01 May 2003

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Recommended Citation

R. B. Overstreet et al., "Sequence Stratigraphy and Depositional Facies of Lower Ordovician Cyclic Carbonate Rocks, Southern Missouri, U.S.A.," *Journal of Sedimentary Research*, vol. 73, no. 3, pp. 421-433, Society for Sedimentary Geology, May 2003.
The definitive version is available at https://doi.org/10.1306/112002730421

SEQUENCE STRATIGRAPHY AND DEPOSITIONAL FACIES OF LOWER ORDOVICIAN CYCLIC CARBONATE ROCKS, SOUTHERN MISSOURI, U.S.A.

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ABSTRACT: **Lower Ordovician cyclic carbonate strata of southern Missouri were deposited in a warm, shallow, epeiric sea on a fully aggraded carbonate platform. Sedimentological characteristics distinguish the Jefferson City and Cotter dolomites from the underlying Gasconade and Roubidoux formations. Mixed carbonate–siliciclastic sedimentation characterizes the Roubidoux Formation, with sandstones accounting for up to 60% of sedimentation. The Gasconade, Jefferson City, and Cotter dolomites exhibit an increased occurrence of chalcedonic chert nodules in very similar shape and texture to the gypsum and anhydrite nodules common on modern sabkha supratidal flats. Casts of halite and ghosts of gypsum laths also exist in the Jefferson City and Cotter strata but are rarely found in the underlying units.**

Facies analysis from drill cores and outcrop sections provides the basis for identifying two major meter-scale cycle types. Type I cycles consist of algal stromatolites, tidal-flat laminites (mechanical and algal), ooid grainstones, wavy peloidal wackestones, and quartz sandstones interpreted as peritidal facies. They are the dominant components of the Roubidoux Formation, Jefferson City Dolomite, and Cotter Dolomite. Type II cycles consist mostly of subtidal facies such as strongly burrowed mudstone, thrombolite boundstone, and stromatolites. Type I cycles are thinner and represent highstand systems tracts, whereas the thicker type II cycles represent transgressive systems tracts and are dominant in the Gasconade Dolomite. The cycle stacking patterns, facies changes, and the intrabasinal correlatability of Fischer plots made from the widely spaced sections argue for a eustatic control on sea-level fluctuation on the platform.

Interbasinal correlation with other North American basins is possible using biostratigraphic information and comparison of Fischer plots. Five Missouri sequences correlate with those described for other regions. The continent-wide uniformity in cycle stacking patterns indicates a primarily eustatic control on Lower Ordovician meter-scale cycle development. Regional tectonic and autocyclic controls probably account for general differences in sedimentation pattern among the correlated basins.

INTRODUCTION

Shallow marine carbonates of Ordovician age were deposited widely under epeiric-sea conditions in several North American basins, most notably on the Appalachian and Cordilleran passive margins, the Southern Oklahoma Aulacogen, and flanking the Ozark Uplift (Goldhammer et al. 1993; He et al. 1997). Lower Ordovician strata in basins throughout North America are composed dominantly of meter-scale shallowing-upward cycles that record high-frequency relative sea-level fluctuations. The thickness of the meter-scale cycles (fourth-order and fifth-order cycles) depends upon several factors, including subsidence, sedimentation rates, and the magnitude of the flooding event (Read et al. 1991). Under greenhouse conditions, series of cycles that become thinner upward indicate long-term relative sea-level fall, whereas series of cycles that thicken upward indicate long term relative sea-level rise. The reverse may be the case for icehouse conditions because of the impact of unfilled accommodation space on cycle thickness (Gianniny and Simo 1996).

Controls on cycle formation generally include tectonic activity, sedimentation processes (such as tidal-channel migration and tidal-flat progradation), and/or eustatic sea-level fluctuation (orbitally forced eustasy). Eustatic sea-level change is likely driven by the interplay of a hierarchy of cycles of different periods and amplitudes (Read and Goldhammer 1988). Theoretically, fifth-order cycles are superimposed upon longer-term fourth-order (100–1000 ky duration) and third-order cycles (1–10 My duration) to form the composite eustatic sea-level curve. In an accommodation plot (i.e., Fischer plot), the systematic change in meter-scale cycle thickness indicates the form of long-term (third-order) cycles. The correlation of the relative sea-level curves, across-platform and interbasinally, has been considered evidence for continent-wide sea-level fluctuation on the North American landmass (Montañez and Read 1992; Osleger and Read 1993).

The Lower Ordovician strata (Ibexian Series) of southern Missouri include 60–120 meter-scale cycles. The equivalent strata of the Beekmantown and Upper Knox Group in the Appalachian Basin, the El Paso Group in west Texas, and the Arbuckle Group in Oklahoma have been used to establish sea-level curves for these regions (Read and Goldhammer 1988; Montañez and Read 1992; Goldhammer et al. 1993). Previous work (He 1995) has established that the Cambro–Ordovician of Missouri is dominantly composed of meter-scale shallowing-upward cycles, but cycle stacking patterns were not investigated in earlier studies. This study, therefore, presents the first detailed descriptions of facies and cycle types in the study area, in addition to an analysis of the cycle stacking patterns and changing accommodation upward through the sections. We discuss the significance of the mixed siliciclastic–carbonate units in the Roubidoux Formation, and the implications of evidence of evaporites in the Jefferson City and Cotter dolomites. In addition to an intrabasinal correlation, we attempt an interbasinal correlation with cycles in other North American basins based on biostratigraphic information and accommodation plots, and we comment on the pattern of Lower Ordovician carbonate deposition across the epeiric sea.

Geologic Setting

Lower Ordovician rocks of southern Missouri occur on and adjacent to the Ozark Uplift (Fig. 1), which is an asymmetric structural dome with a core of Precambrian and Cambrian rocks that crop out in the St. Francois Mountains of southeastern Missouri. The Ozark Uplift is bounded by the Arkoma Basin (to the south), the Forrest City Basin (to the northwest), the Illinois Basin (to the northeast), and the Reelfoot Rift (to the east). The Lower Ordovician strata in Missouri were deposited in a warm, shallow epeiric sea on a fully aggraded platform (He 1995). Localized fossil assemblages occurring in the Lower Ordovician suggest that much of the sequence was associated with a hypersaline nearshore environment (Stinchcomb 1978). This is underscored by the presence of evaporite casts (He 1995; Overstreet 2000). The Ozark region rested on the Laurentian continent between 10° and 25°S in Ordovician time.

The Lower Ordovician rocks studied include the Gasconade Dolomite, the Roubidoux Formation, the Jefferson City Dolomite, and the Cotter Dolomite (Fig.1). The Lower Ordovician Powell Dolomite and Smithville Formation are excluded from this study because in Missouri these units crop out only in a narrow band in the southeastern part of the state, and are absent over the study area. The Gasconade Dolomite rests unconformably on Upper Cambrian carbonates, whereas Mississippian and Pennsylvanian strata rest unconformably upon the Cotter Dolomite throughout southern

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JOURNAL OF SEDIMENTARY RESEARCH, VOL. 73, NO. 3, MAY, 2003, P. 421–433
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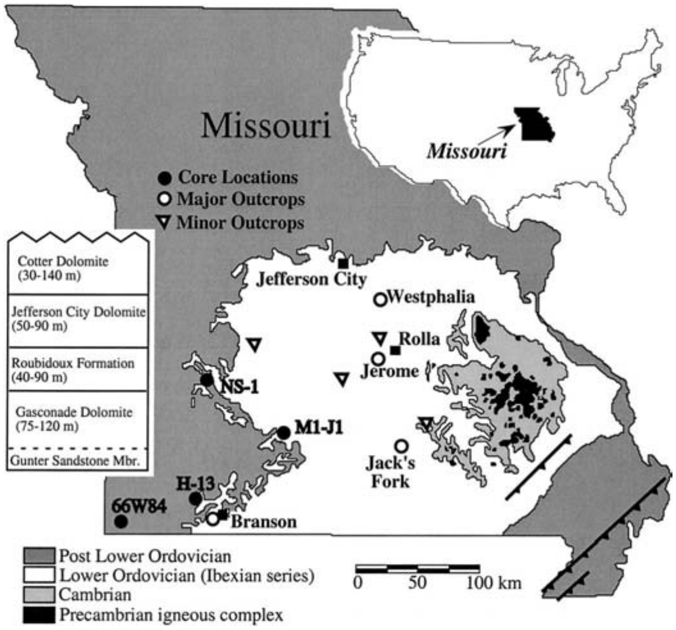

FIG. 1.—Generalized geologic map of Missouri with locations of outcrops and drill cores used in this study. Locations of minor outcrops (which were studied in less detail) are also shown. Inset at left shows the stratigraphy of the Lower Ordovician rocks.

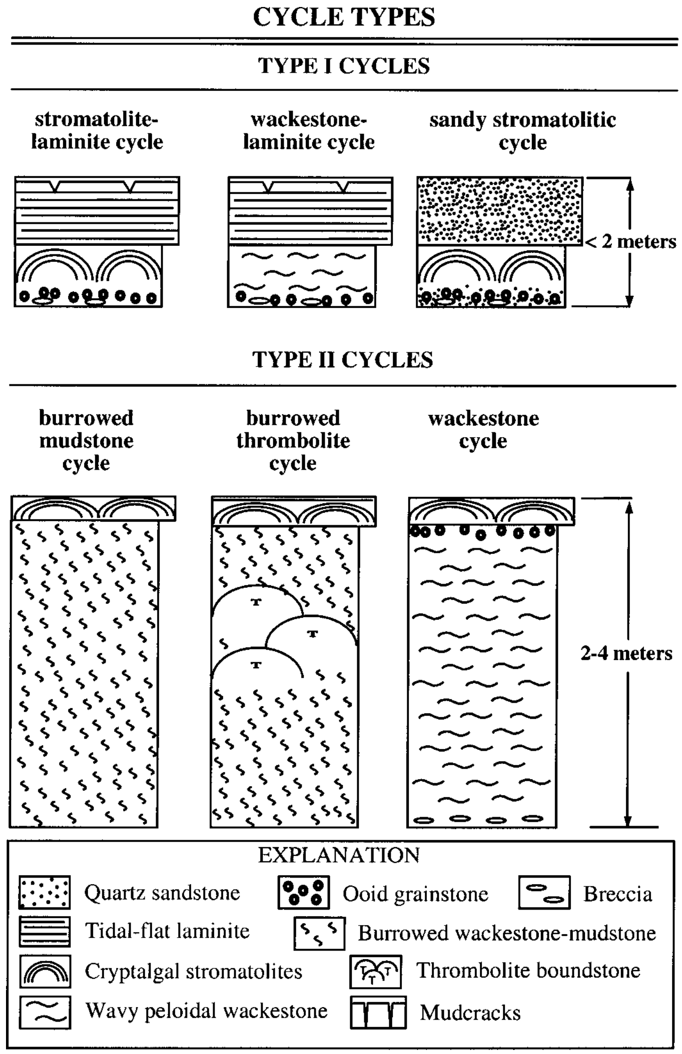

FIG. 2.—Meter-scale cycle types in the Lower Ordovician of the Ozarks. There are two general types based on the relative thickness of the subtidal and peritidal facies. Type I cycles have a relatively thick peritidal portion, whereas type II cycles have a relatively thick subtidal portion. Six common variations of the two cycle types are illustrated.

