Research Paper

GEOSPHERE

GEOSPHERE, v. 15, no. 3

https://doi.org/10.1130/GES01685.1

19 figures; 1 supplemental file

CORRESPONDENCE: erika.danielsen@dnr.state.oh.us

CITATION: Danielsen, E.M., Cramer, B.D., and Kleffner, M.A., 2019, Identification of a global sequence boundary within the upper Homerian (Silurian) Mulde Event: High-resolution chronostratigraphic correlation of the midcontinent United States with Sweden and the United Kingdom: Geosphere, v. 15, no. 3, p. 839–855, https://doi.org/10.1130/GES01685.1.

Science Editor: Shanaka de Silva
Associate Editor: Rhawn Dennison

Received 24 February 2018
Revision received 18 November 2018
Accepted 1 February 2019

Published online 29 March 2019

Identification of a global sequence boundary within the upper Homerian (Silurian) Mulde Event: High-resolution chronostratigraphic correlation of the midcontinent United States with Sweden and the United Kingdom

Erika M. Danielsen[1,*], Bradley D. Cramer[1], and Mark A. Kleffner[2]

[1]Department of Earth and Environmental Sciences, University of Iowa, Iowa City, Iowa 52242, USA
[2]School of Earth Sciences, The Ohio State University at Lima, Lima, Ohio 45804, USA

ABSTRACT

The upper Homerian Mulde Event was an extinction event that devastated graptolite diversity and occurred before and during the onset of a major perturbation to the global carbon cycle, which is recorded as a double-peaked positive carbon isotope excursion (CIE). Whereas the Mulde Extinction and associated CIE are well documented globally, changes in global sea level associated with the Mulde Event have only been investigated in detail in the West Midlands, England, and Gotland, Sweden. A critical step toward understanding both the drivers and results of global climatic change during the Mulde Event is to constrain changes in eustasy. This study integrates carbon isotope chemostratigraphy and conodont biostratigraphy of Homerian strata in Tennessee, Indiana, and Ohio in an effort to determine if a global sequence boundary is recorded within the ascending limb of the Mulde CIE and to produce a high-resolution chronostratigraphic framework for Homerian strata in the midcontinent United States. Six sections, two from each state, were measured and described. Five were sampled for carbon isotope chemostratigraphy, and one was sampled for conodont biostratigraphy. All sections from Tennessee and Indiana evidently contain the Mulde CIE, whereas the sections from Ohio are less clear due to the truncation of upper Homerian strata. These data demonstrate that a sequence boundary identified herein in Indiana and Tennessee is the same sequence boundary that formed during the ascending limb of the Mulde Excursion in the West Midlands and Gotland.

INTRODUCTION

The Silurian System was one of the most dynamic in the Paleozoic, containing several global biogeochemical perturbations (Munnecke et al., 2010; Cramer et al., 2011). Many of these biotic and climatic perturbations are recorded in the marine rock record as extinction events and associated carbon isotope ($\delta^{13}C_{carb}$) excursions (Calner, 2008; Munnecke et al., 2010). Silurian studies over the past few decades have targeted these stratigraphic intervals in an attempt to understand the environmental changes that occurred as both causes and effects of these biogeochemical perturbations (e.g., Jeppsson et al., 1995; Cramer and Saltzman, 2005; Vandenbroucke et al., 2015). However, the lack of data and agreement concerning basic environmental parameters during the Silurian, such as sea level, seawater chemistry, atmospheric conditions, and tectonics, limits our understanding of the relationship between Earth processes and the development of life (Calner, 2008; Munnecke et al., 2010). A critical step toward understanding connections of the Earth-life system is to constrain the eustatic changes associated with these biogeochemical events (Munnecke et al., 2010).

The upper Homerian Mulde Event was an extinction among pelagic invertebrates and the largest among graptolites with up to 95% of species going extinct (Jeppsson and Calner, 2003; Porębska et al., 2004; Lenz et al., 2006; Cooper et al., 2014; Crampton et al., 2016). The Mulde Event is associated with a double-peaked, positive carbon isotope excursion (the Mulde CIE or Mulde Excursion; Cramer et al., 2012), and both are well documented in several major Silurian basins (Corfield et al., 1992; Kaljo et al., 1997; Calner et al., 2006; Cramer et al., 2006; Lenz et al., 2006; Sullivan et al., 2016). A sequence boundary was identified during the onset of the Mulde CIE in both the Baltic and Welsh basins (Corfield et al., 1992; Jeppsson et al., 1995; Calner and Jeppsson, 2003; Calner et al., 2006; Ray et al., 2010; Marshall et al., 2012); therefore, it is hypothesized that this is a global sequence boundary representing a fall and subsequent rise in eustatic sea level. Homerian strata that contain the Mulde CIE have been identified in the midcontinent United States (Cramer et al., 2006, Cramer, 2009; Sullivan et al., 2016), making this an excellent location to test whether or not there is a global sequence boundary associated with the onset of the Mulde Excursion.

Six sections of upper Homerian strata from the midcontinent United States were studied for this project. New carbon isotope data are presented for five of the sections—four from across the Indiana-Ohio border and one from Nashville, Tennessee, from which new conodont data are also presented. A sequence

*Present address: Division of Geological Survey, Ohio Department of Natural Resources, Columbus, Ohio 43229, USA stratigraphic model is applied to these sections and analyzed in the context of biostratigraphy and chemostratigraphy to determine the relationship between the Mulde Extinction, Mulde Excursion, and global sea level.

GEOLOGIC SETTING

The Mulde Event and CIE

The Mulde Event was originally recognized as a graptolite extinction (Jaeger, 1959, 1991) now known as the *lundgreni* Event (Koren', 1991; Porębska et al., 2004; Lenz et al., 2006). The *lundgreni* Event occurred in a stepwise manner with three extinction levels in the *Cyrtograptus lundgreni* Zone and left only three surviving species, *Pristiograptus parvus*, *Pristiograptus dubius,* and *Gothograptus nassa*, that diversified by the end of the Homerian (Porębska et al., 2004; Cramer et al., 2012). A conodont extinction of lesser impact also occurred within the *Cy. lundgreni* Zone and within the lower *Ozarkodina bohemica longa* conodont zone. It is well documented in Gotland, Sweden (Jeppsson and Calner, 2003), where three event levels are recognized: datum 1, which marks the last occurrence of *Ozarkodina sagitta sagitta* and *Kockelella ortus ortus*; datum 1.5, which marks the extinction of *Pseudooneotodus linguicornis* and most *Walliserodus;* and datum 2, which is noted for a turnover in ramiform- to coniform-dominated conodont fauna (Calner and Jeppsson, 2003; Jeppsson and Calner, 2003; Cramer et al., 2012).

The onset of the Mulde carbon isotope excursion is within the upper part of the *lundgreni* graptolite Zone, and the end is below the base of the Ludlow Series at the type area in Shropshire, England (Thomas and Ray, 2011; Cramer et al., 2012). The excursion was first recognized in the West Midlands, England, and immediately associated with the graptolite extinction (Corfield et al., 1992); it is now documented globally and associated with many other biological events (Cramer et al., 2012). Homerian carbonate carbon isotope records ($\delta^{13}C_{carb}$) have baseline values ranging from 0‰ to +1‰ Vienna PeeDee belemnite (VPDB), and a double-peaked, positive excursion is recorded in the upper Homerian. The first peak occurs at values between +2.5‰ and 5‰ VPDB above baseline; values then usually drop to near but higher-than-baseline values before the second peak, which usually has lower values than the first (Kaljo et al., 1997; Calner et al., 2006; Cramer et al., 2006, 2012). High-precision U-Pb zircon dates, in combination with the relatively abundant graptolite biostratigraphy for this Mulde interval, suggest a duration of the entire global carbon cycle perturbation to be <1 m.y. (Cramer et al., 2012).

Paleogeography

The midcontinent United States was part of the southeast region of Laurentia during the Homerian and was located at subtropical latitudes between 25° and 30° south (Fig. 1A; Cocks and Torsvik, 2011). The Welsh and Baltic basins were located across the Iapetus Ocean, which was closing during this time resulting in the Caledonian orogeny by the end of the Silurian (Cocks and Torsvik, 2011).

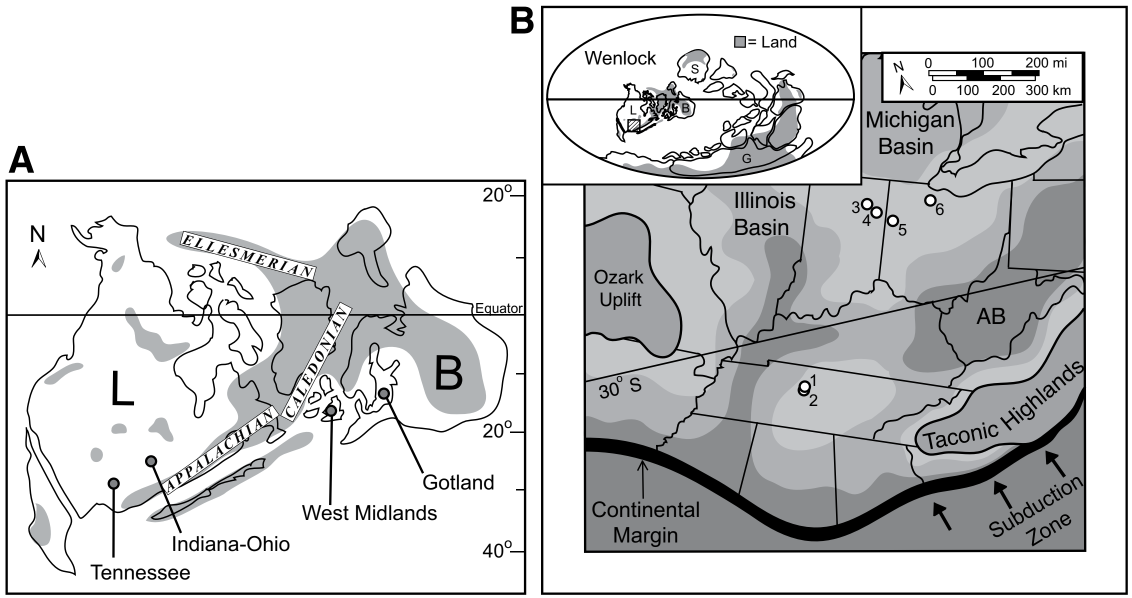


Figure 1. Paleogeography of the study area. (A) Silurian paleogeographic map showing the location of study areas for this project and the location of West Midlands, England, and Gotland, Sweden, for comparison; L—Laurentia; B—Baltica. Modified from Cramer et al. (2012). (B) Paleogeographic map of the southeast region of Laurentia showing the paleobathymetry of the epicontinental sea; darker gray indicates deeper waters; gray outlined in black demarcates land; white dots show six study locations: (1) McCrory Lane, Nashville, Tennessee; (2) Scottsboro, Nashville, Tennessee; (3) Huntington, Indiana; (4) Bluffton, Indiana; (5) Celina, Ohio; (6) West Millgrove, Ohio; AB—Appalachian Basin; Inset: Global Wenlock paleogeography; L—Laurentia; B—Baltica; S—Siberia; G—Gondwana. Modified from Cramer and Saltzman (2005).

Eastern and central Laurentia was dominated by epicontinental seas during the Silurian, bounded by the Taconic highlands on the east coast as a result of the Ordovician Taconic orogeny and the Laurentian continental margin to the south. Local depocenters were provided by the Appalachian, Illinois, and Michigan basins, separated by a series of sub-oceanic structural arches (e.g., Shaver, 1996; Cramer and Saltzman, 2005). The study areas for this project were located on these structural highs (Fig. 1B) dominated by tropical shallow-water carbonate production with minor siliciclastic deposition (i.e., the Waldron Shale; Shaver et al., 1986; Broadhead and Gibson, 1996). These localities are mainly associated with the Illinois Basin, though the strata were deposited on the basin margins.

Stratigraphic Background

The Euphemia, Springfield, and Cedarville were all integrated as members into the Laurel Formation in Ohio by Brett et al. (2012). In this study, we follow the nomenclature of Brett at al. (2012) and therefore refer to the unit underlying the Pleasant Mills and Greenfield formations in the Indiana-Ohio area as the Cedarville Member of the Laurel Formation (Fig. 2). The contact between the Waldron and Lego formations in Tennessee is informally redefined in this study from that of Barrick (1983) and Broadhead and Gibson (1996) (Fig. 2). The Waldron is expanded to include all argillaceous, recessive, shales and limestones above the Laurel Formation and below the Lego Formation. Therefore, the base of the Lego Formation is placed at the base of the carbonate bed overlying the highest argillaceous bed, rather than the base of the lowest clearly carbonate bed overlying the Waldron Formation. Herein the Lego Formation only includes resistant, continuous, medium-bedded limestones as opposed to past studies, which considered the upper limestone and shale of Waldron B and C (herein) as parts of the Lego.

