SEQUENCE STRATIGRAPHY OF UPPER ORDOVICIAN AND LOWER SILURIAN STRATA OF THE CINCINNATI ARCH REGION

Carlton E. Brett and Thomas J. Algeo

Department of Geology
University of Cincinnati
Cincinnati, Ohio 45221-0013

INTRODUCTION

In recent years outcrop-based stratigraphic studies have undergone a paradigmatic shift from a primarily descriptive approach to a focus on understanding the architecture of sedimentary accumulations within a sequence stratigraphic context. This avenue of research has developed indirectly from seismic profiling of continental margin sediments and from the recognition of large, unconformity-bounded depositional wedges ("sequences") in these profiles. Originally, sequences were defined very broadly as large intervals of strata bounded by very major unconformities ("first-" or "second-order" cycles recording tens of millions of years; see Vail et al., 1991), such as the six classic "super sequences" of Sloss (1963). Seismic stratigraphers were able to refine correlations and demonstrate that these large-scale unconformity-bounded packages are subdivisible into smaller intervals representing approximately 0.5 to 3 million years, typically termed "third-order" sequences. Sequence stratigraphers also recognized distinctive phases of sequences ("systems tracts") as the product of sea-level oscillations translated in a biased way into the sedimentary record (Vail et al, 1977, 1991; Van Wagoner et al., 1988; Emery and Meyers, 1996). Subsequently, seismic stratigraphers working in the field recognized that third-order packages could frequently be subdivided into smaller scale, "fourth-", "fifth-", and even "sixth-", "seventh-" and "eighth-order" cycles.

The purpose of this contribution is to examine and discuss classic Upper Ordovician to Silurian strata of the eastern Cincinnati Arch region (Fig. 1) in the context of sequence stratigraphy. We believe that the application of sequence analysis to this classic stratigraphic succession is providing critical new insights into the depositional dynamics and history of this region. In turn, these well-exposed strata may potentially help to refine models and approaches to stratigraphy that will aid in interpretation of other areas.

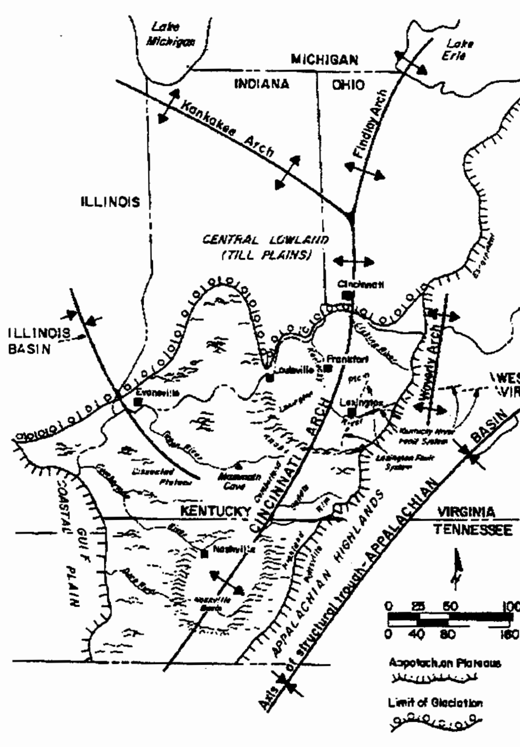

Figure 1. Geomorphic and structural map of the Cincinnati Arch region and adjacent geomorphic provinces. Box outlines the present study area in northern Kentucky. From Ettensohn (1992a).

GEOLOGIC SETTING

Sediments of the Upper Ordovician-Lower Silurian of southern Ohio and northern Kentucky accumulated in a shallow-marine subtropical setting about 20-25° south of the paleoequator (Scotese, 1990; Ettensohn, 1992a,b; Fig. 2). This setting was well situated to be affected by subtropical hurricanes and there is abundant evidence for storm deposition (tempestites) in the Cincinnatian Series.

During the late Middle Ordovician, eastern Laurentia underwent collisions with island arc to microcontinental terranes, first (during the early Blackriveran) in the southern Appalachian region where collision produced the Blountian highlands and later (during the late Shermanian) in the area of the New York Promontory where the Hamburg Klippe (SE Pennsylvania) and Taconic allochthons were emplaced as accretionary wedges onto the Laurentian margin forming the Taconian highlands (Ettensohn, 1992c; Fig. 3). Most of the siliciclastic muds and silts of the Cincinnatian Series were probably derived from these upland areas to the east and northeast. A relatively small gap existed between the two upland region that might have served to funnel storms into the present-day Tristate region (Ohio-Kentucky-Indiana; Ettensohn, 1992b).

The Taconic foreland basin, a relatively narrow trough produced by thrust loading, extended southward from Quebec to

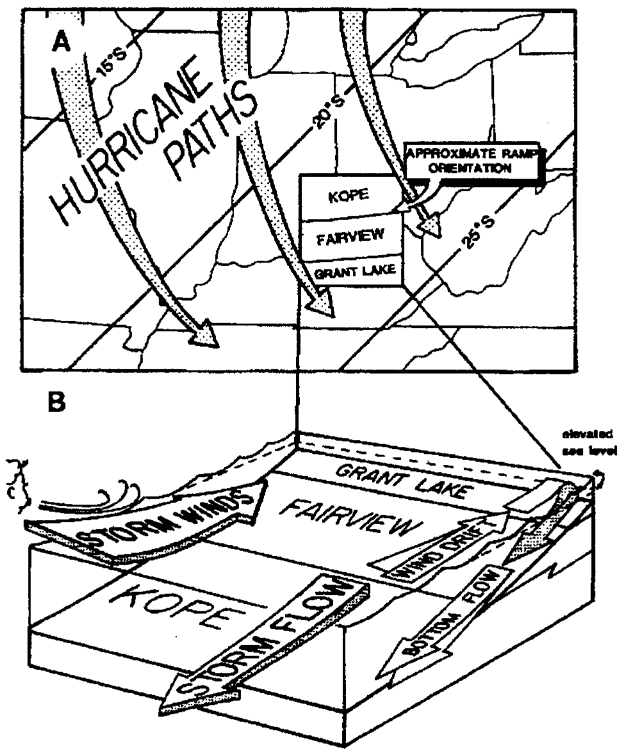

Figure 2. North-dipping ramp in the Ohio-Kentucky-Indiana area during the Late Ordovician. (A) Probable hurricane paths and approximate orientation of ramp dipping into Sebree Trough to north. (B) Inferred southward orientation of storm winds and northward flow of storm-generated gradient currents. Modified from Jennette and Pryor (1993).

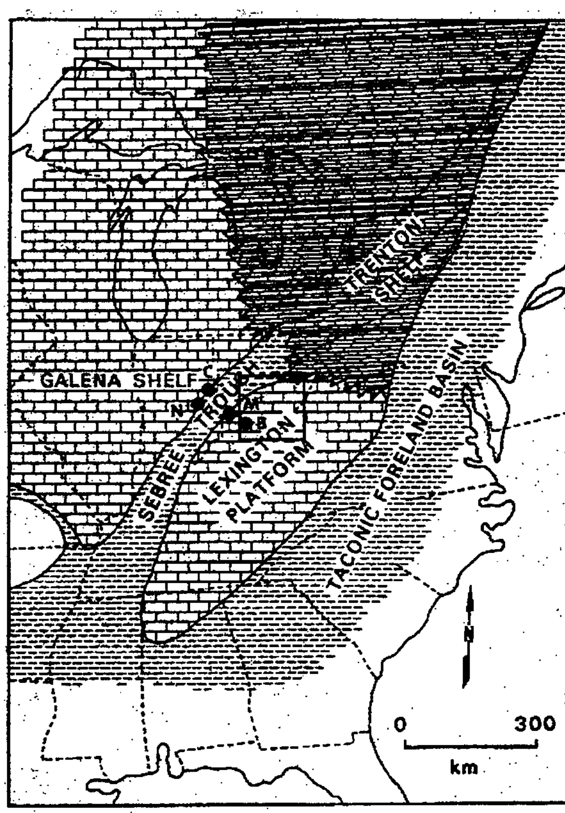

Figure 3. Major paleogeographic features of eastern Laurentia during early Late Ordovician (Edenian) time. The AA Highway, route of the present field trip, is located approximately along the line connecting points M to B. Note the position of the narrow Sebree Trough; the box indicates the area in which an embayment of the trough has been inferred in recent paleogeographic reconstructions (Ettensohn, 1999; in prep.). From Mitchell and Bergström (1991).

Alabama (Fig. 3). This area of active subsidence accumulated a thick wedge of siliciclastic sands, silts and muds during the Late Ordovician. These sediments commence with black shales (e.g., Utica and Antes shales) during late Mohawkian to early Cincinnatian times, and progress upward through thick turbiditic flysch (Martinsburg-Reedsville formations) by the Maysvillian. During late Cincinnatian (Richmondian) time sedimentation began to outstrip subsidence, resulting in upward shallowing and eventually, overfilling of the foreland basin. These shallow molasse-type facies are recorded in the upper Martinsburg, Bald Eagle-Oswego sandstones and Juniata- Queenston redbeds. The Queenston clastic wedge prograded westward with reddish marginal marine sediments reaching east-central Kentucky and Ohio by late Richmondian times.

During early Late Ordovician (Edenian) time, the Cincinnati Arch *per se* was not present in the Tristate region, rather a shallow carbonate platform (the Lexington Platform) existed to the southeast of Cincinnati, and a gentle ramp sloped to the northwest into a narrow elongated NE-SW-oriented basinal area, the Sebree Trough, (Mitchell and Bergström, 1991; Ettensohn, 1992c; Figs. 2-3). Hence, depositional strike in northern Kentucky-southern Ohio was also approximately NE-SW and regional dip was to the north. However, the more recent reconstructions of Ettensohn (1999) indicate the existence of an embayment in the trough, with a southeastern boundary that ran NW-SE roughly coincident with the present Ohio River valley between Cincinnati and Maysville. The Sebree Trough is of uncertain origin but is under close study by Mitchell et al. (1997) and Ettensohn (1999; in review). However, its abrupt appearance during early Edenian time coincided with a major pulse of Taconic orogenic activity and subsidence of the northern foreland basin in Pennsylvania and central New York. One possible interpretation is that the Lexington Platform represents a forebulge and the Sebree Trough as a backbulge basin (terminology of Quinlan and Beaumont, 1984; Beaumont et al., 1988). Alternatively, the trough may represent a branch of the Taconic foreland basin. Ettensohn (1992c, 1999, in review), in particular, has argued that Ordovician tectonic activity represents far-field tectonics. Stresses produced by Taconic thrust loading may have propagated long distances onto the Laurentian craton and produced renewed activity on old, deep-seated basement faults (Fig. 4). Subsurface study of the slightly older Black River and Trenton carbonates indicates that there are no major offsets as would be expected if basement faulting had been responsible for subsidence of the Sebree Trough. However, gentle flexural deformation may have occurred in association with these far-field stresses (Ettensohn, 1999, in review). The Sebree Trough was largely infilled with sediments by mid-Maysvillian time, but a slightly deeper area appears to have persisted until the end of Late Ordovician time (Fig. 5; Mitchell and Bergstrom 1991; Ettensohn, 1999). The orientations of the carbonate ramp and adjacent trough seem to have migrated somewhat through the remainder of Cincinnatian time from NE-SW to more nearly east-west (Hay, 1998).