Missouri. Lower Ordovician strata are composed of three basic lithological components: dolomite, chert, and quartz sand. Most of the Lower Ordovician strata are cherty dolomite with little quartz sand content, but quartz sandstone is volumetrically important in the Gunter Sandstone Member of the Gasconade and parts of the Roubidoux Formation (Carver 1961; Thompson and Robertson 1993; Overstreet 2000).

METHODS

Outcrop sections from four locations in southern Missouri (Jerome outcrop in Phelps County, Westphalia Highway 63 roadcut in Osage County, Jack's Fork roadcut in Texas County, four adjacent roadcuts near Branson in Taney County), as well as four drill cores (in St. Clair, Stone, McDonald, and Webster counties) were measured (Fig. 1). Three additional minor outcrops were also studied, but in less detail. In total, 1220 m of section were measured and logged in detail from drill-core and outcrop sections. (For descriptions of measured sections and core, see Appendix in Overstreet 2000). The work concentrated on detailed lithofacies analysis and measuring the thickness of meter-scale cycles on a centimeter scale. It should be noted that, with the exception of quartz sandstone units, the facies analysis is based entirely on the interpretation of relict features in dolomite and chert.

Fischer plots were constructed from each of the four widely separated drill cores, and three of the four major outcrop sections studied. The outcrop sections were either too short or too incomplete to make statistically significant Fischer plots (Sadler et al. 1993), but the plots did serve as guides for correlating the outcrop sections to the more continuous core sections. Missing strata, such as covered or eroded units, are represented by a gap in the Fischer plot, with no net vertical change. Likewise, noncyclic units such as the Gunter sandstone, and paleosink structures in the Jefferson City Dolomite are also represented by gaps in the Fischer plots. The sections are correlated using laterally extensive marker beds and biostratigraphic information. Interbasinal correlation is based on Early Ordovician trilobite and conodont biostratigraphy, as well as Fischer plots. The biostratigraphic correlations made in this study are based entirely on the work of other authors (e.g., Ethington and Clark 1971; Brand 1976; Stinchcomb 1978; Repetski 1982, 1988; Ethington and Repetski 1984; Ross et al. 1982; Ross et al 1997; Repetski et al. 1998; Repetski et al. 2000; Brezinski et al. 1999).

RESULTS

Mixed Carbonate–Siliciclastic Sedimentation

Extensive siliciclastic deposition during the Early Ordovician resulted in the deposition of the Gunter Sandstone Member at the base of the Gasconade Dolomite and thick sandstone beds in the Roubidoux Formation. The Roubidoux Formation, however, is characterized by mixed carbonate–siliciclastic sedimentation and contains several sandstone units that make up approximately 30–60% of the formation. Carver (1961) interpreted the sandstone–dolomite beds as the result of admixture of quartz sand of extrabasinal origin (from the Canadian shield and the northern Michigan highlands) and calcareous sands of intrabasinal origin. Thinner sandstone units and quartz sand-rich dolomite beds occur in the Jefferson City and Cotter dolomites, but the Gasconade Dolomite (excluding the Gunter Member)

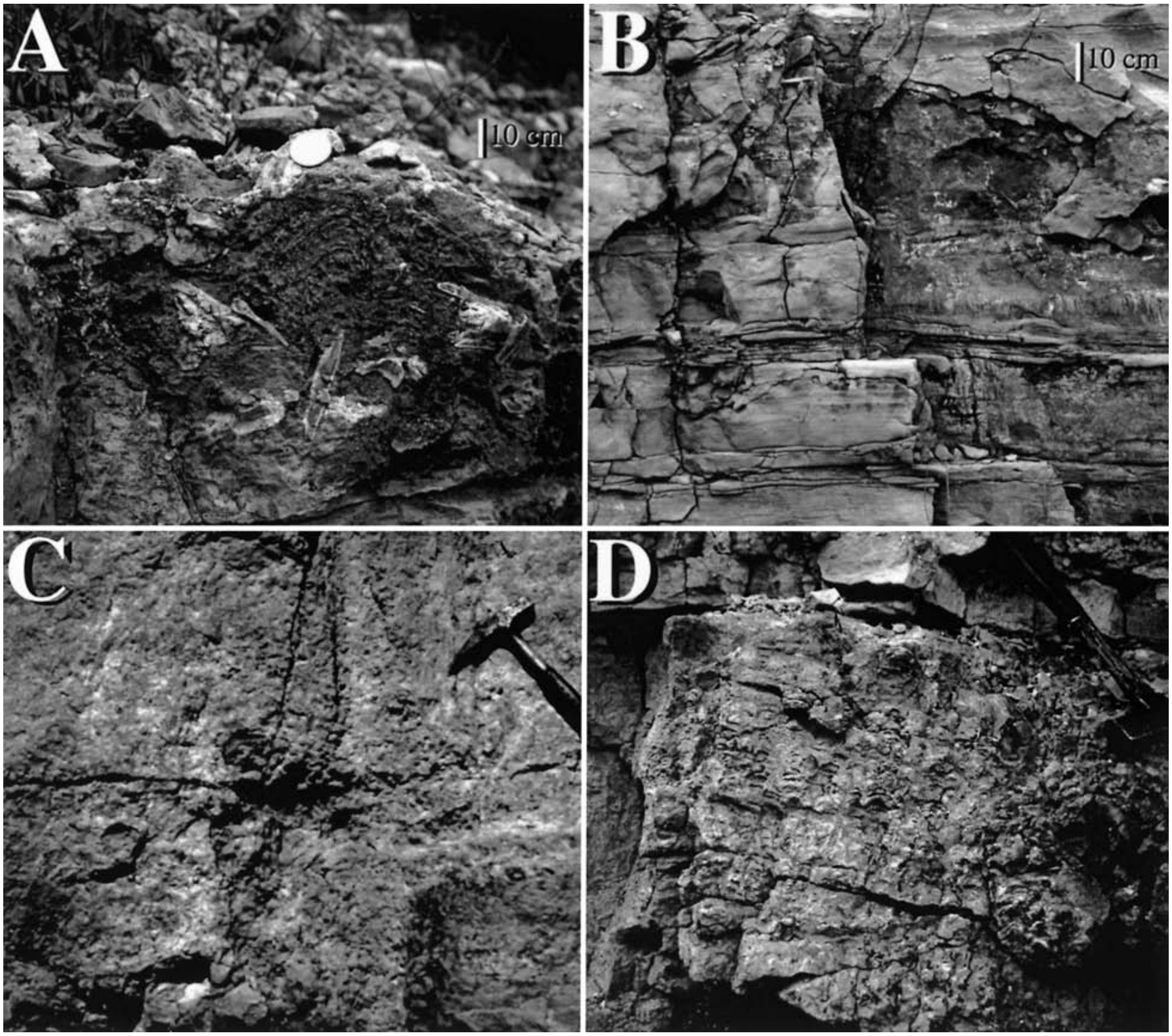

FIG. 3.—**A)** Laterally linked hemispheroid (LLH) stromatolite facies. Continuous laminae extend between adjacent stromatolites. Gasconade Formation, Jerome outcrop. **B)** Wavy-bedded peloidal wackestone facies. This facies is usually present in blue-gray to tan, fine–medium grained dolomite. Cotter Dolomite, Branson outcrop. **C)** Burrowed mudstone facies. This facies is heavily burrowed with centimeter-scale burrows, giving the unit a pitted texture where weathered as the Quarry Ledge Mudstone. Jefferson City Dolomite, Westphalia outcrop. **D)** Digitate Stromatolite Facies. Digitate laminae are approximately 2–3 cm in width and over 20 cm vertically. Roubidoux Formation, Westphalia outcrop.

generally lacks these types of units except in the uppermost part of the formation. Whereas sand-rich beds are laterally distributed in the Roubidoux Formation throughout the study area, they have restricted distribution in the Jefferson City and Cotter dolomites. Our assumption is that the sand grains in the upper formations were likely intrabasinal in origin and locally restricted, an assumption based on Carver's (1961) inference that the source area was reduced to low relief at the close of Roubidoux time. Sand-rich beds occur commonly in association with stromatolitic dolomite (intertidal to supratidal) facies, which is a subtype of type I cycles, but a few thin sand-rich beds are associated with wavy-bedded wackestone (type II, subtidal facies) cycles (Fig. 2).

Meter-Scale Cycles

A total of 418 meter-scale cycles were logged and described. Cycle thickness and composition varies with stratigraphic level and geography. There is little variation in average cycle thickness: the cycles average 2.6 m thick in the northernmost core (NS-1), whereas they are 2.8 m thick in the southernmost cores (66W84 and H-13). Meter-scale cycles from the Ibexian Series of Missouri can be categorized into two general cycle types based on the relative thickness of the subtidal and peritidal facies (Fig. 2). Lithofacies encountered are shown in Figures 2 and 3 and described in Table 1.

Type I Cycles.—Type I cycles have relatively thick peritidal portions that are equal to or thicker than the subtidal facies (Fig. 2). These cycles frequently have a thin ($<$ 10 cm) transgressive lag deposit at their bases that contains rounded intraclasts, ooids, fossil fragments, and/or rounded quartz sand. The main constituents of type I cycles are algal-microbial stromatolites, tidal-flat laminites (mechanical and cryptalgal), ooid grainstones, wavy peloidal wackestones, and quartz sandstones (Table 1). Type I cycles typically include quartz sand and exhibit evidence for subaerial exposure near the cycle caps, such as desiccation cracks. Small-scale teepee structures and silicified solution-collapse breccias are also present. These cycles vary in thickness laterally, although the variation at outcrop scale is

TABLE 1.—*Lithofacies in the Lower Ordovician of southern Missouri*

Burrowed mudstone-wackestone

Deep subtidal. Burrowed mudstone units have a ruddy pitted surface texture, with the pits corresponding to geopetal infilling. The burrows may be partially filled by coarser, light-colored dolomite. Heavily burrowed units are commonly porous and vuggy, whereas other units are only slightly burrowed. Composition is dominantly dolomite, with some chert and void-filling calcite.

Thrombolitic boundstone

Deep subtidal. Broad massive thrombolitic units with clumpy sponge-algal fingers and noncontinuous laminae commonly occur in type II cycles. Throbolites commonly contain peloidal sediment and may be burrowed.

Ooid peloid grainstone

Shallow subtidal. This facies usually occurs as transgressive lag deposits at the bases of type I cycles. Grainstones frequently contain intraclasts, rounded quartz sand, and fossil fragments. Ooid grainstones are commonly preserved as ghosts in chert, although some oomoldic porosity is rarely found in dolomite.

Laterally linked hemipheroid stromatolites

Intertidal. Closely spaced mounds with an internal fabric of mm-scale laminae. Laminae are laterally continuous between the closely spaced stromatolite domes. Individual domes commonly range in size from 0.5–2 m wide and 0.2–0.6 m high. In the Ozarks, LLH stromatolites commonly are silicified into light colored cherts or are replaced by dolomite with fenestral pososity.

Wavy peloidal wackestone

Shallow subtidal to intertidal. Fine grained and often banded, this unit is composed of wavy, cross-laminated wackestone and peloid packstone. Laminations usually are very faint even when viewed up close and peloids are visible only in cherty nodules. This facies commonly occurs in thick, massively bedded units of light gray to tan fine-grained dolomite. Wavy peloidal wackestone facies is probably equivalent to the *ribbon rock facies* of other authors (Demicco 1985; He 1995).