A similar nomenclature is also used in Indiana for the purposes of this study. We consider the "Waldron Member" of the Pleasant Mills Formation to include all limestone and shaly units above the Limberlost Member and below the continuous limestones of the Louisville Member. However, this is an informal designation, and evidence provided by this study shows the "Waldron Member" of the Pleasant Mills Formation at our two study locations in northern Indiana are not equivalent to the Waldron Formation of Tennessee. The "Waldron Member" of northern Indiana will therefore be referred to in quotation marks.

Tennessee

The Homerian of Tennessee is represented by a portion of the Wayne Group (Fig. 2), which is mapped through most of west-central Tennessee and spans the upper Llandovery through at least the lower Ludlow based on conodont biostratigraphy (Barrick, 1983). The Wayne Group is unconformably bounded by the Brassfield Formation at the base and by the Brownsport Formation at the top (Broadhead and Gibson, 1996). It is composed of five formations, in ascending order: the Osgood, Laurel, Waldron, Lego, and Dixon (Broadhead and Gibson, 1996). All formations except for the Waldron are composed of wackestones and packstones with varying degrees of mud (Barrick, 1983; Shaver et al., 1986), and

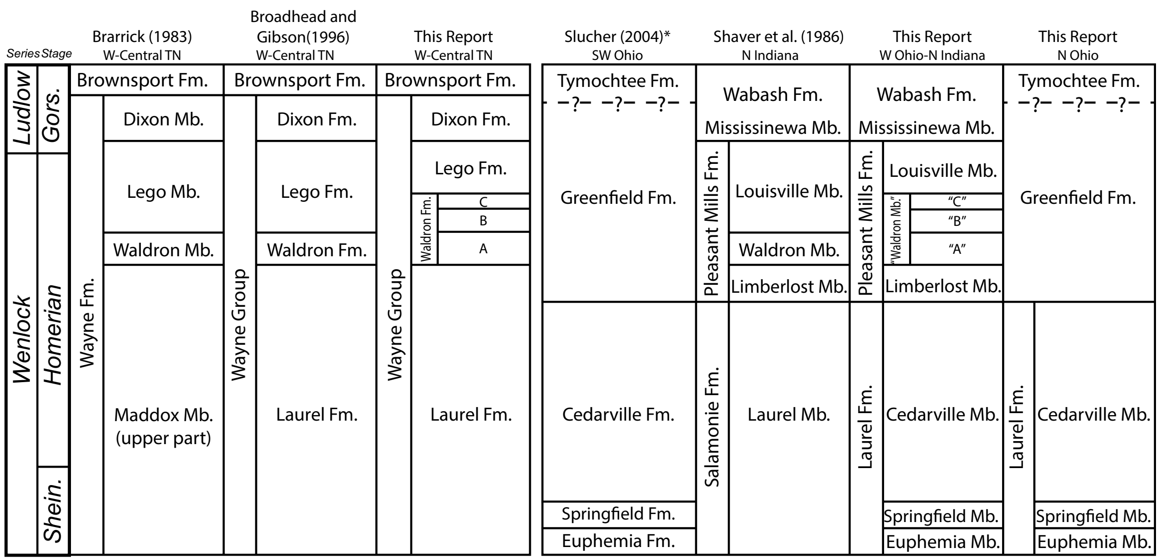


Figure 2. Lithostratigraphic nomenclature of west-central Tennessee and northwestern Ohio to northern Indiana. This diagram is not meant to represent chronostratigraphic correlations. The relationship between these units and the series and stages is generalized; for example, the diagram is not intended to argue the Limberlost in Indiana is equivalent to Laurel of Tennessee. The diagram is not to scale in terms of stratigraphic thickness nor time. It is meant to show lithostratigraphic relationships and the use of the term Waldron in this study (see Stratigraphic Background). *Slucher (2004) placed the base of the Greenfield above the base of the Ludlow. However, this column is also based on data that show the base of the Greenfield is within the Homerian (Cramer, 2009; Swift, 2011).

the Waldron Formation is a calcareous shale and/or marly unit originally recognized in Indiana (Elrod, 1883). Carbon isotope chemostratigraphy constrained the Homerian to the upper Laurel Formation (middle Maddox of Barrick, 1983) through the lower Lego Formation (Cramer and Saltzman, 2005; Cramer et al., 2006).

Indiana

Strata from the upper part of the Laurel Formation and most of the Pleasant Mills Formation represent the Homerian in northern Indiana (Fig. 2), which was generally constrained by macrofaunal assemblages, sparse conodont work (Shaver et al., 1986), and correlation of the Waldron Shale to Tennessee, where the Mulde Excursion was documented (Cramer et al., 2006). The Pleasant Mills is underlain by the Cedarville Member of the Laurel Formation (see Brett et al., 2012) and overlain by the Wabash Formation (Ludlow). It is composed of three members: the Limberlost, "Waldron," and Louisville (Shaver et al., 1986). The Limberlost Member is a resistant unit with multiple facies, including reefal, oolitic, and micritic facies overlain by the "Waldron Member." Whether or not to include the Waldron as a member of the Pleasant Mills Formation has been debated. Droste and Shaver (1982) excluded the term "Waldron" when they defined the Pleasant Mills Formation in northern Indiana because "Waldron" and Louisville lithology can be interbedded in thick sequences obscuring the position of the contact. Shaver et al. (1986) reintroduced the term "Waldron" as a member of the Pleasant Mills in northern Indiana, though noted "this term is not everywhere useful in that part of the state…." In the type area in southern Indiana and locations nearby in Kentucky, the Waldron is a highly fossiliferous shale unit with limestone beds. At the Huntington and Bluffton quarries in northern Indiana, the "Waldron" is dominated by 1–2-cm-thick irregularly shaped, dolomitic limestone nodules in "wraparound" shale devoid of fossils, a different facies than the Waldron in the type area but still mud dominant. The overlying Louisville Member is a resistant, mostly thick-bedded, fine-grained argillaceous limestone with large-scale reef structures (Shaver et al., 1986). Previous carbon isotope work in Oldham County, Kentucky, identified the lower peak of the Mulde CIE in the Waldron Shale and correlated the base of the Homerian to within the underlying Cedarville Member of the Laurel Formation (Cramer, 2009).

Ohio

The Homerian Stage in Ohio is currently represented by the Cedarville Member of the Laurel Formation and the lower portion of the Greenfield Formation (Fig. 2) based on lithologic correlation with the Pleasant Mills in Indiana (Shaver et al., 1986) and preliminary biostratigraphy and chemostratigraphy by Cramer (2009) and Swift (2011). The conodont *Ozarkodina bohemica longa* was recovered from the Greenfield Formation in Buckland Quarry, Auglaize County, Ohio (Cramer, 2009, p. 253), and Swift (2011) recovered *Pseudooneotodus linguicornis* from the Con Ag Quarry, also in Auglaize County, Ohio. Both conodont occurrences clearly place the lower Greenfield within the Homerian Stage. The onset of the Mulde Excursion was interpreted to be within the base of the Greenfield Formation in the OGS-Core #2682, Highland County, Ohio (Cramer, 2009), and a $\delta^{13}C_{carb}$ excursion was identified within the Greenfield at the Con Ag Quarry, Auglaize County, Ohio (Swift, 2011), though it is unclear how much of the Mulde Excursion this represents. The Greenfield Formation is composed of thinly bedded to laminated fine-grained dolomite, is underlain by the Peebles Formation in southern Ohio and the Laurel Formation elsewhere in Ohio, and is overlain by the Tymochtee Formation (Slucher, 2004; Cramer, 2009).

METHODS

Six outcrops were analyzed for this study, two each from Tennessee, Indiana, and Ohio. Locality information for all sections is included in the Supplemental Item[1]. A road cut from Scottsboro, Nashville, Tennessee was sampled bed by bed (10–45 cm) for conodont biostratigraphy and was sampled at 10 cm resolution for carbon isotopic analysis ($\delta^{13}C_{carb}$). Two quarry sections from Huntington and Bluffton, Indiana, were sampled for carbon isotopic analysis at 50 cm and 20 cm resolution, respectively, and two quarry sections from Celina and West Millgrove, Ohio, were also sampled for carbon isotopic analysis at 20-cm resolution. The road cut at the McCrory Lane entrance ramp to I-40 E, Nashville, Tennessee, was previously analyzed for $\delta^{13}C_{carb}$ by Cramer et al. (2006).

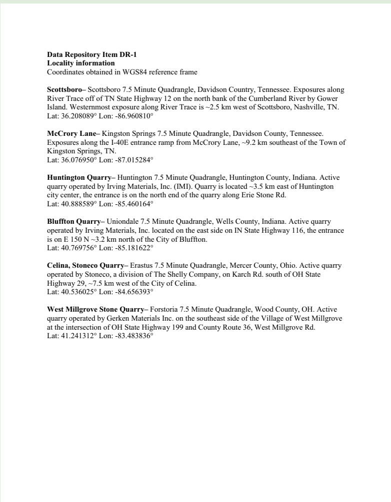
Conodont samples were dissolved in a double buffered formic acid solution (after Jeppsson and Anehus, 1995) sieved through 63 and 1000 micron screens, density separated using lithium metatungstate, picked, and photographed using a Canon 60D with Zerene image-stacking software and a Hitachi S-3400N scanning electron microscope (SEM). Isotope samples were powdered with a 6 mm drill bit avoiding weathered surfaces, veins, and obvious recrystallization (following Saltzman, 2002). Stable-isotope analyses were performed at the Keck Paleoenvironmental and Environmental Laboratory at the University of Kansas. Powdered carbonate material was reacted with phosphoric acid, and the isotopic ratios of the degassed CO_2 were measured using a ThermoFinnigan MAT 253 mass spectrometer. National Bureau of Standards (NBS)-18, NBS-19, TSF-1, SIGMA CALCITE, and 88b Dolomite standards were used for calibration. Precision was better than 0.10‰ for both carbon and oxygen.

RESULTS

Lithostratigraphy

Tennessee

Approximately nine meters of section were analyzed at Scottsboro, Tennessee, from within the upper part of the Laurel Formation into the lower part of the Lego Formation (Figs. 3 and 4). The base of the measured section begins well above



Data Repository Item DR-1
Locality information
Coordinates obtained in WGS84 reference frame

Scottsboro– Scottsboro 7.5 Minute Quadrangle, Davidson Country, Tennessee. Exposures along River Trace off of TN State Highway 12 on the north bank of the Cumberland River by Gower Island. Westernmost exposure along River Trace is ~2.5 km west of Scottsboro, Nashville, TN.
Lat: 36.208089° Lon: -86.960810°

McCrory Lane– Kingston Springs 7.5 Minute Quadrangle, Davidson County, Tennessee. Exposures along the I-40E entrance ramp from McCrory Lane, ~9.2 km southeast of the Town of Kingston Springs, TN.
Lat: 36.076950° Lon: -87.015284°

Huntington Quarry– Huntington 7.5 Minute Quadrangle, Huntington County, Indiana. Active quarry operated by Irving Materials, Inc. (IMI). Quarry is located ~3.5 km east of Huntington city center, the entrance is on the north end of the quarry along Erie Stone Rd.
Lat: 40.888589° Lon: -85.460164°

Bluffton Quarry– Uniondale 7.5 Minute Quadrangle, Wells County, Indiana. Active quarry operated by Irving Materials, Inc. located on the east side on IN State Highway 116, the entrance is on E 150 N ~3.2 km north of the City of Bluffton.
Lat: 40.769756° Lon: -85.181622°

Celina, Stoneco Quarry– Erastus 7.5 Minute Quadrangle, Mercer County, Ohio. Active quarry operated by Stoneco, a division of The Shelly Company, on Karch Rd. south of OH State Highway 29, ~7.5 km west of the City of Celina.
Lat: 40.536025° Lon: -84.656393°

West Millgrove Stone Quarry– Forstoria 7.5 Minute Quadrangle, Wood County, OH. Active quarry operated by Gerken Materials Inc. on the southeast side of the Village of West Millgrove at the intersection of OH State Highway 199 and County Route 36, West Millgrove Rd.
Lat: 41.241312° Lon: -83.483836°

[1]Supplemental File. Locality information, carbon isotope data, and conodont sample information. Please visit https://doi.org/10.1130/GES01685.S1 or access the full-text article on www.gsapubs.org to view the Supplemental File.