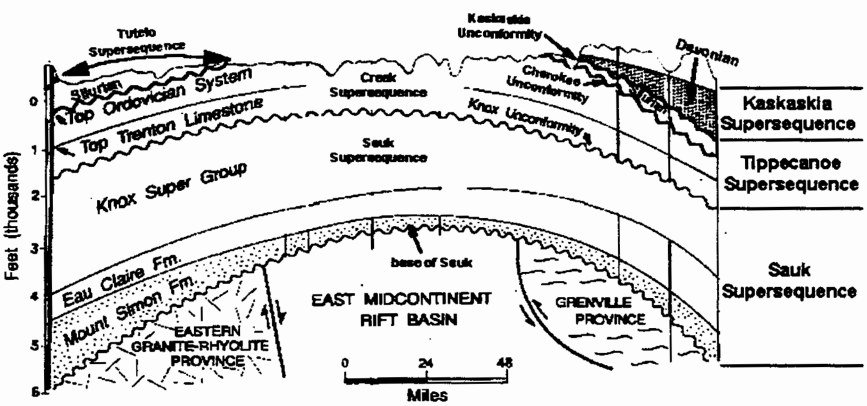

Figure 4. Major unconformities and Sloss sequences in the Ordovician and Silurian of the Cincinnati Arch. Note basement faults that may have reactivated during Ordovician Taconian Orogeny. Modified from Potter (1996).

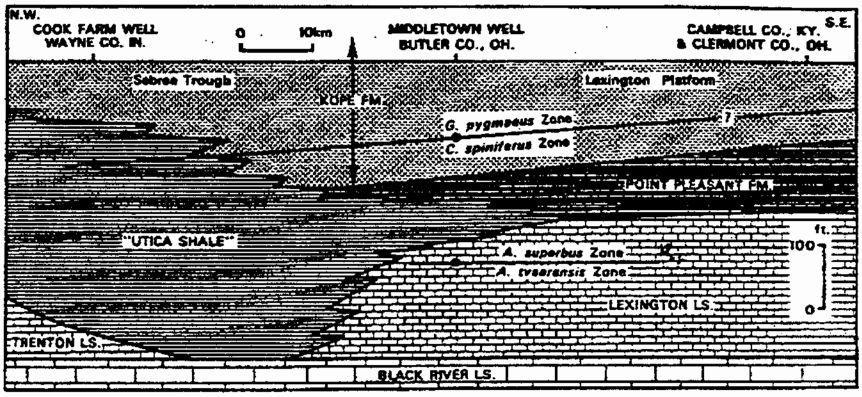

Figure 5. Regional cross-section of Middle-Upper Ordovician strata through south-central Ohio. Note Sebree Trough shale basin. From Mitchell and Bergstrom (1991).

During the latest Ordovician to early Silurian, a major sea-level lowstand, probably related to continental glaciation in North Africa, created the widespread withdrawal of seas from the Cincinnati area and created a major erosion surface. Transgression in the Early Silurian enabled deposition of marine siliciclastics and carbonates over the unconformity. During this interval, the region is typically considered to have been tectonically quiescent. However, a recent study (Ettensohn and Brett, 1998; Fig. 6) indicates that a late tectophase of the Taconic Orogeny may have taken place at this time. This spread a clastic wedge over much of the Appalachian Basin but appears to have had rather little influence in the study area in which Brassfield carbonates were deposited contemporaneously. During medial Silurian (latest Llandovery) time, there is some evidence for renewed tectonism, which produced renewed subsidence and a pulse of siliciclastics into the Appalachian basin. Locally, evidence for this is provided not only by thick shales and siltstones of the Crab Orchard-Estill formations, but also by development of regional angular unconformities (Fig. 7; Lukasik, 1988; Goodman and Brett, 1994; Ettensohn and Brett, 1998). Regional truncation of lower Silurian units in central Ohio and northward into the Hamilton, Ontario, area suggests that the Findlay-Algonquin Arch was uplifted during late Llandovery time. The affected area cuts obliquely across the position of the former Sebree Trough. This could be viewed as evidence of reactivation of older deep-seated structures related to basement faults, but it has also been interpreted as de-

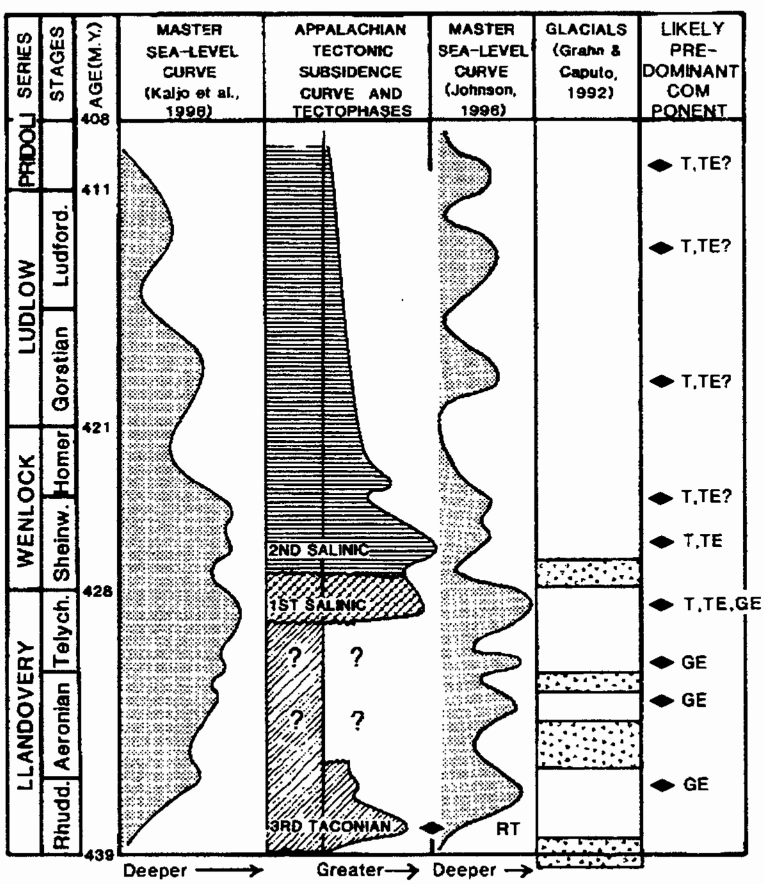

Figure 6. Taconian tectophases of Silurian Period. From Ettensohn and Brett (1998).

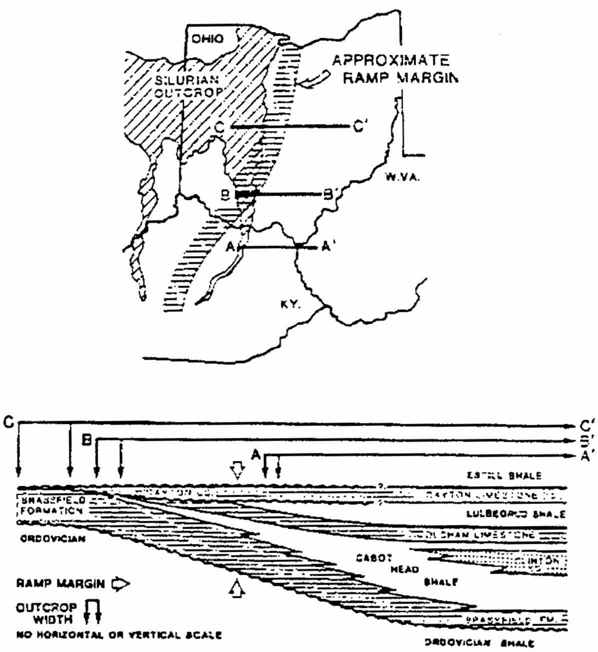

Figure 7. Correlation of Lower Silurian sequences from New York into Ohio. From Brett et al. (1990).

velopment of a forebulge related to thrust loading and subsidence in the adjacent Appalachian foreland basin. In a sense, this could be viewed as the origin of the Cincinnati Arch, although, in fact, the area of uplift was offset from the center of the present structural arch.

SEQUENCE STRATIGRAPHY OF UPPER ORDOVICIAN AND SILURIAN STRATA OF THE EASTERN CINCINNATI ARCH

Supersequences

At the largest scale, the rocks of the Cincinnati Arch region are subdivisible into great unconformity-bounded packages of the scale recognized long ago by Sloss (1963). These large-scale "supersequences" are bounded by major unconformities that are traceable widely over the North American craton and perhaps globally. The first such large-scale or "second-order" sequence embraces the entire Mohawkian (late Middle Ordovician) and Cincinnatian (Late Ordovician) series of rocks, totaling approximately 450-470 meters in thickness and encompassing deposits of about 15-20 million years (Holland and Patzkowski, 1997; Kolata et al., 1996; Potter, 1996). The lower boundary of this supersequence is the Knox Unconformity, a very widespread Middle Ordovician erosion surface that, in places, represents a hiatus of as much as 30 to 40 million years of non-deposition and erosion (Dennison and Head, 1975). This surface is nowhere exposed within the Cincinnati Arch region, although it is known in the subsurface from drill cores (Potter, 1996; Fig. 4).