Stacked hemispheroid stromatolites

Shallow subtidal. SH stromatolites have laminae that extend upward but do not connect adjacent domes. Internally, the upper hemispheroid laminae do not reach the base of the preceding layer. SH stromatolites range in size from 0.3 to 1.0 m wide and from 0.2 to 1.0 m high. Lateral association with ooid grainstone is common. SH stromatolites are frequently replaced by chert and vuggy dolomite, and frequently exhibit excellent fenestral porosity.

Digitate stromatolite

Shallow subtidal. Vertically stacked cm-scale hemisphereoid fingers with closely linked and continuous laminae form the internal structure of digitate stromatolites. Coalesced algal fingers form massive units with good fenestral porosity. These units form broad mounds that may be over 5 m wide and over 1 m in height.

Mechanical laminite

Intertidal to supratidal. Fine grained and commonly light gray to brown with faint mm-scale horizontal laminae. This facies commonly contains mudcracks, replaced evaporite molds and casts, and solution-collapse breccias. Thin beds of mechanical laminite commonly cap meter-scale cycles in the Ozarks. This facies may be equivalent to the nearly featureless tan dolomite units in the Jefferson City and Cotter formations known as *cotton rock* (He 1995).

Cryptalgal laminite

Supratidal. Slightly wavy and undulate algal laminae with fenestral porosity frequently overlie stromatolites. Desiccation cracks, teepees, and solution-collapse breccias commonly occur near the cycle top.

Quartz sandstone

Intertidal to supratidal. Rounded medium-grained quartz arenite. Massive to horizontally bedded. Ooids and fossil fragments frequently occur along with the quartz sand. Quartz sandstone units that cap meter-scale cycles commonly have desiccation cracks at tops. These units range in thickness from 0.1 m to 2.0 m in beds or channel-fill structures.

generally not more than 10 cm. The tops and bases of cycles are marked by changes in facies and/or sharp boundaries.

Three subtypes of type I cycles occur (Fig. 4): (1) Stromatolite–laminite cycles (Fig. 4A) composed of stromatolites and tidal-flat laminites are very common in some sections (especially in the upper Gasconade Formation at Jerome, and the Roubidoux Formation at Westphalia). The stromatolite base generally is composed of dome-shaped or pillow-shaped LLH stromatolites that are preserved poorly by dolomite but are locally preserved very well by chert (Fig. 3A). Stromatolite-laminite cycles typically stand out from a distance because the stromatolite bases of these cycles commonly are replaced by white chert, which contrasts with the tidal-flat laminite (gray dolomite) (Fig. 4B). (2) Stromatolite–sandstone cycles are common in particularly sandy intervals, such as in the Roubidoux Formation. These cycles have rounded, medium quartz sand throughout, but the sand is more concentrated near the bases and tops of cycles. However, the tops are marked by desiccation cracks. Thin beds of sandstone or silicified sandstone commonly overlie LLH stromatolites in sandy type I cycles. (3) Wackestone–laminite cycles occur mainly in the Jefferson City and Cotter dolomites. These consist of a thin unit of wavy peloidal wackestone that is overlain by mechanical laminites. Chalcedonic chert nodules are abun-

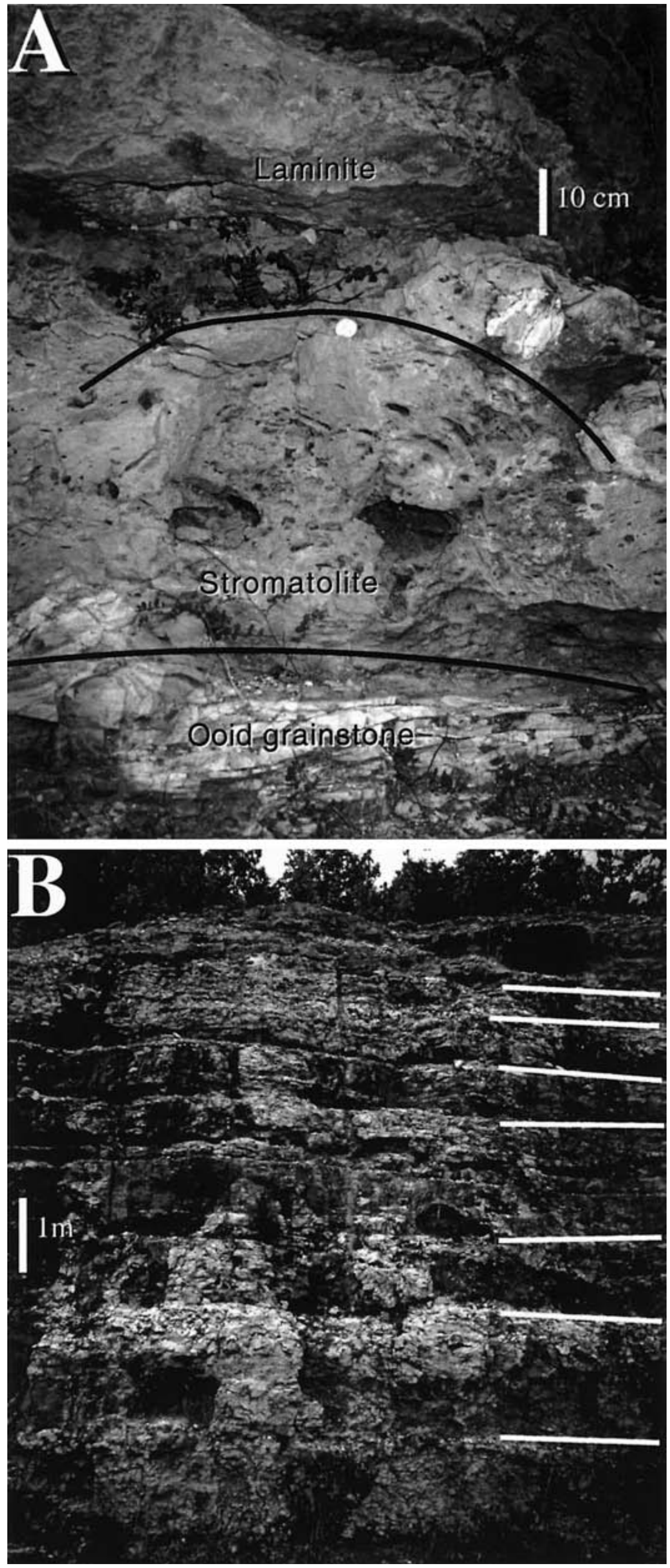

FIG. 4.—Type I cycles: **A)** An intraclastic ooid grainstone base overlain by large LLH stromatolites with excellently developed fenestrae, and capped by tidal-flat laminite. Gasconade Formation, Jerome outcrop. **B)** A series of type I cycles. From a distance the cycles can be resolved, because the intraclastic bases and stromatolites tend to have more chert (usually light colored) than the cycle tops. Gasconade Formation, Jerome outcrop.

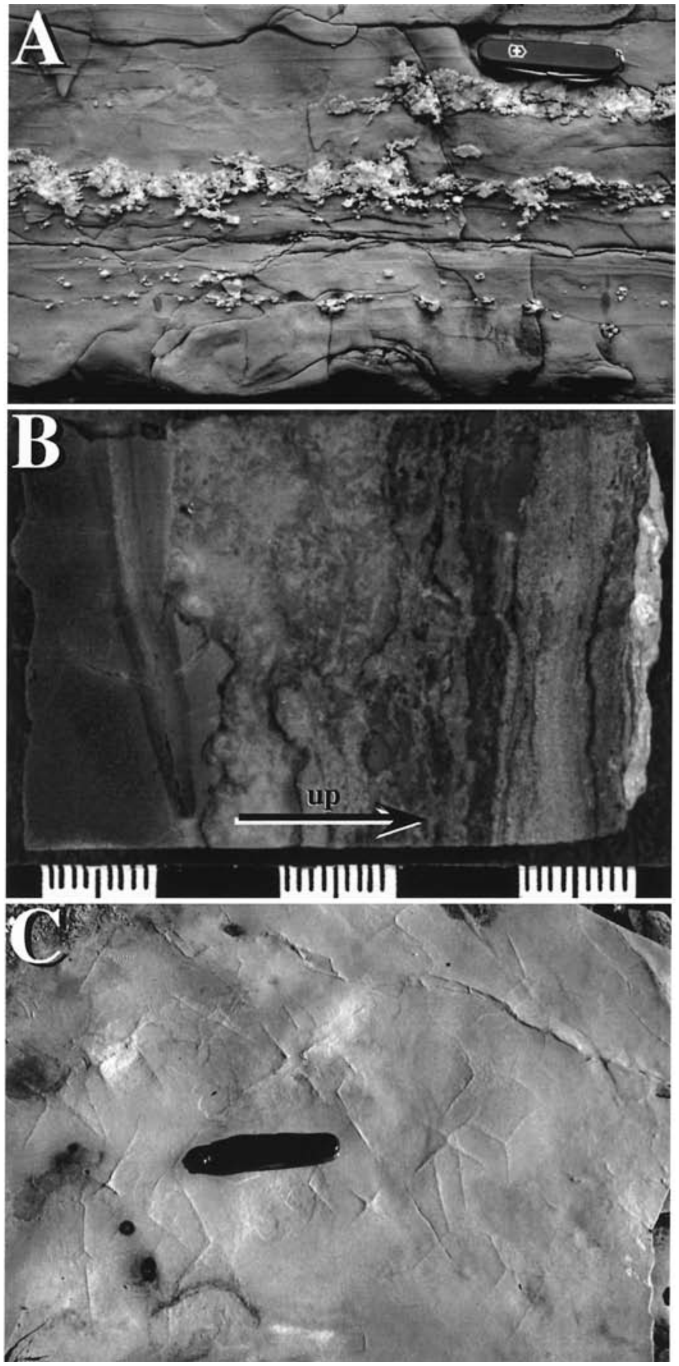

FIG. 5.—Evidence for evaporite deposition. **A)** Chalcedonic chert nodules along bedding horizons in wavy peloidal wackestone. Cotter Dolomite, Branson outcrop. **B)** Chalcedonic chert nodule displaying the ''cauliflower'' texture that is common in evaporite nodules. Jefferson City Dolomite, drill core H-13. **C)** Halite hopper casts occurring in the mechanical laminite cap of a type I cycle; the same unit also contains several mud-cracked horizons. Jefferson City Dolomite, Westphalia outcrop.