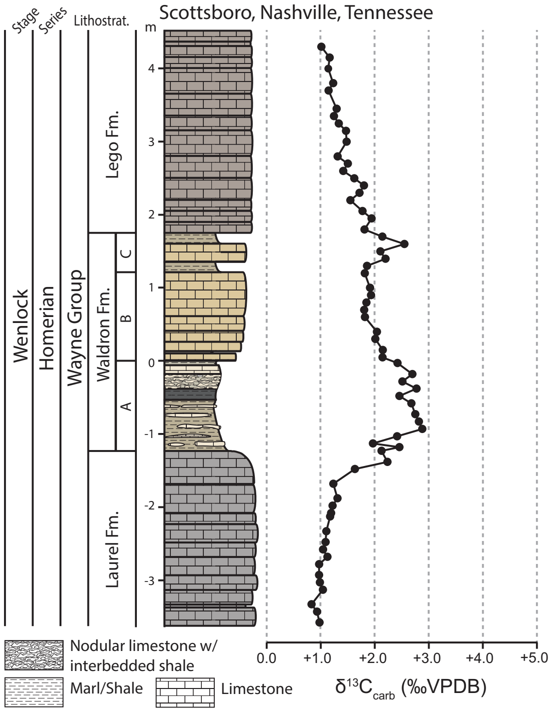


Figure 3. Measured section and carbon isotope data from Scottsboro, Nashville, Tennessee.

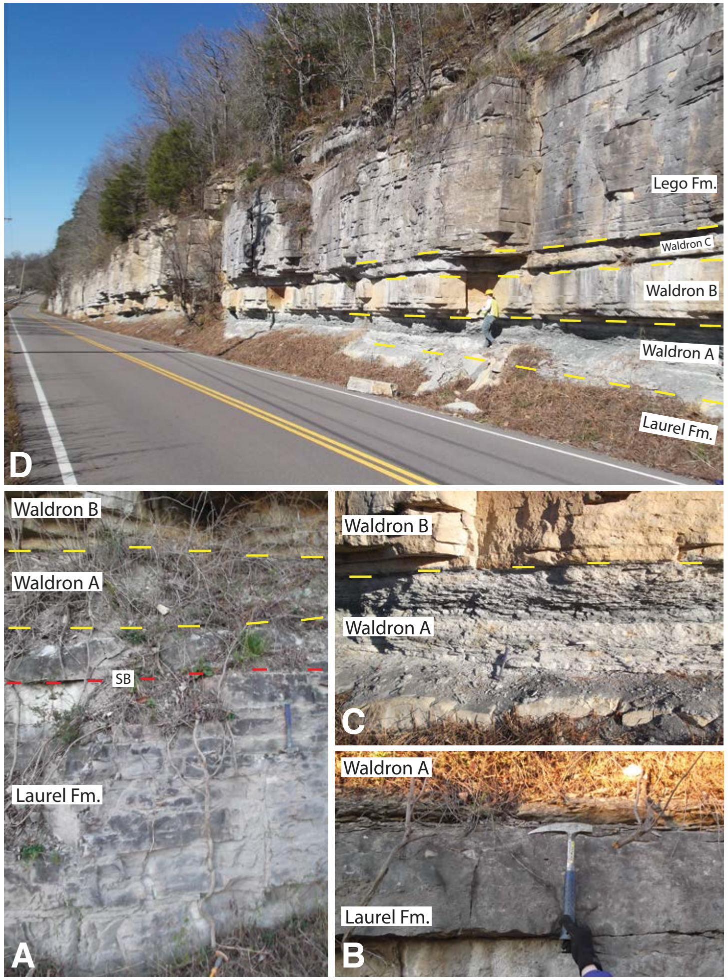


Figure 4. Photographs of the Laurel, Waldron, and Lego Formations exposed on River Trace, in Scottsboro, Nashville, Tennessee; November, 2015. (A) Lower portion of measured section (note hammer for scale); "SB" and red dashed line mark the sequence boundary within the ascending limb of the Mulde carbon isotope excursion; yellow lines mark formation or member contacts. This demarcation scheme is used for all following field photographs; mixed red and yellow lines indicate both a sequence boundary and lithostratigraphic contact. (B) Top of the Laurel Formation; top of the hammer marks the base of ~10 cm of transitional strata that grades into the Waldron Formation. (C) Hammer sitting on Laurel-Waldron contact. (D) View upsection, looking westward on River Trace.

the Osgood-Laurel contact, which is not exposed at this locality, at the base of the first complete bed 20 cm above ground level. There are ~2.5 m of Laurel, which consists of resistant, recrystallized, pink and light-gray to light-tan crinoidal wackestones-packstones with inconsistent moderate dolomitization. There is a distinct change in lithology in the uppermost bed of the Laurel to a light-gray, resistant argillaceous wackestone. The Waldron Formation overlies the Laurel Formation, is about three meters thick at Scottsboro, and is broken into three units: A, B, and C. Waldron A mostly consists of green-gray, wavy-bedded shale with interbedded nodular limestones and lenses up to 3 m in length. Within Waldron A, a 15–20 cm dark-gray laminated shale unit occurs 70 cm from the top of the Laurel; this bed is also identifiable at McCrory Lane. The base of Waldron B is marked by the first continuous, evenly-bedded, resistant limestone within the Waldron Formation, though it is still muddy and less resistant than the Laurel or Lego formations. Waldron B consists of four 10- to 20-cm-thick wackestone beds with an overlying 60-cm-thick wackestone that is topped by Waldron C. Waldron C is a 55-cm-thick shaly unit with a central 25-cm-thick wackestone bed. The Lego Formation overlies the Waldron, and the contact is located at the base of the medium bedded (10–40 cm), continuous, resistant, recrystallized wackestones with infrequent vuggy layers parallel to bedding planes. The lithologic changes and contacts at McCrory Lane (Figs. 5 and 6) are very similar to those at Scottsboro, though the Laurel-Waldron A contact is not well exposed at McCrory Lane, and there are some differences in unit thickness and color.

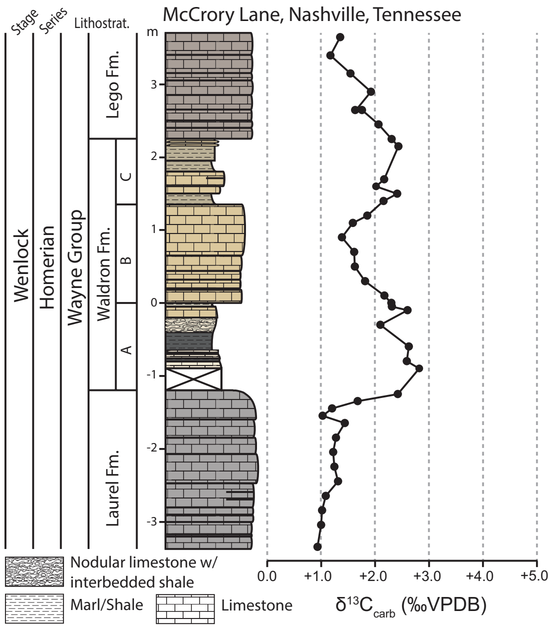


Figure 5. Measured section and carbon isotope data from McCrory Lane, Nashville, Tennessee. Carbon isotope data from Cramer et al. (2006). VPDB—Vienna PeeDee belemnite.

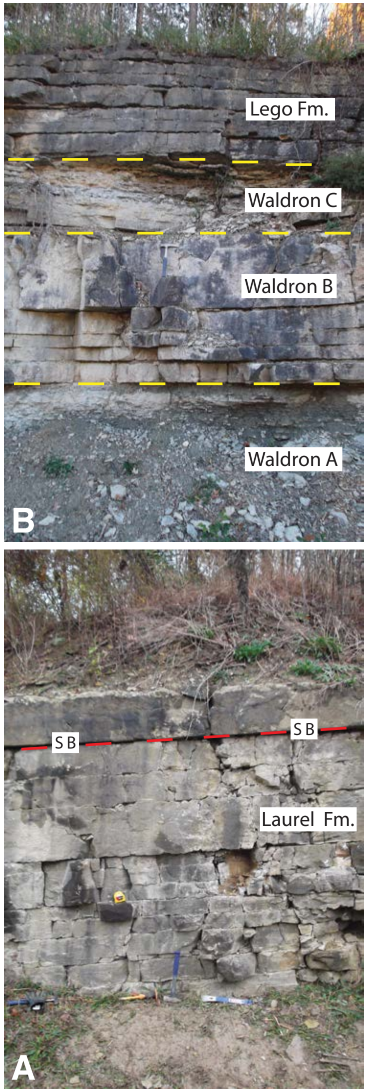


Figure 6. Photographs of the Laurel, Waldron, and Lego formations exposed at McCrory Lane, Nashville, Tennessee; November, 2015. (A) Upper Laurel Formation. (B) Waldron Formation begins at ground level; Lego Formation continues upsection east of this photograph; note hammer for scale within Waldron B.

Indiana

Seventeen meters of section were studied at the Irving Materials quarry in Huntington, Indiana (Figs. 7 and 8A–8C). The lower 2.5 m of section consists of the Cedarville Member of the Laurel Formation—a mottled light- to medium-gray, thick-bedded, microcrystalline, dolomitized wackestone with infrequent small fossil moldic porosity. The upper boundary of the Laurel is marked by a rust-stained unconformity with a couple decimeters of topographic relief developed at its contact with the overlying Limberlost Member of the Pleasant Mills Formation. The Limberlost Member is a light gray-tan-pink, massive, oolitic dolopackstone-grainstone with interparticle porosity. At ~4 m above the base of the Limberlost Member, the unit gradually transitions to a medium- to thick-bedded microcrystalline dolostone with little porosity visible in hand sample aside from sparse 2–5-mm-scale vugs and rare patches of fossil moldic porosity. These beds of the Limberlost become increasingly argillaceous upsection and gradually grade upward into the “Waldron Member,” also divided into three units. “Waldron A” contains 4 m of recessive, medium-gray, microcrystalline dolostone nodules with little to no visible porosity; these nodules are tightly packed and surrounded by dark-gray calcareous shale. “Waldron B” consists of 3.5 m of weathering-resistant, mottled medium-gray and tan, microcrystalline dolowackestone with sparse fossil moldic porosity. “Waldron C” is similar in lithology to “Waldron A.” The Louisville Member overlies the “Waldron” and consists of mottled very light tan to gray, micro- to fine-crystalline dolomitized wackestone with common small fossil moldic porosity that increases in size upsection to ≥1 cm, where vugs also

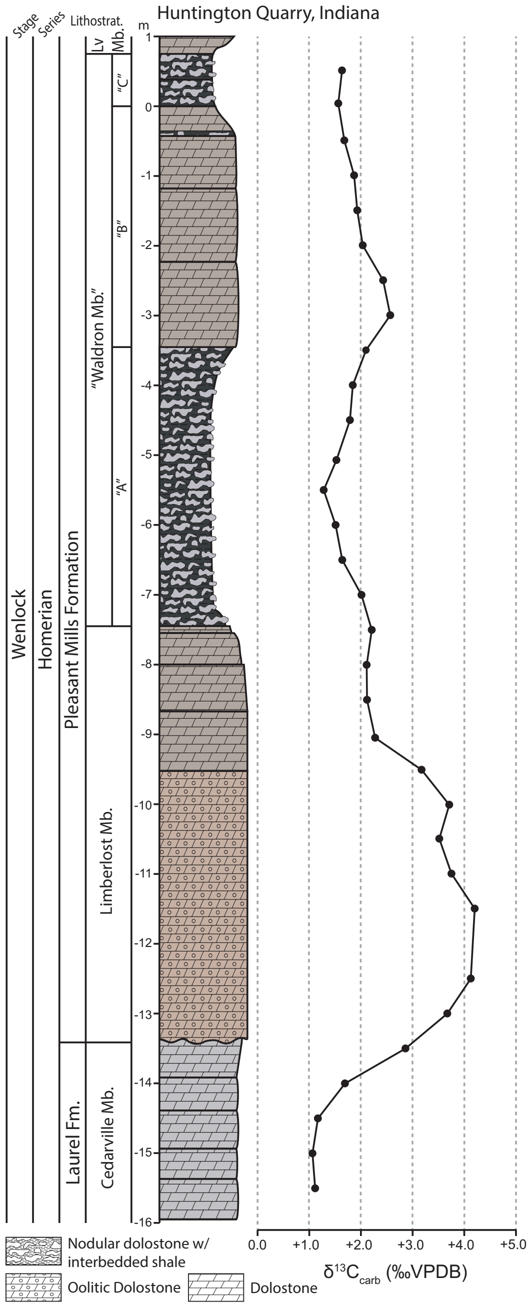


Figure 7. Measured section and carbon isotope data from the Irving Materials quarry in Huntington, Indiana. LV—Louisville; VPDB—Vienna PeeDee belemnite.

