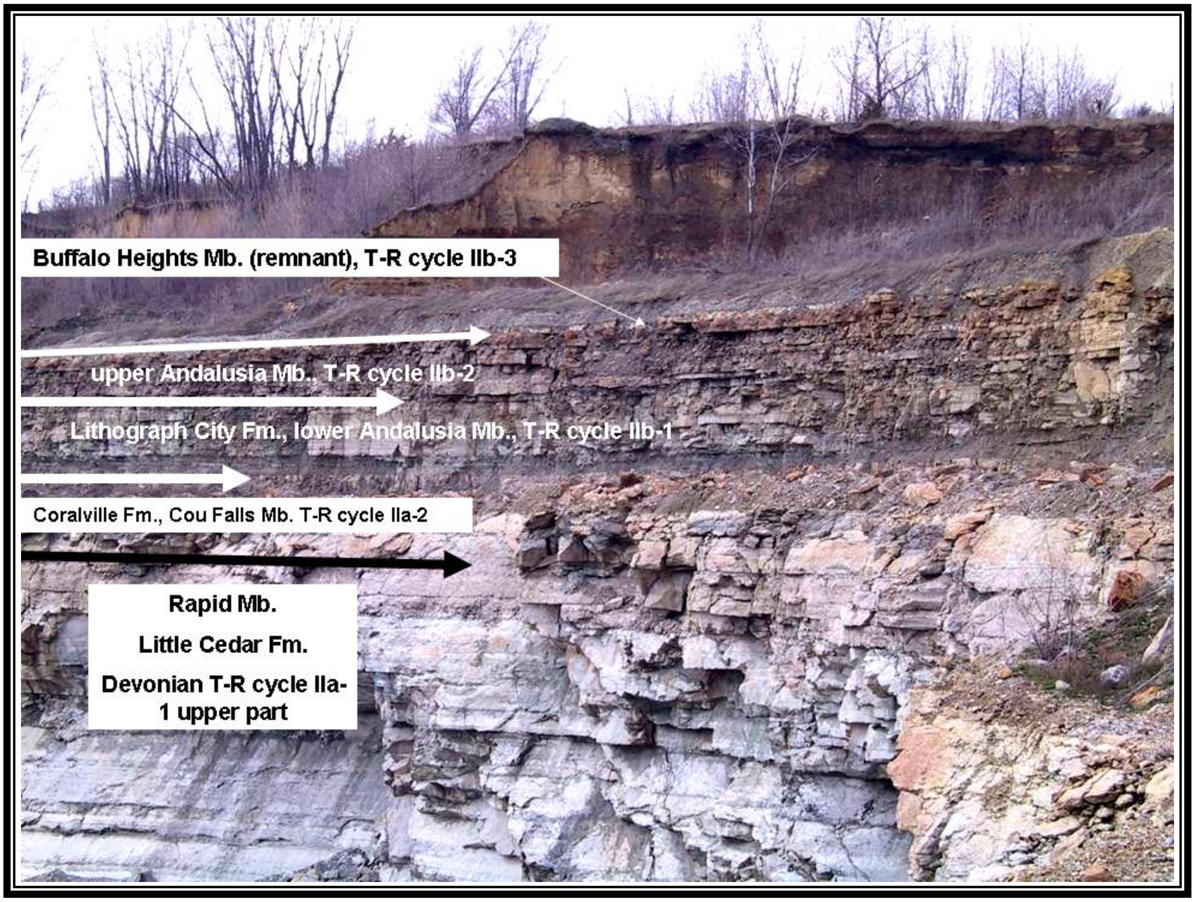
New Perspectives and Advances in the Understanding of Lower and Middle Paleozoic Epeiric Carbonate Depositional Systems of the Iowa and Illinois Basins



Iowa Geological Survey
Guidebook Series No. 26

Guidebook for the 36th Annual Field Conference of the Great Lakes Section, Society for Sedimentary Geology (SEPM), and the 67th Annual Tri-State Field Conference
September 29-October 1, 2006

COVER

Photograph of the upper Cedar Valley Group showing positions of 3rd Order marine flooding surfaces (discontinuities) constituting boundaries defining Devonian T-R cycles IIa-1 to IIb-3 along the north highwall in the Buffalo Quarry, field trip Stop 3.

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Guidebook for the 36th Annual Field Conference of the Great Lakes Section, Society for Sedimentary Geology (SEPM), and the 67th Annual Tri-State Field Conference
September 29-October 1, 2006

Edited by
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September, 2006

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FORWARD

I would like to welcome everyone to the Quad Cities for the 36^{th} Annual Field Conference of the Great Lakes Section of the Society for Sedimentary Geology (GLS-SEPM), and the 67^{th} Annual Tri-State Field Conference. Last year's 35^{th} GLS-SEPM field conference focused attention on the Ordovician System of the upper Mississippi Valley region, and this year's trip will devote its attention to the Devonian System of the Iowa and western part of the Illinois basins, as well as the Silurian System in the conference field area. Two of the contributed guidebook articles discuss aspects of the Ordovician and Silurian systems. This is the first SEPM Field Conference since the 1988 trip led by Greg Ludvigson, Brian Witzke, and Bill Bunker to feature field stops in both Iowa and Illinois, and the first to be hosted in Moline-Rock Island, Illinois.

The Middle and Upper Devonian carbonate platform rocks of the Wapsipinicon and Cedar Valley groups of the Iowa and adjacent Illinois Basin have been the focus of study since the 1850s, starting with studies by James Hall (first Iowa State Geologist). Important exposures in quarries in the Quad Cities area, and cores drilled in Rock Island County, Illinois, and Scott and Muscatine counties in Iowa serve as the principle reference sections that have been targeted for modern biostratigraphic-paleontologic, sequence stratigraphic, chemostratigraphic, and magnetostratigraphic investigations since the early 1980s. The field conference and its guidebook will showcase advances in the understanding of the facies architecture, biostratigraphic, chemostratigraphic, and magetostratigraphic records of regional and global events, and depositional history and of these important epeiric carbonate platform deposits.

I have been involved with a large host of scientists and graduate and undergraduate students focused on deciphering the history of these deposits since my arrival in the region as a Ph.D. student working with Gil Klapper in the 1980s at the University of Iowa, and through subsequent long-term collaboration with Bill Bunker, Greg Ludvigson, and Brian Witzke of the Iowa Geological Survey. Initial stable isotopic work on Devonian carbonates of the Cedar Valley Group began with Greg Ludvigson (formerly of the IGS) and Luis Gonzales and his students at the University of Iowa in the late 1980s, with major studies recently completed on Cedar Valley Group and younger Frasnian age deposits in the Iowa Basin with Michael Joachimski and Robert van Geldern, and ongoing work is in progress with Chris Holmden. More recent significant contributions to the modern stratigraphic and paleontologic understanding of these rocks have included Paul Copper, Brian Glenister, Bill Hickerson, Kurt Klug, Bill Koch, Jim Kralick, Ron Metzger, Gil Klapper, Xueping Ma, Orin Plocher, Jeff Over, Meyoun Pavilcek, Fred Rogers, Jim Sourauf, Carl Stock, and Mike Woodruff.

We are grateful for the generous support from conference sponsors including: the ***Great Lakes Section of SEPM, Illinois Association of Aggregate Producers*** (John Henriksen), the ***Iowa Aggregate Producers Association*** (Mr. Rich White, Ex. Director), the ***Illinois Prairie Foundation***, the ***East-Central Section of the National Association of Geoscience Teachers (NAGT)***, and the ***State Geologist of Iowa*** Bob Libra and the ***Iowa Geological Survey*** for publishing the guidebook for the field conference.

Material support, loan of cores, and access to quarry localities for the field conference were provided by R. Savage of ***Riverstone Group Incorporated***, Rock Island, Illinois, K. Collinson of ***Collinson Brothers Stone Company***, Moline, Illinois, and J. Foss (quarry manager) of ***LaFarge Corporation***, Buffalo Plant, Buffalo, Iowa.

The editors are grateful to all of the guidebook article and field trip stop description-discussion contributors that completed an interesting array of papers for the guidebook including Brad Cramer and Matt Saltzman of The Ohio State University, Mark Kleffner of The Ohio State University at Lima; Brooks Elwood of Louisiana State University; Carl Stock of the University of Alabama-Tuscaloosa; Brian Witzke and Bill Bunker of the Iowa Geological Survey; D. Jeffrey Over of SUNY-Geneseo; Norlene Emerson of the University of Wisconsin-Richland; Toni Simo of the University of Wisconsin-Madison; Robert van Geldern from the Leibniz Institute for Applied Geosciences, Michael Joachimski from the University of Erlangen, Germany, and John Luczaj of the University of Wiscosin-Green Bay.

We also thank Dr. Don Mikulic from the Illinois State Geological Survey for leading the discussion on Silurian strata at the Milan and Allied Quarries.

Bill Bunker and Ray Anderson of the Iowa Geological Survey, Iowa City, Iowa worked to bring final layout and production of the guidebook to completion. We also gratefully acknowledge the Iowa Geological Survey (IGS) for their support and publication of the field conference guidebook through the IGS Guidebook Series, and Bill Bunker and Brian Witzke of the IGS for loan of the IPSCO PPW 3 Core for re-sampling and display at the field conference.

J. Day's fall 2006 Sedimentology and Stratigraphy students assisted in re-boxing and sampling the IPSCO PPW # 3 Core (on loan from the IGS) for micrite powders for stable carbon isotope analysis, and cutting and re-boxing the 67-1 and 67-2 cores of Silurian and Devonian rocks at Allied Quarry on loan to J. Day for study and display at the conference. Former ISU students Dennis Haas and Steven Travers assisted in field sampling of the Coralville and Lithograph City formations at the LaFarge Quarry in Buffalo, Iowa. Former ISU student Sue Taha processed all, and picked most conodont samples from the IPSCO PPW #3 Core in 1998 and 1999. J. Day also would like to extend special thanks and recognition to Gilbert Klapper who examined the IPSCO PPW # 3 Core conodont sample suite during two visits to Day's lab at ISU in 2006 and provided identifications of nearly all Devonian conodonts from the Cedar Valley Group reported herein. J. Day also thanks W. Hickerson and D. Siville who made the initial discovery of shale exposures in 1994 above the Andalusia Member of the Lithograph City Formation at the LaFarge (Buffalo Quarry) now included in the Buffalo Heights Member.

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OVERVIEW OF THE MIDDLE – UPPER DEVONIAN SEA LEVEL HISTORY OF THE WAPSIPINICON AND CEDAR VALLEY GROUPS, WITH DISSCUSSION OF NEW CONODONT DATA FROM THE SUBSURFACE CEDAR VALLEY GROUP OF SOUTHEASTERN IOWA

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INTRODUCTION

This study outlines the key features of biostratigraphy of the fossiliferous parts of the Wapsipinicon and Cedar Valley groups of the Iowa Basin, with discussion of the new conodont data set derived from continuous sampling through the Cedar Valley Group in southeastern Iowa. This study also reviews the present understanding of the timing of major regional sea level change and their relationships with global sea level events as established by previous and recently completed biostratigraphic and stratigraphic investigations (see contributions by Witzke and Bunker, page 23 of this guidebook). Results of carbon, strontium and oxygen stable isotopic studies of brachiopod calcites of Cedar Valley Group brachiopods (van Geldern et al., page 89 of this guidebook) provide insights into climate change in the subtropical Devonian ocean. Results of high-resolution Magnetic Susceptibility (MS) magneto-stratigaphy of the Wapsipinicon and Cedar Valley groups are reported by Ellwood and Day (page 59 of this guidebook). Discussion of the middle-upper Frasnian and Famennian of the Iowa Basin is beyond the scope of the present study, but results of current and previous studies of those deposits can be found in Cramer and others (2006-in press), Day (1989, 1990, 1995, 1996, 1998), Metzger (1989), Day and Copper (1998), Witzke and Bunker (1996, 2002), and Over (2002, and page 75 of this guidebook).

During the Middle and Late Devonian the Iowa Basin was the site of epeiric carbonate platform (ramp) deposition in the southern hemisphere of Laurussia (Fig. 1). The Iowa Basin ramp systems transitioned from the west and northwest to the east and southeast into deeper water in the adjacent Illinois Basin (Fig. 2). The history of Devonian carbonate platform deposits in the Quad Cities area spans large parts of the Middle and part of the Late Devonian ranging in age from late Eifelian to early Frasnian (Fig. 3). Because of the availability of superb quarry exposures and a number of complete core penetrations, the rocks of the Wapsipinicon and Cedar Valley groups in the Iowa Basin and western part of the Illinois Basin have been of interest to geologists since the 1850s, and is the most intensively studied and best documented Middle and Upper Devonian epeiric carbonate platform succession in North America.

Modern investigations of these deposits began in the early 1970s and continue to the present, and have resulted in major advances in our understanding of controls on deposition and carbonate platform development (eustasy and climate), timing of regional and global sea level and climate events, and faunal records providing insights as to the timing, patterns and environmental causes of extinction and biogeographic bioevents in the vast epeiric seaway system that developed and persisted in the interior of central and western Laurussia during the Middle and Late Devonian.

The Devonian succession in the Quad-Cities area of southeastern Iowa and western Illinois serve as the primary reference sections for the open-marine and restricted shallow-water platform facies and three major 3rd order sequence packages of the Eifelian-middle Givetian Wapsipinicon Group, and middle shelf subtidal facies of at least five major middle Givetian-early Frasnian sequence packages that

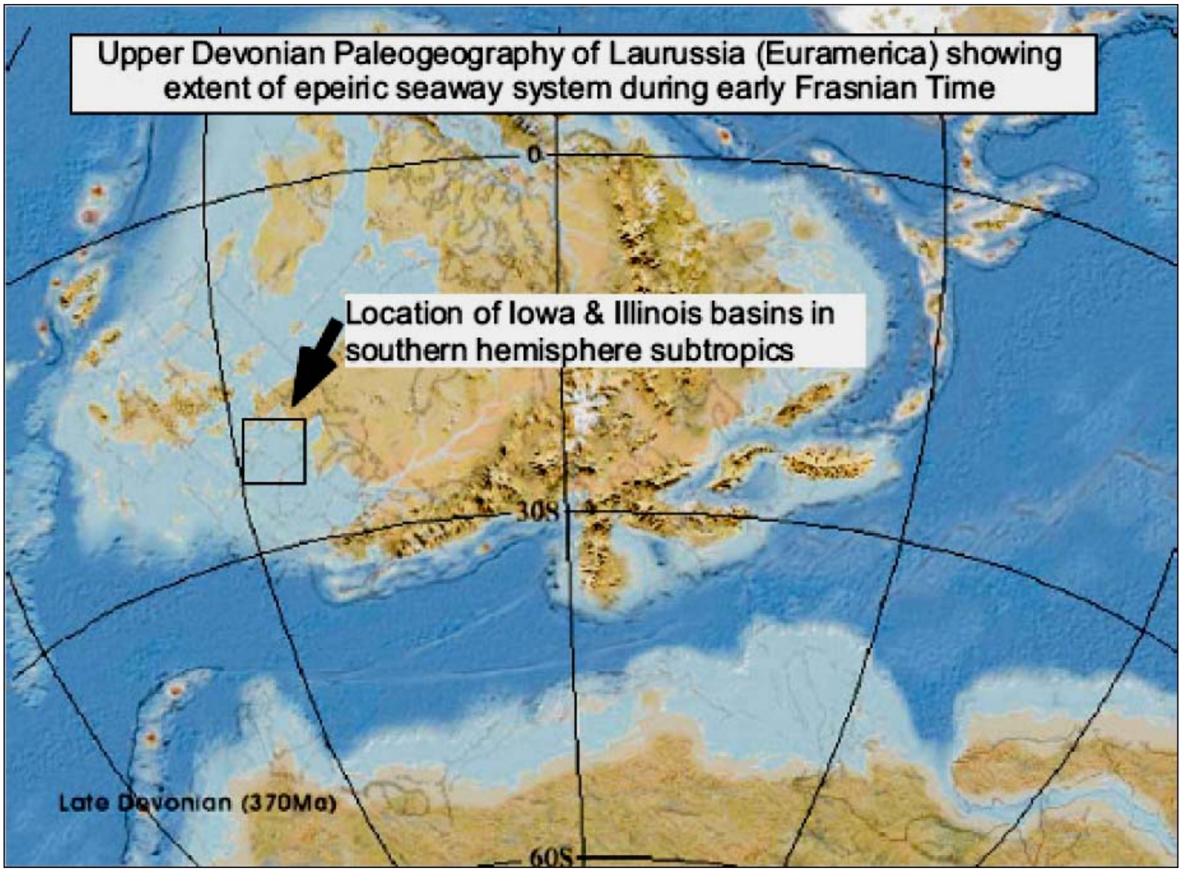

Figure 1. Late Devonian (Frasnian) paleoegeographic reconstruction of Laurussia showing the extent of epeiric seas in central and western Laurussia and the location of the Iowa Basin in the southern hemisphere subtropics. Map courtesy of R. Blakey.

comprise the Cedar Valley Group in this part of the Iowa Basin (Figs. 2 and 3). The most intensely studied reference sections are exposures in the LaFarge Quarry in the town of Buffalo, Scott County, Iowa, and IPSCO PPW #3 Well core drilled in Muscatine County, approximately 4 miles (6.4 km) west of the Buffalo Quarry (Fig. 2).

BIOSTRATIGRAPHY

The integrated conodont-brachiopod biostratigraphic framework for the Iowa Devonian (Fig. 3) has been developed through surface and subsurface investigations of brachiopod (Day, 1986, 1989, 1992, 1994, 1996, 1997, 1998; Day and Copper, 1998; Day and Koch, 1994; Koch and Day, 1996; Ma and Day, 2000, 2003) and conodont faunas (Klapper and Furnish, 1963; Anderson, 1966; Klapper et al., 1971; Ziegler et al., 1976; Klapper and Barrick, 1983; Bunker and Klapper, 1984; Pavilicek, 1986; Witzke et al., 1985, 1989; Rogers, 1990, 1998; Woodruff, 1990; Bunker and Witzke, 1992; Kralik, 1992; Klapper and Foster, 1993; Day, 1990, 1997), and new data from the Cedar Valley Group permitting refinement of the interval of the *varcus* Zone reported below.

This framework (Fig. 3) permits correlations of the late Eifelian Otis and Spillville formations of the lower part of the Wapsipinicon Group (Figs. 2 and 3), although the early-middle Givetian Pinicon Ridge Formation does not yield open-marine shelly faunas or conodonts. Consequently, alignment with early to middle Givetian conodonts zones and recognition of zonal boundaries are not possible in the Pinicon Ridge Formation

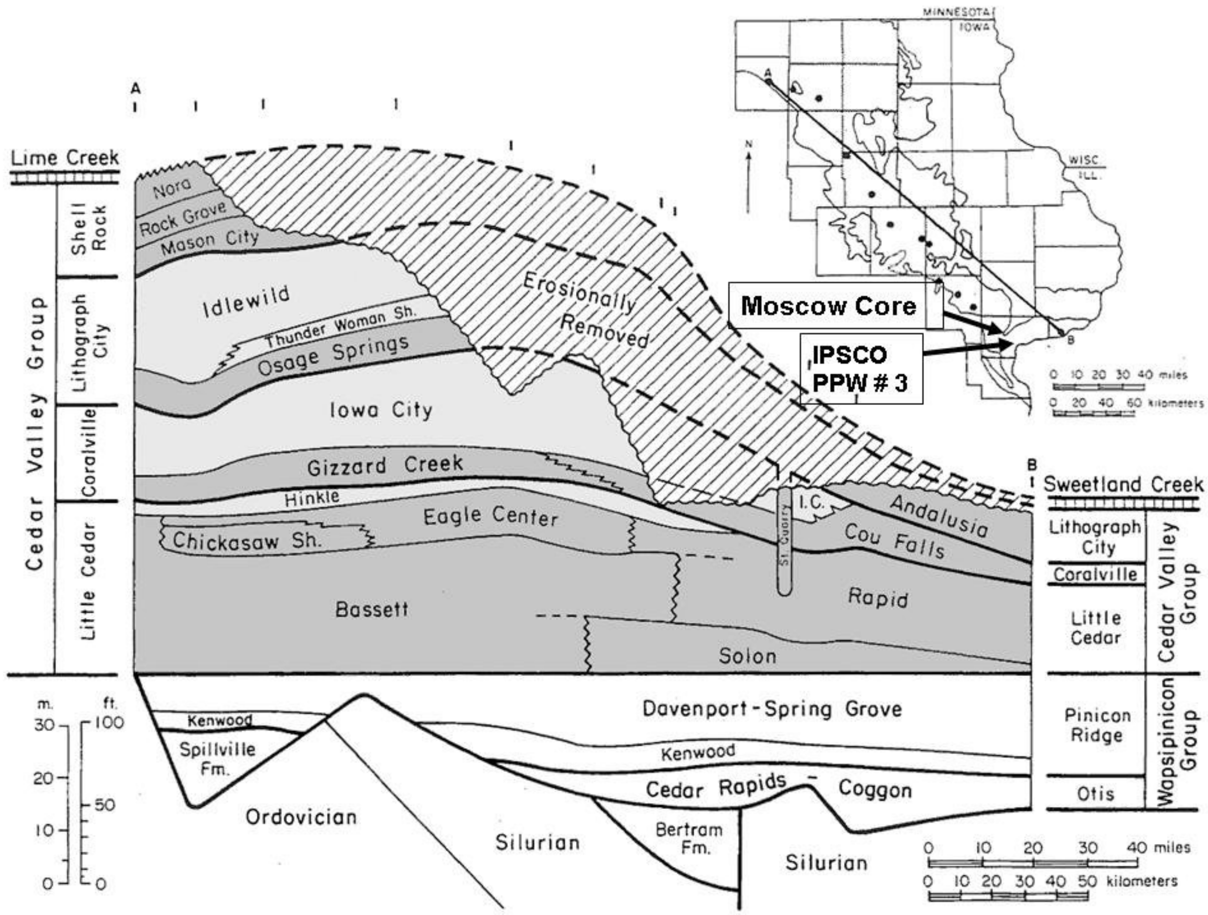

Figure 2. Cross section of the late Eifelian-Frasnian strata of north-central and eastern Iowa. After Fig. 1 of Witzke and others (1989) and Witzke and Bunker (page 23 and 47 of this guidebook). Location map in upper right of figure show locations of core sections MQC (Moscow Quarry Core), IP (IPSCO PPW #3) in Muscatine County, Iowa, and the LaFarge Buffalo Quarry (point B at southern terminus of the line of cross-section) in Scott County, Iowa. Detailed locations in the Appendix of this report.

throughout the Iowa Basin. The lower age range of the Pinicon Ridge must be younger than the underlying late Eifelian Otis and Spillville formations in the basin (Figs. 2 and 3) that contain distinctive Eifelian brachiopods including Emauella in the Otis in the Quad Cities area (Figs. 4, 5 and 6), and the upper age range of Pinicon Ridge is constrained by conodonts of the upper part of the Middle *varcus* Zone from the lowest Little Cedar Formation of the overlying Cedar Valley Group (Fig. 3; Table 1, sample interval 53; also see discussion by Witzke, page 47 of this guidebook).

Significant faunal discontinuities occur in the brachiopod and conodont successions at or near sequence boundaries within the Iowa Devonian succession (Figs. 4, 6-9) indicating that transgressive systems tracts are highly condensed or starved out entirely along major bounding hardgrounds and burrowed discontinuities (disconformities) in southeastern Iowa. Significant numbers of brachiopod range inceptions occur just above basal disconformities or in the lower few meters of subtidal facies flooring Cedar Valley Group carbonate-dominated sequence packages in the inner platform facies belt to the northwest. The cosmopolitan character of diverse and abundant brachiopod faunas of Iowa Devonian T-R cycles indicate that open-marine seaway connections

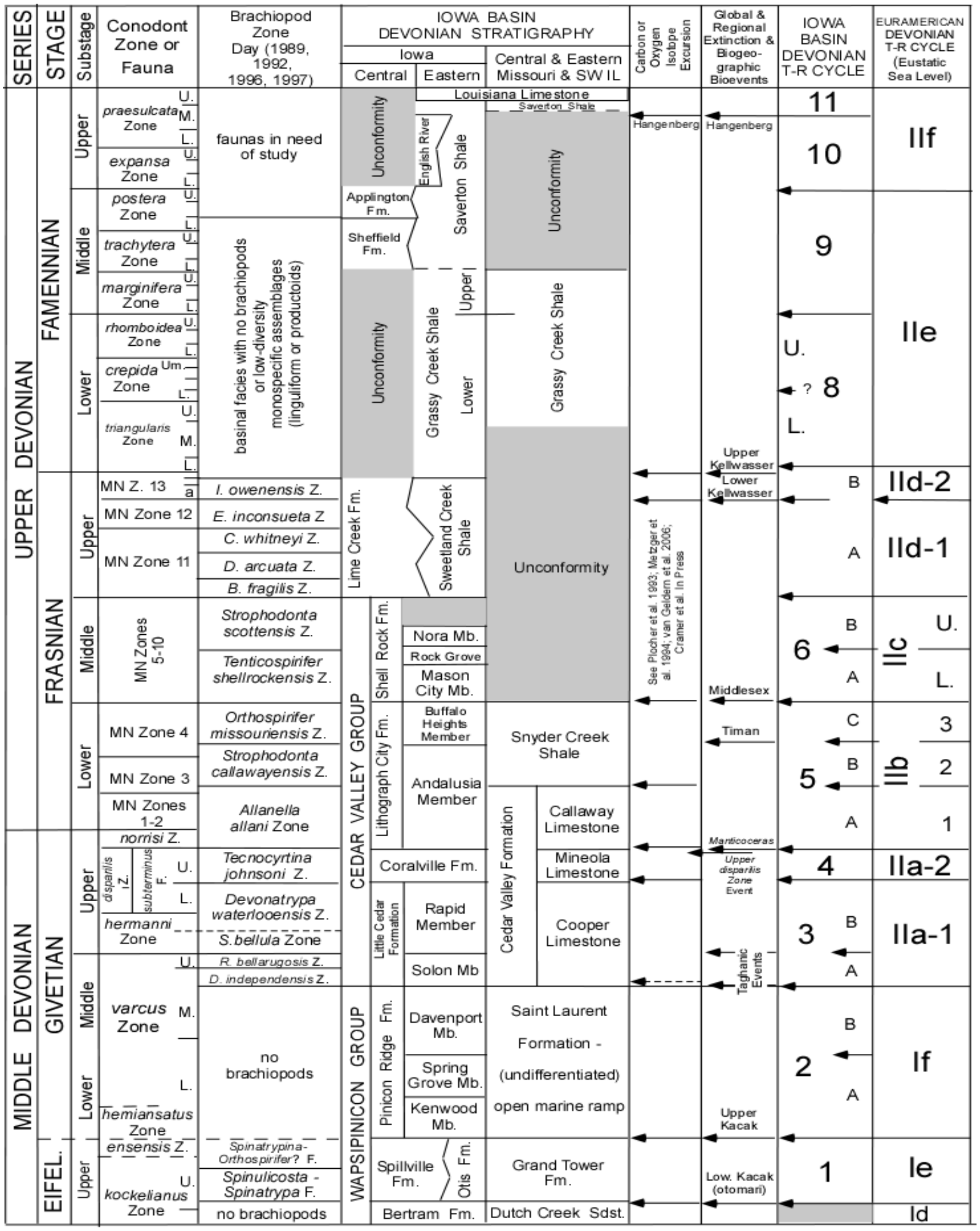

Figure 3. Stratigraphic and biostratigraphic framework for the Middle-Late Devonian (late Eifelian-Famennian) strata of the Iowa Basin showing relationships between: the qualitative eustatic T-R cycles of Johnson and others (1985), Johnson and Klapper (1992), Day and others (1996), Day (1998) and this paper; and Iowa Basin Devonian T-R cycles of Witzke and others (1989), Bunker and Witzke (1992), and Witzke and Bunker (1996, 1997a, 1997b). Iowa Devonian conodont biostratigraphy follows Witzke and others (1985, 1989), Klapper and Johnson (*in* Johnson, 1990), Woodruff (1990), Day (1990), Klapper (*in* Johnson and Klapper, 1992), Bunker and Witzke (1992), Witzke and Bunker (1996), Over (2002, page 75 of this guidebook), Famennian conodont biostratigraphy after Ziegler and Sandberg (1984, 1990). Devonian brachiopod biostratigraphy from Day (1989, 1992, 1996, 1997). Iowa Basin Devonian stratigraphy after Witzke and others (1989), Bunker and Witzke (1992), Witzke and Bunker (1996), and Day (1997). Modified from Day (1997, Fig. 4) and Day (1998, Fig. 3).

were established across the Transcontinental Arch with central and western North American Old World Realm (OWR) shelves during most major transgressions (Day et al., 1996), except during Euramerican Devonian T-R cycle If (Fig. 3). Significant connections were also established at these times with Eastern Americas Realm (EAR) carbonate and clastic shelves in the Michigan and Appalachian basins, although the most significant sources of brachiopod migrants appeared to be western and arctic North American OWR carbonate shelf areas.

Cedar Valley Group Conodont Sequence

The conodont biostratigraphy of the Cedar Valley Group in southeastern Iowa has been documented (Witzke et al., 1985, 1989; and Day, 1994, 1997) in a series of studies of surface exposures, primarily at the LaFarge Corporation Buffalo Quarry (Figs. 3 and 8). For the purposes of recovering conodont apatites and brachiopod calcites for stable isotopic analyses (Joachimski et al., 2004, Breisig et al. 2006; van Geldern and others, page. 89 this guidebook) the IPSCO PPW # 3 Core (Figs. 2 and 8) was split and one half of the core processed for conodonts. The entire Cedar Valley Group was sampled at a 20 cm interval continuously through the succession, and provides unprecedented sample density through the subtidal carbonate platform facies stack. The Cedar Valley Group IPSCO PPW # 3 core conodont sequence is presented in Table 1 and is consistent with the sequence established in previous studies.

Little Cedar Formation

The lower 2.62 meters of the Solon Member yield assemblages of the Middle *varcus* Zone (Table 1, samples 53 to 255) that contain *Polygnathus linguiformis linguiformis* gamma, *Icriodus brevis, and Icriodus latericrescens latericrescens.* Reported here for the first time is the recovery of *Schmidtognathus latifossatus* in sample 315 2.62 meters above the base of the Solon permitting identification of the base Upper *varcus* Zone in the Iowa Basin for the first time in the upper part of the Solon in the Little Cedar Formation.

As is know from other well studied sites including the Buffalo Quarry (Witzke et al., 1985), the base of the *hermanni* Zone is coincident with the base of the Rapid Member, marked by the first occurrence of the fauna that includes *Schmidtognathus wittekindti, I. difficilis, Polygnathus xylus xylus* in sample 384 (Table 1). Of note is the occurrence of *Icriodus* aff. *subterminus* beginning in sample 565 with its highest occurrence in sample 2865 in the lower part of the Andalusia Member of the Lithograph City Formation (Table 1). This species is ancestral *to I. subterminus* (G. Klapper, personal communication) and the ranges of both species overlap in the upper part of the Rapid Member where the lowest occurrence of *I. subterminus* is in sample 1265 (Table 1) 12.12 meters above the base of the Little Cedar Formation. The base of the Lower *Icriodus subterminus* Fauna is defined at the first occurrence of the nominal species and its position is in the middle part of the Rapid Member as discussed above. The Interval of the Icriodus *subterminus* Fauna is considered to coincide to the *disparilis* Zone (see discussions in Witzke et al. 1985, 1989; Rogers, 1990, 1998; and Day et al., 1996).

Coralville Formation

In the Iowa Basin, the base of the Upper *subterminus* Fauna (Fig. 3) is marked by the first occurrence of *Mehlina gradata* in assemblages with *I. subterminus* in northern Iowa (Witzke et al., 1989; Witzke and Bunker 1992). *Mehlina gradata* does not occur in the basal Cou Falls in sections at the Buffalo Quarry (Fig. 8) and in the IPSCO PPW 3 # Core (Fig. 7, Table 1). In the latter subsurface sequence, *M. gradata* has not been recovered in the Cou Falls, and has its first occurrence in the lower Andalusia Member (Fig. 7, upper part of unit 39; Table 1, sample 2805). Consequently the Upper *subterminus* Fauna cannot be identified in the IPSCO PPW # 3 core sequence (Fig. 7; Table 1). The Coralville conodont sequence in the IPSCO PPW #3 core

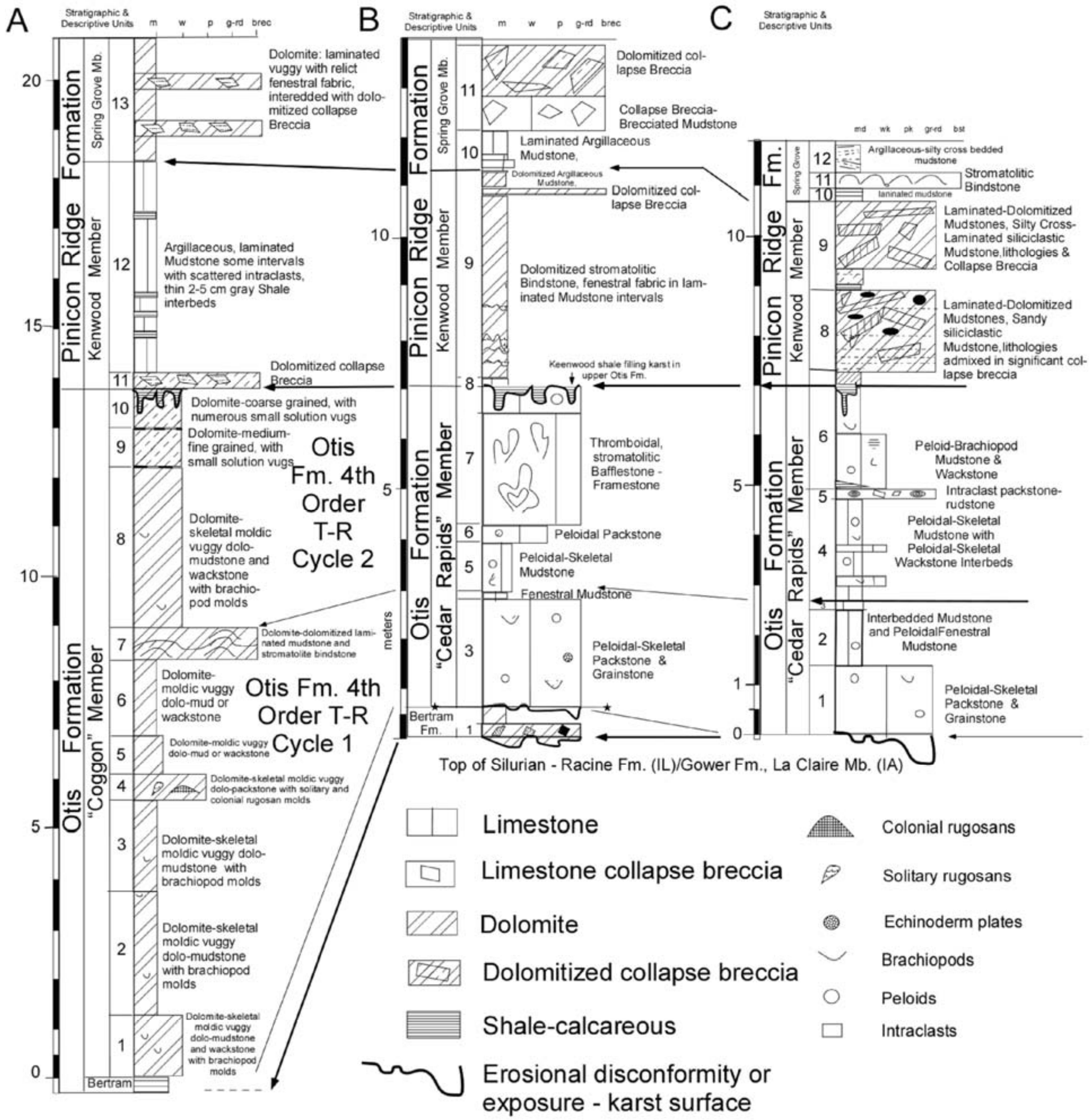

Figure 4. Stratigraphy and cyclostratigraphy of the lower Wapsipinicon Group in cores samples from Muscatine County, Iowa, and the upper ramp road section of the Allied Quarry in Rock Island County, Illinois (Stop 2 of this guidebook). **A.** Section of the Otis and lower Wapsipinicon formations in the Moscow Quarry core, Muscatine Co., Iowa, location: Sec. 08, T. 78 N., R. 02 W. **B.** Section of the Otis and lower Wapsipinicon formations in the IPSCO PPW#3 core, Muscatine Co, Iowa. **C.** Section of the Otis and lower Wapsipinicon formations along the upper ramp road-cut on the west side of Allied Quarry in Rock Island Co., Illinois. Black highlighted arrows are major flooding events associated with sea level rises of Iowa Basin Devonian T-R cycles 1 and 2, with a newly recognized flooding event within the Otis, defining two 4th order T-R cycles.

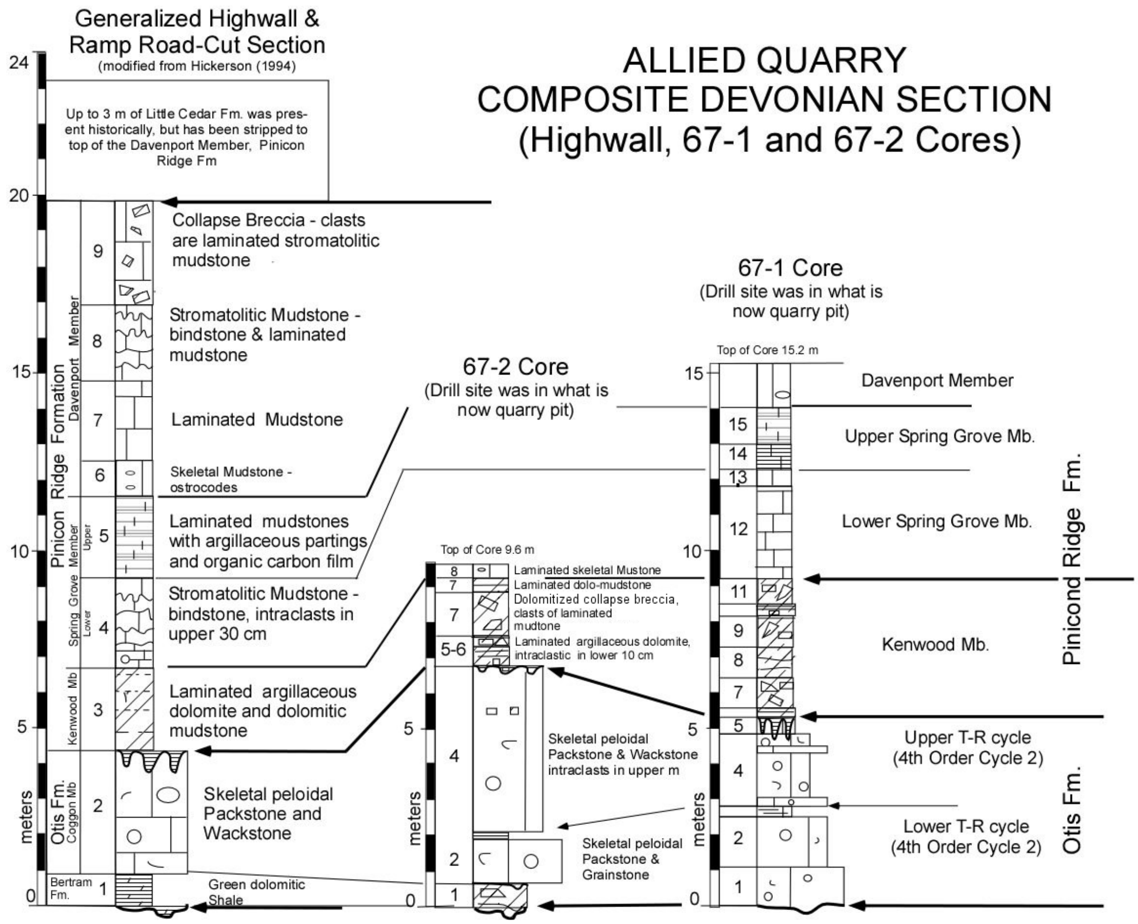

Figure 5. Stratigraphy and Devonian T-R cycles developed in the Wapsipinicon Group in the highwall section and cores 67-1 and 67-2 from the Allied Quarry, Rock Island County, Illinois. Locations given in Stop 2 discussion.

(Table 1, samples 2065 to 2625) is dominated by *Icriodus subterminus*, with *I.* aff. *subterminus*, and *Polygnathus klugi*? The Cou Falls conodont sequence from the Buffalo Quarry is similar although *M. gradata* has been recovered in the in the upper Cou Falls in units 30 and 31 of Figure 8 (Day, 1992, fig. 12, samples 4C and 5C).

In all prior conodont investigations of the Cedar Valley Group conodont sequence, *Pandorinellina insita* has never been recovered from the Coralville Formation. The first entry of this form is known to be no lower than the base of the *norrisi* Zone. In all prior reports it first occurs in the basal the Lithograph City Formation in eastern Iowa. A single specimen was recovered in sample 2645 (Table 1) at a position 70 cm below the top of the Cou Falls in the upper part of unit 30 (Fig. 7). This anomalous occurrence is explained as a stratigraphic leak of shales from the lowest Andalusia Member observed filling the burrows extending downward to this position from the burrowed hardground discontinuity at the top of Cou Falls (Fig. 7, top of unit 37).

Lithograph City Formation

Strata of the lower part of the Lithograph City (Andalusia, State Quarry, and Osage Springs members) contain conodonts of the *insita* Fauna, and *Skeletognathus norrisi* is reported from the State Quarry Member at one locality in Johnson County of eastern Iowa (Witzke et al., 1985; Johnson and Klapper, 1992) supporting correlation of the basal Lithograph City with the *norrisi* Zone. In southeastern Iowa, at both the Buffalo Quarry and in the IPSCO PPW # 3 core (Table 1) conodont faunas recovered from subtidal carbonates and shales of the lower Andalusia Member are assignable to the *Pandorinellina insita* Fauna, and do not feature diagnostic species of *Skeletognathus* and *Ancyrodella* permitting accurate correlations with the latest Givetian *S. norrisi* Zone and early Frasnian Montagne Noire Zones 1 to 3 of Klapper (1989). The incoming of the lowest *P. insita* in the basal Andalusia is correlated the *norrisi* Zone (Witzke et al., 1989), Bunker and Witzke (1992), Witzke and Bunker 1996), Day and others (1996).

The uppermost part of the Andalusia Member at the Buffalo Quarry contains a fauna that includes *Ancyrodella alata* late form, *A. africana*, *A. rugosa*, and *Mesotaxis asymmetrica* (unit 43 of Fig. 8; Day, 1992), and is correlated with Montagne Noire Frasnian Zone 4 of Klapper (1989) constraining the upper age range of Iowa Devonian T-R cycle 5B within the lower part of Zone 4. Day (1992) defined the *Allanella allani* and *Strophodonta callawayensis* zones based on the brachiopod sequence in the lower and upper parts of the Andalusia Member at the Buffalo Quarry with zonal boundaries of both coincident with sequence boundaries of T-R cycles 5A (Fig. 8, at base of unit 32) and 5B (Fig. 8, at base unit 35). The Buffalo Heights Member yields conodont faunas of Montagne Zone 4 in unit 40 at its type section at the Buffalo Quarry in Scott County, Iowa (Figs. 2 and 8). M.N. Zone 4 conodonts occur in association with brachiopods characterizing the *Orthospirifer missouriensis* Zone of Day (1997). The sea level event that initiated Buffalo Heights deposition is constrained as within early Frasnian M.N. Zone 4 (Fig. 3). This fixes the timing of the marine flooding event that initiated Iowa Devonian T-R cycle 3C as an intra M.N. Zone 4 event In Iowa and Missouri (Day, 2004). A major marine flooding event is now recognized in the western Canadian Sedimentary Basin in both the Alberta Rocky Mountain outcrop sections (Day and Whalen, 2003: Whalen and Day, 2005), the central Alberta subsurface (Uyeno and Wendte, 2005; Wendte and Uyeno, 2006), and Poland (T-R cycle IIb/c of Racki et al., 2004). Consequently this event certainly influenced sedimentation across Laurussia and appears to be a global sea level signal.

IOWA BASIN QUALITATIVE SEA LEVEL CHANGES AND RELATION TO PROPOSED EUSTATIC SEA LEVEL EVENT FRAMEWORK

The first eustatic sea level hypothesis for the Devonian Period was proposed by Johnson and others (1985), where the Devonian was divided into two large tectonic-eustatic Depophases I and II. These were further subdivided into smaller eustatic Transgressive-Regressive (T-R) cycles. This hypothesis had been tested and supported in numerous subsequent studies. Further refinements to the Johnson and others (1985) sea level framework have been proposed by Day and others (1996), Day (1998, 2004) and Whalen and Day (2005) that involve subdivisions of Devonian T-R cycles IIa, IIb, and IId shown in Figure 3. Deposition of Wapsipinicon and Cedar Valley Group strata coincided with late Eifelian to early Frasnian Devonian T-R cycles Ie to IIb of the original eustatic sea level scheme of Johnson and others (1985).

Deposition of Wapsipinicon and Cedar Valley Group strata in southeastern Iowa is marked by a series of five major T-R depositional cycles, further divided into additional cycles, most of which can be widely correlated with the current conodont-brachiopod biostratigraphy (Fig. 3). Each major Cedar Valley T-R cycle is bounded regionally by disconformities, and was terminated by progradation of mudflat facies in inner shelf areas of central and parts of eastern Iowa. Evaporite deposition occurred during regressive portions of each cycle in the central parts of the Iowa Basin (Figure 2). Cedar Valley Group T-R cycles are developed entirely in open marine facies in the Scott County area of eastern Iowa, where T-R cycle boundaries consist of cemented and bored submarine hard grounds or discontinuity surfaces (Witzke et al., 1989;

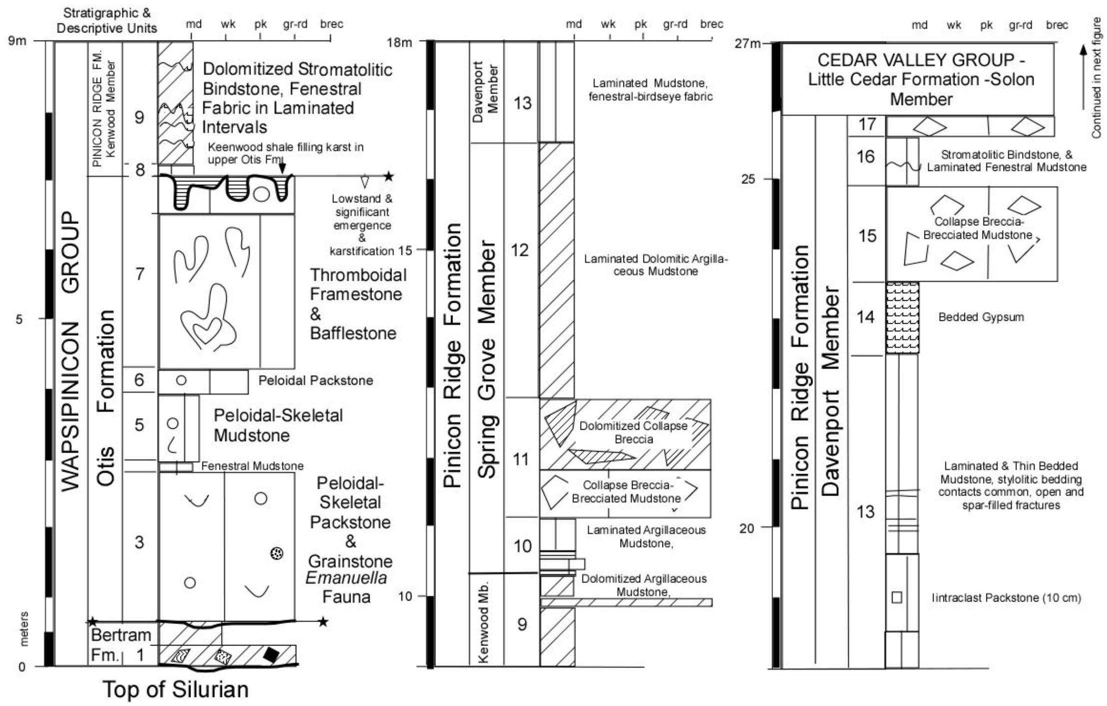

Figure 6. Stratigraphy of the Wapsipinicon Group in the IPSCO PPW # 3 core from Muscatine County, Iowa. Arrows at major discontinuities denote positions of major marine flooding surfaces and define T-R cycle boundaries. Arrow within the Otis Formation shows the position of the minor flooding event of Otis Formation 4th Order T-R cycle 2. Location: SW NE SW Sec. 15, T.77 N., R. 1 E.

Bunker and Witzke, 1992; Witzke and Bunker, 1996, and page 23 of this guidebook). Well developed erosional hiatuses separate the Wapsipinicon and Cedar Valley groups, and the Coralville and Lithograph City formations of the Cedar Valley Group, indicating withdrawal of epeiric seas from the Iowa area in the early (pre-Middle *varcus* Subzone) and late Givetian (Upper *subterminus* Fauna = approximately Upper *disparilis* Zone), respectively. The timing of these withdrawals in Iowa corresponds to regressive events in the central and western Canadian platforms as well (Day et al., 1996). Pre-Lime Creek period of emergence also terminated Shell Rock Formation deposition during the Middle Frasnian and is discussed further by Witzke and Bunker, page 23 of this guidebook (Iowa T-R cycle 6, Fig. 3).

Wapsipinicon Group Sea Level Events

Iowa Devonian T-R Cycle 1 (Otis & Spillville formations). Initial Devonian marine transgression into the Iowa Basin is represented by strata of the Otis and Spillville formations, deposited during the mid-late Eifelian, which correspond to T-R cycle Ie (Witzke et al., 1989; Bunker and Witzke, 1992; Bunker et al., 1996; Johnson and Klapper, 1992). The occurrences of *Ozarkodina raaschi* in the Otis, and more diverse conodonts in the Spillville (approximate *kockelianus* through lower *ensensis* Zones, Klapper and Barrick, 1983) indicate correlation with Euramerican T-R cycle Ie, that began during the *kockelianus* Zone (Johnson et al., 1985, 1996; Johnson and Klapper, 1992, Day et al., 1996). Strata of the Otis Formation yield a single brachiopod species identified as *Emanuella* cf. *E.* sp. II of Caldwell (1968). The occurrence of Old World Realm atrypid and emanuellid brachiopods in Spillville and Otis rocks of northern and eastern Iowa indicates that the T-R cycle Ie transgression breached the Transcontinental Arch, and established faunal connections between the southern Elk Point and Williston basins and the Iowa, Michigan, and Appalachian basins at this time (Fig. 1). The onset of peritidal carbonate and evaporite deposition in the Iowa Basin during T-R cycle

CONDONT ZONE or FAUNA	upper Middle *varcus* Z.						Upper*varcus* Z.				hermanni Zone (continues through sample interval 1245)																							
SAMPLE INTERVAL	53	75	95	115	235	255	315	335	355	375	384	405	425	445	465	485	505	525	545	565	585	605	625	645	665	685	705	725	745	765	785	805	845	865
CONODONT TAXON																																		
Polygnathus linguiformis l. gamma	X	X	X	X																														
Icriodus brevis	X		X																															
Icriodus sp.	X		X						X	X																				X	X	X		
Polygnathus linguiformis indet.frags.		X																																
Icriodus latericrescens latericrescens					X	X																		X										
genus indet. - 1					X																													
Schmidtognathus latifossatus							X																											
Ozarkodina sp. indet.							X	X																										
Icriodus latericrescens latericrescens?								X																										
Polygnathus sp. indet.								X															X											
Icriodus sp. aff. *I. difficilis*									X																									
Icriodus difficilis										X	X	X	X	X	X	X	X	X	X	X	X	X	X				X							
Schmidtognathus wittekindti											X							X																
Polygnathus xylus xylus											X	X		X																				
Polygnathus dubius?													X	X		X	X	X	X															
Schmidtognathus n.sp.?,														X																				
Polygnathus sp.?															X																			
Icriodus aff. *I. subterminus*																				X	X			X	X	X		X	X					X
Polygnathus sp.																				X	X	X						X	X	X	X			
Schmidtognathus wittekindti?																					X													
Elsonella rhenana																					X													
Polygnathus dubius																						X												
Prioniodina sp.																						X						X			X	X		X
Polygnathus klugi																								X	X	X						X	X	
Polygnathus klugi?																																		
STRATIGRAPHIC UNIT	SOLON MEMBER										LITTLE CEDAR FORMATION - RAPID MEMBER																							

Table 1. Middle Givetian to early Frasnian Conodont sequence in the Cedar Valley Group in the IPSCO PPW #3 Core, Muscatine County Iowa. Continuous sampling occurred every 20 cm. Elevations of samples are shown in cm with the lowest Solon Member sample at the base of that unit in the core sequence. The zero cm datum was 53 cm below the contact of the Solon-Davenport Member contact (see Fig. 7).

CONDONT ZONE or FAUNA	***hermanni* Zone**																	***Icriodus subterminus* Fauna**																
SAMPLE INTERVAL	885	905	925	945	965	985	1005	1065	1085	1105	1125	1145	1165	1185	1205	1225	1245	1265	1285	1305	1365	1385	1405	1425	1445	1465	1505	1525	1565	1625	1645	1685	1705	1725
CONODONT TAXON																																		
Polygnathus linguiformis l. gamma																																		
Icriodus brevis																																		
Icriodus sp.						X						X							X			X							X		X		X	
Polygnathus linguiformis indet.frags.																																		
Icriodus latericrescens latericrescens																																		
genus indet. - 1																																		
Schmidtognathus latifossatus																																		
Ozarkodina sp. indet.																																		
Icriodus latericrescens latericrescens?																																		
Polygnathus sp. indet.																X				X		X								X				
Icriodus sp. aff. *I. difficilis*																																		
Icriodus difficilis																																		
Schmidtognathus wittekindti																																		
Polygnathus xylus xylus																																		
Polygnathus dubius?																																		
Schmidtognathus n.sp.?,																																		
Polygnathus sp.?																																		
Icriodus aff. *I. subterminus*	X	X	X	X	X		X		X	X	X				X	X	X	X			X		X	X	X			X						
Polygnathus sp.	X																								X				X		X			
Schmidtognathus wittekindti?																																		
Elsonella rhenana																																		
Polygnathus dubius																																		
Prioniodina sp.		X						X	X		X			X	X				X				X											
Polygnathus klugi		X	X		X		X			X	X	X		X	X		X						X	X			X							
Polygnathus klugi?													X																			X	X	X
Icriodus subterminus																		X					X	X	X	X		X				X		X
Mehlina g radata																									X									
Polygnathus cf. *P. ovatinodosus*																															X			
STRATIGRAPHIC UNIT	**LITTLE CEDAR FORMATION - RAPID MEMBER**																																	

Table 1 (continued). Middle Givetian to early Frasnian Conodont sequence in the Cedar Valley Group in the IPSCO PPW #3 Core, Muscatine County Iowa. Continuous sampling occurred every 20 cm. Elevations of samples are shown in cm with the lowest Solon Member sample at the base of that unit in the core sequence. The zero cm datum was 53 cm below the contact of the Solon-Davenport Member contact (see Fig. 7).

CONDONT ZONE or FAUNA	*subterminus* Fauna																				*Pandorinellina insita* Fauna																							
SAMPLE INTERVAL	1805	1865	1885	2065	2105	2165	2205	2265	2285	2305	2345	2405	2425	2445	2465	2525	2545	2565	2585	2625	2645	2718	2805	2845	2865	2885	2905	2925	2945	2985	3005	3025	3065	3105	3125	2905	2925	2945	2985	3005	3025	3065	3105	3125
CONODONT TAXON																																												
Polygnathus linguiformis l. gamma																																												
Icriodus brevis				X		X	X				X								X																									
Icriodus sp.																																												
Polygnathus linguiformis indet.frags.																																												
Icriodus latericrescens latericrescens																																												
genus indet. - 1																																												
Schmidtognathus latifossatus																																												
Ozarkodina sp. indet.																																												
Icriodus latericrescens latericrescens?																																												
Polygnathus sp. indet.																																												
Icriodus sp. aff. *I. difficilis*																																												
Icriodus difficilis																																												
Schmidtognathus wittekindti																																												
Polygnathus xylus xylus																																												
Polygnathus dubius?																																												
Schmidtognathus n.sp.?,																																												
Polygnathus sp.?																																												
Icriodus aff. *I. subterminus*				X	X		X	X	X	X	X					X			X						X																			
Polygnathus sp.																																												
Schmidtognathus wittekindti?																																												
Elsonella rhenana				X																																								
Polygnathus dubius	X							X					X																															
Prioniodina sp.			X																																									
Polygnathus klugi	X																																											
Polygnathus klugi?	X	X	X		X		X	X	X	X	X					X	X	X	X			X	X	X	X	X	X			X	X		X	X										
Icriodus subterminus											X	X		X	X		X		X	X																X			X	X		X	X	
Mehlina g radata																																												
Polygnathus cf. *P. ovatinodosus*					X																																							
Schmidtognathus ? gracilis						X		X																																				
Polygnathus cf. *P. incompletus*																			X																									
Polygnathus angustidiscus																					X	X			X			X	X		X	X			X									
Pandorinellina insita																						X															X	X		X	X			X
Mehlina g radata?																							X			X																		
Mehlina or *Padorinellina* indet. Pa element																																												
STRATIGRAPHIC UNIT	RAPID			CORALVILLE FORMATION - COU FALLS MB.																	LITHOGRAPH CITY FORMATION - ANDALUSIA MEMBER																							

Table 1 (continued). Middle Givetian to early Frasnian Conodont sequence in the Cedar Valley Group in the IPSCO PPW #3 Core, Muscatine County Iowa. Continuous sampling occurred every 20 cm. Elevations of samples are shown in cm with the lowest Solon Member sample at the base of that unit in the core sequence. The zero cm datum was 53 cm below the contact of the Solon-Davenport Member contact (see Fig. 7).

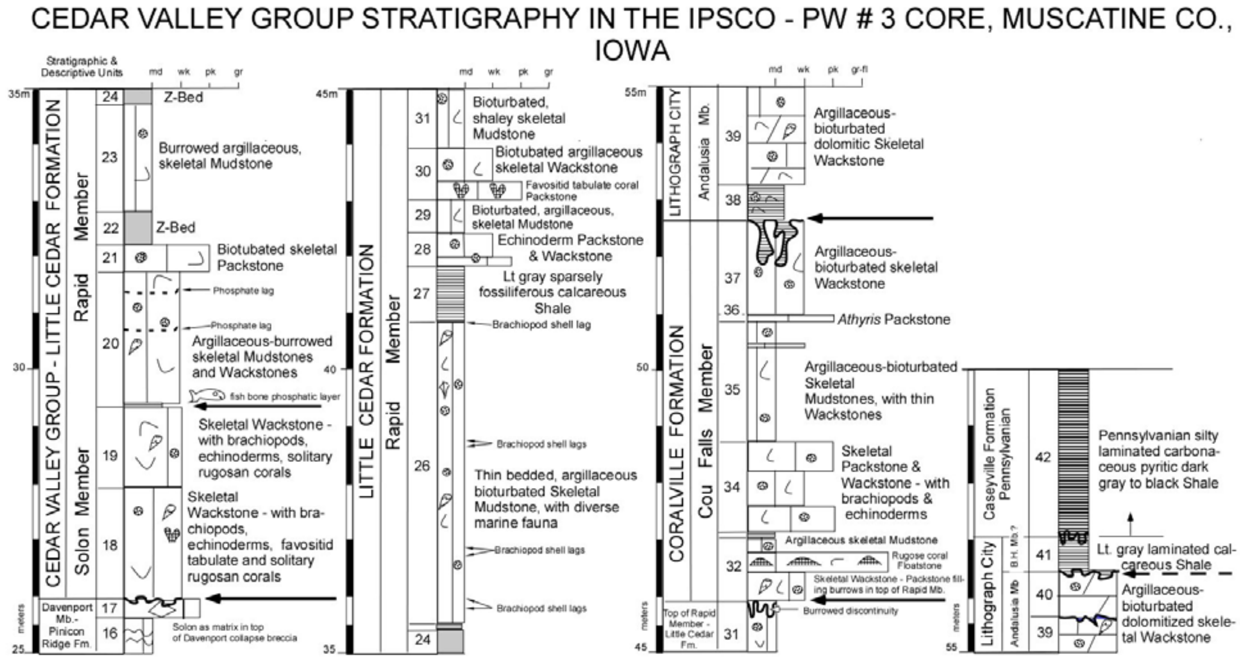

Figure 7. Stratigraphy of the Cedar Valley Group in the IPSCO PPW # 3 core from Muscatine County, Iowa. Arrows at major discontinuities denote positions of major marine flooding surfaces and define T-R cycle boundaries (Fig. 3).

If resulted in the extirpation and/or extinction of the Spillville and Otis shelly invertebrate faunas during the early Givetian.

The Otis can be further subdivided into two smaller-scale 4th order cycles as evidenced by development of two shallowing-up carbonate packages preserved in subsurface sections at the Moscow Quarry and IPSCO-PPW # 3 cores in Muscatine County of southeastern Iowa (Figs. 4 and 5), and in the section exposed in Allied Quarry in Rock Island County of western Illinois (Fig. 6, Stop 2 this guidebook). These small-scale cycles are difficult to recognize in most Otis sections to the northwest in east-central Iowa in its type area where the Otis is represented by predominately dolomite facies (Cedar Rapids Member). Otis platform deposition was terminated by lowstand and platform emergence and development and erosional topography and karst solution cavities later backfilled by Kenwood Member lithologies of the overlying Pinicon Ridge Formation during the resumed sea level rise of T-R cycle 2.

Iowa Devonian T-R Cycle 2 (Pinicon Ridge Formation). Deposition of the Pinicon Ridge Formation during T-R cycle If (Fig. 3; Witzke et al., 1989; Bunker and Witzke, 1992; Witzke and Bunker, 1996, page 47 of this guidebook; Johnson and Klapper, 1992) marked a regional expansion of the epeiric seaway, although the seaway displayed restricted circulation patterns that excluded stenotypic marine organisms across the Iowa Basin (Bunker and Witzke, 1992, page 47 of this guidebook; Bunker et al., 1996; Day et al., 1996). Cyclic deposition of aphanitic mudstone-evaporite-shale sequences is typical of Pinicon Ridge deposition throughout much of the Iowa Basin area during T-R cycle If.

T-R cycles 2A & 2B. Basal Kenwood Member facies of the Pinicon Ridge marks the onset of deposition of one of two subcycles (Fig. 3, Iowa T-R cycle 2A), and overstep older deposits of the Otis and Spillville formations, marking a significant expansion of the Middle Devonian cratonic seaway in the U.S. midcontinent (Witzke et al., 1989; Bunker and

Witzke, 1992, 1996, page 47 of this guidebook). Another major mid-Givetian sea level rise and continued expansion of the seaway system is marked by overstepping of the Kenwood by restricted peritidal facies of the Spring Grove and Davenport members comprising Iowa Devonian T-R cycle 2B of Bunker and Witzke (1992), Witzke and Bunker (1996). Devonian T-R cycle If deposition was terminated by a significant eustatic sea level fall in the mid-Givetian (Johnson et al 1985; Johnson and Sandberg, 1989; Day et al 1996), terminating Pinicon Ridge deposition across the Iowa Basin.

Cedar Valley Group Sea Level Events

Deposition of Cedar Valley Group T-R cycles during the late Givetian and early Frasnian was marked by significant expansion of the seaway with open-marine facies spread across most of Iowa and adjacent areas of Missouri and eastern Nebraska (Witzke et al., 1989; Witzke and Bunker, 1996, Day et al. 1996; Bunker and Witzke, 1992, 1996, page 47 of this guidebook), and the influx of largely cosmopolitan benthic marine faunas in the late Givetian (Taghanic Onlap of Johnson, 1970; T-R cycle IIa of Johnson and others (1985) and early Frasnian (Day, 1989, 1992, 1996).

At present, stratigraphic and biostratigraphic studies have identified six significant sea level rises that controlled the timing of Cedar Valley Group T-R cycles and all of these are widespread and can be identified in most basins in North America and in Devonian basins in Eurasia and represent epeiric records of global sea level signals.

Iowa Devonian T-R Cycle 3 (Little Cedar Formation). The initial marine transgression that imitated deposition of Cedar Valley Group T-R cycle 3 corresponds to one of the most significant eustatic sea level rises of the entire Devonian initially referred to as the Taghanic Onlap by Johnson (1970), and later included in T-R cycle IIa of Johnson and others (1985). The Taghanic Onlap of Johnson (1970) is know to involve at least two stepped sea level rises termed here as the Taghanic events (Fig. 3) the first coinciding with the major flooding initiating Devonian T-R cycle IIa (IIa1 of Day et al., 1996), and a second intra IIa event at the base of the *hermanni* Zone. These two stepped sea level rises were actually predicted in the initial eustatic sea level hypothesis posed by Johnson and others, (1985) on inspection of their qualitative sea level curve in the interval of T-R cycle IIa (see their Fig. 12). They also show a third stepped event in the interval of the IIa cycle, now designated as Devonian T-R cycle IIa-2 (Fig. 3) of Day and others, (1996)

T-R cycle 3A. The initial eustatic sea level rise of Devonian T-R cycle IIa-1 began in the upper part of the Middle *varcus* Subzone (base of the *Desquamatia* (*Independatrypa*) *independensis* Zone in Fig. 3). This event is recorded by the Solon Member of the Little Cedar Formation (T-R cycle 3A, Fig. 3, Figs. 6 and 7). The cemented hard-ground discontinuity capping the Solon Member (Figs. 6 and 7) denotes the position of a second significant widespread Taghanic deepening event of equivalent or even greater magnitude at or near the base of the *hermanni* Zone, coincident with the base of the Rapid Member of the Little Cedar.

T-R cycle 3B. The *hermanni* Zone at the base of the Rapid Member in the Iowa Basin is widely recognized across and outside of North America and marks the base of Iowa T-R cycle 3B (Fig. 3). Analysis of δO^{18} chemostratigraphy of conodont apatites (Joachimski et al., 2004, Fig. 3) and brachiopod calcites (van Geldern et al., page 89 of this guidebook) through the Solon and Rapid members show rapid shifts to negative values indicating a significant sea surface temperature maximum, the highest recorded for the Devonian) coincident with the maximum flooding and highstand of T-R cycle 3B. At this time it is not known whether this is a regional epeiric event in the central Laurussian subtropics, or a global event since the only record to date is from the Iowa Basin upper Givetian. If it is a global event, one might argue that thermoeustasy had some influence in the global sea level rise at that time.