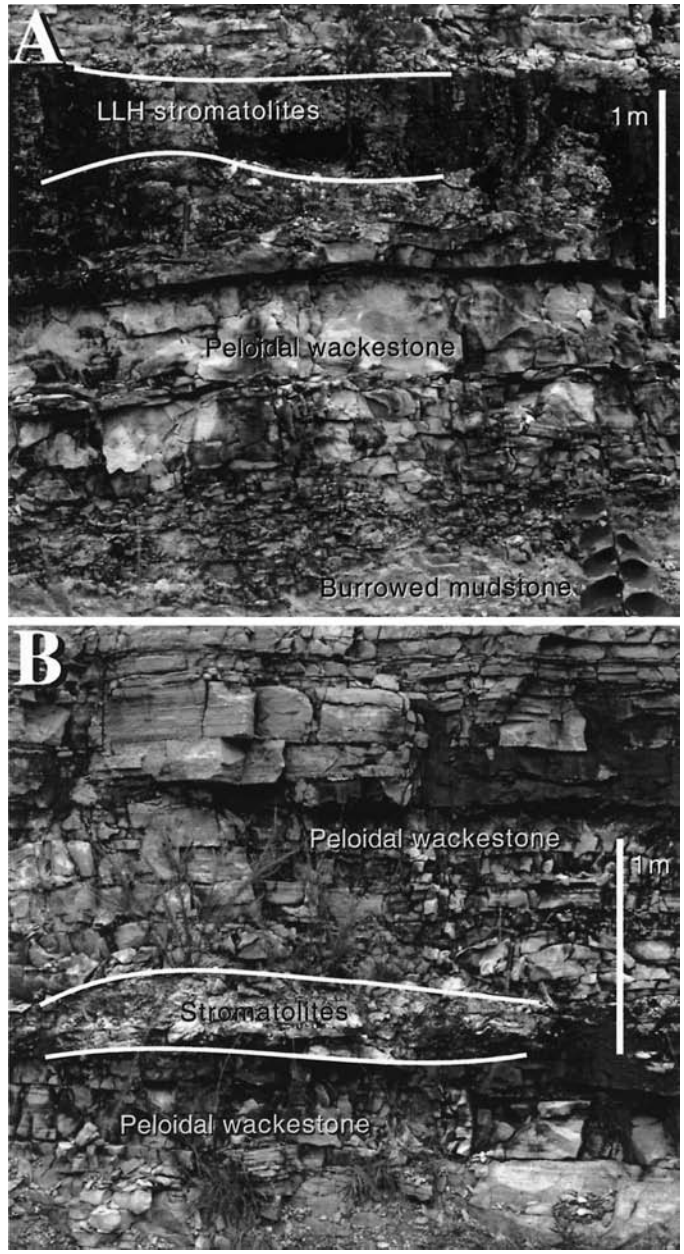

FIG. 6.—Examples of type II cycles. **A)** Burrowed mudstone–wackestone cycle that is capped by stromatolites (bracketed by white lines), Roubidoux Formation, Westphalia section. **B)** The boundary of two type II wackestone cycles. A thin very cherty stromatolitic bed (bracketed by white lines) caps the lower cycle. Cotter Dolomite, Branson section.

dant in peloidal wackestone and laminite type I cycles in the Jefferson City and Cotter dolomites (Fig. 5A, B). The nodules usually form in subrounded white to translucent masses that range in size from 2–5 cm thick and 5–10 cm wide. In addition to the chalcedonic nodules, molds of well formed hopper halite crystals and ghosts of gypsum laths were observed in places at the tops of these cycles (Fig. 5C).

Type II Cycles.—Type II cycles consist mostly of subtidal lithologies, with the thickness of the subtidal facies accounting for 60–90% of the total cycle thickness (Fig. 6). The main constituents of type II cycles include strongly burrowed mudstone (Fig 3C), wavy-bedded peloidal wackestone (Fig. 3B), thrombolite boundstone, stromatolites, and ooid grainstone. Peritidal and shallow subtidal facies such as ooid grainstone, LLH stromatolites, and tidal-flat laminite (mechanical) commonly cap type II cycles (Table 1). Individual cycles are generally 2–4 m thick, are laterally continuous, and have nearly constant thickness. Subtidal-dominated meter-scale cycles rarely display evidence of subaerial exposure and contain less quartz sand than type I cycles.

Three subtypes of type II cycles (Fig. 2) occur: (1) Thick burrowed

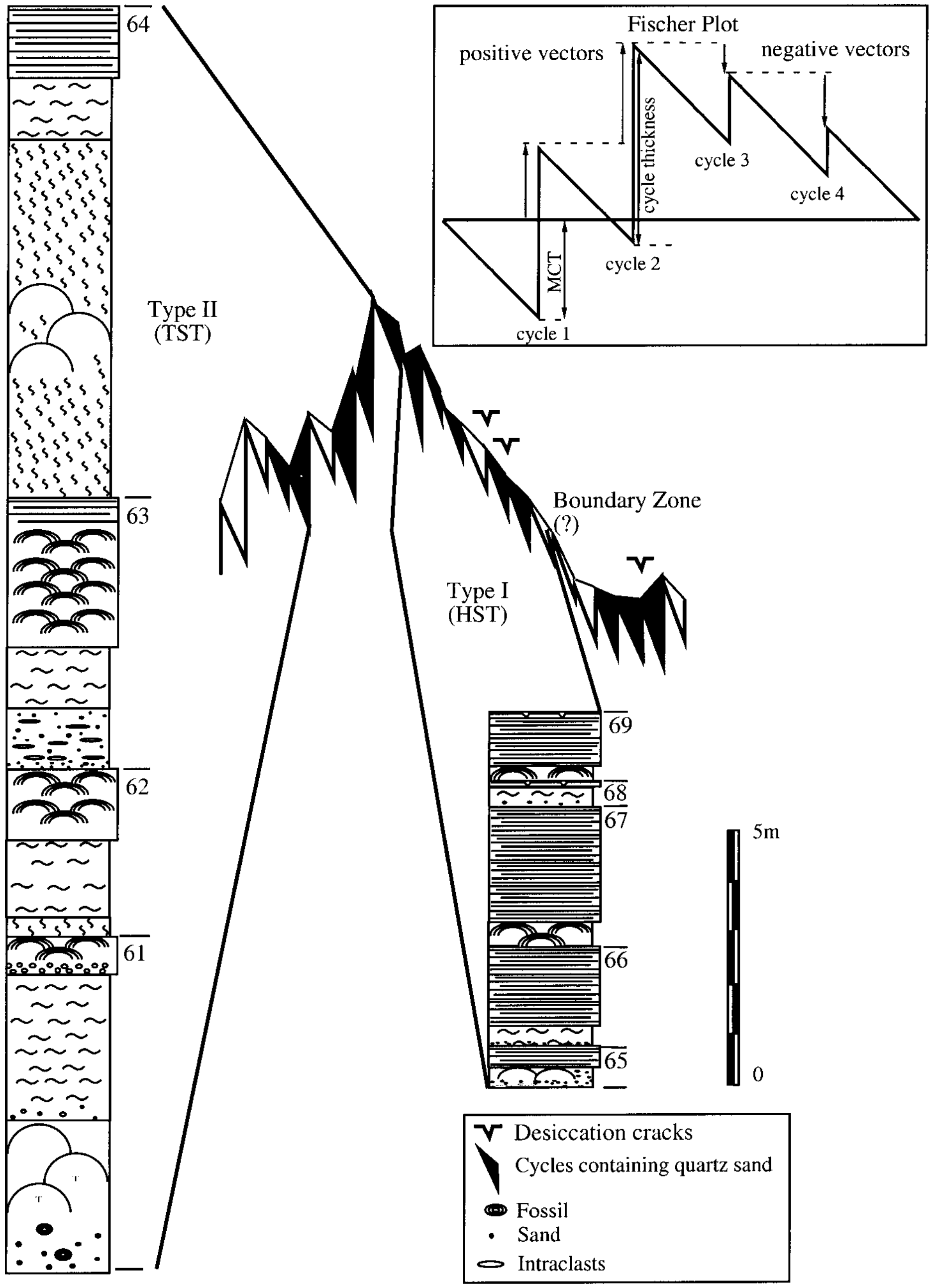

FIG. 7.—Third-order cycle in the Jefferson City Dolomite (drill core H-13). Type I meter-scale cycles of the highstand systems tract (HST) are associated with the negative slopes of the Fischer plot, whereas type II cycles of the transgressive systems tract (TST) are associated with the positive slopes. Note the increase in subaerial exposure and the predominance of quartz sand along the negative slope. See Figure 2 for definitions of lithofacies symbols. On the inset, MCT = mean cycle thickness.

mudstone cycles (Fig. 3C) are common in the lower Gasconade and Jefferson City formations (e.g., cycle 26 at Westphalia [the Quarry Ledge Member], I-44 roadcut A, and cycle 64 in core H-13) (e.g., Fig. 6A). The massively bedded mudstone is strongly burrowed, with centimeter-scale burrows that give this facies a pitted surface texture. Stromatolites and tidal-flat laminites frequently cap burrowed mudstone cycles. (2) Burrowed thrombolitic cycles are particularly common in the lower part of the Gasconade Formation. Thrombolite structures were rarely recognized in outcrop, but the internal thrombolite fabric was found in drill core. 3) Wackestone cycles (Fig. 6B) are most abundant in the upper Jefferson City Dolomite and throughout the Cotter Dolomite. The Main constituent of this cycle subtype is massively bedded wavy, peloidal wackestone. This facies is cross-laminated throughout and generally grades upward into a thin oolitic grainstone. Chalcedonic chert nodules commonly occur, in a single horizon, within wackestone cycles. These nodules usually occur either along horizons in wavy cross-laminated wackestone or in overlying mechanical laminite units. In some sections of the Jefferson City and Cotter dolomites, the nodules become common and constitute approximately 1% of the volume.

Stacking Patterns and Boundary Zones

Fischer plots from the four continuous drill cores represent the changing cycle thickness and cycle type upward through the Lower Ordovician section (Figs. 7, 8). Type II (mostly subtidal) cycles typically stack together. They are thicker than average (> 2 m) and so occur as steep positive slopes on the Fischer plot. By contrast, type I cycles are mostly intertidal to supratidal facies that are thinner than average (< 2 m), and occur as shallow (negative) slopes stacked together. Some cycles, such as Cycle 63 in drill core H-13 (type II) have unusually thick transgressive lag deposits