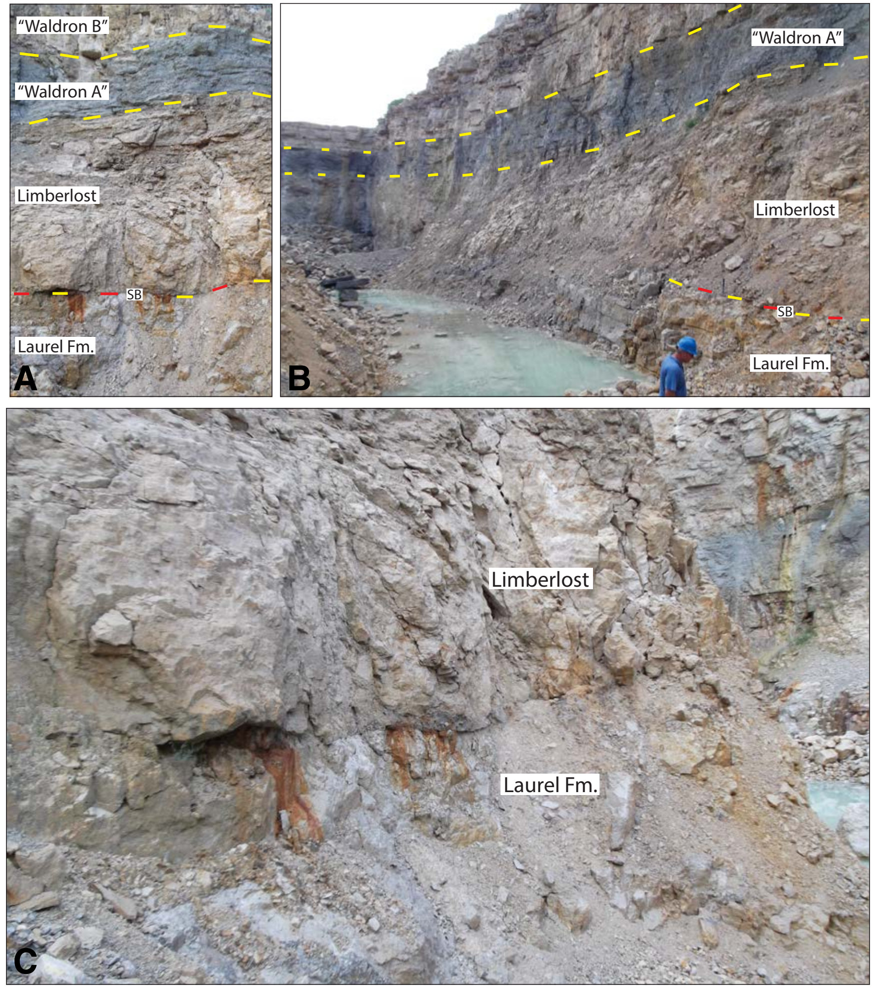


Figure 8. Photographs of the Cedarville Member of the Laurel Formation overlain by the Limberlost and “Waldron” members of the Pleasant Mills Formation at the Irving Materials quarry, Huntington, Indiana; July 2016. (A and B) North-northwest quarry wall south and center of the railroad tracks that cross the quarry. Photograph A taken a few meters east of photograph B. (C) Close-up on the Laurel–Pleasant Mills contact showing rust staining and erosional topography; same location as photograph A.

begin, both of which have rare yellow-orange staining. The Louisville Member of the Pleasant Mills Formation was more accessible at the Irving Materials quarry in Bluffton, Indiana, from where it is described. The section at Bluffton (Figs. 9 and 10) is lithologically similar to that at Huntington, but it begins within the oolitic portion of the Limberlost (Fig. 11). Within the measured section at Bluffton, the Limberlost contains a small patch-reef, the top of which occurs 95 cm below the datum, which is the top of the 25-cm-thick resistant carbonate bed within "Waldron A" and is 80 cm thick in the center.

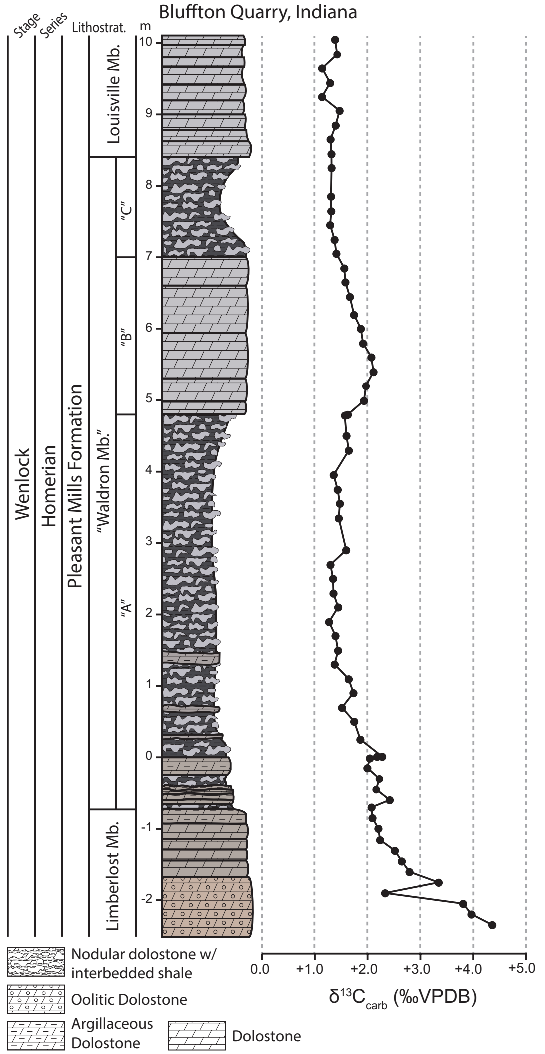


Figure 9. Measured section and carbon isotope data from the Irving Materials quarry in Bluffton, Indiana. VPDB—Vienna PeeDee belemnite.

Ohio

The geology at the Stoneco Quarry in Celina, Ohio, was previously documented by Droste and Shaver (1976) and Shaver et al. (1978). Indiana lithostratigraphic terminology has traditionally been used in the quarry. The identification of these units is difficult due to the drastic difference in lithology from Indiana sections and pervasive, recrystallizing dolomitization; therefore, units are herein referred to with numbers 1–5 (Figs. 12 and 13). The lowest unit, unit 1, is the first meter of section and consists of light-tan and gray-mottled, thinly bedded, medium- to fine-crystalline dolowackestone with moderate small fossil moldic and intercrystalline porosity. The overlying unit 2 is most notable in outcrop for its darker-gray color, though the unweathered surface is a mottled medium tan and gray. Unit 2 is a medium bedded, micro- to fine-crystalline dolopackstone-wackstone with porosity that increases upsection from almost no visible porosity in hand sample to fossil moldic and intercrystalline porosity with rare vugs. The base of unit 3 occurs 1.95 m above the base of unit 2 and is marked by a change in color to a mottled light tan and gray and a change in lithology to a very fine to fine-crystalline dolowackestone-packstone with rare to abundant moldic porosity that weathers yellow-orange in the top 20 cm and contains recrystallized crinoid columnals, rugose corals, and bryozoans. Unit 4 is a ~0.75-m-thick, light brown-gray, micro- to fine-crystalline dolowackestone unit, with moderate small moldic porosity, yellow-orange staining in larger pores, and isolated silty layers and pockets. The top of unit 4 is marked by 1–2 cm of deep purple staining. The overlying unit 5 is recognized in outcrop by a darker brown color and regular 5-cm-scale bedding. Unit 5 is a darker medium brown-gray, micro- to fine-crystalline dolowackestone-packstone, with moderate to common, small moldic porosity, and common sparry crinoids in the upper half of the unit. The uppermost beds of unit 5 have common recrystallized fossils with thin (mm-scale) silt drapes.

The geology at the Gerken Materials quarry in West Millgrove, Ohio, has previously been documented with general Ohio terminology (Shaver et al., 1978). Our target was the Greenfield Formation, but we interpret that only about one meter of possible Greenfield is exposed at the top of the quarry. Lower in the quarry is a large reefal complex assumed to be part of the Cedarville Member of the Laurel Formation. A 3.0 m section at the top of the quarry was analyzed (Figs. 14 and 15). The lower 2.0 m of section consist of mottled yellowish-gray, micro- to fine-crystalline dolowackestones and dolopackstones, with low to abundant fossil moldic porosity. This unit is interpreted as the Cedarville Member of the Laurel Formation, and the overlying 1.0 m is interpreted as the Greenfield Formation. The lower part of the Greenfield Formation consists of an olive-tan dolomudstone with no visible porosity in hand sample.

Figure 10. Photograph of the Pleasant Mills Formation at the eastern wall, northeast corner of the Irving Materials quarry, Bluffton, Indiana; July 2016.

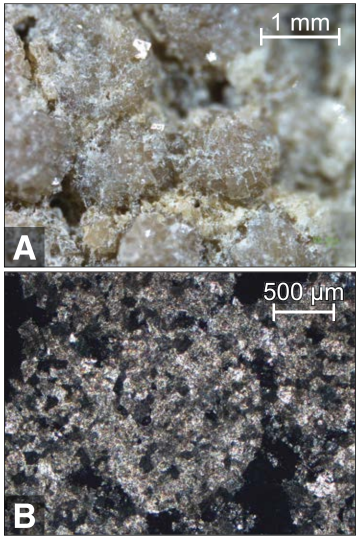


Figure 11. Recrystallized, dolomitized ooids from the Limberlost Member of the Pleasant Mills Formation at Bluffton, Indiana; sample was collected 2.35 m down from the Bluffton quarry datum, which is at the top of the 25 cm resistant carbonate bed within Waldron A (same datum as shown in Fig. 9). (A) Magnified hand sample photograph. (B) Thin section showing an ooid in center of the photograph.

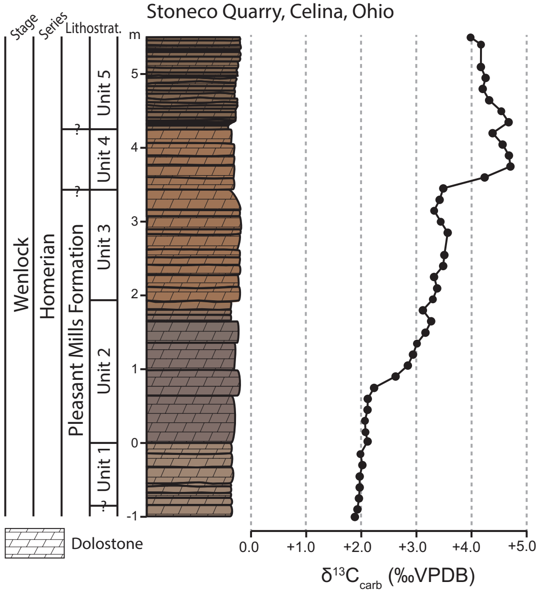


Figure 12. Measured section and carbon isotope data from the Stoneco Quarry in Celina, Ohio. VPDB—Vienna PeeDee belemnite.

Figure 13. Photograph of possibly Homerian strata at the Stoneco Quarry in Celina, Ohio; July 2016; note field pack for scale. SB—sequence boundary.

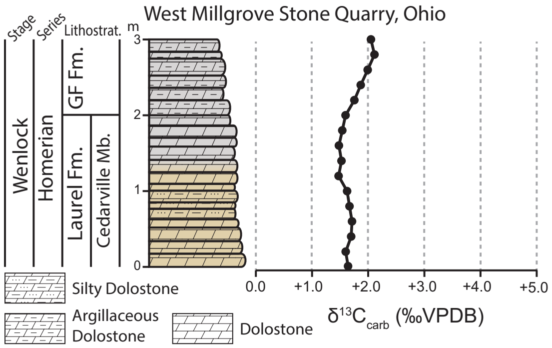


Figure 14. Measured section and carbon isotope data from the Gerken Materials quarry in West Millgrove, Ohio. GF—Greenfield; VPDB—Vienna PeeDee belemnite.