Iowa Devonian T-R Cycle 4 (Coralville Formation). The second Cedar Valley Group T-R cycle is represented by strata of the Coralville Formation which is placed in the upper part of Johnson and others' (1985) T-R cycle IIa (Witzke and others, 1989; Bunker and Witzke, 1992; Johnson and Klapper, 1992), now designated as Euramerican Devonian T-R cycle IIa-2 (Day et al., 1996). As such, the Coralville Formation represents the last intra-IIa cycle deepening event recorded in the Iowa Basin (Fig. 3). Transgressive facies of the lower Cou Falls member of the Coralville yield conodonts of the Upper *subterminus* Fauna (Fig. 3; Table 1; Witzke et al., 1985; Witzke et al., 1989; Bunker and Witzke, 1992), and brachiopod faunas assigned to the *Tecnocyrtina johnsoni* Zone (Day, 1997). The Mineola Limestone of central Missouri yields the same conodont fauna association with the brachiopod *T. missouriensis missouriensis*. Similar conodont and brachiopod faunas also occur in the argillaceous limestone beds of the Souris River Formation in southwestern Manitoba (Day 1992; 1996, Day et al., 1996).

A pronounced regression terminated Coralville deposition in the Iowa Basin, during which Coralville strata and underlying units of the Little Cedar Formation experienced subaerial erosion and meteoric diagenesis (Plocher et al., 1992). In the Johnson County area of eastern Iowa, fluvial channel systems became entrenched in Coralville and older Little Cedar strata (Bunker and Witzke, 1989; Day, 1992). This valley system was subsequently filled by subtidal channel facies of the Lithograph City Formation (State Quarry Member) during the first of three transgressions in the Iowa Basin corresponding to interval originally included in T-R cycle IIb of Johnson and others (1985) and Johnson and Sandberg (1989).

Iowa Devonian T-R Cycle 5 (Lithograph City Formation). Three significant marine flooding events controlled the development of very late Givetian and early Frasnian carbonate platform and mixed carbonate-clastic facies of the Lithograph City Formation in the Iowa Basin defining Iowa Devonian T-R cycles 5A to 5C (Fig. 3). In southeastern Iowa the Lithograph City is divided into a lower Andalusia and upper Buffalo Heights Member (Figs. 2 and 3). The Andalusia comprises two major but condensed 3rd order T-R cycles (T-R cycles 5A and 5B, Fig. 3), and the Buffalo Heights comprises the eroded remnants the third 3rd Order cycle (T-R cycle 5B, Fig. 3).

T-R cycle 5A. The initial late Givetian marine flooding of Devonian T-R cycle IIb of Johnson and others (1985) and Johnson and Sandberg (1989) during the *norrisi* conodont zone (*Allanella allani* brachiopod Zone) is recorded by the lower Andalusia Member included in Iowa T-R cycle 5A as seen at surface exposures at the Buffalo Quarry (Fig. 8) and in the nearby subsurface section in the IPSCO PPW #3 core (Figs. 7 and 8). Although it cannot be identified using traditional zonal biostratigraphy, the Givetian-Frasnian stage boundary in this interval, although appears to fall within unit 30 of the IPSCO PPW # 3 core section (Fig. 7) based on the shallow water conodont faunas of the *Pandorinellina insita* Fauna, characteristic of the lower Andalusia Member in eastern Iowa (Table 1) and magnetic susceptibility data reported by Ellwood and Day, page 59 of this guidebook. .

T-R cycle 5B. Renewed marine flooding across North American platforms during Frasnian Montagne Noir (M.N.) Zone 3 (Iowa Basin *Strophodonta callawayensis* Zone) initiated deposition of the upper Andalusia Member of the Lithograph City Formation in southeastern Iowa and the Snyder Creek Shale in Iowa and Missouri, respectively (Fig. 3). This flooding coincides with Devonian T-R cycle IIb-2 of Day and others (1996). The flooding surface is at the base of unit 35 in the middle part of the Andalusia Member in the Buffalo Quarry section (Fig. 8), and likely is coincident with the hardground discontinuity at the top of unit 30 in the IPSCO PPW #3 core section (Fig. 7). Identification of the T-R cycle 5B flooding surface in the IPSCO PPW #3 core cannot be determined with certainty at this time because of the lack of conodonts diagnostic of M.N. Zone 3 in the upper Andalusia Member at this locality (Table 1).

T-R cycle 5C. The occurrence of brachiopod faunas of the *Orthospirifer missouriensis* Zone with conodonts of M.N. Zone 4 mark the flooding that initiated a second major early Frasnian transgression across the mid-continent carbonate platform (Fig. 3; Day, 1996, 1997). In eastern Iowa, this flooding event coincides with the base of the Buffalo

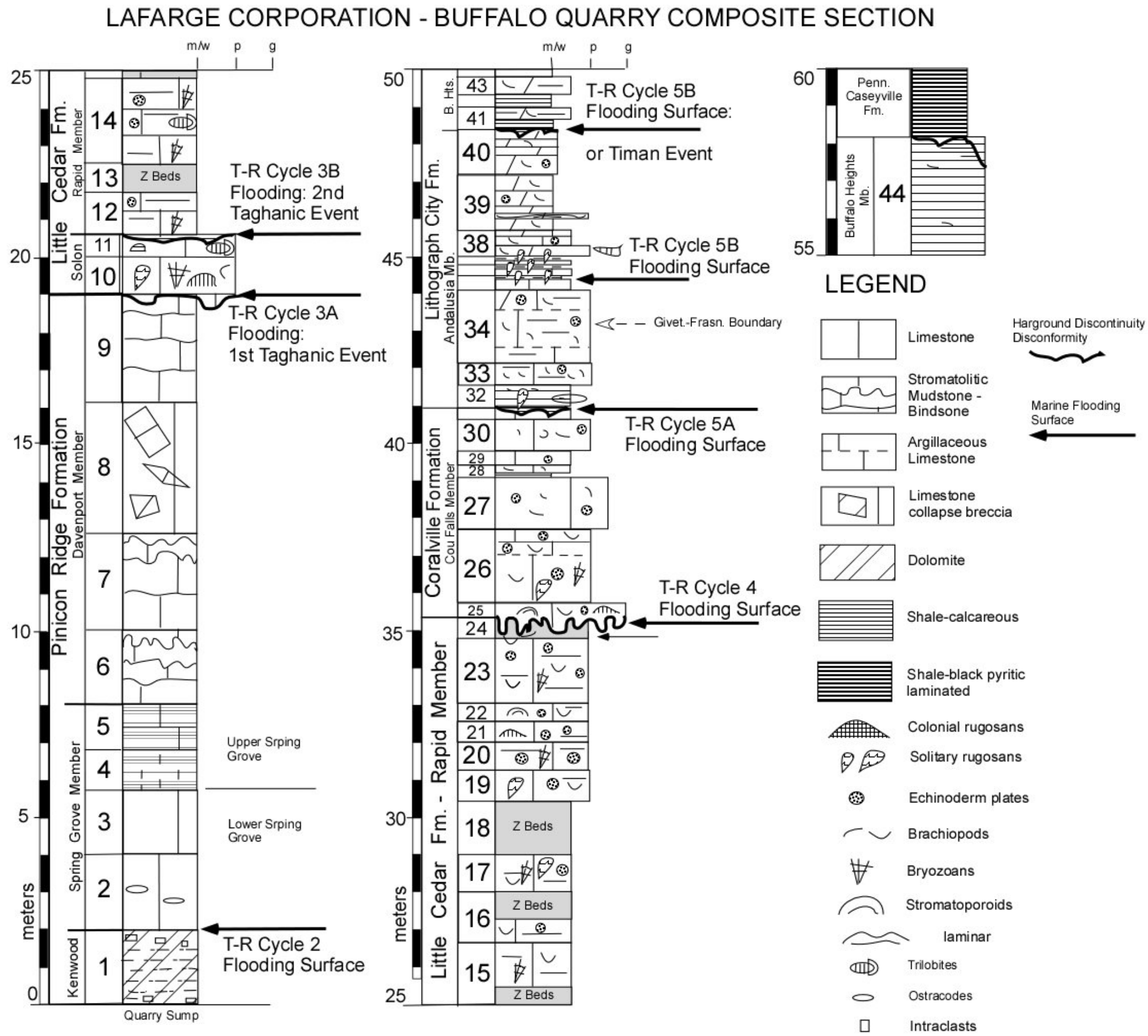

Figure 8. Stratigraphy of the Wapsipinicon and Cedar Valley groups at the Lafarge Corporation's Buffalo Quarry in Buffalo, Scott County Iowa. Arrows at major discontinuities denote positions of major marine flooding surfaces and define Wapsipinicon and Cedar Valley Group T-R cycle boundaries.

Heights Member of the Lithograph City Formation above the pyritic hardground discontinuity. This significant early Frasnian flooding event can be correlated with continental margin successions in western Canada (Alberta Rocky Mountain Devonian depositional sequence 4 of Whalen and Day (2005) and provides a regional record of a potential global event permitting subdivision of Devonian T-R cycle IIb-2 of Day and others (1996). This flooding event is coincident with the Timan event of House (1985)

SUMMARY

Epeiric carbonate platforms provide crucial records of regional relative sea level changes that can be correlated with similar records in widespread areas, hence providing records of global (eustatic) sea level fluctuations. Deposition of the late Eifelian to early Frasnian carbonate platform deposits of the Wapsipinicon and Cedar Valley groups occurred during as many as nine significant transgressive-regressive (T-R cycles). Most of the nine relative sea level rises that controlled deposition of Iowa T-R cycles 1 to 5 and their subdivisions (Fig. 3) are recognized in western North American sedimentary basins and hence likely represent regional records of Middle and Upper Devonian eustatic sea level changes in the subtropical epeiric seas of central Laurussia.

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MIDDLE SHELF FACIES OF THE CEDAR VALLEY GROUP (DEVONIAN) AND THEIR STRATIGRAPHIC RELATIONSHIPS IN EASTERN IOWA

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INTRODUCTION

The Cedar Valley Group of Iowa consists of four formations, each corresponding to a large-scale transgressive-regressive (T-R) depositional sequence and each deposited during a cyclic rise and fall of sea level. In ascending order, these include the Little Cedar, Coralville, Lithograph City, and Shell Rock formations. A revised stratigraphic framework for these strata, encompassing new stratigraphic nomenclature and improved correlations, was proposed by Witzke and others (1988), and the reader is referred to that reference for definitions and interpretations of the constituent formations and members of the Cedar Valley Group. Conodont biostratigraphic studies are summarized elsewhere (Witzke et al., 1985, 1988; Rogers, 1990, 1998; Bunker and Witzke, 1992; Kralik, 1992; Day, 1997; p. 1 of this guidebook). These studies, in conjunction with the proposed brachiopod (Day, 1992, 1997) and miospore (Klug, 1992) zonations, indicate that the Cedar Valley Group was deposited during the late Givetian (late Middle Devonian) and early Frasnian (early Late Devonian). The Middle-Upper Devonian boundary occupies a position within the middle part of the Lithograph City Formation. T-R sequences recognized in the Cedar Valley Group can be correlated across much of the North American continent, suggesting that large-scale eustatic changes in sea level were ultimately responsible for the development and cyclic expression of these stratigraphic intervals.

LITHOFACIES GROUPINGS

Witzke and Bunker (1996, 1997a) recognized two major lithofacies groupings within the Cedar Valley Group of Iowa, each geographically constrained and marked by different suites of lithofacies and significant contrasts in the nature of bounding surfaces within individual sequences. These groupings were used to characterize two general regions of Cedar Valley deposition: 1) a geographically expansive "inner-shelf" region (which includes much of Iowa and adjoining areas of Minnesota, Nebraska, and Missouri), and 2) a "middle-shelf" region (restricted to southeastern Iowa and adjoining areas of western Illinois and northeastern Missouri) (Figs. 1, 2). These regions are clearly separated at a sharp break located at the outer margin of the inner shelf, which marks the maximum distal progradation of peritidal facies in the region (shelf breaks for two of the Cedar Valley sequences are marked at the Hinkle and Iowa City edges shown on Figs. 1, 2).

The inner-shelf region of the Cedar Valley Group includes shallow-marine, peritidal, and mudflat/evaporite lithofacies. Peritidal and evaporitic facies are developed in the regressive (progradational) parts of each sequence, but such facies are completely absent across the middle-shelf area. Each sequence within the Cedar Valley Group is bounded by erosional subaerial exposure surfaces across the inner shelf. Deep erosional channels bound some of the Cedar Valley sequences in the distal inner-shelf area (Fig. 2), but erosional incision is less developed across more proximal areas of the inner shelf. Coral-stromatoporoid biostromes occur at a number of stratigraphic positions and geographic localities within the Cedar Valley succession, but they are best developed within the distal inner-shelf area in the Coralville Formation (Fig. 2).

The middle-shelf region of the Cedar Valley Group in southeastern Iowa is entirely represented by subtidal marine carbonate and argillaceous to shaley carbonate lithofacies, and this area represents a more offshore and deeper-water region of deposition compared to that developed across the inner shelf. Peritidal and

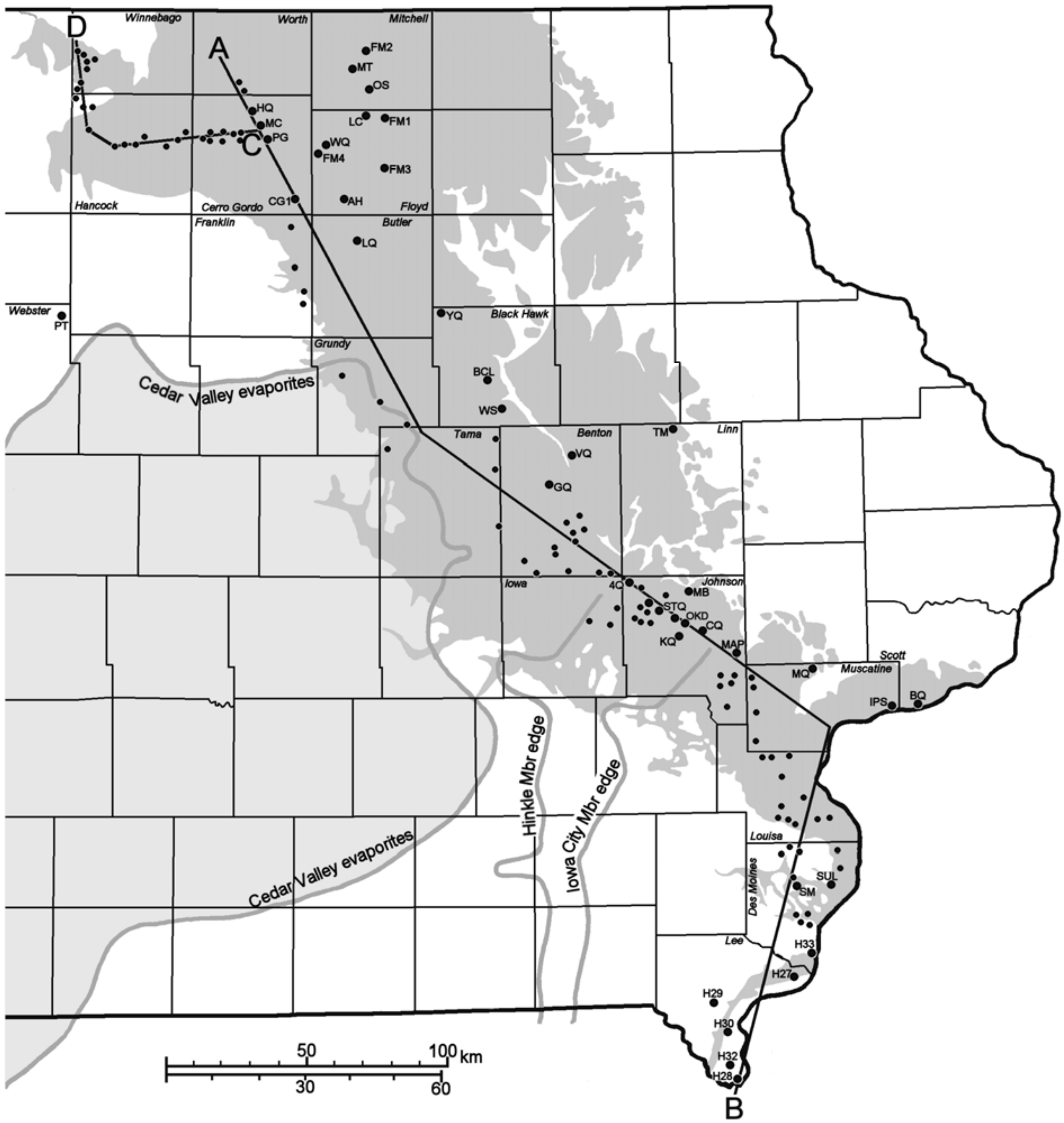

Figure 1. Map of eastern Iowa showing the location of cross-section lines AB (Fig. 2) and CD (Fig. 3). Darker shading depicts the Devonian outcrop belt, and lighter shading shows the extent of evaporites within the Cedar Valley Group (after Witzke et al., 1988). The distal margins of the Hinkle and Iowa City members (labeled lines) mark the general southeastward extent of inner-shelf facies within the Cedar Valley Group. Black dots show the location of surface and subsurface stratigraphic sections used in the construction of the cross sections. County boundaries are outlined and relevant counties are labeled. Labeled dots show the location of core and outcrop sections (see Witzke et al., 1988; Bunker et al., 1986; Witzke and Bunker, 1997a; Witzke, 1998 for descriptions and precise locations); smaller dots correspond to well sections (based on well cuttings only) available on the Iowa Geological Survey's Geosam database (http://gsbdata.igsb.uiowa.edu/geosam/).

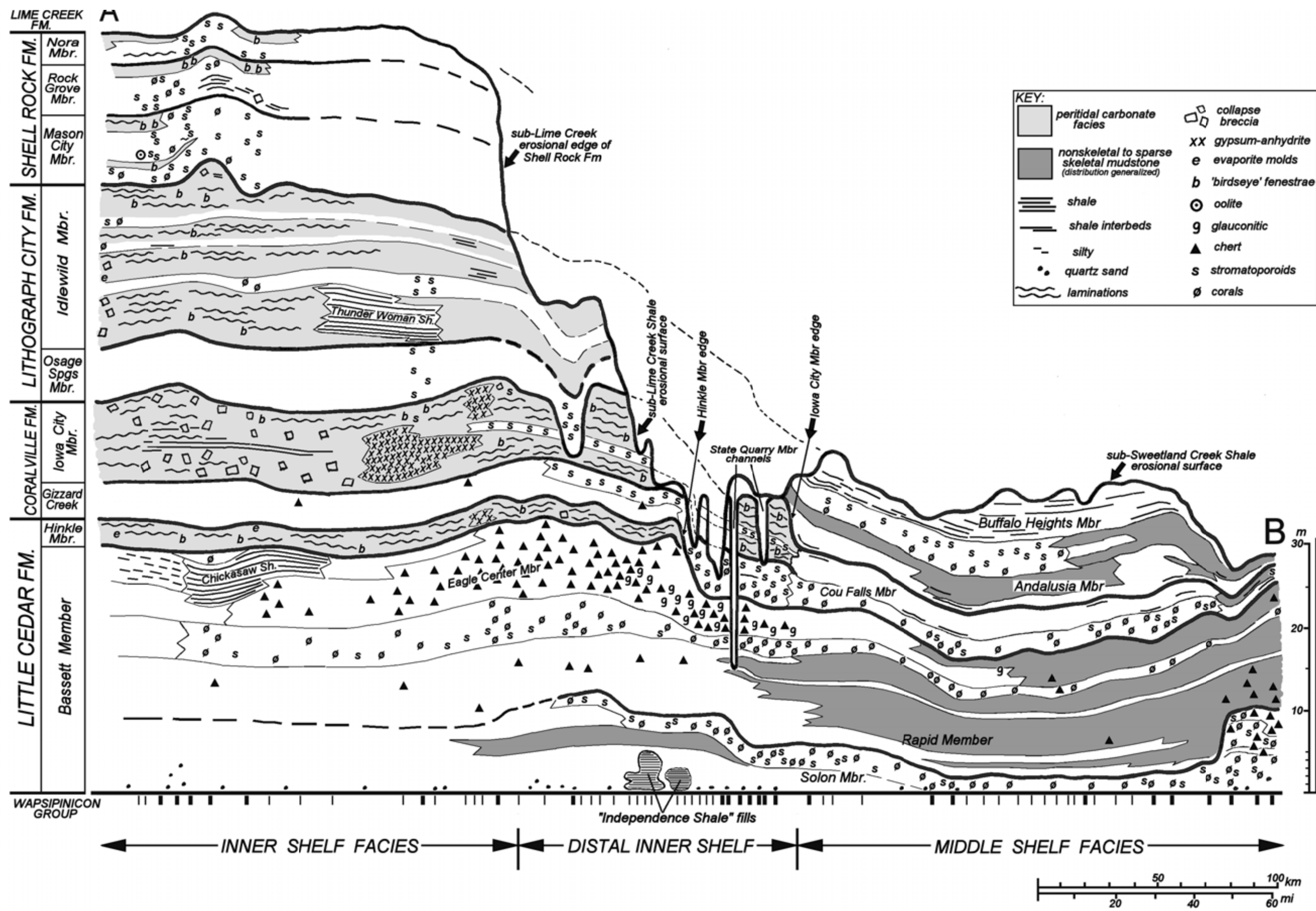

Figure 2. Northwest-southeast stratigraphic cross section of the Cedar Valley Group in eastern Iowa. Significant sub-Lime Creek/Sweetland Creek erosion has truncated Cedar Valley strata, especially in the distal inner-shelf area. "Independence Shale" fills represent stratigraphic leaks of Lime Creek Shale within Cedar Valley karst networks and openings. See Figure 1 for location of cross-section line (AB) and data points used in the construction.

evaporite facies are entirely absent across this region. In addition, the thickness of individual sequences is notably thinner across the middle shelf than seen across the inner shelf, and, by comparison, the middle-shelf sequences are relatively condensed (i.e., slower rates of sediment accumulation in offshore subtidal settings). As discussed later, the middle shelf facies of southeastern Iowa includes notably more evidence for starved and condensed sedimentation, particularly displayed by the development of phosphatic units and numerous subtidal hardground surfaces. The development of sparsely skeletal to nonskeletal argillaceous lime mudstones is largely restricted to the middle-shelf area in Iowa, and these facies are interpreted to represent the deepest-water depositional facies developed within the Cedar Valley Group.

REGIONAL STRATIGRAPHIC RELATIONS OF THE CEDAR VALLEY GROUP

The basal Cedar Valley Group onlaps and oversteps strata of the Middle Devonian Wapsipinicon Group northwestward in Iowa to directly overlie Ordovician strata across northern and northwestern Iowa. The succession of individual formations (T-R sequences) within the group progressively onlaps and oversteps underlying strata in a northwestward direction (Fig. 3), delimiting the depositional margins of the succession of Cedar Valley sequences across northwestern Iowa and south-central Minnesota. The Cedar Valley Group locally overlies Silurian strata along the trends of two erosional Silurian paleoescarpments in northeastern and southeastern Iowa (Witzke et al., 1988). The Cedar Valley strata overstep the Wapsipinicon Group edge across northern Missouri to overlie Ordovician units across much of northern and central Missouri. Cedar Valley depositional facies shallow southward onto the northern margins of the Ozark Dome in central Missouri, where equivalent Cedar Valley-Snyder Creek strata include a mix of lithofacies resembling, in part, transitional inner-shelf to middle-shelf facies of Iowa.

Cedar Valley strata overstep the Wapsipinicon Group edge in west-central to central Illinois along the northern trend of the Sangamon Arch. The general absence of Cedar Valley strata across this arch has been interpreted to be the result of non-deposition (Collinson and Atherton, 1975). Facies relationships within the Cedar Valley succession have not yet been determined along the margins of the Sangamon Arch, but the presence of deeper-water middle-shelf facies immediately northwest of this area in southeast Iowa, as well as similar Cedar Valley facies along its southern margin in western Illinois, raise questions about the presence of a landmass in that area during Cedar Valley deposition. Alternatively, it is proposed here that the absence of Cedar Valley strata across the Sangamon Arch is more likely due to sub-Sweetland Creek (Upper Frasnian) erosion. Increasing southwestward stratigraphic condensation of the Cedar Valley sequences across southeastern Iowa (as discussed subsequently) supports the idea that the Cedar Valley would have been represented by a similar condensed (or even starved) subtidal succession across the Sangamon Arch. Even limited sub-Sweetland Creek erosion could have removed the already thin Cedar Valley succession in that area. Southward in Illinois, Cedar Valley strata are replaced by equivalent carbonate and shaley strata of the Lingle and Alto formations. These latter formations display lithofacies that are closely similar to middle-shelf facies of the Cedar Valley Group in southeast Iowa, and they are included within the expansive middle-shelf grouping of the cratonic interior of the central United States. Lingle-Alto facies, in turn, are replaced southward by correlative black shales of the Blocher Shale (and possibly the basal part of the Selmier Shale) of southeastern Illinois and adjoining Indiana and Kentucky. The Blocher is a finely laminated, calcareous, unburrowed, organic black shale (Cluff et al., 1981) that represents the “outer-shelf” facies grouping of the late Middle Devonian epeiric sea.

As noted above, each large-scale sequence within the Cedar Valley Group of Iowa is bounded by a subaerial erosional surface across

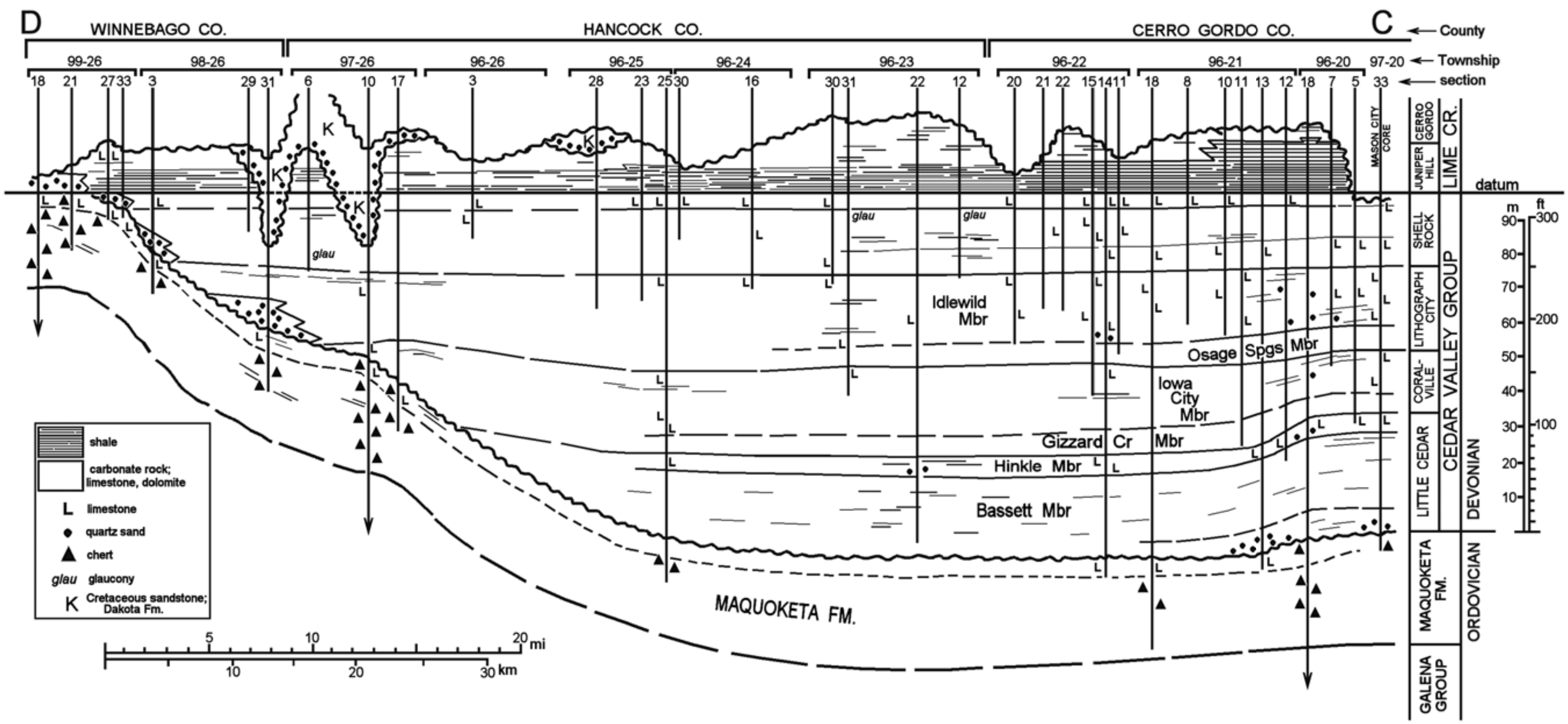

Figure 3. Interpretive stratigraphic cross section showing northwestward onlap of units within the Cedar Valley Group across the Devonian-Ordovician unconformity in north-central Iowa. Datum is base of Lime Creek Formation (interpolated where truncated by Cretaceous strata). See Figure 1 for location of cross-section line (CD) and well points used in the construction (well descriptions and locations available on Geosam database, http://gsbdata.igsb.uiowa.edu/geosam/).

the inner-shelf region. These inter-formational unconformities do not display significant erosional relief in most areas, typically a few decimeters or less. However, significant erosional relief characterizes the sub-Lithograph City Formation surface along portions of the distal inner shelf, as best displayed in areas where the State Quarry Member of the basal Lithograph City Formation infills deep erosional channels cut into underlying Coralville and Little Cedar strata (Fig. 2). These channels are known to incise up to 25 m in Johnson County, Iowa (Witzke and Bunker, 1994a), and, when the northward thickening of underlying strata is considered, an erosional incision of 32 to 35 m is displayed across the distal inner-shelf. These values provide minimum estimates of the magnitude of sea-level fall that occurred between deposition of the Coralville and Lithograph City formations on the inner shelf. Absolute sea-level changes would have been even greater than this, as the total maximum depth of the seaway during deposition of the lower Lithograph City Formation across the inner shelf must also be added to the erosional relief to provide the full magnitude of total sea-level change associated with this depositional cycle.

The upper surface of the Cedar Valley Group is deeply eroded beneath overlying strata of the Lime Creek-Sweetland Creek formations (upper Frasnian). This surface developed during an episode of subaerial erosion during part of the middle Frasnian. The Lime Creek Formation of northern and central Iowa is replaced southeastward by a more condensed but equivalent interval of Sweetland Creek Shale, and these characterize upper Frasnian inner- and middle-shelf facies, respectively, across Iowa (Witzke, 1987). The mid Frasnian erosional episode beveled and truncated units within the upper Cedar Valley Group across Iowa, and the Shell Rock Formation is sharply truncated across the distal inner-shelf area (Fig. 2). No stratigraphic equivalents of the Shell Rock Formation are identified across any part of the middle-shelf region of southeastern Iowa, northeastern to central Missouri, or central Illinois. The occurrence of shallow inner-shelf marine carbonate facies in the Shell Rock Formation of northern Iowa necessitates the presence of marine depositional facies in more offshore middle-shelf environments as well. The presence of middle-shelf Shell Rock facies would also be predicted from the facies patterns seen in older Cedar Valley T-R sequences. (patterns shown on Fig. 2). Therefore, it is concluded that the Shell Rock Formation must have been deposited across the middle shelf, but it was entirely eroded across this region during the mid Frasnian erosional episode.

The total erosional relief developed on the sub-Lime Creek surface exceeds the total thickness of the Shell Rock Formation, and the Lime Creek Formation is locally known to overlie any and all formations of the Cedar Valley Group at various localities in eastern Iowa and northeastern Missouri (locally as low as the upper Little Cedar Formation in parts of southeast Iowa and northeast Missouri). In general, local relief on this surface generally does not exceed 10 m, but when the full regional truncation of Cedar Valley strata across the inner-shelf region of Iowa is considered, an erosional truncation of 65 m of stratigraphic thickness is evident. Of course, depositonal slopes are not fully known, but considering the general southeastward depositional deepening (i.e., southeastward slope) seen in all T-R sequences of the Cedar Valley Group, the actual topographic relief was likely even greater than 65 m. The development of the "Independence Shale" in distal areas of the inner shelf is of additional note. Although originally considered to be a stratigraphic unit that separates Wapsipinicon and Cedar Valley strata, the "Independence Shale" is now known to be a stratigraphic leak of Lime Creek sediments (and fossils) into caverns and other karstic openings developed in the Little Cedar Formation (see Fig. 2), up to 90 m stratigraphically below the highest parts of the regional sub-Lime Creek erosional surface across the inner shelf. Additional fillings of Lime Creek sediments and microfossils have also been identified in karstic openings and fractures developed within Silurian dolomite strata at a number of localities in eastern Iowa (e.g., Bunker et al., 1985, p. 53).

While questions remain about the historic succession of regional paleokarst development and episodes of shale infilling, it seems a possibility that sub-Lime Creek erosional base levels may have been lowered enough to develop karst systems through the entire thickness of the Cedar Valley, Wapsipinicon, and upper Silurian strata in eastern Iowa during the mid Frasnian (in excess of 125 m).

Lowering of erosional base levels (to develop channel incisions and karst systems) in the stable cratonic interior during the Paleozoic would mostly likely be driven by sea-level fall associated with withdrawal of interior seaways, and such changes have been considered to primarily reflect global eustasy (Witzke and Bunker, 1996). Of course, the influence of epeirogenic structural movements should not be discounted offhand, but the stable configuration of facies and thicknesses across such broad areas in Iowa, across both inner and middle shelves, bespeaks relative tectonic stability during the Givetian and Frasnian in the region. If the sub-Lime Creek base level changes were primarily driven by global eustasy, the Iowa shelf provides evidence for the magnitudes of global sea-level change in the Devonian cratonic interior. As discussed above, base-level changes of at least 65 to 90 m (potentially up to 125 m) during the mid Frasnian and at least 35 m during the late Givetian seem to indicate that very large eustatic third-and fourth-order sea-level changes may have characterized portions of the Devonian. These changes seem so large, in fact, that identifying mechanisms for such change presents a challenge to geologic thinking. Although evidence is largely wanting for the Givetian-Frasnian, large sea-level changes in the Quaternary, Carboniferous, and Ordovician-Silurian are known to have been associated with glacial eustatic changes driven by the waxing and waning of continental glaciers.

MIDDLE-SHELF FACIES OF THE CEDAR VALLEY GROUP IN SOUTHEAST IOWA AND THEIR REGIONAL DEPOSITION

Solon Member

The Solon Member forms the basal interval of the Little Cedar Formation in southeastern Iowa. It is included within the larger T-R sequence that includes the entire Little Cedar Formation, but the Solon also comprises its own shallowing-upward succession and it represents a recognizable T-R subcycle (or sequence, if you prefer) (Witzke and Bunker, 1994a). The Solon Member correlates with the lower Bassett Member northwestward across Iowa as well as southward into northeastern Missouri. The type locality of the Solon Member occurs in Johnson County, Iowa (Witzke et al., 1988), where the member averages about 6 m thick (Fig. 4). The Solon disconformably overlies the Wapsipinicon Group in the region, locally displaying up to 1 m or so of vertical relief, and basal Solon strata are locally sandy. The lower Solon ("independensis beds") in Johnson County is characterized by slightly argillaceous fossiliferous limestone (wackestone and packstone) with a diverse marine fauna (brachiopods, crinoid debris, bryozoans, etc.). A widespread submarine hardground surface occurs near the top of the lower Solon interval. The upper Solon ("profunda beds") in Johnson County is dominated by fine skeletal packstone with accumulations of corals and stromatoporoids, in part forming widespread biostromes. Upper Solon strata were deposited in shallower environments than the lower Solon.

Southeastward from Johnson County, the Solon Member becomes significantly thinner, locally as thin as 2 m or less (as seen at the Buffalo Quarry, Fig. 5). In general, the Solon Member shows general southeastward stratigraphic thinning across much of southeast Iowa (Fig. 6), with notably thicker sections recognized to the north and west of Johnson County (e.g., Vinton and Troy Mills sections, Fig. 6). Southeastward thinning of Solon strata reaches its maximum condensation in Scott, eastern Muscatine, Louisa, Des Moines, and northern Lee counties (Figs. 1, 2), where the member is less than 4 m in thickness. Solon strata in this area are dominated by fine skeletal packstones, in part with common to abundant corals and stromatoporoids (locally biostromal). These facies most closely resemble upper Solon facies in Johnson County, and it is possible that the lower Solon "independensis beds" of Johnson County becomes greatly condensed or

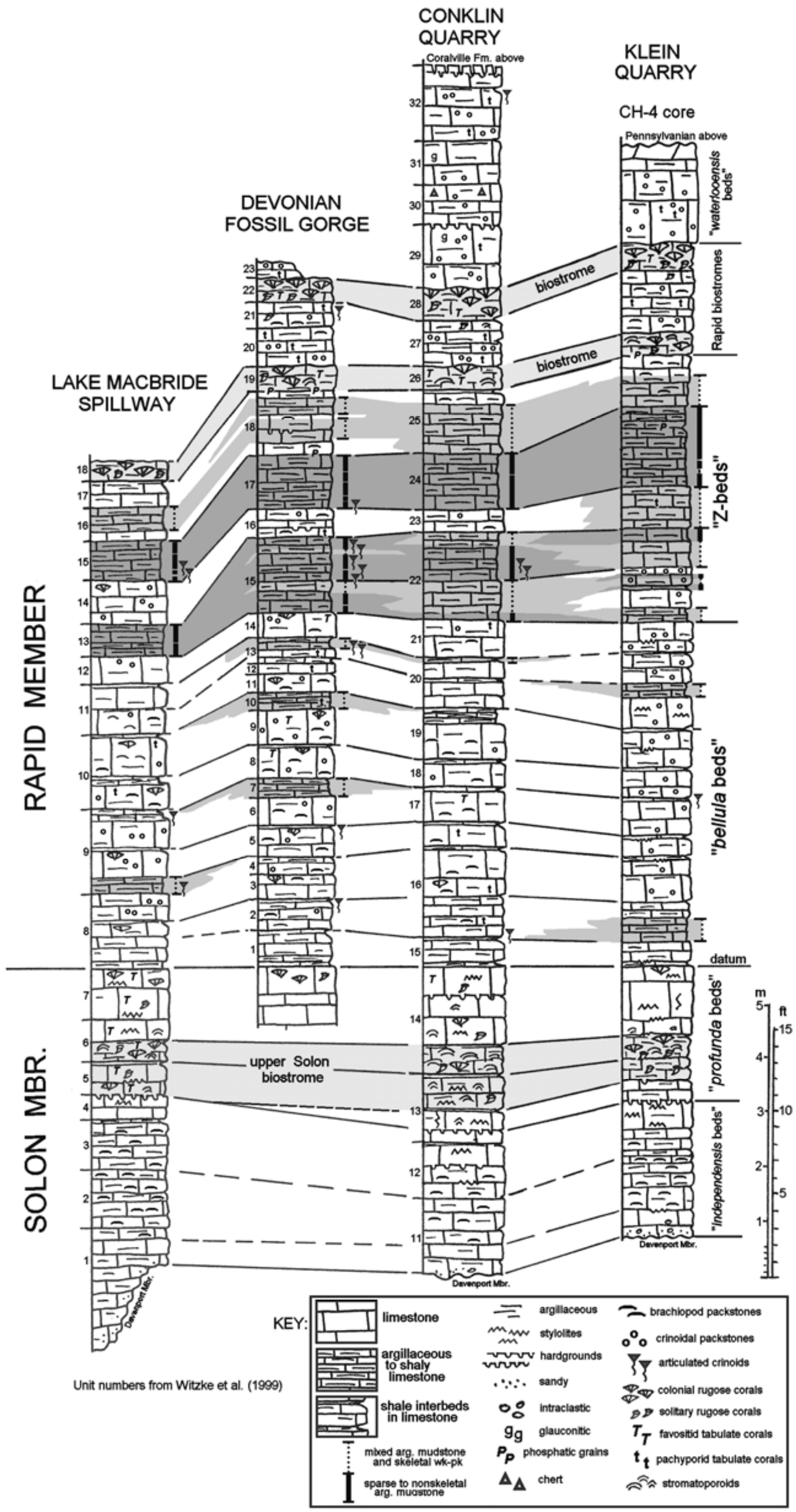

Figure 4. Representative graphic stratigraphic sections of Little Cedar Formation in Johnson County, Iowa. Darker shading corresponds to intervals of sparse skeletal to nonskeletal argillaceous mudstone and mixed mudstone with wackestone-packstone. Positions of Solon and Rapid biostromes shown in lighter shading.

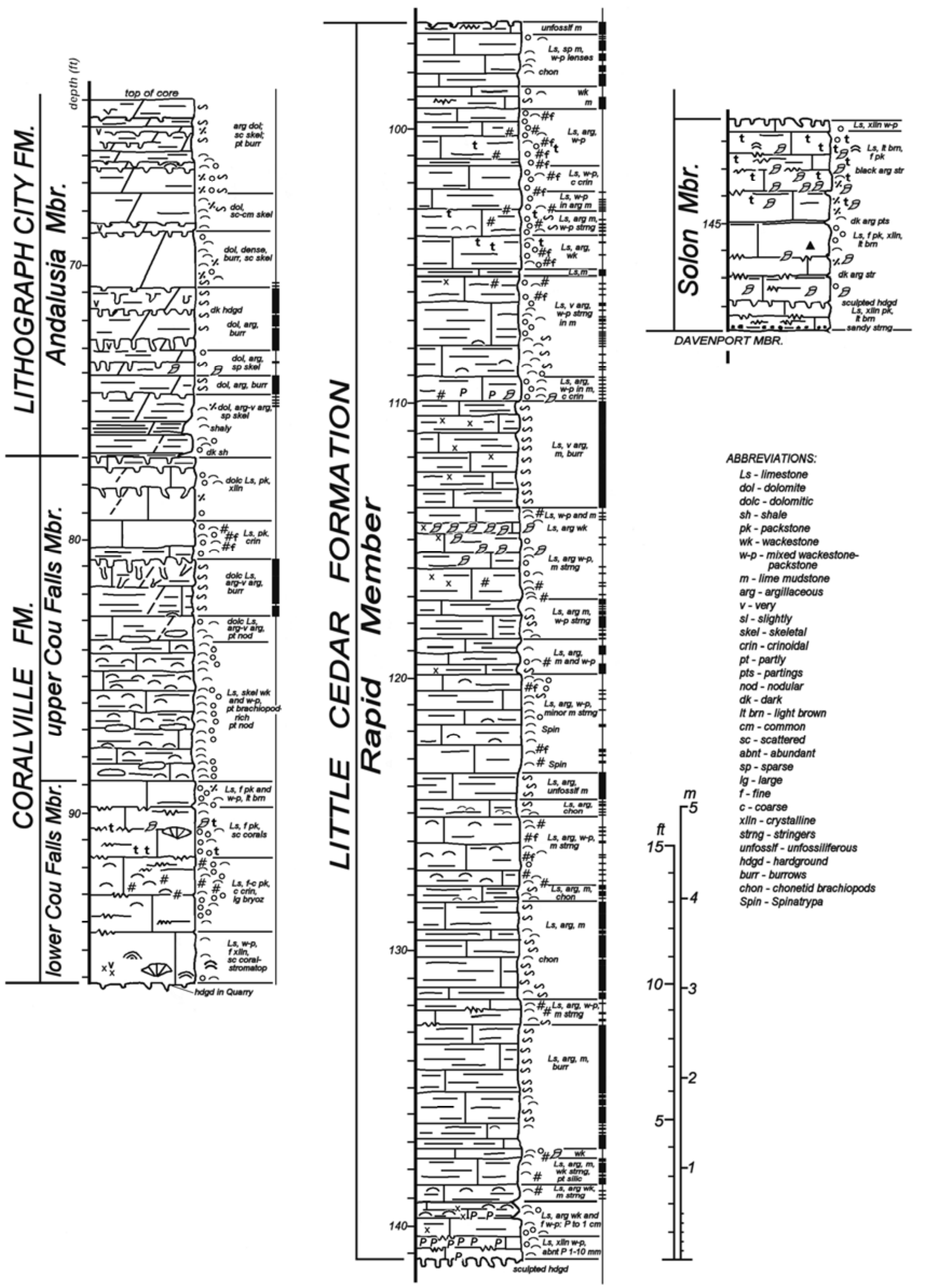

Figure 5. Descriptive and graphic section of Cedar Valley Group strata at the Buffalo Quarry (Loc. BQ); based on the core drilled by the former Davenport Cement Co. and stored at the Iowa Geological Survey. See Figures 4 and 7 for key to lithologic and paleontologic symbols used. Black bars shown on the right side of the graphic section show the distribution of nonskeletal argillaceous mudstones within the succession.

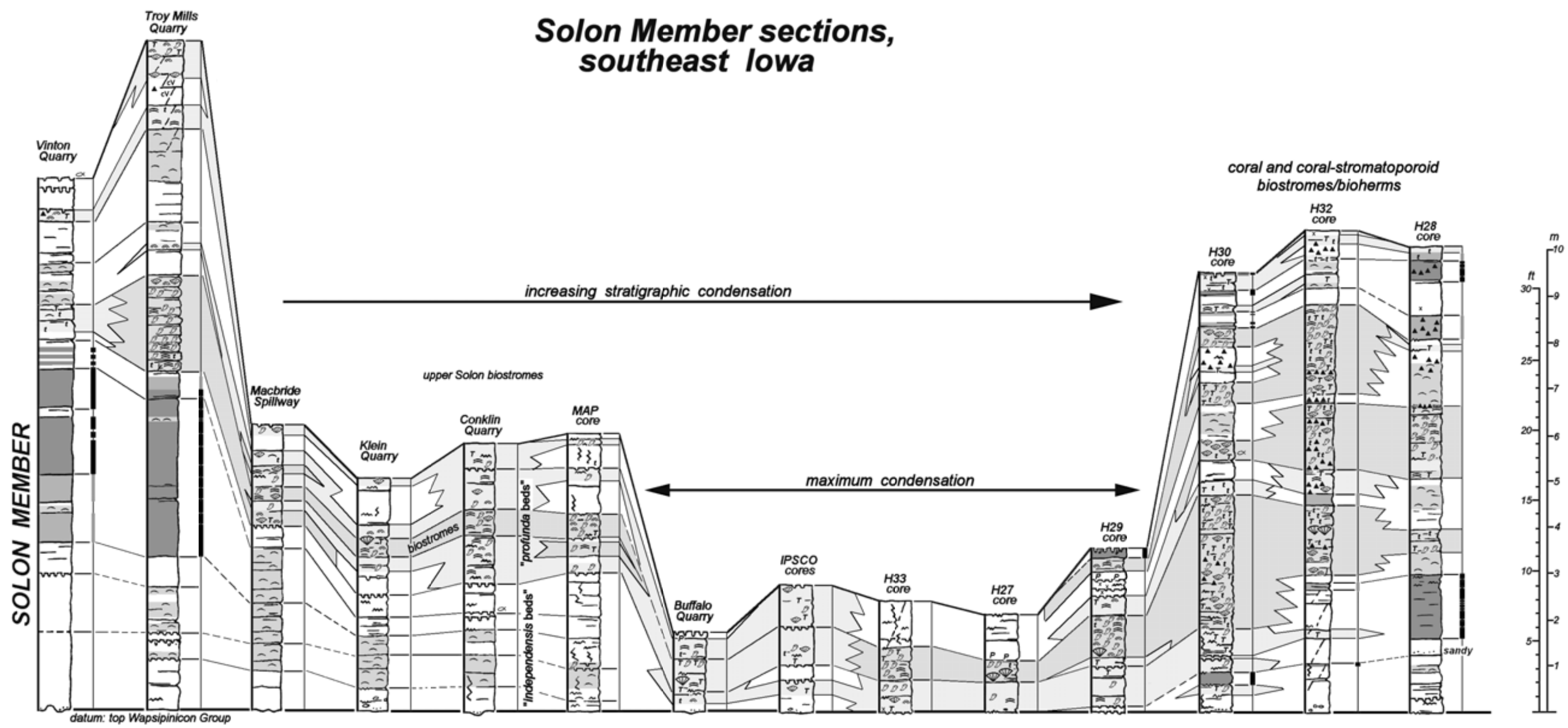

Figure 6. Representative stratigraphic sections of the Solon Member (lower Little Cedar Fm.) in southeastern Iowa showing interpreted correlations. See Figure 1 for location of illustrated graphic sections (includes VQ, TM, MB, KQ, CQ, BQ, IPS). See Figure 7 for explanation of lithologic and paleontologic symbols. Dark shading corresponds to intervals of sparse skeletal to nonskeletal argillaceous mudstones. Medium shading identifies mixed mudstone-wackestone units. Lighter shading shows distribution of coral-stromatoporoid biostromes and brachiopod packstones within the Solon Member.

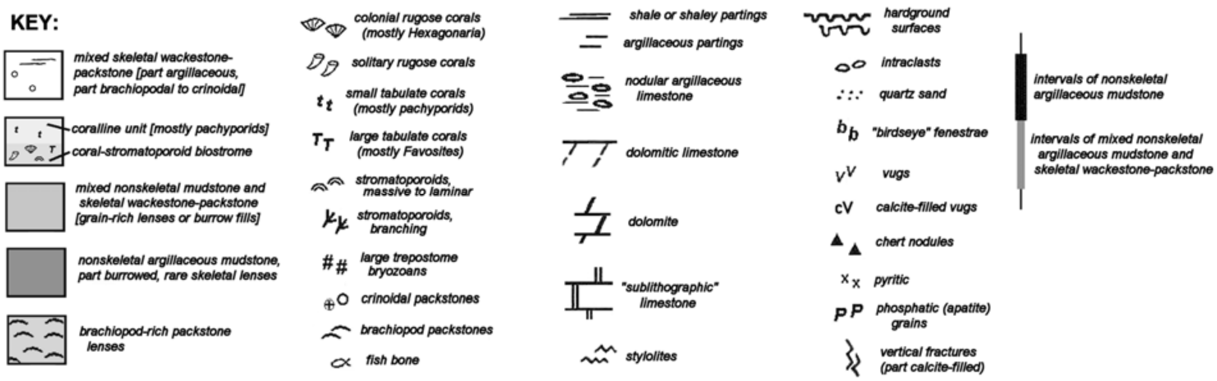

Figure 7. Key for lithologic and paleontologic symbols used in figures 5, 6, 8-11.

starved to the southeast. As such, upper Solon strata are interpreted to downlap a condensed or starved surface in middle-shelf areas of southeastern Iowa. Multiple hardground surfaces are recognized within the thin Solon succession of southeast Iowa, and a well-developed sculpted hardground surface is commonly seen at the top of the Solon in that area.

The Solon T-R subcycle is dissimilar to all other T-R cycles of the Cedar Valley Group of southeastern Iowa, primarily in displaying significant changes in lithofacies and increased thickness in the southeastern-most sections (Fig. 6). These changes are interpreted to reflect a reversal in depositional slope and general depositional shallowing southward onto the margins of the Ozark Dome and Sangamon Arch into Missouri and Illinois during the initial phases of regional Cedar Valley marine transgression (early Taghanic Onlap). The southeastern-most Solon sections in Iowa (H30, H32, H28; Fig. 6) display relatively thick accumulations of corals and stromatoporoids (biostromes and bioherms) above a lower interval of skeletal wackestone and mudstone. The facies succession in these sections closely resembles that seen to the north in Linn and Benton counties, Iowa (e.g., Vinton and Troy Mills, Fig. 6) in an area that encompasses the distal inner-shelf region in subsequent Cedar Valley T-R cycles. The coral- and stromatoporoid-rich facies in these southeastern-most Iowa sections further resemble units within the Callaway Member in central Missouri, and these Iowa sections may represent a southward transition into Callaway-like facies. Of note, strata equivalent to the Solon Member (lower Bassett member) in part of northeast Missouri (Marion County) are known to include peritidal carbonate facies (laminated, stromatolitic, peloidal facies) at the top of the succession (Woodruff, 1990), indicating that the Solon subcycle includes inner-shelf facies to the south, further supporting southward depositional shallowing in the region.

Rapid Member

The Rapid Member comprises the remainder of the Little Cedar Formation above the Solon Member, and it is interpreted to represent two T-R subcycles within the larger Little Cedar T-R sequence (Witzke and Bunker, 1994a). As for the Solon Member, the Rapid Member is also defined from localities in Johnson County, Iowa (Fig. 4), where it averages about 16 m thick. The Rapid Member in this area forms a succession of distinctive subtidal carbonate lithofacies (Witzke and Bunker, 1994a; Witzke et al., 1999):

1) The lower "bellula beds" are characterized by repetitive couplets of skeletal wackestone-packstone (commonly brachiopod-rich, especially the name-bearer *Spinatrypa bellula*) and thinner more argillaceous wackestones and mudstones. These couplets are correlatable across the county (Fig. 4), and they possibly correspond to parasequence-scale units within the larger T-R sequence. The packstone units show local variations in thickness suggestive of large-scale current-generated low-angle bedforms, probably produced by episodic

storm current activity. Scattered colonial corals occur in some beds, especially in the upper parts of individual beds.

2) The overlying "Z-beds" (as defined by Witzke and Bunker, 1994a) are a lithologically distinctive facies dominated by unfossiliferous to sparsely fossiliferous burrowed argillaceous lime mudstones. Laterally discontinuous skeletal stringers and lenses of wackestone-packstone are interspersed within the mudstones, some displayed as starved megaripple bedforms, and some of these stringers contain associations of articulated and semi-articulated crinoids (especially *Megistocrinus* and melocrinitids; Witzke and Bunker, 1997b). The Z-beds also include thin intervals of skeletal wackestone and mixed wackestone-mudstone, with moderately diverse shelly faunas or low-diversity chonetid brachiopod faunas.

3) An interval containing coral-rich biostromes ("Rapid biostromes") occurs above the Z-beds (Fig. 4), characterized in Johnson County by lower and upper biostrome beds with intervening wackestone-packstone strata (in part very crinoidal, commonly with pachyporid corals or large trepostomes bryozoans). The lower biostrome bed commonly shows glauconitic to phosphatic enrichment (apatite grains) at its base.

4) The upper Rapid beds above the biostromes (formerly termed the "waterlooensis beds") is characterized by argillaceous to dolomitic skeletal wackestones-packstones (especially crinoidal), cherty and glauconitic in part. The top surface of the Rapid is marked by a burrowed discontinuity surface or sculpted hardground. However, northward in Johnson County, the highest part of the Rapid is marked by cross-bedded crinoidal packstones and grainstones recording the shallowest depositional facies of the Rapid Member in Johnson County (Witzke and Bunker, 1994a).

Rapid strata are replaced northwestward in Iowa by subtidal inner-shelf facies of the middle to upper Bassett Member, Eagle Center Member, and Chickasaw Shale, and the Little Cedar Formation is capped by peritidal facies of the Hinkle Member across the inner shelf (Fig. 2). The Rapid biostrome beds of Johnson County are replaced northwestward by coral- and stromatoporoid-rich facies (locally biostromal) within the Bassett Member (Fig. 2). Upper Rapid facies are replaced by similar cherty and glauconitic facies of the Eagle Center Member in the central to distal areas of the inner shelf, and by facies of the upper Bassett and Chickasaw Shale in more proximal areas of the inner shelf (Fig. 2). The Hinkle Member marks the final regressive phase of shallowing sedimentation for the Little Cedar sequence, culminating in subaerial exposure (sub-Coralville erosional surface) as the seaway withdrew from the inner-shelf area.

Proceeding south and east of Johnson County, the Rapid Member has received proportionately less study across the broad middle-shelf area of southeastern Iowa and adjacent Illinois. The best exposure in that area is found at the Buffalo Quarry (Fig. 5), where the Rapid Member is dominated by a succession of argillaceous limestone with a higher proportion of sparse skeletal to nonskeletal argillaceous mudstone (burrowed in part) than seen in Johnson County (where such facies are largely restricted to the Z-beds). These mudstones inter-stratify at varying scales with skeletal wackestone and packstone units, commonly seen as skeletal stringers within the mudstone intervals. Chonetid brachiopods occur at several positions within the mudstone succession. The Rapid succession at Buffalo (Fig. 5) also includes thicker units of argillaceous skeletal wackestone-packstone at several stratigraphic positions: 1) basal Rapid strata, in part enriched with phosphatic grains, above the sculpted hardground at the top of the Solon; 2) parts of the middle Rapid that include wackestone-packstone beds (with a fauna similar to that of the "bellula beds" of Johnson County) with minor stringers or inter-burrowing of mudstone internally; 3) coral-rich beds that correlate with the Rapid biostromes of Johnson County; and 4) parts of the upper Rapid that include scattered trepostome bryozoans and small pachyporid corals.

Subsurface cores of the Rapid Member across southeastern Iowa (Fig. 8) reveal lithofacies associations closely similar to those seen at the Buffalo Quarry. The Rapid Member is dominated by nonskeletal to sparse skeletal argillaceous mudstones across this area, and these facies are most prominently developed in

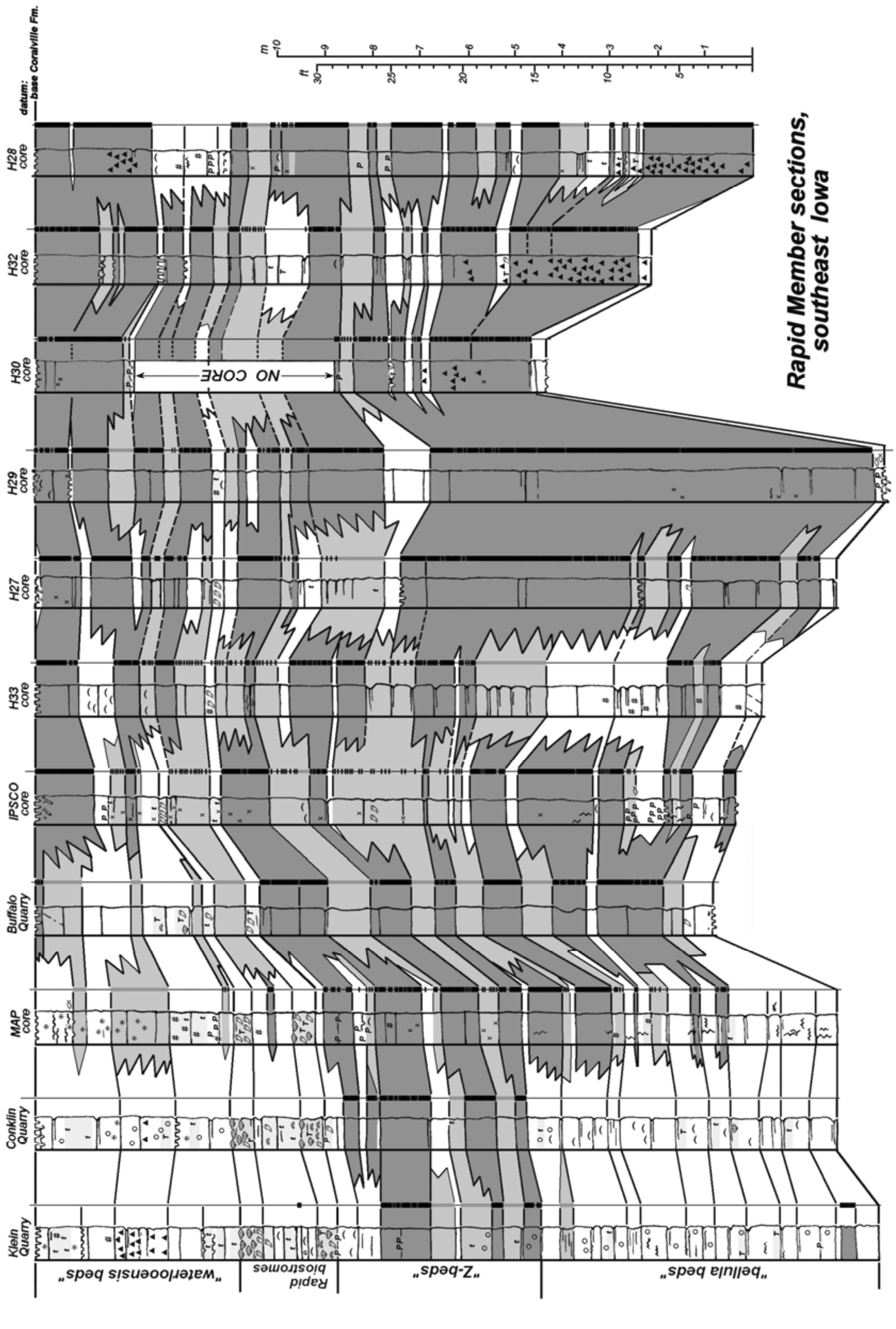

Figure 8. Representative stratigraphic sections of the Rapid Member (middle and upper Little Cedar Fm.) in southeastern Iowa showing interpreted correlations. See Figure 1 for location of illustrated graphic sections (includes KQ, CQ, BQ, IPS). See Figure 7 for explanation of lithologic and paleontologic symbols. Dark shading corresponds to intervals of sparse skeletal to nonskeletal argillaceous mudstones. Medium shading shows distribution of mixed nonskeletal mudstones and skeletal wackestone-packstone units. Light shading shows distribution of coral-stromatoporoid biostromes and coral-rich units within the Rapid Member.

northern and central Lee County (H27, H29; Fig. 8). The southeastern-most sections (H30, H32, H28; Fig. 8) show a general stratigraphic thinning of Rapid strata that appears to be generally complementary with the thickening seen in underlying Solon strata (compare with Fig. 6); the lower and upper Rapid mudstone intervals are variably cherty in those sections. Unlike the succession in Johnson County where the Z-bed mudstone facies are largely restricted to the middle part of the Rapid Member, nonskeletal mudstone facies span large portions of the member across much of southeastern Iowa, including the lower and upper intervals. Nevertheless, thinner units of skeletal wackestone-packstone and mixed lithologies are developed in this area as well, and some of these units appear to correlate between sections (Fig. 8).

A significant shift in facies patterns is observed at the position of the Rapid biostromes in southeastern Iowa, and widespread disruption of mudstone deposition is marked by an extensive wacke-packstone bed (in part with trepostomes and coral biostromes), locally phosphatic in the lower part. This facies shift is marked above by a general northward and northwestward decrease in mudstone facies, and the interval may correspond to a separate T-R depositional cycle or subcycle (IIa-2a of Witzke and Bunker, 1994a). Hardground surfaces and phosphatic-enriched lags are observed at a number of stratigraphic positions within the Rapid succession of southeastern Iowa (Fig. 8), especially in the upper part, and these are interpreted to mark short-term hiatuses and episodes of submarine sediment condensation in the middle-shelf environments.

The Rapid Member of the middle-shelf area is dominated by nonskeletal to sparse skeletal argillaceous mudstones, and an understanding of the deposition of these facies is needed to characterize the environmental setting of this region. The Z-beds of Johnson County represent the proximal extent (shoreward direction) of these facies, and these facies thin and are replaced northwestward by skeletal wackestone and packstone facies moving into the inner-shelf region (schematically shown on Fig. 2; see also Witzke and Bunker, 1994a, p. 20-21). Zawistowski (1971) recognized the lithologic uniqueness of these facies within the middle Rapid Member of Johnson County, and he characterized aspects of the facies and faunas in that area. The paucity to absence of normal shelly benthos in most of the Z-bed mudstones suggests the generally inhospitable nature of the bottom environments during deposition of the Z-beds succession. Benthic stresses are interpreted to result from oxygen-deficient (dysoxic) bottom conditions. However, scattered burrows, including *Chondrites*, indicate that some benthic organisms were capable of surviving in these environments. The interbedding of skeletal stringers also suggests that episodes of oxygenated bottom conditions were developed at times. The abundance of mud in the Z-beds indicates the general absence of current winnowing during deposition. However, distal mud influx (e.g., smothered-bottom crinoid associations) and megaripple bedforms suggest episodic distal storm current activity during at least part of Z-bed deposition in Johnson County (Witzke and Bunker, 1997b). In general, the bulk of Z-beds interval is interpreted to have been deposited at depths at or below storm wave base under a stratified water column (with the oxycline impinging on the bottom). Mudstones of the Z-beds interval are interpreted to be the deepest water depositional facies within the Cedar Valley succession of Johnson County.

The southeastward expansion of nonskeletal mudstone facies across the middle-shelf is interpreted to indicate that benthic oxygen stresses and water depths increased and bottom-current activity decreased in that direction during Rapid deposition (Witzke and Bunker, 1994a, 1994b). A depositional setting within a stratified seaway with oxygen-deficient bottom waters is envisioned (Witzke, 2006). The oxycline, a zone of downward decreasing oxygenation, is interpreted to have impinged on the bottom during much of Rapid mudstone deposition. Fluctuations in the position of the oxycline (due to changes in water depth, storm mixing events, or other factors) may be responsible for episodic development of oxygenated bottom conditions and the interfingering of skeletal benthos at varying scales within the mudstone succession. The distribution of the Rapid mudstone facies does not generally support the idea of southward shallowing onto Sangamon Arch at that time. Sparse to nonskeletal mudstones of the Rapid Member are noted not only in southeastern Iowa, but also along the southern edge of the arch in western Illinois (Calhoun Co.). These merge southeastward with similar facies of the Lingle Formation. The widespread aspect of these facies suggests that similar environments stretched across the middle shelf area from southeastern Iowa toward southern Illinois. These middle-shelf facies are replaced by laminated black shales of the Blocher Shale, which are interpreted to have been deposited in the outer shelf region below the oxycline within the lower anoxic water mass of the southward-deepening seaway.

Coralville Formation

Regional inner- and middle-shelf facies and stratigraphic relations of the Coralville Formation in Iowa have been summarized by Witzke and Bunker (1997a), and most of their discussion need not be reiterated here. Their discussion focused especially on distal inner-shelf facies in the Iowa City area of Johnson County, where coral-stromatoporoid biostromes are particularly well developed along the margins of the inner shelf. The Coralville succession in that area, typified at the Conklin Quarry section (Fig. 9), includes a lower interval (Cou Falls Member) of fine packstones with coral-stromatoporoid biostromes, and an upper interval (Iowa City Member) with peritidal carbonate facies and minor stromatoporoid biostromes. A short distance to the east in eastern Johnson County (MAP core, Fig. 9), the succession abruptly loses the upper peritidal interval, and is replaced offshore by an entirely subtidal succession bounded above and below by subtidal hardgrounds or discontinuity surfaces. These facies changes define the relatively abrupt transition between inner- and middle-shelf facies in eastern Iowa.