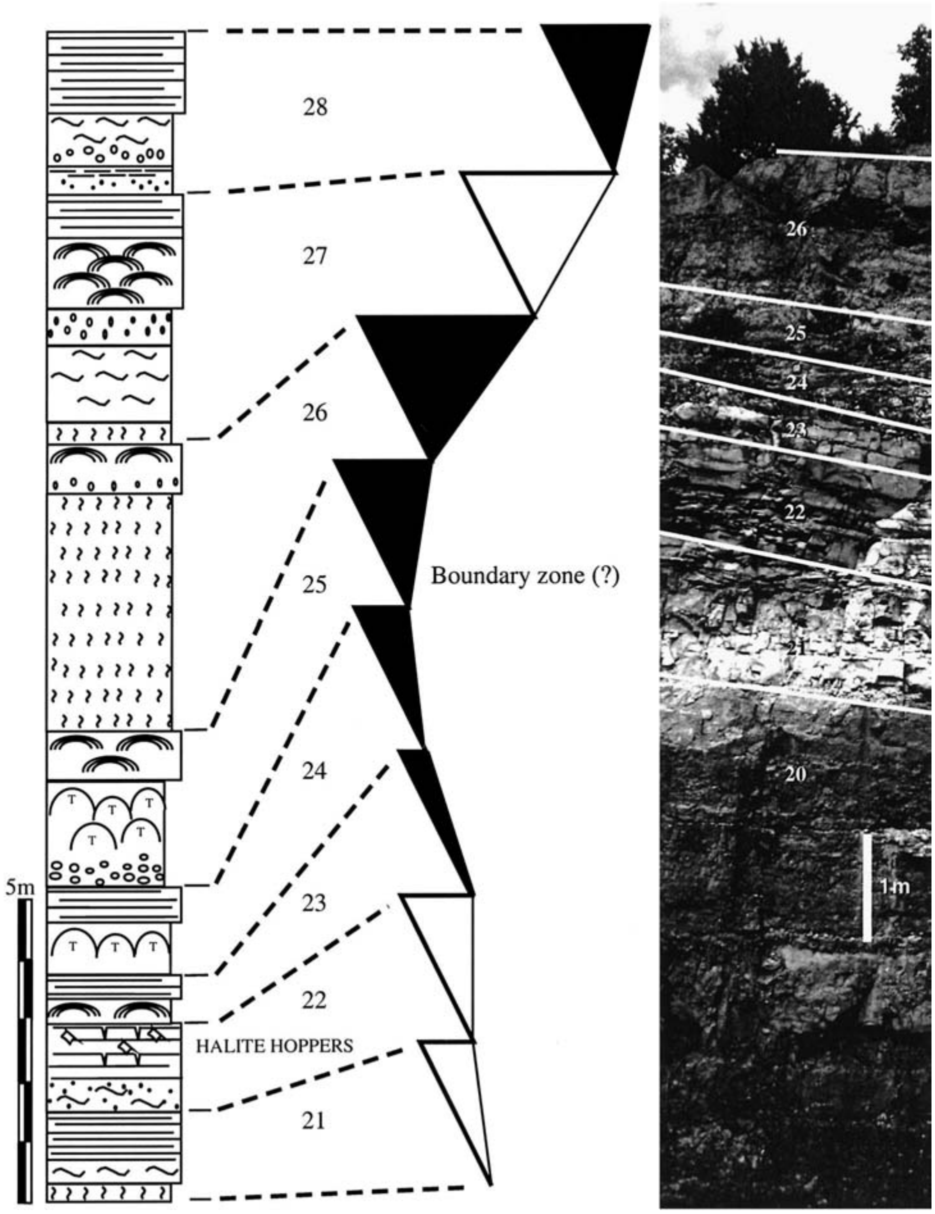

FIG. 8.—Transition zone between third-order sequences in the Jefferson City Dolomite (Westphalia section). Cycles 21–23 are type I cycles that have relatively thick peritidal facies. Note the desiccation cracked horizons in cycle 22. Cycles become progressively thicker upwards, and type II cycles (25–28) become dominant. Quartz sand is common throughout the entire interval. See Figure 7 for legend.

at the base that are characterized by high proportions of reworked sand (Fig. 7). In general, the thickening of cycles upward is accompanied by a transition from type I cycles to type II cycles. Such a boundary is called a transition zone, and may not be present in every section. The cycles in this zone tend to contain rounded, medium-grained quartz sand. In addition, there is an increasing occurrence of cycle tops displaying evidence of subaerial exposure such as desiccation cracks and breccias (e.g., Westphalia outcrop, Fig. 8).

DISCUSSION

Sequence Stratigraphy

The Lower Ordovician strata of the Ozark region comprise five type 2 sequences (Myers and Milton 1996; Fig. 9). The sequences and systems tracts identified are recognized by cycle stacking patterns, cycle types, and the forms of the accommodation plots. The sequences are categorized as third-order sequences, in part on the basis of the age of the strata (Unklesbay and Vineyard 1992) and presence of 13–35 meter-scale cycles (fourth-order and fifth-order) in each sequence. At most locations studied, no distinct erosional surfaces were found in the strata to mark sequence boundaries, and recognizable lowstand systems tracts (LST) are absent. The sequence tops were picked (where possible) near an inflection point on the accommodation plots that coincided with a change from cycle II to cycle I and increasing erosional features. Therefore, sequence tops are represented by a zone of cycles instead of discrete regional unconformities.

A typical sequence includes an initial upward thickening of cycles (type II, dominantly subtidal facies) of the transgressive systems tract (TST), followed by upward thinning cycle (type I, peritidal facies) of the highstand systems tract (HST) (Fig. 7). Subtidal-dominated cycles, therefore, are capped by thin tidal-flat laminites. These cycles contain less quartz sand (see below) than type I cycles, and evidence of subaerial exposure is rare. The transition from TST to HST is generally near an inflection point on the accommodation plot, although major facies changes also distinguish the HST. The HST is recognized on the Fischer plots as a long negative slope. The meter-scale cycles probably form after the initial third-order transgression, when the long-term production of accommodation space is out-

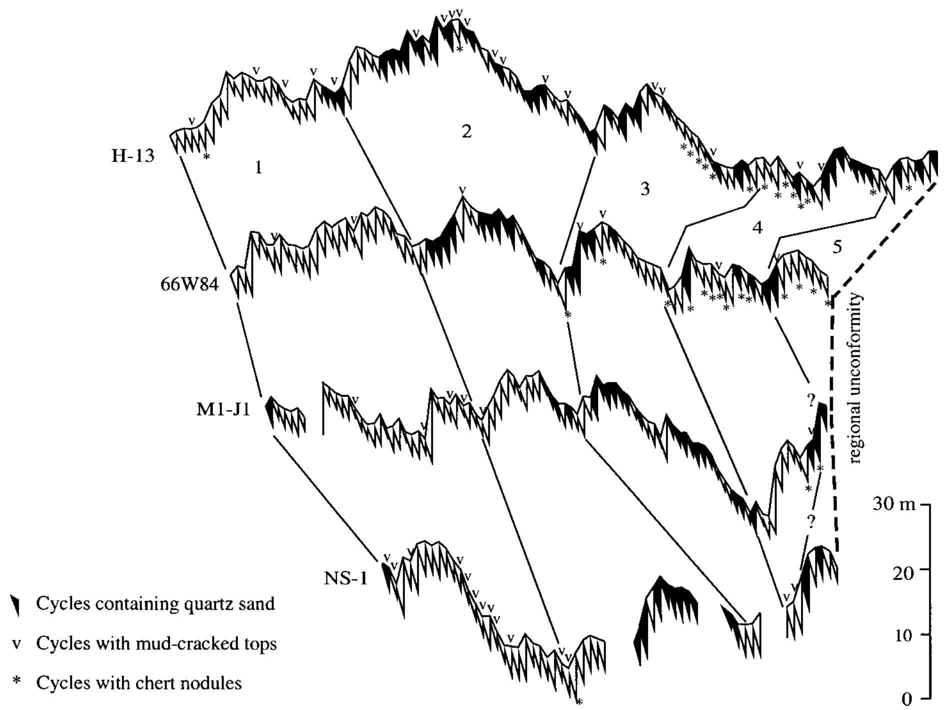

FIG. 9.—Fischer plots of the Missouri Ozarks strata. Section locations are shown in Figure 1. The left border is the top of the Gunter Sandstone Member of the Gasconade Formation, and the right border is the top of the Lower Ordovician. Tie lines indicate the approximate boundaries for sequences 1–5. Gaps in the plots are either noncyclic or absent strata. Fischer plots are correlated using quartz sand-bearing cycles and sandstone beds (shaded), evidence of subaerial exposure, and highstands evident on the plots. The correlated plots define third-order relative sea-level cycles (labeled 1 to 5). Occurrence of chalcedonic chert nodules is used as an indicator of possible evaporites.

paced by sedimentation. HST cycles usually shoal upward to supratidal facies, and individual cycles frequently have desiccation-cracked tops and brecciated components, and include quartz sand. Abundance of quartz sand is generally greater in the transgressive lag deposits at the bases of cycles and at the cycle tops, and is laterally extensive in the Roubidoux Formation. The presence of quartz sand in the type I facies of the HST may be related to a siliciclastic bypass mechanism, which transported sand onto the outer platform during shoreline progradation (Osleger and Read 1991).

Intrabasinal Correlation

Five third-order depositional sequences are recognized in the accommodation plots of the four continuous drill cores through the Lower Ordovician of southern Missouri (Figs. 9, 10). Although sequence thickness and cycles per sequence vary across the platform, the overall forms of each sequence are remarkably similar. Depositional sequence 1 begins in the Gunter Sandstone and ends in the middle to upper Gasconade Dolomite. It contains 18–25 meter-scale cycles in which the TST consists mostly of burrowed mudstone and thrombolitic type II cycles, whereas type I stromatolite–laminite cycles constitute the HST. Many of the type I cycles in sequence 1 and other sequences are further differentiated by the presence of quartz sand and/or desiccation-cracked cycle tops, but sequence 1 (above the Gunter Sandstone) contains the least amount of sand among all five sequences.

Depositional sequence 2 begins in the upper Gasconade Dolomite and includes most of the Roubidoux Formation. This succession contains 18–33 meter-scale cycles. The TST is well developed in cores H-13 and 66W84, and in the lower ten meters of the Jerome outcrop. The transition from TST to HST consists of the thinning of cycles, increasing sand content, and evidence of subaerial exposure. The HST occurs in three of the measured outcrops but not at the Branson section. The transitional sequence boundary between the HST of sequence 2 and the TST of depositional sequence 3 is particularly assessable in the Westphalia outcrop, where cycles 26–33 form the transgressive phase of sequence 3 (Fig. 6A). Sequence 3 begins in the Upper Roubidoux Formation and contains most of the Jefferson City Dolomite, with 15–27 meter-scale cycles in the four drill cores studied. The HST is marked by a stack of thin cycles, which lack quartz sand in the M1-J1 core, possibly because of locally restricted intrabasinal sources for quartz. Sequence 3 is largely absent in drill-core NS-1, owing to karst-related paleosinks that destroyed the original strata.

Depositional sequence 4 begins near the Jefferson City–Cotter Dolomite boundary and includes 14–20 cycles. The complete sequence is observed only in drill-cores H-13 and 66W84, although the initial transgressive phase is present in the M1-J1 core. Portions of the sequence are present in the Branson outcrops, but there are many gaps in this section because of lack of exposure. This sequence is not well defined on the Fischer plots, so observed facies changes within the cycles were particularly important. The boundary between sequence 4 and sequence 5 can be seen in the Branson section, where the base of sequence 5 occurs in the upper Cotter Dolomite, and it is truncated by the regional unconformity at the top of Lower Ordovician strata in Missouri. Much of the TST remains, but the HST is altogether absent in most areas. The TST of sequence 5 was further differentiated from the previous sequence by increasing subtidal fraction and decreasing quartz sand content. Overall, all sequences except sequence 5 are complete.

Although there are similarities among the accommodation plots of the studied sections, there are variations in the thickness and the number of meter-scale cycles they comprise (Figs. 9, 10). There is a general increase in both the sequence thickness and the number of cycles per sequence in a south-southwestward direction, away from the Ozark Dome. Sequence 2, for example, is thicker in the southernmost cores H-13 and 66W84 (85 m and 55 m, respectively). The same sequence in the northern drill cores M1-J1 and NS-1 measures 25 m and 45 m. The number of cycles per sequence in DS2 also decreases in a northward direction, from 35 cycles in H-13 to 16 in M1-J1. The decrease in sequence thickness and number of cycles in a northward direction is likely a consequence of longer emergence times for strata higher on the platform. Many cycles were probably eroded or never deposited, whereas to the south, cycle thickness and numbers gradually increase toward the depocenter in the Arkoma Basin.

Regional processes controlling cycle production probably accounted for the similarity of plots from the widely spaced sections in the study area.

