missed beats" due to exposure. In the first, sea level stays below the platform margin even though sea level is oscillating. In the second, tectonic uplift exposes the platform until subsidence allows submergence and reestablishment of cyclic sedimentation. During exposure, sea level may be rising and falling, but it never rises to the extent that the platform is reflooded. In addition, Goldhammer et al. (1990) recognized "condensed megacycles due to 'missed beats' of submergence" or drowning as a third possible mechanism that may cause beats to be missed or overlooked (Fig. 15B). Indeed, beats may be missed twice during drowning. First, sediment production lags behind initial drowning, until the "carbonate factory" can produce enough sediment to be transported farther onto the platform to build tidal flats (e.g., Hardie and Shinn 1986). Second, sediment production again slows down if drowning continues and the carbonate factory passes into deeper water low in, or below, the euphotic zone (e.g., Schlager 1981).

Our Fischer plots (Fig. 16) show that some "beats" or subsequences are absent or so subtle as to be overlooked either on the platform or at its edge. For example, Subsequence 2F is present at the margin but is missing at platform-interior localities. Subsequence 2F suggests that sea level dropped below the platform margin, then rose but did not cover much of the platform, and then dropped below the margin again (Figs. 12–16). This situation is analogous to Hardie et al.'s (1986) first possibility for "missed beats", in which sea level stays below the platform margin even though sea level is oscillating. The second type of "missed beat" is illustrated by the absence of Subsequence 1A at the platform margin. For this type of "missed beat", Hardie et al. (1986) proposed that tectonic uplift exposes the platform margin until subsidence allows resubmergence. For example, Subsequence 1A is absent at the platform margin, and Subsequence 1B is thin but overlies 1A on the platform. Subsequence 1A is thickest at the platform margin. Absence of Subsequence 1A at the platform margin may be due to northwestward passage of the migrating peripheral bulge previously discussed for Sequence 1.

At least two other sequences are probably absent as a result of drowning. A drowning unconformity (labeled deepening event D_3) is indicated in Subsequence 2C at the margin. The lower part of Subsequence 2C is missing at platform-interior localities (Fig. 12). We have not separated this lower part from the rest of Subsequence 2C because it is bounded above and below by drowning unconformities rather than surfaces of subaerial exposure or shoaling. Drowning unconformity D_3 is the upper surface of the lower part of Subsequence 2C at the platform margin (Fig. 16). Because the lower part of Subsequence 2C is absent on the platform, deepening event D_3 is shown to lie at the upper surface of Subsequence 2B there (Figs. 12, 16). Similarly, Subsequence 2H is present on the platform but was not deposited near its edge (Figs. 12–14). Subsequence 2I probably represents a drowning unconformity at the platform margin and drowning followed by exposure or shoaling on the platform.

CONCLUSIONS

(1) Stratigraphic sequences, subsequences, and parasequences represent shallowing-upward packages. However, these units differ from many reported depositional carbonate cycles in that they do not contain tidal caps. They also differ from the subtidal cycles described by Osleger (1991) in that evidence for exposure and shoaling is often subtle and revealed only through detailed microscopic examination.

(2) Detailed stratigraphic sequence analysis of platform and platform-margin carbonates combined with biostratigraphic data and paleobathy-

metric analysis allows correlation of third-order sequences between the two areas. This reveals that some fourth-order subsequences are missing in one or the other area. If one of these successions had not been studied, our understanding of the sequence stratigraphy of this succession would be highly distorted. Thus, a serious limitation of this type of analysis is that there may be still other beats that are missed at our localities but present at other platform or margin positions.

(3) Many upper (exposure) surfaces of sequences and subsequences are stratigraphically preceded rather abruptly by either drowning unconformities (condensed sections) or by deepening events. For example, the surface between Subsequences 2C and 2B on the platform appears to have been drowned and then exposed (Fig. 14). Similarly, deepening event D_8 lies immediately below the upper Subsequence 2H surface at both platform-interior and margin localities, and deepening event D_9 lies immediately below the upper Subsequence 3A surface on the platform. The latter two instances suggest that deeper-than-average water was followed by exposure. These examples suggest that some type of tectonism may have been involved. Platform to platform-margin geometries atypical of a siliciclastic succession (Van Wagoner et al. 1990) appear to be the result where condensed sections or deepening events are closely followed by exposure within this succession (Fig. 14).