Coral-stromatoporoid biostromal facies of the lower Coralville occupy an expansive region of the distal inner shelf in a belt about 90 km wide (Figs. 2, 10). These coralline facies are replaced by dolomitized skeletal wackestones and mudstones of the Gizzard Creek Member across the central and proximal areas of the inner shelf (Fig. 10). The Iowa City Member is characterized by peritidal carbonate, shale, and evaporite facies (and their correlative collapse breccias) across the inner shelf, but a thin stromatoporoid biostrome (the "Amphipora beds") is developed in its lower part across a 125 km swath of the distal inner shelf (Figs. 2, 10). Strata correlative with the Coralville Formation in central Missouri include inner-shelf coralline and biostromal units and sandy carbonate facies of the Mineola Member along the margin of the Ozark Dome (Day, 1997).

The succession of middle-shelf facies of the Coralville Formation is best seen at the Buffalo Quarry (Figs. 5, 9) and nearby exposures (e.g. Wildcat Den; see Witzke and Bunker, 1997c). The entire Coralville succession across the middle-shelf area has been assigned to an expanded Cou Falls Member (Witzke et al., 1988; Witzke and Bunker, 1997a), but it may prove desirable to give a new stratigraphic name for upper Coralville strata in this area (possibly the "Wildcat Den Member"; Old Mill section of Witzke and Bunker, 1997c, p. 12, 66-67). For now, the upper interval is termed the "upper Cou Falls" (Fig. 5) following previous usage. The middle-shelf sections shown in Figure 9 parallel those shown by Witzke and Bunker (1997a), but the southeastern-most sections (H30, H32, H28) differ from those illustrated by Witzke and Bunker (1997a, p. 81) due to stratigraphic re-interpretation of the position of the Rapid-Coralville contact in those sections.

The lower Cou Falls interval on the middle shelf correlates with the entire Cou Falls Member of the distal inner-shelf area, and like the facies seen in the Iowa City area, lower Cou Falls strata are characterized by packstones with common to abundant corals and stromatoporoids, biostromal in part. However, unlike the Iowa City succession, the middle-shelf sections differ in a number of features: 1) the proportion of biostromal units is relatively less, 2) branching stromatoporoids are not identified, 3) non-coralline wacke-packstone beds are present, 4) pachyporids and bryozoans are more abundant, 5) basal strata are locally phosphatic, and 6) hardground surfaces are more common. In addition, the middle-shelf interval is markedly thinned compared to the Iowa City section (about half as thick), and it becomes progressively thinner still in the southeastern-

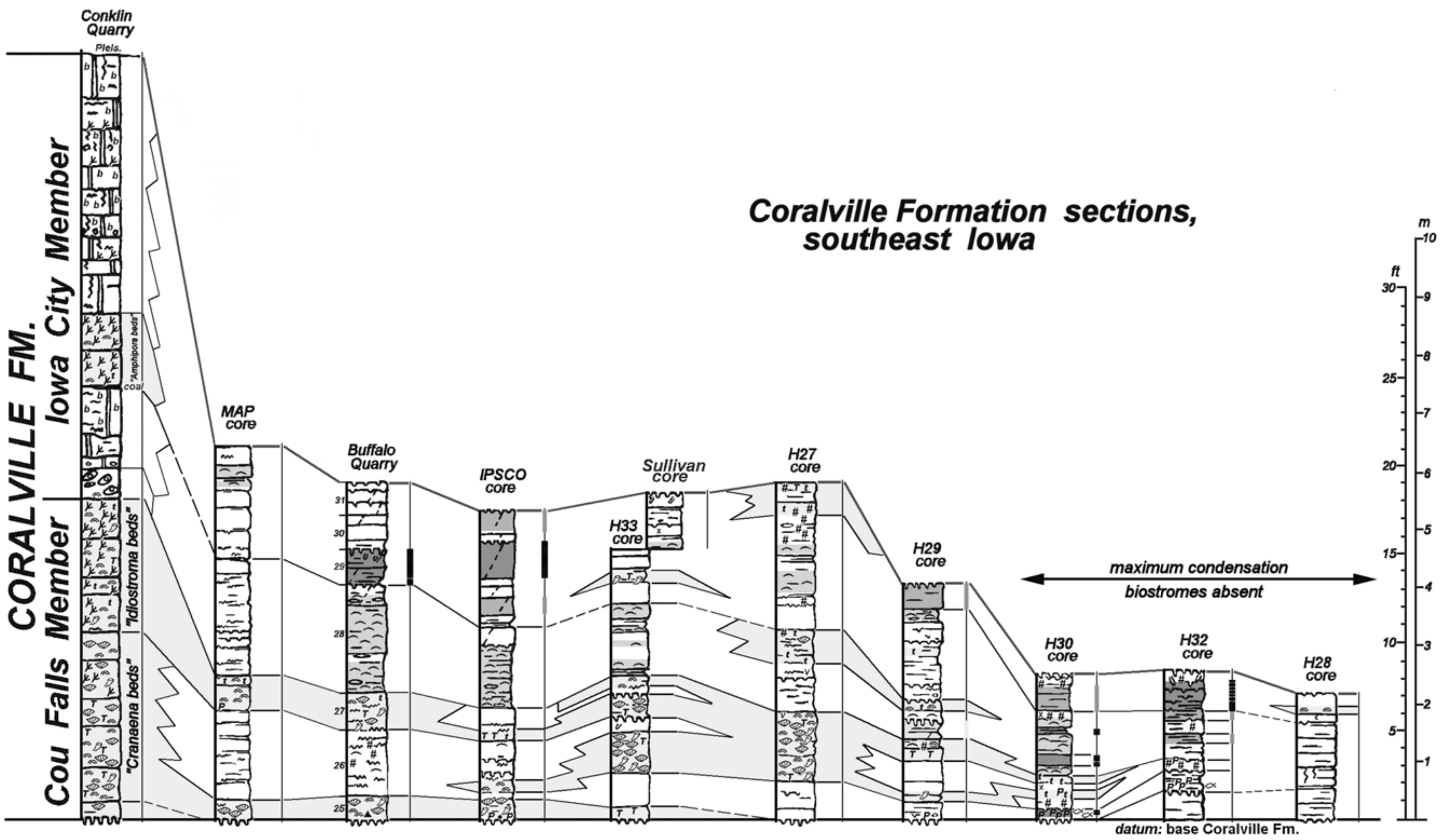

Figure 9. Representative stratigraphic sections of the Coralville Formation in southeastern Iowa showing interpreted correlations. See Figure 1 for location of illustrated graphic sections (includes CQ, BQ. IPS, SUL). See Figure 7 for explanation of lithologic and paleontologic symbols. Dark shading corresponds to intervals of sparse skeletal to nonskeletal mudstone. Medium shading shows distribution of mixed nonskeletal mudstones and skeletal wackestone-packstone units. Light shading with brachiopod symbols shows brachiopod-rich units. Lightest shading shows distribution of coral-stromatoporoid and stromatoporoid biostromes within the Coralville Formation.

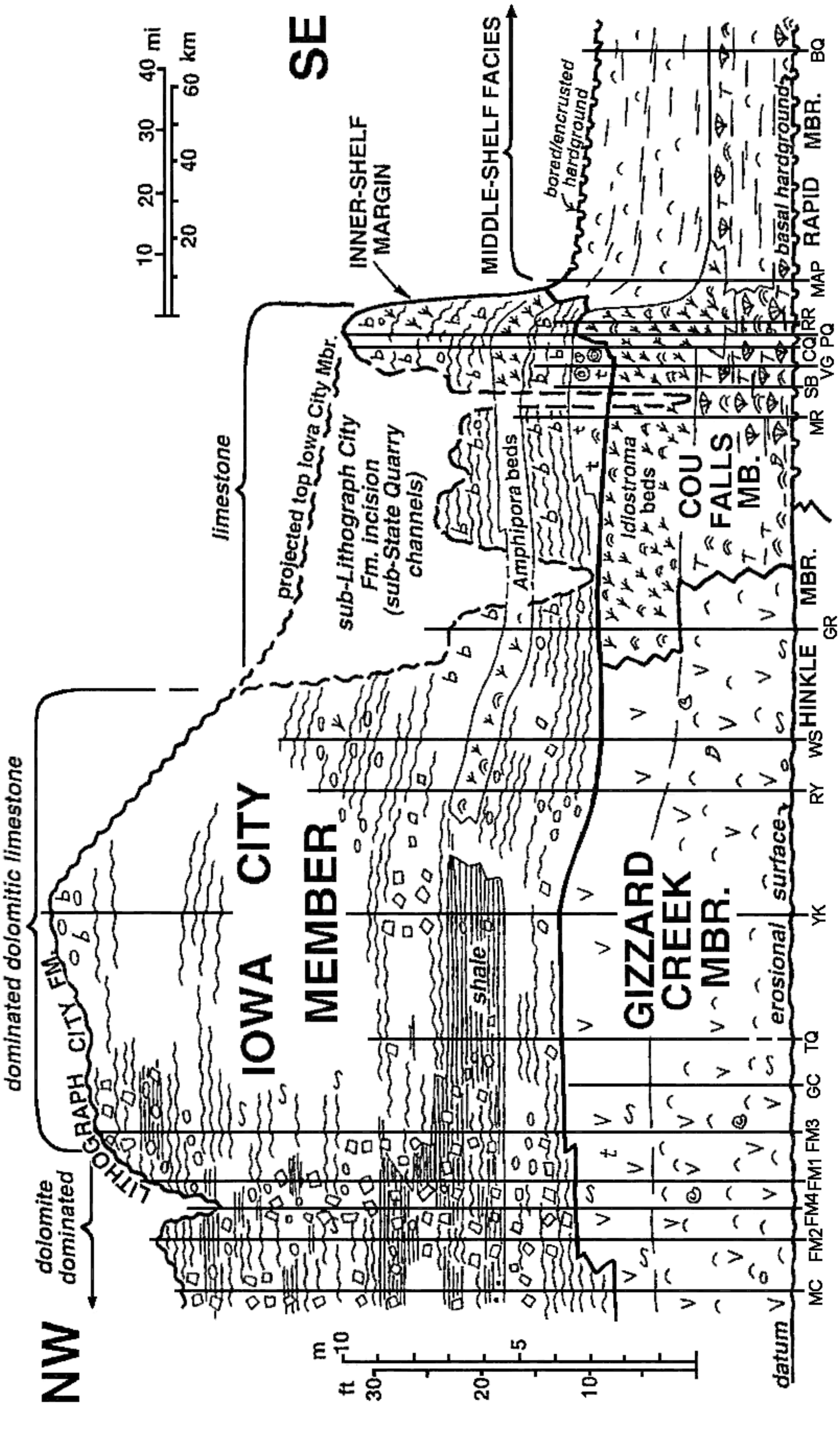

Figure 10. Northwest-southeast stratigraphic cross section of the Coralville Formation across eastern Iowa (from Witzke and Bunker, 1997). The line of cross section corresponds to most of line AB shown on Figure 1 northwest of Locality BQ; see Witzke and Bunker (1997a, Fig. 3) for actual cross-section line and locations (letter abbreviations along bottom of section). Symbols as in figures 2 and 7.

most sections, the area of maximum relative stratigraphic condensation (Fig. 9). These southeastern-most sections (H30-H28; Fig. 9) also show additional lithofacies changes: 1) presence of mudstone and wackestone lithologies, 2) increase in argillaceous content, 3) biostromes, rugose corals, and stromatoporoids are absent, 4) trepostome bryozoans are locally abundant, and 5) local increase in phosphatic content.

Lithofacies of the upper Cou Falls interval across the middle shelf differ significantly from correlative peritidal facies of the Iowa City Member on the inner shelf. The middle-shelf facies are entirely subtidal, and hardground surfaces are developed at a number of stratigraphic positions (Fig. 9). The interval is relatively condensed compared to the thicker Iowa City Member section developed on the inner shelf. Argillaceous wackestones and packstones (including the brachiopod-rich "Athyris beds, Witzke and Bunker, 1997c), nodular in part, are common in proximal areas of the middle shelf in the lower part of the upper interval, as seen at the Buffalo Quarry (Fig. 5). Unfossiliferous to sparsely skeletal burrowed argillaceous mudstones are also noted within the upper Cou Falls interval of the middle-shelf area, likely reflecting episodic oxygen stresses in the middle-shelf environments, similar to those proposed for the Rapid Member. Small corals and trepostome bryozoans are locally common in some of the upper beds. The top of the Coralville Formation is marked by a prominent sculpted submarine hardground surface across the middle-shelf region.

The bulk of Coralville deposition across the middle shelf likely occurred in shallower environments than those interpreted for the Rapid Member. The relative abundance of skeletal packstone lithologies in the lower interval suggests relatively greater bottom current activity, probably storm-generated, than seen in the Rapid Member. However, upper Coralville carbonate facies of the middle shelf do not unequivocally demonstrate the sort of shallowing-upward lithofacies succession seen so clearly on the inner shelf, even though depositional shallowing can reasonably be inferred for the depositional sequence across the region. Witzke and Bunker (1997a) proposed that general shallowing deposition across the middle shelf produced changes in bottom circulation patterns as the seaway withdrew from the inner shelf. Possible euryhaline environmental restrictions accompanied changes in bottom circulation, leading to changes in the benthic faunas as the seaway shallowed across the middle shelf. But the area remained entirely subtidal for the duration of the Coralville sequence, with no evidence of peritidal facies or subaerial exposure during its shallowing depositional phases.

Lithograph City Formation

Inner- and middle-shelf lithofacies groupings in the Lithograph City Formation contrast significantly across Iowa (Fig. 2). Stratigraphic and facies relationships of the formation are summarized by Bunker and others (1986), Witzke and others (1988), and Bunker and Witzke (1992). For the inner-shelf area, they defined a lower marine unit of mostly dolomitized skeletal wackestone and packstone (Osage Springs Member), and an upper interval which displays an interstratified succession of peritidal and shallow-marine limestone, dolomite, and shale facies (Idlewild and Thunder Woman members). The Idlewild succession shows a series of three or four transgressive-regressive subcycles within the larger sequence, with marine transgressive pulses recorded by fossiliferous (in part, stromatoporoid-rich) units. Erosional channels cut into underlying strata of the Coralville and Little Cedar formations (see earlier discussion) were infilled by packstone-grainstone and wackestone facies, in part stromatoporoidal, in the distal areas of the inner shelf during the early phases of Lithograph City transgression (State Quarry Member and related strata).

The middle-shelf facies of the Lithograph City Formation are subdivided into two members (Fig. 11): a lower interval of largely

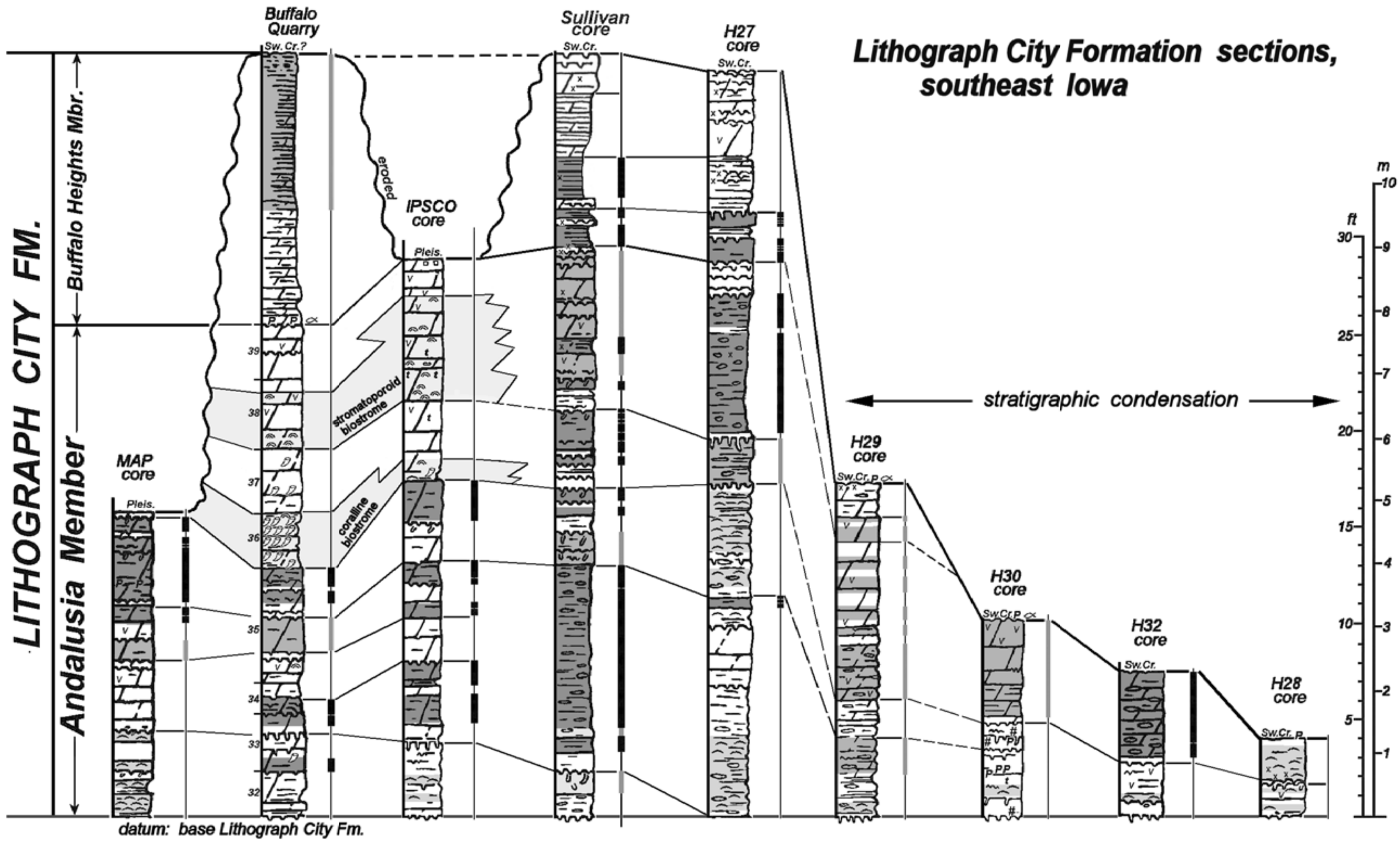

Figure 11. Representative stratigraphic sections of the Lithograph City Formation in southeastern Iowa showing interpreted correlations. See Figure 1 for location of illustrated graphic sections (includes BQ, IPS, SUL). See Figure 7 for explanation of lithologic and paleontologic symbols. Dark shading shows units of sparse skeletal to nonskeletal argillaceous mudstone. Medium shading corresponds to intervals of mixed nonskeletal mudstone and skeletal wackestone-packstone. Light shading with brachiopod symbols represents brachiopod-rich units. Lightest shading shows distribution of coral and stromatoporoid biostromes. Section of the Buffalo Heights Member at the Buffalo Quarry (its type locality) adapted from J. Day (2006, pers. comm.).

dolomitized, variably argillaceous to shaley, mudstones, wackestones, and packstones (Andalusia Member); and an upper interval of shale and argillaceous carbonate (Buffalo Heights Member). Middle-shelf facies are extensively dolomitized across much of their extent, but equivalent limestone facies are also noted at many localities, especially in Des Moines and Lee counties (Fig. 11). All middle-shelf facies were deposited in subtidal marine settings, and there is no evidence of peritidal deposition or subaerial exposure within the formation in southeastern Iowa. The type locality for both members has been designated at the Buffalo Quarry (Figs. 5, 11), which provides the best exposed section of the formation in the middle-shelf area. The formation shows considerable stratigraphic thinning in the southeastern-most sections (H29 through H28, Fig. 11), which is interpreted to reflect offshore stratigraphic condensation.

The Andalusia Member is punctuated by numerous submarine hardground and discontinuity surfaces, some prominently sculpted by complex burrow networks or darkened by pyritic or phosphatic impregnation. Some hardgrounds are bored or encrusted. Hardground and discontinuity surfaces are identified at 25 different stratigraphic positions within the Andalusia succession, but only a few of these appear to be persistent regionally.

The lower half of the Andalusia Member includes a complex mixture of variably dolomitized mudstone and wackestone-packstone (Figs. 5, 11). Basal strata locally include brachiopod-rich wackestones and packstones. As in the Rapid Member, many of the mudstones are nonskeletal and moderately burrowed. Argillaceous nodular carbonate facies characterize portions of the member, especially in the southern sections (Fig. 11). Upper Andalusia strata in Muscatine, Scott, and Louisa counties (e.g., Buffalo and IPSCO sections, Fig. 11) are characterized by less argillaceous and more massive dolomitic beds with scattered to abundant corals and stromatoporoids (locally biostromal). These coralline units likely represent a shallowing phase of deposition across the proximal middle-shelf area. Southward into Des Moines and Lee counties the upper Andalusia Member lacks corals and stromatoporoids, where it is dominated by nonskeletal mudstones and mixed mudstone-wackestone facies. This facies change is interpreted to reflect southward environmental deepening and increasingly condensed sedimentation. Even though the southern-most Iowa sections show considerable stratigraphic thinning and condensation, the general succession of lithofacies closely resembles that seen in thicker sections farther north: 1) a lower interval dominated by argillaceous wackestone and packstone, and 2) an upper interval of more massive crystalline dolomite or wackestone.

Upper strata of the Lithograph City Formation above the Andalusia Member were not recognized in the initial studies of the Buffalo Quarry section (Witzke et al., 1985, 1988), at a time when quarrying activity did not expose any higher strata within the Cedar Valley succession (Andalusia eroded beneath the sub-Pennsylvanian surface). Day (1997) was the first to recognize and define a new member within the upper Lithograph City Formation that was exposed during expanded quarrying activity at the Buffalo Quarry. He named this interval the Buffalo Heights Member. The new member, that formerly reached thicknesses to 4.3 m at the quarry, is dominated by a succession of calcareous or dolomitic mudstones and shales that overlies a pyrite-encrusted hardground disconformity surface at the base of the member. The conodont and brachiopod faunas of this interval were noted by Day (1997). Subsequent subsurface studies (core and other well sections) across the middle-shelf area of southeastern Iowa have recently recognized shaley and argillaceous dolomitic mudstone and wackestone facies at a number of localities that are here included within the Buffalo Heights Member (e.g., Fig. 11; also Fig. 2). As seen at the Buffalo Quarry, two or three hardground surfaces are commonly identified in the basal part. Additional hardground surfaces are locally recognized in the upper part, and the upper surface is erosionally beveled beneath the Sweetland Creek Shale. Correlation of the

Buffalo Heights Member southward into Lee County is not known with certainty, but it appears that the interval becomes condensed or starved in that direction (Fig. 11). This would be consistent with increasing southward stratigraphic condensation seen within the Coralville and lower Lithograph City formations. The Buffalo Heights Member correlates with strata of the Snyder Creek Shale in central Missouri (Day, 1997).

Lithofacies of the Lithograph City Formation across the middle shelf were deposited entirely within subtidal marine environments. Nonskeletal burrowed mudstones resemble those of the Rapid Member, and a similar depositional setting with oxygen stressed bottom conditions is envisioned. The middle-shelf succession is relatively condensed compared to the inner-shelf area, reflecting slower rates of sediment accumulation. Numerous hardground surfaces within the succession are interpreted to record episodes of sediment starvation within the condensed section. The middle-shelf succession likely includes two T-R depositional cycles or subcycles (IIb-1, IIb-2; see Day, 1997): 1) a lower subcycle is represented by the Andalusia Member (which shows a general shallowing-upward succession culminating in the progradation of biostromal facies in the proximal areas), and 2) an upper subcycle corresponding to the Buffalo Heights Member.

Shell Rock Formation

As discussed earlier, the Shell Rock Formation is entirely absent across the middle-shelf area, probably due to erosion and/or starved deposition. The Shell Rock Formation is well developed, however, across the central and proximal areas of the inner shelf, where it is dominated by shallow-marine facies containing several intervals of stromatoporoid biostromes (Fig. 2). The shallow-marine succession is punctuated by the progradation of peritidal facies at three or more stratigraphic positions in proximal inner-shelf areas (Fig. 2), each of which can be used to subdivide several smaller-scale T-R subcycles within the larger Shell Rock sequence. All previous sequences of the Cedar Valley Group display a thinned succession of subtidal middle-shelf facies, and this pattern would be expected to characterize the Shell Rock sequence as well. The absence of middle-shelf Shell Rock facies is anomalous for the Cedar Valley Group. There is no evidence for any sort of large-scale structural uplift across southeast Iowa, so its absence in that area must be due to other factors. Its stratigraphic position beneath a regional erosional unconformity (sub-Sweetland Creek-Lime Creek) must provide at least part of the explanation.

Extreme sediment condensation (stratigraphic thinning) of any Shell Rock facies on the middle shelf would have made their erosional removal even easier. Dramatic southeastward stratigraphic condensation is evident in the previous two Cedar Valley sequences (Figs. 8, 11), so it does not seem beyond reason to infer at least similar patterns for the Shell Rock sequence. It is also possible that the middle-shelf Shell Rock succession may have been entirely starved due to changes in seaway circulation patterns or changes in bottom water chemistry in a stratified seaway (e.g., carbonate dissolution). Witzke and Bunker (1996) and Witzke (1998) suggested that some cratonic sequences are absent across middle-shelf areas due to long-term sediment starvation resulting in the development of widespread submarine disconformities. A major submarine disconformity surface is recognized across large areas of the middle-shelf beneath the Mississippian Burlington Formation in the same general area (southeast Iowa and adjacent Illinois, Missouri), even though carbonate deposition was widespread on the inner shelf coincident with the development of this middle-shelf disconformity. Witzke and Bunker (2002) interpreted widespread offshore subtidal middle shelf sediment starvation and storm-generated submarine erosional planation for the sub-Burlington disconformity. Although speculative, it is possible that the Shell Rock sequence may have shown a similar pattern of non-deposition across the middle shelf.

SUMMARY OF MIDDLE-SHELF FACIESOF THE CEDAR VALLEY GROUP

Recurring patterns of sedimentation and stratigraphic architecture are evident in most of the Cedar Valley sequences across the middle-shelf area of southeastern Iowa. A summary of salient observations about Cedar Valley stratigraphy and deposition across the middle-shelf area is presented below.

1) Each sequence displays relative stratigraphic condensation compared to the inner-shelf succession.

2) The Shell Rock sequence is entirely absent, probably due to the combined effects of sediment starvation, submarine planation, and sub-Sweetland Creek erosion.

3) Each sequence is bounded by submarine hardground discontinuity surfaces.

4) There is a complete absence of peritidal and evaporitic facies across the middle shelf, and there is no evidence for subaerial exposure for the entire temporal span of the Cedar Valley Group (i.e. entirely subtidal).

5) Compared to the inner shelf, middle-shelf facies show a significant increase in the number of hardground surfaces (submarine hiatuses) and condensed phosphatic units.

6) Each sequence in the middle-shelf area displays facies of nonskeletal argillaceous mudstone, especially prominent in the Rapid Member and Lithograph City Formation. These facies are interpreted to have been deposited in oxygen-stressed deeper-water environments.

7) There is a general offshore decrease in coral-stromatoporoid biostromal facies in each sequence, and a general offshore increase in trepostome bryozoans over corals within correlative strata.

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STRATIGRAPHY OF THE WAPSIPINICON GROUP (MIDDLE DEVONIAN) IN SOUTHEASTERN IOWA

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INTRODUCTION

The Wapsipinicon Group overlies a deeply eroded megasequence boundary (Sloss's Tippecanoe-Kaskaskia cratonic unconformity) in eastern Iowa, where it is known to unconformably overlie Silurian (Gower, Scotch Grove, Hopkinton-Blanding formations) and Ordovician units (Maquoketa Formation, Galena Group). The general stratigraphy of the group has been considered by previous workers, and an overview is provided by Bunker and others (1985) and Witzke and others (1988). Studies by Church (1967) and Sammis (1978) further characterize the Wapsipinicon lithofacies of eastern Iowa. Reference sections for the Buffalo Quarry (Witzke et al., 1985) and the Iowa City area (Conklin and Klein quarries, Fig. 1; see also Witzke et al., 1999) provide additional information. The strata of the Wapsipinicon Group are economically important for eastern Iowa providing high quality aggregate and gypsum resources. Stratigraphic nomenclature within the Wapsipinicon Group was modified by Witzke and others (1988) who recognized the succession, in ascending order: Bertram Formation, Otis Formation, and Pinicon Ridge Formation (Kenwood, Spring Grove, Davenport members).

The age of the Wapsipinicon Group is difficult to constrain because of the general paucity of biostratigraphically useful fossils. The basal Bertram Formation overlies an unconformity on Silurian strata, and it has not yielded any fossils. Bertram deposition is likely allied with the overlying Otis Formation, possibly associated with rising base levels associated with Otis marine transgression (Witzke et al., 1988). The Otis Formation has yielded an impoverished conodont fauna consisting only of *Ozarkodina raaschi*; the species is well represented in the Spillville Formation of northern Iowa, whose conodont faunas indicate an upper Eifelian to basal Givetian age (Klapper and Barrick, 1983). The Otis Formation of southeastern Iowa is apparently correlative with the Spillville Formation and is considered to be the same age. Zonally significant miospores from the Otis Formation agree with this age assignment (Klug, 1994). With the exception of Klug's (1994) miospore study of the Wapsipinicon Group, no other biostratigraphically significant fossils are known from higher strata of the group. The miospores generally support a Givetian age for the Pinicon Ridge Formation (Klug, 1994). The Wapsipinicon Group is constrained above by basal Cedar Valley strata which contain conodonts of the middle *varcus* subzone (mid Givetian age). Therefore, the Pinicon Ridge Formation appears to be a lower Givetian unit by its stratigraphic position.

BERTRAM FORMATION

The Bertram Formation is the most geographically restricted stratigraphic unit of the Wapsipinicon Group. It was considered by Bunker and others. (1985) to be entirely restricted to the area north of the Plum River Fault Zone in a small asymmetrical basin primarily limited to areas of Linn and Benton counties. The formation in that area is characterized by unfossiliferous dolomite, in part vuggy, laminated, argillaceous, or sandy, and locally brecciated to intraclastic. Discontinuous silty to sandy shale units are commonly developed above the basal unconformity surface. The stratigraphic relationships between the upper Bertram and overlying Otis Formation are not fully clarified, but a sharp contact and disconformable relationships have been proposed (Sammis, 1978). Nevertheless, the Bertram-Otis contact at some localities (e.g., Beverly Quarry, Linn Co.) appears to be arbitrary and gradational, suggesting

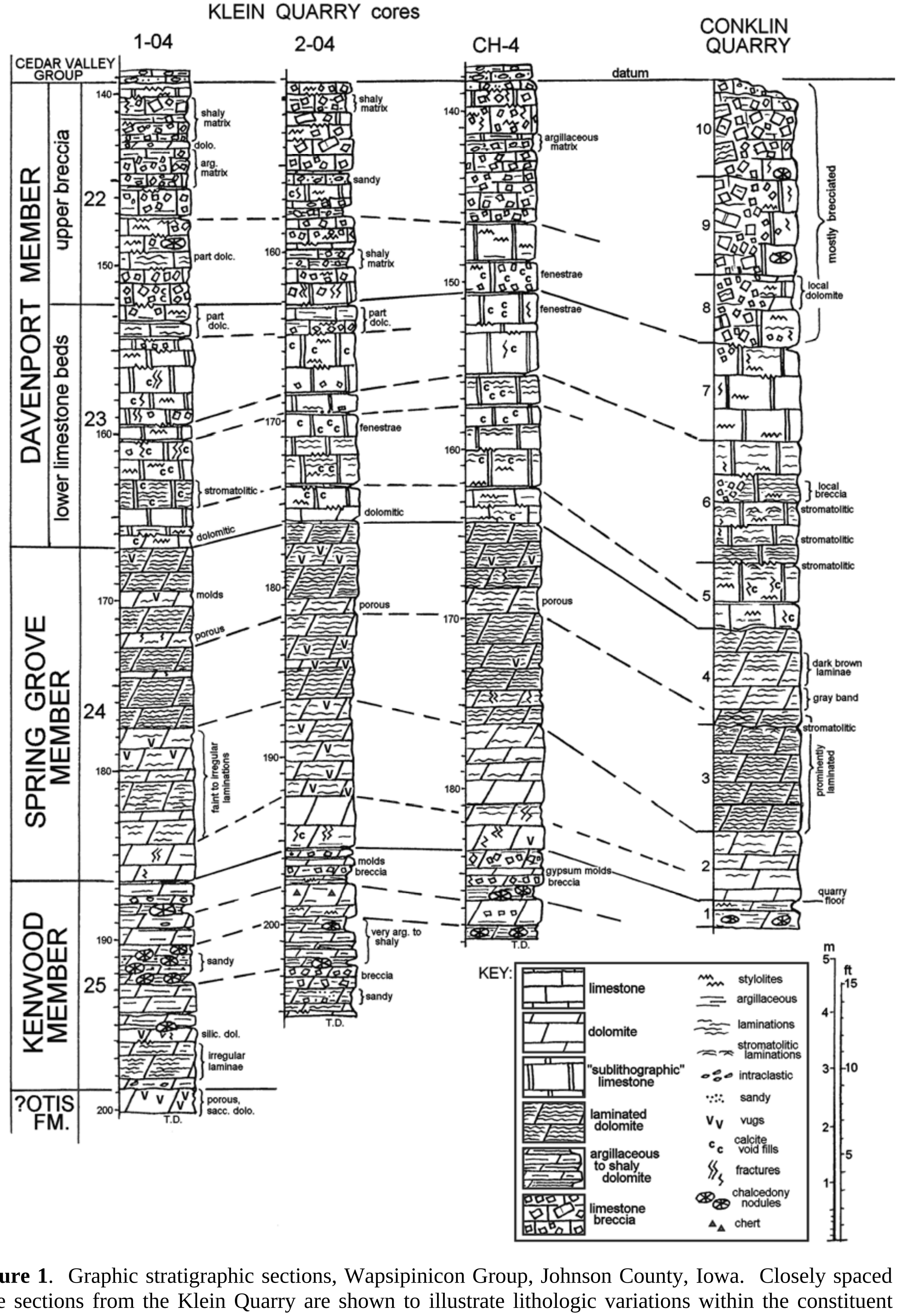


Figure 1. Graphic stratigraphic sections, Wapsipinicon Group, Johnson County, Iowa. Closely spaced core sections from the Klein Quarry are shown to illustrate lithologic variations within the constituent members over short lateral distances (<1 km). Conklin Quarry section adapted from Witzke and others (1999). Cores stored at the Iowa Geological Survey; core depths in feet.

depositional continuity of the Bertram succession within the Otis depositional sequence.

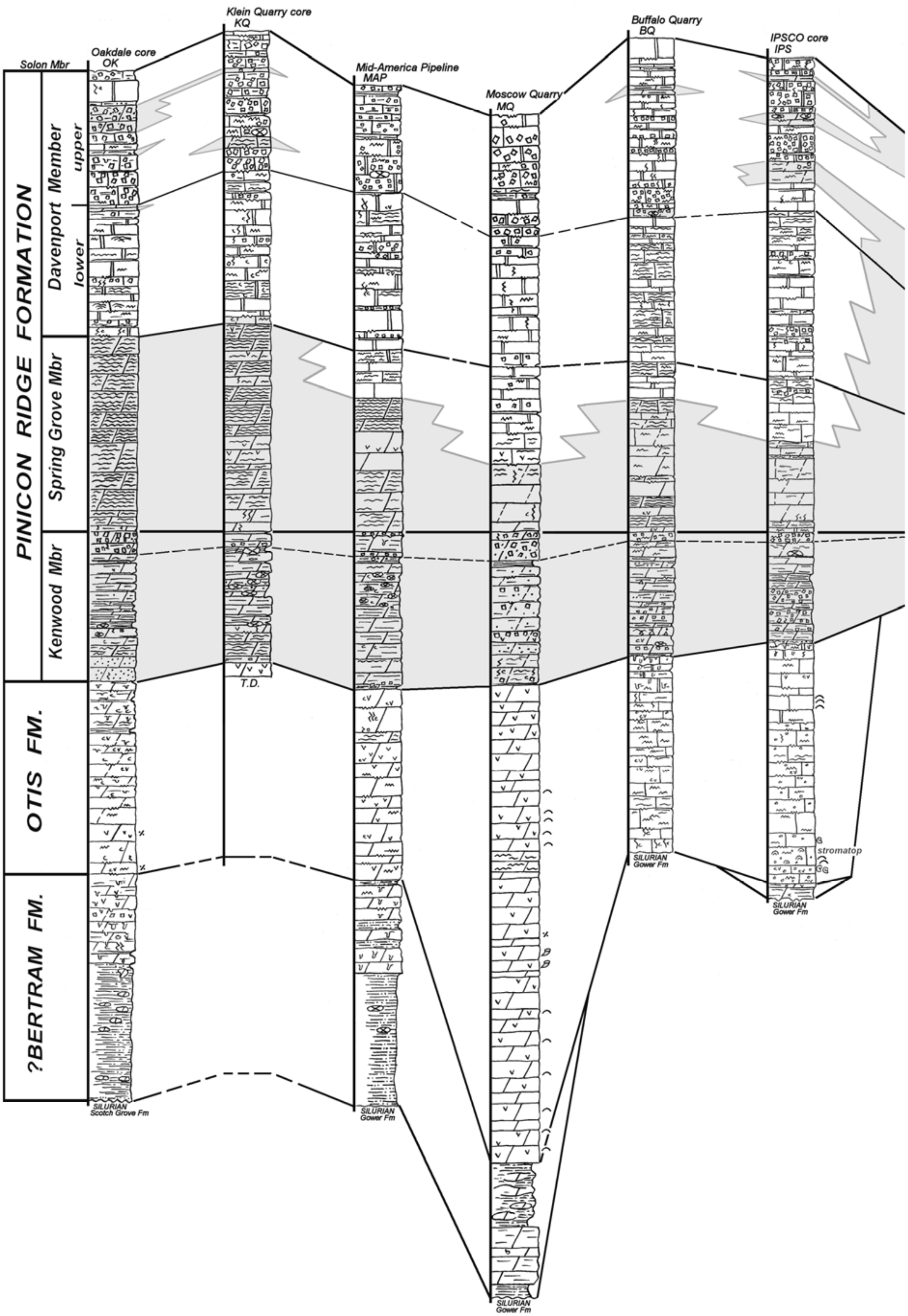
The recent examination of core sections from Johnson and Muscatine counties has revealed a stratigraphic interval within the basal Wapsipinicon Group that lies above the Silurian unconformity and below characteristic Otis strata (Fig. 2, Oakdale, MAP, Moscow). It ranges from less than 1 m (IPSCO, Fig. 2) to 6 m (Oakdale, MAP, Fig. 2) thick. This interval, of course, occupies the same stratigraphic position as the Bertram Formation to the north in Linn County, and it is tentatively considered to belong to the same formation (labeled ?Bertram Fm. on Fig. 2) pending further study. The interval also lithologically resembles the Bertram Formation of Linn and Benton counties, characterized by unfossiliferous dolomite, part vuggy, brecciated, or argillaceous, and silty to sandy shale. It differs primarily in containing proportionately more shale than seen in Linn County, although the Bertram of Benton County also locally contains considerable shale. The ?Bertram interval of Johnson and Muscatine counties appears to be gradational with the overlying Otis Formation. Although elevated to formational status by Bunker and others (1985), it is possible that the Bertram could also be considered as the basal member of an expanded Otis Formation, as both share lithologic similarities (carbonate dominated) and both may belong within the same depositional sequence.

OTIS FORMATION

The Otis Formation occupies areas of Iowa and adjoining Illinois, and its southern margin stretches across the northern part of southeastern Iowa in Johnson, Muscatine and Scott counties (Bunker et al., 1985). It oversteps the Bertram Formation, and the Otis unconformably overlies an eroded Silurian surface across most of its extent. The Otis Member is characterized by carbonate strata comprising a succession of shallow-marine, restricted-marine, and peritidal facies. In Linn County the formation has been subdivided into two members (Bunker et al., 1985; Witzke et al., 1988): the lower Coggon Member, an interval of dolomite, vuggy in part, with scattered molds of brachiopods (*Emanuella*), gastropods, rostroconchs, and trilobites; and an upper Cedar Rapids Member of limestone and dolomite, including sparsely fossiliferous dolomite and limestone (*Emanuella*, gastropods, bryozoans), pelletal limestone (locally with spirorbids), locally oolitic limestone, laminated peritidal carbonates (in part with stromatolites, “birdseye,” and mudcracks), and intraclastic to brecciated units (Sammis, 1978). Southward in Johnson, Cedar and northern Muscatine counties the Otis Formation is entirely dolomitized, where a similar succession of depositional facies and faunas is observed (Fig. 2). Of note, a bed with abundant molds of solitary and colonial rugose corals is developed at the Moscow Quarry (Fig. 2).

Eastward into eastern Muscatine and Scott counties, and adjoining areas of Illinois, the Otis Formation is represented entirely by limestone facies, where it is much easier to observe primary depositional fabrics and fossil content. The formation ranges between about 5 and 8 m thick in this area. Representative sections from this area are shown for the IPSCO and Buffalo Quarry cores (Fig. 3). A variety of limestone facies are observed in this area, including: 1) skeletal, skeletal-intraclastic, and peloidal-skeletal pack-grainstones and mud-wackestones containing low-diversity faunas of brachiopods (primarily *Emanuella*), gastropods, rostroconchs, ostracodes, rare echinoderm grains, and stromatoporoids (small stromatoporoids in lower Otis strata in the IPSCO core represent a new fossil occurrence for the formation); 2) peloidal and peloidal-intraclastic pack-grainstones; 3) coated-grain to oolitic pack-grainstones, locally oncolitic; 4) laminated mudstones and stromatolitic units; 5) fenestral limestones (“birdseye” bearing).

The Otis Formation is the only stratigraphic unit of the Wapsipinicon Group in southeastern Iowa that contains normal marine fauna in some beds, including brachiopods, trilobites, corals, and stromatoporoids. Its deposition was limited geographically to a paleoembayment in eastern Iowa and northwestern Illinois, and the Otis



Solon Mbr
PINICON RIDGE FORMATION
Davenport Member
upper
lower
Spring Grove Mbr
Kenwood Mbr
OTIS FM.
?BERTRAM FM.
Oakdale core
OK
Klein Quarry core
KQ
Mid-America Pipeline
MAP
Moscow Quarry
MQ
Buffalo Quarry
BQ
IPSCO core
IPS
T.D.
stromatop
SILURIAN
Scotch Grove Fm
SILURIAN
Gower Fm
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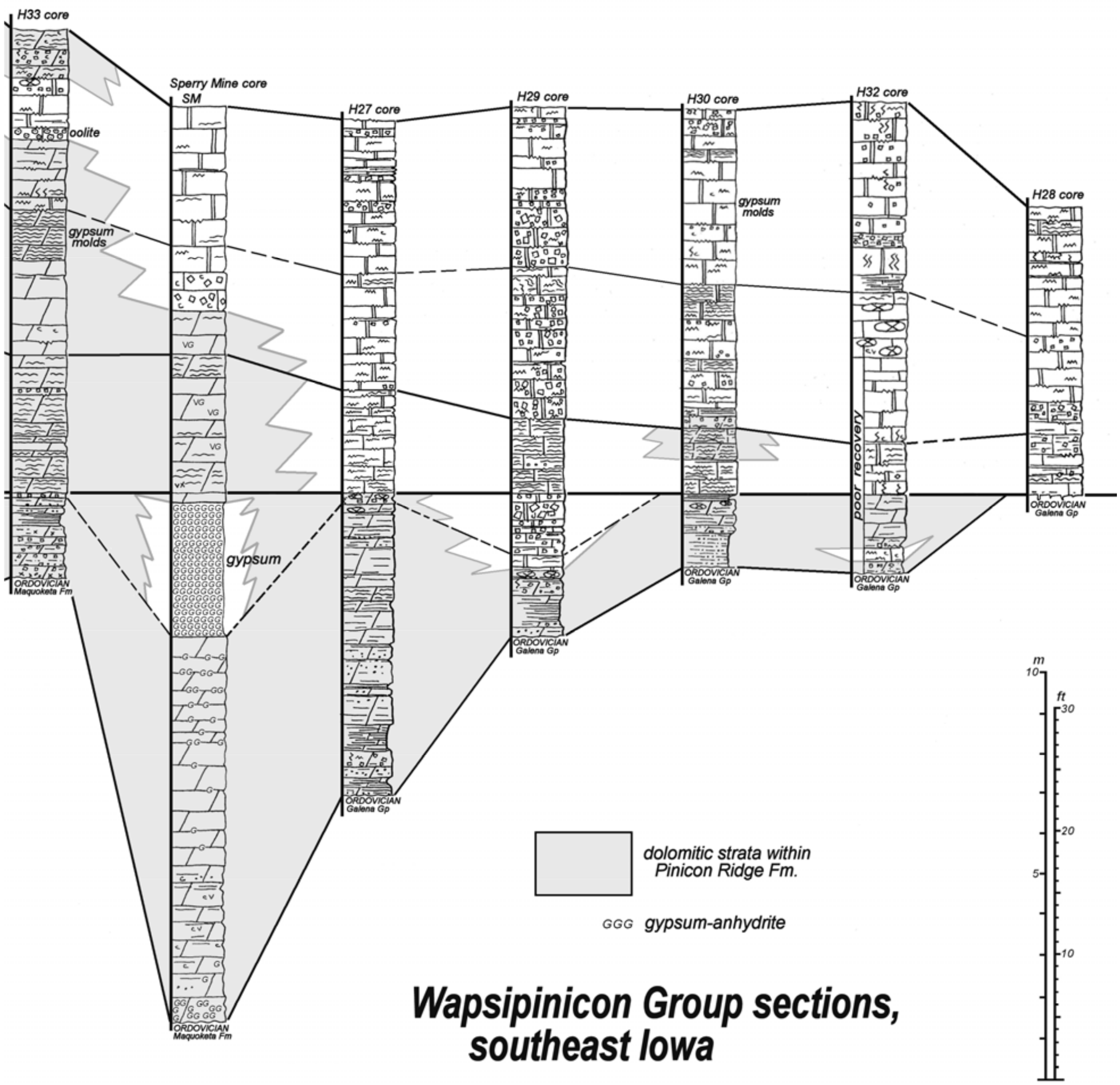

Figure 2. Graphic sections and proposed correlation of Wapsipinicon Group strata in southeastern Iowa. Locations are shown on Figure 1 in the accompanying article on Cedar Valley Group stratigraphy. Symbols as in Figure 1 (see also Fig. 7 in Witzke and Bunker, p. 23 of this guidebook). Cores are archived at the Iowa Geological Survey. Moscow Quarry (MQ) and Sperry Mine (SM) sections are based on core logs stored at the Iowa Geological Survey; MQ Otis section after J. Day (2006, pers. comm.).

marine transgression into this area during the late Eifelian marked the first incursion of Devonian seas into eastern Iowa (Witzke et al., 1988). The Otis correlates with the Spillville Formation of northern Iowa, which contains marine fauna throughout most of the interval, and contains more open-marine facies and more diverse faunas than the Otis (Day and Koch, 1994). This suggests that the initial Devonian transgression proceeded from the north or northeast, with a major southern barrier (the Sangamon Arch) separating marine Eifelian deposition of southern Illinois from shallower and more restricted deposition of the Otis Formation (ibid.). Otis strata of eastern Iowa were interpreted to record a general shallowing-upward depositional sequence (cycle) by Witzke and others (1988). The presence of peritidal facies (including laminated and fenestral limestones) in the middle part of the Otis succession (Figs. 2, 3) suggests that the Otis cycle can be further subdivided into two subcycles (Otis T-R cycles 1 and 2 of Day, page 1 of this guidebook).

An episode of erosion and karstification separated Otis and Kenwood deposition in the area, and this is reflected by the infilling of Kenwood shale across an irregular karstic surface developed on the upper Otis (see Day, Allied Quarry, page 1 of this guidebook). At many localities, the upper Otis displays fractures and solutional openings that are infilled with pods and partings of shale and dolomite that resemble lithologies of the overlying Kenwood Member. These include argillaceous dolomite, gray shale (part silty to sandy) and green shale, as well as calcite void fills, and such fillings are seen to occur up to 3 m below the base of the overlying Kenwood Member (as in the Oakdale core, Fig. 2).

PINICON RIDGE FORMATION

Kenwood Member

The Kenwood Member is the basal unit of the Pinicon Ridge Formation. It oversteps the edge of the Otis Formation, and it unconformably overlies eroded Ordovician and Silurian strata across most of its extent (Iowa, northeast Missouri, northwestern Illinois). The Kenwood Member (also called the Kenwood Shale) is dominated by unfossiliferous argillaceous to shaley dolomite, in part silty to sandy, with lesser interbeds of gray to green shale, in part silty to sandy. Silt and sand grains are composed of quartz and chert. Some dolomite beds are irregularly laminated to mottled. Intraclastic and brecciated beds are common. Concretionary masses of chalcedony and chert are seen in many sections, and some dolomite beds are siliceous. The Kenwood Member includes gypsum and anhydrite evaporite units at localities in southeastern Iowa, and economic gypsum deposits are extracted from the upper Kenwood in subsurface mines near Sperry, Iowa (Sperry Mine section, Fig. 2). Nodular, mosaic, and bedded gypsum-anhydrite are identified, especially in the upper part (Giraud, 1986), and gypsum-anhydrite nodules and stringers are known to interstratify with dolomite beds in the lower part. Where evaporite facies are absent in southeastern Iowa, correlative breccia intervals are recognized, most notably in the upper part of the member (dashed correlations, Fig. 2). These breccias are interpreted to have formed by solution-collapse of interbedded carbonate-evaporite strata, recording the presence of formerly widespread evaporite units within the member. Gypsum crystal molds are locally observed within the upper Kenwood breccias (Fig. 1).

The Kenwood Member lacks evidence of marine biota, and burrow fabrics are also absent in most beds. Possible burrow fabrics and stromatolitic laminations at a few localities are the only evidence of possible benthic biota in the member. Klug (1994) recovered undiagnostic miospores from the Kenwood. The general absence of benthic fauna and the presence of evaporite units and evaporite collapse breccias suggest a highly restricted environment of deposition, certainly hypersaline at times, and probably with elevated salinities through much or all of its deposition. Even though the Kenwood shows significant geographic expansion over the Otis Formation, a unit that includes marine limestone facies, the Kenwood lacks normal marine facies and faunas. This suggests that the basin of deposition had

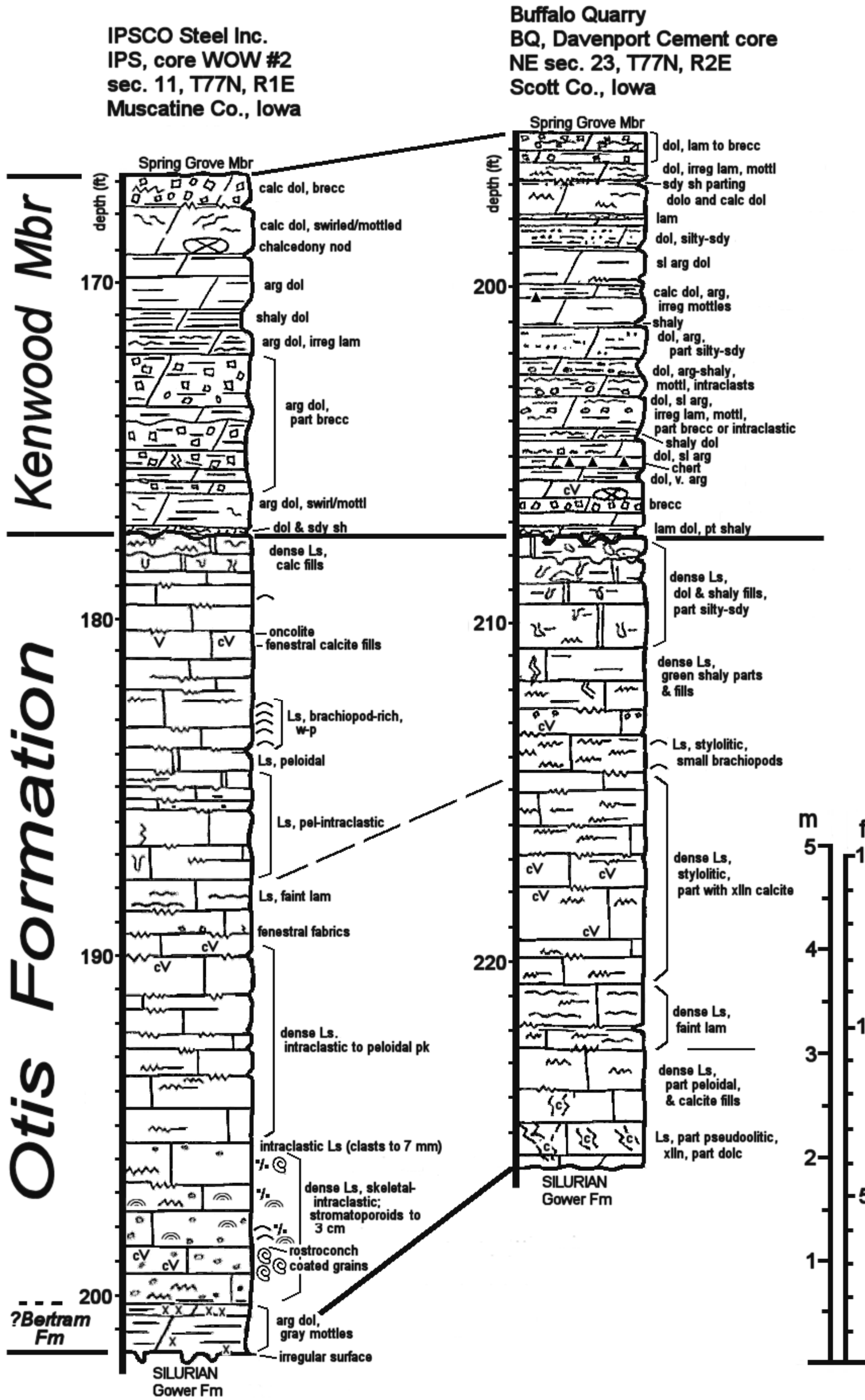

Figure 3. Graphic sections of lower Wapsipinicon Group strata from two cores in southeastern Iowa. Symbols as noted for Figures 1 and 2. See Figure 5 in the accompanying Cedar Valley Group article for explanation of abbreviations. Cores are archived at the Iowa Geological Survey.

marginal circulatory barriers which restricted open marine circulation and promoted widespread hypersalinity through net evaporation over a broad area (Witzke et al., 1988). The widespread continuity of the upper Kenwood evaporite and equivalent collapse breccias is interpreted to reflect overall depositional shallowing and increasing hypersalinity in the restricted basin, and the Kenwood is interpreted to represent a general transgressive-regressive (T-R) depositional sequence (Witzke et al., 1988).

Spring Grove and Davenport Members

The Spring Grove and Davenport members of the Pinicon Ridge Formation are considered collectively, as they are interpreted to represent part of the same T-R depositional sequence. In Linn and Johnson counties, the lower Spring Grove Member is dominated by laminated petroliferous dolomite strata, whereas the overlying Davenport Member is characterized by limestone strata with collapse breccias (especially in the upper part). Elsewhere in southeastern Iowa and parts of northern Iowa the distinction between limestone and dolomite strata is less distinct. In fact, the stratigraphic position that separates limestone and dolomite facies in southeastern Iowa varies significantly (Fig. 2), and Spring Grove strata locally include limestone facies, and Davenport strata are variably dolomitic in some sections. Except where coincident with the shift from dolomite to limestone, the boundary between the Spring Grove and Davenport members is gradational and arbitrary. The limestone-dolomite facies boundary within the succession (Fig. 2) is interpreted to be a diagenetic facies transition and not a primary depositional feature. The Spring Grove-Davenport interval is recognized over a broad area of eastern, northern, central, and southern Iowa, and it is known to extend into adjoining areas of southern Minnesota, northern Missouri, and western Illinois (Witzke et al., 1988). The interval generally overlies the Kenwood Member, possibly disconformably, but it unconformably overlies Ordovician or Silurian strata where the Kenwood Member is locally absent (especially above Silurian paleoescarpments).

Typical Spring Grove dolomite strata are dominated by thinly-laminated dolomite facies, and the laminated units are petroliferous to varying degrees, producing a distinctive fetid odor when freshly broken. The organic-rich carbonaceous laminations are brown to black in color in unoxidized sections. The thin horizontal laminations, typically marked by alternations in organic content and dolomite crystal size, are often seen to be laterally continuous. Some crenulated to domal laminations are probably stromatolitic in origin (Fig. 1). The Spring Grove dolomites are porous to vuggy to varying degrees. Some units within the member are only faintly laminated, and non-laminated vuggy dolomite beds are also observed. The member appears to be generally unfossiliferous, but burrows, stromatolites, ostracodes, indeterminate medusoid forms, and placoderms have been noted (Witzke et al., 1988; Hickerson, 1994), the latter two groups noted from a single locality (Milan Quarry, Illinois). Minor breccias and intraclastic units are seen at some localities (Figs. 2, 4). Giraud (1986) observed nodular to mosaic anhydrite in the Spring Grove within evaporite-bearing Wapsipinicon successions in southeastern Iowa, and gypsum-anhydrite void fills are also noted locally.

The laterally continuous laminations and general absence of desiccation features within the Spring Grove Member at most localities was interpreted by Sammis (1978) to support deposition in a subtidal setting within a restricted basin of elevated salinity. However, Hickerson (1994) observed a prominent desiccation surface exhibiting large polygonal cracks in the upper 50 cm of the Spring Grove at the Milan Quarry, as well as a disconformity that separates upper and lower strata. He also interpreted upper Spring Grove deposition to include peritidal/supratidal environments, based on his discovery of a local desiccation surface. As such, the Spring Grove succession may represent a general shallowing-upward T-R cycle.

Hickerson's (1994) remarkable discoveries of ptycodontid placoderm skeletons (bitumen impregnated) in the upper Spring Grove and a possible arthrodire placoderm cranium in the lower Spring Grove at the Milan Quarry (Fig. 4) are particularly enlightening. Although the Spring Grove Member is largely devoid of macrofauna, these discoveries indicate that certain fish taxa were capable of living in the shallow restricted environments of Spring Grove deposition, at least at times.

The Davenport Member derives its name from exposures of upper Wapsipinicon Group strata in the Davenport area. Sammis (1978, p. 163) designated the Buffalo Quarry as a surface reference section for the member, but no type locality has ever been formally designated. It is proposed here that the natural exposure along Duck Creek at Devil's Glen Park in the eastern part of the Quad Cities area be designated the type locality for the member (location and graphic section shown on Fig. 4). The Davenport section at that locality exposes about 7 m of laminated to brecciated limestone strata above more massive beds of Spring Grove dolomite strata.

The Davenport Member is dominated by limestone across most of its extent, primarily characterized by dense 'sublithographic' limestone, laminated to stromatolitic in part, and with common stylolites. The term 'sublithographic' refers to the resemblance to limestones used in lithographic engraving, and these dense lime mudstones often break with a conchoidal fracture. The Davenport limestones are dominantly mudstones, but pelletal and intraclastic units are also commonly present. Rare oolitic packstone-grainstone beds are noted (e.g., H33, Fig. 2). A few limestone beds display calcite-filled fenestral and 'birdseye' fabrics and gypsum crystal molds (Figs. 1, 2). Scattered chalcedony concretions are recognized locally. Although the member is dominated by limestone, discontinuous and local dolomite and dolomitic limestone beds are recognized at a number of localities (Figs. 1, 2, 4). Thin shales (in part silty to sandy) and argillaceous to shaley units are observed in many sections. The Davenport Member is dominated by evaporite facies in some areas of southeastern Iowa, where nodular, mosaic, and massive gypsum-anhydrite units are observed to interbed with limestone and dolomite strata (Giraud, 1986).

The Davenport Member is best known for its well developed limestone breccias, a characteristic feature in most sections across its geographic extent. These breccias consist of irregular unsorted angular clasts of limestone (varying in size from a few millimeters to large blocks in excess of 1 meter diameter) generally in a limestone to argillaceous limestone matrix. The Davenport breccias have been interpreted to have formed by solution-collapse processes (Sammis, 1978). This process results from the dissolution of evaporite layers causing the fracturing and internal collapse of intervening carbonate beds. Most breccia clasts consist of lithologies seen within the Davenport Member, primarily sublithographic and laminated limestone. However, the upper breccias also contain scattered fossiliferous limestone clasts derived from overlying strata of the Solon Member.

The Davenport Member can be divided into upper and lower units across much of its extent in southeastern Iowa. The lower interval consists predominantly of sublithographic limestone beds, commonly laminated to stromatolitic (Figs. 1, 2, 4). Breccias are locally present, but they are subordinate to the bedded limestone strata. By contrast, the upper interval contains abundant limestone breccias, and breccias form the dominant lithology at many localities (Figs. 1, 2, 4). Nevertheless, breccia units are replaced laterally by bedded limestone units at some localities, and the upper interval, although brecciated in part, is dominated by bedded limestones in the Quad Cities area (Fig. 4).

Except for an abundance of stromatolitic laminations in the Davenport limestones, the member is mostly unfossiliferous. Burrows and ostracodes are noted in some beds, but skeletal macrofauna is entirely absent in the member. The absence of a flourishing benthic biota suggests a stressed, probably hypersaline, environment of deposition for the Davenport. The presence of evaporites and evaporite solution-collapse breccias in the member underscores the hypersaline nature of Davenport deposition. Some Davenport strata were deposited in subaequeous environments,

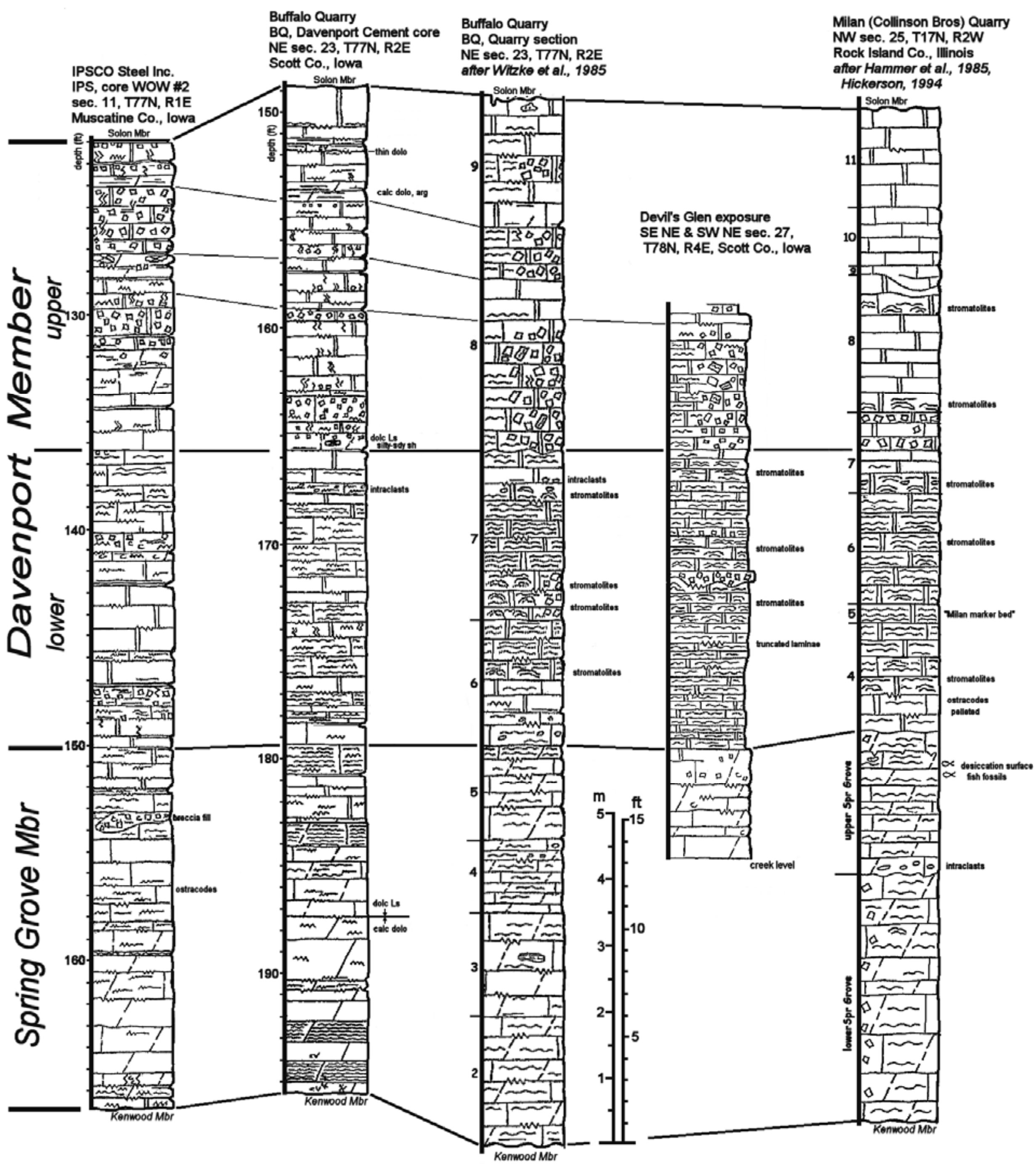

Figure 4. Representative graphic sections of upper Wapsipinicon Group strata in the Quad Cities area, Iowa and Illinois. Symbols as in Figures 1 and 2. IPSCO and Buffalo Quarry cores are stored at the Iowa Geological Survey. Milan Quarry section adapted from Hammer and others (1985) and Hickerson (1994). The natural exposure at Devil's Glen is here designated the type locality of the Davenport Member. Symbols as noted for Figures 1 and 2. Cores are archived at the Iowa Geological Survey.

particularly the pelletal and oolitic units. Limestone facies that display continuous laminations, similar to those seen in the Spring Grove, and some of the evaporite units were also likley deposited in subtidal settings, possibly within a salinity stratified sea (Sammis, 1978; Witzke et al., 1988). However, the presence of fenestral limestones and desiccation surfaces within the Davenport Member indicates that peritidal/supratidal facies were part of the depositional mosaic. In general, the Davenport-Spring Grove forms a generalized shallowing-upward succession, with an overall upward increase in supratidal and evaporitic facies.