At their top, the Upper Ordovician rocks are bounded by a second great unconformity, the Cherokee Unconformity (Dennison and Head, 1975). This unconformity is of global extent but of shorter duration (3-4 million years) than the Knox Unconformity, having removed only the uppermost Ordovician Gamachian Stage over most of North America. The Cherokee Unconformity is typically attributed to a major lowstand or drop in global sea level, probably of glacio-eustatic origin and related to coeval continental glaciation in North Africa. This unconformity is typically nearly planar in outcrop but may display minor relief. In southern Ohio and northern Kentucky, the unconformity is in places very sharply delineated at the top of Upper Ordovician shales of the Drakes Formation, a greenish to red mottled mudstone with abundant thin siltstone layers that appears to represent the distal feather edge of the Queenston clastic wedge. These variegated mudstones are sharply overlain by the Silurian Brassfield Dolostone, a massive orange weathering, cherty carbonate unit (Gordon and Ettensohn, 1984). Although the Cherokee Unconformity is typically nearly flat and featureless, it clearly truncates different units in various localities and is a regionally angular beveled surface.

Together the Knox and Cherokee unconformities bound a very large sequence set or "holostrome" commonly referred to as the Creek Megasequence of the Tippecanoe Supersequence (Fig. 4). The Silurian strata are typically assigned to the Tutelo Supersequence (formerly combined with Creek as the Tippecanoe Megasequence of Sloss, 1963). The top of the Silurian in eastern Kentucky and southern Ohio is defined by a second major "second-order" sequence boundary comprising actually a combination of two or more unconformities. The lower, or Wallbridge Unconformity, separates upper Lower to Middle Devonian (Emsian-Eifelian) deposits of the Kaskaskia Supersequence (Sloss, 1963; Dennison and Head, 1975) from Upper Silurian to Lower Devonian deposits. In most areas of the Midcontinent, a higher Taghanic unconformity that occurred during a late Middle Devonian sea-level drawdown oversteps the Wallbridge Unconformity, and Middle Devonian deposits are absent. Both unconformities appear to have a combination of tectonic and eustatic signatures in their formation.

Third-Order Sequence Stratigraphy of Upper Ordovician-Silurian Strata of Cincinnati Arch Region

Somewhat smaller scale, unconformity-bounded depositional sequences are present within Upper Ordovician and Silurian strata of the Cincinnati Arch region as well. These are comparable in duration (1 to 5 million years) to the "third-order" sequences recognized by seismic stratigraphers in many aspects. In particular, they are subdivisible into smaller sequences, parasequences, and systems tracts. Before discussing these stratigraphic packages in detail, the basic concepts of sequence stratigraphy will be reviewed briefly (Fig. 8).

Sequence Stratigraphic Concepts: Sequences are relatively conformable packages of strata bounded by unconformities formed during sea-level lowstands. Depending upon their topographic situation, sequence boundaries may be strongly erosional and display substantial erosional relief or nearly planar. It has been recognized for some time that larger scale sequences typically are overgeneralized and that most such sequences are composite sequences (Milton and Meyers, 1996). Such composite sequences can be subdivided into smaller scale sequences. Some of these are unconformity-bounded units that exhibit a pattern of relative deepening followed by shallowing ("sequences"), whereas others are bounded not by unconformities but by flooding surfaces and are distinctly asymmetrical units that mainly record shallowing ("parasequences," Vail et al., 1991).

Based partly upon the stacking patterns of parasequences or architecture of portions of sedimentary sequences, stratigraphers have been able to recognize distinct groupings of facies within sequences, referred to as systems tracts (Fig. 8). Briefly, these include lowstand (LST; or "shelf margin"), transgressive (TST), and highstand (HST) systems tracts. In some instances, sequence stratigraphers also recognize early highstand and regressive divisions of the HST. LSTs comprise a suite of facies that typically shallow (or prograde) and include non-marine channel fillings that may occur locally immediately above a sequence boundary or erosion surface. In deeper water areas turbidite fans are another potential expression of lowstand accumulation during times when sediments are flushed from shallow water areas into deeper water regions (Fig. 8).

The transgressive systems tract (TST) may show a sharply incised transgressive erosion surface at its base, a type of ravinement surface, when it overlies more marginal marine deposits of the lowstand systems tract. This transgressive surface reflects a rapid relative rise of sea level. In many cases, including most sequences discussed herein, the sequence boundary and transgressive surfaces are combined into a single erosion surface. The transgressive systems tract itself shows a deepening upward, retrogradational stacking pattern of smaller scale cycles or parasequences, and is bounded at its top by a surface of maximum flooding (Fig. 8). This surface, which may be very distinct in some sequences, represents a time of minimal sedimentation in offshore marine settings associated with rapid sea-level rise, drowning of coastlines, and sequestering of clastic sediments in nearshore estuarine and lagoonal depositional settings. Maximum flooding surfaces are typically marked by distinct but thin lag accumulations, phosphatic nodules, conodonts, or bones. Immediately underlying and overlying the maximum flooding surface is a thin, time-rich section referred to as a condensed section that represents strongly sediment-starved conditions at times of maximum deepening.

The highstand systems (HST) tract typically commences with deeper water deposits, such as dark shales, that sharply overlie the maximum flooding surface (Fig. 8). The highstand systems tract may show a progradational succession of smaller parasequences, i.e., an overall shallowing upward pattern. Sometimes the HST can be subdivided into an early aggradational phase, in which little change in relative sea-level elevation is evident, and a late highstand or regressive phase, in which progradational stacking of parasequences reflects an overall upward shallowing. In some cases, a thin condensed lag bed may occur at the base of the boundary between these two HST phases. The highstand systems tract ultimately exhibits an overall shallowing and may be truncated at its top by the next major sequence boundary.

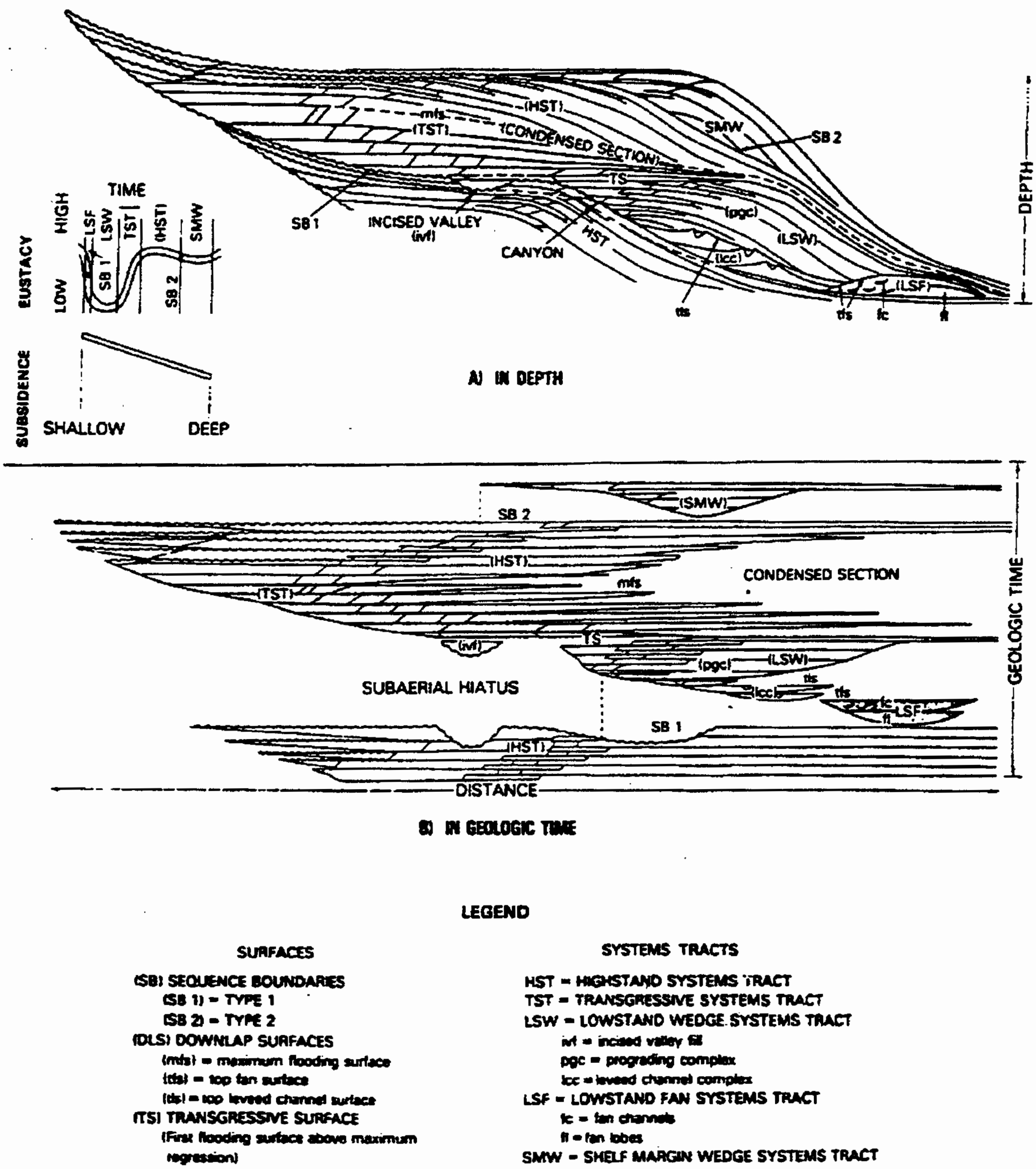

Figure 8. SLUG diagram of sequence stratigraphy. Upper figure shows actual thicknesses of units; lower figure gives time stratigraphic section. From Haq et al. (1987).

Third-Order Sequences of the Upper Ordovician: Holland (1993, 1998) and Holland and Patzkowsky (1996) have defined a series of six sequences in the Upper Ordovician (Cincinnatian Series), comprising the Edenian, Maysvillian, and Richmondian stages (Fig. 9). Sequence boundaries for these units are relatively subtle and occur at the bases of thin phosphatic, skeletal-rich limestones that are interpreted to be transgressive systems tracts. The majority of these sequences comprise thick coarsening/shallowing -upward successions of mudstone and calcisiltite and, toward the top, closely bundled skeletal packstones or grainstones, wavy-bedded packstones and wackestones and, in some cases, bioturbated to laminated peritidal facies. These represent late highstand or regressive systems tracts separated by relatively planar and subtle unconformities. No lowstand deposits were identified and, as such, sequence boundaries and transgressive surfaces appear to be combined.

Five of the six sequences identified by Holland are exposed in the eastern Cincinnati Arch region. The sixth has been removed by pre-Silurian erosion at the Cherokee Unconformity. The lowest two of the six Cincinnatian sequences, the Edenian-age Kope Formation (sequence C1) and the lower Maysvillian-age Fairview Formation (sequence C2) were originally combined in a single very long-ranging sequence (Holland, 1993); however, with subsequent study these were subdivided (Holland and Patzkowski, 1996). Units equivalent to Sequence C1 and the base of Sequence C2 will be discussed in detail in this paper and will be a primary focus of the present field excursion.