(4) Meter-scale (fifth-order) parasequences in this succession are seldom correlative between localities and probably do not represent widespread sea-level change. Instead, these may represent migration of environments and thus are interpreted to be of autocyclic origin.

ACKNOWLEDGMENTS

Ruppel (1979) developed the initial stratigraphic framework used for this work and provided about 1/5 of the total thin sections used to developed the water-depth curves. Unpublished point-count data were provided by Ruppel (1979), Breland (1980), and Jernigan (1987), and unpublished biostratigraphic data were provided by K.E. Roberson (University of Tennessee) and Anita Harris (U.S. Geological Survey). Roberson also provided valuable help in the field and a small suite of thin sections from the lowermost parts of the Old Thorn Hill and Idol Mine sections. Ruppel (1979), Johnson (1988), and Jernigan (1987) provided 21, 47, and 50 thin sections, respectively, from the Red House Branch section. Additional rock samples from Red House Branch were provided by Jernigan. Preparation costs for the article were provided by National Science Foundation grants EAR9103491 to Walker and EAR9315651 to Walker and K.J. Tobin. The Southeastern Section of the Geological Society of America provided a modest grant to Steinhauff. The Carden Fund, the Mobil Carbonate Fund, and the Discretionary Funds of the Department of Geological Sciences of The University of Tennessee provided additional support. S.G. Driese, M.L. McKinney, J.M. Armentrout, U. Hammes, and R.K Goldhammer are thanked for reviews of previous versions of this paper.

REFERENCES

Benedict, G.L., and Walker, K.R., 1978, Paleobathymetric analysis in Paleozoic sequences and its geodynamic significance: American Journal of Science, v. 278, p. 579–607.

Bergström, S.M., 1971, Conodont biostratigraphy of the Middle and Upper Ordovician of Europe and eastern North America: Geological Society of America Memoir 127, p. 83–162.

Bergström, S.M., 1973, Biostratigraphy and facies relationships in the lower Middle Ordovician of easternmost Tennessee: American Journal of Science, v. 273A, p. 261–293.

Bergström, S.M., 1977, Early Paleozoic conodont biostratigraphy in the Atlantic Borderland, *in* Swain, F.M., ed., Stratigraphic Micropaleontology of Atlantic Basin Borderlands: New York, Elsevier, p. 85–110.

Bergström, S.M., and Carnes, J.B., 1976, Conodont biostratigraphy and paleoecology of the Holston Formation (Middle Ordovician) and associated strata in Eastern Tennessee, *in* Barnes, C.R., ed., Conodont Paleoecology: Geological Association of Canada Special Publication 15, p. 27–58.

Bond, G.C., Kominz, M.A., and Grotzinger, J.P., 1988, Cambro-Ordovician eustasy: Evidence from geophysical modeling of subsidence in Cordilleran and Appalachian passive margins, *in* Kleinspehn, K., and Paola, C., eds., New Perspectives in Basin Analysis: New York, Springer-Verlag, p. 131–160.

Breland, F.C., 1980, Stratigraphy, paleoenvironmental, and echinoderm distributional patterns in an unfaulted Middle Ordovician (Chickamauga Group) shelf-edge to on-shelf transect in East Tennessee [unpublished Ph.D. thesis]: Knoxville, University of Tennessee, 217 p.

Byerly, D.W., Walker, K.R., Diehl, W.W., Ghazizadeh, M., Johnson, R.E., Lutz, C.T., Schoner, A.K., Simmons, W.A., Simonson, J.C.B., Weber, L.J., and Wedekind, J.E., 1986, Thorn Hill: A classic Paleozoic stratigraphic section in Tennessee, *in* Neathering, T.L., ed., Geological Society of America, Southeastern Section, Centennial Field Guide, v. 6, p. 131–136.