Prior to initial transgression of the Cedar Valley seaway, "Davenport strata were subaerially exposed and subjected to freshwater diagenesis" (Sammis, 1978, p. 226), and there is evidence for minor erosional relief on the upper Davenport surface. Evaporite solution-collapse was likely initiated during this episode of subaerial exposure and freshwater diagenesis. However, the incorporaton of fossiliferous clasts derived from the Solon Member within the upper Davenport breccias indicates that solution collapse brecciation continued coincident with early Cedar Valley deposition. The incursion of the Cedar Valley seaway with waters of normal-marine salinity could also result in the dissolution of Wapsipinicon evaporites, as normal seawater, as with freshwater, is undersatured with respect to gypsum. The contemporaneity of evaporite solution with early Cedar Valley deposition is best illustrated at sections in Benton County and northward, where Solon strata are extensively brecciated in places (the upper part of the so-called "Fayette Breccia"), most likely related to the ongoing collapse of underlying evaporite units within the Davenport Member.

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MAGNETIC SUSCEPTIBILITY MAGNETOSTRATIGRAPHY FOR THE MIDDLE-UPPER DEVONIAN SEQUENCES IN SOUTHEASTERN IOWA, AND PROVISIONAL CORRELATION TO THE EIFELIAN-GIVETIAN AND GIVETIAN-FRASNIAN GSSPS IN NORTH AFRICA AND EUROPE

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INTRODUCTION

Results of preliminary investigation of Magnetic Susceptibility (MS) of platform carbonates of the Wapsipinicon and Cedar Valley groups at two well studied subsurface sites (Fig. 1) spanning Middle and Upper Devonian stage boundaries (Fig. 2) are presented here. We apply the magnetosusceptibility event and cyclostratigraphy (MSEC) method to correlate and calibrate the late Eifelian-early Frasnian MS record the Iowa Basin with global reference and boundary stratotype sections for the Eifelian-Givetian stages and Givetian-Frasnian stages in North Africa and southern France, respectively. Data plots of MS measurements from core sections of the Wapsipinicon and Cedar Valley groups display shape structures that in some respects mimic stable isotope data plots such as δC^{13}, and show a correspondence with relative sea level changes designated as Iowa Devonian T-R cycles documented in Iowa Basin carbonate platform facies (Fig. 2). If MS in ancient marine sedimentary rocks is modulated by and record climate change, then it may prove to be a relatively inexpensive proxy for study of climate change in deep time.

It is now well established that magnetic susceptibility (MS) data sets in both unlithified and lithified marine Phanerozoic sediments often record Milankovitch cyclicity, and the cyclostratigraphy of these sequences can be used for astronomical calibration of geologic time scales (Mead et al., 1986; Hartl et al., 1995; Weedon et al., 1997; Shackleton et al., 1999b; Weedon et al., 1999). It has been argued that of those climate cyclicities observed, the ~400,000 year eccentricity cycle has a robust, long-term paleoclimatic stratigraphic record that is often preserved (Shackleton et al., 1999a). Testing of the utility of MS data sets as climate proxy record for the Devonian is still being investigated and investigations are presently in progress to independently verify its applicability for climate studies in deep time through correlation with other independently derived coeval climate proxy records such as sea surface temperature (SST) records derived from study of δO^{18} values in conodont apatite (see Joachimski et al., 2004; Breisig et al., 2006).

In addition to its utility in paleoclimatic studies, magnetostratigraphy-susceptibility can be used for high-resolution correlation among marine sedimentary rocks of broadly differing facies of regional and global extent (Crick et al., 1997, 2000; Ellwood et al. 1999, 2000). MSEC (magnetosusceptibility event and cyclostratigraphy) is a correlation method that provides a robust data set to independently evaluate and adjust stratigraphic position among geological sequences. It requires reasonable biostratigraphic control to initially develop a chronostratigraphic framework where distinctive MS chrons can be directly correlated with high precision among sections, even when biostratigraphic uncertainties or slight unconformities are known to exist within sections (Ellwood et al., 2006a). The MS method is particularly useful as an independent age control because it can extract data from sections that are not amenable to other magnetostratigraphic techniques, such as remnant magnetization (Berggren et al., 1995).

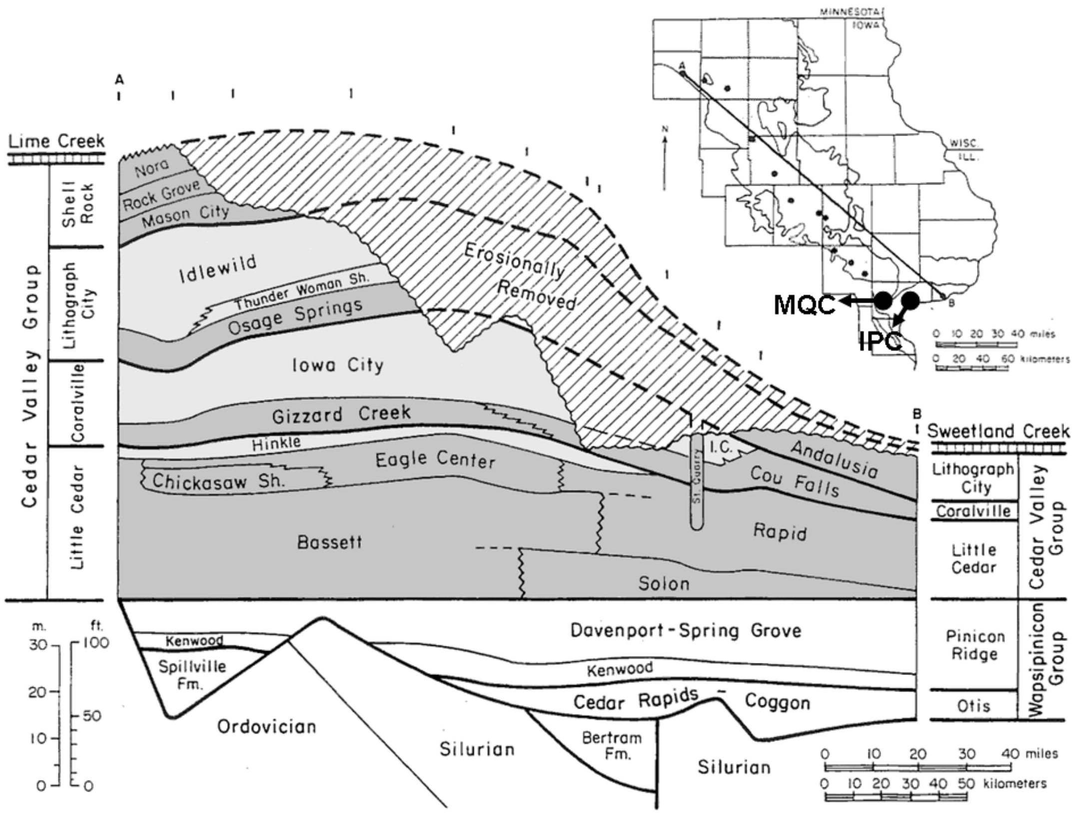

Figure 1. Cross section of the late Eifelian-Frasnian strata of north-central and eastern Iowa. After Fig. 1 of Witzke and others (1989) and Witzke and Bunker (p. 23 and p. 47 of this guidebook). Location map in upper right of figure shows locations core sections MQC (Moscow Quarry Core), IP (IPSCO PPW #3) in Muscatine County, Iowa, and the LaFarge Buffalo Quarry (point B at southern terminus of the line of cross-section) in Scott County, Iowa. Detailed locations in the appendix of Day (2006 this guidebook). After Fig. 1 of Day (p. 1of this guidebook).

as it does not require that the rock or sediment analyzed be consolidated or orientated. This study presents provisional correlations of the Iowa Basin carbonate platform succession spanning the interval of the upper Eifelian through the lower Frasnian employing the MSEC method, that can be independently verified in most of the succession by traditional biostratigraphic zonal correlations (see Day, 2006, this guidebook).

IOWA BASIN WAPSIPINICON AND CEDAR VALLEY GROUP TARGET SECTIONS

Magnetic susceptibility records were developed from two main sites in Muscatine County in southeastern Iowa (Fig. 1) where cores spanning the entire Wapsipinicon and Cedar Valley groups were well preserved and relatively well studied. The Moscow Quarry core (Figs. 3A and 10) was targeted for study because it includes one of the thickest section of the Otis Formation of the Wapsipinicon Group thus far documented in eastern Iowa, and the Otis and lower part of the Pinicon Ridge Formation span the Eifelian-Givetian Stage boundary of the Middle Devonian (Fig. 2). The IPSCO PPW #3 core features the entire Wapsipinicon Group, and nearly all of the Cedar Valley Group as typically developed in eastern Iowa, except for the upper part of the Lithograph City Formation. Both the Eifelian-Givetian and Givetian-Frasnian stage boundaries are known to be represented in this core, although their precise positions have proven difficult to determine because of a lack of diagnostic

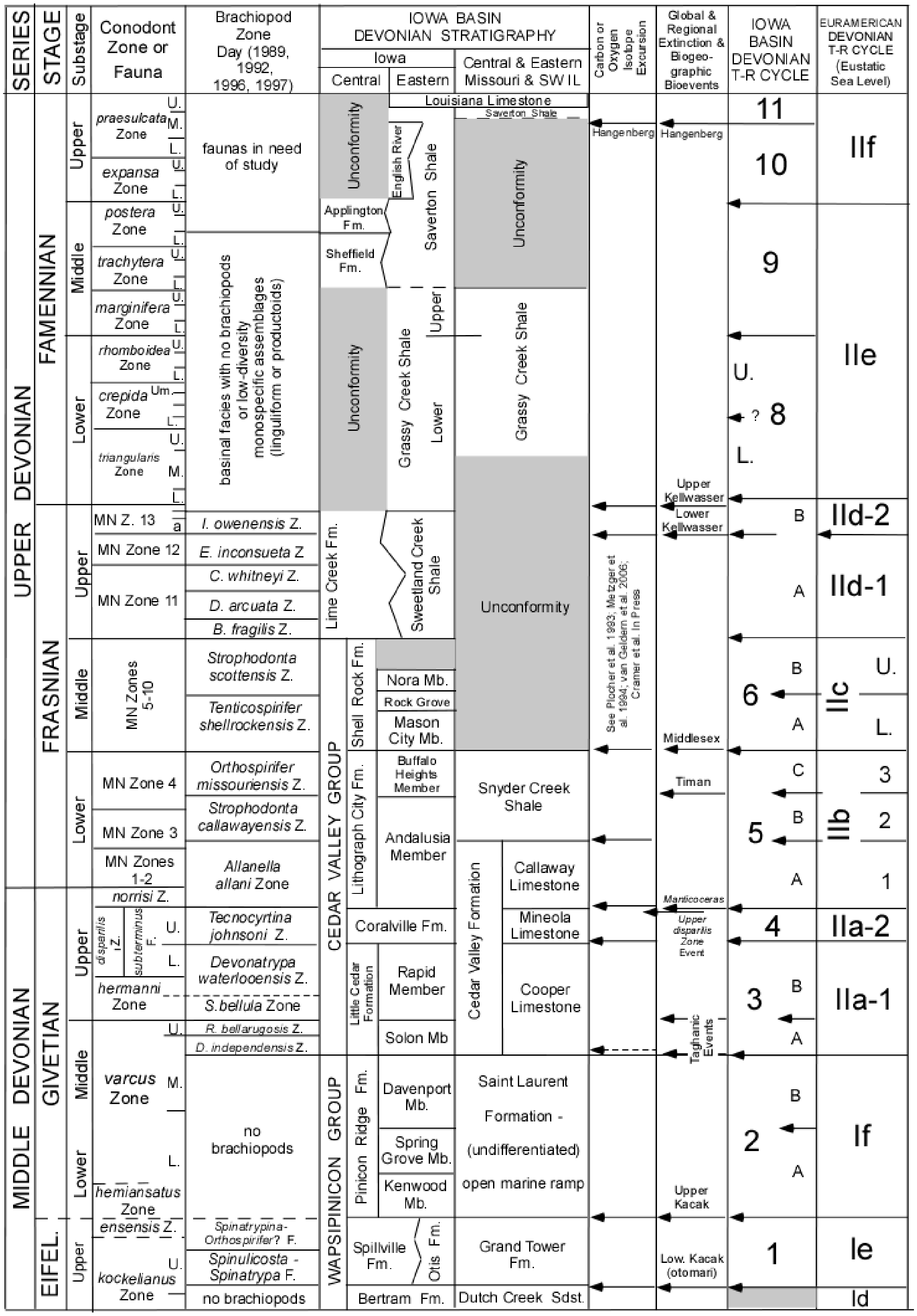

Figure 2. Stratigraphic, biostratigraphic and regional and global sea level event framework for the Middle-Late Devonian (late Eifelian- Famennian) strata of the Iowa Basin showing relationships between: the qualitative eustatic T-R cycles and Iowa Basin Devonian T-R cycles. After Fig. 2 of Day (2006, this guidebook).

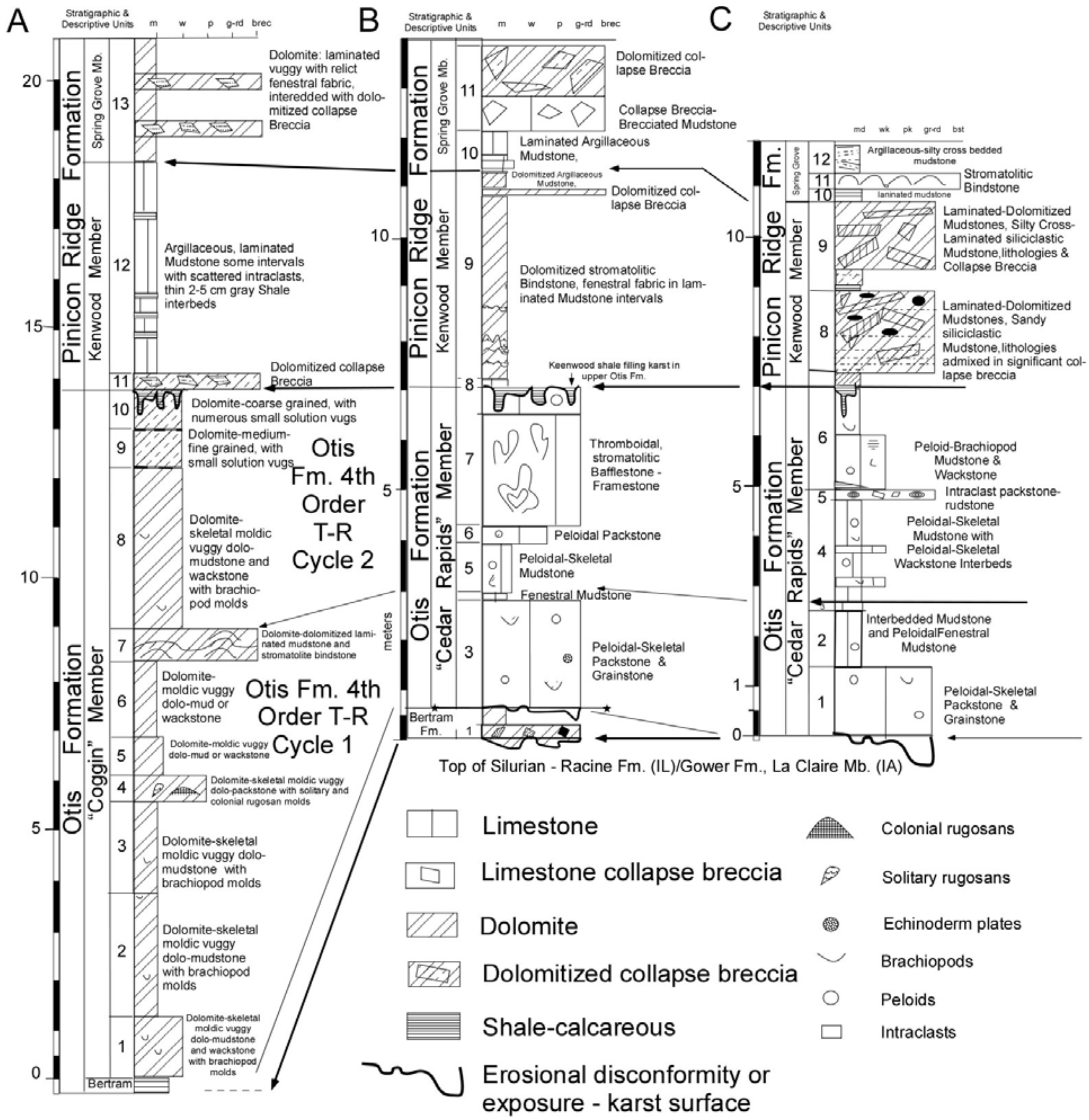

Figure 3. Stratigraphy and cyclostratigraphy of the lower Wapsipinicon Group in well cores samples from Muscatine County Iowa, and the upper ramp road section the Allied Quarry in Rock Island County, Illinois (Stop 2 of this guidebook). **A.** Section of the Otis and lower Wapsipinicon formations sampled for MS (Fig. 10) in the Moscow Quarry core, Muscatine Co, IA. **B.** Section of the Otis and lower Wapsipinicon formations sample for MS (Fig. 6) in the IPSCO PPW#3 core, Muscatine Co, IA. **C.** Section of the Otis and lower Wapsipinicon formations measured along the upper ramp road-cut on the west side of Allied Quarry in Rock Island Co., IL. Black highlighted arrows are major flooding events associated with sea level rises of Iowa Basin Devonian T-R cycles 1 and 2 of Fig. 2, with a newly recognized flooding event within the Otis, defining two 4th order T-R cycles. After Fig. 3 of Day (p. 1 of this guidebook).

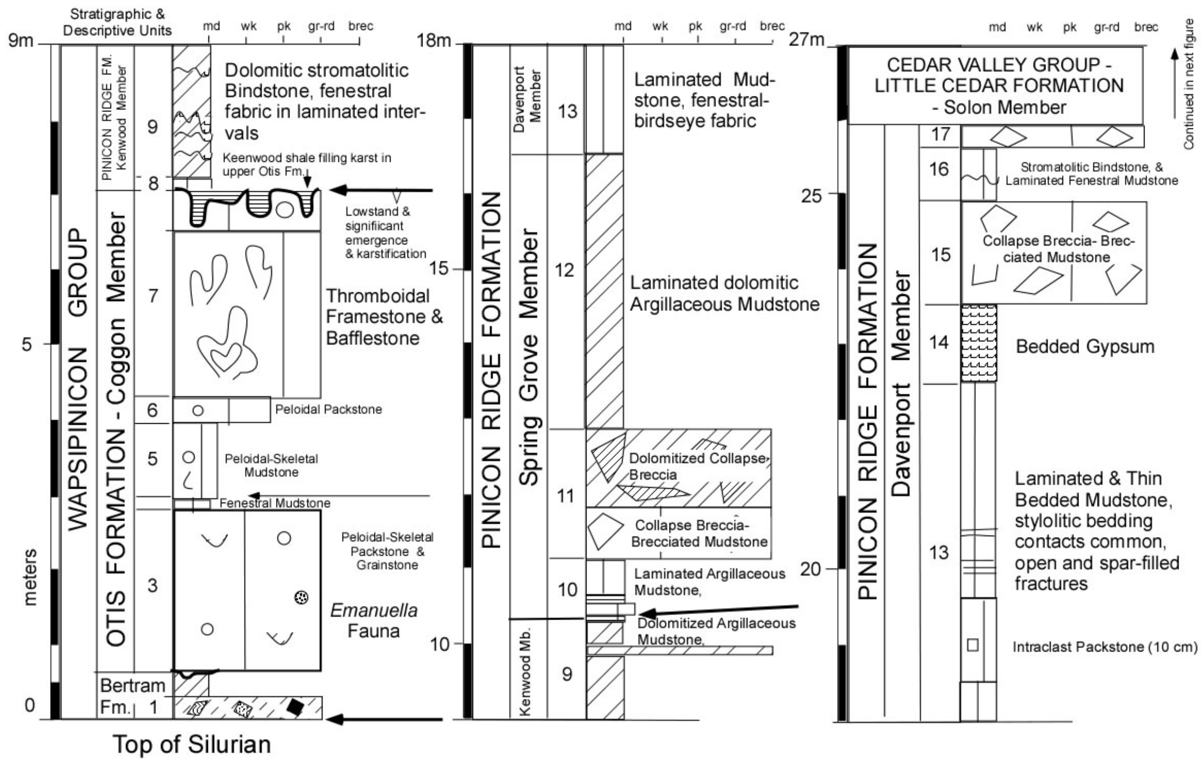

Figure 4. Stratigraphy and cyclostratigraphy of the Wapsipinicon Group sampled for MS (Fig. 7, lower part of data plot up to 25.9 m) from IPSCO PPW#3 core, Muscatine Co, IA. Black highlighted arrows are major flooding events associated with sea level rises of Iowa Basin Devonian T-R cycles 1, 2A, and 2B of Fig. 2.

conodont and brachiopod faunas in the boundary intervals.

MAGNETIC SUSCEPTIBILITY-GENERAL COMMENTS AND METHODS

All mineral grains are "susceptible" to becoming magnetized in the presence of a magnetic field, and MS is an indicator of the strength of this transient magnetism within a material sample. MS is very different from remanent magnetism (RM), the intrinsic magnetization that accounts for the magnetic polarity of materials. MS in sediments is generally considered to be an indicator of iron, ferromagnesian or clay mineral concentration, and can be quickly and easily measured on small samples. In the very low inducing magnetic fields that are generally applied, MS is largely a function of the concentration and composition of the magnetizable material in a sample. It is much less susceptible to remagnetization than is the remanent magnetization (RM) in rocks and can be measured on small, irregular lithic fragments and on highly friable material that are difficult to sample for RM measurement.

Besides the ferrimagnetic constituents such as the iron oxide minerals magnetite and maghemite, magnetizable materials in sediments include iron sulfide and sulphate minerals, including pyrrhotite and greigite, which may acquire an RM (required for reversal magnetostratigraphy). In addition there are many other less-magnetic, paramagnetic compounds, that because of their abundance, are often more important than the ferrimagnetic constituents when measuring MS. These include the clays, particularly illite and chlorite, ferromagnesian silicates such as biotite, pyroxene and amphiboles, iron sulfides including pyrite and marcasite, iron carbonates such as siderite and

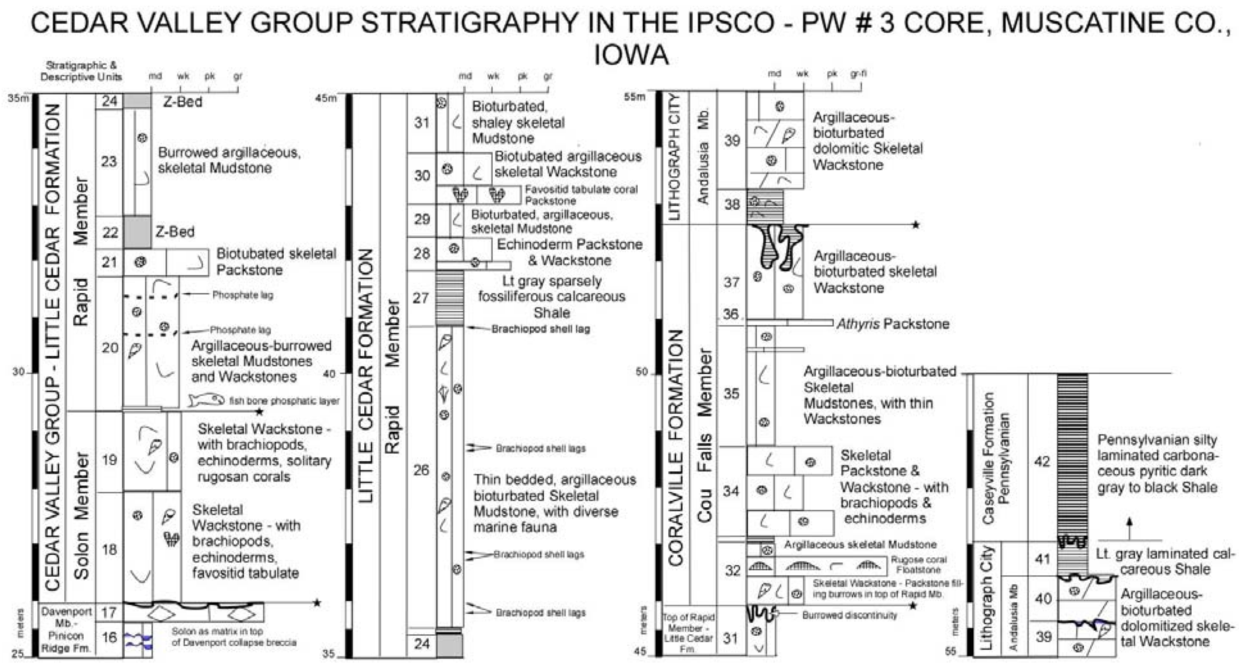

Figure 5. Stratigraphy and cyclostratigraphy of the Cedar Valley Group sampled for MS (Fig. 7, upper part of data plot from 25.9 m to 57.1 m) from IPSCO PPW#3 core, Muscatine Co, IA. Black highlighted arrows are major flooding events associated with sea level rises of Iowa Basin Devonian T-R cycles 1, 2A, and 2B of Fig. 2.

ankerite, and other iron and magnesium bearing minerals.

In addition to the ferrimagnetic and paramagnetic grains in sediments, calcite and-or quartz may also be abundant, as are organic compounds. These compounds typically acquire a very weak negative MS when placed in inducing magnetic fields, that is, their acquired MS is opposed to the low magnetic field that is applied. The presence of these diamagnetic minerals reduces the MS in a sample. Therefore, factors such as changes in biological productivity or organic carbon accumulation rates may cause some variability in MS values.

Presentation of MS Data from Lithified Sequences

For presentation purposes and inter data-set comparisons, the bar-log format, similar to that previously established for magnetic polarity data presentations, is recommended. These bar-logs should be accompanied by both raw and smoothed MS data sets. Here, raw MS data (Fig. 6) are smoothed using splines (solid data curve in Fig. 6). The following bar-log plotting convention is used; if the MS cyclic trends increase or decrease by a factor of two or more, and if the change is represented by two or more data points, then this change is assumed to be significant and the highs and lows associated with these cycles are differentiated by black (high MS values) or white (low MS values) bar-logs (shown in Fig. 1). This method is best employed when high-resolution data sets are being analyzed (large numbers of closely spaced samples). High-resolution data sets help resolve MS variations associated with anomalous samples. Such variations may be due to weathering effects, secondary alteration and metamorphism, longer-term trends due to factors such as eustacy, as opposed to shorter term climate cycles, or event sequences such as impacts (Ellwood et al., 2003), and to other factors. In addition, variations in detrital input between localities or a change in detrital

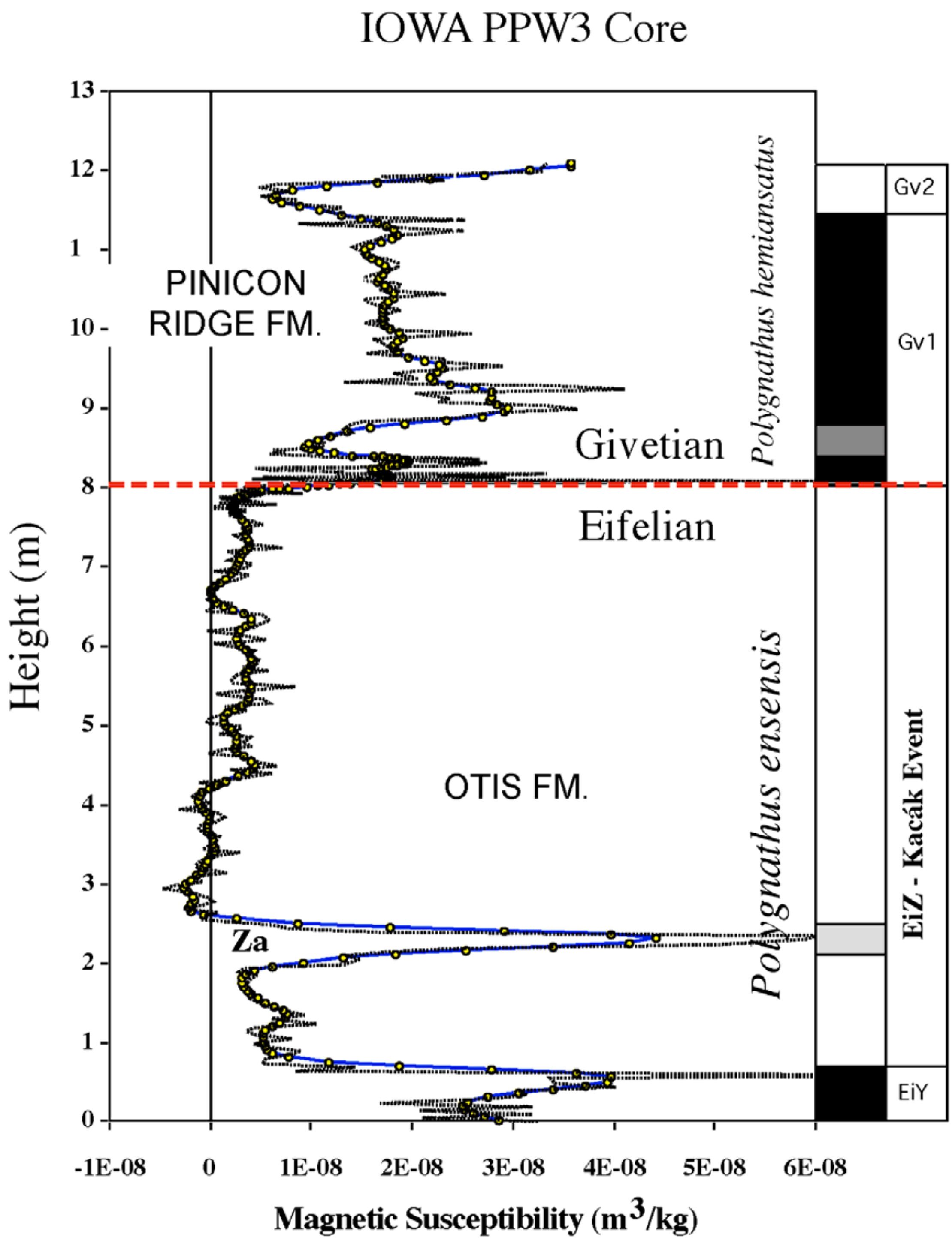

Figure 6. MS data for the Eifelian-Givetian interval in the IPSCO PPW#3 Core, Iowa. Measurements using the MS bridge at LSU. Bar-logs (filled – high MS; open – low MS; methods discussed in text) developed from the MS data that were smoothed using splines (solid data curve; raw MS data are shown as dotted curve). MS data in m^3-kg. MS chron numbers are: Gv1 corresponding to MS Zone Mech Irdane of Crick et al. (2000); Gv2 to the complete MS Zone Rissani (Crick et al., 2000). Within the Eifelian stage, MS chrons are labeled in increasing age from EiZ immediately below the boundary. MS chron EiZ corresponds to the Kačák Event discussed by Crick et al. (2000). Za is an MS subchrons. The Eifelian-Givetian boundary is represented by an unconformity (dashed horizontal line).

sediment source is resolved by comparing bar-logs between different localities.

MS SAMPLING, MEASUREMENT AND RESULTS

Portions of two biostratigraphically well-studied cores from Iowa were used for this study. These include: the IPSCO PPW#3 core covering the upper part of the Eifelian, all or most of the Givetian, and the lower part of the Frasnian Stage; and the Moscow Quarry core covering much of the latest Eifelian and Eifelian-Givetian Stage boundary (Fig. 2). Samples were collected for MS measurement at ~5 cm intervals from the lowest 12 m of the PPW#3 core and from the Moscow Core. In addition, the entire PPW#3 core was measured at 5 cm intervals using a Bartington field probe designed for that purpose. Collected samples were measured using the susceptibility bridge at LSU. We report MS in terms of sample mass because it is much easier and faster to measure with high precision than is volume. Each sample is measured three times and the mean and standard deviation of these measurements is calculated. The mean of these measurements is reported here.

Results for measurement on the same sample intervals using the LSU bridge and the Bartington probe were mathematically compared using simple regression analysis and using a linear equation the Bartington numbers converted to correspond to equivalent MS values relative to mass. Because the LSU MS instrument is more sensitive than is the Bartington instrument, and because a "rounding off effect" artifact is produced by the Bartington instrument (often producing the same counts for different low MS in samples), an apparent truncation effect is produced in the data for the core (Fig. 7). However, we believe there is sufficient resolution in this data set to adequately characterize MS variations for the Givetian.

DISCUSSION AND PRELIMINARY CONCLUSIONS

The base of the IPSCO PPW#3 core shows that the MS chron zonation is well defined (Figs. 6 and 7) with values in the Eifelian that are very low (<1 x 10-8), or in some cases diamagnetic (negative MS values). The unconformity (disconformity) between the Otis and basal Pinicon Ridge formations coincides to the boundary (dashing line in Figs 6 and 7) but it does not appear to represent a significant amount of time. When all the data for the core are presented (Fig. 7) there is a well-defined MS chron zonation that emerges from the smoothed data (using splines) and this zonation can then be compared to the climate-correlated standardized MS CRS (MS composite reference section) recently developed by Ellwood et al. (2006b). This new MS CRS zonation (Fig. 8) provides a compilation and timing of the major conodont zones, the Kačák, Taghanic and Frasnes bio-events, and the lesser known (perhaps only regional to North Africa and Europe) middle Devonian Upper and Lower *pumilio* marker beds.

When the MS chron zonation from the IPSCO core is compared to the standardized MS CRS, the correspondence is good. Of interest is that relative sediment accumulation rates for the Givetian of SE Iowa, as recorded in PPW#3 by the LOCs in Fig. 9, are similar to those represented in the climate standardized MS CRS developed from Europe and North Africa. One exception is the latest Eifelian in PPW#3, where Otis Formation carbonate platform sediment accumulation rates in southeast Iowa appear to be higher relative to condensed offshore sections in Europe and North Africa. This is supported by the latest Eifelian results from the Moscow Quarry core we examined (Fig. 10), where the MS chron zonation is significantly expanded, and sedimentation rates, relative to the MS CRS,

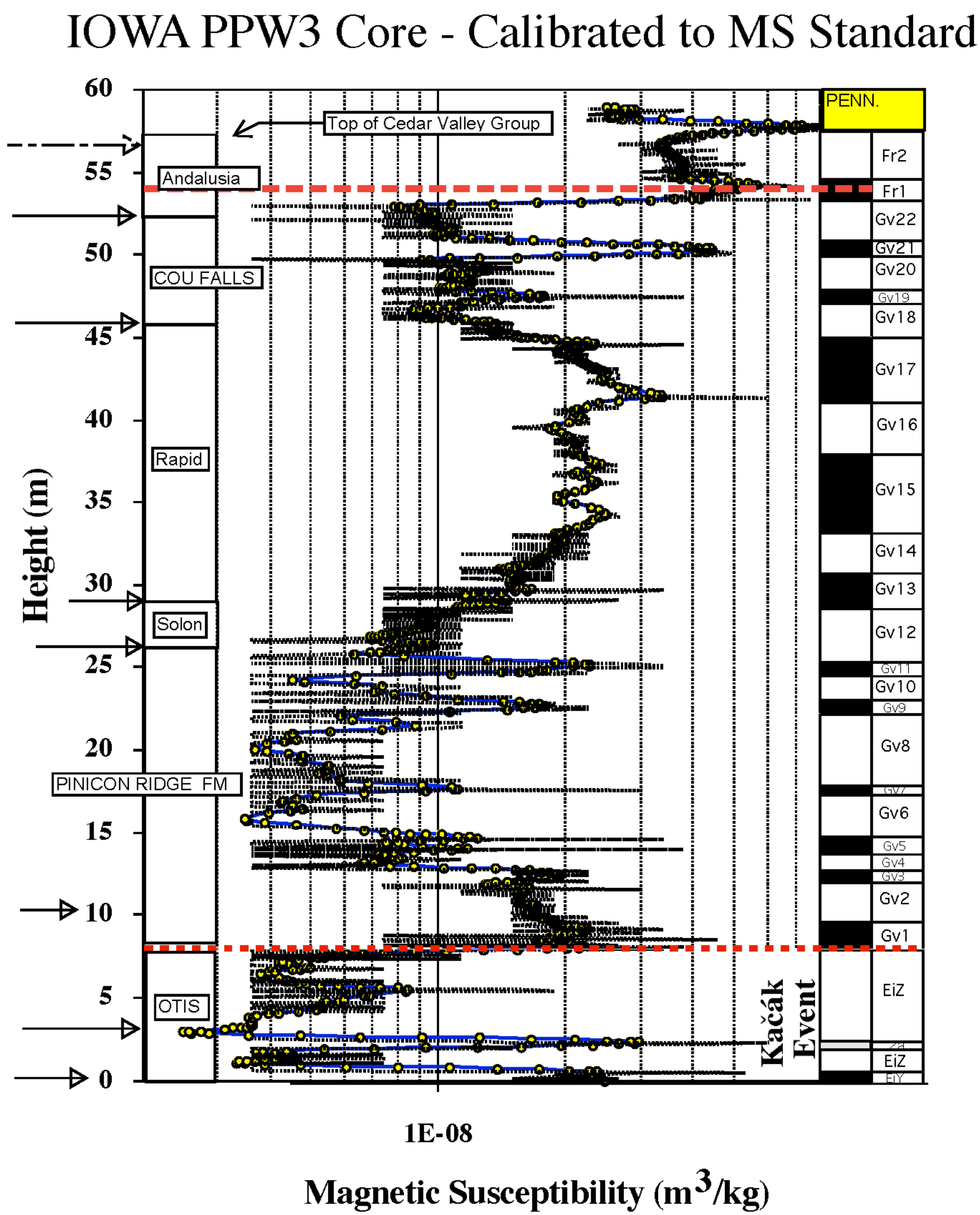

Figure 7. MS data for the upper Eifelian, Givetian and lower Frasnian stages of the Middle and upper Devonian from the IPSCO PPW#3 Core, Iowa. Most of these measurements were performed using the Bartington Field Coil system. Results were calibrated to the MS bridge at LSU by measuring samples from Fig. 6 with the Bartington instrument and then using linear regression of the two data sets. MS data then reported as in Fig. 6. MS chrons notation from Fig. 8. The Eifelian-Givetian boundary is represented by an unconformity (dashed horizontal line at 7.1 m), and the Givetian-Frasnian boundary is positioned at 54 m (dashed horizontal line) within unit 39 of the lower Andalusia Member (see Fig. 5).

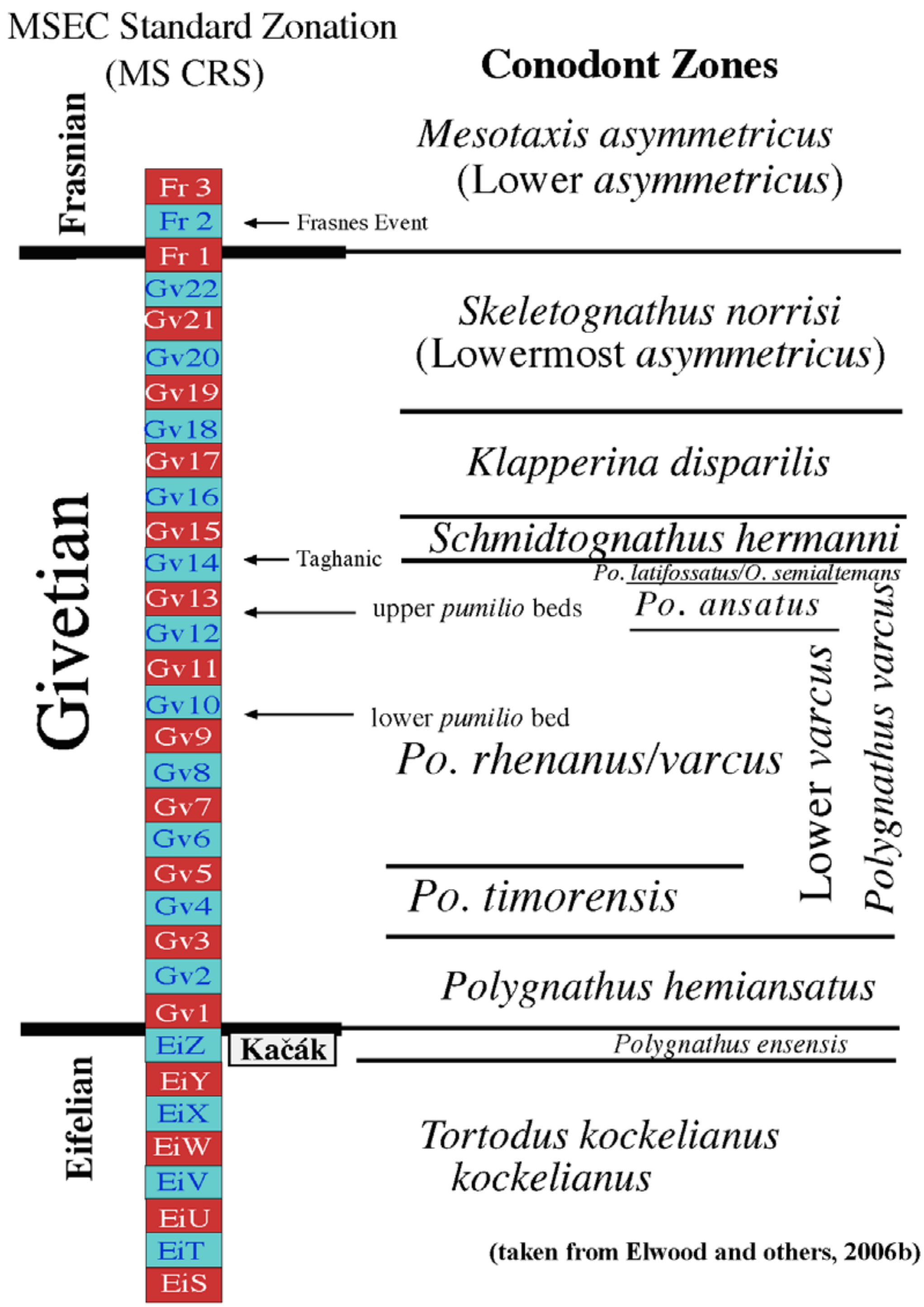

Figure 8. The MS CRS for the Givetian, latest Eifelian and earliest Frasnian of the middle Devonian where MS chrons are plotted assuming uniform climate cyclicity from Ellwood and others (2006a), from sections in Morocco, France and Germany, including the Eifelian-Givetian GSSP at Mech Irdane (Walliser et al., 1995), Morocco, and the Givetian-Frasnian GSSP at St. Nazaire-de-Ladarez, France (Klapper et al., 1987). Also plotted are conodont zones for the middle Devonian as well as the positions of the Kačák, Taghanic and Frasnes bioevents and the middle Devonian Upper and Lower *pumilio* marker beds. This standardized zonation was developed from Time-Series Analysis of MS data and constrained to a uniform Milankovitch climate cyclicity in the eccentricity band (Ellwood et al., 2006b).

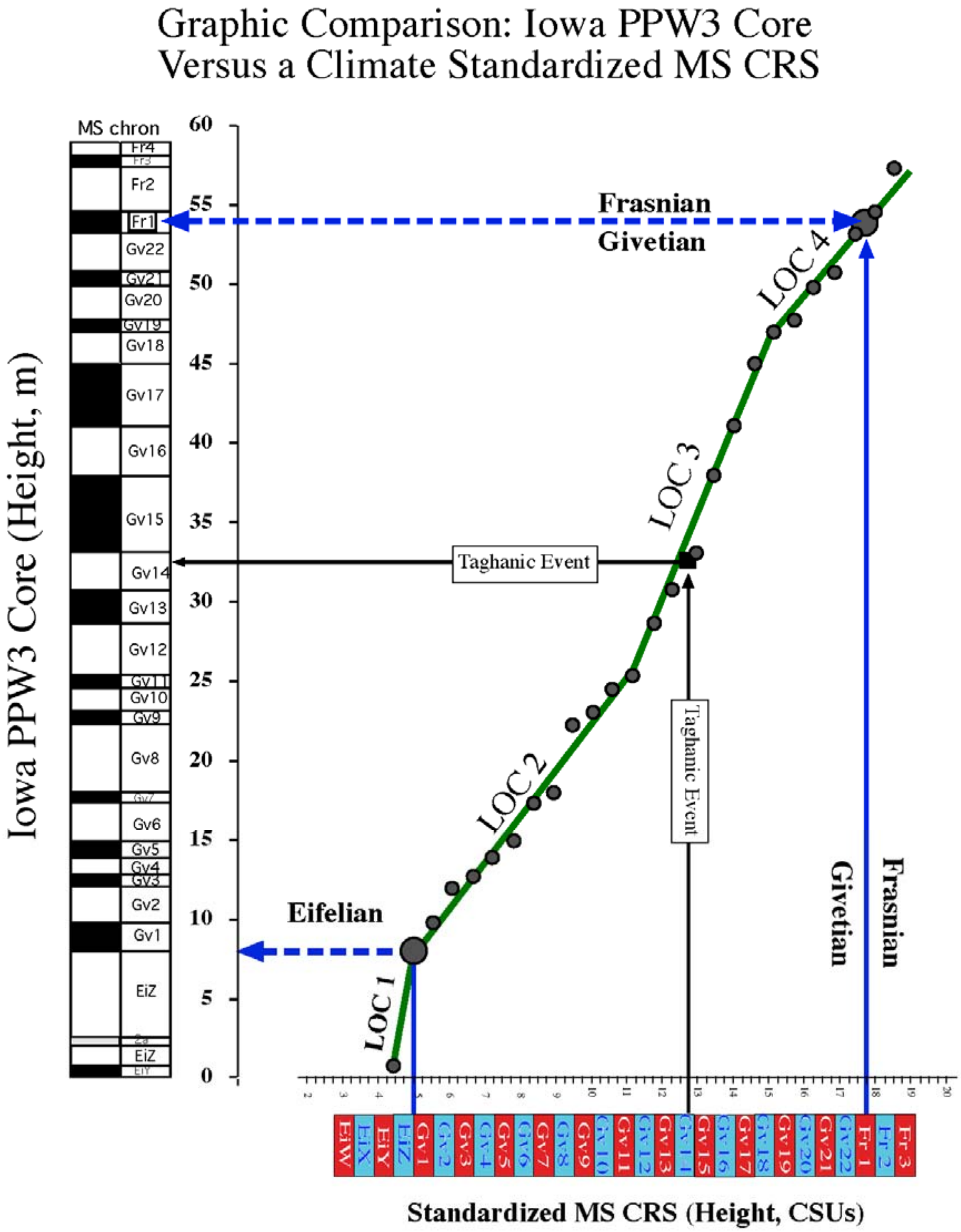

Figure 9. Graphic comparison of the MS chrons for the Givetian interval from the IPSCO PPW#3 Core, Iowa (Fig. 2), versus the climate cyclicity-constrained MS CRS (Fig. 3). Eifelian-Givetian boundary is unconformable; the Givetian-Frasnian boundary level is picked based on MS results from the GSSP (Ellwood et al., 2006b), comparison to the MS chron zonation presented in Fig. 8, and estimates from imprecise biostratigraphic information. The predicted level of the Taghanic bio-event is extrapolated into the core. Patterned circles represent the intersection of corresponding MS chron tops and bases between the two sections. Four line-of-correlations (LOCs) are fit to these data. Deviation of points from the LOCs is low, indicating a fairly good fit.

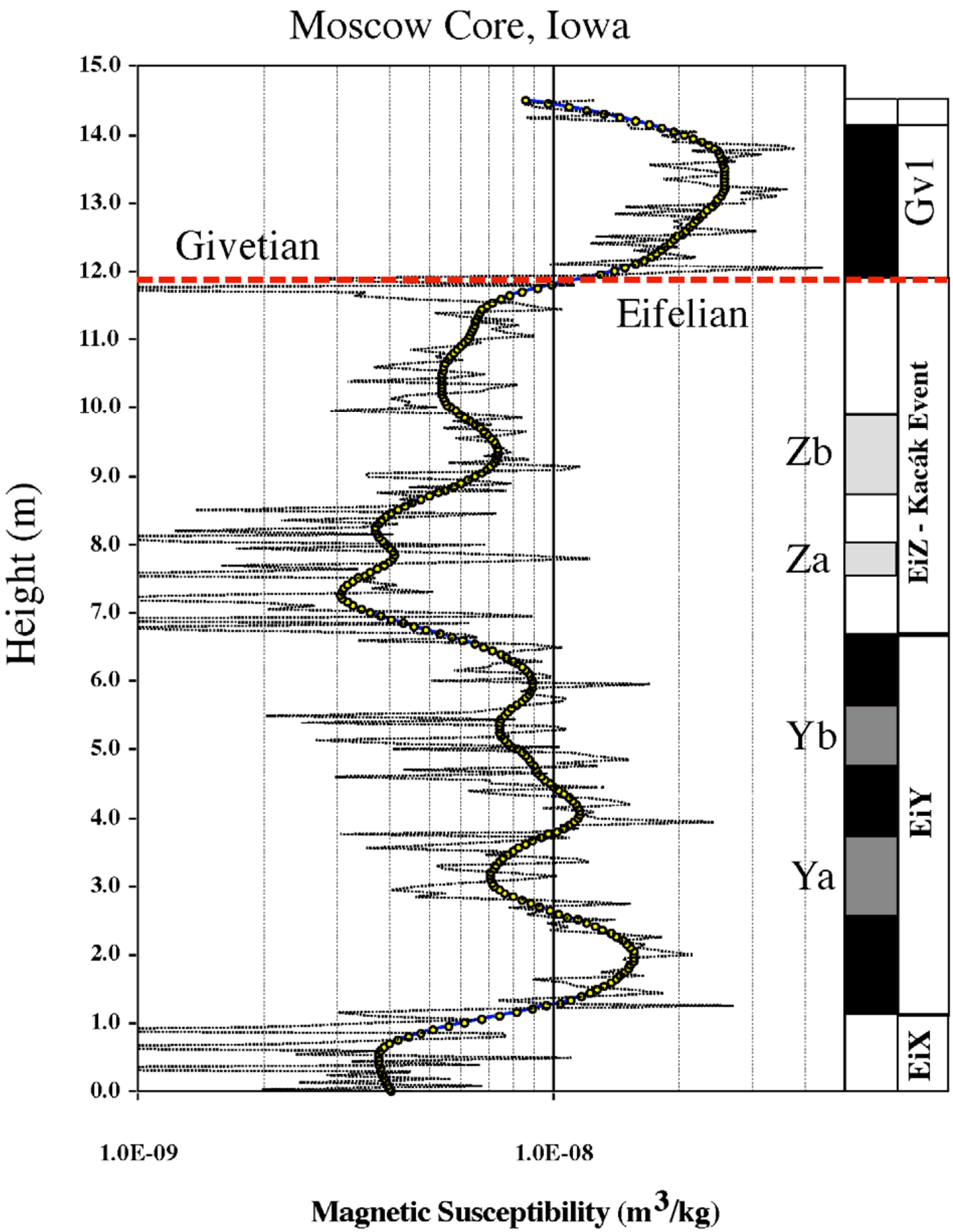

Figure 10. MS data for the latest Eifelian Stage from a Moscow Quarry core (Fig. 1, locality MQC). MS data reported as in Fig. 6. MS chrons notation from Fig. 8. Za, Zb, Ya, and Yb are MS subchrons. The Eifelian-Givetian boundary is represented by an unconformity (dashed horizontal line).

Moscow Quarry Core, Iowa, versus a Standardized MS CRS

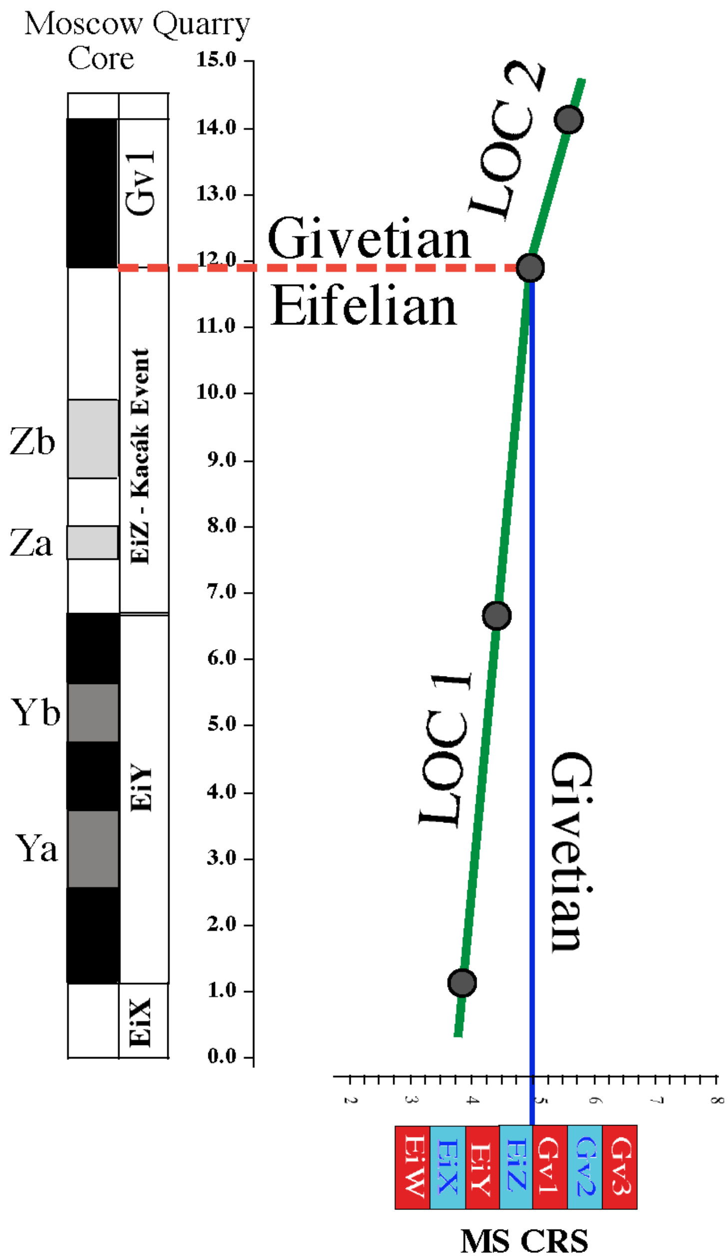

Figure 11. Graphic comparison of the MS chrons from the Moscow Core, Iowa, versus the climate cyclicity-constrained MS CRS (Fig. 8). The steep inclination of LOC 1 indicates that sediment accumulation rates were high during the latest Eifelian at the Moscow Quarry core site, relative to the standardized MS CRS. This steep inclination (LOC 1) is similar to that observed for the latest Eifelian for the IPSCO PPW#3 core (LOC 1 in Fig. 9).

are high (Fig. 11). The expanded MS chron zonation observed yields MS subchrons Za and Zb for chron EiZ, and subchrons Yb and Ya within chron EiY. Such subchrons are useful for high-resolution correlation. Here we observe that MS subchron Za is also seen in the PPW#3 data set (Fig. 6). In addition, MS subchron 2a of Crick et al. (1997) is at the same level within chron EiZ as subchron Za.

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FRASNIAN-FAMENNIAN BOUNDARY AT THE TYPE SWEETLAND CREEK SHALE LOCALITY

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INTRODUCTION

The Fransnian-Famennian (F-F) boundary divides the Upper Devonian into the lower Frasnian Stage and the upper Famennian Stage. This boundary marks the culmination of a series of events that are recognized as one of the most significant mass extinctions in the Phanerozoic (Sepkoski, 1986; Hallam and Wignall, 1999; Racki, 2005). Globally the latest Frasnian is characterized by the demise of reef-forming corals and stromatoporoids, as well as the extinction of numerous brachiopods, conodonts, ostracodes, tentaculitids, and trilobites. The boundary is recognized by the extinction of several Frasnian conodonts and defined by the first occurrence of the conodont *Palmatolepis triangularis* (Klapper et al., 1994). The boundary is immediately followed by an interval of low faunal diversity and then faunal diversification as apparently environmental conditions stabilized. While the extinction has been related to global warming, global cooling, sea level fluctuations, and bolide impact the most recent interpretations indicate earth bound environmental stresses during a relatively warm period (Over et al., 1997; Murphy et al., 2000; Joachimski and Buggish, 2002).

The Sweetland Creek Shale at the type locality, and the overlying Grassy Creek Shale, along Sweetland Creek east of Muscatine, Iowa (Fig. 1) contain a poor macrofauna dominated by inarticulate brachiopods, an abundance of the trace fossils *Chondrites* and *Planolites*, and an abundant and diverse conodont fauna. These

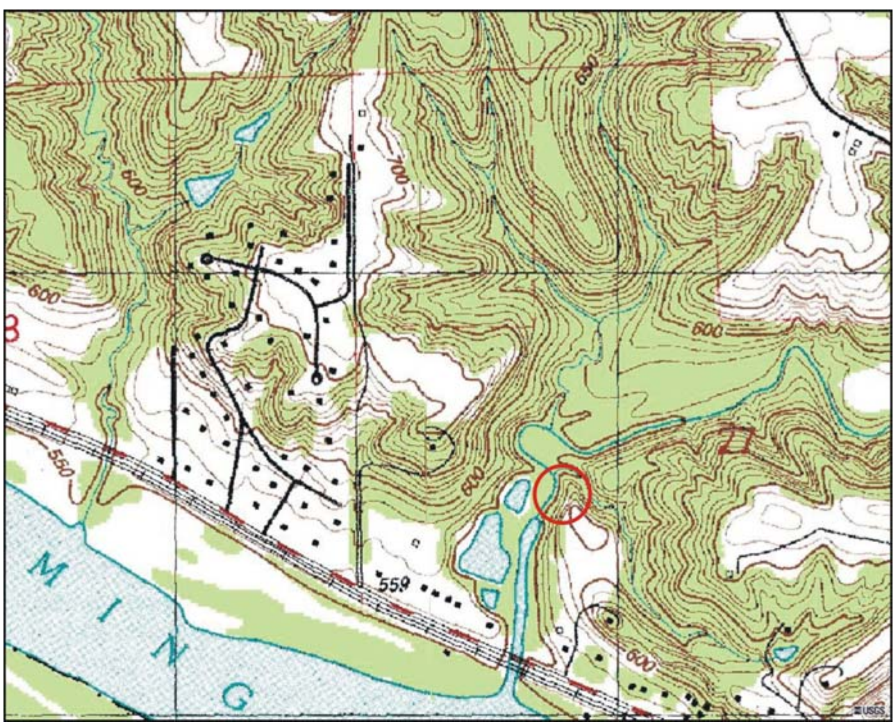

Figure 1. Location of the type Sweetland Creek Shale on east bank of Sweetland Creek, north of Iowa Highway 22 bridge, approximately 6.7 km (4.2 miles) east of the junction with US 61 in Muscatine, Muscatine County, Iowa.

conodonts have been the focus of several reports dating from the 1930s, summarized by Klapper and Furnish (1963), as well as later studies. Conodonts, the phosphatic tooth-like remains of an extinct primitive chordate, are the primary fossil used for biozonation in the Paleozoic and are critical in delineating relative time and recognizing major boundaries in marine strata. The Frasnian-Famennian boundary is at the base of the middle green shale band in the black Grassy Creek Shale 4.86 m above the base of the Sweetland Creek Shale (Fig. 2).

STRATIGRAPHY AND CONODONTS

The Sweetland Creek Shale along Sweetland Creek consists of approximately 4 m of predominantly light green-gray siltstone and shale that overlies the Middle Devonian Cedar Valley Formation. Conformably overlying the Sweetland Creek Shale is approximately 1.2 m of dark colored "black" shale, assigned to the Grassy Creek Shale, that contains several thin green-gray interbeds; these two green-gray and black lithologic units can be much thicker in the subsurface, as indicated in IDNR Borehole H-30 in southeastern Iowa. The Grassy Creek Shale is unconformably overlain by black Upper Carboniferous shales. The lowest 30 cm of the Sweetland Creek Shale has been assigned to Montagne Noire (MN) Zone 9 of the 13 part Frasnian conodont zonation scheme of Klapper (1989; 1997; see Johnson and Klapper, 1992). The light colored shale from 0.3 to 0.5 meters is assigned to MN Zone 10. The next 90 cm thick siltstone interval is largely unfossiliferous and unzoned. The next 50 cm thick interval of green-gray shale overlying the siltstone, characterized by *Palmatolepis foliacea, Pa. hassi, Pa. winchelli, Ancyrodella buckeyensis, Polygnathus decorosus, Po. unicornis, Po. webbi*, as well as other taxa (Table 1) is assigned to MN Zone 12. MN Zone 13, defined by the first occurrence of *Pa. bogartensis*, extends from 1.7 m above the base to 4.86 m. Black shales assigned to the Grassy Creek Shale are the dominant lithology above 3.9 m. Important conodont occurrences in this interval are the first appearance of *Palmatolepis linguiformis*, which marks the base of the Lower *linguiformis* Zone in the zonal scheme of Ziegler (1962) as updated by Ziegler and Sandberg (1990) as well as Girard et al. (2005), at 3.8 m. Just above this at 3.85 m is the lowest occurrence of *Pa. ultima*, the precursor to *Pa. triangularis* (see Klapper et al., 2004). *Ancyronathus ubiquitus* first occurs at 4.25 m, which in association with *Pa. ultima* and typically the absence of *Pa. linguiformis*, marks the base of the Upper *linguiformis* Zone, although *Pa. linguiformis* continues to occur higher in this section to 4.74 m. At 4.62 m there is a thin discontinuous bed of light colored pasty shale that contains only large broken and worn conodonts. This presumed ash bed seems to have accumulated on a disconformity and may be correlative to the Center Hill Ash, which in the Appalachian Basin is several decimeters below the F-F Boundary – attempts to date the zircons from this bed have proven unsuccessful. *Icriodus alternatus* first occurs at 4.71 m, but does not become a significant part of the conodont fauna until the F-F boundary at 4.86 m where it comprises more than 50 % of the platform elements.

F-F BOUNDARY

The Frasnian-Famennian boundary is marked by the abundant occurrence of *Palmatolepis triangularis* at 4.86 m in the middle green-gray shale band, which defines the base of the Lower *triangularis* Zone, the lowest Famennian conodont zone. Also first occurring in this sample horizon is *Ancyrognathus cryptus*, characterized by a relatively straight P_1 element that generally lacks a free blade and lateral process. Schülke (1996) reviewed the early Famennian ancyrognathids, and the specimens from the Sweetland Creek locality appear to be earlier forms than *Ancyrognathus cryptus* Morph 1 and Morph 2, and they have a tendency toward *Ancyrognathus sinelaminus* based on the relatively straight platform.

Diverse conodonts that include *Pa. delicatula delicatula, Pa. platys*, and *Pa. subperlobata*, typical of the Middle *triangularis* Zone, first occur in the upper green-gray shale

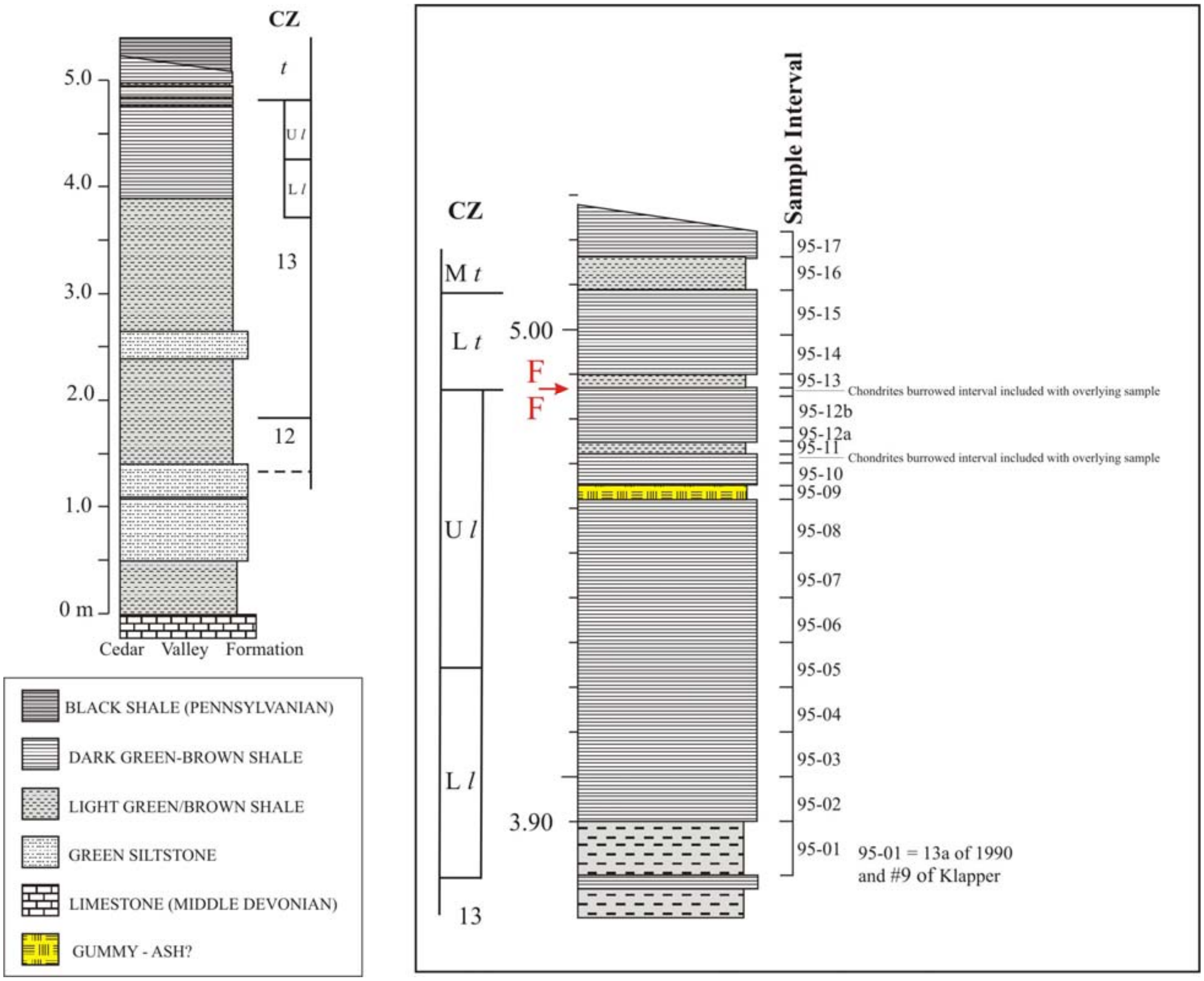

Figure 2. Stratigraphic column and inset of Frasnain-Famennian boundary interval showing sample information and conodont zonation. CZ = conodont zone; 12 = MN Zone 12; 13 = MN Zone 13; L *l* = Lower *linguiformis* Zone; U *l* = Upper *linguiformis* Zone; L *t* = Lower *triangularis* Zone; M *t* = Middle *triangularis* Zone; *t* = *triangularis* Zone undifferentiated.

interbed at 5.08 m. A thin to absent Lower *triangularis* Zone interval is typical of the Lower Famennian strata in the Illiniois and Appalachian basins, where the Lower *triangularis* Zone is probably relatively short and the base of the Middle *triangularis* Zone is often a disconformity marking the base of the extensive Morgan Trail – Gassaway - Huron – Dunkirk shales (Over, 2002).