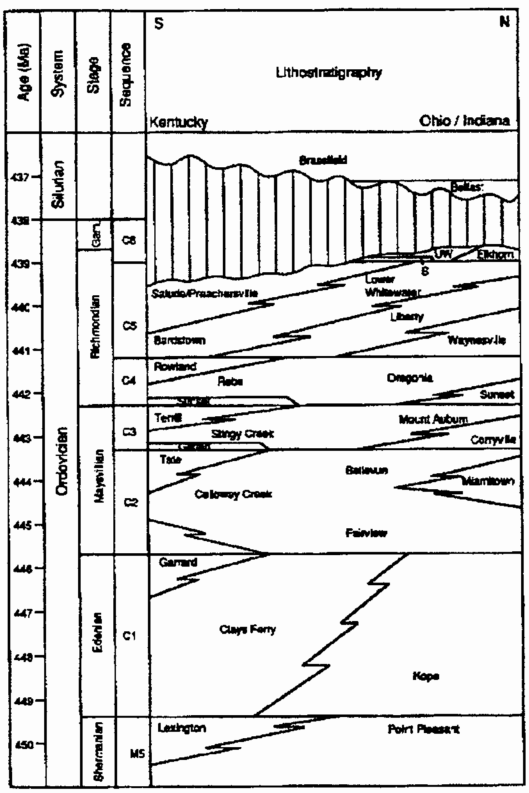

Figure 9. Third-order sequences in the Upper Ordovician Cincinnatian Series (from Holland etl al., 1997).

Sequence C1 is the thickest and longest of Holland's Cincinnatian sequences (Fig. 9), comprising some 70-75 m of section and representing the entire Edenian Stage (ca. 4 million years in duration). This sequence commenced with an abrupt flooding surface near the base of the Kope Shale. This abrupt deepening above Point Pleasant grainstones apparently occurred within the *Climacograptus spiniferus* Zone (Mitchell and Bergstrom, 1991); as such it coincided with a major pulse of deepening in the Taconic Basin, i.e., the lower part of the Indian Castle Shale or the Utica Shale proper. Dark Utica-type shales were deposited coevally in the Sebree Trough also, where they overstep the latest Shermanian Point Pleasant limestones and intrude locally upon the Lexington Platform as a dark graptolitic shale tongue (the Fulton beds) at the base of the Kope Formation. This highstand event may reflect a eustatic sea-level rise, a pulse of widespread subsidence, or both. The major Edenian C1 deepening has been recognized by Holland and Patzkowsky (1996) throughout the southern and central Appalachians.

Despite complexities, the Kope Formation shows a general shallowing upward trend, at least to the level of the Grand Avenue beds, a bundle of closely spaced fossiliferous limestones about 10-11 m below the Fairview contact (Brett and Algeo, this volume). The Upper Kope, above the Grand Avenue beds, is shale rich and shows some faunal evidence for deeper water conditions. This abrupt deepening could be considered as a higher-order deepening superimposed upon a "third-order" shallowing trend but it should be noted that the occurrence of deeper water facies near the very top of sequence C1 is problematical.

Holland et al. (this volume) discuss in some detail the placement of the C1/C2 sequence boundary. This was formerly placed at the base of the Fairview Formation, the lowermost portion of which is composed of a relatively compact non-cyclic bundle of limestone beds containing abundant *Strophomena* (see Schumacher, 1992). However, Holland et al. suggest on the basis of faunal data that the shallowest level is actually present several meters higher near the base of the shaly Wesselman submember of the Fairview Formation.

The second Cincinnatian sequence (C2) comprises the lower Fairview Formation through the Bellevue limestone tongue of the Grant Lake Formation (Fig. 9), which together represent the bulk of the Maysvillian Stage with an estimated duration of about 2 million years. Again, this succession shows a gross shallowing upward trend from shaly packstones through thin-bedded bryozoan-rich limestones and shales, and finally to rubbly, wavy-bedded and closely stacked limestones of the Bellevue. However, the Fairview exhibits some retrogradation and the maximum flooding may be represented in the Miamitown Shale, a tongue of presumably deeper water facies that lies between Fairview and Bellevue limestones north of the Cincinnati region (S. Holland, pers. comm., 1999). This shale thins dramatically into northern Kentucky and is only barely recognizable in outcrops near Alexandria. The Miamitown carries a distinctive fauna, typically dominated by molluscs, including the gastropod *Loxoplocus*, and bivalves such as *Modiolopsis*, *Ambonychia*, and *Caritodens*. The Miamitown and its subdivisions recently have been studied and correlated in detail by Datillo (Fig. 10; 1996; 1998). The unit thickens and merges with the Kope Formation north of the outcrop belt in the subsurface. We consider the Miamitown to Bellevue succession to record another, as yet unrecognized sequence.

In Kentucky, the beds above the Fairview Formation consist predominantly of wavy-bedded packstones and grainstones with thinner intervals of shale and thin-bedded packstones and grainstones. This interval is assigned by the Kentucky Geological Survey to the Grant Lake Formation; however, some differentiated intervals, originally recognized as separate formations in the Cincinnati area, can still be recognized in northern Kentucky and are now considered to be members of the Grant Lake Formation. These are, in ascending order, the Bellevue, Corryville, and Mt. Auburn/Straight Creek members.

The Bellevue Limestone, as recently defined, consists of 6 to 21.3 meters of closely spaced thin- to medium-bedded shell-rich packstones and grainstones. It thickens to the southeast at the expense of the Corryville Shale; conversely, a tongue of Corryville-like lithology divides the Bellevue

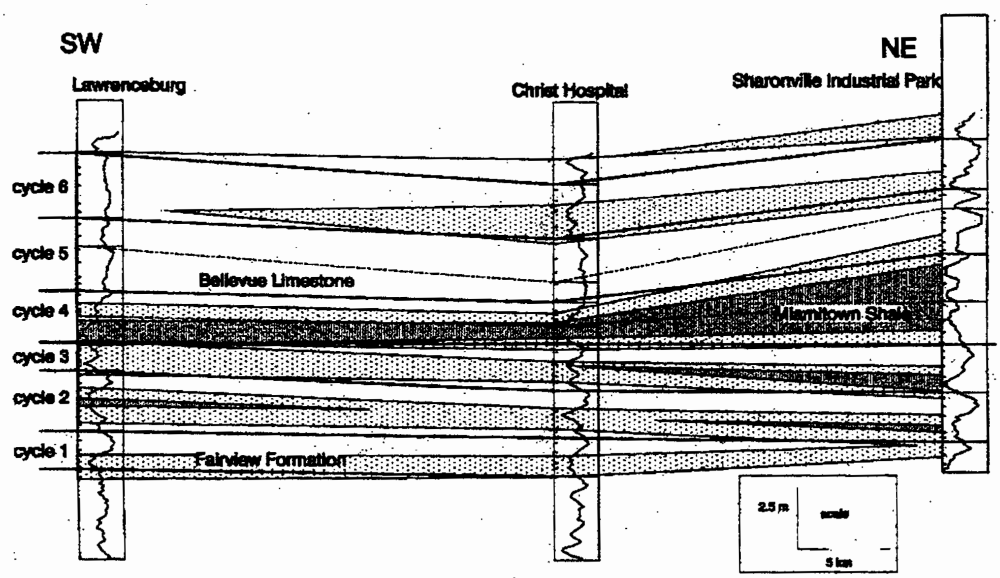

Figure 10. Stratigraphic cross-section of Fariview-Miamitown-Bellevue interval, corresponding to Holland's C2 sequence, from north to south through the Greater Cincinnati area. From Datillo (1996).

north of Cincinnati. Otherwise, shale forms a very minor constituent of the Bellevue, and limestone beds of this unit typically are amalgamated with only minor shaly partings, giving the Bellevue a ribbed appearance in outcrops. The Bellevue contains a fauna rich in robust brachiopods, especially large specimens of *Platystrophia ponderosa*, that are considered to represent shallow-water, near-wavebase conditions associated with a late highstand phase.

Holland's third depositional sequence (C3; Fig. 9), dated as late Maysvillian in age, is substantially thinner than the first two and may represent less than a million years. It commences with shaly beds of the Corryville Member of the Grant Lake Formation, which yield upward to rubbly, wavy-bedded packstones and grainstones of the Mt. Auburn Member.

In classic exposures in the city of Cincinnati, Bassler (1906) originally recognized a shale-rich interval overlying the Bellevue which he named Corryville. In this area, near the present-day University of Cincinnati, the Corryville was about 20 m thick and consists of medium gray fossiliferous mudstone with thin brachiopod-rich packstones. The unit contains a rich, diverse fauna including exceptionally well-preserved trilobites and crinoids (Goldman, 1998). The lower portion of the Corryvile becomes more limestone rich and is considered to merge with the upper Bellevue Member toward the southeast, accounting for the decrease in thickness of the Corryville to only about 6 m in the Maysville area. Hence, this thickness change is facies dependent rather than a reflection of laterally variable sedimentation rates. In any case, the Corryville appears to record another deepening event and a return to Fairview or even Kope-like facies, with a maxcimum flooding surface probably in the upper half of the unit. Overlying the Corryville, the Mt. Auburn-Straight Creek members of the Grant Lake Formation record shallowing into an environment very similar to the Bellevue.

Holland's fourth depositional sequence (C4) is also short and consists of the Sunset and Oregonia members of the Arnheim Formation (Fig. 9; n.b., these members were each given formational status by Holland). Once again, this succession commences with shales and nodular limestones and progresses upward into wavy-bedded packstones and grainstones. The base of the Richmond Group (Richmondian Stage)is presently set at the base of the Arnheim Formation (base of C4).