Carnes, J.B., 1975, Conodont biostratigraphy in the lower Middle Ordovician of the western Appalachian thrust-belts in northeastern Tennessee [unpublished Ph.D. thesis]: Columbus, The Ohio State University, 291 p.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, *in* Ham, W.E., ed., Classification of Carbonate Rocks: American Association of Petroleum Geologists Memoir 1, p. 108–121.

Dunham, R.J., 1969, Early vadose silt in Townsend mound (reef), New Mexico, *in* Friedman, G.M., ed., Depositional Environments of Carbonate Rocks: Society of Economic Paleontologists and Mineralogists Special Publication 14, p. 139–182.

Elias, M.K., 1937, Depth of deposition of the Big Blue (Late Paleozoic) sediments in Kansas: Geological Society of America Bulletin, v. 48, p. 403–432.

Esteban, M., and Klappa, C.F., 1983, Subaerial exposure environment, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., Carbonate Depositional Environments: American Association of Petroleum Geologists Memoir 33, p. 1–54.

Fischer, A.G., 1964, The Lofer cyclothems of the Alpine Triassic: Kansas Geological Survey Bulletin 169, p. 107–149.

Flügel, E., 1982, Microfacies Analysis of Limestones: New York, Springer-Verlag, 633 p.

Ginsburg, R.N., 1971, Landward movement of carbonate mud: New model for regressive cycles in carbonates [abstract]: American Association of Petroleum Geologists Bulletin, v. 55, p. 340.

Goldhammer, R.K., Dunn, P.A., and Hardie, L.A., 1987, High frequency glacioeustatic sea level oscillations with Milankovitch characteristics recorded in Middle Triassic platform carbonates in northern Italy: American Journal of Science, v. 287, p. 853–892.

Goldhammer, R.K., Dunn, P.A., and Hardie, L.A., 1990, Depositional cycles, composite sea-level changes, cycle stacking patterns, and the hierarchy of stratigraphic forcing: Examples from Alpine Triassic platform carbonates: Geological Society of America Bulletin, v. 102, p. 535–562.

Goldhammer, R.K., Lehmann, P.J., and Dunn, P.A., 1993, The origin of high-frequency platform carbonate cycles and third-order sequences (Lower Ordovician El Paso Gp, west Texas): constraints from outcrop data and stratigraphic modeling: Journal of Sedimentary Petrology, v. 63, p. 318–359.

Goodwin, P.W., and Anderson, E.J., 1985, Punctuated aggradational cycles: a general hypothesis of episodic stratigraphic accumulation: Journal of Geology, v. 93, p. 515–533.

Hardie, L.A., and Shinn, E.A., 1986, Carbonate depositional environments, modern and ancient, 3, tidal flats: Colorado School of Mines Quarterly, v. 81, no. 1, 74 p.

Hardie, L.A., Boselli, A., and Goldhammer, R.K., 1986, Repeated subaerial exposure of subtidal carbonate platforms: Evidence for high frequency sea level oscillations on a 10^4 year scale: Paleoceanography, v. 1, p. 447–457.

Hardie, L.A., Dunn, P.A., and Goldhammer, R.K., 1991, Field and modeling studies of Cambrian carbonate cycles, Virginia Appalachians—Discussion: Journal of Sedimentary Petrology, v. 61, p. 636–646.

Jernigan, D.G., 1987, Comparative diagenetic histories of the Holston and Rockdell Formations, Middle Ordovician of northeastern Tennessee [unpublished M.S. thesis]: Knoxville, University of Tennessee, 234 p.

Johnson, R.E., 1988, Petrogenesis of carbonate lithofacies along an evolving Paleozoic shelf, lower Chickamauga Group and equivalents, Middle Ordovician, northeastern Tennessee [unpublished Ph.D. thesis]: Knoxville, University of Tennessee, 391 p.

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

Kennett, J.P., 1982, Marine Geology: Englewood Cliffs, New Jersey, Prentice-Hall, 813 p.

Koerschner, W.F., III, 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., 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.