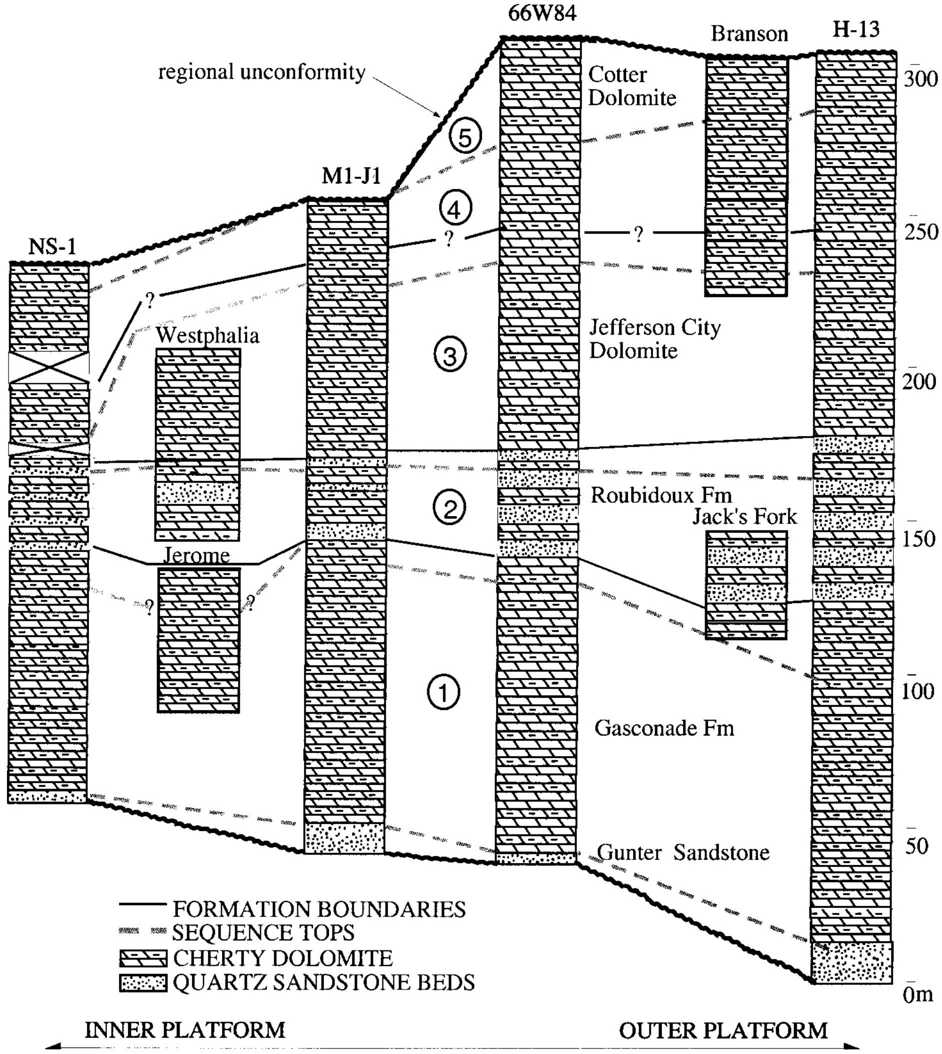

FIG. 10.—Correlation of vertical sections. The individual sections are arranged from the inner platform (which is basically northward) to the outer platform (southward). Cores H-13 and 66W84 are continuous through the entire Lower Ordovician but the other cores are not continuous. Several short outcrop sections from four locations in southern Missouri (Jerome, Westphalia, Jack's Fork, and Branson) are included. Sequence tops and formation boundaries (the latter defined by the Missouri Division of Geology and Land Survey on the cores used in this study) are shown. For detailed measured sections and cores, see Appendix in Overstreet (2000).

Eustatic sea-level fluctuation seems to be the most plausible explanation for the correlatable cyclicity in the Missouri Ozarks because it has been shown to account for intrabasinal correlation of accommodation events and the widespread nature of cyclic shallow-water carbonates of the same age in other areas (e.g., Montañez and Read 1992). This inference is supported by sedimentological evidence. Long-term sea-level rises on Fischer plots are defined by stacks of thicker subtidal-dominated cycles characterized by burrowed mudstones, thrombolitic facies, and peloidal wackestones. However, relative sea-level falls on Fischer plots are defined platformwide by thinner, intertidal- to supratidal-dominated cycles with chalcedonic chert nodules and relict evaporite structures.

Interbasinal Correlation

Biostratigraphy.—The correlation of Ozarks strata with other Lower Ordovician basins was based on published conodont and trilobite biostratigraphy (Fig. 11). Although the conodont and trilobite biostratigraphy in the Ozarks lacks high resolution, it is sufficient to establish the relative age of the strata and attempt to correlate the strata interbasinally. The lowest occurrence of trilobites above the Eminence Dolomite (Upper Cambrian) is a species of *Hystricurus*, which is probably *H. politus*, and a species similar to *H. millardensis* from Utah (Ross 1951; Hintze 1952; Stinchcomb 1978). Both faunas are characteristic of zone B of Ross (1951), and the *Symphysurina* Zone recognized in various regions. The *Symphysurina* Zone overlies the lowest Ordovician *Missisquoia* trilobite zone in many areas. The *Symphysurina* Zone trilobites occur 0–85 feet (0–27 meters) above the Gunter Sandstone Member of the Gasconade Formation (Stinchcomb 1978). Stitt (1971) defined the base of the *Symphysurina* Zone from two locations in the Arbuckle Mountains of Oklahoma as approximately 30 feet (10 meters) above the base of the McKenzie Hill Limestone. Higher up the stratigraphic sequence in the Arbuckles, Loch (1995) used trilobite faunas in the Kindblade Formation to redefine the Jeffersonian Stage, which correlates with the *Hintzeia celsaora* and *Protopliomerella contracta* zones of Ross et al. (1997). These zones can be correlated with the Jefferson City Dolomite in southern Missouri.

The Ibexian Series has been subdivided on the basis of ten conodont zones and one faunal interval defined in Ross et al. (1997). Eight of these units are within the Lower Ordovician part of the Ibexian, following the recent standardization of the base of the Ordovician (Cooper et al. 2001). With the exception of the uppermost *Reutterodus andinus* Zone, species of seven of these intervals are recognized in the Missouri strata. Species of the *Cordylodus proavus* Zone have been found in the uppermost Eminence Dolomite (Fig. 11). These conodont zones are also recognized in the Arbuckles (Derby et al. 1991; see Fig. 11). In addition, the Low Diversity Interval (between the *Rossodus manitouensis* and *Macerodus dianae* zones) occurs in both regions; in the Cool Creek Formation of the Arbuckles and in the uppermost part of the Gasconade

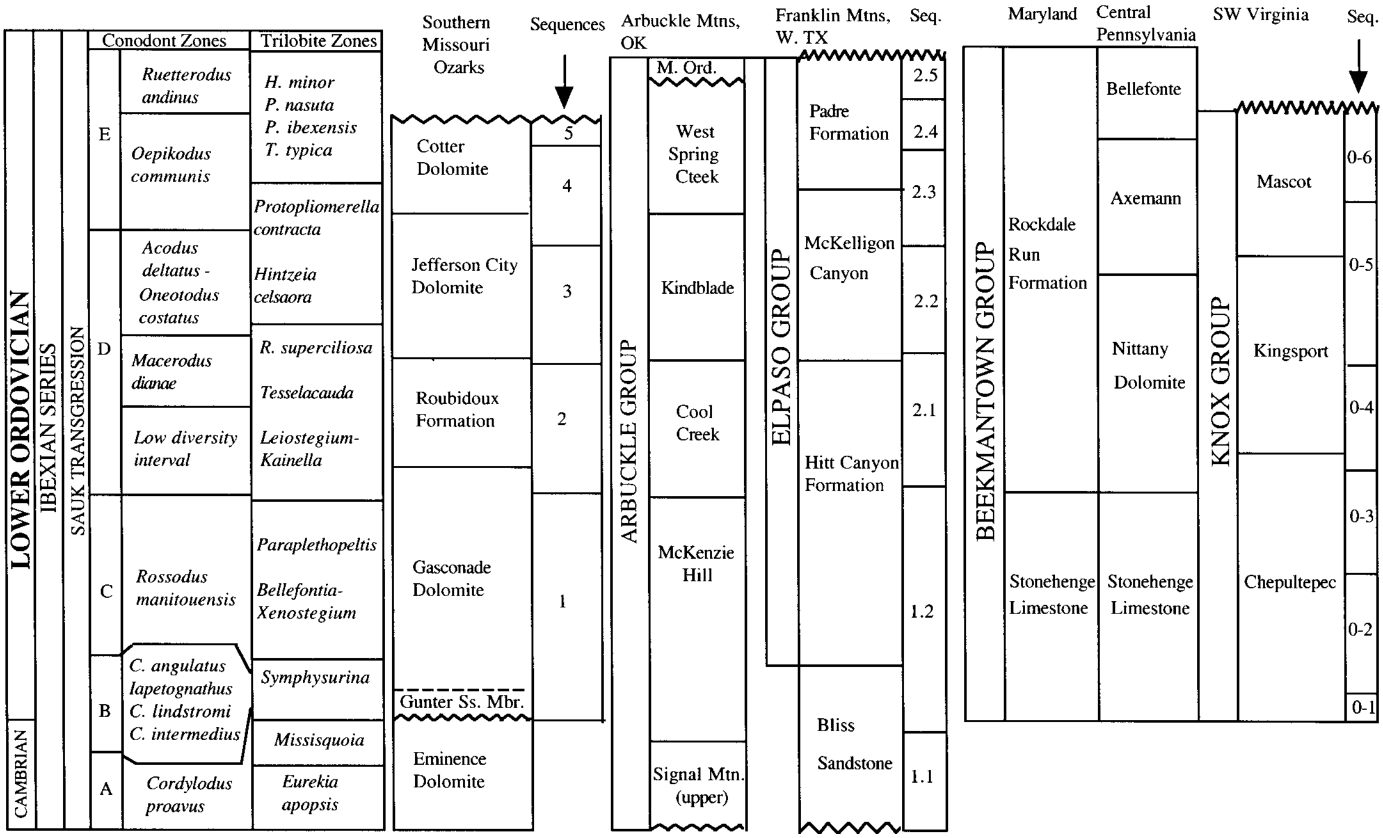

FIG. 11.—Correlation diagram of the Lower Ordovician of southern Missouri, the Arbuckle Group of Oklahoma, the El Paso Group of western Texas, and the Beekmantown and Knox groups in the Appalachians. Third-order sequence boundary ages and sequences numbers in the Arbuckle Mountains, the Franklin Mountains, and the Appalachians are from Read and Goldhammer (1988), Montañez and Read (1992), and Goldhammer et al. (1993). The *Symphysurina* trilobite zone was based on biostratigraphic interpretation in the Gasconade Formation by Stinchcomb (1978), in the Appalachians by Brezinski et al. (1999), and in the Arbuckles by Stitt (1971). Conodont biostratigraphy is from Ethington and Clark (1971), Brand (1976), Fagerlin (1980), Mills (1980), Repetski (1982, 1988), Ross et al. (1982), Ross et al. (1997), Ethington and Repetski (1984), Derby et al. (1991), Brezinski et al. (1999), Repetski et al. (1998), and Repetski et al. (2000).

Formation and lower part of the Roubidoux Formation in the Ozarks. We have also attempted to correlate the Lower Ordovician Ozarks rocks to the El Paso Group in the Franklin Mountains of western Texas (Hayes and Cone 1975). Ross et al. (1982) and Repetski (1982, 1988) identified conodont taxa of the *Rossodus manitouensis* Zone and younger zones in that succession. For example, the lower sandy member of the Hitt Canyon Formation contains species from the *R. manitouensis* Zone, whereas the base of the *Oepikodus communis* Zone is within the McKelligon Canyon Formation.