Holland's fifth depositional sequence (C5; Fig. 9) is well developed and shows well-defined transgressive and early highstand systems tracts. It falls within the middle Richmondian and comprises the Waynesville, Liberty, and lower Whitewater formations, a shallowing upward succession. Its base is marked locally by about 1.5 m of phosphatic grainstone. This bed is abruptly overlain by gray shales of the Waynesville Formation, which contains a fauna dominated by bivalves, trilobites, and the brachiopods *Onniella* and *Sowerbyella* (or *Thaerodonta*) that strongly suggests a return to deeper water Kope-like conditions. Facies of the Waynesville, representing transgressive to highstand conditions, may correspond to a major early Richmondian deepening event seen elsewhere in the Frankfort and Blue Mountain formations (dark gray to black shales) of New York and Ontario, respectively, and the Maquoketa Shales of the upper Mississippi Valley region. Along the western flank of the Cincinnati Arch, the shaly Waynesville grades upward into packstones and grainstones of the Liberty Formation, and the latter, in turn, grades upward into-wavy bedded limestones of the Whitewater Formation. Overlying the last-named unit are bioturbated, coral-rich "lagoonal" mudstones and laminated peritidal dolostones of the Saluda Formation.

On the eastern flank of the Cincinnati Arch, the correlative section is composed of shallowing upward facies of the Bull Fork Formation. A Waynesville equivalent is recognized in the base of this sequence and shallows through variably shaly carbonates into variegated greenish gray to reddish mudstones of the Preachersville Member of the Drakes Formation. These sediments reflect westward progradation of the Queenston clastic wedge and are apparently coeval with the muddy dolostones of the Saluda Formation to the west. Sequence C5 also shows an incursion of a number of taxa such as corals, stromatoporoids, and the brachiopod *Lepidocyclus* that was referred as the "Richmondian invasion" by Holland and Patzkowsky (1994) and Holland (1997). Holand and Patzkowsky (1994) attributed this faunal change to a general warming of the Cincinnatian seas, possibly accompanied by changes in seawater chemistry.

Finally, Holland (1998) recognized remnants of a sixth and highest Cincinnatian sequence (C6). This sequence has apparently been completely removed at the major sub-Silurian Cherokee Unconformity on the east flank of the Cincinnati Arch (Fig. 4). However, on the west flank of the arch it is reflected in a return to packstones and shales assigned to the Upper Whitewater or Elkhorn Fomation, above the Saluda dolostones.

Third-Order Sequences of the Silurian: Research on the sequence stratigraphy of Silurian rocks in the northern Appalachian Basin (Brett et al., 1990, 1994, 1998) has resulted in recognition of about eight widespread, unconformity-bounded packages that may be assigned "third-order" status, as well as a large number of smaller ("fourth-order") sequences (Fig. 11). Recently, sequence analysis of correlative units in Ohio and Kentucky has led to recognition of about six, possibly correlative "third-order" sequences in the Cincinnati Arch region. Interregional correlation of these sequences is facilitated by the conodont biostratigraphic studies of Kleffner (1989) as well as the detailed subsurface study of Lukasik (1988).

The first Silurian sequence (S1) is the Medina or Tuscarora sandstone succession of the Appalachian Basin, which is recorded by the Lower Silurian (lower Llandovery) Brassfield Formation in Ohio and Kentucky (Fig. 11). It is bounded at its base by the Cherokee Unconformity and at its top by a more subtle and previously unrecognized sequence boundary marked by a hematitic bed near the top of the Brassfield (Fig. 12). The sequence consists of the lower portion of the Clinton Group, comprising mixed shales, carbonates and ironstones in the Appalachian Basin. In the Cincinnati Arch region, its basal unit is the Belfast Member of the Brassfield Formation, an argillaceous dolostone that may resemble the underlying Drakes dolomitic shales. This interval apparently represents lowstand or initial transgressive conditions, and over the sequence boundary the Belfast locally features a phosphatic, glauconitic lag. The bulk of the Brassfield Formation is a massive orange buff-weathering dolostone with layers of

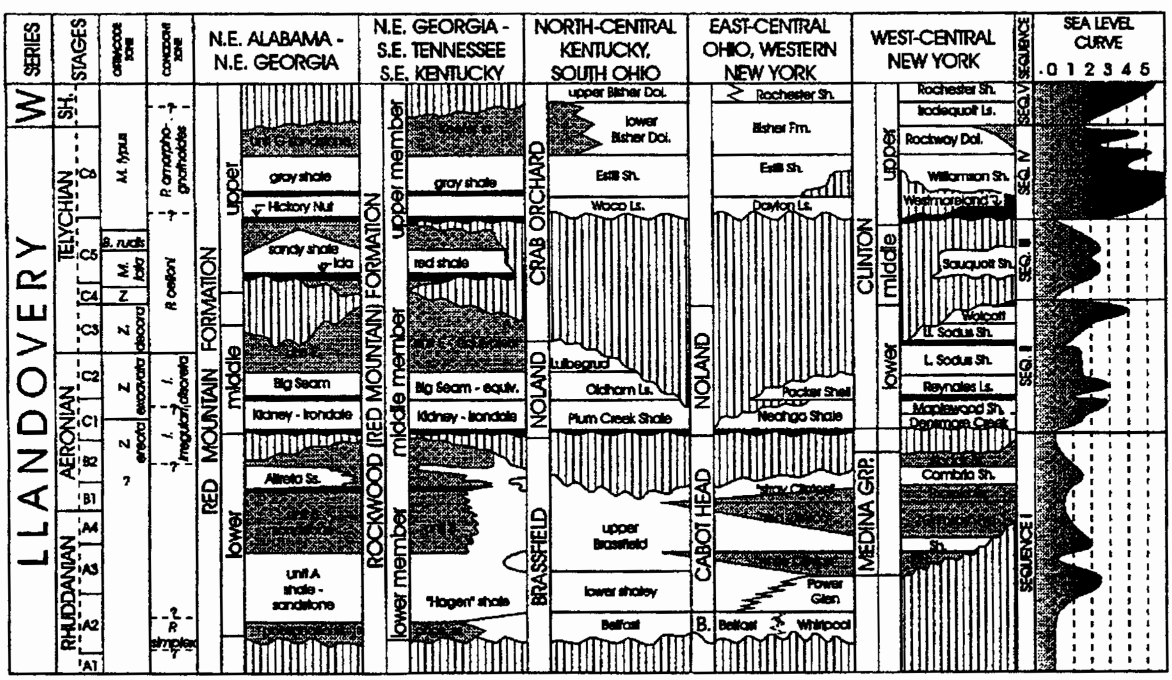

Figure 11. Correlation of medial Silurian units in New York State. Ontario, and central Ohio. From Brett et al. (1990).

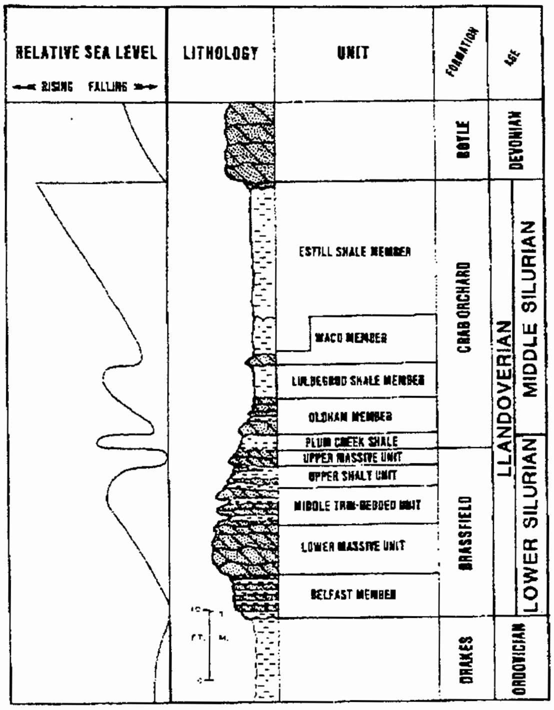

Figure 12. Composite column of Silurian stratigraphic units of the eastern Cincinnati Arch area. Modified from Ettensohn (1992).

light gray chert. This unit contains some fossils in common with the Manitoulin Dolostone of Ontario, its probable lateral equivalent. Like the Manitoulin, the cherty Brassfield is interpreted as the TST of sequence S1. An upper division of the Brassfield in Kentucky consists of gray shale with thin-bedded dolomitic siltstones (Fig. 12). This interval probably consititutes the HST of sequence S1 and corresponds to the Cabot Head Formation of northern Ohio, Michigan and Ontario. A minor sequence may be represented by an upper Brassfield dolostone unit that is capped by a hematitic bed rich in cystoid columnals, the so-called "bead bed."

The second Silurian sequence (S2) is represented by a thin, poorly exposed succession assigned to the Noland or Crab Orchard formations (or groups) in southern Ohio and northern Kentucky, respectively (Fig. 11). The basal Plum Creek Shale represents a TST; its base is marked by a thin, hematitic phosphatic nodule bed. Also included within sequence S2 in Ohio are the overlying Oldham Limestone and Lulbegrud Shale, which have been tentatively correlated with the Reynales Limestone and Sodus Shale of the classic New York section (Brett et al., 1990, 1998). In Ohio these units are truncated to the northwest and overstepped by the Dayton Limestone, a distinctive, thin glauconitic carbonate (Lukasik, 1988). The Dayton has been dated as late Llandovery (mid-Telychian) on the basis on conodonts (Kleffner, 1990). The Dayton is thus approximately coeval with the Merritton Limestone and upper Fossil Hill Dolostone, which similarly overstep strata of sequence S2 in the Bruce Peninsula area of southern Ontario, Canada. Brett et al. (1990) inferred that the sub-Dayton unconformity of central Ohio and the sub-Merrittton-Fossil Hill unconformity in Ontario are local manifestations of the same regional unconformitiy. It probably represents a minor episode of uplift and erosion along the Alonquin-Findlay Arch, which was evidently active during the medial Silurian. Goodman and Brett (1994) suggested that this activity may reflect an isostatic response to thrust loading during early phases of the Salinic Orogeny.

The third and fourth Silurian sequences (S3 and S4) are represented by the Estill Shale (a member of the Crab Orchard Formation in Kentucky terminology), which overlies the Dayton Limestone (Fig. 11). These units are separated by a subtle but possibly regionally angular unconformity. The lower Estill Shale consists of purplish shales and contains an ostracode and conodont fauna suggestive of a late Telychian age; this would correlate with sequence S2 (Sauquoit Shale) in the New York succession (Brett et al., 1990, 1998). At the Charters roadcut on the AA Highway, a subtle but slightly angular discordance appears between the lower purplish shales and the overlying greenish-grey shales and siltstones of the upper Estill. At most, a thin transgressive lag deposit occurs at the base of sequence S4.