SECTION LOCATION

Illinois City Quad
UTM 15T 067085(E) 458970 (N)

Iowa Route 22 crosses Sweetland Creek 6.7 km (4.2 miles) east of the junction with US 61 in Muscatine, Mascatine County, Iowa; access to cutbank north of bridge (by permission only) is from private drive east of bridge; steep cut bank on east side of creek between the bridge near the mouth of creek and down stream from westward meander.

Sample	90 - 1	90 - 2	90 - 3	90 - 4	5' of K	90 - 5	90 - 6	90 - 7	90 - 8	90 - 9	90 - 10	90 - 10 b	90 - 11	90 - 12	95 - 01	90 - 13a	90 - 13b	95 - 02	90 - 14	95 - 03	95 - 04	95 - 05	90 - 15	95 - 06	95 - 07	95 - 08	90 - 16	95 - 09	95 - 10	90 - 17	95 - 11	95 - 12a	95 - 12b	90 - 18	95 - 13	95 -14	95 - 15	90 - 19	95 - 16	95 - 17
m above base	1.3	1.4	1.40-1.70	1.70-2.00	1.85-2.05	2.0-2.30	2.30-2.40	2.70-2.90	2.90-3.10	3.10-3.30	3.30-3.50	3.45-3.50	3.50-3.70	3.70-3.90	3.78-3.90	3.85-3.90	3.90-3.95	3.90-4.00	3.95-4.25	4.00-4.10	4.10-4.20	4.20-4.30	4.25-4.60	4.30-4.40	4.40-4.50	4.50-4.62	4.60-4.75	4.62-4.65	4.65-4.71		4.71-4.74	4.74-4.77	4.77-4.86		4.86-4.89	4.89-4.98	4.98-5.08		5.08-5.15	5.15-5.26
Lithology	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	gr	bl	bl	bl	bl	bl	bl	bl	bl	bl	bl	bl	bl	br	bl	gr	gr	bl	bl	gr	gr	bl	bl	gr	gr	bl
Zone	12	12	12	12	13	13	13	13	13	13	13	13	13	13	L *l*	L *l*	L *l*	L *l*	L *l*	L *l*	L *l*	L *l*	U *l*	U *l*	U *l*	U *l*	U *l*	U *l*	U *l*	U *l*	U *l*	U *l*	U *l*	L *t*	L *t*	L *t*	L *t*	M *t*	M *t*	
fauna																																								
Pa. foliacea	x	x	x																																					
Po. decorosus	x	x	x	x	x	x	x	x		x	x		x	x	x	x		x	juv	x	x	x	x					x		x		x	x				x	x		
Po. unicornis	x	x		x	x	x																																		
***Pa.* sp.**	x	x	x	x	x	x	x	x		x	x		x	x		x	x		juv	x	x	x	x					x		x										
***Po.* sp.**	x	x	x	x	x	x								x				x			x							x		x				x	x					x
Ad. buckeyensis		x	x	x	x	x	x	x		x	x		x	x	x	x	x	x					x																	
Pa. hassi		x	x	x																																				
***Pa.* sp. I**			x	x			x																																	
***Ad. curvata* - late form**			x	x	x	x																																		
Po. webbi			x	x	x	x				x	x				x	x		x		x		x	x					x		x			x							
Ag. asymmetricus			x	x	x		x	x														x											x							
Pa. winchelli				x	x	x	x	x		x	x		x	x	x	x	x	x					x				x	x		x			x							
Ag. triangularis				x																																				
Pa. bogartensis					x						x		x		x	x	x				x	x	x				x													
Ag. calvini					x																																			
***Ag.* sp.**					x																																			
Ad. lobata						x														x	x						x	x												
***Pa.* sp. J**													x																											
Pa. ultima														x																										
Pa. linguiformis																x		x									x			x										
Pa. boogaardi															x	x		x	juv				x						x	x										
Ag. ubiquitus																				x			x				x													
Ag.* aff. *Ag. alatus																							x				x													
I. alternatus																											x													
Pa. triangularis																														x		x	x	x	x			x		
***Ag. cryptus* - early form**																																		x	x		x	x	x	
Po. brevicarina																																			x			x		
Pa. delicatula delicatula																																						x		
Pa. platys																																						x		
Pa. subperlobata																																						x		

Table 1.—Faunal list, sample number, sample interval above top of Cedar Valley Limestone, general lithology (gr = green-gray; bl = "black"; br = light brown), conodont zonation – note the Lower and Upper *linguiformis* zones are within the upper portion of MN Zone 13 (see Fig. 2 and text for abbreviations), and conodont occurrence for type Sweetland Creek and overlying Grassy Creek Shale. 90 –x and 95 – x are collections of Over; sample 8 of Johnson and Klapper

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STROMATOPOROIDS IN THE IDLEWILD MEMBER OF THE LITHOGRAPH CITY FORMATION IN IOWA: HOW THEY REFLECT GLOBAL PALEOBIOGEOGRAPHIC TRENDS OF THE MIDDLE-LATE DEVONIAN

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INTRODUCTION

The Middle Devonian (Eifelian and Givetian Ages) and the first half of the Late Devonian (Frasnian Age) represent a time of overall global sea-level rise. During the upper part of the Middle Givetian, sea level reached a point where the primary barrier to tropical marine organism migration was breached, in an episode known as the Taghanic Onlap--it is during this event that the stratigraphic record of Devonian stromatoporoids in Iowa begins, and it continues through the Frasnian. The lowermost Frasnian Idlewild Member of the Lithograph City Formation contains 14 genera of stromatoporoids, higher than in any member below or above, representing a time of optimal conditions for stromatoporoids.

The Idlewild Member of the Lithograph City Formation of north-central Iowa contains abundant, well-preserved stromatoporoids. It is just one of several Givetian-Frasnian age lithostratigraphic units that make up the Cedar Valley Group in Iowa in which stromatoporoids occur in abundance; however, current knowledge indicates that stromatoporoid genus diversity is higher in the Idlewild Member than in any other member, be it older or younger.

Stromatoporoids are a group of fossil sponges that originated in the Early Ordovician, and became extinct at the close of the Devonian (Stearn et al., 1999). They were severely affected by both the end-Ordovician and Late Devonian (Frasnian-Famennian) mass extinctions. Although not unique, stromatoporoids are unusual among the sponges in lacking any evidence of spicules; however, they did produce a massive calcium carbonate skeleton. Ecologically, they required warm, clear, turbulent seawater of normal salinity, and moderately firm substrates at shallow depth. Stromatoporoid fossils are found mostly in limestones or dolostones, but some can be found in calcareous shales. Stromatoporoids were the major builders of Silurian and Devonian reefs, but they also occurred in level-bottom communities—there are no stromatoporoid bioherms in the Givetian-Frasnian of Iowa.

DEVONIAN PALEOBIOGEOGRAPHY AND SEA LEVEL

Paleobiogeographic Realms

Traditionally, paleobiogeographers have divided the marine environments of the Early and Middle Devonian into three realms, regions that are differentiated on the basis of having a high percentage of unique genera (Johnson and Boucot (1973). The Malvinokaffric Realm included cooler parts of the Southern Hemisphere, in which the seawater was too cold to sustain stromatoporoids. The tropical to subtropical seas in which stromatoporoids thrived were separated into two realms: 1) the Eastern Americas Realm (EAR), which included eastern North America and northeastern South America—the latter was too cold for stromatoporoids; and 2) the tropical Old World Realm (OWR), which included northern and western North America, Australia, Asia, Europe, and northernmost Africa. These two realms were separated by a land barrier composed of the Canadian Shield and the mid-continent or Transcontinental Arch (Fig.1). Multiple realms are not recognized for the Late Devonian.

The EAR and OWR were defined originally by paleontologists working with brachiopods (Johnson and Boucot, 1973) and rugose corals (Oliver, 1977). Subsequently other taxa were studied in this same framework, gastropods by Blodgett and others (1990), and stromatoporoids by Stock (1990).

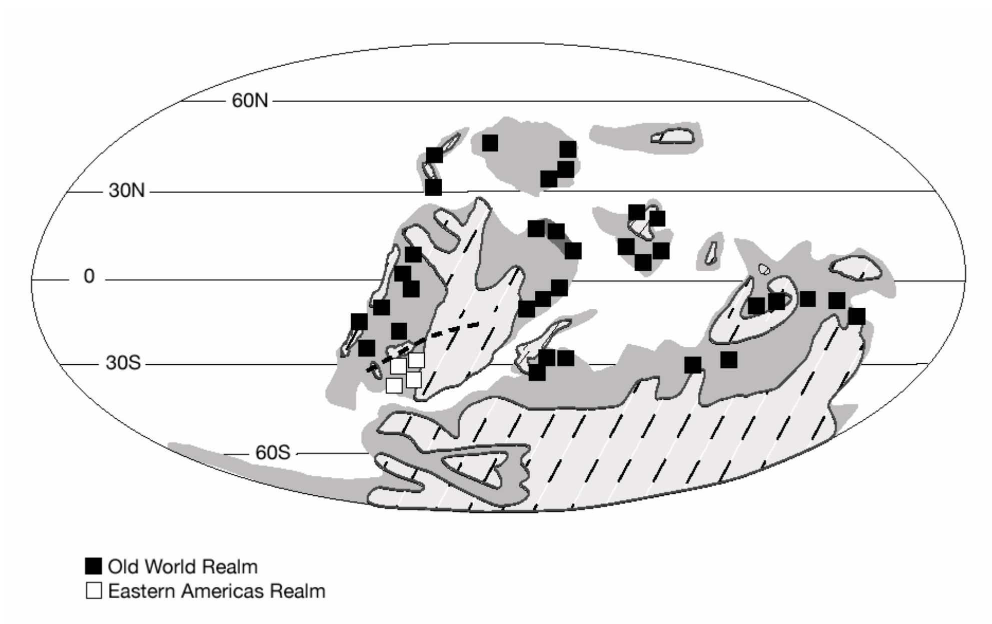

Figure 1. Givetian paleogeography of the world (after Copper, 2002; Stock, 2005) on which are plotted stromatoporoid occurrences. The thick dashed line represents the barrier between the OWR and EAR. Light gray areas with diagonal lines are land, and dark gray areas are epeiric or continental margin seas.

Sea Level

Eustatic sea level reached a low point late in the Early Devonian, marking the end of the Tippecanoe Sequence of Sloss (1963), which had begun in the Middle Ordovician. At the start of the Middle Devonian, eustatic sea level began to rise, issuing in Sloss' Kaskaskia Sequence, which ended in the Late Mississippian. Most workers agree that sea level continued to rise episodically through the Middle Devonian, and the first half of the Late Devonian (Frasnian Age), before an abrupt fall at the Frasnian-Famennian boundary (Johnson and Sandberg, 1988).

During the latter part of the Givetian Age, a major sea level rise known as the Taghanic Onlap occurred (Johnson, 1970; Johnson and Sandberg, 1988) (Fig. 2, Devonian T-R cycle IIa of Johnson et al., 1985). During the Taghanic Onlap, rising sea level breached the land barrier separating the EAR from the OWR, allowing communication between the marine faunas of the two realms. The faunal interchange between the two former tropical realms favored genera from the OWR over those of the EAR. This asymmetry has been reported for the rugose corals (Oliver and Pedder, 1989) and brachiopods (Boucot, 1990); data presented by Stock (2005) for the stromatoporoids show a similar pattern. Iowa, Missouri, and Illinois contain ample Givetian evidence of how stromatoporoids, on what was then the North American craton, were affected by the Taghanic Onlap; however, the subsequent Frasnian impact that resulted is known almost exclusively from Iowa.

STRATIGRAPHY

The lithostratigraphy of the Iowa Basin and contiguous areas has undergone a great deal of change in the past 25 years. According to Collinson (1968) the Middle Devonian of Iowa consisted of the Wapsipinicon Formation (Eifelian-lower Givetian) and the overlying Cedar Valley Formation (middle-late Givetian), the latter of which contained in ascending order the Solon, Rapid, and Coralville Members. In north-central Iowa the Cedar Valley was overlain by the upper Devonian (Frasnian) Shell Rock and Lime Creek Formations. The modern stratigraphy of the Givetian-Frasnian of Iowa

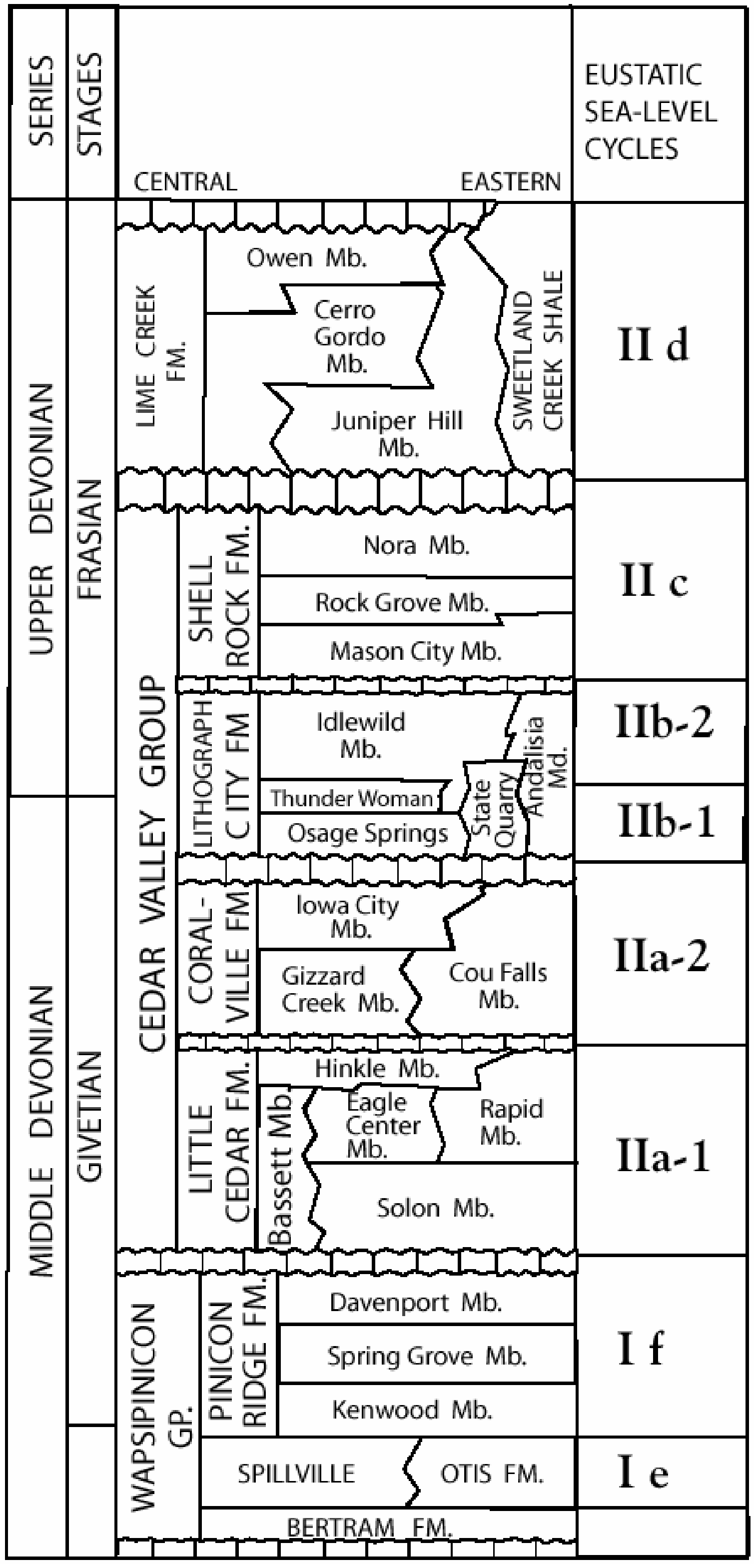

Figure 2. Iowa Basin Middle Devonian and lower Upper Devonian chronostratigraphy, lithostratigraphy, and accompanying eustatic sea-level cycles (after Day, 1996, Day et al. 1996). T-R cycle IIa is the Taghanic Onlap of Johnson (1970) following Johnson and others (1985) and Johnson and Sandberg (1988).

used here is that of Witzke and others (1989) and Day (1996) (Fig. 2). Most of the changes in lithostratigraphy were to the Middle Devonian and lowermost Frasnian presented by Witzke and others (1989) and Day (1997). A few examples include raising the Wapsipinicon and Cedar Valley to group status, with the Cedar Valley including four formations in ascending order: Little Cedar Formation; Coralville Formation (raised from member status); Lithograph City Formation; and Shell Rock Formation. The Givetian-Frasnian boundary is no longer between the Coralville and Shell Rock Formations, but within the Lithograph City Formation, within the Osage Springs Member (Fig. 2).

STROMATOPOROID GENERA

The oldest Middle Devonian stromatoporoids in Iowa are found in the Solon and Rapid Members of the Little Cedar Formation. Shapo (2003) described four stromatoporoid genera from the Solon (*Coenostroma, Petridiostroma, Schistodictyon, Stictostroma),* and four from the Rapid Member (*Clathrocoilona, Coenostroma, Petridiostroma, Stictostroma*). Abundant stromatoporoids from the Coralville Formation have not been described; this is also the case of stromatoporoids from the Osage Springs, State Quarry, and Andalusia Members of the Lithograph City Formation.

Smith (1994) described 13 genera from the Idlewild Member of the Lithograph City Formation. Information in subsequent publications by Stearn and others (1999) and Stearn (2001) indicate that there are 14 genera present (Table 1). The stromatoporoids of the Mason City Member of the Shell Rock Formation were first described by Stock (1982), who determined that there were 10 genera present; again, subsequent literature indicates that there are 11 genera. Unpublished data from my collections reveal that there are 11 genera in the Nora Member of the Shell Rock Formation, and seven genera in the combined Cerro Gordo and Owen Members of the Lime Creek Formation—there are only two genera in the Cerro Gordo, and these also occur in the Owen.

Overall, stromatoporoid generic diversity is low in the middle Givetian, with only four genera each in the Solon and Rapid Members of the Little Cedar Formation. Generic diversity in the remainder of the upper Givetian of Iowa remains unknown. In the lowermost Frasnian, a maximum of 14 genera are present in the Idlewild Member of the Lithograph City Formation. The Mason City and Nora Members of the Shell Rock Formation contain 11 genera each, and the combined Cerro Gordo and Owen Members of the Lime Creek Formation contain seven genera of stromatoporoids.

What we see, then, is low diversity at the onset of the Taghanic Onlap of Johnson (1970), with a probable increase in diversity during the remainder of the Givetian, as more OWR stromatoporoids entered Iowa. The high diversity of the Idlewild Member represents a maximum. Subsequent decrease in genus diversity through the Frasnian might be due to continued competition among Eastern American Realm (EAR) and Old World Realm (OWR) stromatoporoids. Before the Taghanic Onlap, two separate faunas of tropical (OWR) to subtropical (EAR) stromatoporoids co-existed. After the inter-realm barrier was breached by the initial major marine transgression of Devonian T-R cycle IIa of Johnson and others (1985), it appears that EAR and OWR stromatoporoids co-existed, at least until the earliest Frasnian; however, the decreased levels of generic diversity through the remainder of the Frasnian may very well be due to increased competition and subsequent extinction. As Stock (1997) has pointed out, during the Frasnian the area of the Laurussian Plate (also know as the Euramerican Plate) occupied by cratonic seas able to support stromatoporoids, progressively decreased through the Middle and Late Devonian, due primarily to the influx of siliciclastic sediments—a decrease in available habitat could result in a decrease in diversity.

SUMMARY

Iowa contains the most complete record of middle Givetian through upper Frasnian stromatoporoids in epeiric seas in North America. Appearance of the oldest

Table 1. Frasnian Stromatoporoid Genera in Iowa

Lime Creek Formation	
Cerro Gordo & Owen Members (7 genera)	
Arctostroma	*Stictostroma*
Clathrocoilona	New genus 1
Gerronostroma	New genus 2
Hermatoporella	
Shell Rock Formation	
Nora Member (11 genera)	
Actinostroma	*Hermatostroma*
Amphipora	*Stachyodes* (?)
Anostylostroma	*Stictostroma*
Arctostroma	*Trupetostroma*
Clathrocoilona	New genus 3
Hermatoporella	
Mason City Member (11 genera)	
Actinostroma	*Hermatostroma*
Amphipora	*Stachyodes*
Atelodictyon	*Stictostroma*
Clathrocoilona	*Trupetostroma*
Hammatostroma	New genus 3
Hermatoporella	
Lithograph City Formation	
Idlewild Member (14 genera)	
Actinostroma	*Hermatoporella*
Amphipora	*Hermatostroma*
Atelodictyon	*Parallelopora*
Bullulodictyon (?)	*Pseudoactinodictyon*
Clathrocoilona	*Stachyodes*
Habrostroma	*Stictostroma*
Hammatostroma	*Trupetostroma*

stromatoporoids in the Solon member of the Little Cedar Formation coincides with the beginning of the Taghanic Onlap, an episode of sea-level rise that breached the Transcontinental Arch land barrier that separated the Old World Realm from the Eastern Americas Realm, the latter of which the Iowa and Illinois Basins had been a part. Initial low generic diversity of stromatoporoids in the Little Cedar Formation rose to 14 genera in the lower Frasnian Idlewild Member of the Lithograph City Formation. Subsequent generic diversity in the Iowa Basin epeiric seaway declined through the remainder of the Frasnian.

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DEVONIAN STABLE ISOTOPE RECORDS FROM THE IOWA BASIN

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INTRODUCTION

Low magnesium calcite (LMC) is the carbonate modification used in most Paleozoic isotope studies. Besides studies of marine cements (Carpenter et al., 1991), the LMC shell of articulate brachiopods is of particular interest (Popp et al., 1986a; Grossman et al., 1993; Mii et al., 1999; Veizer et al., 1999; van Geldern et al., 2006 among others). Brachiopods are abundant and widespread in Paleozoic shallow marine sediments. Their shells are relatively resistant to diagenetic alteration and have the potential to serve as an archive of the primary isotope composition of past oceans. While the carbon isotope composition ($\delta^{13}C$) serves as an indicator of changes in the global carbon cycle (Kump and Arthur, 1999), the oxygen isotope ratio ($\delta^{18}O$) can be used to reconstruct paleoenvironmental conditions like sea surface temperatures (e.g. Bruckschen et al., 1999; Mii et al., 2001). Secular variations in $^{87}Sr/^{86}Sr$ of biogenic carbonates were interpreted to represent changes in the strontium fluxes (continental weathering vs. hydrothermal activity) that determine the strontium isotope ratio of the oceans (Veizer et al., 1997) and were used as a correlation and dating tool (McArthur et al., 2001; McArthur and Howarth, 2004). Studies on calcium (Böhm et al., 2004) or boron isotopes (Joachimski et al., 2005) were also performed on fossil brachiopod shells.

The data presented here are part of a study carried out on Devonian brachiopods from different paleogeographic locations (North America, Spain, Morocco, Russia, and Germany). The $\delta^{13}C$, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ data from the different locations were combined and isotope curves ranging from the middle Emsian to the middle Famennian were calculated using a nonparametric locally weighted regression method "Locfit" (Loader, 1997). The Devonian isotopic records are discussed in detail in van Geldern and others (2006).

This contribution focuses on the data received from Iowa, namely the Buffalo Quarry (BQ) and IPSCO core (PWW) sections with additional data from State Quarry (SQ) from eastern Iowa, sampled along with other sections from northern Iowa (Fig. 1).

METHODS

All brachiopod shells were cut parallel to the plane of symmetry (longitudinal section) and cut slabs were slightly polished. The state of preservation of the brachiopod shells was assessed using cathodoluminescence microscopy (Technosyn 8200 MK II). Nonluminescent shells were further investigated by means of trace element analysis (Sr, Mn, Fe) and scanning electron microscopy (SEM).

Strontium, manganese and iron concentrations were determined using ICP-AES (Spectroflame, University of Erlangen; Zeiss Plasmaquant, University of Halle). Reproducibility was calculated on replicate analyses of standards and was better than ±5% (1 std.dev.) for Sr, Mn and Fe.

For SEM analysis, transverse sections perpendicular to the plane of symmetry were carried out on selected shells. Longitudinal sections proved to be unsuitable for the characterization of the shell ultrastructure, since the convex-concave shape of the secondary layer fibers cannot be studied.

Oxygen and carbon isotope analyses were performed with a carbonate preparation line (Kiel device) connected online to a ThermoFinnigan 252 mass spectrometer. Oxygen and carbon isotope values are reported

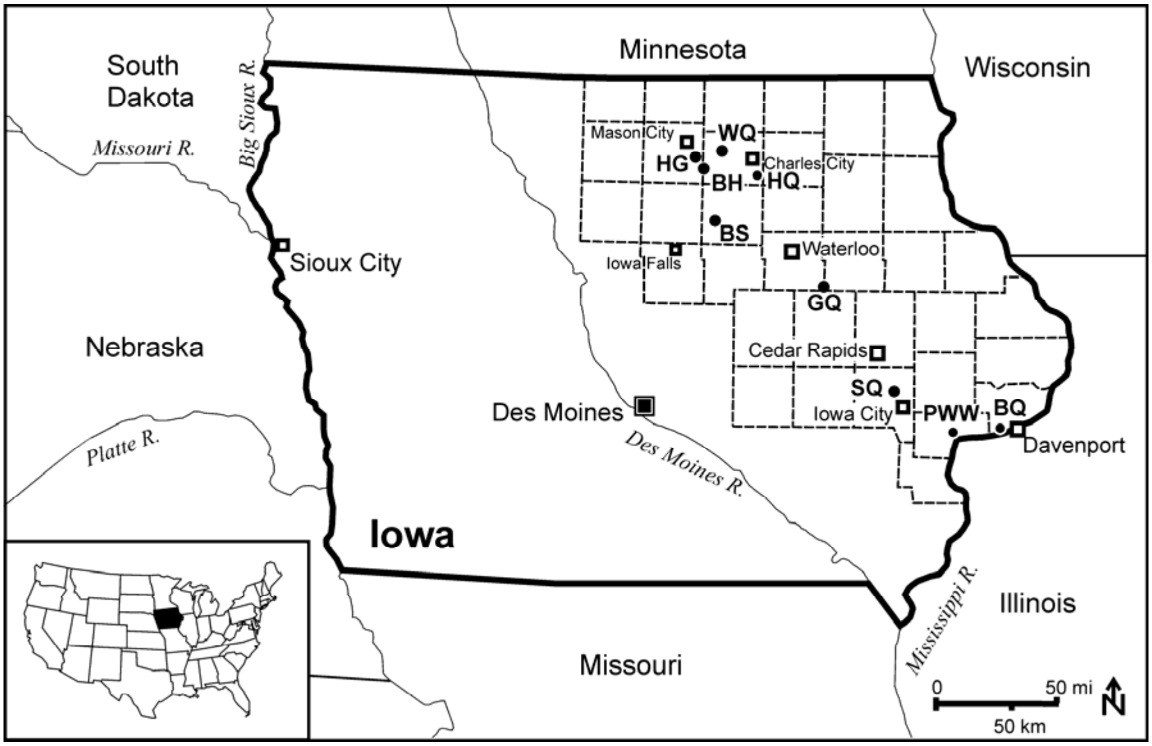

Figure 1. Sample locations in Iowa. BQ: Buffalo Quarry, PWW: IPSCO core, SQ: State Quarry, GQ: Glory Quarry, BS: Buseman Quarry, HQ: Hanneman Quarry, BH: Bird Hill, HG: Hackberry Grove, WQ. Williams Quarry.

in ‰ relative to V-PDB by assigning a $\delta^{18}O$ value of -2.20‰ and a $\delta^{13}C$ value of +1.95‰ to NBS 19. Reproducibility of the isotope measurements was controlled by replicate analyses of laboratory standards and NBS 19 and was ±0.03‰ (1 std.dev.) for $\delta^{13}C$ and ±0.05‰ (1 std.dev.) for $\delta^{18}O$. All values are given in the standard delta (δ) notation.

For strontium isotope analysis, 5 to 10 mg of calcite powder was milled from the valves with a microdrill. All analyses were performed at the Department of Geology, Mineralogy and Geophysics of the Ruhr-University in Bochum (Germany) using a ThermoFinnigan 262 mass spectrometer. The $^{87}Sr/^{86}Sr$ values were normalized to a value of 0.710248 for NIST 987 and 0.709175 for EN-1 by adding +31×10-6 to the measured values (McArthur et al., 2001). The typical 2sigma mean (standard error) for a single sample was better than $\pm 8\times10^{-6}$.

RESULTS

State of preservation

Cathodoluminescence (CL) was used as a first method for the identification of diagenetic recrystallization of the brachiopod shells (e.g. Popp et al., 1986b; Mii et al., 1999; Samtleben et al., 2001). Mn_2+ and Fe_2+ are the ions regarded as the main activators of an orange/dark red colored luminescence in calcite (Machel et al., 1991). Therefore, an orange-colored or dull luminescence is indicative for a diagenetic recrystallization of brachiopod shell calcite. Fossil punctate shells and samples showing a bright yellow to dull luminescence were discarded.

From Buffalo Quarry (BQ) a total of 120 samples and from IPSCO core (PWW #3) 59 samples were checked by CL. 66 (55%) and 37 (63%) shells were classified as non-luminescent, respectively. From State Quarry (SQ) 7 samples were investigated with 4 (57%) showing no luminescence. Examples of well preserved shells from eastern Iowa are shown in Fig. 2.

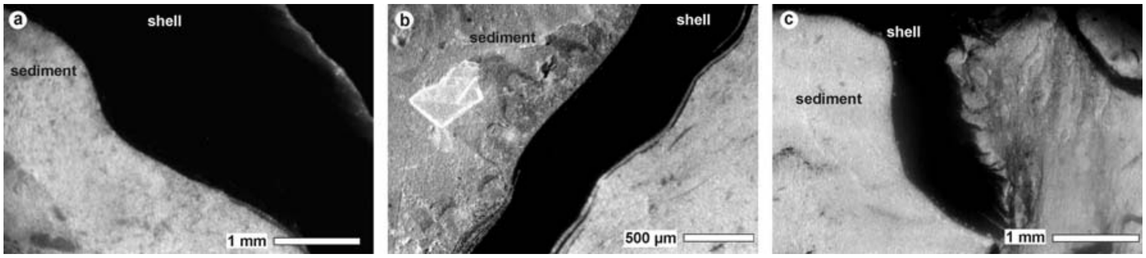

Figure 2. Cathodoluminescence photomicrographs of non-luminescent brachiopod shells (dark). The surrounding sediment usually shows an orange luminescence (light colored) (a) *Pseudoatrypa sp.* (Buffalo Quarry, Sample BQ 78-2). (b) *Pseudoatrypa sp.* (IPSCO core, Sample PWW-050) (c) *Spinatrypa sp.* (IPSCO core, Sample PWW-040).

Selected non-luminescent shells were studied with SEM. The calcite fibers forming the secondary layer of well-preserved Devonian brachiopod shells show a convex-concave shape with rounded surfaces comparable to the ultrastructure of recent brachiopods. This convex-concave structure is destroyed during diagenetic recrystallization (see Samtleben et al., 2001).

Trace element chemistry (Sr, Mn, Fe) is the standard method used for the identification of diagenetic alteration in fossil brachiopod shells. Recent brachiopod shells typically show low concentrations of Mn and Fe and high concentrations of Sr (Brand, 2004). Diagenetic recrystallization is expected to result in a decrease in Sr and increase in Mn and Fe contents (for theory see Brand and Veizer, 1980; Veizer, 1983a; Veizer, 1983b). During this study, shells with Mn, Fe and Sr contents <100 ppm, <400 ppm and >500 ppm, respectively, were classified as well-preserved. Two samples (one from BQ and one from PWW) showed Sr concentrations of 408 ppm and 384 ppm. These shells do not differ in their $^{87}Sr/^{86}Sr$ ratios in comparison to contemporaneous shells from BQ and PWW with strontium contents above 500 ppm. The $^{87}Sr/^{86}Sr$ data of these two samples are therefore interpreted as primary values. The results of the trace element analysis of the shells from BQ, PWW and SQ are shown in Fig. 3.

Strontium isotope results

The $^{87}Sr/^{86}Sr$ ratios of the brachiopod shells from eastern Iowa as well as the calculated Locfit curve based on the complete Devonian data set from van Geldern (2006) are shown in Table 1 and Fig. 4. The $^{87}Sr/^{86}Sr$ values measured on the two samples from the

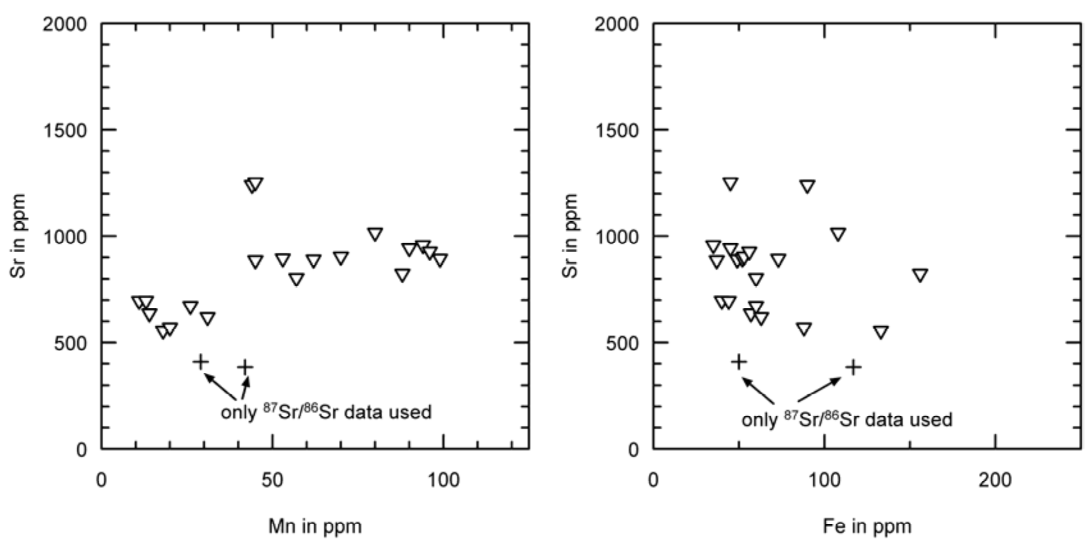

Figure 3. Trace element contents (Sr, Mn and Fe) of non-luminescent brachiopod shells from BQ, PWW and SQ.

Solon Mb. and Rapid Mb. in the IPSCO core are 0.7078. The two samples from the Rapid Mb. in Buffalo Quarry show also values around 0.7078. These values are in the same range as the relatively uniform values which persist from the early Eifelian up to the late Givetian (Fig. 4). Samples from the Cou Falls Mb. and Andalusia Mb. in Buffalo Quarry show continuously increasing $^{87}Sr/^{86}Sr$ values which mark the onset of a general $^{87}Sr/^{86}Sr$ increase of the seawater strontium isotope composition. This increase continues during the Frasnian.

Carbon and oxygen isotope results

The results of the $\delta^{13}C$ and $\delta^{18}O$ measurements from Buffalo Quarry and IPSCO core are shown in Fig. 5. In both sections, the $\delta^{13}C$ values range between -0.2‰ and +1.9‰ V-PDB. $\delta^{13}C$ and $\delta^{18}O$ values of brachiopod shells from State Quarry are in the same range. The isotope values of different brachiopod species from the same horizon reveal that no species dependent difference in $\delta^{13}C$. The $\delta^{13}C$ values of the surrounding sediment which is characterized by an orange-colored luminescence (see Fig. 2) range from -0.7‰ to -1.4‰. These values as well as the luminescence indicate that the carbonate sediment was diagenetically altered during the stabilization of high magnesium calcite/aragonite to diagenetic low magnesium calcite (dLMC). The lower $\delta^{13}C$ values of dLMC compared to the higher values of the unaltered brachiopod shell calcite in PWW and BQ are taken as another indicator of the good preservation of the shells (cf. Mii et al., 2001).

The oxygen isotope values in the IPSCO core show a decrease from -5.2‰ in the lower part of the Rapid Mb. to values around -6‰ in the middle and upper part of this member. In the Buffalo Quarry a similar decline can be observed with $\delta^{18}O$ values ranging between -5.5‰ and -6.9‰ in the upper part of the Rapid Mb. In the uppermost part of the Rapid Mb. an increase by about 1‰ can be observed in both sections. In the lower Cou Falls Mb. $\delta^{18}O$ values between -4‰ and -5‰ are measured. $\delta^{18}O$ values from the Andalusia Mb. are only available from Buffalo Quarry and show again a slight decrease to values around -5.6‰.

As observed for carbon isotopes, no species dependence of the oxygen isotope values can be observed. $\delta^{18}O$ values of the surrounding carbonate matrix show values between -6.2‰ and -6.8‰, which are always lower than the $\delta^{18}O$ values of the brachiopod. Coarse-grained, late diagenetic sparite cements from Buffalo Quarry have $\delta^{18}O$ values of -7.3‰ to -9.5‰.

DISCUSSION

Strontium isotopes

The $^{87}Sr/^{86}Sr$ ratio of the ocean is driven mainly by (i) continental runoff and ground-water discharge which supplies radiogenic ^{87}Sr to the ocean (high $^{87}Sr/^{86}Sr$ ratio), and (ii)

Table 1. Results of $^{87}Sr/^{86}Sr$ measurements from IPSCO core (PWW) and Buffalo Quarry (BQ).

sample	section	lithostratigraphy	conodont zone	$^{87}Sr/^{86}Sr$
PWW 003	IPSCO core	Solon Mb., Little Cedar Fm.	*middle varcus*	0.707819
PWW 016	IPSCO core	Rapid Mb., Little Cedar Fm.	*cristatus hermanni*	0.707828
BQ 35-01	Buffalo Quarry	Rapid Mb., Little Cedar Fm.	*cristatus hermanni*	0.707836
BQ 46-03	Buffalo Quarry	Rapid Mb., Little Cedar Fm.	*early disparilis*	0.707832
BQ 54-01	Buffalo Quarry	Cou Falls Mb., Coralville Fm.	*early disparilis*	0.707866
BQ 64-02	Buffalo Quarry	Cou Falls Mb., Coralville Fm.	*early disparilis*	0.707885
BQ 92-01	Buffalo Quarry	Andalusia Mb., Lithograph City Fm.	*early falsiovalis*	0.707915

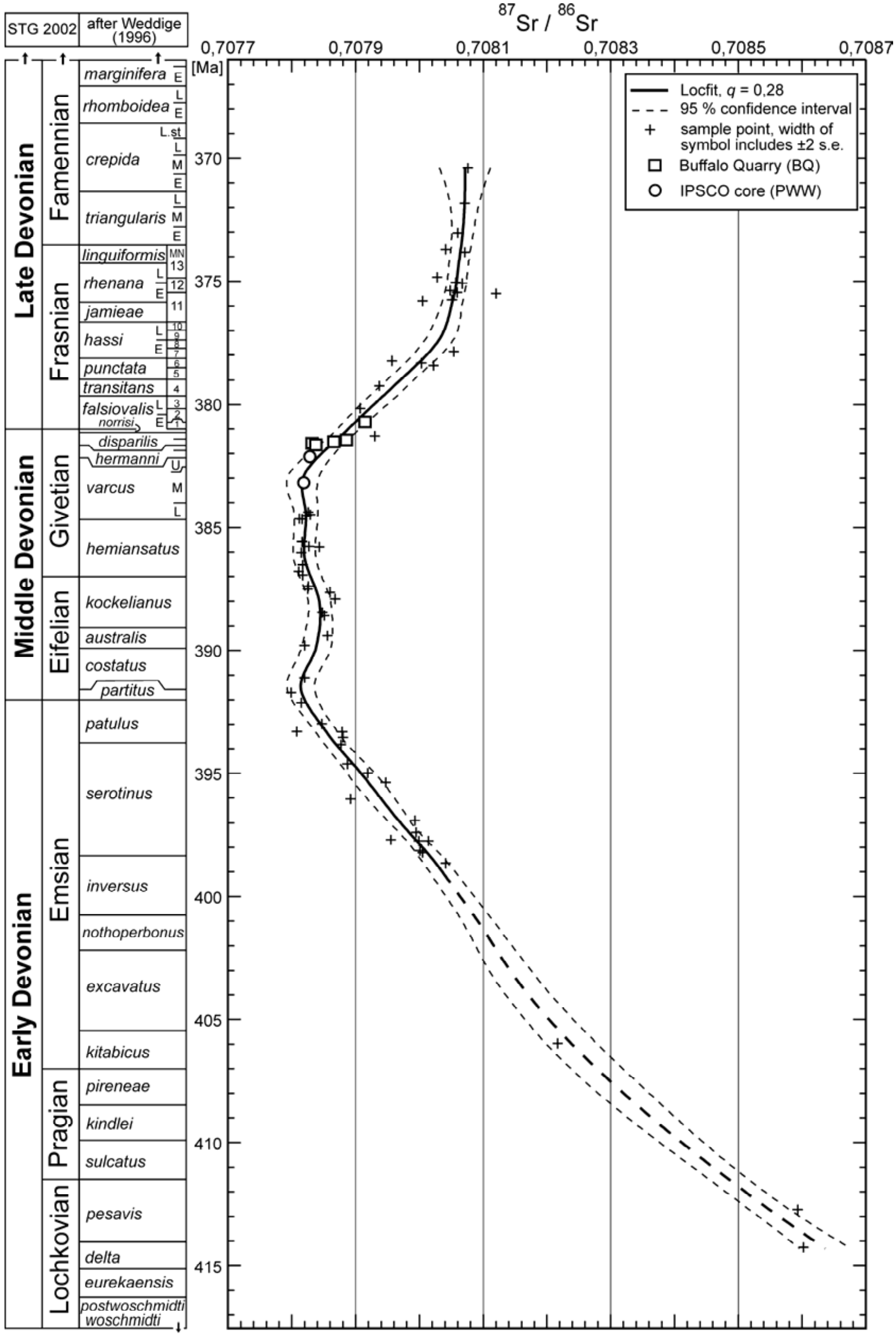

Figure 4. $^{87}Sr/^{86}Sr$ ratios of well-preserved Devonian brachiopod shells and Locfit trend line. Time chart is after STG 2002, and the conodont zonation is after Weddige (1996).

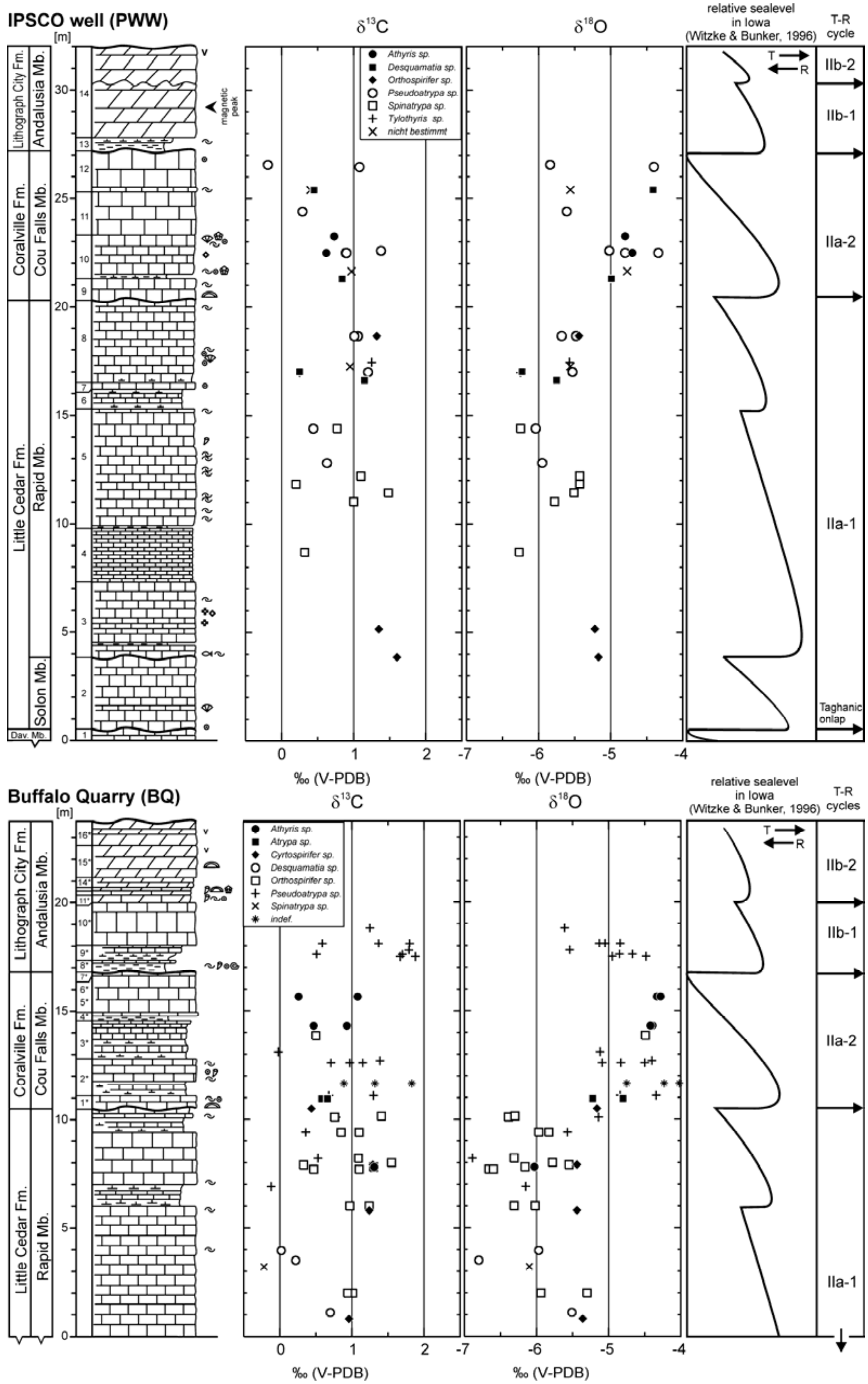

Figure 5. Results of $\delta^{13}C$ and $\delta^{18}O$ measurements of well-preserved Devonian brachiopod shells from IPSCO well and Buffalo Quarry.

seawater–oceanic crust interaction particularly at mid-ocean ridges that depletes seawater in ^{87}Sr due to the low $^{87}Sr/^{86}Sr$ ratio of fresh basalts (cf. Jones and Jenkyns, 2001).

The Eifelian and early Givetian time intervals are characterized by relatively uniform $^{87}Sr/^{86}Sr$ values which are explained by a balance (or steady-state) of the riverine- and mantle-derived strontium flux. The increase in the $^{87}Sr/^{86}Sr$ ratio starts in the late Givetian. According to Johnson and others (1985), a prominent, long-term rise in sea level (Taghanic transgression) started in the upper part of Middle *varcus* Zone (base of T-R cycle IIa) which was interpreted to be the result of enhanced spreading. Intensified spreading should have resulted in an increased flux of low radiogenic, mantle-derived strontium. Consequently, a decrease in the marine strontium isotope ratio is expected which is opposite to the observed trend in $^{87}Sr/^{86}Sr$. On the other hand, the Eovariscan orogeny may have uplifted ^{87}Sr-rich continental crust and exposed it to weathering. This collisional event is dated to have occurred in late Frasnian to Famennian times and led to the formation of mountain chains including the Ellesmerian Fold Belt, the Antler orogen, part of the Appalachian orogen as well as parts of the Hercynian (Variscan) Belt in Europe and northern Africa (cf. Golonka, 2000). As indicated by the $\delta^{18}O$ curve (see discussion below) a warmer climate was present in the Late Devonian, which intensified chemical weathering and the flux of ^{87}Sr to the Devonian oceans.

Carbon and oxygen isotopes

The carbon and oxygen isotope records from eastern Iowa are shown in Fig. 6. During the Givetian and early Frasnian, the $\delta^{13}C$ curve declines gradually from its Middle Devonian maximum at the Eifelian-Givetian boundary which is interpreted to be related to the upper Kacàk event (House, 1985). The potential minor negative $\delta^{13}C$ excursion in the latest Givetian is rather an artifact from the Locfit regression calculation than an event in the carbon cycle since the shape of the curve is strongly influenced by the sparse data points in the middle Givetian and early Frasnian. Accordingly, the $\delta^{13}C$ values of brachiopod shells from eastern Iowa do not record a significant change in the global carbon cycle during the late Givetian to early Frasnian time interval.

Low $\delta^{18}O$ values $< -5‰$ are often interpreted as diagenetically overprinted or to be non-representative for open marine conditions (see e.g. Land, 1995; Land and Lynch, 1996; Muehlenbachs, 1998). Since the brachiopod shells analyzed in this study were carefully checked, the $\delta^{18}O$ values are interpreted to be primary signals. The interpretation of the Devonian oxygen isotope curve as an proxy for sea surface temperature (SST) in combination with a potential secular variation of the oxygen isotope composition of seawater (Veizer et al., 1999) is discussed in detail elsewhere (Joachimski et al., 2004; van Geldern et al., 2006) and is not reviewed here in detail.

A comparison of the $\delta^{18}O$ values from Buffalo Quarry and IPSCO core with the relative sea-level curve in Iowa taken from Witzke and Bunker (1996) shows that the lowest $\delta^{18}O$ values occur in the middle and near the end of T-R cycle IIa-1 (Fig. 5). According to Witzke and others (1988) the facies of southeastern Iowa represents the deepest and most open marine part of the Iowa Basin. The shelf area in southeastern Iowa was not subaerally exposed during the regressions (Witzke and Bunker, 1996). There is no evidence from facies, fossils and sequence stratigraphy for a higher influx of fresh water which could have lowered the oxygen isotope composition of sea water ($\delta^{18}O_w$).

A climatic warming is suggested by the brachiopod oxygen isotope record from Iowa, since $\delta^{18}O$ of brachiopod calcite is dependent on temperature during precipitation of the shell (e.g. O'Neil et al., 1969). However, the decrease in $\delta^{18}O$ recorded in the late Middle Devonian (Fig. 6) is considered to be too large to be explained exclusively by a temperature increase. Evaluation of the parameters determining $\delta^{18}O$ of shell calcite suggests that neither a secular decrease in $\delta^{18}O_w$ of seawater (Veizer et al., 1999), nor a change in surface water pH can explain the $\delta^{18}O$ (for details see van Geldern et al., 2006). Therefore, we propose the combination of a temperature rise and a moderate decrease in $\delta^{18}O_w$ from the Middle to Late Devonian to explain the lower $\delta^{18}O$ values of brachiopods from the late Givetian and Late Devonian.

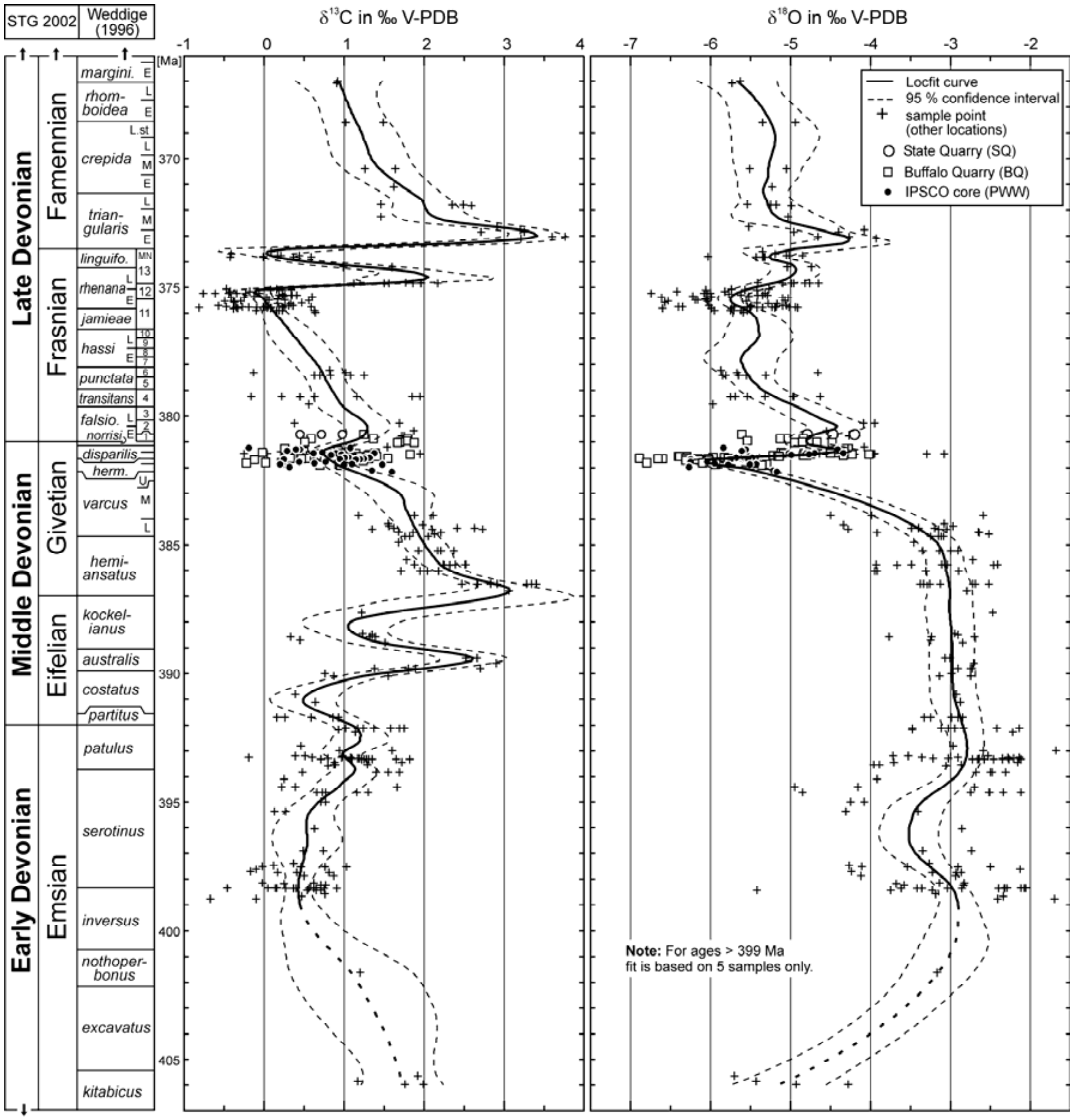

Figure 6. $\delta^{13}C$ and $\delta^{18}O$ results from PWW, BQ and SQ in the context of the Devonian Locfit trend lines.

AKNOWLEDGEMENTS

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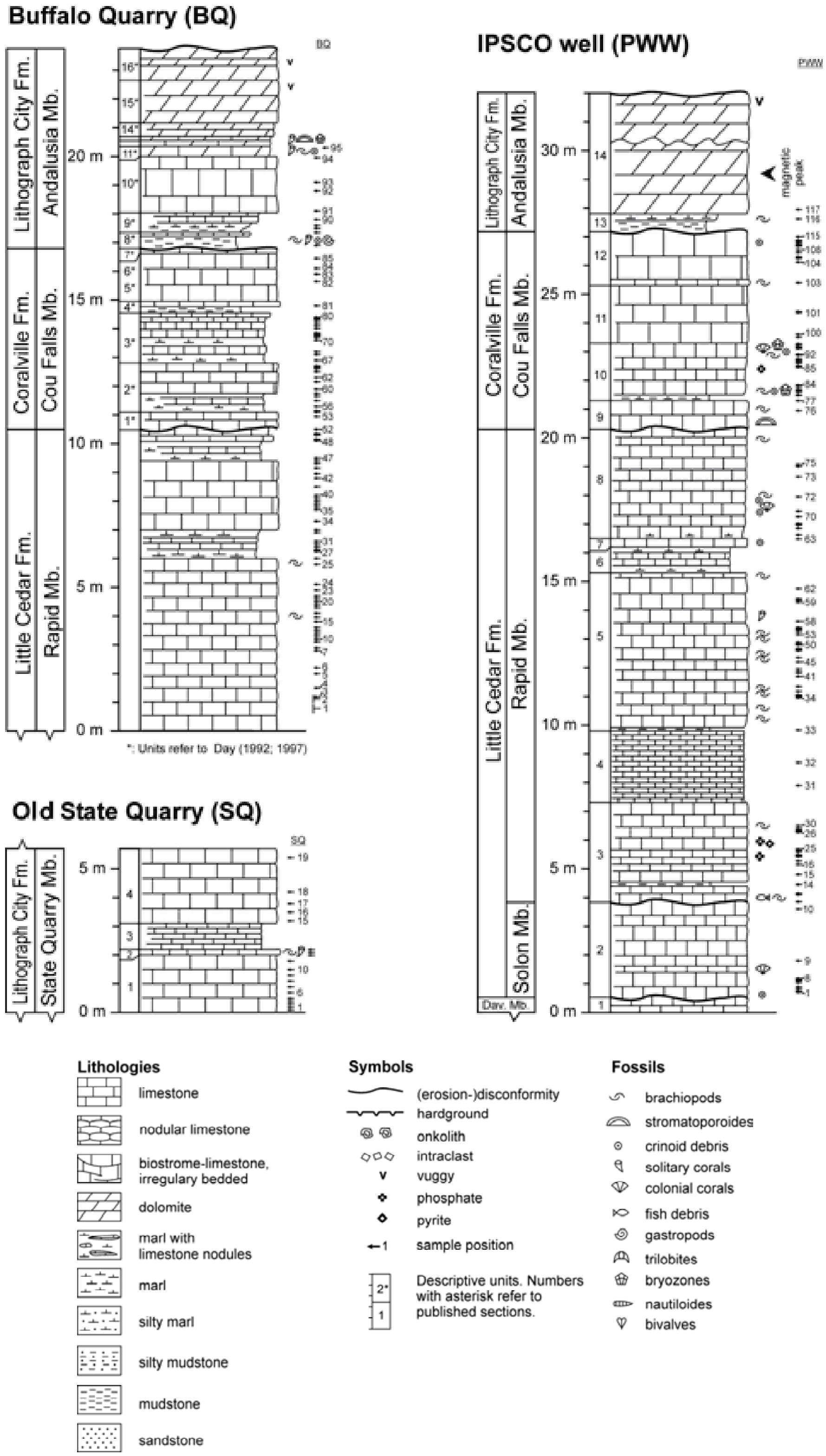
APPENDIX

Stratigraphic sections at the LaFarge Corporation Buffalo Quarry, IPSCO PPW # 3 core and State Quarry Member of the Lithograph City Formation at the Old State Quarry showing sample positions. For a detailed description of the other sections shown in Fig. 1 refer to the Appendix in van Geldern (2004). For section locations for the Buffalo and the ISPSCO PPW # 3 core see Day (p. 1 of this guidebook), and the Old State Quarry (called the State Capitol Quarry) in Day (1989, Fig. 3).



CHEMOSTRATIGRAPHIC CORRELATION OF LOWER SILURIAN DEPOSITS IN EASTERN IOWA: PLACING THE LLANDOVERY-WENLOCK BOUNDARY IN THE MID-CONTINENT

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INTRODUCTION

The carbonate rocks of Silurian age that outcrop throughout east-central Iowa have undergone extensive lithostratigraphic research starting as early as the 1840s. The work of James Hall brought the stratigraphic nomenclature of the classical New York Silurian to the outcrops of east-central Iowa (Hall and Whitney, 1858). By the turn of the century, the Iowa Geological Survey had erected a regional stratigraphy independent of the New York nomenclature, which has mostly persisted into the modern era. The most recent major revision to the Iowa sequence was formally introduced by Witzke (1985) with the addition of the Scotch Grove Formation as a unit between the Hopkinton Formation (Llandovery) and the Gower Formation (Wenlock). The characteristically low conodont yields of Silurian carbonates in the mid-continent have hindered precise location of the Llandovery-Wenlock boundary, but previous work has suggested a placement somewhere within the Scotch Grove Formation (Witzke, 1981; Metzger, 2005).

The proliferation of high-resolution carbon isotope $\delta^{13}C_{carb}$ stratigraphy during the past decade has provided a powerful new tool for stratigraphic correlation, particularly during intervals of major excursions in $\delta^{13}C_{carb}$ or in regions where the level of biostratigraphic control is low. The Llandovery-Wenlock boundary is associated with a major positive carbon isotope excursion (Ireviken Excursion), which has been precisely correlated to both conodont and graptolite biostratigraphic schemes. The recovery of the Ireviken Excursion in the Scotch Grove Formation from the IPSCO core OW-5 (Cramer and Saltzman, 2005) allows a more precise placement of the Llandovery-Wenlock boundary in Iowa and provides insight into the complex lateral arrangement of members and facies of the Scotch Grove Formation (Fig. 1).

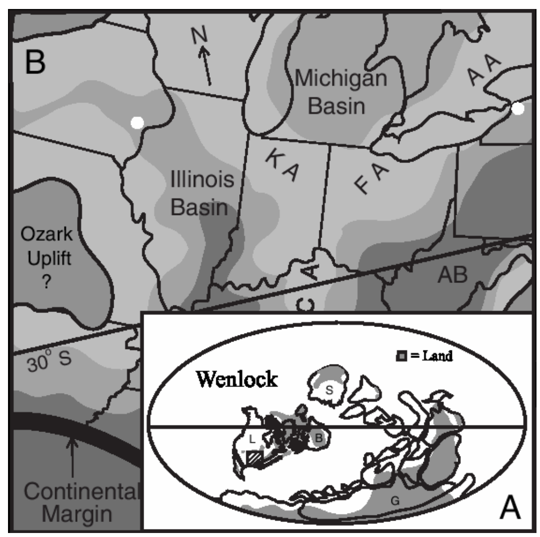

Figure 1. Figure modified from Cramer and Saltzman, (2005) and Cramer and others (2005). Two white dots represent the IPSCO core OW-5 in Iowa and the Robert Moses Power Plant S-1 core in New York.

CHRONOSTRATIGRAPHY

The Llandovery-Wenlock boundary occurred during a protracted extinction event known as the 'Ireviken Event' (Jeppsson, 1987; 1990). Precise correlation of the Ireviken Extinction Event (Jeppsson, 1990; 1997) with the GSSP (Global Stratotype Section and Point) at Leasows, U.K. (Mabillard and Aldridge, 1985) has demonstrated that the Llandovery-Wenlock boundary has been placed at datum two of the Ireviken Event. High-resolution carbon isotope stratigraphy of the Swedish island of Gotland, which has become the global standard for Wenlock conodont biostratigraphy (Jeppsson, 1997), has also shown that the major positive carbon isotope excursion, known as the Ireviken Excursion, began (maximum positive rate of change) at datum four of the extinction event. The cosmopolitan conodont *Pterospathodus amorphognathoides amorphognathoides* went extinct at datum three of the Ireviken Extinction Event (Jeppsson, 1997). The Ireviken Excursion ended within the Lower *Kockelella walliseri* zone.

IOWA STRATIGRAPHY

Silurian sedimentation in Iowa produced a labyrinth of carbonate lithofacies, which created a mosaic of members and facies within each of the formally designated 'formations'. Below, we discuss the bio-, chemo-, and chronostratigraphic correlations of the Hopkinton, LaPorte City, Scotch Grove, and Gower formations concentrating on the Scotch Grove Formation (Fig. 2). The carbonate sedimentology of these formations is beyond the scope of this investigation and the reader is referred instead to Witzke (1981).

Hopkinton Formation

The Llandoverian Hopkinton Formation was returned by Witzke (1981) to the previous definition of Calvin (1896) as beds above the Blanding Formation and below what is now known as the Scotch Grove Formation. The degree of conodont biostratigraphic control on the dolowackestones of the Hopkinton Formation has left a great many questions unanswered regarding the age and correlation of the Hopkinton Formation. The formation has been informally divided in three units designated as the Hopkinton A, B, and C. The Hopkinton C interval ranges into the mid-late Llandovery as shown by the presence of Pterospathodid conodonts (e.g. *P. celloni* - Rexroad and Nicoll, 1971; Witzke, 1981, p. 342; Männik, 1998).

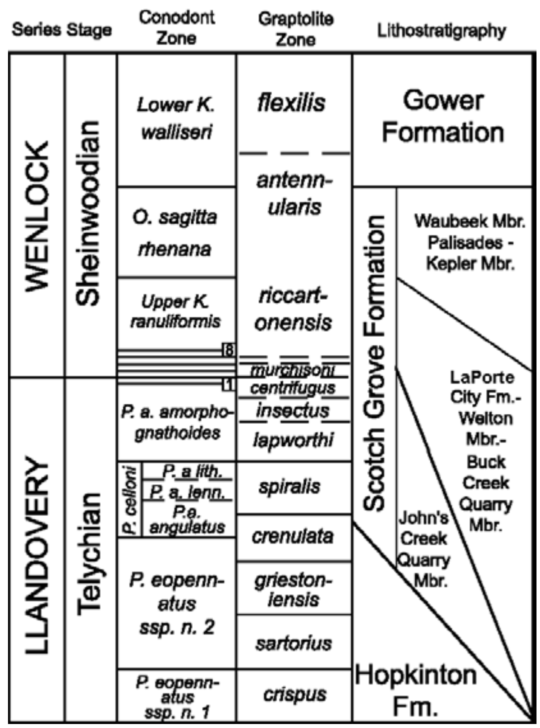

Figure 2. Upper Telychian conodont zonation after Männik (1998). Wenlock conodont zonation after Jeppsson (1997). Correlation with graptolite biostratigraphy from Loydell and others (2003). See text for details regarding the diachroneity of the stratigraphic units in Iowa.

LaPorte City Formation

The LaPorte City Formation is a time transgressive unit that correlates with the Upper Hopkinton and Lower Scotch Grove formations. Ludvigson and others (1992) suggested that the LaPorte City Formation avoided the pervasive dolomitization typical of the mid-continent Silurian (e.g. Hopkinton and Scotch Grove formations) by virtue of meteoric phreatic diagenesis. Due to the fact that the LaPorte City Formation is a limestone, whereas the Hopkinton and Scotch Grove are typically dolomitic, more extensive conodont biostratigraphy is available from the LaPorte City Formation. Metzger (2005) demonstrated that the LaPorte City Formation is at least as old as the *Pterospathodus eopennatus* zone of Männik (1998), and ranges at least as high as the *Pterospathodus amorphognathoides* amorphognathoides zone.

In the Delhi West section sampled by Metzger (2005), what has been identified as Scotch Grove strata underlie the LaPorte City Formation sampled for conodont biostratigraphy. The presence of *P. eopennatus* in the LaPorte City Formation in this section demonstrates that the base of the Scotch Grove must also be at least as old as the *P. eopennatus* zone.