The Ozarks strata were also correlated with the Beekmantown and Upper Knox groups in the Appalachians (Fig. 11). The *Symphysurina* trilobite zone is recognized in the Stonehenge Limestone in western Maryland (Brezinski et al. 1999). Conodont zones are also recognized in central Pennsylvania, southwestern Virginia, and Maryland. The conodont *Cordylodus angulatus* (Fauna B of Ethington and Clark 1971) occurs both in the lower part of the Stonehenge Limestone of the central Appalachians and in the lowest Gasconade Formation of the midcontinent. Conodonts typical of the *Rossodus manitouensis*, *Macerodus dianae*, *Oneotodus costatus–Acodus deltatus*, and *Oepikodus communis* zones follow the *Cordylodus angulatus* Zone. Typically, *C. angulatus* ranges from the base of its eponymous zone through much of the *R. manitouensis* Zone. The Low Diversity Interval that is common to Lower Ordovician strata in both the Ozarks (uppermost Gasconade Formation and lower Roubidoux Formation) and Arbuckle Mountains (Cool Creek Formation) has been recognized in the Appalachians. It is found in the lower Rockdale Run Formation in western Maryland, the lower Nittany Dolomite in central Pennsylvania, and the uppermost Chepultepec to lower Kingsport formations in southwestern Virginia.

Cycles.—Biostratigraphic correlation between Ozarks strata and equivalent strata from the Arbuckles, the Franklin Mountains, and the Appalachians was sufficiently precise for comparison of the accommodation plots from these regions. In the Arbuckles and the Franklin Mountains, Goldhammer et al. (1993) derived two third-order sequences, 2.2 and 2.3 (Figs. 11, 12) from the stratigraphic interpretation of the cyclic strata. Sequence 2.2 is found mostly in the Kindblade Formation of the Arbuckles, and in the McKelligon Canyon Formation (upper part of the *Acodus deltatus–Oneotodus costatus* Zone) in the Franklin Mountains. This sequence appears to be equivalent to the Ozarks sequence 3, which occupies most of the Jefferson City Dolomite because the steep negative HST and boundary zone of 2.2 is similar to the HST of sequence 3 from the Ozarks. Sequence 2.3 occurs in the uppermost part of the Kindblade Formation, and in the upper McKelligon Canyon Formation, and the lower sandy member of the Padre Formation. This sequence appears to correlate with Ozarks sequence 4, which occurs in the uppermost Jefferson City and Cotter dolomites.

Fischer plots constructed from the Lower Ordovician strata of the Appalachians in southwestern Virginia and central Pennsylvania (Read and Goldhammer 1988; Montañez and Read 1992) were compared with equivalent Lower Ordovician strata in the Missouri Ozarks (Fig. 12). Appalachian sequences 0–2 and 0–3 appear to be equivalent with sequence 1 of the Ozarks (Gasconade Formation), and 0–4 is likely equivalent to Ozarks sequence 2 (upper Gasconade and Roubidoux formations). Sequences 0–5

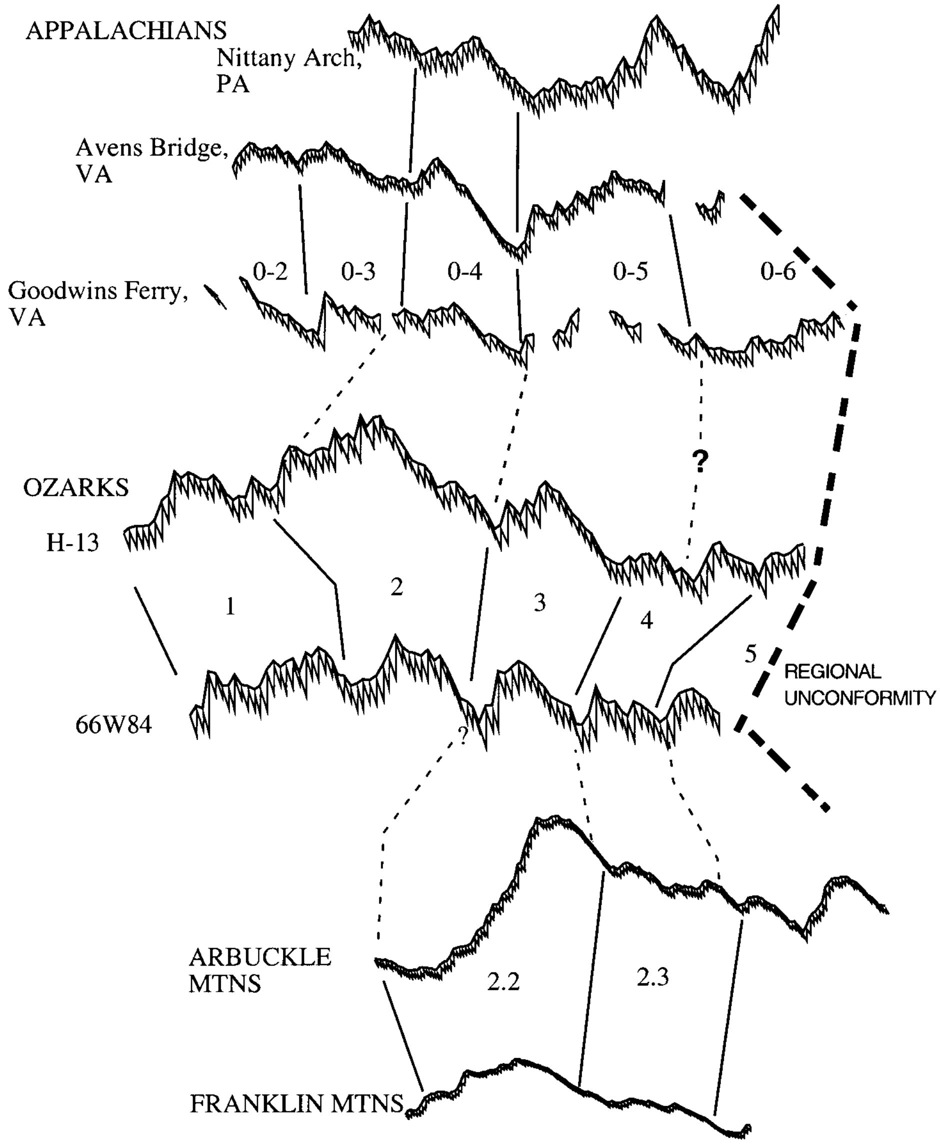

FIG. 12.—Correlation of Fischer plots in Lower Ordovician basins. See caption of Figure 9 for the criteria used for correlation of plots. Solid lines represent the third-order sequences that are defined for each region, and dashed lines connecting the plots are correlation lines connecting sequence tops between the regions. The Fischer plots from Appalachian sections are from Read and Goldhammer (1988) and Montañez and Read (1992), and the plots from the Arbuckle and Franklin Mountains are taken from Goldhammer et al. (1993).

and 0–6 correspond to the time interval represented by sequences 3–5, but the sequence boundaries do not correlate. Sequence 0–5 corresponds to the sequence 3 and the lower part of sequence 4, whereas sequence 0–6 appears correlative with the upper part of sequence 4 and sequence 5. The tops of sequence 0–6 and sequence 5, however, are truncated by regional unconformities. Tectonic and paleogeographic differences between the basins probably account for the smaller-scale differences between the accommodation plots.

Depositional Pattern

The Ibexian Series in North America was deposited toward the end of the Sauk transgression and is dominated by dolomites and limestones, with isolated sandstone deposition. Eustatic sea-level fluctuations controlled sedimentation, although differences in the thickness of coeval sedimentary sequences in different parts of the continent are due to detailed interaction of other factors such as differential subsidence, uplift, and proximity to depocenters. Much of the craton lay just south of the paleoequator, and the warm sea teemed with plant and animal life.

The warm climate favored widespread deposition of limestones over much of the platform and evaporites in some basins. In areas near regional highs, such as the Ozark Dome, that were far from depocenters, and on the inner platform, large-scale diagenesis resulted in the dolomitization of most of these sediments. In southern Missouri and the Appalachians, for example, there is evidence for early dolomitization, and the association of dolomite with silicified evaporite nodules, chicken-wire texture, mud-cracked laminites, and peloidal wackestones is indicative of initial dolomitization in a sabkha setting (Folk and Pittman 1971; Stinchcomb 1978; Charpentier 1984; Montañez and Read 1992; He et al. 1997). Our observation of chalcedonic chert nodules with chickenwire texture, halite hopper molds, and ghosts of gypsum laths in the Jefferson City and Cotter dolomites (Fig. 5) are consistent with extensive evaporite deposition in these units. The inferred presence of evaporites in the Ordovician section represent a significant source of sulfur and hypersaline fluids, which may have implications for Mississippi Valley-type sulfide mineralization in southeast Missouri (see Gregg and Shelton 1989). Br/Cl ratios of included fluids in ore minerals and associated dolomite cements from the underlying Cambrian section indicate the presence of seawater-derived brines evaporated to beyond halite precipitation (Kendrick et al. 2002). The underlying Gasconade and Roubidoux formations, in contrast, rarely include chalcedonic chert nodules or evidence of evaporite growth (Stinchcomb 1978). Sandstone beds at the base of the Gasconade (Gunther Member) and the Roubidoux indicate brief periods of subaerial erosion and beach conditions (Unklesbay and Vineyard 1992).

Secondary dolomitization in the Missouri Ozarks resulted in the formation of dissolution features, including stylolites, sinkholes, and caves. Although diagenesis resulted in poor preservation of fossils in Missouri and other areas, trilobites, conodonts, molluscs, and graptolites have been recovered from several horizons. Biostratigraphic zones are, however, based on trilobites and conodonts (Ross et al. 1997).

The stacking pattern of meter-scale, upward-shoaling cycles in the accommodation plots of the correlated basins appear to be similar. The deeper water cycles (e.g., our type II subtidal and open marine cycles of Montañez and Read 1992) are thicker and represent times of sea-level rise. They typically stack together and represent steep (positive) slopes on the Fischer plot. On the other hand, shallower water facies are thinner, represent times of sea level fall, and occur as shallow (negative) Fischer plot slopes stacked together. Most cycles are capped by tidal-flat laminites, and some of them contain quartz sand. Regional tectonic and autocyclic controls affect the thickness and number of cycles because they vary in the different basins. In southern Missouri, for example, sequence thickness and the number of cycles per sequence increase generally in a south-southeastward direction, toward the depocenter (Fig. 10).

Vertically, there is a shift to cycles dominated by shallow peritidal facies in younger sequences. Our study revealed a dominance of shallower-water cycles in sequences 4 and 5 from the upper Jefferson City and Cotter dolomites, whereas deeper-water cycles are more common in sequence 2. A somewhat similar trend occurs in the Appalachians, where stacks of restricted cycles dominate the upper part of sequence 0–5 and sequence 0–6; stacks of open marine cycles are more common in the lower sequences (Montañez and Read 1992). As the epeiric sea retreated during the later part of Ibexian time, HST facies predominated and the warm climate led to hypersaline conditions in restricted basins.

CONCLUSIONS

Two Major meter-scale cycle types (type I, type II) occur in the Lower Ordovician strata of southern Missouri. Type I cycles are relatively thin and are composed mostly of peritidal facies. By contrast, type II cycles are thicker and are dominated by subtidal facies. Type I cycles, which are distinguished by a higher quartz sand content and more extensive subaerial exposure and occasional evidence for evaporites at cycle tops, more commonly dominate the Roubidoux Formation, the Jefferson City Dolomite, and the Cotter Dolomite. The Roubidoux Formation experienced extensive mixed carbonate–siliciclastic sedimentation. Fischer plots from several widely spaced locations in the Lower Ordovician of the Missouri Ozarks reveal five correlative third-order cycles. The similarity of the plots suggests a eustatic control on cycle formation in the basin.