The upper Estill Shale is assigned a latest Llandovery (late Telychian) age on the basis of graptolites of the *Monograptus clintonensis* Zone and conodonts of *the Pterospathodus amorphognathoides* Zone (Kleffner, 1987). The lower five meters of shale and thin, fossiliferous siltstones appear to correlate directly with the uppermost Rose Hill Shale of the Appalachian Basin and with the Williamson-Willowvale shales (sequence S4-A) of the standard New York section. This represents the highest stand of relative sea level during the Silurian in eastern North America and may be a global eustatic highstand (Johnson et al., 1998).

The uppermost Estill dolomitic siltstone unit (previously assigned to the overlying Bisher Formation; Potter, et al., 1991; Mason, et al., 1991), which is regionally removed under the S5 unconformity, comprises thin- to medium-bedded dolomitic and somewhat fossiliferous carbonates and greenish-grey shales. This dolomitic siltstone appears to correlate directly with the Rockway Formation of Ontario and New York State and with the lower Keefer Sandstone or sandy uppermost Rose Hill Formation in Pennsylvania (late highstand of sequence S4; subsequence S4-B). Also, probable K-bentonites have been found in this interval, which may correlate with beds in the Osgood Shale on the western flank of the Cincinnati Arch (Ray and Brett, 1999). These ash beds may also correlate with K-bentonites found in the upper Llandovery of the southern Appalachians (Kolata et al., 1996).

A very distinct sequence boundary at the base of the Bisher Dolostone separates overlying Sequence S5 from the underlying Estill Shales (Fig. 11). At this surface, the uppermost Estill dolomitic siltstones and shales are regionally truncated in a series of outcrops near Vanceburg, Kentucky (Stop 8 of field trip, p. 21). Sequence S5 shows a well-defined transgressive systems tract, recorded in crinoid-rich dolomitic packstones and grainstones of the lower unit of the undifferentiated Bisher Formation. This is sharply overlain by a thin shaly HST interval, apparently correlative with the Rochester Shale in the Appalachian Basin. No more than a half meter of shales and thin calcisiltites occurs at this level in Kentucky, however, to the north near Hillsboro, Ohio, a succession of nearly four meters of typical Rochester Shale occurs overlying the basal grainstones of the Bisher Dolostone. The top of the lower Bisher unit is thus interpreted as a major flooding surface.

A cryptic, but important, sequence boundary occurs above the overlying calcisiltite and shale interval. This sequence boundary appears to correlate with the base of the Lockport Group and the base of the McKenzie Formation in Pennsylvania and Maryland and represents the base of sequence S6. This interval is represented by hummocky to herringbone cross-stratified crinoidal dolostones, assigned to the upper Bisher Formation in Kentucky and to the Bisher or lower Lilly Formation in Adams County, Ohio (Kleffner and Ausich, 1988; Kleffner, 1990). The top of this succession contains a distinctive, poorly bedded interval consisting of mounds or blocks of dolomicrite surrounded by poorly bedded dolomitic mudstones. This interval has been interpreted as a collapse breccia associated with karstification during the Devonian because it lies just below the Kaskaskia unconformity. However, its association with poorly preserved corals and stromatoporoids and the occurrence of in-situ crinoid holdfasts on the surfaces of the dolomicrite mounds indicate that, instead, these structures may represent bioherms or mud mounds. If so, they are associated with the early highstand/maximum flooding surface of sequence S6. As such, they would correlate with a widespread zone of coral-stromatoporoid reefs in the lower Lockport Group in New York State and thrombolitic mounds in the McKenzie Formation of Pennsylvania and West Virginia (Crowley, 1973; Brett et al., 1990). The overlying Lilly-Peebles dolostone succession of southern Ohio has been largely removed by Devonian erosion in northern Kentucky.

In the study area gray to black pyritic shales of the Upper Devonian (Famennian) are juxtaposed directly upon eroded Silurian carbonates (see Over et al., this volume). The unconformity typically displays a small amount of relief and may be overlain by a thin lag deposit of dark bone and conodont-rich pyritic to phosphatic limestone. Corrosion and some dissolution of the underlying Silurian carbonates is common and in places minor sandstone dikes may intrude downward into Silurian dolostones.

This field trip will provide an opportunity to examine both the Cherokee and Wallbridge unconformities, as well as a number of the less profound but widespread surfaces discussed above. In the context of sequence stratigraphy, these represent sequence boundaries or, in some cases, maximum flooding surfaces.

COMBINED REFERENCE LIST FOR BRETT AND ALGEO PAPERS

Aigner, T., 1985, *Storm Depositional Systems: Dynamic Stratigraphy in Modern and Ancient Shallow Marine Sequences*, Lecture Notes in the Earth Sciences 3: Berlin, Springer, 174 p.

Alexander, R.R., 1975, Phenotypic lability of the brachiopod *Rafinesquina alternata* (Ordovician) and its correlation with the sedimentologic regime: *Journal of Paleontology*, v. 49, p. 607-618.

Bassler, R.S., 1906, A study of the James types of Ordovician and Silurian Bryozoa: *Proceedings of the U.S. National Museum*, v. 30, no. 1442, p. 1-66.

Beadle, S.C., and Johnson, M.E., 1986, Paleoecology of Silurian cyclocrinitid algae: *Palaeontology*, v. 29, p. 585-601.

Beaumont, C., Quinlan, G., and Hamilton, J., 1988, Orogeny and stratigraphy: Numerical models of the Paleozoic in the eastern interior of North America: *Tectonics*, v. 7, p. 389-416.

Brandt, D.S., 1985, Ichnologic, taphonomic, and sedimentologic clues to the deposition of Cincinnatian shales (Upper Ordovician), Ohio. In: Curran, H.A., ed., *Biogenic Structures: Their Use in Interpreting Depositional Environment*: Society of Economic Paleontologists and Mineralogists, Special Publication 35, p. 299-307.

Brandt, D.S., Meyer, D.L., and Lask, P.B., 1995, *Isotelus* (Trilobita) "hunting burrow" from Upper Ordovician strata, Ohio: *Journal of Paleontology*, v. 69, p. 1079-1083.

Brett, C.E., 1995, Sequence stratigraphy, biostratigraphy, and taphonomy in shallow marine environments: *Palaios*, v. 10, p. 597-516.

Brett, C.E., 1998, Sequence stratigraphy, paleoecology, and evolution: Biotic clues and responses to sea-level fluctuations: *Palaios*, v. 13, p. 241-262.

Brett, C.E., and Allison, P.A., 1998, Paleontological approaches to environmental interpretation of marine mudrocks. In: Schieber, J., Zimmerle, W., and Sethi, P.S., eds., *Shales and Mudstones, Vol. 1: Basin Studies, Sedimentology, and Paleontology*: Stuttgart, E. Schweizerbart'sche, p. 301-349.

Brett, C.E., and Baird, G.C., 1993, Taphonomic approaches to temporal resolution in stratigraphy: Examples from Paleozoic marine mudrocks. In: Kidwell, S.M., and Behrensmeyer, A.K., eds., *Taphonomic Approaches to Time Resolution in Fossil Assemblages*: Paleontological Society, Short Courses in Paleontology G, p. 250-274.

Brett, C.E., and Baird, G.C., 1997, Epiboles, outages, and ecological evolutionary bioevents: Taphonomic, ecological, and evolutionary factors. In Brett, C.E., and Baird, G.C., eds., *Paleontological Events: Stratigraphic, Ecological, and Evolutionary Implications*: New York, Columbia University Press, p. 249-285.

Brett, C.E., Baarli, B.G., Chowns, T., Cotter, E., Driese, S., Goodman, W., and Johnson, M.E., 1998, Early Silurian condensed horizons, ironstones, and sequence stratigraphy in the Appalachian foreland basin. In: Lansing, E., and Johnson, M.E., eds., Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes: *New York State Museum Bulletin*, v. 491, p. 89-143.

Brett, C.E, Baird, G.C., and Speyer, S.E., 1997, Fossil Lagerstätten: Stratigraphic record of paleontological and taphonomic events. In Brett, C.E., and Baird, G.C., eds., *Paleontological Events: Stratigraphic, Ecological, and Evolutionary Implications*: New York, Columbia University Press, p.3-40.

Brett, C.E., Boucot, A.J., and Jones, B., 1993, Absolute depths of Silurian benthic assemblages: *Lethaia*, v.26, p. 25-40.

Brett, C.E., Goodman, W.M., and LoDuca, S.T., 1990, Sequences, cycles, and basin dynamics in the Silurian of the Appalachian foreland basin: *Sedimentary Geology*, v. 69, p. 191-244.

Brett, C.E., Goodman, W.M., and LoDuca, S.T., 1994, Ordovician and Silurian strata in the Genesee Valley area: Sequences, cycles, and facies: *New York State Geological Association Field Trip Guidebook*, 66th Annual Meeting, Rochester, New York, p. 381-442.

Brett, C.E., Moffat, H. A., and Taylor, W.L., 1997, Echinoderm taphonomy, taphofacies, and Lagerstätten. In Waters, J.A., and Maples, C.G., eds., *Geobiology of Echinoderms*: Paleontological Society Papers, v. 3: p. 147-190.

Brett, C.E., Tepper, D.H., Goodman, W.M., LoDuca, S.T., and Lin, B.Y., 1995, Revised stratigraphy and correlation of the Niagaran Provincial Series (Medina, Clinton, and Lockport groups) in the type area of western New York: *U.S. Geological Survey Bulletin*, v. 2086, 66 p.

Caster, K.E., Dalvé, E.A., and Pope, J.K., 1955, *Elementary Guide to the Fossils and Strata of the Ordovician in the Vicinity of Cincinnati, Ohio*: Cincinnati Museum of Natural History, 47 p.

Clifton, H.E., 1988, *Sedimentologic Consequences of Convulsive Geologic Events*: Geological Society of America, Special Paper 229, 157 p.

Cuffey, R.J., 1998, An introduction to the type-Cincinnatian. In: Davis, R.A. and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, p. 2-9.

Dattilo, B.F., 1996, A quantitative paleoecological approach to high-resolution cyclic and event stratigraphy: The Upper Ordovician Miamitown Shale in the type Cincinnatian: *Lethaia*, v. 29, p. 21-37.

Dattilo, B.F., 1998, The Miamitown Shale: Stratigraphic and historic context (Upper Ordovician, Cincinnati, Ohio, region). In: Davis, R.A. and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, p. 49-59.

Davis, R.A., ed., 1992, *Cincinnati Fossils: An Elementary Guide to the Ordovician Rocks and Fossils of the Cincinnati., Ohio, Region*: Cincinnati Museum of Natural History, 61 p.