The *P. eopennatus* recovered from the LaPorte City Formation most closely resembles the *P. eopennatus* ssp. nov. 2 morphotype 4 of Männik (1998). This morphotype is restricted to the uppermost *P. eopennatus* subzone. It is interesting to note that according to Männik (1998), the *P. eopennatus* morphotype found in Iowa does not co-occur with *Pterospathodus amorphognathoides angulatus*, however the two species coexist for over three meters of section at the Delhi West section (Metzger, 2005), suggesting that the record of *P. eopennatus* in Iowa may be among the youngest occurrences of the species worldwide.

Scotch Grove Formation

The Scotch Grove Formation contains a complex array of facies and members that has complicated chronostratigraphic correlation of the members within the formation. There are clearly two major divisions of Scotch Grove strata, each with several interfingering and overlapping facies/members. The lower division consists of the John's Creek Quarry and Welton members along with the Castle Grove mound facies while the upper division consists of the Palisades-Kepler and Waubeek members. The facies known as the Buck Creek Quarry facies persists throughout the Scotch Grove Formation.

As discussed above, the conodont fauna present in the Delhi West section demonstrates that the lower Scotch Grove is at least as old as *P. eopennatus*. The basal Scotch Grove Formation occasionally contains the John's Creek Quarry Member. Although often diagrammed as being exclusively older than the Welton and/or B.C.Q. (Buck Creek Quarry) members, Witzke (1994) demonstrated that the John's Creek Quarry Member is a lateral equivalent of at least a portion of the Welton/B.C.Q. facies. Lower Scotch Grove strata of the Welton Member from the Hanken Quarry section (Witzke, 1981) contain the conodont P. a. amorphognathoides.

The stable carbon isotope data of Cramer and Saltzman (2005) show that the maximum rate of positive change (and therefore the onset of the Ireviken Excursion) can be found at the top of the John's Creek Quarry Member in the IPSCO core (Fig. 3). This is important because the excursion begins at datum four of the Ireviken Event. P. a. amorphognathoides (found high in the Welton Member at Hanken Quarry) went extinct at datum three. Therefore, all of the Scotch Grove Formation up to the level high in the Welton where the *P. a. amorphognathoides* was recovered at Hanken Quarry correlates to a position within the John's Creek Quarry Member in the IPSCO core. The presence of Welton Member strata in the IPSCO core above the onset of the Ireviken Excursion and correlation with the stable isotope data from New York (Cramer et al., 2005) and Gotland (Munnecke et al., 2003) demonstrates that the top of the Welton Member in the IPSCO core is above the last extinction datum of the Ireviken Event.

Based on the above biostratigraphic and chemostratigraphic information, the Llandovery-Wenlock boundary can be confidently placed within the John's Creek

Quarry Member in the IPSCO core, which is apparently a very condensed lateral equivalent of the Welton Member in the outcrop belt. In the thicker sections of the outcrop belt, the Llandovery-Wenlock boundary would be placed high in the Welton Member of the Scotch Grove Formation.

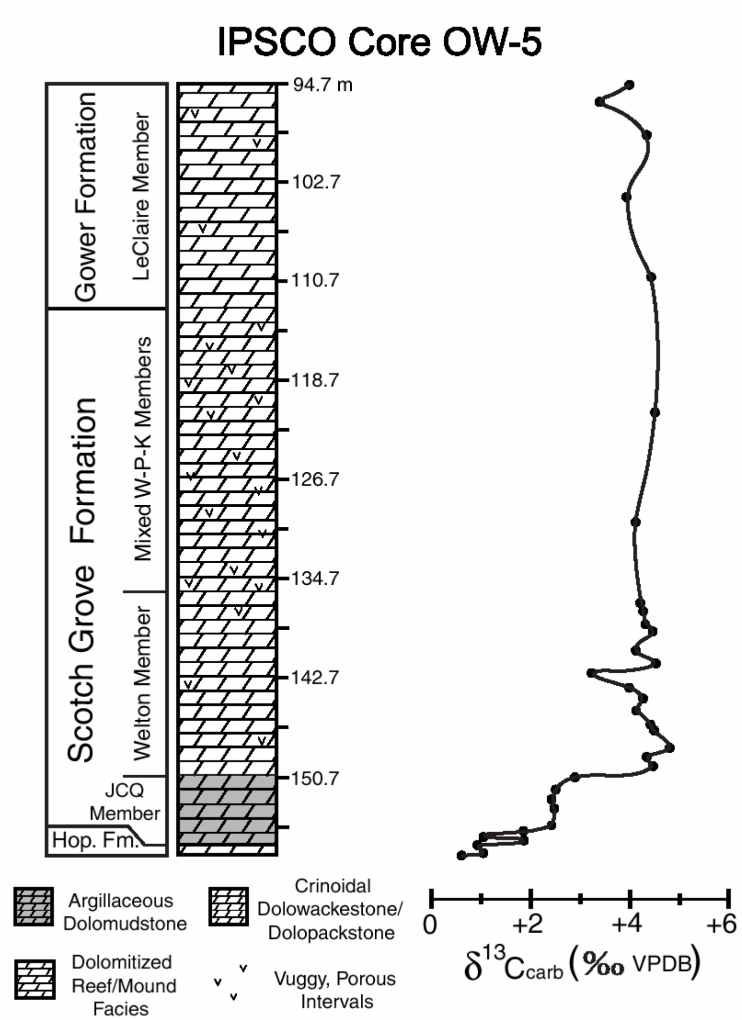

Figure 3. IPSCO core OW-5 stable carbon isotope stratigraphy from Cramer and Saltzman (2005). Note the onset of the Ireviken Excursion (datum 4) at the top of the John's Creek Quarry Member in the core. This helps demonstrate that the JCQ Member is a condensed lateral equivalent of the Welton Member in the outcrop belt.

The upper division of the Scotch Grove Formation (Waubeek, Palisades-Kepler) also contains conodonts diagnostic of Sheinwoodian age. Conodont collections (Witzke, 1981) from the type area of the Waubeek, as well as the Freeman Quarry, of upper Scotch Grove strata contain the conodont *Ozarkodina sagitta rhenana.* Although the extremely small collections make positive zonation difficult, the presence of *O. s. rhenana* and the absence of *K. walliseri* in upper Scotch Grove strata combined with the presence of elevated isotope values >+4‰ indicate placement within the *O. s. rhenana* zone of Jeppsson (1997), which places the top of the Scotch

Grove Formation clearly within the middle Sheinwoodian.

Gower Formation

Unfortunately, the Gower Formation is yet to yield biostratigraphically useful conodont species. Likewise, most other biostratigraphic groups are equally unhelpful. There are however several important insights into the age and global correlation of the Gower Formation that can be made from the limited data available.

The stable carbon isotope data recorded from the Gower Formation in the IPSCO core show values >+4‰ indicating that the Ireviken Excursion continued into the time of Gower deposition. The IPSCO core OW-5 penetrated a section where the Gower is thinner than in the outcrop belt, and likely has had the top of the formation removed by erosion. Immediately above the Ireviken Excursion in New York (Fig. 4), peculiar laminated hypersaline strata of the upper Goat Island and Eramosa formations (Brett et al., 1995) closely resemble the hypersaline strata of the Gower Formation in the outcrop belt in Iowa (Witzke, 1981). Both of these however would correlate to a position above the highest Gower strata recorded in the IPSCO core (Fig. 5).

CONCLUSIONS

Due to the diachroneity of the lithostratigraphic units in Iowa, a precise location of the Llandovery-Wenlock boundary cannot be placed within the nomenclature of the Iowa Basin on a member basis. It can be said with certainty that the boundary is within the Scotch Grove Formation, and beyond that within the lower package of Scotch Grove deposition. The combination of biostratigraphic and chemostratigraphic data in the current study has brought some interesting points to light that deserve further investigation.

The conclusion that the LaPorte City Formation is primarily a lateral equivalent of Hopkinton and Scotch Grove strata is partially based on the work by Ludvigson and others (1992). Their work concentrated on diagenesis and used the variable carbon isotope values within the Iowa sequence as an indicator of diagenetic history. The presence of a large positive carbon isotope excursion in the early Wenlock had not been demonstrated at the time of their publication. It is much more likely that the changes in carbon isotope values seen by Ludvigson and others (1992) simply represent the Ireviken Excursion and the samples they analyzed came from stratigraphically distinct horizons.

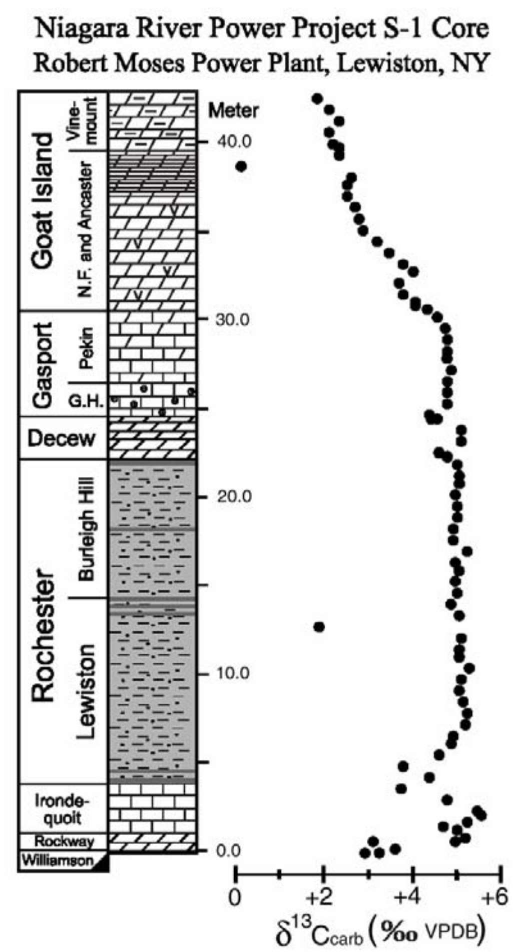

Figure 4. Stable carbon isotope stratigraphy of the classical New York Silurian sequence from Cramer and others (2005). The Ireviken Excursion began at the Rockway-Irondequoit contact and persisted until low in the Goat Island Formation. The values of +2‰ in the Goat Island represent the 'baseline' values prior to and after the excursion.

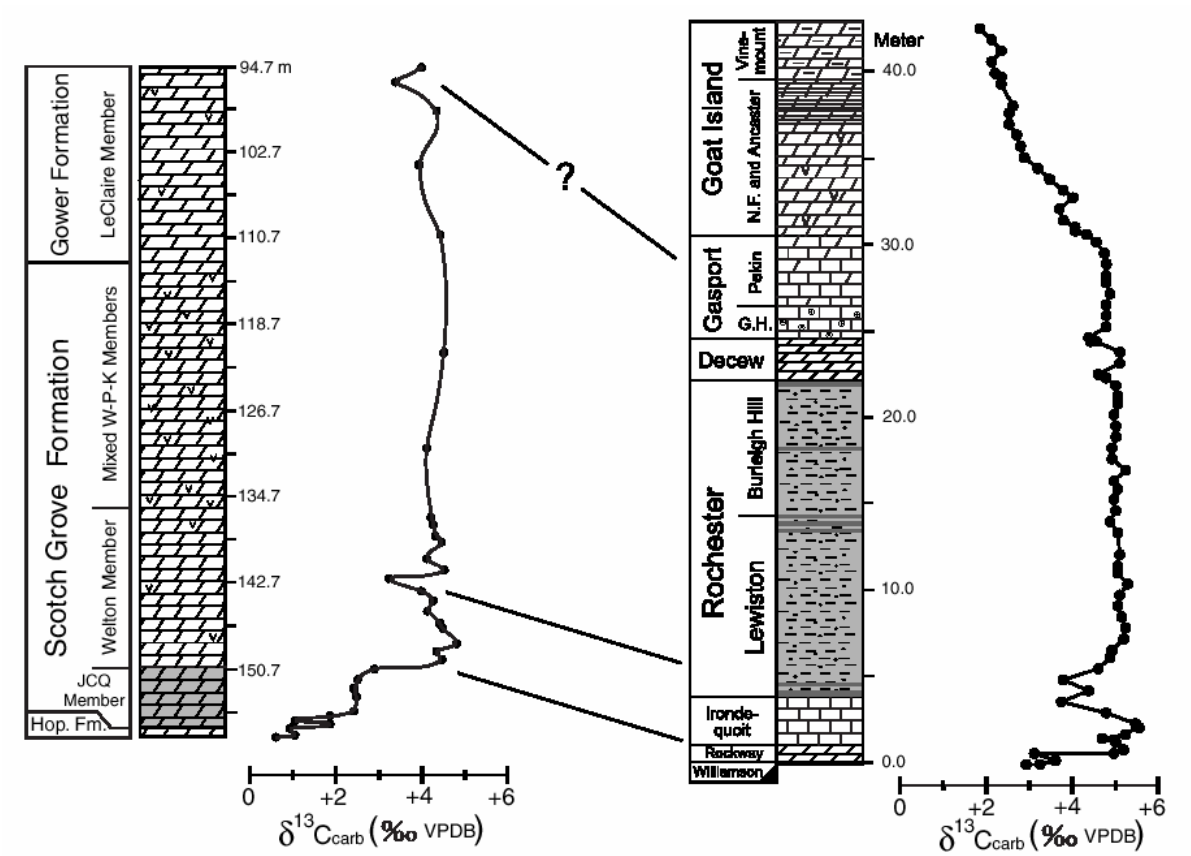

Figure 5. Chemostratigraphic correlation of the Iowa sequence with the New York sequence. Lack of detailed biostratigraphic control in Iowa and the extreme diachroneity of the lithostratigraphic units in this study prevent a precise member by member correlation with the New York Sequence. However, we can say with certainty that the top of the John's Creek Quarry Member in the IPSCO core is correlated with the Rockway-Irondequoit contact.

The LaPorte City Formation has not been sampled for carbon isotope stratigraphy (other than the handful of samples in Ludvigson et al., 1992), and the conodont biostratigraphy demonstrates an age range from the *P. eopennatus* to the *P. a. amorphognathoides* zone. In the dolomite belt of Iowa, this corresponds to much of the Welton Member of the Scotch Grove Formation as well as all of the John's Creek Quarry Member in the subsurface. The presence of a presumably continuous carbonate succession of mid-Telychian through mid-Sheinwoodian in the Iowa basin represents a unique opportunity to investigate this interval of time in carbonate rocks. As demonstrated in Jeppsson (1997), Loydell and others (2003) and Cramer and Saltzman (2005), this interval is almost exclusively missing in cratonic interiors or occurs in shaley/condensed intervals.

Despite the exceedingly low conodont yields of Silurian rocks from Iowa, much more biostratigraphic control is needed before the complex relationship of the mosaic of facies in eastern Iowa can be deduced. Likewise, detailed carbon isotope stratigraphy is needed from the well-known conodont localities in order to improve our chemostratigraphic correlation of the Iowa sequence.

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SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY OF A MIXED CARBONATE-SILICICLASTIC SYSTEM WITHIN THE ORDOVICIAN (CARADOCIAN, MOHAWKIAN) EPEIRIC SEA, DECORAH FORMATION, UPPER MISSISSIPPI VALLEY REGION, USA

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INTRODUCTION

Upper Ordovician rocks found on cratons commonly consist of mud-rich lithologies with evidences of storm reworking, heterozoan fauna, and numerous hardgrounds (Lindstrom, 1979) suggesting deposition on a shelf/ramp setting with mesotrophic to eutrophic waters and sediment starvation. We describe and interpret the Decorah Formation (Upper Ordovician, Caradocian, Mohawkian; Fig. 1) as an example that typifies a mixed carbonate-siliciclastic succession deposited on a cratonic epeiric sea that, as like many other shelf sequences around the world at this time, lacks coated grains, peloids, and calcareous algae/stromatolites in spite of forming at low latitude. Such a succession probably reflects control of deposition by eustasy, climate, trophic levels, paleotopography and dominant fauna.

The Decorah Formation was deposited across a wide region of the mid-continent epeiric sea (the upper Mississippi Valley or UMV, Fig. 2). The formation is exposed in southwest Wisconsin, southeast Minnesota, eastern Iowa, and northeast Missouri. The Decorah contains both carbonates and shales, is rich in benthic marine fauna, and records abundant changes in stable isotopes, total organic carbon (TOC), and brachiopod species. The main purposes of this investigation were to describe the lithologic and faunal architecture of the Decorah Formation in the upper Mississippi Valley region, and to discuss the sedimentological model of a carbonate/siliciclastic epeiric sea. We discuss the interplay of antecedent topography, relative sea-level variations, and changes in siliciclastic and carbonate sediment supply as controlling factors within an epeiric sea.

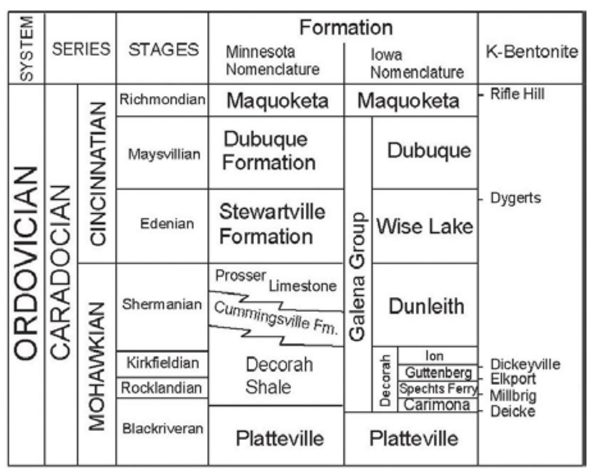

Figure 1. Chronostratigraphy (Bergström and Mitchell, 1992; Goldman et al., 1994) and lithostratigraphy (Minnesota nomenclature following Weiss, 1957; Iowa nomenclature following Templeton and Willman, 1963) of the Middle and Upper Ordovician in the upper Mississippi Valley.

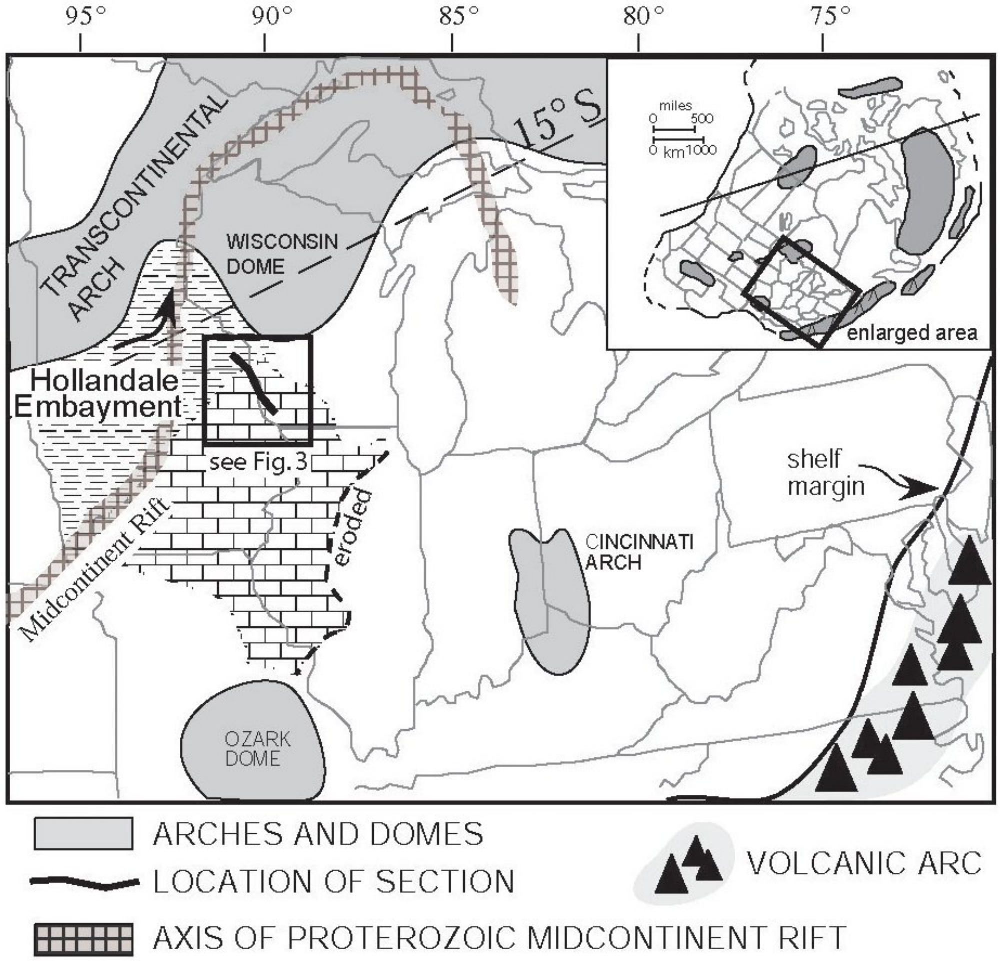

Figure 2. Middle Ordovician paleogeographic reconstruction of the eastern portion of the United States and Canada showing major land areas, basins, and patterns of deposition (modified from Witzke, 1980). The dashed and brick patterns represent the general shale- vs carbonate-rich facies distribution of the Decorah Formation. Position of Hollandale Embayment coincides with the subsurface Proterozoic failed rift system (modified from Sims et al., 1993). Inset map shows the southern latitude position of most of North America during the Middle to Late Ordovician. Exposed land areas shaded gray.

STRATIGRAPHY

The stratigraphic nomenclature and chronostratigraphy of the Caradocian in the upper Mississippi Valley are given in Figure 1. The Platteville Formation (Turinian) and overlying Galena Group (Chatfieldian) are dominated by carbonate lithologies and display great lateral continuity (Willman and Kolata, 1978; Levorson and Gerk, 1983; Delgado, 1983). Fossils within the Galena Group indicate a marine shelf environment commonly below fair weather wave base (Choi and Simo, 1998).

Paleomagnetic data indicate that North America was in a low-latitude setting during the Ordovician, with the upper Mississippi Valley located approximately 15°S (Witzke, 1990; Scotese and McKerrow, 1990). During the Caradocian (Mohawkian to Cincinnatian, Fig. 1) a subequatorial epeiric sea covered most of North America. A tectonic depression, referred to as the Hollandale Embayment (Fig. 2), underlay part of the upper Mississippi Valley region, between the Transcontinental Arch and the Wisconsin Dome (Bunker et al., 1988). These two positive structural features were intermittently developed during the early Paleozoic (Runkel et al., 1998). The axis of this embayment approximately coincides with the subsurface Middle Proterozoic Midcontinent Rift System (Sims et al., 1993).

The Decorah Formation comprises the basal unit of the Galena Group (Fig. 1) and is a mixed shale and carbonate unit with the same overall thickness (~13 to 18 m) across the study area, but with increased shale content northward and for the most part, facies changes are gradual. Figure 3 shows a map of the study area, which at the southern end (Fig. 4) includes the Carimona, Spechts Ferry, Guttenberg, and Ion (equivalent to Buckhorn and St. James) Members (Fig. 1). Approximately midway between the southern and northern ends of the study area (Decorah, Iowa; Fig. 3) the upper members (Guttenberg and Ion) begin to lose their distinguishing characteristics (Fig. 5). The members are not generally recognized in the shalier northern sections in Minnesota where the formation is not subdivided (Figs. 3 and 6) and the formation is simply referred to as the Decorah Shale.

The Decorah Formation contains four closely spaced K-bentonites (Kolata et al. 1986, 1987; Huff et al., 1992). One of these, the Millbrig K-bentonite from the Decorah, Iowa locality (Fig. 3), has been dated using 40Ar/39Ar methods at 450.2 ± 1.7 (2σ) Ma (Leslie, 2002) and more recently at 449.3 ± 0.9 (2σ) Ma (Chetel, 2004). Further, new 40Ar/39Ar dates for the Dygerts (447.1 ± 0.9 Ma) and Rifle Hill (444.0 ± 2.8 Ma) K-bentonites of the Wise Lake and Maquoketa Formations respectively (Fig. 1), provide an approximation for average sediment accumulation rates of 24.5 m/my for the lower Galena Group (Chetel, 2004).

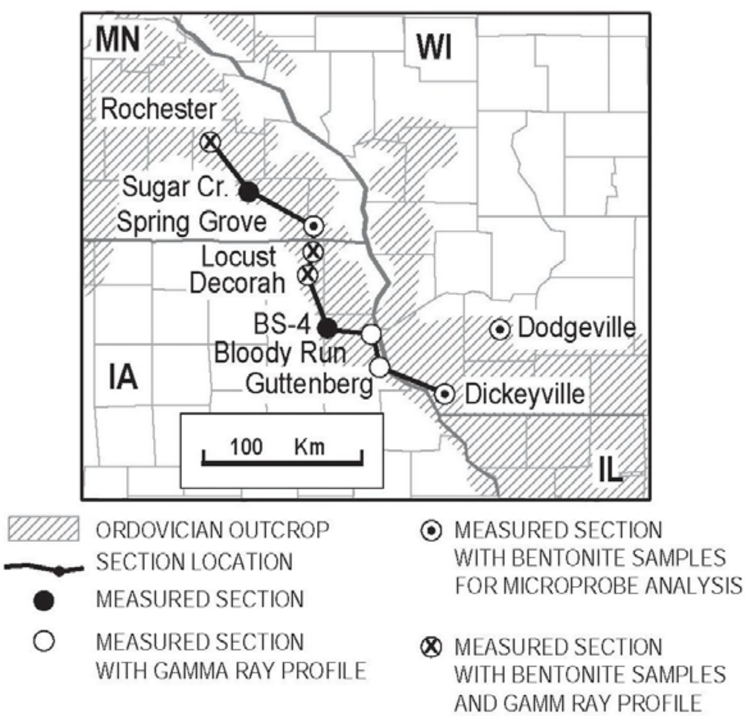

Figure 3. Map showing the locations of stratigraphic sections used in this study. Hatched pattern represents local distribution of Ordovician rock (Kolata et al., 1996). See Table 1 for specific details concerning site locations. Section locations: *Rochester*: composite section of quarry on west side of county road 11, 0.4 km north of intersection of county roads 11 and 36, southeast of Rochester, MN, and from east side of US Hwy 52, southwest of Rochester, MN; *Sugar Creek*: quarry on south side of county road E, 2.3 km west of Fountain, MN; *Spring Grove*: Spring Grove-Roverud Quarry on south side of state Hwy 44, 5 km west of Spring Grove, MN; *Locust*: Locust-Brueing Quarry on north side of county road A26, 0.8 km west of Locust, IA; *Decorah*: Decorah-Brueing Quarry on south side of IA Hwy 9, 0.8 km east of Decorah, IA; *BS-4*: core from east side of county road W62, 9.4 km northwest of Clermont, IA; *Bloody Run*: roadcut along north side of US Hwy 18, 5.9 km southwest of Marquette, IA; *Guttenberg*: roadcut along west of US Hwy 52, 2.4 km south of Guttenberg, IA; *Dodgeville*: roadcut along north side of US Hwy 151, 4.8 km east of intersection of Hwy 151 and 23, Iowa Co., WI.

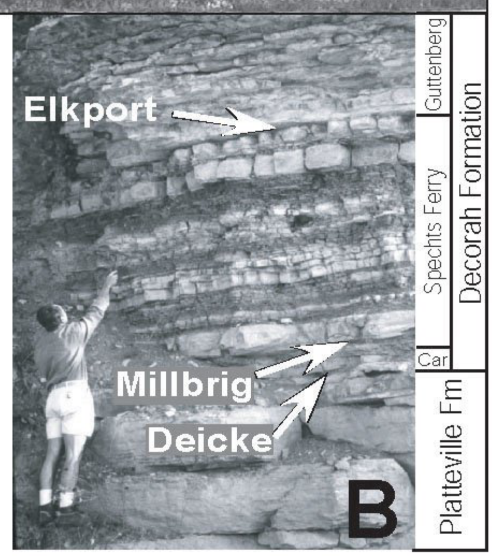

Figure 4. Field photographs of the Decorah Formation. A) Photograph of Guttenberg, Iowa site showing typical carbonate-rich lithology of the Decorah in the southern end of the research area. See Figure 1 for Iowa stratigraphic nomenclature. Photo shows approximately 10 meters of section. B) Photograph of Dickeyville, Wisconsin site which shows the lower portion of the Decorah not exposed at the Guttenberg site. Photo shows approximately 4.5 meters of section.

METHODOLOGY

Nine stratigraphic sections were measured and sampled at the decimeter-scale along a NW-SE cross section (Fig. 3). These sites have undergone minimal dolomitization and span a lateral transect perpendicular to depositional strike which covers a lithofacies change from carbonate to shale. The lithologies are subdivided into 18 lithofacies and grouped into five facies associations (Table 1).

Spectral gamma ray profiles were constructed using a hand-held gamma ray spectrometer (Exploranium GR-320, with a sodium iodide crystal detector and an internal 0.5uCi cesium source) at five sites along the NW-SE cross section (Fig. 3). Sample spacing along each profile was at 40-cm intervals with 90-second count times.

K-bentonite samples were fingerprinted based on apatite phenocryst chemistry. Approximately 10-20 grains (between 60 – 200 microns) from each of 13 K-bentonite samples were mounted for electron microprobe analysis (EMPA) with an average of five points analyzed per grain. Details of the analytical methods used and results from the apatite microprobe work are described in Emerson and others (2004).

CORRELATION

Based on the correlation of K-bentonites, gamma ray profiles, and the tracing of key surfaces and lithologies, a detailed cross section of the Decorah Formation was constructed (Fig. 7). The Decorah Formation can be described as two major packages: a lower part (from the Deicke to the Elkport K-bentonite) that becomes shalier upward and is punctuated by thin beds of carbonate mudstone and brachiopod shell beds (Carimona to the Spechts Ferry Member), and an upper part where the shale abundance diminishes upward and carbonates dominate (Guttenberg and Ion Members). The shale facies depocenter was primarily within the Hollandale Embayment to the northwest and the facies thins against the Wisconsin Dome to the southeast (Fig. 2). The northward shale-rich thickness trend is corroborated by the widening of a gamma ray peak and presence of the phosphate/iron-rich interval within the Spechts Ferry Member (Fig. 7). The overlying carbonate facies is thickest on the Wisconsin Dome and is thinner, less grainy, and shalier northwestward into the Hollandale basin (Fig. 2). This interpretation and correlation is different from previous interpretations (Kolata et al., 1987, 1996, 1998, 2001; Witzke and Kolata, 1988; Ludvigson et al., 1996). Our reconstruction demonstrates that the majority of the shales to the north are older than the majority of the carbonates to the south.

One of the keys to this new interpretation is the K-bentonite chemical fingerprinting and correlation. Trace element analysis of apatite phenocrysts collected from the Deicke, Millbrig, Elkport, and Dickeyville K-bentonites using EMPA allowed for a relatively inexpensive and quick method for geochemically identifying the K-bentonites. For this particular group of bentonites, elemental weight percents of magnesium and manganese proved to be the most useful discriminating and diagnostic tools (see Emerson et al., 2004 for further details of the K-bentonite analysis). The microprobe data from apatite phenocrysts from all six sampled localities fell into four clusters (cross-plot of Mg and Mn weight per cent: Fig. 8A). That these clusters represent the four bentonites in the Decorah can be demonstrated at the Dickeyville, Wisconsin locality where all four K-bentonites are present and can clearly be distinguished stratigraphically (Fig 4B); the plot of Dickeyville data shows the same four clusters (Fig 8B). We believe that the clustering provides a sufficient method of identifying the bentonites, as long as multiple grains are analyzed from each sample (Emerson et al., 2004). Figure 7 shows the K-bentonite-based correlation across a NW-SE cross-section using the Elkport K-bentonite as datum. K-bentonite correlation provided a framework on which to trace unique lithologies, distinctive surfaces, and to plot gamma ray profiles.

The Decorah Formation contains surfaces and lithologic units of great lateral extent. For example, between the Millbrig and Elkport K-bentonites, a phosphate-rich zone can be traced across two-thirds of the study area (Fig. 7). This zone is consistently approximately 90 cm below the Elkport K-bentonite and thickens from ~ 1 cm in the southern end of the research area to ~1 meter thick to the north where it becomes coarser-grained. Based on its relative position, the phosphate zone correlates further north with an iron-ooid-rich zone at the Rochester Minnesota locality (Figs. 7 and 9).

A unique, thin, easily-recognized, carbonate bed within the shaly facies in the northern-half of the study area was also used for correlation. This marker bed is a rusty-brown fine-grained grainstone riddled with *Chondrites*. The burrows are filled with soft orange mud that weathers out easily, leaving open galleries. At the Rochester site, this bed approximates the transition between the gray shale (GRS, Table 1) and green shale (GS, Table 1) lithofacies. It has a hummocky bed form and averages 3-5 cm thick. This bed is traced to a similar but thinner bed (< 1 cm) at the same relative stratigraphic position to the south at the Spring Grove, Locust, and Decorah localities (Fig. 7).

Another key lithology used for correlation lies directly above the Elkport K-bentonite. The lithologies at this stratigraphic level change from shale- to carbonate-dominated. These basal carbonate strata (the lower Guttenberg Member) contain wavy-bedded mudstones with thin brown shale partings rich in the organic-walled, likely algal, microfossil *Gloeocapsomorpha prisca*. This facies is consistent throughout the southern and central study area, and contains a widely-correlated δ13C excursion (Ludvigson et al., 2000).

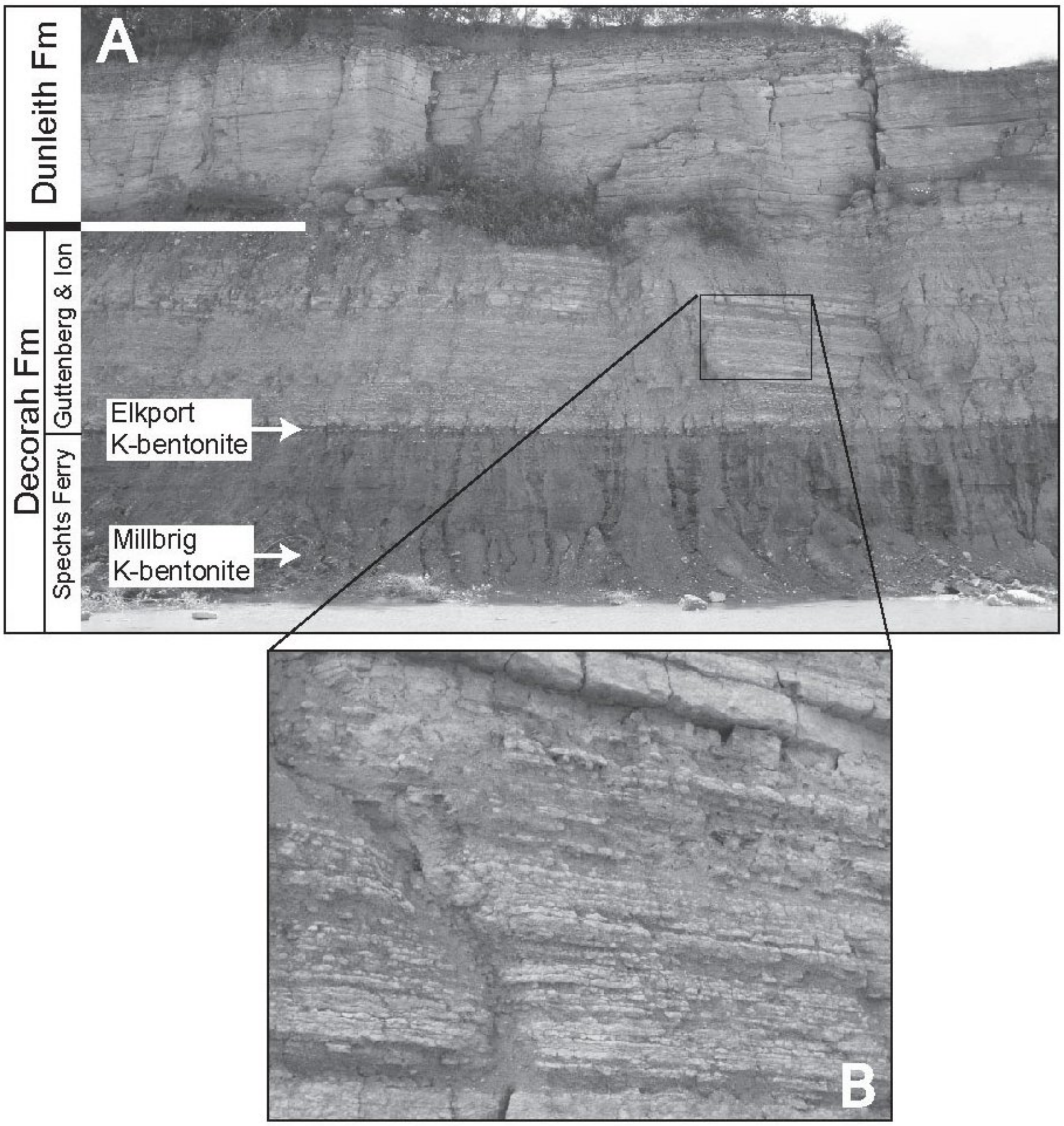

Figure 5. Field photographs of the Decorah Formation. A) Photograph of the Decorah, Iowa site showing the transition in the lithology of the upper portion of the formation from the more carbonate-rich facies in the south end to shale-rich facies in the north end of the research area. Here at Decorah, Iowa the lower Decorah Formation (Spechts Ferry Member) retains its shale-dominated characteristics while the upper Decorah (Guttenberg and Ion Members) becomes more argillaceous and consists of abundant interbedded nodular limestones and calcareous shales. Photo shows approximately 20 meters of section. B) Close up view of the nodular argillaceous Ion lithofacies. Photo shows approximately 2.5 meters of section.

A *Prasopora* epibole was also correlated across the study area (Fig. 7). This zonule can be correlated across several hundred kilometers in the upper Mississippi Valley and appears to be a time line. The zonule is approximately 45 cm thick and is rich in brachiopods, bryozoa (including *Prasopora*), minor rugose corals, and crinoid fragments. It is present in the study area from the Guttenberg to Locust localities and also in outcrops surrounding, and north of, the Spring Grove and Rochester localities. The *Prasopora* epibole marks a sedimentary reorganization in the basin, as it separates two different lithologies as well as different brachiopod communities, along with the introduction of brachiopod species - *Platystrophia amoena* and *P. extensa* to the region (Sardeson, 1892; Weiss, 1953, 1957; Sloan and Weiss, 1956; Levorson and Gerk, 1972; Witzke and Bunker, 1996; Ludvigson et al., 1996; Emerson, 2002; Sanders et al., 2002).

Gamma ray profiles show a distinctive trend that correlates across the cross section (Fig. 7). The profiles record relatively low radiation values for the underlying Platteville Formation, Carimona, and basal Spechts Ferry Members. At all localities, within the Spechts Ferry Member, there is a marked increase in total gamma radiation as well as increases in individual K, Th, and U concentrations (Emerson, 2002). This peak lies consistently between the Millbrig and Elkport K-bentonites (Fig. 7) and below the phosphate/iron-ooid zone; it becomes wider northward, forming a "broad band". Above this interval, gamma radiation values at all localities return to lower levels throughout the rest of the Decorah Formation (Fig. 7).

SEDIMENTOLOGY AND STRATIGRAPHY

Eighteen lithofacies are defined within the Decorah Formation on the basis of major lithologies, sedimentary structures, carbonate textural classification, shale color and content, bioturbation, macrofossil composition, and taphonomy. These lithofacies summarized in Table 1, are grouped into five facies associations. Figure 10 shows the distribution of the five facies associations within the correlated profile.

The Decorah stratigraphic succession starts with a regional angular unconformity (Choi et al., 1999) overlain by the "Lower-mid to Outer Carbonate Ramp" facies association (Table 1), represented by the Carimona Member (Figs. 1 and 10). The Carimona extends across the entire research area from north to south, thinning to the south (from ~ 1.5 m to 20 cm thick), and is always located stratigraphically between the Deicke and Millbrig K-bentonites (Fig. 10). There are four lithofacies in the "Lower-mid to Outer Carbonate Ramp" facies association, of which three are recognized within the Carimona. These include (Table 1) the medium to thin wavy bedded greenish-gray to purplish-brown, mud-rich wackestones (FW) and packstones (FP), and interbedded thin (1-3 cm), fissile, yellowish-brown to olive-brown calcareous shales (BS). Fossils within these carbonates include brachiopods, cephalopods, trilobites, gastropods, ostracodes, and bryozoans. Within the northern-half of the study area (Locust to Rochester localities, Fig. 3) the Carimona Member is capped by large wave ripples with crests oriented 051o, wavelengths averaging 1 to 1.5 m, and amplitudes 1 to 3 cm (Fig. 6). In the southern part of the study area, the Carimona is capped by an irregular burrowed, bored, and mineralized hardground overlain with minor phosphate grains.

The "Lower-mid to Outer Carbonate Ramp" facies association is overlain by the "Dysoxic to Anoxic Outer Shale Ramp" facies association (Fig. 10) which ranges in thickness from ~0.5 m to 4.5 m south to north respectively. Stratigraphically this association consists of the lower Spechts Ferry Member and is composed of three lithofacies (Table 1). Between the Carimona Member and the Millbrig K-bentonite the lithology consists of fossil-poor, laminated, pyrite-rich dark gray shales (GRS) that grade upward into gray shale with interbedded carbonate mudstones (M) and thin mud-rich coquinas (CGP). The basal gray shales contain *Chondrites* and *Planolites* burrows and commonly show mud-rich shell beds consisting of well-preserved nearly monospecific

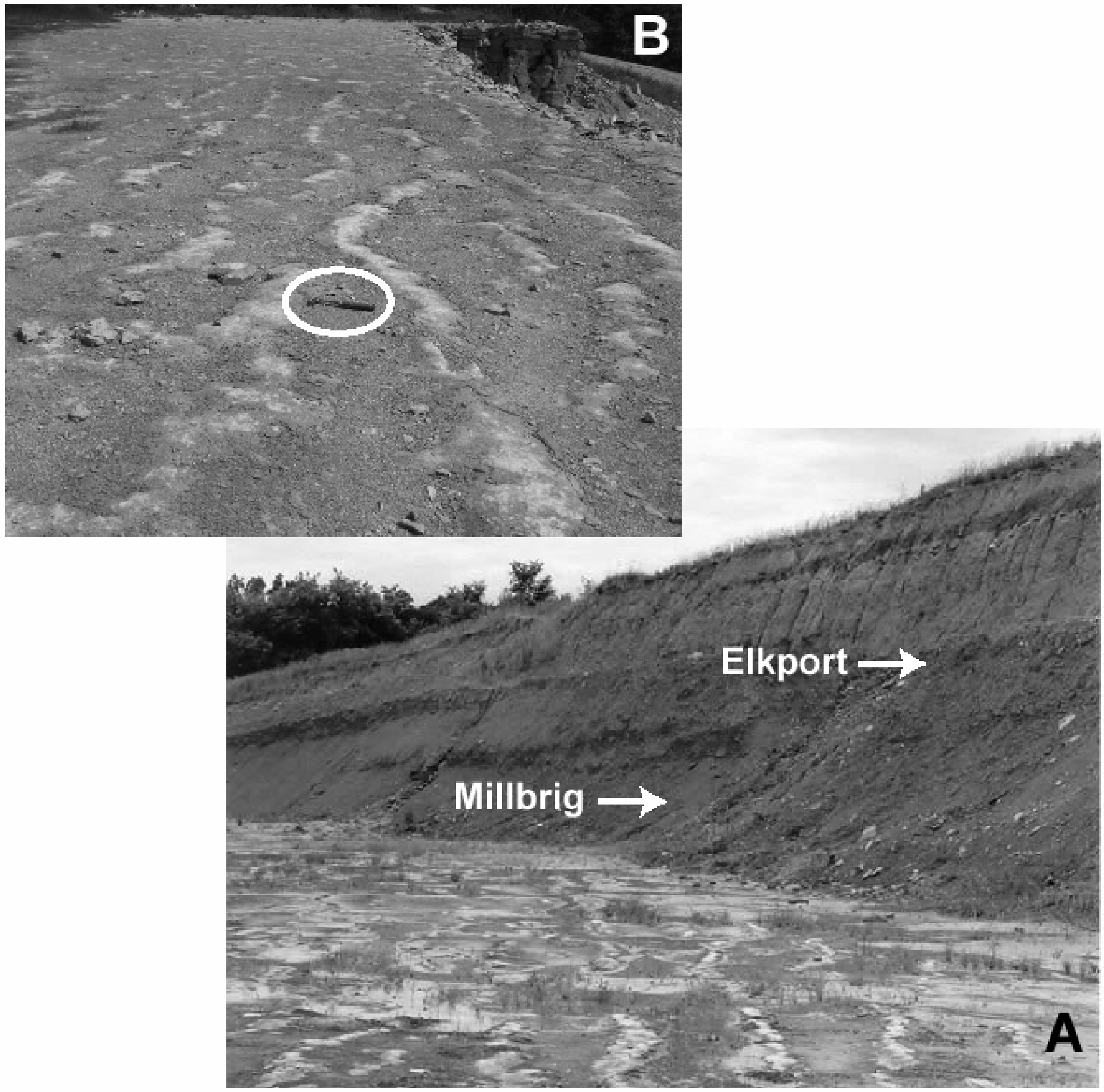

Figure 6. Field photographs of the Decorah Formation. A) Photograph of the Locust, Iowa site showing typical shale-rich lithology of the Decorah in the northern end of the research area. Photo shows approximately 11 meters of section. Long arrows point to the stratigraphic locations of the Elkport and Millbrig K-bentonites. Lower portion of the photo shows the upper surface of the Carimona. B) Photograph in the Kroshus-Bruening Quarry located on the west side of county road 360th street, 8 km northeast of Highlandville, Iowa. Photo shows the upper surface of the Carimona Member with mega-ripples. Ripple crests are oriented at 051^{0} with wavelengths averaging 1.5 meters.

disarticulated blackened brachiopod valves. These shell beds consist of concave-down, well preserved, unworn but fragmented brachiopod shells showing low species diversity (average 3.3 species per sample horizon, Emerson, 2002) dominated by Doleroides pervetus and/or *Pionodema subaequata*. Minor brachiopods in this unit include *Strophomena filitexta*, *Hesperothis tricenaria*, and rare *Rostricellula ainsliei, R. minnesotensis, Petrocrania halli*, *Diorthelasma parvum, D. weissi, Zygospira lebanonensis, Z. plinthii,* and *Z. recurvirostris*. The upper part of this package contains thin shale beds but more abundant and thicker coquinas.

The "Oxic Shale Lower-mid Ramp to Outer Ramp" facies association extends across the research area over the "Dysoxic to Anoxic Outer Shale Ramp" facies association (Fig. 10) and is consistently between the Millbrig and the Elkport K-bentonites (Figs. 7 and 10) and ranges in thickness from ~2 m to 6.5 m south to north respectively. The "Oxic Shale Lower-mid Ramp to Outer Ramp" facies association (upper Spechts Ferry Member) is composed of (Table 1) burrowed green shales (GS), clay-rich carbonate mudstones (CM), and grain-rich shell beds consisting of broken disarticulated, mostly not blackened, brachiopod valves with a matrix of sand-sized skeletal grains (FC). Brachiopods include *Doleroides pervetus, Pionodema subaequata, Strophomena filitexta, Hesperorthis tricenaria, Rostricellula ainsliei, Glyptorthis bellarugosa, Dinorthelasma parvum, D. weissi, Skenidioides anthonense, Cranops minor, Protozyga nicolleti, Zygospira lebanonensis, Z. plinthii, Dinorthis pectinella, D. sweenyi, and Oepikina inquassa*. Abundant dark brown to

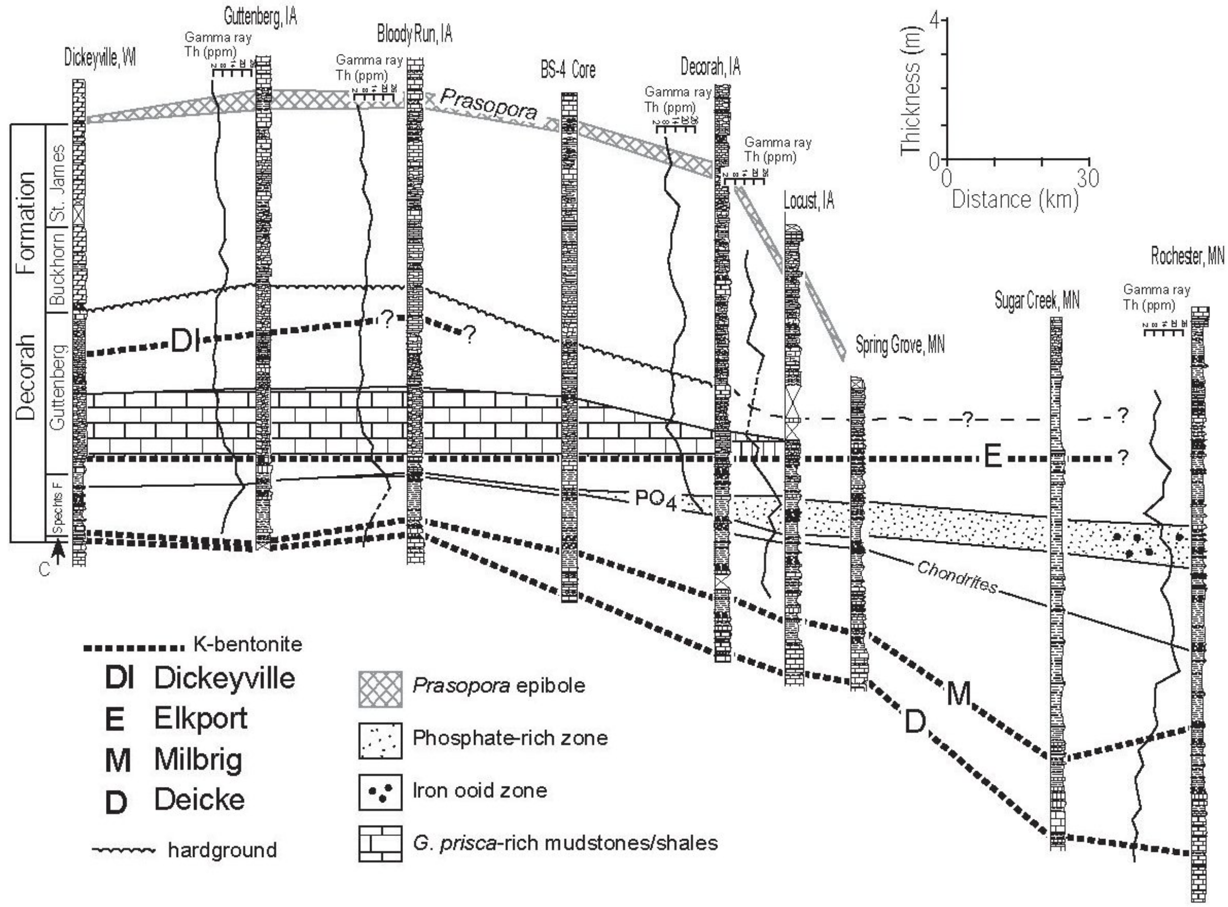

Figure 7. Correlation of measured sections along the line shown in Figures 2 and 3. Datum is the Elkport K-bentonite. See Figure 3 caption for specific locations of measured sections. See Emerson (2002) for stratigraphic details of the measured sections and gamma ray profiles. Line labeled "*Chondrites*" marks a unique rusty-brown fine-grained grainstone riddled with *Chondrites* that are filled with soft orange mud which easily weathers out leaving behind open burrows. See text (Correlation) for descriptions of other correlation tools. C= Carimona Member, Buckhorn and St. James Members are equivalent to the Ion Member in northern sections.

tan, coarse sand- to pebble-size, smooth phosphate-rich grains occur both in the green shale facies and in the interbedded shell beds (Fig. 9) within a zone that thickens from a few centimeters at the Dickeyville locality to approximately 70 cm at the Spring Grove locality (Fig. 10). The phosphate-rich zone is not present at the Rochester locality. Instead, a zone of abundant 1-2 mm, bronze-colored, iron-ooids (hematite, concentrically laminated, possibly originally chamosite ooids; Crews, 1982) is concentrated within the green shale facies and interbedded shell beds (Fig. 9).

The "Oxic Shale Lower-mid Ramp to Outer Ramp" facies association is overlain gradationally by the "Lower-mid to Outer Carbonate Ramp" facies association represented by the lowest portion of the Guttenberg Member. The typical lithofacies for this interval is interbedded brown carbonate mudstones to wackestones (BMW / OBS, Table 1) with well-preserved, diverse, open marine fauna (brachiopods, crinoids, trilobites, gastropods), abundant carbonate mud, and organic-rich brown shale partings containing abundant microfossil G. prisca. It is within this lithologic interval that Ludvigson and others (1996) described total organic carbon values up to 51.7%, as well as a positive $\delta^{13}C$ excursion. To the south this lithofacies is generally 1.5 to 2 meters thick while to the north this lithofacies thins and eventually cuts out at the northern end of the research area (Fig. 10). Brachiopods within these less argillaceous more muddy carbonates are more difficult to extract for identification to the species level than from other units within the Decorah. Those that could be identified include *Dalmanella sculpta, Paucicrura rogata, Sowerbyella curdsvillensis,* and *S. minnesotensis, Rostricellula minnesotensis, R. decorahensis?, Rhynchotrema wisconsinense, Rafinesquina trentonensis, Hesperorthis tricenaria, Oepikina inquassa, Strophomena filitexta.*

The overlying facies associations, from south to north, are the "Mid Carbonate Ramp" and "Outer Carbonate/Shale Ramp." Both associations are capped by the Prasopora epibole (Fig. 10). The "Mid Carbonate Ramp" facies association (upper Guttenberg Member and Ion Member of the Decorah Fm., Figs. 1 and 10) is composed of four lithofacies (Table 1). Beds of this association within the Guttenberg Member contain cross-stratified packstones to grainstones (CPG) interbedded with centimeter-thick dark brown to gray-green shales (BGS). The cross-stratified layers show ripple geometries, with amplitudes averaging 2 cm and wavelengths averaging 20 to 40 cm; crests are oriented at 0470, indicating a dominant current from the southeast. This package averages a thickness of 0.5 m and contains brachiopods, bryozoans, rugose corals, and trilobites. Dominant brachiopod species within this package includes *Dalmanella sculpta, Paucicrura rogata, Sowerbyella curdsvillensis,* and *S. minnesotensis,* with lesser amounts of *Rostricellula minnesotensis, R. decorahensis?, Rhynchotrema wisconsinense, Rafinesquina trentonensis, Hesperorthis tricenaria, Oepikina inquassa, Strophomena filitexta,* and *Dinorthelasma weissi*. These lithologies are overlain by pinkish-gray to gray-green, wavy, irregular, medium to thick-bedded, skeletal packstones with intercalating grainstones (BSPG) (total thickness of ~ 2.5 m to the south and thins to ~10 cm at the Locust, IA location, see Fig. 10) and are capped by a mineralized, burrowed (*Thalassinoides*), and bored (*Trypanites*) hardground. The hardground has moderate erosional relief and can be regionally traced across Wisconsin, Iowa, and Illinois.

The "Mid Carbonate Ramp" facies association within the Ion Member of the Decorah (Figs. 1 and 10) consists of an alternation of shale, argillaceous carbonates and grainy-packstones (Table 1). Much of this facies association is a repetition of nodular, fossil-rich, calcareous shale, which grades upward into bioturbated packstones and grainstones (SPG and BSPG, Table 1, Fig. 6) that coarsen upward and contain thin interbedded shales. Taphonomic characteristics of brachiopod fossils in this succession include poorly preserved shells in a variety of orientations that display higher species diversity (average 6.3 species per sample horizon, Emerson, 2002), and are associated with abundant rounded, fragmented shell debris. This biofabric is indicative of a shell accumulation deposited in high-energy environments (Norris, 1986). In situ sediment, if any, is totally

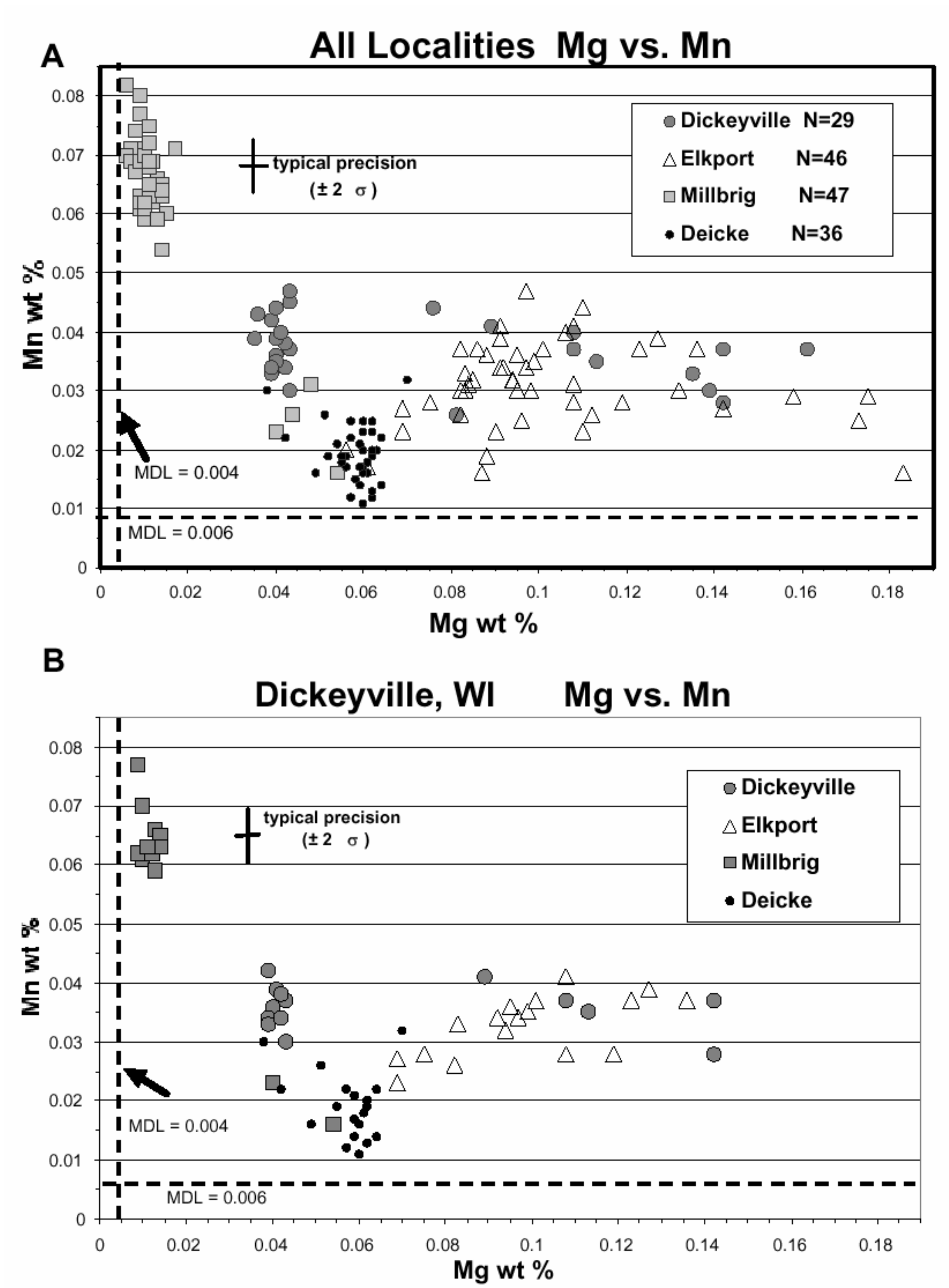

Figure 8. Plot of Mg vs. Mn (elemental wt %) of apatite grains analyzed using EMPA. MDL= minimum detection limits. N = number of grains analyzed. Each data point represents probe values averaged from 3-5 points taken from a single grain. See Figure 3 caption for specific details on location of collection sites. A) Plot of all 171 grains analyzed from all six collection sites (see Figure 3). B) Plot of 69 total grains analyzed from the Dickeyville, WI site (modified from Emerson, 2002 and Emerson et al., 2004).

bioturbated with reworked material. Brachiopod species are virtually the same as those within the Mid Carbonate Ramp facies association within the Guttenberg Member.

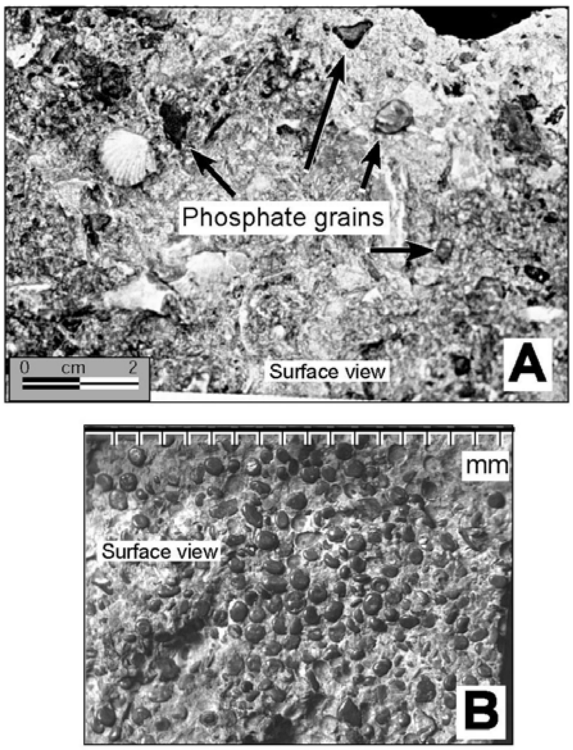

Figure 9. A) Rock slab photograph (upper surface view) of phosphate-rich carbonate within the Spechts Ferry Member (Locust location). Phosphate grains range from coarse sand to pebble size grains and are found concentrated within interbedded shales as well as fossil-rich grainstones such as shown here. See Figure 6 for correlation of phosphate-rich zone with the iron ooid-rich zone. **B)** Rock slab photograph of iron ooid-rich carbonate within the Decorah Formation (Rochester location). The ooids are flattened ellipsoidal grains with a shiny outer surface the color of polished bronze or brass. They are found in concentrations within a zone (approximately 1 meter thick) at the Rochester locality. This interval (see Fig. 6) correlates to the zone rich in phosphate grains (approximately 1 meter thick) at the Spring Grove, Minnesota locality.

The "Mid Carbonate Ramp" facies association grades to the north into the "Outer Carbonate / Shale Ramp" facies association which consists of four lithologies (Table 1): argillaceous, highly burrowed packstones (BP), calcareous gray shale (CS), interbedded nodular limestones and shales (NL), and bryozoan-rich bioturbated packstones / wackestones (BPW). The burrowed packstones (BP) contain abundant small Thalassinoides that are filled with well cemented, coarse sand-size bioclasts and minor quartz grains. In outcrop, the burrowed packstone weathers into a unique rubbly debris consisting of separated, pencil-size segments (1-4 cm long) that is easily recognized and traced between nearby outcrops (Fig. 10). The shales that are interbedded with the nodular limestones (NL) are medium gray to green calcareous shales with abundant sand-sized bioclasts. The limestones (NL) are orange-brown to gray irregular wackestone to skeletal packstone nodules and lenses containing some floating quartz grains. Bioturbation is moderate with zones of abundant *Thalassinoides* burrows. At the Rochester, MN site (Fig. 10) the shales contain zones rich in iron-ooids and the interbedded packstones to grainstones show rippled bed forms with amplitudes averaging 2-3 cm and wavelengths averaging 40 cm. Overall brachiopods collected from this association are less abundant than in underlying associations but include specimens of *Dinorthis sweeneyi, D. pectinella, Diorthelasma weissi, Glyptorthis bellarugosa, Hesperorthis tricenaria,* lingulaceans, *Oepikina inquassa, Parastrophina hemiplicata, Paucicrura rogata, Plaesiomys meedsi, Rhynchotrema wisconsinense, Skenidioides anthonense, Sowerbyella curdsvillensis, Strophomena filitexta,* and *Zygospira recurvirostris.*

The upper boundary of the Decorah Formation is marked by the *Prasopora* epibole that consists of strongly bioturbated (common *Chondrites* and *Thalassinoides*), medium to thin, wavy-bedded, bryozoan-rich, argillaceous packstones/wackestones (BPW, "Outer Carbonate / Shale Ramp" facies association, Table 1), containing intercalating grainstones

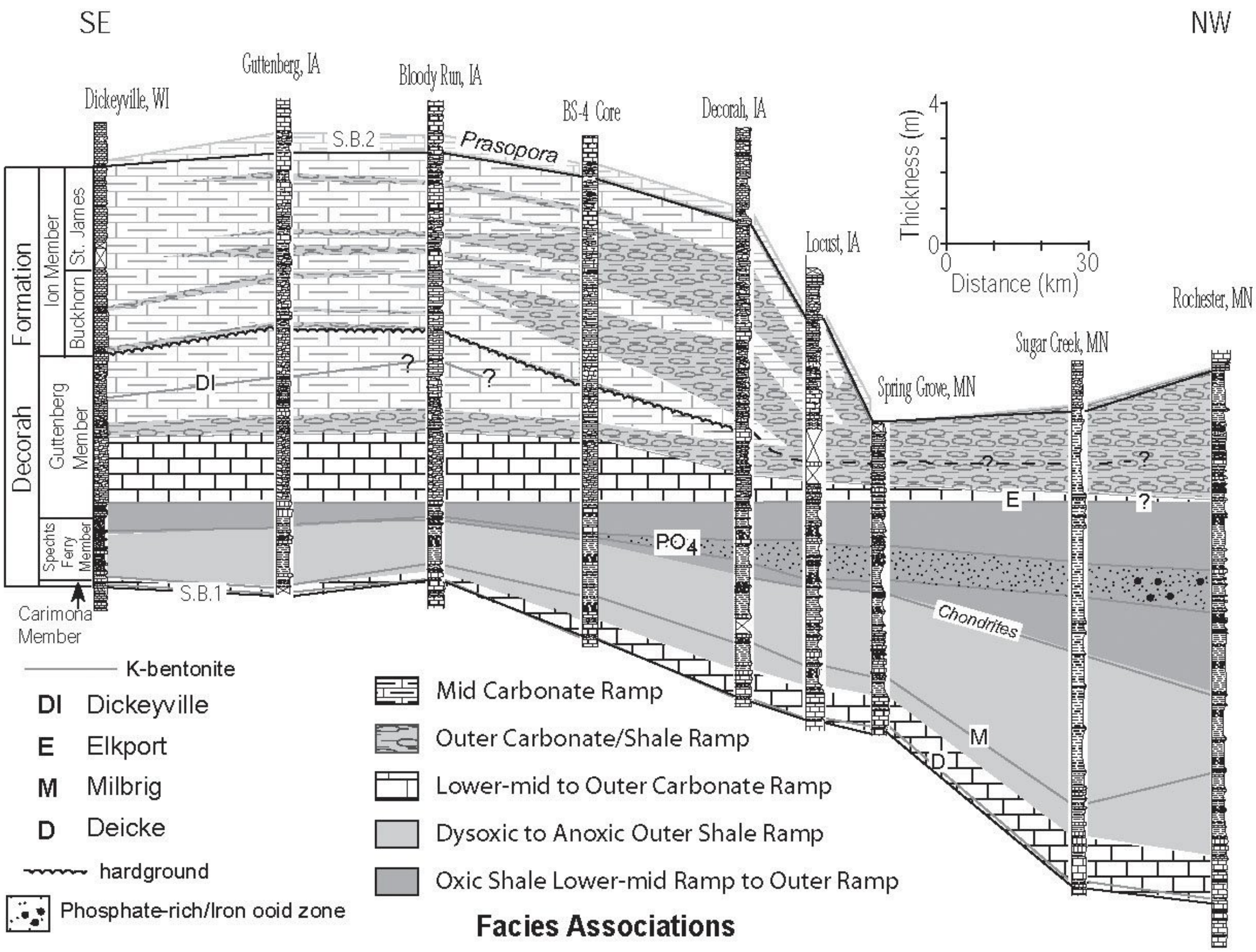

Figure 10. Facies associations distributions and correlation of measured sections along the line shown in Figure 3. Datum is the Elkport K-bentonite. See Figure 3 caption for specific locations of measured sections. See Emerson (2002, appendix-II) for stratigraphic details of the measured sections. See Table 1 for facies association details. S.B.1 and S.B. 2 = sequence boundaries 1 and 2.

that are rich in brachiopods dominated by *Platystrophia amoena, P. extensa?, Rhynchotrema wisconsinense, Dalmanella sculpta,* and *Paucicrura rogata*, bryozoans (including *Prasopora*), minor rugose corals, and crinoid ossicles (Fig. 11). This unit's average thickness is approximately 0.5 meters.