There are some variable laminations, and the immediately overlying bed is a highly laminated dolomudstone.

Conodont Biostratigraphy

Thirteen samples from the Laurel, Waldron, and Lego formations at Scottsboro, Tennessee, yielded a conodont fauna dominated by genus *Panderodus* Ethington, 1959. A few individual occurrences of *Belodella silurica* Barrick,

Figure 15. Photograph of the three-meter section at the top of the Gerken Materials quarry in West Millgrove, Ohio; July 2016. SB—sequence boundary.

1977, and *Ozarkodina bohemica longa* Jeppsson in Calner and Jeppsson, 2003 place these strata within the Homerian (Table S1 [footnote 1]; Figs. 16 and 17).

Carbon Isotope Analysis

Carbon isotopic analysis demonstrates that the Mulde CIE occurs at Scottsboro (Fig. 3; Table S2). Baseline values for $\delta^{13}C_{carb}$ are ~+1.0‰ VPDB within the upper part of the Laurel Formation. Increases in $\delta^{13}C_{carb}$ values begin in the second to last bed of the Laurel with slight elevation to +1.31‰. Within the uppermost bed of the Laurel, there is a high rate of increase in values from +1.23‰ to +2.24‰ over 30 cm. Values continue to increase and peak within Waldron A at +2.88‰ and then decrease to +1.81‰ within Waldron B. Values then rise again to the second peak within Waldron C at +2.55‰, and from there gradually decrease and reach baseline values 2.5 m into the Lego Formation. A similar carbon isotope trend is recorded at McCrory Lane, reaching peak values just under +3.0‰ for the first peak and approaching +2.5‰ for the second peak (Cramer et al., 2006; Fig. 5; Table S3).

Both peaks of the Mulde Excursion are also recorded in Indiana and reach higher maximum values than in Tennessee. At Huntington, baseline values just over +1.0‰ are recorded within the Laurel Formation, and then values begin to rise about one meter below the contact with the Limberlost Member of the Pleasant Mills Formation. Values continue to rise across the Laurel-Limberlost contact and peak at >+4.0‰ within the oolitic portion of the Limberlost. Values decrease to just above baseline levels within "Waldron A" and begin to rise again reaching second peak values of about +2.5‰ within the lower portion of "Waldron B." Values then steadily decrease through the rest of "Waldron B" and "C" (Fig. 7; Table S4 [footnote 1]). Similar isotopic trends are recorded at Bluffton, though the section begins within the oolitic Limberlost at or after peak values of >+4.0‰ and reach second peak values of >+2.0‰ (Fig. 9; Table S5).

Increases in $\delta^{13}C_{carb}$ values are recognized at two levels in the Celina section (Fig. 12; Table S6). Unit 1 recorded values ~+2.0‰. The first increase in $\delta^{13}C_{carb}$ values begins ~0.75 m into unit 2; values increase gradually to +3.5‰ in the overlying two meters. The second increase in values begins at the boundary between units 3 and 4 and values rise from +3.5‰ to >+4.5‰ over 30 cm. Values remain elevated but decrease to +4.0‰ at the top of the section. The section at West Millgrove recorded $\delta^{13}C_{carb}$ values that stay ~+1.5‰–2.0‰ with no significant change (Fig. 14; Table S7).

DISCUSSION

Stratigraphic Interpretations

Carbon isotopic excursions are considered to be more isochronous than lithostratigraphic units for timescales on the order of a few thousand years. Ocean mixing time occurs on approximately a 1000-year timescale, and the

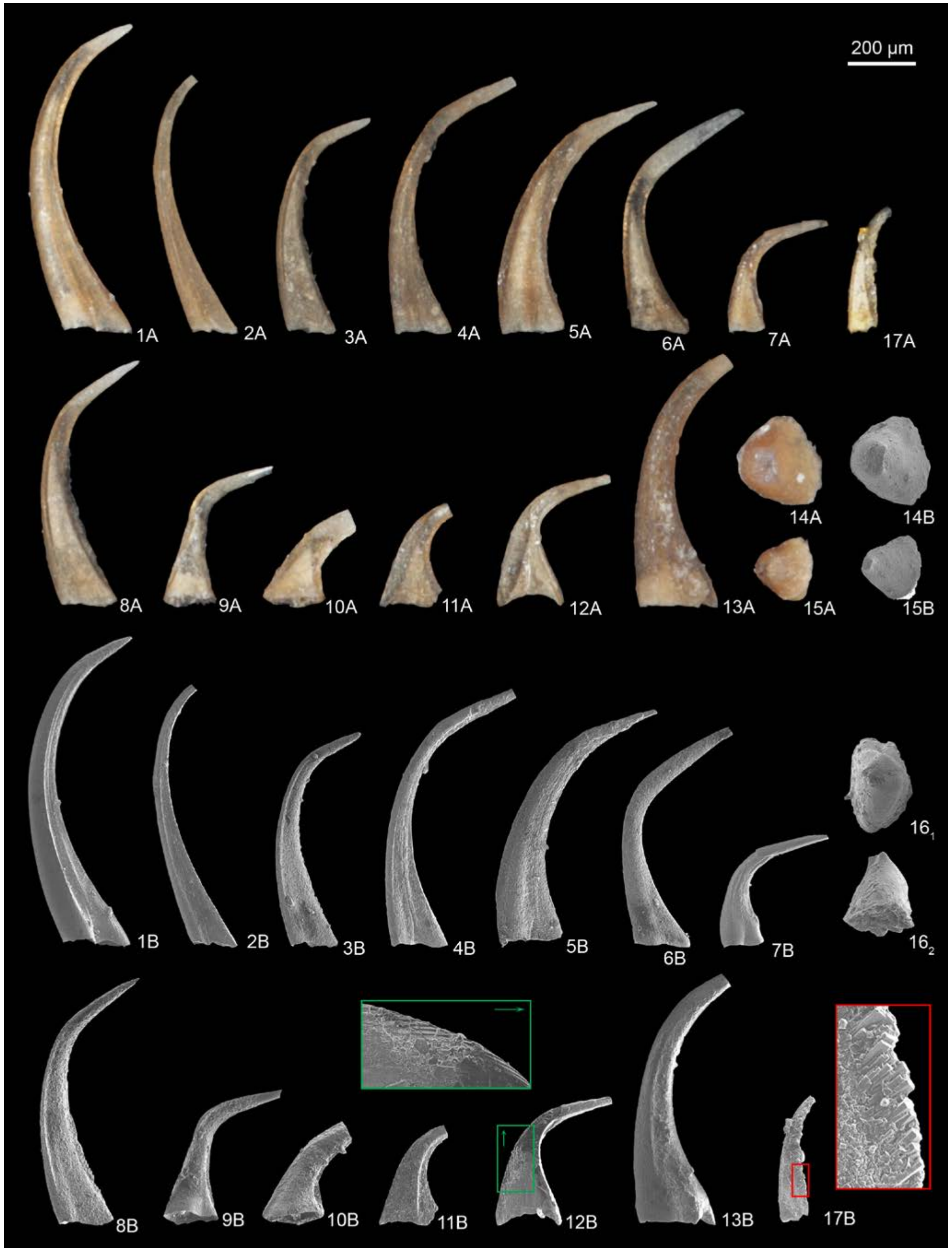


Figure 16. Photographs of coniform conodont elements from the Laurel, Waldron, and Lego Formations at Scottsboro, Tennessee. Canon stack-shot images are in color marked with an A following the specimen numbers; scanning electron microscope (SEM) images are in grayscale marked with a B following specimen numbers (A and B of the same number are the same specimen). Below, genus and/or species identifications are given followed by the stratigraphic sample interval in meters and the repository number for each specimen. The datum for the sample intervals is the same as the datum in Figure 3, the base of Waldron B at Scottsboro. All imaged specimens are stored at the University of Iowa Paleontology Repository with call numbers SUI 146770–SUI 146786. [1, 2, 13] *Panderodus equicostatus* (Rhodes, 1953). [1] 0.91 m to 1.21 m, SUI 146770; [2] −2.08 m to −1.68 m, SUI 146771; [13] −1.68 m to −1.23 m, SUI 146772. [3–5] *Panderodus unicostatus* (Branson and Mehl, 1933). [3] −2.48 m to −2.23m, SUI 146773; [4] −1.68 m to −1.23 m, SUI 146774; [5] −2.48 m to −2.23 m, SUI 146775. [6, 7] *Panderodus panderi* (Stauffer, 1940). [6] −1.68 m to −1.23 m, SUI 146776; [7] −1.68 m to −2.08 m, SUI 146777. [8] *Panderodus unicostatus*?, −2.48 m to −2.23 m, SUI 146778. [9] *Walliserodus sancticlairi* Cooper, 1976, −2.48 m to −2.23 m, SUI 146779. [10] *Decoriconus fragilis* (Branson and Mehl, 1933), −2.23 m to −2.48 m, SUI 146780. [11, 12] *Dapsilodus obliquicostatus* (Branson and Mehl, 1933). [11] −0.38 m to −0.18 m, SUI 146781; [12] 2.20 m to 2.05 m, SUI 146782. [14–16] *Pseudooneotodus bicornis* Drygant, 1974. [14] Oral view, −1.68 m to −1.23 m, SUI 146783. [15] Oral view, −1.68 m to −1.23 m, SUI 146784. [16] 16_1 oral view; 16_2 oblique basal-lateral view, −1.68 m to −1.23 m, SUI 146785. [17] *Belodella silurica* Barrick, 1977, 0.41 m to 0.26 m, SUI 146786.

residence time of carbon is ~100 k.y. (e.g., Saltzman and Thomas, 2012). Because the mixing time of the ocean is shorter than the residence time of carbon, a change in the isotopic ratio of the dissolved inorganic carbon (DIC) reservoir will propagate through the oceans on the order of a few thousand years. In terms of Paleozoic temporal resolution, this global propagation of $\delta^{13}C$ values dictates that $\delta^{13}C$ variations observed in the rock record are considered more or less isochronous and can be used for high-resolution chronostratigraphic correlation (e.g., Saltzman and Thomas, 2012; Cramer et al., 2015). The identification of the Mulde Excursion in this study, paired with sequence stratigraphic observations, provides new information for correlation of Homerian strata in the midcontinent United States.

The Mulde Excursion is present in all studied sections with the exception of West Millgrove, Ohio (Fig. 18). The newly presented conodont data from Tennessee agree with the previously documented faunas of Barrick (1983), and the recovery of *Oz. bohemica longa* and *Belodella silurica* in this study places these strata within the upper Homerian. Therefore, the elevated $\delta^{13}C_{carb}$ values in Tennessee presented herein clearly represent the Mulde Excursion, and both peaks of the excursion are recorded. A double-peaked excursion is also recorded in Indiana, and based on the previous assignment of the Pleasant Mills Formation to the Homerian Stage, this is also the Mulde CIE. At Celina, Ohio, the Mulde Excursion is present, but only in part. Previous work considered these units at the Stoneco Quarry to be equivalent to the Pleasant Mills Formation of Indiana (Droste and Shaver, 1976; Shaver et al., 1978) and therefore Homerian. Assuming this correlation is accurate, the elevated $\delta^{13}C_{carb}$ values recorded at Celina, can be interpreted in two ways: (1) the lower peak of the Mulde Excursion was not accessible in the quarry, and only strata that record an expanded trough and the upper peak were accessible; or (2) there is an expanded lead up to the first peak of the Mulde Excursion, and the trough and second peak are not exposed in the quarry. Currently, there are not enough strata present in the quarry or enough biostratigraphic data to resolve this problem further. The carbon isotope record at West Millgrove does not show any significant change to identify a possible excursion, and there are currently not enough Homerian strata identified in the area to make further interpretations.