Davis, R.A., and Cuffey, R.J., eds., 1998, *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, 194 p.

De Boer, P.L., and Wonders, A.A.H., 1984, Astronomically induced rhythmic bedding in Cretaceous pelagic sediments near Moria (Italy). In: Berger, A.L., et al., eds., *Milankovitch and Climate*: Dordrecht, D. Reidel, p. 177-190.

Dennison, J.M., and Head, J.M., 1975, Sea-level variations interpreted from the Appalachian Basin Silurian and Devonian: *American Journal of Science*, v. 275, p. 1089-1120.

Desjardins, L.H., 1934, *The Preglacial Physiography Of The Cincinnati Region*: M.S. thesis (unpubl.), University of Cincinnati, 43 p.

Diekmeyer, S.C., 1998, Kope to Bellevue formations: The Reidlin Road/Mason Road site (Upper Ordovician, Cincinnati, Ohio region). In: Davis, R.A. and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, p. 10-35.

Emery, D., and Meyers, K.J., 1996, *Sequence Stratigraphy*: Oxford, Blackwell, 297 p.

Ettensohn, F.R., 1991, Flexural interpretation of relationships between Ordovician tectonism and stratigraphic sequences, central and southern Appalachians, U.S.A. In: Barnes, C.R., and Williams, S.H., eds., *Advances in Ordovician Geology*: Geological Survey of Canada Paper 90-9, p. 213-224.

Ettensohn, F.R., 1992a, *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*: Ohio Division of Geological Survey, Miscellaneous Report 5, 184 p.

Ettensohn, F.R., 1992b, Basic flexural models. In: Ettensohn, F.R., ed., *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*: Ohio Division of Geological Survey, Miscellaneous Report 5, p. 9-12.

Ettensohn, F.R., 1992c, General Ordovician paleogeographic and tectonic framework for Kentucky. In: Ettensohn, F.R., ed., *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*: Ohio Division of Geological Survey, Miscellaneous Report 5, p. 19-21.

Ettensohn, F.R., 1999, Taconian far-field effects and the origin of the Middle-Late Ordovician Lexington Platform and Sebree Trough, east-central United States: *Geological Society of America, Abstracts with Programs*, v. 31, p. A-15.

Ettensohn, F.R., and Brett, C.E., 1998, Tectonic components in Silurian cyclicity: Examples from the Appalachian Basin and global implications. In: Lansing, E., and Johnson, M.E., eds., Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes: *New York State Museum Bulletin*, v. 491, p. 145-162.

Ettensohn, F.R., and Pashin, J.C., 1992, A brief structural framework of Kentucky. In: Ettensohn, F.R., ed., 1992, *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*: Ohio Division of Geological Survey, Miscellaneous Report 5, p. 6-9.

Ettensohn, F.R., Kulp, M.A., and Rast, N., in press, Evidence for possible far-field responses to the Taconian Orogeny: Middle-Late Ordovician Sebree Trough and Lexington Platform, east-central United States: source?

Foerste, A.F, 1905, The classification of the Ordovician rocks of Ohio and Indiana: *Science*, new ser., v. 22, no. 553, p. 149-152.

Ford, J.P., 1967, Cincinnatian geology in southwest Hamilton County, Ohio: *American Association of Petroleum Geologists Bulletin*, v. 51, p. 918-936.

Goldman, D., Mitchell, C.E., Bergström, S.M., Delano, J.W., and Tice, S., 1994, K-bentonites and graptolite biostratigraphy in the Middle Ordovician of New York State and Quebec: A new chronostratigraphic model: *Palaios*, v. 9, p. 124-143.

Goldman, L.I., 1998, The Corryville Member of the Grant Lake Formation (Upper Ordovician, southwestern Ohio). In: Davis, R.A., and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, p. 64-78.

Goodman, W.M., and Brett, C.E., 1994, Tectonic vs. eustatic controls on the stratigraphic architecture of the Silurian, northern Appalachian Basin. In: Dennison, J.M., and Ettensohn, F.M., eds., *Tectonic and Eustatic Controls on Sedimentary Cycles*: Society of Economic Paleontologists and Mineralogists, Concepts in Sedimentology and Paleontology, v. 4, p. 147 169.

Gordon, L.A., and Ettensohn, F.R., 1984, Stratigraphy, depositional environments, and regional dolomitization of the Brassfield Formation (Llandoverian) in east-central Kentucky: *Southeastern Geology*, v. 25. p. 101-115.

Hagadorn, J.W., and Bottjer, D.J., 1997, Weinkle structures: Microbially mediated sedimentary structures common in subtidal siliciclastic settings at the Proterozoic-Phanerozoic transition: *Geology*, v. 11, p. 1047-1050.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea-levels since the Triassic: *Science*, v. 235, p. 1153-1165.

Hay, H.B., 1998, Paleogeography and paleoenvironments, Fairview through Whitewater formations (Upper Ordovician, southeastern Indiana and southwestern Ohio). In: Davis, R.A., and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, p. 120-134.

Holland, S.M., 1993, Sequence stratigraphy of a carbonate-clastic ramp: The Cincinnatian Series (Upper Ordovician) in its type area: *Geological Society of America Bulletin*, v. 105, p. 306-322.

Holland, S.M., 1997, Using time/environment analysis to recognize faunal events in the Upper Ordovician of the Cincinnati Arch. In: Brett, C.E., ed., *Paleontological Event Horizons: Ecological and Evolutionary Implications*: New York, Columbia University Press, p. 309-334.

Holland, S. M., 1998, Sequence stratigraphy of the Cincinnatian Series (Upper Ordovician, Cincinnati, Ohio, region). In: Davis, R.A. and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, p. 135-151.

Holland, S.M., Miller, A.I., Dattilo, B.F., Meyer, D.L., and Diekmeyer, S.L., 1997, Cycle anatomy and variability in the storm-dominated type Cincinnatian (Upper Ordovician): Coming to grips with cycle delineation and genesis: *Journal of Geology*, v. 105, p. 135-152.

Holland, S.M., and Patzkowski, M.E., 1996, Sequence stratigraphy and long-term lithologic change in the Middle and Upper Ordovician of the eastern United States. In: Witzke, B.J., Ludvigsen, G.A., and Day, J.E., eds,. *Paleozoic Sequence Stratigraphy : Views from the North American Craton*: Geological Society of America Special Paper 306, p. 117-130.

House, M.R., 1985, A new approach to an absolute time scale from measurements of orbital cycles and sedimentary microrhythms: *Nature*, v. 315, p. 721-725.

House, M. R. and Gale, A.S., eds., 1995, *Orbital Forcing Timescales and Cyclostratigraphy*: Geological Society of London, Special Publication 85, p.37-49.

Hughes, N.C., and Cooper, D.L., 1999, Paleobiologic and taphonomic aspects of the "Granulosa" trilobite cluster, Kope Formation (Upper Ordovician, Cincinnati region): *Journal of Paleontology*, v. 73, p. 306-319.

Hyde, D.E., 1959, A structural and stratigraphic study of the Fairview-McMillan formational contact in the Cincinnati area: *Compass*, v. 36, p. 161-171.

Jennette, D.C., and Pryor, W.A., 1993, Cyclic alternation of proximal and distal storm facies: Kope and Fairview formations (Upper Ordovician), Ohio and Kentucky: *Journal of Sedimentary Petrology*, v. 63, p. 183-203.

Johnson, M.E., Rong, J.-Y., and Kershaw, S., 1998, Calibrating Silurian eustasy by erosion and burial of coastal paleotopography. In: Lansing, E., and Johnson, M.E., eds., Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes: *New York State Museum Bulletin*, v. 491, p. 3-13.

Kidwell, S.M., 1991, The stratigraphy of shell concentrations. In: Allison, P.A., and Briggs, D.E.G., eds., *Taphonomy: Releasing the Data Locked in the Fossil Record*: New York, Plenum, p. 211-290.

Kidwell, S.M., and Bosence, D.W.J., 1991, Taphonomy and time-averaging of marine shelly faunas. In: Allison, P.A., and Briggs, D.E.G., eds., *Taphonomy: Releasing the Data Locked in the Fossil Record*: New York, Plenum, p. 116-210.

Kleffner, M.A., 1987, Conodonts of the Estill Shale and Bisher Formation (Silurian, southern Ohio): Biostratigraphy and distribution: *Ohio Journal of Science*, v. 87, p. 78-89.

Kleffner, M.A., 1989, A conodont-based Silurian chronostratigraphy: *Geological Society of America Bulletin*, v. 101, p. 904-912.

Kleffner, M.A., 1990, Wenlockian (Silurian) conodont biostratigraphy, depositional environments, and depositional history along the eastern flank of the Cincinnati Arch in southern Ohio: *Journal of Paleontology*, v. 64, p. 319-328.

Kleffner, M.A., and Ausich, W.I., 1988, *Lower and Middle Silurian of the Eastern Flank of the Cincinnati Arch and the Appalachian Basin Margin, Ohio*: Field Trip 1, Society of Economic Paleontologists and Mineralogists, Fifth Midyear Meeting, Columbus, Ohio, 25 p.

Kolata, D.R., Huff, W.D., and Bergström, S.M., 1996, *Ordovician K-bentonites of Eastern North America*: Boulder, Colorado, Geological Society of America, Special Paper 313, 84 p.

Lehmann, D.M., Brett, C.E., and Cole, R., 1994, Tectonic and eustatic influences upon the sedimentary environments of the Upper Ordovician strata of New York and Ontario. In: Dennison, J.M., and Ettensohn, F.M., eds., *Tectonic and Eustatic Controls on Sedimentary Cycles*: Society for Economic Paleontologists and Mineralogists, Concepts in Sedimentology and Paleontology, v. 4., p. 181-201.

Lukasik, D.M. 1988, *Lithostratigraphy of Silurian rocks in southrn Ohio and adjacent Kentucky*: Ph.D. dissertation (unpubl.),University of Cincinnati, 313 p.

Mason, C.E., Lierman, R.T., Ettensohn, F.R., and Pashin, J.C., 1992, Sandbelt lithofacies of the Bisher Dolostone, the Crab Orchard Shale, the Upper Olentangy Shale, and the Huron Member of the Ohio Shale in northeastern Kentucky. In: Ettensohn, F.R., ed., *Changing Interpretations of Kentucky Geology: Layer-Cake, Facies, Flexure and Eustasy*: Ohio Division of Geological Survey, Miscellaneous Report 5, p. 156-158.