Throughout the Decorah, macrofauna is dominated by heterotrophs (especially epifaunal brachiopods and bryozoans). Work done by Pancost and others (1999) with molecular indicators revealed that derivatives of green sulfur bacteria are abundant in the basal Spechts Ferry shales while cyanobacteria biomarkers are low indicating to them that water conditions were dysoxic to intermittently anoxic during this time. Within the overlying Guttenberg Member green sulfur bacteria derivatives were not detected, cyanobacterial biomarkers remained low, but *G. prisca* becomes very abundant. These indices along with increased bioturbation and macrofossil diversity suggest a more oxygenated environment. Molecular indicators used by Pancost and others (1999) suggest bottom waters remained oxygenated during deposition of the Ion Member. Q-mode cluster analyses of brachiopod species (Emerson, 2002) show two major clusters reflecting the change from the shale-rich Spechts Ferry to the carbonate-rich Guttenberg and Ion Members indicating a close link between the environment and fauna.

SEQUENCE STRATIGRAPHY

The Decorah Formation is bounded below and above by sequence boundaries (Witzke and Bunker, 1996). The lower sequence boundary is a low-angle unconformity marked by a hardground of wide correlation that truncates older strata (Choi et al., 1999). This hardground marks the top of the Platteville Formation (a few centimeters below the Deicke K-bentonite) and possibly represents exposure of the Platteville over a large area and later reworking during transgression. The upper sequence boundary is gradational and marked by the *Prasopora* epibole (described above) that is correlated across several hundred kilometers in the upper Mississippi Valley.

The high-resolution, K-bentonite based correlation demonstrates that the Decorah Formation comprises two separate phases of deposition. The initial phase is dominated by shale-rich facies which become thicker and represent lower oxygenated waters to the northwest while the overlying carbonate-dominated phase, shows its thickest accumulation centered to the southeast with ample evidence of sediment reworking and burrowing (Fig. 10).

Based on the facies and faunal interpretations, the initial deposition within the sequence (Carimona Member) appears to represent the drowning of the underlying sequence boundary. Deposition of skeletal grain-rich carbonate (lower-mid to outer carbonate ramp) sediments at the base suggests an initial transgression that reworked the underlying Platteville Formation and continued concentrating fossil debris in sand waves. There is no compelling evidence of deep water facies to the north during deposition of the transgressive carbonates (Carimona Member.)

Following the transgressive carbonates, separated by a prominent hardground in the south and a rippled horizon in the north, there is the "Dysoxic to Anoxic Outer Shale Ramp" facies association (lower Spechts Ferry Member) which does show evidences of deep water to the north. The gray-colored shale within the lower Spechts Ferry Member suggests the presence of the deepest, and episodically dysoxic, bottom water conditions to the north. In this facies association the abundance of carbonate diminishes, the shell beds are more mud-rich, and the amount of laminated shale with abundant pyrite increases, all suggesting deeper water conditions and/or oxygen restriction to the north. It is possible that runoff from a land source supplied clastic sediment as well as fresh water, causing dysoxic conditions in the water column. Capping the deposition of the "Dysoxic to Anoxic Outer Shale Ramp" facies association are phosphate grains, iron-ooids, and corroded and abraded biota suggest possible slow sedimentation rates and deposition of a condensed section due to drowning of topographic highs, temporarily or partially shutting off the siliciclastic supply.

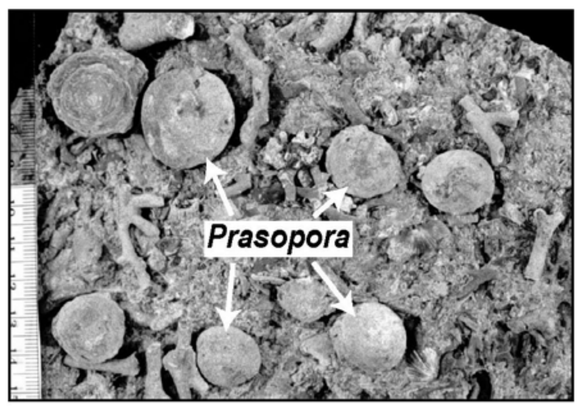

Figure 11. Rock slab photograph (upper surface view) of the Bryozoa-rich bioturbated Packstone/Wackestone lithofacies (BPW) with abundant domal *Prasopora* as well as twig-like ramose bryozoa (Locust location). See Figures 6 and 9 for correlation of the Prasopora zone across the research area. Scale is in centimeters.

Dissolved-oxygen levels in the water column improved during the deposition of the "Oxic Shale Lower-mid Ramp to Outer Ramp" facies association, suggesting shallowing and an improved mixture of the water column. Oxygen levels probably fluctuated between oxic and dysoxic at the sediment-water interface to account for the deposition of phosphate and iron-rich oolites.

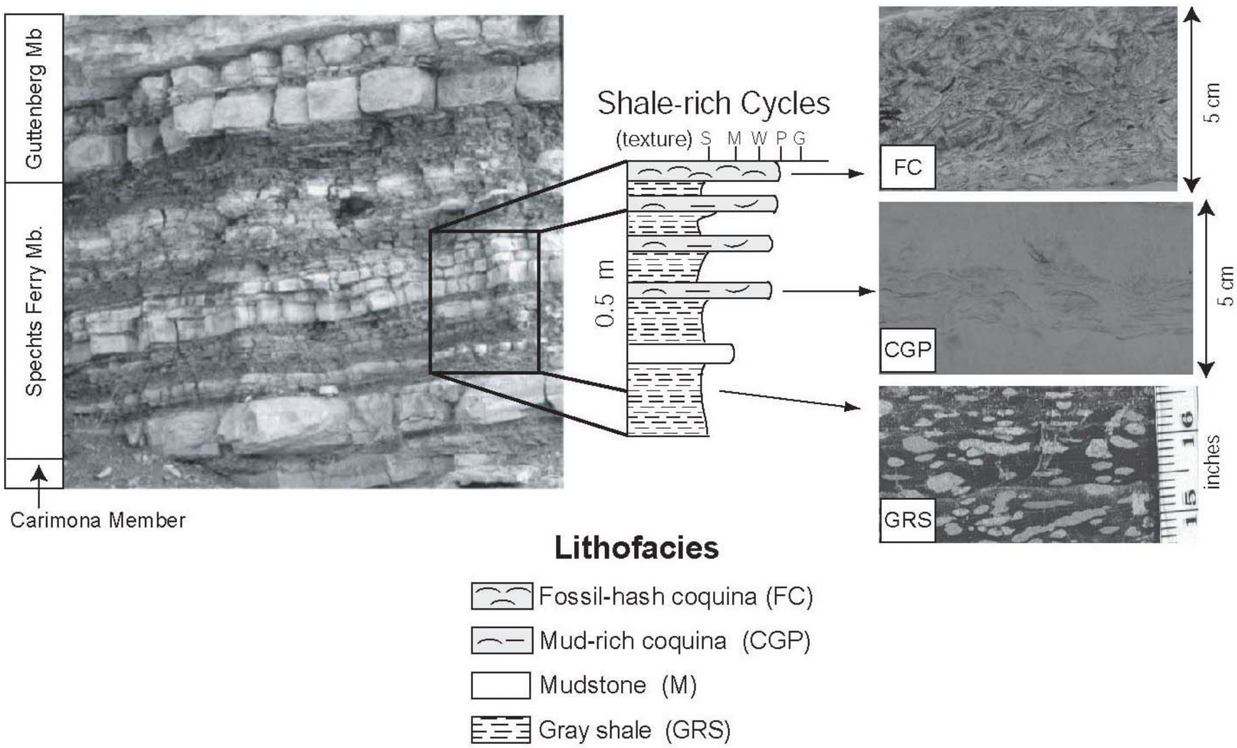

Figure 12. Ideal vertical succession for typical shale-rich cycles within the Decorah Formation. See Table 1 for lithofacies descriptions and abbreviations. Carbonate textures follow Dunham's (1962) classification. Texture abbreviations: S = shale, M = mudstone, W = wackestone, P = packstone, G = grainstone. Rock slab photographs (cross-section view) of typical shale and carbonate textures found in the shale-rich cycles (Spring Grove location). The shale slab (GRS) is composed of medium-dark gray shale containing abundant *Chondrites* filled with light-green mud. Carbonate slab (CGP) is composed of Coquinoid Grainstones and Packstone lithofacies. Note abundant light gray carbonate-mud matrix and common whole valves within this brachiopod coquina. Carbonate slab (FC) is composed of Fossil-hash Coquina lithofacies. Note abundant broken brachiopod valves and minor light-gray siliciclastic-mud matrix within this brachiopod coquina.

The initial shaly phase changed approximately after the deposition of the Elkport K-bentonite, with the initiation of an interpreted shallowing-upward succession dominated by carbonate accumulation in the south that graded to the north into a starved deeper-water basin (Fig. 10). This change is interpreted to result from the abrupt diminution of run-off and supply of terrigenous mud into the Hollandale embayment due to an increase in aridity. The initial deposition of carbonate-dominated facies consists of organic-rich limestones with an open-marine benthic fauna and little shale. Apparently, shutting down the clastic source prompted increasing carbonate production and high phytoplankton productivity, resulting in high TOC, accumulations of *G. prisca*, and a carbon-isotopic positive excursion (Ludvigson et al., 1996; Pancost et al., 1999; Simo et al., 2003). These strata, the "Lower-mid to Outer Carbonate Ramp" facies, reflect normal marine conditions, below storm wave base, with episodes of high phytoplankton production and preservation. The isotopic excursion seems to coincide with the eulithification of the water column in part due to increase in water clarity and the disappearance of a fresh-water lid that reduced oxygen levels in the water column

(Simo et al., 2003). The isotopic excursion appears to be global in character but in detail appears to initiate differently in the basin due to local effects.

Shallowing shown by the presence of cross-bedded carbonates, followed by cyclic deposition of abraded skeletal and burrowed carbonate packstones and grainstones, and argillaceous wackestones and packstones ended the accumulation of organic-rich carbonate mud. Upward, the carbonate phase (Guttenberg and Ion Members), shows an increase in both skeletal-grain content and cross-stratification indicating greater storm reworking due to shallowing. The thickness of the wave-reworked and burrowed grainy carbonates (Mid Carbonate Ramp facies association) is consistent between the localities of Dickeyville and Decorah but thins rapidly from Locust to Spring Grove localities (Fig. 10). This thickness change parallels the change into facies to the north that are intensely burrowed and with no apparent wave reworking, indicating deeper water and sediment starved conditions. The carbonate unit may represent an overall dryer climate with possible seasonality with times of dominant clastic influx and times with increased evaporation and carbonate production on shallow water areas. The stratigraphic succession resembles the system tracks described in Kentucky and Ohio (McLaughlin et al., 2004) but also has major differences. The similarities are in the lower sequence boundary and the overall stratigraphic succession with a lower and upper carbonate dominated package and an intermediate shale-rich unit. In the UMV case, the greatest majority of the intermediate shale-unit (Spechts Ferry) is older than the overlying carbonate package (Guttenberg and Ion) and there are a clear depocenters for accumulation of the different depositional packages. The main difference is in the presence of facies that appear to represent depositional conditions affected by environmental factors (i.e. change in climate, clarity of water) and not sea level. Examples of these facies are the organic-rich "Lower-mid to Outer Carbonate Ramp" straddling the shale- and carbonate-rich units and the upper sequence boundary represented by the *Prasopora* epibole. The lithofacies within the epibole do not change dramatically with those of the underlying Ion Member it but yet these strata contain an important change in fauna with the overwhelming dominance of *Prasopora* and the inclusion of brachiopod species not found in underlying beds.

The overall shale to carbonate succession described above is reproduced at the meter-scale in which shales dominate the cycle base and carbonates the top but with different proportions. The meter-scale repetitions are described below.

Meter-Scale Cycles

Meter-scale cycles within the Decorah sequence are defined as 0.5–1.5 meter thick successions with shale-rich bases grading into skeletal grain-rich tops. Cycle boundaries are placed at the sharp base of the shale-rich part of the cycle. Overall, cyclicity within the Decorah shows no evidence for subaerial exposure. Two cycle types, shale- and carbonate-rich, are recognized and described below (Figs. 12 and 13).

Ideally, the shale-rich cycles consist of a fossil-poor, laminated shale base that grades upward into interbedded shale and carbonate mudstones and thin mud-rich coquinas (Fig. 12). The laminated shale is not present in each of the cycles and the shales may be gray in color or may have a greenish tone.

The shale-rich cycles are interpreted to represent deposition within outer-ramp environments below storm wave base. The characteristics of the gray-shales suggest an open marine subtidal setting with sporadic dysoxic bottom water conditions, while the green-shale represents oxygenated conditions. Sediment is dominated by carbonate and terrigenous mud deposited from suspension, with only the most severe storms affecting the sea floor with infrequent wave reworking, winnowing, and formation of shell beds dominated by monospecific thin delicate whole-valved brachiopod fossils. The mud-rich shell bed biofabric (CGP, Fig. 12) is interpreted to develop when occasional deep storm waves had enough energy to "uproot" and concentrate local fauna and lift mud into suspension that would resettle into openings around re-deposited shells (Norris, 1986). The grain-rich shell bed biofabric (FC, Fig. 12) is interpreted to develop when storm wave energy was strong enough to transport, abrade, and rework shells while winnowing away most of the fine sediment (Norris 1986).

The carbonate-rich cycles consist of nodular, fossil-rich, calcareous shale bases which grade upward into bioturbated, carbonate layers that overall coarsen upward and contain interbedded shales (Figs. 13).

The carbonate-rich cycles are interpreted to develop within the mid-ramp environment where frequent storm waves reworked bottom sediment. Periods of increased siliciclastic influx deposited within a lower mid-ramp energy regime created calcareous shaly cycle bases (Fig. 13), containing articulated or whole-valve brachiopod specimens, during times when the carbonate productivity was diluted and mixed with clay sediments. The upper portions of the cycles mark times of less siliciclastic influx and increased energy resulting in grainier, more amalgamated beds containing more fragmented fossil debris (Fig. 13). Abundant and diverse skeletal grains and bioturbation indicate open-marine moderate to high-energy conditions in which carbonate production was high.

Cycles within the Ion Member show a consistent thickness from Dickeyville, WI to Decorah, IA but northward of Decorah, they thin and become shalier and amalgamated. The shaly base of the Ion is interpreted to represent a regional influx in shale above a surface (the top of the Guttenberg hardground, Fig. 10) representing slow or no sediment accumulation developed over mid-ramp carbonate rocks. Sedimentation of carbonate-rich cycles above this hardground is interpreted as lateral translation of deeper (shale-rich) and shallower (carbonate-rich) facies belts. Each consecutive cycle shows a thinning and shallowing upward trend suggesting reduction in accommodation space. The uppermost cycles in the Ion are composed of grain-supported, bioturbated, wavy-bedded packstones and grainstones that suggest deposition in a high energy, open marine upper mid-ramp environment. This occurs prior to the *Prasopora* epibole which is interpreted to represent a period of slow sedimentation during which a rapid increase in accommodation may have shut off sediment supply. During this time water energy concentrated biotic remains of macrofossils such as brachiopods and bryozoans while winnowing away finer sediment. Water conditions during this time proved favorable for abundant *Prasopora* accumulation.

DISCUSSION

The most appropriate depositional model for the carbonate-siliciclastic system of the Decorah is that of an epeiric ramp environment (Lukasik et al., 2000) or a ramp developed on cratonic interior epeiric seas (Wright and Burchette, 1998). The carbonate epeiric ramp model has wide facies belts, negligible slope, depths of few tens of meters, no shoals, and low energy shorelines (Lukasik et al., 2000). Storms and possible tidal currents dominate, but their effect on the shallow-water areas is minimal as a result of friction. Similar environments are described in Ginsburg (1982) and Choi and Simo (1998). There is no evidence to support that the epeiric ramp shoaled up to sea level by sediment accumulation. Instead, the driving forces for facies change would appear to be sea level and/or climate change. Generally, sediment was distributed by currents across wide areas resulting in gradual lateral facies changes but sharp vertical facies transitions. Individual facies are only meters thick (or less), and probably represent deposition at depths ranging tens of meters.

Epeiric seas within a continent are different from continental shelves. Subtle bathymetric changes of the epeiric sea floor (such as the Hollandale Embayment and the Wisconsin Dome) can modify storm currents within the sea and somewhat restrict the connection with the open ocean. Where circulation is restricted, small variations in runoff and evaporation can change the seawater chemistry, resulting in major facies and faunal changes. Variations in the epeiric sea bathymetry, runoff, and sea level may well explain the sedimentary architecture observed in the Decorah sequence. These factors compete in importance with sea level changes in the reorganization of depositional facies and formation of sequence boundaries.

The high-resolution K-bentonite and stratigraphic correlation of the Decorah Formation allows for the evaluation of processes affecting an epeiric ramp. Based on physical and paleontological evidence, most of the exposed

Decorah Formation represents deposition in outer- and mid-ramp settings. The interpreted

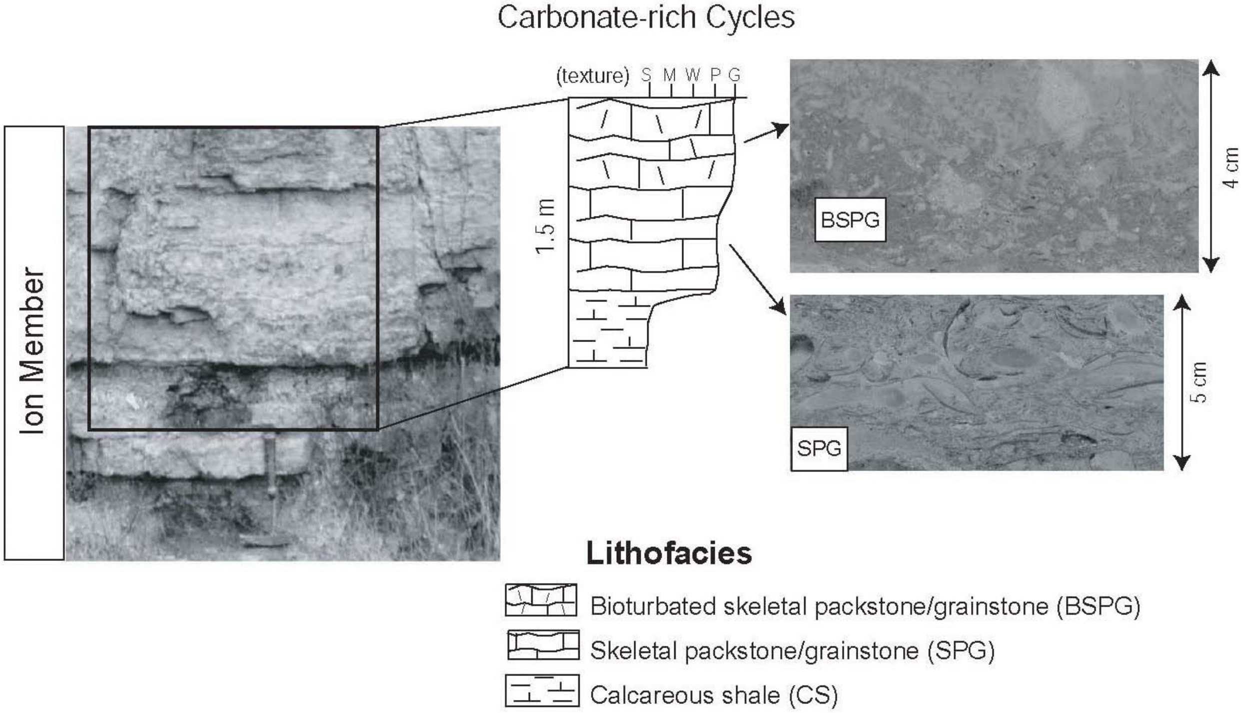

Figure 13. Ideal vertical succession for typical carbonate-rich cycles within the Decorah Formation. See Table 1 for lithofacies descriptions and abbreviations. Carbonate textures follow Dunham's (1962) classification. Texture abbreviations: S = shale, M = mudstone, W = wackestone, P = packstone, G = grainstone. Rock slab photographs (cross-section view) of typical carbonate textures found in the carbonate-rich cycles (Guttenberg location). Carbonate slab (SPG) is composed of Skeletal Packstone/Grainstone lithofacies. Slab contains abundant sand- to pebble-size bioclasts and blackened grains with moderate amounts of whole brachiopod valves. Carbonate slab (BSPG) is composed of Bioturbated Skeletal Packstone/Grainstone lithofacies. Slab contains abundant sand-size bioclasts. Light-gray areas are small burrows and areas of intense bioturbation.

bathymetry is of a low area to the northwest (Hollandale Embayment) that trapped a thicker and deeper water shale succession, and a high area to the southeast (Wisconsin Dome) that was the source of carbonate sediment prograding downramp. Most of the shale is older than the carbonates however. The facies interpretation and cycle stacking indicate a common sedimentary motif at different scales. However, the processes that originated the two types of cycles are different. At the base of the section the carbonate lithologies capping shale-rich cycles are interpreted as storm beds reflecting episodic reworking of brachiopod shells and winnowing of shales. Varying strength in the storm currents generated the mud-rich and grain-rich shell beds. Shell bed biofabrics and diversity data indicate weakening of storms to the northwest. The origin of the cycles appears to be controlled by the differences of stronger or weaker storm activity. During times of weaker storm activity shales were deposited, and during times of more intense storm activity closely spaced brachiopod shell-beds were created. It is important to notice that the majority of the thickness of the section is shale; thus storm activity was minor during the early shale phase of deposition and the shell beds are the anomaly punctuating the succession and allowing distinction of cycles.

The opposite situation appears to be the case for the younger carbonate-rich cycles. Within these cycles, the carbonate rocks dominate and show evidences of continuous intense wave reworking that fragmented, abraded, and blackened skeletal grains. In this scenario, the shales punctuate the carbonate succession and help to define cycles. It is interesting to notice that during this time the shale thickness appears to have been the same in the embayment as on the ramp. Assuming a source to the north, this observation suggests episodes of intense river discharge and long distance transport of fines above a pycnocline. The shale blanket was either well preserved or partially incorporated via bioturbation into argillaceous carbonates. Once more, this observation points towards a stratified water column that reflects the semi-enclosed setting and the interaction of the basin with different rates in evaporation and fresh-water influx.

At a sequence scale, the early phase is characterized by shales that were preferentially deposited in the deeper outer-ramp areas under episodic dysoxic conditions while the mid-ramp was sediment starved and oxic. Probably the subtle topography formed by the Wisconsin Dome was enough to semi-enclose the Hollandale Embayment, trapping mud and freshwater, with the net result of a positive freshwater balance and stratified water column. The later reduction in runoff and mud influx resulted in carbonate deposition and the formation of the upper carbonate-dominated phase. The change from shale- to carbonate-dominated systems coincides with a change in 143Nd/144Nd isotope ratios that suggest high sea level and expansion of the "Taconian water mass" towards the upper Mississippi Valley region (Fanton et al., 2002). It is possible that higher sea level flooded the Transcontinental Arch, reducing the supply of mud and freshwater into the embayment. The resulting mixing of water masses could have increased productivity, generating the anomalous carbonates rich in organic content and *G. prisca*.

After the initial transgression and highest sea level, conditions shifted to a high-energy, probably shallower water, carbonate ramp that was established on the flank of the Wisconsin Dome. Clastic influx was minor over the area. This perhaps was due to an arid climate, or the reduction of the Transcontinental Arch land area by earlier erosion, or redirection of the streams into a different part of the epeiric sea.

The proposed model has similarities with the Lukasik and others (2000) model: climate overall controls main facies types. During seasonally dry climate low mesotrophic conditions develop with less runoff, less terrigenous clay and nutrient influx, and increased water clarity allowing for an active carbonate factory. During wet climate conditions shale facies dominate due to high runoff, clay and nutrient influx, and a reduction in the carbonate factory. However, the Ordovician epeiric sea in the upper Mississippi Valley does not show a discrete trophic structure. The fauna appears to be mostly controlled by the substrate and no lateral variation in fauna exists representing various trophic levels. Deposition of shales may have brought nutrients but also fresh-water that stratified the water column preventing active carbonate factory production.

CONCLUSIONS

The Ordovician Decorah Formation in the upper Mississippi Valley is interpreted as a sequence which is subdivided into smaller cycles. The sequence is bounded above and below by regional surfaces that mark abrupt depositional and faunal changes. The sedimentary motifs of lower shales and upper carbonates occur at different stratigraphic scales.

A new, high-resolution correlation provides an important framework for interpretation of the depositional history of a mixed carbonate-siliciclastic ramp deposited within an epeiric sea. The present correlation shows a reciprocal facies pattern with a lower shale-rich unit that fines upward and thickens northwestward. This unit is overlain by a coarsening-upward carbonate-rich unit that thickens to the southeast.

Antecedent topography formed a broad shallow and semi-enclosed depression (Hollandale Embayment) located between the Transcontinental Arch and the Wisconsin Dome. The embayment, with its low-relief margins, influenced sedimentation patterns during this time. During deposition of the lower unit, fine clastic sediments derived from the Transcontinental Arch were deposited in deep water (some laminated and containing abundant pyrite). Freshwater runoff from the land helped to stratify the water column, leading to dysoxia at depth. Later, transgressive drowning shut off clastic and freshwater influx and allowed for deposition of a carbonate-dominated prograding unit.

The Decorah Formation typifies deposition in an embayment within an epeiric sea in which subtle bathymetric highs and lows together with changes in sea level and climate control the stratigraphic architecture. Similarities in lithologic repetitions permit the establishment of a consistent hierarchal framework, although the origin of the carbonate and shale facies may be controlled by a stratified water column, intensity of storms, introduction of nutrient-rich ocean waters, and possibly shifts in drainage systems.

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Table 1. Facies association and lithofacies summary of the Decorah Formation

Facies Association	Lithofacies name (abbreviation)	Description	Sedimentary structures, bedding type, sorting	Characteristic biota and taphonomy (in decreasing relative abundance)	Bioturbation and trace fossils	Environmental interpretation
Lower-mid to Outer Carbonate Ramp	Fossiliferous Wackestone (FW)	Greenish-gray to purplish-brown, yellowish brown when weathered; mud-rich wackestone; contains Deicke K-bentonite	Wavy, medium to thin bedded with minor shale partings; poorly sorted	Brachiopods (mostly whole well preserved valves), large cephalopods, trilobite, gastropods,ostrocodes, and bryozoans	Moderate	Open marine, moderate to low energy
	Fossiliferous Packstone (FP)	Brownish-gray to brown, yellowish brown when weathered; mud-rich packstone; abundant whole brachiopod valves	Thin to medium bedded; moderately sorted	Brachiopods (mostly fragmented valves), fragments of trilobites, crinoids, and bryozoans	Moderate	Open marine, moderate to low energy
	Brown Shale (BS)	Yellowish brown to olive brown; calcareous	Fissile, very thin to medium bedded; well sorted	Very few macrofossils	Weak to none	Open marine, low energy, increased siliciclastic influx
	Interbedded Brown Mudstone/ Wackestone/ Organic-rich Shale(BMW / OBS)	Light gray to brown, whitish when weathered, interbedded with a few discontinuous grainstones; contains $\delta^{13}C$ and TOC excursions; interbedded shale- dark brown, weathers whitish; thin (< 1-3 cm) shale partings; high TOC	Wavy, thin to medium bedded; shale fissile, thinly laminated; well to moderate sorting	Brachiopods (mostly whole well preserved valves, some articulated), crinoids (some articulated stem sections) in mudstone; Brachiopods, bryozoans, gastropods, minor trilobites and crinoids in grainstones; abundant *G. prisca* microfauna in shale	Weak to moderate, some *Chondrites*	Open marine, low to moderate energy, abundant influx of organic matter
Dysoxic to Anoxic Outer Shale Ramp	Gray Shale (GRS)	Dark gray to blue-gray; abundant silt grains; pyrite common; few blackened fossils; contains Millbrig K- bentonite	Fissile, thinly laminated; well to moderate sorting	Few blackened brachiopod “pavements” (mostly whole well - preserved valves) with minor bryozoans	Weak to none, some *Chondrites* and minor *Thalassinoides*	Open marine, low energy, periods of dysoxia in sediment and water column
	Mudstone (M)	Light gray; rare to common pyrite; few blackened fossils or thin grainstone lenses or interbeds	Medium bedded; well to moderate sorting	Very few macrofossils, brachiopods (mostly whole well preserved valves), bryozoans, crinoids	Moderate to strong	Open marine to semi-restricted, low energy, some dysoxia of sediment
	Coquinoid Grainstones and Packstones (CGP)	Medium gray; brachiopod coquinas with mud matrix; well preserved whole blackened valves; abundant tempestites	Minor graded bedding; moderate sorting; modal grain size - 1 cm	Brachiopods (mostly monospecific, whole well preserved valves), bryozoans, crinoids, trilobites	Weak to moderate	Open marine, medium energy, periods of storm reworking

Table 1 (continued). Facies association and lithofacies summary of the Decorah Formation

Facies Association	Lithofacies name (abbreviation)	Description	Sedimentary structures, bedding type, sorting	Characteristic biota and taphonomy (in decreasing relative abundance)	Bioturbation and trace fossils	Environmental interpretation
Oxic Shale Lower-mid Ramp to Outer Ramp	Green Shale (GS)	Green to gray-green; minor fine sand-size quartz grains and bioclasts; contains Elkport K-bentonite	Fissile, thinly laminated; well to moderate sorting	Few brachiopod "pavements" (mostly whole well preserved valves) with minor bryozoa	Weak to none, some *Chondrites*	Open marine, low energy, return to more oxic environment
	Clay-rich Mudstone (CM)	Light gray, weathers whitish; moderate siliciclastic clay; few "floating" fossils; some contain minor PO4 grains	Medium bedded; moderate sorting	Very few macrofossils, brachiopods, bryozoans, crinoids	Moderate to strong	Open marine, low energy
	Fossil-hash Coquina (FC)	Medium gray to orangish gray; coquinas with bioclast matrix; some whole brachiopod valves, mostly fragments; abundant tempestites	Some graded bedding; poorly sorted; bimodal grain sizes -1 cm and 2 mm	Brachiopods (few whole valves, mostly fragments, moderately worn), bryozoans, crinoids	Weak	Open marine, medium to high energy, periods of storm reworking
Mid Carbonate Ramp	Cross-bedded Packstone / Grainstone (CPG)	Orangish-brown to light gray; mud-rich packstones and grainstone; abundant tempestites	Wavy bedded, irregular upper and lower surfaces, sand-wave geometry; poorly sorted; bimodal grain sizes - 1 cm and 1 mm	Brachiopods (mostly whole valves, some fragments, moderately worn), bryozoans, rugose coral, trilobites	Moderate to weak	Open marine, medium to high energy, storm reworking
	Brown / Gray Shale (BGS)	Dark brown to gray-green	Thinly laminated; well to moderately sorted	Very few macrofossils	Weak	Open marine, low energy
	Bioturbated Skeletal Packstone / Grainstone (BSPG)	Pinkish-gray to gray-green to light orange-brown, weathers medium gray; skeletal packstones with few intercalating grainstones; some floating quartz grains; slightly argillaceous;	Wavy, irregular, to amalgamated discontinuous medium to thick bedded; poor to moderately sorted; modal grain size - 1-2 mm	Brachiopods (few whole valves, mostly fragments, moderately to highly worn), bryozoans, rugose coral	Moderate to strong	Open marine, high energy,
	Skeletal Packstone / Grainstone (SPG)	Medium gray to gray-green; mud-lean skeletal packstones with minor grainstones; abundant sand- to pebble-size bioclasts and blackened grains; floating quartz grains common	Medium bedded sharp lower contacts with radational upper contacts, some low-angle cross-stratification moderately sorted; modal grain size - 1 mm	Brachiopods (few whole valves, mostly fragments, moderately to highly worn), bryozoans, trilobites, rugose corals, ostrocodes	Moderate to intense	Open marine, high energy, oxic conditions

Table 1 (continued). Facies association and lithofacies summary of the Decorah Formation

Facies Association	Lithofacies name (abbreviation)	Description	Sedimentary structures, bedding type, sorting	Characteristic biota and taphonomy (in decreasing relative abundance)	Bioturbation and trace fossils	Environmental interpretation
Outer Carbonate / Shale Ramp	Calcareous Shale (CS)	Medium gray; very calcareous to soft green shale; some grainy packstone nodules and/or lenses	Medium bedded to thinly laminated; moderately sorted	Brachiopods (many articulated, moderately worn), bryozoans	Intensive to moderate	Open marine, medium energy, oxic conditions
	Burrowed Packstone (BP)	Brown to rusty-brown; very argillaceous; poorly cemented grain filled burrows abundant; grains consist of bioclasts and quartz	Thick bedded; amalgamated; moderate to well sorted; modal grain size - 1-2 mm	Macrofossils rare, some brachiopod and bryozoan fragments	Pervasive, abundant small *Thalassinoides*	Open marine, high energy, oxic conditions
	Interbedded Nodular Limestone/ Shale (NL)	Orange brown to gray; nodular discontinuous layers with argillaceous wackestones; floating quartz common in some layers; shale medium gray to green; calcareous to soft; sand-size bioclasts common	Wavy, nodular, discontinuous medium bedded; poorly sorted	Brachiopods (some whole well preserved, mostly disarticulated but well preserved), bryozoans, crinoids	Moderate to intense, zones of abundant *Thalassinoides* and *Chondrites*	Open marine, medium energy, oxic conditions
	Bryozoa-rich bioturbated Packstone / Wackestone (BPW)	Gray brown to greenish gray to orangish-brown; argillaceous in zones	Wavy, medium to thinly bedded; poorly sorted	Bryozoans (*Prasopora* abundant), brachiopods, rugose corals, crinoids	Moderate to strong, *Chondrites* and *Thalassinoides* common	Open marine, slow sedimentation

SULFUR ISOTOPES FROM MISSISSIPPI VALLEY-TYPE MINERALIZATION IN EASTERN WISCONSIN

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INTRODUCTION

The author recently conducted a regional scale reconnaissance study (Fig. 1) of epigenetic mineralization in eastern Wisconsin (Luczaj, 2000; Luczaj, 2006). This research has revealed the existence of a pervasive ancient regional hydrothermal system that operated in eastern Wisconsin during or after Middle Devonian time. Paleozoic sedimentary rocks in eastern Wisconsin preserve a hydrothermal signature and contain abundant epigenetic dolomite and ubiquitous trace Mississippi Valley-type (MVT) mineralization in rocks ranging in age from Early Ordovician through Late Devonian. Petrographic and geochemical evidence suggest that the MVT mineralization, K-silicate mineralization, and the dolomites found in eastern Wisconsin are genetically related to the same regional hydrothermal system which operated at temperatures between about 60 and 120˚C (Luczaj, 2006).

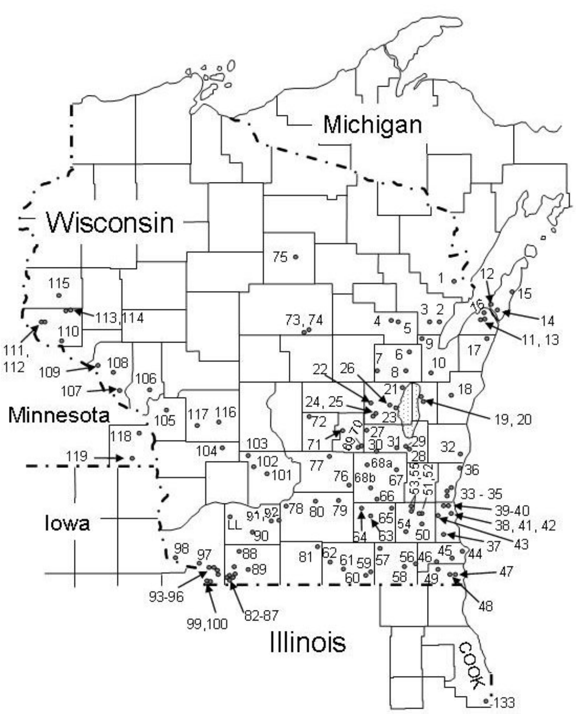

Figure 1. Numbered localities of samples from Luczaj (2000, 2006) in Wisconsin, Minnesota, and Illinois.

Most of the radiometric ages of authigenic K-feldspar and illite in Wisconsin and the Michigan basin range from Devonian to Mississippian (448 to 322 Ma) (Marshall et al., 1986; Matthews, 1988; Hay et al., 1988; Girard and Barnes, 1995; Liu, 1997), but some of the late illite in northwestern Illinois yields a Permian age of 265 Ma (Duffin et al., 1989). In addition, sphalerite from the Upper Mississippi Valley lead-zinc district yielded a Rb-Sr age of 270 Ma (Brannon et al., 1992). At least two separate water-rock interaction systems likely operated in the region at different times. The predominant Middle Paleozoic age K-feldspar suggests that the Middle Paleozoic episode of mineralization was far-reaching, and may have “set the stage” for later mineralization by altering the permeability pathways during regional dolomitization. The later (Permian) hydrothermal dolomitization and MVT mineralization associated with the Upper Mississippi Valley district appears to reach as far east as the Wisconsin arch near Sun Prairie, Wisconsin (Luczaj, 2006).

The purpose of this paper is to present new sulfur isotopic data from eastern Wisconsin for comparison to similar data available for the Upper Mississippi Valley lead-zinc ore district and surrounding areas. Stable isotopic analyses of sulfur were analyzed on samples of sphalerite, galena, marcasite, pyrite, chalcopyrite, and barite collected from cores, outcrop, and quarries located throughout eastern Wisconsin and parts of northeastern Illinois in host rocks ranging in age from Lower Ordovician to

Middle/Late Devonian. No sulfur isotopic data on Mississippi Valley-type minerals have been published for the eastern Wisconsin region, although limited data exist for groundwater SO_4^{2-}(aq) and secondary gypsum (Siegel, 1990). Abundant sulfur isotopic data exist for MVT deposits in the UMV ore district and surrounding areas, especially areas to the south and west (Pinckney and Rafter, 1972; McLimans, 1977; Garvin et al., 1987; Kutz and Spry, 1989).

SULFUR ISOTOPIC ANALYSES OF MVT MINERALS

Sulfur isotopic analyses of $\delta^{34}S$ from various sulfide and sulfate minerals can be used to understand conditions of mineralization, sources of sulfur, and chemical processes in operation during mineral precipitation. They can also be useful as a comparative geochemical indicator to determine if different sets of minerals are related to the same mineralization processes or whether or not conditions such as pH and f_{O_2} have changed during mineralization (Ohmoto, 1972). Fractionation of $\delta^{34}S$ between two different coprecipitated sulfide minerals can also be used to evaluate temperatures of mineral precipitation (Pinckney and Rafter, 1972; McLimans, 1977).

The typical range in $\delta^{34}S$ encountered in natural materials is between about -60 and +45‰. Evaporites, meteorites, igneous rocks, Phanerozoic seawater, and many hydrothermal systems exhibit $\delta^{34}S$ values ranging from near zero to strongly positive values. Marine sediments and biogenic pyrite in modern seawater exhibit $\delta^{34}S$ values that are strongly negative to moderately positive (Nielsen, 1979).

Methods

Samples of galena, sphalerite, pyrite, marcasite, and barite were isolated by breaking small pieces of the mineral away from the host specimen using a razor blade. The samples were crushed in a small agate mortar and pestle and were placed in glass vials for shipment. All stable isotopic analyses of sulfur were performed by Geochron Laboratories of Cambridge, Massachusetts using a Vg Micromass 903 Mass Spectrometer. Refer to Luczaj (2000) for a description of the procedure used by Geochron Laboratories. S-isotopic results are reported as $\delta^{34}S$ using the Canon Diablo troilite (CDT) standard.

EXISTING SULFUR ISOTOPE DATA

UMV Ore district

All of the previous work has concentrated on the UMV ore district and the outlying MVT mineralization surrounding the district. Early work in the UMV ore district by Pinckney and Rafter (1972) showed that variations in the $\delta^{34}S$ in the main sulfide ore minerals were relatively small and ranged from +6.3‰ to +15.9‰ (Table 1), with most of the variability due to fractionation between different minerals such as sphalerite and galena. They also used sulfur isotopic fractionation between coprecipitated sphalerite and galena to estimate temperatures of ore deposition.

Subsequently, McLimans (1977) performed a more thorough study of the S-isotopic composition of MVT minerals from pitch and flat deposits in the UMV ore district. He measured $\delta^{34}S$ values for sphalerite and galena that ranged from +5.4 to +18.1‰, with marcasite, pyrite, and barite ranging from +11.1 to +35.9‰ (Table 1). Although the entire sequence of mineralization shows some variability, McLimans showed that for more than 95% of the ore-stage sphalerite deposited, the $\delta^{34}S$ of sphalerite is +15.5 $\pm$ 1.5‰, indicating precipitation from a fluid bearing H_2S with a nearly constant $\delta^{34}S$. Although shifted to lower $\delta^{34}S$ values due to fractionation effects, galena exhibits a nearly constant $\delta^{34}S$ value of about +12 $\pm$ 2‰. Near the end of the ore-stage mineralization, $\delta^{34}S$ values begin to deviate somewhat from their relatively constant values during the main stage of ore mineralization due to unknown changes to the system.

Ludvigson and Millen (1988) reported additional $\delta^{34}S$ data on galena from gash-vein deposits in the Fessler Mine, which is on the fringe of the UMV ore district near Dubuque,

Main UMV ore district (1, 2, 3, 4)	sphalerite (1, 2)	+10.5 to +15.9
	sphalerite (4)	+8.8 to +18.1
	galena (1)	+6.3 to +11.4
	galena (2, 3, 5)	+1.2 to +4.9
	galena (4)	+5.4 to +13.9
	marcasite	+11.9 to +32.2
	pyrite	+11.1 to +17.5
	sulfates	+22.3 to +35.9
Outlying occurrences of MVT minerals		
Northeastern Iowa (2, 3, 6)	sphalerite	-18.9 to +16.4
	galena	-16.9 to +8.5
	pyrite, chalcopyrite	-22.3 to +27.7
	marcasite	-10.7 to +35.1
	barite	+22.4 to +30.7
Northwestern Illinois (2, 3, 6)	sphalerite	-12.9 to +15.4
	galena	-7.5 to +2.9
	pyrite	-21.0 to +28.5
Southwestern Wisconsin (3, 6)	sphalerite	-0.8 to +3.7
	galena	-4.0 to +8.8
Eastern Wisconsin and Northeast Illinois MVT minerals	sphalerite (*, 2)	-11.0 to +10.5
Data from this study (*) and from (2)	galena (*, 2)	-6.4 to +9.1
	marcasite (*)	-1.1 to +13.0
	pyrite (*)	+15.3
	iron sulfide (2)	+0.6 to +11.8
	chalcopyrite (*)	+6.0
	barite (*)	+20.2, +26.5, +35.4
	all minerals	-11.0 to +35.4
Other Sulfate		
Michigan basin Silurian Evaporites (7, 8)	anhydrite, gypsum	+25.6 to +32.2 (ave. ~28.3)
Southeast Wisconsin and northeast Illinois groundwater sulfate (9)	unconfined aquifer	-5 to +40
	confined aquifer	+16 to +23 (ave. ~20)
Eastern Wisconsin late gypsum (9)	gypsum	+17.5

1. Data from Pinckney and Rafter (1972)
2. Unpublished Data from Timothy Millen
3. Data from Garvin and others (1987)
4. Data from McLimans (1977)
5. Data from Ludwigson and Millen (1988)
6. Data from Kutz and Spry (1989)
7. Data from Das and others (1990)
8. Data from Fritz and others (1988)
9. Data from Siegel (1990)

Table 1. Sulfur-isotopic data for MVT minerals in the Upper Mississippi Valley ore district and surrounding areas. Values of $\partial^{34}S$ are relative to Canon Diablo troilite (CDT).

Iowa. Although the $\delta^{34}S$ data are consistent, between 1.2 and 1.9‰, they are depleted in $\delta^{34}S$ relative to galena in the pitch and flat deposits of the UMV district reported by Pinckney and Rafter (1972) and McLimans (1977) (Table 1). This $\delta^{34}S$ depletion is similar to that observed in the outlying MVT mineralization from the Mount Carroll deposits further to the south in Illinois (Ludvigson and Millen, 1988).

Outlying Mineralization

Garvin and others (1987), Ludvigson and Millen (1988), and Kutz and Spry (1989) focused on the "outlying" MVT mineralization, much of which exhibits $\delta^{34}S$ values that are highly variable compared to those of the main UMV ore district mineralization (Table 1; Figure 2). The $\delta^{34}S$ in sphalerite and galena from these areas ranges from strongly negative to strongly positive (-18.9 to +16.4‰), with the largest variability observed in Iowa and Illinois. Differing opinions exist as to whether or not the outlying mineralization is genetically related to the UMV ore district mineralization.

Garvin and others (1987) distinguished three different groups (I, II, and III) of outlying MVT deposits. They described Group I deposits as being characterized by positive $\delta^{34}S$ values and a lack of barite in the mineral assemblages. The general mineralogy, paragenetic sequence, and sulfur isotope values for MVT minerals in these deposits is similar to the main Upper Mississippi Valley district deposits (Garvin et al., 1987), although the UMV ores are associated with barite. Group I deposits are consistent with transport of reduced sulfur and metals in the same solution, with sulfur derived from an evaporitic source. Group II deposits are characterized by the presence of barite and an overall paragenesis that is dissimilar to the main UMV ore district deposits, specifically, that the calcite is generally early and the sulfides are late. In addition, they generally display negative $\delta^{34}S$ isotope values, which is in contrast with Group I deposits and deposits in the main UMV ore district. Several possibilities exist that might explain the isotopic systematics in these deposits, including (1) derivation of sulfide by leaching of $\delta^{34}S$-depleted diagenetic iron disulfides, (2) the involvement of a sulfide-rich fluid, with partial reduction to sulfide, and nonequilibrium sulfate-sulfide isotope fractionation. They suggested that the isotopically depleted sulfide may have been produced at the depositional site either by microbial sulfate reduction or by sulfate reduction caused by reaction with organic matter or methane (Garvin et al., 1987, p. 1392). Garvin and others (1987) suggested that the differences in paragenesis and sulfur isotope composition between Group II and the UMV deposits are due to the existence of different episodes of mineralization within the Upper Mississippi Valley region. Group III deposits were intermediate and were recognized at Mount Carroll, Illinois. This type of deposit, upon later inspection by Ludvigson and Millen (1988), actually seems quite similar to some of the UMV ore district mineralization in the form of gash vein deposits.

Ludvigson and Millen (1988), and references therein, reported on the geology and isotope geochemistry of MVT mineralization in deposits inside and outside the main UMV ore district. They noticed Garvin and others' (1987) S-isotopic work that showed the gross dissimilarity between the UMV pitch and flat deposits described by McLimans (1977) and some of the outlying MVT mineral deposits. All of McLimans (1977) work was performed on pitch and flat deposits in the UMV ore district. Ludvigson and Millen noted the geometric similarity between the outlying gash vein mineral deposits at Mount Carroll, Illinois (Garvin et al.'s, 1987, Group III), and the UMV gash vein deposits. Further investigation of the paragenetic sequence of mineralization at Mount Carroll indicated that the mineral paragenesis was quite similar to that of the main UMV ores. In addition, they studied galenas from the gash vein deposits within the UMV ore district at the Fessler Mine near Dubuque, Iowa, to determine if they had similar S-isotopic systematics to some of the outlying MVT deposits. The S-isotopic values from the Fessler Mine (UMV ore district gash vein) overlap with those from the outlying MVT deposit at Mount Carroll, Illinois (Ludvigson and Millen, 1988, Figure 6; and Kutz and Spry, 1989, Figure 7), suggesting that mineralization at Mount Carroll is genetically related to the ore minerlization in the UMV district, in addition to other outlying MVT mineralization in Iowa and Illinois. They suggested that the isotopic differences between the UMV ores and the outlying mineralization may be due to incomplete sampling in the UMV district.

Kutz and Spry (1989) reported more $\delta^{34}S$ values for MVT sulfides and sulfates from outlying MVT deposits in Iowa, Illinois, and Wisconsin. They reported sulfides with highly variable $\delta^{34}S$ values, ranging from -22.3 to +33.1‰, that were similar to those reported by Garvin and others (1987). They also recognized two distinct types of mineralization in the outlying deposits, which are essentially the same as Garvin and others' ,1987, Groups I and II. However, Kutz and Spry admit that their data, in conjunction with Garvin et al.'s data, suggest an almost continuum of $\delta^{34}S$ values for the sulfides in the outlying deposits and that the $\delta^{34}S$ values do not fall into three statistically distinct groups as Garvin et al. imply. Kutz and Spry (1989) concluded, based upon S-isotopes and other geochemical data, that there appear to be at least two types of outlying MVT mineralization: (1) those that occur north and northwest of the UMV district in Wisconsin, as well as some along the Plum River fault zone, which show paragenetic, mineralogical, and stable isotope (particularly sulfur) characteristics similar to occurrences associated with the pitch and flat deposits in the main district; and (2) those that occur northeast of the main Upper Mississippi Valley district in Wisconsin and to the southwest in Iowa, which exhibit paragenetic, mineralogical, and some fluid inclusion and stable isotope (particularly sulfur, carbon, and oxygen) characteristics significantly different from those associated with pitch and flat deposits in the main district.

For the outlying mineral occurrences near the UMV ore district, it is clear that considerable variability exists regionally as well as locally within the same quarry or deposit. The precise relationship that the UMV deposits have to the outlying mineralization is not fully understood.

SULFUR ISOTOPE DATA FROM EASTERN WISCONSIN

The $\delta^{34}S$ values of sulfur from sphalerite, galena, pyrite, chalcopyrite, marcasite, and barite collected from eastern Wisconsin are presented in Table 2. Ranges in $\delta^{34}S$ for each of the different minerals are shown in Figure 2. Excluding samples from the breccia body at the Racine Vulcan Quarry (locality 44), sphalerite exhibits the largest $\delta^{34}S$ range of any of the MVT sulfide minerals (-11.0 to +11.4‰). Galena, marcasite, and chalcopyrite have a smaller range from near zero to moderately positive values (-1.1 to +9.1‰). Although most localities display a moderate range for $\delta^{34}S$ from sulfides, a considerable range in $\delta^{34}S$ values exists for these minerals regionally, and at a few localities they exhibit large variations in $\delta^{34}S$ (Table 2).

The largest $\delta^{34}S$ range for a single locality was found in minerals from an unusual breccia pipe at the Racine Vulcan Quarry in southeastern Wisconsin (locality 44). Most of the MVT mineralization observed there is texturally unlike other mineralization from eastern Wisconsin. Values of $\delta^{34}S$ for marcasite, pyrite, and sphalerite ranged from extremely negative (-38‰) to positive (+15.3‰). See Luczaj (2001) for a detailed description of mineralization in this breccia body.

No systematic regional trends were found for $\delta^{34}S$ in the sphalerite from eastern Wisconsin and northeastern Illinois. Early sphalerite (purple, black, and colorless) exhibits the same $\delta^{34}S$ range as late sphalerite (orange, red, yellow-orange). However, at some localities (e.g., Markesan and Oshkosh, Wisconsin) the early sphalerite has a lighter $\delta^{34}S$ isotopic composition than the later generation of sphalerite, suggesting that there may have been a difference between the chemistry of the two fluids responsible for mineralization at these locations. Additional data are needed to determine whether or not there is a statistically significant difference between the two populations. There is a trend in $\delta^{34}S$ for galena in northeastern Illinois and eastern Wisconsin,

Locality (number + description)	SAMPLE #	Mineral	Description	$\delta^{34}S$ (‰)
3. Montevideo Quarry; Oconto County	97-OCO-2-S14	sphalerite	Early zoned-Black, colorless, brn./yellow	-2.5
5. Highway 29 Quarry; Bonduel, WI (x)	99-SH-CC-1-S22	sphalerite	Early-purple colored	-3.0
	99-SH-CC-1-S23	sphalerite	Late-yellow colored	-3.8
8. Mackville Quarry; Appleton, Wisconsin	98-OUT-2-S19	barite	Interior inclusion-rich zone of crystal	+20.2
	98-OUT-4-S20	sphalerite	Purple and colorless	+9.0
9. McKeefry & Sons Quarry; Brown Cty.	96-BR-2-S21	sphalerite	Variable purple, colorless, tan, lt. yellow	+5.1
21. Bencarrie Quarry; Neenah, WI	97b-WIN-5-S15 *	marcasite	Vein marcasite from small fault zone	+4.4
	97b-WIN-5-S15 *	marcasite	Vein marcasite from small fault zone	-1.1
	97b-WIN-5-S15 *	marcasite	Vein marcasite from small fault zone	-0.1
	IV-A-29-S-26	galena	Samples from Jenkins (1968) M.S. Thesis	+4.6
	IV-A-29-S-27	sphalerite	Zoned black, orange, green, yellow	+11.4
23. Vulcan Quarry; Oshkosh, Wisconsin	96-WIN-9-S11	sphalerite	Early zoned-purple, green, colorless	+4.2
	96-WIN-9-S12 *	sphalerite	Late-red colored	+2.7
	96-WIN-9-S12 *	sphalerite	Late-red colored	+4.5
	96-WIN-8-S13	galena	Isolated cubic crystal found with calcite	+9.1
	97-WIN-LB-S24	sphalerite	Late-outer rim of yellow orange color	+7.2
26. Leonard Point Road Quarry;	97-WIN-3-S1	barite	From one inch long crystal group	+35.4
(west of Oshkosh, Wisconsin)	97-WIN-3-S3	sphalerite	Orange-red late sphalerite	+7.0
	97-WIN-3-S4	chalcopyrite	Isolated crystal	+6.0
28. Rademann Stone & Landscape Quarry	96-FDL-3A-S16	sphalerite	Zoned blue/purple colored	-7.0
(south of Fond du Lac, Wisconsin)	96-FDL-3A-S17	sphalerite	Late - Orange, yellow, and red colors	-8.0
38. Estabrook Quarry; Milwaukee, Wisc.	Loc. # 11826-S28	sphalerite	Early zoned-black, purple, green, colorless	-9.4
44. Vulcan Quarry; Racine, Wisconsin	96-RA-1-S5 *	sphalerite	Colloform sphalerite	+10.5
(Threemile breccia body samples)	96-RA-1-S5 *	sphalerite	Colloform sphalerite	+7.1
	96-RA-1-S5 *	sphalerite	Colloform sphalerite	+8.5
	96-RA-1-S6	marcasite	Colloform marcasite	+13.0
	96-RA-1-S7	pyrite	Massive, pre-sphalerite/marcasite	+15.3
	96-RA-1-S8	sphalerite	Variable colored 3 mm crystals	-2.6
	96-RA-1-S9 #	sphalerite/marcasite	Coprecipitated, very late, post calcite	-38.0
55. Mobil Corporation Drill Core	D-311-WK-1547X-S2	galena	Occurs with sphalerite	-0.7
(Waukesha County, Wisconsin)	)-311-WK-1547X-S3	sphalerite	Variable-yellow, colorless, some darker	+6.2
	BD-311-WK-1547X-S3	sphalerite	Variable-yellow, colorless, some darker	+8.6
69. Michels Materials Quarry	98-GL-5-S18	barite	barite crystal	+26.6
(near Markesan, Wisconsin)	98-GL-6-S10	sphalerite	Early zoned-purple, colorless, green, tan	-11.0
	98-GL-6-S25	sphalerite	Late-red and orange colors	+2.5
133. Thornton Quarry; Chicago, Illinois (y	92-T-8-S31 *	sphalerite	Brown, greenish-tan, colorless	-7.5
	92-T-8-S31 *	sphalerite	Brown, greenish-tan, colorless	-6.9
Elmhurst Quarry; Elmhurst, Illinois (z)	ELM-T1B	galena	Data from Millen, personal comm., 1999	-6.4
	ELM-T1B	sphalerite	Data from Millen, personal comm., 1999	+7.9
	ELM-1WB	galena	Data from Millen, personal comm., 1999	-6.0
	ELM-1WB	sphalerite	Data from Millen, personal comm., 1999	+1.4
	ELM-1WB	iron sulfide	Data from Millen, personal comm., 1999	+11.4
	ELM-1WC	iron sulfide	Data from Millen, personal comm., 1999	+11.8
	ELM-1E1A	iron sulfide	Data from Millen, personal comm., 1999	+0.6
	ELM-BE7N	sphalerite	Data from Millen, personal comm., 1999	+2.5

Explanation of symbols

(*) Replicate analyses are on separate crystals from same sample.

(#) Sample was fine grained coprecipitated sphalerite and marcasite that could not be separated.

(x) Samples from Carl Cochrane. (y) Samples from Don Mikulic. (z) Unpublished data from Timothy Millen (written communication, 1999)

Table 2. Sulfur isotopic analyses of sulfide and sulfate minerals from eastern Wisconsin and northeastern Illinois. Values of $\partial^{34}S$ are relative to Canon Diablo troilite (CDT).

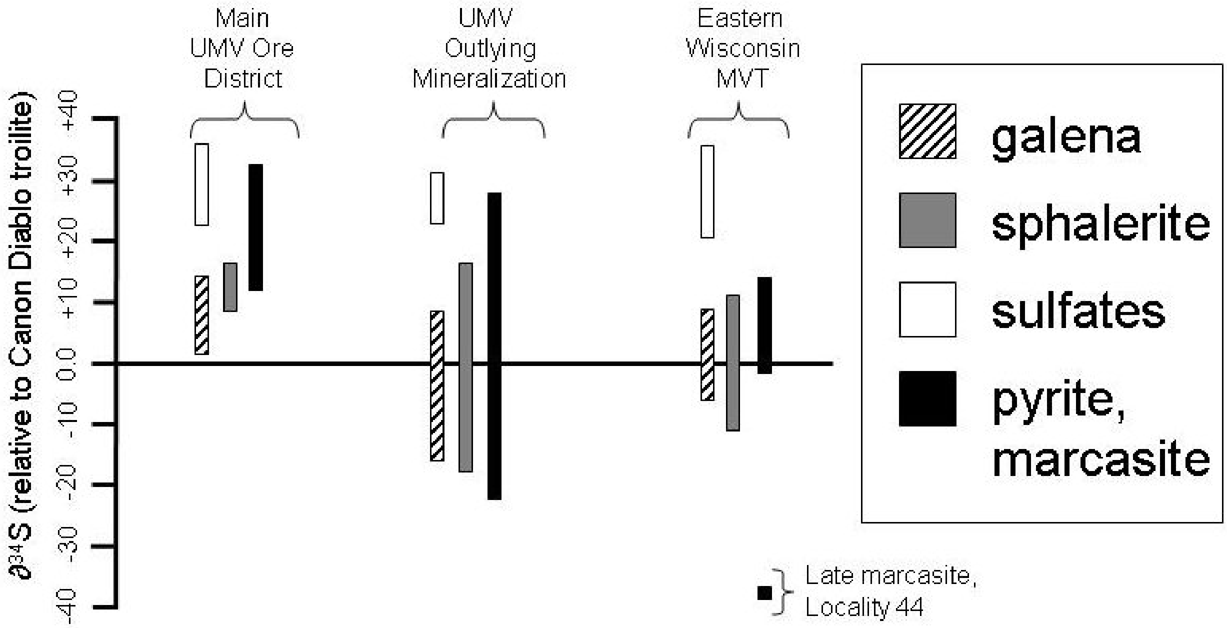

Figure 2. Plot comparing the $\delta^{34}S$ distributions of various MVT minerals in the Upper Mississippi Valley ore district with UMV outlying mineralization and eastern Wisconsin/northeastern Illinois mineralization. The $\delta^{34}S$ values for eastern Wisconsin sulfide minerals are similar to MVT minerals in the outlying mineralization, but are significantly lighter than $\delta^{34}S$ values for sulfides in the UMV ore district. Late marcasite at locality 44 is from the unusual Threemile Road breccia body. The $\delta^{34}S$ for barite is similar throughout the region.

although only a few data have been collected. Five measurements of $\delta^{34}S$ for galena indicate that the sulfide in galena from northeastern Wisconsin ($\delta^{34}S$ = +9.1, +4.5 ‰) is isotopically heavier than that from the samples in northeastern Illinois ($\delta^{34}S$ = -6.0, -6.4 ‰). Galena sulfide in southeastern Wisconsin yields an intermediate value (-0.7 ‰). Three barite samples from eastern Wisconsin yielded $\delta^{34}S$ values between +20 and +36‰, which is similar to previously reported $\delta^{34}S$ values for barite and gypsum/anhydrite from the region.

DISCUSSION

The isotopic composition of sulfur in hydrothermal minerals is strongly controlled by the fO_2 and pH values of hydrothermal fluids as well as by the temperature of the fluid, the isotopic composition of oxygen and sulfur in the fluid, the total S content of the fluid, and the ionic strength of the fluid (Ohmoto, 1972; Faure, 1986). The sulfur-bearing species important in hydrothermal ore-forming fluids below 500˚C include: $H_2S_{(aq)}$, HS^-, S^{2-}, SO_4^{2-}, HSO_4^-, KSO_4^{2-}, and $NaSO_4^{2-}$ (Faure, 1986). Even moderate changes in temperature, pH, and fO_2 can be responsible for large variations in the $\delta^{34}S$ composition of MVT minerals. Additional changes in the total S content of the fluid and the ionic strength of the fluid can further alter the isotopic system. Many of these variables are difficult to measure for ancient hydrothermal MVT systems, and measured values of $\delta^{34}S$ in sulfide and sulfate minerals from these systems must be interpreted carefully.

With the exception of the unusual mineral deposit associated with the breccia body at locality 44, $\delta^{34}S$ values for MVT minerals from eastern Wisconsin and northeastern Illinois span a considerable range of values, from moderately negative (-11.0‰) to moderately positive (+11.8‰). Sphalerite from eastern Wisconsin and northeastern Illinois is depleted in ^{34}S ($\delta^{34}S$ = -11.0 to +10.5‰) compared to sphalerite from the UMV ore district (+8.8 to 18.1‰), with very little overlap in $\delta^{34}S$ (see Table 1). A similar relationship exists for galena from the two regions, although more overlap is present in the $\delta^{34}S$ values.

Overall, sphalerite, galena, and marcasite in eastern Wisconsin and northeastern Illinois exhibit a smaller range in $\delta^{34}S$ isotopic values than the MVT minerals in outlying areas near the UMV lead-zinc ore district (Table 1), especially when compared to sulfides from northeastern Iowa. This is important for two reasons. First, the eastern Wisconsin region is larger than the area in northeastern Iowa, where large variations in $\delta^{34}S$ have been measured. Second, the overall paragenetic sequence of mineralization appears to be similar throughout eastern Wisconsin, in contrast to mineralization in the areas south and west of the UMV ore district (e.g., Garvin et al., 1987; Kutz and Spry, 1989). Together, these two observations suggest that while areas surrounding the UMV ore district may have been exposed to multiple episodes of MVT mineralization, the eastern Wisconsin region, especially northeastern Wisconsin, has likely only been exposed to one episode of MVT mineralization.

Bacterial sulfate reduction may play an important role in the ore forming process over the temperature range encountered during MVT mineralization (e.g., Sverjensky, 1986). In addition, local changes in oxygen fugacity, pH, and temperature could also explain the variations observed in the MVT minerals in the region. The exact mechanisms responsible for the sulfur isotopic signature are unclear because there are too many variables left unconstrained in the system. However, they do provide a method of comparing the sulfide mineralization to help interpret regional similarities and differences among mineralized regions.

The similarity of the sulfur isotopes in eastern Wisconsin to those from some of the outlying mineralization surrounding the Upper Mississippi Valley ore district (Fig. 2) suggest two possibilities: (1) the physical mechanisms and conditions responsible for the trace mineralization in both areas is similar and/or (2) some of the outlying mineralization surrounding the ore district might be related to the mineralization in eastern Wisconsin and formed earlier than the main ore district mineralization. Additional geochemical research, in addition to isotopic studies, will be necessary to resolve these problems.

SUMMARY

Sulfur isotope data on MVT sulfides and barite from eastern Wisconsin are quite similar to some of the outlying MVT mineralization surrounding the UMV ore district, but they are clearly different from those of MVT minerals within the UMV ore district. $\delta^{34}S$ data show that the sulfur in the UMV ore district minerals is significantly heavier than sulfur from eastern Wisconsin, suggesting that there were compositional differences between the two mineralizing fluids.