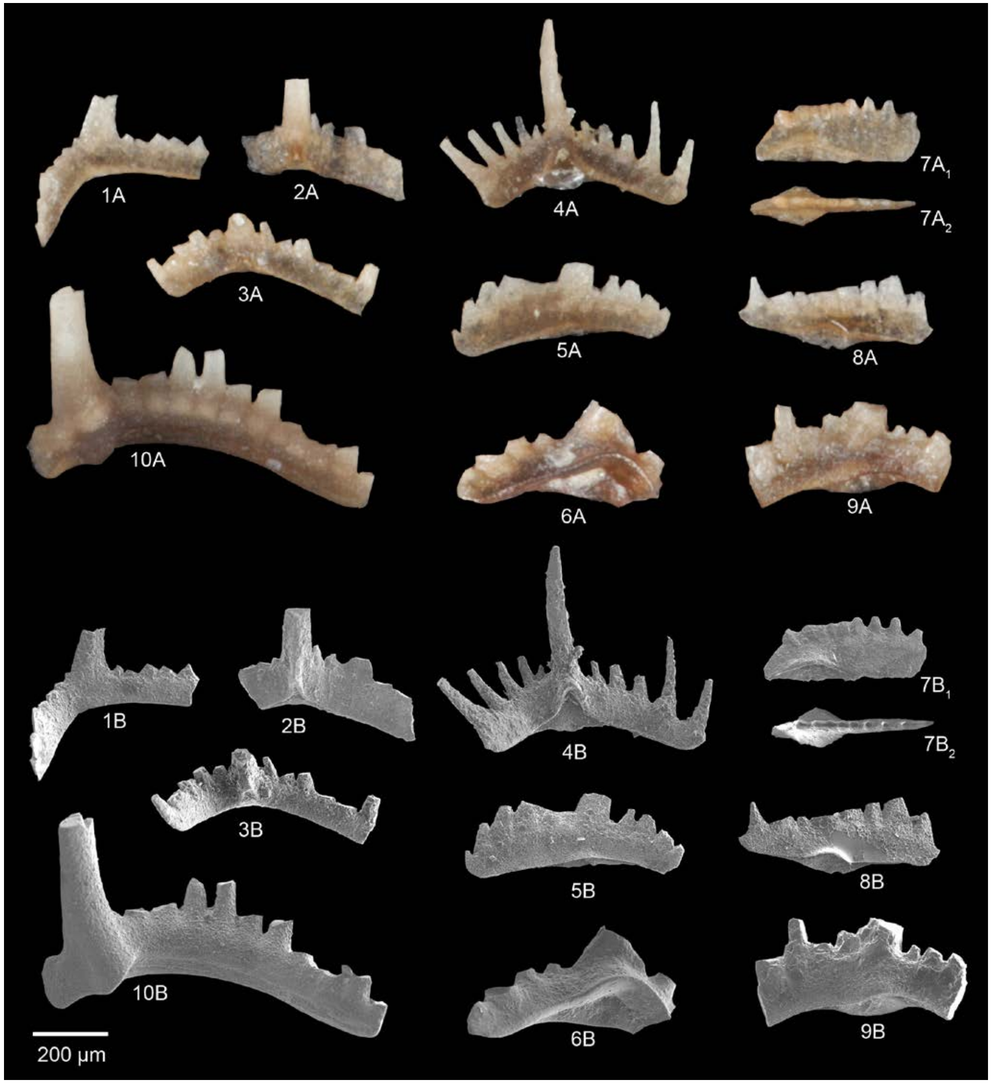


Figure 17. Photographs of ramiform conodont elements from the Laurel, Waldron, and Lego Formations at Scottsboro, Tennessee. Canon stack-shot images are in color marked with an A following the specimen numbers; scanning electron microscope (SEM) images are in grayscale marked with a B following specimen numbers (A and B of the same number are the same specimen). Below, genus and/or species identifications are given followed by the stratigraphic sample interval in meters and the repository number for each specimen. The datum for the sample intervals is the same as the datum in Figure 3, the base of Waldron B at Scottsboro. All imaged specimens are stored at the University of Iowa Paleontology Repository with call numbers SUI 146787–SUI 146796. [1–3, 5, 10] *Wurmiella excavata* (Branson and Mehl, 1933). [1] Dextral $S_{3/4}$ element, adaxial view, –0.18 m to –0.05 m, SUI 146787; [2] S_0 element, adaxial view, –0.38 m to –0.18 m, SUI 146788; [3] Dextral S_1 element, adaxial view, –1.68 m to –1.23 m, SUI 146789; [5] Dextral P_1 element, caudal view, –3.62 m to –3.33 m, SUI 146790; [10] Dextral M element, dorsal view, –0.18 m to –0.05 m, SUI 146791. [4] *Kockelella* sp., S_0 element, adaxial view, –1.68 m to –1.23 m, SUI 146792. [6] *Oulodus*? sp., dextral? $S_{1–2}$ element?, adaxial view, –0.18 m to –0.05 m, SUI 146793. [7] *Ozarkodina bohemica longa* Jeppsson in Calner and Jeppsson, 2003, sinistral P_1 element, A_1B_1 caudal view, A_2B_2 oral view, –0.38 m to –0.18 m, SUI 146794. [8–9] Gen. et sp. indet. [8] P_1/P_2 element, caudal view, –2.48 m to –2.23 m, SUI 146795; [9] Dextral P_2 element, caudal view, 1.60 m to 1.75 m, SUI 146796.

The section from the Huntington Quarry in Indiana preserves the most obvious record of an erosive unconformity in the studied sections and clearly demonstrates the sequence boundary associated with the onset of the Mulde CIE. Rising isotope values within the onset of the Mulde CIE begin in the upper part of the Cedarville Member of the Laurel Formation, and values continue to rise across the contact with the overlying Limberlost Member of the Pleasant Mills Formation (Figs. 7 and 8). This contact is an irregular undulatory surface, unlike the other planar bedded contacts in the quarry, and there is an accumulation of iron staining at and beneath this contact (i.e., at the top of the Cedarville Member). The overlying Limberlost Member fines upwards from an oolitic dolostone into progressively more argillaceous facies and eventually into "Waldron A." Therefore, the Limberlost Member is interpreted to be a transgressive unit, and the underlying Cedarville-Limberlost contact is interpreted as a sequence boundary (Fig. 18).

Prior to the introduction of the term Limberlost as a member of the Pleasant Mills Formation (Droste and Shaver, 1982), strata currently identified as Limberlost were part of the Laurel Formation, which included all strata between the top of the Clinton Limestone, now the Brassfield Formation, and the base of the Waldron Shale (Shaver et al., 1986). The terms Pleasant Mills and Limberlost were never extended southward into Tennessee, where the term Laurel still applies to carbonates all the way up to the base of the Waldron. Therefore, the designation Limberlost Member is used for the strata that underlie the "Waldron Member" in Indiana, whereas the term Laurel is still applied to the strata subjacent to the Waldron in Tennessee (Fig. 2). The difference in nomenclature between Indiana and Tennessee demonstrates a correlation issue that cannot be resolved solely with lithostratigraphic analysis. However, the carbon isotope data and field observations presented in this study offer new insights into the chronostratigraphic correlation of these sections.

In Tennessee, there is a sharp change in lithology at the base of the uppermost bed of the Laurel, as it is a more argillaceous wackestone compared to the skeletal wackestone-packstones in the underlying beds. Also, at Scottsboro,

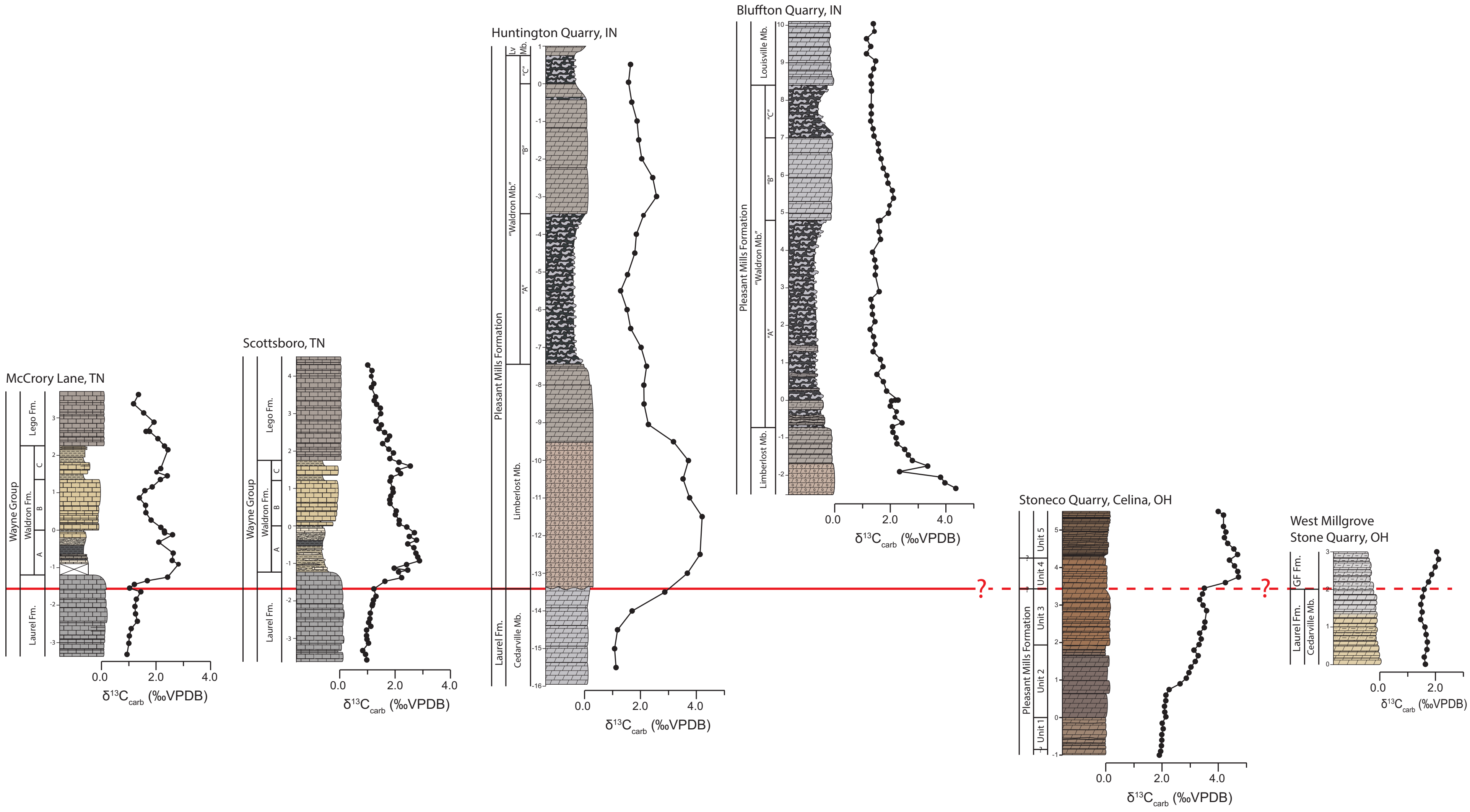


Figure 18. Correlation of the primary sequence boundary (red line) within the ascending limb of the Mulde carbon isotope excursion in Tennessee (TN) and Indiana (IN). The section at Bluffton, Indiana began above the sequence boundary based on correlation to the Huntington section. The correlation to Celina and West Millgrove, Ohio (OH), is only speculation based on the limited data available. Height is in meters. LV—Louisville; GF—Greenfield; VPDB—Vienna PeeDee belemnite.

Tennessee, the contact between the top of the Laurel and Waldron A is well exposed and appears to be gradational (Figs. 4B and 4C). Overlying the resistant uppermost bed of the Laurel is ~10 cm of strata that transition from the carbonate-dominated Laurel to the siliciclastic-dominated Waldron (Fig. 4B). We therefore infer that a cryptic sequence boundary occurs at the base of the uppermost bed of the Laurel, and that the influx of argillaceous material overlying this boundary represents transgression. We interpret this to be the same sequence boundary as the one identified in Indiana and that the base of the uppermost bed of the Laurel Formation in Tennessee is correlative to the base of the Limberlost Member in Indiana (Figs. 4, 6, and 18). The carbon isotope values from the Tennessee sections, however, begin to increase at a high rate at the sequence boundary, as opposed to the Indiana sections, where the values begin to increase at a high rate beneath the sequence boundary. This suggests that there may be some missing time at the sequence boundary in Tennessee.