Interbasinal correlation, based on biostratigraphy and accommodation plots, was attempted between the Missouri strata and the Arbuckle Mountains of Oklahoma, the Franklin Mountains of Texas, and the Beekmantown and Upper Knox groups of central Pennsylvania and southwestern Virginia. Biostratigraphic constraints provided a good control for correlating the accommodation plots between the basins. Stacking patterns of meter-scale cycles are generally similar, and there is a predominance of shallower-water facies and hypersaline conditions as the epeiric sea retreated toward the end of the Early Ordovician. This resulted in precipitation of voluminous evaporite minerals, which may have played a role in regional sulfide mineralization.

ACKNOWLEDGMENTS

We would like to thank the Missouri Department of Natural Resources, Division of Geology and Land Survey, Rolla, for the use of their core library and facilities. The assistance of James Palmer in selecting cores is greatly appreciated. Ray Ethington aided greatly by selecting the surface sections that were studied and helped us with the biostratigraphic interpretations. The manuscript benefited greatly from critical reviews by journal reviewers Beverly Saylor, John Repetski, Mark Harris, associate editor David Osleger, and editor David Budd.

REFERENCES

Brand, U., 1976, Lower Ordovician conodonts from the Kindblade Formation, Arbuckle Mountains, Oklahoma [Unpublished M.S. thesis]: University of Missouri–Columbia, 112 p.

Brezinski, D.K., Repetski, J.E., and Taylor, J.F., 1999, Stratigraphic and paleontologic record of the Sauk III regression in the central Appalachians, *in* Santucci, V.L., and McClelland, L., eds., National Park Service Paleontological Research, Technical Report NPS/ NRGRD/ GRDTR-99/03, 32 p.

Carver, R.E., 1961, Petrology and paleogeography of the Roubidoux Formation (Ordovician) of Missouri [Unpublished Ph.D. Dissertation]: University of Missouri, 168 p.

Charpentier, R.R., 1984, Conodonts through time and space: studies in conodont provincialism, *in* Clark, D.L., ed., Conodont Biofacies and Provincialism: Geological Society of America, Special Paper 196, p. 11–32.

Cooper, R.A., Nowlan, G.S., and Williams, S.H., 2001, Global stratotype section and point for base of the Ordovician System: Episodes, v. 24, p. 19–28.

Demicco, R.V., 1985, Platform and off platform carbonates of the Upper Cambrian of western Maryland, U.S.A.: Sedimentology, v. 32, p. 1–22.

Derby, J.R., Bauer, J.A., Creath, W.B., Dresbach, R.I., Ethington, R.L., Loch, J.D., Stitt, J.H., McHargue, T.R., Miller, J.F., Miller, M.A., Repetski, J.E., Sweet, W.C., Taylor, J.F., and Williams, M., 1991, Biostratigraphy of the Timbered Hills, Arbuckle, and Simpson Groups, Cambrian and Ordovician, Oklahoma: a review of correlation tools and techniques available to the explorationist, *in* Johnson, K.S., ed., Late Cambrian–Ordovician Geology of the Southern Midcontinent: Oklahoma Geological Survey, Circular 92, p. 15–41.

Ethington, R.L., and Clark, D.L., 1971, Lower Ordovician conodonts in North America, *in* Sweet, W.C., and Bergström, S.M., eds., Conodont Biostratigraphy: Geological Society of America, Memoir 127, p. 63–82.

Ethington, R.L., and Repetski, J.E., 1984, Paleogeographic distribution of Early Ordovician conodonts in central and western United States, *in* Clark, D.L., ed., Conodont Biofacies and Provincialism: Geological Society of America, Special Paper 196, p. 89–101.

Fagerlin, S.C., 1980, Lower Ordovician conodonts from the Jefferson City Formation of Missouri [Unpublished Ph.D. dissertation]: University of Missouri–Columbia, 105 p.

Folk, R.L., and Pittman, J.S., 1971, Length-slow chalcedony: a new testament for vanished evaporites: Journal of Sedimentary Petrology, v. 41, p. 1045–1058.

Gianniny, G.L., and Simo, J.A., 1996, Implications of unfilled accommodation space for sequence stratigraphy on mixed carbonate–siliciclastic platforms; an example from the lower Desmoinesian (Middle Pennsylvanian), southwest Paradox Basin, Utah, *in* Longman, M.W., and Sonnenfeld, M.D., eds., Paleozoic Systems of the Rocky Mountain Region: SEPM, Rocky Mountain Section, p. 213–234.

Goldhammer, R.K., Lehman, 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.

Gregg, J.M., and Shelton, K.L., 1989, Geochemical and petrographic evidence for fluid sources and compositions during southeast Missouri lead-zinc mineralization: A review: Carbonates and Evaporites, v. 4, p. 153–175.

Hayes, P.T., and Cone, G.C., 1975, Cambrian and Ordovician rocks of southern Arizona and New Mexico and westernmost Texas: U.S. Geological Survey, Professional Paper 873, 98 p.

He, Z., 1995, Sedimentary facies and variations of stable isotope composition of Upper Cambrian to Lower Ordovician strata in southern Missouri: implications for the origin of MVT deposits, and the geochemical and hydrological features of regional ore-forming fluids [Unpublished Ph.D. dissertation]: University of Missouri–Rolla, 124 p.

He, Z., Gregg, J.M., Shelton, K.L., and Palmer, J.R., 1997, Sedimentary facies control of fluid flow and mineralization in Cambro–Ordovician strata, southern Missouri, *in* Montañez, I.P., Gregg, J.M., and Shelton, K.L., eds., Basin-Wide Diagenetic Patterns; Integrated Petrologic, Geochemical, and Hydrologic Considerations: SEPM, Special Publication 57, p. 81–99.

Hintze, L.F., 1952, Lower Ordovician trilobites from western Utah and eastern Nevada: Utah Geological and Mineralogical Survey, Bulletin 48, 259 p.

Kendrick, M.A., Burgess, R., Leach, D., and Patrick, R.A.D., 2002, Hydrothermal fluid origins in Mississippi Valley-type ore districts: Combined noble gas (He, Ar, Kr) and halogen (Cl, Br, I) analysis of fluid inclusions from the Illinois–Kentucky Fluorpsar District, Viburnum Trend, and Tri-State Districts, Midcontinent United States: Economic Geology, v. 97, p. 453–469.

Loch, J.D., 1995, An affirmation of the Jeffersonian Stage (Ibexian) of North America and a proposed boundary stratotype, *in* Cooper, J.D., Droser, M.L., and Finney, S.C., eds., Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System, SEPM, Pacific Section, p. 45–48.

Mills, W.H., 1980, Conodont biostratigraphy of the upper West Spring Creek Formation, Arbuckle Mountains, Oklahoma [Unpublished M.S. thesis]: University of Missouri–Columbia, 83 p.

Montañez, I.P., and Read, J.F., 1992, Eustatic control on early dolomitization of cyclic peritidal carbonates: Evidence from the Early Ordovician Upper Knox Group, Appalachians: Geological Society of America, Bulletin, v. 104, p. 872–886.

Myers, K.J., and Milton, N.J., 1996, Concepts and principles of sequence stratigraphy, *in* Emery, D.D., and Myers, K.J., eds., Sequence Stratigraphy: Oxford, U.K., Blackwell Scientific Publications, p. 11–41.

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

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

OVERSTREET, R.B., 2000, Sequence stratigraphy and depositional facies of Lower Ordovician cyclic carbonates, southern Missouri [Unpublished M.S. thesis]: University of Missouri–Rolla, 68 p.

READ, J.F., AND GOLDHAMMER, R.K., 1988, Use of Fischer plots to define third-order sea-level curves in Ordovician peritidal cyclic carbonates, Appalachians: Geology, v. 16, p. 895–899.

READ, J.F., KOERSCHNER, W.F., III, OSLEGER, D.A., BOLLINGER, G.A., AND CORUH, C., 1991, Field and modeling studies of Cambrian carbonate cycles, Virginia Appalachians—Reply: Journal of Sedimentary Petrology, v. 61, p. 647–652.

REPETSKI, J.E., 1982, Conodonts from El Paso Group (Lower Ordovician) of westernmost Texas and southern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 40, p. 1–121.

REPETSKI, J.E., 1988, Ordovician conodonts from the Bliss Sandstone in its type area, west Texas: New Mexico Bureau of Mines and Mineral Resources, Memoir 44, p. 123–127.

REPETSKI, J.E., LOCH, J.D., AND ETHINGTON, R.E., 1998, Conodonts and biostratigraphy of the Lower Ordovician Roubidoux Formation in and near the Ozark National Scenic Riverways, southeastern Missouri, *in* Santucci, V.L., and McClelland, L., eds., National Park Service Paleontological Research, Technical Report NPS/ NRGRD/GRDTR-98/01, p. 109–115.

REPETSKI, J.E., LOCH, J.D., ETHINGTON, R.E., AND DRESBACH, R.I., 2000, A preliminary reevaluation of the stratigraphy of the Roubidoux Formation of Missouri and correlative Lower Ordovician Units in the southern Midcontinent: Oklahoma Geological Survey, Circular 101, p. 103–106.

ROSS, R.J., JR., 1951, Stratigraphy of the Garden City Formation in northeastern Utah and its trilobite faunas: Yale University, Peabody Museum of Natural History, Bulletin 6, 161 p.

ROSS, R.J., JR., ET AL., 1982, Ordovician System in the United States of America: International Union of Geological Sciences, Publication 12, 73 p., with correlation chart.

ROSS, R.J., JR., HINTZE, L.F., ETHINGTON, R.L., MILLER, J.F., TAYLOR, M.E., REPETSKI, J.E., SPRINKLE, J., AND GUENSBURG, T.E., 1997, The Ibexian, Lowermost Ordovician Series in the North American Ordovician: U.S. Geological Survey, Professional Paper 1579, p. 1–50.

SADLER P.M., OSLEGER, D., AND MONTAÑEZ, I.P., 1993, On the labeling, length, and objective basis of Fischer plots: Journal of Sedimentary Petrology, v. 63, p. 360–368.

STINCHCOMB, L.B., 1978, The paleontology and biostratigraphy of the Lower Ordovician Gasconade Formation of Missouri [Unpublished Ph.D. dissertation]: University of Missouri–Rolla, 83 p.

STITT, J.H., 1971, Late Cambrian and earliest Ordovician trilobites, Timbered Hill and Lower Arbuckle groups, western Arbuckle Mountains, Murray County, Oklahoma: Oklahoma Geological Survey, Bulletin 110, 83 p.

THOMPSON, T.L., AND ROBERTSON, C.E., 1993, Guidebook to the geology along Interstate 44 (I-44) in Missouri: Missouri Department of Natural Resources, Division of Geology and Land Management, Report of Investigations 71 (Guidebook 23), 200 p.

UNKLESBAY, A.G., AND VINEYARD, J.D., 1992, Missouri Geology: Three Billion Years of Volcanoes, Seas, Sediments, and Erosion: Columbia, University of Missouri Press, 189 p.

Received 30 May 2002; accepted 20 November 2002.