Meyer, D.L., 1990, Population paleoecology and comparative taphonomy of two edrioasteroid (Echinodermata) pavements: Upper Ordovician of Kentucky and Ohio: *Historical Biology*, v. 4, p. 155-178.

Miller, A.I., 1997, Counting fossils in a Cincinnatian storm bed: Spatial resolution in the fossil record. In: Brett, C.E., and Baird, G.C., eds., *Paleontological Events: Stratigraphic, Ecological, and Evolutionary Implications*: New York, Columbia University Press, p. 57-72.

Miller, A.I., Holland, S.M., Dattilo, B.F., and Meyer, D.L., 1997, Stratigraphic resolution and perceptions of cycle architecture: Variations in meter-scale cyclicity in the type Cincinnatian Series: *Journal of Geology*, v. 105, p. 737-743.

Miller, K.B., Brett, C.E., and Parsons, K.M., 1988, The paleoecological significance of storm-generated disturbance within a Middle Devonian muddy epeiric sea: *Palaios*, v. 3, p. 35-52.

Mitchell, C.E., and Bergström, S.M., 1991, New graptolite and lithostratigraphic evidence from the Cincinnati region, U.S.A., for the definition and correlation of the base of the Cincinnatian Series (Upper Ordovician). In Barnes, C.R., and Williams, S.H., eds., *Advances in Ordovician Geology*: Geological Survey of Canada Paper 90-9, p. 59-77.

Myers, K.J., and Milton, N.J., 1996, Concepts and principles. In: Emery, D., and Myers, K.J., eds., *Sequence Stratigraphy*: Oxford, Blackwell, p. 11-44.

Mitchell, C.E., Bergström, S.M., and Schumacher, G.A., 1997, Stratigraphic sequences of the Sebree Trough and Jessamine Dome as an expression of basement reactivation during the Taconic Orogeny: *Geological Society of America, Abstracts with Programs*, v. 29, p. 61.

Nickles, J.M., 1902, The geology of Cincinnati: *Cincinnati Society of Natural History Journal*, v. 20, p. 49-100.

Nummedal, D., 1991, Shallow marine storm sedimentation: The oceanographic perspective.

O'Brien, N.R., Brett, C.E., and Taylor, W.L., 1994, Microfabric and taphonomic analysis in determining sedimentary processes in marine mudstones: Example from the Silurian of New York: *Journal of Sedimentary Research*, v. A64, p. 847-852.

O'Brien, N.R., Brett, C.E., and Woodard, M.J., 1998, Shale fabric as a clue to sedimentary processes: Example from the Williamson-Willowvale Shales (Silurian), New York. In: Schieber, J., Zimmerle, W., and Sethi, P.S., eds., *Shales and Mudstones, Vol. 2: Petrography, Petrophysics, Geochemistry, and Economic Geology*: Stuttgart, E. Schweizerbart'sche, p. 55-66.

Parsons, K.M., Brett, C.E., and Miller, K.B., 1988, Taphonomy and depositional dynamics of Devonian shell-rich mudstones: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 63, p. 109-140.

Pope, J.K., and Martin, W.D., eds., 1977, *Field Guidebook to the Biostratigraphy and Paleoenvironments of the Cincinnatian Series of Southeastern Indiana*: Society of Economic Paleontologists and Mineralogists, Great Lakes Section, 7th Annual Field Conference, Miami University, 88 p.

Pope, M.C., Read, J.F., Bambach, R., and Hoffman, H.J., 1997, Late Middle to Late Ordovician seismites of Kentucky, southwest Ohio and Virginia: Sedimentary recorders of earthquakes in the Appalachian Basin: *Geological Society of America Bulletin*, v. 109, p. 489-503.

Potter, P.E., 1996, *Exploring the Geology of the Cincinnati/Northern Kentucky Region*: Kentucky Geological Survey, Special Publication 22, Series XI, 115 p.

Potter, P.E., Ausich, W.I., Klee,J., Krissek, L.A., Mason, C. E., Schumacher, G.A., Wilson, T.R. and Wright, E.M., 1991, Geology of the Alexandria-Ashland Highway (Kentucky Highway 546), Maysville to Garrison: Lexington, Kentucky Geological Survey Joint field Conference,Geological Society of Kentucky and Ohio Geological Society, 64 p.

Pfluger, F., 1999, Matground structures and redox facies: *Palaios*, v. 14, p. 25-39.

Quinlan, G.M., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the eastern interior of North America: *Canadian Journal of Earth Science*, v. 21, p. 973-996.

Raiswell, R., 1976, The microbiological formation of carbonate concretions in the Upper Lias of NE England: *Chemical Geology*, v. 18, p. 227-244.

Richards, R.P., 1972, Autecology of Richmondian brachiopods (Late Ordovician of Indiana and Ohio): *Journal of Paleontology*, v. 46, p. 386-405.

Schumacher, G.A., 1992, Lithostratigraphy, cyclic sedimentation, and event stratigraphy of the Maysville, Kentucky area. In: Ettensohn, F.R., ed., 1992, *Changing Interpretations of Kentucky Geology: Layer Cake, Facies, Flexure, and Eustasy*: Ohio Division of Geological Survey, Miscellaneous Report 5, p. 165-172.

Schumacher, G.A., 1998, A new look at the Cincinnatian Series from a mapping perspective. In: Davis, R.A., and Cuffey, R.J., eds., *Sampling the Layer Cake That Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian*: Ohio Division of Geological Survey, Guidebook No. 13, p. 111-119.

Schumacher, G.A., and Shrake, D.L., 1997, Paleoecology and comparative taphonomy of an *Isotelus* (Trilobita) fossil Lagerstätten from the Waynesville Formation (Upper Ordovician, Cincinnatian Series) of southwestern Ohio. In: Brett, C.E., and Baird, G.C., eds., *Paleontological Events: Stratigraphic, Ecological and Evolutionary Implications*: New York, Columbia University Press, p. 131-161.

Scotese, C.R., 1990, *Atlas of Phanerozoic Plate Tectonic Reconstructions*: International Lithophase Program (IUU-IUGS), Paleomap Project Technical Report 10-90-1.

Seilacher, A.,1982, *Posidonia* Shales (Toarcian, S. Germany): Stagnant basin model revalidated. In: Gallitelli, E.M., ed., *Paleontology: Essential of Earth History*: Modena, STEM Mucchi, p. 25-55.

Seilacher, A., 1991, Events and their signatures: An overview. In: Einsele, G., Ricken, W., and Seilacher, A., eds., *Cycles and Events in Stratigraphy*: New York, Springer, p. 222-226.

Seilacher, A., and Aigner, T., 1991, Storm deposition at the bed, facies, and basin scale: The geologic perspective. In: Einsele, G., Ricken, W., and Seilacher, A., eds., *Cycles and Events in Stratigraphy*: New York, Springer, p. 227-248.

Seilacher, A., Reif, W.E., and Westphal, F., 1985, Sedimentological and temporal patterns of fossil lagerstätten: *Philosophical Transactions of the Royal Society of London, Biological Sciences*, v. B311, p. 5-23.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin , v. 74, p. 93-114.

Sweet, W.C., 1979, Conodonts and conodont biostratigraphy of post-Tyrone Ordovician rocks of the Cincinnati region: *U.S. Geological Survey Professional Paper* 1066-G, 26 p.

Sweet, W.C., and Bergström, S.M., 1984, Conodont provinces and biofacies of the Late Ordovician: *Geological Society of America, Special Paper 196*, p. 69-87.

Tobin, R.C., 1982, *A Model for Cyclic Deposition in the Cincinnatian Series of Southwestern Ohio, Northern Kentucky, and Southeastern Indiana*: Ph.D. dissertation (unpubl.), University of Cincinnati, 483 p.

Tobin, R.C., and Pryor, W.A., 1981, Sedimentological interpretation of an Upper Ordovician carbonate-shale vertical sequence in northern Kentucky. In: Roberts, T.G., ed., Geological Society of America, *1981 Annual Meeting Field Trip Guidebooks. Vol. I: Stratigraphy and Sedimentology*: Falls Church, Virginia, American Geological Institute, p. 1-10.

Ulrich, E.O., 1888, A correlation of the Lower Silurian horizons of Tennessee and of the Ohio and Mississippi valleys with those of New York and Canada (4 parts): *American Geologist*, v. 1, p. 100-110, 179-190, 305-315, and v. 2, p. 39-44.

Ulrich, E.O., and Bassler, R.S., 1914, *Report on the Stratigraphy of the Cincinnati, Ohio Quadrangle*: U.S. Geological Survey open-file report, Washington, D.C., 122 p. (incomplete manuscript)

Vail, P.R., Mitchum, R.M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes in sea level. In: Payton, C.E., ed., *Seismic Stratigraphy—Applications to Hydrocarbon Exploration*: American Association of Petroleum Geologists, Memoir 26, p. 83-97.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., and Perez-Cruz, C., 1991, The stratigraphic signatures of tectonics, eustasy and sedimentation: An overview. In: Einsele, G., Ricken, W., and Seilacher, A., eds., *Cycles and Events in Stratigraphy*: New York, Springer, p. 617-659.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., III, 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., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., *Sea-Level Changes: An Integrated Approach*: Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 39-45.

Weiss, M.P., and Sweet, W.C., 1964, Kope Formation (Upper Ordovician): Ohio and Kentucky: *Science*, v.145, p. 1296-1302.

Wilgus, C.K., Hastings, B.S., Kendall, C.G., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., 1988, *Sea-Level Changes An Integrated Approach*: Society of Economic Paleontologists and Mineralogists, Special Publication 42.

Wilkinson, B.H., Diedrich, N.W., and Drummond, C.N., 1996, Facies successions in peritidal carbonate sequences: *Journal of Sedimentary Research*, v. 66, p. 1065-1078.

Wilkinson, B.H., Drummond, C.N., Rothman, E.D., and Diedrich, N.W., 1997, Stratal order in peritidal carbonate sequences: *Journal of Sedimentary Research*, v. 67, p. 1068-1082.

Wilson, M.A., 1985, Disturbance and ecological succession in an Upper Ordovician cobble-dwelling hardground fauna: *Science*, v. 228, p. 573-577.

Witzke, B.J., Ludvigson, G.A., and Day, J.E., 1996, Introduction: Paleozoic applications of sequence stratigraphy. In: Witzke, B.J., Ludvigsen, G.A., and Day, J.E., eds,. *Paleozoic Sequence Stratigraphy : Views from the North American Craton*: Geological Society of America Special Paper 306, p. 1-6.