The chronostratigraphic correlation of the upper limit of the Limberlost Member across the study area is less clear. In Tennessee, the first and second peaks of the Mulde Excursion are recorded within the shale units of the Waldron Formation (A and C) during episodes of increased preservation of siliciclastic sediments. This is in contrast to northern Indiana where the peaks of the excursion are recorded in the Limberlost and "Waldron B," both carbonate-dominated units. The record of the Mulde CIE at different positions with respect to the "Waldron" demonstrates that the Waldron Formation in Tennessee and the "Waldron Member" in Indiana were deposited at different times and are not equivalent units (Fig. 18). Which "Waldron" unit is actually equivalent to the Waldron Shale in the type area is not certain. The lower peak of the Mulde was identified in the Waldron in Oldham County, Kentucky (Cramer, 2009) in lithofacies similar to the Waldron in both Tennessee and the type area. The nodular "Waldron" facies in northern Indiana does not match the lithofacies of the more southern Waldron and also does not contain peak values of the Mulde. Therefore, it is likely that the Waldron Formation in Tennessee is the equivalent to the type Waldron Shale, and that the northern Indiana "Waldron" is a misnomer. However, to accurately reconcile this potential misuse of the name Waldron, a detailed study of the Waldron Shale in the type area needs to be completed.

Sequence stratigraphic interpretations and further correlations cannot be made for the Ohio sections with the limited data available from the area, though particular bedding surfaces that could represent sequence boundaries do stand out at both Celina and West Millgrove (Figs. 13, 15, and 18). At Celina, the top of unit 4 marks a distinct change in lithology, and the purple staining at the contact is unique for the section. At West Millgrove, a prominent bedding surface stands out at the Cedarville-Greenfield contact because there is a sharp change in lithology with no gradational strata between the units.

Eustasy and the Mulde Excursion

The primary sequence boundary associated with the Mulde Event and Excursion was first documented on Gotland, Sweden, and the West Midlands, England. On Gotland, the sequence boundary represented by the contact between the Gannarve Member of the Fröjel Formation and the Bara Oolite Member of the Halla Formation was extensively studied in lateral context and traced to its correlative conformity in a shoreline to basin transect (Calner and Jeppsson, 2003; Calner et al., 2006). In the Hunninge-1 drill core (Fig. 19), the carbon isotope excursion begins within a regressive systems tract (RST) in the Gannarve Member (Calner et al., 2006), a mixed carbonate-siliciclastic unit dominated by interbedded silty limestones, mudstones, and siltstones (Calner, 1999). Carbon isotopic values continue to rise across the unconformity that marks the top of the Gannarve Member, where there is strong evidence of subaerial erosion (Calner, 2002), and values continue to rise into the base of the Bara Oolite Member of the Halla Formation (Calner, 2002; Calner and Jeppsson, 2003; Calner et al., 2006). The Bara Oolite Member represents the start of a transgressive systems tract (TST) and consists of oolitic and oncoidal facies that onlap the epikarstic surface at the top of the Gannarve Member (Calner, 2002; Calner and Jeppsson, 2003; Calner et al., 2006), clearly demonstrating that the Gannarve-Bara contact is a sequence boundary. Based on carbon isotope, biostratigraphic, and lithostratigraphic comparison, this is interpreted as the same sequence boundary seen in the midcontinent United States documented in this study.

In the composite data set for the West Midlands, England, UK (Fig. 19), the onset of the Mulde Excursion is recorded in the upper part of the Coalbrookdale Formation, a fossiliferous silty mudstone-dominated unit with occasional nodular carbonates (Ray et al., 2010; Marshall et al., 2012). The ascending limb of the Mulde Excursion continues to rise into the Lower Quarried Limestone Member of the Much Wenlock Limestone Formation, where a sequence boundary was identified 1.5 m into the unit (Ray et al., 2010; Marshall et al., 2012). The Lower Quarried Limestone Member consists of mostly wackestones and packstones that have stacked reefal development throughout and contain oncoids within the lower portion of the unit (Ray et al., 2010), similar to the basal TST at this position in Gotland. As documented on Gotland, the sequence boundary recorded in the Lower Quarried Limestone Member of the West Midlands occurs within the ascending limb of the Mulde Excursion.

The sequence boundary at the base of the Limberlost Member in Indiana also occurs within the ascending limb of the Mulde Excursion and is interpreted to be correlative to those on Gotland and in the West Midlands (Fig. 19). Therefore, this sequence boundary is now identified in three major Silurian basins: the Baltic, Welsh, and Illinois. Similar to Gotland and the West Midlands, the transgressive systems tract that records part of the ascending limb of the Mulde CIE in Indiana is also oolitic.

The correlation of upper Homerian strata using carbon isotope stratigraphy, biostratigraphy, and sequence stratigraphy presented here, combined with the evidence from the Baltic and Welsh basins demonstrates that there was a global sea level change during the ascending limb of the Mulde carbon isotope excursion, and that the excursion began during regression and continued to increase through the subsequent transgression. The majority of the ascending limb appears to be restricted to the transgressive phase of the eustatic sea

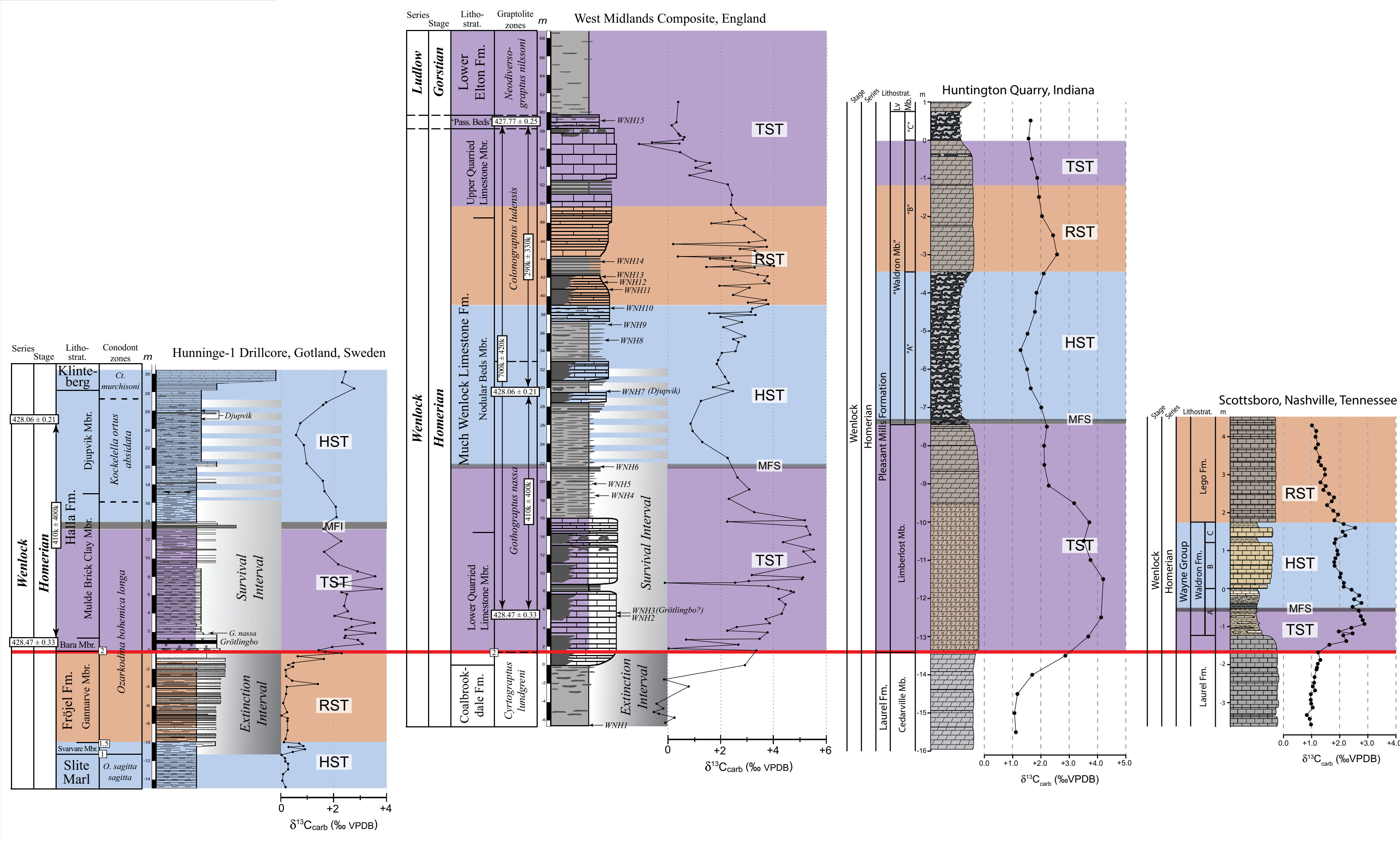


Figure 19. Homerian strata that contain the Mulde carbon isotope excursion from Gotland (data: Calner et al., 2006, figure: Cramer et al., 2012), West Midlands (data: Ray et al., 2010; Marshall et al., 2012; figure: Cramer et al., 2012), Indiana, and Tennessee (this study); Tennessee and Indiana sections are drawn at one scale, Gotland and West Midlands sections are drawn at another scale. Stratigraphic sections are correlated at the sequence boundary (red line) that occurs within the ascending limb of the Mulde Excursion. The sequence stratigraphic interpretations above the sequence boundary in Tennessee and Indiana are highlighted to draw comparisons to Gotland and the West Midlands; however, this is showing only one possible interpretation. TST—transgressive systems tract; HST—highstand systems tract; RST—regressive systems tract; MFI/S—maximum flooding interval/surface; VPDB—Vienna PeeDee belemnite.

level rise following the global sequence boundary of the late Homerian. Furthermore, the Mulde Extinction occurred during a global regression. However, it is important to note that mostly pelagic faunas were impacted by this event, and the stepwise extinction that occurs at multiple stratigraphic levels begins well below the unconformity. Based on the stratigraphic order of events, it cannot be assumed that the changes in sea level represented by the sequence boundary have any causal impact on either the Mulde Extinction or Excursion.

CONCLUSIONS

A complete record of the Mulde carbon isotope excursion is now documented in the Laurel and Pleasant Mills formations in Indiana and is confirmed in the Wayne Group of Tennessee. Elevated carbon isotope values in Homerian strata in Ohio confirm a record of the Mulde Excursion, though it is incomplete. A sequence boundary correlative to those found within the ascending limb of the Mulde Excursion on Gotland, Sweden, and in the West Midlands, England, is identified in the midcontinent United States demonstrating that the sea-level change represented by the sequence boundary was a global event. This sequence boundary is now documented in three separate basins—the Baltic, Welsh, and Illinois—and in each basin, an oolitic or oncoidal transgressive unit overlies the sequence boundary. Carbon isotope records of the Mulde Excursion in all three basins confirm the isochroneity of this sequence boundary and allow for correlation of this surface to Homerian strata in Tennessee, where there appears to be missing time below the sequence boundary. This study precisely constrains a major eustatic change during the Mulde Extinction Event and global carbon cycle perturbation and demonstrates that $\delta^{13}C_{carb}$ values began to rise during a global regression and continued to rise during global transgression.

ACKNOWLEDGMENTS

We thank Neo McAdams, Jon Havens, Rick Lucas, and Dave Kruse for their help with field work for this project, as well as Matt Wortel and Brittany Stolfus for help with conodont processing. Thank you to the companies and quarry managers who provided access to their quarries for this study, specifically Irving Materials, Stoneco, and Gerken Materials, and thank you to Mikael Calner, Carlton Brett, an anonymous reviewer, and the editors who provided helpful reviews that strengthened this paper. This project was partially funded by National Science Foundation grant no. CAREER-1455030 to B.D. Cramer.

REFERENCES CITED

Barrick, J.E., 1977, Multielement simple-cone conodonts from the Clarita Formation (Silurian), Arbuckle Mountains, Oklahoma: Geologica et Palaeontologica, v. 11, p. 47–68.

Barrick, J.E., 1983, Wenlockian (Silurian) conodont biostratigraphy, biofacies, and carbonate lithofacies, Wayne formation, Central Tennessee: Journal of Paleontology, v. 57, p. 208–239.

Branson, E.B., and Mehl, M.G., 1933, Conodonts from the Bainbridge (Silurian) of Missouri: The University of Missouri Studies, v. 8, p. 39–52.

Brett, C.E., Cramer, B.D., McLaughlin, P.I., Kleffner, M.A., Showers, W.J., and Thomka, J.R., 2012, Revised Telychian-Sheinwoodian (Silurian) stratigraphy of the Laurentian mid-continent: Building uniform nomenclature along the Cincinnati Arch: Bulletin of Geosciences, v. 87, p. 733–753, https://doi.org/10.3140/bull.geosci.1310.