Krumbein, W.C. and Sloss, L.L., 1951, Stratigraphy and Sedimentation: San Francisco, W.H. Freeman, 660 p.

Loutit, T.S., Hardenbol, J., Vail, P.R., and Baum, G.R., 1988, Condensed sections: the key to dating and correlations of continental margin sequences, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., Sea Level Changes: An Integrated Approach: SEPM Special Publication 42, p. 183–216.

Maitland, M.R., 1979, The paleobathymetric and paleoenvironmental distribution of Middle Ordovician trilobites within a portion of the Valley and Ridge of East Tennessee [unpublished M.S. Thesis]: Knoxville, University of Tennessee, 140 p.

Moore, N.K., 1978, Taxonomy and paleoenvironmental distribution of the benthic algal flora from Middle Ordovician carbonate rocks of East Tennessee [unpublished Ph.D. thesis]: Knoxville, University of Tennessee, 148 p.

Osleger, D.A., 1991, Subtidal carbonate cycles: implications for allocyclic vs. autocyclic controls: Geology, v. 19, p. 917–920.

Read, J.F., 1989, Controls on evolution of Cambrian–Ordovician passive margin, U.S. Appalachians, *in* Crevello, P.D., Sarg, J. , Wilson, J.L., and Read, J.F., eds., Controls on Carbonate Platform and Basin Development: SEPM Special Publication 44, p. 147–165.

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.

Roberson, K.E., 1987, Tidal flat stromatactis from the Middle Ordovician of Alabama [abstract]: SEPM Annual Midyear Meeting Abstracts, v. 4, p. 71.

Roberson, K.E., 1994, Stratigraphy and depositional history of Middle Ordovician peritidal carbonate rocks overlying the post-Knox unconformity, East Tennessee [unpublished Ph.D. thesis]: Knoxville, University of Tennessee, 210 p.

Roberson, K.E., and Foreman, J.L., 1989, Sedimentology and diagenesis of tidal flat Stromatactis, Middle Ordovician, Alabama, *in* Walker, K.R., ed., The Fabric of Cements in Paleozoic Limestones: University of Tennessee Studies in Geology 20, p. 105–117.

Roberson, K.E., and Walker, K.R., 1990, Regional Appalachian disconformity produced solely by environmental migration within a Chazy (Middle Ordovician) transgressive sedimentary sequence [abstract]: Geological Society of America, Abstracts with Program, v. 22, p. 334.

Ruppel, S.C., 1979, The stratigraphy, carbonate petrology, and depositional environments of the Chickamauga Group (Middle Ordovician) of northern East Tennessee [unpublished Ph.D. thesis]: Knoxville, University of Tennessee, 231 p.

Ruppel, S.C., and Walker, K.R., 1982, Sedimentology and distinction of platformal and downslope carbonate buildups: Middle Ordovician, East Tennessee: Journal of Sedimentary Petrology, v. 52, p. 1055–1071.

Ruppel, S.C., and Walker, K.R., 1984, Petrology and depositional history of a Middle Ordovician carbonate platform: Chickamauga Group, northeastern Tennessee: Geological Society of America Bulletin, v. 95, p. 568–583.

Sadler, P.M., Osleger, D.A., and Montañez, I.P., 1993, On the labeling, length, and objective basis of Fisher plots: Journal of Sedimentary Petrology, v. 63, p. 360–368.

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.

Simonson, J.B.C., 1985, the stratigraphy, carbonate petrology, depositional environments, and paleoecology of the Middle Ordovician Moccasin Formation near Thorn Hill, Tennessee [unpublished M.S. thesis]: Knoxville, University of Tennessee, 279 p.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geologic Society of America Bulletin, v. 74, p. 93–113.

Steinhauff, D.M., 1993, Sequence stratigraphy and comparative diagenesis of Middle Ordovician shelf to shelf-edge limestones, the Copper Creek Allochthon, East Tennessee [unpublished Ph.D. thesis]: Knoxville, The University of Tennessee, 460 p.