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STOP DESCRIPTIONS AND DISCUSSIONS

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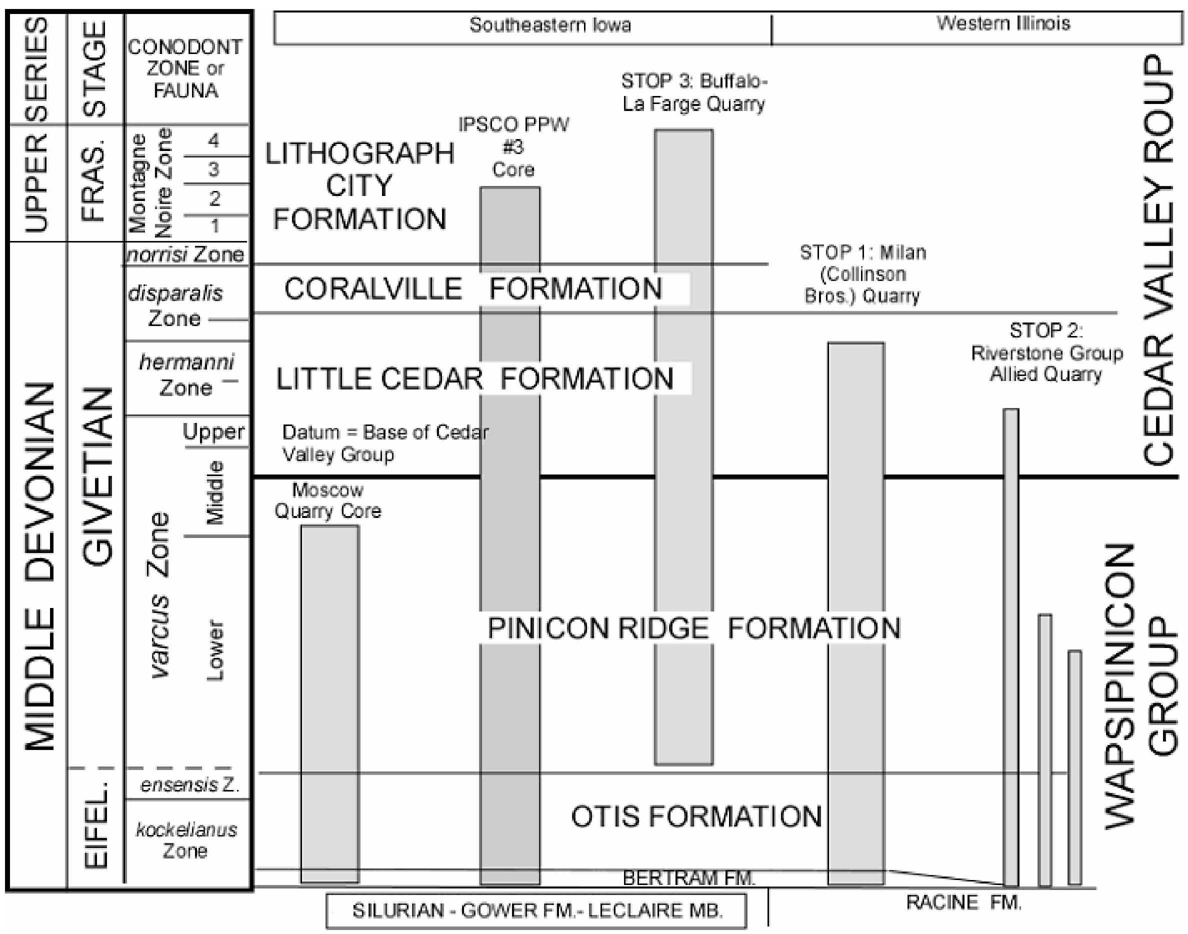

Figure 1. Chart showing Silurian and Devonian Wapsipinicon and Cedar Valley Group stratigraphic units exposed in quarries and present in cores shown in Stop Descriptions. At the Allied Quarry (Stop 2) the longest column is the generalized stratigraphic section and the two shorter columns are the 67-1 and 67-2 core sections. The IPSCO PPW # 3 and 67-1 and 67-2 cores will be on display for inspection in the Field Conference banquet hall.

STOP 1. Milan Quarry (Collinson Brothers Co.):

NW 1/4., Section 25, T. 17 N., R. 2 W, Milan,
Rock Island County, Illinois.

Silurian Geology

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The Collinson Stone Company quarry at Milan, Illinois, has long been known for its extensive exposures of Middle Devonian strata. Only since the early 1990s have underlying Silurian rocks been exposed and quarried at this site. Currently, only about 60 feet of the upper part of the Silurian are exposed near the south end of the pit. These strata are very similar, if not identical, to those exposed more extensively at the nearby Allied quarry (Stop 2).

The Silurian rocks at this quarry have been identified as being part of the "Racine Formation (Gower Formation, LeClaire Member)" by Hickerson and Anderson (1994). Their use of the name Racine follows the most recent revision of Silurian stratigraphy in northwestern Illinois by Willman (1973), however, other authors such as Witzke (1992, 1994) have questioned the use of this term. The age and correlation of this part of the Silurian throughout the region have long been controversial (Mikulic and Hickerson, 1994). The primary reasons for this controversy include: 1) the absence of fossil taxa that have accurately defined biostratigraphic ranges; 2) the limited vertical sections which seldom provide information about contacts with other rock units; and 3) the generalized lithologic characteristics that may recur at several different horizons within the Silurian.

In the Collinson quarry, the Racine contains locally abundant and diverse fossils, including corals, brachiopods, and cephalopods. Because some of the same fossils occur in the Port Byron area, Savage (1926) proposed the name Port Byron Formation for exposures of these rocks in the northern portion of Rock Island County. This name is no longer in use (Willman, 1973). These strata may be equivalent to the LeClaire Member of the Gower Formation, as described by Witzke (1994). Lithologically, they are a high-purity, crystalline, locally vuggy and porous, fossiliferous dolomite. Commonly described as reefy in nature, the exposures here show evidence of mounding and strongly dipping beds in places; however, distinct reef bodies and flank strata are not readily evident. The rocks probably represent more of a bank-like deposit rather than individual reef masses.

The Silurian-Devonian unconformity is well exposed in the Collinson quarry. The long period of emergence represented by this contact resulted in an irregular Silurian surface with well-developed karst features, including fissures and caves, which have been filled extensively with clay and other sediments of the Bertram Formation deposited at the beginning of the Middle Devonian transgression in the late Eifelian.

The Silurian section will be described in greater detail at the Allied quarry (Stop 2), where it is better exposed.

Devonian Geology

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Devonian exposures at the Milan Quarry provide an excellent opportunity to see stratigraphic relationships and basic features of cyclostratigraphy of the Middle Devonian Wapsipinicon Group in the Quad-Cities area (Fig. 2). The most complete Middle Devonian section in northwestern Illinois occurs in the Milan Quarry and in the stream-cut and abandoned quarry exposures along adjacent Mill Creek (Hickerson and Anderson, 1994). Exposures at the Milan Quarry feature complete sections of the Otis and Pinicon Ridge formations of Wapsipinicon Group overlying the Racine throughout the quarry (Figs. 2 & 3), and are readily visible in the eastern and southern highwalls of the south pit.

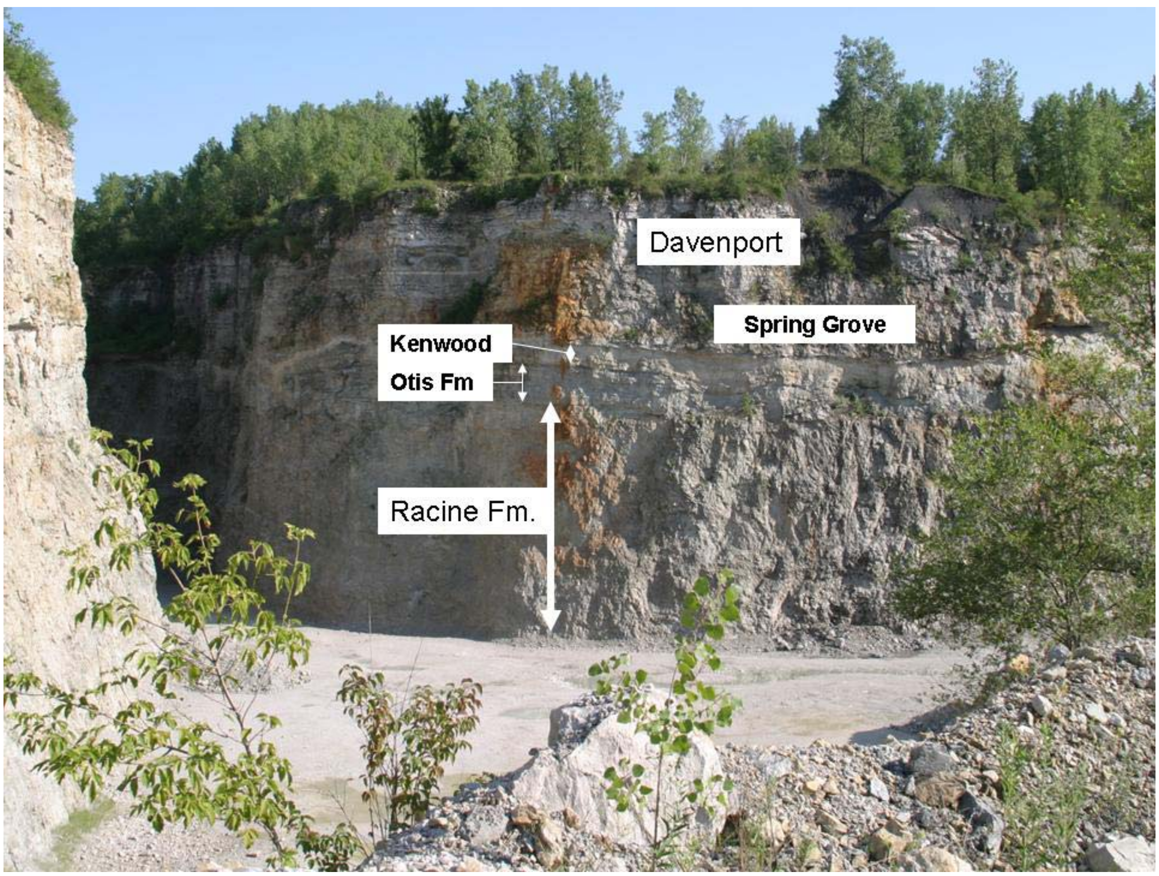

Figure 2. Photograph of the southeastern highwall southeast of the ramp road into the main active working pit showing the Silurian Racine Formation making up half of the highwall exposure, overlain by a complete section of the Wapsipinicon Group (see Devonian stratigraphy in Fig. 2). Photograph by J. Day, August 2006.

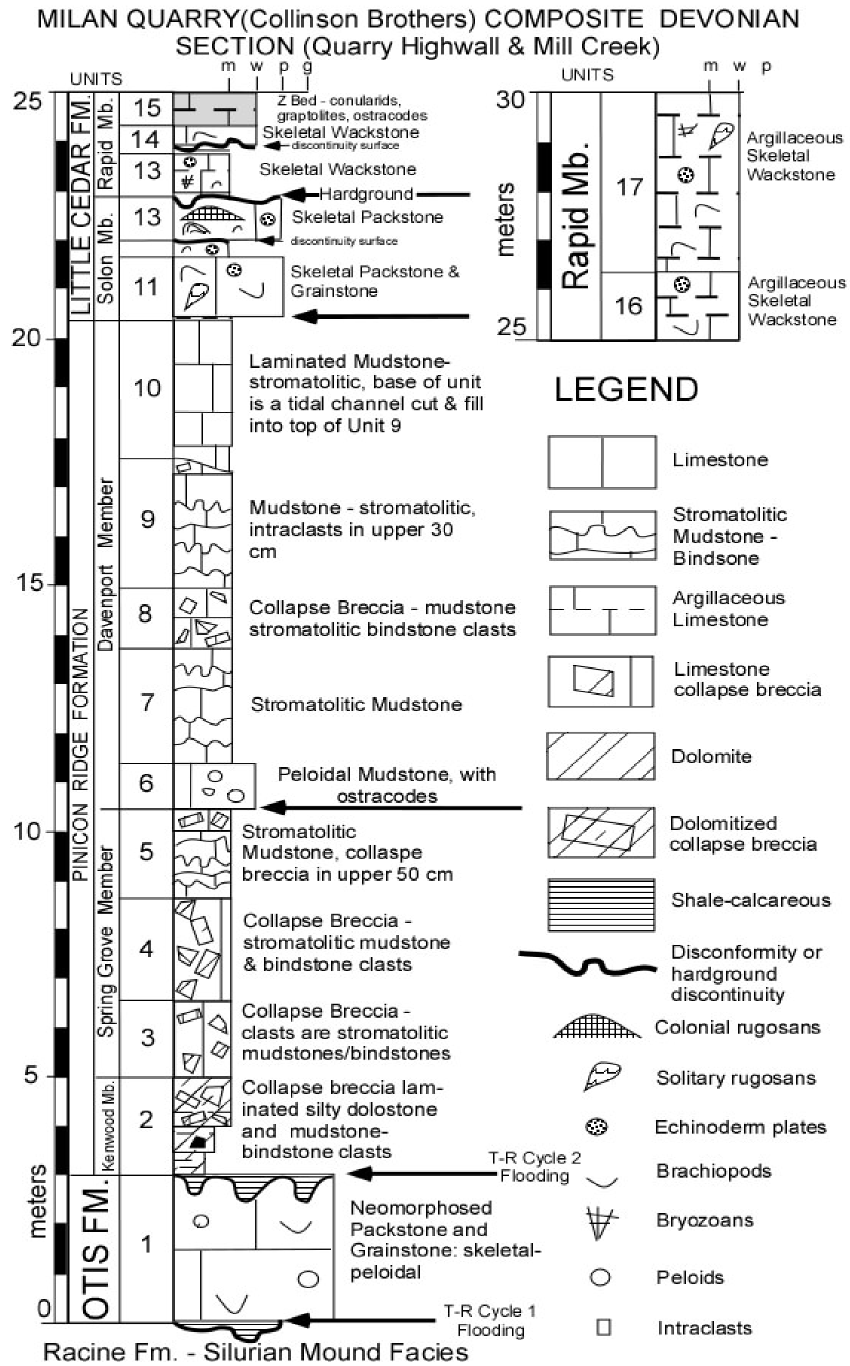

Figure 3. Generalized Devonian section exposed in the Collinson Brothers Milan Quarry and along the adjacent Mill Creek featuring a complete section of the Otis and Pinicon Ridge formations of the Wapsipinicon Group, and lower half of the Little Cedar Formation of the Cedar Valley Group. Modified from Fig. 2 of Hickerson and Anderson (1994).

The lower part of the Little Cedar (thin Solon Mb., and lower Rapid Mb.) are exposed along ramp road and upper bench on the north side of the quarry and have yielded numerous middle and upper Givetian trilobites discussed and illustrated by Hickerson (1992, 1994), and abundant and diverse brachiopods discussed by Day (1992, 1994).

The Devonian strata exposed in the quarry highwalls (Figs. 1 to 3) include the locally thin to absent Bertram Formation (not well developed here), overlain by shallow marine platform carbonates of the late Eifelian Otis Formation, the early to middle Givetian age Pinicon Ridge Formation, and capped locally (along the east and northern part of the quarry) the Little Cedar Formation. The Bertram Formation is reworked erosional residium and shallow water and arid coastal plain-sabhka deposits likely deposited during rising base level associated with the late Eifelian sea rise that initiated Otis Formation deposition during Iowa Devonian T-R cycle 1 (Day, page 1 of this guidebook; Witzke and Bunker, page 47 of this guidebook). It is locally present in topographic lows, paleochannel and karst fillings on the eroded surface of the Racine Formation. These are best seen at Stop 2.

The Otis Formation is developed entirely in limestone facies assigned here to the Coggon Member is comprised of shallow water subtidal to intertidal carbonate platform facies, between 3-4 meters in the quarry highwall exposures (Fig. 3). The Otis 3rd order T-R cycle is further divided into two small-scale 4th order cycles (Otis 4th order T-R cycles 1 and 2), and it appears that most of the upper Otis 4th order package is eroded in the vicinity of the Milan Quarry, although well preserve and exposed in the Allied Quarry and in cores section in Scott and Muscatine counties in Iowa (Fig. 1). The subtidal recrystallized pelleted-skeletal grain to packstones (Fig. 3) contain well preserved an moderately abundant ambocoeliid brachiopod Emanuella that is widespread in central and western North American carbonate platforms during the late Eifelian and early Givetian (Day and Koch, 1994).

The Pinicon Ridge Formation makes up most of the exposures in the upper half of the south highwall, and most of the east highwall (Figs. 2 and 3). The Kenwood Member oversteps the edge of the Otis Formation, and it unconformably overlies eroded Ordovician and Silurian strata across most of its extent (Iowa, northeast Missouri, northwestern Illinois). The Kenwood Member (also called the Kenwood Shale) is dominated by unfossiliferous argillaceous to shaly dolomite, in part silty to sandy, with lesser interbeds of gray to green shale, in part silty to sandy. Silt and sand grains are composed of quartz and chert. Some dolomite beds are irregularly laminated to mottled. Intraclastic and brecciated beds are common. Concretionary masses of chalcedony and chert are seen in many sections (Stop 2), and some dolomite beds are siliceous. The Kenwood Member includes gypsum and anhydrite evaporite units at localities southeastern Iowa, and economic gypsum deposits are extracted from the upper Kenwood in subsurface mines near Sperry, Iowa (see Witzke and Bunker, Sperry Mine section, Fig. 2, page 51 of this guidebook).

The Spring Grove and Davenport members of the Pinicon Ridge are well exposed here (Figs. 2 and 3) and grouped together into the early to middle Givetian Iowa Devonian T-R cycle 2 (see articles by Day, page 1 of this guidebook; Witzke and Bunker, page 47 of this guidebook)

The Spring Grove Member appears to be generally unfossiliferous, but burrows, stromatolites, and ostracodes, indeterminate medusoid forms, and placoderms have been noted (Witzke et al., 1988; Hickerson, 1994), the latter two groups noted from a single locality (Milan Quarry, Illinois). Minor breccias and intraclastic units are seen at some localities (Figs. 2, 4). Giraud (1986) observed nodular to mosaic anhydrite in the Spring Grove within evaporite-bearing Wapsipinicon successions in southeastern Iowa, and gypsum-anhydrite void fills are also noted locally.

The laterally continuous laminations and general absence of desiccation features within the Spring Grove Member at most localities was interpreted by Sammis (1978) to support deposition in a subtidal setting within a restricted basin of elevated salinity. However, Hickerson (1994) observed a prominent desiccation surface exhibiting large polygonal cracks in the upper 50 cm of the Spring Grove at the Milan Quarry, as well as a disconformity that separates upper and lower strata. He also interpreted upper Spring Grove deposition to include peritidal/supratidal environments, based on his discovery of a local desiccation surface. As such, the Spring Grove succession may represent a general shallowing-upward T-R cycle.

The Davenport Member (Figs. 2 and 3) is dominated by limestone at Stop 1, and across most of its extent, primarily characterized by dense ‘sublithographic’ limestone, laminated to stromatolitic in part, and with common stylolites. The term 'sublithographic' refers to the resemblance to limestones used in lithographic engraving, and these dense lime mudstones often break with a conchoidal fracture. The Davenport limestones are dominantly mudstones, but pelletal and intraclastic units are also commonly present. Rare oolitic packstone-grainstone beds are noted. A few limestone beds display calcite-filled fenestral and 'birdseye' fabrics and gypsum crystal molds (Stop 3). Scattered chalcedony concretions are recognized locally. Although the member is dominated by limestone, discontinuous and local dolomite and dolomitic limestone beds are recognized at a number of localities. Thin shales (in part silty to sandy) and argillaceous to shaly units are observed in many sections. The Davenport Member is dominated by evaporite facies in some areas of southeastern Iowa, where nodular, mosaic, and massive gypsum-anhydrite units are observed to interbed with limestone and dolomite strata (Giraud, 1986).

The Davenport Member is best known for its well-developed limestone breccias (Fig. 3), a characteristic feature in most sections across its geographic extent. These breccias consist of irregular unsorted angular clasts of limestone (varying in size from a few millimeters to large blocks in excess of 1 meter diameter) generally in a limestone to argillaceous limestone matrix. The Davenport breccias have been interpreted to have formed by solution-collapse processes (Sammis, 1978). This process results from the dissolution of evaporite layers causing the fracturing and internal collapse of intervening carbonate beds. Most breccia clasts consist of lithologies seen in within the Davenport Member, primarily sublithographic and laminated limestone. However, the upper breccias also contain scattered fossiliferous limestone clasts derived from overlying strata of the Solon Member.

Overlaying the Davenport Member throughout the Iowa Basin is the Little Cedar Formation of the lower Cedar Valley Group (Figs. 1-3). The Solon Member forms the basal interval of the Little Cedar Formation in southeastern Iowa and northwestern Ilinois. It is included within the larger T-R sequence 3 that includes the entire Little Cedar Formation, but the Solon also comprises its own shallowing-upward succession and it represents a recognizable T-R subcycle (T-R cycle 3A of Witzke and Bunker, 1994, 1996). The Solon disconformably overlies the Wapsipinicon Group in the region, locally displaying up to 1 m or so of vertical relief, and basal Solon strata are locally sandy. Southeastward from Johnson County, the Solon Member becomes significantly thinner, locally as thin as 2 m or less (as seen at the Buffalo Quarry, Stop 3). The lower Solon ("independensis beds") in Johnson County and Scott counties in Iowa and Rock Island County in Illinois is characterized by slightly argillaceous fossiliferous limestone (wackestone and packstone) with a diverse marine fauna (brachiopods, crinoid debris, bryozoans, etc.). A widespread submarine hardground surface occurs near the top of the Solon.

The Rapid Member comprises the remainder of the Little Cedar Formation above the Solon Member, and it is interpreted to represent the upper Little Cedar subcycle within the larger Little Cedar T-R sequence (Iowa Devonian T-R cycle 3B Witzke and Bunker, 1994). As for the Solon Member, the Rapid Member is also defined from localities in Johnson County, Iowa (Fig. 4), where it averages about 16 m thick. The Rapid Member in this area forms a succession of distinctive subtidal carbonate lithofacies discussed further in the Buffalo Quarry Stop 3 description.

STOP 2. Allied Quarry (Riverstone Group, Inc.)

SE ¼, Sec. 14, T. 17 N., R. 2 W., Rock Island,
Rock Island County, Illinois.

Middle Devonian strata here had been weathered extensively and cut by caves and channels, which subsequently were filled with Early Pennsylvanian sediments (Leary and Trask, 1985). Noted especially for its fossil "upland" flora, the biota of these channel fills has been the subject of a number of papers by Leary (see Leary, 1994). More recently, the biota has been highlighted with a diorama and specimen display in the new exhibit hall "Changes: Dynamic Illinois Environments" at the Illinois State Museum in Springfield.

Silurian Geology

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Until at least the late 1970s, only Devonian and Pennsylvanian rocks were exposed in the Allied quarry. Currently, approximately 160 feet of Silurian also are exposed. As in the Collinson Stone Company quarry, the top of the Silurian shows evidence of being eroded extensively prior to the Middle Devonian transgression. Exactly when Silurian deposition ended here and how many feet of Silurian rock may have been removed by erosion at this site since then are unknown. The potential length of time for emergence of the Silurian surface prior to Middle Devonian transgression could be as much as, or more than, 30 million years.

Throughout the Allied quarry, the eroded Silurian surface undulates broadly. Large-scale karst features, including collapse structures, caves, and sinkholes can be seen in the upper Silurian strata, whereas common, solution-enhanced joints, extend down through much of the exposed Silurian section. All of these features are filled predominantly with clay, presumably of Devonian in age. A similar relationship between Silurian and Devonian strata can be observed in many other parts of the Midwest.

The Allied quarry exhibits one of the most extensive exposures of local Silurian rocks, and, in combination with subsurface information, provides an important opportunity to establish the general character of these rocks for the region. The uppermost Silurian strata here have the same characteristics as seen at the Collinson Stone Company quarry. These rocks are characterized by high-purity, crystalline, locally vuggy or porous, brownish- to yellowish-grey dolomite. The rock is massive to thick- and irregular-bedded. It displays local "reef" mounding and dipping "flank" beds. On a broad scale, however, as at the Collinson quarry, individual reef bodies generally are difficult to define and commonly lack the extensive surrounding flank deposits as are seen in association with reefs in other areas of the Midwest. Silurian non-reef strata here are also very similar in appearance to reef lithologies, making it difficult to separate the two primary environments throughout the quarry. Lowenstam (1949, 1950) noted that exposures of these rocks near Cordova, to the north of Rock Island, show "there is little lithologic contrast between reefs and their surrounding inter-reef deposits," which resulted from "the prevalence of rough-water conditions which scattered the reef detritus widely over the inter-reef tract." He used the Cordova exposures as a "type section" for his Coe Group, a term he applied to this widespread facies, which he defined as a reef-bearing clastic-free belt. The Allied quarry now offers exposures that are more extensive vertically, providing additional insight into the nature of these "reefs." For example, it is now clear that they extend through a much thicker section than what is seen at Cordova.

Exposed Silurian strata at the Allied quarry are part of the Racine Dolomite, as defined by Willman (1973). Hickerson and Anderson (1994) identified these strata as belonging to the mounded facies of the LeClaire Member of the Gower (Racine) Formation. Most of these strata are equivalent to the Welton Member of the Scotch Grove Formation in Iowa, as defined by Witzke (1992, 1994); the uppermost strata may be equivalent to parts of the overlying Gower Formation of Iowa.

Subsurface data at this site indicate that approximately 140 feet of Silurian strata underlie the present quarry floor, for a total Silurian thickness of about 300 feet. This is similar to what is known at other locations in and around Rock Island County. Of the subsurface section, approximately 50 feet belong to the Racine Dolomite, which has characteristics similar to that exposed in the quarry walls. The basal 30 feet of the Racine comprises a conspicuous zone of white and gray mottled, fine to coarse crystalline dolomite characterized by abundant biomoldic porosity, which is dominated by pelmatozoans and commonly displays a grainstone texture. This part of the Racine may be correlative with the Romeo Member of the Joliet Dolomite in northeastern Illinois and the St. Clair Limestone to the south.

Below the Racine are as much as 20 feet of well-bedded, dense, non-porous, even-textured, very finely crystalline dolomite, which have not been named formally in northwestern Illinois. The lower approximately one-third of these strata exhibits a pale pink or green coloration in places and may be laminated, whereas the upper part is gray and may contain chert locally. R. D. Norby (2006, personal communication) has recovered the conodont *Pterospathodus amorphognathoides* from this interval at other nearby localities, suggesting a late Llandovery age for the lower portion of this interval. Typical Wenlock macrofossils characterize the lower part of the Racine here, indicating that the Llandovery/Wenlock boundary is located within the upper portion of this unnamed interval. Lithologically, these upper strata resemble the Markgraf Member of the Joliet Dolomite and the lower strata are nearly identical to the Brandon Bridge Member of that unit in northeastern Illinois. This unit may be, in part, equivalent to the Johns Creek Quarry Member of the Scotch Grove Formation in eastern Iowa.

Lying below this are approximately six feet of the Marcus Formation, which is predominantly light brownish-gray, dense, massive, very finely crystalline dolomite that contains layers of common to abundant pentamerid brachiopods. The upper foot or so of the Marcus is more coarsely crystalline and porous and may be characterized by *Thalassinoides* burrows. The contact between the Marcus and overlying strata closely resembles that between the Plaines Member of the Kankakee Dolomite and Brandon Bridge, with is a sequence boundary, in northeastern Illinois (Kluessendorf and Mikulic, 1994).

Approximately 40 feet of light brown to light yellowish-gray, fine to medium crystalline dolomite belonging to the Sweeney Formation underlie the Marcus. These strata contain common argillaceous partings and biomoldic porosity with a wackstone to grainstone texture. They are typified by common chertified ?stromatoporoids and corals, primarily *Favosites, Halysites* and *Syringopora*.

The Sweeney is underlain by about 22 feet of the Blanding Formation, which consists of light gray, dense, very finely crystalline dolomite containing common to abundant white chert nodules. A possible bentonite is present near the top of the Blanding throughout the Rock Island area. The Blanding, Sweeney and Marcus are equivalent to the Offerman, Troutman and Plaines Members of the Kankakee Dolomite of northeastern Illinois. In both areas, this package of rocks is bracketed by sequence boundaries. At the Allied quarry, the Blanding succeeds the Ordovician strata unconformably; the Mosalem and Tete des Morts are absent.

Devonian Geology

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Exposures of Devonian carbonate platform rocks at the Allied Quarry feature primarily the Bertram, Otis, and Pinicon Ridge formations of the Wapsipinicon Group (Figs. 1, 4, 5, 6, 7, 8), although locally along the upper parts the north and south quarry highwalls thin remnants of the basal Little Cedar Formation of the Cedar Valley Group are still present (see Hickerson and Anderson, 1994, stop 1). Riverstone Group quarry operators have stripped off virtually all of the Little Cedar as overburden to expose units of the Wapsipincon Group and older Silurian Racine preferred for aggregate production.

We will focus attention here on the stratigraphic relationships and stratigraphy of the lower Wapsipinicon Group because of extensive highwall exposures and easy access to the lower Wapsipinicon facies along the west quarry ramp road into the main active pit. We will have opportunities to see additional exposures of the upper Pinicon Ridge and superb exposures of the entire Cedar Valley Group at Stop 3 this afternoon.

The Devonian strata exposed in the long north and south quarry highwalls (Figs. 1 to 3) include the locally developed thin lenses and moderately thick (up to two meters in thickness) channel filling Bertram Formation (not well developed here), beneath its contact with the overlying late Eifelian Otis Formation (Figs. 4 and 5). The Pinicon Ridge Formation makes up the upper part of most the highwalls.

The Bertram Formation in the Quad Cities area ranges (Fig. 6) in thickness (where present) from a few cm to up to two meters in local channel fillings on the Silurian erosional surface and is much thicker in Johnson, Linn and Benton counties. It is characterized by unfossiliferous dolomite, part vuggy, brecciated, or argillaceous, and silty to sandy shale. The Bertram interval of Johnson and Muscatine counties appears to be gradational with the overlying Otis Formation. It was elevated to formational status by Bunker and others (1985), but could be considered as the basal member of an expanded Otis Formation, as both share lithologic similarities (carbonate dominated) and both may belong within the same depositional sequence comprising the transgressive system tract (TST) of a Bertram-Otis T-R cycle (Iowa Devonian T-R cycle 1; Day, this guidebook; Witzke and Bunker, page 47 of this guidebook).

The Otis Formation is developed entirely in limestone facies assigned here to the Coggon Member. The Otis is relatively thick in exposures at the Allied Quarry ranging from 5.5 to nearly 7 m in thickness, versus those seen earlier at Stop 1. Exposures along the west ramp road just above the maintenance shop is comprised of shallow water subtidal to intertidal carbonate platform facies are up to 7 m thick, although significant and abrupt lateral changes in thickness are the result of erosional stripping and karstification during the lowstand that terminated Iowa Devonian T-R cycle 1 deposition (Figs. 4 to 7).

The Otis 3rd order T-R cycle is further divided into two small-scale 4th order cycles (Otis 4th order T-R cycles 1 and 2) as seen in the ramp road-cut section on the west side of the quarry (Figs. 4, 6 and 8). The lower Otis 4th Order T-R cycle 1 ranges thickness from 2.1 to nearly three m thickness in the Allied Quarry, and makes up the lower nine meters of the Otis in the Moscow Quarry core in Muscatine County in Iowa (Figs. 5 and 6). Otis subcycles preserved in their original limestone facies

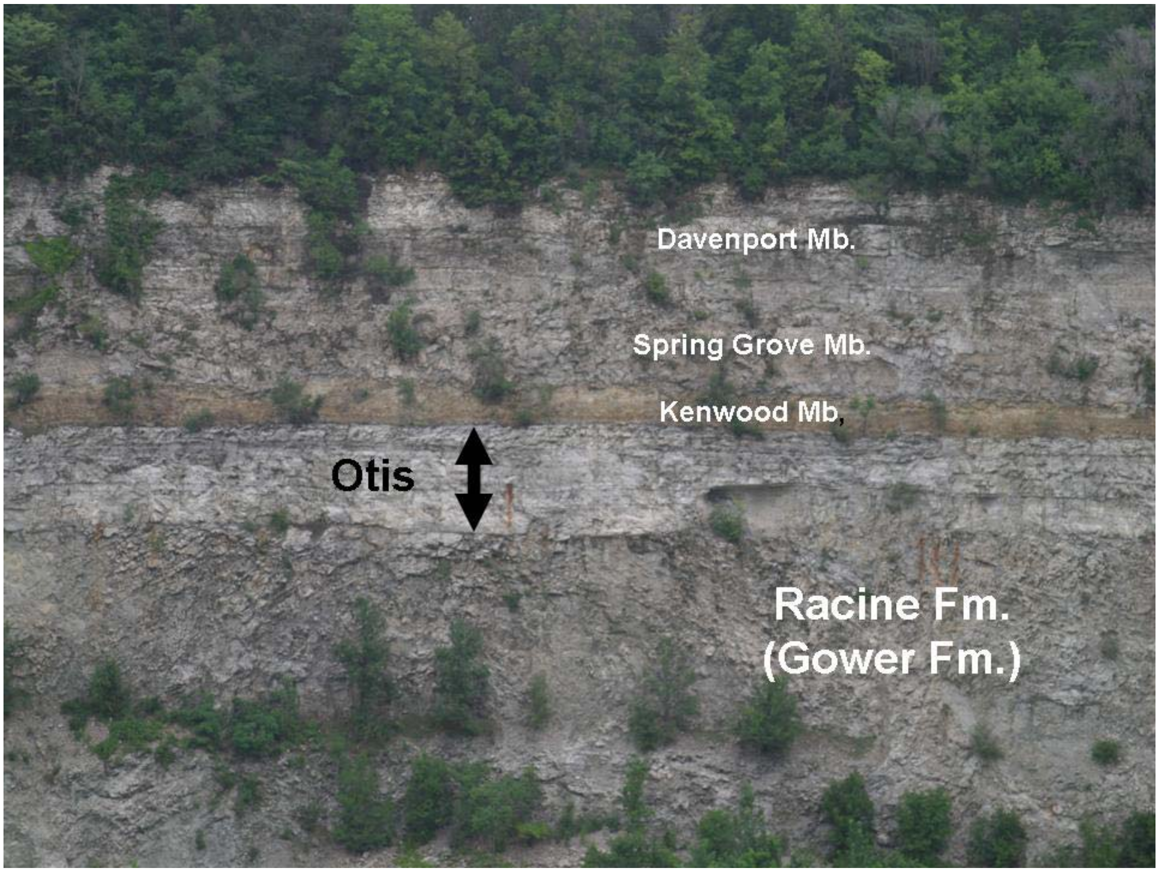

Figure 4. Photograph of the Devonian section exposed on the north highwall showing the Silurian and Devonian units that are currently being quarried (mainly Silurian Racine Fm.) or historically (Devonian Wapsipinicon Group) for aggregate at the Allied Quarry.

consist of shallowing-up packages floored by shallow subtidal pelletal-skeletal packstones or grainstones, wackstones (locally with intraclastic and oncolitic wackstone and packstones) capped by peritidal pelletal fenestral (birds-eye) mudstones and wackstones (Fig. 5). Some of the capping facies include stromatolitic bindstones (top Otis cycle 1 in the Moscow Quarry Core, Fig. 6), or thromboidal bind to framestones (see top of Otis subcycle 2 in the IPSCO PPW # 3 core, Fig. 6).

A relatively brief period of platform emergence during a latest Eifelian to earliest Givetian sea level lowstand resulted in emergence of the Otis carbonate platform package during which and erosional topography (Fig. 7) and karst solutional cavity network and dolines formed, and subsequently were infilled by sandy dolomitic shales and other lithologies typical of the Kenwood Member of the Pinicon Ridge during the initial phase of deposition of Iowa Devonian T-R cycle 2A (Figs. 5, 6, and 7). The Kenwood Member facies exposed in the Allied Quarry are typical of the member and are dominated by unfossiliferous argillaceous to shaly dolomite, in part silty to sandy, with lesser interbeds of gray to green shale, in part silty to sandy. Silt and sand grains are composed of quartz and chert. Some dolomite beds are irregularly laminated to mottled. Intraclastic and brecciated beds are common at the Allied Quarry (Fig. 6C). Concretionary masses of chalcedony and chert are seen in many sections including exposures along the ramp road-cut section at Allied (Fig. 6C).

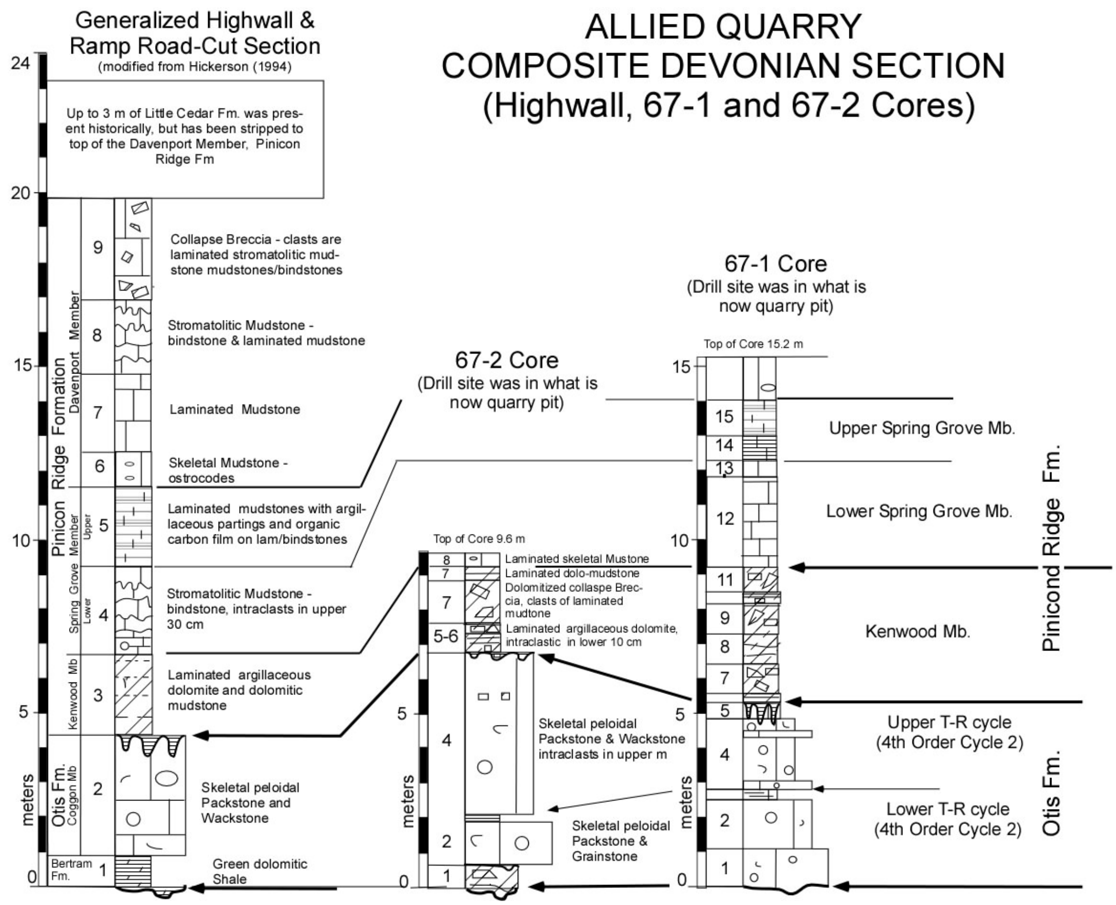

Figure 5. Generalized stratigraphy of the Middle Devonian (late Eifelian and early-middle Givetian) Wapsipinicon Group in the Allied Quarry compiled from Hickerson (1994) and recent descriptions of Riverstone Group, Inc., cores 67-1 and 67-2 cores on loan to J. Day. Splits of these cores will be available for inspection in the conference banquet hall. .

The Spring Grove Member of the Pinicon Ridge is accessible along the upper part of the west quarry ramp road-cut section (Fig. 6C) and consists of thinly laminated dolomitic mudstones and stromatolitic bindstone, brecciated where involved in collapse of the underlying Kenwood that originally contained evaporites. The Spring Grove and Davenport members will examined further at our next stop this afternoon in the Buffalo Quarry in Scott County, Iowa.

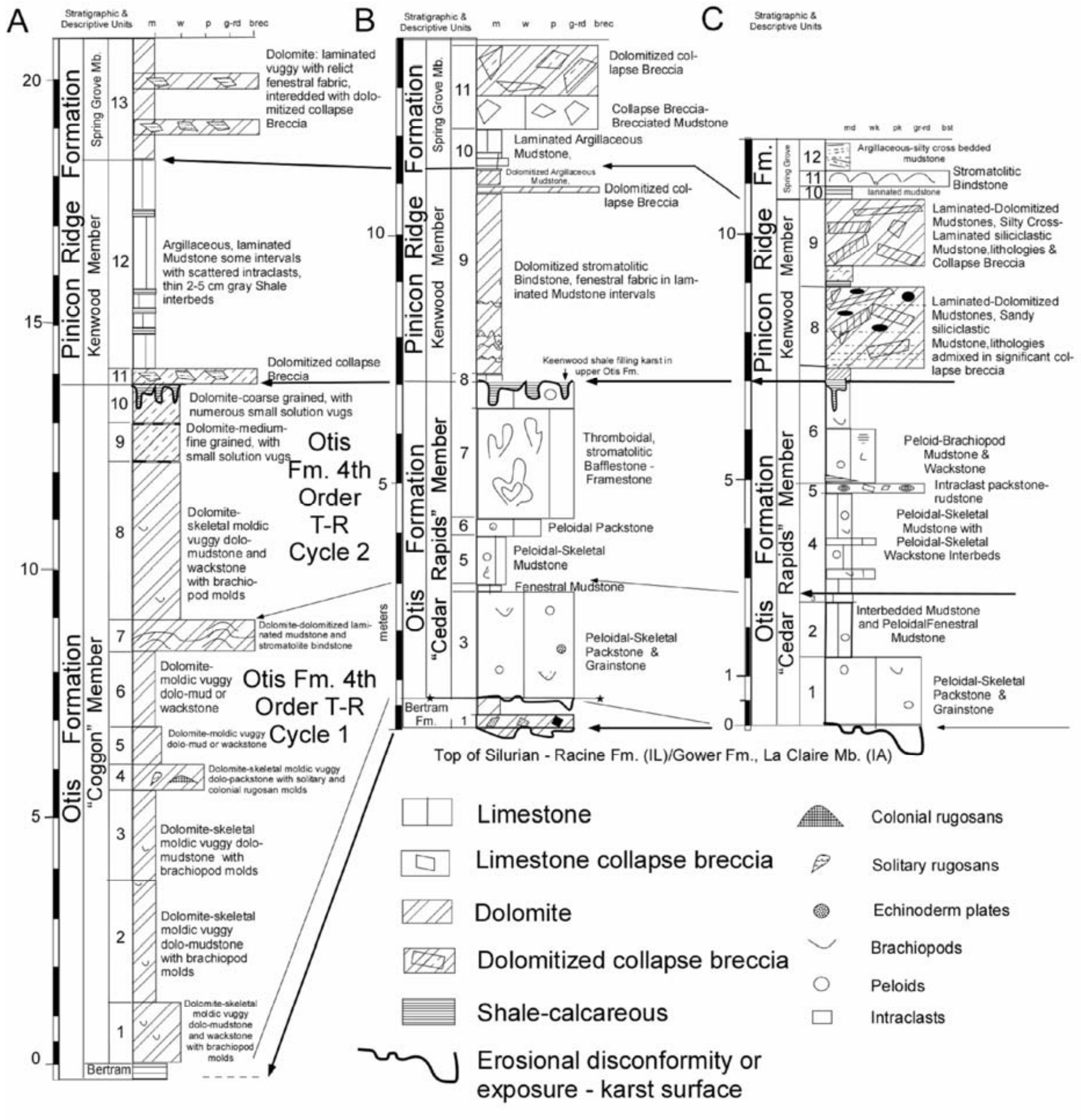

Figure 6. Stratigraphy and cyclostratigraphy of the lower Wapsipinicon Group in well cores samples from Muscatine County Iowa, and the upper ramp road section the Allied Quarry in Rock Island County, Illinois. **A.** Section of the Otis and lower Wapsipinicon formations in the Moscow Quarry core, Muscatine Co, IA. **B.** Section of the Otis and lower Wapsipinicon formations in the IPSCO PPW#3 core, Muscatine Co, IA. **C.** Section of the Otis and lower Wapsipinicon formations measured along the upper ramp road-cut on the west side of Allied Quarry in Rock Island Co., IL. Black highlighted arrows are major flooding events associated with sea level rises of Iowa Basin Devonian T-R cycles 1 and 2 of Fig. 2, with a newly recognized flooding event within the Otis, defining two 4th order T-R cycles. After Fig. 3 of Day (p. 4 of this guidebook).

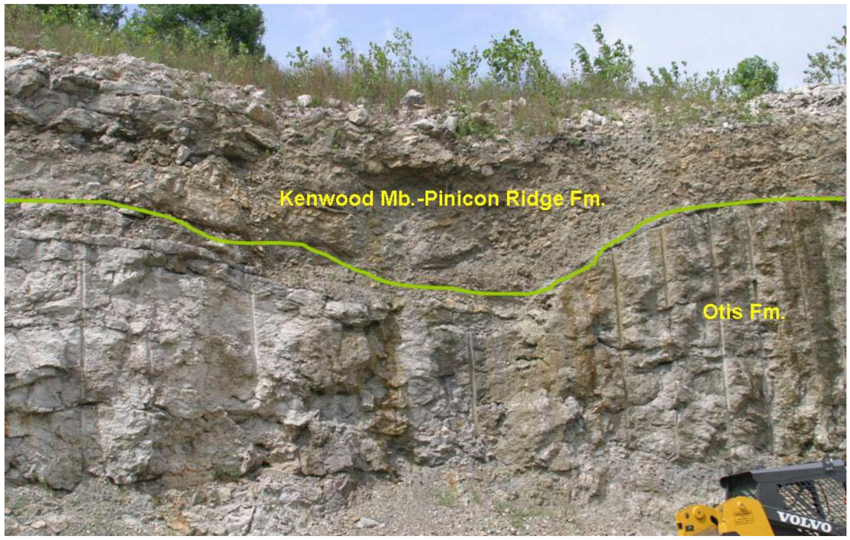

Figure 7. Photograph of the exposure of the Otis and lower Pinicon Ridge (Kenwood and lower Spring Grove mbrs.) in the highwall immediately north of the quarry maintenance garage.

STOP 3. Buffalo Quarry (LaFarge Corporation)

SW1/4, Sec. 13, T. 77 N., R. 2 E., Buffalo,
Scott County, Iowa

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The classic exposures of the Wapsipinicon and Cedar Valley Group in the LaFarge Corporation's Buffalo Quarry have been the focus on major stratigraphic, paleontologic-biostratigraphic studies since the 1850s, and comprise the principle surface reference section for the Cedar Valley Group in the Quad Cities area (Figs 1 and 8).

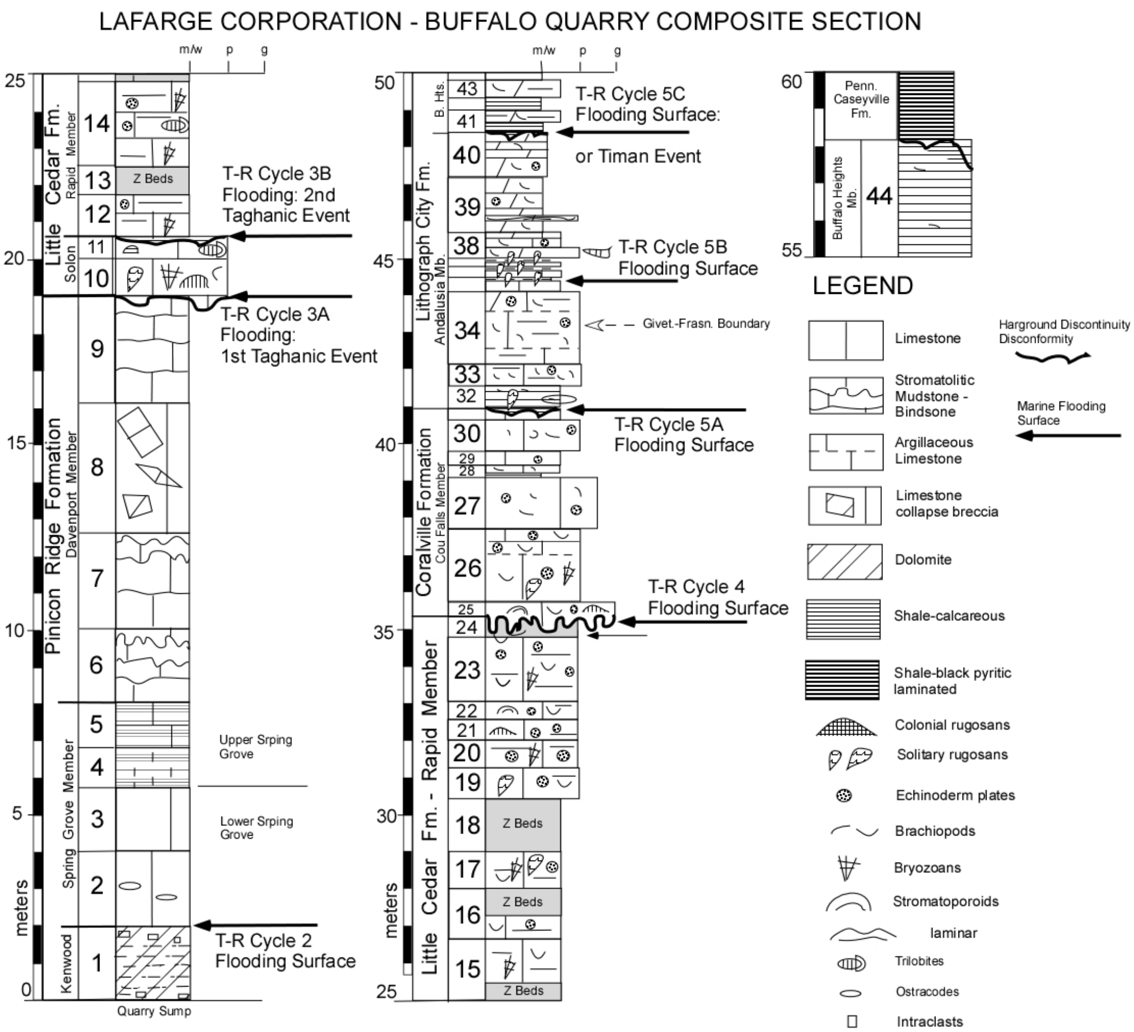

Figure 8. Generalized stratigraphic section of the Devonian Wapsipinicon and Cedar Valley Group strata exposed in the LaFarge Corporation Buffalo Quarry at Buffalo, Scott County, Iowa. Modified from Figures 3, 4, and 5 of Witzke and others. (1985), Figure 10 of Day (1992), Figure 4 of Hickerson and Anderson (1994), and Figure 5 of Day (1997).

Upper Wapsipinicon Group. The Spring Grove and Davenport members of the Pinicon Ridge Formation are exposed throughout the Buffalo Quarry at working bench levels 3 (Spring Grove and lower Davenport), and 2 (upper Davenport, and Solon Mb.-Little Cedar Fm.). The Kenwood Member is locally exposed in the quarry sump pit, although it is not seen in highwalls of the working bench levels (Fig. 8). As mentioned above, the Spring Grove and Davenport are considered collectively to a large-scale T-R depositional sequence.

The Spring Grove Member of the Pinicon Ridge is approximately 6 meters thick in the Buffalo Quarry (Fig. 8, units 2-5) and elsewhere in the Quad Cities area (Allied and Milan quarries), is divided into informal "Lower" and "Upper" intervals. The "Lower" Spring Grove (Fig. 8, units 2 and 3) is characterized by dense faintly laminated carbonate mudstones, stromatilitic and locally brecciated in the lower part (see IPSCO PPW core, Fig. 6B). The "Upper" Spring Grove is commonly comprised of thinly laminated bituminous dolomites or dolomitic mudstones. Hickerson's (1994) spectacular discoveries of ptycodontid placoderm skeletons (bitumen impregnated) in the upper Spring Grove and a possible arthrodire placoderm cranium in the lower Spring Grove at the Milan Quarry (Fig. 3) are particularly enlightening. Although the Spring Grove Member is largely devoid of macrofauna, these discoveries indicate that some fish taxa may have tolerated shallow restricted environments of Spring Grove deposition, at least at times.

The Davenport Member is the thickest unit of the Pinicon Ridge Formation throughout the Quad Cities area (Figs. 3, 5, and 8). The lower half of the Davenport (Fig. 8, units 6 and 7) are laminated mudstones with intervals of low amplitude to domal stromatolites, and occasional intraclast floatstone and rudstone beds. The upper Davenport differs significantly in that it consists of collapse breccias (Fig. 8, unit 8) The breccias contain carbonate mudstone rubble clasts (1mm to up to a meter), locally with shaly matrix, or calcite spar cements. These may grade laterally into fractured but bedded units of laminated mudstones (Fig. 8, unit 9).

Cedar Valley Group. The Cedar Valley Group of southeastern Iowa consists of five major disconformity bounded packages of subtidal middle shelf facies representing five major 3rd order Iowa Devonian T-R cycles signaling a major change of from restricted, to open marine conditions in this part of the Iowa Basin. The Little Cedar Formation provides a regional record of major middle and upper Givetian global sea level rises that continued for the duration of the Frasnian Age of the Late Devonian.

Little Cedar Fm. The Little Cedar Formation includes the basal Solon (Fig. 8, units 10 and 11), and much thicker Rapid (Fig. 8, units 12-24) members containing an incredibly diverse and locally abundant marine invertebrate fauna dominated by brachiopods, echinoderms, and byrozoans (see discussion of fauns in Witzke et al., 1985; Day, 1992, 1994, 1997). The Solon disconformably overlies the Davenport in the region, locally displaying up to 1 m or so of vertical relief, and basal Solon strata are locally sandy. The lower Solon is characterized by slightly argillaceous fossiliferous limestone (wackestone and packstone) with a diverse marine fauna (brachiopods, crinoid debris, bryozoans, etc.). A widespread submarine hardground surface occurs near the top of the lower Solon interval (contact of units 10 and 11, Fig. 8). The upper Solon is dominated by fine skeletal packstone with scattered corals and stromatoporoids, and forms significant localized biostromes in the subsurface of southeastern Iowa (see Fig. 6 in Witzke and Bunker, page 32 of this guidebook) reflecting shallowing conditions during Iowa Devonian T-R cycle 3A.

The Rapid Member in the region is dominated by argillaceous skeletal mudstones and wackstones with scattered skeletal material and locally with major skeletal lag beds, and some intervals of concentrated skeletal packstones, especially in the upper part of the member (Fig. 8, units 19-23). In section at the Buffalo Quarry the Rapid ranges between 14-15 meters in thickness (Fig. 8). The base of the Rapid coincides to a major marine flooding surface marking a major expansion of the epeiric seaway locally and across North America, marking the onset of Iowa Devonian T-R cycle 3B in the upper part of Devonian eustatic T-R cycle IIa-2 of Day and others (1996). The contact of the Rapid Member and overlying Coralville Formation is a prominent burrowed discontinuity surface in surface quarry sections (Figs. 8, 9, and 10), and core sections of southeastern Iowa.

Coralville Fm.—The Coralville Formation in the Quad Cities area is developed entirely in subtidal ramp facies of the Cou Falls Member (Figs. 8 and 9), and record resumed marine transgression in the Iowa Basin associated with Iowa T-R cycle 4, and Devonian T-R cycle IIa-2 (Fig. 9) of Day and others (1996). The lower Cou Falls consists of basal skeletal grainstone and packstones with stomatoporoid-rich "biostromal" intervals (Fig. 8, unit 25), with sandy skeletal packstone filling burrows penetrating up to 30 into the top of the underlying Rapid Member of the Little Cedar at its basal contact (Fig. 10). The overlying argillaceous and dolomitic skeletal wackstones and packstones of the remainder of the Cou Falls record subtidal highstand middle ramp deposition until Coralville deposition was terminated by rapid deepening associated with the initial Lithograph City Formation transgression in the very late Givetian.

Lithograph City Fm.—The Lithograph City Formation in southeastern Iowa consists of the Andalusia and overlying Buffalo Heights members. Both members have their type sections at the Buffalo Quarry, although the Andalusia Member is named for a small town immediately across the Mississippi River in Illinois. Three major marine deepening events controlled the development of the subtidal ramp succession of the Lithograph City. As with all Cedar Valley Group T-R cycles, Lithograph City sequence packages are bounded by hardground discontinuity surfaces formed by prolonged sediment starvation, marine cementation, and bioerosion of the cemented hardground surfaces during marine flooding events (see Fig. 11).

The major sea level rise at or near the base of the very late Givetian *norrisi* Zone imitated Lithograph City Formation deposition throughout the Iowa Basin, recorded by Iowa Basin T-R cycle 5A (Fig. 8; Fig. 9, T-R cycle IIb-1 flooding surface). The Lower Andalusia Member facies consist of extremely fossiliferous calcareous shales immediately overlying the flooding surface on the uppermost Coralville (Fig. 8, unit 32) followed by argillaceous skeletal wackstones and packstones with abundant brachiopods and scattered solitary rugosan corals and echinoderm plates recording aggrading ramp sedimentation during the sea level highstand of T-R cycle 5A. Renewed deepening is signaled by flooding and sediment starvation (hardground development) followed by deposition of interbedded coralline-rich (*Tabulophyllum callawayense*) skeletal packstone-wackstones and dark gray to black planar to low angle cross-laminated platy skeletal-siltite shales (Fig. 8, units 35-37; Fig. 9, T-R cycle IIb-2 flooding surface). Units 38 to 40 (Fig. 8) accumulated in an outer ramp setting during the Iowa Devonian T-R cycle 5B highstand.

The onset of Buffalo Heights Member deposition marks the final episode of Cedar Valley Group sedimentation in eastern Iowa, and a marked shift from carbonate-dominated to mixed clastic-carbonate ramp deposition during an major marine sea level rise (Fig. 8, Iowa Devonian T-R cycle 5C; Fig. 9, eustatic T-R cycle IIb-3) that began within the early Frasnian Montagne Nore Zone 4 of Klapper (1989). The interbedded argillaceous dolomitic carbonate mudstones, and pyritic calcareous shales with pyritized-moldic shelly fossils in units 41 to 44 record outer muddy ramp sedimentation in the outer ramp through the remainder of the early Frasnian in southeastern Iowa.

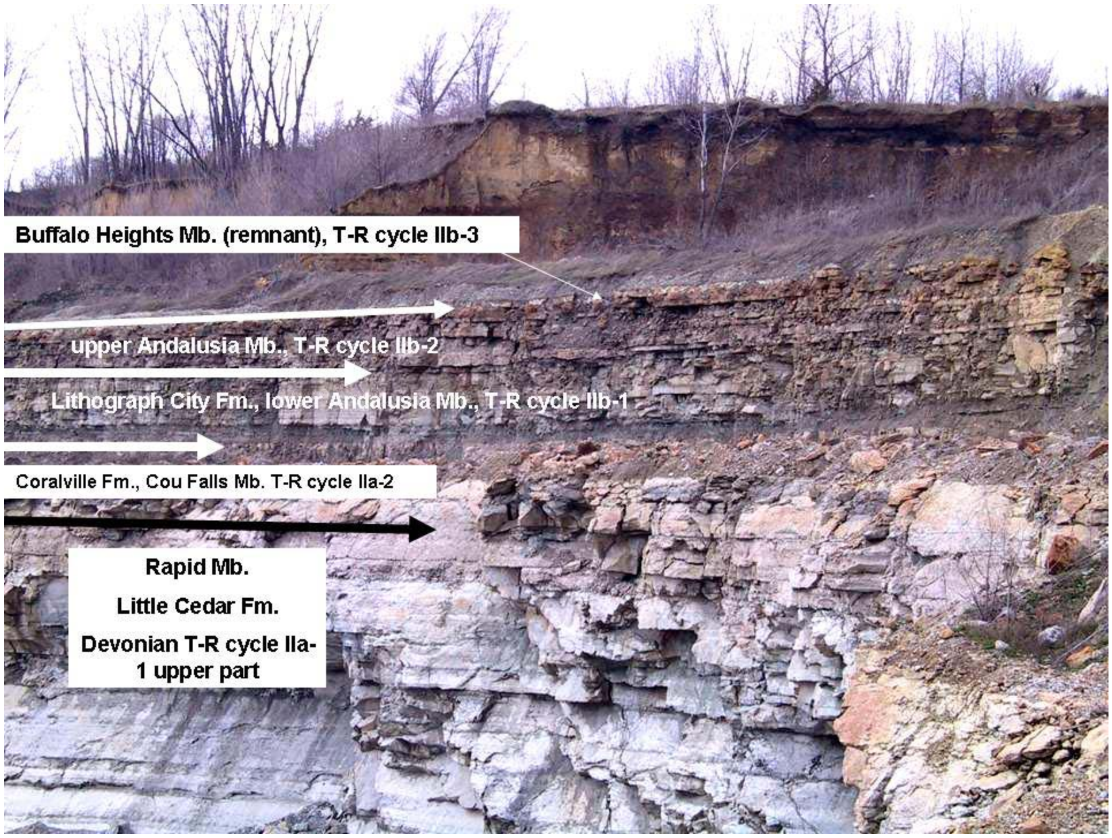

Figure 9. Photograph of the upper Cedar Valley Group showing positions of 3rd Order marine flooding surfaces (discontinuities) constituting boundaries defining Devonian T-R cycles IIa-1 to IIb-3 along the north highwall of the Buffalo Quarry (Fig. 8, units 16 to 41). These are in ascending order: T-R cycle IIa-1 (upper Rapid Mb., Little Cedar Fm.), T-R cycle IIa-2 (Cou Falls Mb., Coralville Fm.), T-R cycle IIb-1 (lower Andalusia Mb., Lithograph City Fm.), T-R cycle IIb-2 (upper Andalusia Mb., Lithograph City), T-R cycle IIb-3 (Buffalo Heights Mb., Lithograph City Fm.). See further discussion of Iowa Devonian and Devonian eustatic T-R cycles in articles by Witzke and Bunker (p. 23 of this guidebook) and Day (p. 1 of this guidebook).

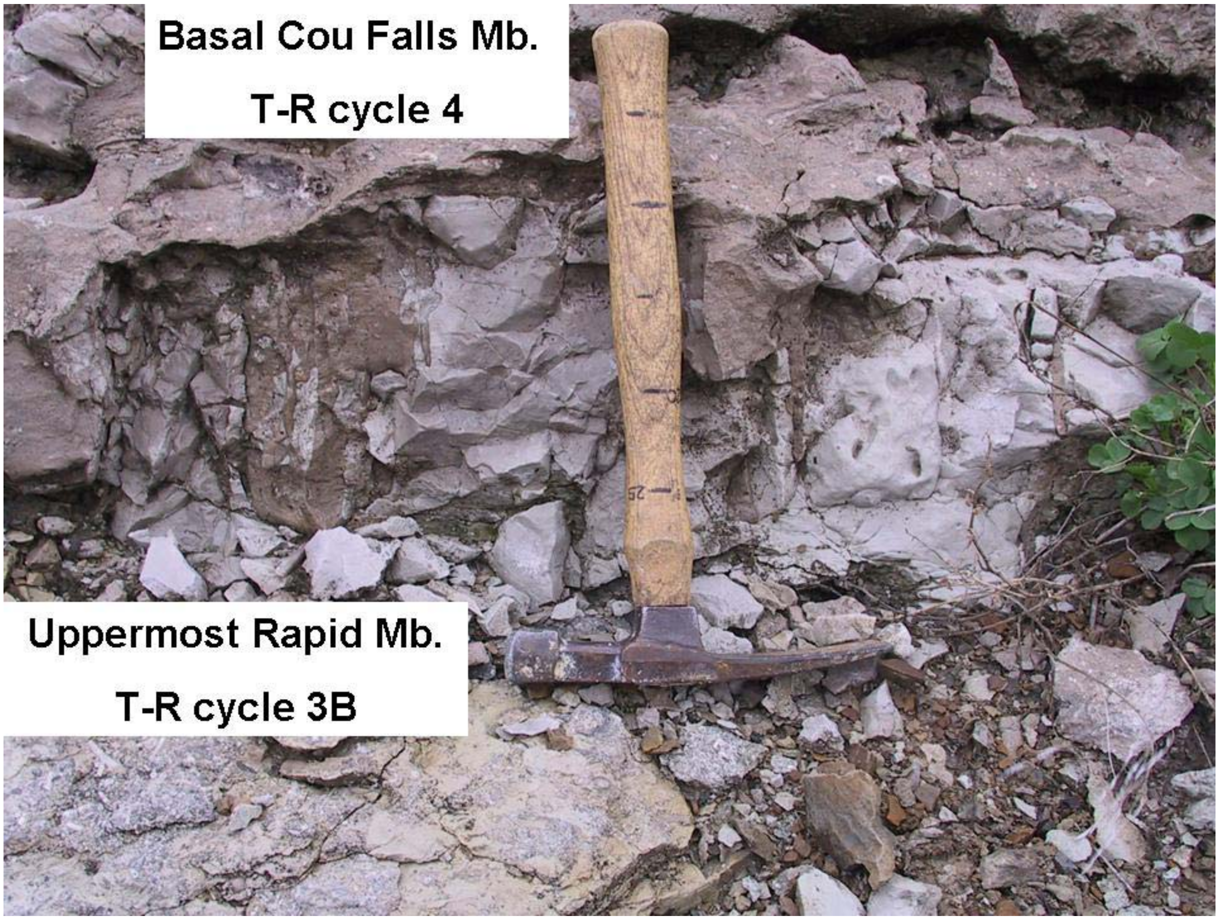

Figure 10. Photograph of burrowed discontinuity at the contact of the Rapid Member of the Little Cedar and Cou Falls Member of the Coralville formations along the ramp road exposure on the north highwall of Buffalo Quarry. Distance between lines on the hammer handle is 5 cm.

Figure 11. Photograph of burrowed phosphatic-pyritic, encrusted, and bored (bioeroded) hardground discontinuity (sequence boundary) on the upper surface of a float block from unit 31 (Fig. 8) of the uppermost Cou Falls Member of the Coralville. Block collected along the ramp road exposure on the north highwall of Buffalo Quarry.

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Location of field stops in the Quad Cities area of southeastern Iowa and northwestern Illinois for the 36th Annual Field Conference of the Great Lakes Section, Society for Sedimentary Geology (SEPM), and the 67th Annual Tri-State Field Conference, September 30, 2006.