Broadhead, T.W., and Gibson, M.A., 1996, Late Silurian sedimentary environments and biotas of west-central Tennessee, *in* Broadhead, T.W., ed., Sedimentary Environments of Silurian Taconia Fieldtrips to the Appalachians and Southern Craton of Eastern North America: University of Tennessee Department of Geological Sciences Study in Geology 26, p. 1–30.

Calner, M., 1999, Stratigraphy, facies development, and depositional dynamics of the Late Wenlock Fröjel Formation, Gotland, Sweden: GFF, v. 121, p. 13–24, https://doi.org/10.1080/11035899901211013.

Calner, M., 2002, A lowstand epikarstic intertidal flat from the middle Silurian of Gotland, Sweden: Sedimentary Geology, v. 148, p. 389–403, https://doi.org/10.1016/S0037-0738(01)00144-0.

Calner, M., 2008, Silurian global events—At the tipping point of climate change, *in* Elewa, A.M.T., ed., Mass Extinctions: Berlin, Heidelberg, Springer-Verlag, p. 21–57, https://doi.org/10.1007/978-3-540-75916-4_4.

Calner, M., and Jeppsson, L., 2003, Carbonate platform evolution and conodont stratigraphy during the middle Silurian Mulde Event, Gotland, Sweden: Geological Magazine, v. 140, p. 173–203, https://doi.org/10.1017/S0016756802007070.

Calner, M., Kozłowska, A., Masiak, M., and Schmitz, B., 2006, A shoreline to deep basin correlation chart for the Middle Silurian coupled extinction-stable isotopic event: GFF, v. 128, p. 79–84, https://doi.org/10.1080/11035890601282079.

Cocks, L.R.M., and Torsvik, T.H., 2011, The Palaeozoic geography of Laurentia and western Laurussia: A stable craton with mobile margins: Earth-Science Reviews, v. 106, p. 1–51, https://doi.org/10.1016/j.earscirev.2011.01.007.

Cooper, B.J., 1976, Multielement conodonts from the St. Clair Limestone (Silurian) of southern Illinois: Journal of Paleontology, v. 50, p. 205–217.

Cooper, R.A., Sadler, P.M., Munnecke, A., and Crampton, J.S., 2014, Graptoloid evolutionary rates track Ordovician–Silurian climate change: Geological Magazine, v. 151, p. 349–364, https://doi.org/10.1017/S0016756813000198.

Corfield, R.M., Siveter, D.J., Cartlidge, J.E., and McKerrow, W.S., 1992, Carbon isotope excursion near the Wenlock-Ludlow (Silurian) boundary in the Anglo-Welsh area: Geology, v. 20, p. 371–374, https://doi.org/10.1130/0091-7613(1992)020<0371:CIENTW>2.3.CO;2.

Cramer, B.D., 2009, Application of Integrated High-Resolution Biochemostratigraphy to Paleozoic Chronostratigraphic Correlation: Recalibrating the Silurian System [Ph.D. thesis]: Columbus, The Ohio State University, 286 p.

Cramer, B.D., and Saltzman, M.R., 2005, Sequestration of ^{12}C in the deep ocean during the early Wenlock (Silurian) positive carbon isotope excursion: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 219, p. 333–349, https://doi.org/10.1016/j.palaeo.2005.01.009.

Cramer, B.D., Kleffner, M.A., and Saltzman, M.R., 2006, The Late Wenlock Mulde positive carbon isotope ($\delta^{13}C_{carb}$) excursion in North America: GFF, v. 128, p. 85–90, https://doi.org/10.1080/11035890601282085.

Cramer, B.D., Brett, C.E., Melchin, M.J., Männik, P., Kleffner, M.A., McLaughlin, P.I., Loydell, D.K., Munnecke, A., Jeppsson, L., Corradini, C., Brunton, F.R., and Saltzman, M.R., 2011, Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and $\delta^{13}C_{carb}$ chemostratigraphy: Lethaia, v. 44, p. 185–202, https://doi.org/10.1111/j.1502-3931.2010.00234.x.

Cramer, B.D., Condon, D.J., Söderlund, U., Marshall, C., Worton, G.J., Thomas, A.T., Calner, M., Ray, D.C., Perrier, V., Boomer, I., Patchett, P.J., and Jeppsson, L., 2012, U-Pb (zircon) age constraints on the timing and duration of Wenlock (Silurian) paleocommunity collapse and recovery during the "Big Crisis": Geological Society of America Bulletin, v. 124, p. 1841–1857, https://doi.org/10.1130/B30642.1.

Cramer, B.D., Vandenbroucke, T.R.A., and Ludvigson, G.A., 2015, High-Resolution Event Stratigraphy (HiRES) and the quantification of stratigraphic uncertainty: Silurian examples of the quest for precision in stratigraphy: Earth-Science Reviews, v. 141, p. 136–153, https://doi.org/10.1016/j.earscirev.2014.11.011.

Crampton, J.S., Cooper, R.A., Sadler, P.M., and Foote, M., 2016, Greenhouse-icehouse transition in the Late Ordovician marks a step change in extinction regime in the marine plankton: Proceedings of the National Academy of Sciences of the United States of America, v. 113, no. 6, p. 1498–1503, https://doi.org/10.1073/pnas.1519092113.

Droste, J.B., and Shaver, R.H., 1976, The Limberlost Dolomite of Indiana a key to the great Silurian facies in the southern Great Lakes Area: Indiana Geological Survey Occasional Paper 15, 21 p.

Droste, J.B., and Shaver, R.H., 1982, The Salina Group (Middle and Upper Silurian) of Indiana: Indiana Geological Survey Special Report 24, 41 p.

Drygant, D.M., 1974, Simple conodonts from the Silurian and lowermost Devonian of the Volyno-Podolian: Paleontologicheskiy Sbornik, v. 10, p. 64–69.
Elrod, M.M., 1883, Geology of Decatur County: Indiana Department of Geology and Natural History Annual Report, v. 12, p. 100–152.
Ethington, R.L., 1959, Conodonts of the Ordovician Galena Formation: Journal of Paleontology, v. 33, p. 257–292.
Jaeger, H., 1959, Graptolithen und Stratigraphie des Jüngsten Thüringer Silurs: Abhandlungen der Deutschen Akademie der Wissenschaften zu Berlin, Klasse für Chemie, Geologie und Biologie 2, 197 p.
Jaeger, H., 1991, Neue Standard-Graptolithenzonenfolge nach der "Großen Krise" an der Wenlock/Ludlow-Grenze (Silur): Neues Jahrbuch für Geologie und Palaontologie. Abhandlungen, v. 182, p. 303–354, https://doi.org/10.1127/njgpa/182/1991/303.
Jeppsson, L., and Anehus, R., 1995, A buffered formic acid technique for conodont extraction: Journal of Paleontology, v. 69, p. 790–794, https://doi.org/10.1017/S0022336000035319.
Jeppsson, L., and Calner, M., 2003, The Silurian Mulde Event and a scenario for secundo-secundo events: Transactions of the Royal Society of Edinburgh. Earth Sciences, v. 93, p. 135–154, https://doi.org/10.1017/S0263593300000377.
Jeppsson, L., Aldridge, R.J., and Dorning, K.J., 1995, Wenlock (Silurian) oceanic episodes and events: Journal of the Geological Society of London, v. 152, p. 487–498, https://doi.org/10.1144/gsjgs.152.3.0487.
Kaljo, D., Kiipli, K., and Martma, T., 1997, Carbon isotope event markers through the Wenlock–Pridoli sequence at Ohesaare (Estonia) and Priekule (Latvia): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 132, p. 211–223, https://doi.org/10.1016/S0031-0182(97)00065-5.
Koren', T., 1991, The lundgreni extinction event in central Asia and its bearing on graptolite biochronology within the Homerian: Proceedings of the Estonian Academy of Sciences, v. 40, p. 74–78.
Lenz, A.C., Noble, P.J., Masiak, M., Poulson, S.R., and Kozłowska, A., 2006, The lundgreni extinction event: Integration of paleontological and geochemical data from Arctic Canada: GFF, v. 128, p. 153–158, https://doi.org/10.1080/11035890601282153.
Marshall, C., Thomas, A.T., Boomer, I., and Ray, D.C., 2012, High resolution $\delta^{13}C$ stratigraphy of the Homerian (Wenlock) of the English Midlands and Wenlock Edge: Bulletin of Geosciences, v. 87, p. 669–679, https://doi.org/10.3140/bull.geosci.1306.
Munnecke, A., Calner, M., Harper, D.A.T., and Servais, T., 2010, Ordovician and Silurian sea-water chemistry, sea level, and climate: A synopsis: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 296, p. 389–413, https://doi.org/10.1016/j.palaeo.2010.08.001.
Porębska, E., Kozłowska-Dawidziuk, A., and Masiak, M., 2004, The lundgreni event in the Silurian of the East European platform, Poland: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 213, p. 271–294, https://doi.org/10.1016/j.palaeo.2004.07.013.
Ray, D.C., Brett, C.E., Thomas, A.T., and Collings, A.V.J., 2010, Late Wenlock sequence stratigraphy in central England: Geological Magazine, v. 147, p. 123–144, https://doi.org/10.1017/S0016756809990197.
Rhodes, F.T.H., 1953, Some British lower Paleozoic conodont faunas: Philosophical Transactions of the Royal Society of London, Series B, v. 237, p. 261–338.
Saltzman, M.R., 2002, Carbon isotope ($\delta^{13}C$) stratigraphy across the Silurian–Devonian transition in North America: evidence for a perturbation of the global carbon cycle: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 187, p. 83–100, https://doi.org/10.1016/S0031-0182(02)00510-2.
Saltzman, M.R., and Thomas, E., 2012, Carbon Isotope Stratigraphy, *in* Gradstein, F.M., Ogg, J.G., Schmitz, M., and Ogg, G., eds., The Geologic Time Scale 2012: Elsevier, p. 207–232, https://doi.org/10.1016/B978-0-444-59425-9.00011-1.
Shaver, R.H., 1996, Silurian sequence stratigraphy in the North American craton, Great Lakes area, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, p. 193–202, https://doi.org/10.1130/0-8137-2306-X.193.
Shaver, R.H., Ault, C.H., Ausich, W.I., Droste, J.B., Horowitz, A.S., James, W.C., Okla, S.M., Rexroad, C.B., Suchomel, D.M., and Welch, J.R., 1978, The Search for a Silurian Reef Model Great Lakes Area: Indiana Geological Survey Special Report 15, 36 p.
Shaver, R.H., Ault, C.H., Burger, A.M., Carr, D.D., Droste, J.B., Eggert, D.L., Gray, H.H., Harper, D., Hasenmueller, N.R., Hasenmueller, W.A., Horowitz, A.S., Hutchison, H.C., Keith, B.D., Keller, S.J., Patton, J.B., Rexroad, C.B., and Wier, C.E., 1986, Compendium of Paleozoic rock-unit stratigraphy in Indiana—A revision: Indiana Geological Survey Bulletin 59, 203 p.
Slucher, E.R., 2004, Generalized column of the bedrock units in Ohio: Ohio Department of Natural Resources, Division of Geological Survey, 1 p.
Stauffer, C.R., 1940, Conodonts from the Devonian and associated clays of Minnesota: Journal of Paleontology, v. 14, p. 417–435.
Sullivan, N.B., McLaughlin, P.I., Emsbo, P., Barrick, J.E., and Premo, W.R., 2016, Identification of the late Homerian Mulde Excursion at the base of the Salina Group (Michigan Basin, USA): Lethaia, v. 49, p. 591–603, https://doi.org/10.1111/let.12168.
Swift, R.J.A., 2011, Conodont biostratigraphy and $\delta^{13}C$ chemostratigraphy of the Salina Group (Silurian) in western Ohio and eastern Indiana [M.S. thesis]: Columbus, The Ohio State University, 91 p.
Thomas, A.T., and Ray, D.C., 2011, Pitch Coppice: GSSP for the base of the Ludlow Series and Gorstian Stage, *in* Ray, D.C., ed., Siluria Revisited: A Field Guide: International Subcommission on Silurian Stratigraphy, Field Meeting 2011, p. 80–84.
Vandenbroucke, T.R.A., Emsbo, P., Munnecke, A., Nuns, N., Duponchel, L., Lepot, K., Quijada, M., Paris, F., Servais, T., and Kiessling, W., 2015, Metal-induced malformations in early Palaeozoic plankton are harbingers of mass extinction: Nature Communications 6, article 7966, 7 p., https://doi.org/10.1038/ncomms8966.