Steinhauff, D.M., and Roberson, K.E., 1989, Stop 7—Uppermost Knox Group, the Knox unconformity, and Middle Ordovician transition between shallow shelf and deeper basin near Dandridge, Tennessee, *in* Walker, K.R., Read, J.F., and Hardie, L.A., eds., Cambro-Ordovician Carbonate Banks and Siliciclastic Basins of the United States Appalachians, *in* Field Trip Guidebook T161, Knoxville Tennessee to Hagerstown, Maryland, June 30–July 9, 1989, 28th International Geological Congress: Washington D.C., American Geophysical Union, p. 24–27.

Steinhauff, D.M. and Walker, K.R., 1993, Comparative early-stage diagenesis and shelf to shelf-edge Middle Ordovician limestones, East Tennessee [abstract]: Geological Society of America Annual Meeting, Abstracts with Program, v. 25, no. 6, p. A226.

Steinhauff, D.M., and Walker, K.R., in press, Sequence stratigraphy of an apparently noncyclic carbonate succession: Recognizing subaerial exposure in largely subtidal stratigraphic sequences, Middle Ordovician, East Tennessee, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic Sequence Stratigraphy: North American Perspectives: Geological Society of America Special Paper.

Steinhauff, D.M., Walker, K.R., and Goldberg, S.A., 1993, Comparative late-stage diagenesis of shelf to shelf-edge Middle Ordovician limestones, East Tennessee [abstract]: Geological Society of America Annual Meeting, Abstracts with Program, v. 25, no. 6, p. A226–A227.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S. III, Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level, *in* Payton, C.E., Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 49–212.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High-Resolution Correlation of Time and Facies: American Association of Petroleum Geologists Methods in Exploration Series, No. 7, 55 p.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., Sea level Changes: An Integrated Approach: SEPM Special Publication 42, p. 39–45.

Walker, K.R., 1977, A brief introduction to the ecostratigraphy of the Middle Ordovician of Tennessee (southern Appalachians, U.S.A.), *in* Ruppel, S.C., and Walker, K.R., eds., The Ecostratigraphy of the Middle Ordovician of the Southern Appalachians (Kentucky, Tennessee, and Virginia), U.S.A.: A Field Excursion: Knoxville, University of Tennessee Department of Geological Sciences Studies in Geology 1, p. 12–17.

Walker, K.R., 1980, Introduction to the stratigraphy and paleoenvironments of the Middle Ordovician of Tennessee, *in* Walker, K.R., Broadhead, T.W., and Keller, F.B., eds., Middle Ordovician Carbonate Shelf to Deep Water Basin Deposition in the Southern Appalachians, Field Trip 10, Geological Society of America Annual Meeting, Atlanta, 1980: University of Tennessee Studies in Geology 4, p. 4–12.

Walker, K.R., ed., 1985, The Geologic History of the Thorn Hill Paleozoic Section (Cambrian–Mississippian), Eastern Tennessee: Knoxville, University of Tennessee Studies in Geology 10, 128 p.

Walker, K.R., 1992, Marine flooding interval between the Moccasin and Overlying "Martinsburg" Formations: A 3rd order sequence boundary, *in* Driese, S.G, Mora, C.I., and Walker, K.R., eds., Paleosols, Paleoweathering Surfaces, and Sequence Boundaries: University of Tennessee Department of Geological Sciences Studies in Geology 21, p. 26–34.

Walker, K.R., Broadhead, T.W., and Keller, F.B., eds., 1980, Middle Ordovician Carbonate Shelf to Deep Water Basin Deposition in the Southern Appalachians, Field Trip 10, Geological Society of America Annual Meeting, Atlanta, 1980: University of Tennessee Studies in Geology 4, 120 p.

Wedekind, J.E., 1986, The stratigraphy, depositional environments, bryozoan paleoecology, and taphonomy of the Middle Chickamauga Group near Thorn Hill, Grainger County, Tennessee [unpublished M.S. Thesis]: Knoxville, University of Tennessee, 200 p.

Wilson, J.L., 1975, Carbonate Facies in Geologic History: New York, Springer-Verlag, 471 p.

Received 10 March 1994; accepted 26 July 1994.